A shortcut to new physics:
using the archive of LHC measurements to constrain new physics

L. Corpe (UCL) for the CONTUR team

RAL seminar, 2nd Sept 2020

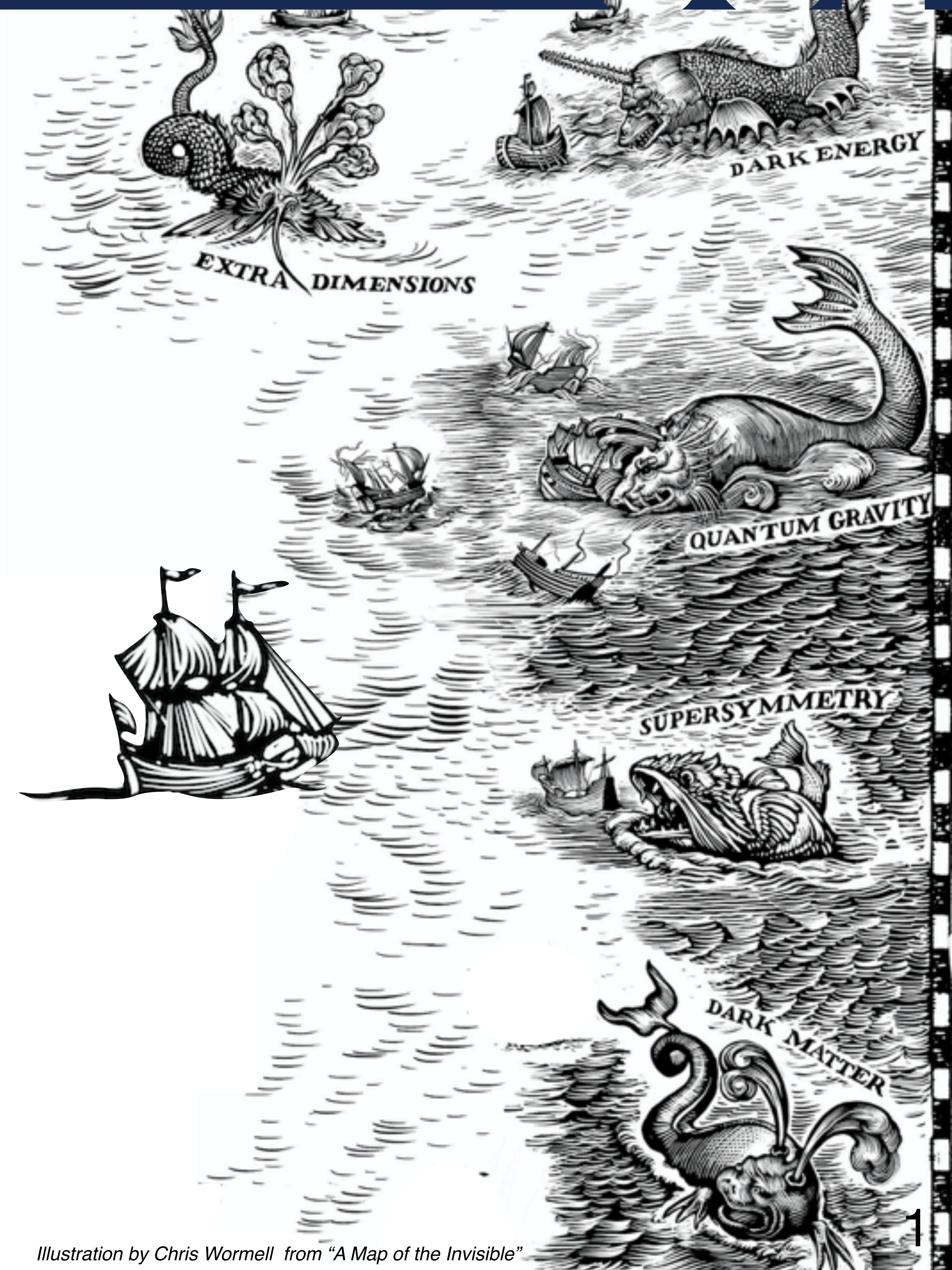

Illustration by Chris Wormell from "A Map of the Invisible"

Introduction

- Our recent paper used CONTUR [arxiv] re-interpretation software to test a whole class of new physics models which involve "vector-like quarks" (VLQs)
- More generally, I will motivate re-interpretation, and the CONTUR method
- I'll then use the VLQ results to illustrate the power of the method and its complementarity to the LHC search programme
- I'll end with some tips for making your LHC analysis more CONTUR-friendly !

https://arxiv.org/abs/2006.07172

SciPost Physics Submission

New sensitivity of current LHC measurements to vector-like quarks

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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.

The LHC vs new physics

A game of hide and seek

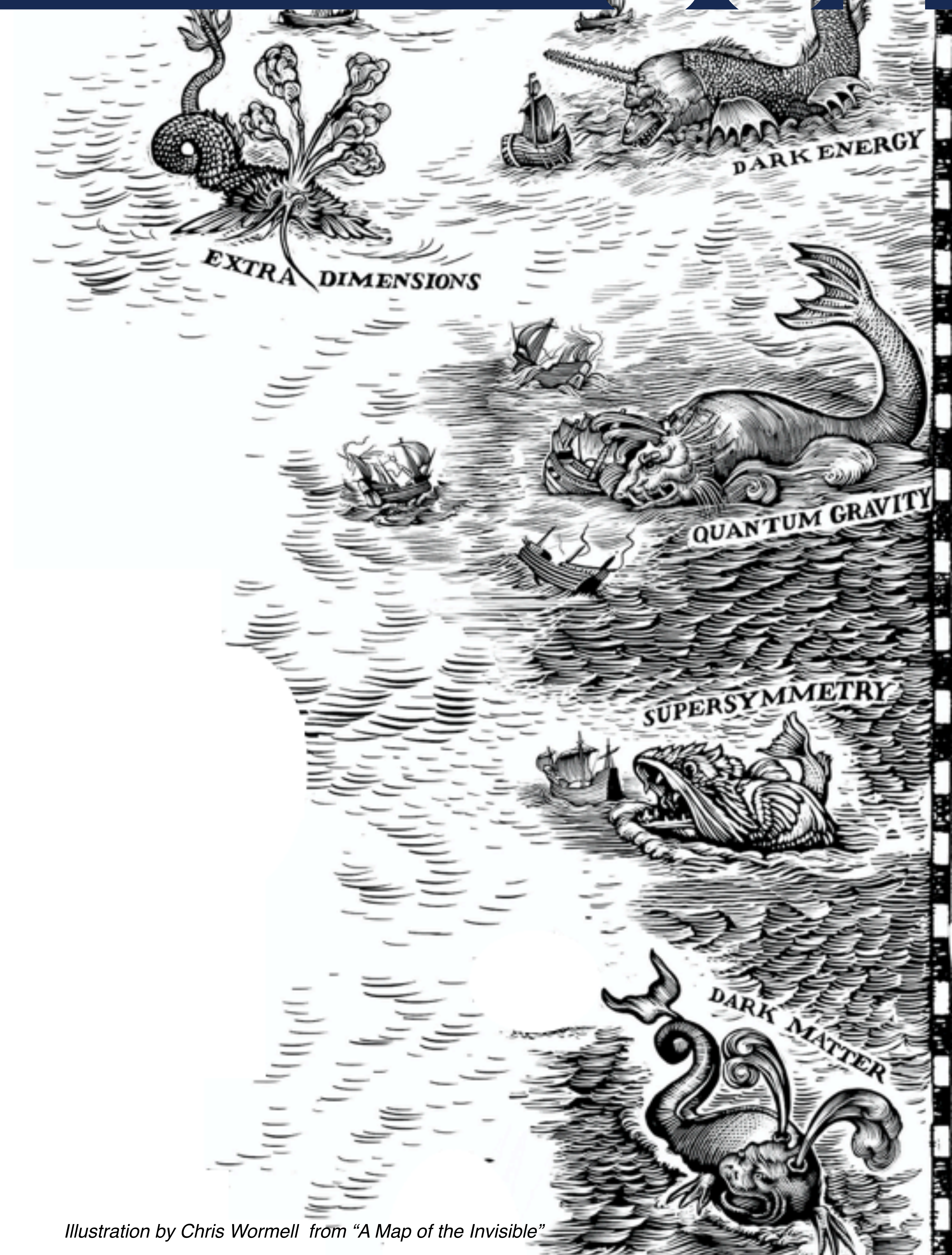


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

The Standard Model (SM)

UCL

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (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^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu 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^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu 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^0_\mu Z^0_\mu 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^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(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^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}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^0_\mu Z^0_\mu (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^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu 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^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\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}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\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}^+ 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^0_\mu(\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}gM\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{gathered}
$$

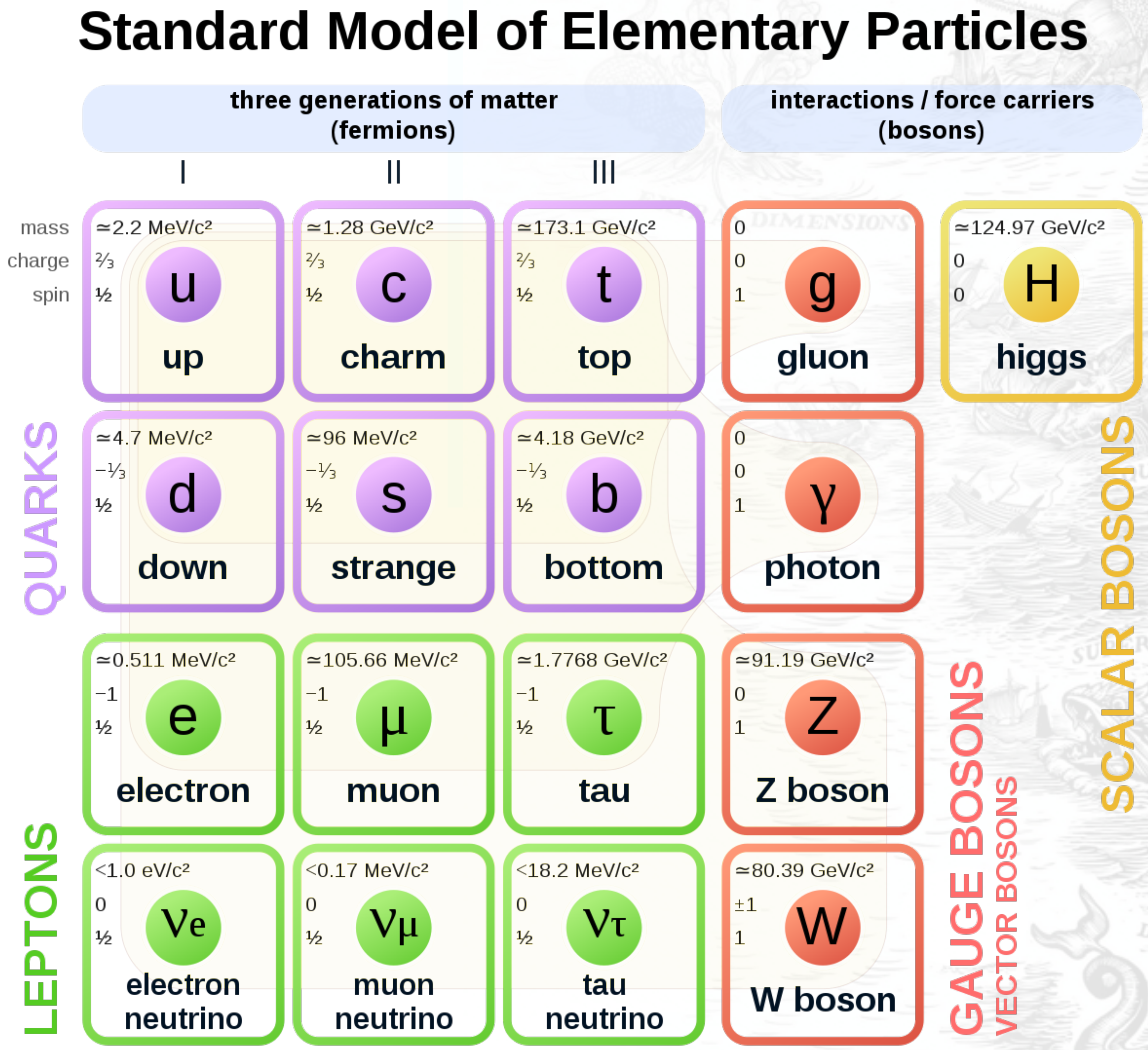
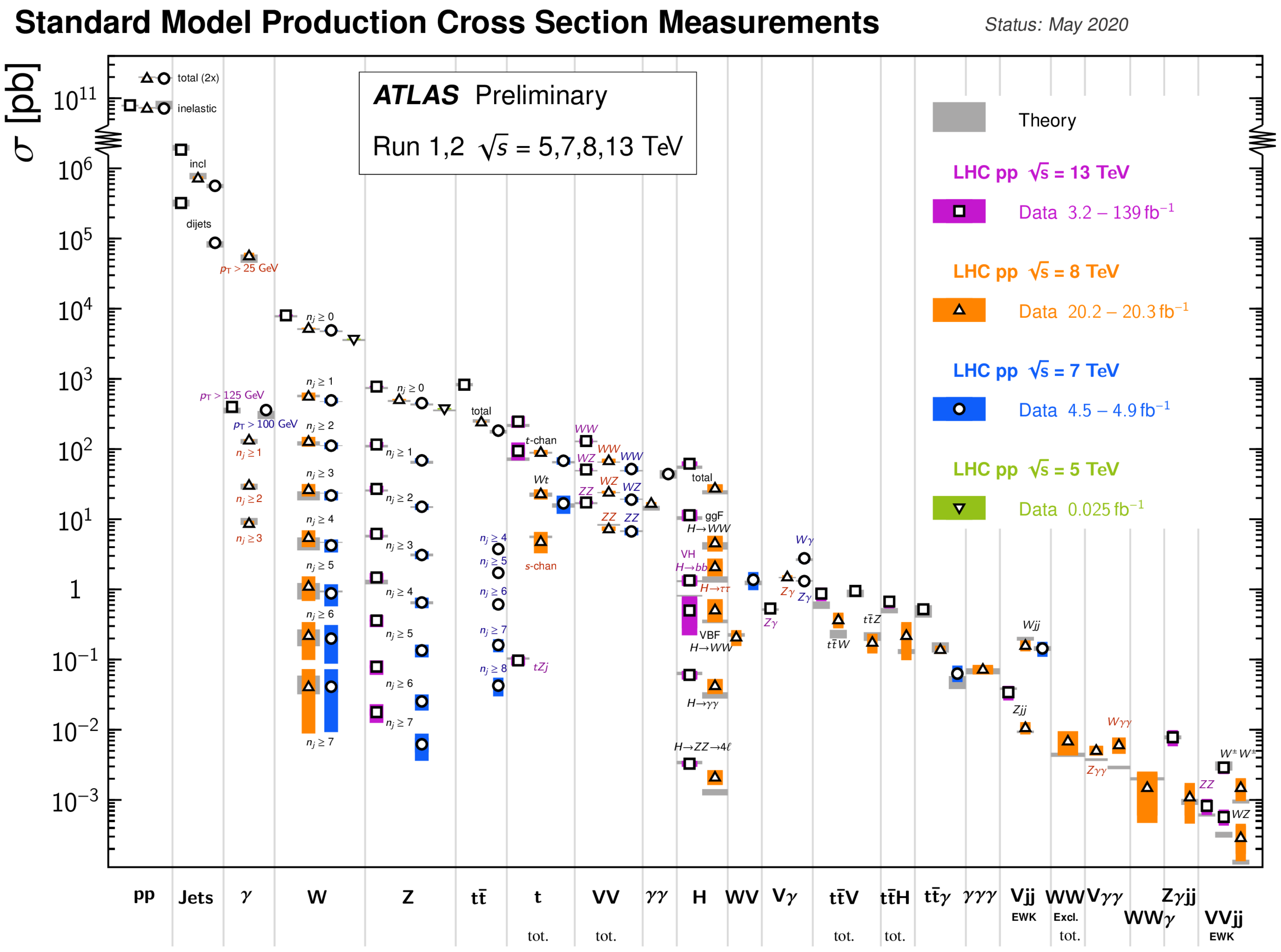


Illustration by Chris Wormell from "A Map of the Invisible"

The Standard Model

- Standard Model is undoubtedly one of the triumphs of modern science
- Completed by Higgs discovery in 2012. All measurements to date, across 14 orders of magnitude, agree with its predictions
- …but we know it's incomplete



Louie Corpe, UCL (l.corpe@ucl.ac.uk)

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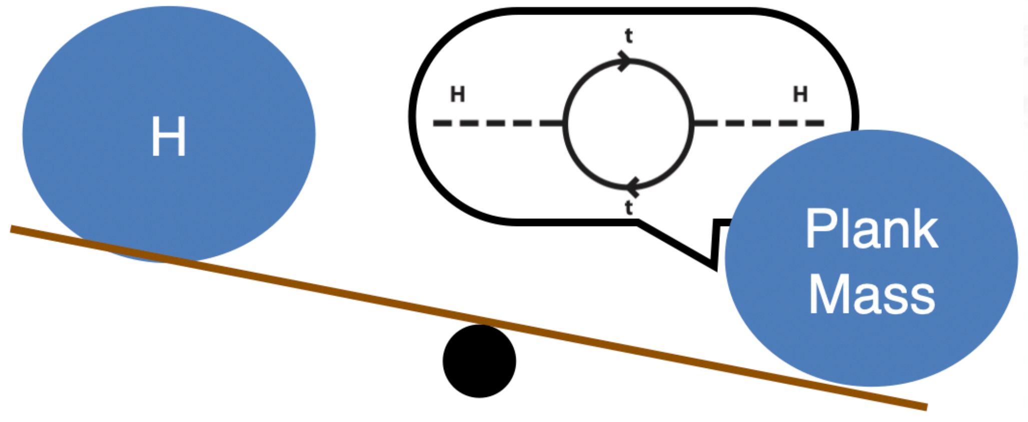
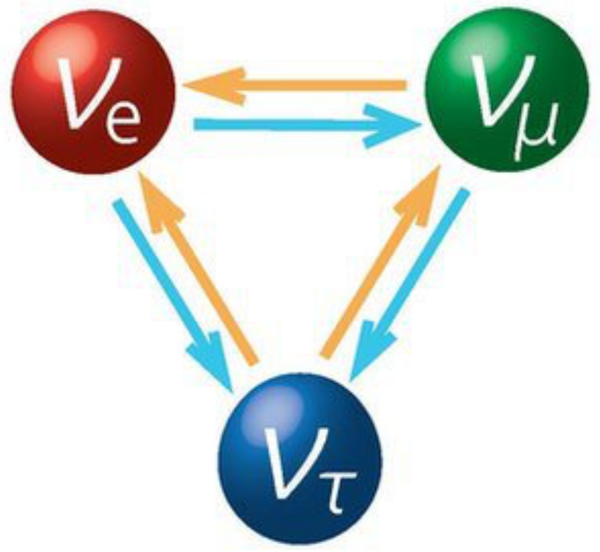
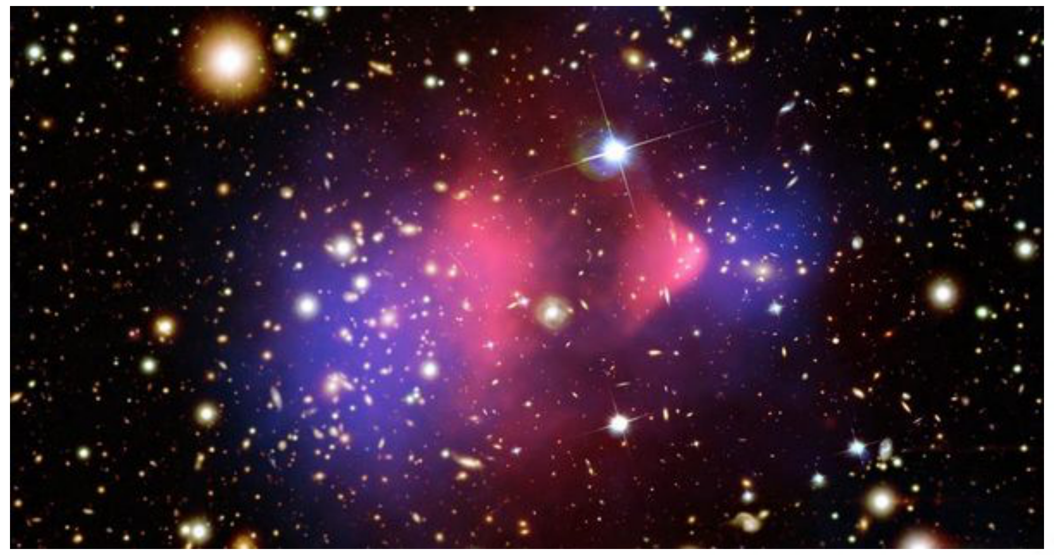
The Standard Model

- The SM has serious flaws…
  - Why is H so light ?
    (**Hierarchy Problem**)
  - **Neutrino oscillations** + masses
  - What is **Dark Matter**?

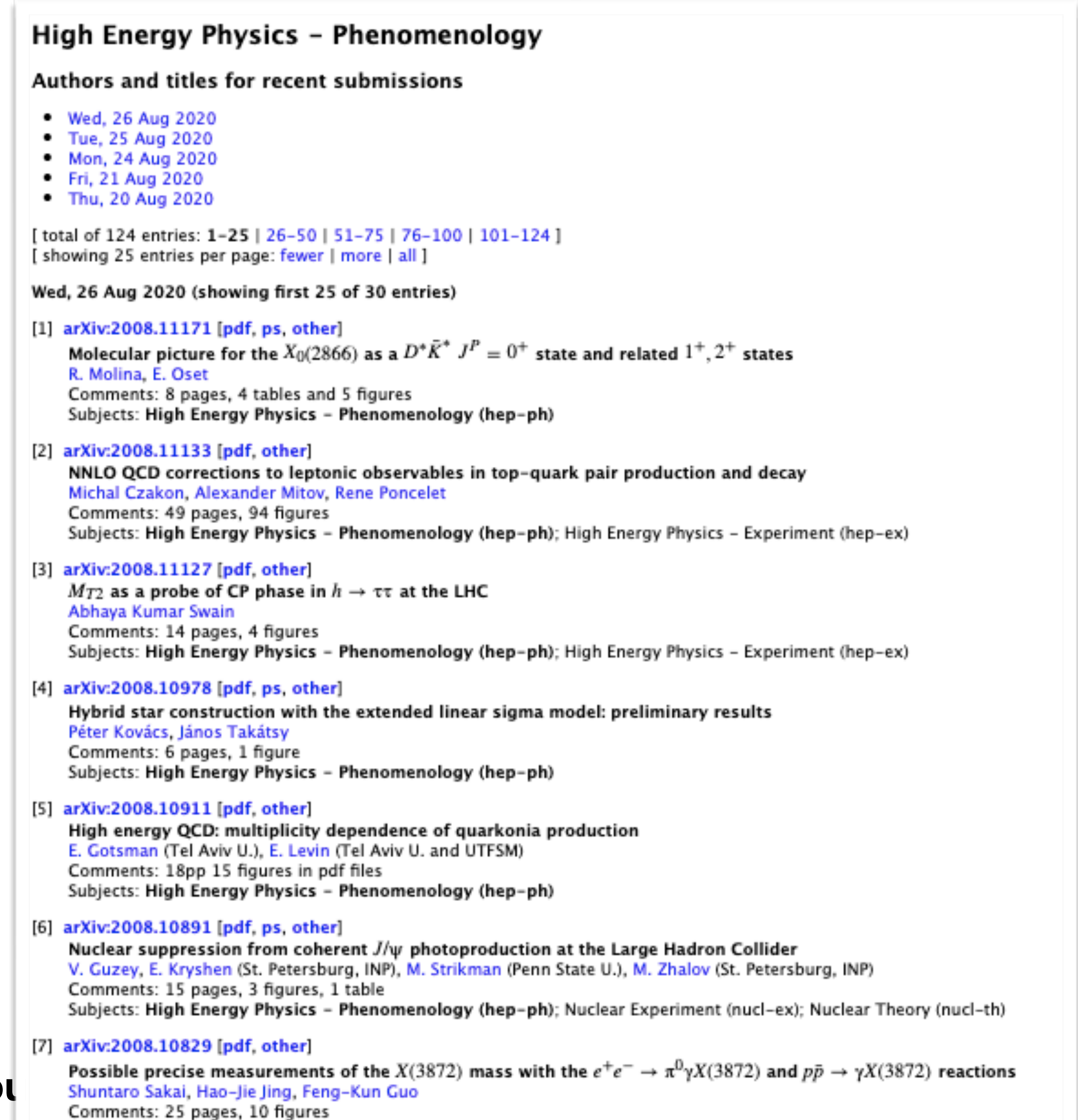






Beyond the Standard Model (BSM)

- A myriad of new models have been dreamt up by theorists to extend SM and explain outstanding issues. Thousands of hep-ph papers per year on the arXiv!


High Energy Physics – Phenomenology

Authors and titles for recent submissions

- Wed, 26 Aug 2020
- Tue, 25 Aug 2020
- Mon, 24 Aug 2020
- Fri, 21 Aug 2020
- Thu, 20 Aug 2020

[total of 124 entries: **1–25** | 26–50 | 51–75 | 76–100 | 101–124]
[showing 25 entries per page: fewer | more | all]

Wed, 26 Aug 2020 (showing first 25 of 30 entries)

[1] **arXiv:2008.11171 [pdf, ps, other]**
Molecular picture for the $X_0(2866)$ as a $D^*\bar{K}^*$ $J^P = 0^+$ state and related $1^+, 2^+$ states
R. Molina, E. Oset
Comments: 8 pages, 4 tables and 5 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**

[2] **arXiv:2008.11133 [pdf, other]**
NNLO QCD corrections to leptonic observables in top-quark pair production and decay
Michal Czakon, Alexander Mitov, Rene Poncelet
Comments: 49 pages, 94 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)

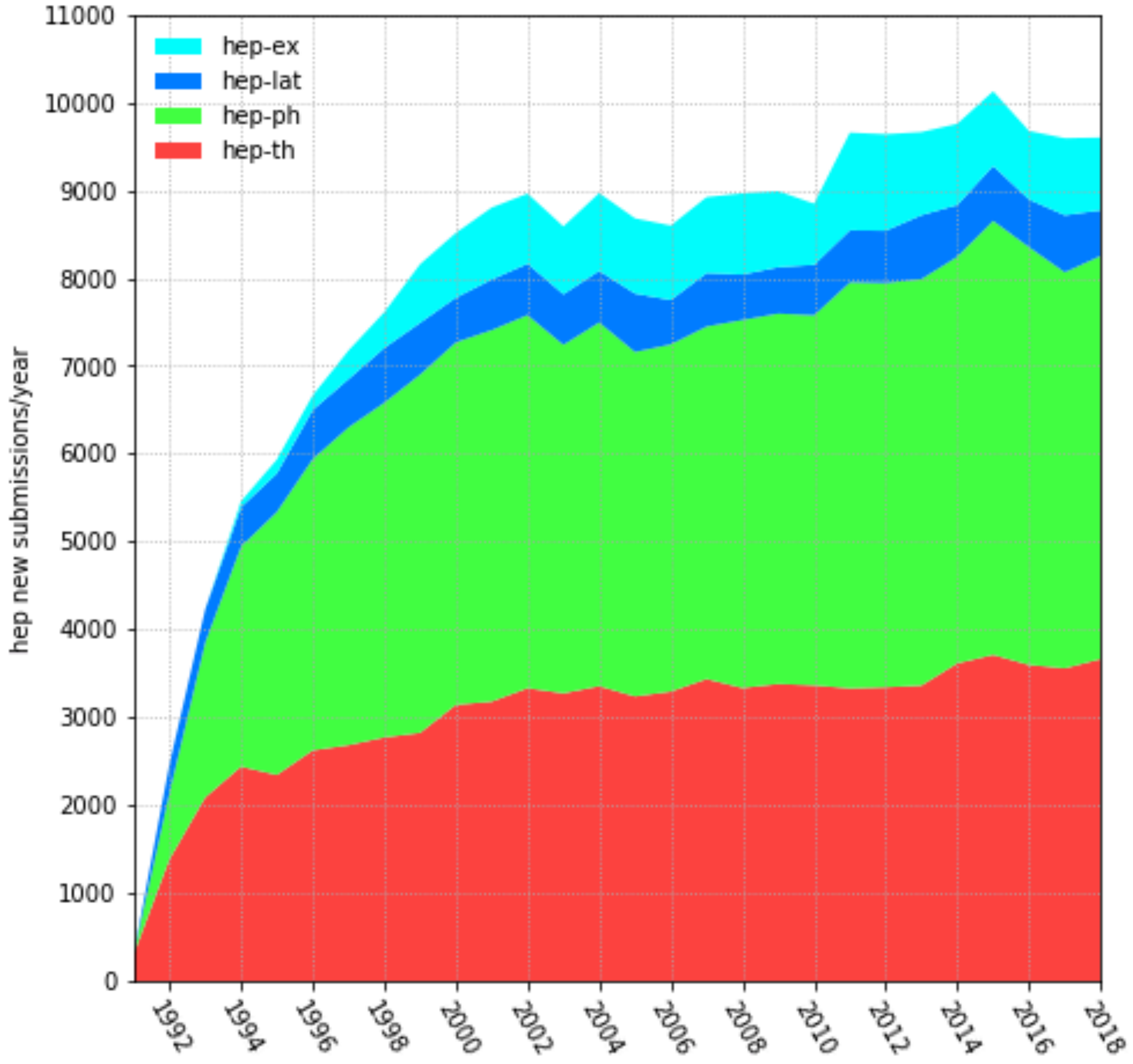
[3] **arXiv:2008.11127 [pdf, other]**
M_{T2} as a probe of CP phase in $h \to \tau\tau$ at the LHC
Abhaya Kumar Swain
Comments: 14 pages, 4 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex)

[4] **arXiv:2008.10978 [pdf, ps, other]**
Hybrid star construction with the extended linear sigma model: preliminary results
Péter Kovács, János Takátsy
Comments: 6 pages, 1 figure
Subjects: **High Energy Physics – Phenomenology (hep-ph)**

[5] **arXiv:2008.10911 [pdf, other]**
High energy QCD: multiplicity dependence of quarkonia production
E. Gotsman (Tel Aviv U.), E. Levin (Tel Aviv U. and UTFSM)
Comments: 18pp 15 figures in pdf files
Subjects: **High Energy Physics – Phenomenology (hep-ph)**

[6] **arXiv:2008.10891 [pdf, ps, other]**
Nuclear suppression from coherent J/ψ photoproduction at the Large Hadron Collider
V. Guzey, E. Kryshen (St. Petersburg, INP), M. Strikman (Penn State U.), M. Zhalov (St. Petersburg, INP)
Comments: 15 pages, 3 figures, 1 table
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)

[7] **arXiv:2008.10829 [pdf, other]**
Possible precise measurements of the $X(3872)$ mass with the $e^+e^- \to \pi^0\gamma X(3872)$ and $p\bar{p} \to \gamma X(3872)$ reactions
Shuntaro Sakai, Hao-Jie Jing, Feng-Kun Guo
Comments: 25 pages, 10 figures



