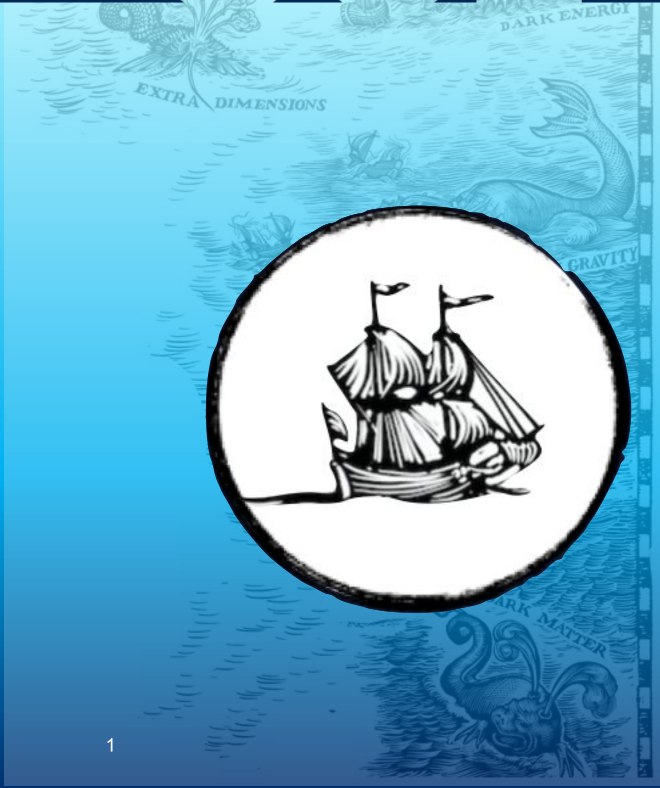
Introduction to CONTUR

Jon Butterworth (UCL),

Slides evolved from Louie Corpe and others in the Contur team

SJTU/ UCL workshop, 1 March 2022



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 be **already ruled out,** because they would cause visible distortions in spectra of ‘’standard’’ processes!

- The challenge is figuring out how the “signal injection” from a new model impacts on **hundreds of measured distributions…**

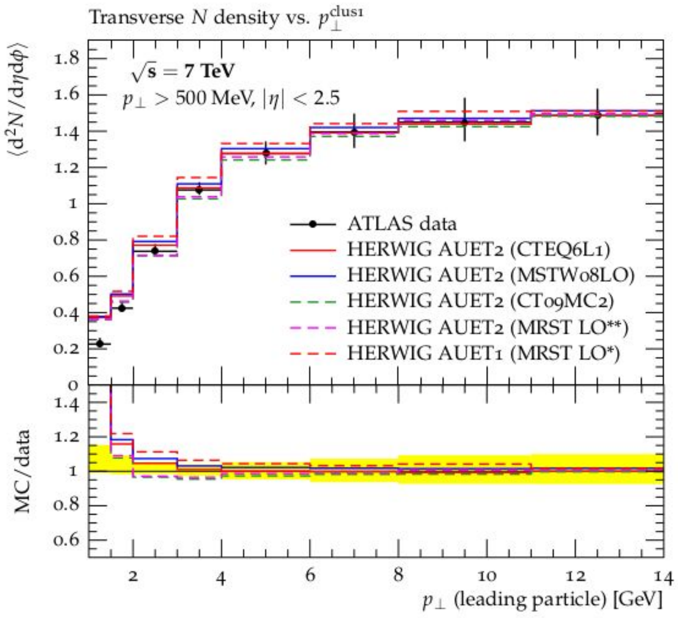
- …and therefore understanding **whether the model is consistent with the measured data** within uncertainties

