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

L. Corpe (UCL) for the CONTUR team

MCNet Meeting, Sept 2020

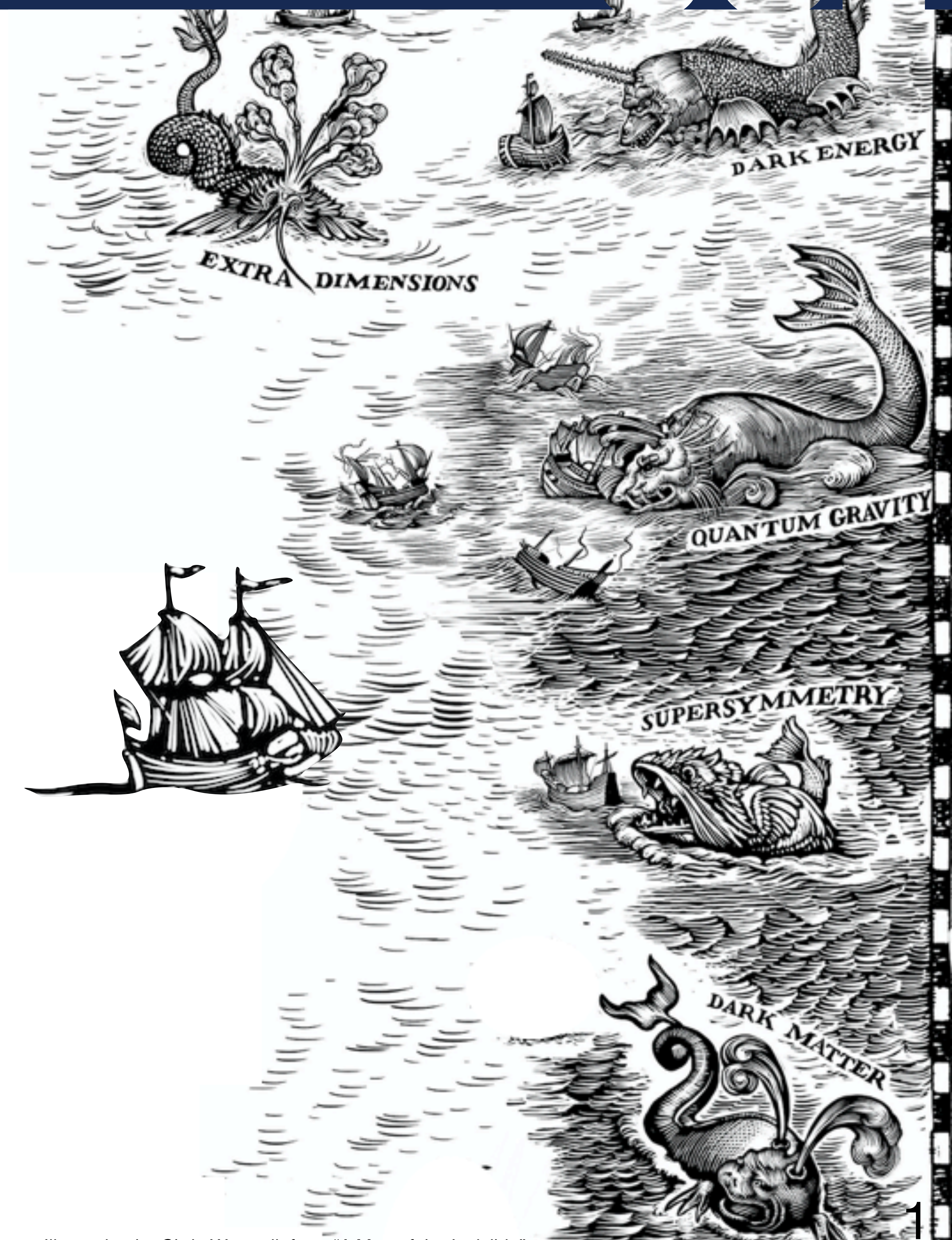


Illustration by Chris Wormell from "A Map of the Invisible"

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

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

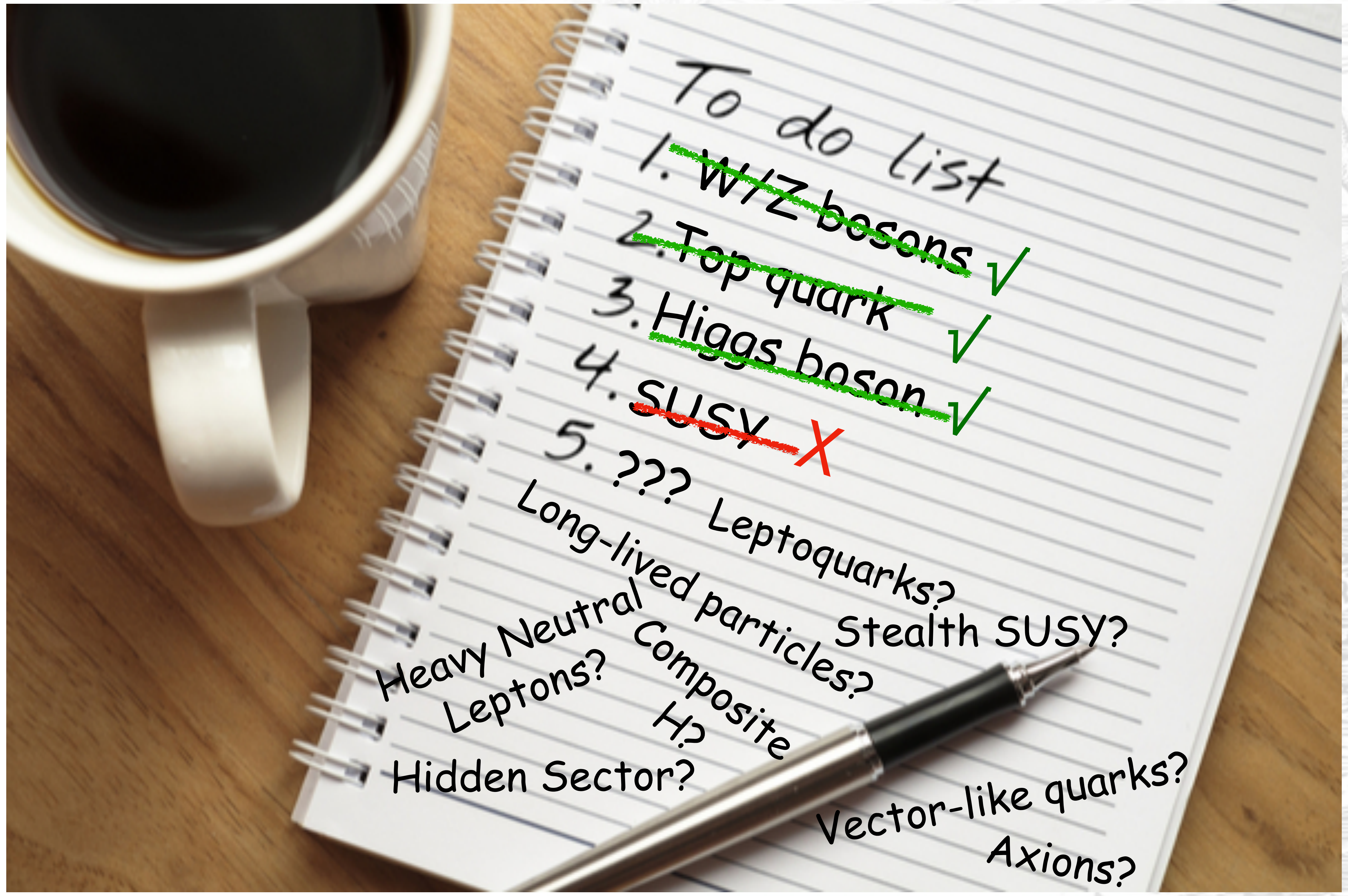
June 15, 2020

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.

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

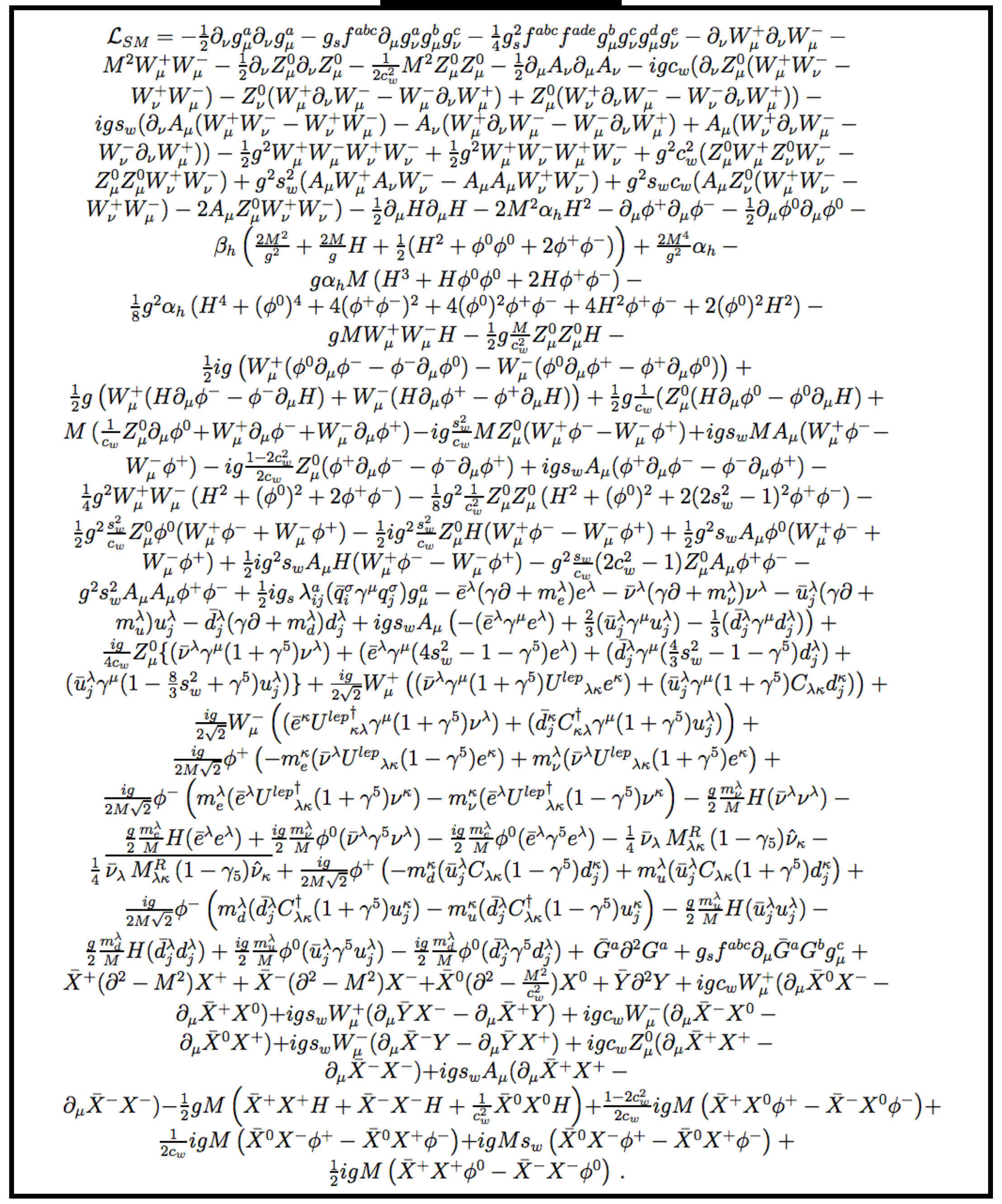


Louie Corpe, UCL (l.corpe@ucl.ac.uk)