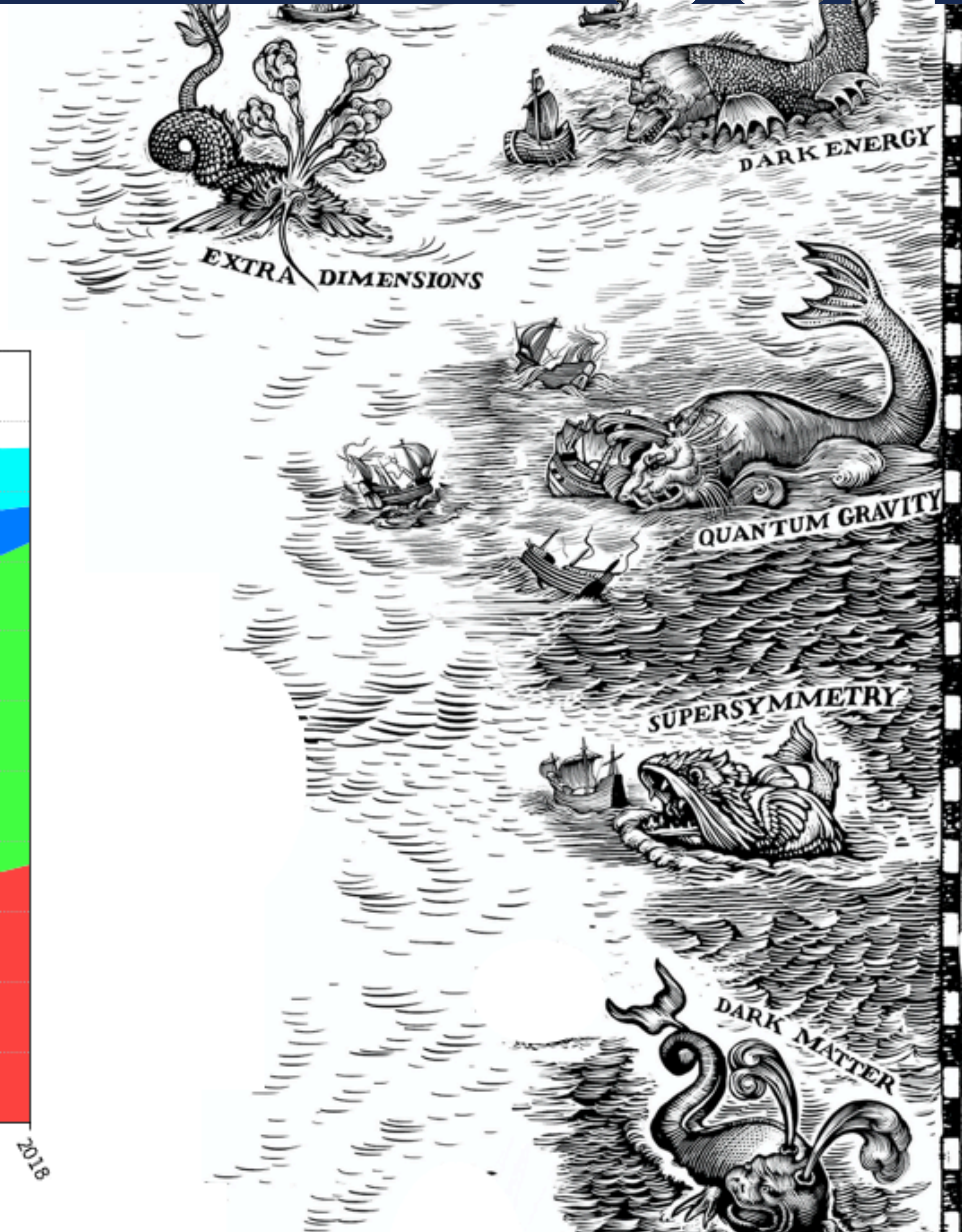
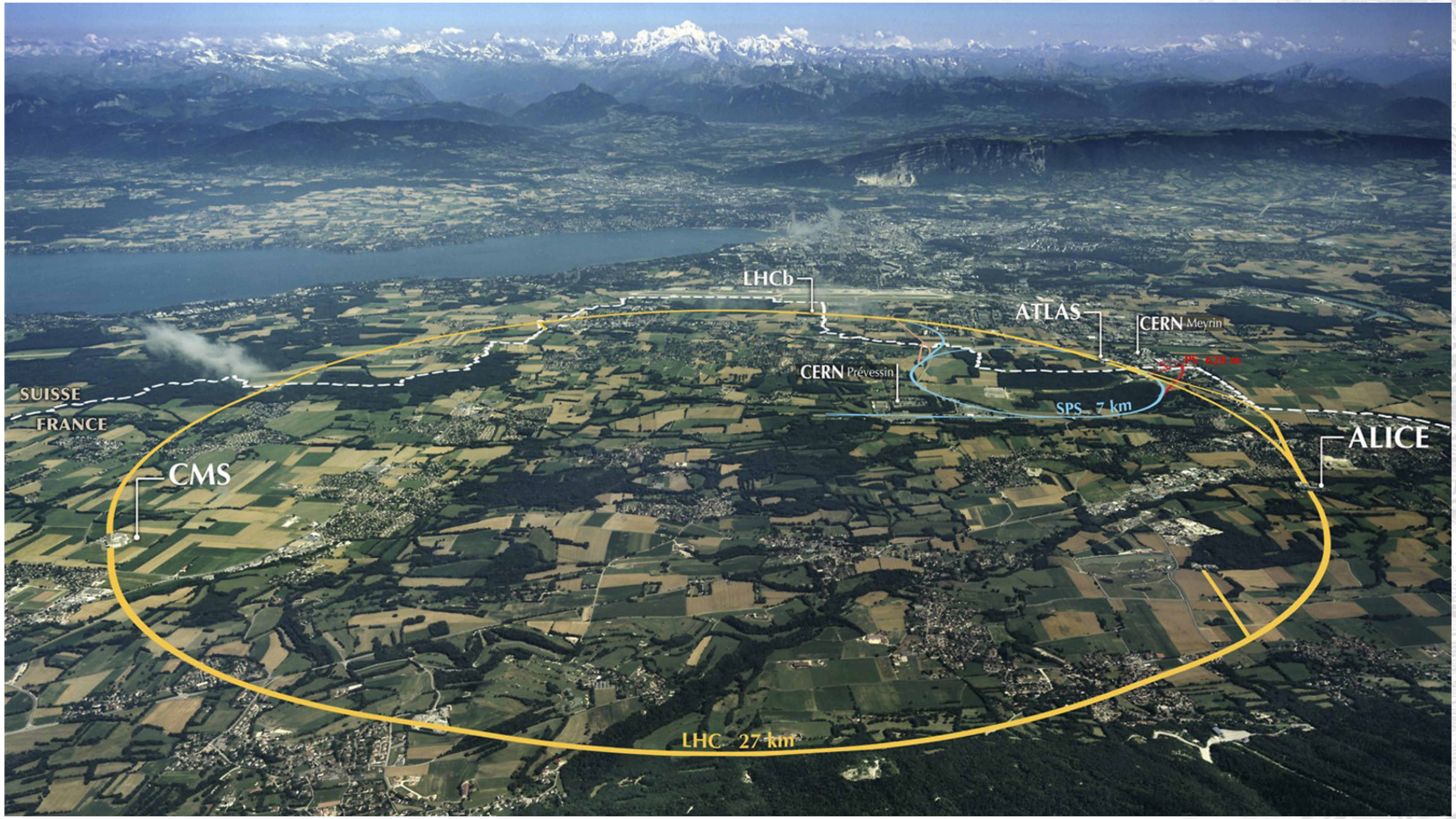


Illustration by Chris Wormell from "A Map of the Invisible"

The Large Hadron Collider (LHC)

- World's largest proton collider - 27km ring
- Two multi-purpose experiments: ATLAS and CMS, built with orthogonal technologies
- Built to test SM and look for exotic particles or effects from new physics



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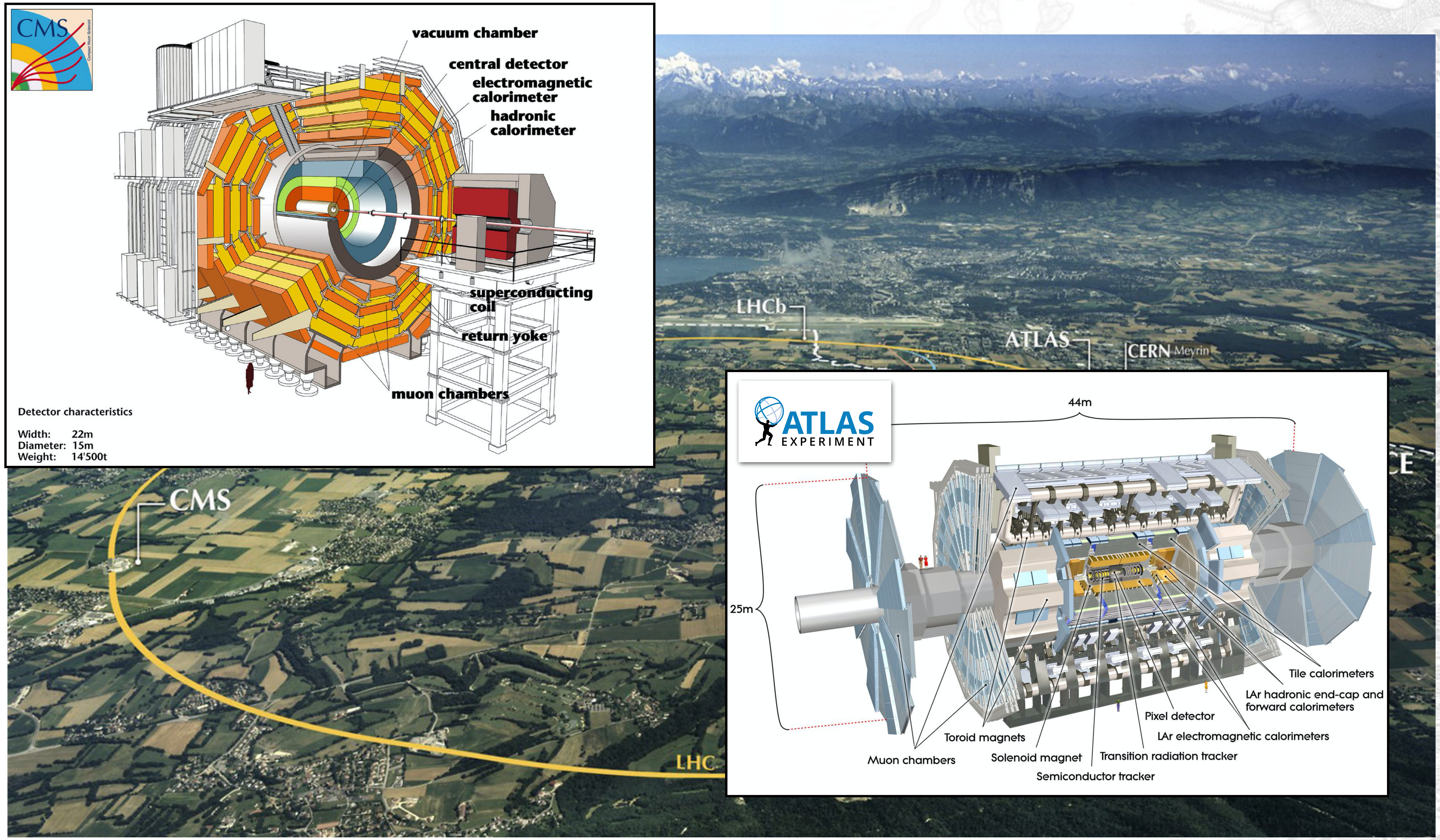


Illustration by Chris Wormell from "A Map of the Invisible"

Needle in a haystack

- Poses a conundrum for Experimentalist
- An LHC search paper typically covers 1 handful of models, takes a small team 1-2 years to analyse data and publish…
  - This is fine when we expect new particles in a particular form (from eg SUSY, obvious mass resonances, etc)…
  - … but this has become inefficient now that the “low-hanging fruits” have been ruled out!
- Like checking each piece of hay individually before finding the needle
  - And we don’t event know what the needle looks like!
- We need a change of approach

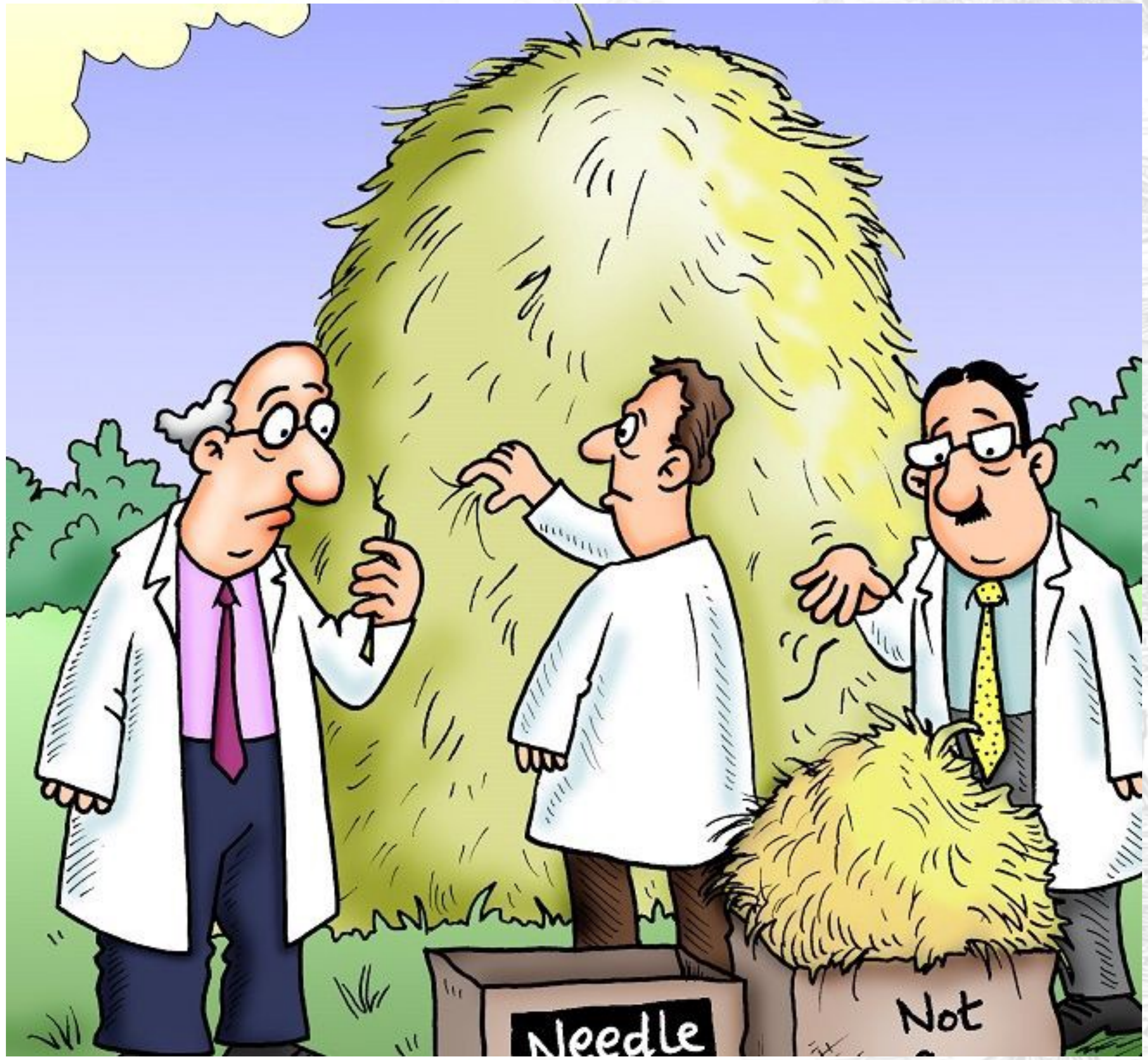
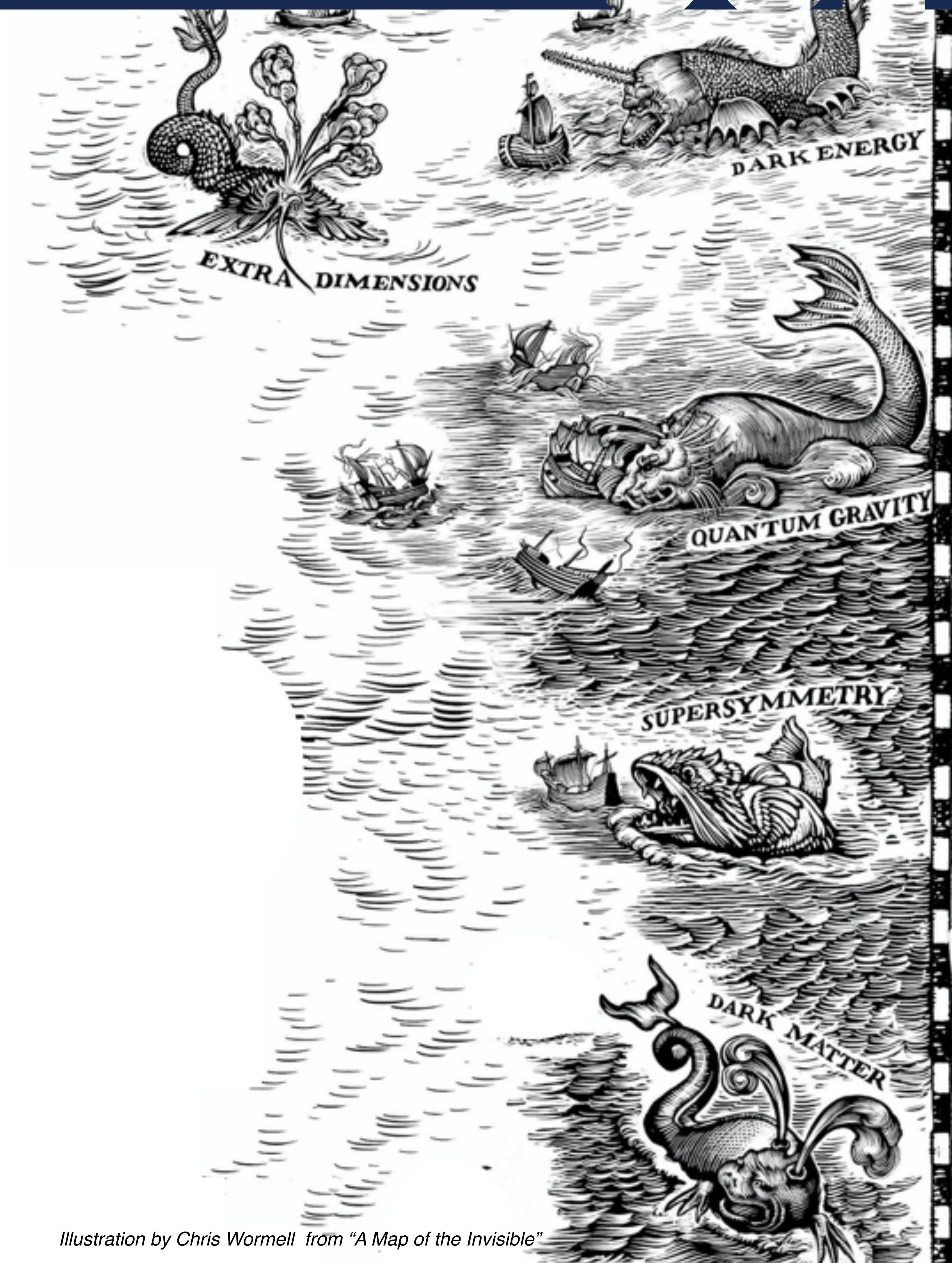


Illustration by Chris Wormell from “A Map of the Invisible”

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

Re-interpretation

What is it, and why should we do it?



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A change of paradigm

- For the last ~50 years, we've known what to look for at each step: Z boson, W boson, top quark, Higgs boson…
- Many expected SUSY particles to follow shortly after the Higgs, but now increasingly disfavoured…
- Today, we **no longer have a single guiding theory to motivate discoveries**, but we do have largest HEP dataset every collected
- Need a paradigm shift from **top-down/ theory-driven** approach to **bottom-up/ data-driven** approach

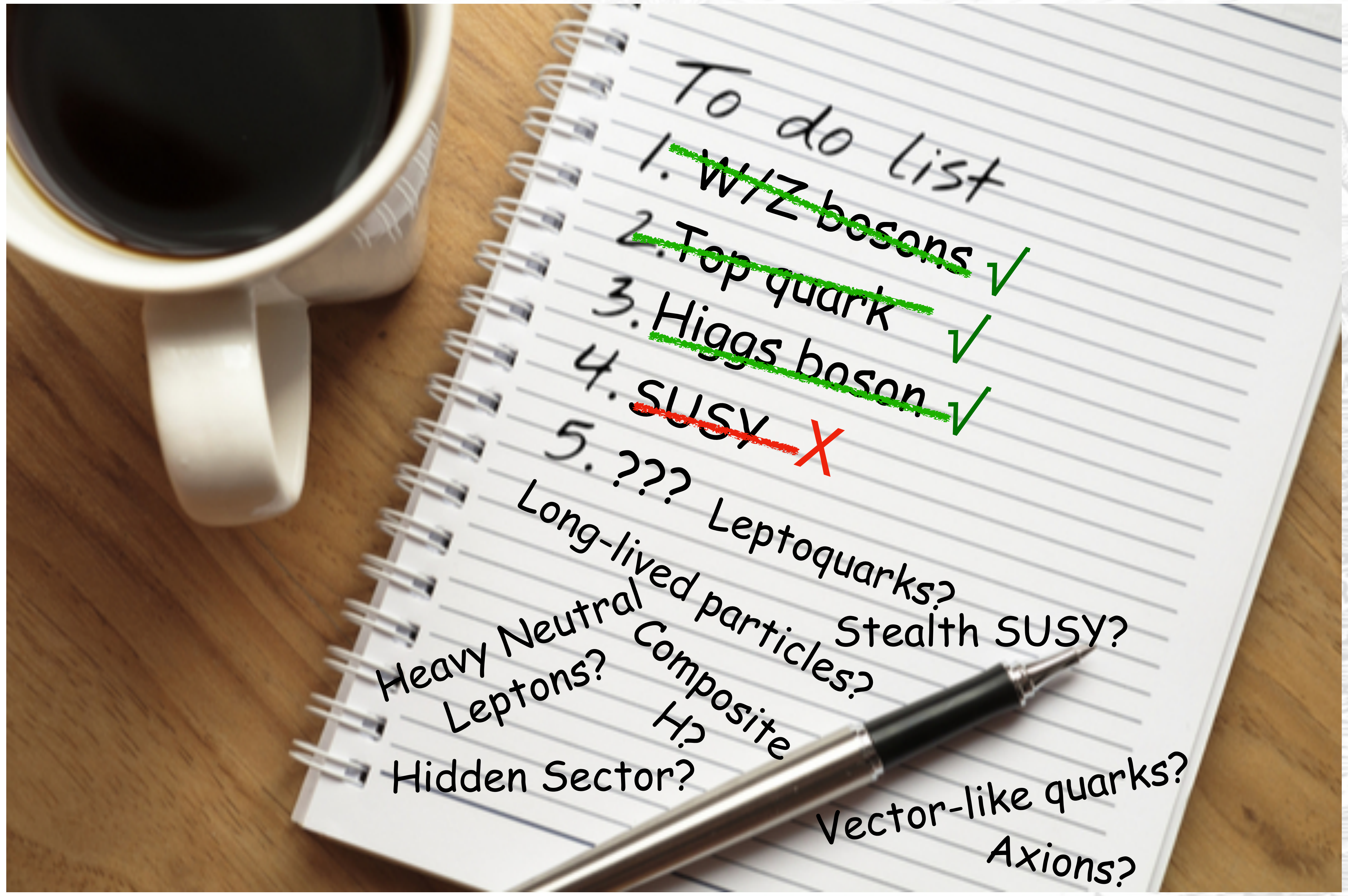


Illustration by Chris Wormell from "A Map of the Invisible"

Analysis Recycling

- The HEP field does not currently work efficiently in data-driven mode
- Searches take years, only to probe a handful of models…
    - …which may already be excluded by other analyses anyway.
- This is a waste of precious person power and computing resources
- We must learn to recycle our work
  This is know as **re-interpretation**

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

Re-interpretation

- Whether measurement or search, result of an LHC analysis is a measurement of the number of events/cross-section in a particular region of phase space.

- Compared to a background prediction from the SM. Insert prediction from a new physics model, and see if signal+SM agrees with the data. If it disagrees, signal can be excluded at some confidence level.

- Reinterpretation means preserving the analysis results such that new signals can still be tested at a later date

- This process works particularly well if the data are “unfolded” to particle-level (corrected for detector effects) so that one can easily and cheaply insert a new signal.

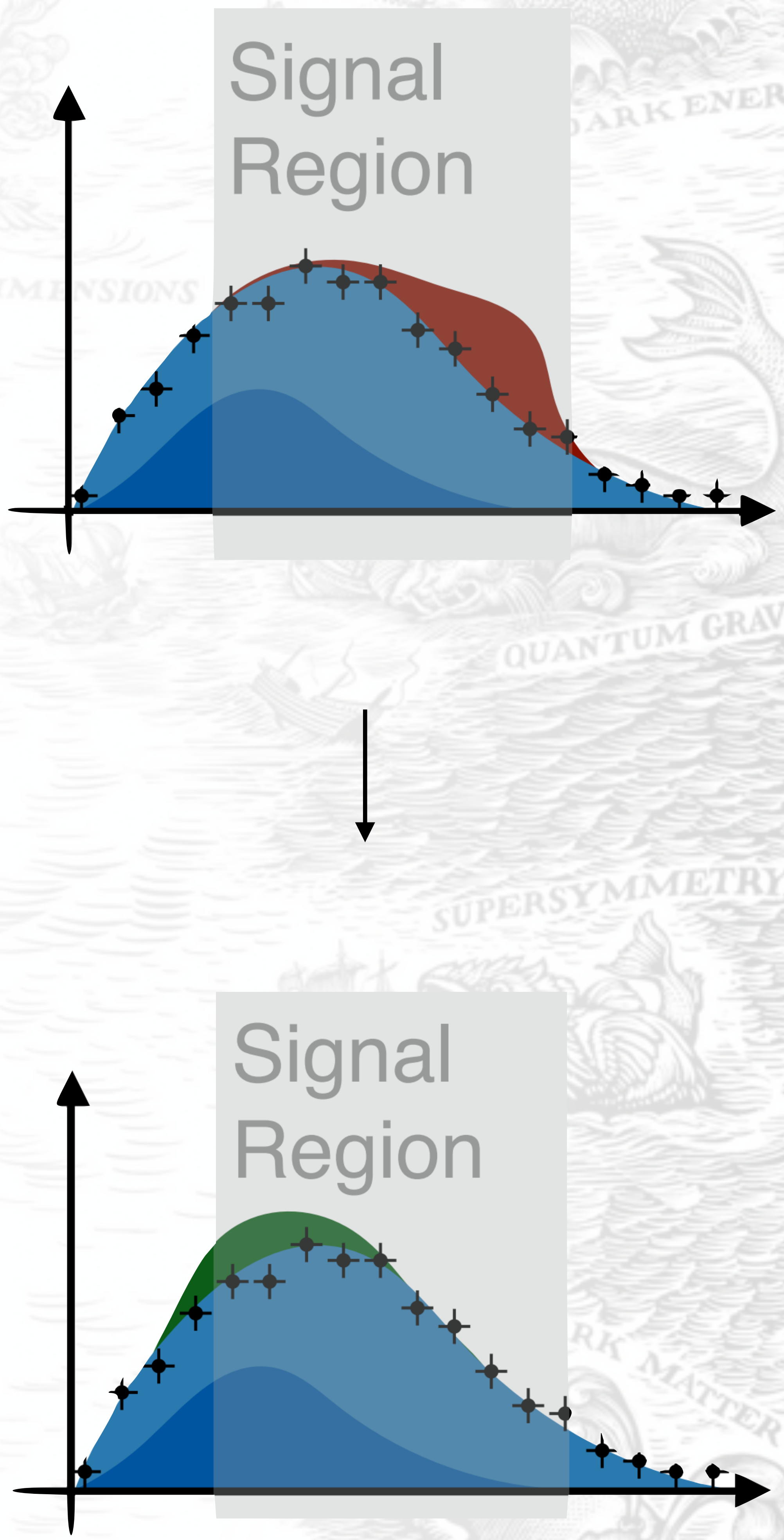


Illustration by Chris Wormell from “A Map of the Invisible”

CONTUR

A tool for fast re-interpretation of LHC results

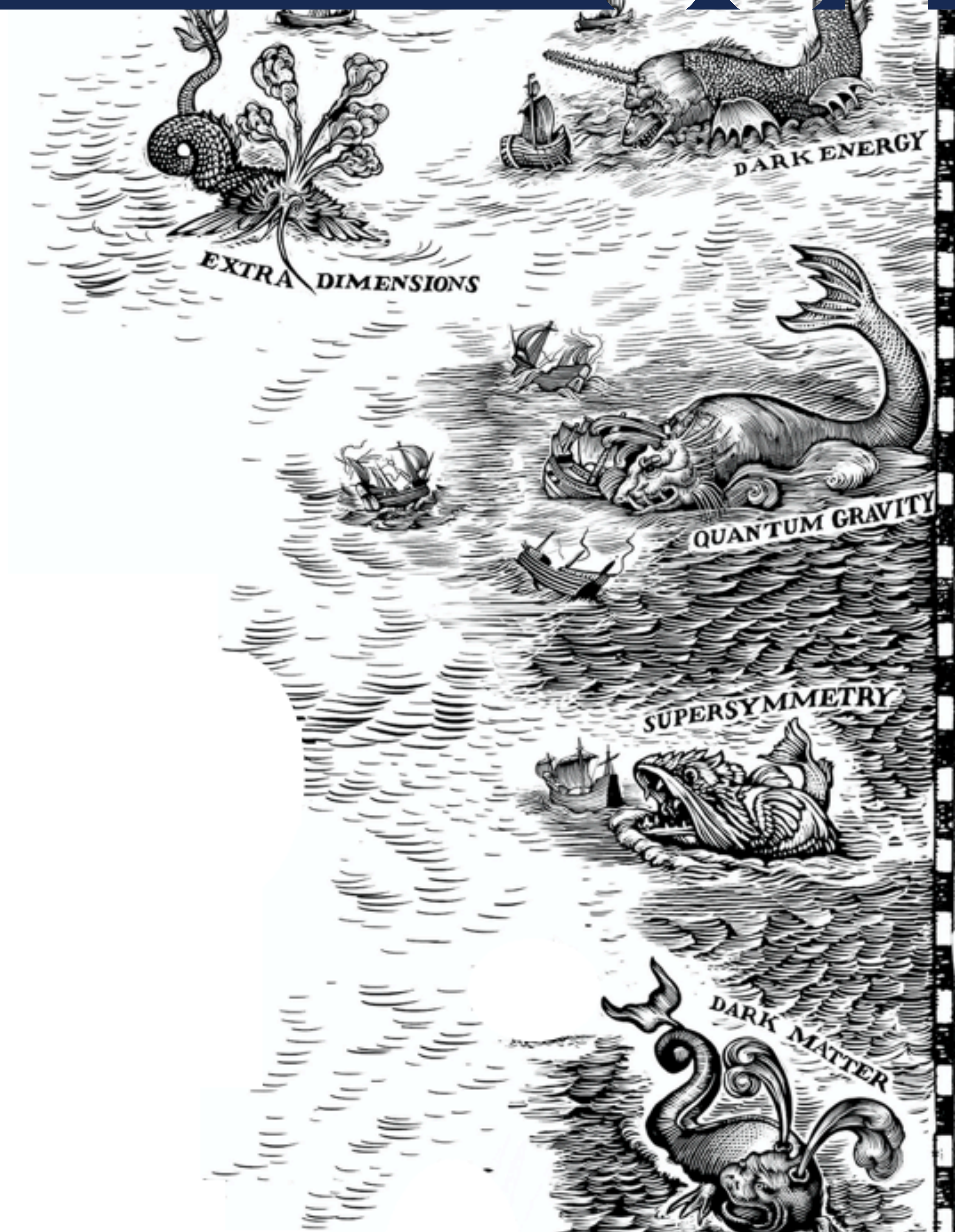


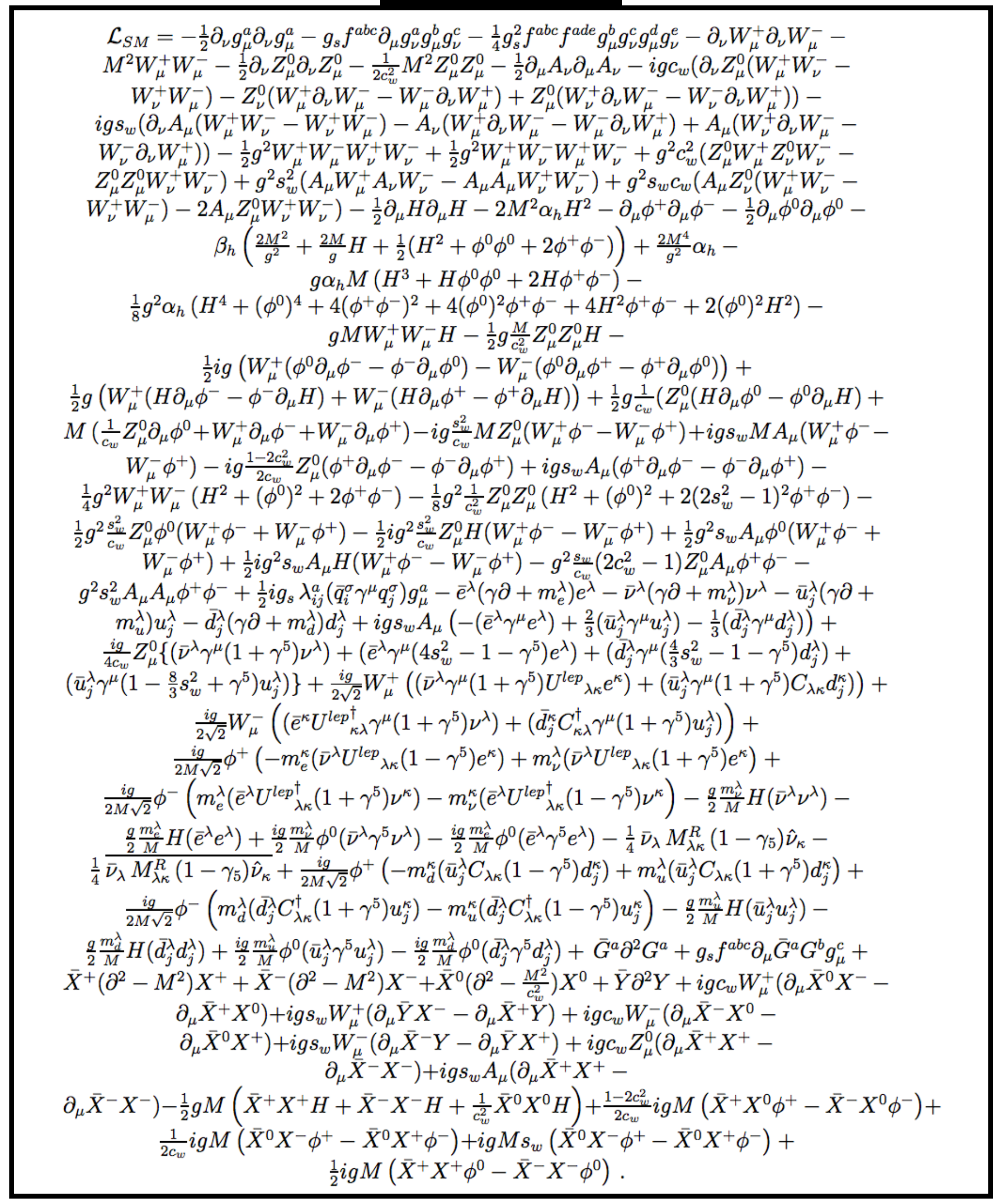
Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

