Status of CONTUR

Jon Butterworth (UCL),

on behalf of the CONTUR development team

Slides heavily borrowed from Louie Corpe's talk at TOOL2021

MCnet, Manchester, 7 December 2021

What is CONTUR?

Constraints On New Theories Using RIVET

- The LHC search programme often **focuses on most spectacular signatures** of a new model…
- But many models might **already be ruled out** because they would cause visible distortions in spectra of ''standard'' processes!
- Challenge is **figuring out how a new model compares to hundreds of measured distributions…**
- …and understanding **whether the model is consistent with the measured data within uncertainties**
- **… eventually, including the *Standard* Model**

Does this sound familiar?

Illustration by Chris Wormell from "A Map of the Invisible"

We have the technology

- <u>**We have the infrastructure to make rapid particle-level Data/MC comparisons**</u>.
- We use it all the time: it's called **RIVET!**
    - Originally for MC Generator comparisons of SM predictions, and tuning
    - **Trivial to switch out so we compare to a SM+BSM prediction!**
- We already have 100s of precision measurements from LHC ready to be used in this way...
  More analyses being added all the time as part of the ATLAS and CMS approval procedures.

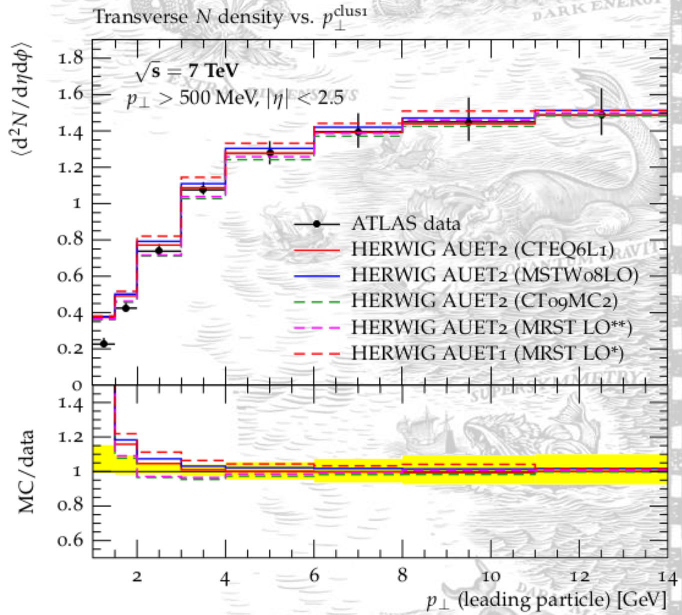

Illustration by Chris Wormell from "A Map of the Invisible"

Overview of the CONTUR method

- Input: **Universal Feynrules Object** (new physics Lagrangian coded up in python) or SLHA specification for a built-in model
- MC Generation of events. By default, Herwig to inclusively generate events involving new particles (works with any MC generator which RIVET can read)
- Pass through ~150 RIVET routines from particle-level LHC results: quick since everything is at particle-level! *Only possible because of design principles of RIVET: eg caching of expensive operations*
- **Routines categorised into 'pools' grouped by experiment, √s and final state to ensure orthogonality**
- Compare size of deviation to reference data from HEPData (including correlations within a measurement when provided) to check if signal would already have been seen.

UFO describing BSM model

Herwig: event generation for all new 2->2 processes

RIVET+HEPdata to determine effect of BSM on existing measurements

CLs method for exclusion

Repeat for each point in parameter space

Constraints **O**n **N**ew **T**heories **U**sing **RIVET**

Overview of the CONTUR method

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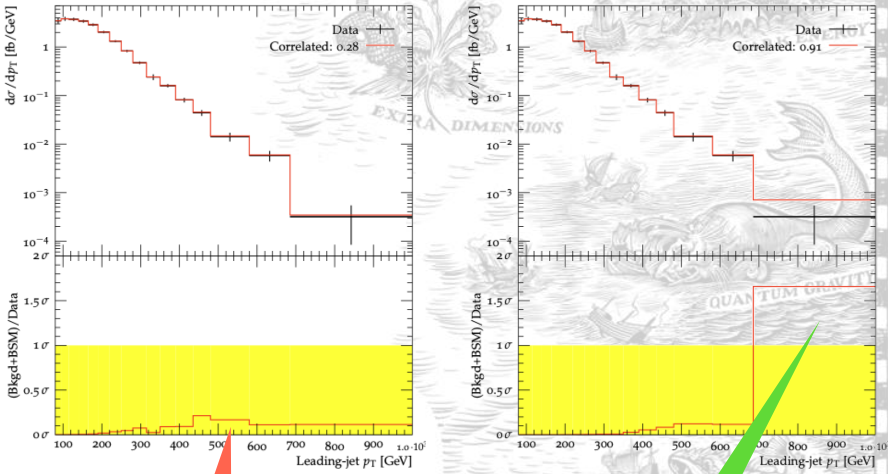
- **Routines categorised into 'pools' grouped by experiment, √s and final state to ensure orthogonality**
- Compare size of deviation to reference data from HEPData (including correlations within a measurement when provided) to check if signal would already have been seen. **If it would be statistically distinct, the model is eliminated!**

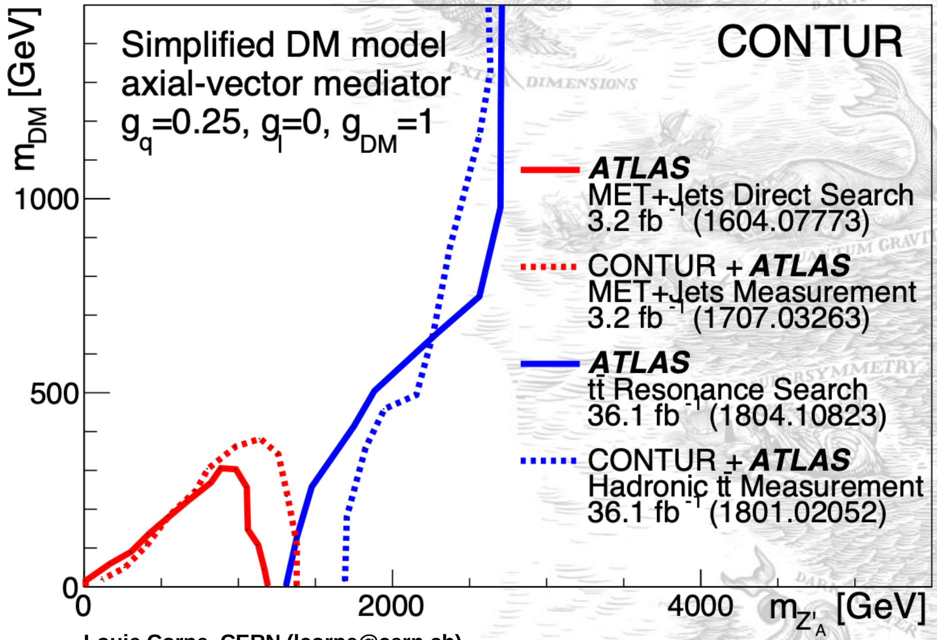


Signal would have small effect wrt uncertainties, can't exclude it (28 % CL)

Signal would have large effects above measured uncertainties: can exclude at high confidence level (91 % CL)

Do measurements really give comparable exclusions?

- ***Bold claim:*** For the **same final state** and **luminosity, searches and measurements** have roughly **the same exclusion power.**
- Not surprising: searches and measurements would both use similar calibrations, reco techniques etc...
- A search might use machine-learning or other optimisation to eke out sensitivity to benchmark models (at the cost of model dependence)
    - Can be quite hard to recast search results in terms of other models or other parameter choices.
- A measurement would have the advantage of being performed in a BSM-agnostic way, but typically unfolded to particle-level and has analysis logic preserved. **Hit in sensitivity, but easy to re-use!**



Louie Corpe, CERN (lcorpe@cern.ch)

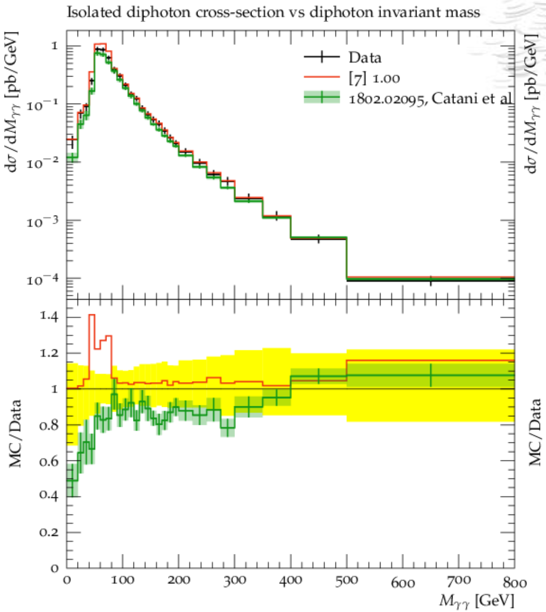
Illustration by Chris Wormell from "A Map of the Invisible"

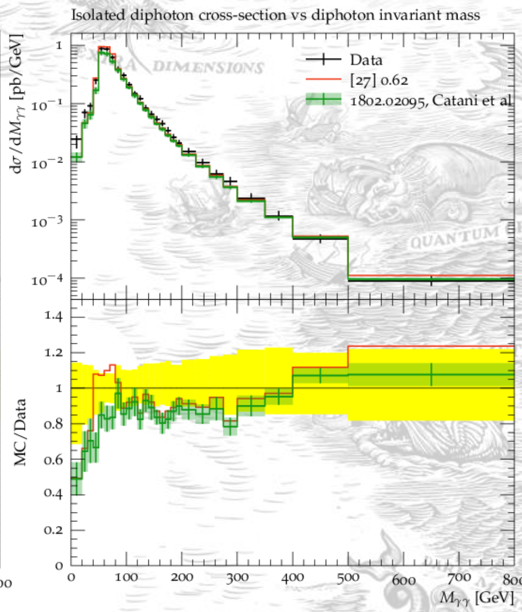
State of the art MC predictions and correlations

- Absence of unambiguous BSM in LHC measurements to date => make 0th-order assumption that data=SM
  Can be improved with high-precision SM theory predictions and uncertainties!

- **Correlation between bins can be accounted for** if uncertainty breakdowns on HEPData!
  If not, forced to take only most sensitive bin !

SQRT(S)	13000 GEV	
m_{4l} [GEV]	Measured $d\sigma/dm_{4l}$ [FB GEV-1]	Predicted $d\sigma/dm_{4l}$ (with Sherpa + NLO EW) [FB GEV-1]
7.500000e+01 - 1.000000e+02	5.100341e-01 ±2.346437e-02 syst ±3.442822e-02 stat	5.182588e-01 ±3.545342e-02 total
1.000000e+02 - 1.200000e+02	9.334923e-02 ±4.205973e-03 syst ±1.800903e-02 stat	7.834322e-02 ±4.277496e-03 total



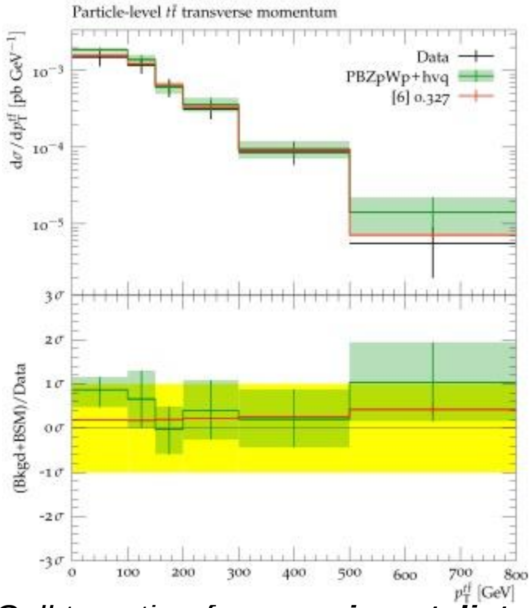


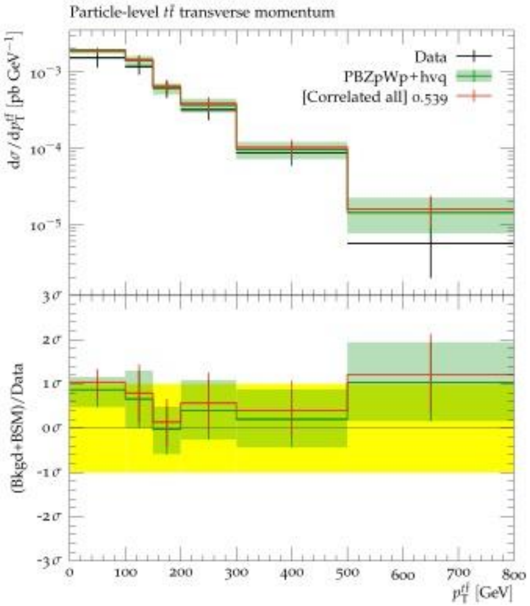
- *Call to action for **experimentalists**:*
  Please add your uncertainty breakdowns and SM background predictions to your HEPData records

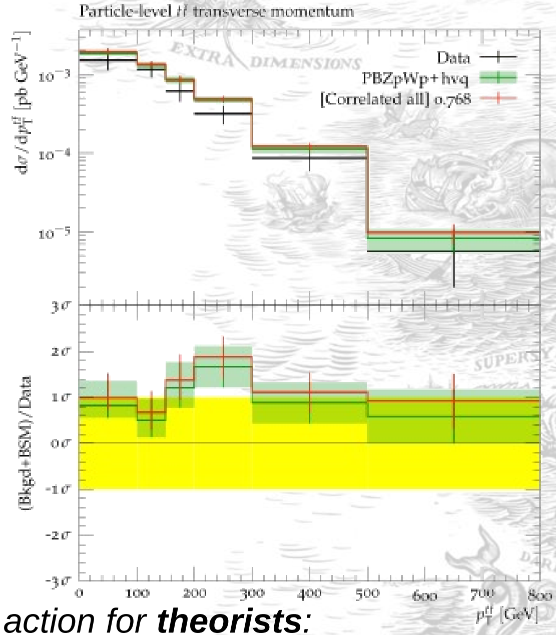
- *Call to action for **theorists**:*
  Please add your rivet-compatible SM calculations on HEPData too!

State of the art MC predictions and correlations

- Absence of unambiguous BSM in LHC measurements to date => make 0th-order assumption that data=SM
  Can be improved with high-precision SM theory predictions and uncertainties! From M. Altakach et al, [2111.15406]







- *Call to action for **experimentalists**:*
  Please add your uncertainty breakdowns and SM background predictions to your HEPData records
- *Call to action for **theorists**:*
  Please add your rivet-compatible SM calculations on HEPData too!

LHC Constraints on a $B-L$ Gauge Model using Contur

S. Amrith, J. M. Butterworth, F. F. Deppisch, W. Liu, A. Varma, and D. Yallup

Collider Constraints on Z' Models for Neutral Current $B-$Anomalies

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[b] Department of Physics & Astronomy, University College London, Gower St, London, WC1E 6BT, United Kingdom

[c] The Niels Bohr International Academy, Blegdamsvej 17, University of Cope[n]

Copenhagen, Denmark

E-mail: B.C.Allanach@damtp.cam.ac.uk, j.butterworth@ucl.ac.uk, corbett.t.s@gmail.com

Abstract: We examine current collider constraints on some simple Z' mo[dels] ... tral current ... Model (SM ... the SM me...

... ca[n]tly imp... 'third family baryon number minus second family lepton number' (B_3-L_2) model and the 'third family hypercharge' model and variants. The constraints are applied on parameter regions of each model that fit the $b \to s\mu^+\mu^-$ transition data and come from high-mass Drell-Yan di-muons and measurements of Standard Model processes. This latter set of observables place particularly strong bounds upon the parameter space of the B_3-L_2 model when the mass of the Z' boson is less than 300 GeV.

SciPost Physics — Submission

New sensitivity of current LHC measurements to vector-like quarks

A. Buckley[1] J. M. Butterworth[2], L. Corpe[2], D. Huang[2], P. Sun[1]

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[2] Department of Physics & Astronomy, University College London, Gower St, WC1E 6BT, London, UK

Higgs phenomenology as a probe of ster[ile neutrinos]

Jonathan M. Butterworth,[1,*] Mikael Chala,[2,3,†] Christoph Englert,[4,‡] Micha[el] ...