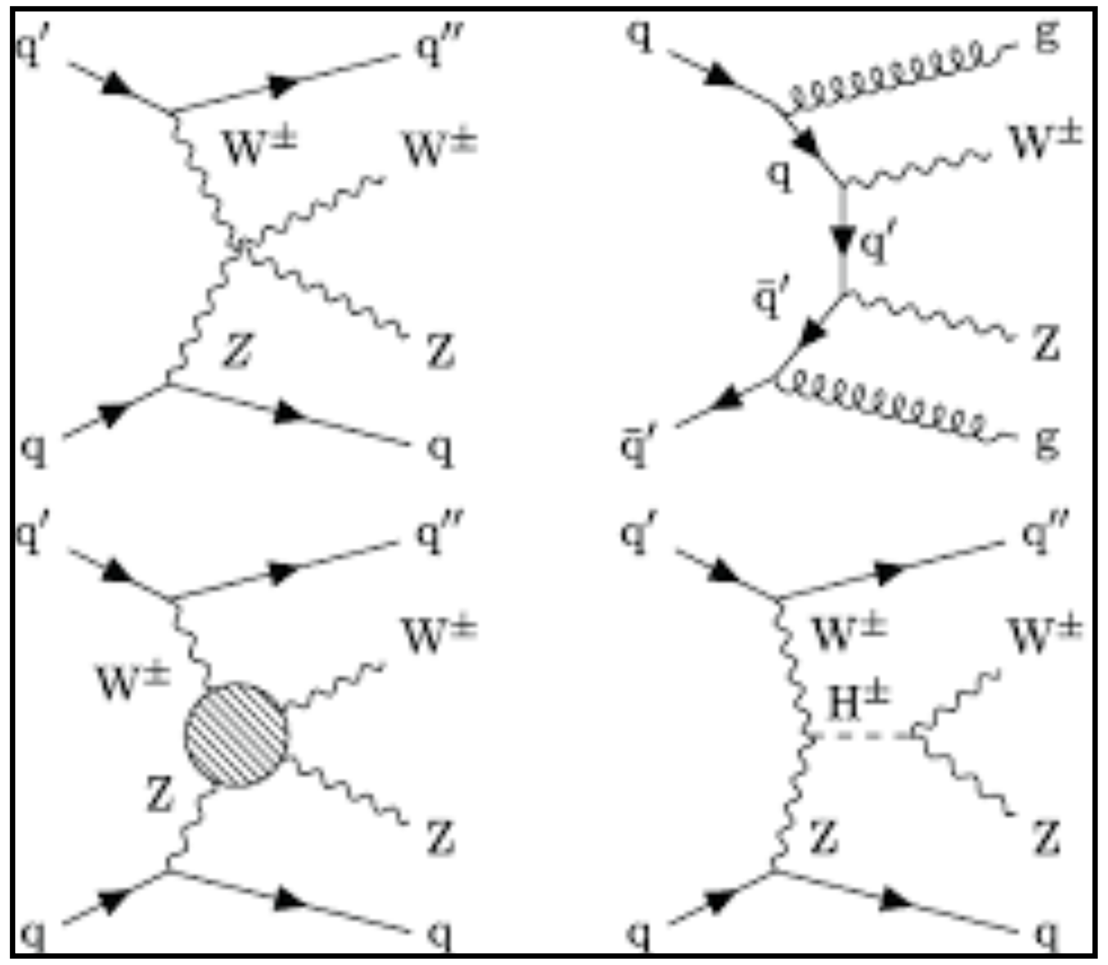
CONTUR 101

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

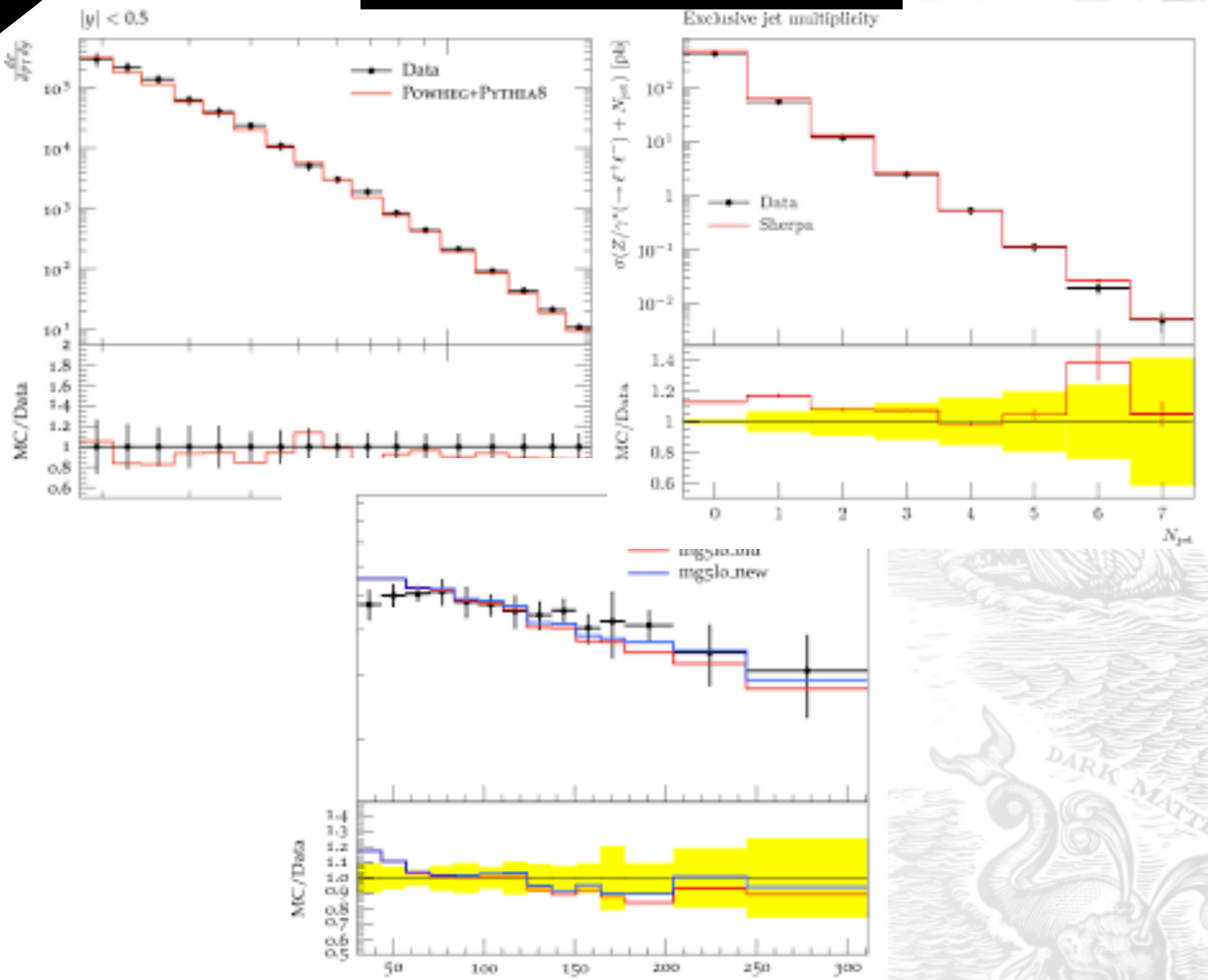
SM



Processes



LHC measurements



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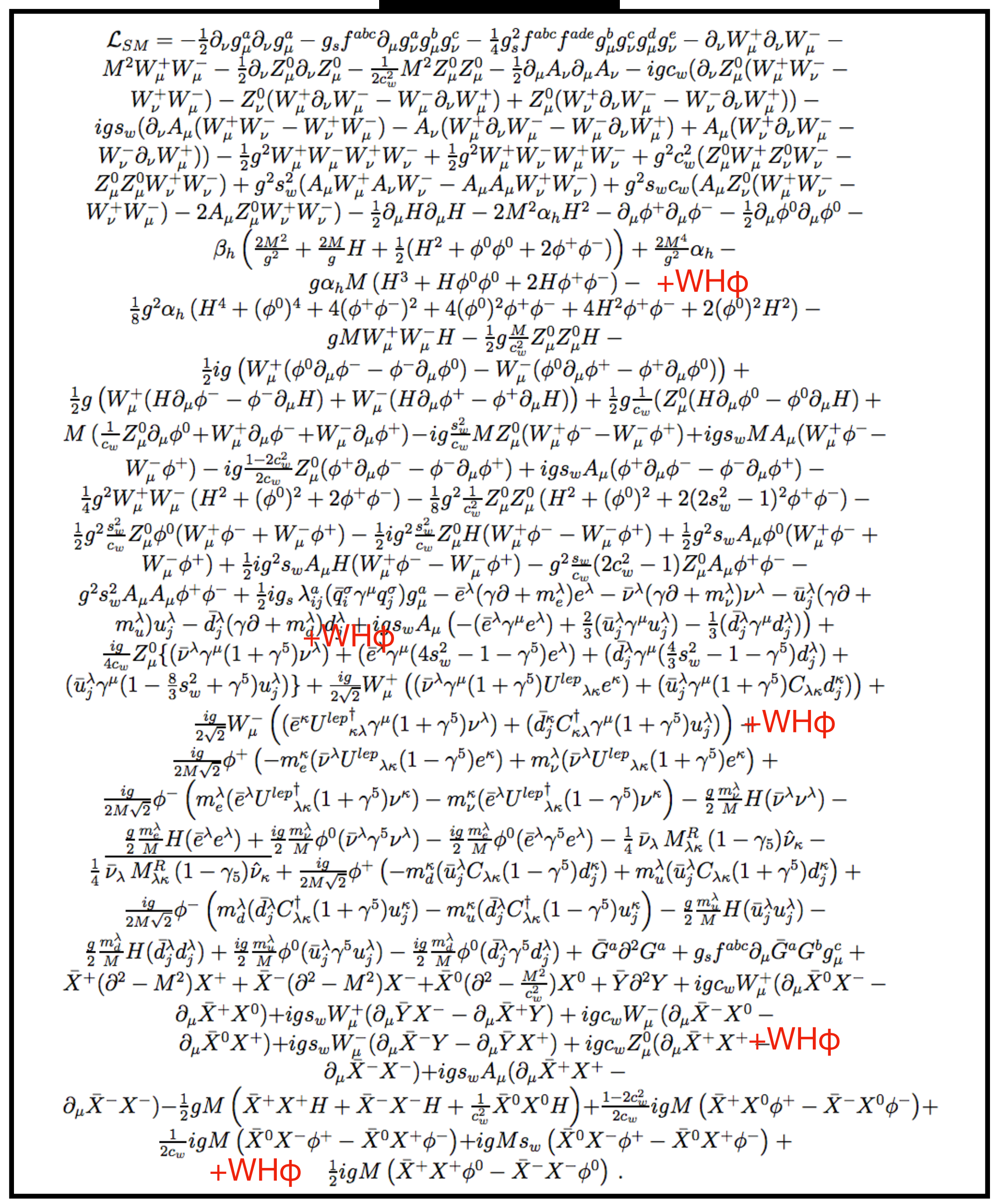
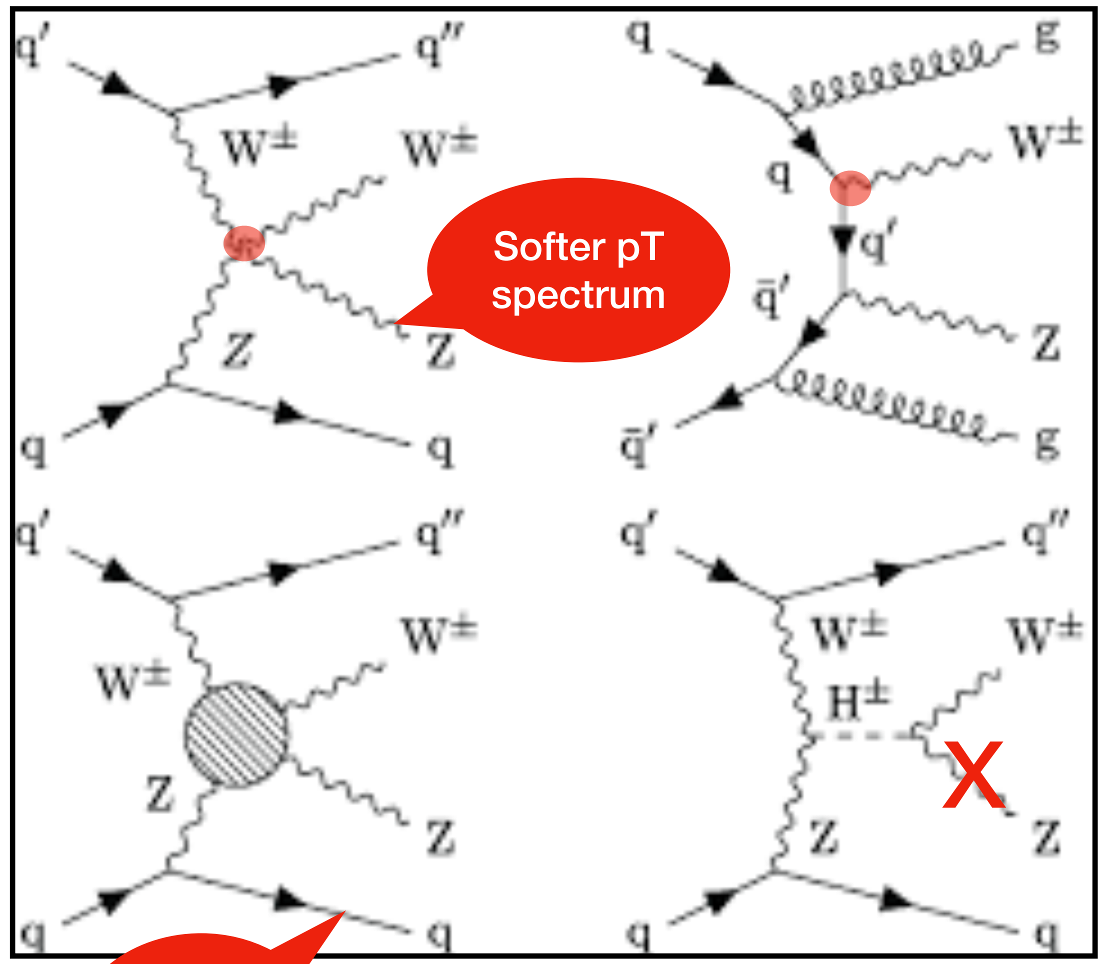
SM + BSM



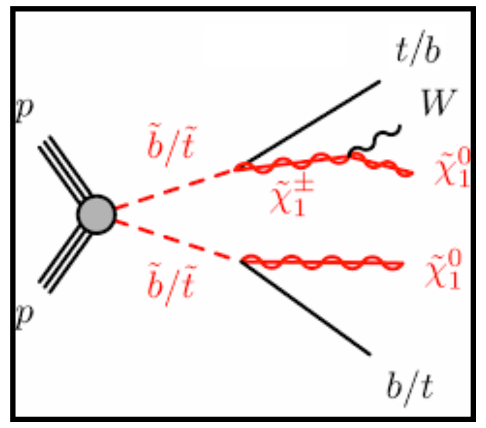
\+ BSM

Processes

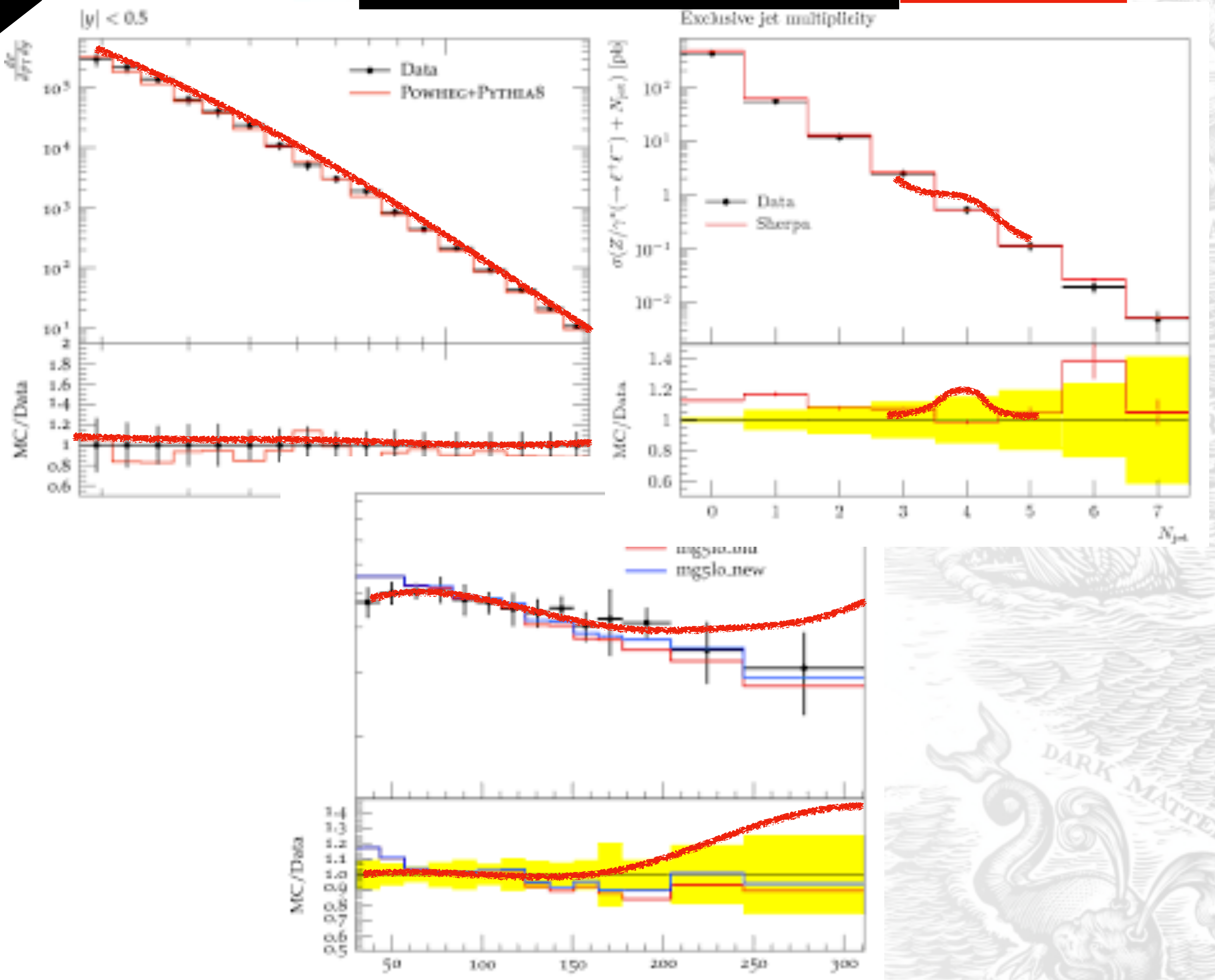


More boosted

\+



LHC measurements + BSM



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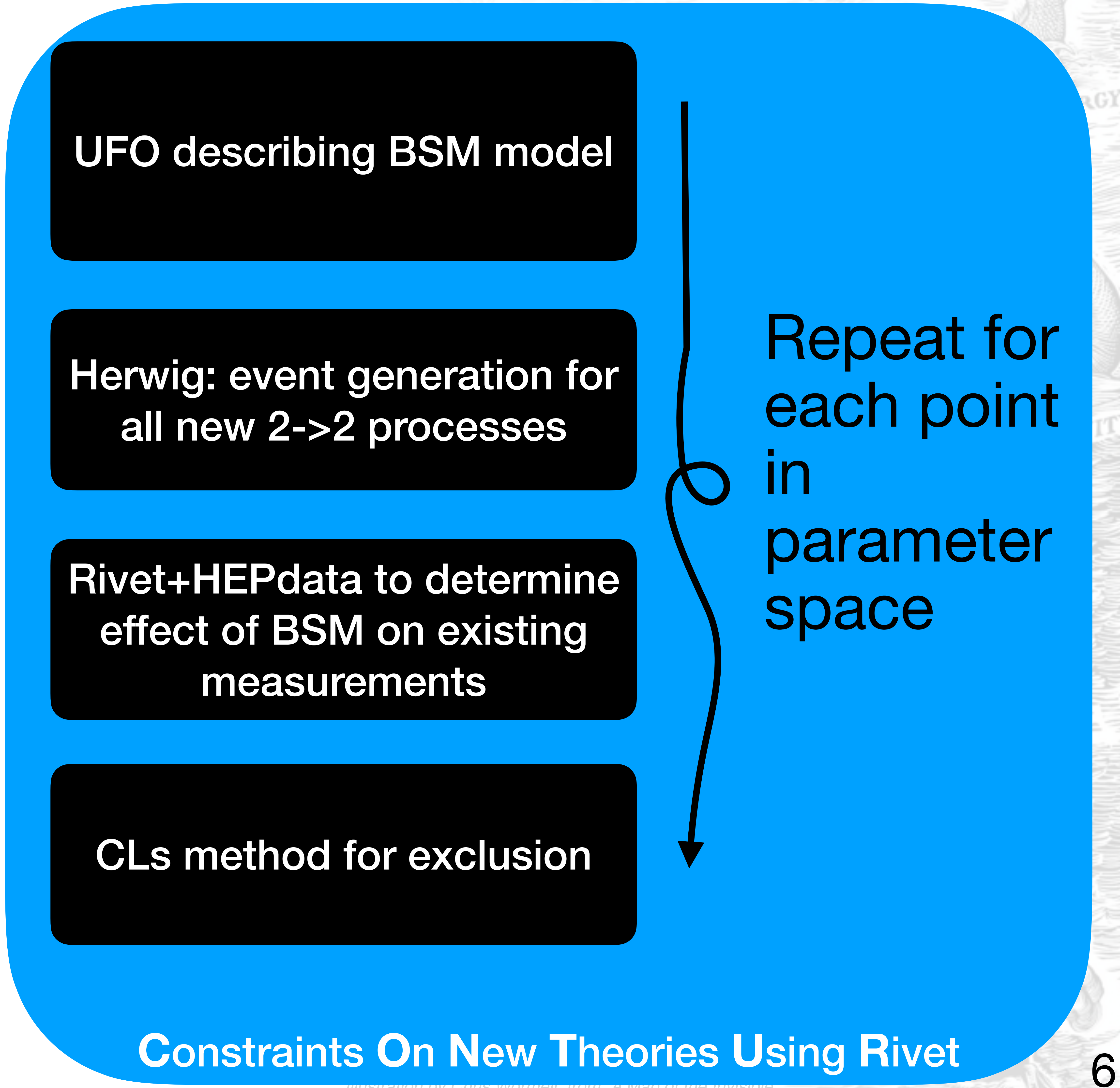
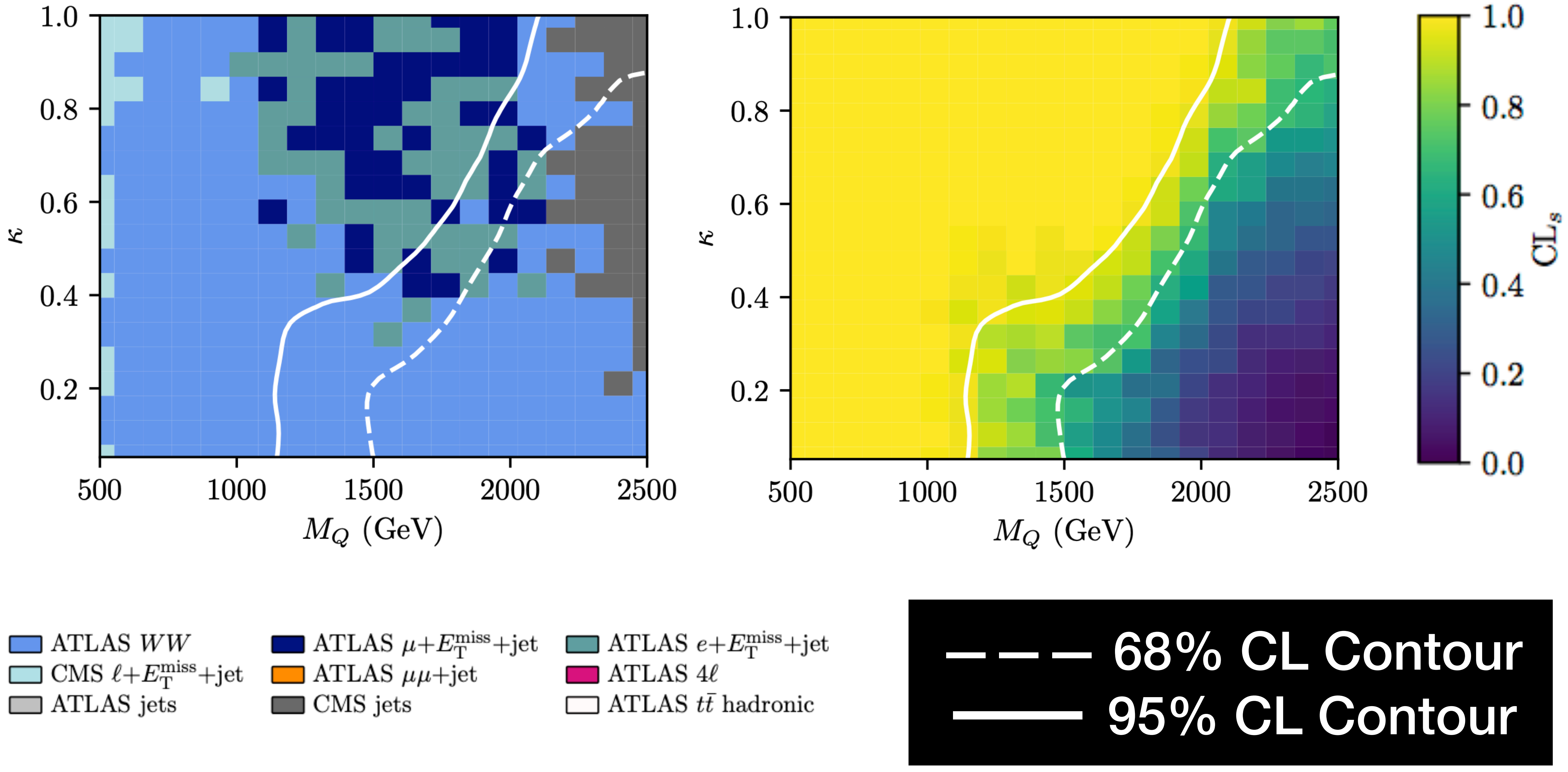
Overview of the CONTUR method

