Status of RIVET and CONTUR

L. Corpe (CERN),

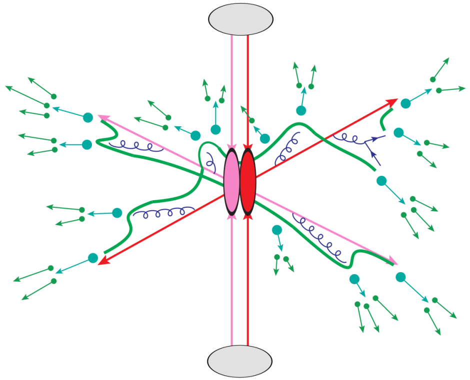
on behalf of the RIVET and CONTUR development teams

TOOLS2021, 26 November 2021

Setting the scene
What is RIVET?

What is RIVET?
Robust Independent Validation of Experiment and Theory

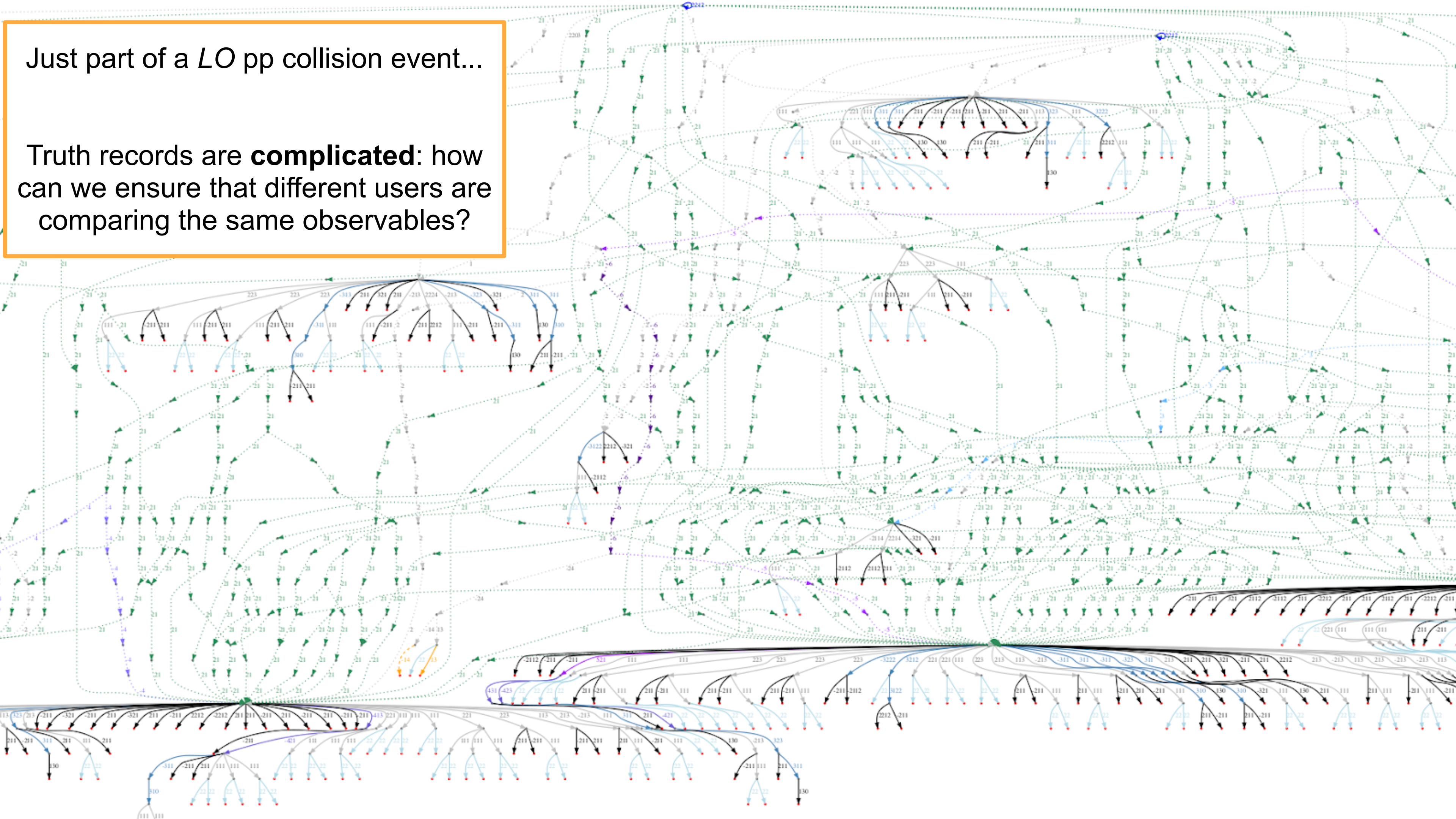
- The “LHC standard” Monte Carlo analysis toolkit
- RIVET can be thought of as a **language** facilitating **communication** between **experimentalists, phenomenologists, theorists...**
  => As any language, point is to **<u>ensure common definitions</u>**
- *Concretely*: A software project to **preserve the logic of HEP data analyses** and further experiment-pheno-theory collaboration. Contains:
  - An event loop
  - Physics object / observable calculators (Physically safe!)
  - Fiducial / generator-independence emphasis
  - Integration with HEPData
  - Transparent weight-stream handling
  - **1000+ analyses!**



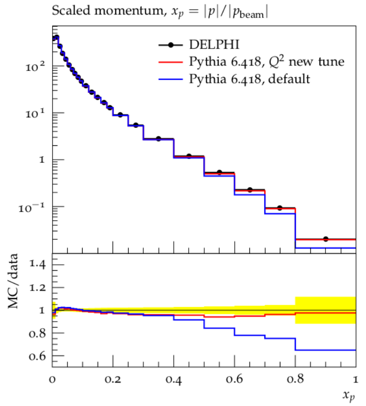
- RIVET now sits at the **centre of a web of analysis reinterpretation tools,** linking experiment to theory

Just part of a *LO* pp collision event...

Truth records are **complicated**: how can we ensure that different users are comparing the same observables?



Design Principles
Lessons learned from HZTool and a decade of LHC



- ***Runnable*** versions of analysis logic: simple and impactful way to communicate physics results. Reproducing a key plot (or not!): powerful way to understand the underlying physics, communicate issues reproducibly, and eventually improve Monte Carlo descriptions

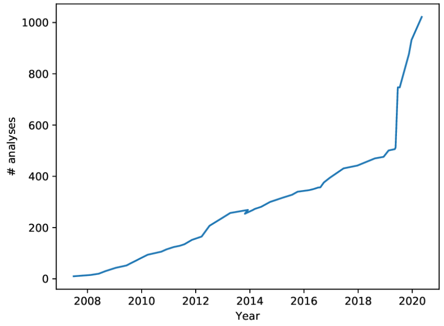
- But there are **many pitfalls:**
  - eg, Partons, bosons, etc. direct from the event graph are frequently unphysical / depend on approximations / may not even exist!
  - Does adding a new generator mean patching ~all analyses?

  ⇒ predict "real" observables, from well-defined final states, which do not depend on event graph or event generator

- And it needs to be performant:
  - **Standardisation**: event format conventions, PDG particle numbering, etc.
  - **Scalability**: cache, not repeat, lots of expensive operations e.g. jet finding
    Important when running 1000+ analysis routines in parallel!

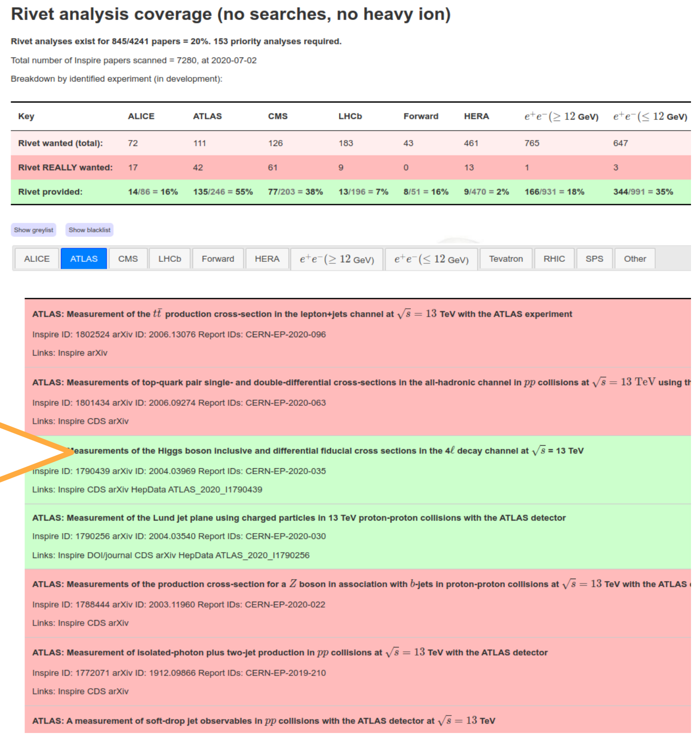
Status of RIVET
Where we are now

- **Version 3.1.0 crossed the 1000 analysis mark**
  A steady flow of analysis submissions, plus the occasional deluge of routines from Herwig devs!



- **Official support from the LHC experiments is crucial**
  preservation = just part of how we do science;
  but still some way to go! Coverage monitoring:

https://rivet.hepforge.org/rivet-coverage



Rivet analysis coverage (no searches, no heavy ion)

Rivet analyses exist for 845/4241 papers = 20%. 153 priority analyses required.

Total number of Inspire papers scanned = 7280, at 2020-07-02

Breakdown by identified experiment (in development):

Key	ALICE	ATLAS	CMS	LHCb	Forward	HERA	$e^+e^-(\geq 12$ GeV)	$e^+e^-(\leq 12$ GeV)
Rivet wanted (total):	72	111	126	183	43	461	765	647
Rivet REALLY wanted:	17	42	61	9	0	13	1	3
Rivet provided:	14/86 = 16%	135/246 = 55%	77/203 = 38%	13/196 = 7%	8/51 = 16%	9/470 = 2%	166/931 = 18%	344/991 = 35%

Show greylist Show blacklist

ALICE | ATLAS | CMS | LHCb | Forward | HERA | $e^+e^-(\geq 12$ GeV) | $e^+e^-(\leq 12$ GeV) | Tevatron | RHIC | SPS | Other

ATLAS: Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s} = 13$ TeV with the ATLAS experiment

Inspire ID: 1802524 arXiv ID: 2006.13076 Report IDs: CERN-EP-2020-096

Links: Inspire arXiv

ATLAS: Measurements of top-quark pair single- and double-differential cross-sections in the all-hadronic channel in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ using th

Inspire ID: 1801434 arXiv ID: 2006.09274 Report IDs: CERN-EP-2020-063

Links: Inspire CDS arXiv

easurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s}$ = 13 TeV

Inspire ID: 1790439 arXiv ID: 2004.03969 Report IDs: CERN-EP-2020-035

Links: Inspire CDS arXiv HepData ATLAS_2020_I1790439

ATLAS: Measurement of the Lund jet plane using charged particles in 13 TeV proton-proton collisions with the ATLAS detector

Inspire ID: 1790256 arXiv ID: 2004.03540 Report IDs: CERN-EP-2020-030

Links: Inspire DOI/journal CDS arXiv HepData ATLAS_2020_I1790256

ATLAS: Measurements of the production cross-section for a Z boson in association with b-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS

Inspire ID: 1788444 arXiv ID: 2003.11960 Report IDs: CERN-EP-2020-022

Links: Inspire CDS arXiv

ATLAS: Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Inspire ID: 1772071 arXiv ID: 1912.09866 Report IDs: CERN-EP-2019-210

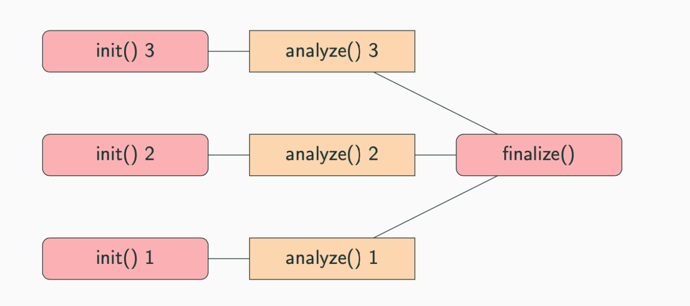
Links: Inspire CDS arXiv

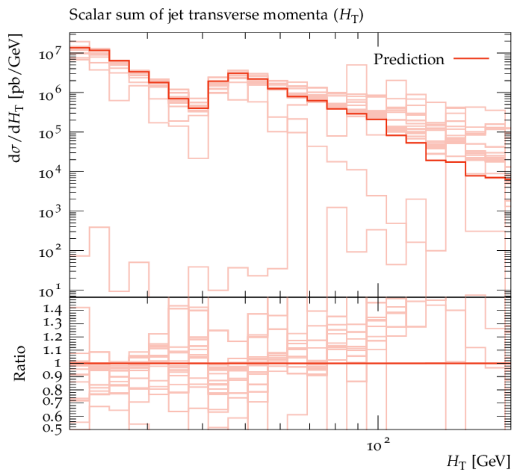
ATLAS: A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV

- **Many “new” features since RIVET v1 (2010):**
  systematics multiweights, “perfect merging”, heavy ions, detector smearing functions, analysis options

Example of new Features: *Multiweights and Re-entry*

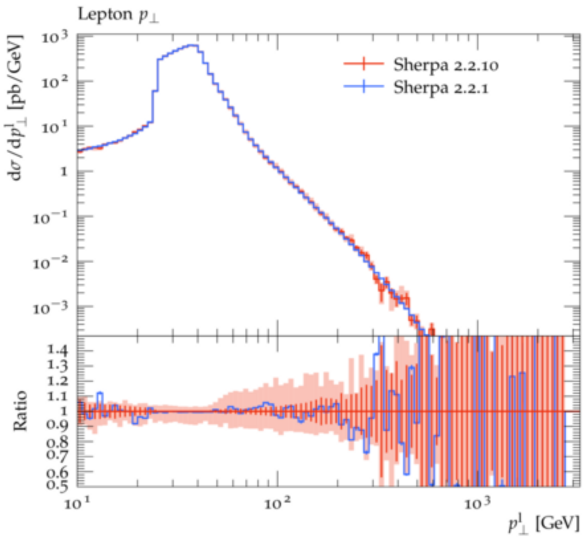
- **Can now re-call finalisation to combine runs:** RAW histogram stage preserves pre-finalize objects
- ⇒ "re-entrant" perfect data-object merging
  - Key for e.g. *pA/pp or W/Z* ratios, + BSM recasting
- **MC weight vectors allow expression of increasingly complex theory uncertainties.** But a burden for analysis chains: have to propagate and correctly combine O(200) weight streams!
- **RIVET 3: complex automatic handling of weights** ~invisible to users: data objects *look* like histograms etc. but are secretly multiplexed

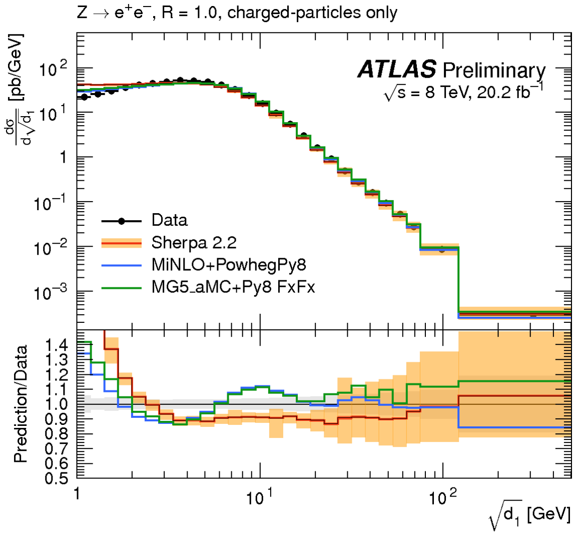


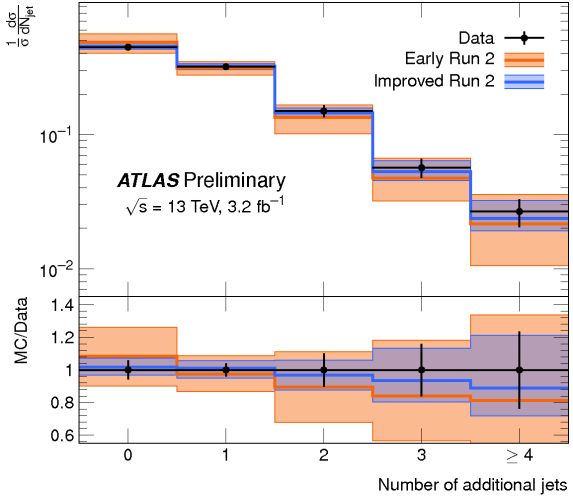


New Features:
Multiweights in action

ATLAS MC studies have been a significant driver of this feature
(thanks to Chris Gutschow)





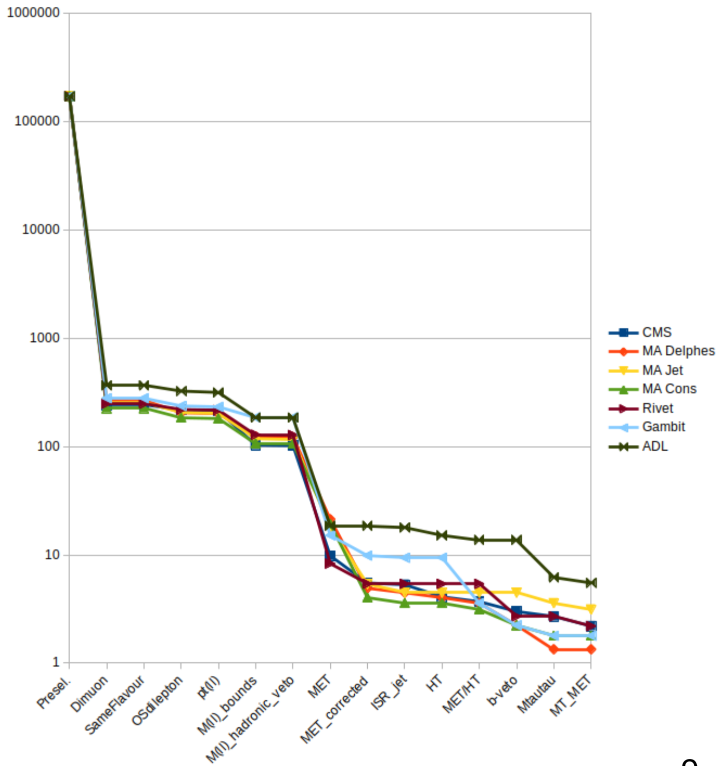


Weight-naming standardisation underway via MCnet

New Features:
Detector Emulation and Searches

- Detector smearing is built into RIVET's projection system: opens door for reco-level analyses
- Similar to Delphes, but more flexible and can be analysis-specific: allows "tuned" jet-substructure smearing, systematic studies, upgrade studies...

- Reco-level RIVET routines: **preserve searches**
    - Phase-space specific detector smearing/efficiency functions
    - Similar mechanisms in other recasting tools. **Can we do for Searches what we did for Measurements?**



Les Houches 2019 CMS soft-lepton recasting-tools comparison

The Future of RIVET
What's on the horizon?

- **Vision: RIVET as a standard for “truth-level” observables, across collider physics**
- Not just standalone, but as a library in pheno & experiment frameworks, too: standard MC definitions, seamless systematics handling, etc.
- At its core: a physics-oriented system for physicists to **compare MC predictions to one another and to data, on many simultaneous observables, in myriad ways**
  We don’t know all the use-cases yet! **See second half of this talk for one which we had not imagined when we started!**
- **Challenges:**
  - Extension of HepData and other community infrastructure for ever more precise data. Even our compressed data format is struggling with the volume of analyses and data. Work needed on multiweight-oriented data format and tools
  - Improved, modernised visualisation and exploration
  - Connections to global fitting tools
  - Preserving MVAs: BDT and NN in vanilla C++

Find a RIVET ten-minute tutorial in the backup slides!

CONTUR

Leveraging RIVET to determine BSM exclusions at scale

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**

Does this sound familiar?

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

We have the technology

- <u>We already 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.

