A shortcut to new physics

Using the archive of LHC measurements to constrain BSM models with **Contur**

by
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on behalf of the →Contur team

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

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Introduction

Contur - “Constraints On New Theories Using Rivet”

- reinterpretation tool that helps to constrain BSM models using existing LHC measurements
- 3 major physics studies with Contur so far:
  - B–L Gauge Model [→JHEP **2019**, 154 (2019)]
  - Vector-like Quarks [→SciPost Phys. 9, 069 (2020)]
  - Two Higgs Doublet Model + Pseudoscalar [→2009.02220]

➔ beyond stage of mere concept, user-facing version **Contur 2.0.0** recently released
➔ up-to-date documentation in new Contur manual [→2102.04377]

Want to get started?

→Contur webpage

→Contur code

This Talk:

1. The Contur method
2. An Example
3. Making your analysis available in Contur

Contur overview

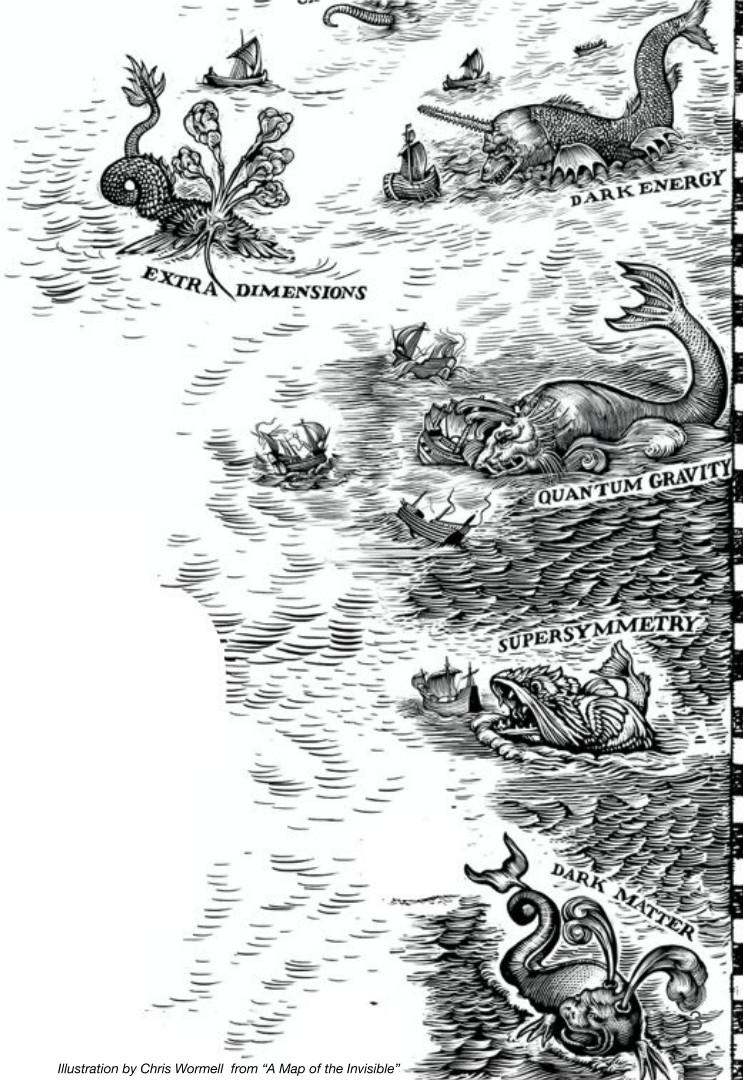
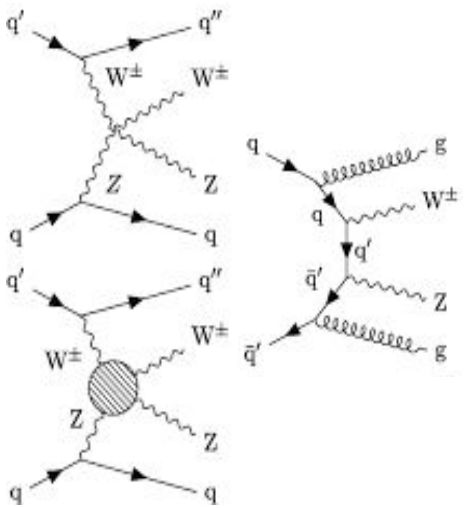


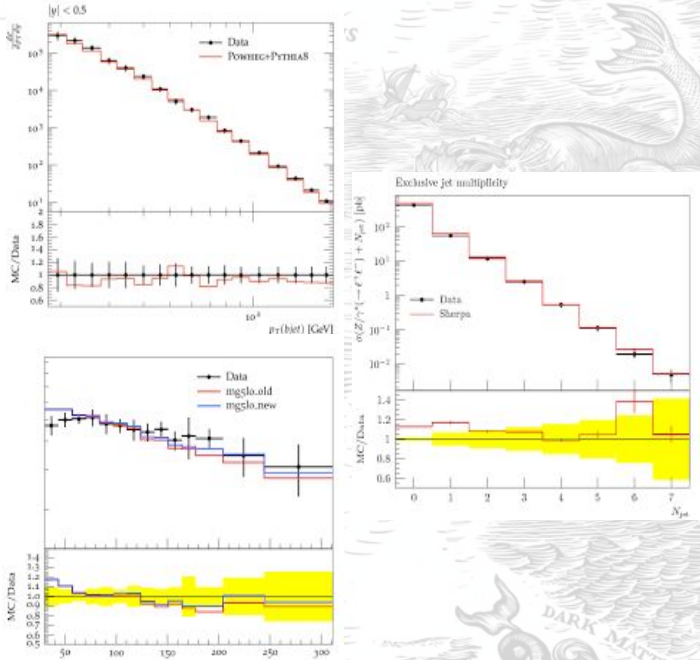
Illustration by Chris Wormell from "A Map of the Invisible"

Contur approach

SM → **Processes** → **LHC measurements**

$$
\begin{aligned}
&\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc}\partial_\mu g_\nu^a g_\mu^b g_\nu^c - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
&M^2 W_\mu^+ W_\mu^- - \tfrac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \tfrac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
&W_\mu^+ W_\nu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
&igs_w(\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
&W_\nu^- \partial_\nu W_\mu^+)) - \tfrac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + \tfrac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
&Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
&W_\mu^- W_\nu^+) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \\
&\tfrac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2) - \\
&gMW_\mu^+ W_\mu^- H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
&\tfrac{1}{2}ig\left(W_\mu^+(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W_\mu^-(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W_\mu^+(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W_\mu^-(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z_\mu^0(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w}Z_\mu^0\partial_\mu\phi^0 + W_\mu^+\partial_\mu\phi^- + W_\mu^-\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ_\mu^0(W_\mu^+\phi^- - W_\mu^-\phi^+) + igs_w MA_\mu(W_\mu^+\phi^- - \\
&W_\mu^-\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z_\mu^0(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{2}g^2 W_\mu^+ W_\mu^-(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z_\mu^0 Z_\mu^0(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-) - \\
&\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z_\mu^0\phi^0(W_\mu^+\phi^- + W_\mu^-\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z_\mu^0 H(W_\mu^+\phi^- - W_\mu^-\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W_\mu^+\phi^- + \\
&W_\mu^-\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W_\mu^+\phi^- - W_\mu^-\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z_\mu^0 A_\mu\phi^+\phi^- - \\
&g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda_0^a(\bar{q}_\sigma^\lambda\gamma^\mu q_\sigma^\lambda)g_\mu^a - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + \\
&m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)\right) + \\
&\tfrac{ig}{4c_w}Z_\mu^0\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(\tfrac{8}{3}s_w^2 - 1 - \gamma^5)d_j^\lambda) + \\
&(\bar{u}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u_j^\lambda)\} + \tfrac{ig}{2\sqrt{2}}W_\mu^+\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)\right) + \\
&\tfrac{ig}{2\sqrt{2}}W_\mu^-\left((\bar{e}^\kappa U^{lep}{}_{\lambda\kappa}^*\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^*\gamma^\mu(1+\gamma^5)u_j^\lambda)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa) + \right. \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^*(1+\gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^*(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m_e^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m_e^\lambda}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M_\nu^\lambda(1-\gamma_5)\delta_{\kappa\lambda} - \\
&\tfrac{1}{4}\bar{\nu}_\lambda M_{\nu\kappa}^\lambda(1-\gamma_5)\delta_{\kappa} + \tfrac{ig}{2\sqrt{2}}\tfrac{1}{M}\phi^+\left(-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^*(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^*(1-\gamma^5)u_j^\kappa)\right) - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \\
&\tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda)) + G^a\partial^2 G^a + g_s f^{abc}\partial_\mu G^a G^b g_\mu^c + \\
&\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W_\mu^-(\partial_\mu\bar{X}^0 X^- - \\
&\partial_\mu\bar{X}^+ X^0) + igs_w W_\mu^+(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^-\bar{Y}) + igc_w W_\mu^-(\partial_\mu\bar{X}^- X^0 - \\
&\partial_\mu\bar{X}^0 X^+) + igs_w W_\mu^-(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z_\mu^0(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}igM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
&\tfrac{1}{2}igM\left(\bar{X}^+ X^-\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{aligned}
$$