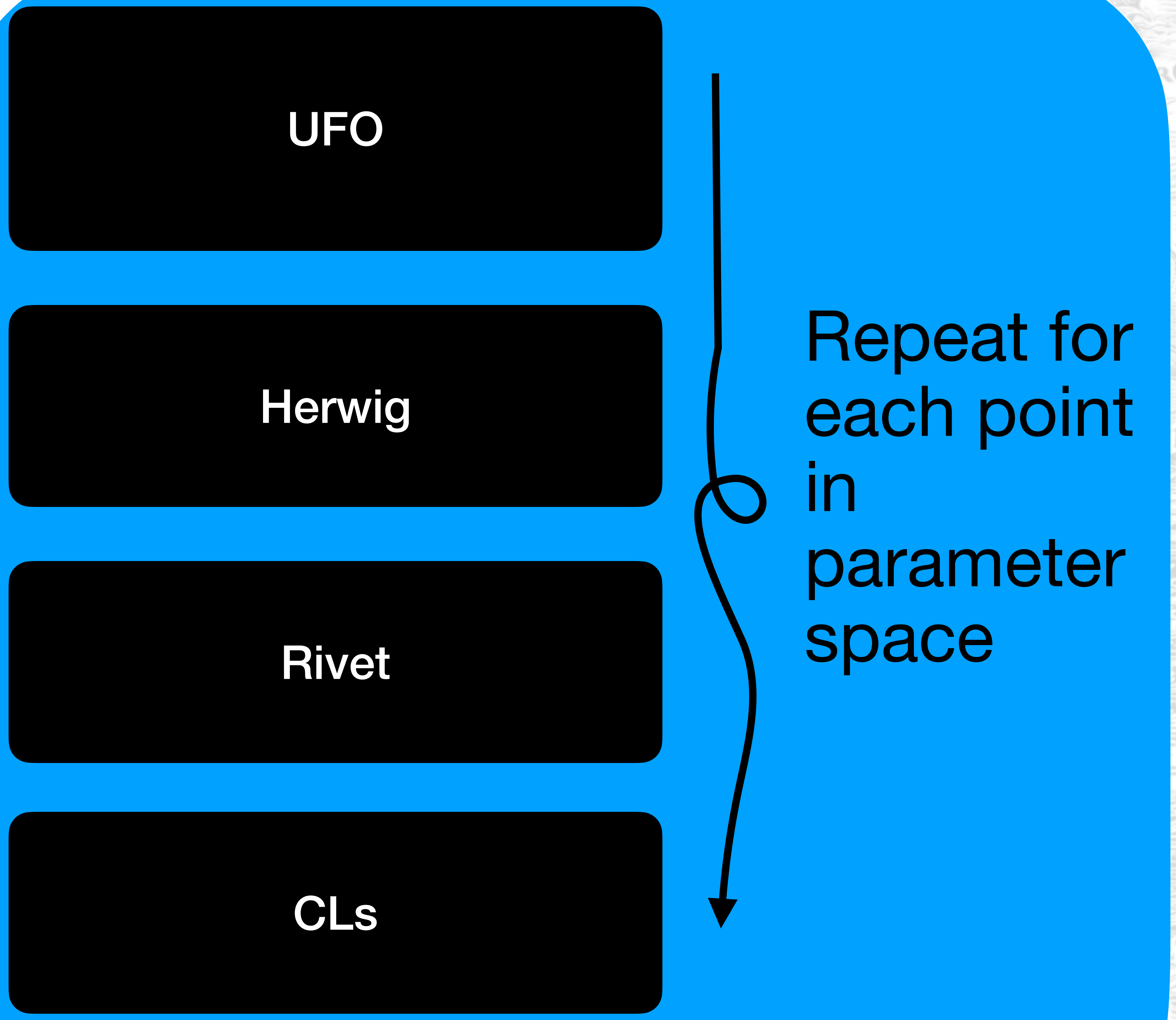
- CONTUR uses bank of LHC results preserved in Rivet to rapidly check if new models are already ruled out
- Input: Universal Feynrules Object
(new physics Lagrangian coded up in python by theorist)
- Herwig: generate events for all 2->2 processes involving new particles, for a given set of parameter 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 √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



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





Constraints On New Theories Using Rivet

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 ith generation**
  - ξ_V: relative **coupling of B,T to V in {W, H, Z}**

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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.

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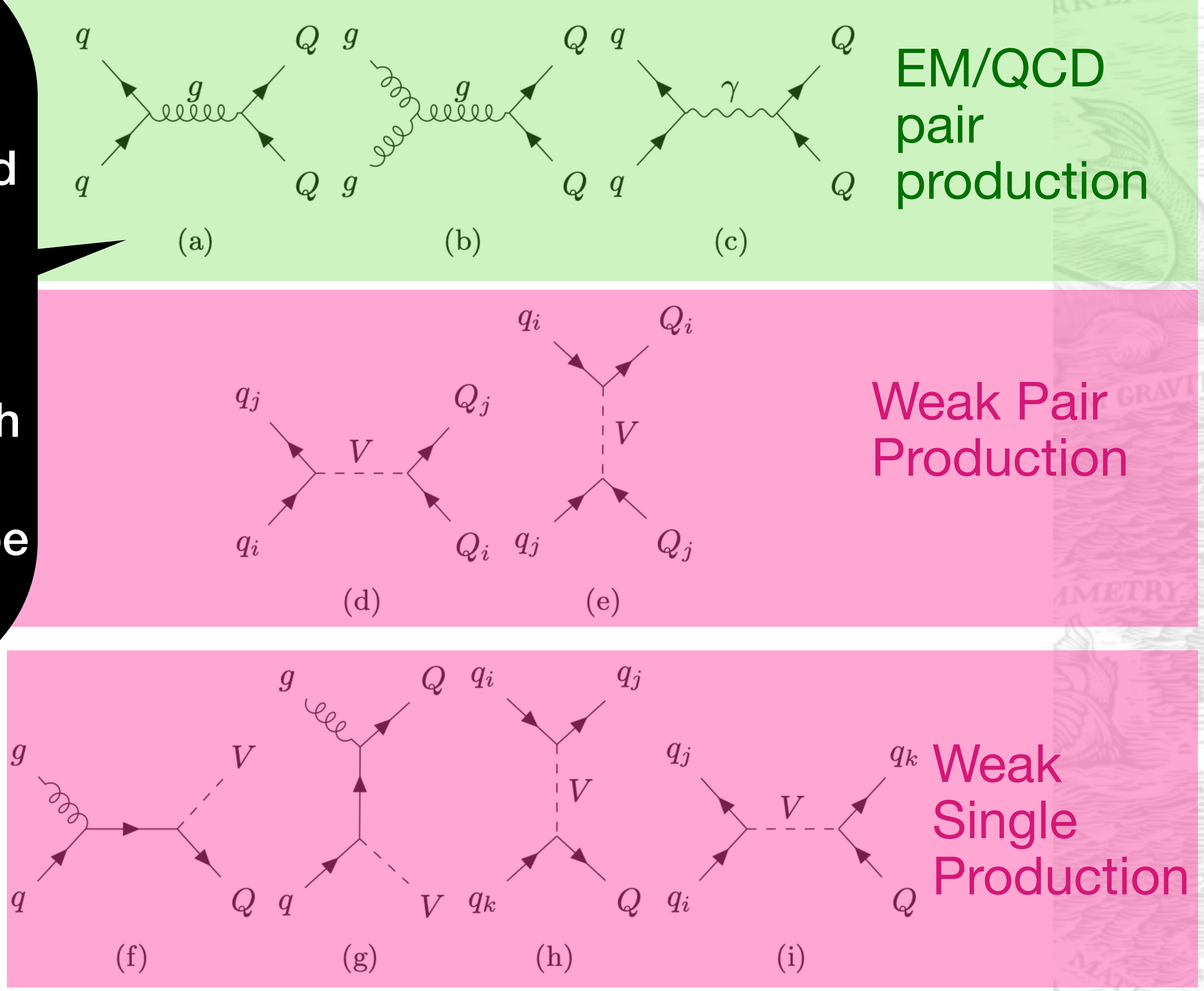
LHC programme has mostly focused here since reduced κ-dependence,

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

CONTUR vs Direct searches

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

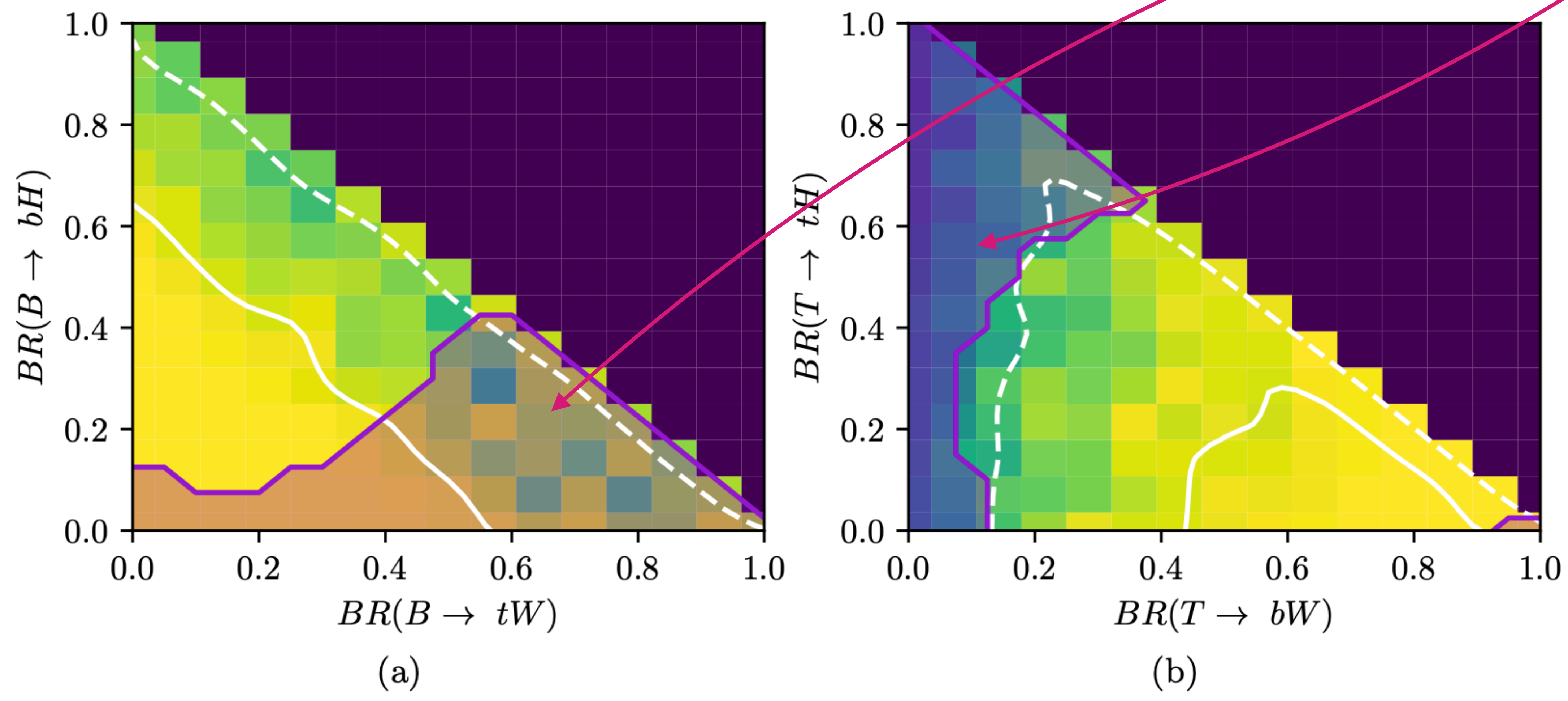


Figure 5: Sensitivity of LHC measurements to (a) B-production for $M_B = 1200$ GeV and (b) T-production for $M_T = 1350$ GeV. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed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

Assumes pair-production only !

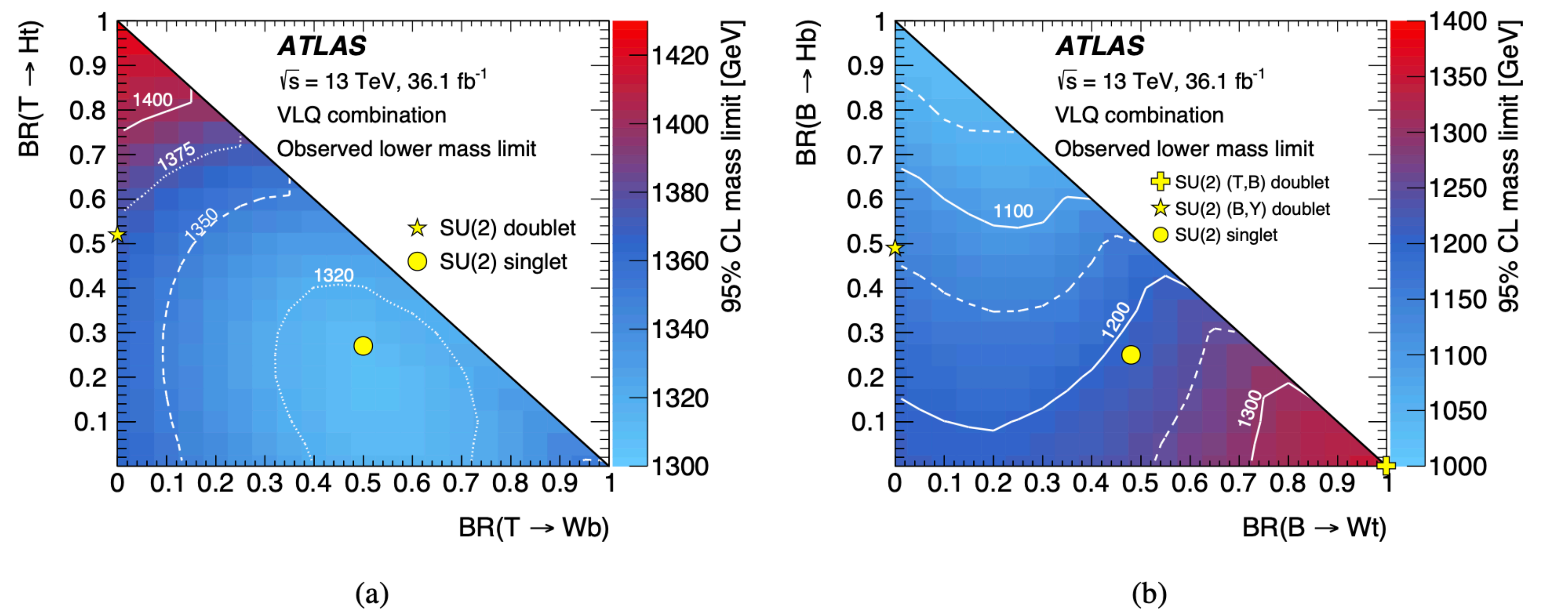


Figure 4: Observed lower limits at 95% CL on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T \to Ht) + \mathcal{B}(T \to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Hb) + \mathcal{B}(B \to Zb) + \mathcal{B}(B \to Wt) = 1$. The yellow markers indicate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