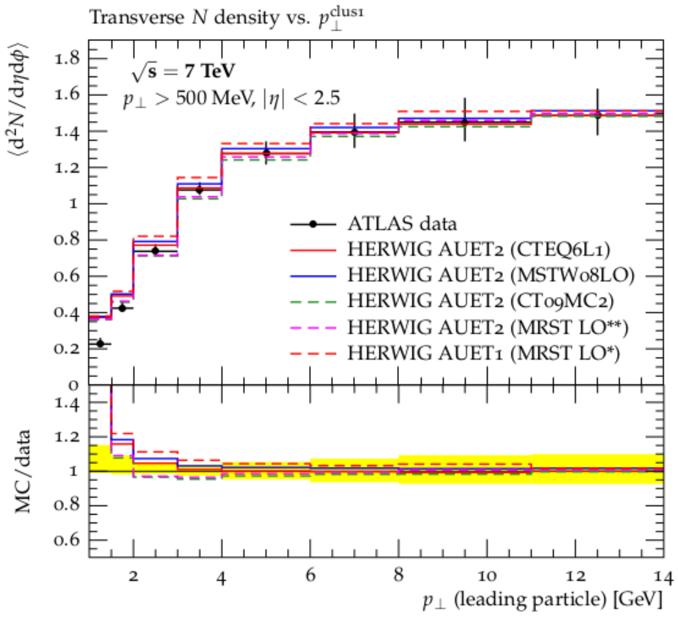
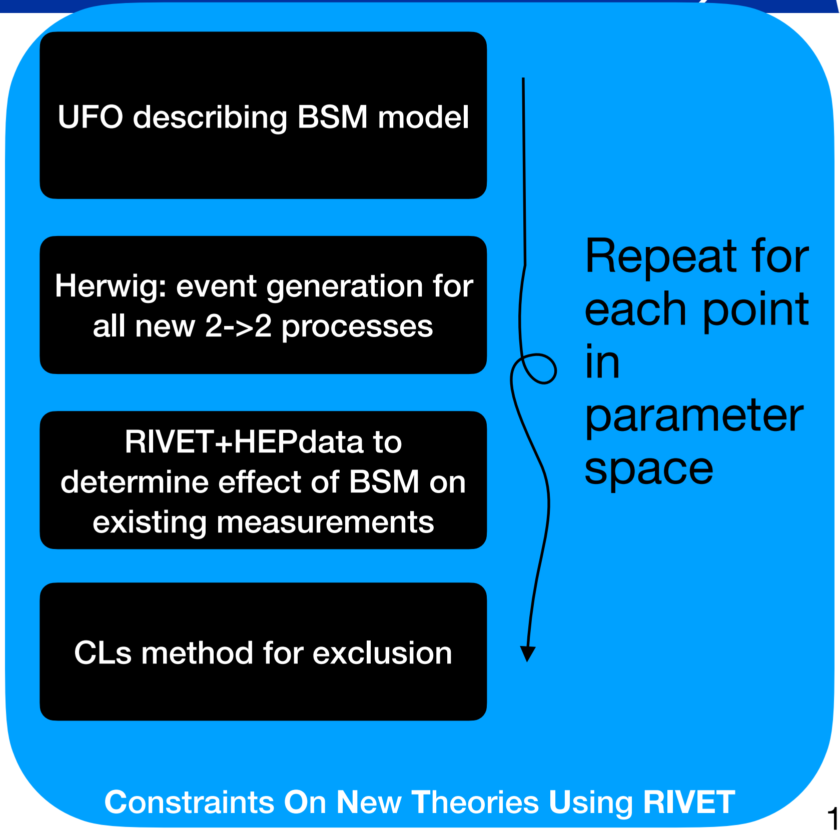


Illustration by Chris Wormell from "A Map of the Invisible"

Overview of the CONTUR method

- Input: **Universal Feynrules Object** (new physics Lagrangian coded up in python)
- 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 √s and final state to ensure orthogonality**
- Compare size of deviation to reference data from HEPData (including correlations!) to check if signal would already have been seen



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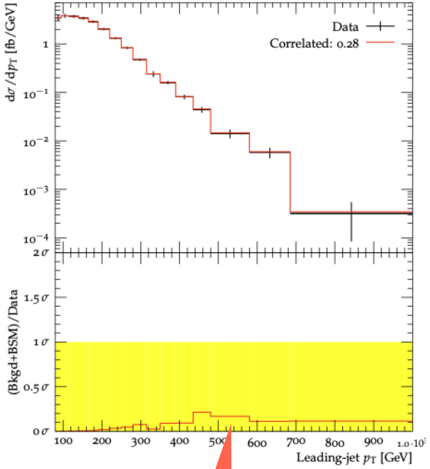
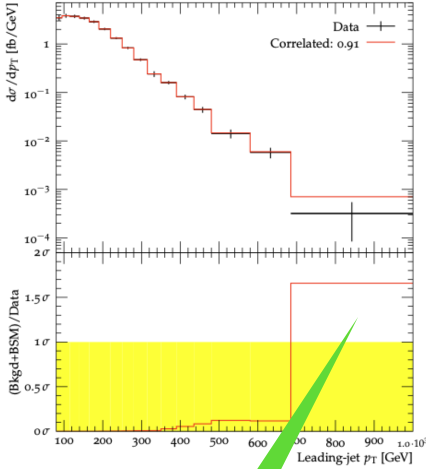
- **Routines categorised into 'pools' grouped by √s and final state to ensure orthogonality**

- Compare size of deviation to reference data from HEPData (including correlations!) to check if signal would already have been seen: **if it would be statistically distinct, the model is eliminated!**



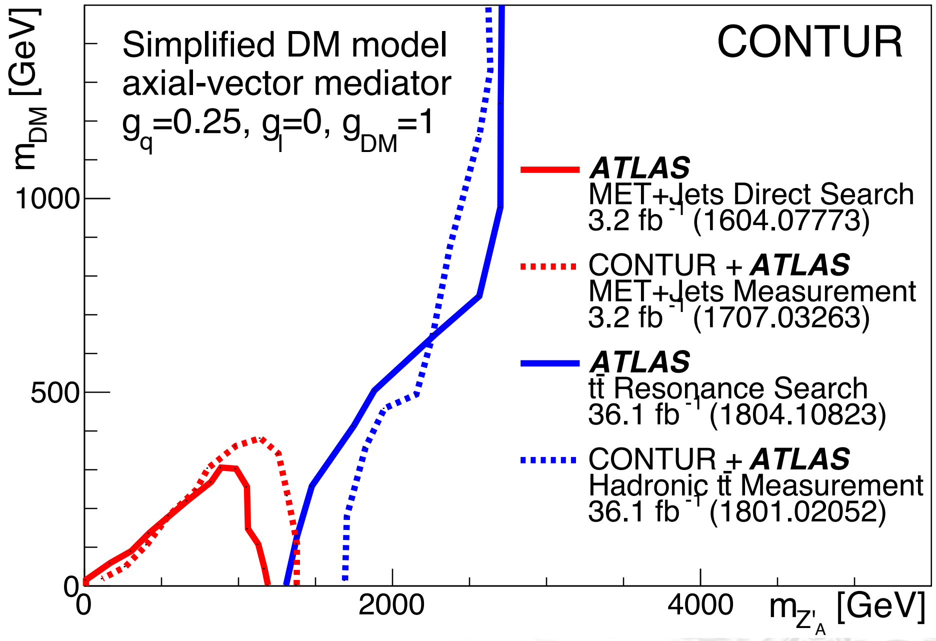
Signal would have small effect wrt uncertainties, can't exclude it (28 % CL)



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

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 eek 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!**

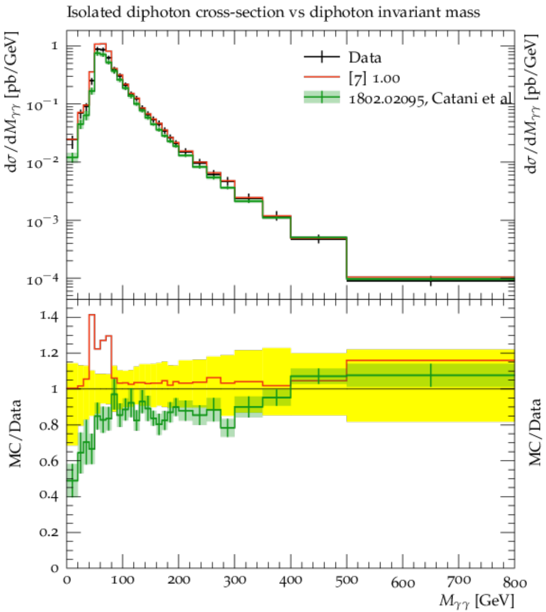


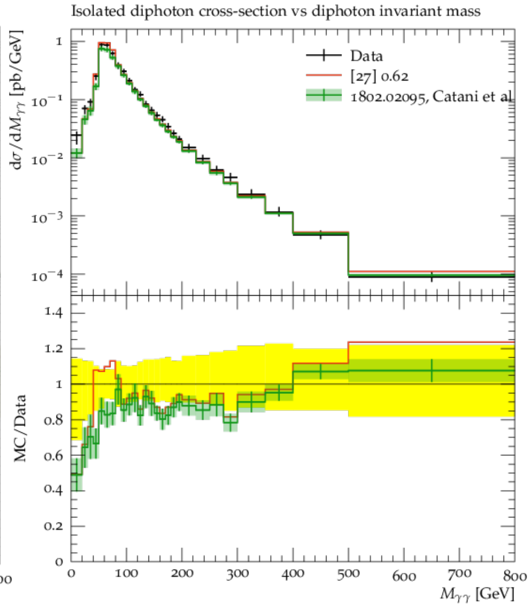
State of the art MC predictions And correlations

- 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!

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

arXiv:1811.11452

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

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Abstract: The large and growing library of measurements from the Large Hadron Coll has significant power to constrain extensions of the Standard Model. We consider s constraints on a well-motivated model involving a gauged and spontaneously-broken B symmetry, within the Contur framework. The model contains an extra Higgs boso gauge boson, and right-handed neutrinos with Majorana masses. This new particle con implies a varied phenomenology highly dependent on the parameters of the model, well-suited to a ge... significantly constr... remain open, some

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

arXiv:1904.10954

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[a] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, United Kingdom*

[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 Copenhagen, DK-2100 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' models that fit neutral current $B-$anomalies, including constraints coming from measurements of Standard Model (SM) signatures at the LHC. The 'MDM' simplified model is not constrained by the SM measurements but *is* strongly constrained by a 139 fb^{-1} 13 TeV ATLAS di-muon search. Constraints upon the 'MUM' simplified model are much weaker. A combination ... ATLA ... e case ... $M_{Z'}$ <

SciPost Physics arXiv:2006.07172 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]

[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

September 8, 2020

Abstract

Quark partners with non-chiral couplings appear in several extensions of the Standard Model. They may have non-trivial generational structure to their couplings, and may be produced either in pairs via the strong and EM interactions, or singly via the new couplings of the model. Their decays often produce heavy ... ady-measured ... f the sensitiv- ... st comparing ... ning to some

SciPost Physics arXiv:2009.02220 Submission

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

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

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

January 12, 2021

Abstract

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

EPJ manuscript No.
(will be inserted by the editor)

arXiv:2110.13518

Large Hadron Collider Constraints on Some Simple Z' Models for $b \to s\mu^+\mu^-$ Anomalies

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Abstract. We examine current Large Hadron Collider constraints on some simple Z' models that significantly improve on Standard Model fits to $b \to s\mu^+\mu^-$ transition data. The models that we consider are the '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.

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

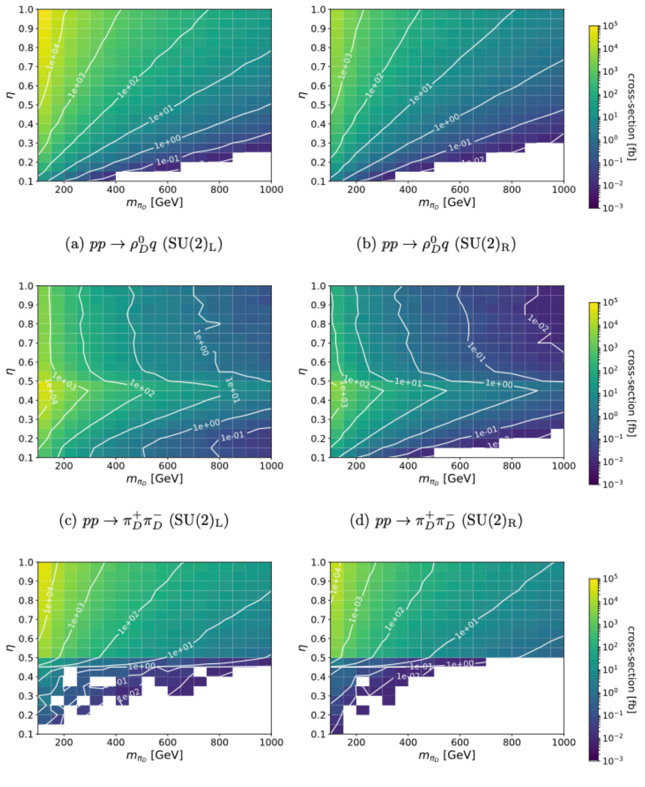
- What if **dark matter** is a **composite particle** arising from **non-Abelian dynamics**? eg SU(4) which confines at some scale Λ_{dark}

- 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)$_L$)

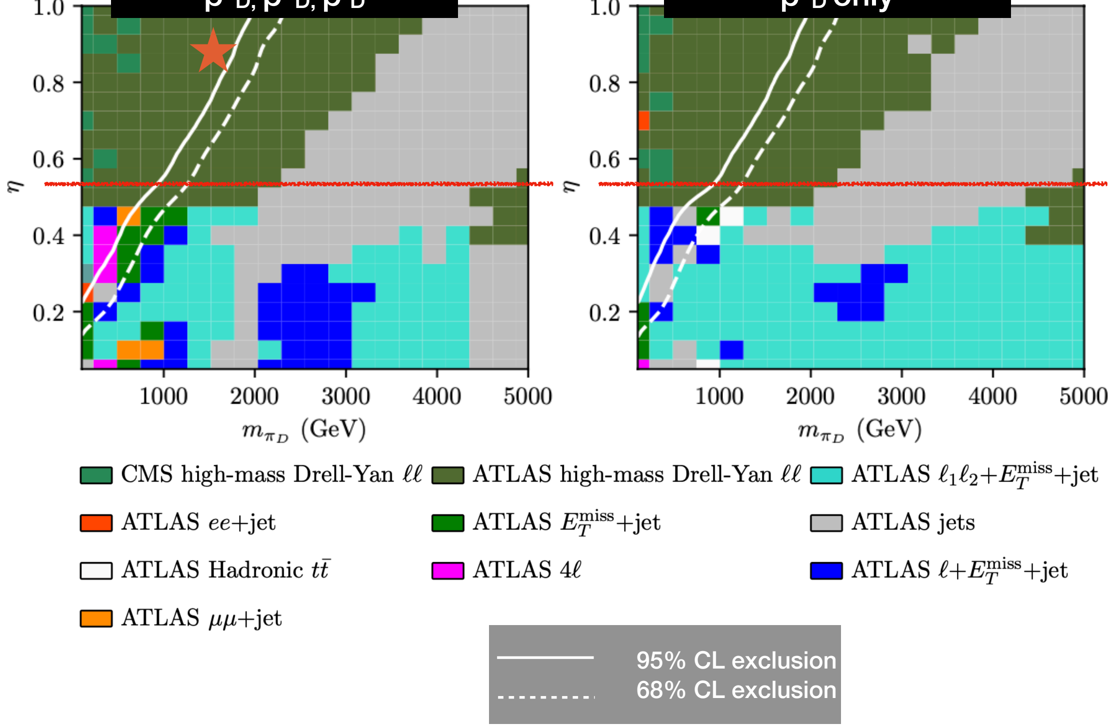
(f) s-channel $pp \to \rho_D \to l^+ l^-$ (SU(2)$_R$)

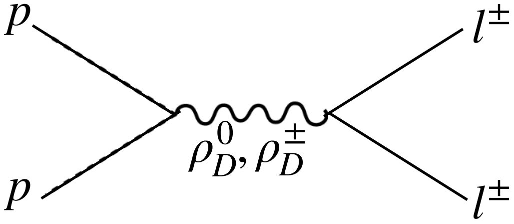
CONTUR results

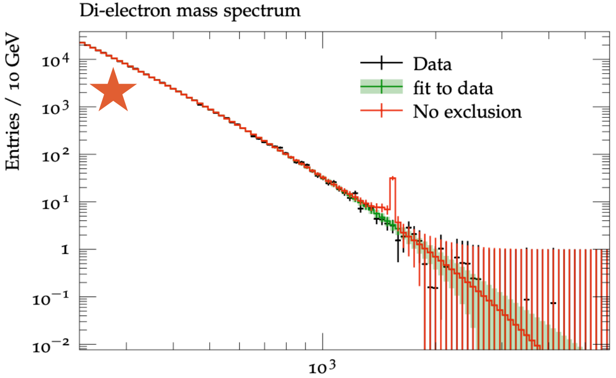
$\eta := m(\rho_D) / m(\pi_D)$

Left-handed model
$\rho^0_D, \rho^+_D, \rho^-_D$

Right-handed model
ρ^0_D only



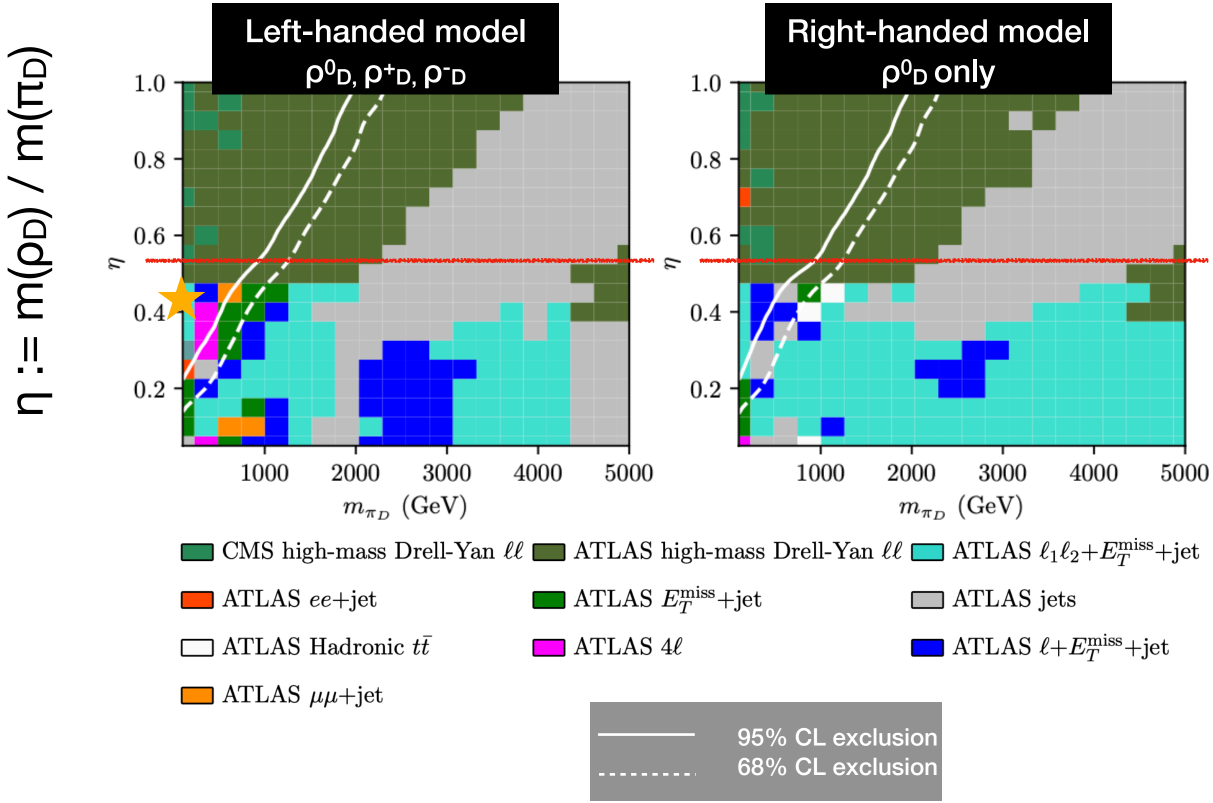


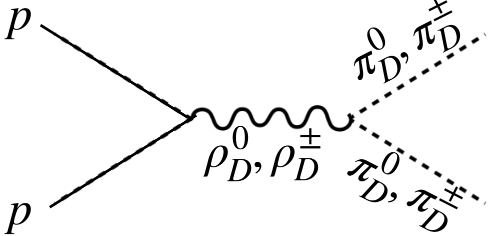


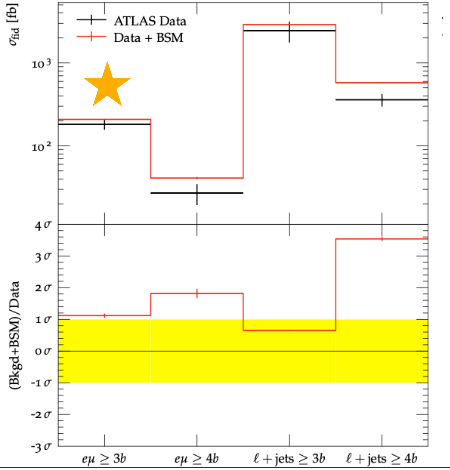
Search for high-mass dilepton resonances using 139/fb pp collision data collected at 13 TeV with the ATLAS detector
https://arxiv.org/abs/1903.06248