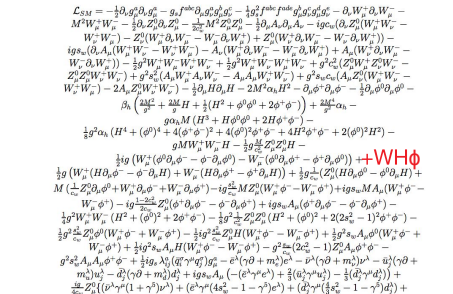


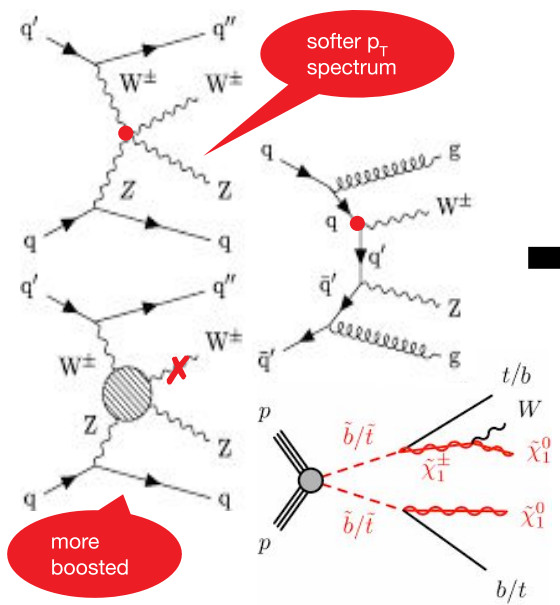
Contur approach

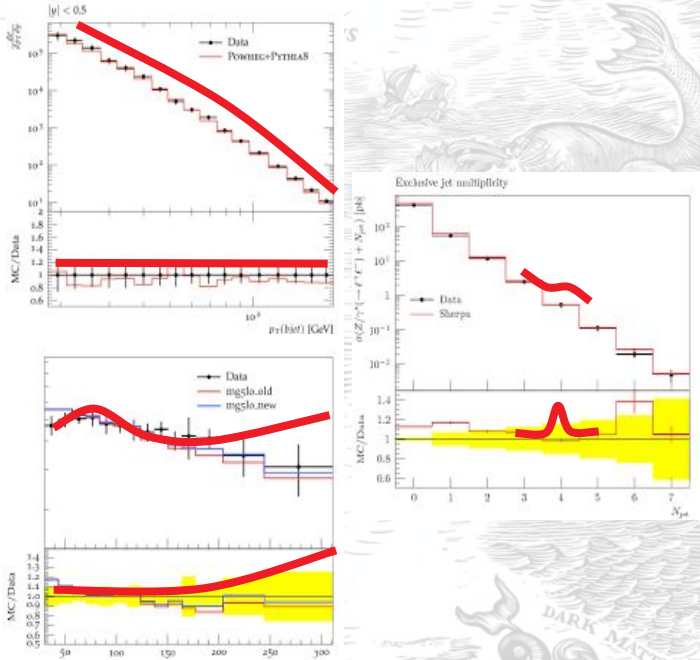
SM + BSM

Processes + BSM

LHC measurements + BSM







- SM is finely balanced and well measured
- ➔ cannot simply add BSM model without it showing up in SM distributions
- ➔ **Contur**: check hundreds of such measurements simultaneously

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

Contur method

Sampling model parameters
contur-batch

↓

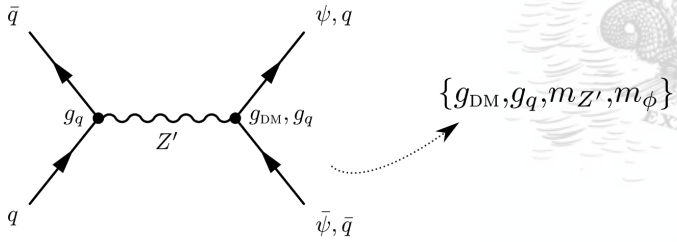
Calculate observables
external tools

↓

Evaluating the likelihood for a model
contur

↓

Visualisation of parameter space
contur-plot



- many BSM models encoded in →Universal Feynrules Output (UFO) format

➔ switching between models easy

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

Contur method

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contur-batch

↓

Calculate observables
external tools

↓

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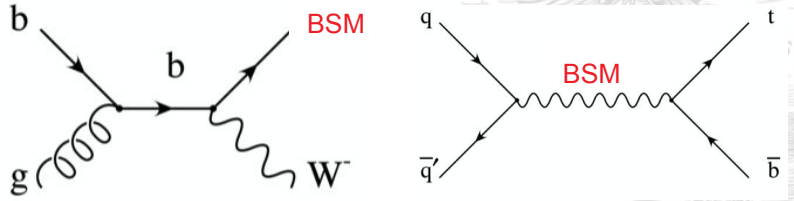
contur

↓

Visualisation of parameter space
contur-plot

1. Event generation
   - ideally **inclusive generation** to not miss signatures



2. Effect on existing measurements?
   - results of LHC measurements stored on **HEPData** by default
   - many (~150) LHC measurements also available as **Rivet routine**

↓

   - runnable plugin that preserves analysis logic (selection, cuts, histograms, …)
   - defined on particle level: no detector simulation needed

   - Rivet optimised for speed, can evaluate impact in hundreds of routines with negligible runtime compared to event generation

Contur method

Sampling model parameters
contur-batch

↓

Calculate observables
external tools

↓

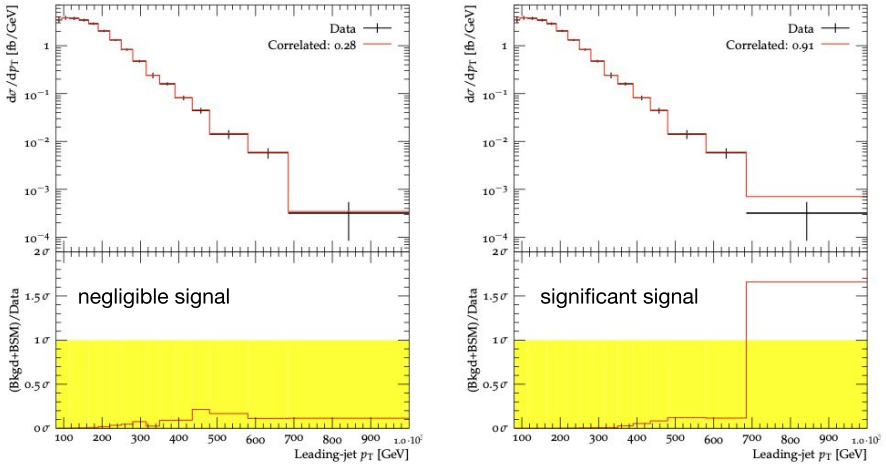
Evaluating the likelihood for a model
contur

↓

Visualisation of parameter space
contur-plot

- group Rivet routines into orthogonal pools
- use CL_s method to determine confidence level of excluding **signal(+bkg)** considering **data** and **uncertainties**

$$L(\mu) = P(n_{obs} \mid \mu) = \frac{(\mu s+b)^{n_{obs}}}{n_{obs}!} e^{(\mu s+b)}$$



- caveat: often SM prediction not given in HEPData

➔ assume SM=data

  - ugly hack, but it works, since we claim no significant deviations seen at LHC so far
  - cannot claim discovery, only falsify BSM model

Contur method

Sampling model parameters
contur-batch

↓

Calculate observables
external tools

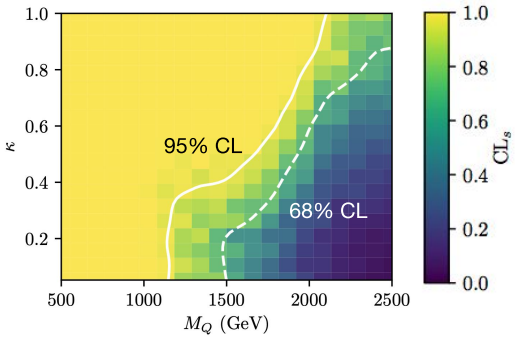
↓

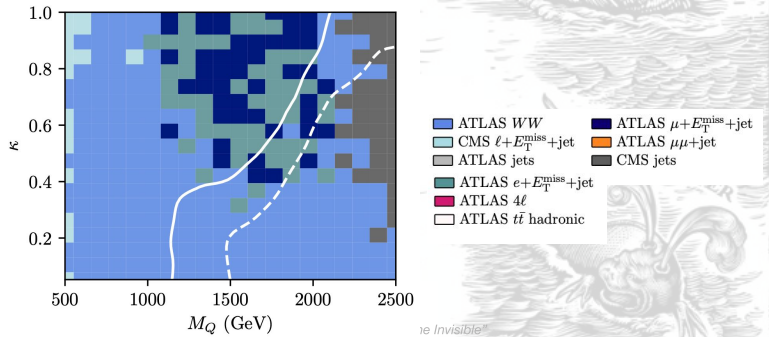
Evaluating the likelihood for a model
contur

↓

Visualisation of parameter space
contur-plot

- repeat this process over a grid of parameter values
- book-keeping and steering machinery provided by Contur





Contur method

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contur-batch

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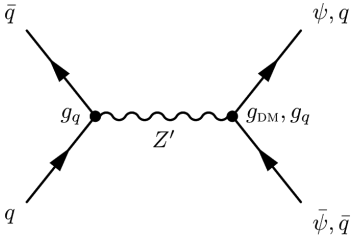
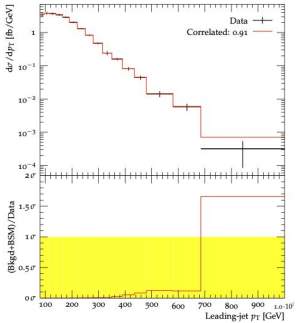
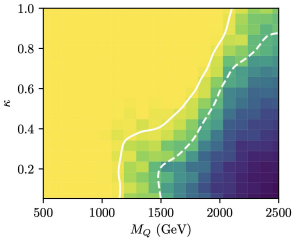
contur-plot





$$\mathrm{L}(\mu) = \mathrm{P}(n_{\mathrm{obs}} \mid \mu) = \frac{(\mu s+b)^{n_{\mathrm{obs}}}}{n_{\mathrm{obs}}!} e^{(\mu s+b)}$$



- can set up whole chain in short time
- running takes O(hours)

"A shortcut to new physics"!