- **… eventually, including the *Standard* Model**

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

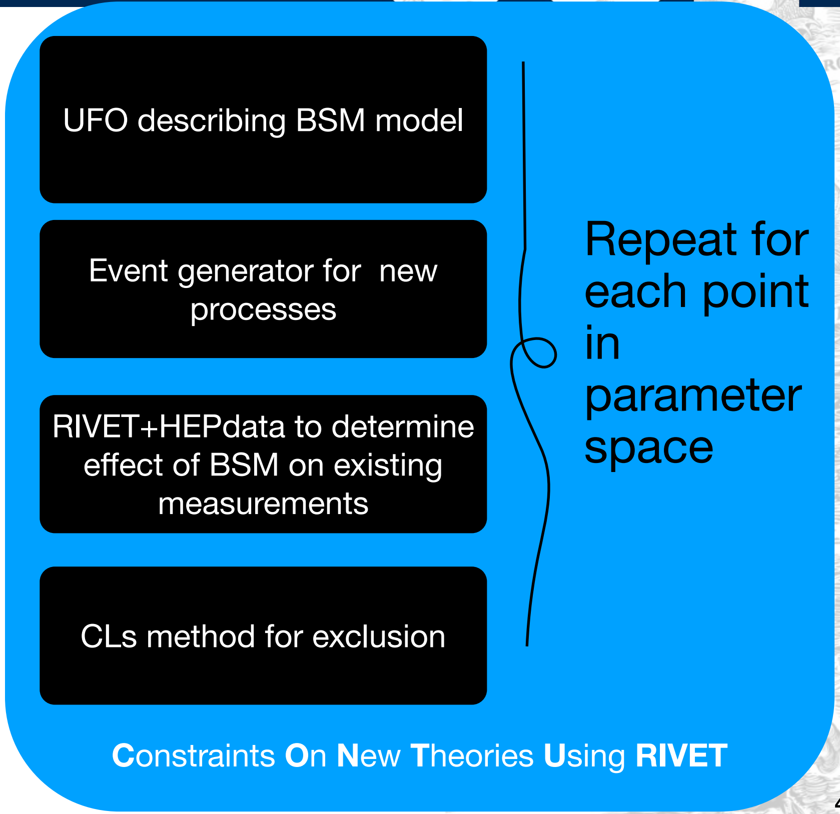
We have the technology

- We have the infrastructure to make rapid particle-level Data/MC comparisons.
- 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.



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
  Also MG, Pythia: **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.
- **Can also use SM theory as the background if available**



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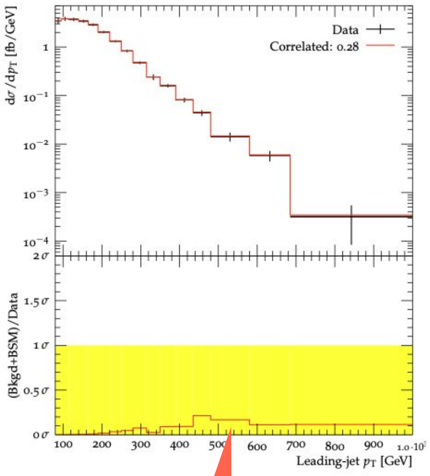
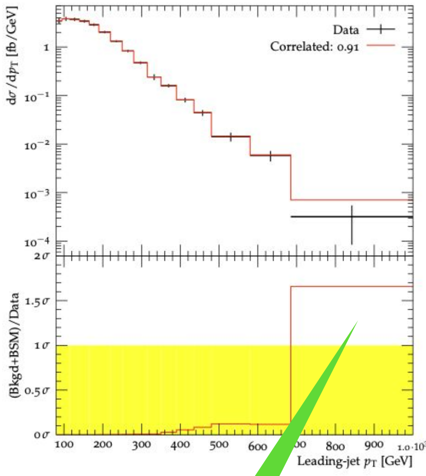


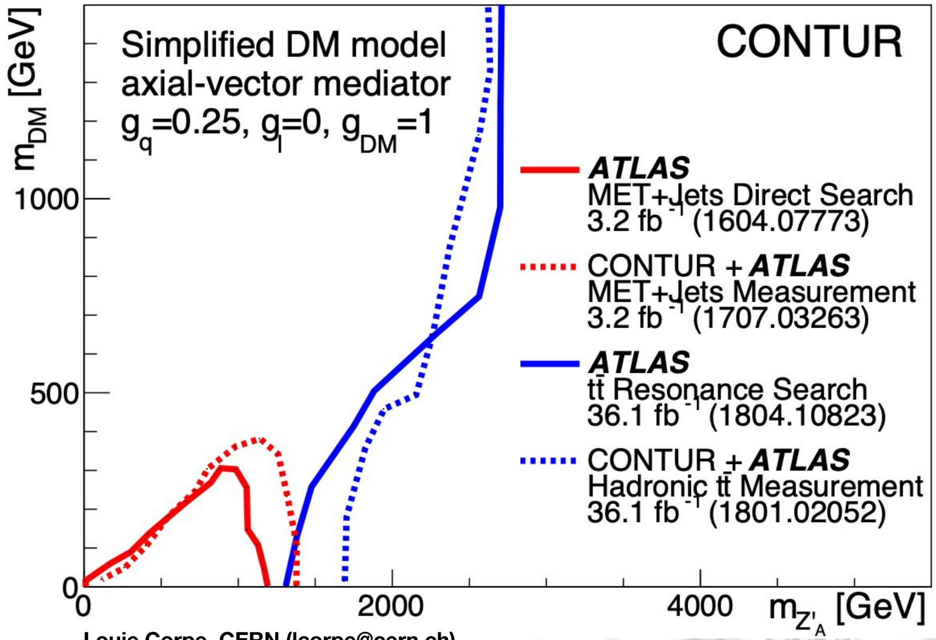


Signal would have small effect wrt uncertainties, can't exclude it (28 % CL)

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 *should* have the advantage of being performed in a BSM-agnostic way, but typically unfolded to particle-level and has analysis logic preserved. **Potential in sensitivity, but easy to re-use.**