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

CONTUR results



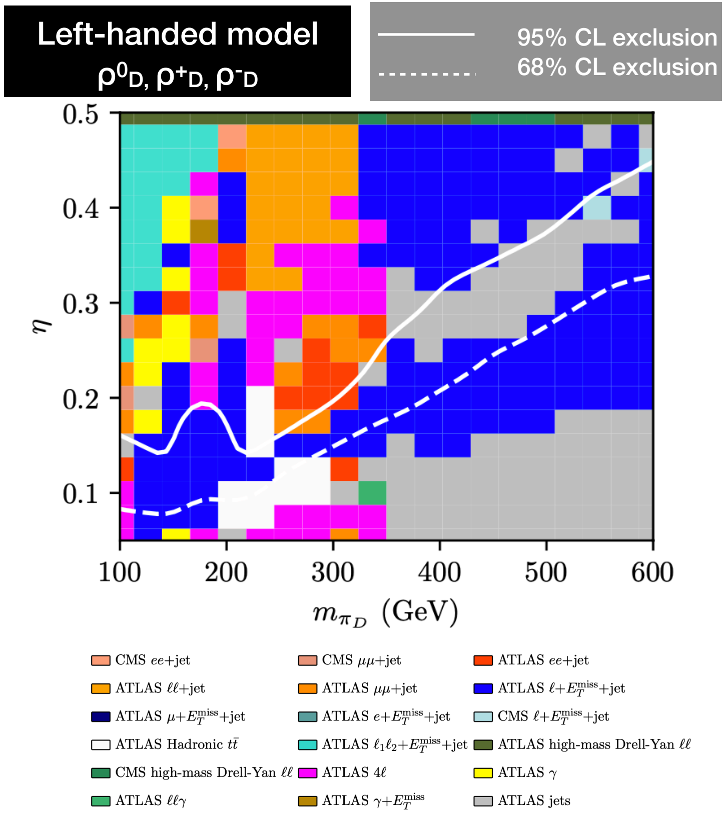




Measurements of fiducial and differential cross-sections of tt production with additional heavy-flavour jets in proton-proton collisions at 13 TeV with the ATLAS detector (36/fb)
https://arxiv.org/abs/1811.12113

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 ɣɣ measurements, as π_D->ɣɣ 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 $b \to s\mu^+\mu^-$

Fresh from the arXiv

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

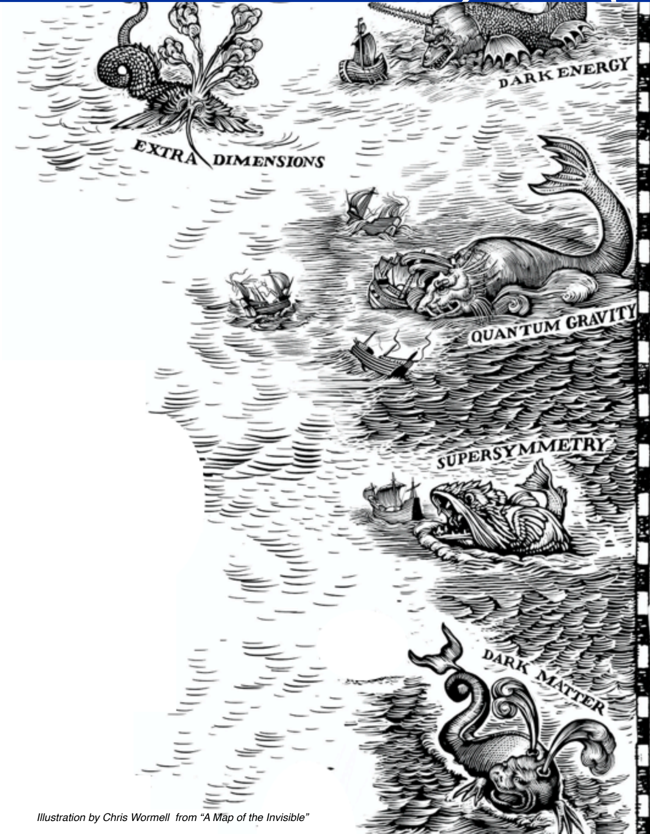


Illustration by Chris Wormell from "A Map of the Invisible"

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

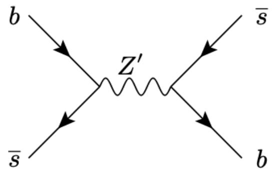
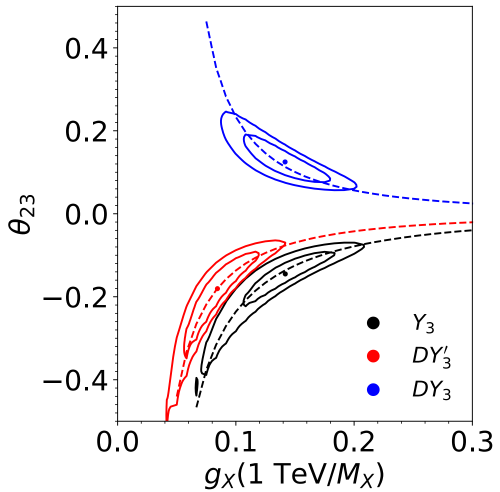
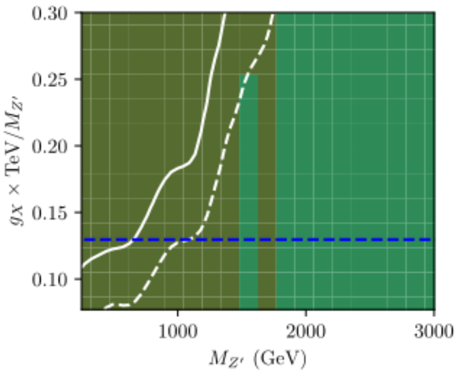


Fig. 2: Tree-level Feynman diagram of a Z'-mediated process which contributes to $B_s - \overline{B_s}$ mixing.



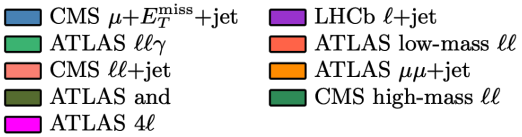
Z’ models motivated by LFV anomalies

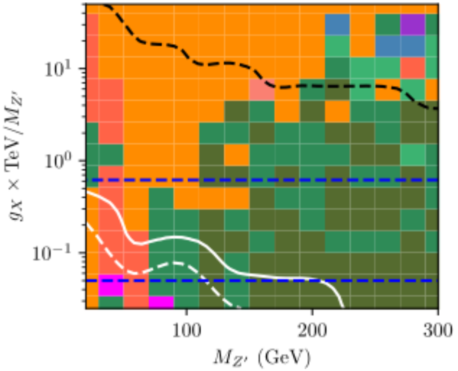
- Main signature is dimuons
- In the high Z’ mass regions, what sensitivity there is comes from the ATLAS dimuon search, which is implemented in RIVET/CONTUR. For TFHM models that’s all there is.
- The B_3-L_2 model, the “window” at low mass largely is closed by low mass Drell Yan and Z ->ll measurements



Deformed 3rd Family Hypercharge Model (DY3’).

Favoured region is below the blue line. Above the white line, 95% exclusion.



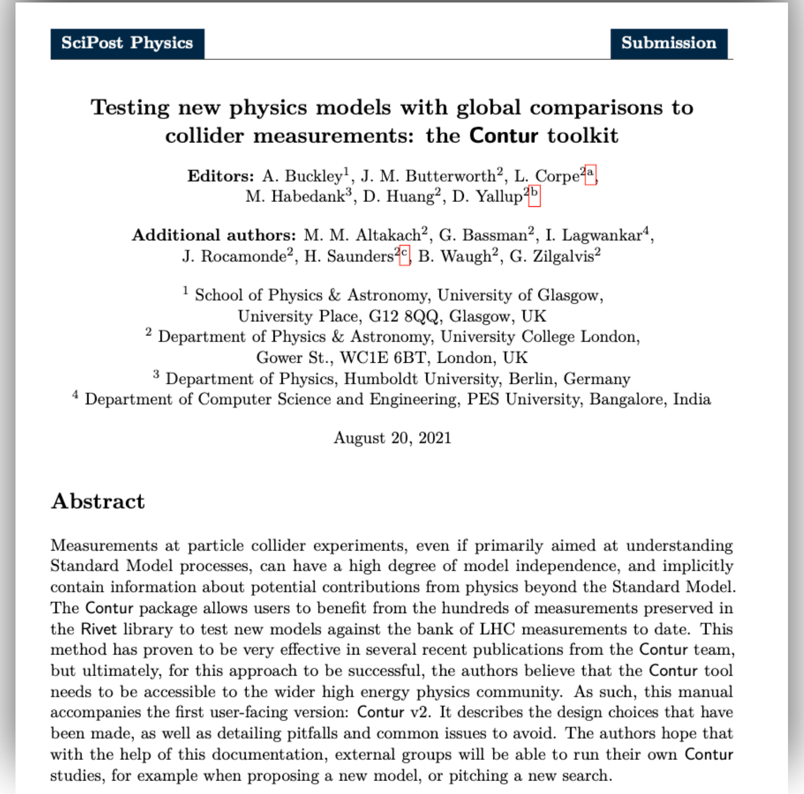


B_3-L_2 Model.

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)
    - Docker images and tutorials available (**Join us this afternoon!**)
    - Support channel on Mattermost https://mattermost.web.cern.ch/cedar/channels/contur
- Latest release is CONTUR v2.1.1
  - Support for non-LHC beams
  - Speed optimisations, correlations used by default for little cost in processing time
  - Increasing bank of SM predictions



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]

[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
[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.

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    - Released with dedicated com
(arXiv:2102.04377)
    - Docker images and tutorials
(**Join us this afternoon!**)
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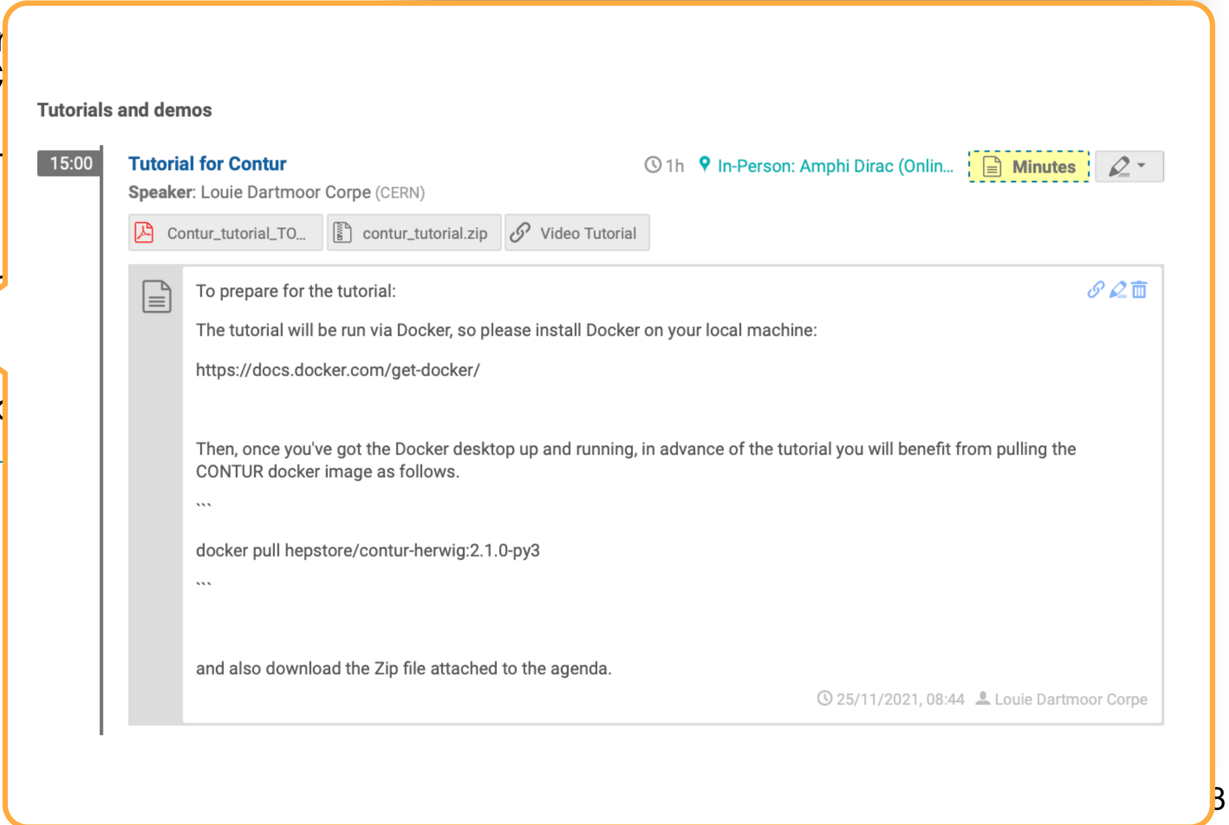
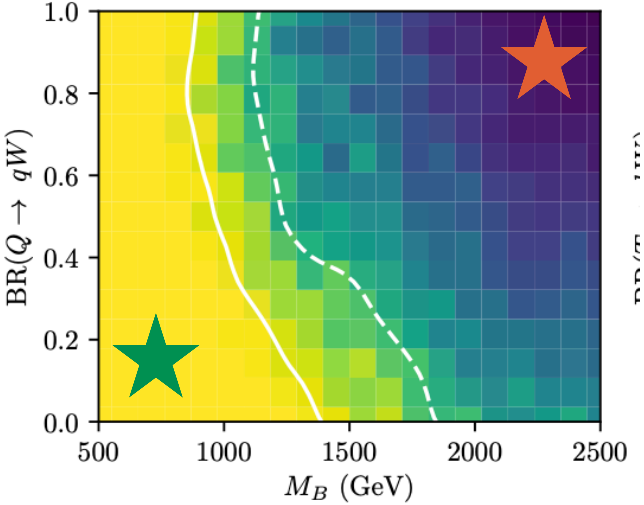


What's on the Horizon?
Machine-learning assisted parameter scanning

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!

What's on the Horizon?
Machine-learning assisted parameter scanning

Paper in preparation!

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- Next CONTUR version 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

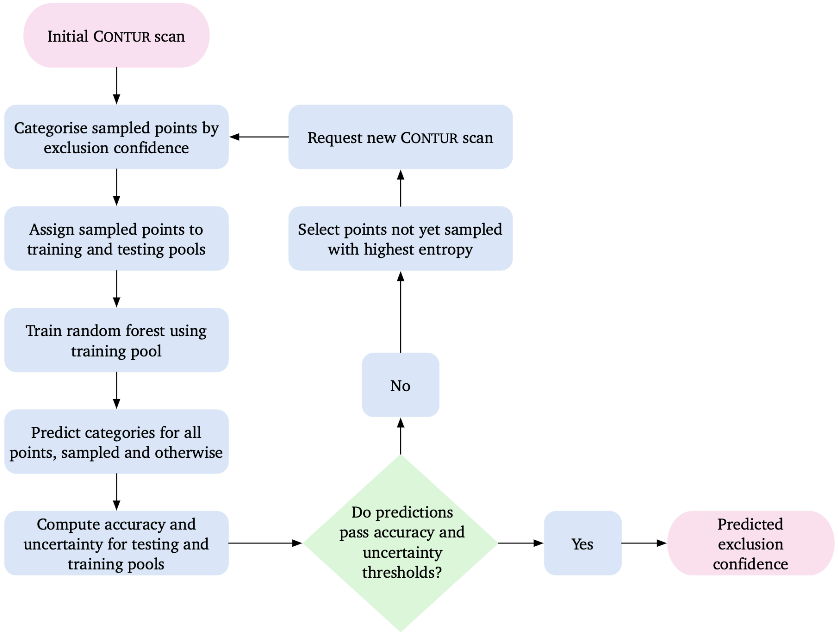

Figure 2: Process of the CONTUR ORACLE

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Machine-learning assisted parameter scanning

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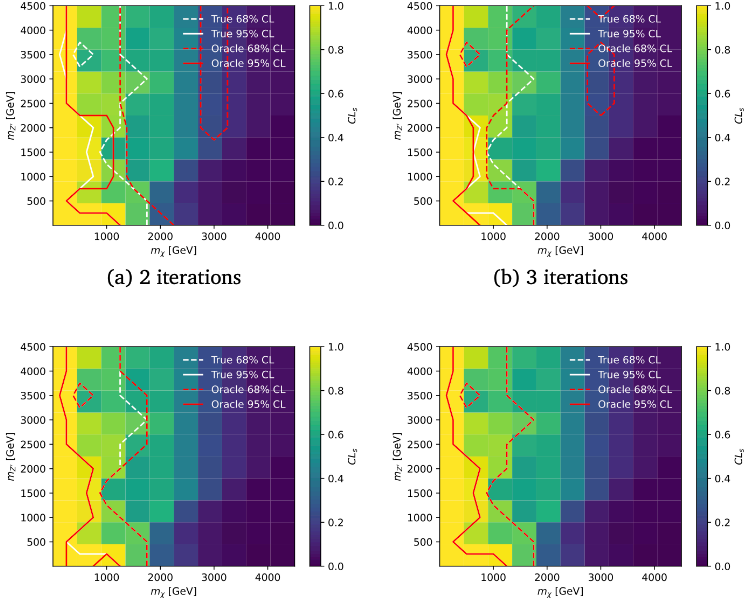


(a) 2 iterations

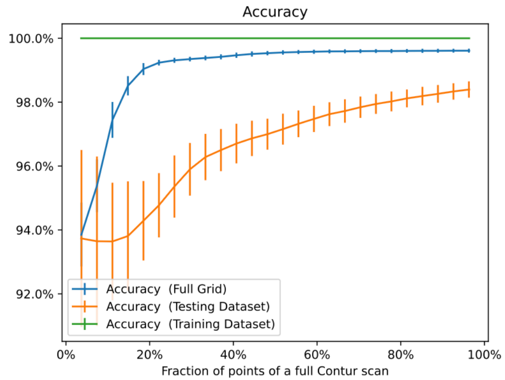
(b) 3 iterations

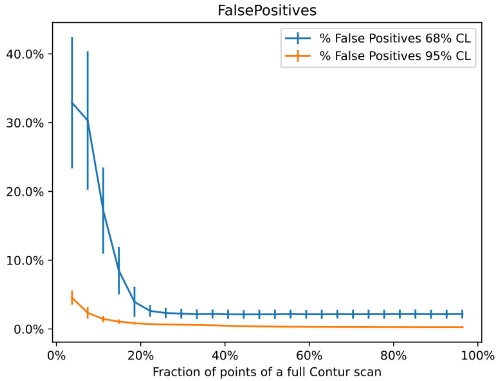
(c) 4 iterations

(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





Louie Corpe, CERN (lcorpe@cern.ch)

Summary

- Today I presented a summary of the RIVET toolkit for analysis preservation and data-MC comparison
  - Presented design principles, applications and future developments

- I then highlighted the CONTUR tool, which wraps around RIVET to create a powerful recasting tool, with a decade of LHC results at it's fingertips
  - Showed some of the most recent physics studies, and future prospects
  - CONTUR v2 was a public-facing release:
    you can use it for your own physics studies and phenomenology papers!

- This afternoon: CONTUR tutorial, we hope to see you there!

Thank you!