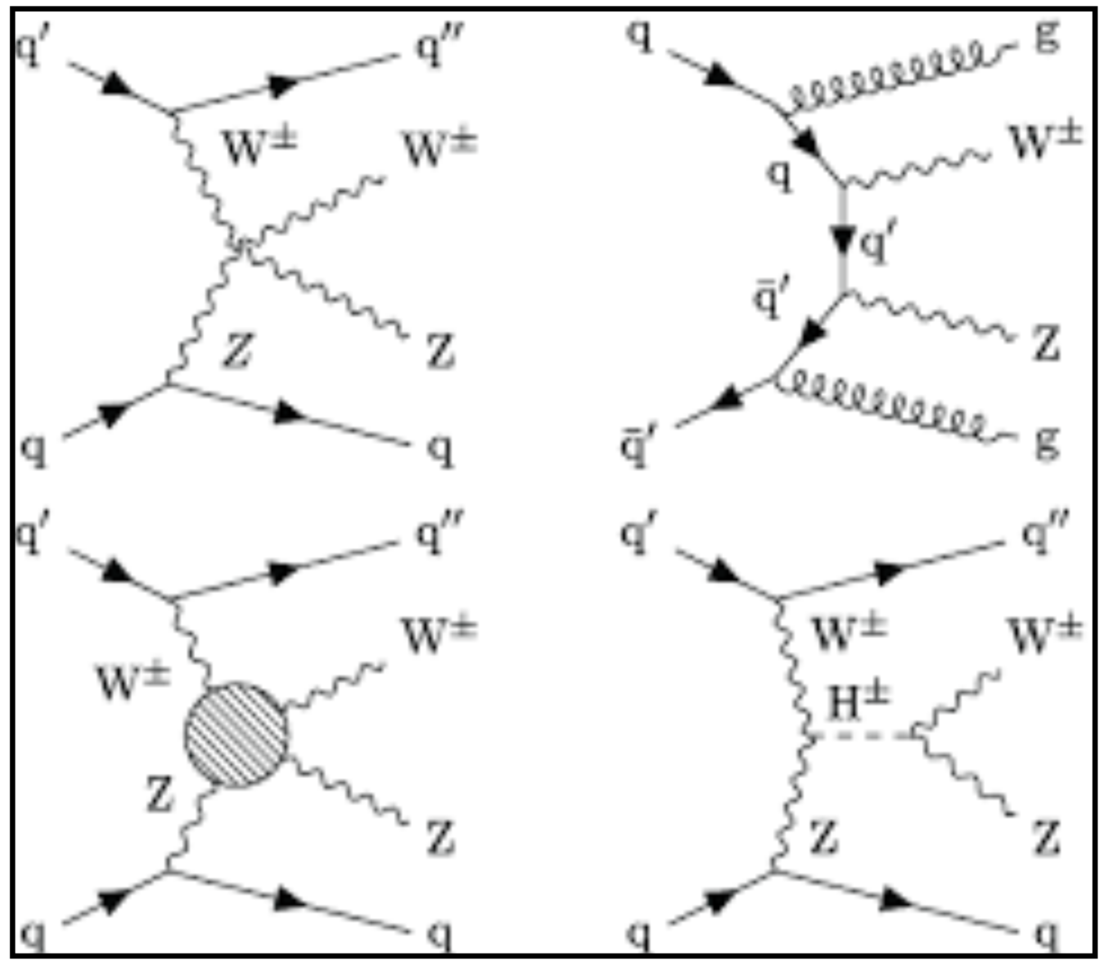
CONTUR 101

- 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

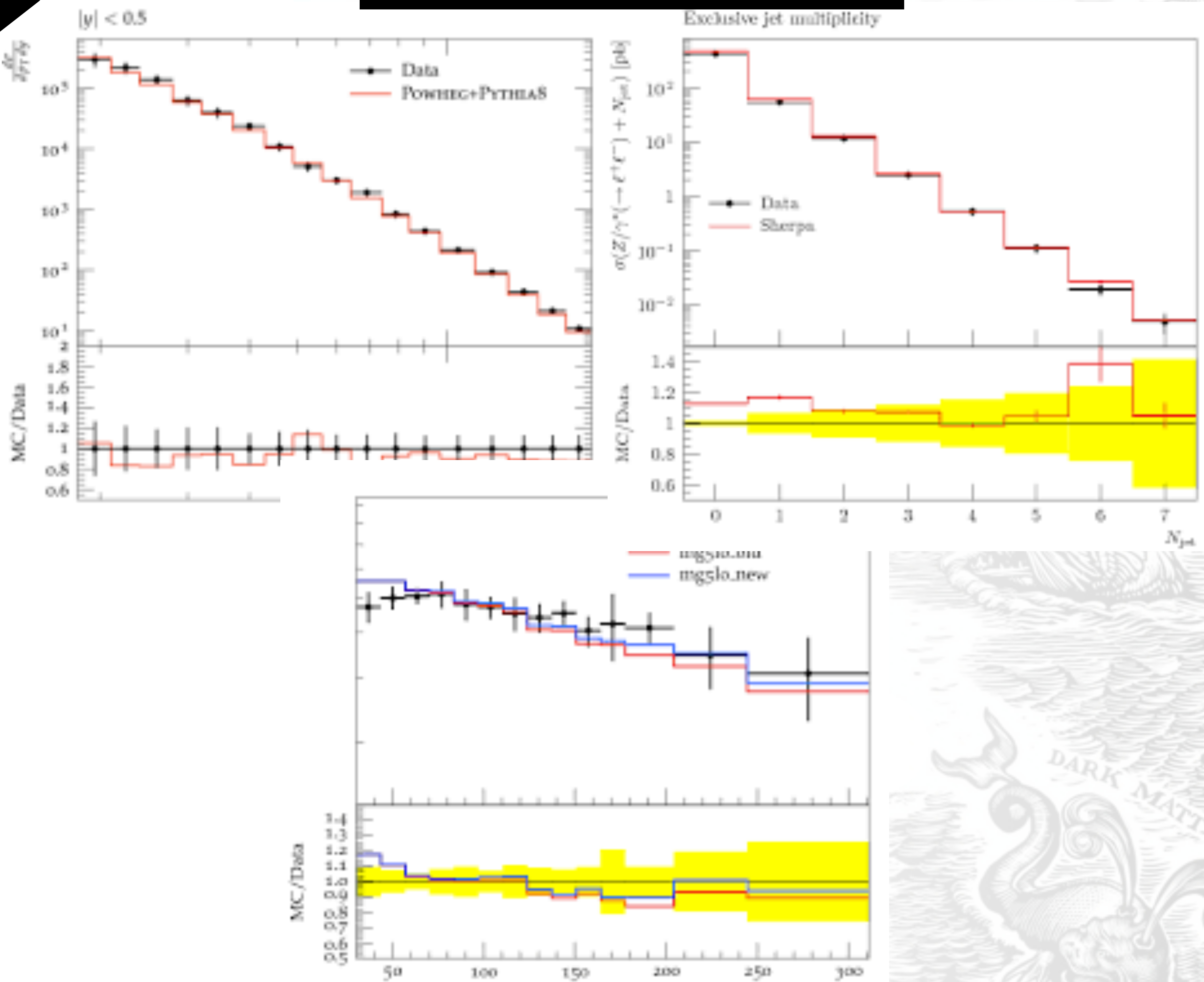


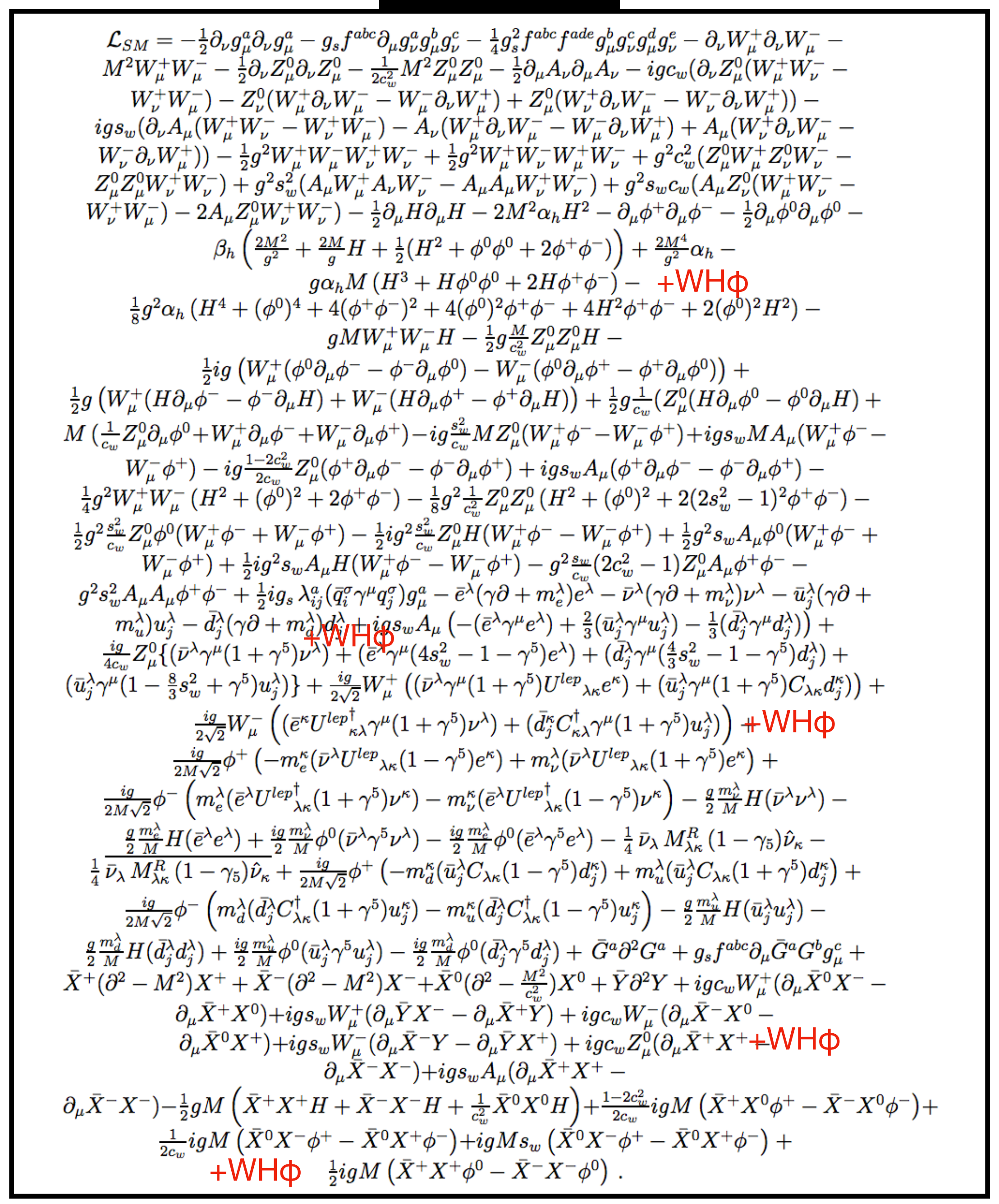
Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR 101

UCL

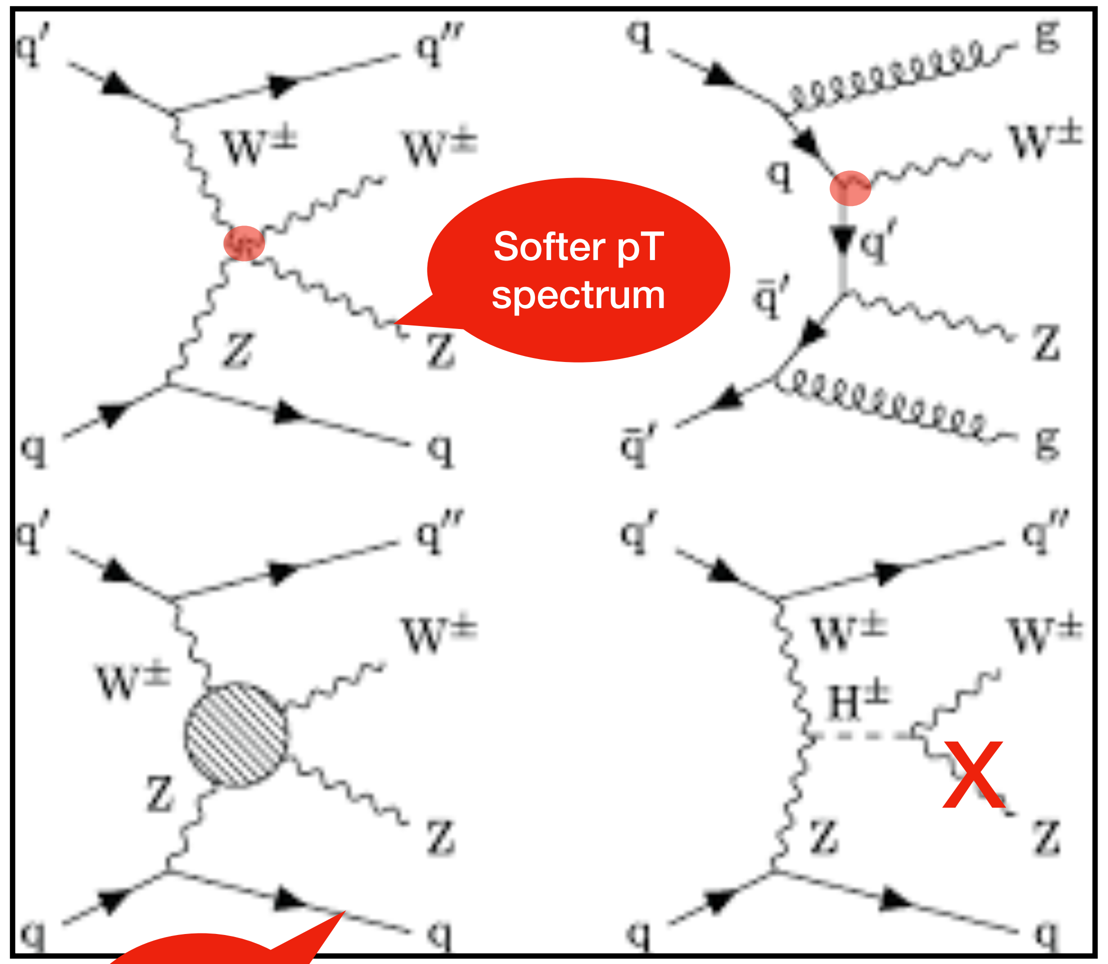
- Key idea: the SM Lagrangian is very finely balanced. You can't easily add BSM particles without the effect showing up in SM distributions

SM + BSM



+ BSM

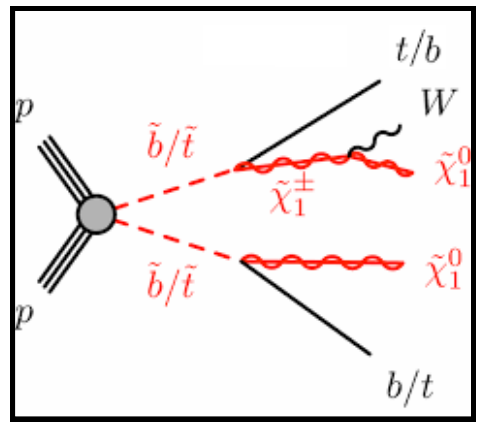
Processes



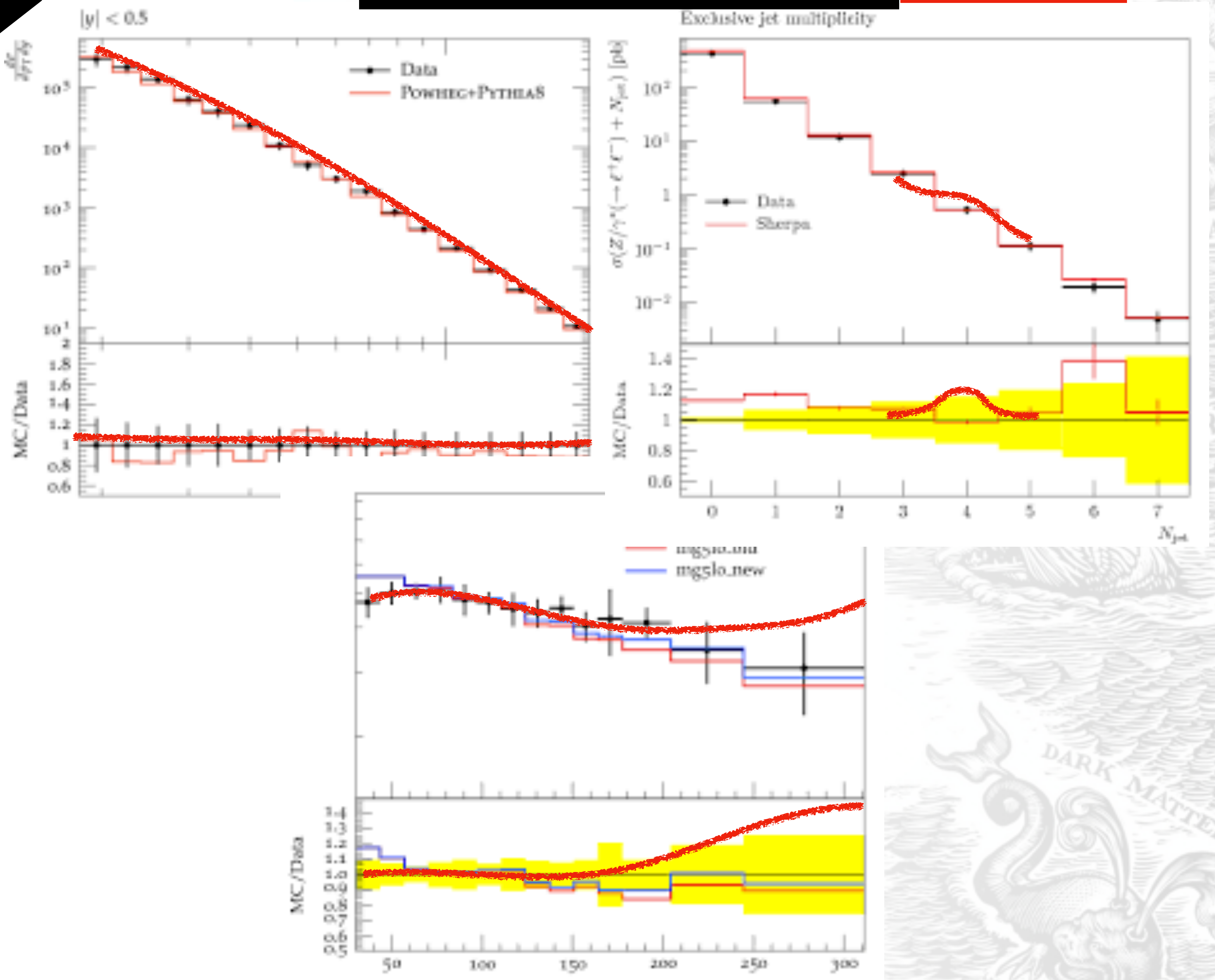
Softer pT spectrum

More boosted

+



LHC measurements + BSM



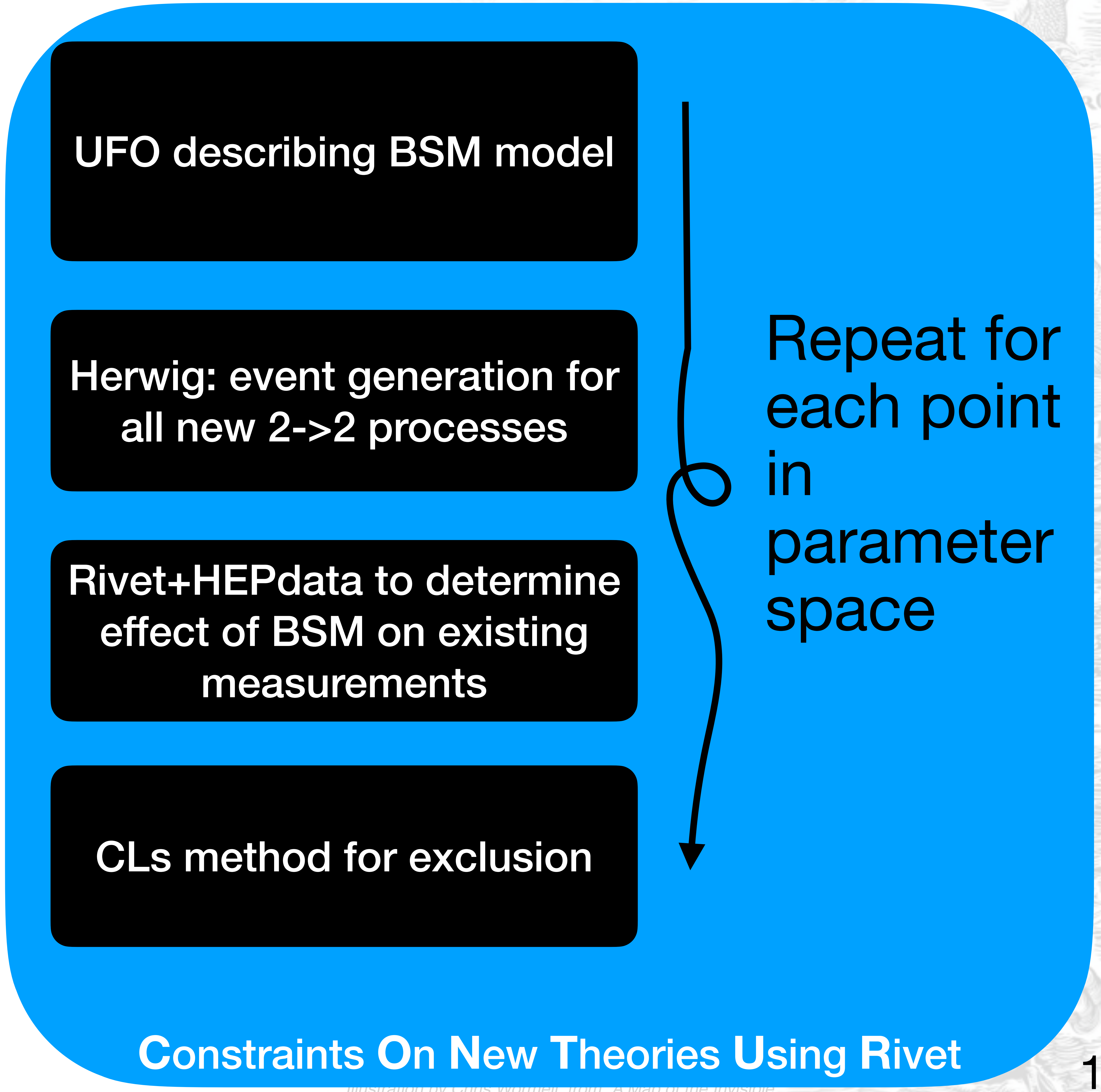
CONTUR 101

- The LHC programme often focuses on most spectacular signature of a new model…
- But many models might already be ruled out because would cause visible distortions in spectra of ‘’standard” processes!
  - We already have hundreds of such measurements !
- Challenge is figuring out how a model might impact hundreds of measured distributions for a given point of BSM parameter space…
- …and understanding whether the variation is consistent with the measured data within uncertainties

You don’t need to see where the stone fell to feel the ripple

Overview of the CONTUR method

- CONTUR uses bank of LHC results preserved in Rivet to rapidly check if new models are already ruled out
- Input: Universal Feynrules Object
(new physics Lagrangian coded up in python by theorist)
- Herwig: generate events for all 2->2 processes involving new particles, for a given set of parameter values
- Pass through ~150 Rivet routines from particle-level LHC results
  - This is quick since everything is at particle-level!
  - Routines categorised into 'pools' grouped by $\sqrt{s}$ and final state to ensure orthogonality
- Compare size of any deviation to reference data from HEPData (including correlations!) to check if signal would already have been seen or whether it is OK within errors -> CLs value
- CONTUR does book-keeping to repeat over arbitrary array of parameter values



The key point

Running 30,000 events on a grid of 200 points takes <24h on standard batch farm

A dedicated search takes 2 years, our latest paper took 3 months and probed whole range of configurations

CONTUR can address whole classes of models extremely quickly, so that ATLAS and CMS search analysts can focus on the ones which are really tricky!

"A shortcut to new physics"

UFO describing BSM model

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

Rivet+HEPdata to determine effect of BSM on existing measurements

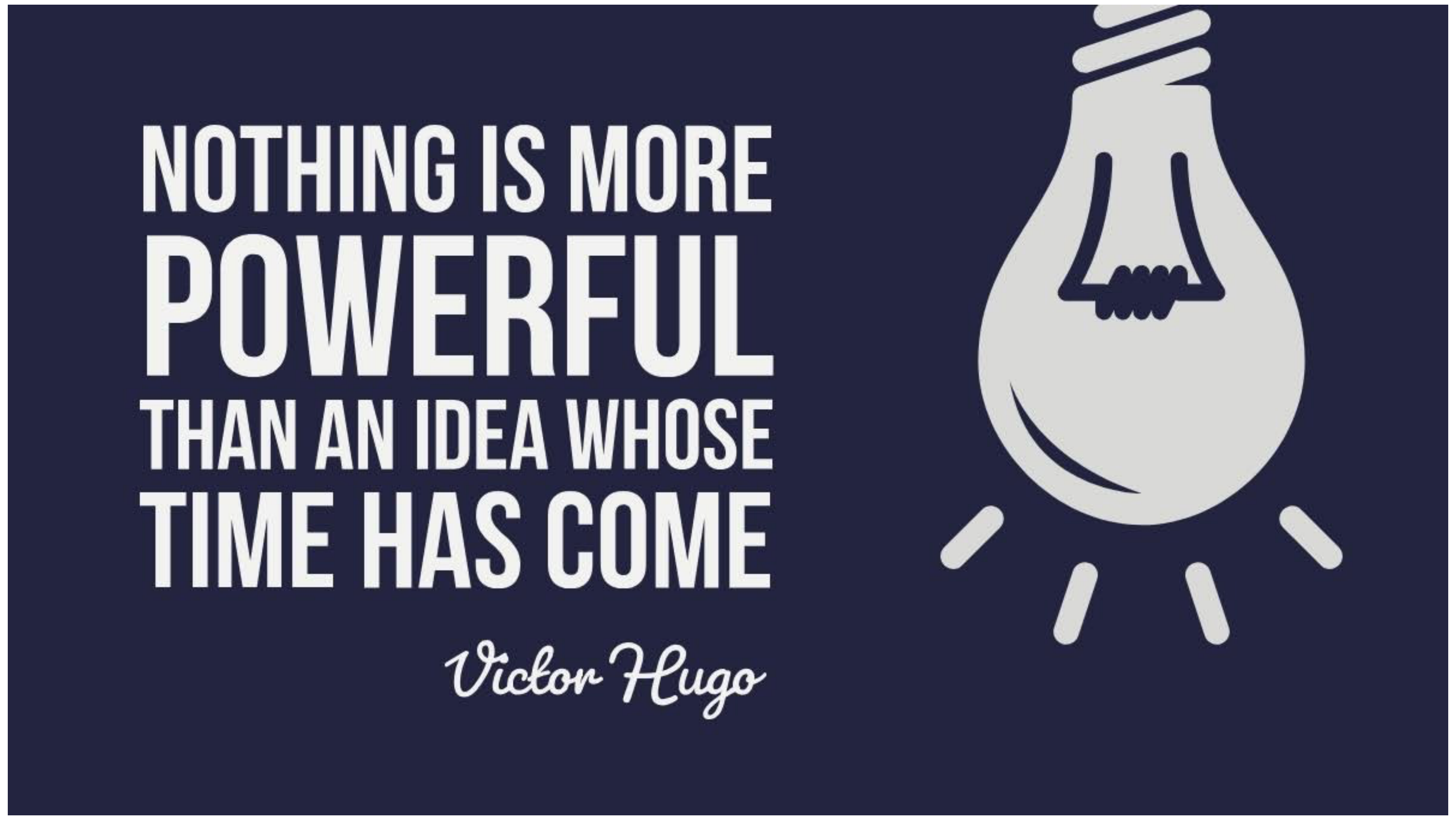
CLs method for exclusion

Repeat for each point in parameter space

Constraints On New Theories Using Rivet

CONTUR step by step

- CONTUR is a system which benefits from many existing forward-thinking technologies, formats and agreements, which were not intended for this project but which together may allow a paradigm shift



- Let's zoom in on each step…

UFO describing BSM model

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

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Repeat for each point in parameter space

Constraints On New Theories Using Rivet

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

UFO models

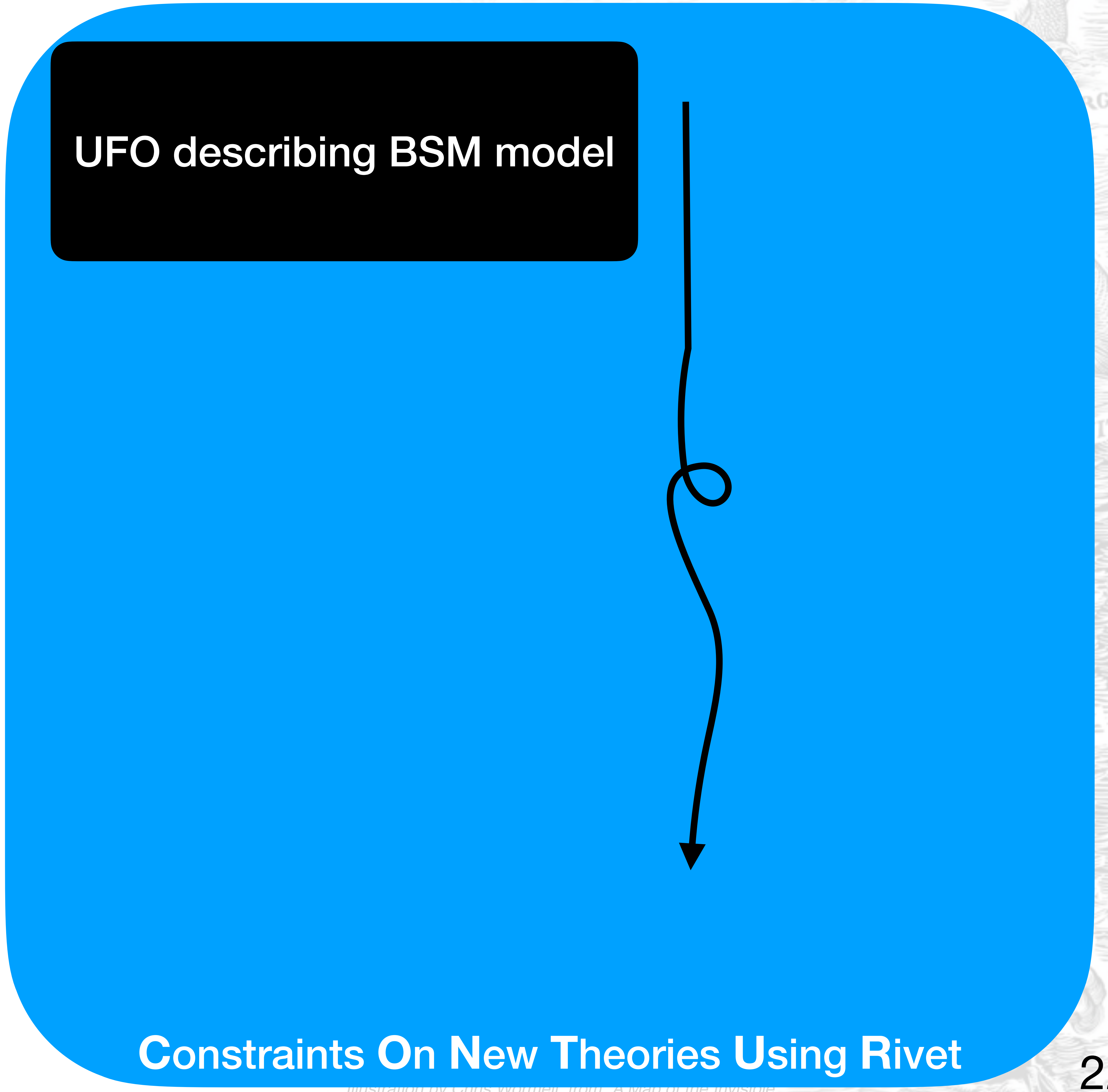
- Universal FeynRules Output [2011, arxiv]

Abstract

We present a new model format for automatized matrix-element generators, the so-called *Universal FeynRules Output (UFO)*. The format is universal in the sense that it features compatibility with more than one single generator and is designed to be flexible, modular and agnostic of any assumption such as the number of particles or the color and Lorentz structures appearing in the interaction vertices. Unlike other model formats where text files need to be parsed, the information on the model is encoded into a PYTHON module that can easily be linked to other computer codes. We then describe an interface for the MATHEMATICA package FEYNRULES that allows for an automatic output of models in the UFO format.

- Database of UFOs with many new models:
  https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

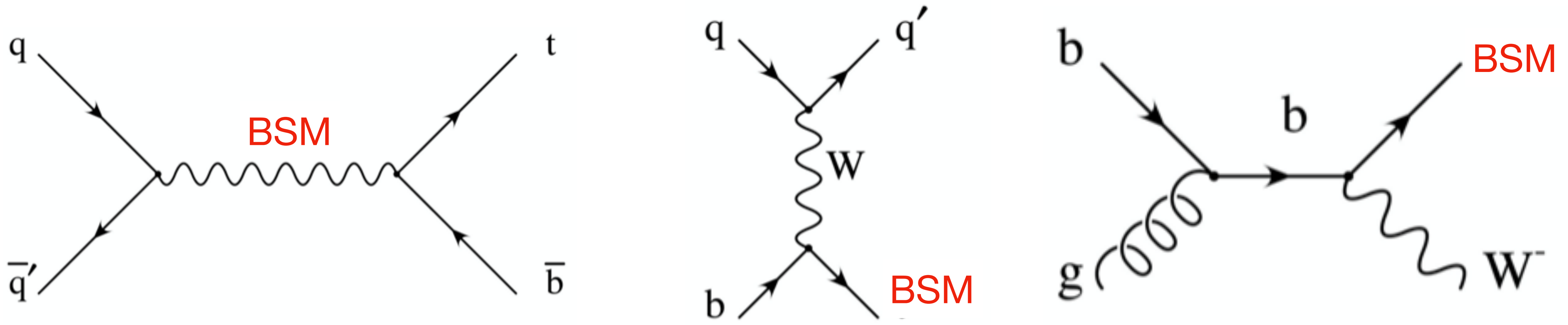
- Theorists typically prepare UFOs to go with their preprints, or can do so fast. This means new models are quickly available for CONTUR study in a widely-accepted format!