CONTUR vs Direct searches

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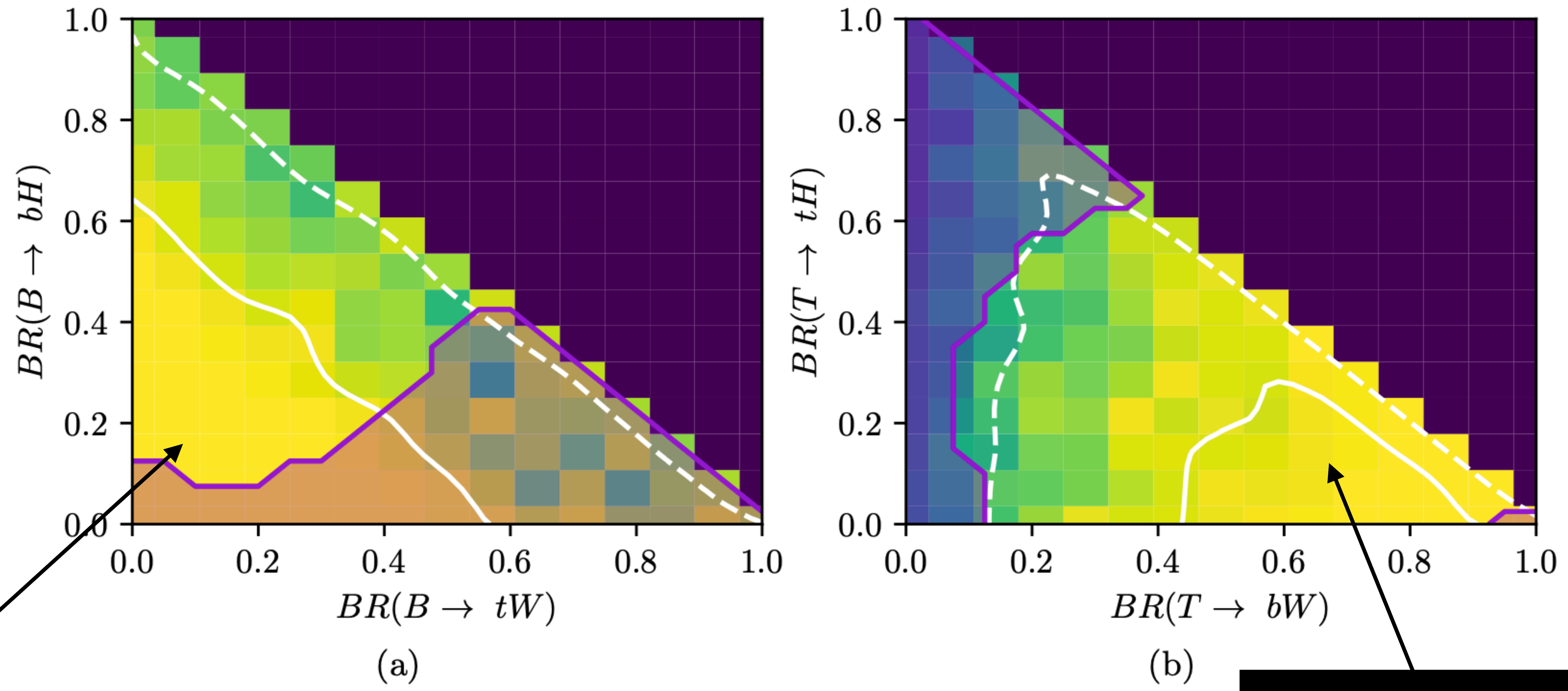

CONTUR sensitivity comes mainly from Z+jets measurements !

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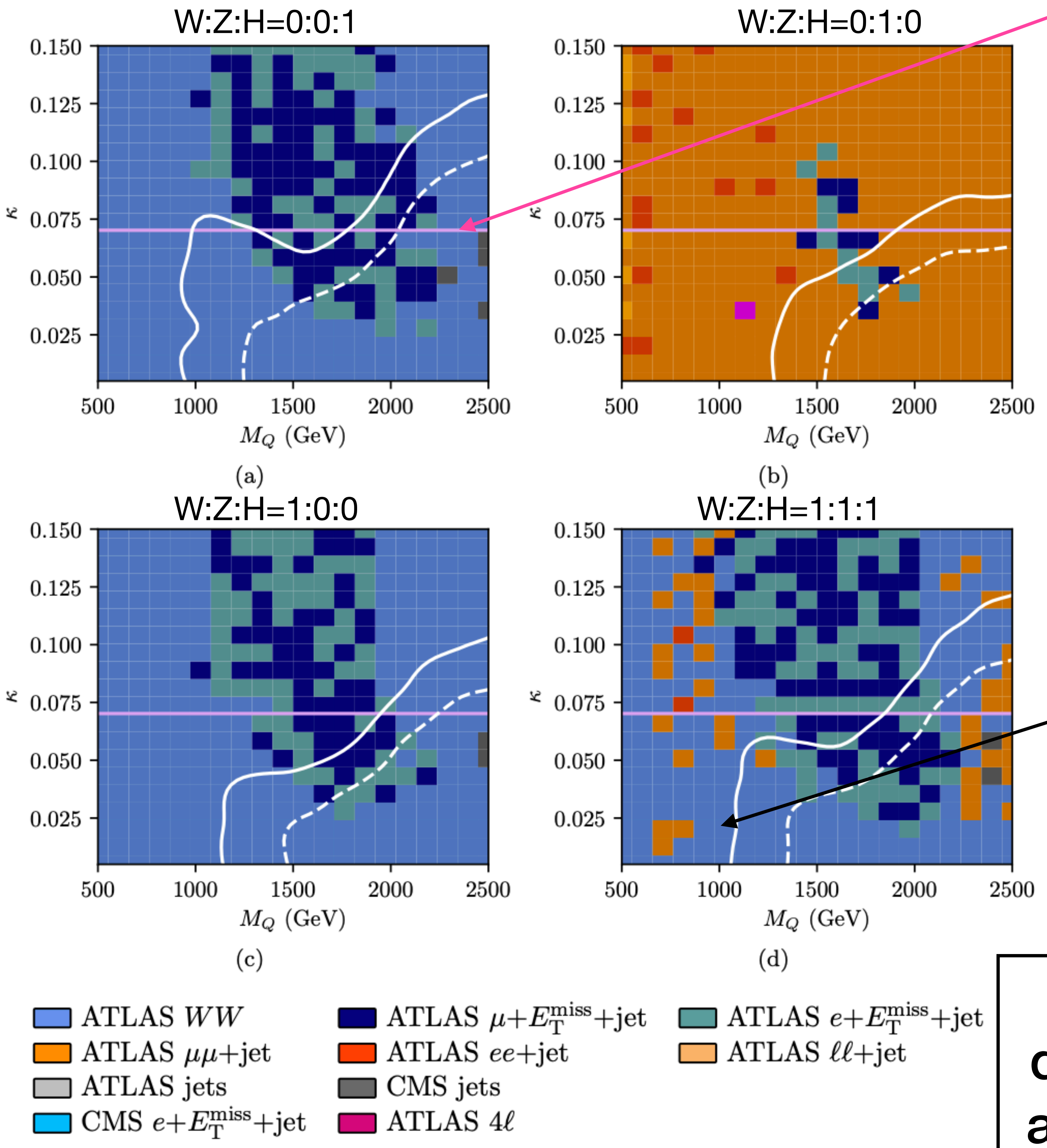
CONTUR sensitivity comes mainly from Top or W measurements

- 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

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

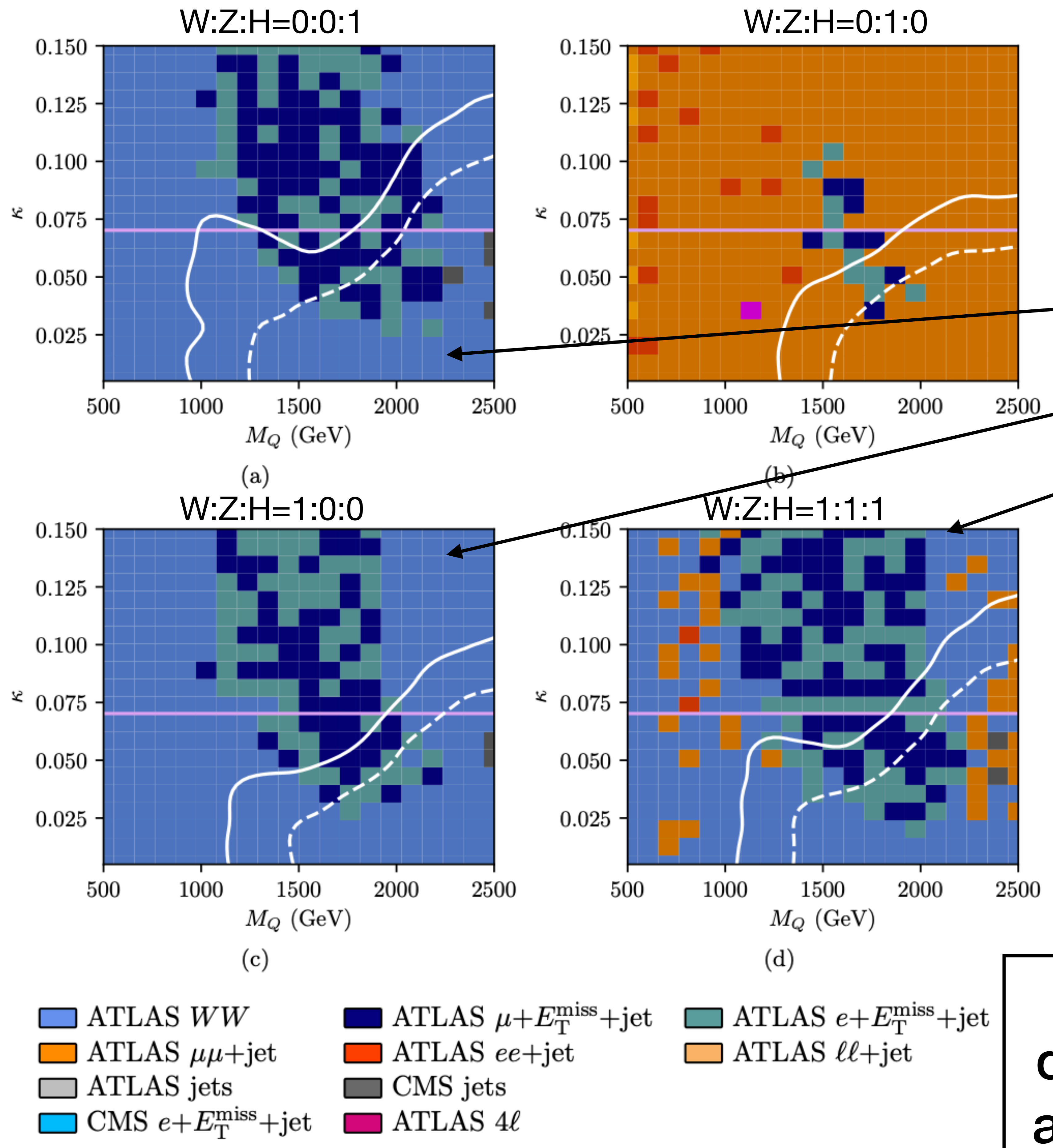
Colours indicate dominant pool of LHC analyses in each point of param space

- 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

UCL

VLQs coupling to 1st Gen



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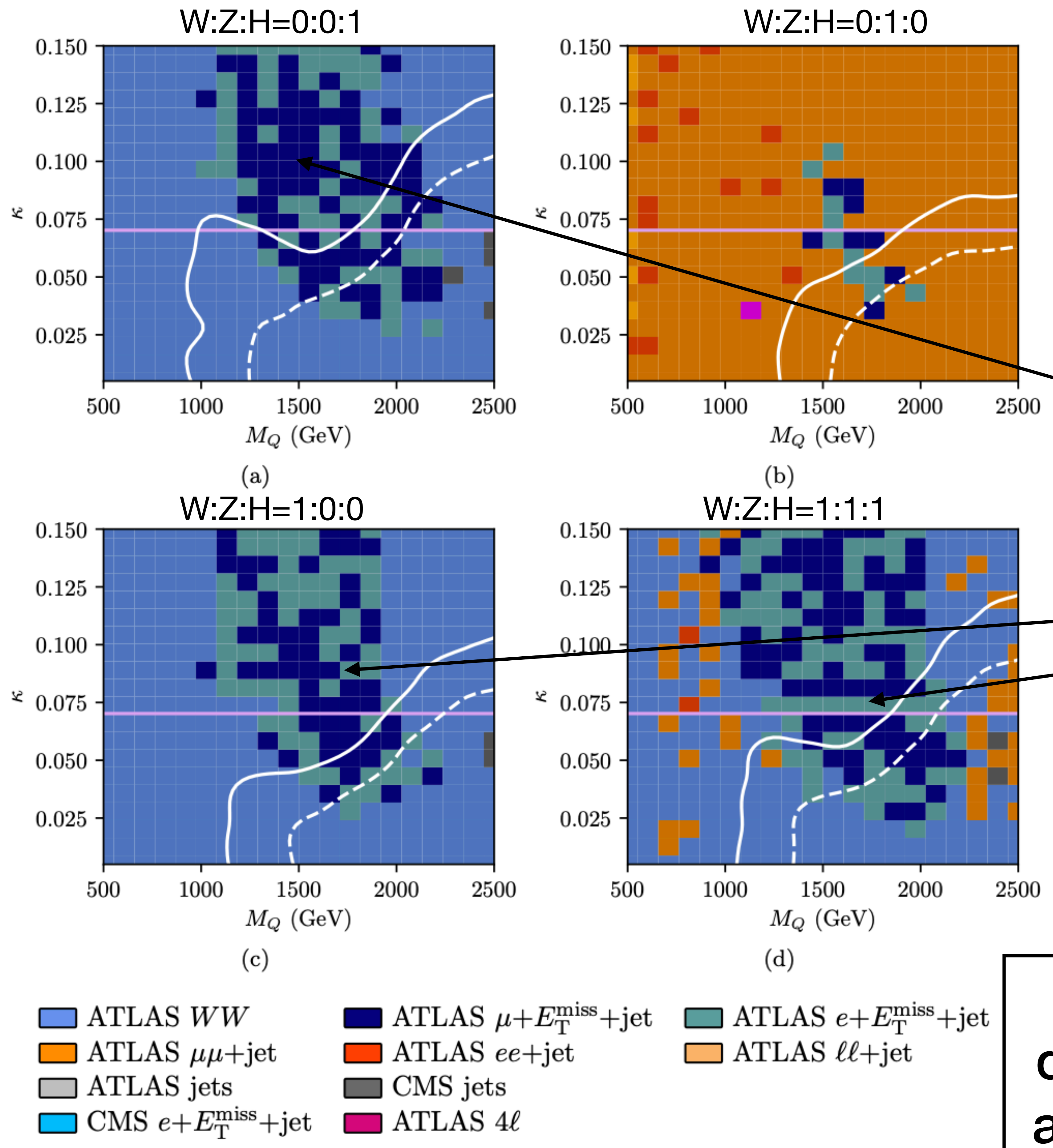

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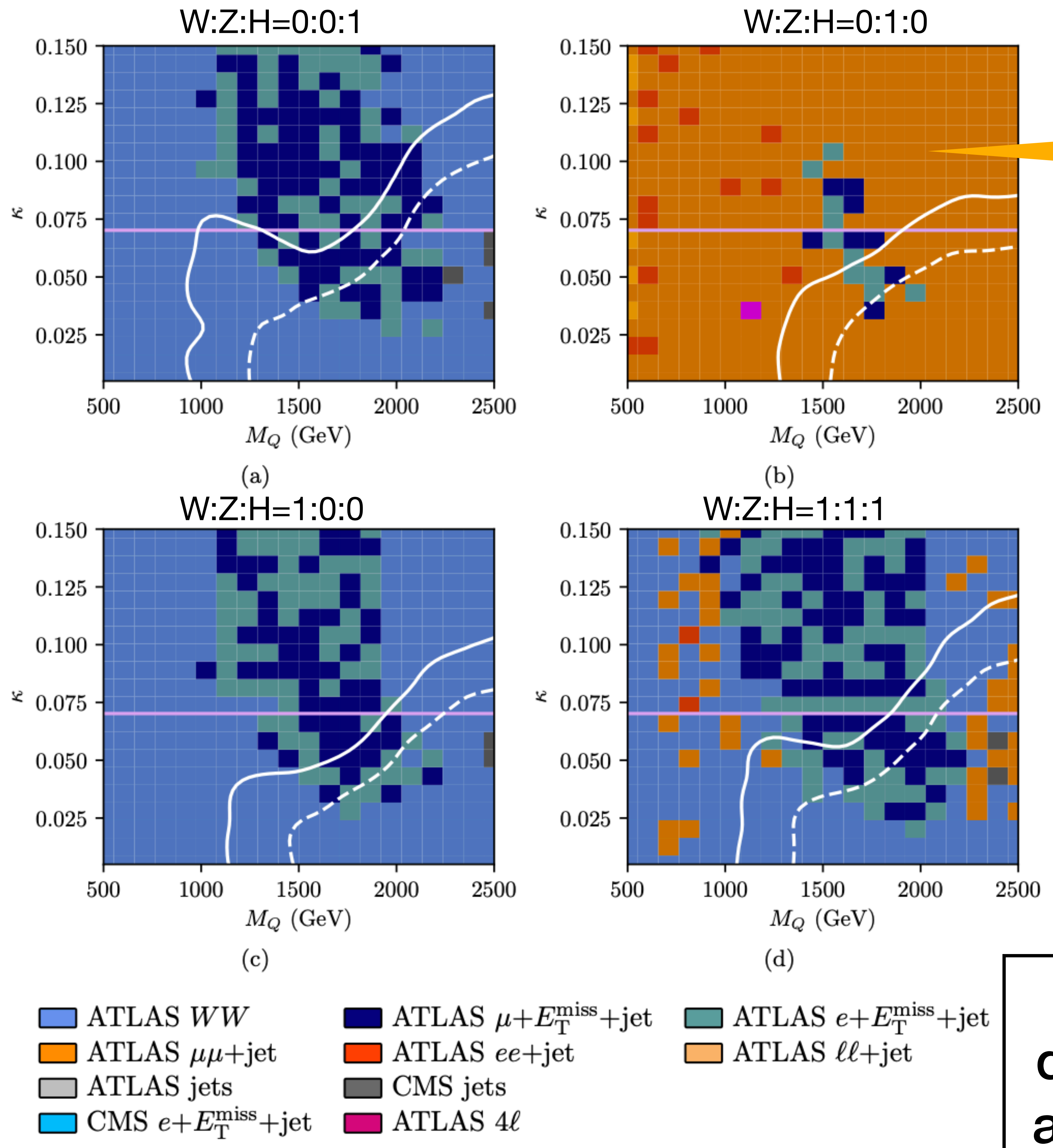
VLQs coupling to 1st Gen