Questions?

home.cern

RIVET 10-min tutorial
(CONTUR tutorial this afternoon 3pm)

Getting & using Rivet

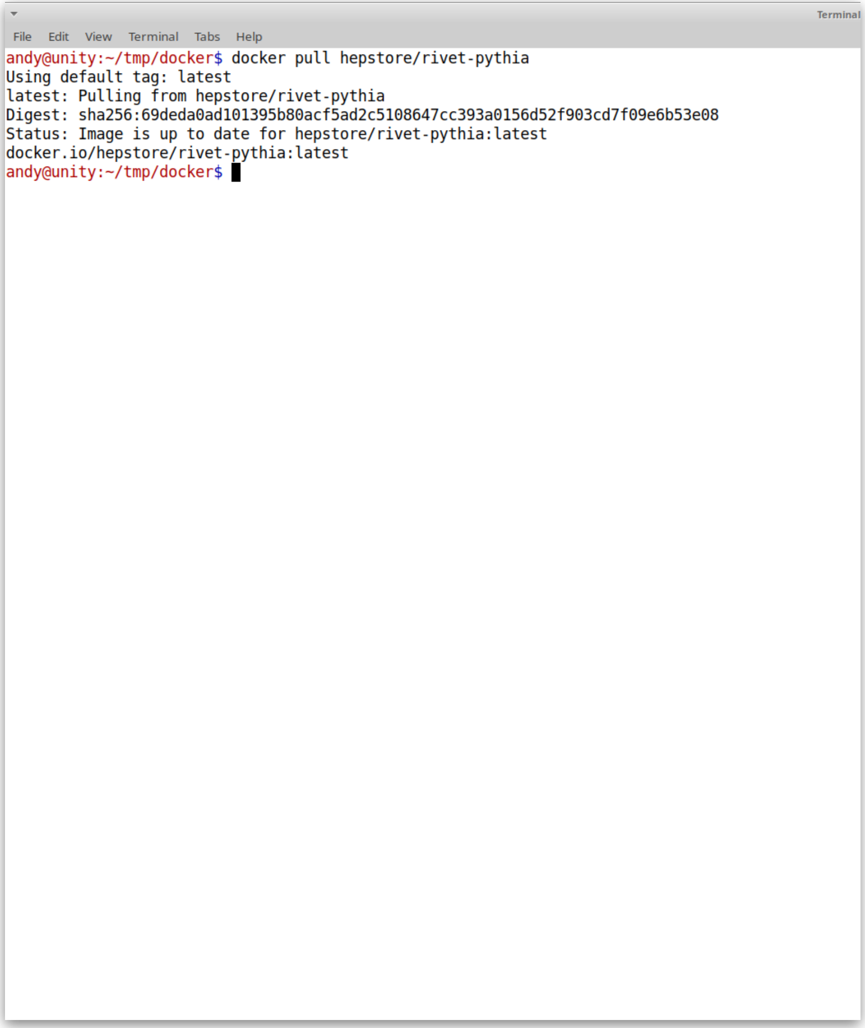
Lightweight analysis preservation is valuable… and easy to start

As either a “user” or analysis author, the barrier is lower than ever: we recommend using our Docker images to get started

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



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```
andy@unity:~/tmp/docker$ docker pull hepstore/rivet-pythia
Using default tag: latest
latest: Pulling from hepstore/rivet-pythia
Digest: sha256:69deda0ad101395b80acf5ad2c5108647cc393a0156d52f903cd7f09e6b53e08
Status: Image is up to date for hepstore/rivet-pythia:latest
docker.io/hepstore/rivet-pythia:latest
andy@unity:~/tmp/docker$ docker run -it --rm -v $PWD:/out hepstore/rivet-pythia
root@fd5bf204ef9e:/work#
```

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```
File  Edit  View  Terminal  Tabs  Help
root@d8c06acf8f66:/work# cp /usr/local/share/Pythia8/examples/main93.cmnd py.cmnd
root@d8c06acf8f66:/work# nano py.cmnd
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```
File  Edit  View  Terminal  Tabs  Help
  GNU nano 4.8
! Command file for testing different functionalities of main93
! Note that for the various output functionalities to work,
! HepMC, YODA, RIVET and ROOT respectively needs to either
! be installed to system path, or appended before compiling.

! 1) Settings related to the physics processes generated. Here
! a simple pp soft QCD run at 7 TeV.
Beams:idA = 2212        ! first beam p = 2212
Beams:idB = 2212        ! second beam p = 2212
Beams:eCM = 7000.       ! CM energy of collision
SoftQCD:all = on        ! All soft QCD processes are on,

! 3) Settings related to output
Main:runRivet = on              ! Run Rivet (specify analyses below)
Main:analyses = ATLAS_2010_S8817804,ALICE_2010_S8625980,CMS_2011_S8957746
          ! Names of Rivet analyses to be run, as a comma-separated list
Main:writeHepMC = off           ! Write .hepmc events to a file.
Main:writeRoot = off            ! Write particle level output to a root file
Main:outputLog = on             ! Put all printed output to a log file.

^G Get Help    ^O Write Out   ^W Where Is    ^K Cut Text    ^J Justify     ^C Cur Pos
^X Exit        ^R Read File   ^\ Replace     ^U Paste Text  ^T To Spell    ^_ Go To Line
```

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root@d8c06acf8f66:/work# nano py.cmnd
root@d8c06acf8f66:/work# pythia8-main93 -c py.cmnd -n 10000
```

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root@d8c06acf8f66:/work# nano py.cmnd
root@d8c06acf8f66:/work# pythia8-main93 -c py.cmnd -n 10000

The MCnet usage guidelines apply to Rivet: see http://www.montecarlonet.org/GUIDELINES
Please acknowledge Rivet in results made using it, and cite https://arxiv.org/abs/1912.05451
root@d8c06acf8f66:/work# ls
Rivet.yoda  ex.cmnd  py.cmnd  pythia.log
root@d8c06acf8f66:/work#
```

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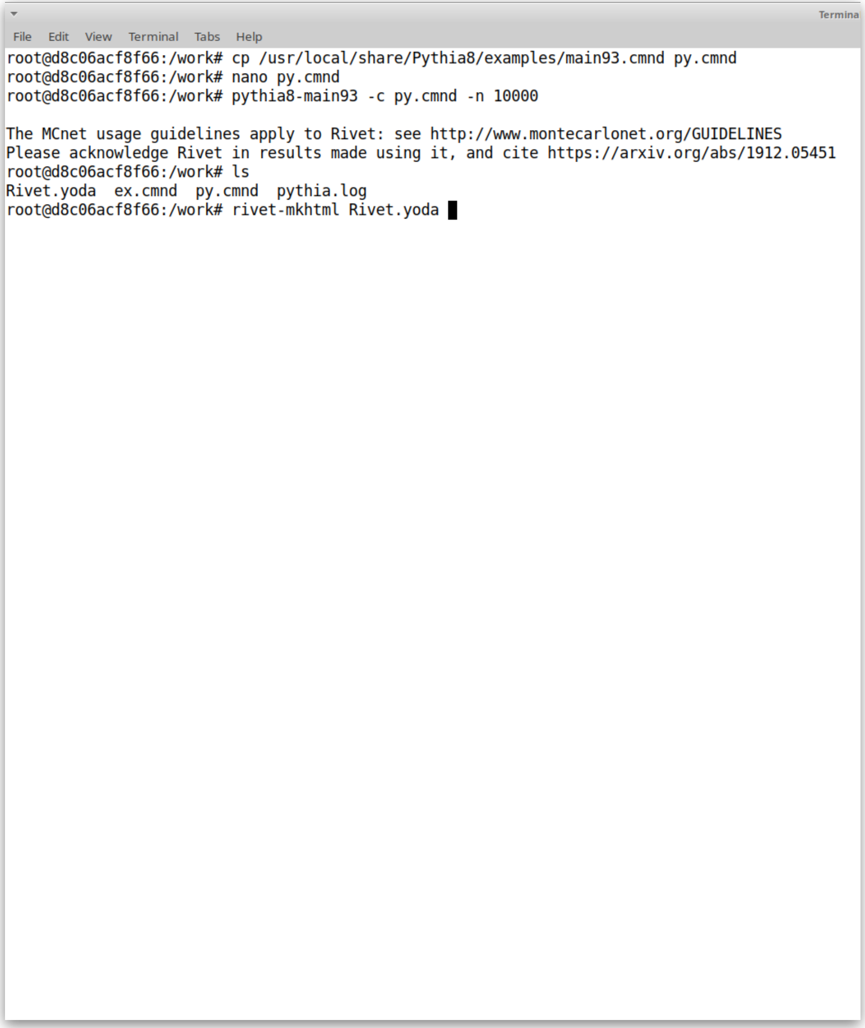

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Rivet.yoda  ex.cmnd  py.cmnd  pythia.log
root@d8c06acf8f66:/work# rivet-mkhtml Rivet.yoda
Making 35 plots
Plotting ./rivet-plots/ALICE_2010_S8625980/Nevt_after_cuts.dat (35/35 remaining)
Plotting ./rivet-plots/ALICE_2010_S8625980/d03-x01-y01.dat (34/35 remaining)
Plotting ./rivet-plots/ALICE_2010_S8625980/d06-x01-y01.dat (33/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d01-x01-y01.dat (32/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d02-x01-y01.dat (31/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d03-x01-y01.dat (30/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d04-x01-y01.dat (29/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d05-x01-y01.dat (28/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d06-x01-y01.dat (27/35 remaining)
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root@d8c06acf8f66:/work# rivet-mkhtml Rivet.yoda
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Plotting ./rivet-plots/ATLAS_2010_S8817804/d06-x01-y01.dat (27/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d07-x01-y01.dat (26/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d08-x01-y01.dat (25/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d09-x01-y01.dat (24/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d10-x01-y01.dat (23/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d11-x01-y01.dat (22/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d12-x01-y01.dat (21/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d13-x01-y01.dat (20/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d14-x01-y01.dat (19/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d15-x01-y01.dat (18/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d16-x01-y01.dat (17/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d17-x01-y01.dat (16/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d18-x01-y01.dat (15/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d19-x01-y01.dat (14/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d20-x01-y01.dat (13/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d21-x01-y01.dat (12/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d22-x01-y01.dat (11/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d23-x01-y01.dat (10/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d24-x01-y01.dat (9/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d25-x01-y01.dat (8/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d26-x01-y01.dat (7/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d01-x01-y01.dat (6/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d02-x01-y01.dat (5/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d03-x01-y01.dat (4/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d04-x01-y01.dat (3/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d05-x01-y01.dat (2/35 remaining)
Plotting ./rivet-plots/CMS_2011_S8957746/d06-x01-y01.dat (1/35 remaining)
root@d8c06acf8f66:/work#
```

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Plotting ./rivet-plots/ALICE_2010_S8625980/d03-x01-y01.dat (34/35 remaining)
Plotting ./rivet-plots/ALICE_2010_S8625980/d06-x01-y01.dat (33/35 remaining)
Plotting ./rivet-plots/ATLAS_2010_S8817804/d01-x01-y01.dat (32/35 remaining)
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root@d8c06acf8f66:/work# cp -r rivet-plots/ /out/
root@d8c06acf8f66:/work#
```

Getting & using Rivet

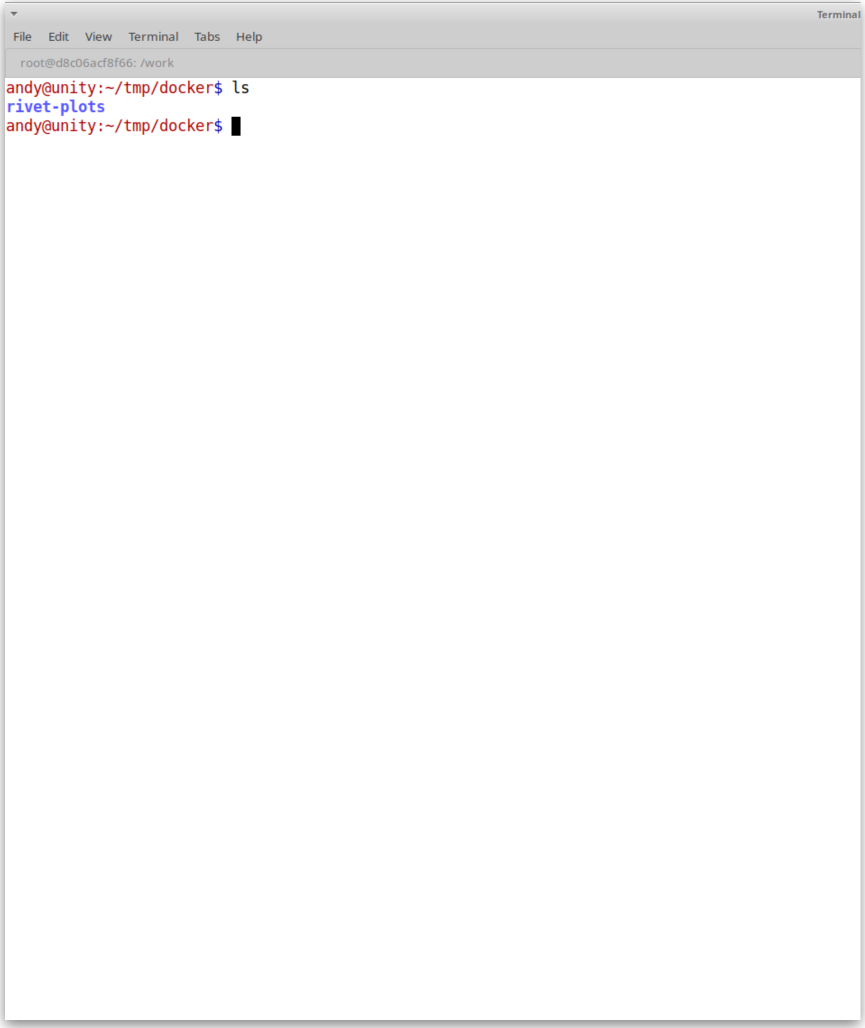
Lightweight analysis preservation is valuable… and easy to start

As either a “user” or analysis author, the barrier is lower than ever: we recommend using our Docker images to get started

Ideal for student projects!

Tutorials available from the Rivet website, a walkthrough in the R3 paper

Imitation the highest form of flattery ⇒ copy an existing analysis!



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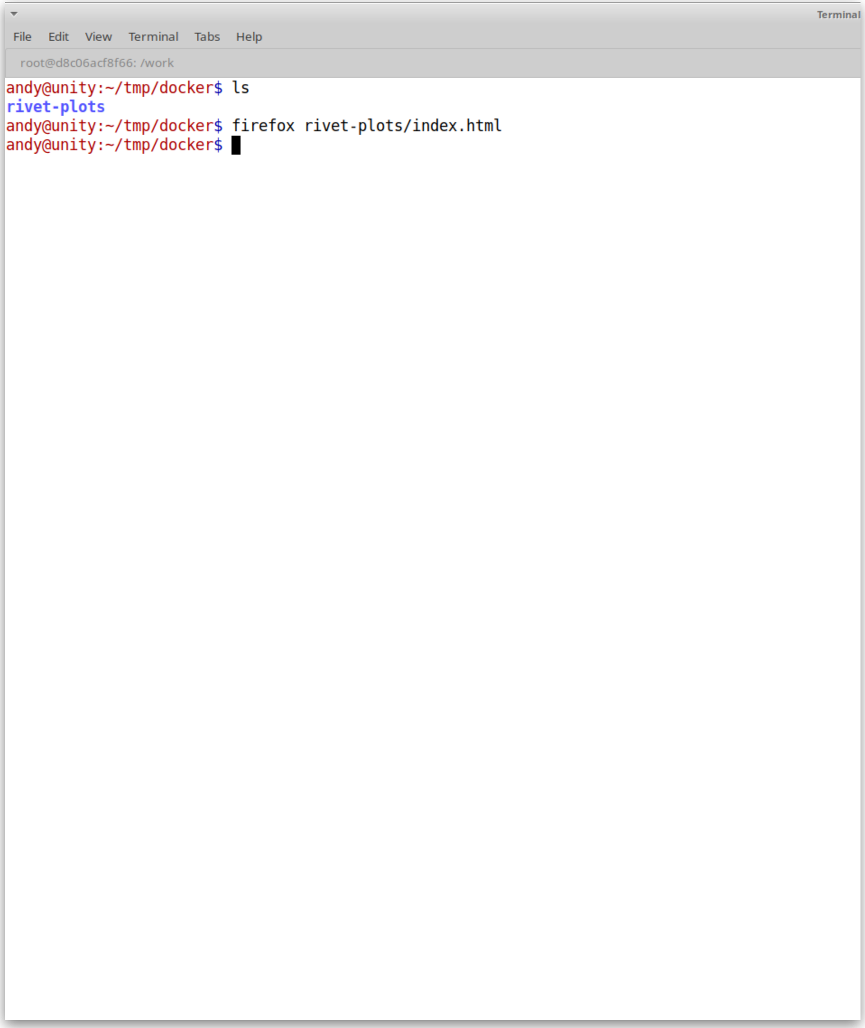

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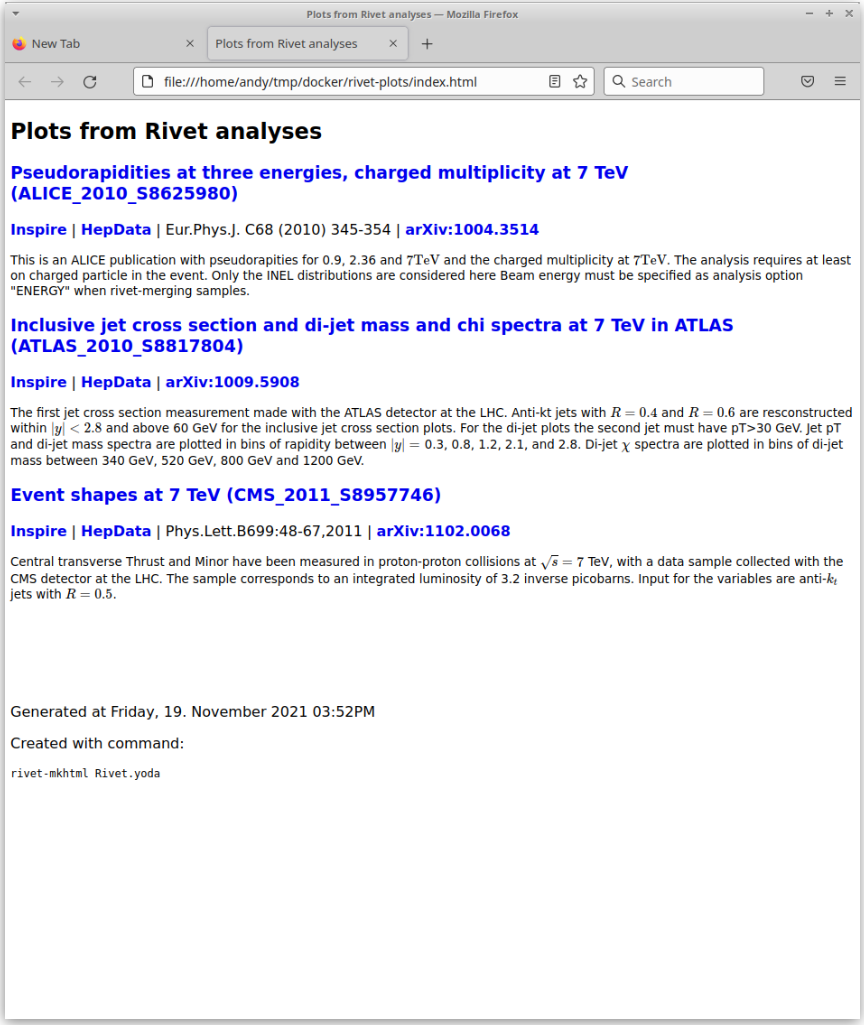

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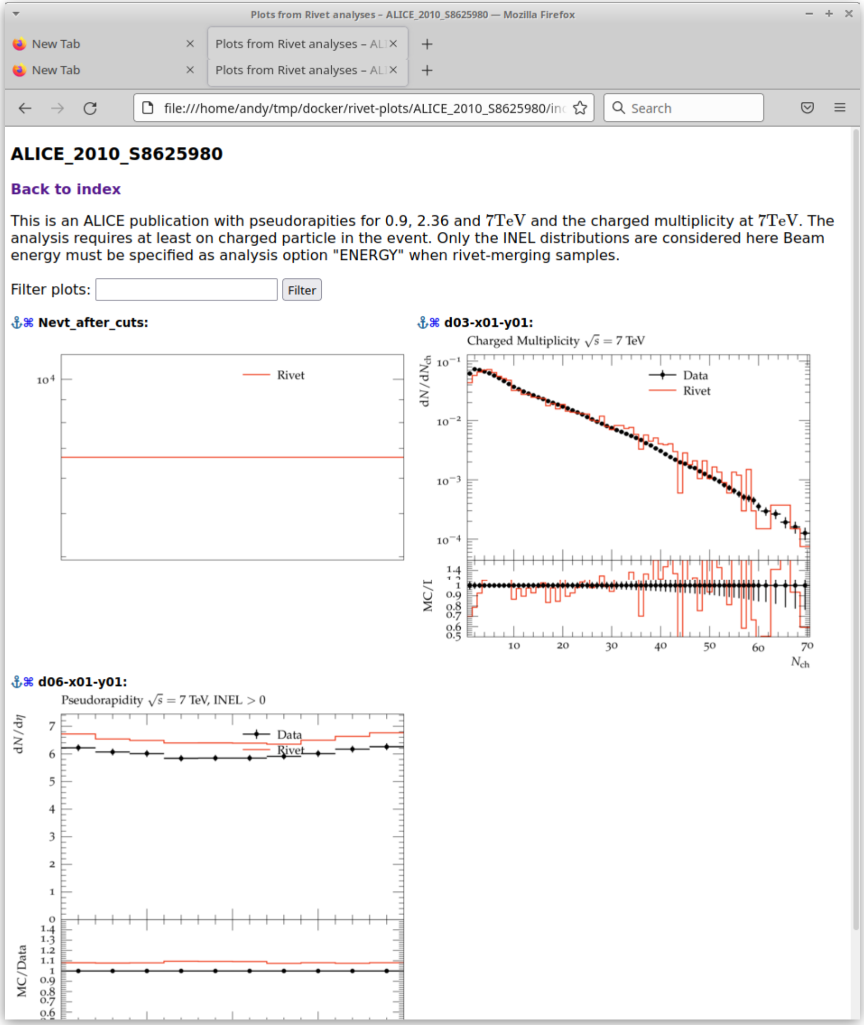


Additional Material

RIVET
Additional material

New Features: *Heavy Ion support*

- **“Adding heavy-ion support” sounds trivial!**
  ... Actually a stern test, with far-reaching impacts.
  - HI observables often require centrality calibration curves: we need a 2-pass run. That wasn’t planned.
  - And event/event correlations… centrality-binned!

- Jan 2020 "RIVET for HI" paper: https://arxiv.org/abs/2001.10737
  - Huge step towards, involving effort from all sides of the community
  - Now an integral part of core RIVET : not a separate tool
  - Still A work in progress! Improvements possible
  - *Result: Features to allow comparison between heavy ion data and MC*

- *HI MC standards are also in flux: having a common tool enables discussion on common standards*

LU TP 20-04
MCNET-20-04

Confronting Experimental Data with Heavy-Ion Models

RIVET for Heavy Ions

Christian Bierlich,[1,2] Andy Buckley,[3] Christian Holm Christensen,[1] Peter Harald Lindenov Christiansen,[4] Cody B. Duncan,[5,6] Jan Fiete Grosse-Oetringhaus,[7] Przemyslaw Karczmarczyk,[8,7] Patrick Kirchgaeßer,[6] Jochen Klein,[9,7] Leif Lönnblad,[2] Roberto Preghenella,[10] Christine O. Rasmussen,[2] Maria Stefaniak,[8,11] and Vytautas Vislavicius[1]

[1]*Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2]*Dept. of Astronomy and Theoretical Physics, Lund University, Sölvegatan 14A, S-223 62 Lund, Sweden*
[3]*School of Physics and Astronomy, University of Glasgow, G12 8QQ, Glasgow, UK*
[4]*Dept. of Physics, Lund University, Professorsgatan 1, S-223 62 Lund, Sweden*
[5]*School of Physics and Astronomy, Monash University, Clayton, VIC 3800, Australia*
[6]*Institute for Theoretical Physics, Karlsruhe Institut für Technologie, Wolfgang-Gaede-Straße 1, 76131 Karlsruhe Germany*
[7]*CERN, Esplanade de Particules 1, Geneva, Switzerland*
[8]*Faculty of Physics, Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland*
[9]*Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy*
[10]*Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy*
[11]*Subatech – IMT Atlantique, 4 rue Alfred Kastler, 44307 Nantes, France*

(Dated: January 30, 2020)

arXiv:2001.10737v1 [hep-ph] 29 Jan 2020

RIVET: What's the benefit for experimentalists?