[1] Department of Physics & Astronomy, University College London, Lond[on]

New sensitivity of LHC measurements to Composite Dark Matter [Mod]els

... Kong, and M. Thomas

...ics & Astronomy, ... E 6BT, London, UK

...rpe[†]

...s 1, 1211 Geneva, Switzerland

...karni[‡]

... Graz, University of Graz, ...-8010 Graz, Austria

... 19, 2021)

...ract

...section measurements to so-called "stealth dark ...uge group, where constituents are charged under ...-energy theory contains mesons which can be ...atter (DM) candidate which cannot. We evaluate ... the impact of LHC measurements on the dark meson masses. Using existing lattice results, we then

SciPost Physics — Subm[ission]

11 Dec 2019

A study of collider signatures for two Higgs doublet m[odels] with a Pseudoscalar mediator to Dark Matter

J. M. Butterworth[1], M. Habedank[2*], P. Pani[3], A. Vaitkus[1]

[1] Department of Physics & Astronomy, UCL, Gower St., WC1E 6BT, London,

[2] Department of Physics, Humboldt University, Berlin, Germany

[3] DESY, Hamburg and Zeuthen, Germany

*martin.habedank@physik.hu-berlin.de

January 12, 2021

Abstract

Two Higgs doublet models with an additional pseudoscalar particle cou[pling to] the Standard Model and to a new stable, neutral particle, provide an at[tractive] and fairly minimal route to solving the problem of Dark Matter. Th[ey have] been the subject of several searches at the LHC. We study the impact of existing LHC measurements on such models, first in the benchmark regions addressed by searches and then after relaxing some of their assumptions and broadening the parameter ranges considered. In each case we study how the new parameters change the potentially visible signatures at the LHC, and identify which of these signatures should already have had a significant impact on existing measurements. This allows us to set some first constraints on a number of so far unstudied scenarios.

SciPost Physics — Submission

[hep-ph] 30 Nov 2021

Probing a leptophobic top-colour model with cross section measurements and precise signal and background predictions: a case study

M. M. Altakach[1,2,4], J. M. Butterworth[3], T. Ježo[2], M. Klasen[2], I. Schienbein[1]

[1] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, 38026 Grenoble, France

[2] Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Str. 9, 48149 Münster, Germany

[3] Department of Physics & Astronomy, UCL, Gower St., WC1E 6BT, London, UK

[4] Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warsaw, Poland

December 1, 2021

Abstract

The sensitivity of particle-level fiducial cross section measurements from ATLAS, CMS and LHCb to a leptophobic top-colour model is studied. The model has previously been the subject of resonance searches. Here we compare it directly to state-of-the-art predictions for Standard Model top quark production and also

CONTUR vs Composite Dark Matter (heavy dark mesons)

A case study

https://arxiv.org/abs/2105.08494

J. M. Butterworth, L. Corpe, X. Kong, S. Kulkarni, M. Thomas

Illustration by Chris Wormell from “A Map of the Invisible”

Dark meson phenomenology at the LHC

arXiv:2105.08494

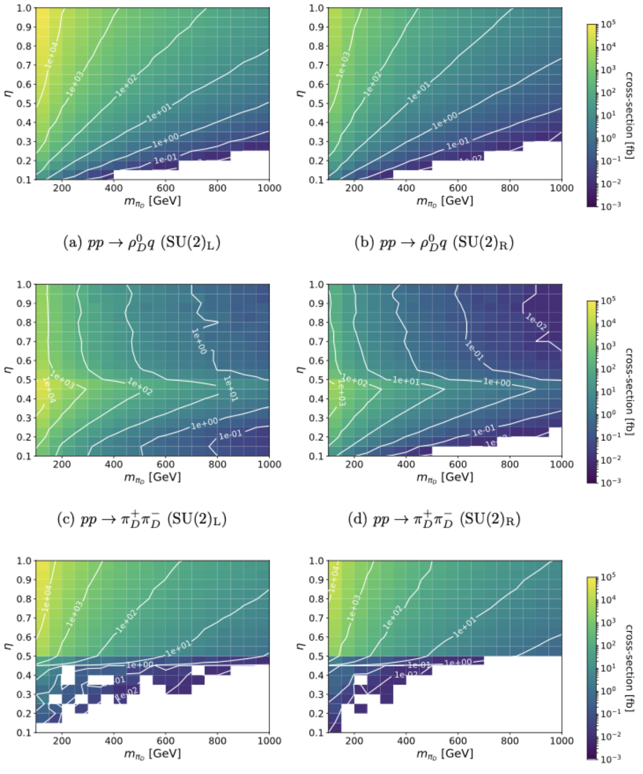
- What if **dark matter** is a **composite particle** arising from **non-Abelian dynamics**? eg SU(4) which confines at some scale Λ_{dark}

- Leads to bound states of mesons and baryons. Simplest case, **dark pions** π_D and **dark rho** ρ_D, in addition to dark baryons (DM candidates)—> **Heavy Dark Mesons**
(Kribs et al. arXiv:1809.10183)

- Dark fermions transform under electroweak part of the Standard Model: communication with SM

- There are no direct searches for this model by ATLAS or CMS: instead to **constrain this model using the bank of existing LHC measurements using CONTUR**

- Dynamics of the theory depend a lot on $\eta = m_{\pi_D}/m_{\rho_D}$



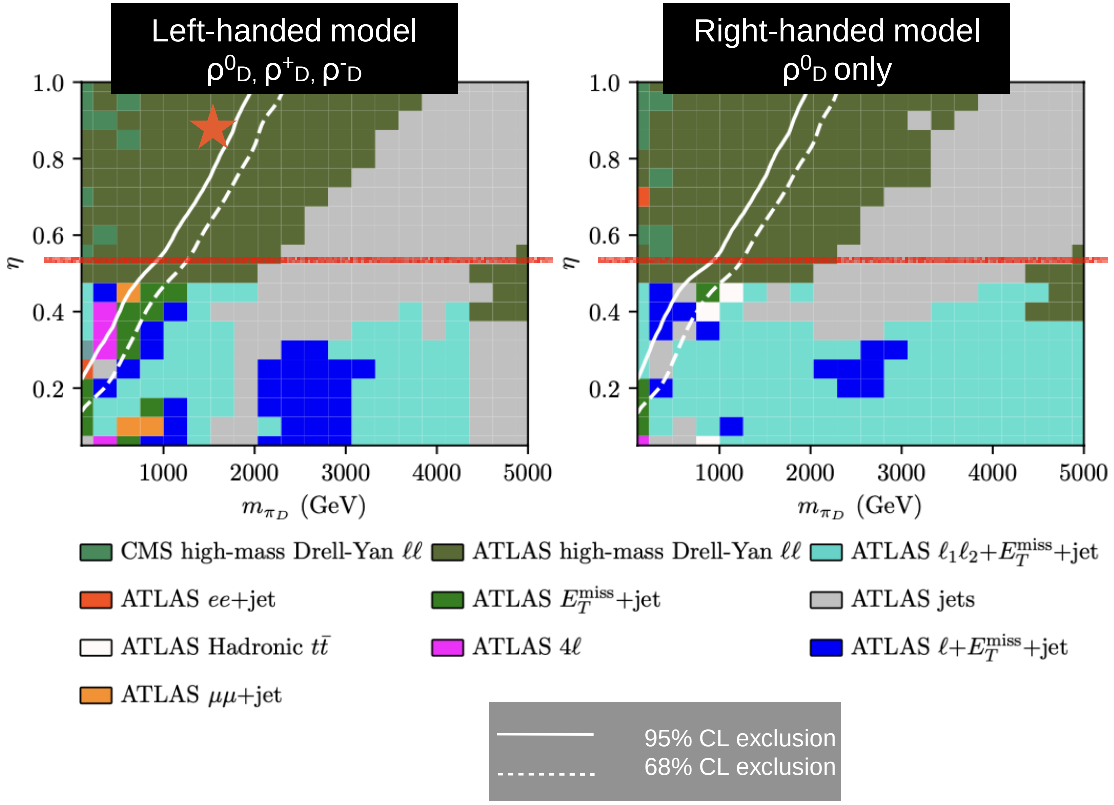
(a) $pp \to \rho_D^0 q$ (SU(2)$_L$) (b) $pp \to \rho_D^0 q$ (SU(2)$_R$)

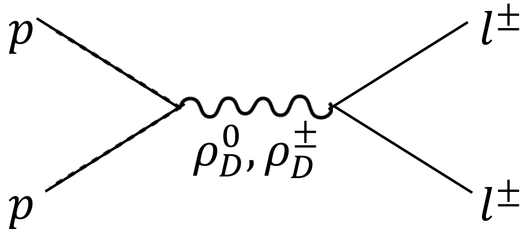
(c) $pp \to \pi_D^+ \pi_D^-$ (SU(2)$_L$) (d) $pp \to \pi_D^+ \pi_D^-$ (SU(2)$_R$)

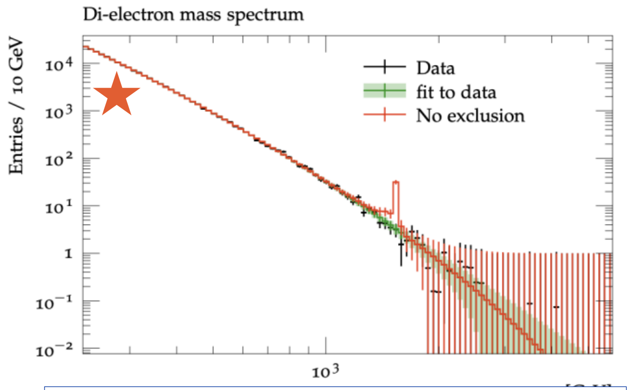
(e) s-channel $pp \to \rho_D \to l^+ l^-$ (SU(2)$_L$) (f) s-channel $pp \to \rho_D \to l^+ l^-$ (SU(2)$_R$)

CONTUR results

$\eta := m(\rho_D) / m(\pi_D)$





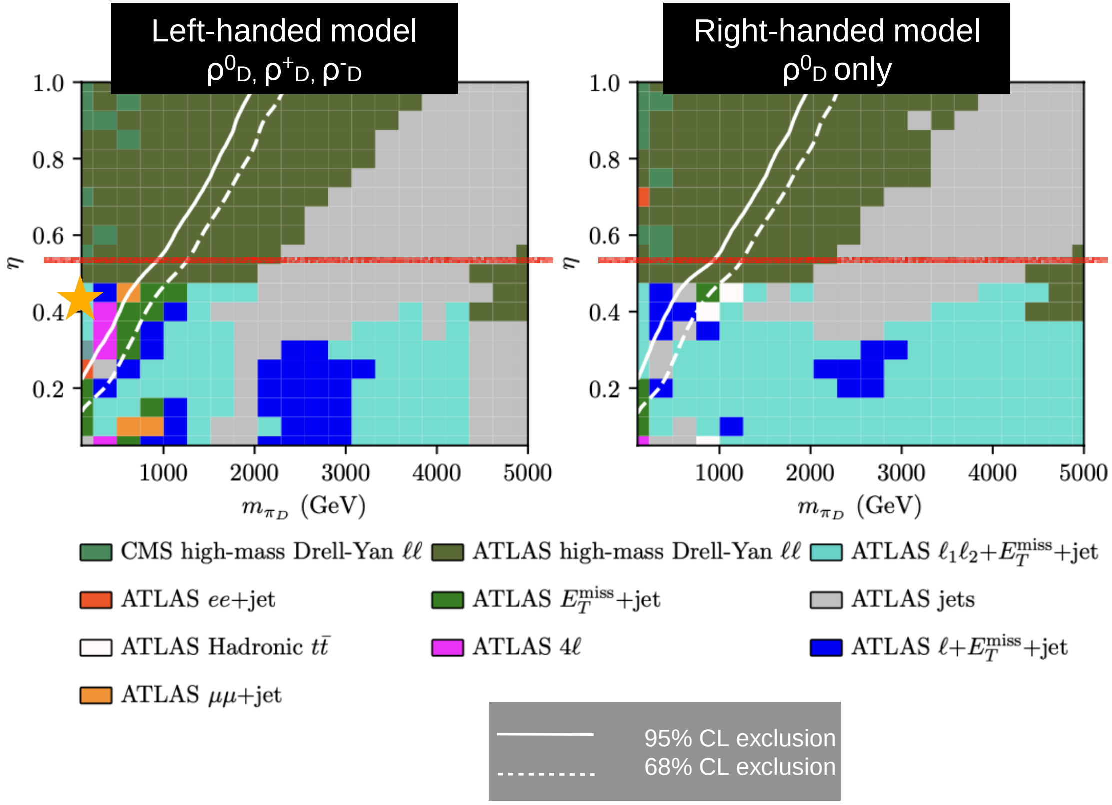


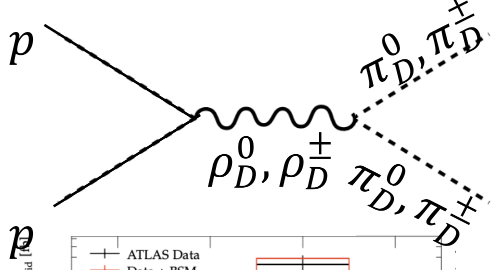
Search for high-mass dilepton resonances using 139/fb pp collision data collected at 13 TeV with the ATLAS detector
https://arxiv.org/abs/1903.06248

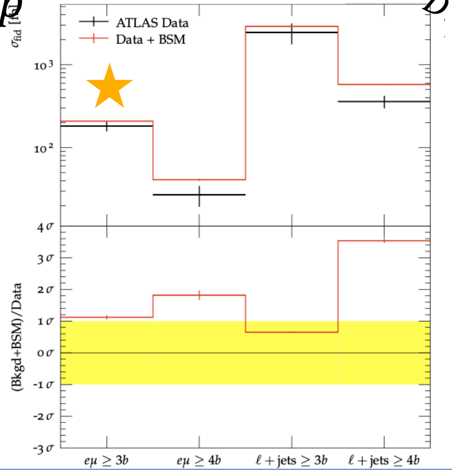
One of a few detector-level analyses in RIVET thanks to dedicated smearing functions!

CONTUR results

η := m(ρ$_D$) / m(π$_D$)



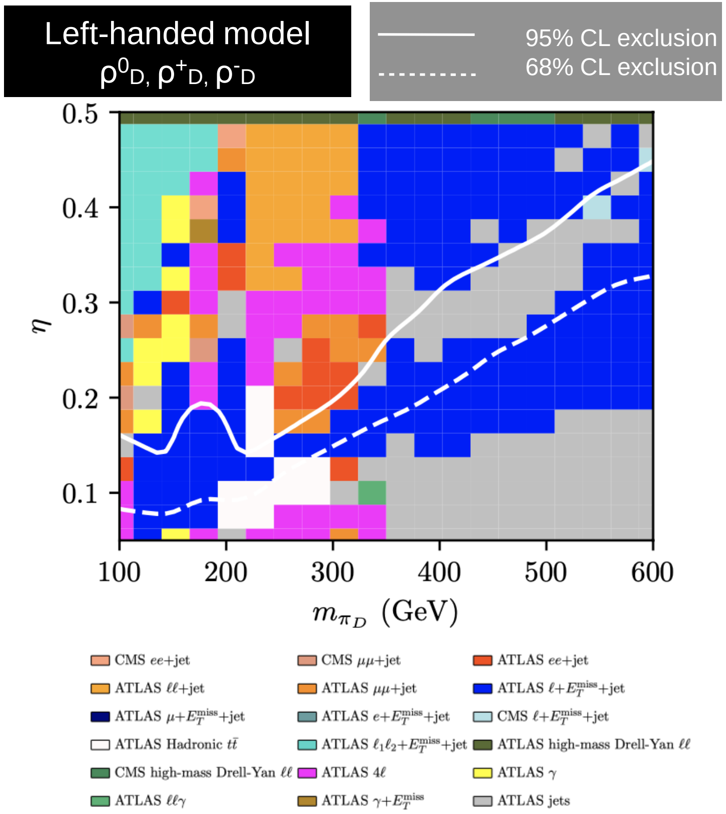




Measurements of fiducial and differential cross-sections of tt production with additional heavy-flavour jets in proton-proton collisions at 13 TeV with the ATLAS detector (36/fb)
https://arxiv.org/abs/1811.12113

ttbb final state (both dark pions decay to tb)

CONTUR results: zoom on low-η region



- Excluding the most sensitive analysis
  - DY resonant search: *because signal would not cause a "bump" in this region*

- CONTUR still excludes large areas of this region . What measurements contribute?
  - Higgs mass bin, contributions from γγ measurements, as $\pi_D \to \gamma\gamma$ becomes important even if decay mode is suppressed
  - Boosted hadronic tt measurements play a role around $m(\pi_D)$ 200 GeV: expected from dominant decay of pions to *tb*, and the fact they are boosted at that mass
  - Lots of sensitivity from tt-like measurements
  - Further High-mass Drell-Yan measurements, in particular of **ττ** + jets, could be helpful in future!