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

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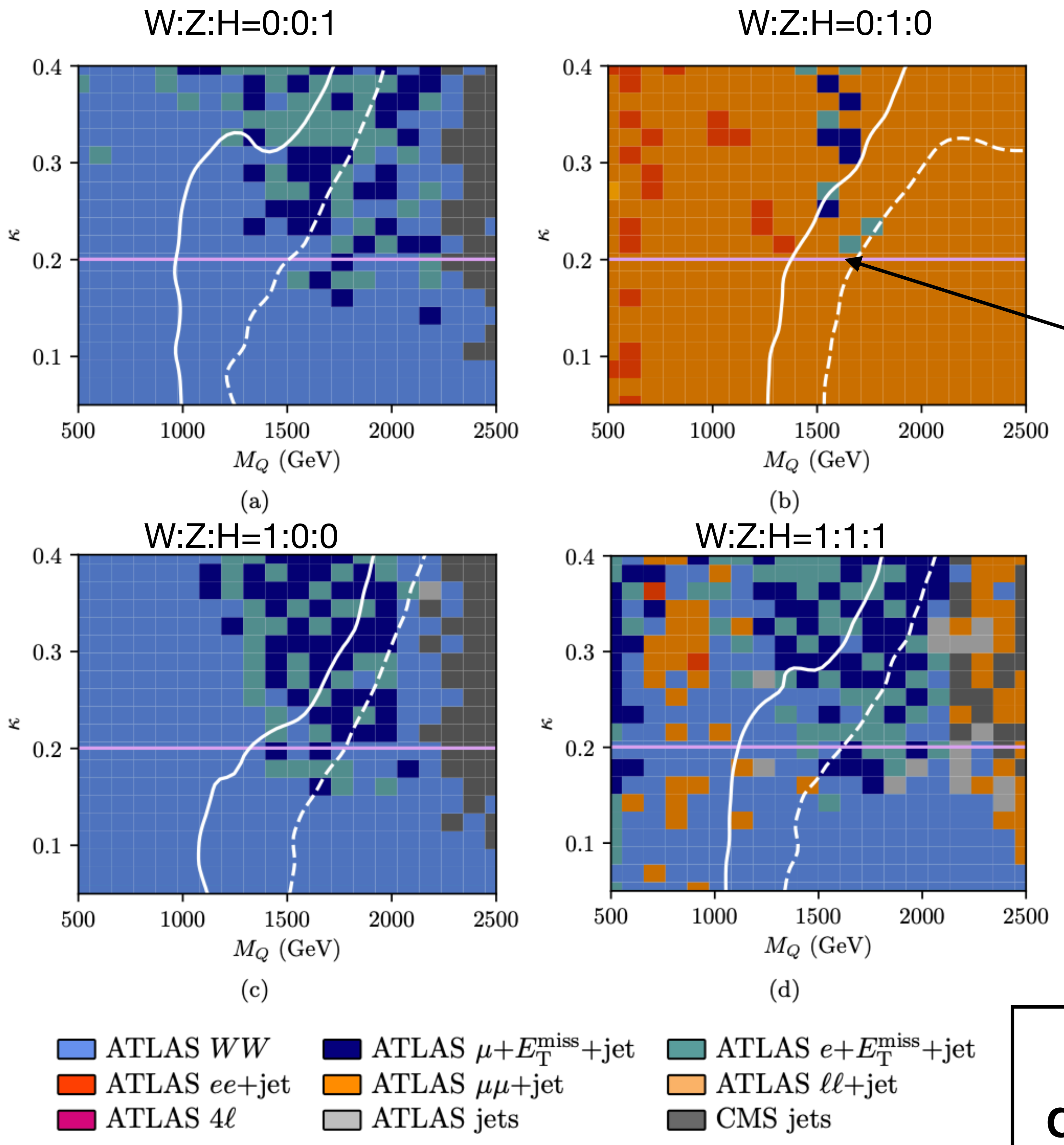
CONTUR to explore new regions

VLQs coupling to 2nd Gen



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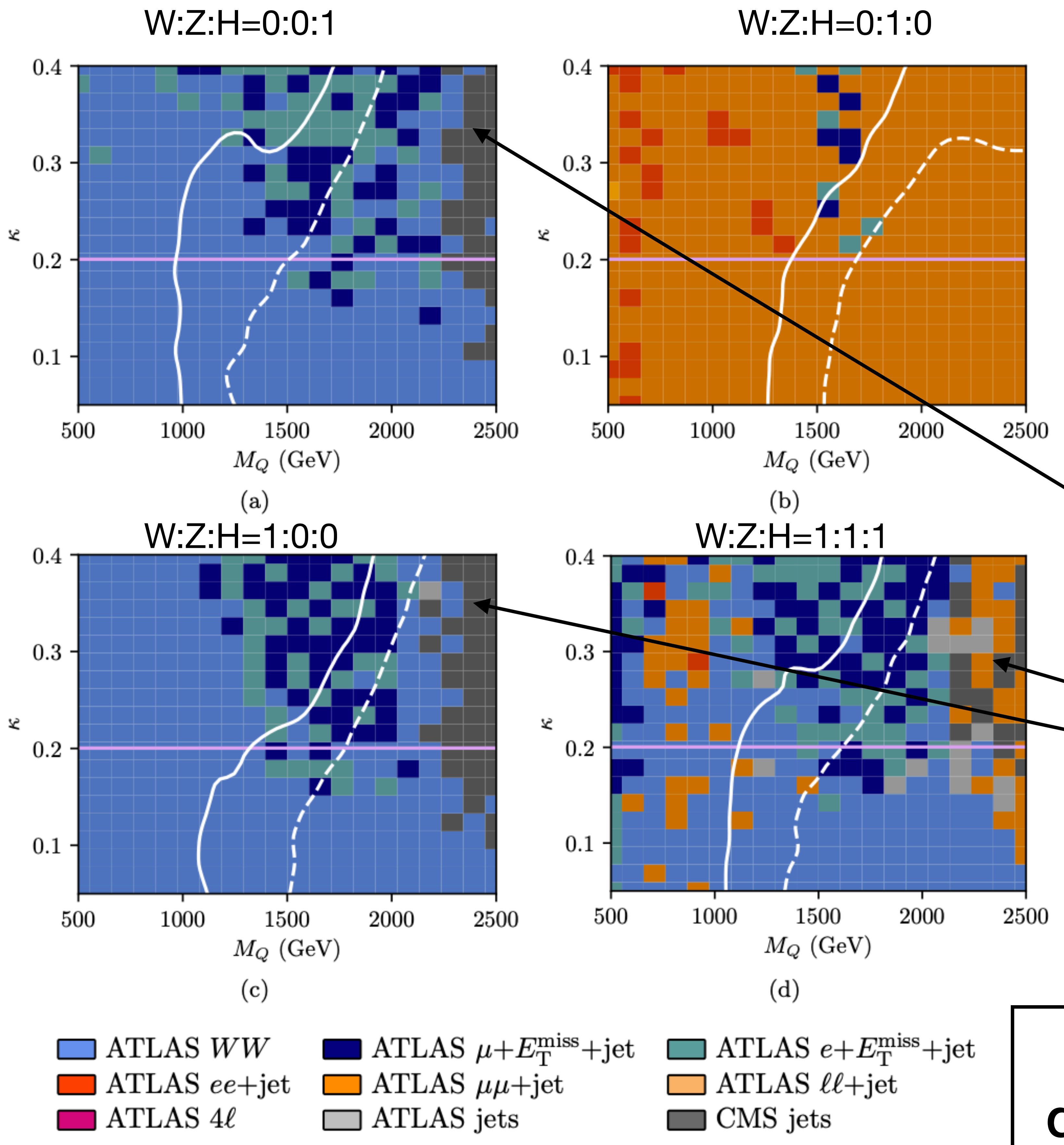
- Difference in exclusion pattern wrt 1st-gen scan driven by proton PDF!
- κ-dependent single-production modes were only appreciable if VLQs could couple to valence quarks
  - This explains why 2nd-gen scan has reduced κ-dependent shape
- Impact of QCD jet analyses also seen for higher masses (CMS 13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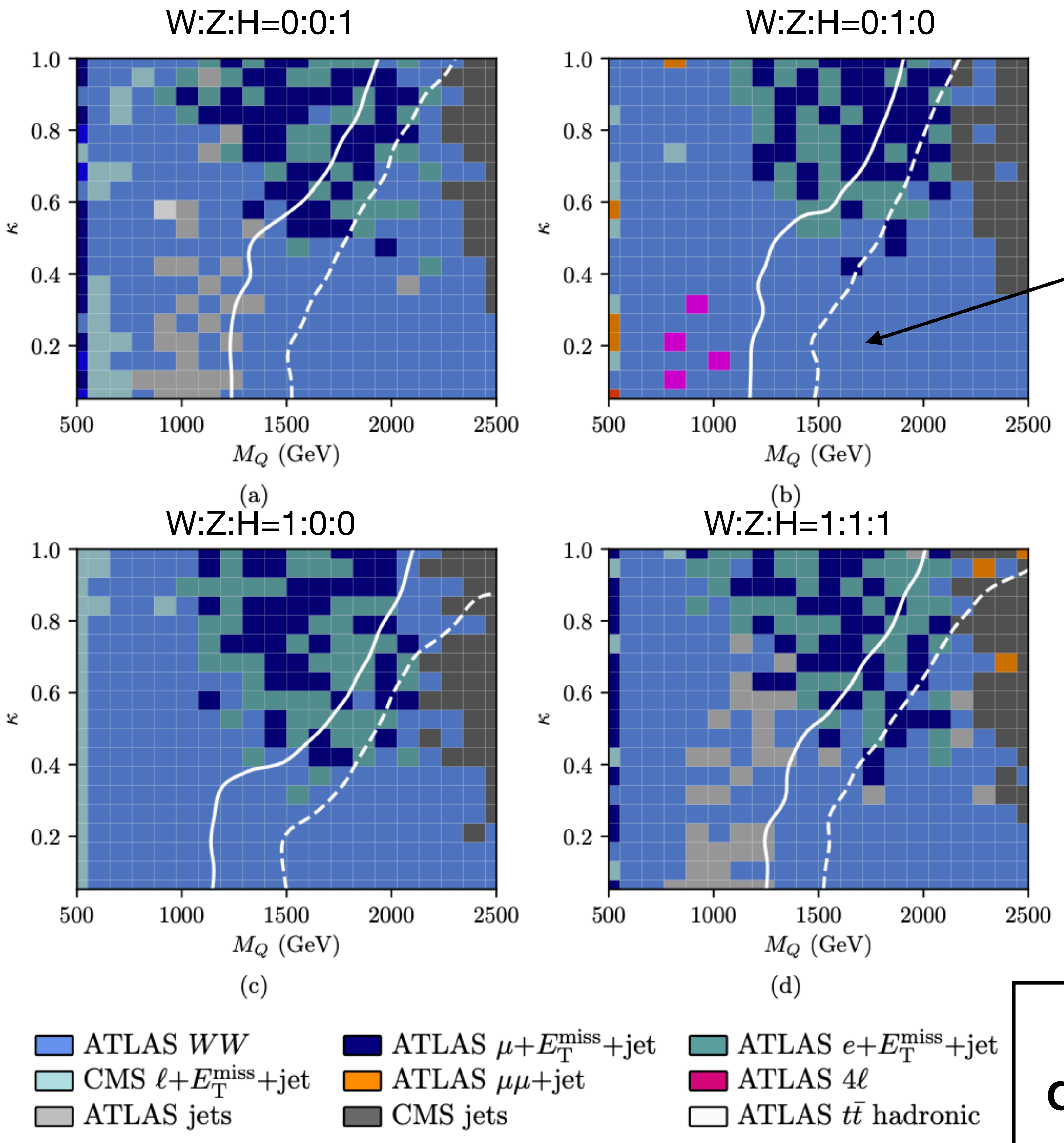
CONTUR to explore new regions

VLQs coupling to 3rd Gen



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

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)!

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

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

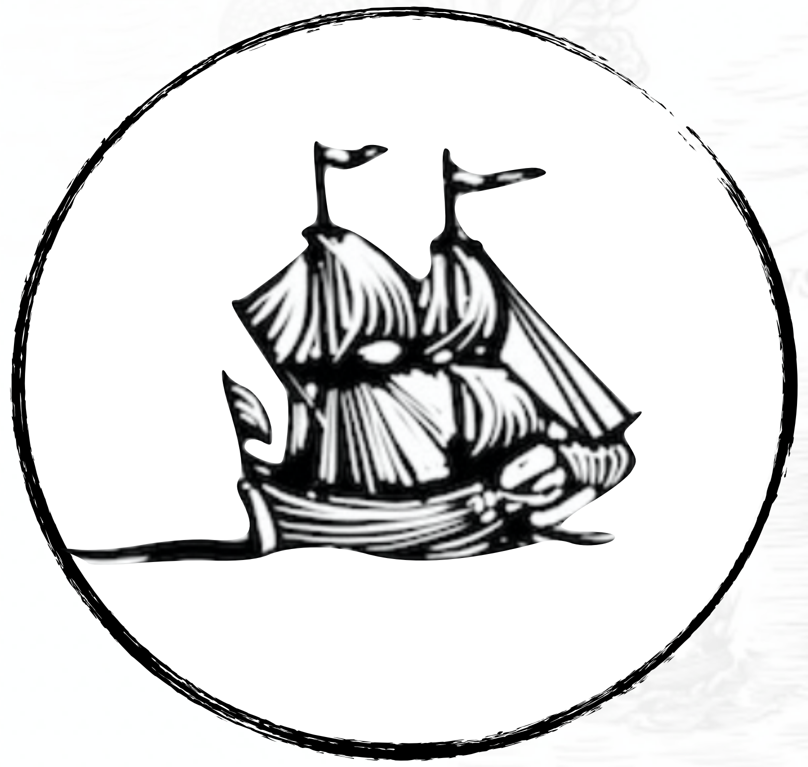


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Illustration by Chris Wormell from "A Map of the Invisible"

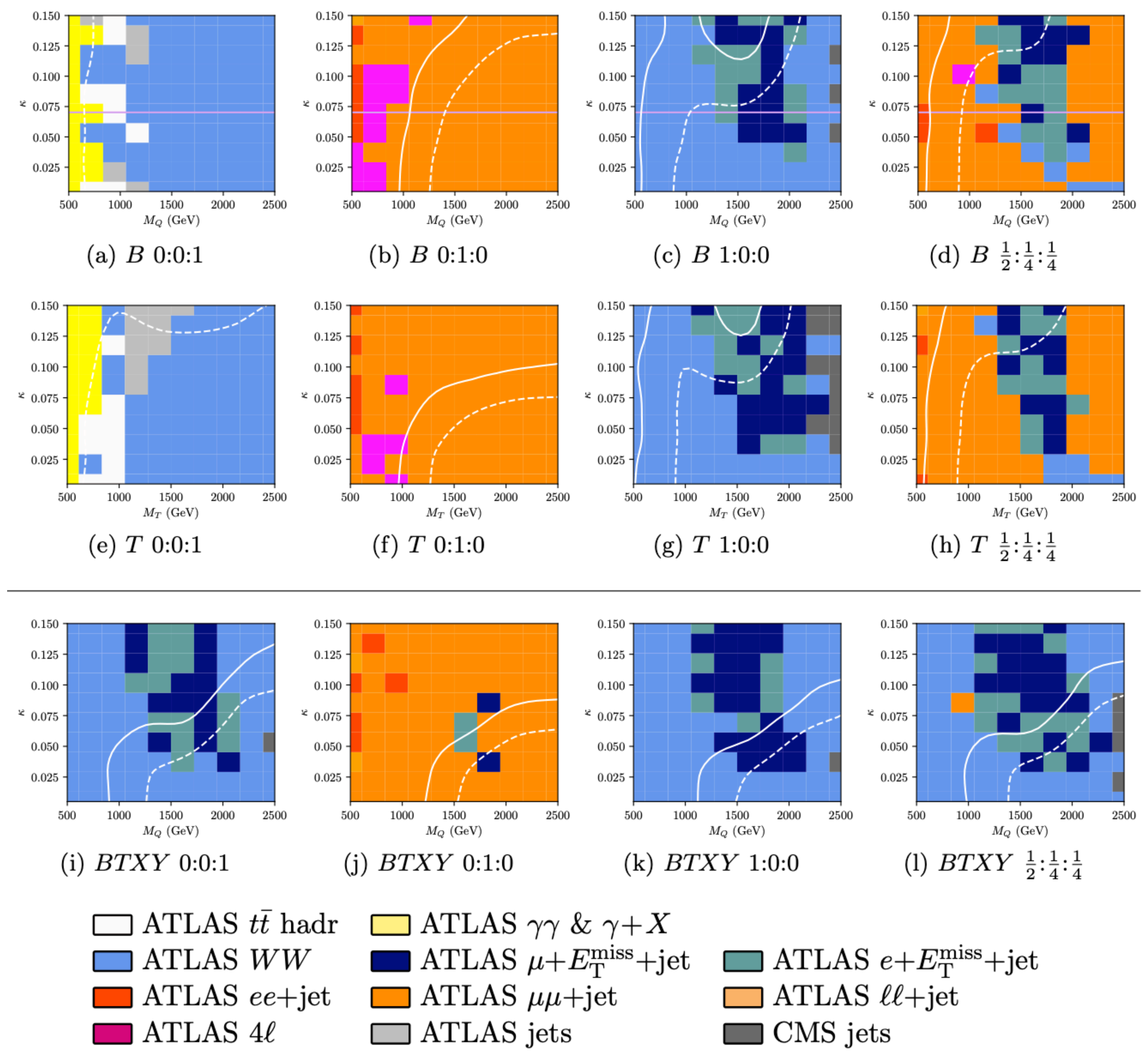
What about the (many) more realistic scenarios?