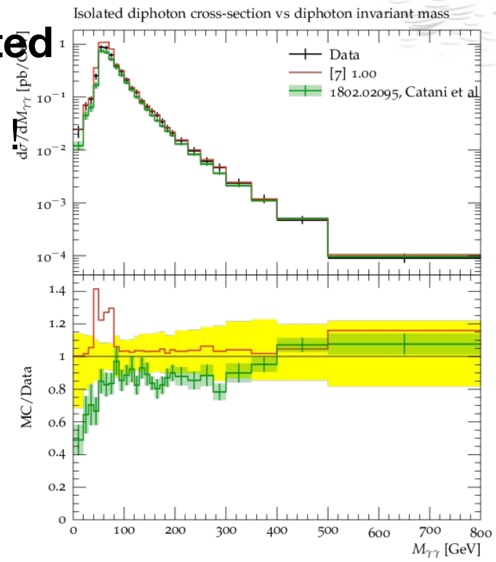
Louie Corpe, CERN (lcorpe@cern.ch)

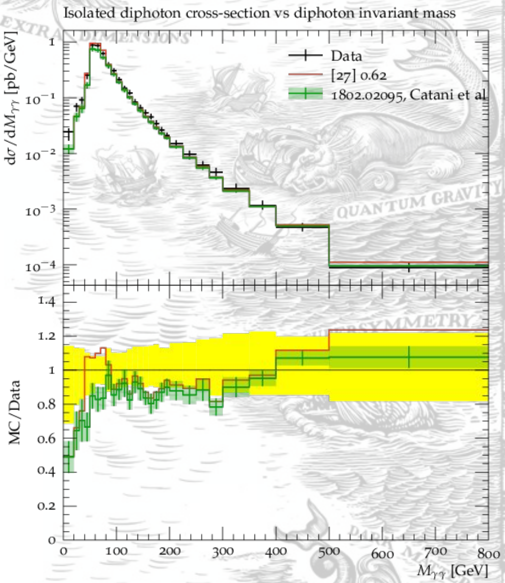
Illustration by Chris Wormell from "A Map of the Invisible"

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 !

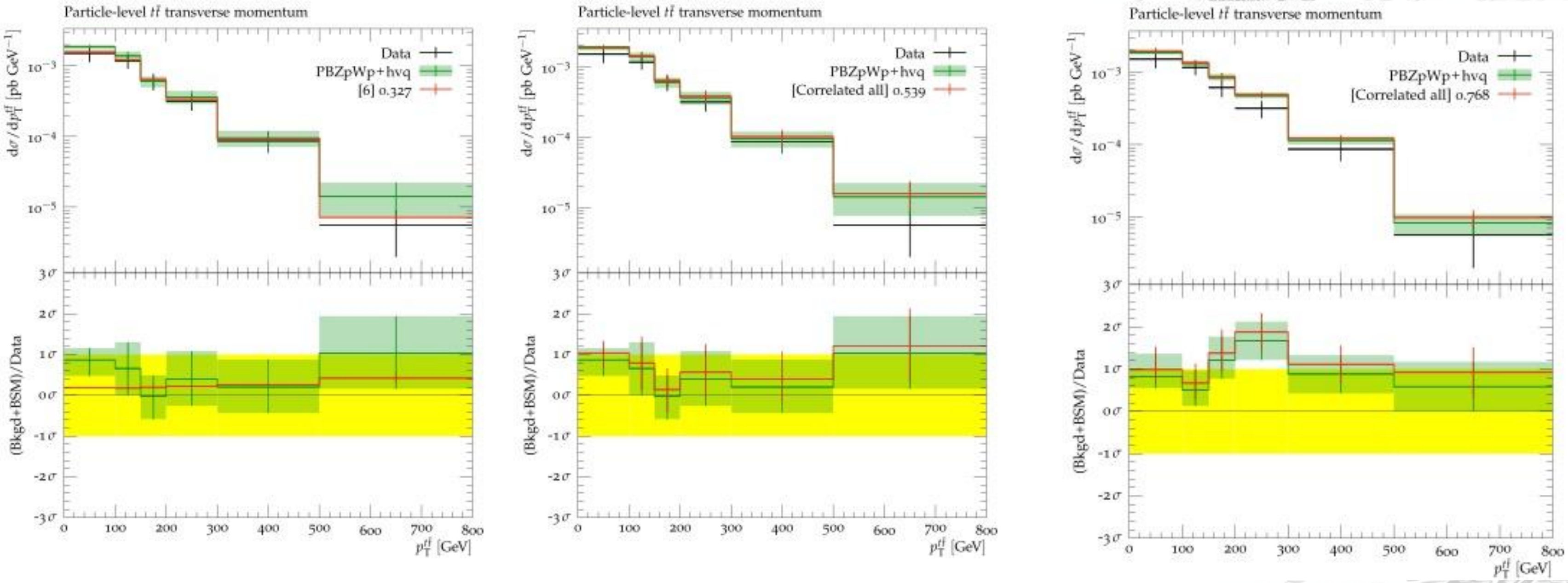
SQRT(S)	13000 GEV	
m_{4l} [GEV]	Measured $d\sigma/dm_{4l}$ [FB GEV-1]	Predicted $d\sigma/dm_{4l}$ (with Sherpa + NLO EW) [FB GEV-1]
7.500000e+01 - 1.000000e+02	5.100341e-01 ±2.346437e-02 syst ±3.442822e-02 stat	5.182588e-01 ±3.545342e-02 total
1.000000e+02 - 1.200000e+02	9.334923e-02 ±4.205973e-03 syst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





State of the art MC predictions and correlations

From M. Altakach et al, 2111.15406



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

Department of Physics and Astronomy, UCL

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 Copen... 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... tral current ... Model (SM ... the SM me... cantly 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

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[1] School of Physics & Astronomy, University of Glasgow, University Place, G12 8QQ, Glasgow, UK

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

Higgs phenomenology as a probe of ster...