An Example

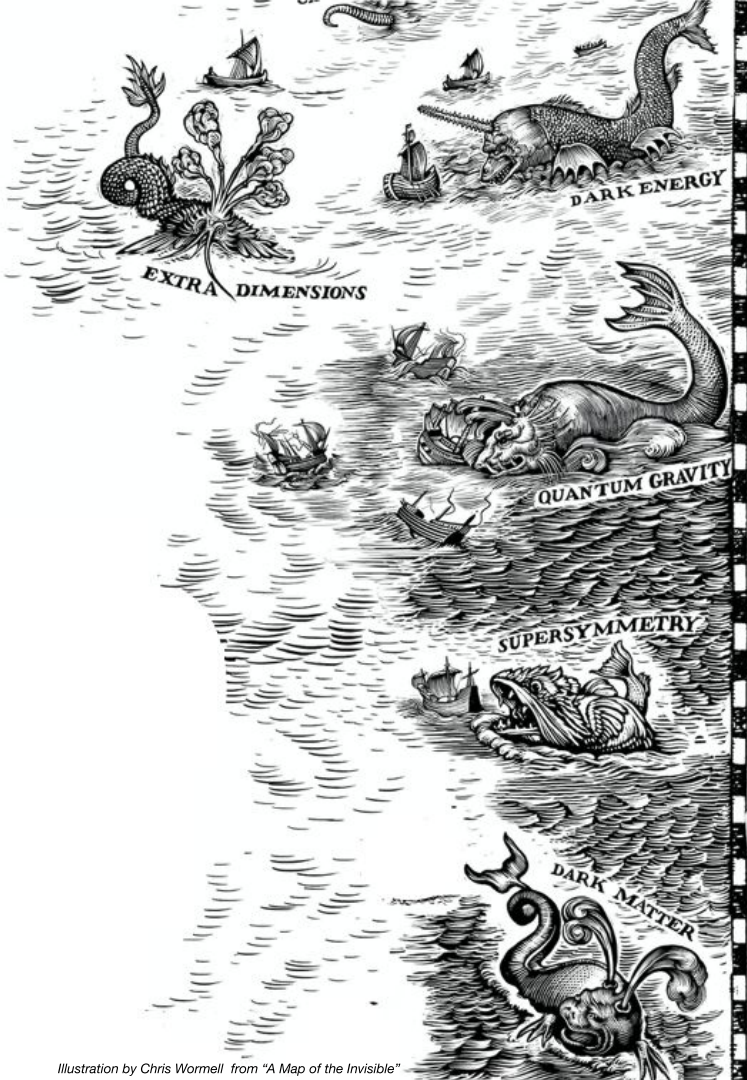


Illustration by Chris Wormell from "A Map of the Invisible"

Example 1: Two Higgs Doublet Model + Pseudoscalar

- **pseudoscalar mediator** that couples to DM and SM particles
- **additional second Higgs doublet** (→"2HDM") to avoid strong constraints by Higgs boson couplings
- mediator-SM coupling through mixing of mediator and second Higgs doublet

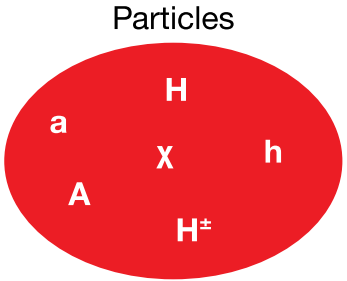


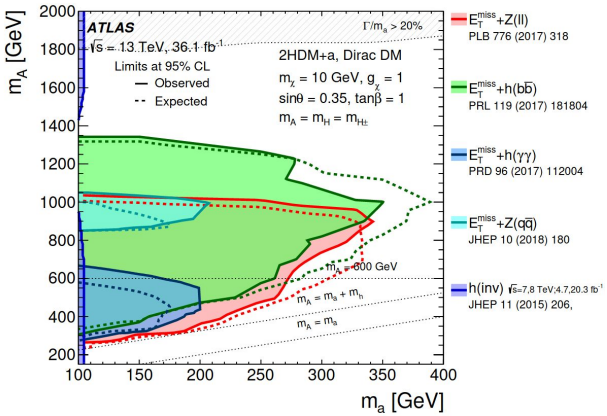
Illustration by Chris Wormell from "A Map of the Invisible"

[→JHEP05(2017)138]

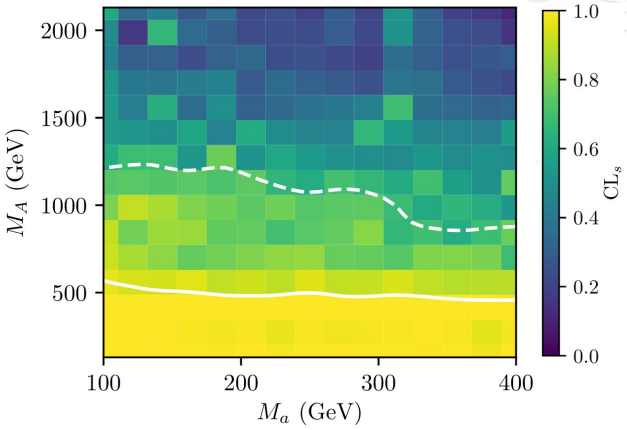
Example 1: Two Higgs Doublet Model + Pseudoscalar

assuming $M_{H\pm}=M_H=M_A$

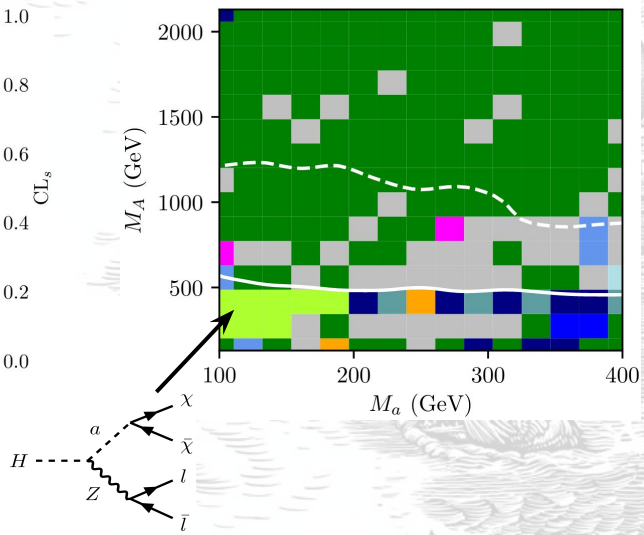
→ATLAS summary paper



our results [→2009.02220]
sensitivity map in terms of CL_s



most sensitive measurements



Contur exclusion

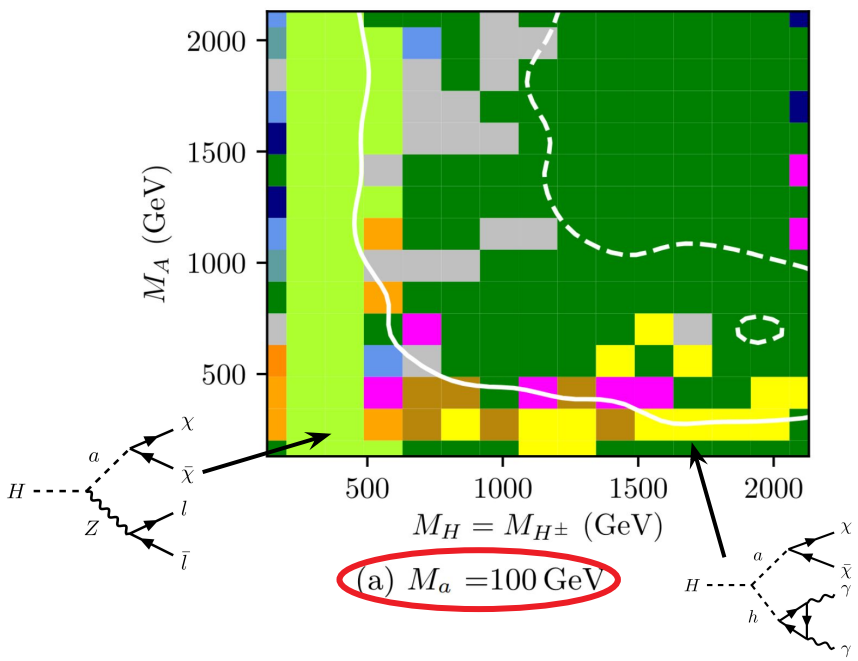
- orthogonal to ATLAS searches
  - searches: require large E_T^{miss} (= DM signature)
  - measurements: do not require E_T^{miss}
- from many different contributions

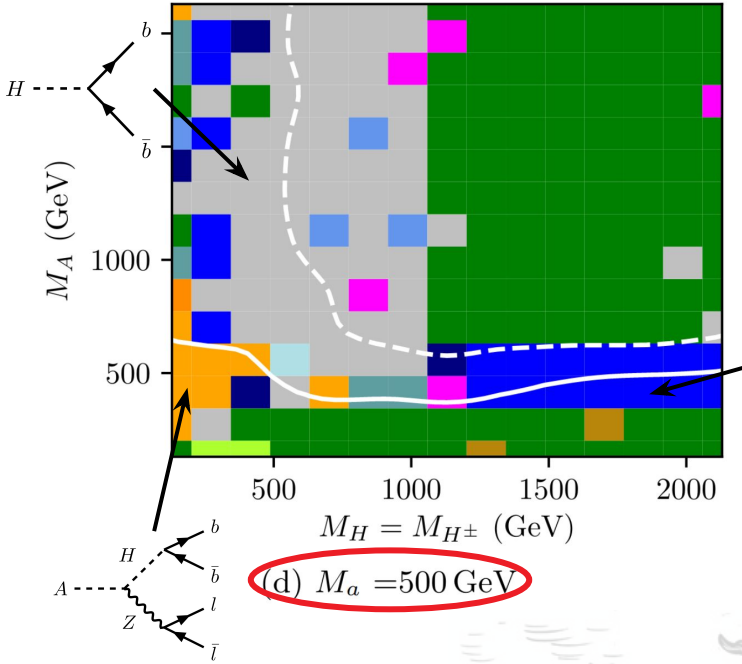
ATLAS $\mu+E_T^{miss}$+jet
CMS $\ell+E_T^{miss}$+jet
ATLAS $\ell\ell$+jet
ATLAS 4ℓ
ATLAS $e+E_T^{miss}$+jet
ATLAS WW
ATLAS jets
ATLAS $ll+E_T^{miss}$
ATLAS $l+E_T^{miss}$+jet
ATLAS $\mu\mu$+jet
ATLAS E_T^{miss}+jet

for further parameter settings see backup

Example 1: Two Higgs Doublet Model + Pseudoscalar

assuming $M_H = M_{H^\pm} \neq M_A$





ATLAS $\mu+E_T^{\text{miss}}$+jet
CMS $e+E_T^{\text{miss}}$+jet
ATLAS $\mu\mu$+jet
ATLAS jets
ATLAS 4ℓ
ATLAS $\gamma + E_T^{\text{miss}}$
ATLAS $e+E_T^{\text{miss}}$+jet
CMS $\ell+E_T^{\text{miss}}$+jet
ATLAS ee+jet
CMS jets
ATLAS $ll+E_T^{\text{miss}}$
CMS $\mu\mu$+jet
ATLAS $l+E_T^{\text{miss}}$+jet
ATLAS WW
ATLAS $\ell\ell$+jet
ATLAS E_T^{miss}+jet
ATLAS γ