28 days later…

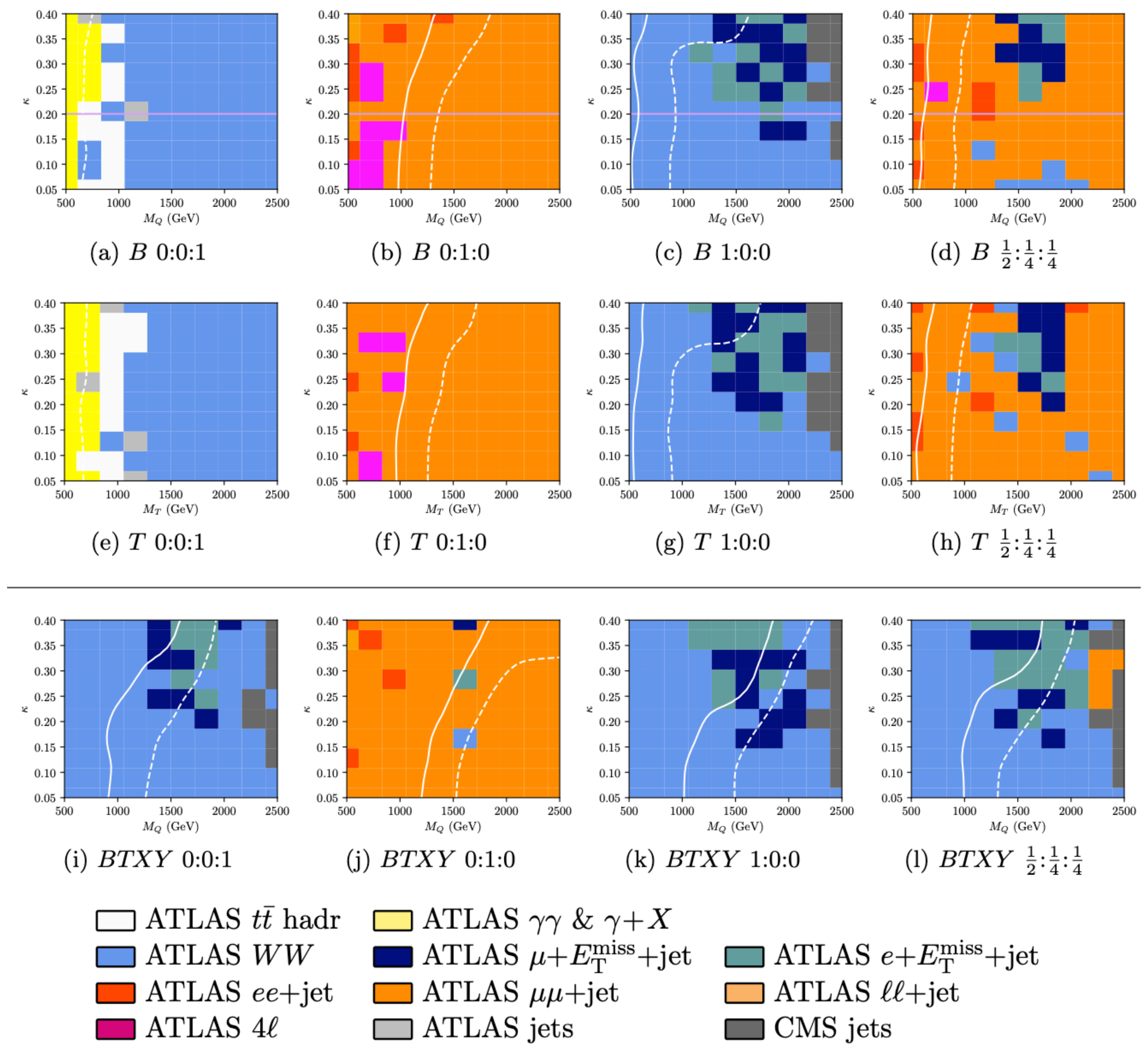
Illustration by Chris Wormell from "A Map of the Invisible"

What about Singlets?

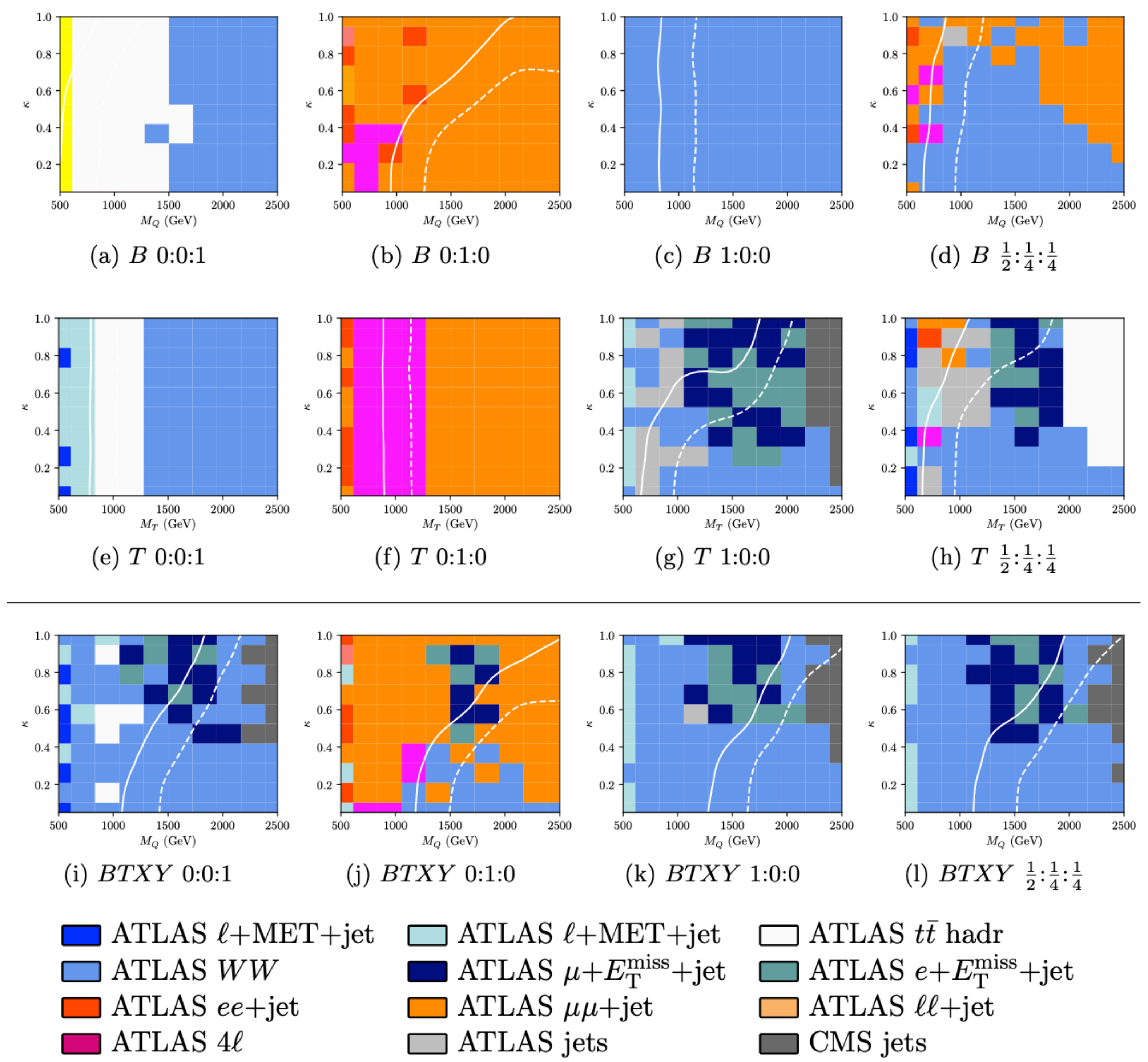
1st-Generation



2nd-Generation



3rd-Generation



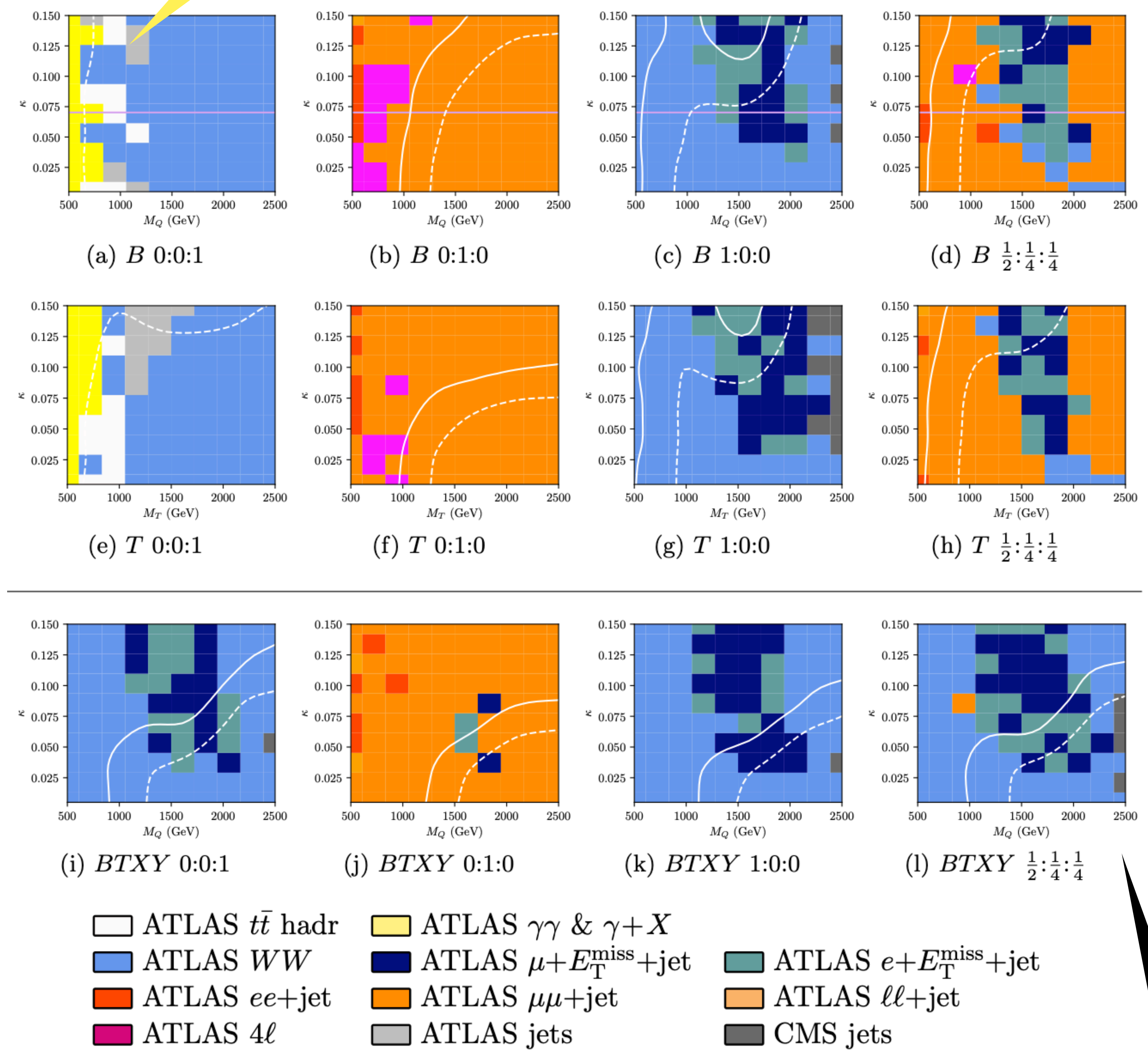
What about Singlets?

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



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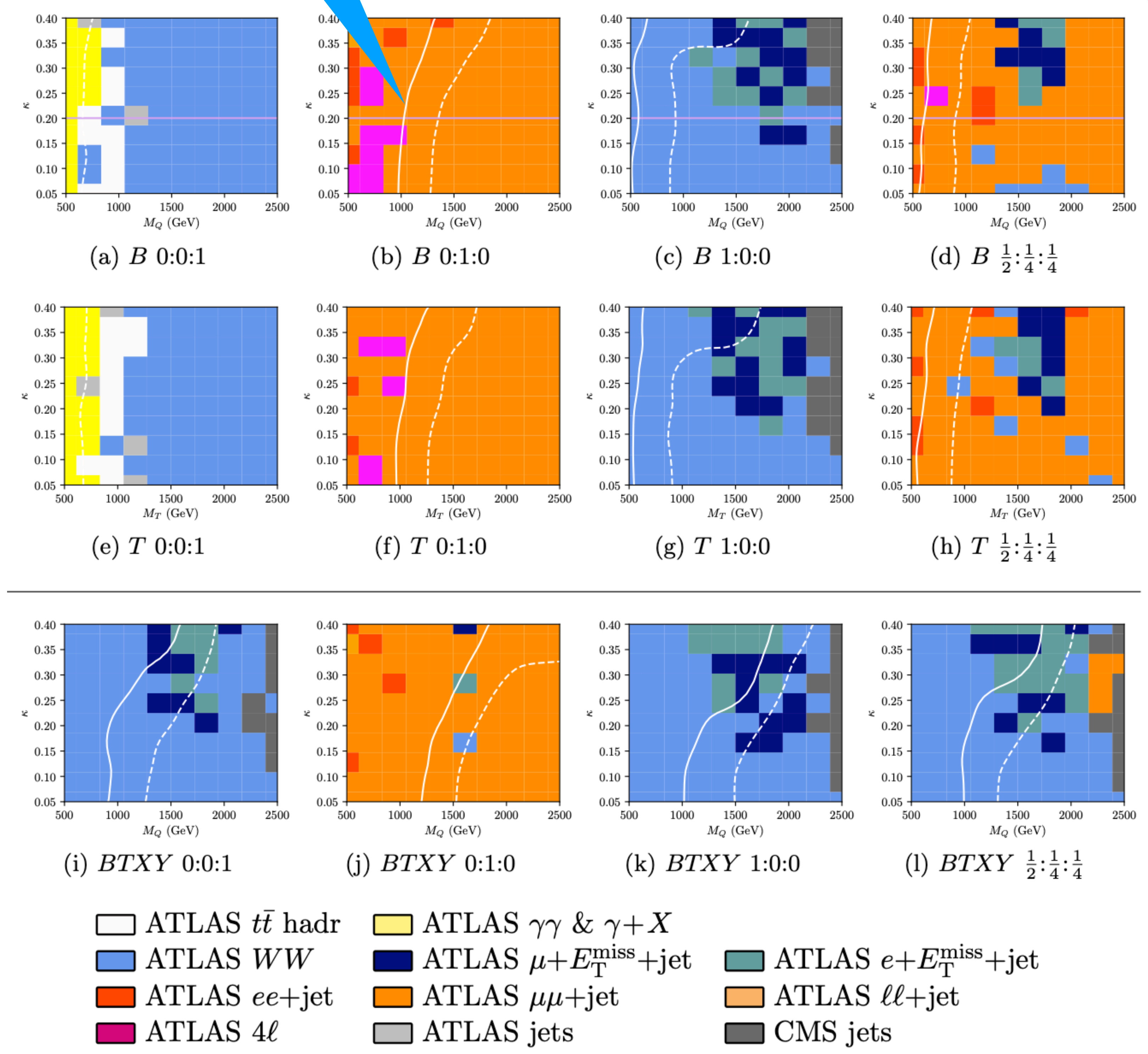
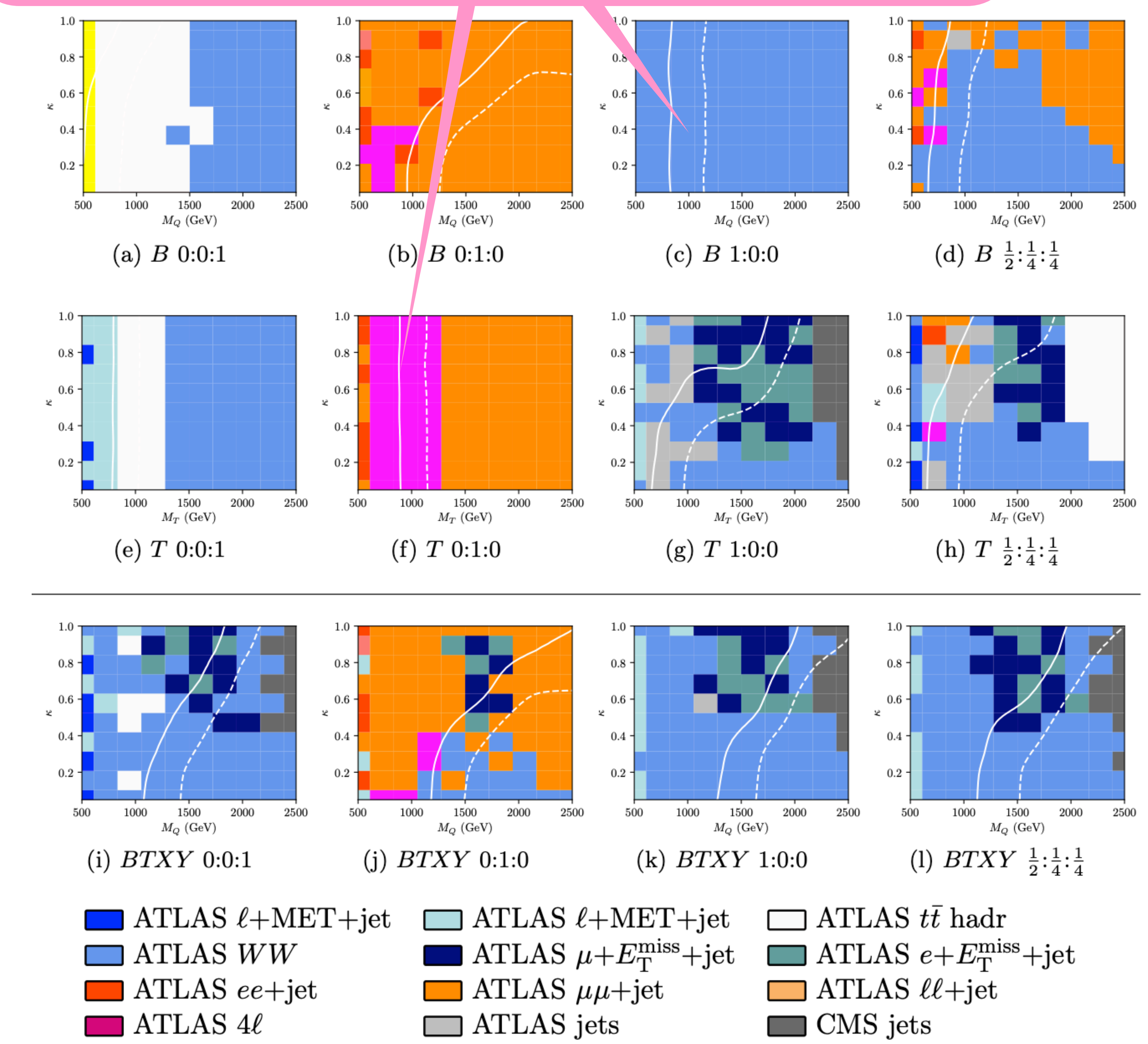
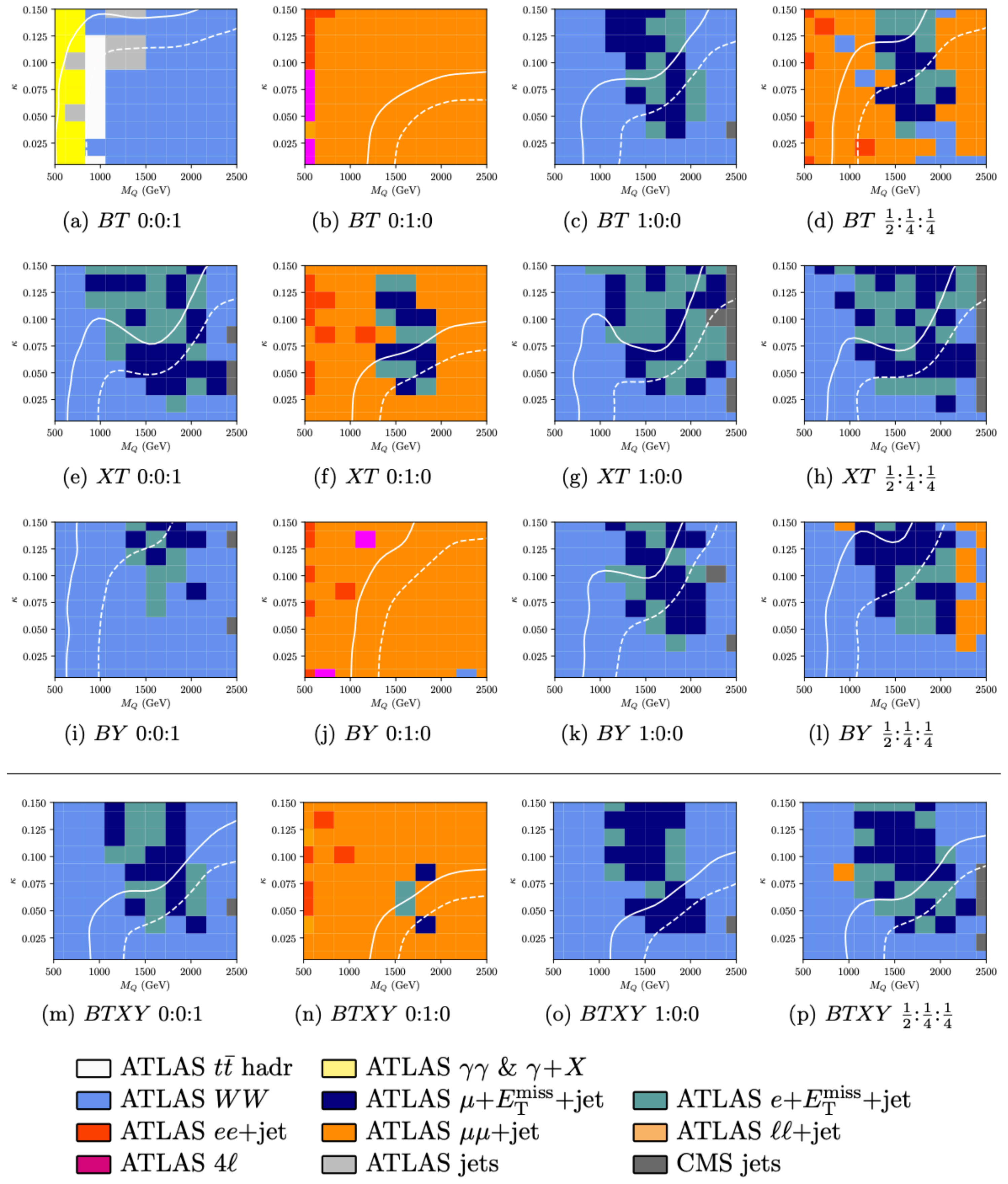