HERWIG7

- Herwig7 differs from other generators: by default it produces *all* new final states for a given model (unlike other where one requests individual processes)

- Filter all 2->2 processes involving BSM particle in internal or outgoing leg



- Very quickly generate signal events for a new model which cover all final states, even the “boring” ones!

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

Rivet  and HEPData

- Robust Independent Validation of Experiment and Theory (RIVET), originally for validation of event generators
- C++ code structure, allows particle-level measurements to preserve the analysis logic in a runnable plugin. Particle-level: no detector simulation/smearing needed
- Results of measurements are already stored in HEPData in Rivet-friendly format, and synchronised with Rivet database
- It's FAST: Passing simulated events through Rivet, can run hundreds of plugins, and produce output for hundreds of distributions with negligible time cost wrt event generation
- So a generator developer can easily test new features against existing data…
- ***…And we can easily test effect of new models on measured spectra from ~150 LHC analyses at 7, 8 and 13 TeV, which CONTUR places into orthogonal pools***

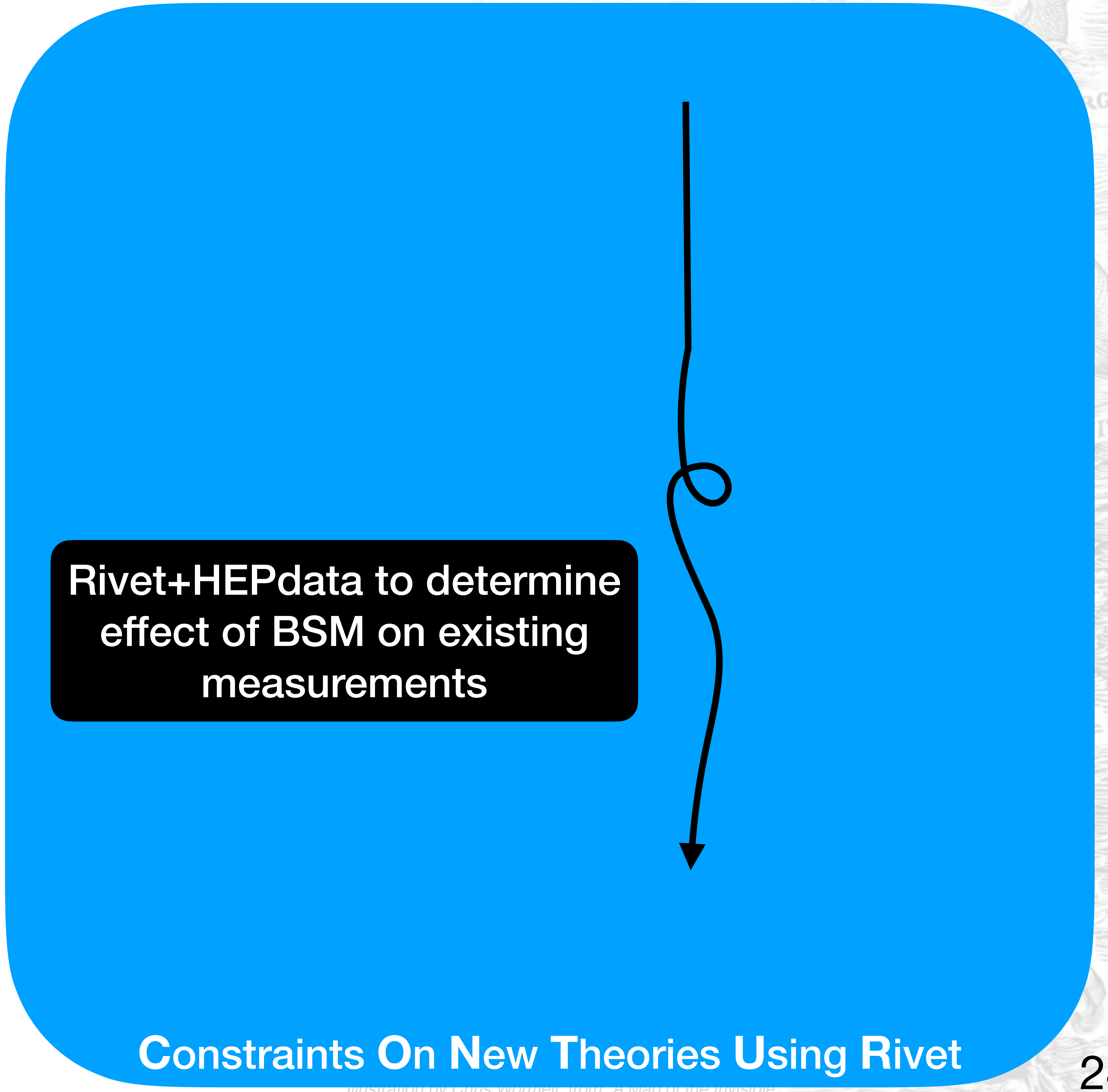
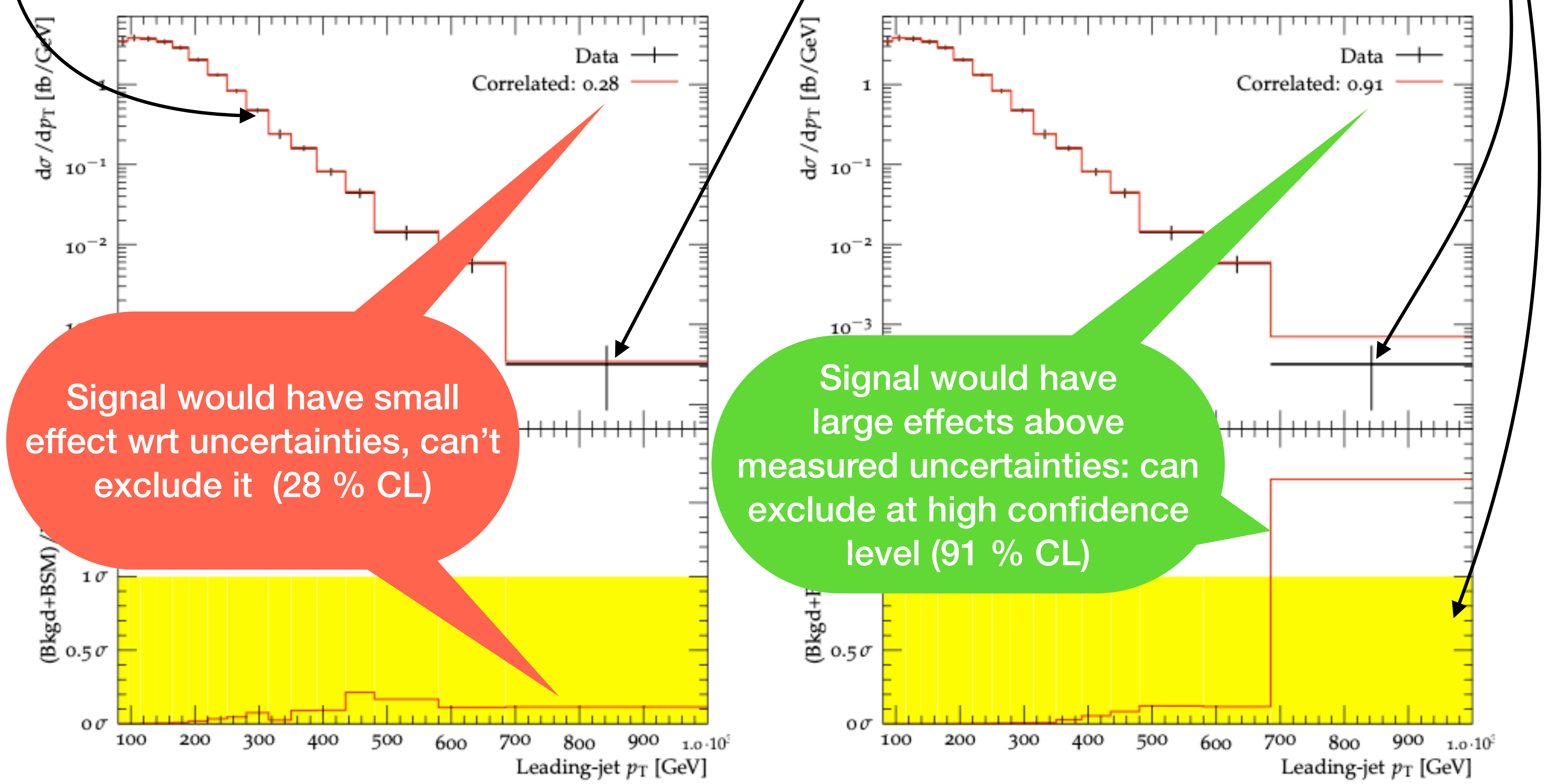


Illustration by Chris Wormell from 'A Map of the Invisible'

Stats analysis

UCL

- Use standard CLs method to determine confidence with which we can exclude signal (+bkg) in face of data+uncertainties (and bin-bin correlations if available)



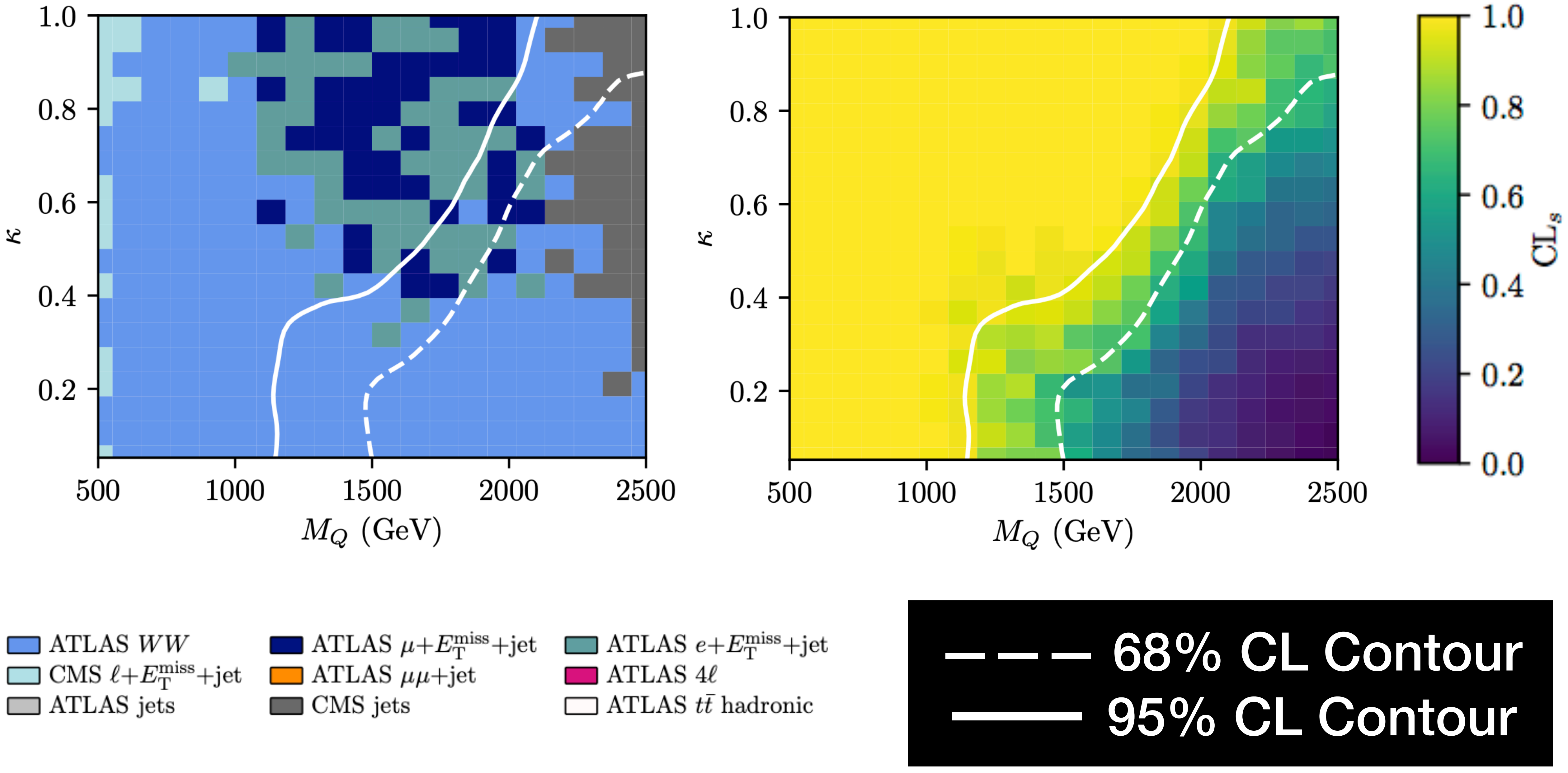
NB: if SM prediction not available, CONTUR assumes Data=SM. It's an ugly hack, but it works, since we claim no significant deviations seen at LHC so far

CLs method for exclusion

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

CONTUR Steering

- CONTUR provides the book-keeping and steering machinery to repeat this process over a grid of parameter values
- Run grid for 7, 8, 13 TeV separately, then combine by taking most sensitive measurement from orthogonal analysis pools



UFO

Herwig

Rivet

CLs

Repeat for each point in parameter space

Constraints On New Theories Using Rivet

CONTUR vs Vector-like Quarks

A case study

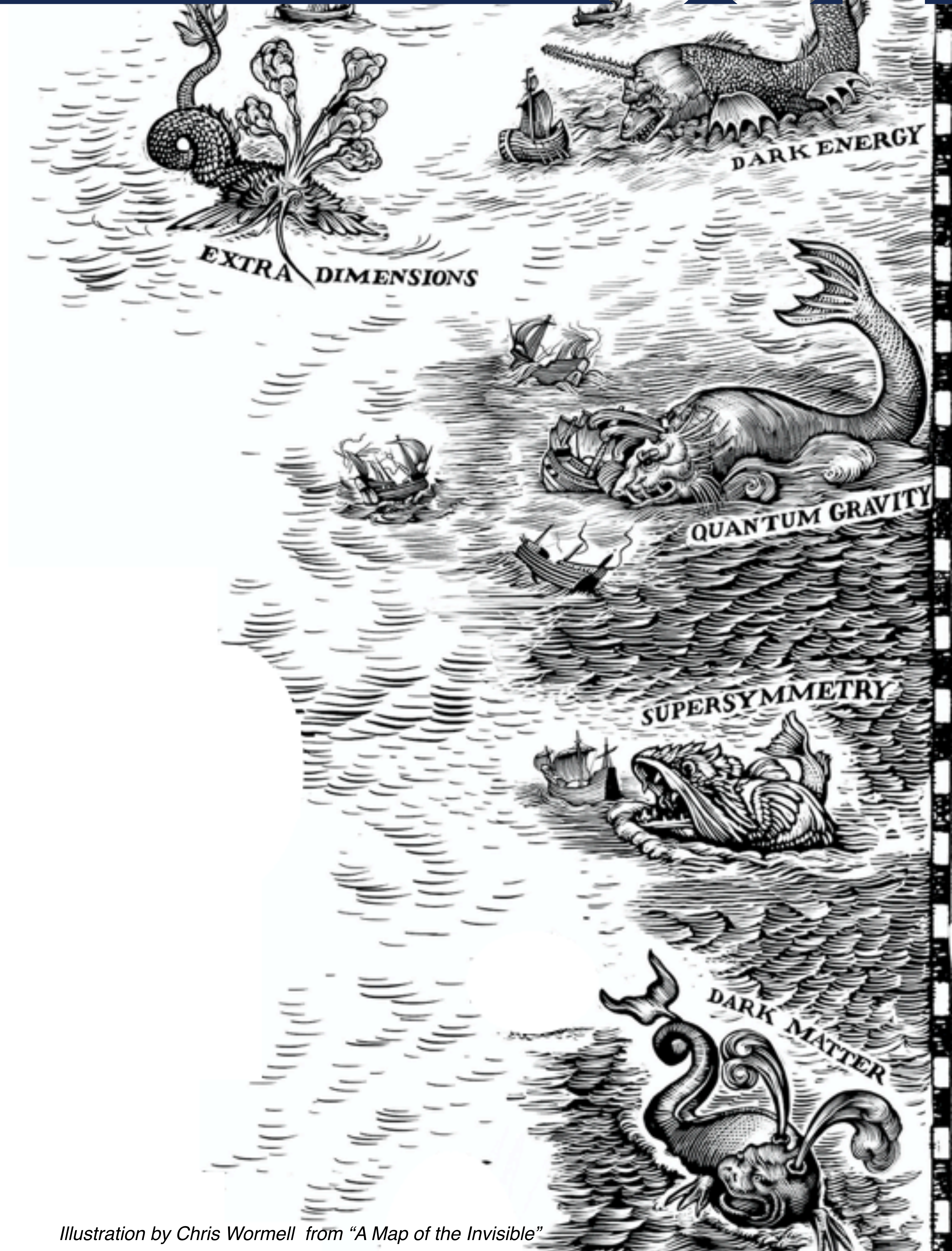


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

VLQs

- Latest paper tackles a class of models: vector-like quarks, using framework from Buchkremer et al (arXiv:1305.4172)
- Introduces quark partners:

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

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

https://arxiv.org/abs/2006.07172

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]

[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

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.

VLQs

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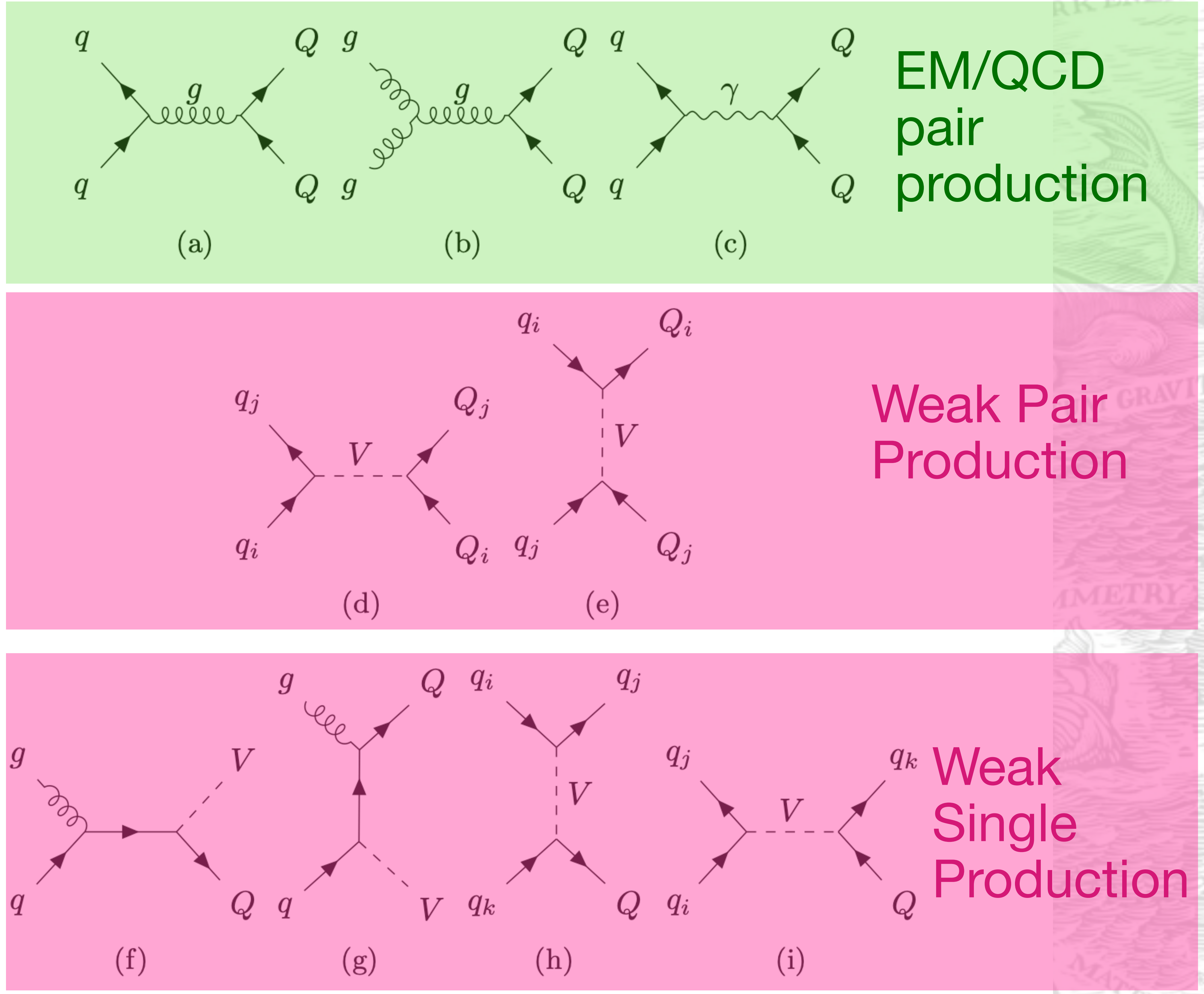
- Three params:
  - κ: **absolute coupling** of VLQs to SM quarks
  - ζ_i: relative **coupling of VLQs to i^{th} generation**
  - ξ_V: relative **coupling of B,T to V in {W, H, Z}**



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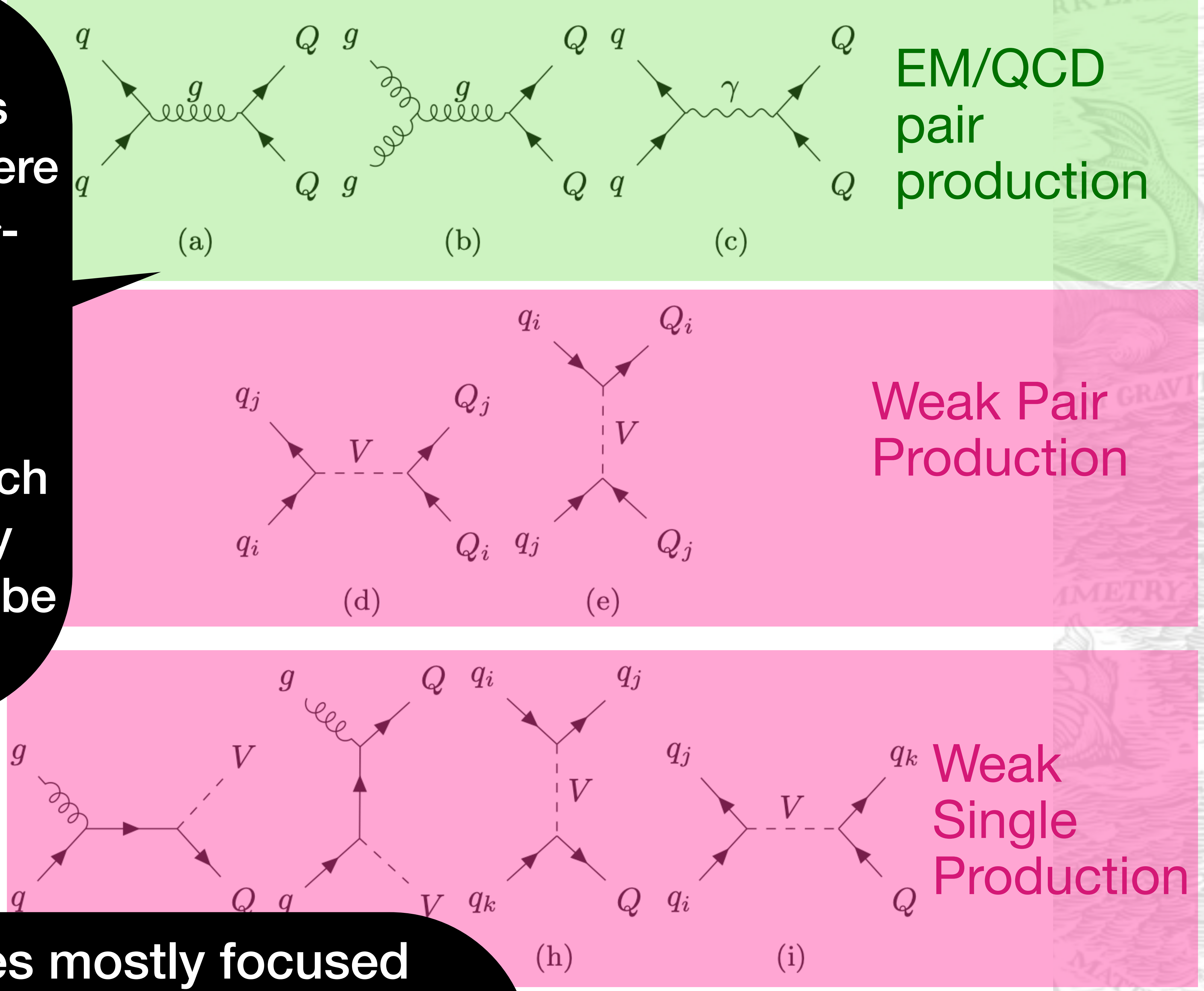


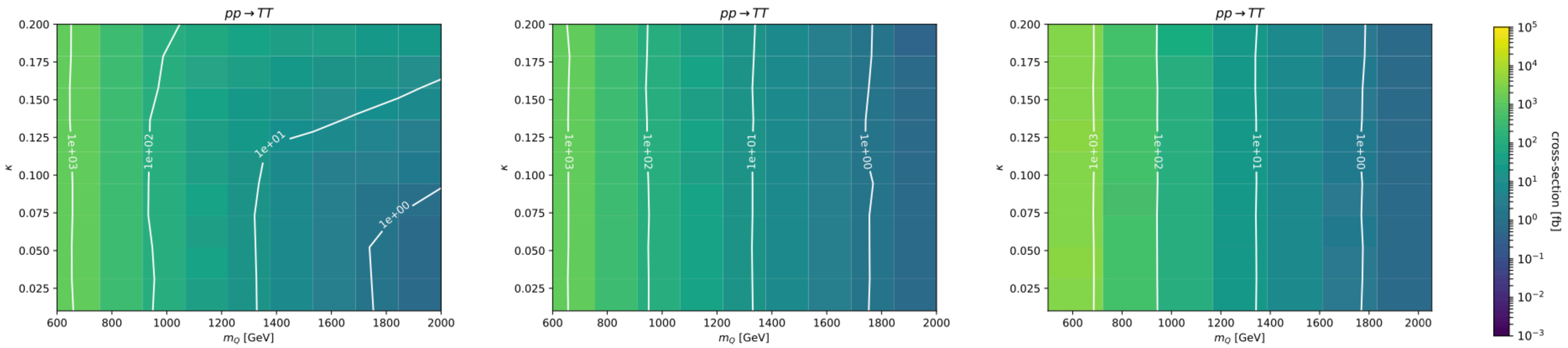
LHC programme has mostly focused here since reduced κ-dependence,

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

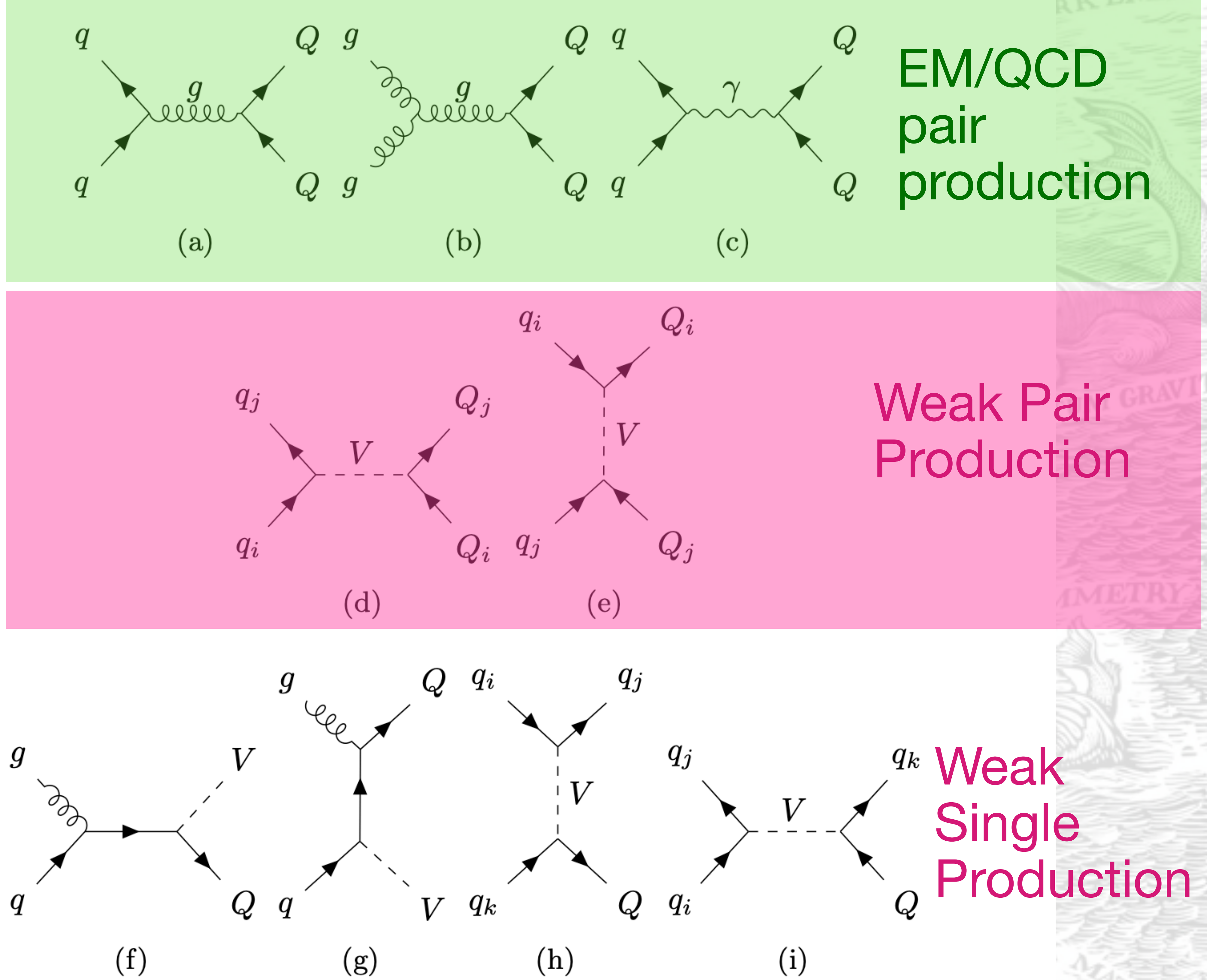
LHC searches mostly focused on 3rd-gen, but 1st-gen has richer phenomenology due to valence-quark-induced production

VLQs

Assuming ξ such that W:Z:H=1:1:1



(a) T coupling to u, d only (b) T coupling to c, s only (c) T coupling to t, b only

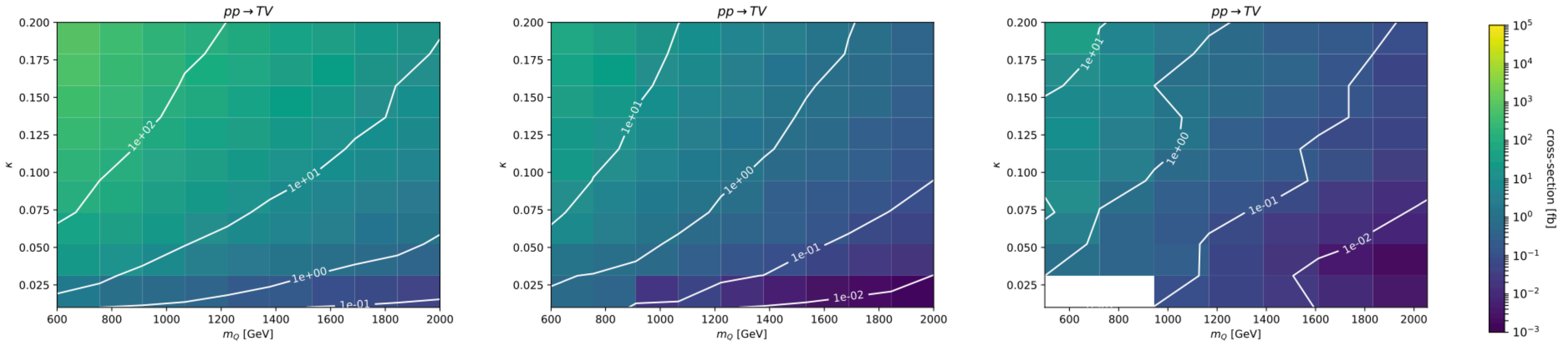


1st-gen couplings: even pair-production has κ-dependence due to weak production initiated by valence quarks