Making your analysis available to Contur

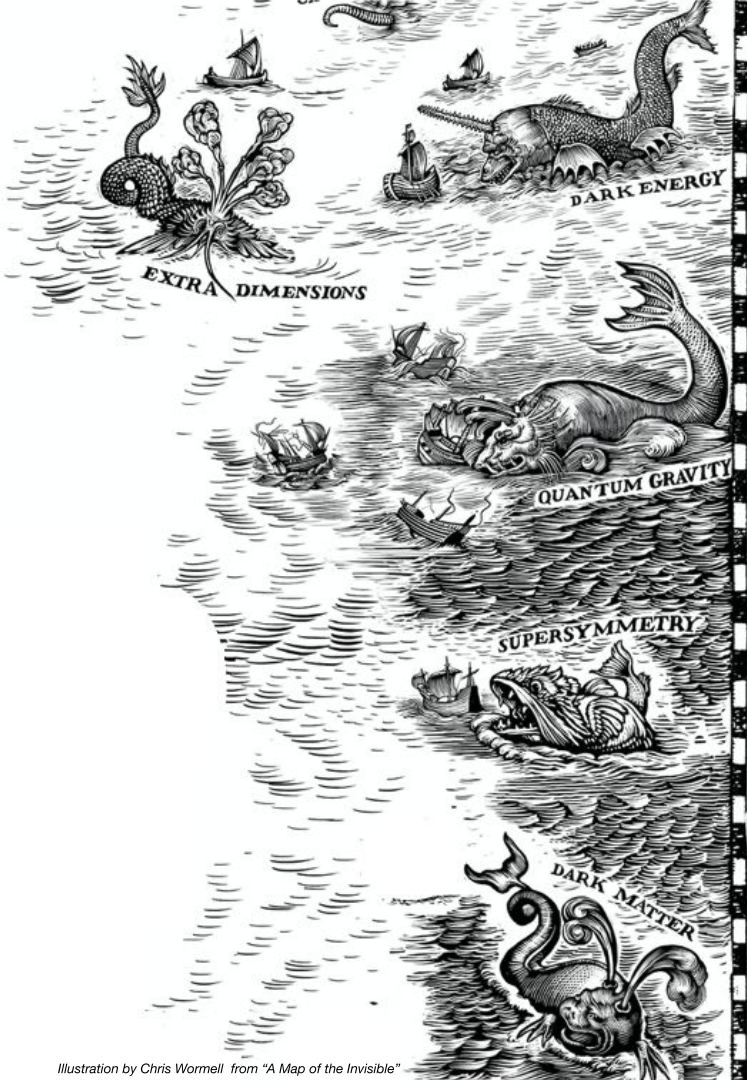
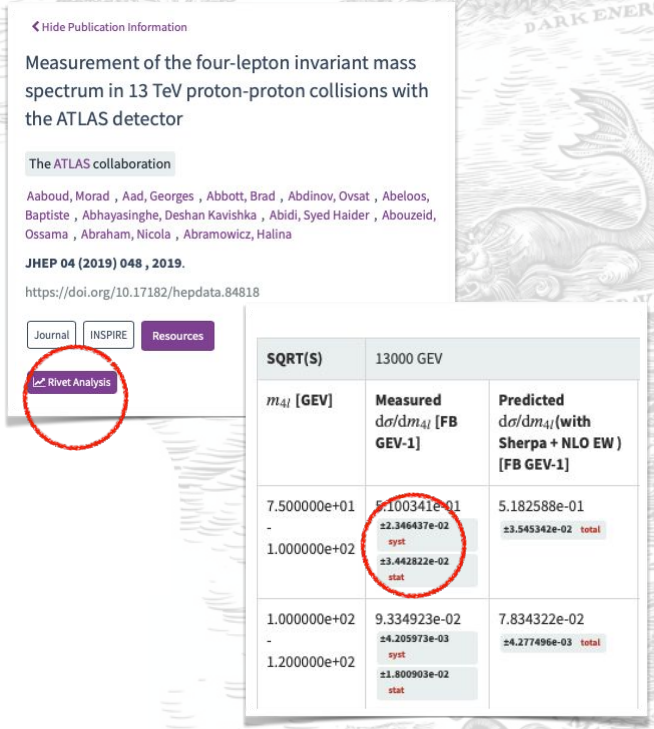


Illustration by Chris Wormell from "A Map of the Invisible"

Measurements and Contur

- **measurements** are bread and butter of Contur method
- things which make measurements easy to include:
  - **unfolding** to particle-level
  - **no model-dependent assumptions**, e.g.
    - don't check flavours of neutrinos
    - no unnecessary background subtractions
    - detector-level b-vetos, b-jet control regions
    - ...
  - **HEPData** published
    - with breakdown of major uncertainties in each bin
      - in standard format
      - as labels, not a separate table
    - include best-available SM prediction as extra column in your HEPData tables
  - preservation in **Rivet routine**
    - available at same time as arXiv submission

Not years later! Some very powerful measurements are still without a Rivet routine, making them unusable. A waste of physics!



→HEPData entry

- note: also **searches** can contribute! (with smeared Rivet routines)

Which analyses are available in Rivet?

- which analyses are available in Rivet can be checked →here
- on the following slides: excerpt showing **available** & **really wanted** Run-2 analyses for ATLAS, CMS, LHCb
  - roughly ordered by EW, Higgs, Jets, Top, Other

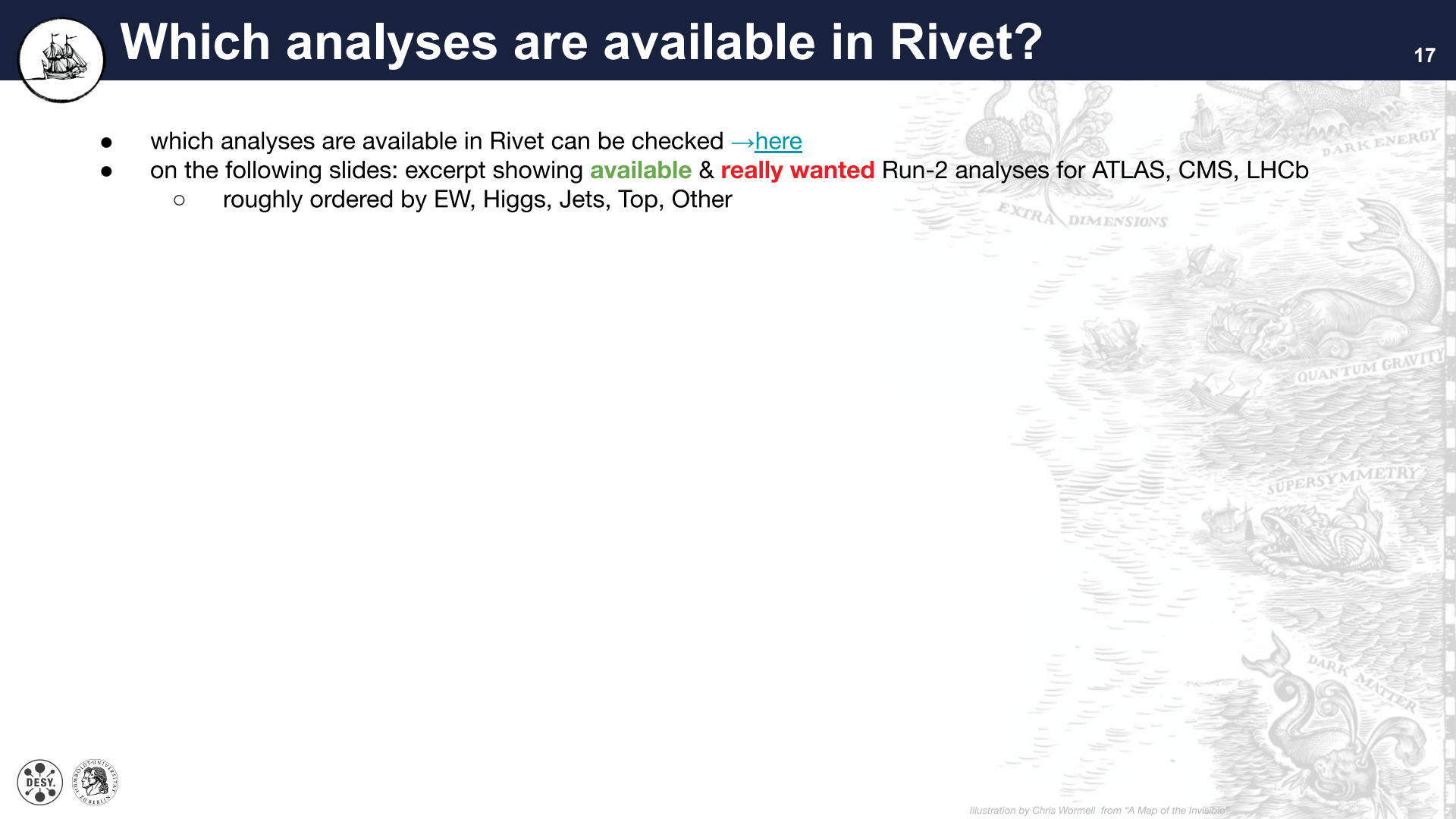


Illustration by Chris Wormell from "A Map of the Invisible"

Which analyses are available in Rivet?