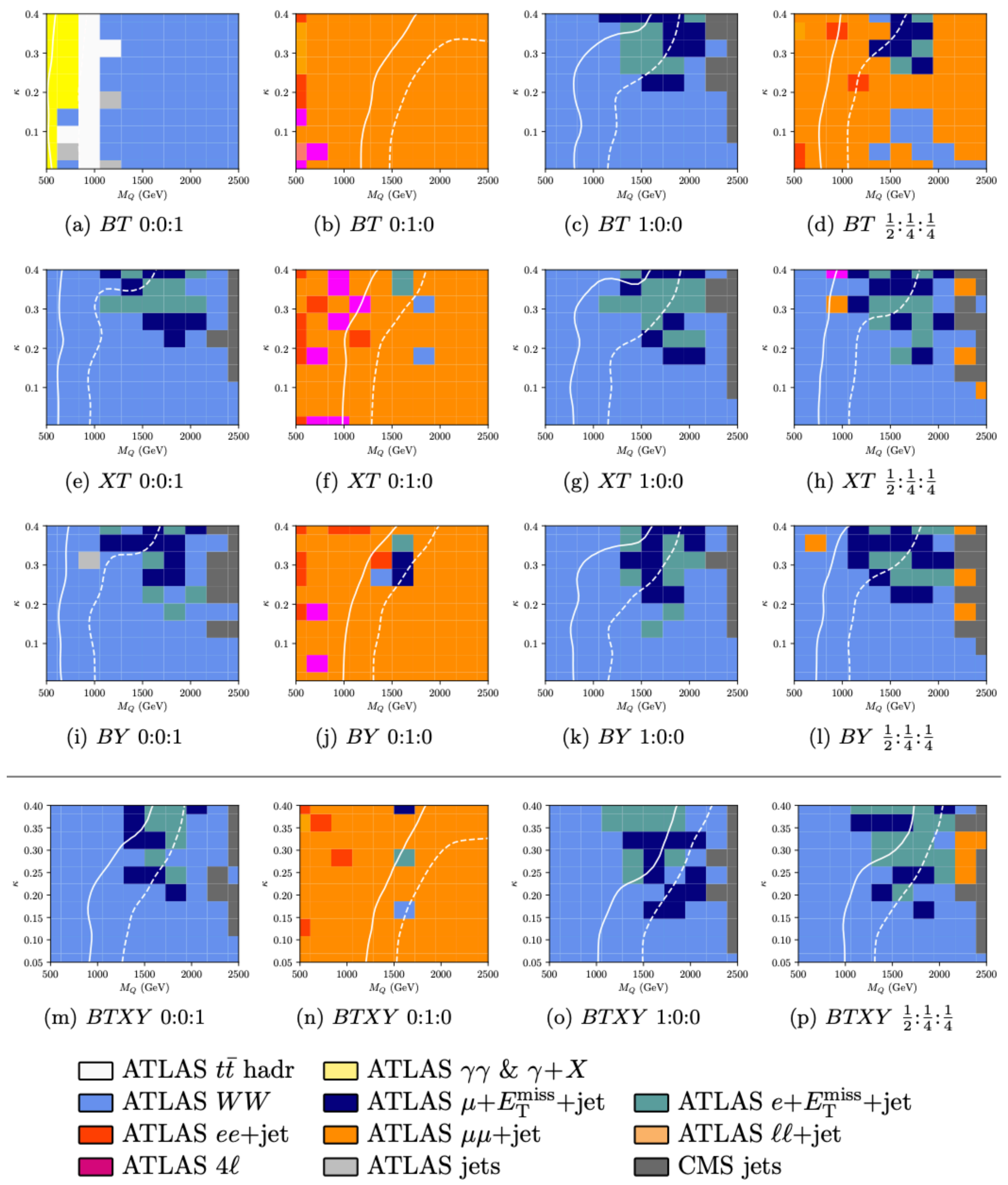
Original BTXY results for reference in final row

What about Doublets?

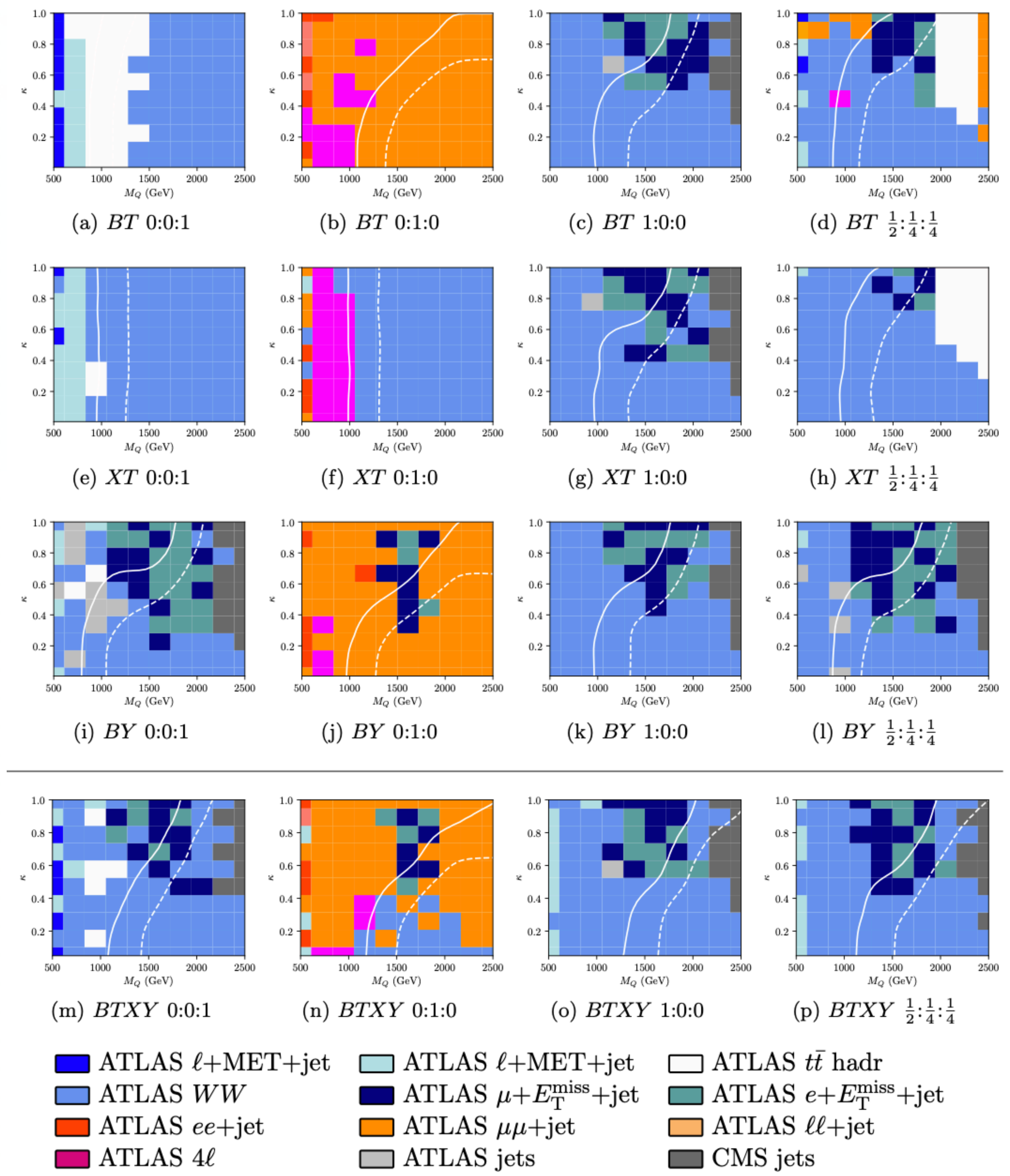
1st-Generation



2nd-Generation

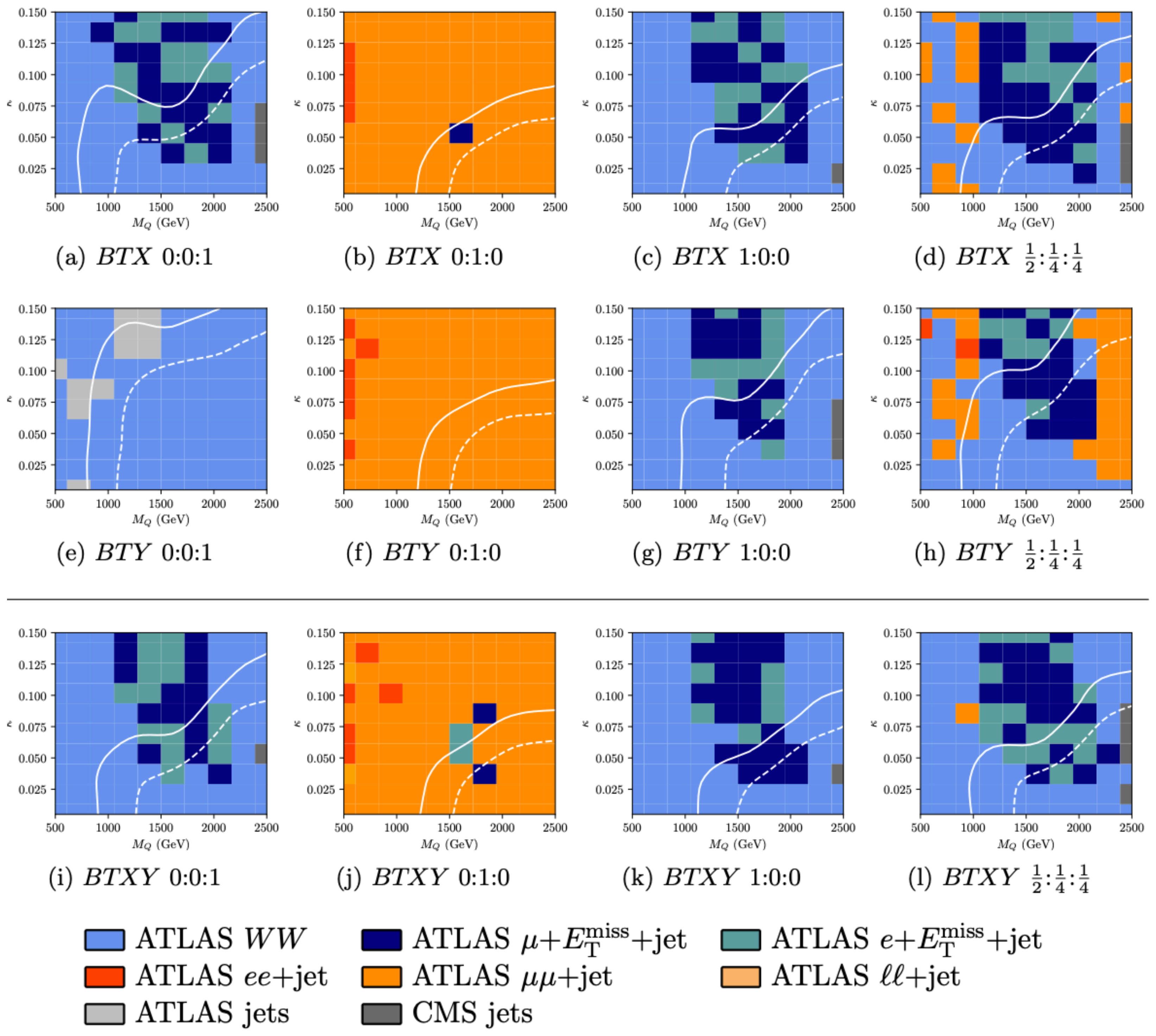


3rd-Generation

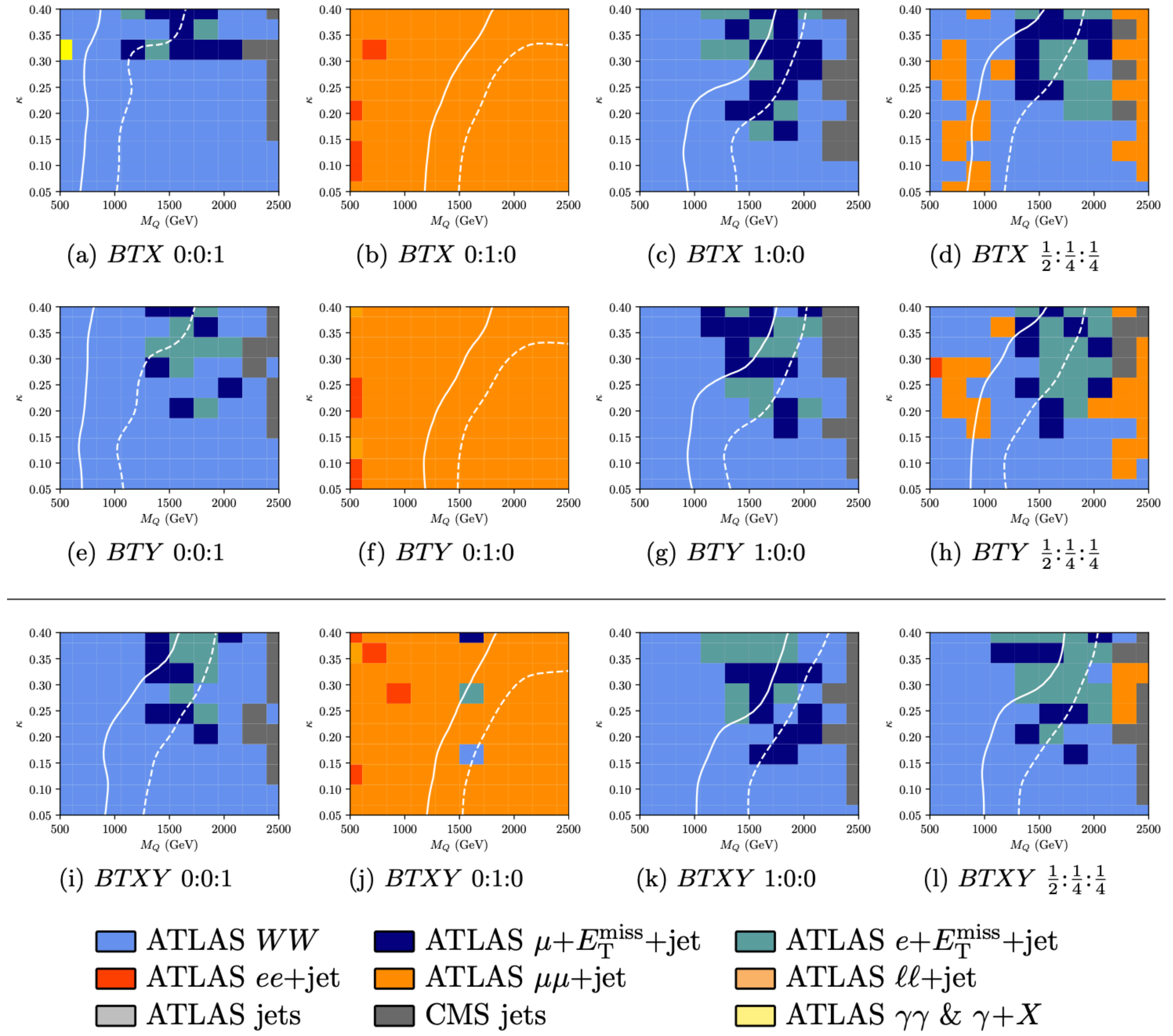


What about Triplets?