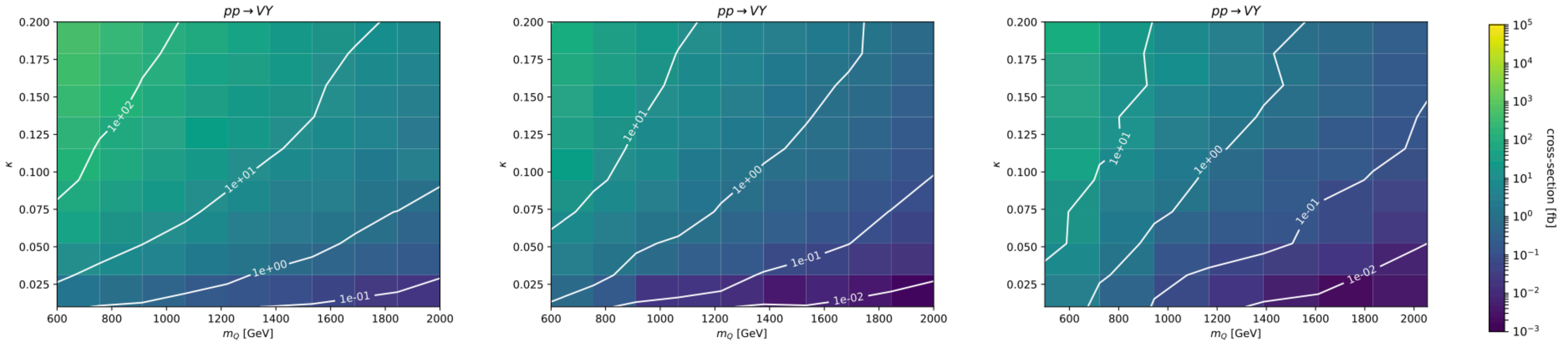
VLQs

UCL

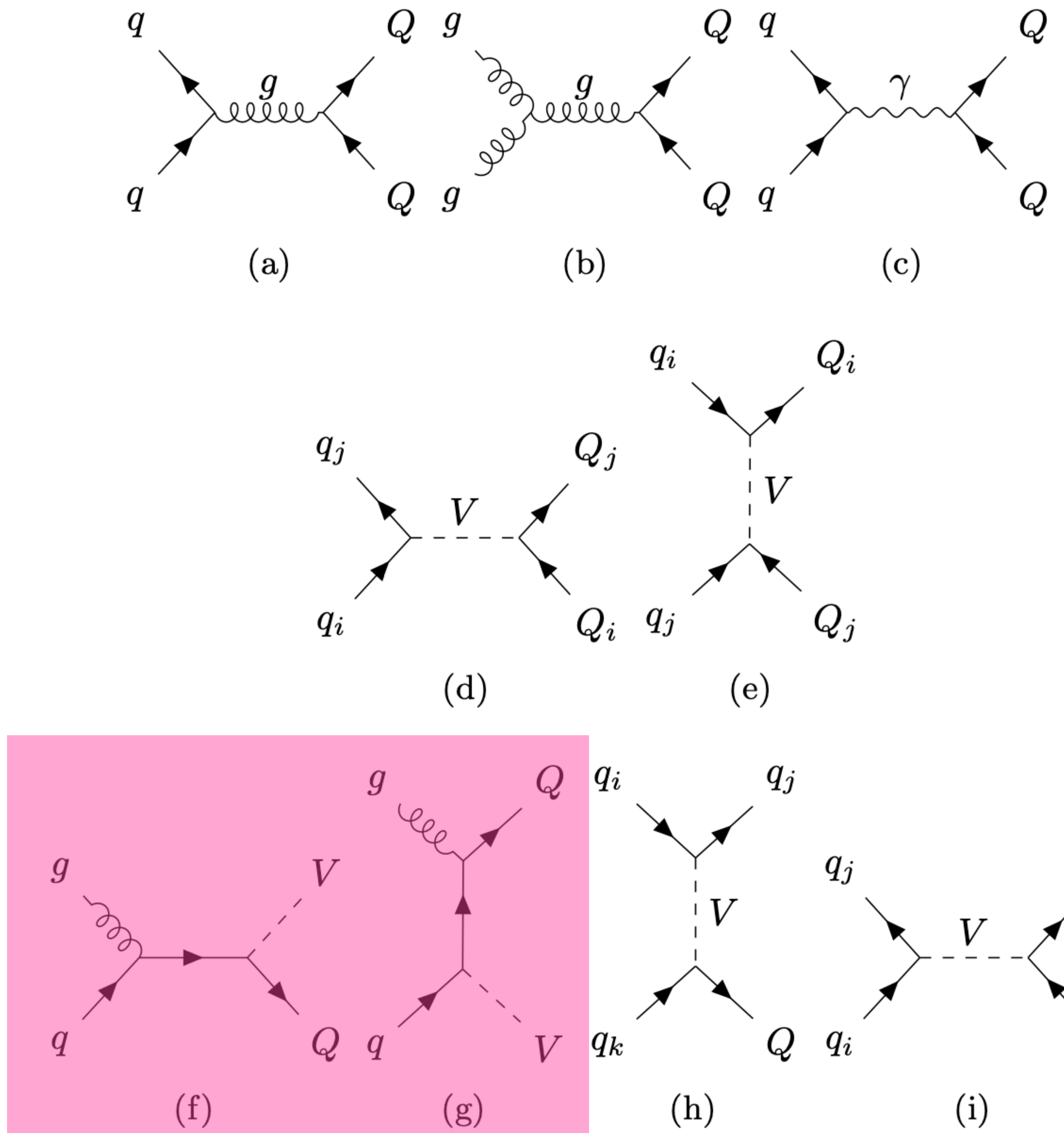
Assuming ξ such that W:Z:H=1:1:1



(a) T coupling to u, d only (b) T coupling to c, s only (c) T coupling to t, b only



(d) Y coupling to u, d only (e) Y coupling to c, s only (f) Y coupling to t, b only



EM/QCD pair production

Weak Pair Production

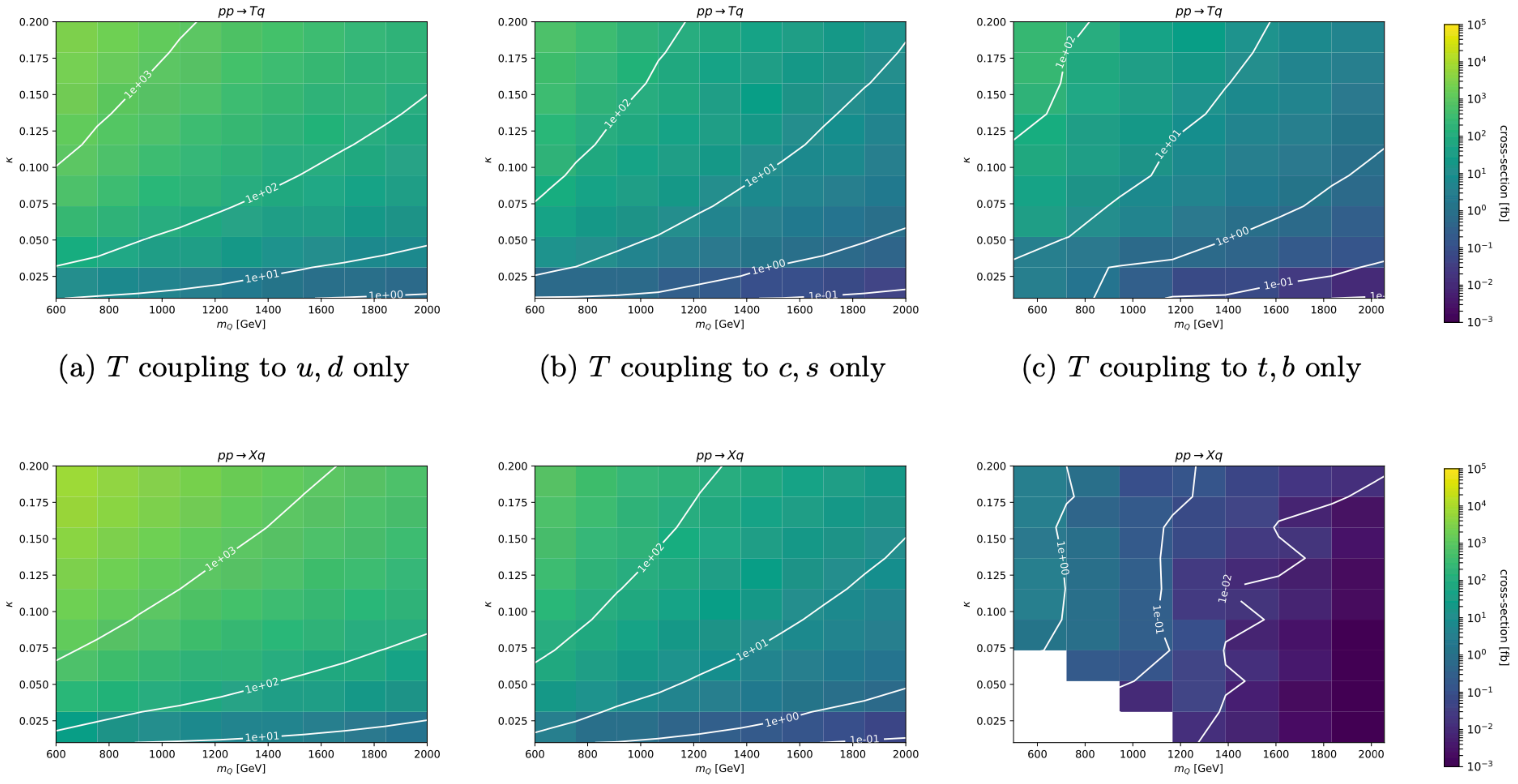
Weak Single Production

VLQ production with associated weak boson (for X and Y, this is only possible via W)

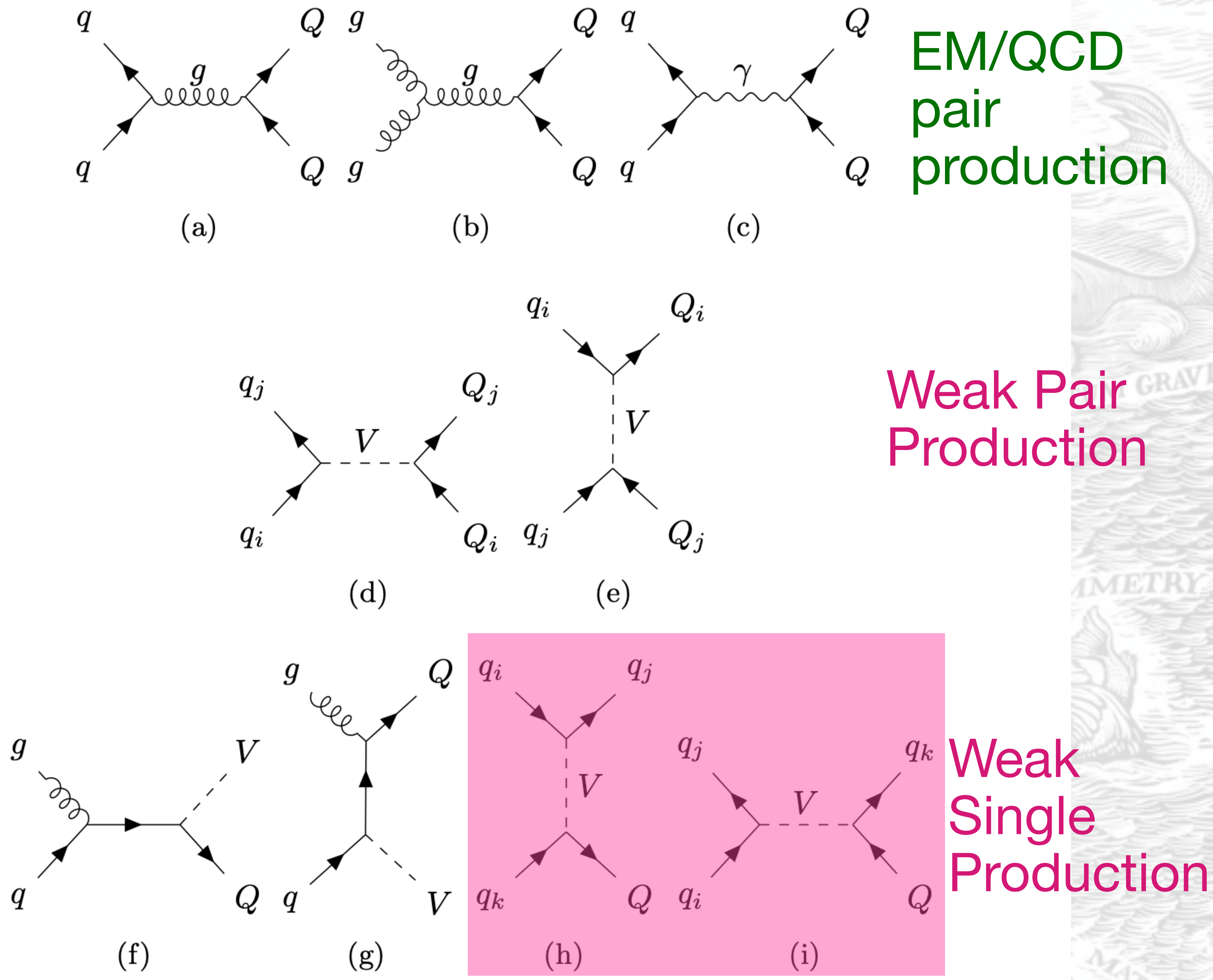
Louie Corpe, UCL (l.corpe@ucl.ac.uk)

VLQs

Assuming ξ such that W:Z:H=1:1:1



(a) T coupling to u, d only
(b) T coupling to c, s only
(c) T coupling to t, b only
(d) X coupling to u, d only
(e) X coupling to c, s only
(f) X coupling to t, b only



VLQ production with SM quark: can be dominant over pair-production in 1st-gen scenario!

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

CONTUR vs Direct searches

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

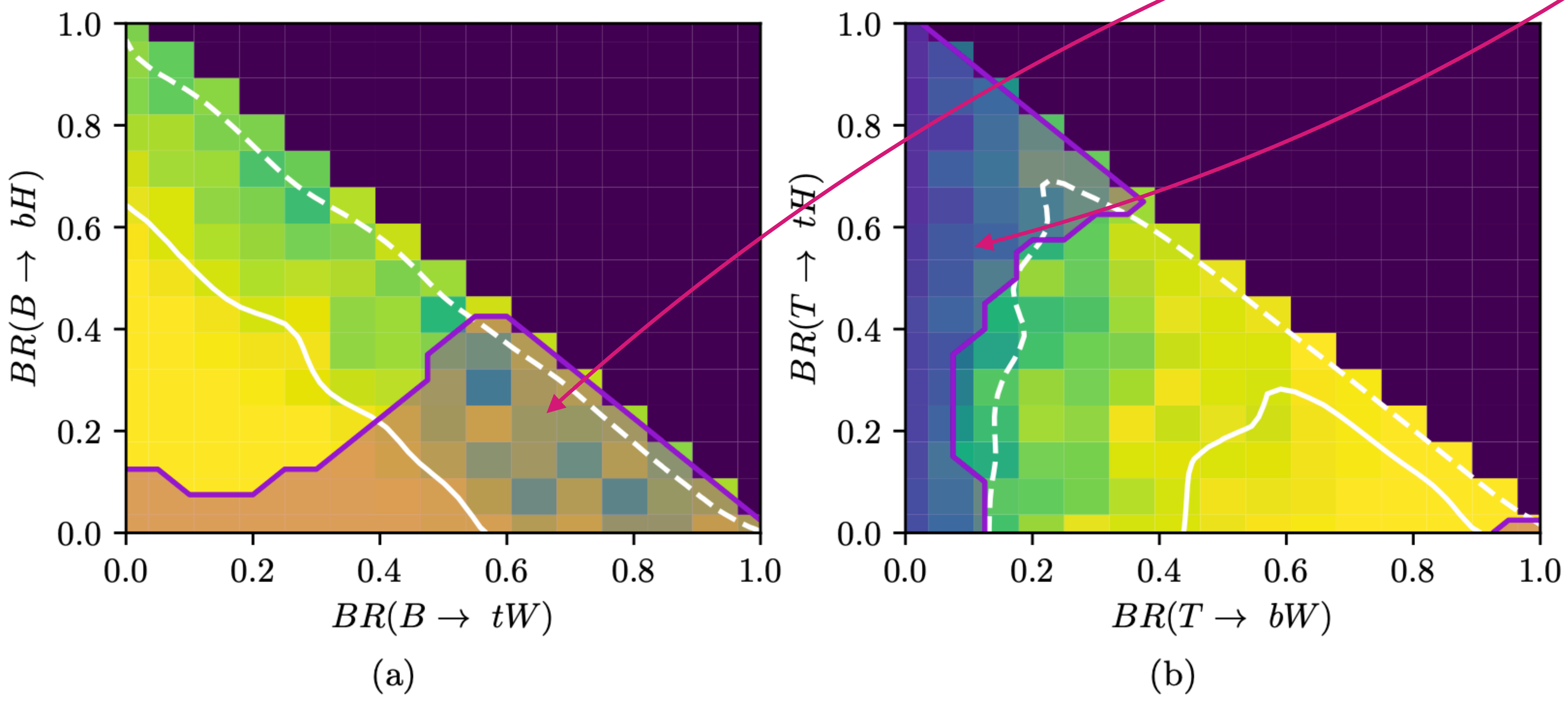
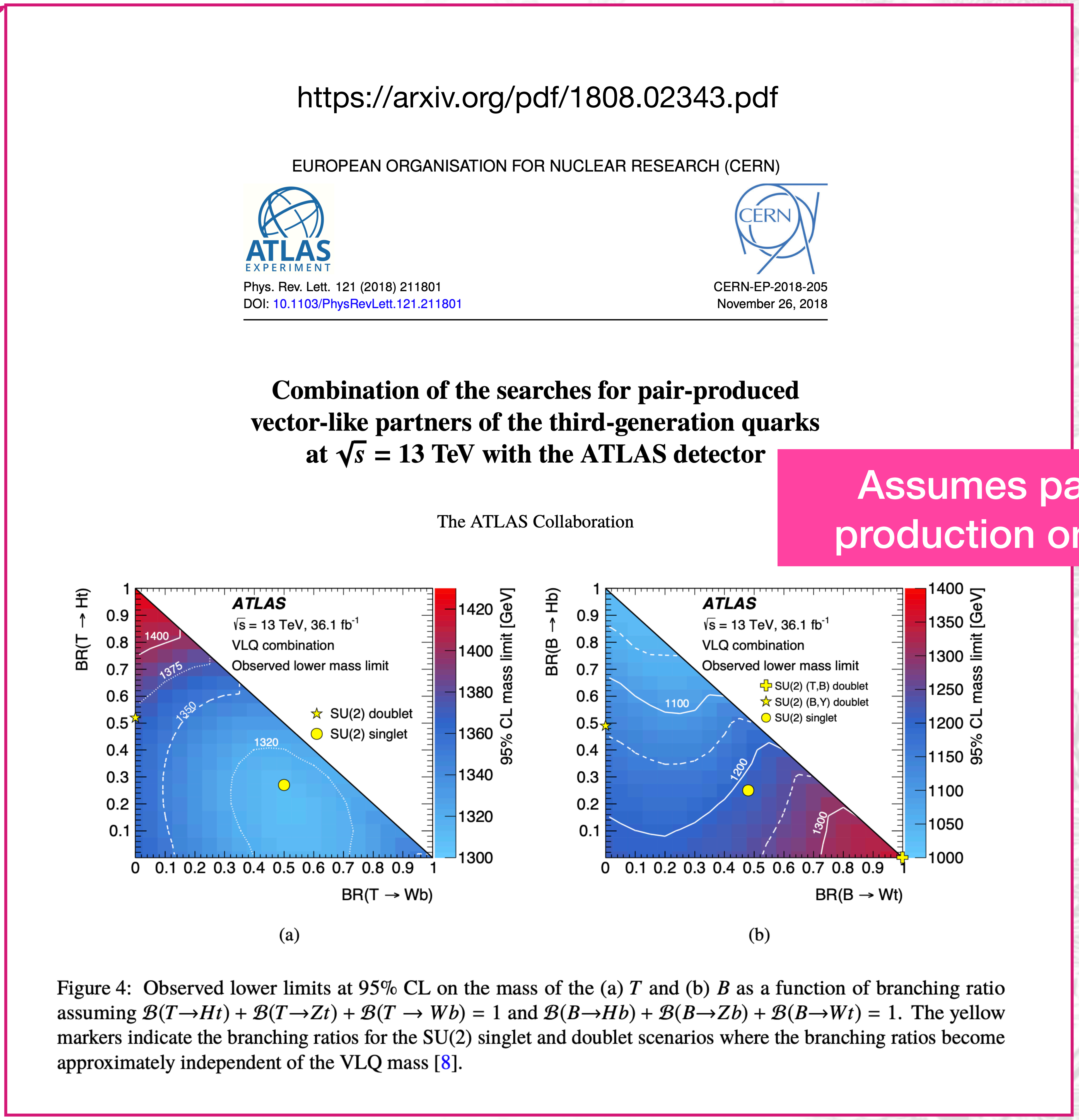


Figure 5: Sensitivity of LHC measurements to (a) B-production for $M_B = 1200$ GeV and (b) T-production for $M_T = 1350$ GeV. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed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



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

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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

CERN-EP-2018-205
November 26, 2018

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

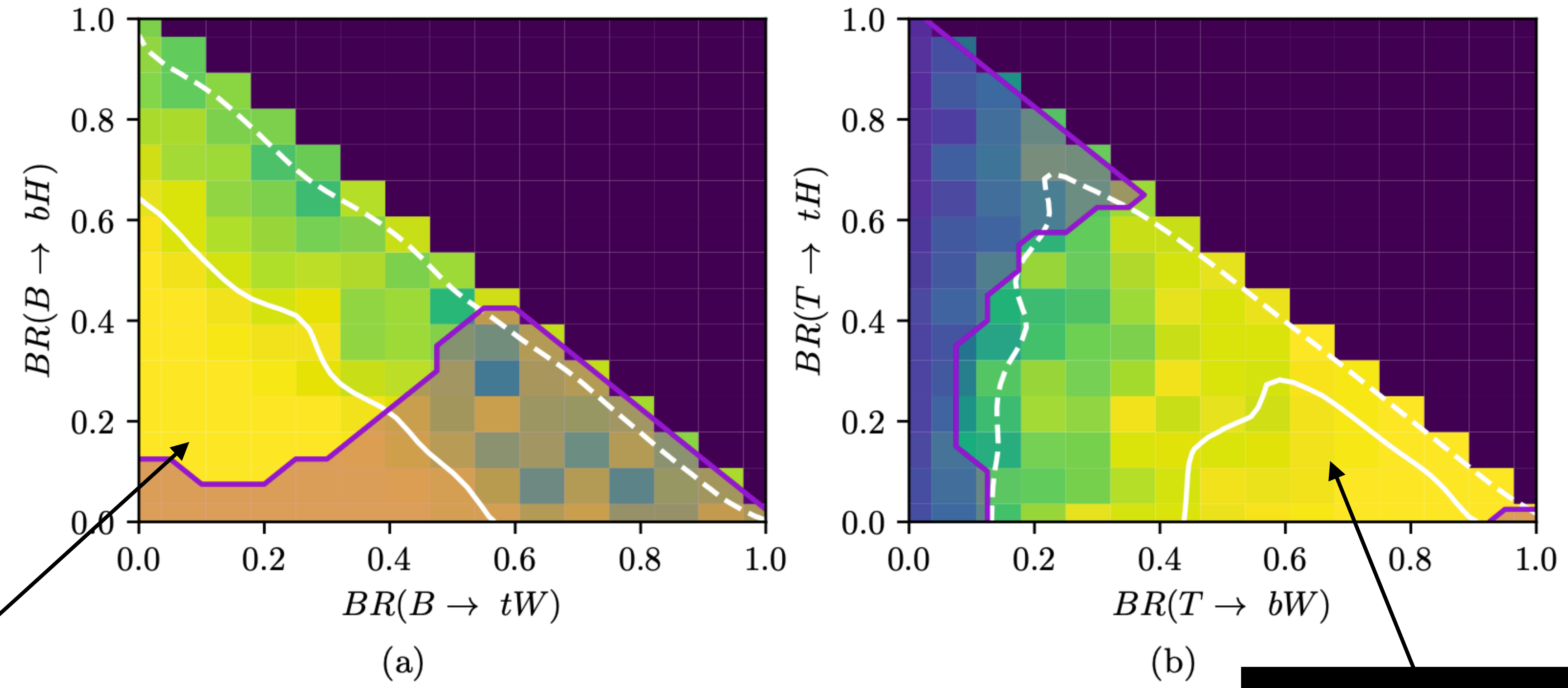
The ATLAS Collaboration

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

Assumes pair-production only !

CONTUR vs Direct searches

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



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% CL by the ATLAS combination [16].

CONTUR sensitivity comes mainly from Z+jets measurements !

CONTUR sensitivity comes mainly from Top or W measurements

- 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 to explore new regions

Assuming 3rd gen couplings only
Assuming B,T,X,Y have same mass

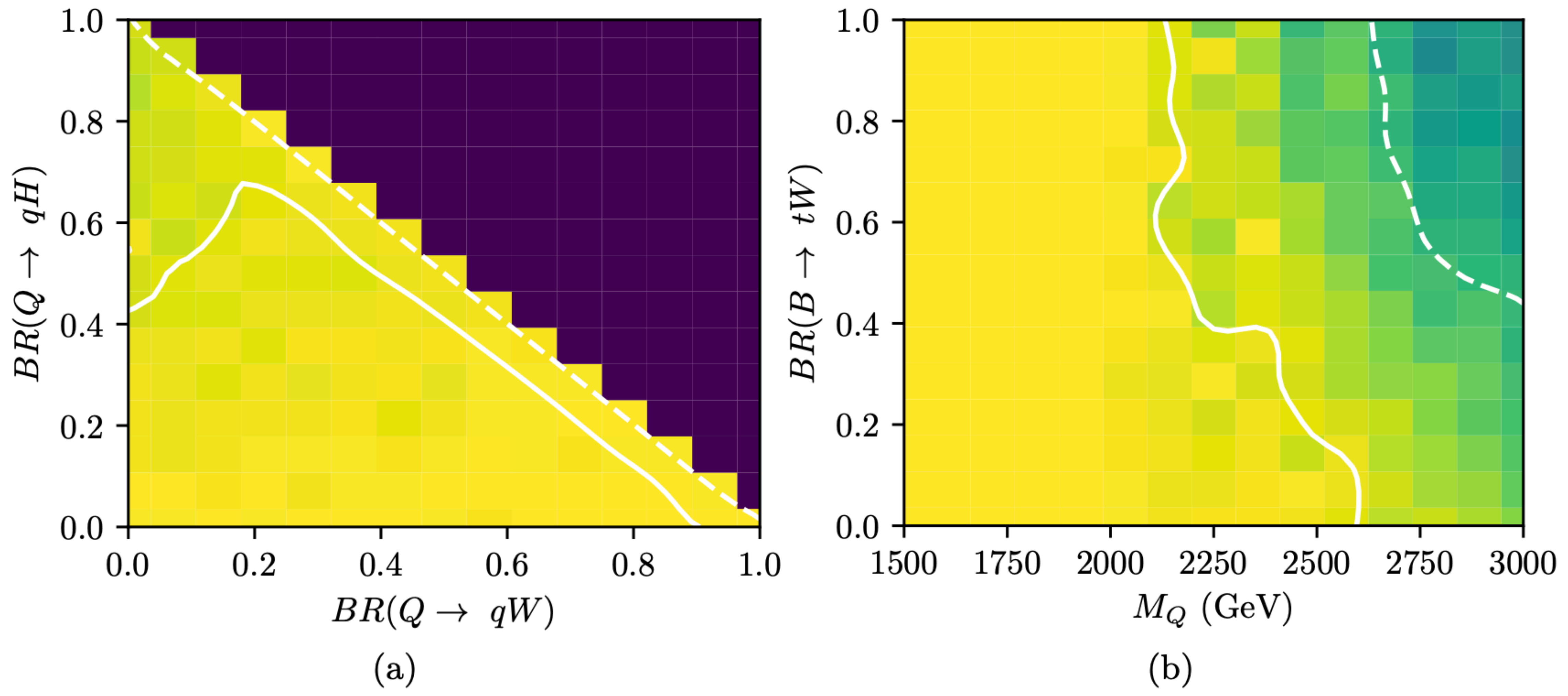
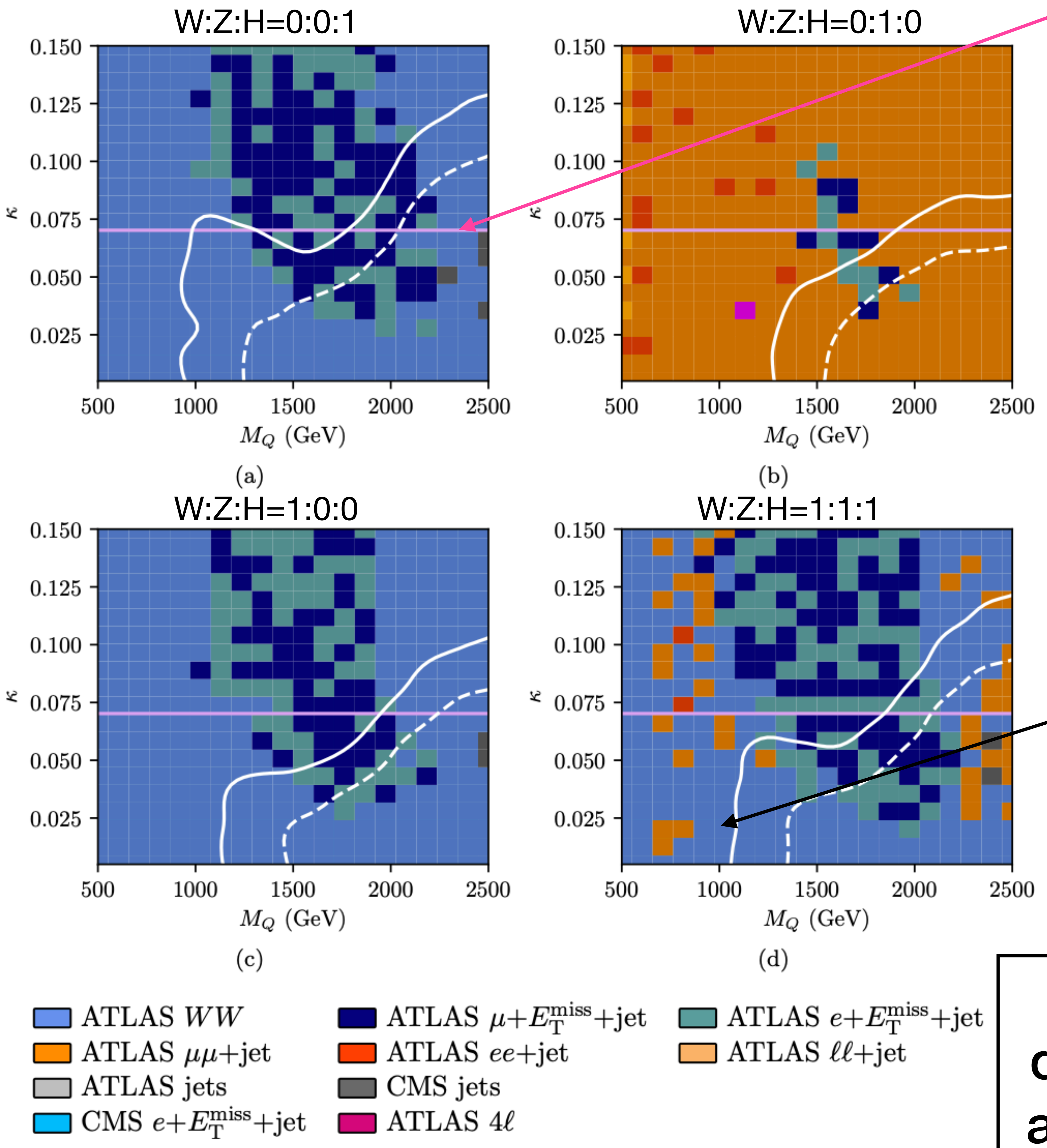


Figure 6: Sensitivity of LHC measurements to VLQ production when B, T, X, Y are degenerate in mass. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed white) exclusion contours superimposed. (a) Limit in the the branching fraction plane for $M_Q = 2000\,\mathrm{GeV}$. (b) Limit in the plane of M_Q and $\mathrm{BF}(Q \to Wq) = 1 - \mathrm{BF}(Q \to Zq)$, for $\mathrm{BF}(Q \to Hq) = 0$

- Allowing all VLQs to have same mass (why not? Decoupling X/Y is usually done for simplicity of benchmarks) shows much greater sensitivity, with much of the parameter space already excluded

CONTUR to explore new regions

VLQs coupling to 1st Gen



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

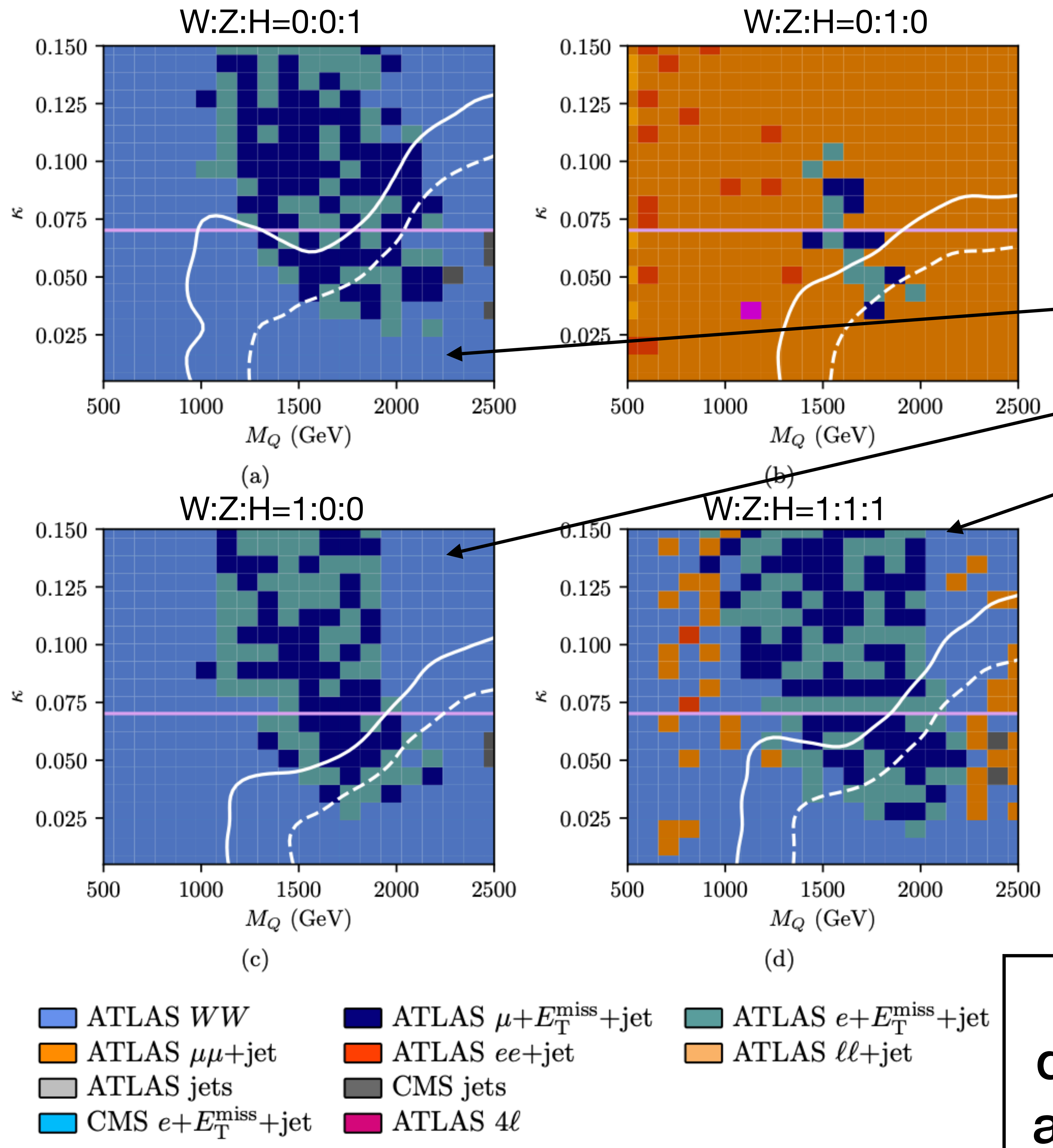
Region to left is excluded at 90% CL by CONTUR