CONTUR vs
Z' Models for $b \to s\mu^+\mu^-$

Fresh from the arXiv

https://arxiv.org/abs/2110.13518

B.C. Allanach, J. M. Butterworth, Tyler Corbett

Illustration by Chris Wormell from “A Map of the Invisible”

Z' models motivated by LFV anomalies

- Models containing a Z' with non-trivial flavour interactions
  - Mass, mixing angle, coupling

- Central values of fits to LHCb results allows one parameter to be expressed in terms of the others, leading to favoured regions in a 2D plane.
- Scan over those regions with CONTUR

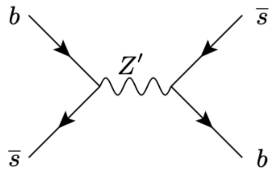
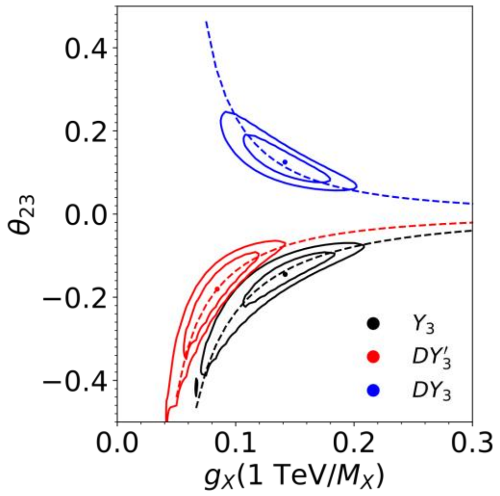
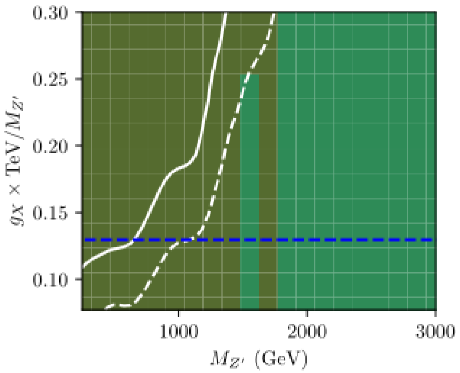


Fig. 2: Tree-level Feynman diagram of a Z'-mediated process which contributes to $B_s - \overline{B_s}$ mixing.

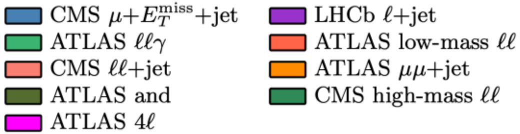


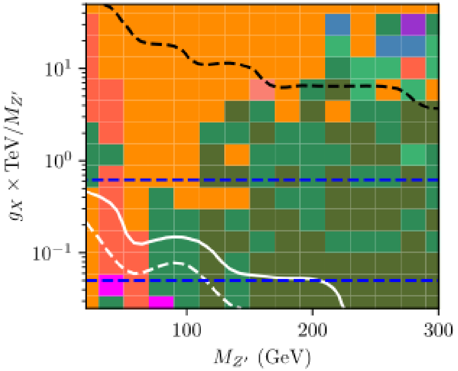
Z’ models motivated by LFV anomalies

- Main signature is dimuons
- In the high Z’ mass regions, what sensitivity there is comes from the ATLAS dimuon search, which is implemented in RIVET/CONTUR. For TFHM models that’s all there is.
- The B_3-L_2 model, the “window” at low mass largely is closed by low mass Drell Yan and Z ->ll measurements



Deformed 3rd Family Hypercharge Model (DY3’).
Favoured region is below the blue line. Above the white line, 95% exclusion.

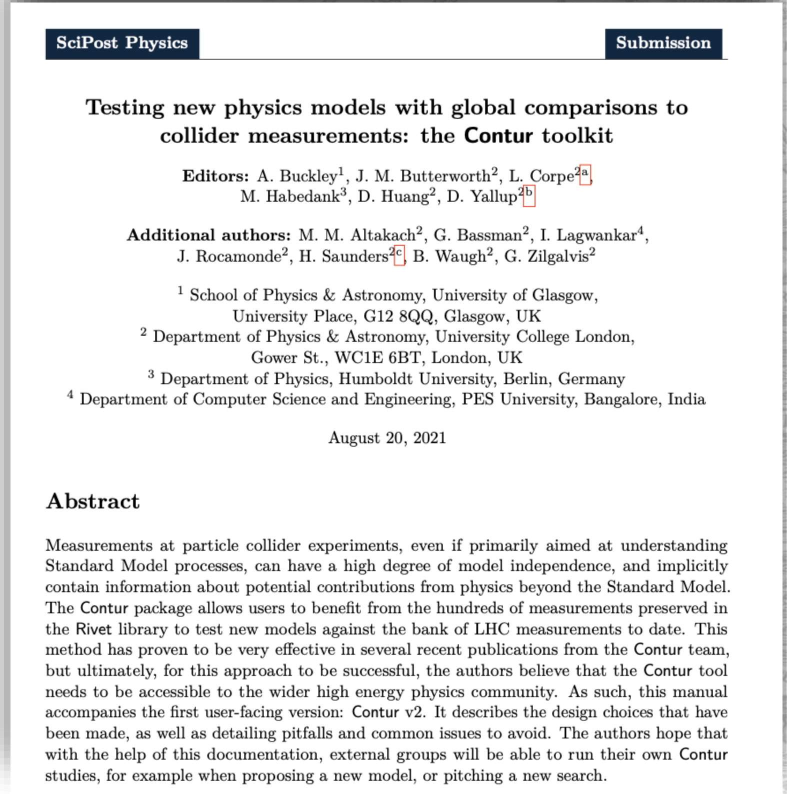




B_3-L_2 Model.
Favoured region is between the blue lines. Above the black line, Z’ width >30% of mass. Below the white line, 95% exclusion.

Status of CONTUR

- CONTUR v2 was released in summer 2021: first public-facing, production ready version of CONTUR
- Released with dedicated companion manual (arXiv:2102.04377)
- v2.2.0 is imminent, accompanies rivet 3.1.5, includes:
  - better Madgraph support (S Jeon, O Mattelaer)
  - Pythia support (D Wilson et al)
  - changes for GAMBIT interface (T Proctor et al)
  - speed improvements and regressions testing (S Bray)
  - support for non-LHC beams,, more SM predictions, improved analysis tools, “oracle” parameter scanning,
- Support channel on Mattermost https://mattermost.web.cern.ch/cedar/channels/contur


SciPost Physics Submission

Testing new physics models with global comparisons to collider measurements: the Contur toolkit

Editors: A. Buckley[1], J. M. Butterworth[2], L. Corpe[2a], M. Habedank[3], D. Huang[2], D. Yallup[2b]

Additional authors: M. M. Altakach[2], G. Bassman[2], I. Lagwankar[4], J. Rocamonde[2], H. Saunders[2c], B. Waugh[2], G. Zilgalvis[2]

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[2] Department of Physics & Astronomy, University College London, Gower St., WC1E 6BT, London, UK
[3] Department of Physics, Humboldt University, Berlin, Germany
[4] Department of Computer Science and Engineering, PES University, Bangalore, India

August 20, 2021

Abstract

Measurements at particle collider experiments, even if primarily aimed at understanding Standard Model processes, can have a high degree of model independence, and implicitly contain information about potential contributions from physics beyond the Standard Model. The Contur package allows users to benefit from the hundreds of measurements preserved in the Rivet library to test new models against the bank of LHC measurements to date. This method has proven to be very effective in several recent publications from the Contur team, but ultimately, for this approach to be successful, the authors believe that the Contur tool needs to be accessible to the wider high energy physics community. As such, this manual accompanies the first user-facing version: Contur v2. It describes the design choices that have been made, as well as detailing pitfalls and common issues to avoid. The authors hope that with the help of this documentation, external groups will be able to run their own Contur studies, for example when proposing a new model, or pitching a new search.

Machine-learning assisted parameter scanning

Paper in preparation!

Special thanks to J. Rocamonde, G. Zilgalvis, M. Avramidou

- When running with a rectilinear grid, we spend a lot of compute time to evaluate the CONTUR exclusion on points which are already **quite obviously going to be excluded**, or **obviously going to be not excluded**

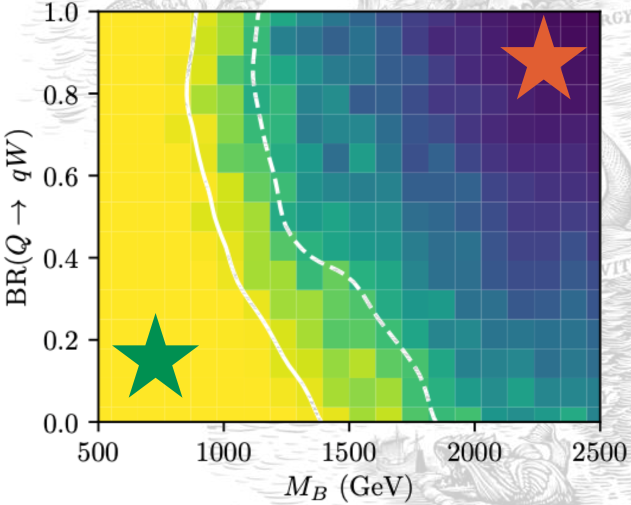
- We don't particularly care if something is excluded at 0.1 %CL or 0.3 % CL, and likewise we don't care if something is excluded at 99% CL or 98%CL …

    - In other words, the only regions we really care about are those in the vicinity of the 68% and 95% CL exclusion surfaces.

- Can we use this fact to save ourselves some compute?

- And if so, does that mean we can do scans in far more dimensions than previously possible ?

    - Given that for models with >3 params, a rectilinear grid is computationally unaffordable, this development could open up CONTUR to much more complex models



We propose to iteratively train a RandomForest classier to locate the 95 and 65% CL contours, and thereby spend most of our compute budget on regions we are actually interested in!

Machine-learning assisted parameter scanning

Paper in preparation!

Special thanks to J. Rocamonde, G. Zilgalvis, M. Avramidou

- CONTUR version 2.2.0 will contain the tools for what we call the "CONTUR Oracle"
- Basic idea: for large datasets only sample small fraction of points at a time, and train classifier to predict exclusion status of the rest.
- For next iteration: prioritise the points where classifier is least confident.
- Stop once predetermined thresholds of accuracy have been met.
- As a result, only need some fraction of full dataset to understand the dynamics of parameter space

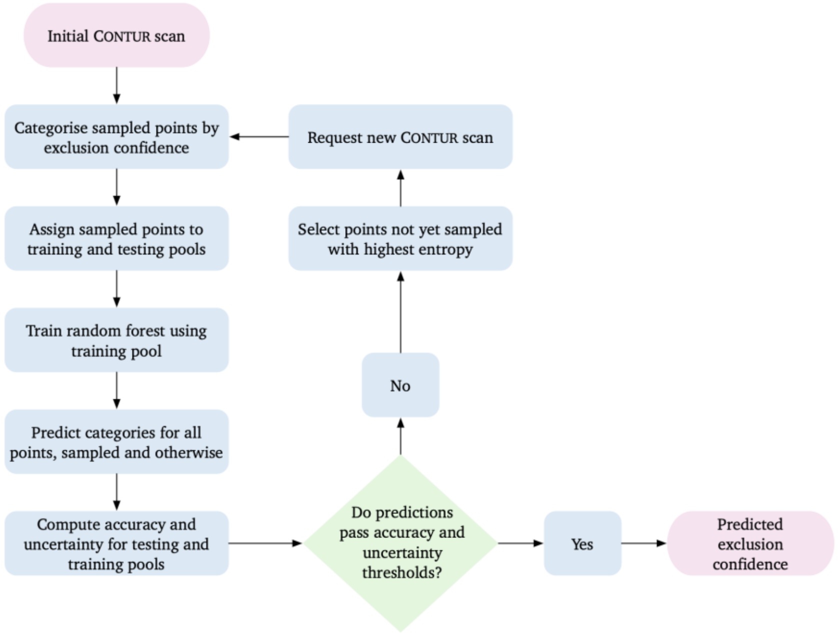
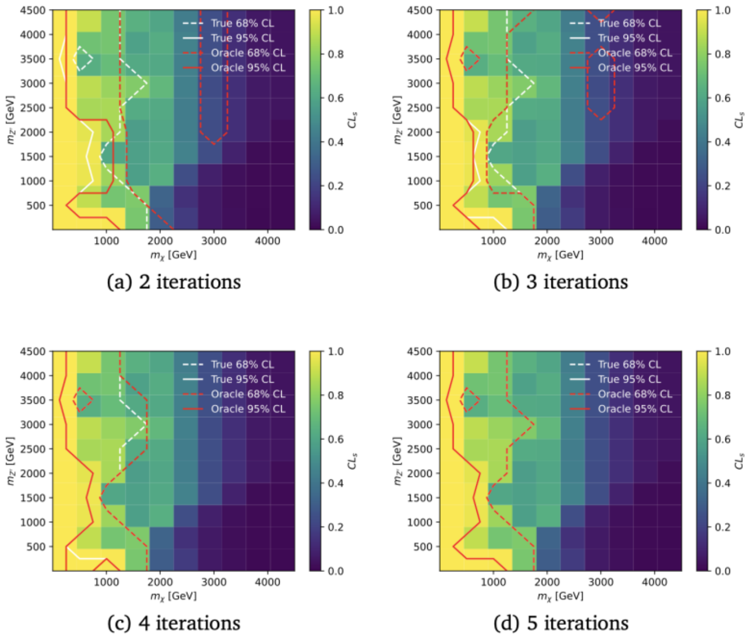


Figure 2: Process of the CONTUR ORACLE

Machine-learning assisted parameter scanning

Paper in preparation!

Special thanks to J. Rocamonde, G. Zilgalvis, M. Avramidou



(a) 2 iterations

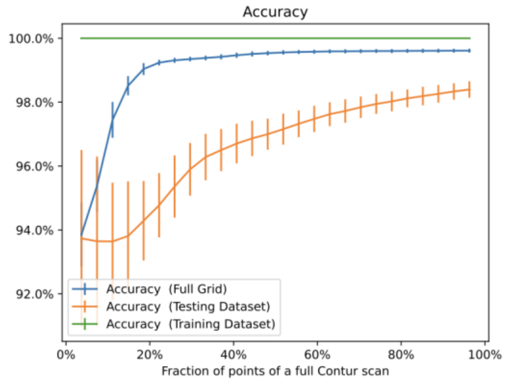
(b) 3 iterations

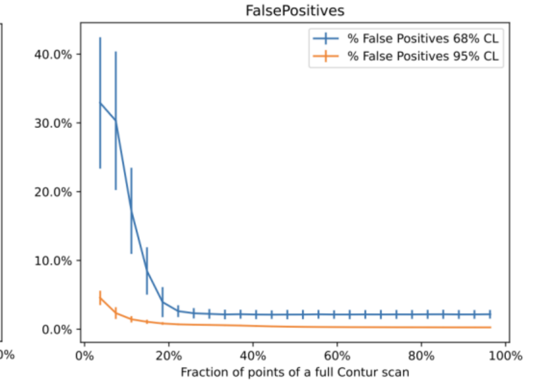
(c) 4 iterations

(d) 5 iterations

Visualisation of convergence of Oracle predictions in 2-D slice of 4-D simplified DM model space

- Test performance on large grids (>8000 points) in benchmark DM model (and others). Thats nearly 20,000 h of compute to probe full model space!
- Promising performance: for 4-dimensional model, only ~20% of points need to be sampled, for > 95% accuracy and < 5% false positives





Summary

Contur is a great way of releasing the potential of Rivet, of the particle level measurements it includes, and of the MC event generators, in a new direction

- Steady flow of new physics results

Many contributions from MCnet people (as well to the above tools, of course)

Lots of scope for new development

- One priority: make more direct use of the state-of-the-art SM predictions (see previous talks today…!)