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

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

New sensitivity of LHC measurements to Composite Dark Matter ...lels

...Kong, and M. Thomas

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...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 Submission

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

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[3] DESY, Hamburg and Zeuthen, Germany

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

January 12, 2021

11 Dec 2019

Abstract

Two Higgs doublet models with an additional pseudoscalar particle cou... the Standard Model and to a new stable, neutral particle, provide an at... and fairly minimal route to solving the problem of Dark Matter. Th... 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]

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[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"

Louie Corpe, CERN (lcorpe@cern.ch)

Dark meson phenomenology at the LHC

arXiv:2105.08494

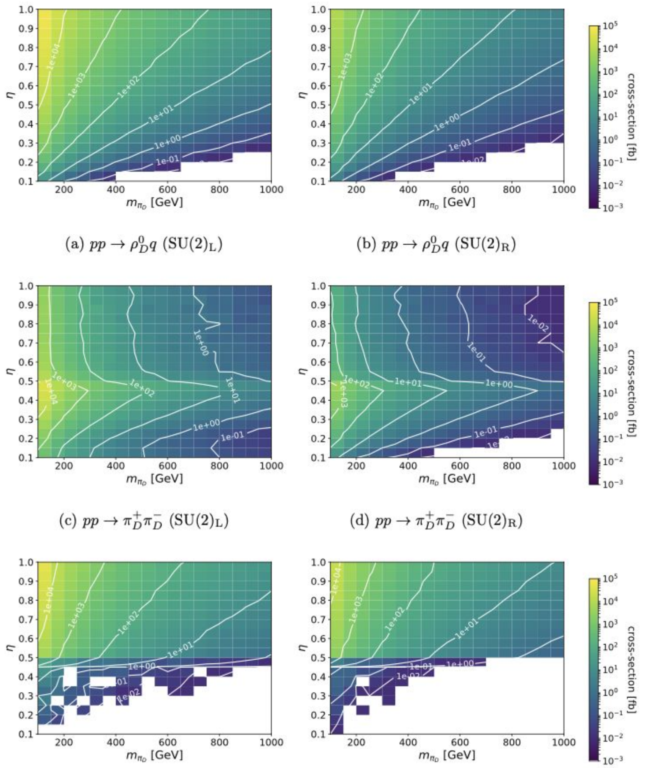
- What if **dark matter** is a **composite particle** arising from **non-Abelian dynamics**? eg SU(4) which confines at some scale Λ_{dark}

- 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 $\eta = m_{\pi_D}/m_{\rho_D}$