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

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

CONTUR to explore new regions

VLQs coupling to 1st Gen



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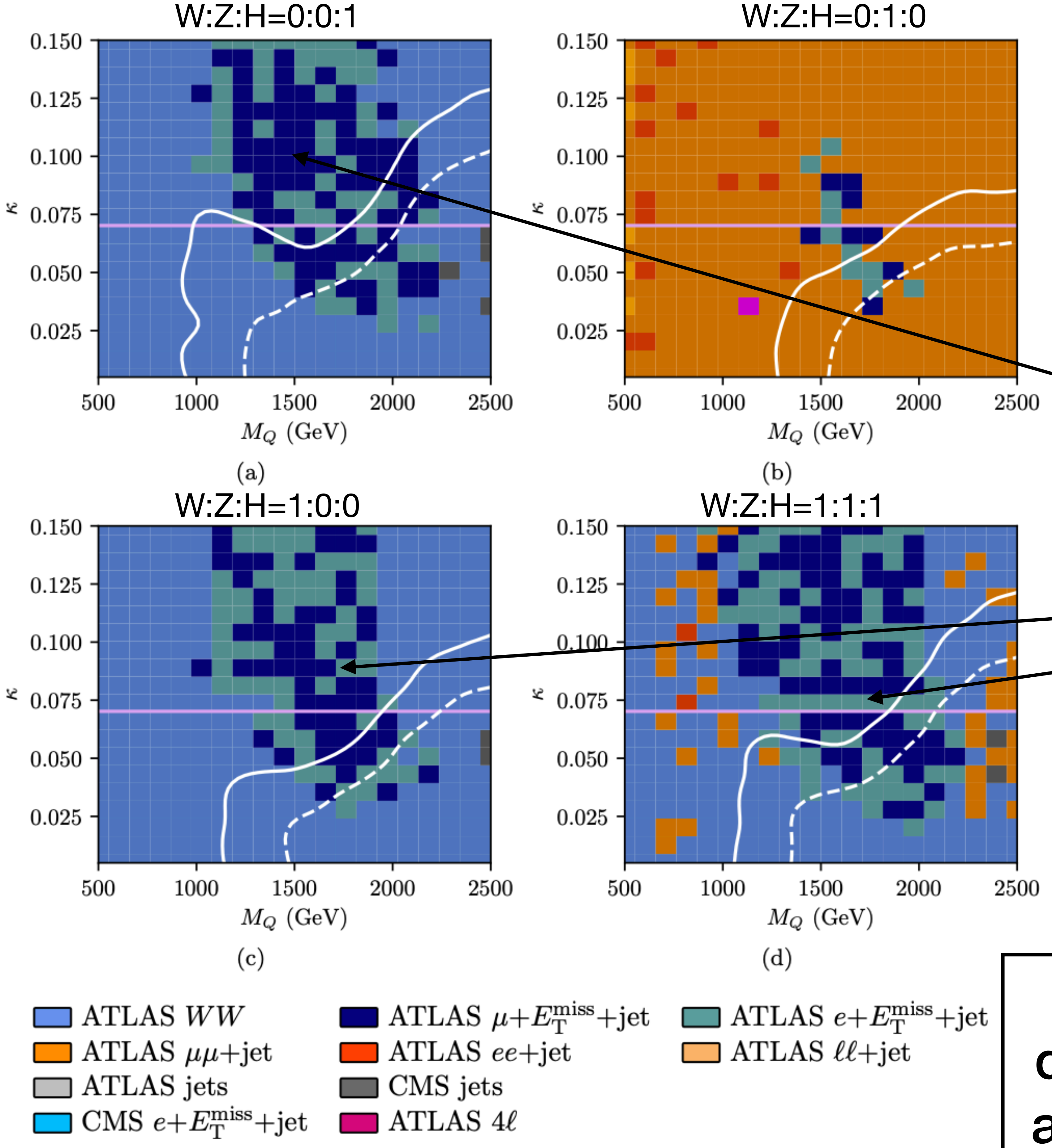

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Sensitivity driven by control region measurements in an 8 TeV Wjj measurement

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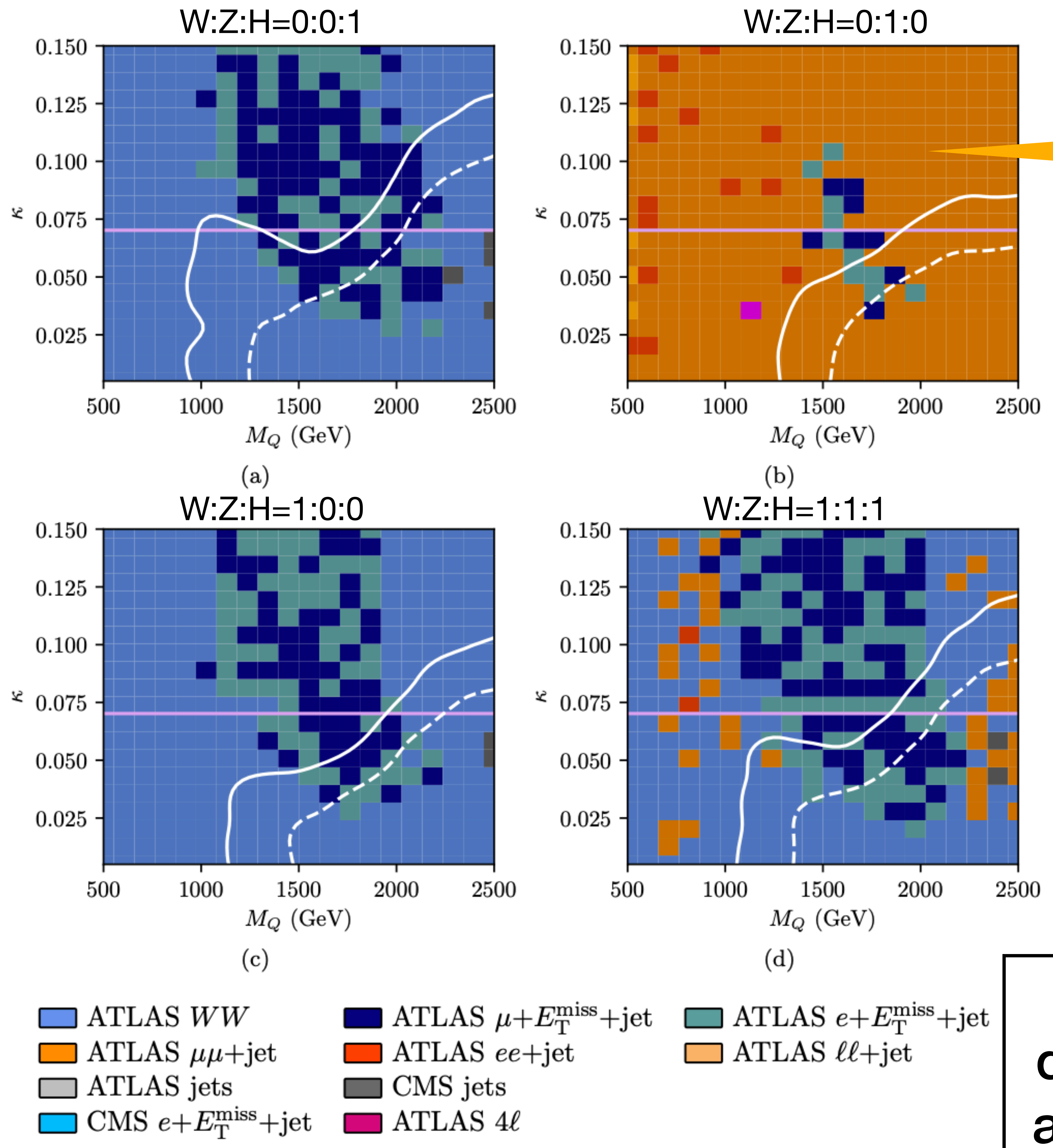
CONTUR to explore new regions

VLQs coupling to 1st Gen



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

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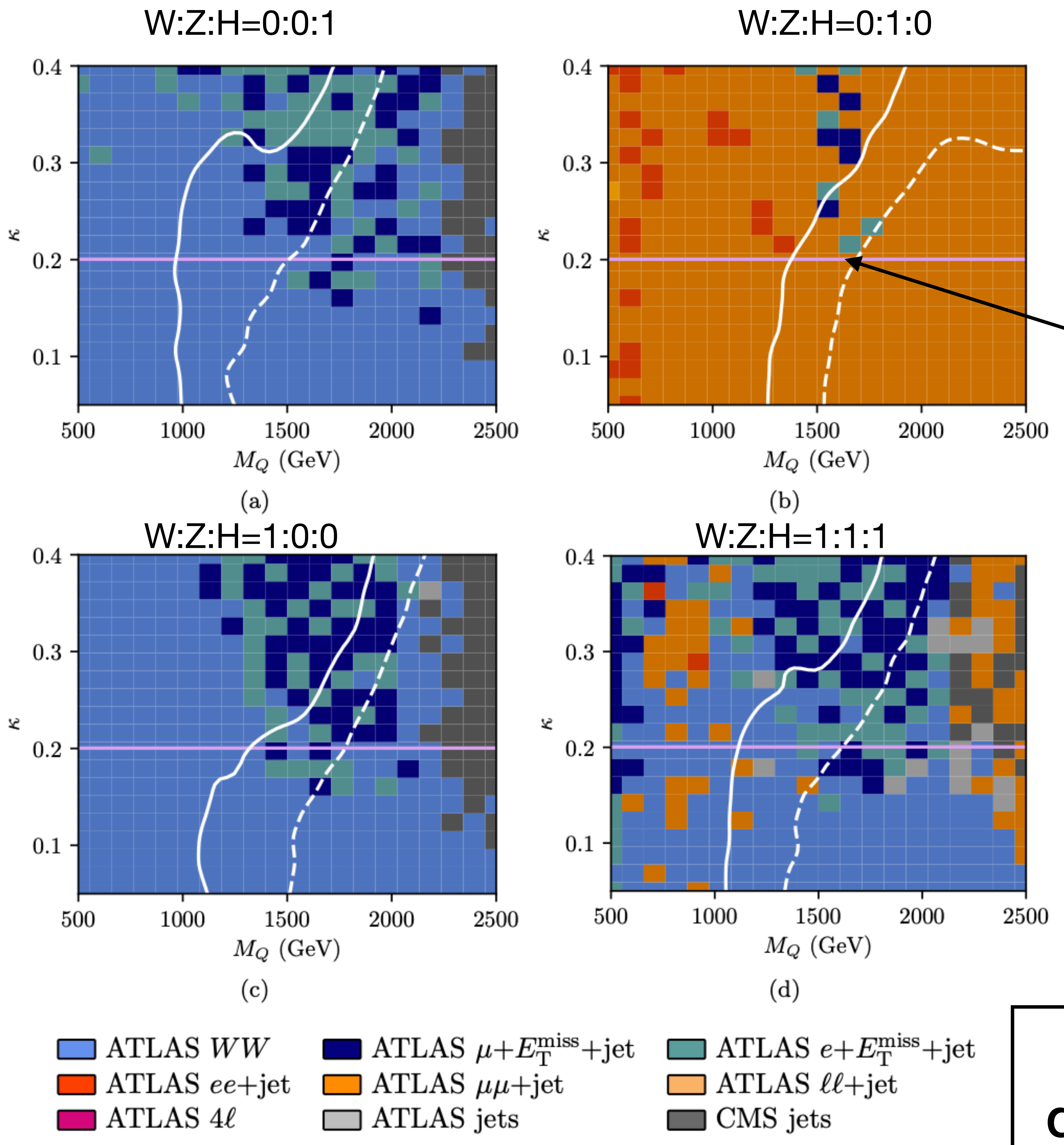
CONTUR to explore new regions

VLQs coupling to 2nd Gen

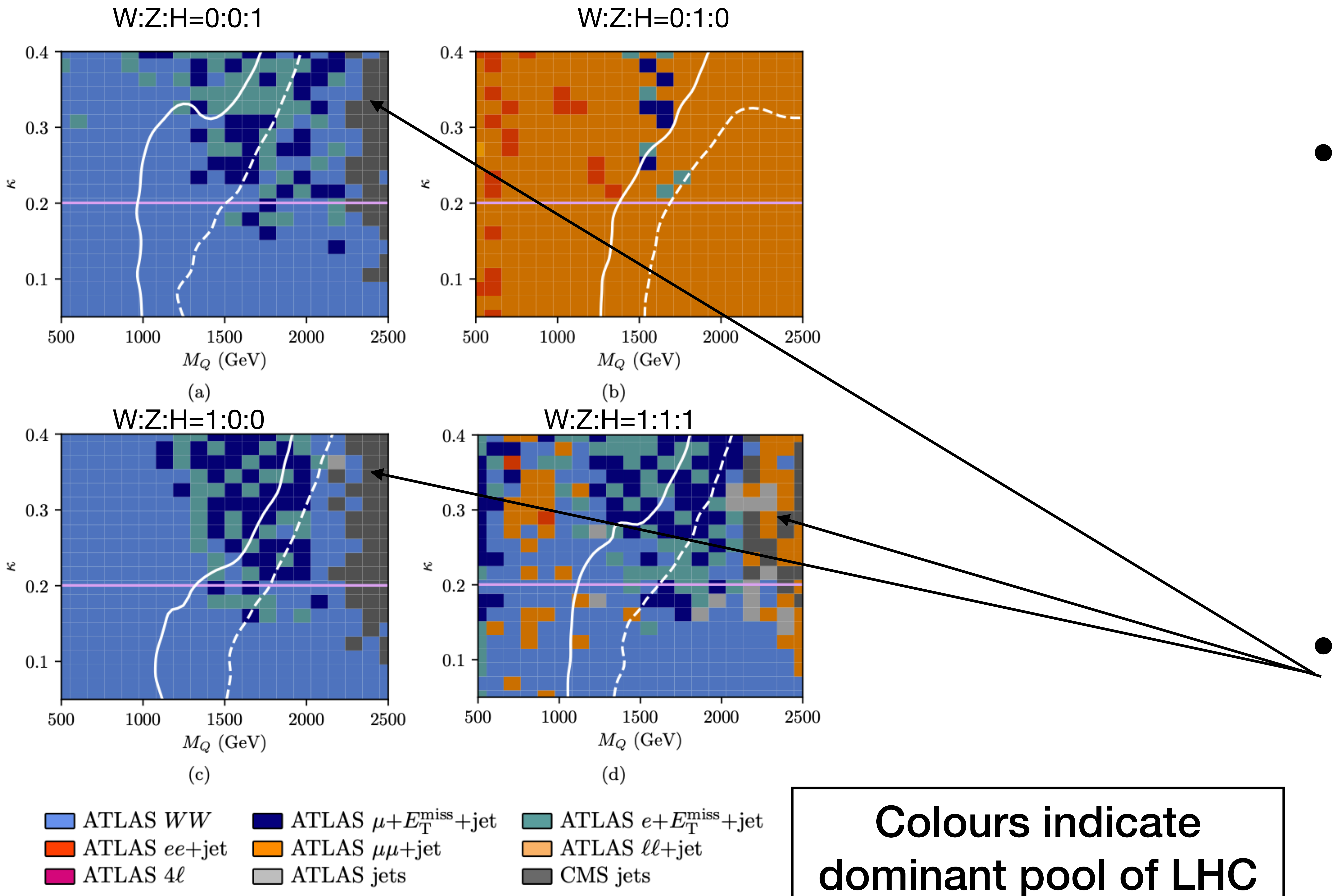


Colours indicate dominant pool of LHC analyses in each point of param space

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

CONTUR to explore new regions

VLQs coupling to 2nd Gen



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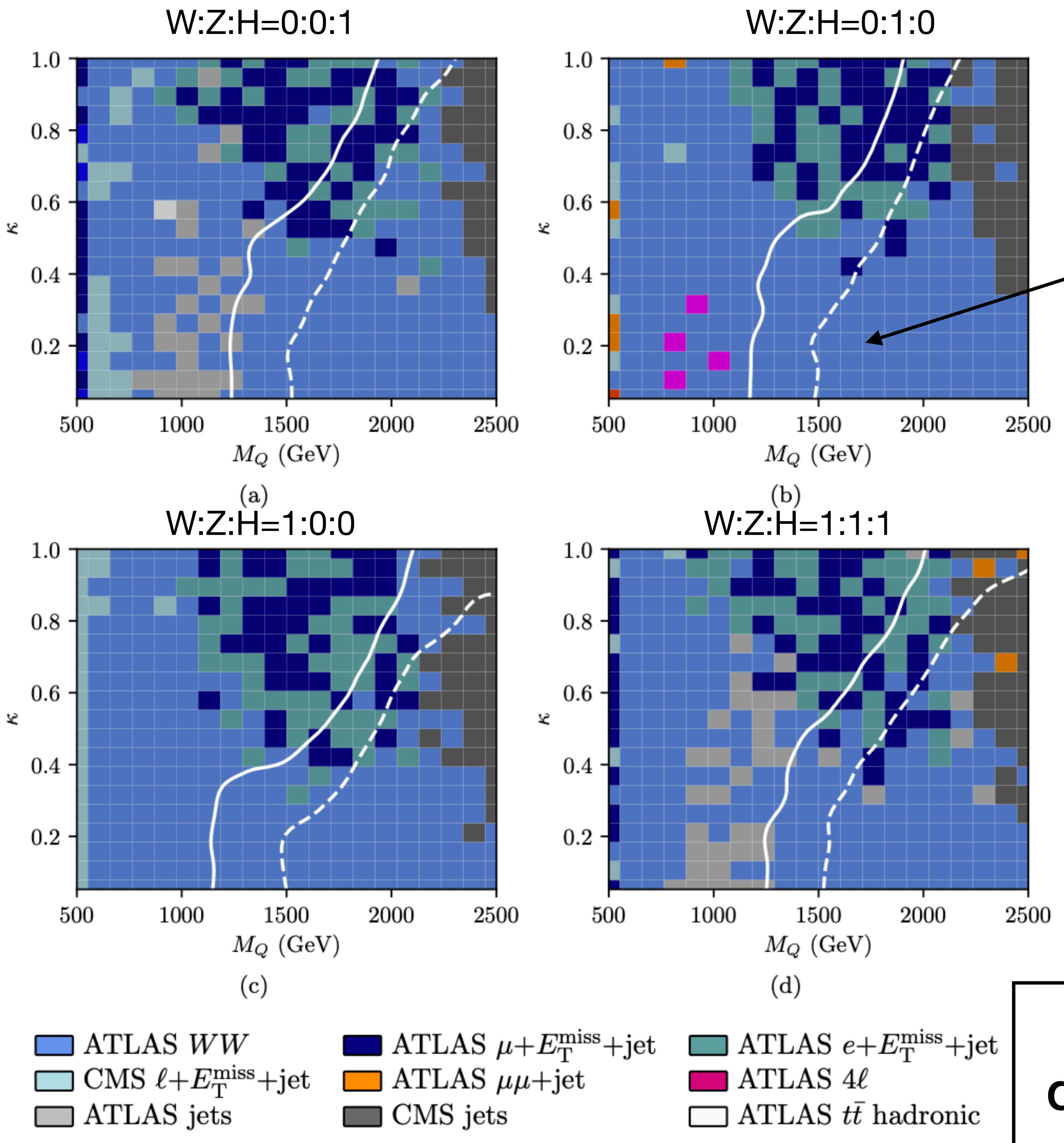
CONTUR to explore new regions

VLQs coupling to 3rd Gen



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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 between bins to be accounted for
- Exclusion much more modest if error breakdowns would not have been published (see backup)!

What about the (many) more realistic scenarios?

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

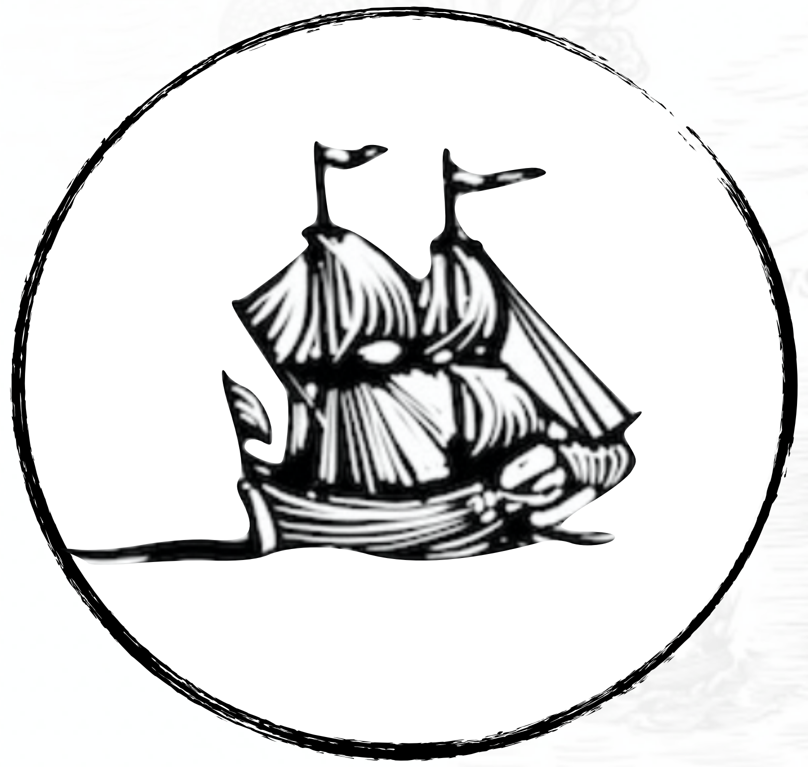

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Illustration by Chris Wormell from "A Map of the Invisible"

What about the (many) more realistic scenarios?

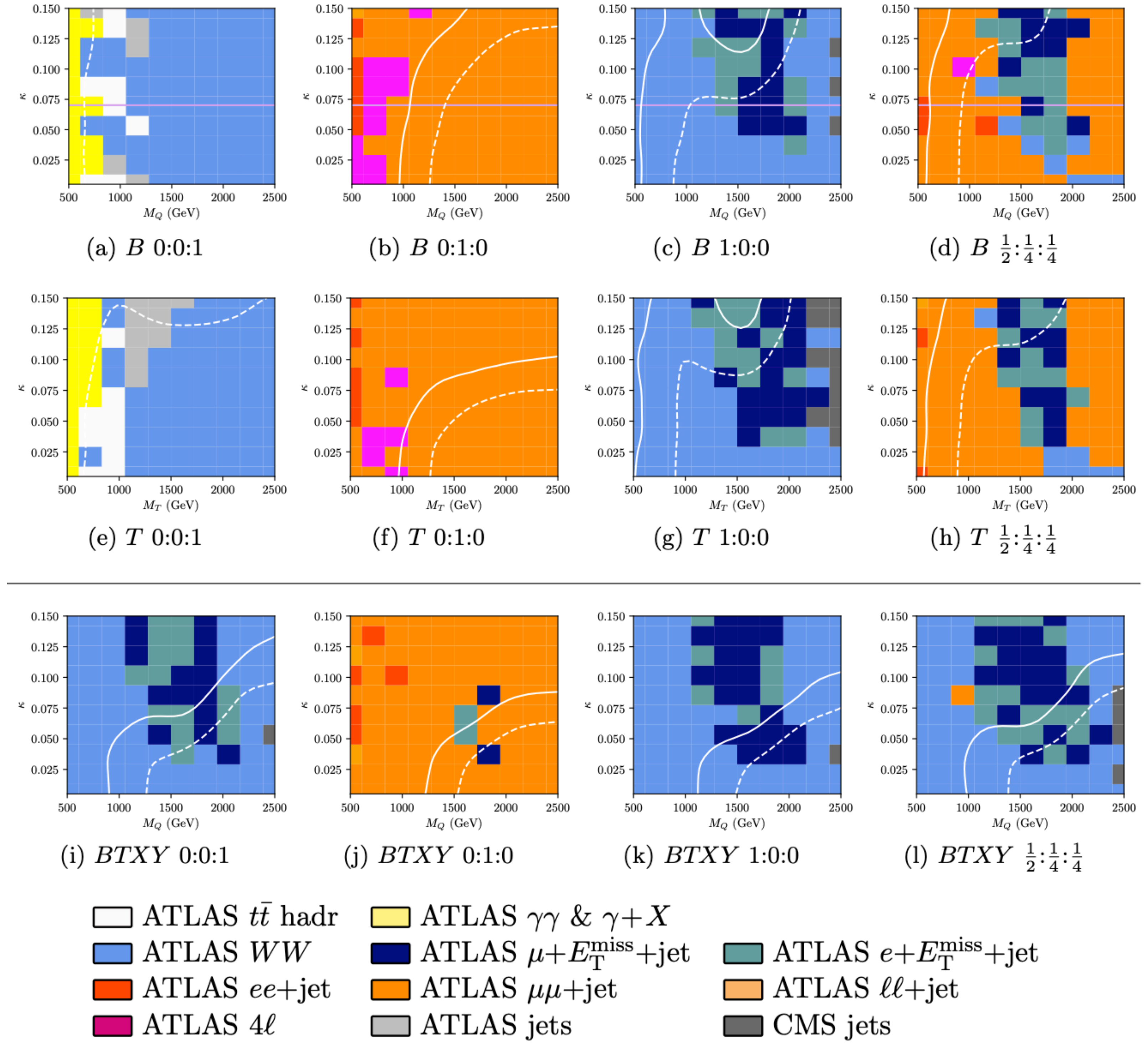
28 days later…

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

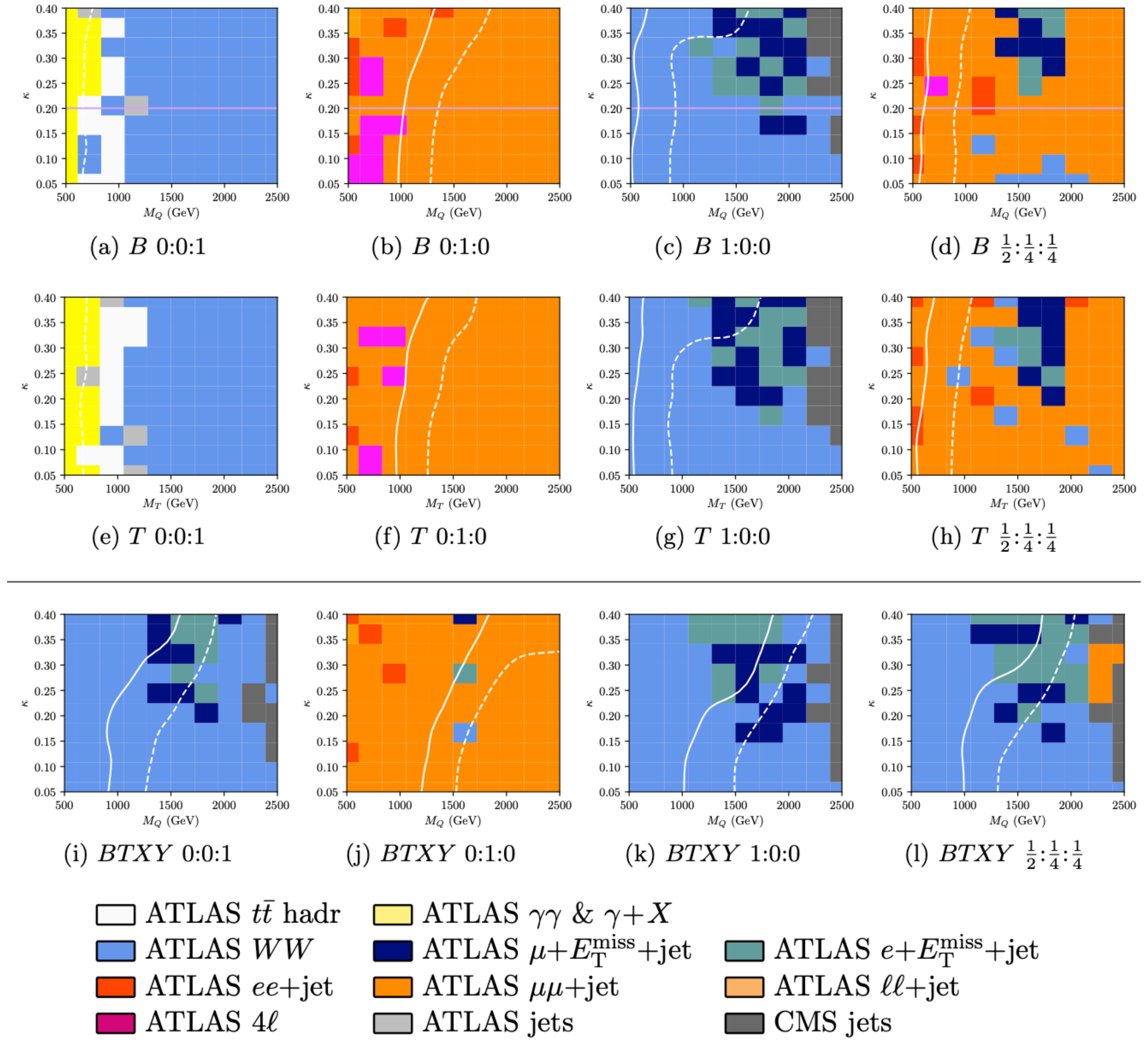
What about Singlets?