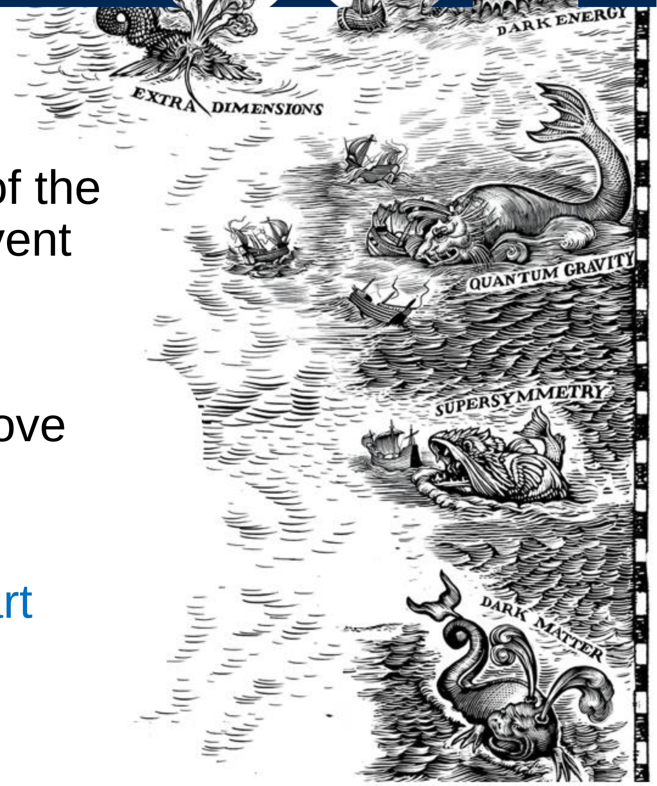


Illustration by Chris Wormell from "A Map of the Invisible"

extras

Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR workflow and pools

⟨*Final state*⟩ tag	Description of target final state
3L	Three leptons
4L	Four leptons
EEJET	e^+e^- at the Z pole, plus optional jets
EE_GAMMA	e^+e^- plus photon(s)
EMETJET	Electron, missing transverse momentum, plus optional jets (typically W, semi-leptonic $t\bar{t}$ analyses)
EMET_GAMMA	Electron, missing transverse momentum, plus photon
GAMMA	Inclusive (multi)photons
GAMMA_MET	Photon plus missing transverse momentum
HMDY	Dileptons above the Z pole
HMDY_EL	Dileptons above the Z pole, electron channel
HMDY_MU	Dileptons above the Z pole, muon channel
JETS	Inclusive hadronic final states
LLJET	Dileptons (electrons or muons) at the Z pole, plus optional jets
LL_GAMMA	Dilepton (electrons or muons) plus a photon
LMDY	Dileptons below the Z pole
LMETJET	Lepton, missing transverse momentum, plus optional jets (typically W, semi-leptonic $t\bar{t}$ analyses)
METJET	Missing transverse momentum plus jets
MMETJET	Muon, missing transverse momentum, plus optional jets (typically W, semi-leptonic $t\bar{t}$ analyses)
MMET_GAMMA	Muon, missing transverse momentum, plus photon
MMJET	$\mu^+\mu^-$ at the Z pole, plus optional jets
MM_GAMMA	$\mu^+\mu^-$ plus photon(s)
TTHAD	Fully hadronic top events
L1L2MET	Different-flavour dileptons plus missing transverse momentum (*i.e.* WW and $t\bar{t}$ measurements)

Table 1: Description of the currently considered ⟨*Final state*⟩ tags used to sort analysis histograms into orthogonal pools.

For ATLAS/CMS, 7/8/13 TeV

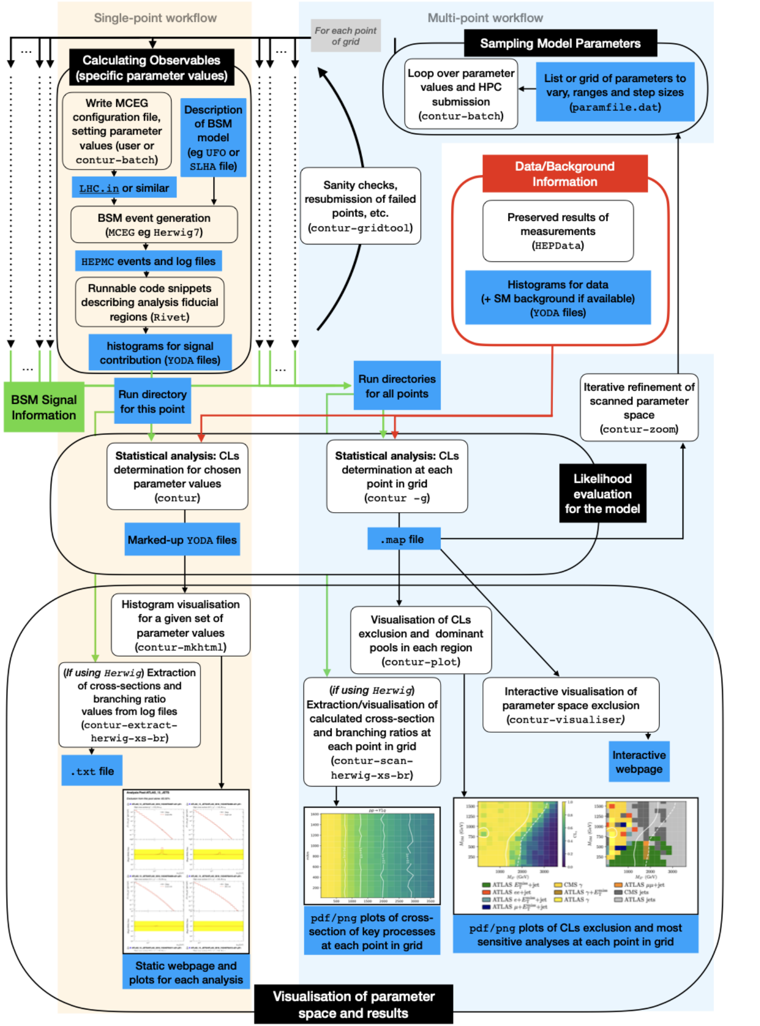


Illustration by Chris Wormell from "A Map of the Invisible"

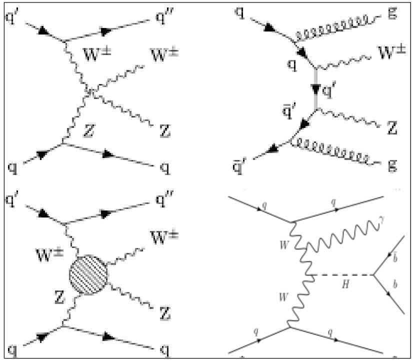
Louie Corpe, CERN (lcorpe@cern.ch)

CONTUR 101

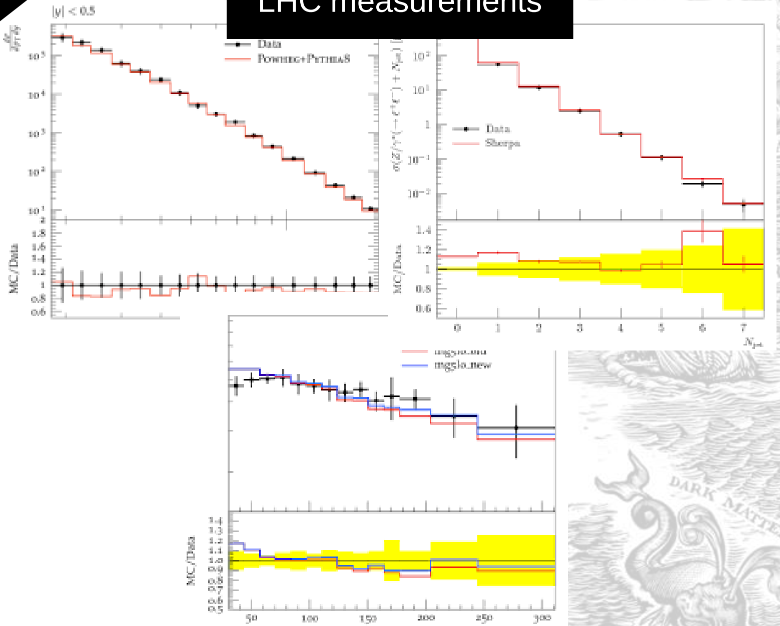
- Key idea: the SM Lagrangian is very finely balanced. You can't easily add BSM particles without the effect showing up in SM distributions

SM

Processes



LHC measurements

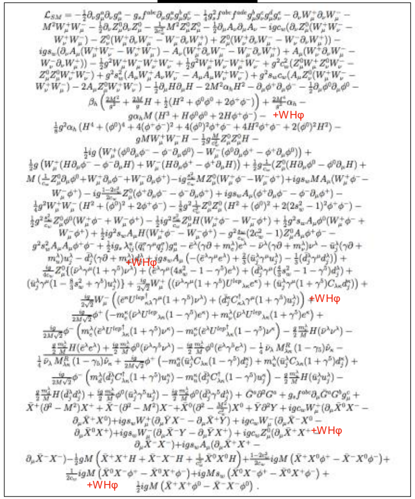


Louie Corpe, CERN (lcorpe@cern.ch)

CONTUR 101

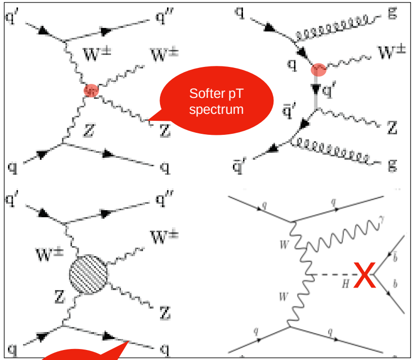
- Key idea: the SM Lagrangian is very finely balanced. You can't easily add BSM particles without the effect showing up in SM distributions

SM + BSM



+ BSM

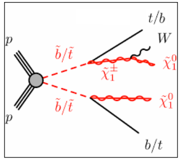
Processes



Softer pT spectrum

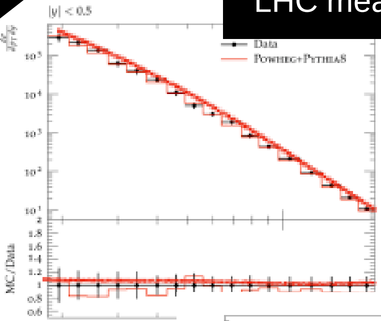
More booste d

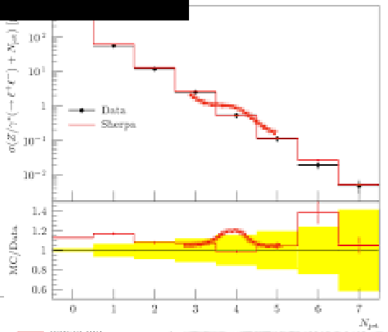
\+



LHC measurements

\+ BSM





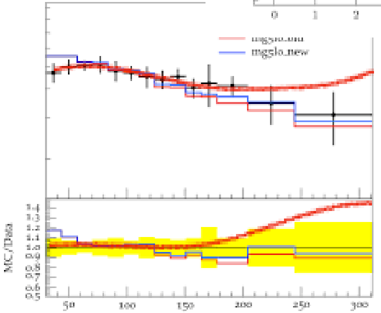


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, CERN (lcorpe@cern.ch)

CONTUR vs Vector-like Quarks

A case study

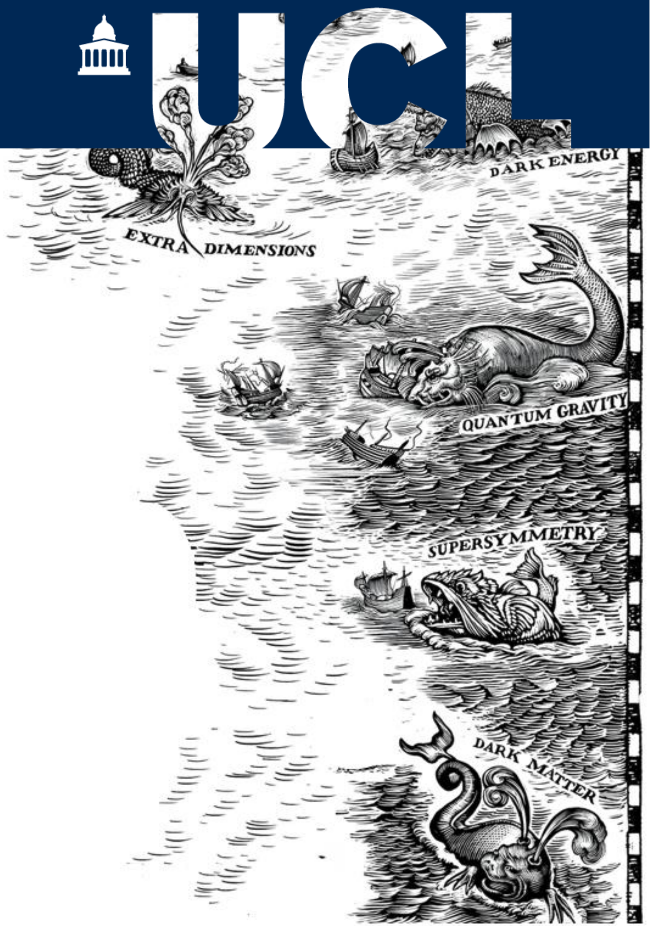


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, CERN (lcorpe@cern.ch)

VLQs

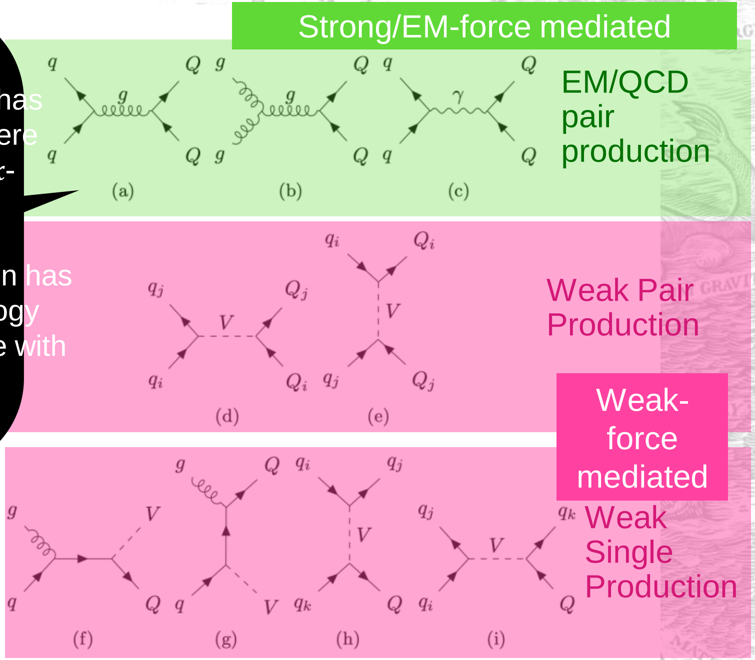
- Standard VLQ framework from Buchkremer et al (arXiv:1305.4172), comes with UFO file (also used by ATLAS)
- Introduces quark partners:

$$B^{(-1/3)} \quad T^{(2/3)} \quad X^{(5/3)} \quad Y^{(-4/3)}$$

- Couple to SM via usual quark EM/strong couplings, but modified W/Z/H couplings:
  - B,T: interact with W, Z or H via modified weak coupling
  - X, Y: interact only with W via modified weak coupling
    So X -> Wt, Y->Wb due to charge conservation
- Three params:
  - κ: **absolute coupling** of VLQs to SM quarks
  - ζ_i: relative **coupling of VLQs to ith generation**
  - ξ_V: relative **coupling of B,T to V in {W, H, Z}**

LHC programme has mostly focused here since reduced κ-dependence,

But single-production has rich phenomenology which we can probe with CONTUR!