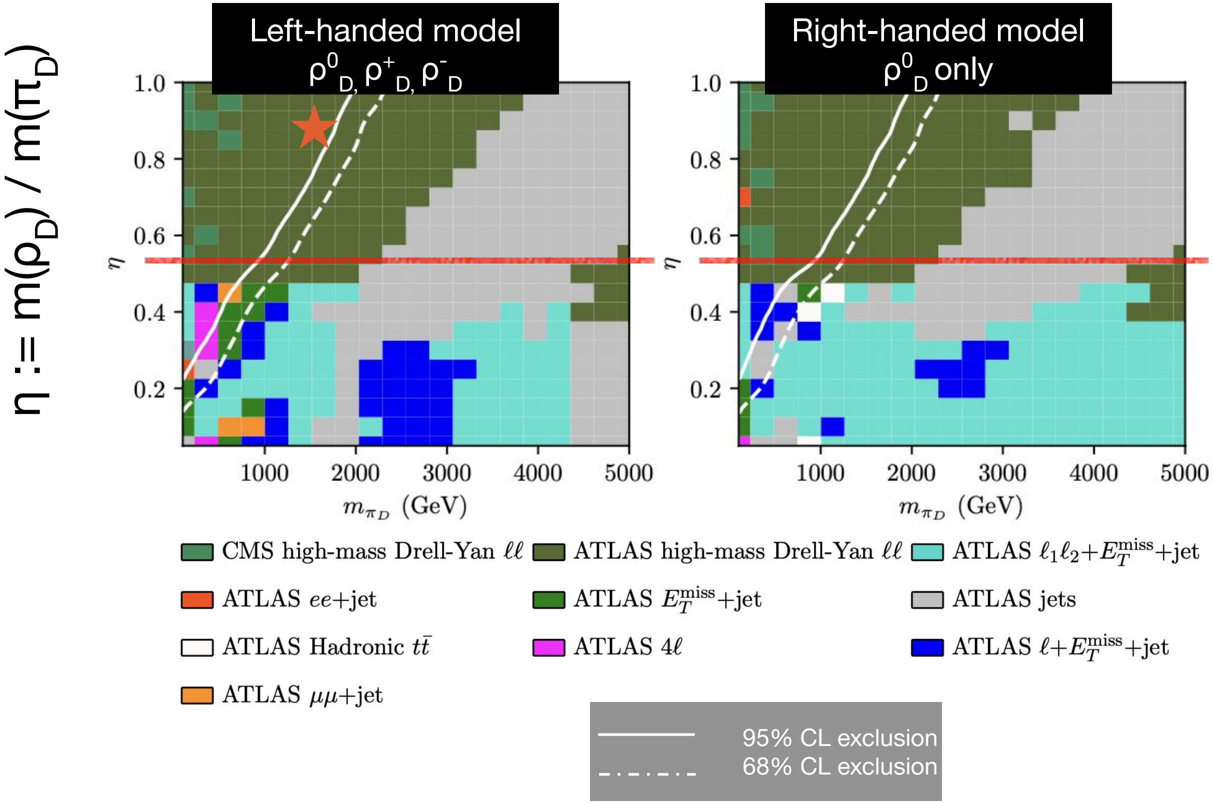


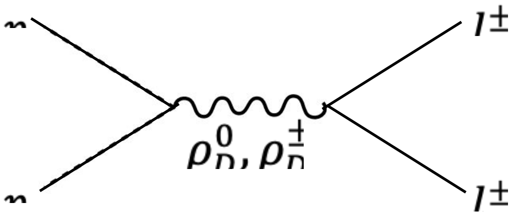
(a) $pp \to \rho_D^0 q$ $(\mathrm{SU(2)_L})$ (b) $pp \to \rho_D^0 q$ $(\mathrm{SU(2)_R})$

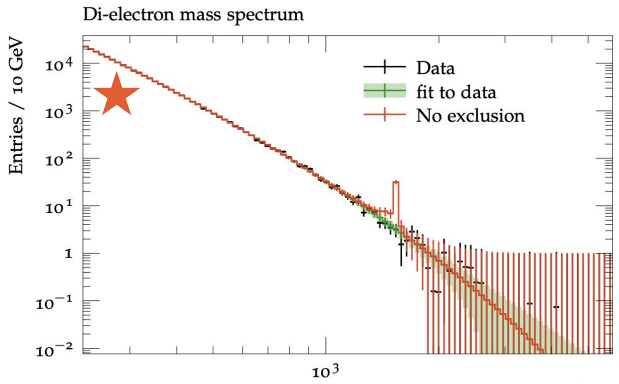
(c) $pp \to \pi_D^+ \pi_D^-$ $(\mathrm{SU(2)_L})$ (d) $pp \to \pi_D^+ \pi_D^-$ $(\mathrm{SU(2)_R})$