UCL

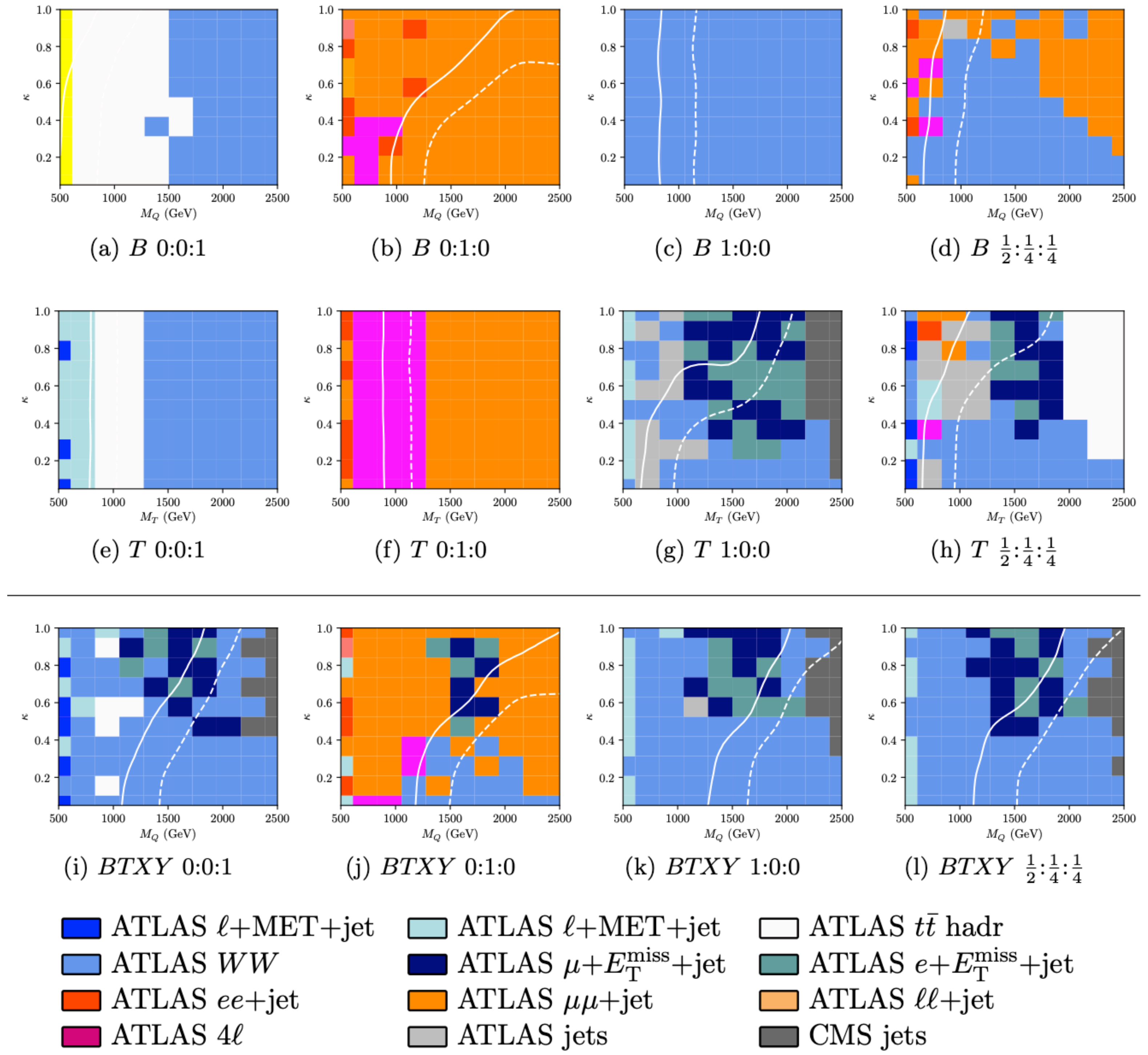
1st-Generation



2nd-Generation



3rd-Generation



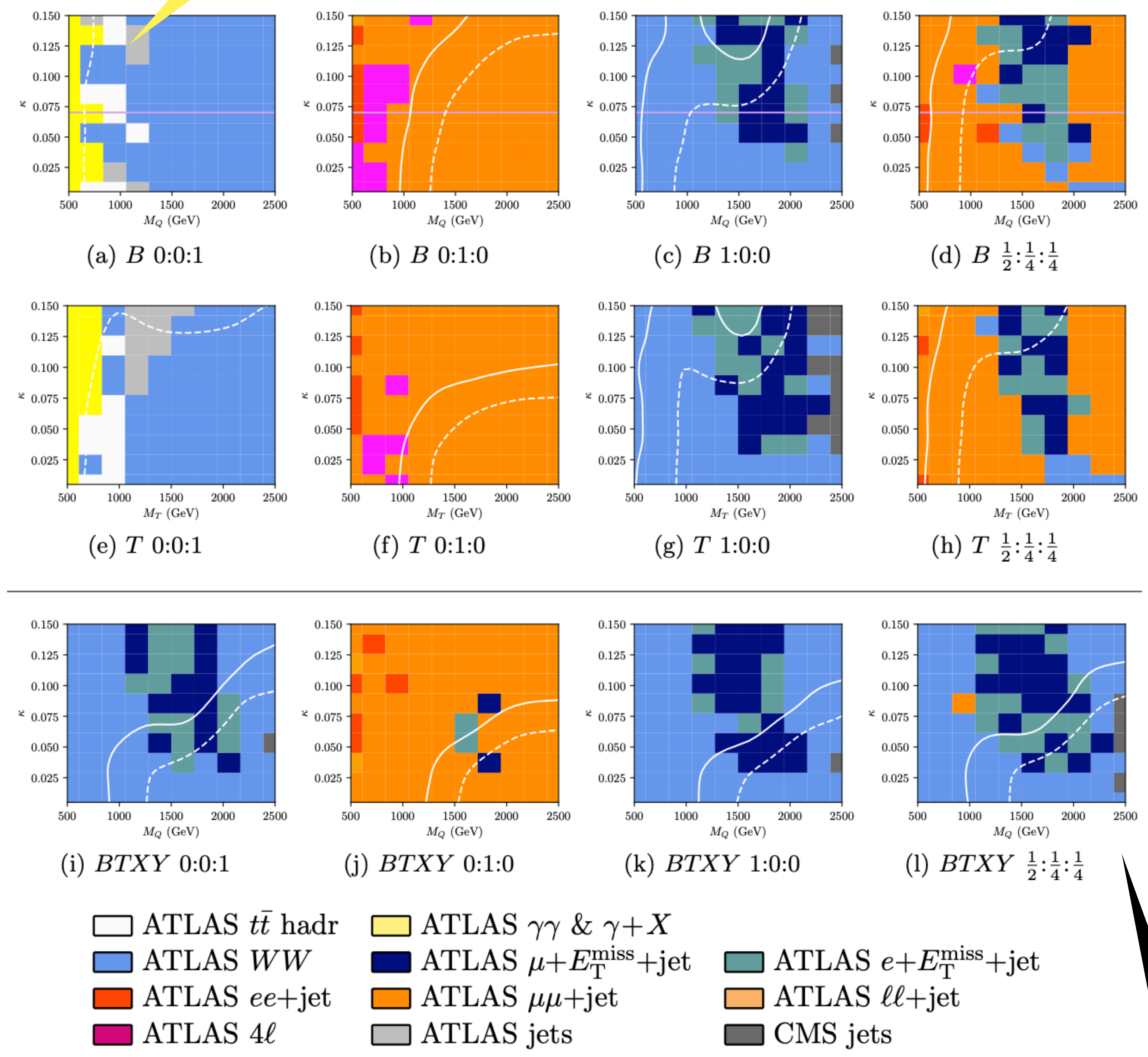
What about Singlets?

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

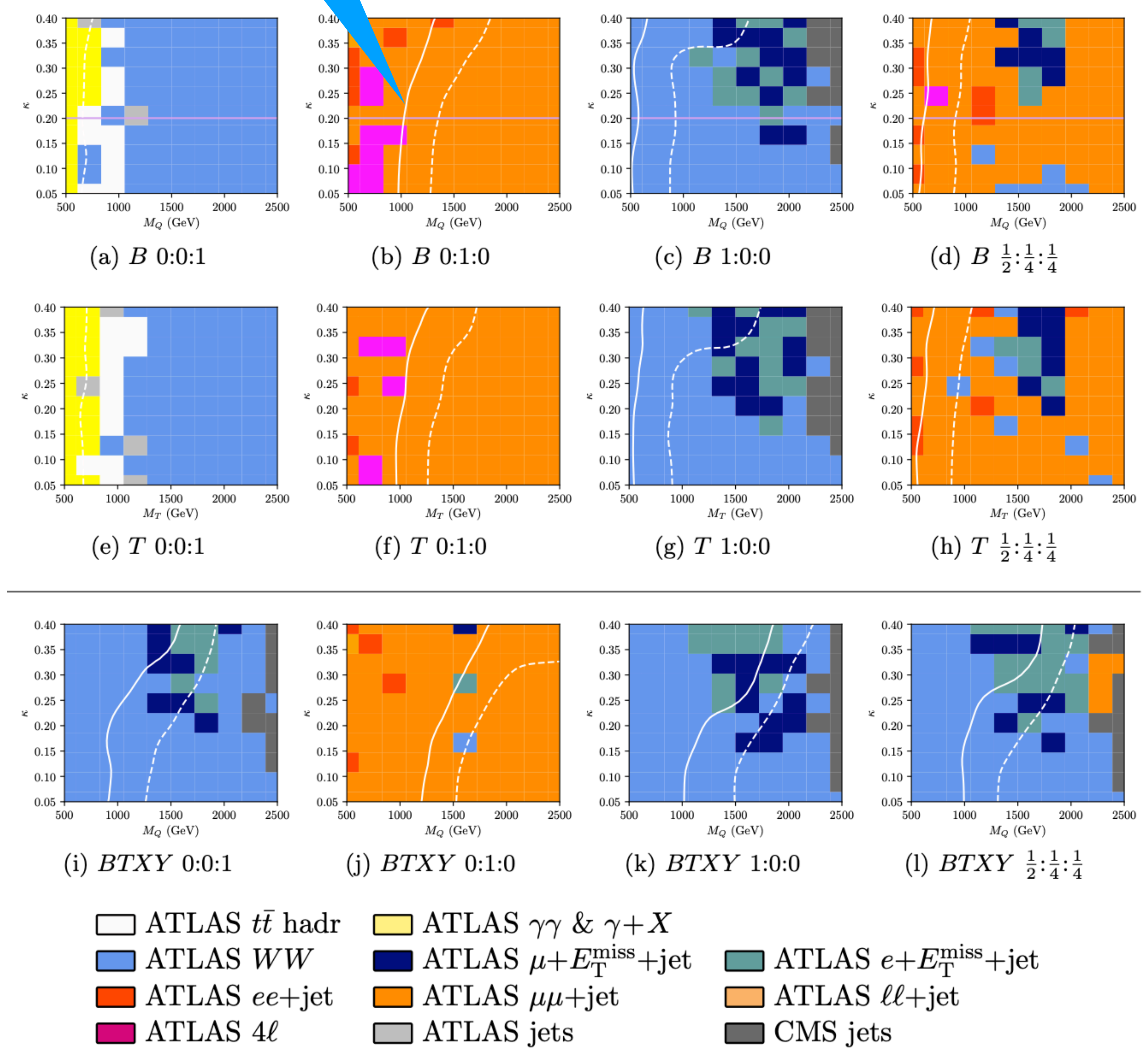
In general, fewer new VLQs lead to weaker constraints

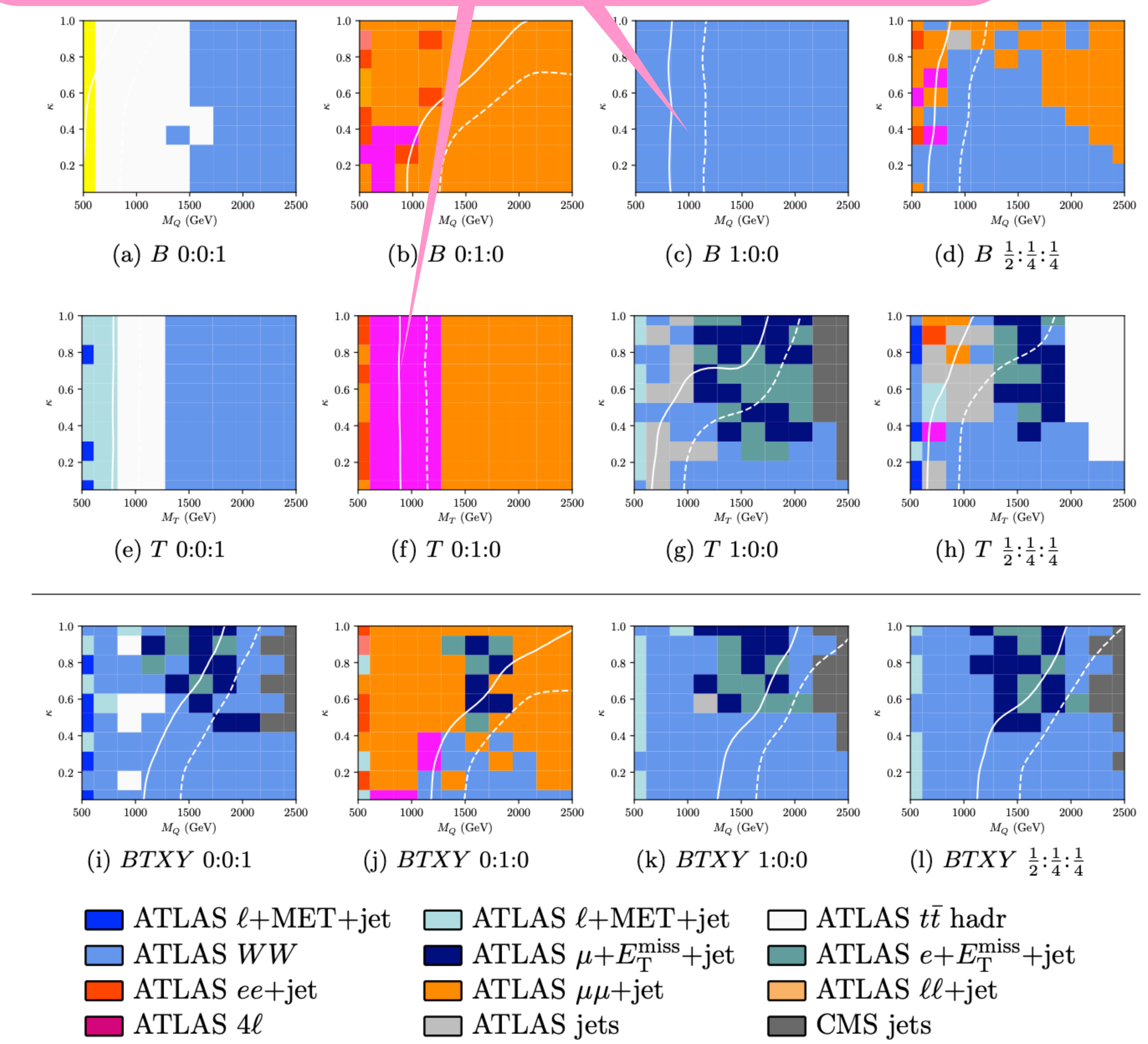
In 3rd-gen cases, lack of top density in proton PDF can prevent single-VLQ production. So only pair-production is viable, which is ~independent of κ

1st-Generation



2nd Generation





Original BTXY results for reference in final row

What about Doublets?

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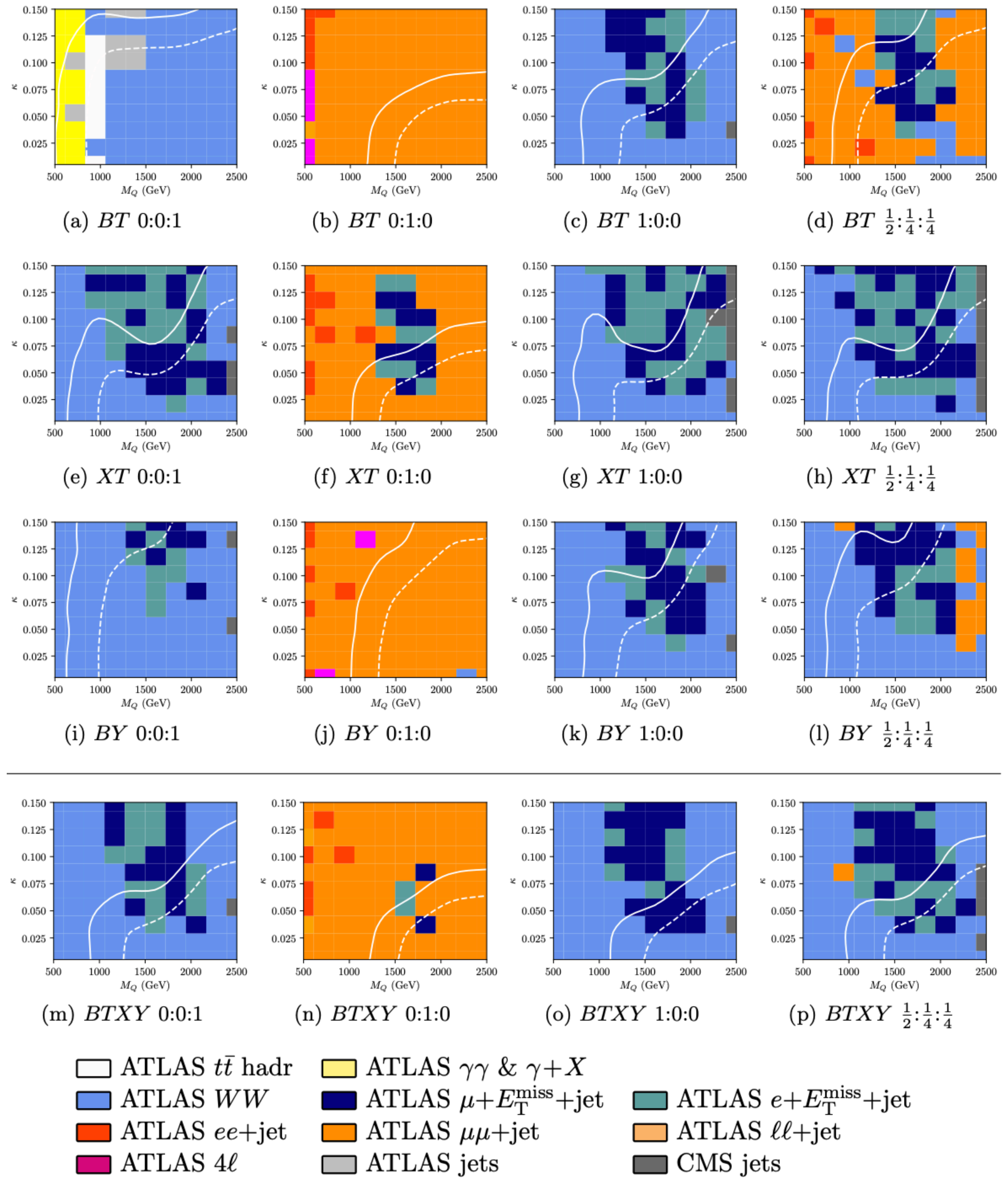
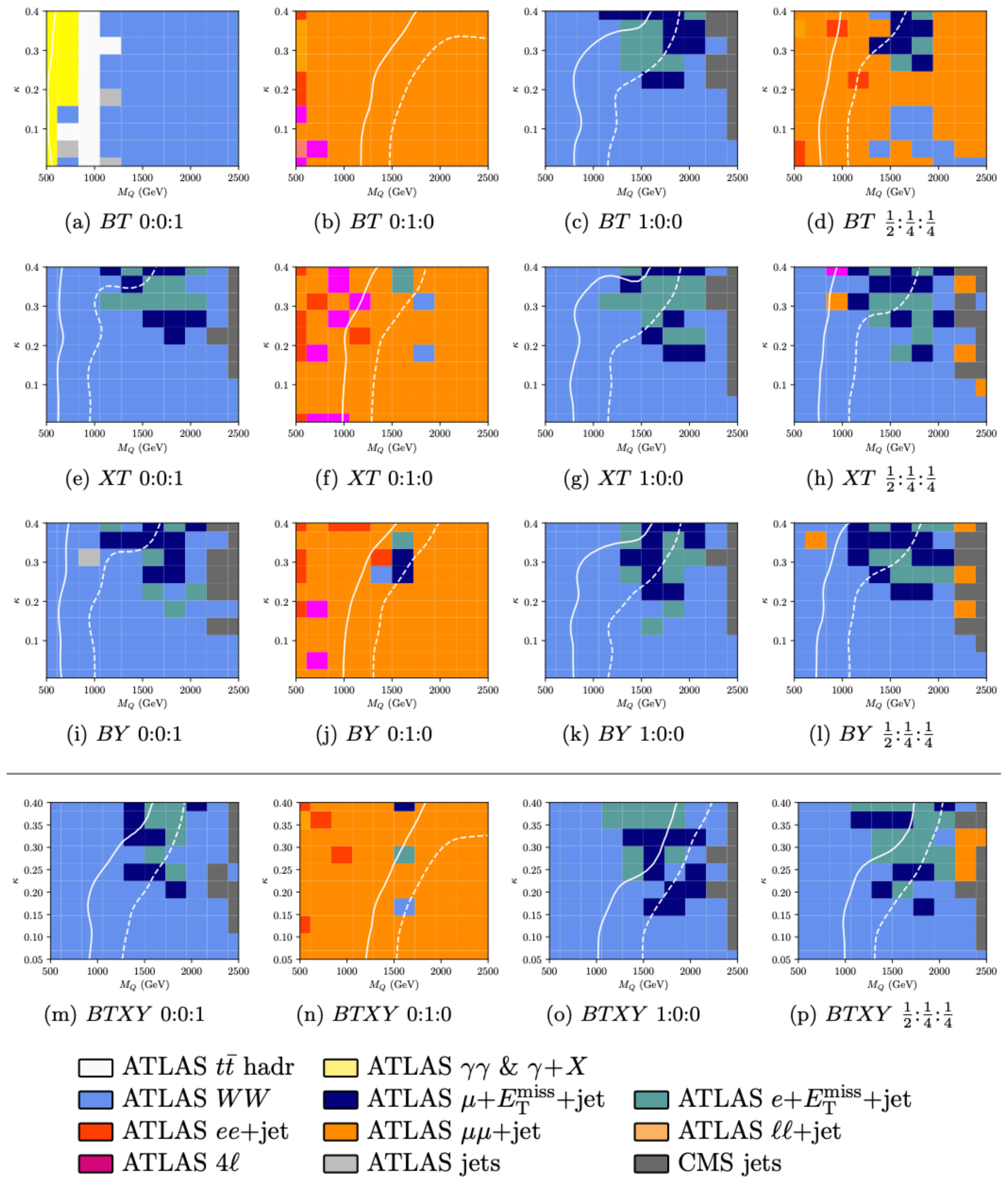
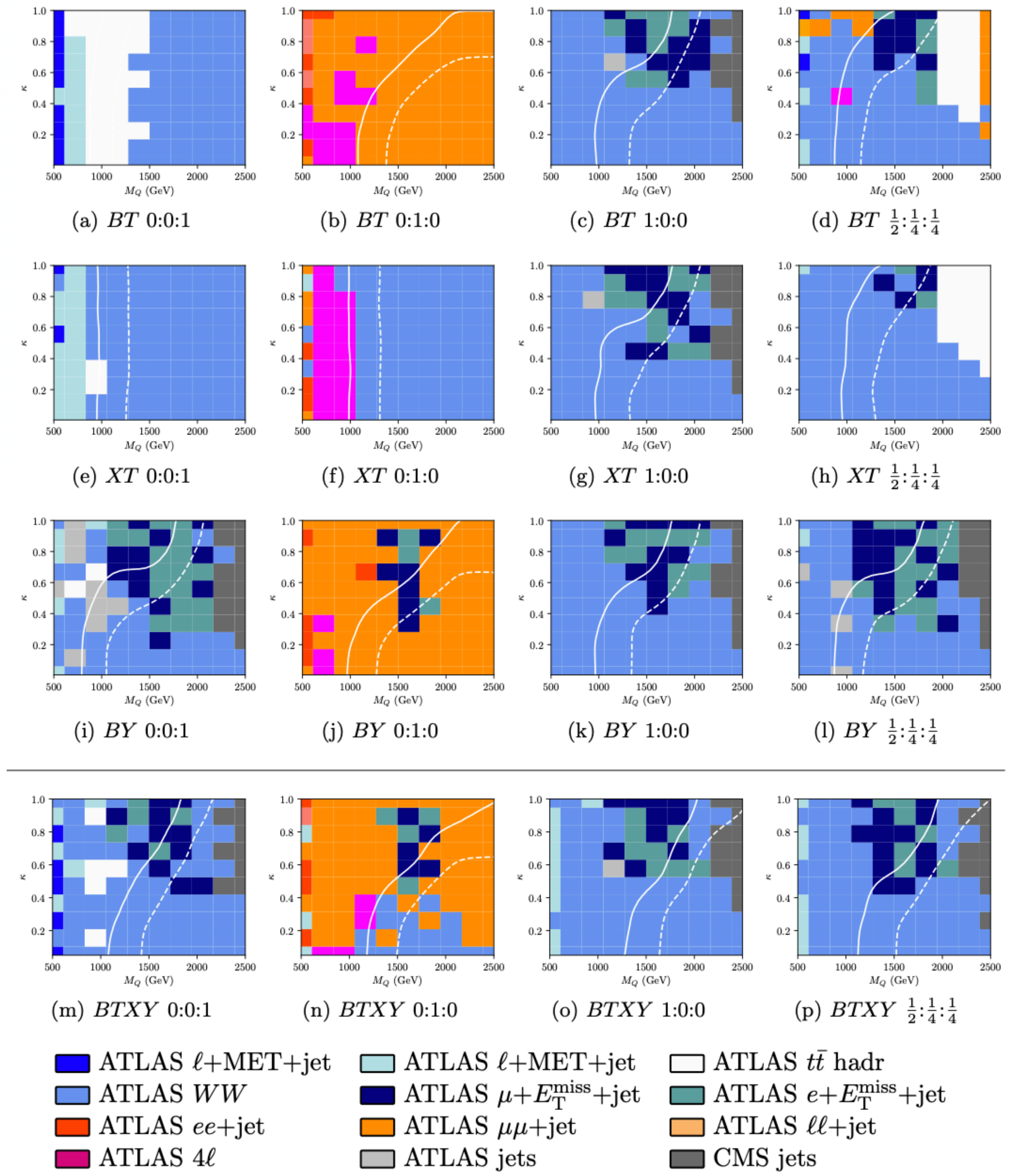
1st-Generation



2nd-Generation

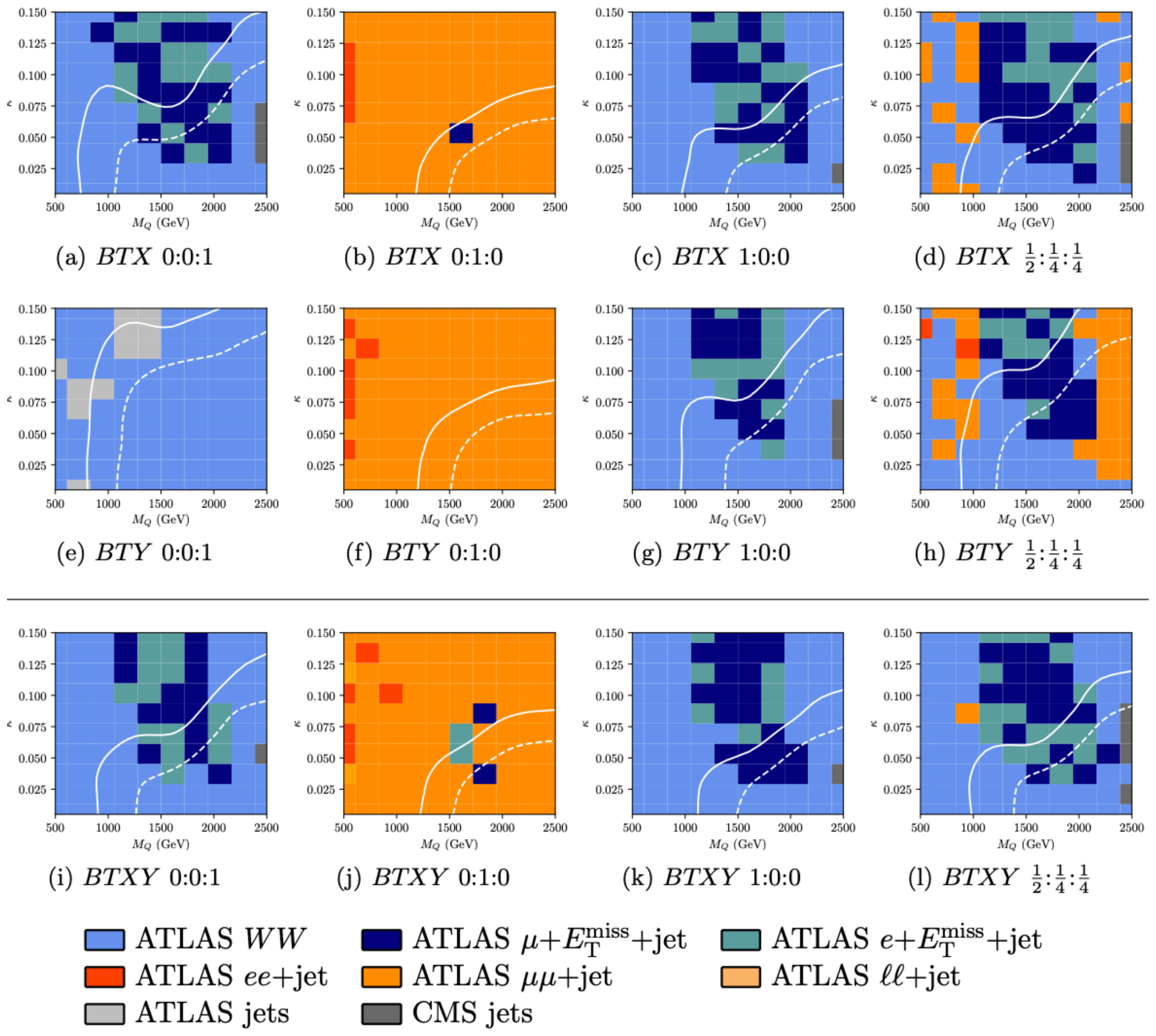


3rd-Generation

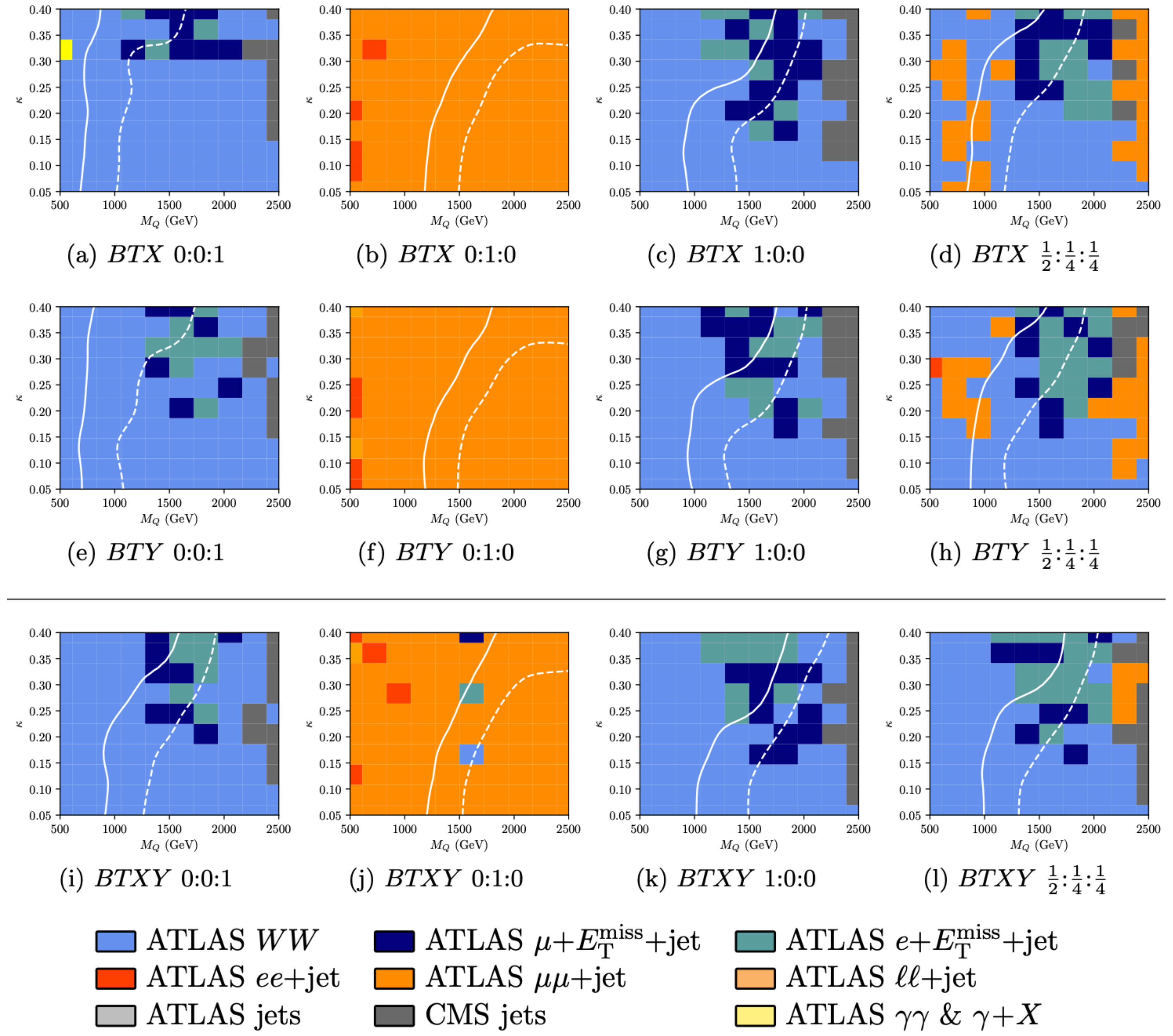


What about Triplets?