- **Preservation: Store your analysis once, and others will maintain it.**
- **Reproducibility: What happens when your student graduates?**
- **Ensure that your results are used.**
- **Don't leave it to theorists to re-implement your analysis!**
- **"Do upon others…": Generate MC tunes using other people's work!**
- **Can I be sure that the framework will live on?**
  Yes! Large investment by HEP community and MCEG authors. O(1000) analyses already implemented. Active dev team, open to new improvements: If a feature is needed, we can look into it!

RIVET: What’s the benefit for theorists?

- **A library of validated measurements to test your models against**
  - Does your generator’s latest version fix feature X in a spectrum, without breaking feature Y ?
  - Find out in minutes!

- **A common testing ground for different models**
  - Apples to apples comparisons to other generators

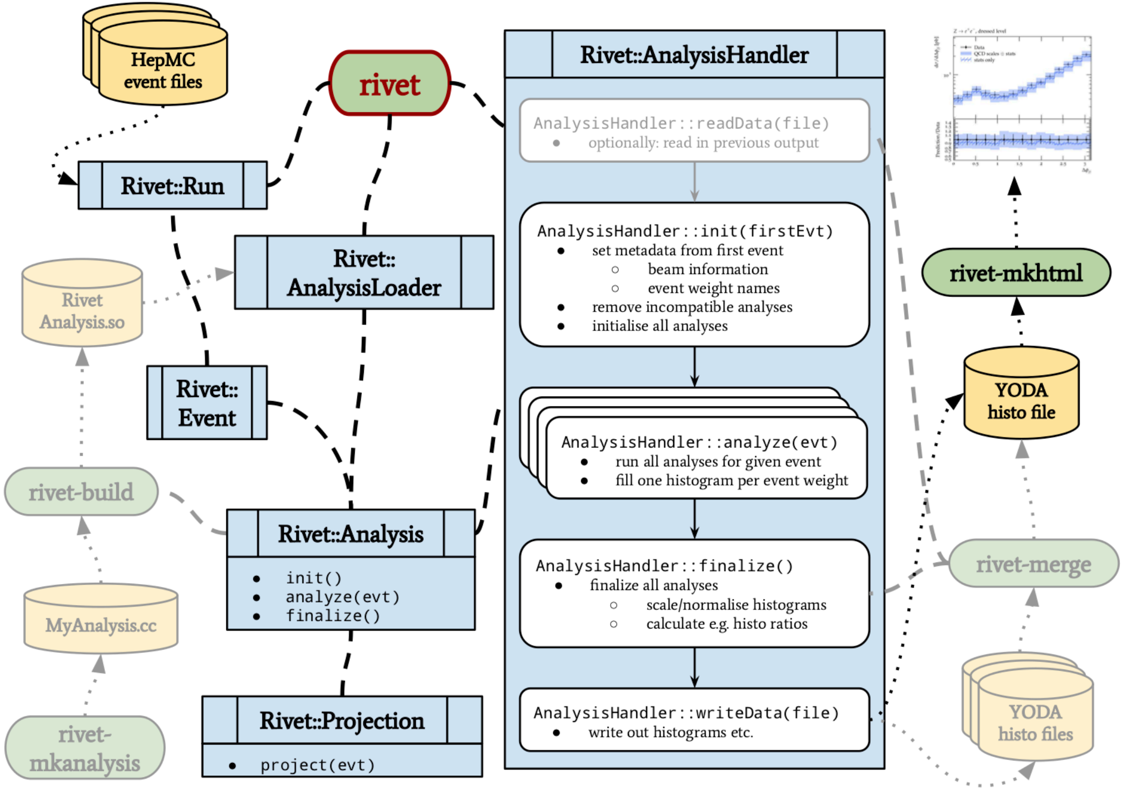
- **Boost your model’s credentials:**
  - **Use RIVET as a model-development tool**
  - Easy to convince experimentalists to use a new model if you can show that it leads to a clear improvement in data/MC agreement
    - While still agreeing in the rest of the body of experimental data
    - Avoid single-observable models and overfitting

RIVET workflow

- **2010: RIVET v1 for LHC Run 1**
- **2019: RIVET v3.1.0 (arXiv:1912.05451)**

- Streamlined set of tools from analysis coding to event processing to plotting (and other applications)

- And a key gateway to connect your analysis to theory (and back again)



CONTUR

Additional material

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

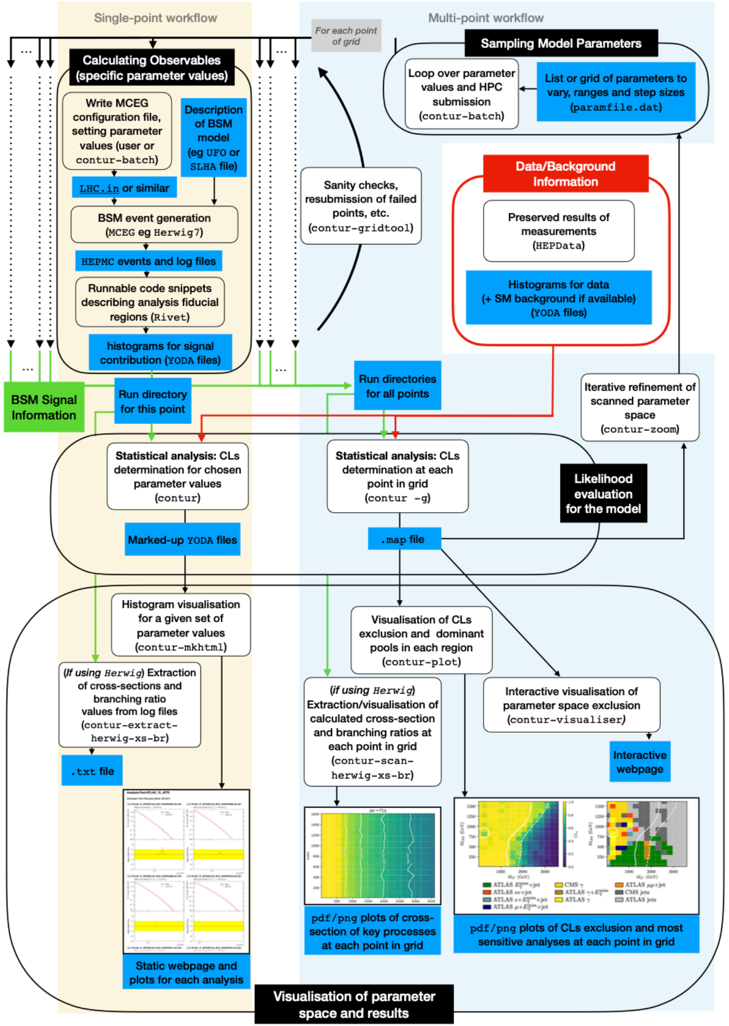
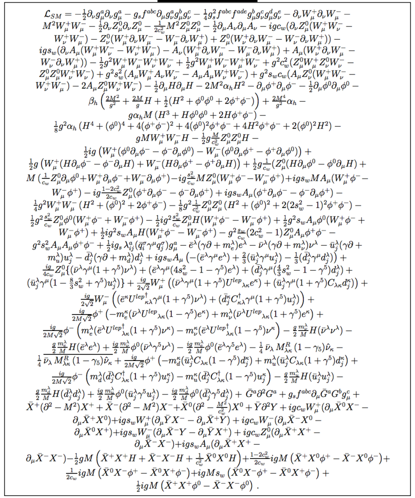


Illustration by Chris Wormell from "A Map of the Invisible"

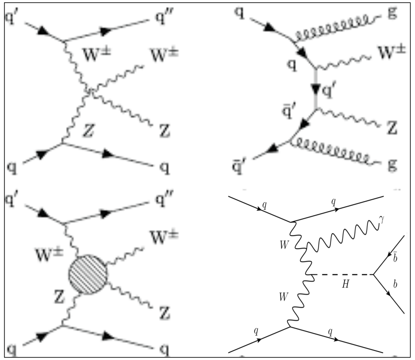
CONTUR 101

- 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

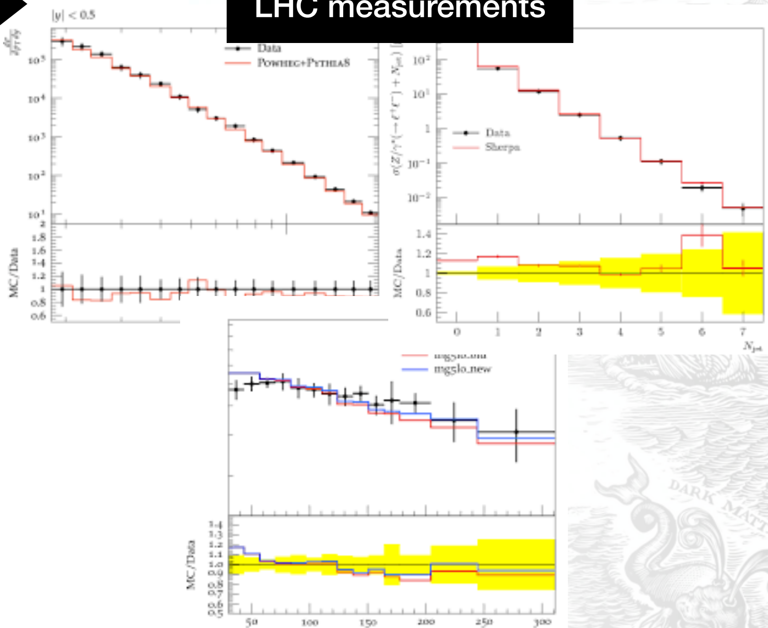
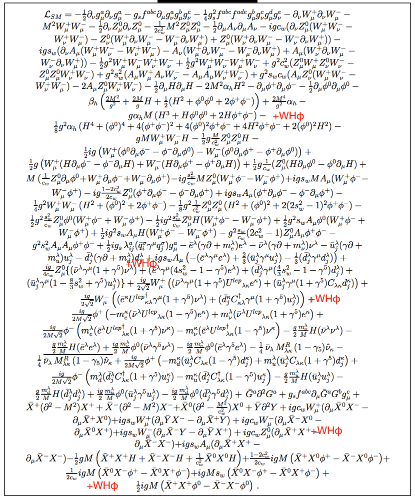


Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR 101

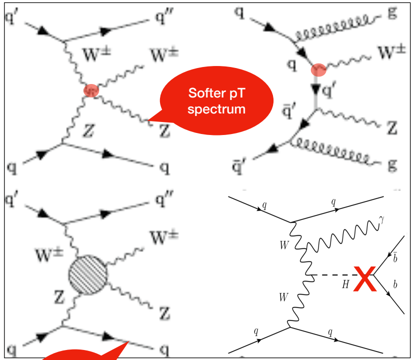
- Key idea: the SM Lagrangian is very finely balanced. You can't easily add BSM particles without the effect showing up in SM distributions

SM + BSM



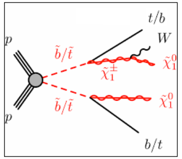
+ BSM

Processes

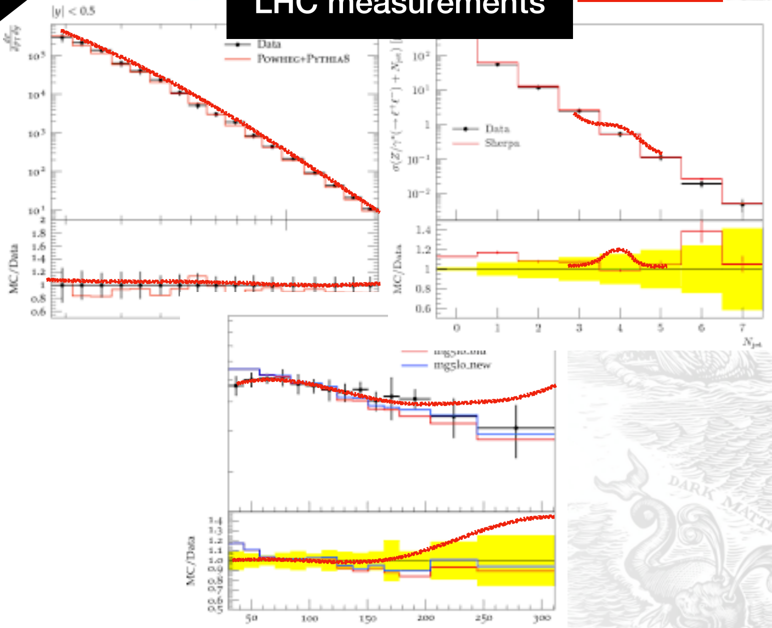


More boosted

+



LHC measurements + BSM



CONTUR vs Vector-like Quarks

A case study

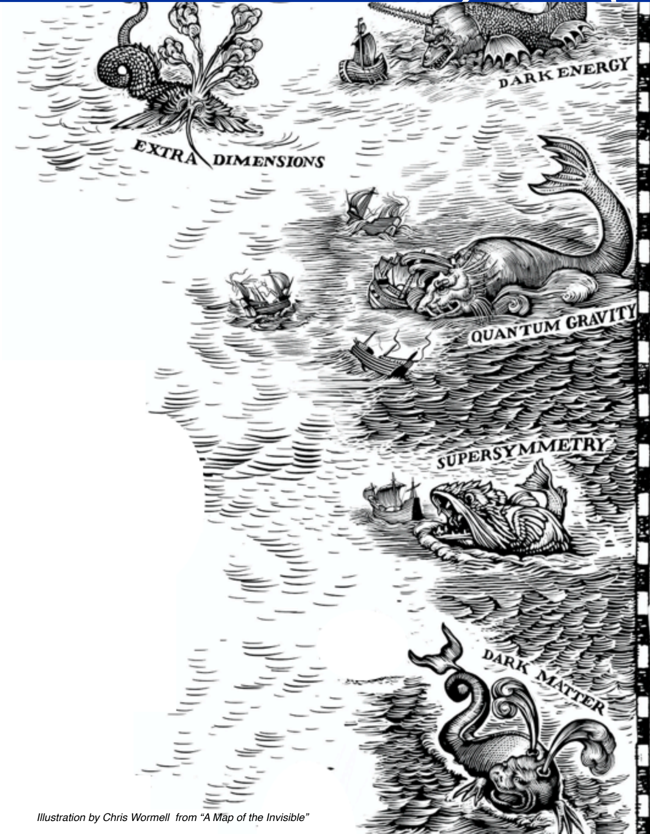


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, CERN (lcorpe@cern.ch)

VLQs

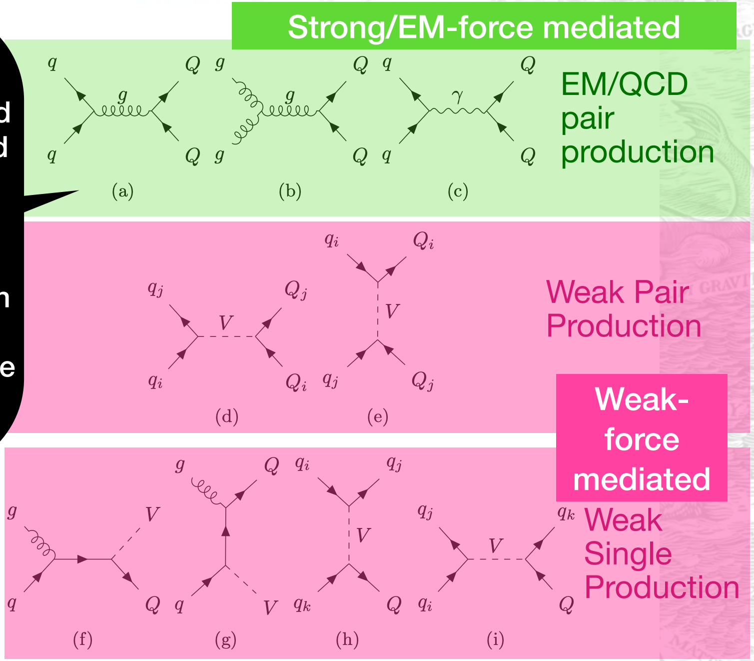
- Standard VLQ framework from Buchkremer et al (arXiv:1305.4172), comes with UFO file (also used by ATLAS)
- Introduces quark partners:

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

- 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 coupli[ng] 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 i[th] 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

CONTUR vs Direct searches

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

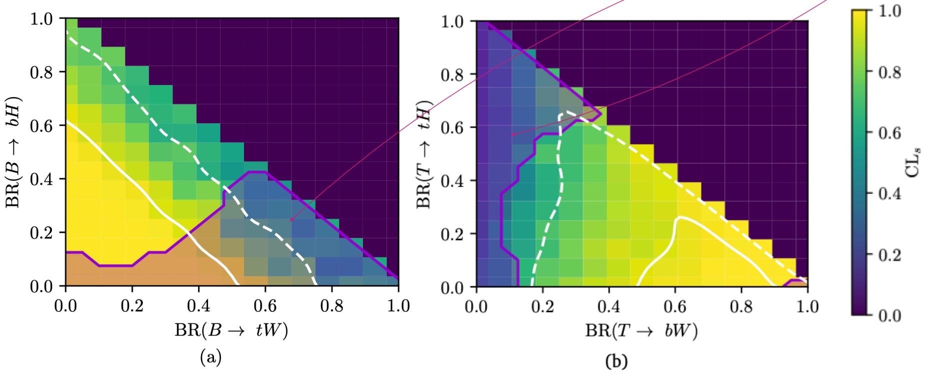


Figure 5: Sensitivity of LHC measurements to (a) B-production for $M_B = 1200$ GeV and (b) T-production for $M_T = 1350$ GeV. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed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

95% CL exclusion
68% CL exclusion

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

Assumes pair-production only !

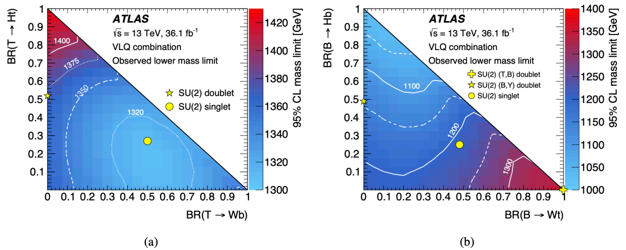
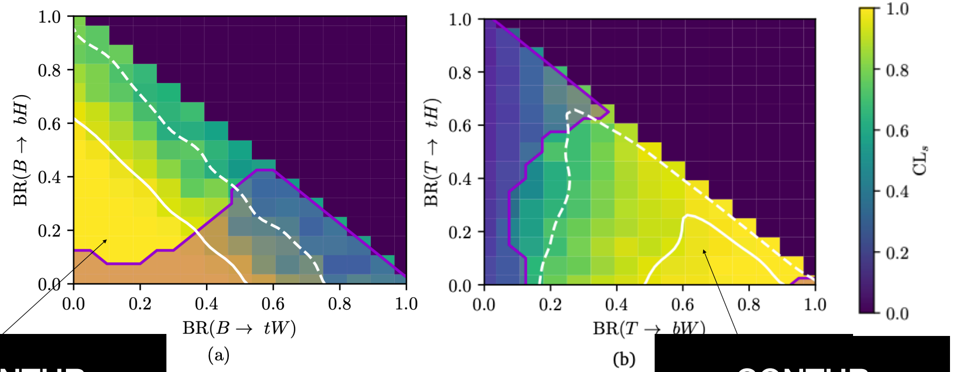


Figure 4: Observed lower limits at 95% CL on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T\to Ht) + \mathcal{B}(T\to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B\to Hb) + \mathcal{B}(B\to Zb) + \mathcal{B}(B\to Wt) = 1$. The yellow markers indicate the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

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 !

itivity of LHC measurements to (a) B-productio
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d 68% CL (dashed white) exclusion contours superi
95% CL by the ATLAS combination [16].