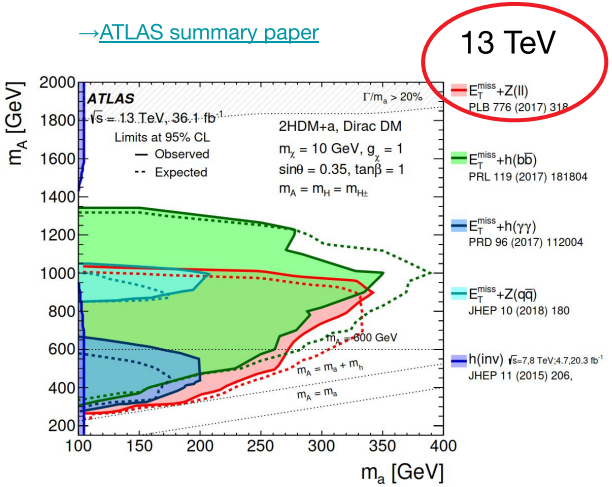
ATLAS - EW

Charged-particle distributions in $\sqrt{s}$ = 13 TeV pp interactions measured with the ATLAS detector at the LHC	1602.01633	available
Charged-particle distributions at low transverse momentum in $\sqrt{s} = 13$ TeV pp interactions measured with the ATLAS detector at the LHC	1606.01133	available
Measurement of the $W^{\pm}Z$ boson pair-production cross section in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS Detector	1606.04017	available
Measurement of the W^+W^- production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV with the ATLAS experiment	1702.04519	wanted
Measurement of the ratio of cross sections for inclusive isolated-photon production in pp collisions at $\sqrt s = 13$ and 8 TeV with the ATLAS detector	1901.10075	wanted
Measurement of the four-lepton invariant mass spectrum in 13 TeV proton-proton collisions with the ATLAS detector	1902.05892	available
Measurement of fiducial and differential W^+W^- production cross-sections at $\sqrt{s}=13$ TeV with the ATLAS detector	1905.04242	available
Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector	1905.09752	wanted
Measurement of the $Z(\rightarrow\ell^+\ell^-)\gamma$ production cross-section in pp collisions at $\sqrt{s} =13$ TeV with the ATLAS detector	1911.04813	available
Measurement of the transverse momentum distribution of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1912.02844	wanted
Measurement of the Z\gamma \to \nu \overline{\nu}\gamma production cross section in pp collisions at \sqrt{s}=13 TeV with the ATLAS detector and limits on anomalous triple gauge-boson couplings	1810.04995	wanted
Measurement of ZZ production in the \ell\ell\nu\nu final state with the ATLAS detector in pp collisions at \sqrt{s} = 13 TeV	1905.07163	wanted

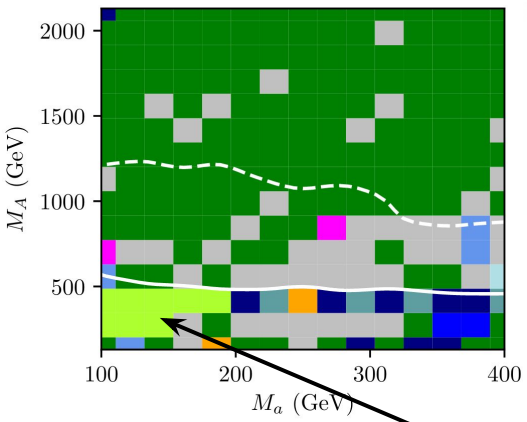

Which analyses are available in Rivet?

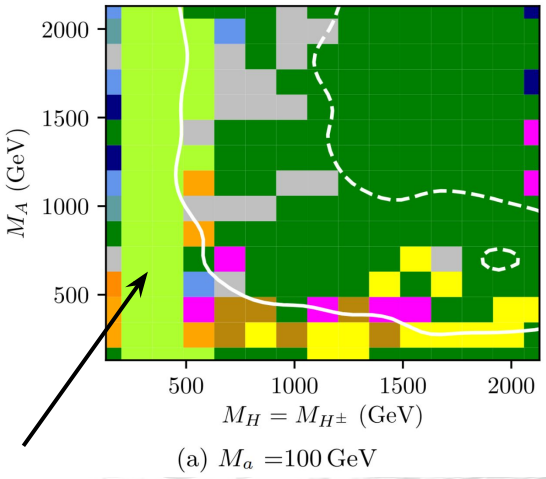
missing Rivet routines can have large impact!
example: ATLAS ZZ→ llvv

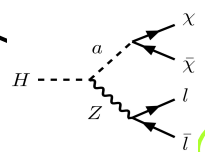
→ATLAS summary paper



our results [→2009.02220]
most sensitive measurements







7 TeV

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

Which analyses are available in Rivet?

ATLAS - Jets

Measurement of charged-particle distributions sensitive to the underlying event in $ \sqrt{s}=13 $ TeV proton-proton collisions with the ATLAS detector at the LHC	1701.0539	available
Measurements of the production cross section of a Z boson in association with jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector	1702.05725	available
Measurement of b-hadron pair production with the ATLAS detector in proton-proton collisions at $\sqrt{s}=8$ TeV	1705.03374	available
Measurement of detector-corrected observables sensitive to the anomalous production of events with jets and large missing transverse momentum in pp collisions at $\mathbf {\sqrt{s}=13}$ TeV using the ATLAS detector	1707.03263	available
Measurement of inclusive jet and dijet cross-sections in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1711.02692	available
Measurement of the Soft-Drop Jet Mass in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector	1711.08341	available
Measurement of the cross section for isolated-photon plus jet production in pp collisions at $\sqrt s=13$ TeV using the ATLAS detector	1801.00112	available
Properties of $g\rightarrow b\bar{b}$ at small opening angles in pp collisions with the ATLAS detector at $\sqrt{s}=13$ TeV	1812.09283	available
Measurement of jet-substructure observables in top quark, W boson and light jet production in proton-proton collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1903.02942	available
Properties of jet fragmentation using charged particles measured with the ATLAS detector in pp collisions at $\sqrt{s}=13$ TeV	1906.09254	wanted
Measurement of the inclusive cross-section for the production of jets in association with a Z boson in proton-proton collisions at 8 TeV using the ATLAS detector	1907.06728	available
Measurement of the jet mass in high transverse momentum $Z(\rightarrow b\overline{b})\gamma$ production at $\sqrt{s}= 13$ TeV using the ATLAS detector	1907.07093	wanted
A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV	1912.09837	wanted
Measurement of isolated-photon plus two-jet production in pp collisions at $\sqrt s=13$ TeV with the ATLAS detector	1912.09866	wanted

Which analyses are available in Rivet?

ATLAS - Top

Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b-tagged jets in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector	1606.02699	available
Measurement of jet activity produced in top-quark events with an electron, a muon and two b-tagged jets in the final state in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1610.09978	available
Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	1708.00727	available
Measurements of $t\bar{t}$ differential cross-sections of highly boosted top quarks decaying to all-hadronic final states in pp collisions at $\sqrt{s}=13\,$ TeV using the ATLAS detector	1801.02052	available
Measurements of differential cross sections of top quark pair production in association with jets in ${pp}$ collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	1802.06572	available
Measurement of colour flow using jet-pull observables in $t\bar{t}$ events with the ATLAS experiment at $\sqrt{s} = 13\,\hbox {TeV}$	1805.02935	wanted
Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1806.04667	available
Measurements of fiducial and differential cross-sections of $t\bar{t}$ production with additional heavy-flavour jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector	1811.12113	available
Measurements of inclusive and differential fiducial cross-sections of $t\bar{t}\gamma$ production in leptonic final states at $\sqrt{s}$ = 13 TeV in ATLAS	1812.01697	available
Measurements of top-quark pair spin correlations in the $e\mu$ channel at $\sqrt{s} = 13$ TeV using pp collisions in the ATLAS detector	1903.0757	wanted
Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s}=13$ TeV using the ATLAS detector	1908.07305	available
Measurement of the $t\bar{t}$ production cross-section and lepton differential distributions in $e\mu$ dilepton events from pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1910.08819	available

Which analyses are available in Rivet?

ATLAS - Higgs

Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ* \rightarrow 4\ell$ decay channel in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector	1708.0281	wanted
Combined measurement of differential and total cross sections in the $H \rightarrow \gamma \gamma$ and the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS detector	1805.10197	wanted
Measurement of VH, $ \mathrm{H}\to \mathrm{b}\overline{\mathrm{b}} $ production as a function of the vector-boson transverse momentum in 13 TeV pp collisions with the ATLAS detector	1903.04618	wanted

CMS - EW

Measurement of the differential cross sections for the associated production of a W boson and jets in proton-proton collisions at $\sqrt{s}=13$ TeV	1707.05979	available
Measurement of the underlying event activity in inclusive Z boson production in proton-proton collisions at $ \sqrt{s}=13 $ TeV	1711.04299	available
Measurement of differential cross sections for inclusive isolated-photon and photon+jets production in proton-proton collisions at $\sqrt{s} =$ 13 TeV	1807.00782	wanted
Measurement of associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{s} =$ 13 TeV	1811.10021	available
Measurement of the differential Drell-Yan cross section in proton-proton collisions at $\sqrt{s} =$ 13 TeV	1812.10529	available
Measurements of the pp $\to$ WZ inclusive and differential production cross section and constraints on charged anomalous triple gauge couplings at $\sqrt{s} =$ 13 TeV	1901.03428	wanted
Measurements of differential Z boson production cross sections in proton-proton collisions at $ \sqrt{s} $ = 13 TeV	1909.04133	available
Measurement of the cross section for electroweak production of a Z boson, a photon and two jets in proton-proton collisions at $\sqrt{s} =$ 13 TeV and constraints on anomalous quartic couplings	2002.09902	wanted

Which analyses are available in Rivet?