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

CONTUR results





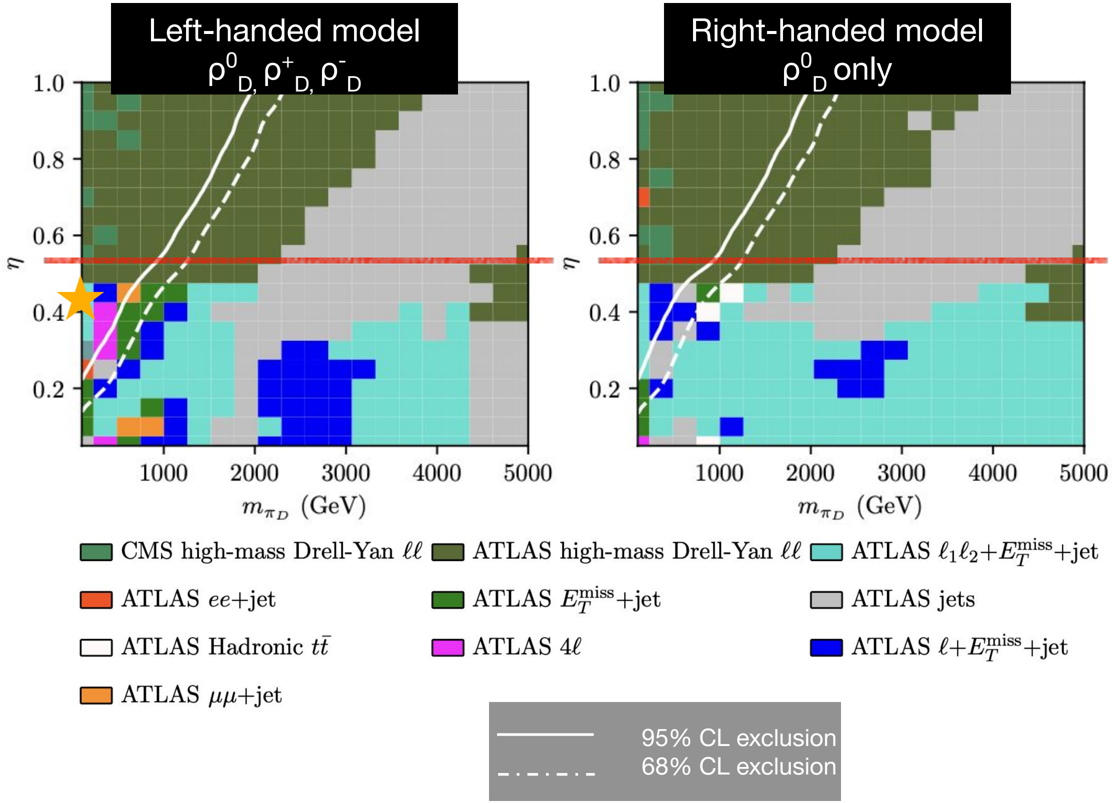


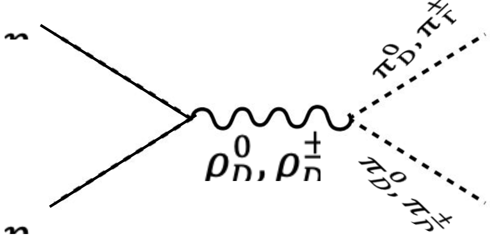
Search for high-mass dilepton resonances using 139/fb pp collision data collected at 13 TeV with the ATLAS detector
https://arxiv.org/abs/1903.06248

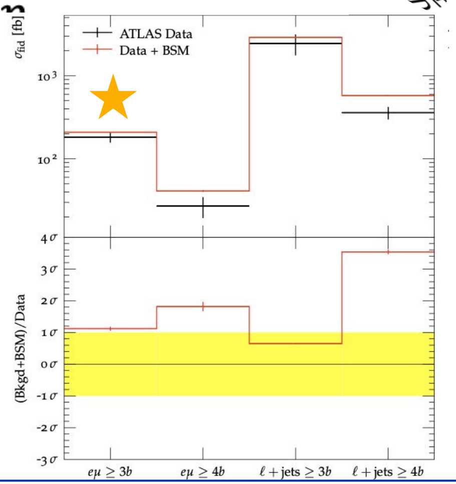
One of a few detector-level analyses in RIVET thanks to dedicated smearing functions!

CONTUR results

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



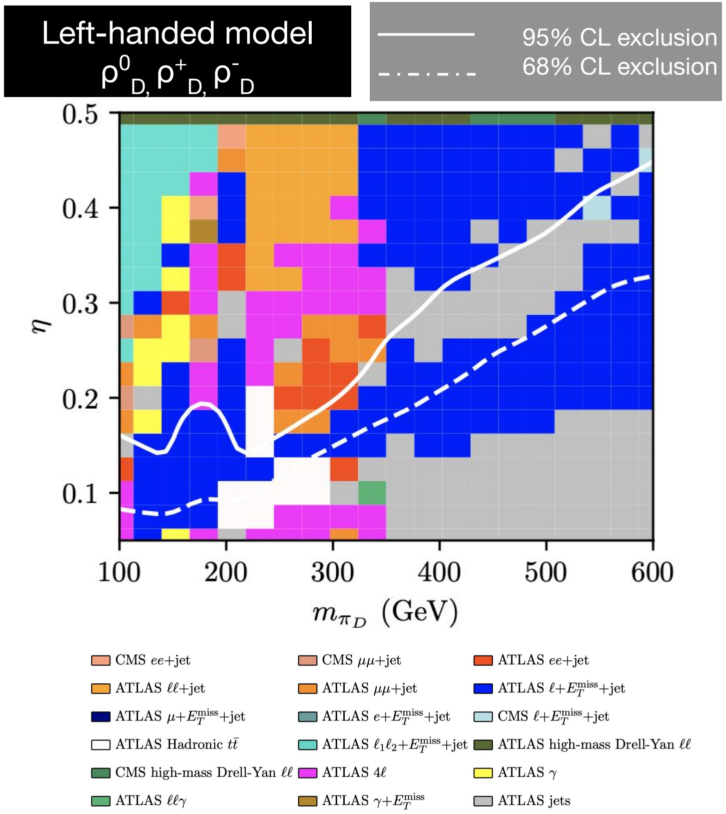




Measurements of fiducial and differential cross-sections of tt production with additional heavy-flavour jets in proton-proton collisions at 13 TeV with the ATLAS detector (36/fb)
https://arxiv.org/abs/1811.12113

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 π_D->γγ becomes important even if decay mode is suppressed
  - Boosted hadronic tt measurements play a role around m(π_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 $b \to s\mu^+\mu^-$