CONTUR sensitivity comes mainly from Top or W measurements

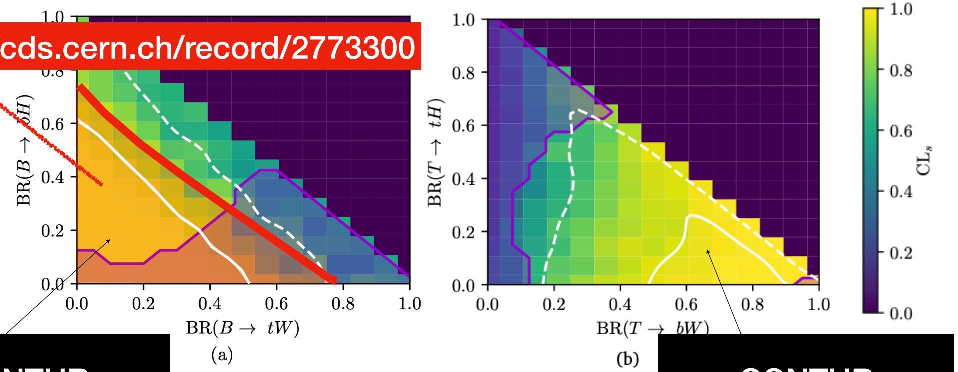
95% CL exclusion
68% CL exclusion

- 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!

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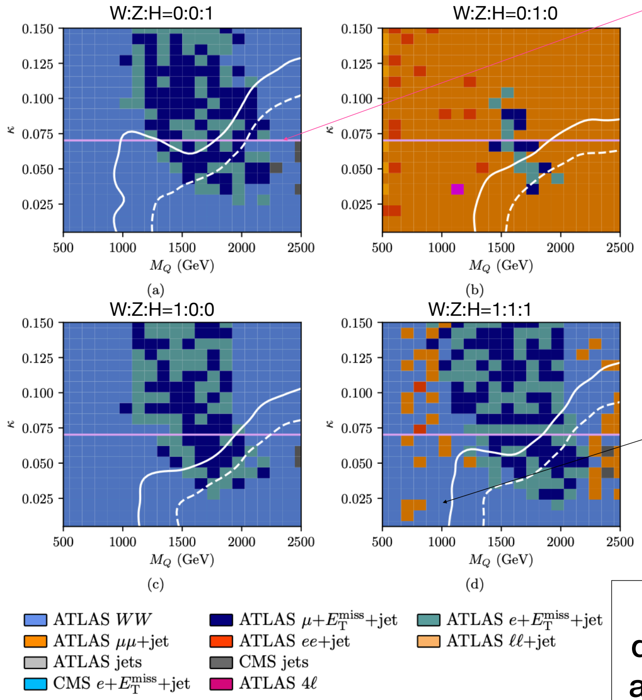
- Latest **ATLAS VLQ search for Z-channel decays** came out as a CONF note for EPS
- Beats the CONTUR exclusion, but using 139/fb instead of the 3.2/fb Z+jets measurement!
- CONTUR result excluded much of this region a full year before the dedicated search came out

> 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

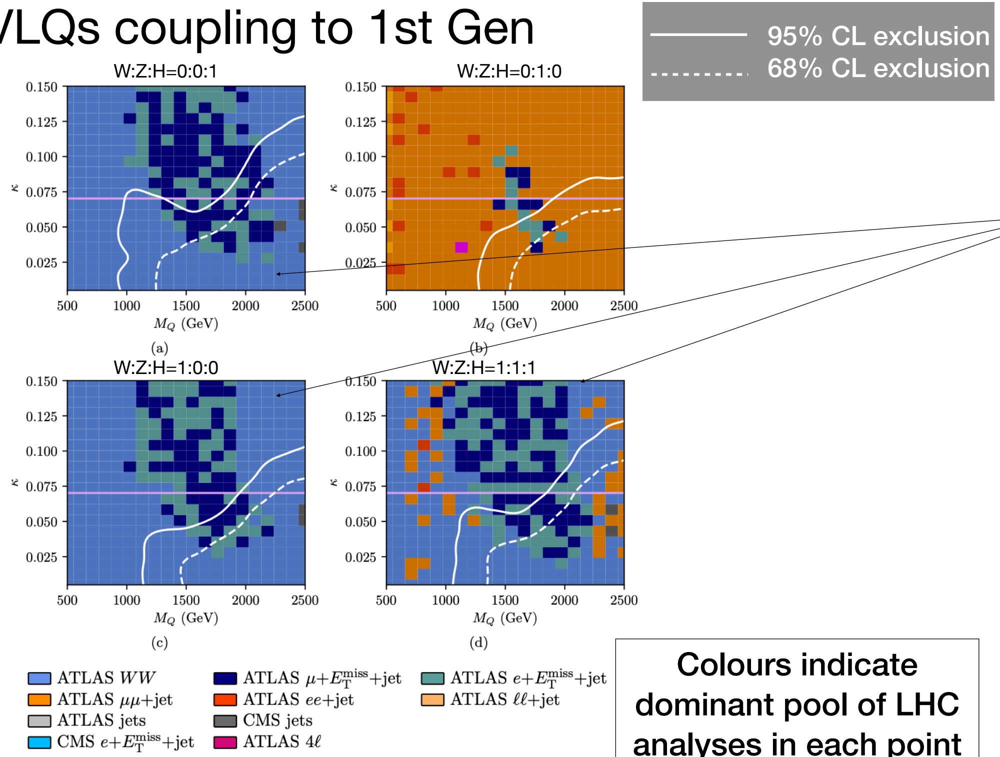
Colours indicate dominant pool of LHC analyses in each point of param space

- 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 !

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

CONTUR to explore new regions

VLQs coupling to 1st Gen



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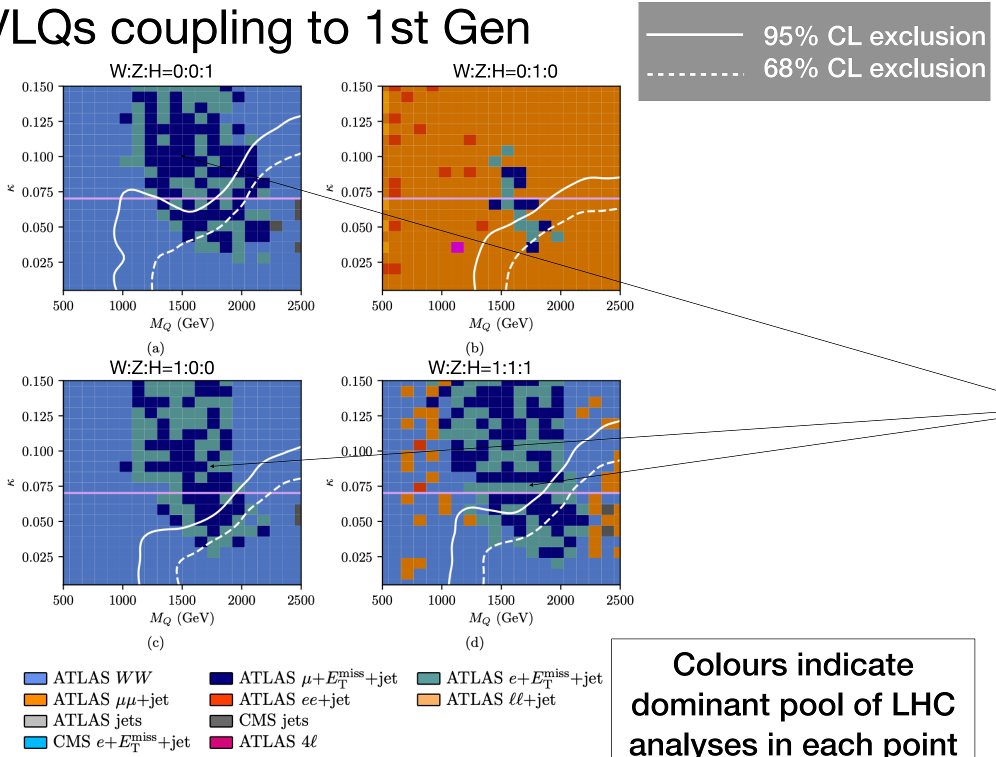

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Sensitivity driven by control region measurements in an 8 TeV Wjj measurement

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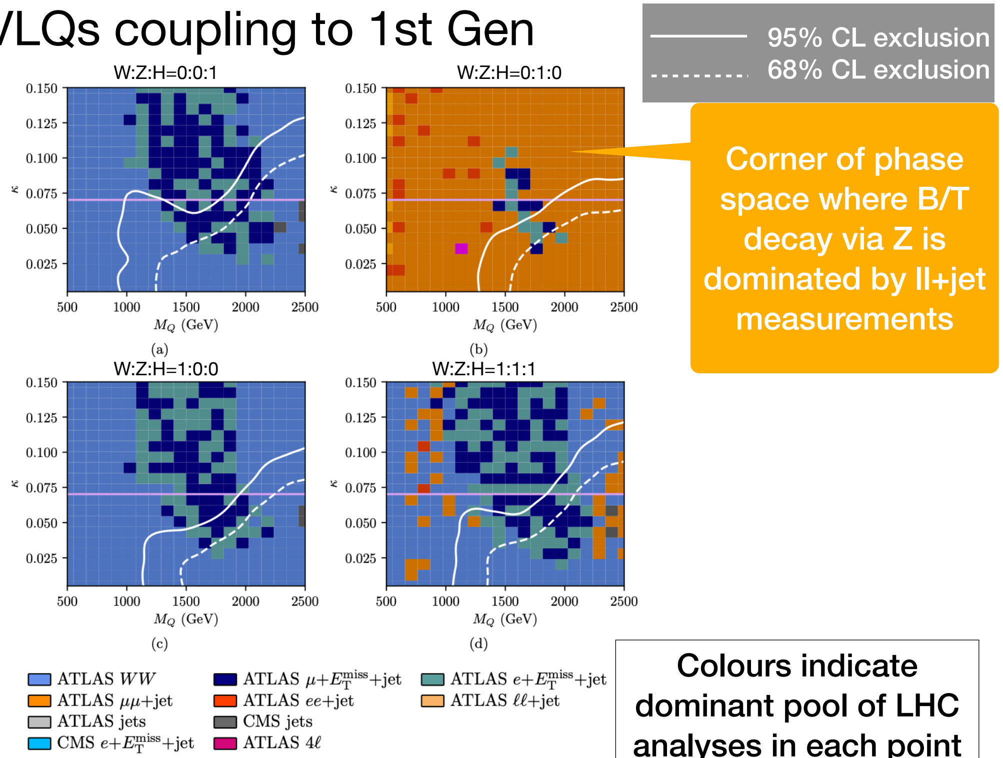
CONTUR to explore new regions

VLQs coupling to 1st Gen



Corner of phase space where B/T decay via Z is dominated by ll+jet measurements

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

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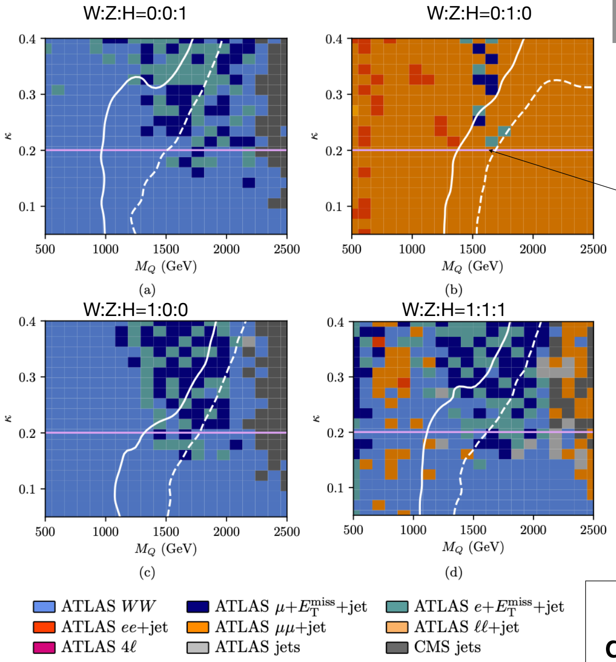
CONTUR to explore new regions

VLQs coupling to 2nd Gen



95% CL exclusion
68% CL exclusion

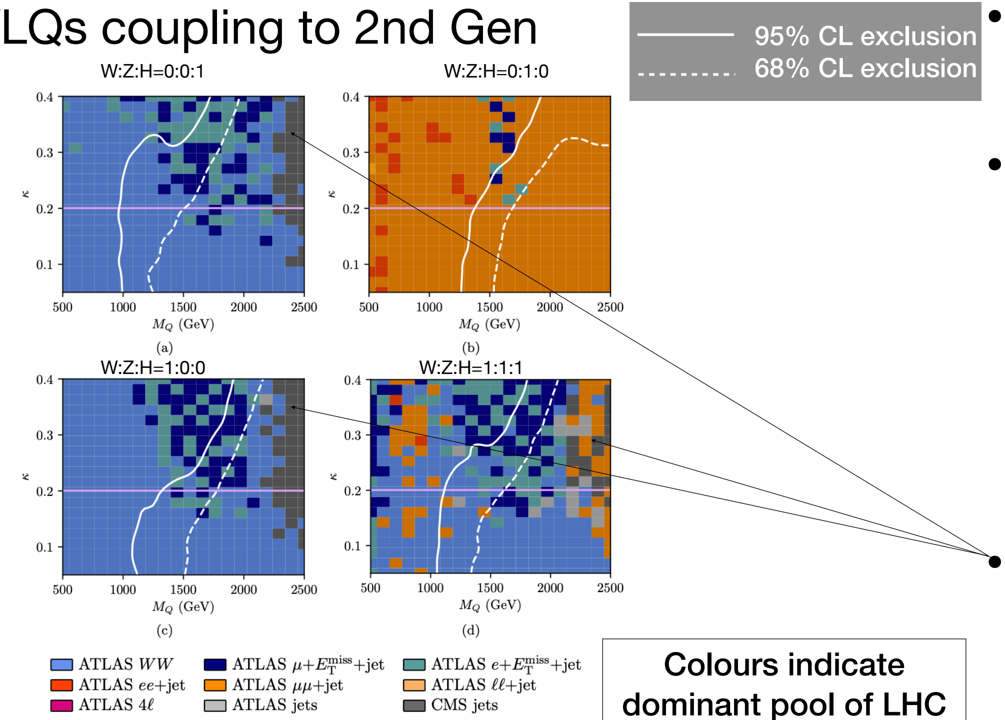
Colours indicate dominant pool of LHC analyses in each point of param space

- 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)

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

CONTUR to explore new regions

VLQs coupling to 2nd Gen



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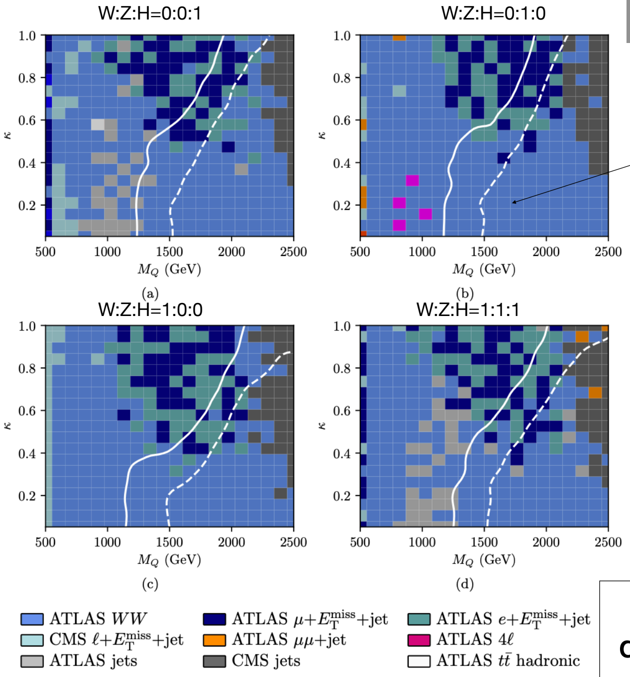
CONTUR to explore new regions

VLQs coupling to 3rd Gen



95% CL exclusion
68% CL exclusion

Biggest difference with lower-generation scans is the WZH=010 case, where Z+jets-like measurements cease to play a leading role: VLQs will decay chiefly to tops, leading to missing-energy signatures

- 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)!

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

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

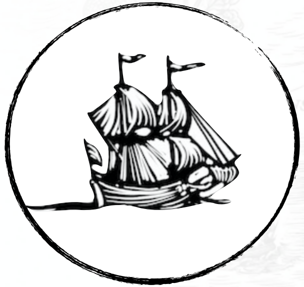


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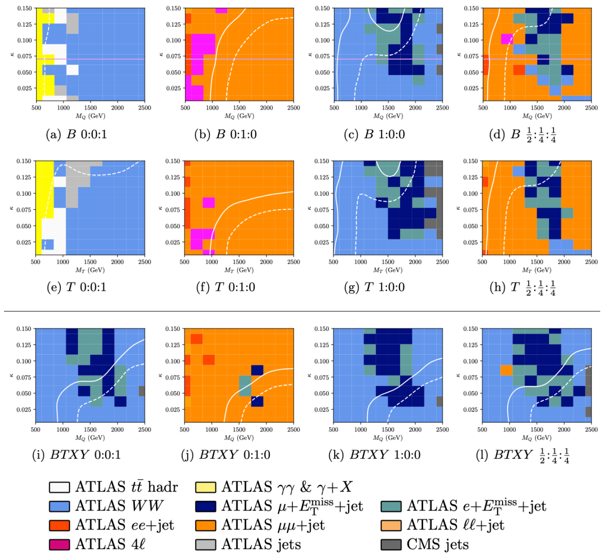
Illustration by Chris Wormell from "A Map of the Invisible"

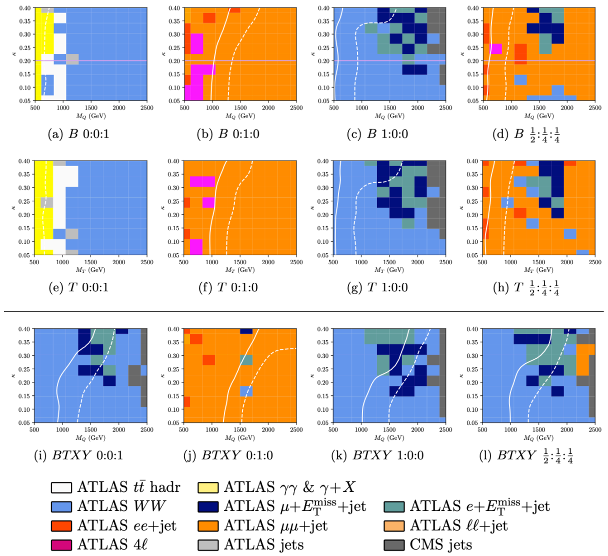
What about VLQ Singlets?

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

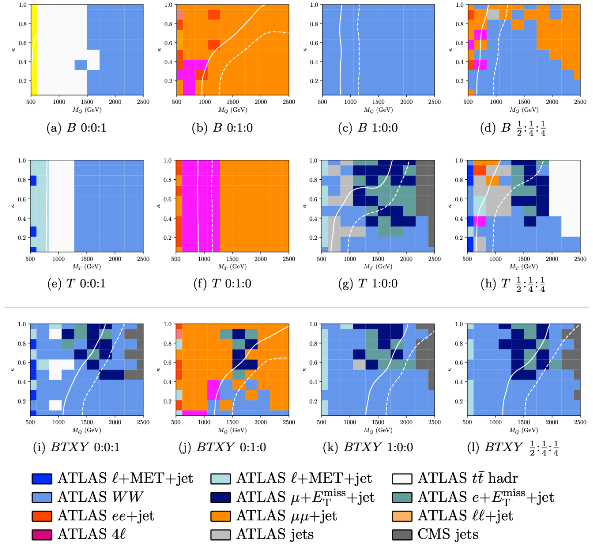
1st-Generation



2nd-Generation



3rd-Generation

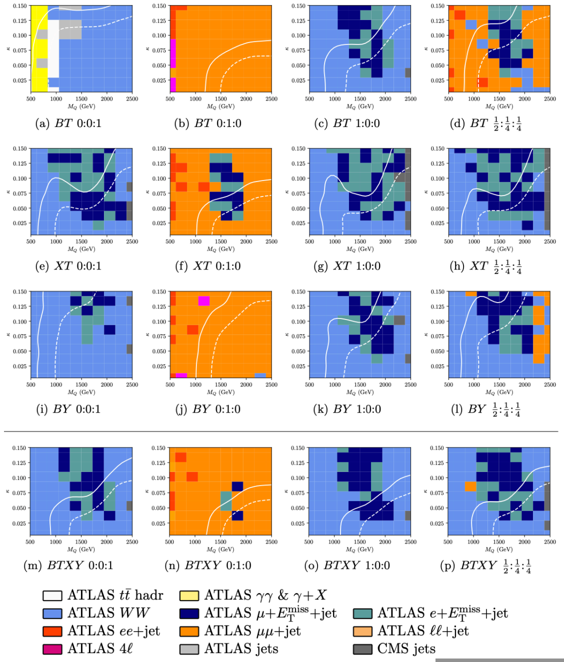


95% CL exclusion
68% CL exclusion

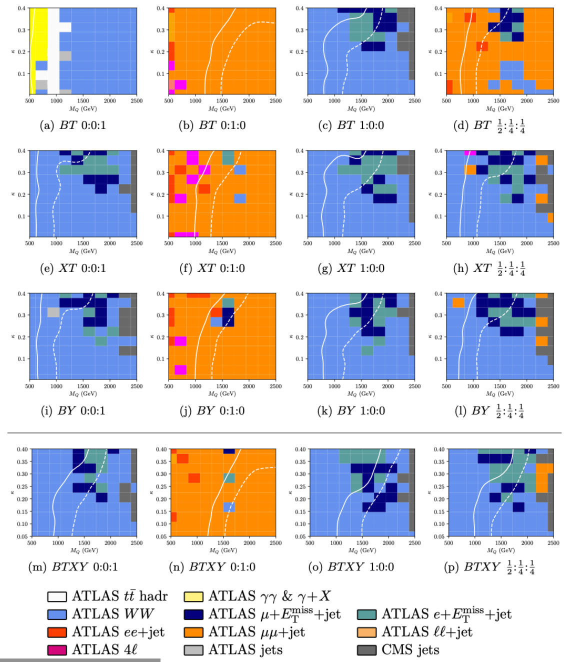
What about VLQ Doublets?