LHC searches mostly focused on 3rd-gen, but 1st-gen has richer phenomenology due to valence-quark-induced production

Louie Corpe, CERN (lcorpe@cern.ch)

CONTUR vs Direct searches

Assuming 3rd gen couplings only
Assuming X/Y are decoupled (v. High mass)

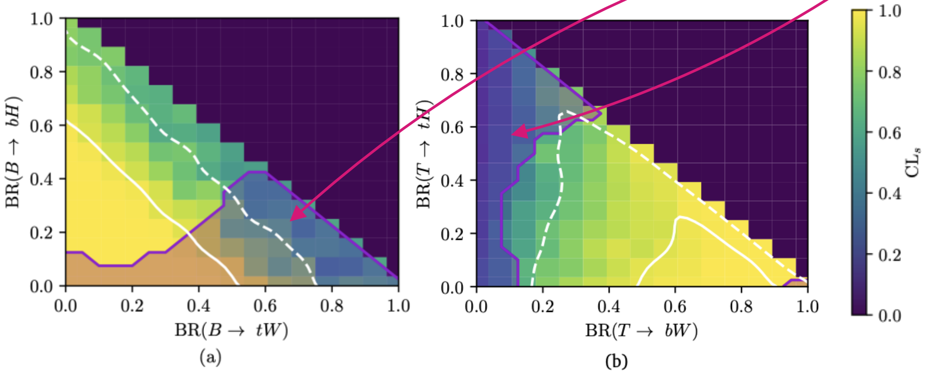
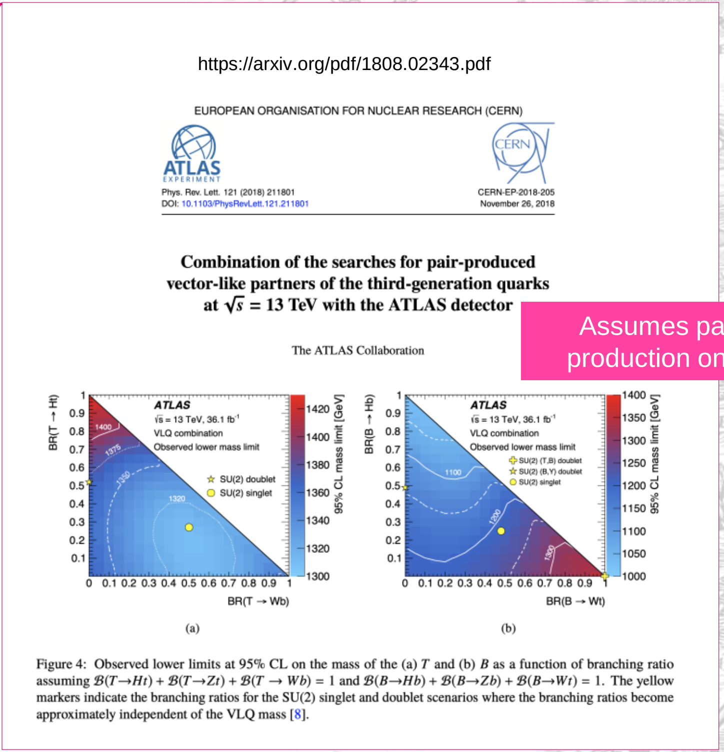


Figure 5: Sensitivity of LHC measurements to (a) B-production for $M_B = 1200$ GeV and (b) T-production for $M_T = 1350$ GeV. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed white) exclusion contours superimposed. The mauve region is excluded at 95% CL by the ATLAS combination [16].



https://arxiv.org/pdf/1808.02343.pdf

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Rev. Lett. 121 (2018) 211801
DOI: 10.1103/PhysRevLett.121.211801

CERN-EP-2018-205
November 26, 2018

Combination of the searches for pair-produced vector-like partners of the third-generation quarks at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Figure 4: Observed lower limits at 95% CL on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T\to Ht) + \mathcal{B}(T\to Zt) + \mathcal{B}(T\to Wb) = 1$ and $\mathcal{B}(B\to Hb) + \mathcal{B}(B\to Zb) + \mathcal{B}(B\to Wt) = 1$. The yellow markers indicate the branching ratios for the SU(2) singlet and doublet scenarios where the branching ratios become approximately independent of the VLQ mass [8].

Assumes pair-production only !

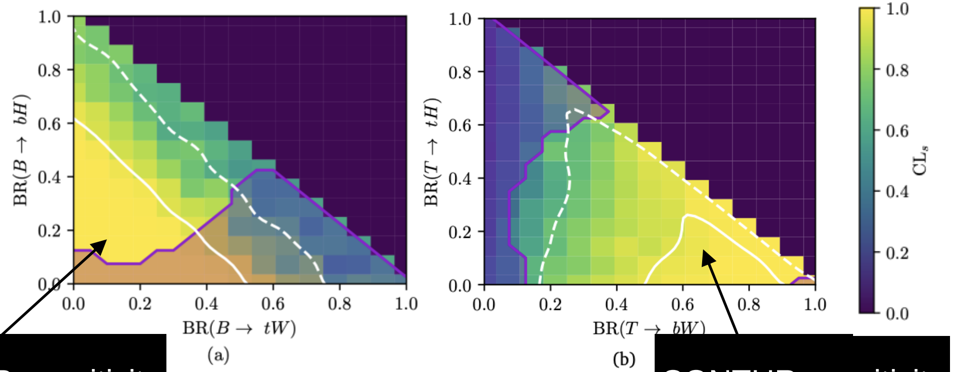
95% CL exclusion
68% CL exclusion

Louie Corpe, CERN (lcorpe@cern.ch)

Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR vs Direct searches

Assuming 3rd gen couplings only
Assuming X/Y are decoupled (v. High mass)



CONTUR sensitivity comes mainly from Z+jets measurements !

CONTUR sensitivity comes mainly from Top or W measurements

itivity of LHC measurements to (a) B-productio
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95% CL exclusion
68% CL exclusion

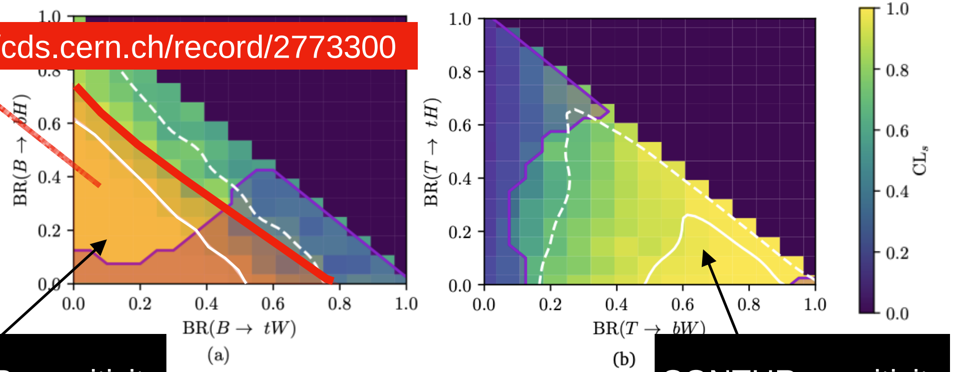
- VLQ decays may enter phase space of a many measured LHC cross-sections: b-jets, Z/W+jets, dibosons, multipletons…
- Additional CONTUR sensitivity can be explained partly by the fact that we consider other production modes than pair-production!

Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR vs Direct searches

Assuming 3rd gen couplings only
Assuming X/Y are decoupled (v. High mass)

https://cds.cern.ch/record/2773300



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CONTUR sensitivity comes mainly from Z+jets measurements !

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95% CL exclusion
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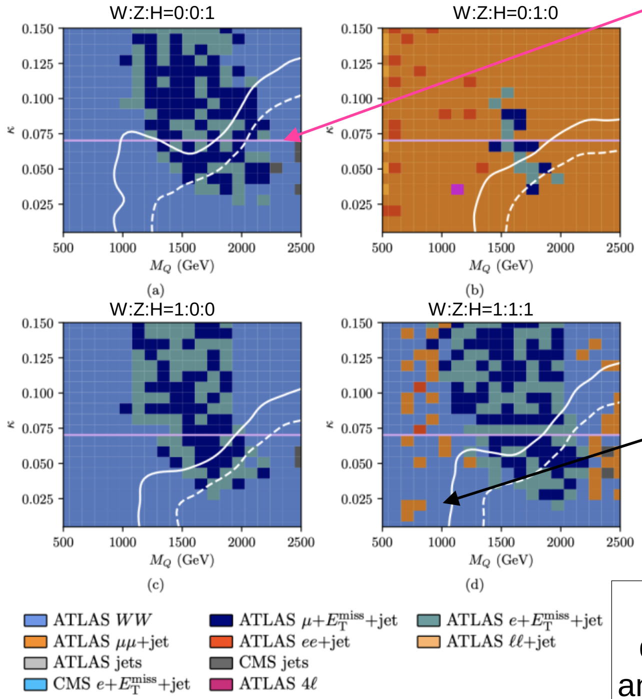
- Latest **ATLAS VLQ search for Z-channel decays** came out as a CONF note for EPS
- Beats the CONTUR exclusion, but using 139/fb instead of the 3.2/fb Z+jets measurement!
- CONTUR result excluded much of this region a full year before the dedicated search came out

> VLQs have been searched for at ATLAS and CMS in Run 1, and more recently with an early Run 2 dataset, focusing mainly on the pair-production mode [12–24]. Constraints on VLQ production have also been recently derived [25] using a range of differential cross-section measurements at the LHC, complementing the direct searches. VLQ pair production, proceeding primarily via the strong interaction

- Highlights the potential role of CONTUR as a scouting tool to determine regions where dedicated searches are needed

CONTUR to explore new regions

VLQs coupling to 1st Gen



Bounds from by non-collider constraints: Region above is excluded

95% CL exclusion
68% CL exclusion

Region to left is excluded at 90% CL by CONTUR

Colours indicate dominant pool of LHC analyses in each point of param space

- Despite lack of dedicated searches, the 1st-generation κ-m_{VLQ} plane is largely excluded
- 'ATLAS WW' pool contains measurements in control regions of a search for leptoquarks. In many parts of plane, this is most sensitive analysis (unusual phase space probed!)
  - A strong argument for searches to make auxiliary particle-level measurements in their papers!
- The lep+MET+jet inclusions occur where pair production has died off but single-production retains appreciable cross-section
  - Sensitivity driven by control region measurements in an 8 TeV Wjj measurement
- "One model's control region is another model's search region": model-independent measurements may be key to handling this conundrum !

CONTUR to explore new regions

VLQs coupling to 1st Gen

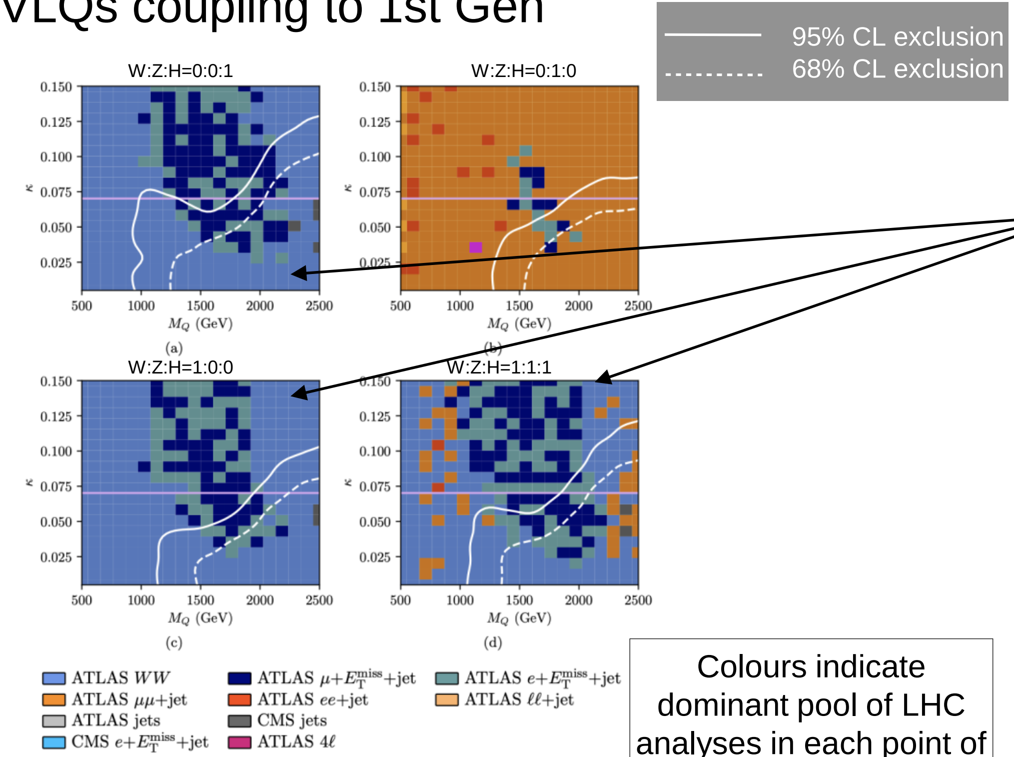


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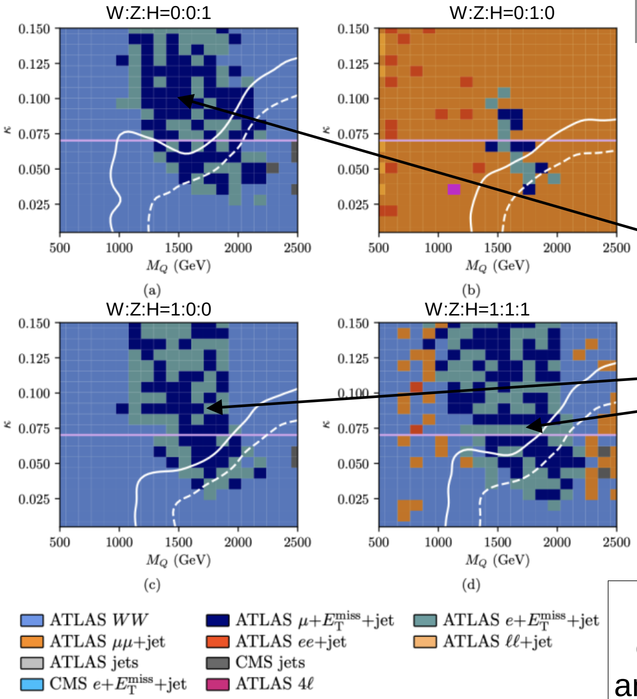
Illustration by Chris Wormell from “A Map of the Invisible”

CONTUR to explore new regions

VLQs coupling to 1st Gen

95% CL exclusion
68% CL exclusion



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CONTUR to explore new regions

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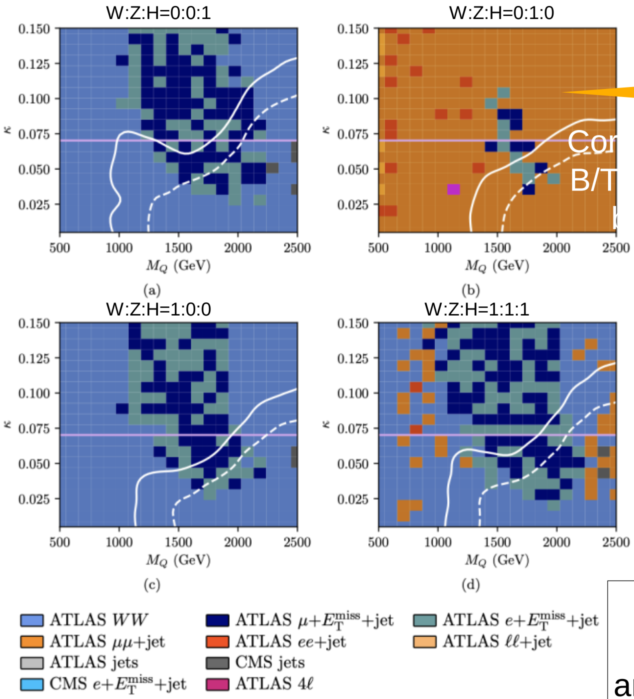