https://arxiv.org/abs/2110.13518
B.C. Allanach, J. M. Butterworth, Tyler Corbett

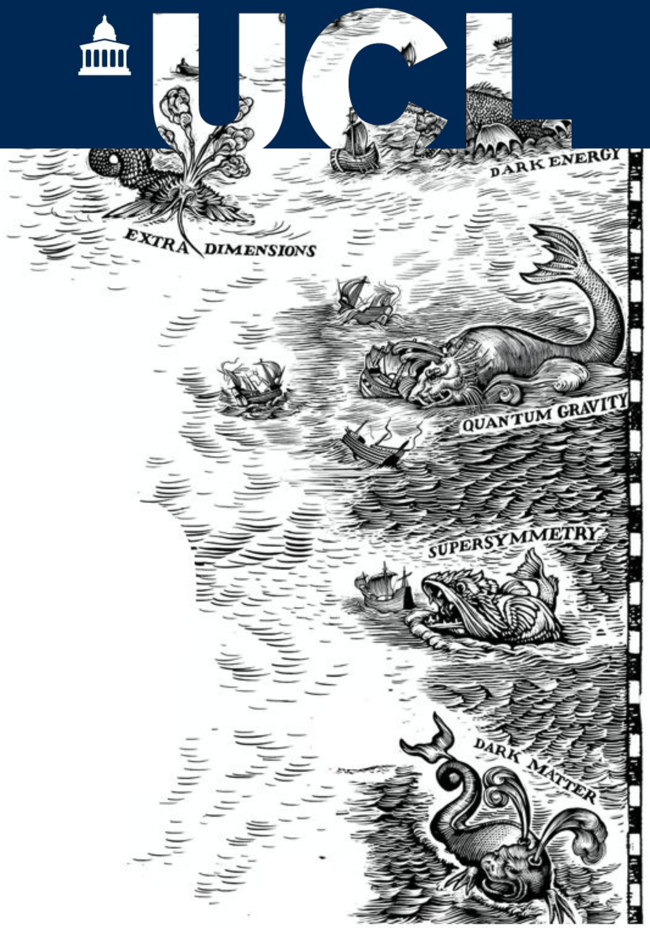


Illustration by Chris Wormell from "A Map of the Invisible"

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

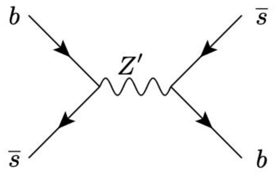
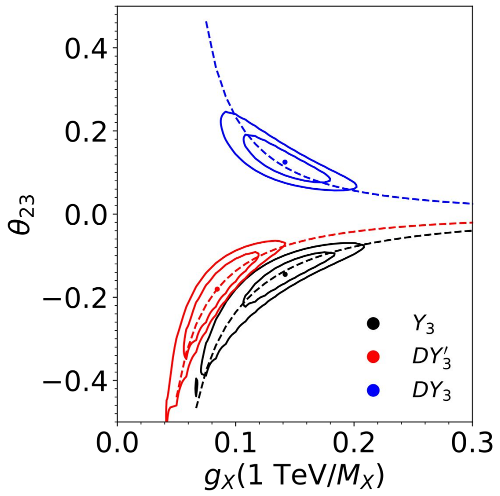
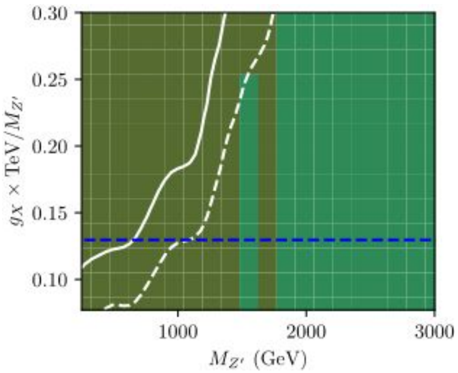


Fig. 2: Tree-level Feynman diagram of a Z'-mediated process which contributes to $B_s - \overline{B_s}$ mixing.

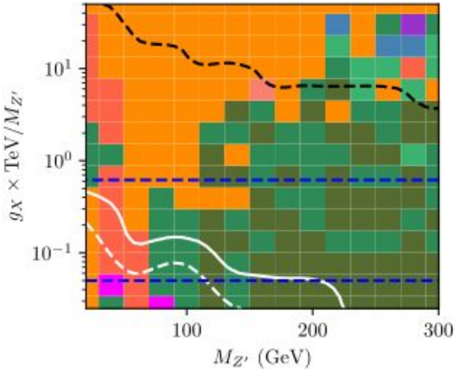


Z’ models motivated by LFV anomalies

- 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



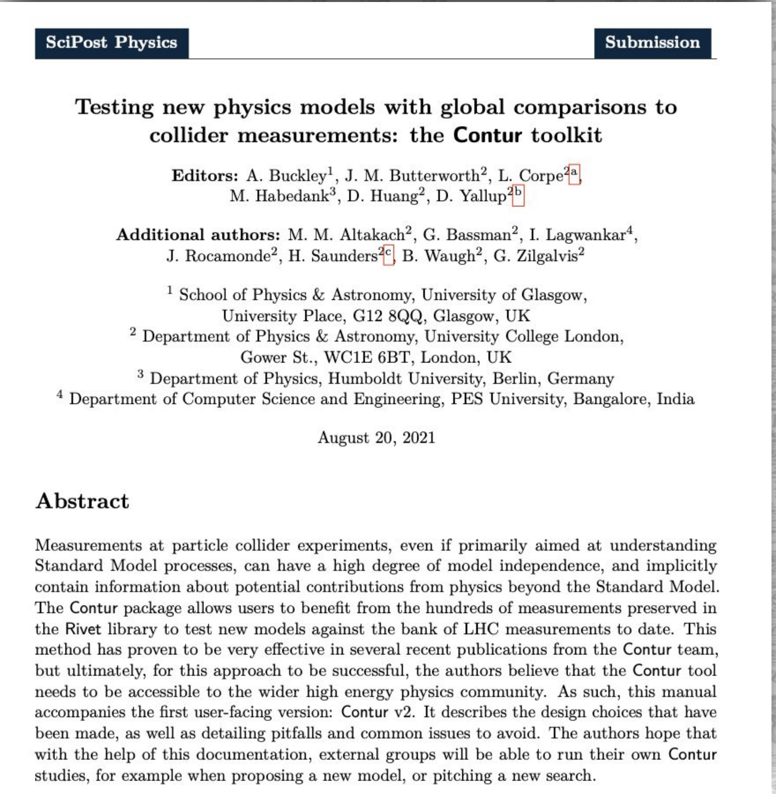
Deformed 3rd Family Hypercharge Model (DY3’).
Favoured region is below the blue line. Above the white line, 95% exclusion.