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

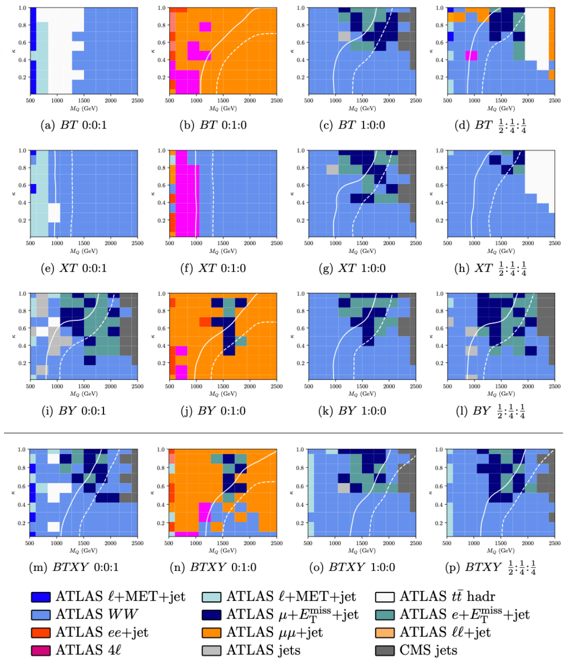
1st-Generation



2nd-Generation



3rd-Generation

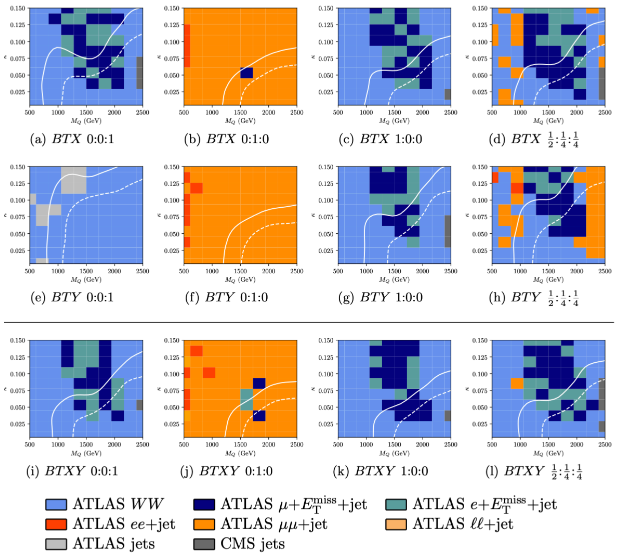


95% CL exclusion
68% CL exclusion

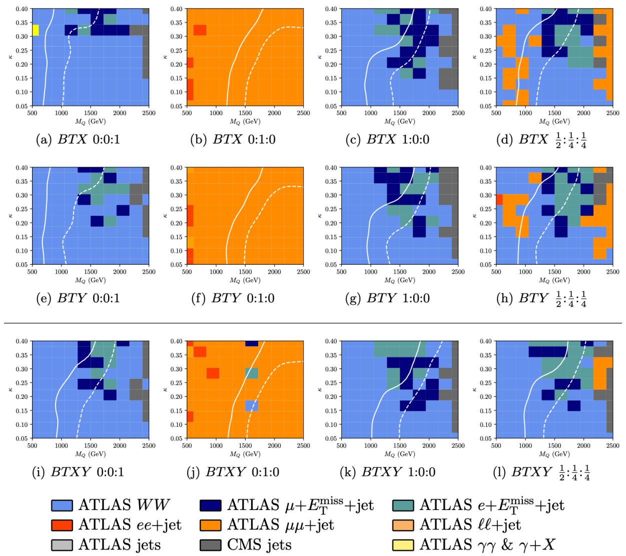
What about VLQ Triplets?

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

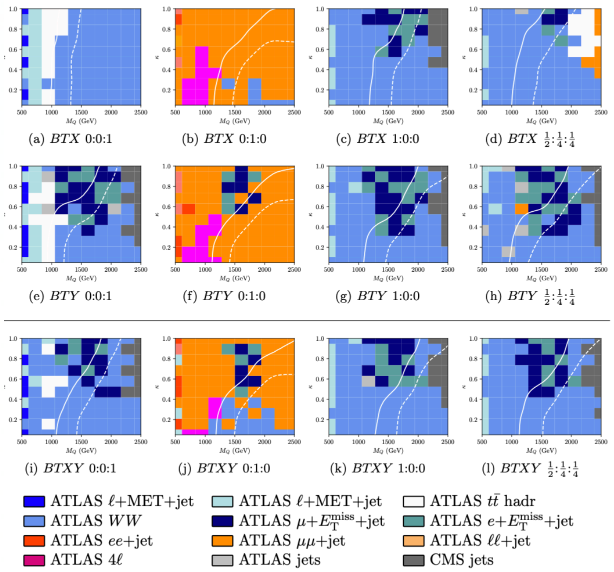
1st-Generation



2nd-Generation



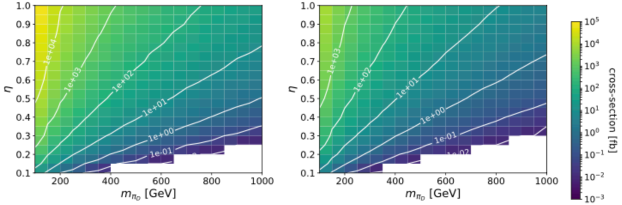
3rd-Generation



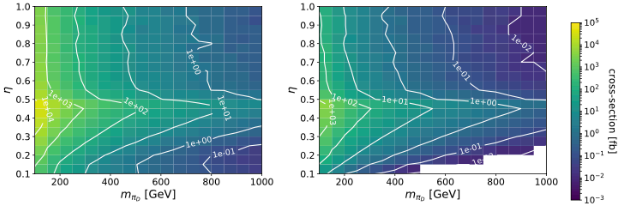
95% CL exclusion
68% CL exclusion

Heavy Dark Mesons

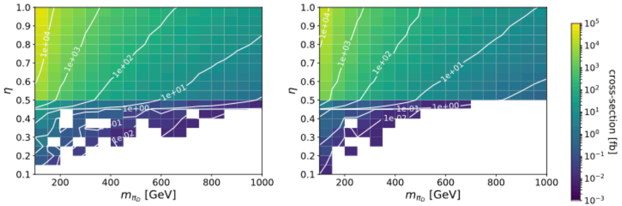
Dark meson phenomenology at the LHC



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



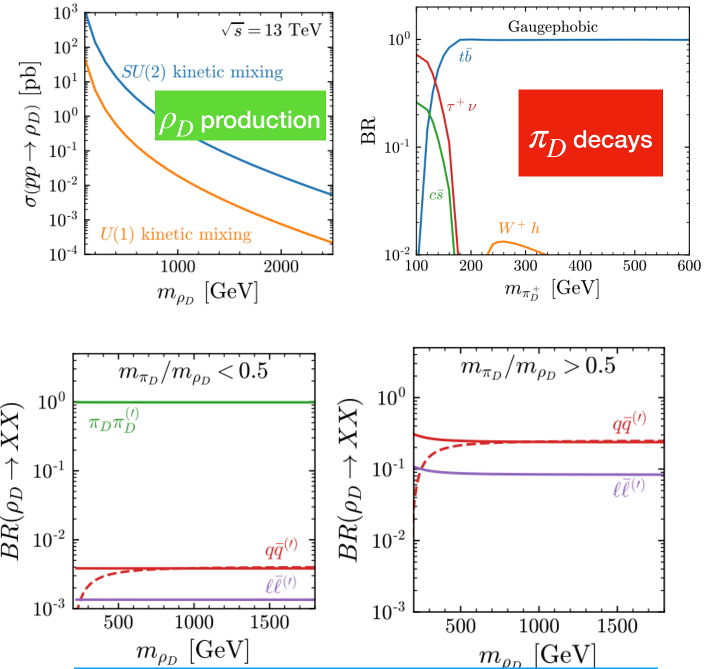
(c) $pp \to \pi_D^+ \pi_D^-$ $(\mathrm{SU(2)_L})$ (d) $pp \to \pi_D^+ \pi_D^-$ $(\mathrm{SU(2)_R})$



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

- 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 τν 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

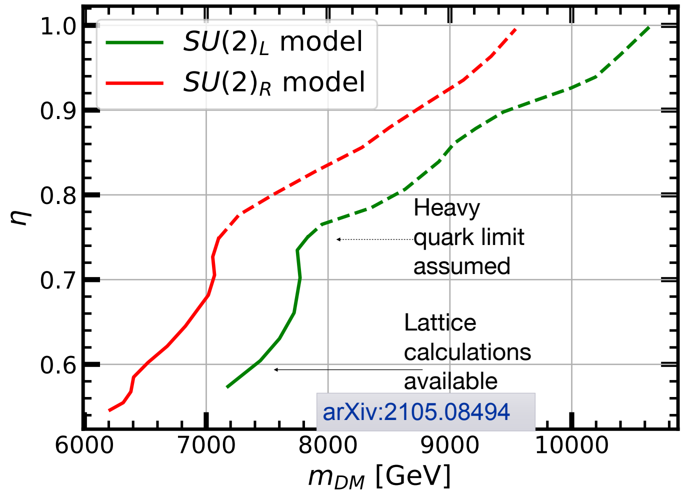


ρ_D decays: depends on mass hierarchy

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

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

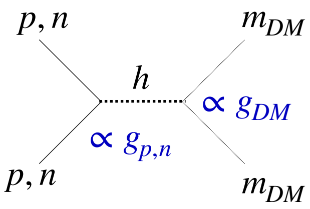
Appelquist et al (arXiv:1503.04203)

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

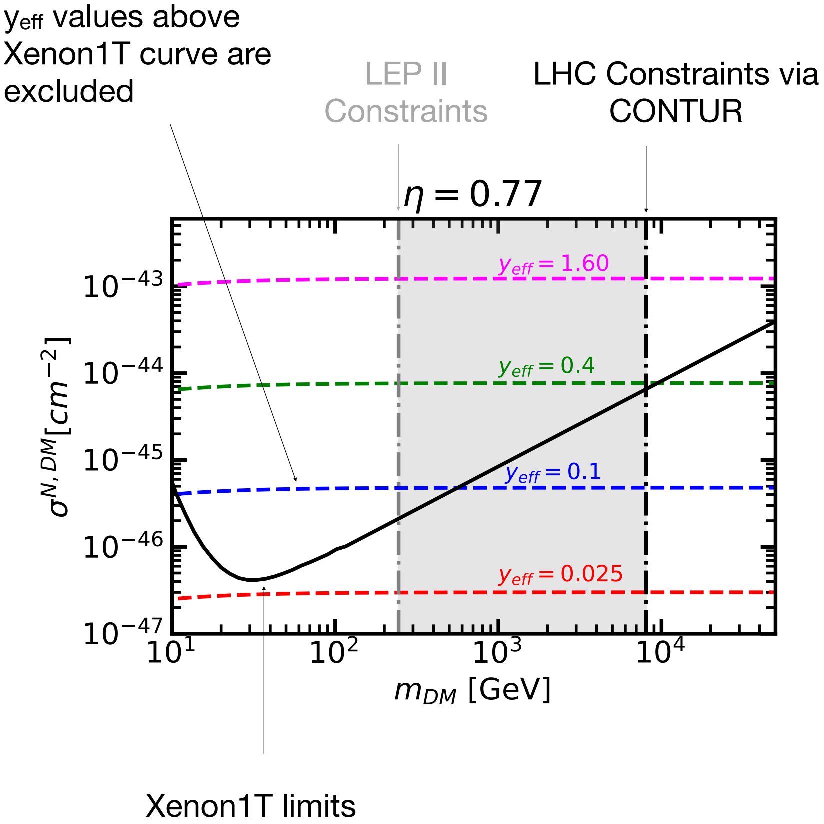
Combining with Direct Detection results

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

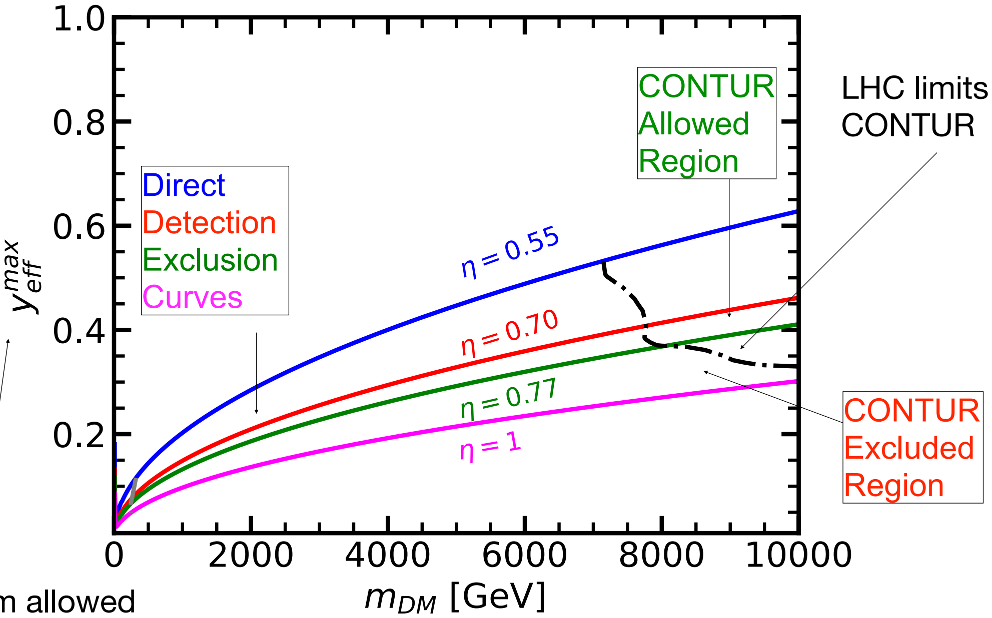
$$g_{\rm DM} \simeq y_{\rm eff} \times f_f^{\rm DM}$$



- 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



Bringing Direct Detection and LHC limits together



LHC limits via CONTUR

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

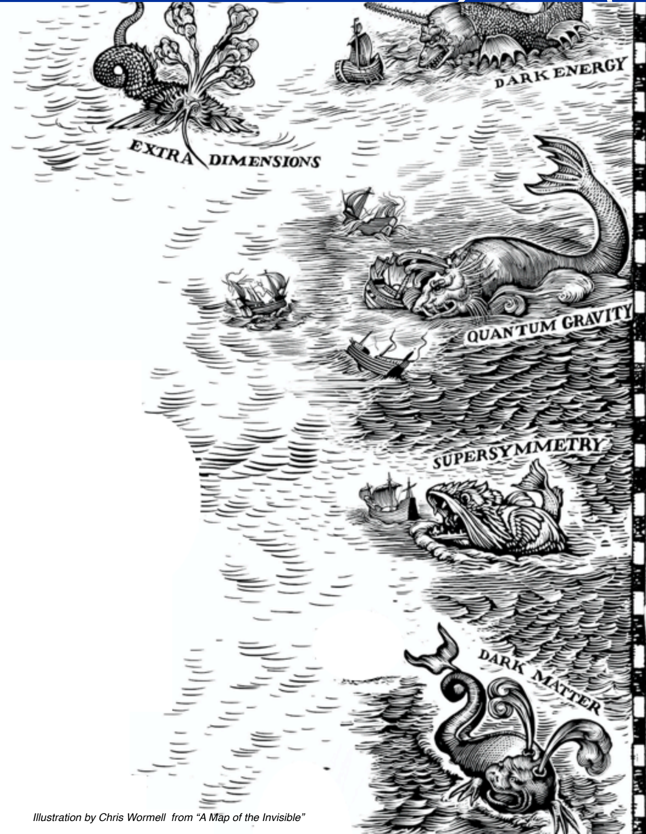


Illustration by Chris Wormell from "A Map of the Invisible"

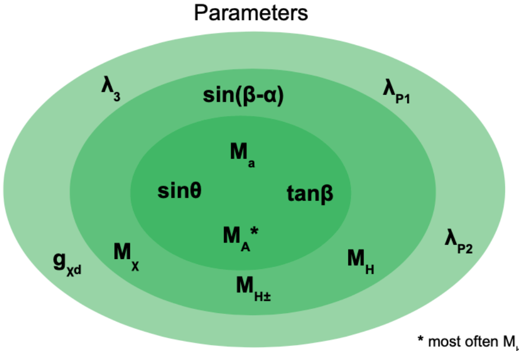
Louie Corpe, CERN (lcorpe@cern.ch)

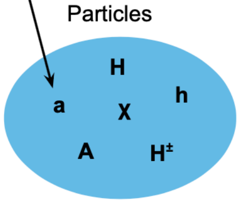
The 2HDM+a model

Slides: Martin Habedank (DESY)

Two-Higgs-doublet model with a pseudoscalar mediator

- **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





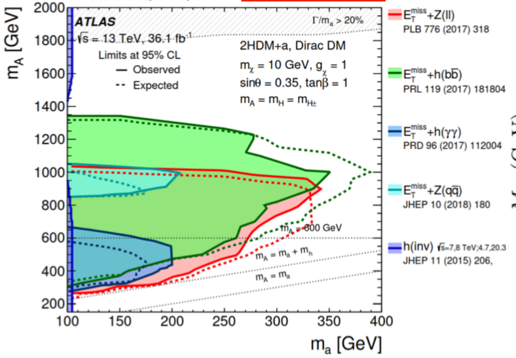
* most often $M_{H\pm}=M_H=M_A$ is used

Benchmark Scenarios (comparison to ATLAS)

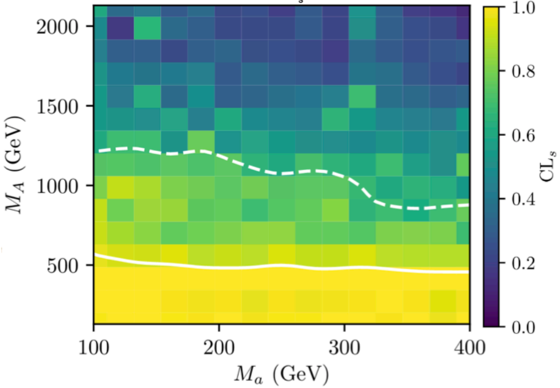
Slides: Martin Habedank (DESY)

ATLAS summary paper
→JHEP05(2019)142

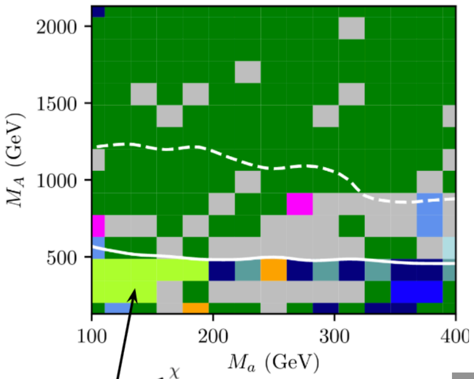
ATLAS summary At the time of this CONTUR paper

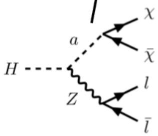


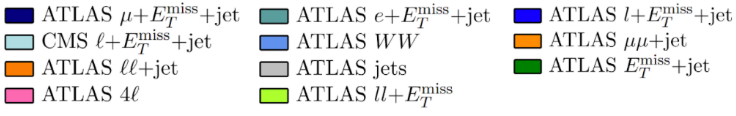
Results of this paper →2009.02220
sensitivity map in terms of CL_s



most sensitive measurements







95% CL exclusion
68% CL exclusion

exclusion

- orthogonal to ATLAS searches
- from many different contributions

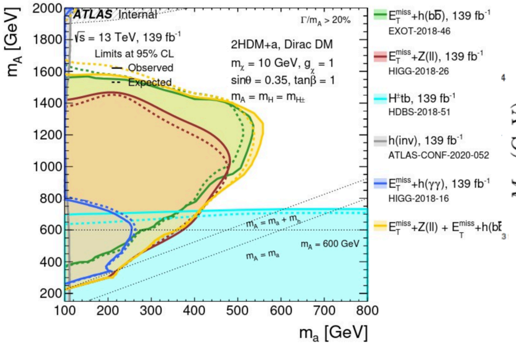
At low m_a, A-> tt and H± -> tb become important, picked up by lep+MET+jet measurements in CONTUR
With no equivalent search (at the time)

Benchmark Scenarios (comparison to ATLAS)

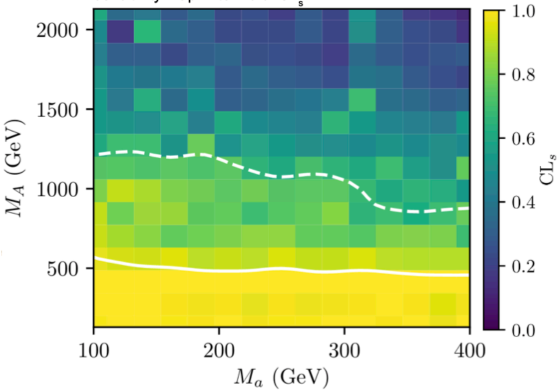
Slides: Martin Habedank (DESY)

ATLAS summary paper →JHEP05(2019)142

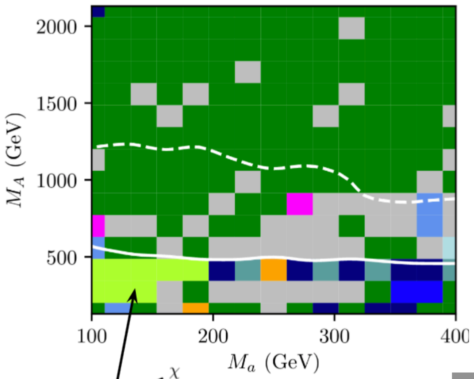
Latest ATLAS summary currently in approval

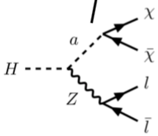


Results of this paper →2009.02220
sensitivity map in terms of CL_s



most sensitive measurements





95% CL exclusion
68% CL exclusion

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

5

exclusion
- orthogonal to ATLAS searches
- from many different contributions

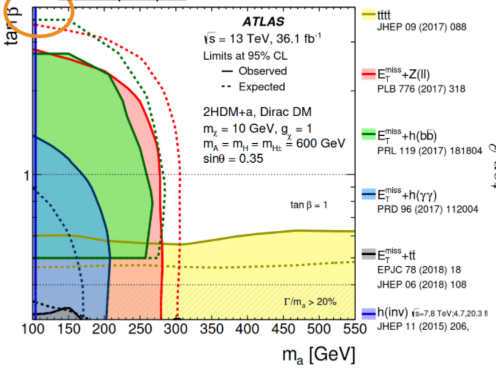
Low-m_a region filled in by dedicated searches, ~1 year later.