Cor... of phase space where B/T... ay via Z is dominated b... -jet measurements

Colours indicate dominant pool of LHC analyses in each point of param space

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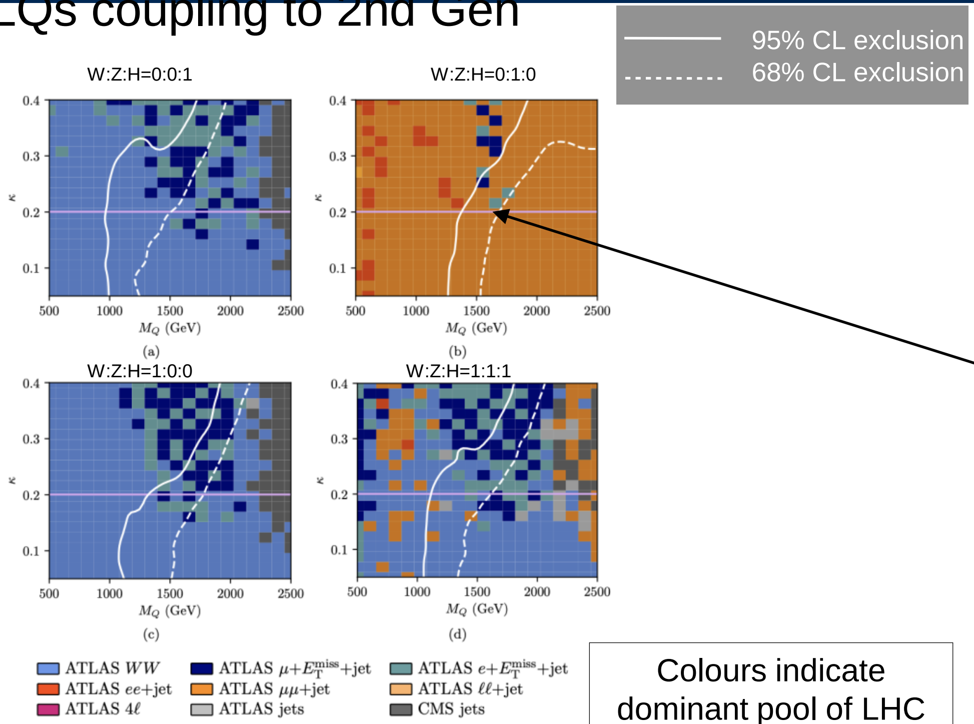
CONTUR to explore new regions

VLQs coupling to 2nd Gen

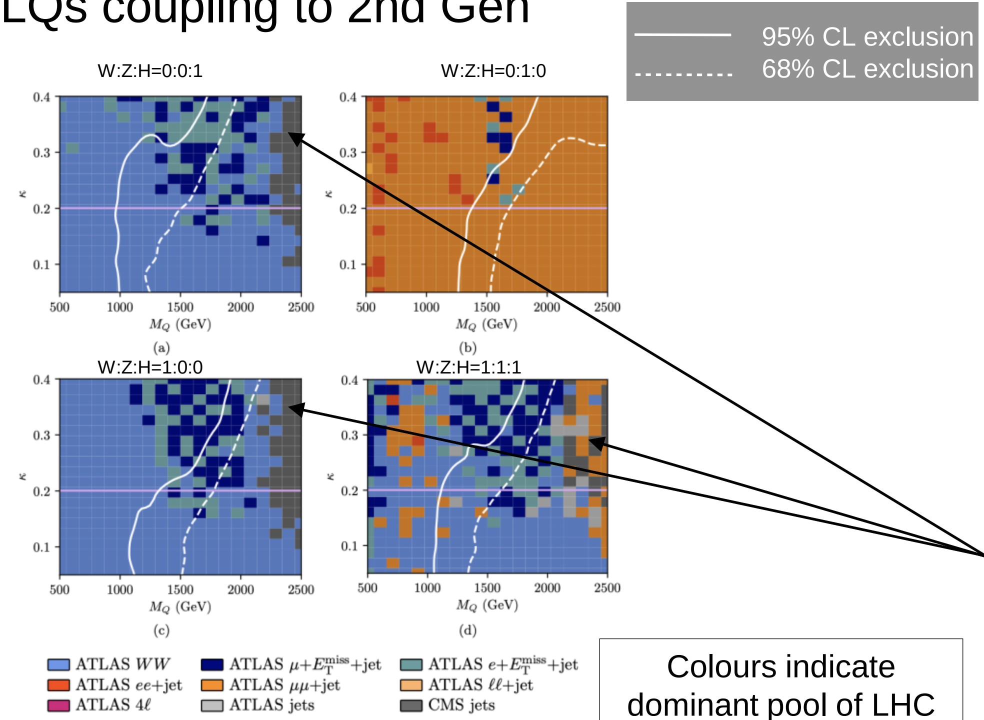


Colours indicate dominant pool of LHC analyses in each point of param space

- Difference in exclusion pattern wrt 1st-gen scan driven by proton PDF!
- κ-dependent single-production modes were only appreciable if VLQs could couple to valence quarks
    - This explains why 2nd-gen scan has reduced κ-dependent shape
- Impact of QCD jet analyses also seen for higher masses (CMS 13 TeV jet mass, and ATLAS 13 TeV dijet and inclusive jet analyses)

CONTUR to explore new regions

VLQs coupling to 2nd Gen



Colours indicate dominant pool of LHC analyses in each point of param space

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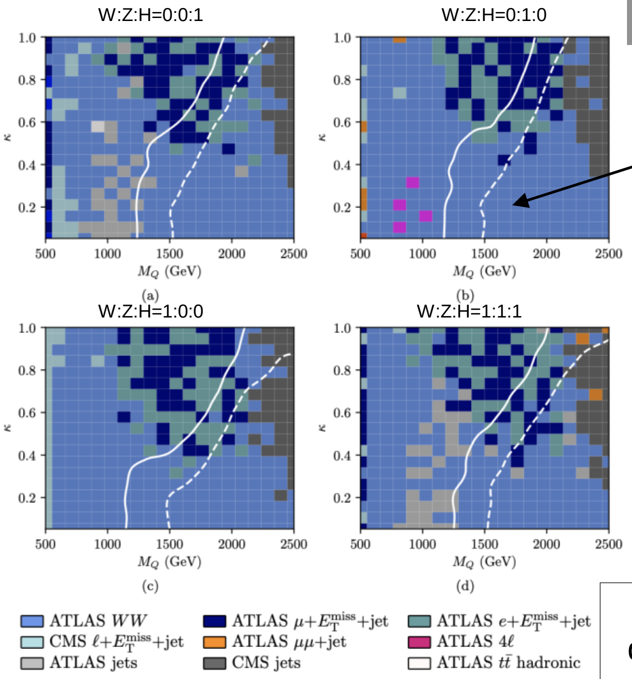
CONTUR to explore new regions

VLQs coupling to 3rd Gen

95% CL exclusion
68% CL exclusion



Colours indicate dominant pool of LHC analyses in each point of param space

- Also notable is **that a lot of the sensitivity in this scan is only possible because of published uncertainty breakdowns in these measurements,** which allow correlations to be accounted for

- Exclusion much more modest if error breakdowns would not have been published (see backup)!

What about the (many) more realistic scenarios?

- During journal review, it has been pointed out to us that the scenario with all 4 extra VLQs is unrealistic — unlikely that new particles would form a quadruplet. Instead, we should consider:
    - Singlets: (B), (T)
    - Doublets: (BT), (XT), (TY)
    - Triplets: (BTX), (BTY)
- Each for 1st, 2nd, 3rd-generation couplings, and 4 benchmark W/H/Z-coupling assumptions
- That's 7 multiplets, each with 3 generation-couplings, each with 4 W/H/Z-couplings, each with 300 points per scan, running 30,000 events at each point…
- Determining the constraints for this many scenarios in short order would normally take months… but can it be done with CONTUR?
- We wanted to use this challenge to put the CONTUR machinery to the test, and demonstrate the flexibility/speed of the method

=

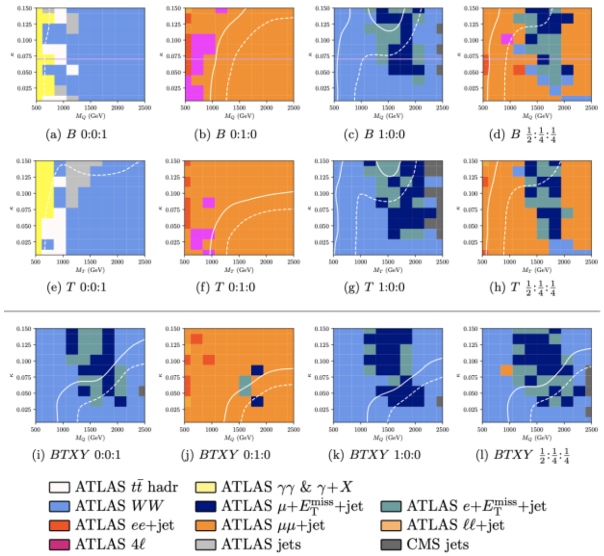
?

Illustration by Chris Wormell from "A Map of the Invisible"

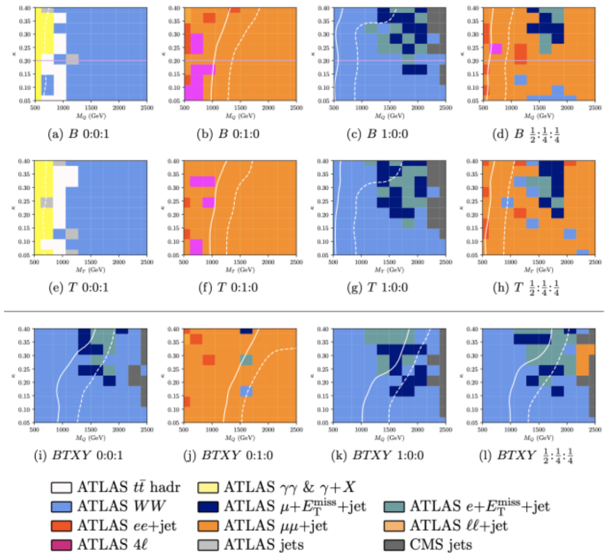
What about VLQ Singlets?

Speed of CONTUR means we can rapidly explore more permutations of this complex model

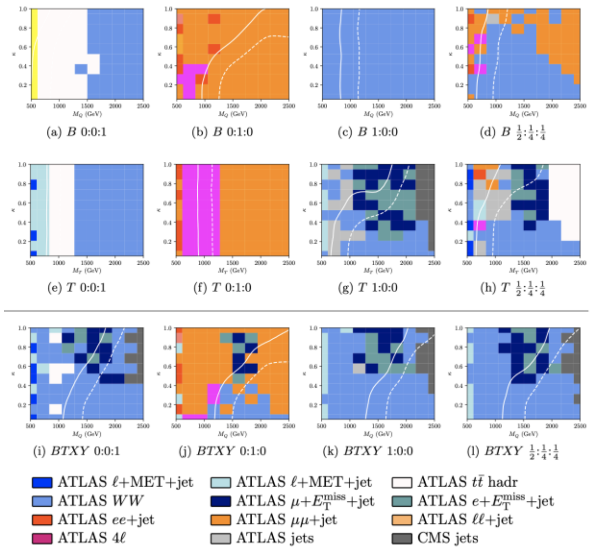
1st-Generation



2nd-Generation



3rd-Generation

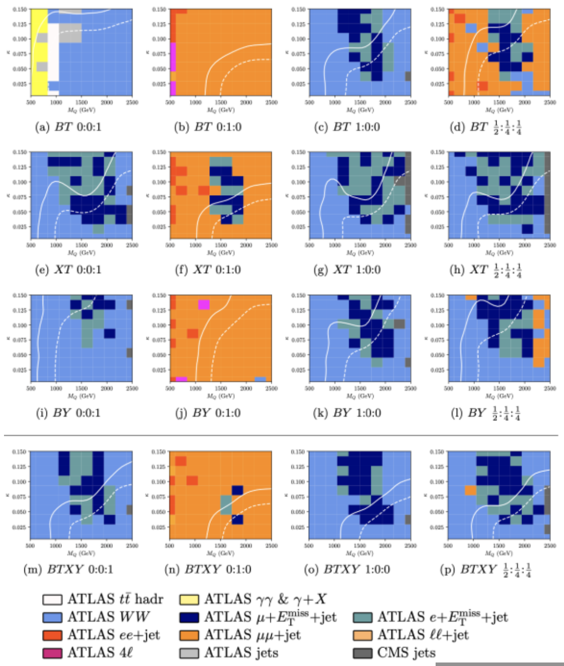


95% CL exclusion
68% CL exclusion

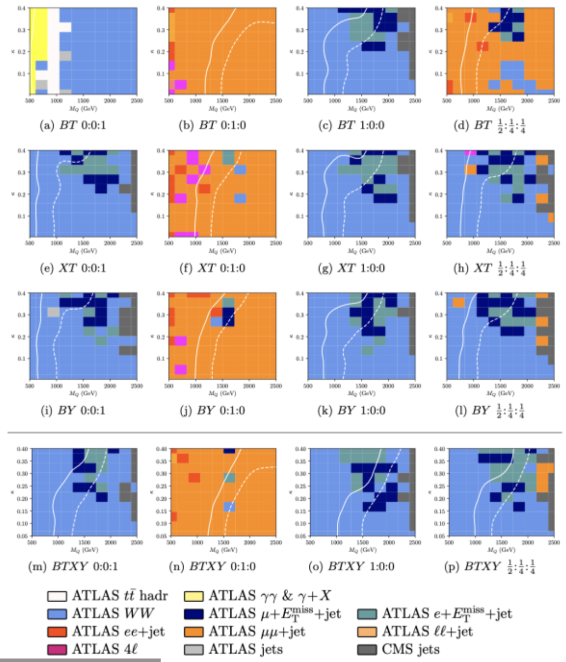
What about VLQ Doublets?

Speed of CONTUR means we can rapidly explore more permutations of this complex model

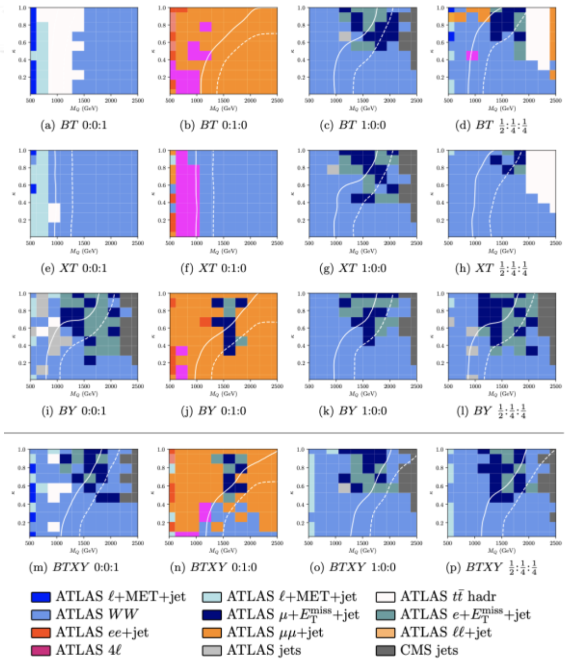
1st-Generation



2nd-Generation



3rd-Generation



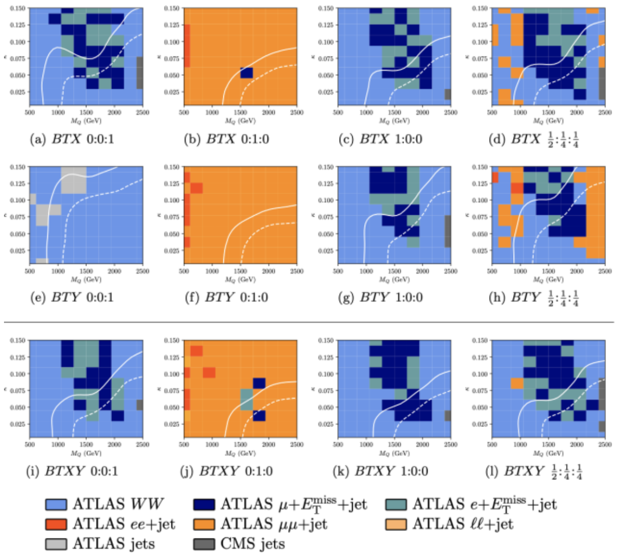
95% CL exclusion
68% CL exclusion

Louie Corpe, CERN (lcorpe@cern.ch)

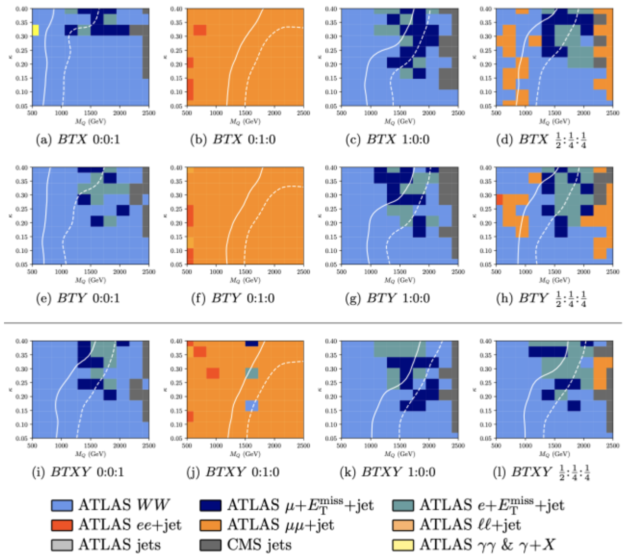
What about VLQ Triplets?