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 out now, 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
    - ML-assisted parameter scanning: Contour Oracle: **arXiv:2202.05882**
- 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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[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.

Some important pleas

- Uncertainty correlations in HEPData are great ✔
- Please add SM theory particle-level to HEPData ✔
- Include all significant cuts in the fiducial phase space and minimise extrapolations ✔
    - For example, vetoing on b-jets, or extra leptons, may have minimal impact on the SM process and be good for background suppression, but can can have a huge impact on a BSM injection which Rivet/Contur should be told about
- Move toward “final state” measurements (MET, dileptons etc) not process-driven (neutrinos, Z, W…) ✔
- (Make new SM predictions available as yoda/HEPData records) ❌
- (Make new BSM models available as UFO files) ✔

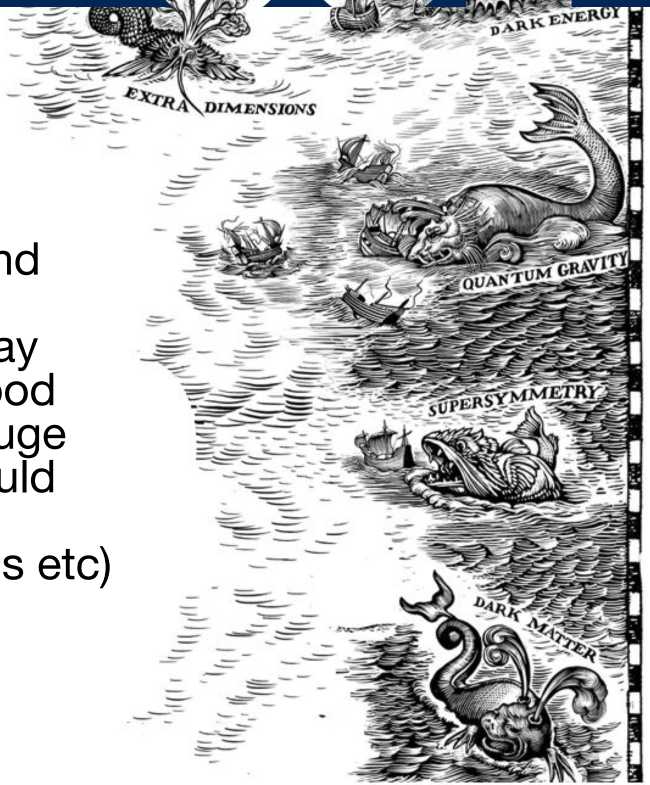
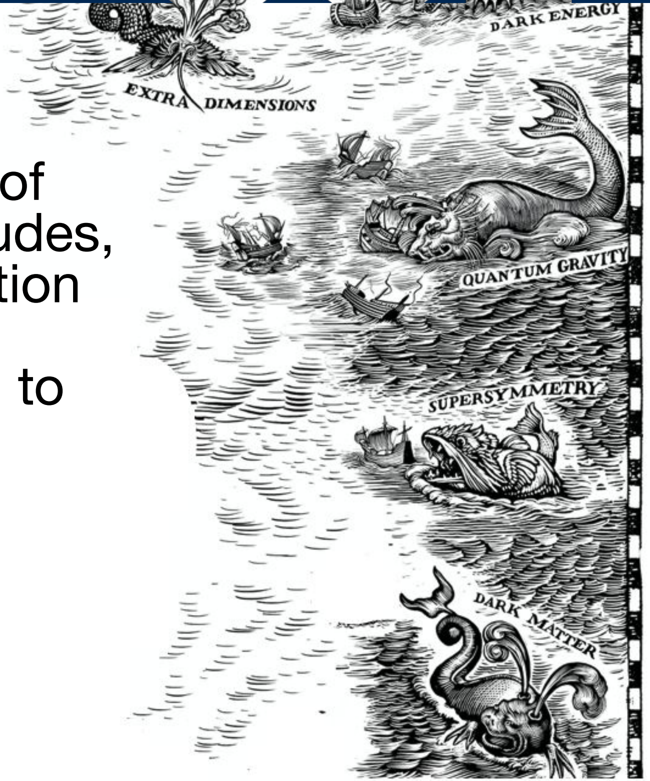


Illustration by Chris Wormell from “A Map of the Invisible”

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, move for “exclusion only” to “hints and discovery?”



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