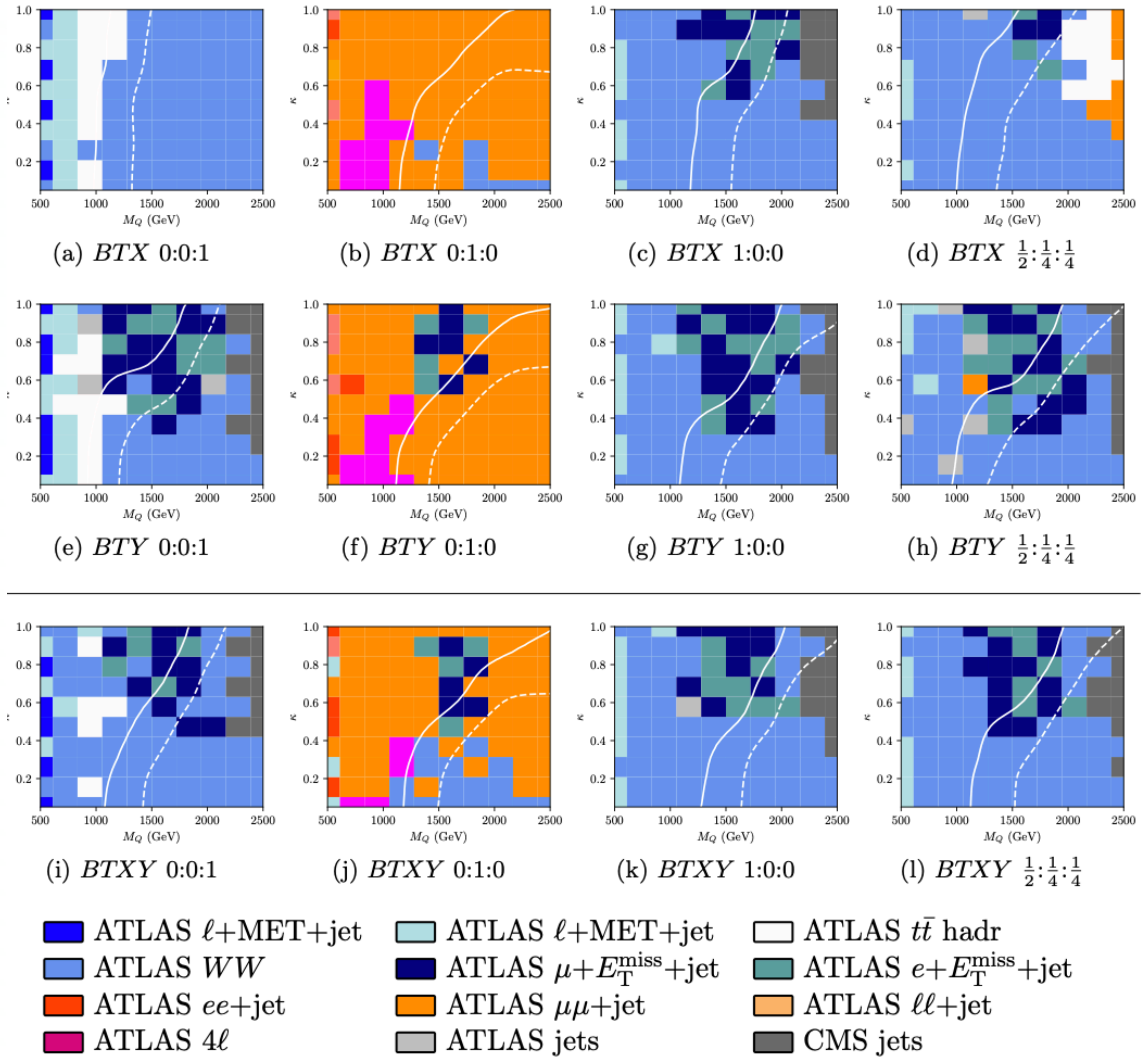
1st-Generation



2nd-Generation



3rd-Generation



VLQ Summary

- Using CONTUR, we have been able to to comprehensively probe a whole class of VLQ models, no just in a few benchmark scenarios…
  - Demonstrated speed of method
  - Demonstrated complementarity of method to LHC search programme: in some cases, made inroads into previously-open parameter space
- The same approach can be used for any model or class of models, so long as it's coded up in UFO format.
- The library of Rivet-preserved measurements just keeps growing. New measurements can be included in CONTUR as soon as their rivet routines and HEPData entries are published

How to make your analysis CONTUR-friendly

Some tips for experimentalists

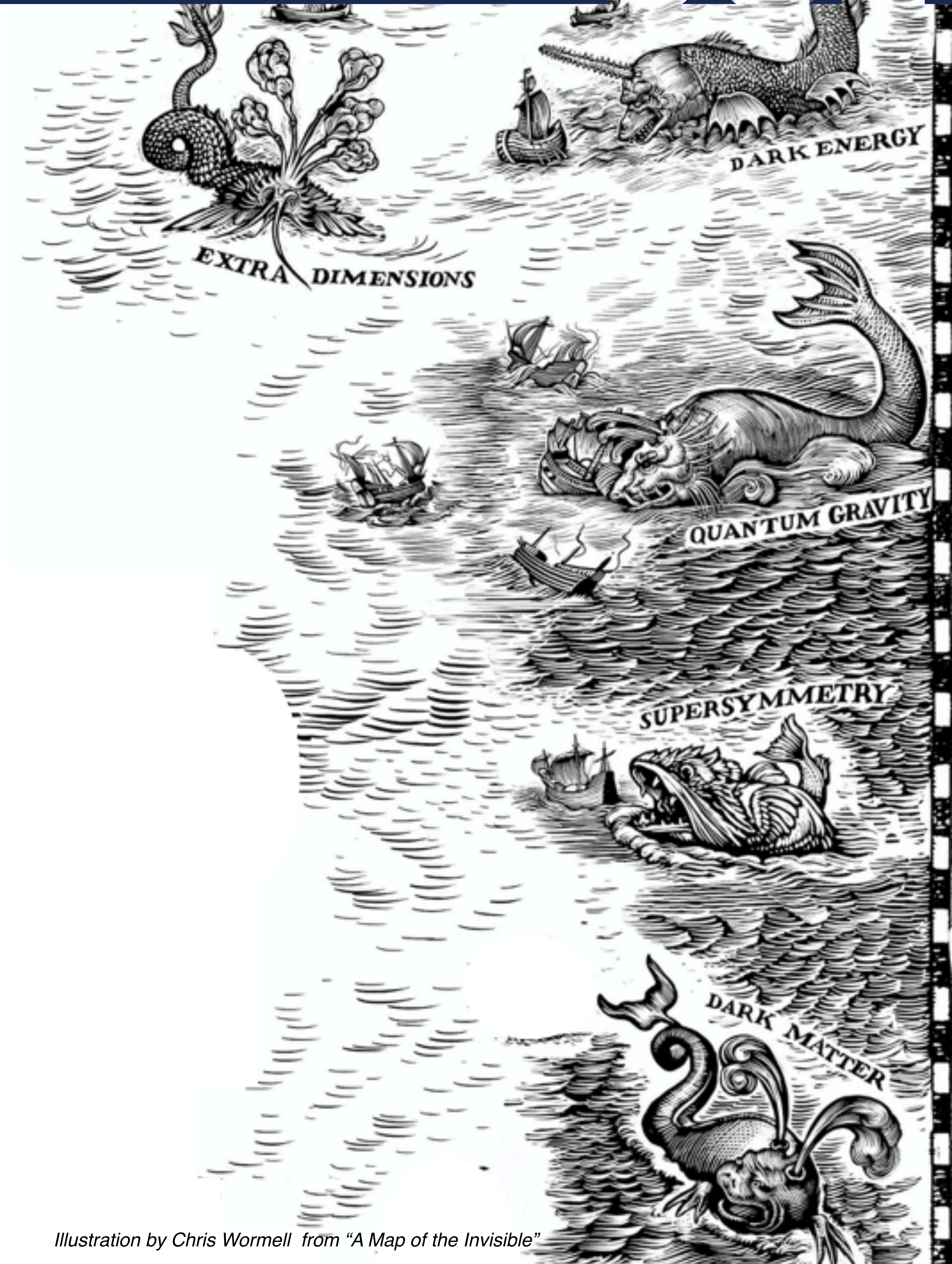
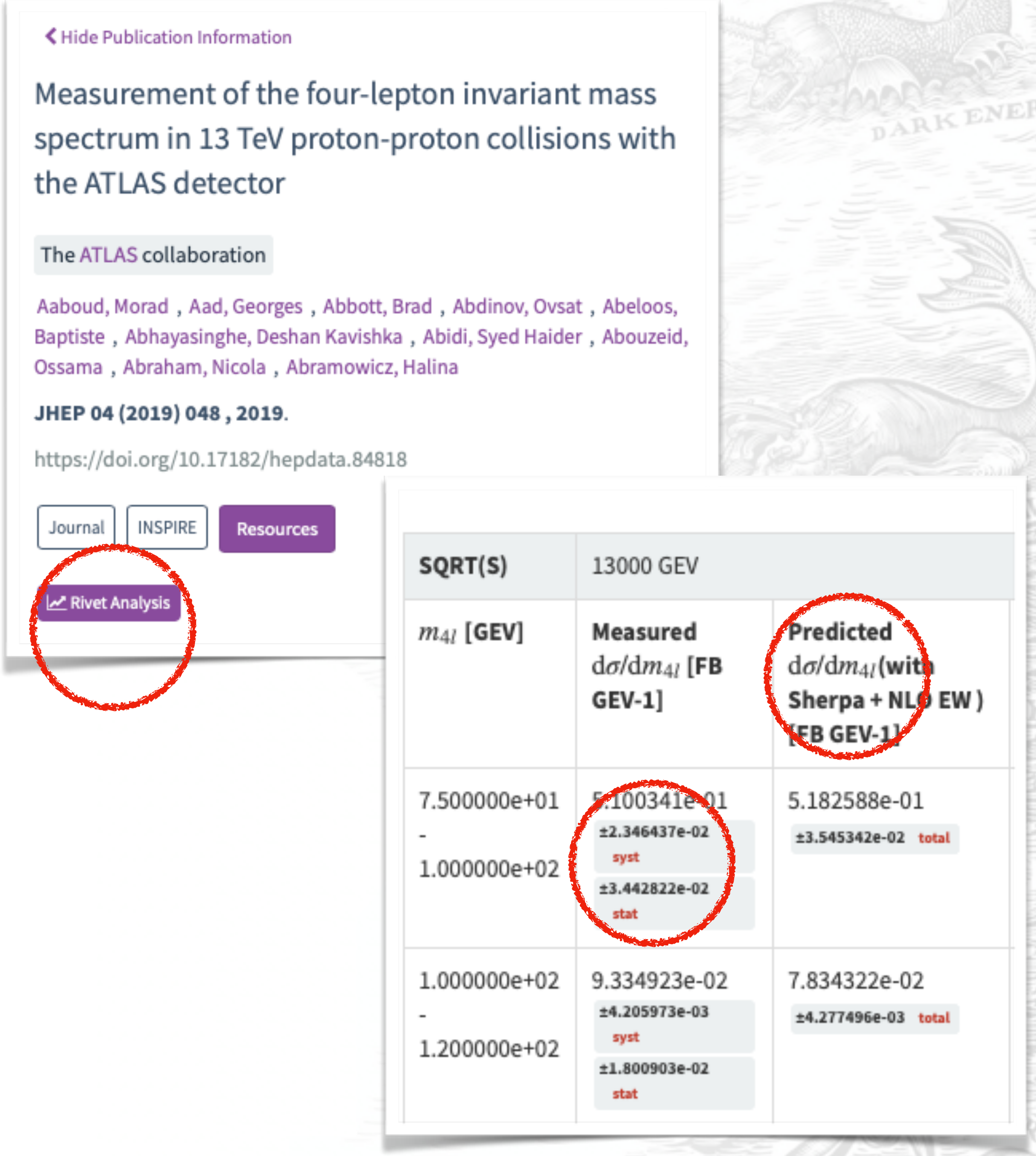


Illustration by Chris Wormell from "A Map of the Invisible"

Louie Corpe, UCL (l.corpe@ucl.ac.uk)

Measurements and CONTUR

- Measurements are the bread and butter of the CONTUR method. Here are things which make measurements easy to include:
  - Unfolded to particle-level
  - No model-dependent assumptions (Eg don't check flavours of neutrinos, no unnecessary background subtractions etc)
  - Preserved 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 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



https://www.hepdata.net/record/ins1720442

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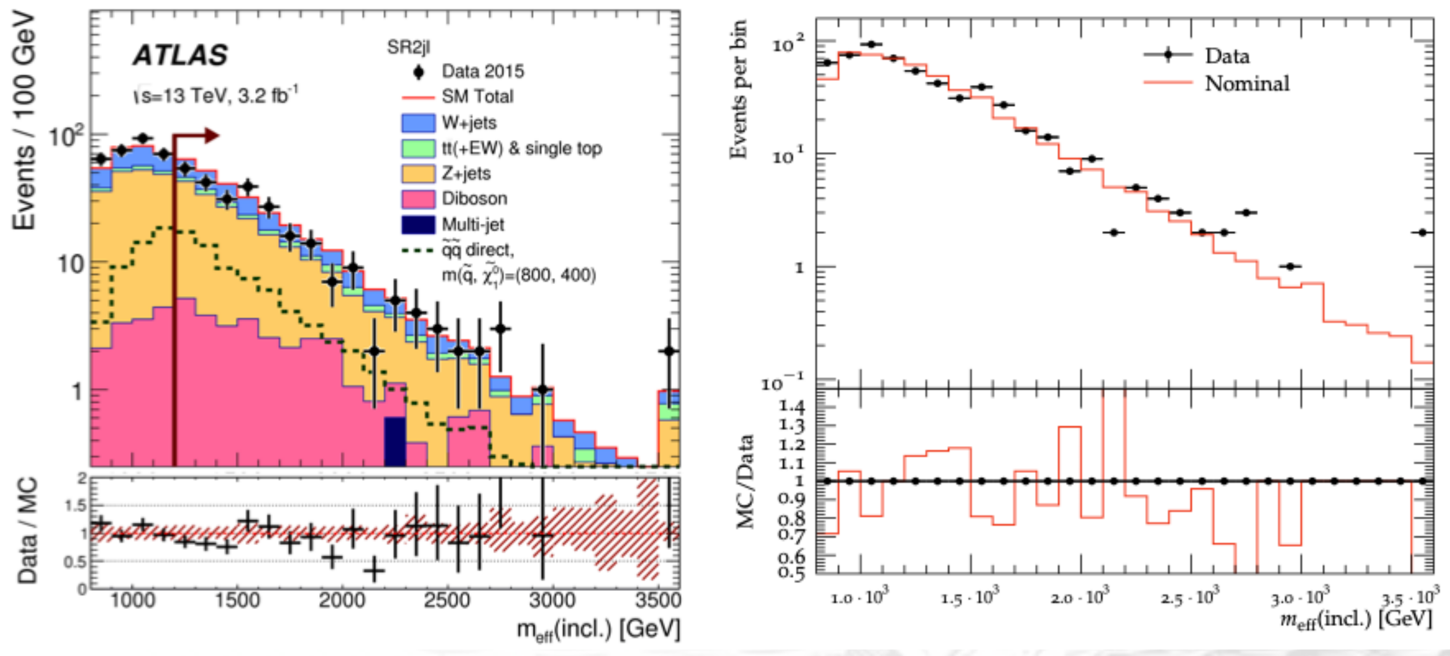
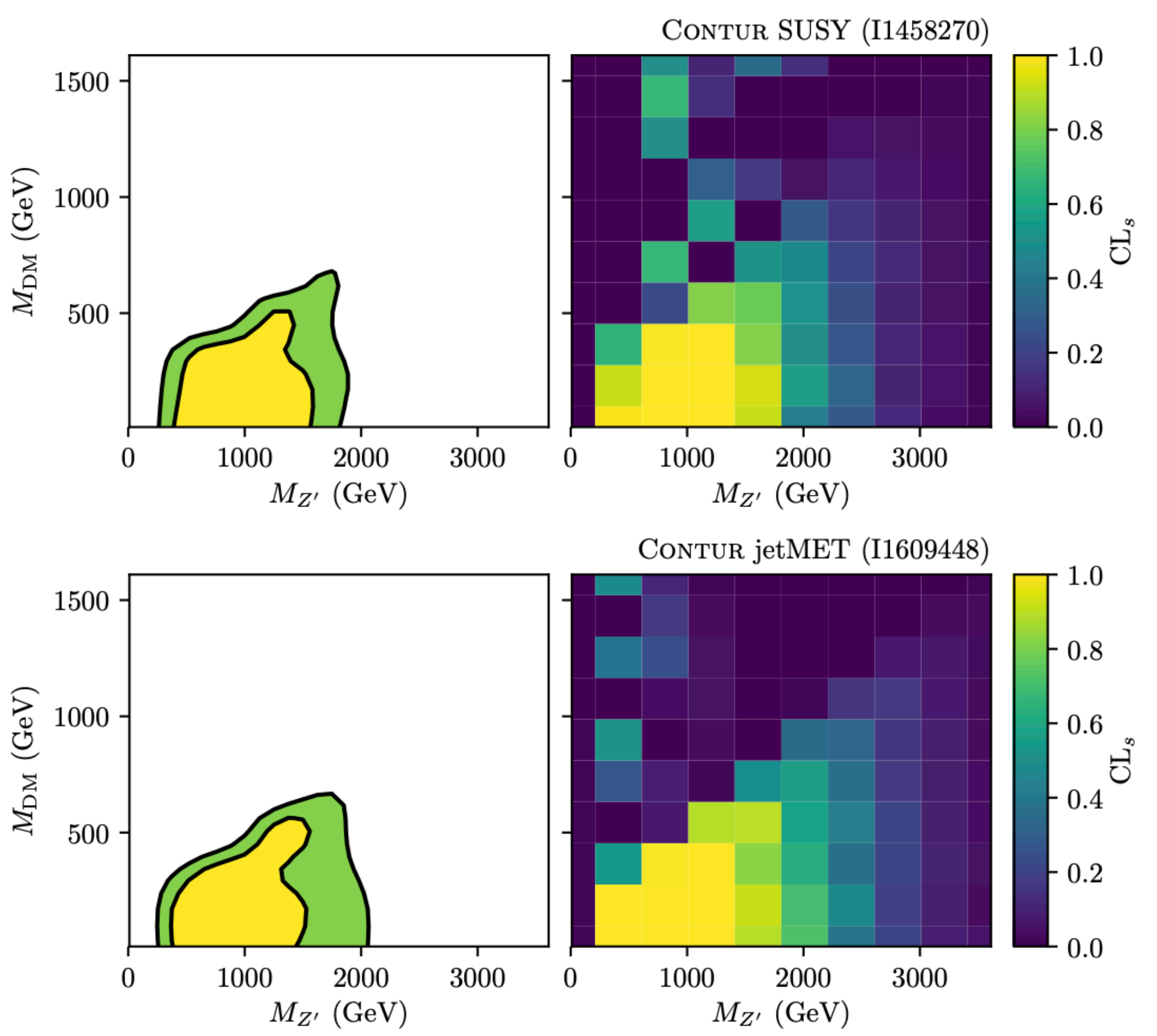
Searches and CONTUR

- CONTUR designed to work with particle-level measurements, but now also handles searches if preserved with a smeared Rivet routine (see Rivet smearing paper https://arxiv.org/abs/1910.01637)
- For a 2HDM model, 3.2/fb squarks+gluinos (jet+MET) smeared Rivet routine was shown to exhibit similar sensitivity to 3.2/fb MET+jets measurement in Proceedings of Les Houches 2019 (https://arxiv.org/pdf/2002.12220.pdf)
- Control-region measurements from searches have great potential (see LQ CR measurement). 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, eg 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



Conclusions and Next steps

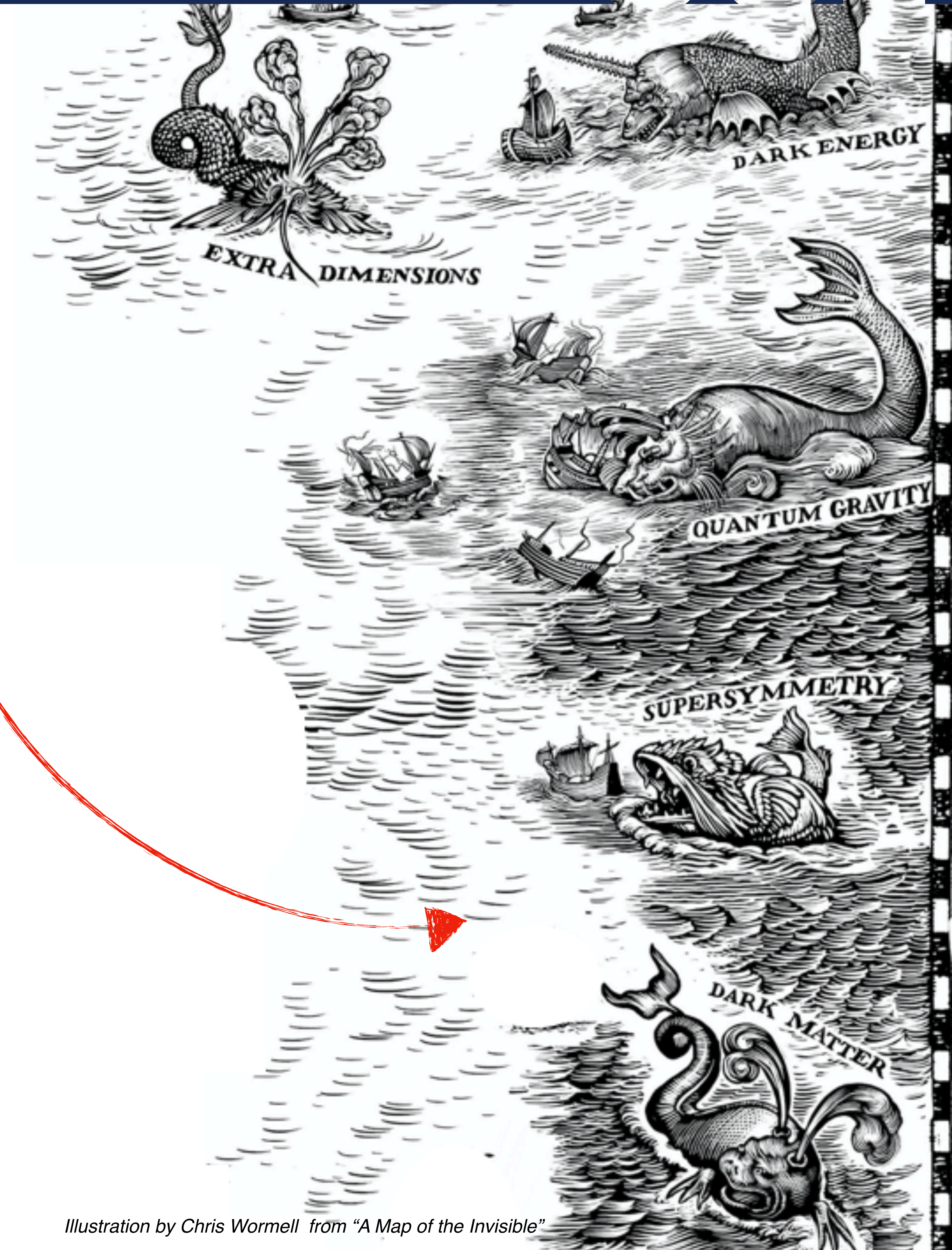


Illustration by Chris Wormell from "A Map of the Invisible"

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Conclusions and Discussion

- CONTUR allows study of existing LHC sensitivity to whole classes of models, here focusing on VLQs. Many other results available at https://hepcedar.gitlab.io/contur-webpage/results/index.html
- Extract all 2->2 processes from Lagrangian: more comprehensive picture than just working on most spectacular signatures of model
- Measurements not explicitly designed for this purpose can exclude significant regions of VLQ parameter space, in a wider range of models than typically considered by search programme
- ***Should this sort of scan (which takes ~days on a cluster) be part of the 'due diligence' when proposing a new model or designing a search ?***
    - Increasing amounts of data and pressure on computing resources makes this a compelling argument
- Highly complementary approach to search programme, which is liberated to pin down the most elusive parts of parameter space (e.g. areas like long-lived particles, exotic signatures, etc…)
- Searches can also contribute to CONTUR, e.g. unfolded measurements in control (+ search ?) regions, or providing smeared Rivet routines
- CONTUR can be run by anyone! Please ask us about installing it on your cluster. User manual coming soon!
- Not discussed: CONTUR potential for analysis prototyping, upgrade studies, and more!

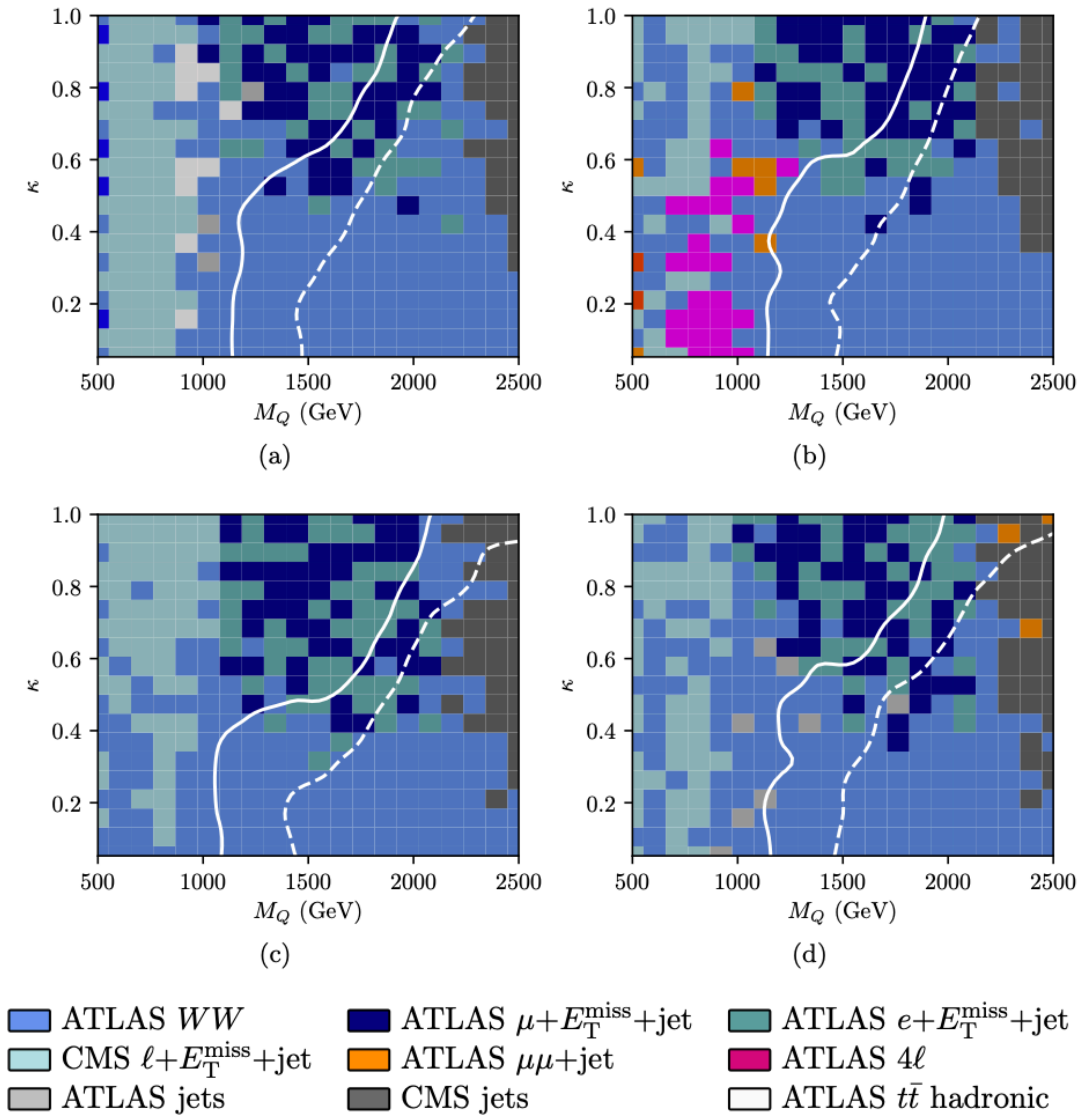
Thank you

PS: ask us about CONTUR tutorials, running via docker, or installing it on your institute cluster!

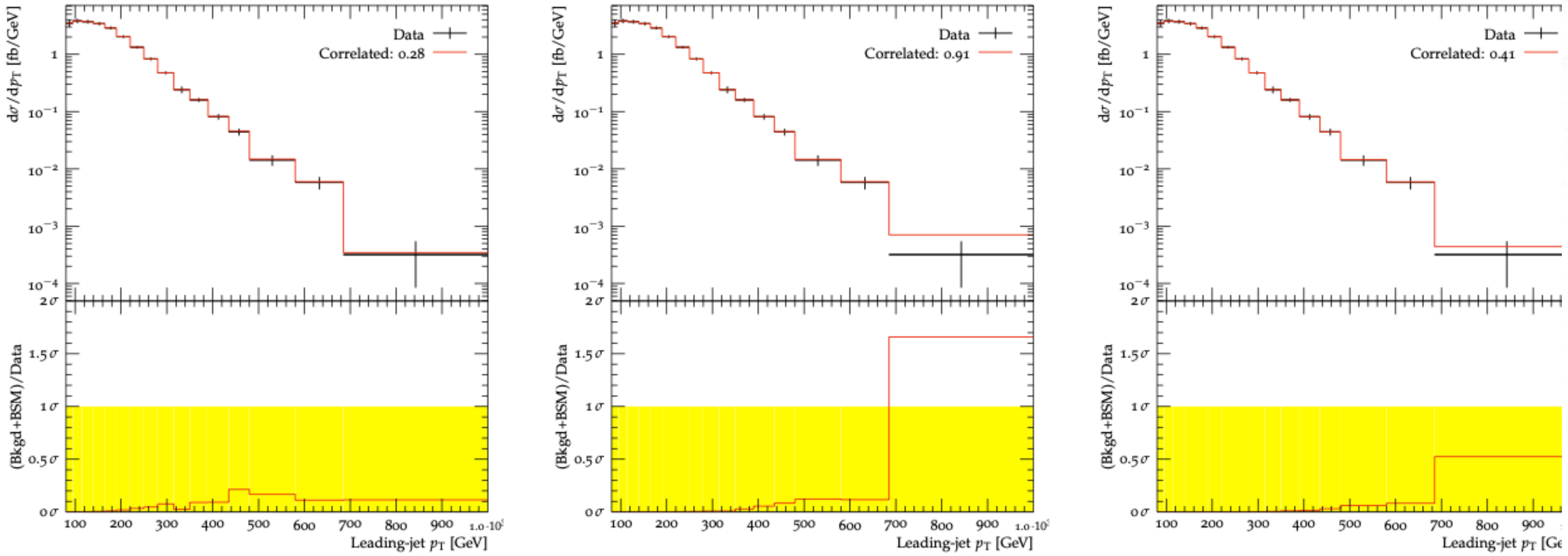
Illustration by Chris Wormell from "A Map of the Invisible"

UCL

B Uncorrelated 3rd generation dominant-analyses maps



Extra Material



(a) (b) (c)

Figure 8: ATLAS 8 TeV Wjj forward-lepton control region leading-jet p_T distributions at three points on the 95% exclusion contour for $W{:}Z{:}H = 1{:}0{:}0$, respectively at M_Q values of (a) 1000 GeV, (b) 1750 GeV, and (c) 2250 GeV. The rise and subsidence of a 90% CL_s exclusion from a single Wjj bin is seen as the contour passes from below 1 TeV to above 2 TeV. The black points are data, the red histogram is the VLQ contribution stacked on top of the data. In the lower insets, the ratio is shown and the yellow band indicates the significance, taking into account the statistical and systematic uncertainties on the data. The legend gives the exclusion (i.e. one minus the p-value) for that histogram after fitting nuisance parameters for the correlated systematic uncertainties.

Extra Material

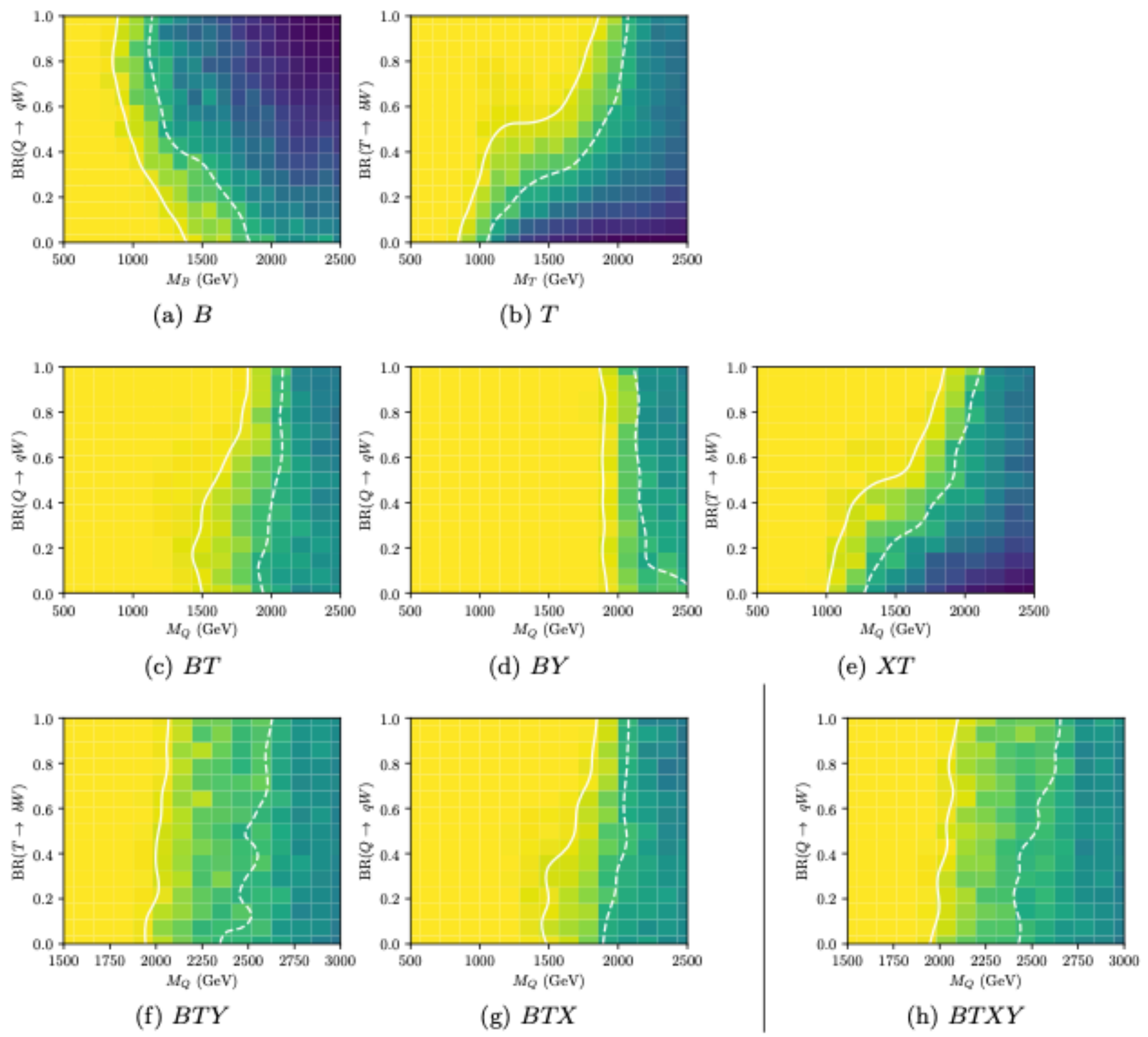


Figure 6: Sensitivity of LHC measurements to VLQ production when B, T, X, Y are degenerate in mass. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed white) exclusion contours superimposed. Limit in the plane of M_Q and $\mathrm{BF}(Q \to Wq) = 1 - \mathrm{BF}(Q \to Zq) - \mathrm{BF}(Q \to Hq)$, for $\mathrm{BF}(Q \to Hq) = \mathrm{BF}(Q \to Zq)$.