Speed of CONTUR means we can rapidly explore more permutations of this complex model

1st-Generation



2nd-Generation



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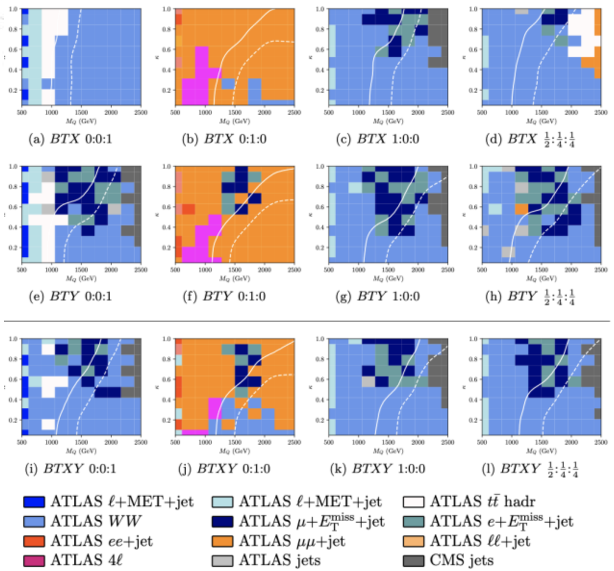

95% CL exclusion
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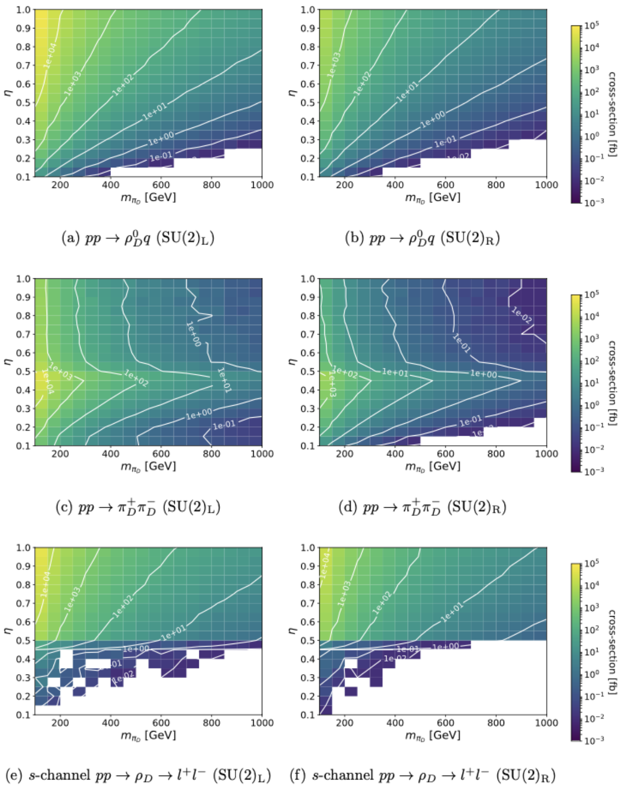
Illustration by Chris Wormell from "A Map of the Invisible"

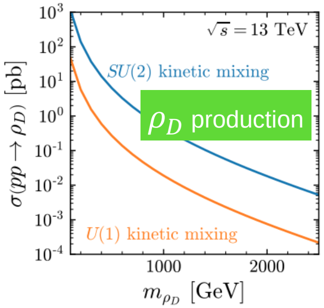
Heavy Dark Mesons

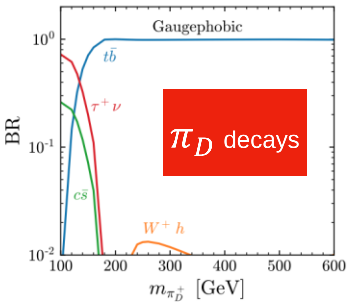
Dark meson phenomenology at the LHC

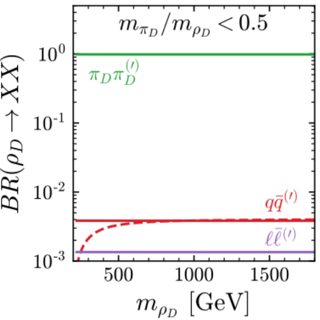


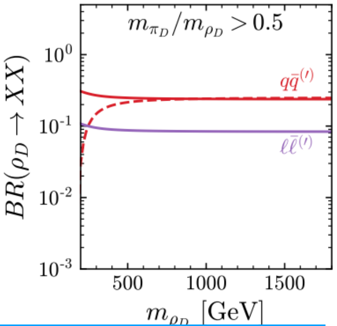
- Define $\eta = m_{\pi_D}/m_{\rho_D}$
- Above η > 0.5, ρ_D can decay to diquark/dilepton pairs, expect this model to be picked up by High-mass Drell-Yan measurements (and the smeared particle-level HDMY search which is in CONTUR)
- Below, η < 0.5, ρ_D decays almost exclusively to π_D
  - Chiefly decay to $\tau\nu$ for π_D below 200 GeV, and *tb* above.
    - Missing energy and multiple (b-)jets
    - Or take advantage of single-pion production with a W or Z: Missing energy, jets, leptons

Dark meson phenomenology at the LHC







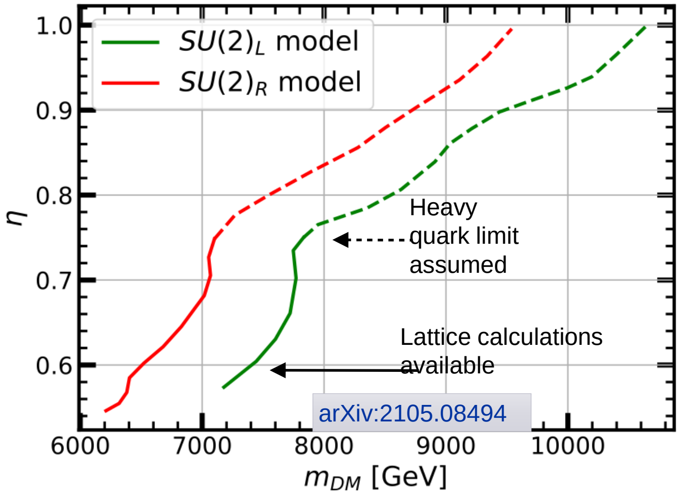


ρ_D decays: depends on mass hierarchy

Kribs et al. arXiv:1809.10183

- Distinguish two cases for Dark Sector:
  - *"Left-handed case"*: DS gauged under SM $SU(2)_L$, mix with SM W/Z/ɣ. Gives Three ρ_D with charges 0, +1, -1
  - *"Right-handed case":* SM U(1) -> ρ_D mixing only with SM ɣ, only have neutral ρ_D.
- Phenomenology depends on π_D/ρ_D mass hierarchy
- If ρ_D cannot decay to π_D, it chiefly decays to leptons: Z' like resonance signature
- If ρ_D can decay to π_D, it will almost always do so
- Dark pion decays feature a variety of final states specially featuring third generation SM fermions

Translating results to limits of m_{DM}



η	$amps$	amv	$amS0$	f_f^{DM}
0.77	0.3477	0.4549	0.9828	0.153
0.70	0.2886	0.4170	0.8831	0.262
0.50	0.2066	0.3783	0.7687	0.338

Appelquist et al (arXiv:1503.04203)

- Follow similar strategy to Appelquist et al (arXiv:1503.04203) to connect collider limits to DM analysis: connect non-DM signatures (π_D) to DM via fundamental SU(4) representation, which fixes mass scales, and lattice calculations

$$m_{\mathrm{DM}}(\eta) = \frac{amS0(\eta)}{amps(\eta)} \times m_{\pi_D}(\eta)$$

Lattice dimensionless mass prediction for dark baryon

Lattice dimensionless mass prediction for pseudo-scalar

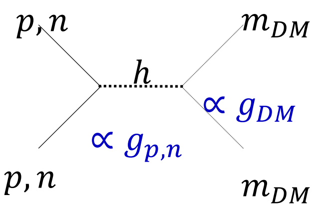
Appelquist et al (arXiv:1503.04203)

- LHC exclusions together with the lattice results push the dark matter mass limits to multi-TeV mass range. Results interpolated between different η scenarios.

Combining with Direct Detection results

$$\mathcal{M}_{p,n} = \frac{g_{p,n}\, g_{DM}}{m_h^2}$$

$$g_{\rm DM} \simeq y_{\rm eff} \times f_f^{\rm DM}$$

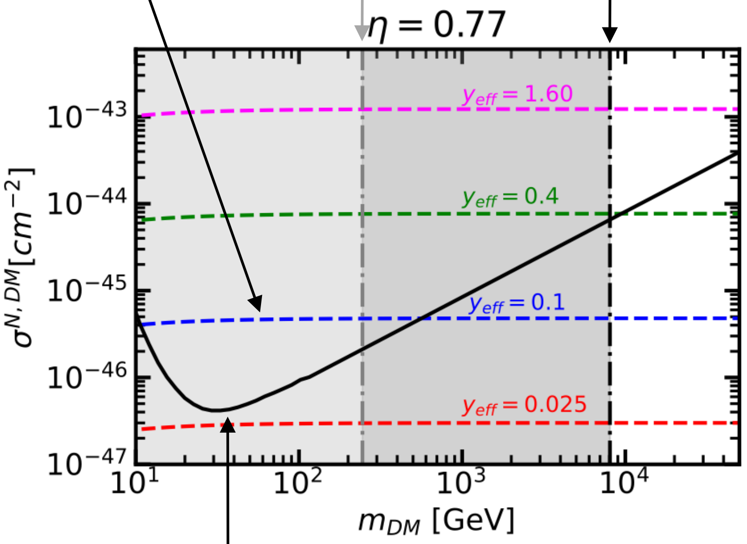


- Higgs-mediated DM production cross-section related to effective dark quark - Higgs coupling $y_{\rm eff}$
  - Using inputs from lattice, eg f_f^{DM}
- LHC CONTUR limits, which are independent can be used to compare to Xenon1T constraints
  - Can then extract maximum allowed $y_{\rm eff}$ for each DM mass hypothesis

$y_{\rm eff}$ values above Xenon1T curve are excluded

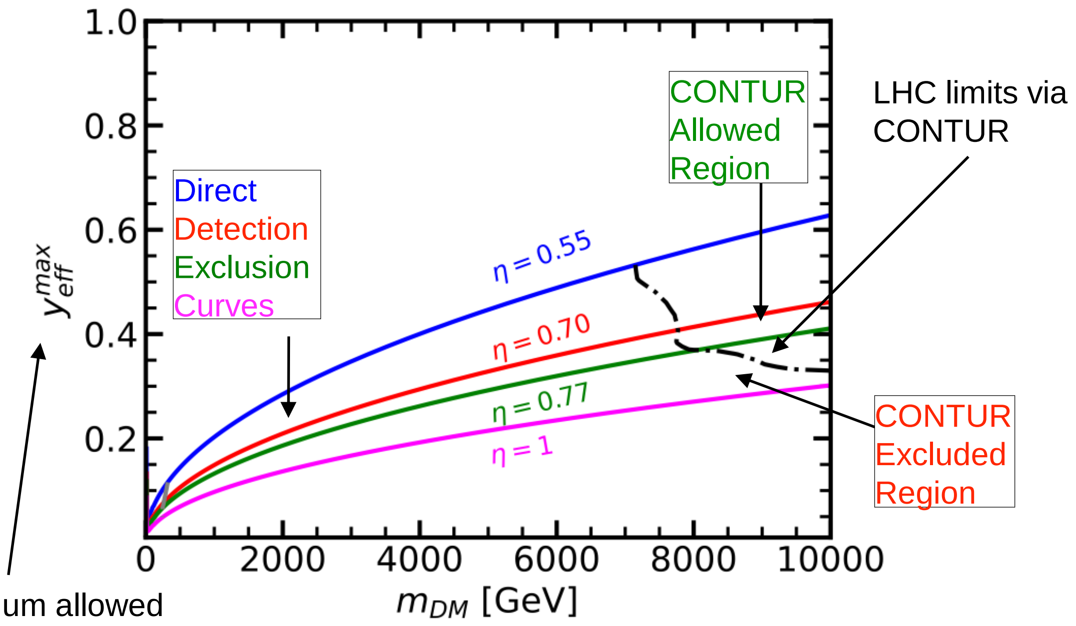
LEP II Constraints

LHC Constraints via CONTUR



Xenon1T limits

Bringing Direct Detection and LHC limits together



Maximum allowed coupling between dark quarks and Higgs

Either require low values of Higgs - dark quark effective Yukawa coupling or require very heavy dark matter

CONTUR vs Two-Higgs Doublet Model + pseudo scalar mediator *a*

Another case study

Illustration by Chris Wormell from “A Map of the Invisible”

Louie Corpe, CERN (lcorpe@cern.ch)

The 2HDM+a model

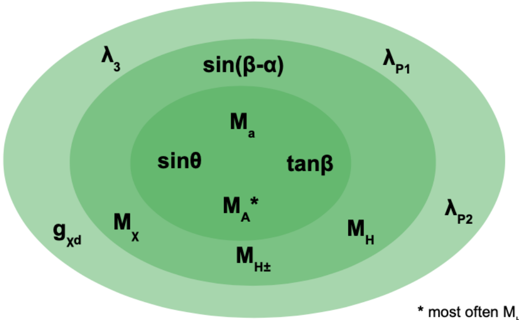
Slides: Martin Habedank (DESY)

Two-Higgs-doublet model with a pseudoscalar mediator

JHEP05(2017)138

- **pseudoscalar mediator** that couples to DM and SM particles
- **additional second Higgs doublet** (→"2HDM") to avoid strong constrains by Higgs boson couplings
  - ratio of vacuum expectation values: tanβ
- mediator-SM coupling through **mixing** of mediator and second Higgs doublet
  - a-A mixing angle: sinθ
- simplest theoretically consistent extension of simplified DM models with pseudoscalar mediators

Parameters



* most often $M_{H\pm}=M_H=M_A$ is used

Particles

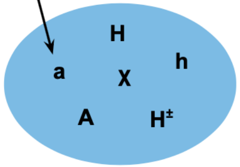


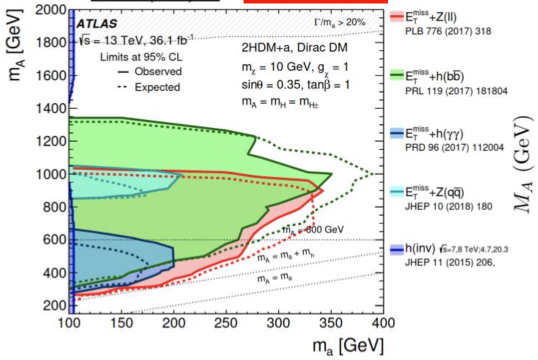
Illustration by Chris Wormell from "A Map of the Invisible"

Benchmark Scenarios (comparison to ATLAS)

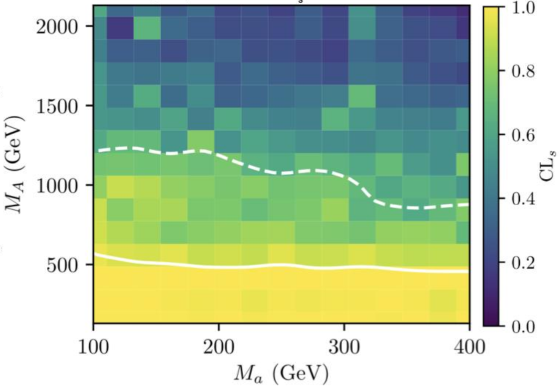
Slides: Martin Habedank (DESY)