CMS - Higgs

Measurement of inclusive and differential Higgs boson production cross sections in the diphoton decay channel in proton-proton collisions at $\sqrt{s}=$ 13 TeV	1807.03825	wanted
Measurement and interpretation of differential cross sections for Higgs boson production at $\sqrt{s}=$ 13 TeV	1812.06504	wanted

CMS - Jets

Measurement of the double-differential inclusive jet cross section in proton–proton collisions at $\sqrt{s} = 13\,\text {TeV} $	1605.04436	available
Azimuthal correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at $\sqrt{s}= $ 13 TeV	1712.05471	available
Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at $\sqrt{s} =$ 13 TeV	1804.05252	available
Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s} =$ 8 and 13 TeV	1806.11073	wanted
Measurements of the differential jet cross section as a function of the jet mass in dijet events from proton-proton collisions at $ \sqrt{s}=13 $ TeV	1807.05974	available
Measurement of jet substructure observables in $\mathrm{t\overline{t}}$ events from proton-proton collisions at $\sqrt{s}=$ 13TeV	1808.0734	available
Event shape variables measured using multijet final states in proton-proton collisions at $ \sqrt{s}=13 $ TeV	1811.00588	wanted
Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s}=$ 13 TeV	1902.04374	wanted
Measurement of the associated production of a Z boson with charm or bottom quark jets in proton-proton collisions at $\sqrt {s}$=13 TeV	2001.06899	wanted
Dependence of inclusive jet production on the anti-k_T distance parameter in pp collisions at $\sqrt{s} =$ 13 TeV	2005.05159	wanted

Which analyses are available in Rivet?

CMS - Top

Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV	1610.04191	available
Measurement of the $t \bar t$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s}$ = 13 TeV	1701.06228	wanted
Measurements of $t\bar{t}$ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV	1705.10141	wanted
Measurements of differential cross sections of top quark pair production as a function of kinematic event variables in proton-proton collisions at $ \sqrt{s}=13 $ TeV	1803.03991	available
Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} =$ 13 TeV	1803.08856	available
Study of the underlying event in top quark pair production in pp collisions at 13 TeV	1807.0281	wanted
Measurements of $\mathrm{t\overline{t}}$ differential cross sections in proton-proton collisions at $\sqrt{s}=$ 13 TeV using events containing two leptons	1811.06625	wanted
Measurement of $\mathrm{t\bar t}$ normalised multi-differential cross sections in pp collisions at $\sqrt s=13$ TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions	1904.05237	wanted
Measurement of the top quark polarization and $\mathrm{t\bar{t}}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} =$ 13 TeV	1907.03729	wanted
Measurement of differential cross sections and charge ratios for t-channel single top quark production in proton-proton collisions at $\sqrt{s}=$ 13 TeV	1907.0833	available
Measurement of the $\mathrm{t\bar{t}}\mathrm{b\bar{b}}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} =$ 13 TeV	1909.05306	wanted
Measurement of the jet mass distribution and top quark mass in hadronic decays of boosted top quarks in pp collisions at $\sqrt{s} =$ 13 TeV	1911.038	available
Measurement of the top quark pair production cross section in dilepton final states containing one τ lepton in pp collisions at $\sqrt{s}=$ 13 TeV	1911.13204	wanted
Measurement of the top quark forward-backward production asymmetry and the anomalous chromoelectric and chromomagnetic moments in pp collisions at $\sqrt{s}=$ 13 TeV	1912.0954	wanted
Measurement of the cross section for $\text{t}\bar{\text{t}}$ production with additional jets and b jets in pp collisions at $\sqrt{s}=$ 13 TeV	2003.06467	wanted

Which analyses are available in Rivet?

CMS - Other

Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV	1507.05915	available
Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt s =$13 TeV	1510.03068	wanted
Measurement of the total and differential inclusive B^+ hadron cross sections in pp collisions at $\sqrt{s}$ = 13 TeV	1609.00873	wanted
Measurement of the inclusive energy spectrum in the very forward direction in proton-proton collisions at $ \sqrt{s}=13 $ TeV	1701.08695	available
Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s}=13$ TeV	1706.10194	wanted
Measurement of the inelastic proton-proton cross section at $ \sqrt{s}=13 $ TeV	1802.02613	available
Measurement of charged particle spectra in minimum-bias events from proton–proton collisions at $\sqrt{s}=13\,\text {TeV} $	1806.11245	available
Measurement of the energy density as a function of pseudorapidity in proton-proton collisions at $\sqrt{s}=$ 13 TeV	1812.04095	available
Measurement of the average very forward energy as a function of the track multiplicity at central pseudorapidities in proton-proton collisions at $\sqrt{s}=$ 13 TeV	1908.0175	wanted

LHCb

Measurements of prompt charm production cross-sections in pp collisions at $ \sqrt{s}=13 $ TeV	1510.01707	available
Measurement of the b-quark production cross-section in 7 and 13 TeV pp collisions	1612.0514	wanted
Measurement of forward top pair production in the dilepton channel in pp collisions at $\sqrt{s}=13$ TeV	1803.05188	wanted
Measurement of the inelastic pp cross-section at a centre-of-mass energy of 13 TeV	1803.10974	wanted

Conclusions and Discussion

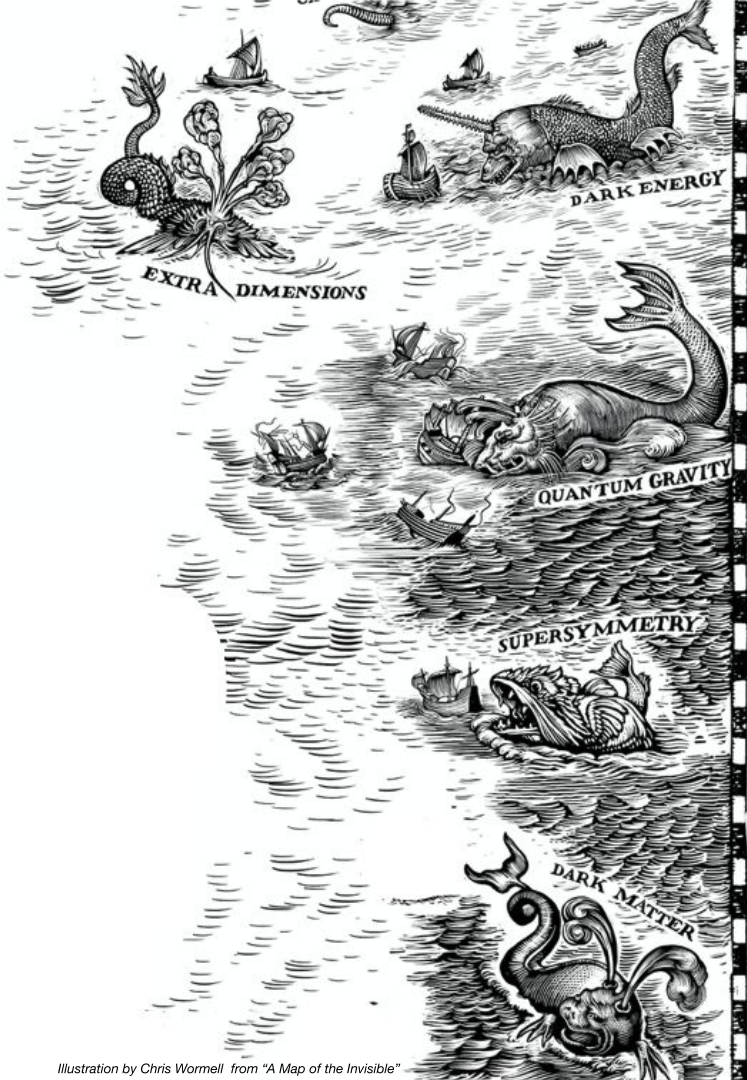


Illustration by Chris Wormell from "A Map of the Invisible"

Conclusions and Discussion

- Contur allows study of existing LHC sensitivity to new models
- inclusive event generation: more comprehensive picture than just working on most spectacular signatures of model
- existing measurements can exclude unexpected parameter spaces of models

- it's not hard …
  … to make your analysis be used by Contur
  … to run Contur yourself

Check out the →Contur tutorial on Friday, 19/02/2021, 10:00 to see for yourself!

Should this sort of scan be part of the 'due diligence' when proposing a new model or designing a search?

\+ free person power for more elusive signatures
\+ free computing resources

The End

(of this talk)

Thanks to Louie Corpe for the ideas for many slides!

Backup

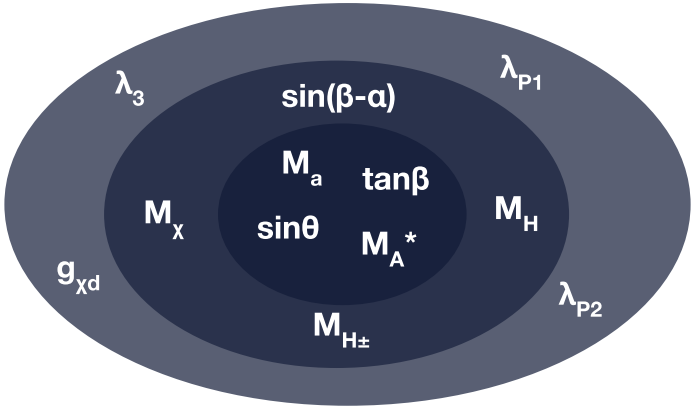
↓

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

Example 1: Two Higgs Doublet Model + Pseudoscalar

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

Parameters



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

Particles

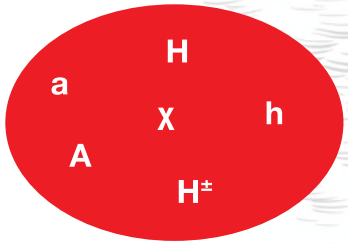


Illustration by Chris Wormell from "A Map of the Invisible"

[→JHEP05(2017)138]

Example 1: Two Higgs Doublet Model + Pseudoscalar

- generate all s-channel resonances and 2→2 processes with Herwig 7, ensure that 2→3 processes are negligible with Madgraph5_aMC@NLO
- not considering interference effects
- use →LHC measurements + 1 search (→0-lepton SUSY search)
- default parameters (following →LHC DM WG recommendations):