Louie Corpe, CERN (lcorpe@cern.ch)

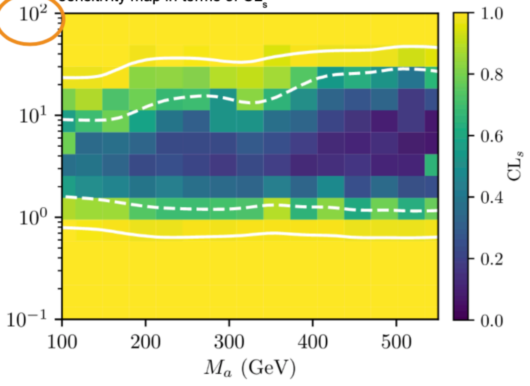
Benchmark Scenarios (comparison to ATLAS)

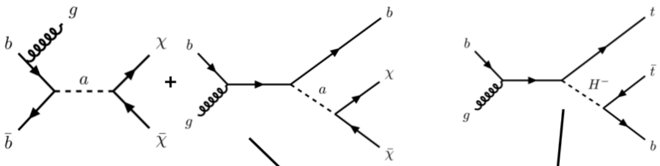
Slides: Martin Habedank (DESY)

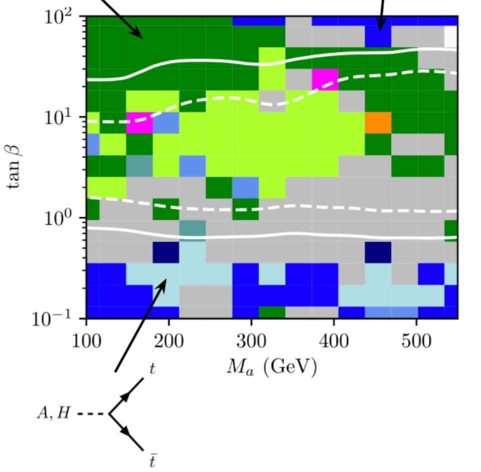
ATLAS summary paper →JHEP05(2019)142

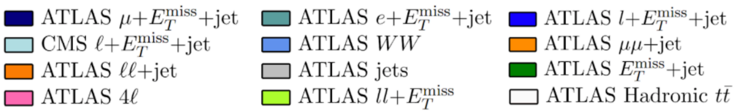


Results of this paper →2009.02220
sensitivity map in terms of CL_s









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95% CL exclusion
68% CL exclusion

What about varied mixing parameters?

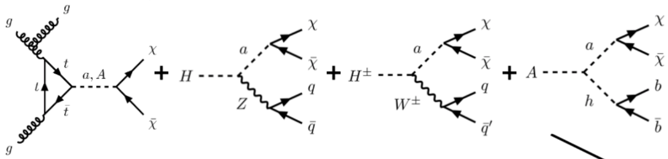
Slides: Martin Habedank (DESY)

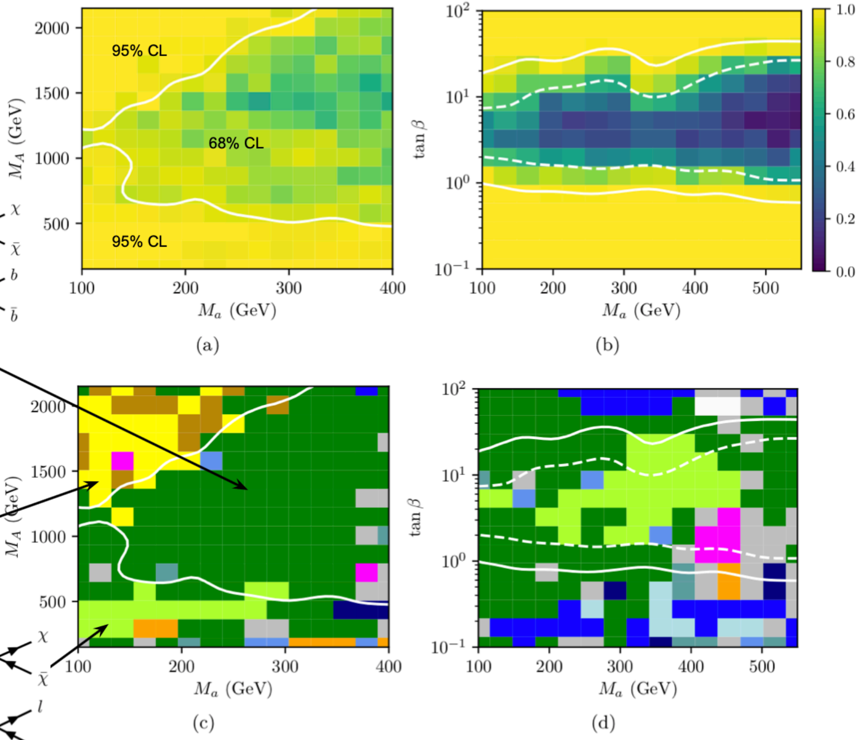
now:

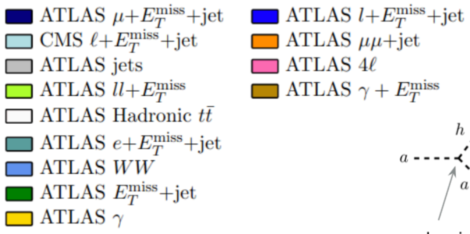
- degenerate masses $M_{H\pm}=M_H=M_A$=600GeV again
- change mixing parameter sinθ=1/√2 (maximum mixing)

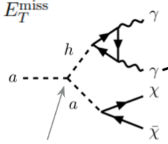
→ a-χ coupl. **de**creased, a-SM coupl. **in**creased
→ A-χ coupl. **in**creased, A-SM coupl. **de**creased

- sinθ>1/√2: a↔A switch roles

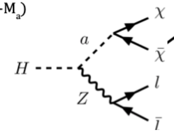








coupl. ∝ sinθ, (M_A-M_a)



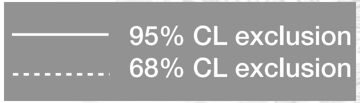


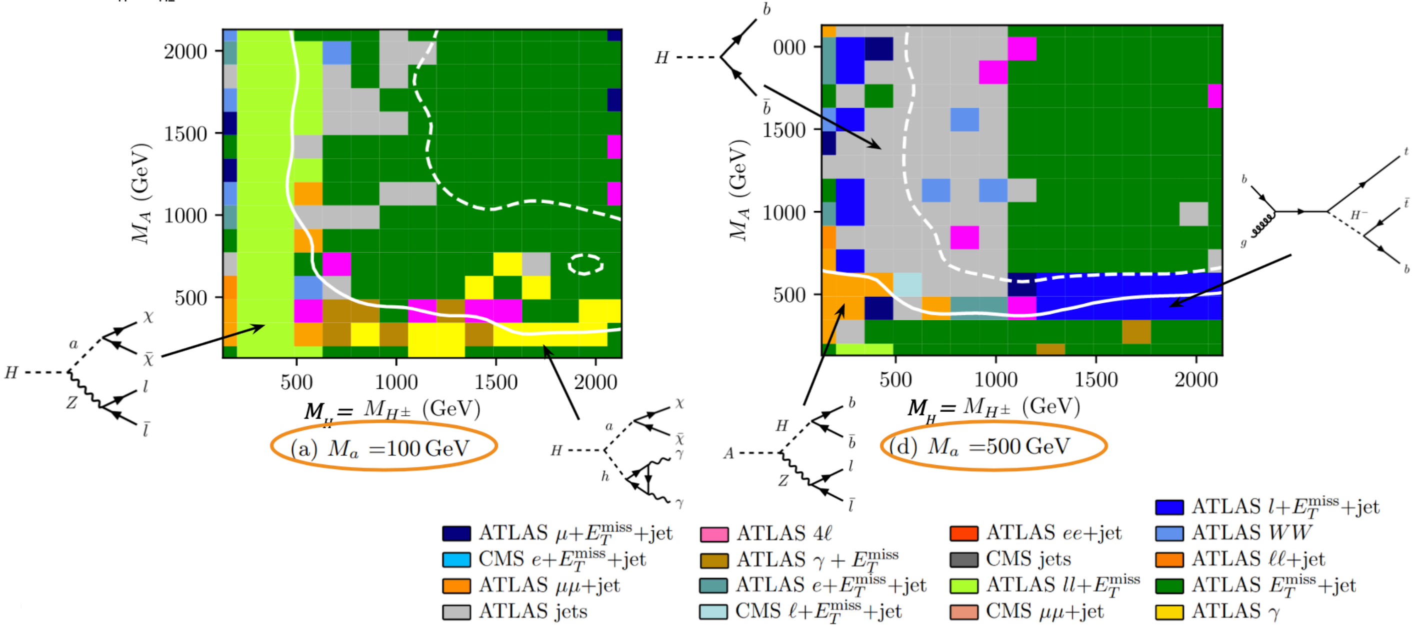
Illustration by Chris Wormell from "A Map of the Invisible"

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

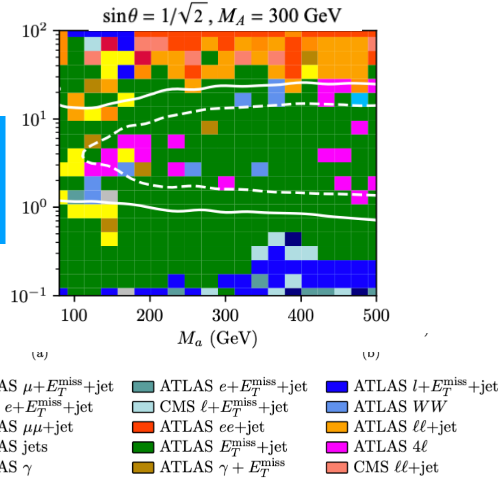
Louie Corpe, CERN (lcorpe@cern.ch)

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

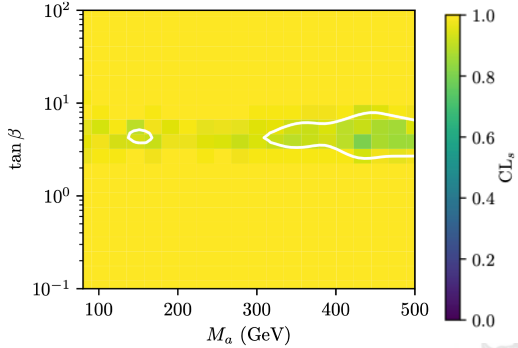
- For example: I am currently working on 139/fb MET+jets measurement. What does it bring to the table?

Another non-degenerate mass case



Add prototype 139/fb MET+jets measurement routine

95% CL exclusion
68% CL exclusion

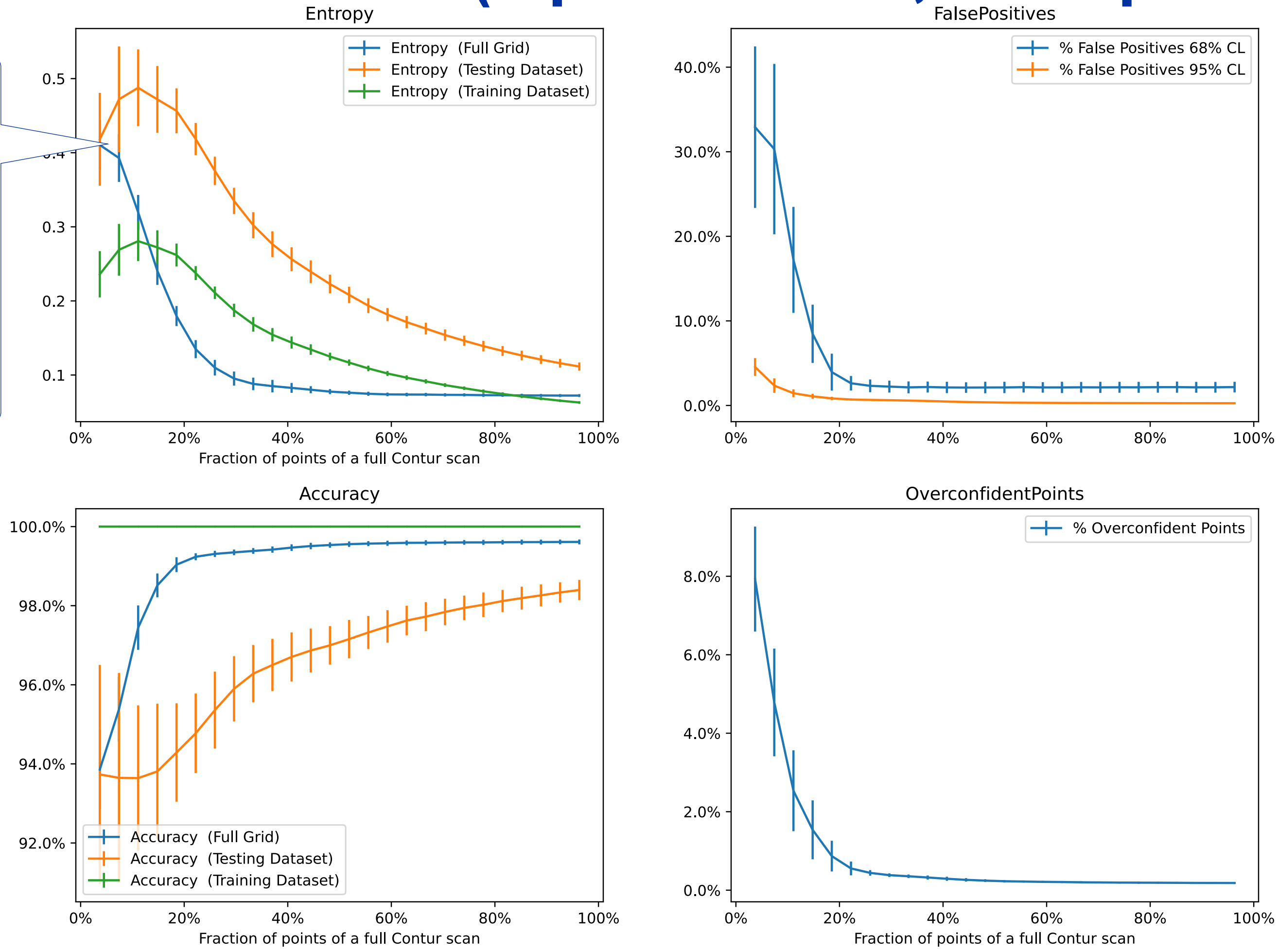


This measurement will exclude large fraction of plane

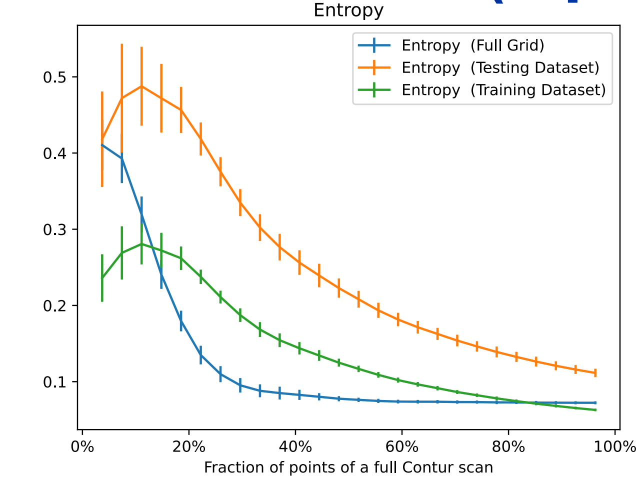
CONTUR Oracle
Additional material

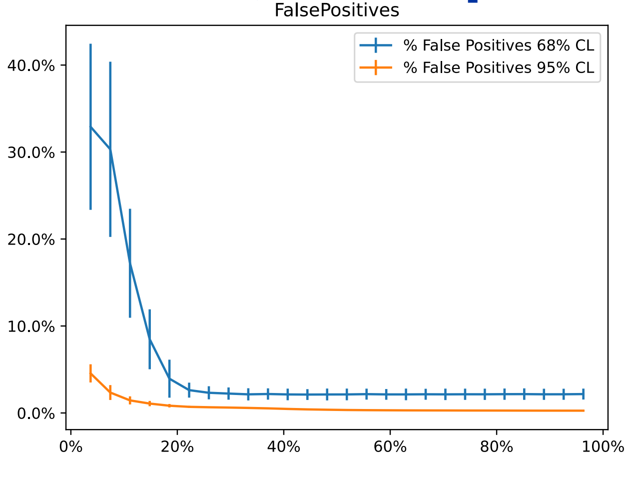
Simplified DM model (4 parameters, 8100 points)

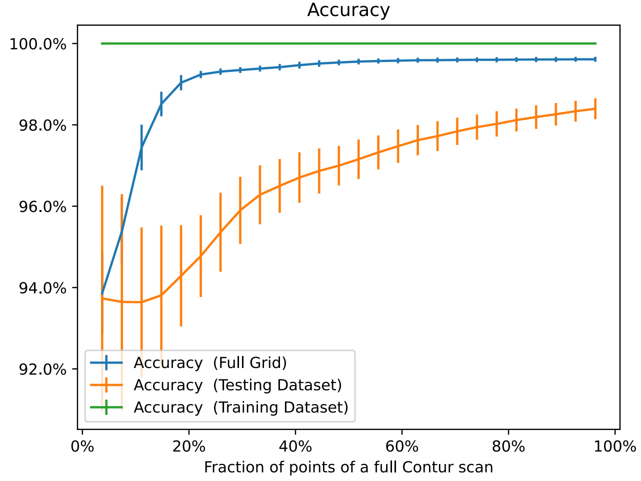
Entropy has a “bump” (network is confident but wrong on some points), and steadily drops

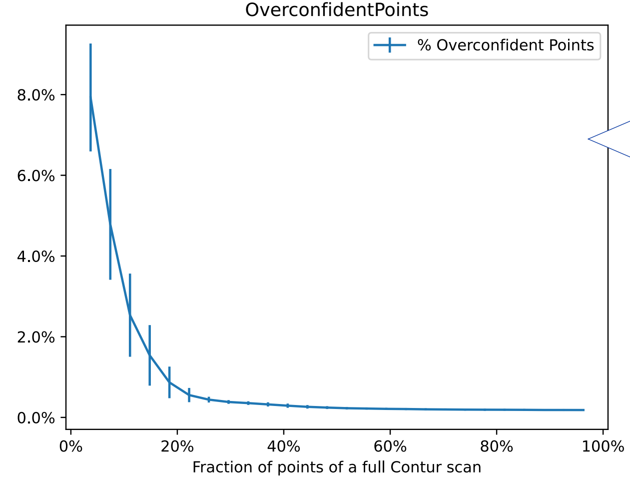


Simplified DM model (4 parameters, 8100 points)









Overconfident points defined as those where Prob(95%)*0.95 > true CLs value.

Drops very quickly

2HDM+a (4 params, ~7500 points)

- tan beta:
  related to ratio of vacuum expectation values
  0.05 to 100.05 in steps of 20 GeV

- mh4:
  mass of the extra Higgses (mostly degenerate)
  1 GeV to 1000 GeV in steps of 100 GeV

- mXd:
  DM mass
  1 GeV to 1000 GeV in steps of 100 GeV

- sinp:
  #umm, not sure what this one represents physically!
  0.01 to 0.91 in steps of 0.1

2HDM+a (4 params, ~7500 points)