ATLAS summary paper →JHEP05(2019)142

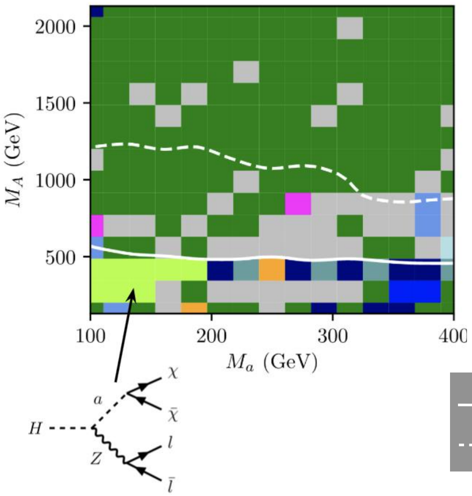
ATLAS summary At the time of this CONTUR paper



Results of this paper →2009.02220
sensitivity map in terms of CL_s



most sensitive measurements



95% CL exclusion
68% CL exclusion

- ATLAS $\mu+E_T^{miss}$+jet
- CMS $\ell+E_T^{miss}$+jet
- ATLAS $\ell\ell$+jet
- ATLAS 4ℓ
- ATLAS $e+E_T^{miss}$+jet
- ATLAS WW
- ATLAS jets
- ATLAS $ll+E_T^{miss}$
- ATLAS $l+E_T^{miss}$+jet
- ATLAS $\mu\mu$+jet
- ATLAS E_T^{miss}+jet

5

exclusion
- orthogonal to ATLAS searches
- from many different contributions

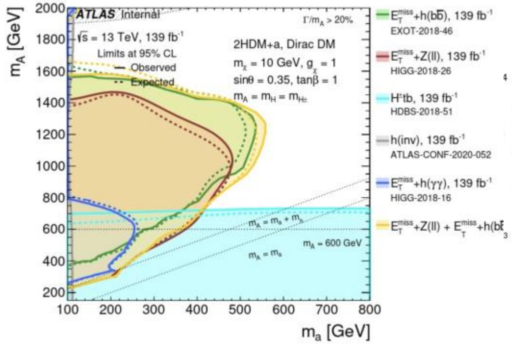
At low m_a, A-> tt and H± -> tb become important, picked up by lep+MET+jet measurements in CONTUR
With no equivalent search (at the time)

Benchmark Scenarios (comparison to ATLAS)

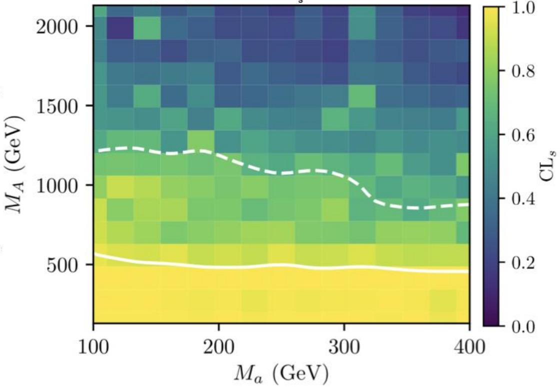
Slides: Martin Habedank (DESY)

ATLAS summary paper →JHEP05(2019)142

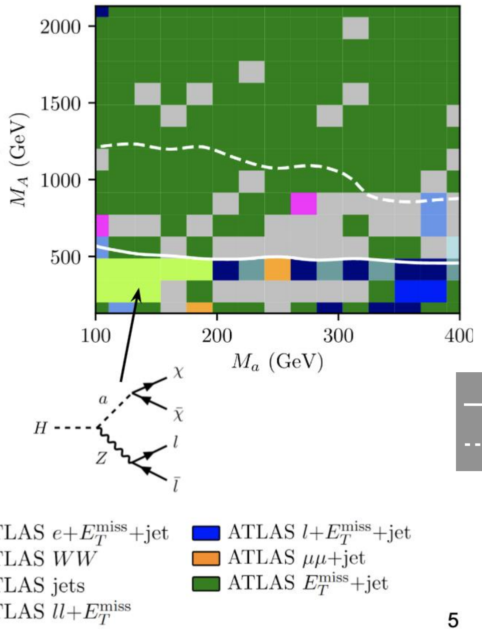
Latest ATLAS summary currently in approval



Results of this paper →2009.02220
sensitivity map in terms of CL$_s$



most sensitive measurements



95% CL exclusion
68% CL exclusion

exclusion
- orthogonal to ATLAS searches
- from many different contributions

Low-m$_a$ region filled in by dedicated searches, ~1 year later.

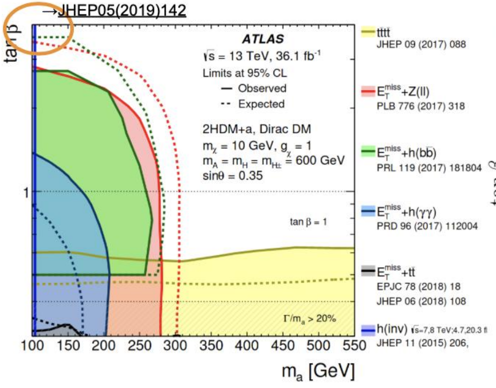
5

Illustration by Chris Wormell from "A Map of the Invisible"

Benchmark Scenarios (comparison to ATLAS)

Slides: Martin Habedank (DESY)

ATLAS summary paper →JHEP05(2019)142



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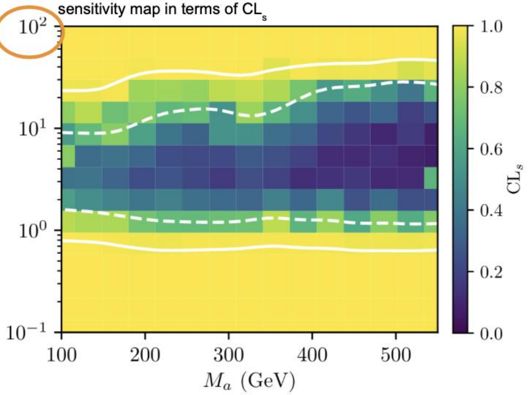
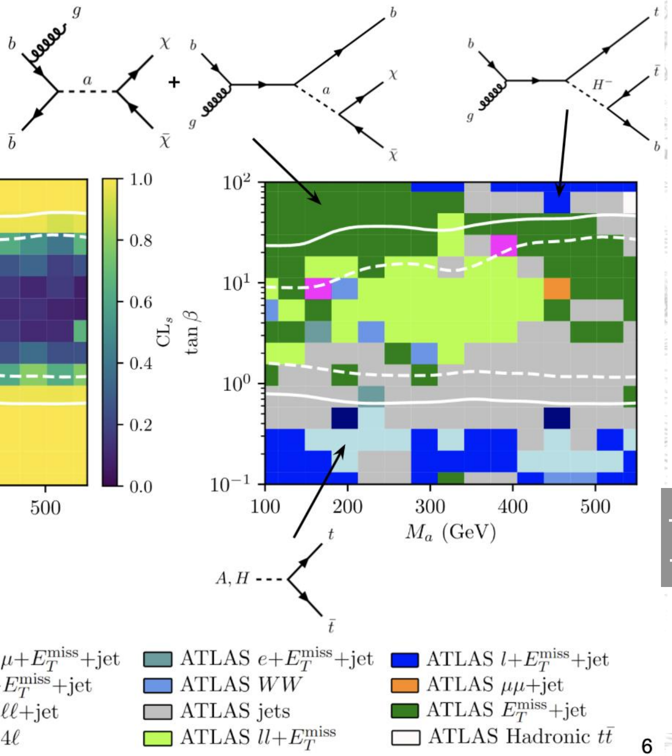




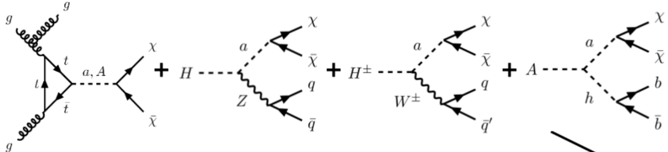
95% CL exclusion
68% CL exclusion

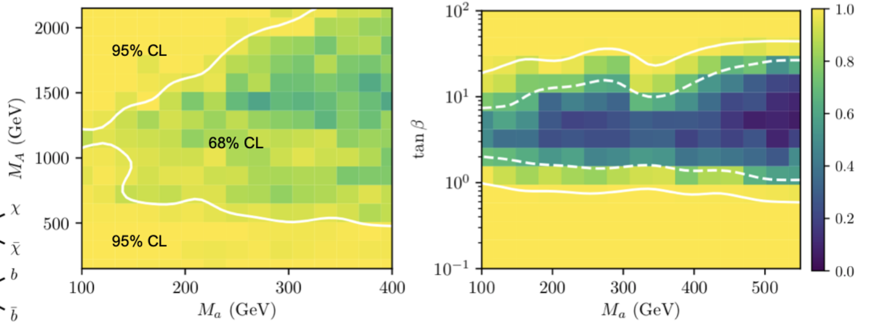
What about varied mixing parameters?

Slides: Martin Habedank (DESY)

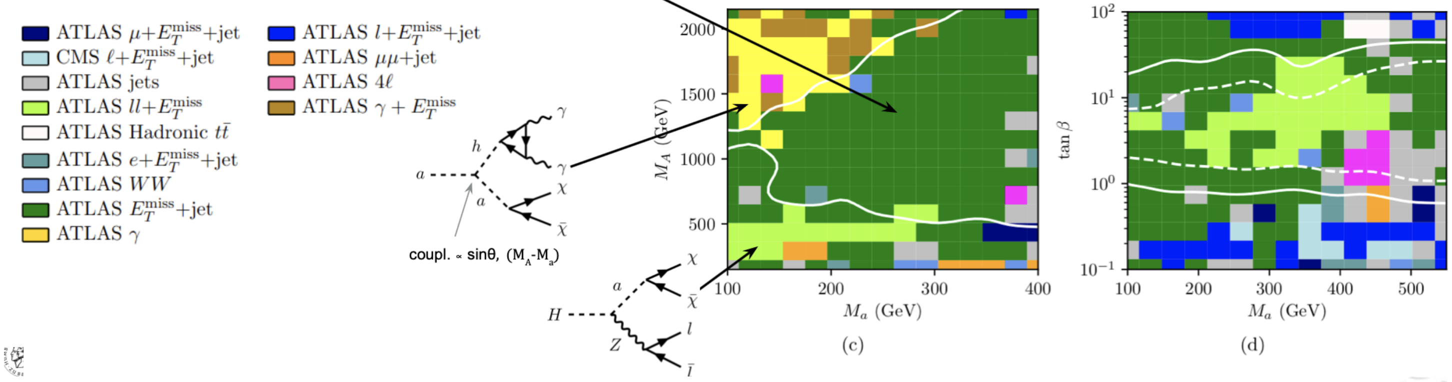
now:
- degenerate masses $M_{H\pm}=M_H=M_A=600\text{GeV}$ again
- change mixing parameter $\sin\theta=1/\sqrt{2}$ (maximum mixing)

→ a-χ coupl. **de**creased, a-SM coupl. **in**creased
→ A-χ coupl. **in**creased, A-SM coupl. **de**creased
- $\sin\theta>1/\sqrt{2}$: a↔A switch roles





(a) (b)



(c) (d)

95% CL exclusion
68% CL exclusion

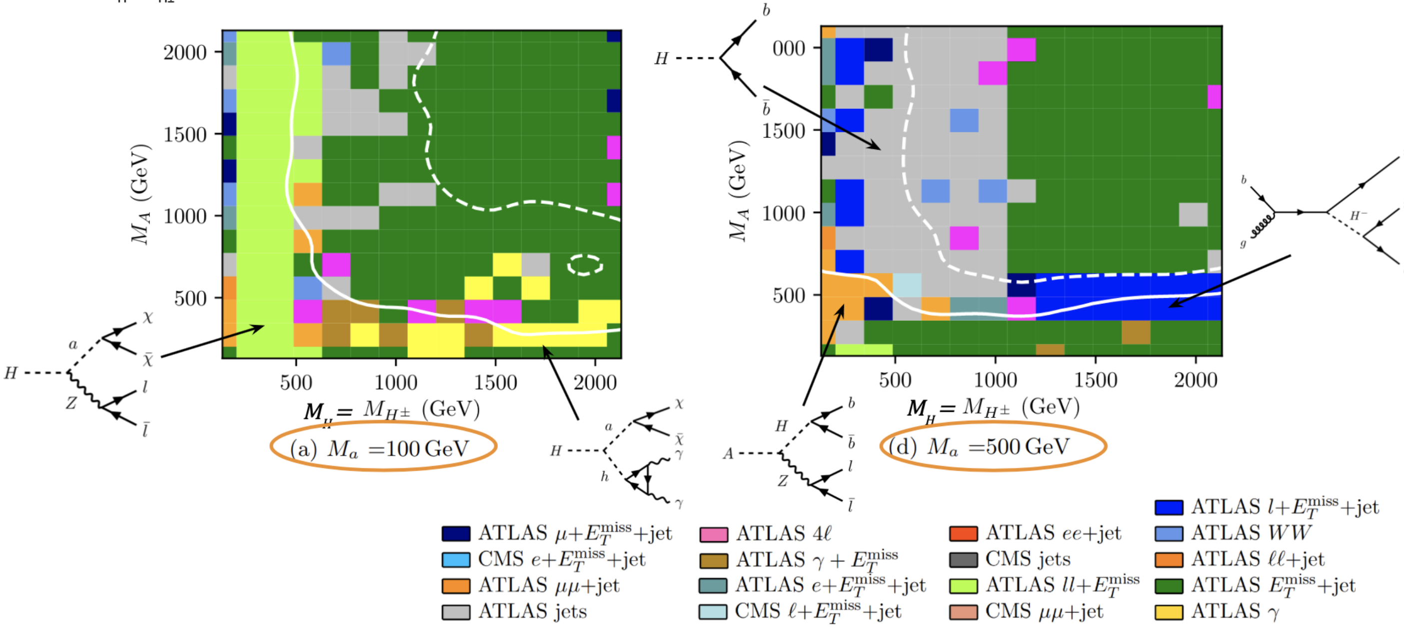
Illustration by Chris Wormell from "A Map of the Invisible"

What about non-degenerate Masses?

Slides: Martin Habedank (DESY)

now:

- deviate from default parameters by dropping $M_{H\pm}=M_H=M_A$
- still need either $M_H=M_{H\pm}$ or $M_A=M_{H\pm}$ to meet electroweak precision constraints
- choose $M_H=M_{H\pm}$



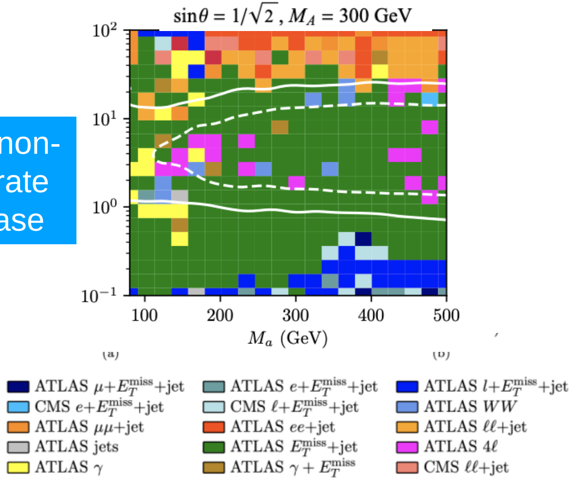
95% CL exclusion

68% CL exclusion

CONTUR as an analysis prototyping tool

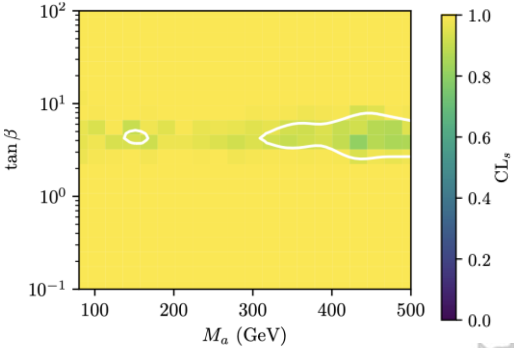
- Since it's easy to add in a RIVET routine to CONTUR, one can test different analysis designs to gauge sensitivity of future results or preliminary data
- For example: I am currently working on 139/fb MET+jets measurement. What does it bring to the table?

Another non-degenerate mass case



Add prototype 139/fb MET+jets measurement routine

95% CL exclusion
68% CL exclusion



This measurement will exclude large fraction of plane