Higgs potential quartic couplings

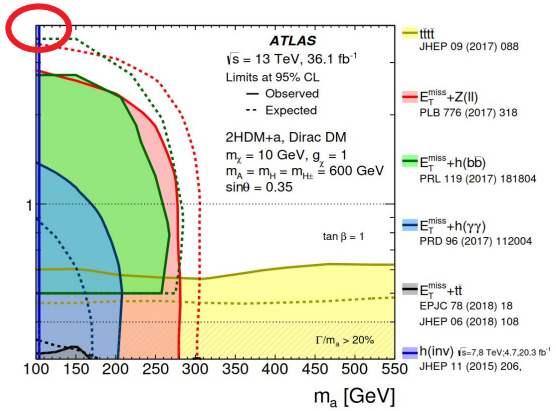
a-χ coupling

$M_H = M_A = M_{H^\pm}$	M_χ	tanβ	sinθ	$g_{\chi d}$	sin(β−α)	$\lambda_3, \lambda_{P1}, \lambda_{P2}$
600 GeV	10 GeV	1	0.35	1	1	3

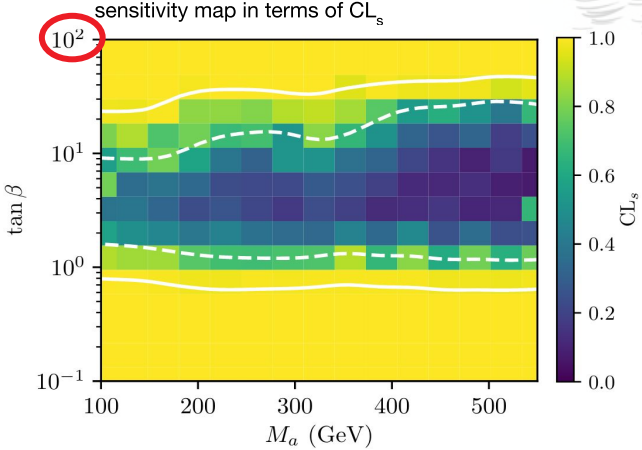
sine of the difference of the mixing angles,
sin(β−α)=1: lightest mass eigentstate has SM Higgs couplings

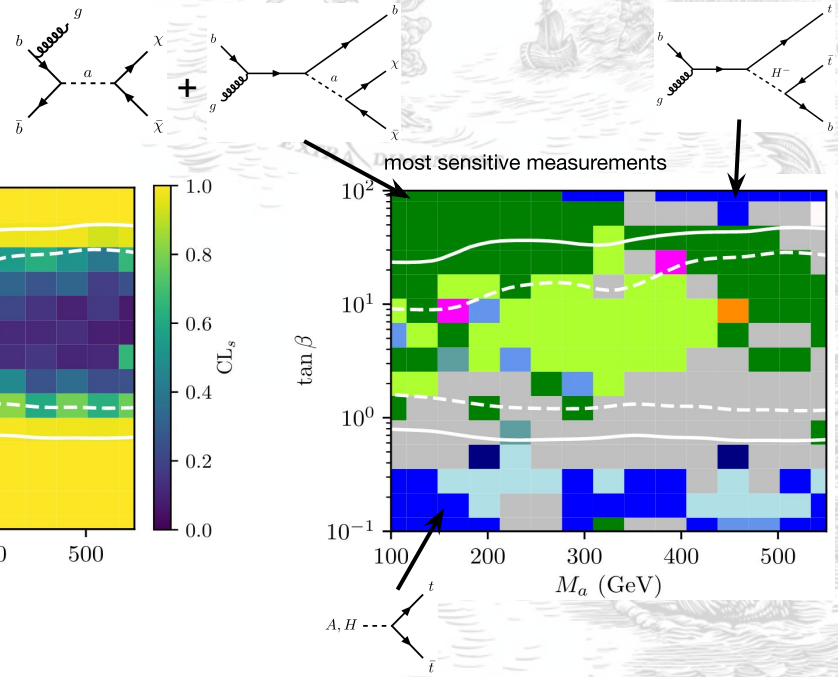
Example 1: Two Higgs Doublet Model + Pseudoscalar

→ATLAS summary paper



our results [→2009.02220]
sensitivity map in terms of CL_s

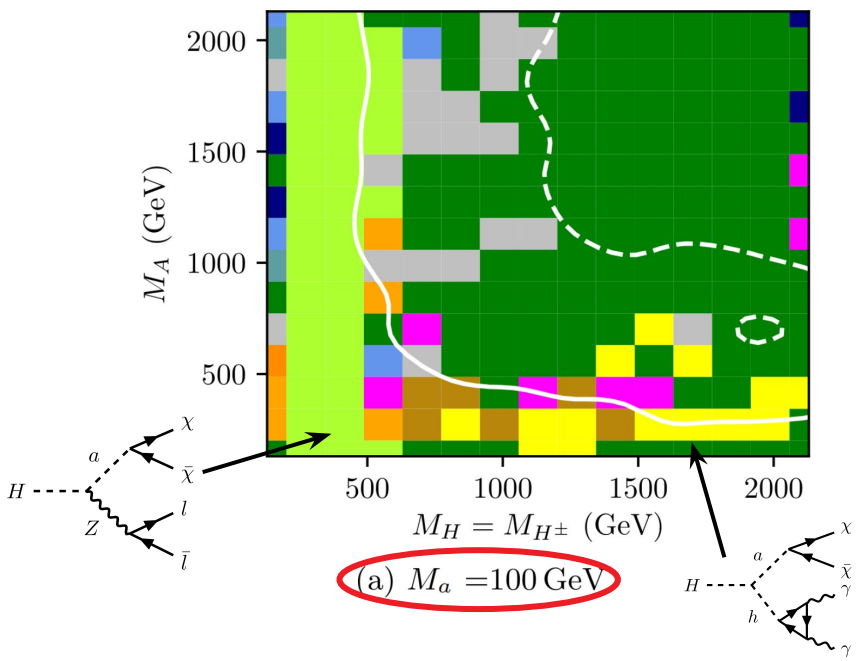


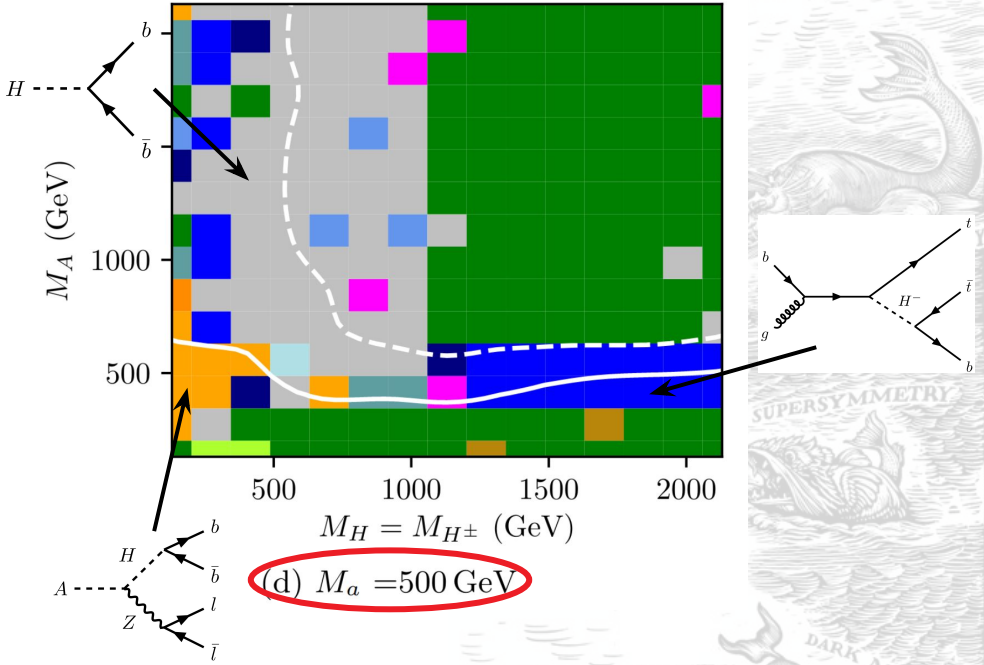


ATLAS $\mu+E_T^{\text{miss}}$+jet
CMS $\ell+E_T^{\text{miss}}$+jet
ATLAS $\ell\ell$+jet
ATLAS 4ℓ
ATLAS $e+E_T^{\text{miss}}$+jet
ATLAS WW
ATLAS jets
ATLAS $ll+E_T^{\text{miss}}$
ATLAS $l+E_T^{\text{miss}}$+jet
ATLAS $\mu\mu$+jet
ATLAS E_T^{miss}+jet

Example 1: Two Higgs Doublet Model + Pseudoscalar

assuming $M_H = M_{H^\pm} \neq M_A$





ATLAS $\mu+E_T^{\text{miss}}$+jet
CMS $e+E_T^{\text{miss}}$+jet
ATLAS $\mu\mu$+jet
ATLAS jets
ATLAS 4ℓ
ATLAS $\gamma + E_T^{\text{miss}}$
ATLAS $e+E_T^{\text{miss}}$+jet
CMS $\ell+E_T^{\text{miss}}$+jet
ATLAS ee+jet
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ATLAS $ll+E_T^{\text{miss}}$
CMS $\mu\mu$+jet
ATLAS $l+E_T^{\text{miss}}$+jet
ATLAS WW
ATLAS $\ell\ell$+jet
ATLAS E_T^{miss}+jet
ATLAS γ

Example 2: Vector-like Quarks

- paper [→2006.07172] tackles whole class of models: **vector-like quarks**, using framework from Buchkremer et al [→1305.4172]

- introduces quark partners:

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

- coupling to SM via usual quark EM/strong couplings, but modified W/Z/H couplings:
  - B,T: interact with W, Z or H via modified weak coupling
  - X, Y: interact only with W via modified weak coupling
    ➔ X → Wt, Y→ Wb due to charge conservation

- Three parameters:
  - 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}**

SciPost Physics Submission

New sensitivity of current LHC measurements to vector-like quarks

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

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

June 15, 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 quarks and gauge bosons, which will contribute to a variety of already-measured "Standard Model" cross-sections at the LHC. We present a study of the sensitivity of such published LHC measurements to vector-like quarks, first comparing to limits already obtained from dedicated searches, and then broadening to some so-far unstudied parameter regions.

Example 2: Vector-like Quarks

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- introduces quark partners:

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

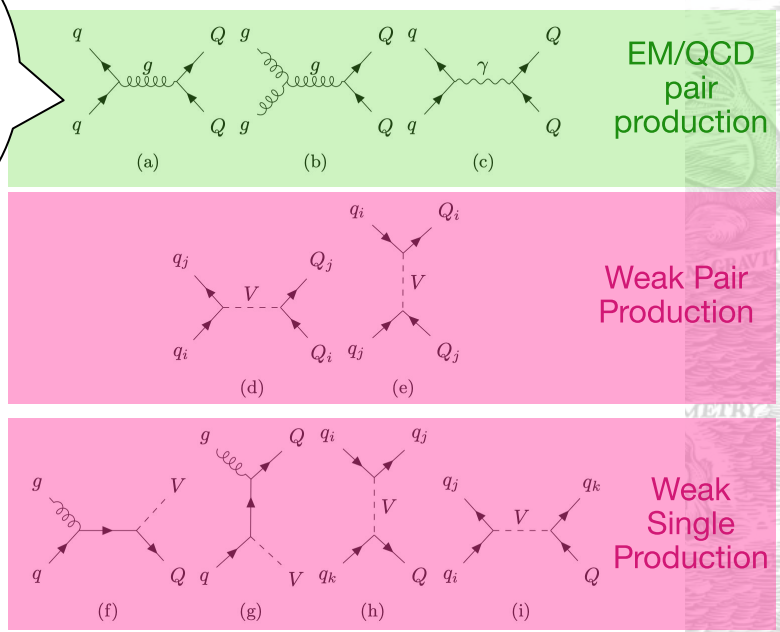
- coupling to SM via usual quark EM/strong couplings, but modified W/Z/H couplings:
  - B,T: interact with W, Z or H via modified weak coupling
  - X, Y: interact only with W via modified weak coupling

    ➔ X → Wt, Y→ Wb due to charge conservation
- Three parameters:
  - κ: **absolute coupling** of VLQs to SM quarks
  - ζ_i: relative **coupling of VLQs to ith generation**
  - ξ_V: relative **coupling of B,T to V in {W, H, Z}**

LHC programme has mostly focused here because pf reduced κ-dependence

-

but single-production has rich phenomenology which we can probe with Contur!

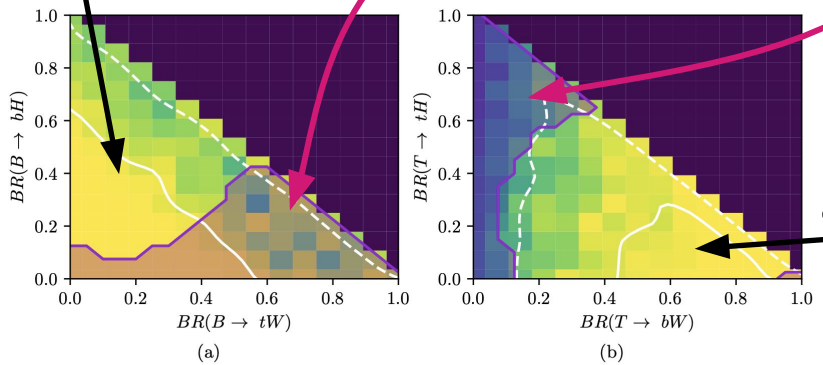


LHC searches mostly focused on 3rd-gen, but 1st-gen has richer phenomenology due to valence-quark-induced production

Example 2: Vector-like Quarks

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

Contur sensitivity comes mainly from Z+jets measurements !



Contur sensitivity comes mainly from Top or W measurements

Figure 5: Sensitivity of LHC measurements to (a) B-production for $M_B = 1200\,\text{GeV}$ and (b) T-production for $M_T = 1350\,\text{GeV}$. 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].

→1808.02343

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

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

CERN-EP-2018-205
November 26, 2018

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

The ATLAS Collaboration

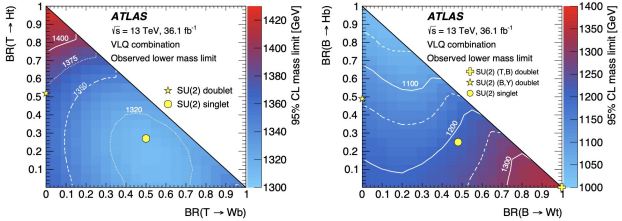


Figure 4: Observed lower limits at 95% CL on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T\to Ht) + \mathcal{B}(T\to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B\to Hb) + \mathcal{B}(B\to Zb) + \mathcal{B}(B\to Wt) = 1$. The yellow markers indicate the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

Example 2: Vector-like Quarks

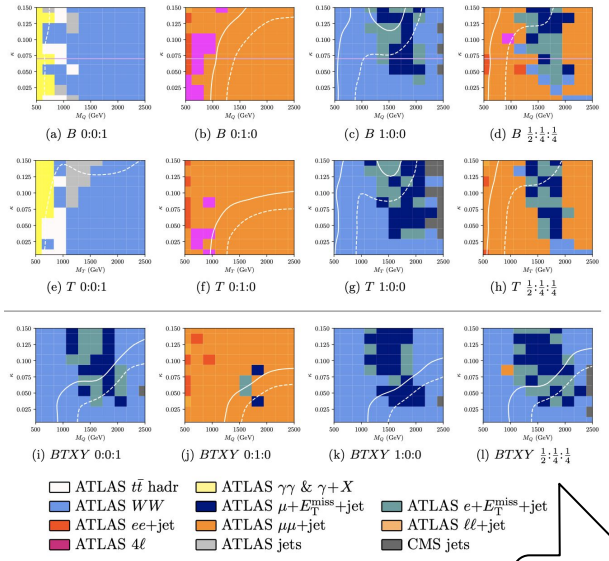
What about Singlets?

if no X or Y in the multiplet, WZH=001 scenarios weaker since no W-decays, and thus only Higgs measurements are sensitive

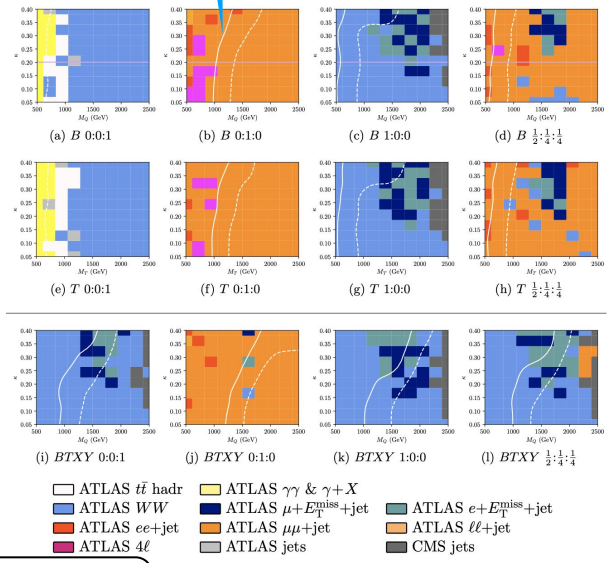
In general, fewer new VLQs lead to weaker constraints

In 3rd-gen cases, lack of top density in proton PDF can prevent single-VLQ production. So only pair-production is viable, which is ~independent of κ

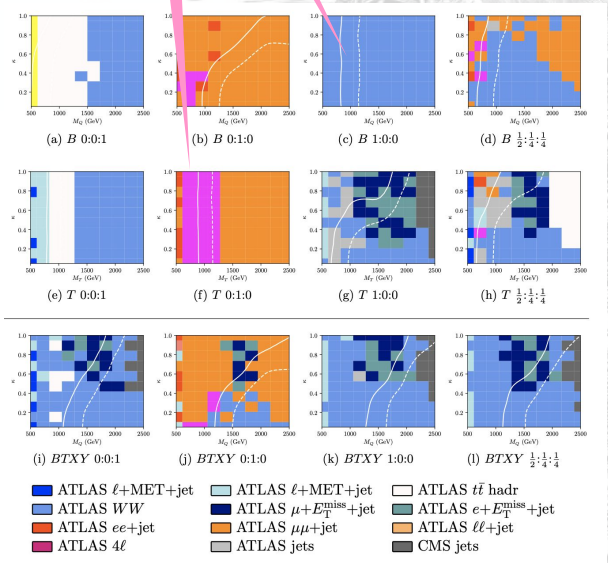
1st-Generation



2nd-Generation



3rd-Generation



Original BTXY results for reference in final row

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

Searches and Contur

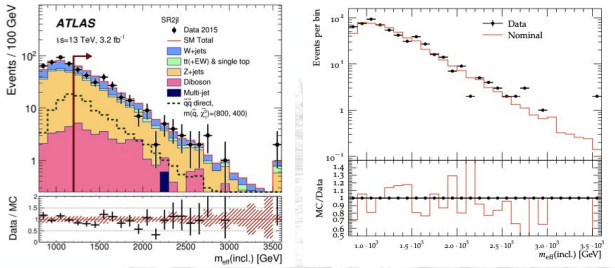
- Contur designed to work with particle-level measurements
- but: now also handles searches if preserved with a →smeared Rivet routine

- proof of principle [→2002.12220]: for a 2HDM model, squarks+gluinos smeared Rivet routine was shown to exhibit similar sensitivity to 3.2/fb MET+jets measurement

- Control-region measurements from searches have great potential
  - especially if uncertainty breakdown and SM background predictions are published on HEPData!

- Contur scans can help liberate search teams to cover the most challenging parts of model space, e.g. Long-lived Particles!

Example: 3.2/fb 13TeV squarks+gluinos has a Rivet Routine
https://www.hepdata.net/record/ins1458270
https://rivet.hepforge.org/analyses/ATLAS_2016_I1458270



Example from LH19 proceedings: sensitivity to SUSY search and equivalent measurement for a 2HDM model