1st-Generation



2nd-Generation



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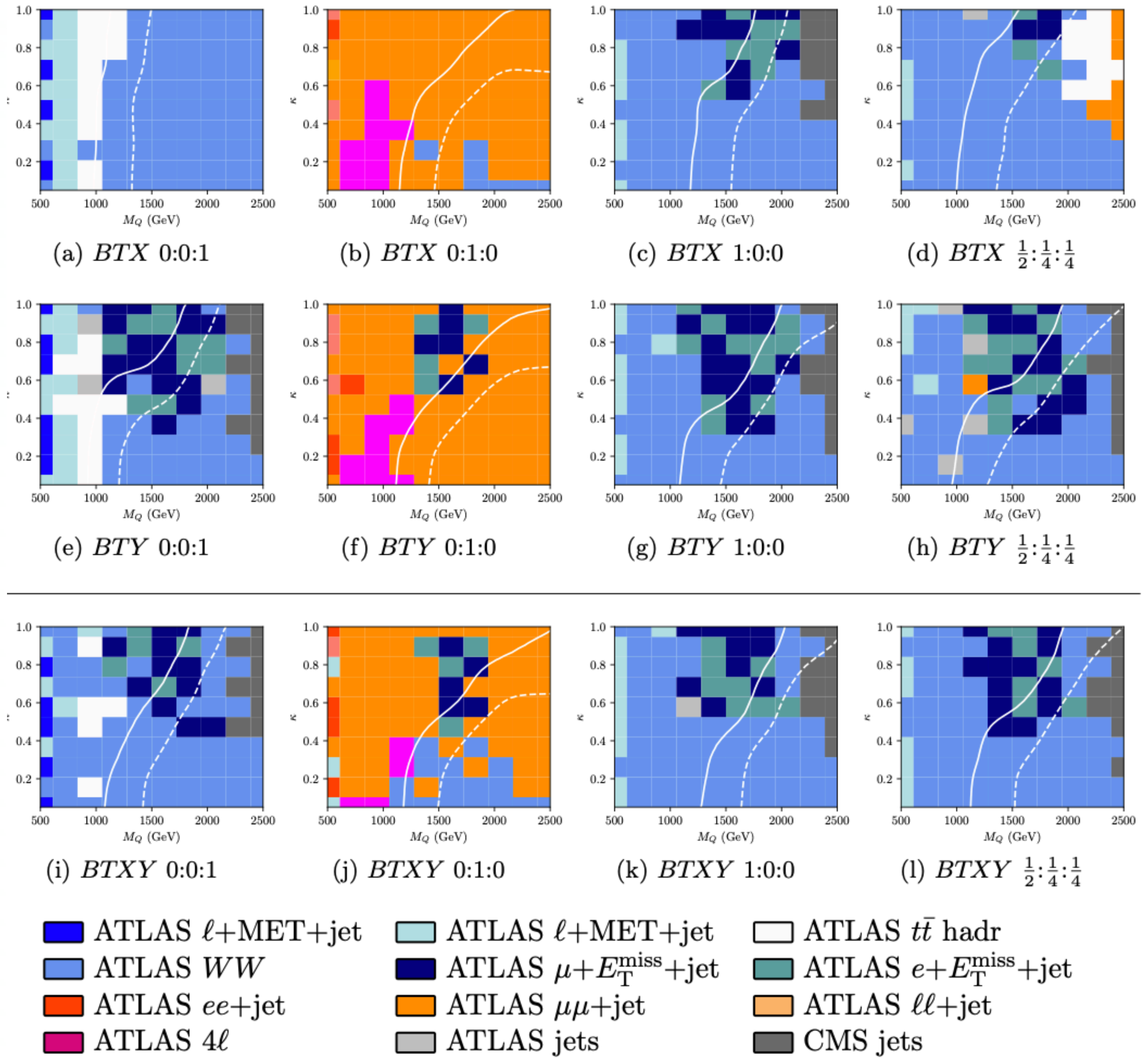


Bonus model:
Inert Doublet Model

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

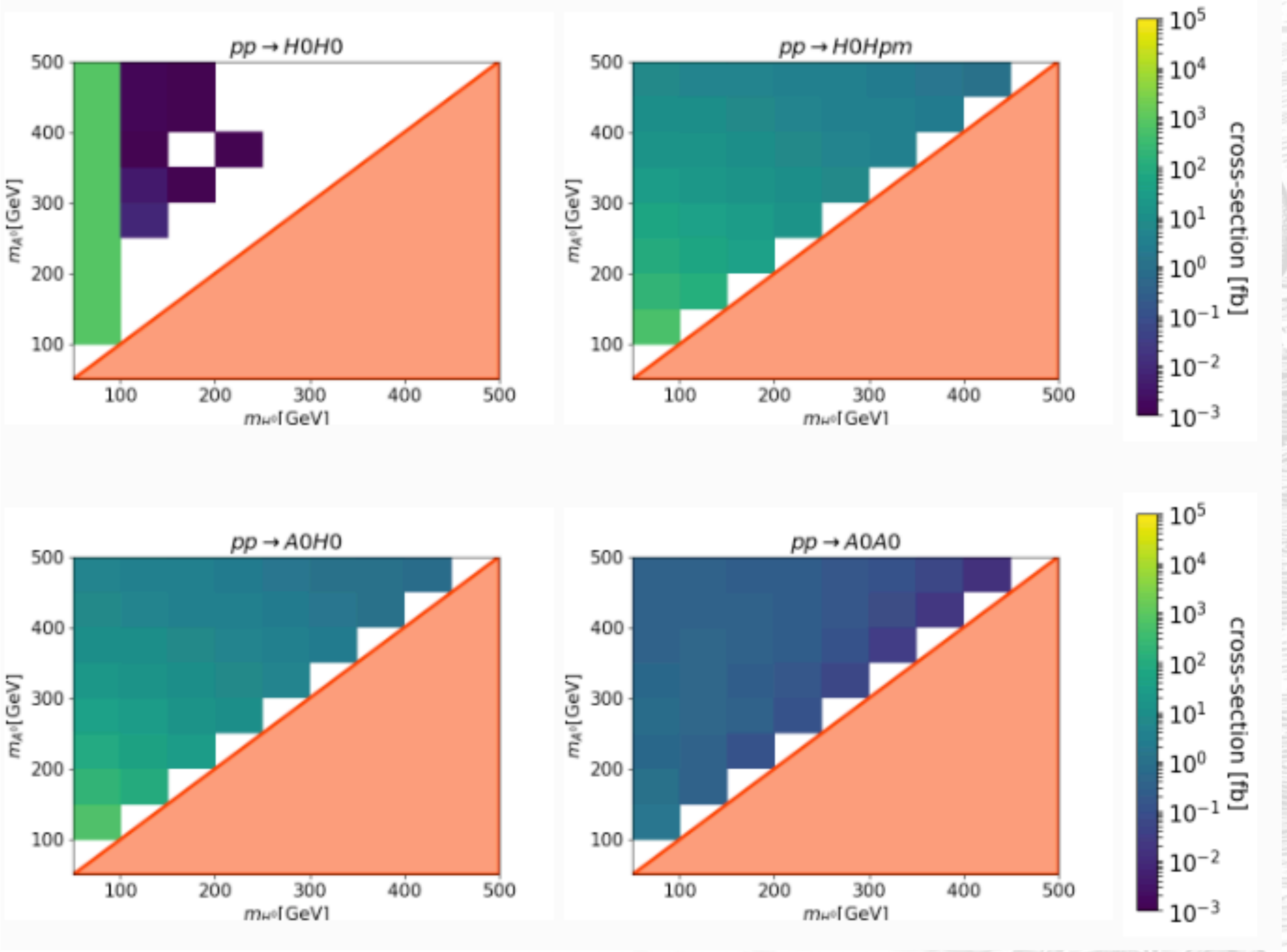
Inert Doublet Model

- Inert Doublet Model: simple 2HDM that obeys discrete Z_2 symmetry.
  New particles: A^0, $H^\pm$, H^0 (DM candidate)
  Large mass splittings excluded by prevision EW, so take $m_{H^\pm} = m_{A^0}$ +20 GeV

- Dominant BSM production diagrams show that we expect highest cross-sections from difficult MET-only signature…

- … but could also be sensitive from MET+Jets or multilepton processes

https://link.aps.org/doi/10.1103/PhysRevD.18.2574
arXiv:0708.2939
arXiv:hep-ph/0603188

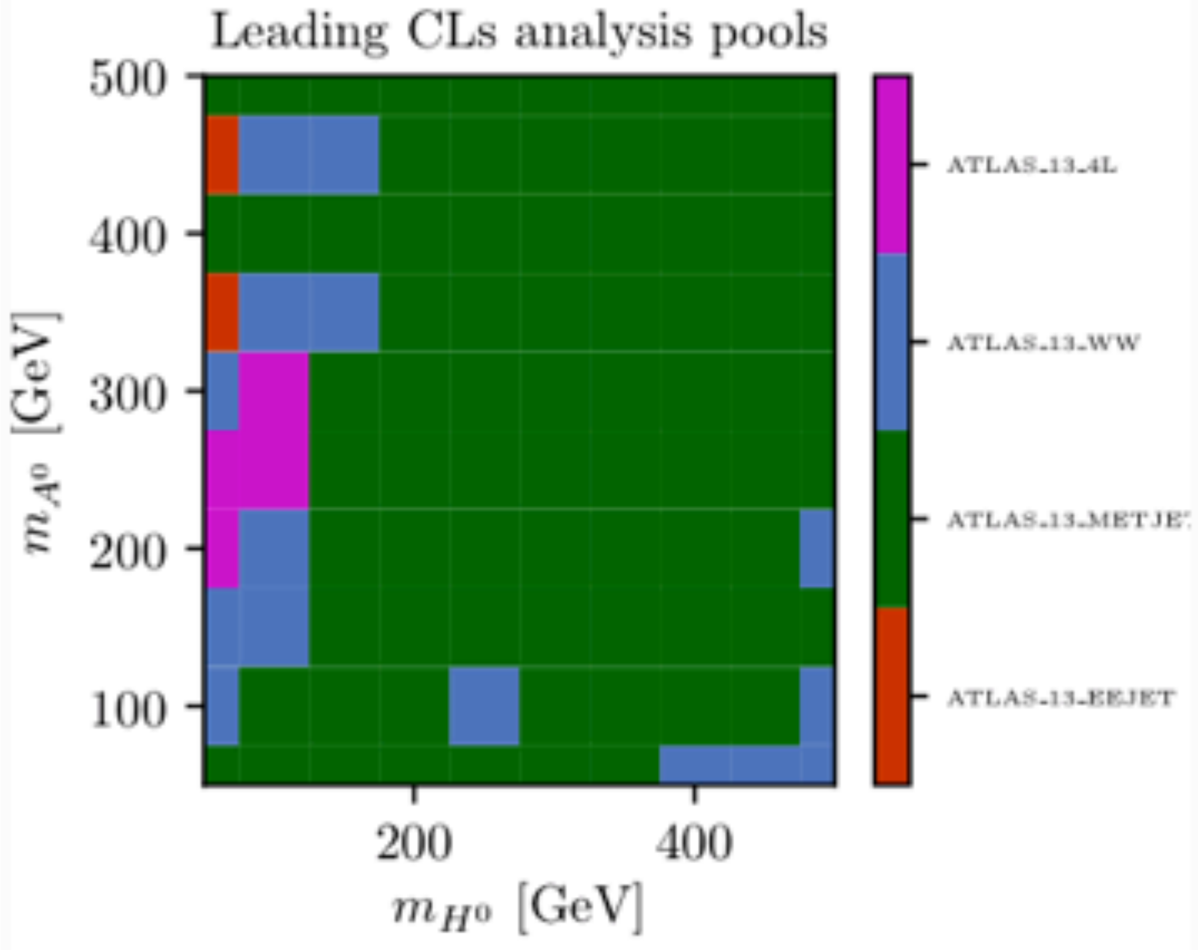


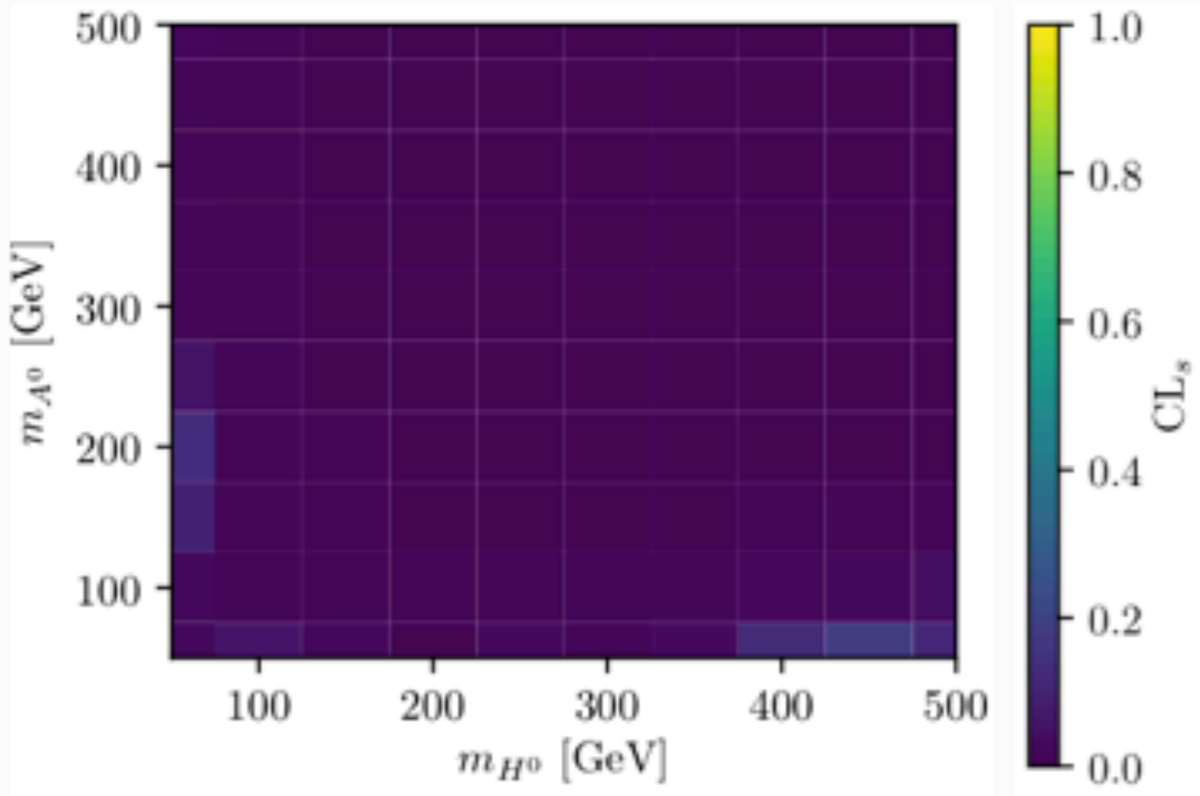
Thanks to G. Zilgavis (UCL undergrad) who ran this nice study!

Inert Doublet Model

https://link.aps.org/doi/10.1103/PhysRevD.18.2574
arXiv:0708.2939
arXiv:hep-ph/0603188

- Results: very little sensitivity from existing measurements!
- Better sensitivity could come from updates to these measurements:
  - MET+X (only have 3.2/fb analysis)
  - 4lepton cross-section (only have 36/fb analysis) $A^0A^0 \rightarrow H^0H^0ZZ \rightarrow H^0H^0\ell\ell\ell\ell$





- Also candidate for dedicated search!

Thanks to G. Zilgavis (UCL undergrad) who ran this nice study!

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!

Advert

- UCL has one MCNet studentship left:
  - Projects on CONTUR available
  - please get in touch with myself or Jon Butterworth if interested!

- We are very keen to get SM predictions for existing Rivet measurements so they can be used in CONTUR (and avoid making certain assumptions)
  - Please get in touch if you think you can help!

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

Thank you

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

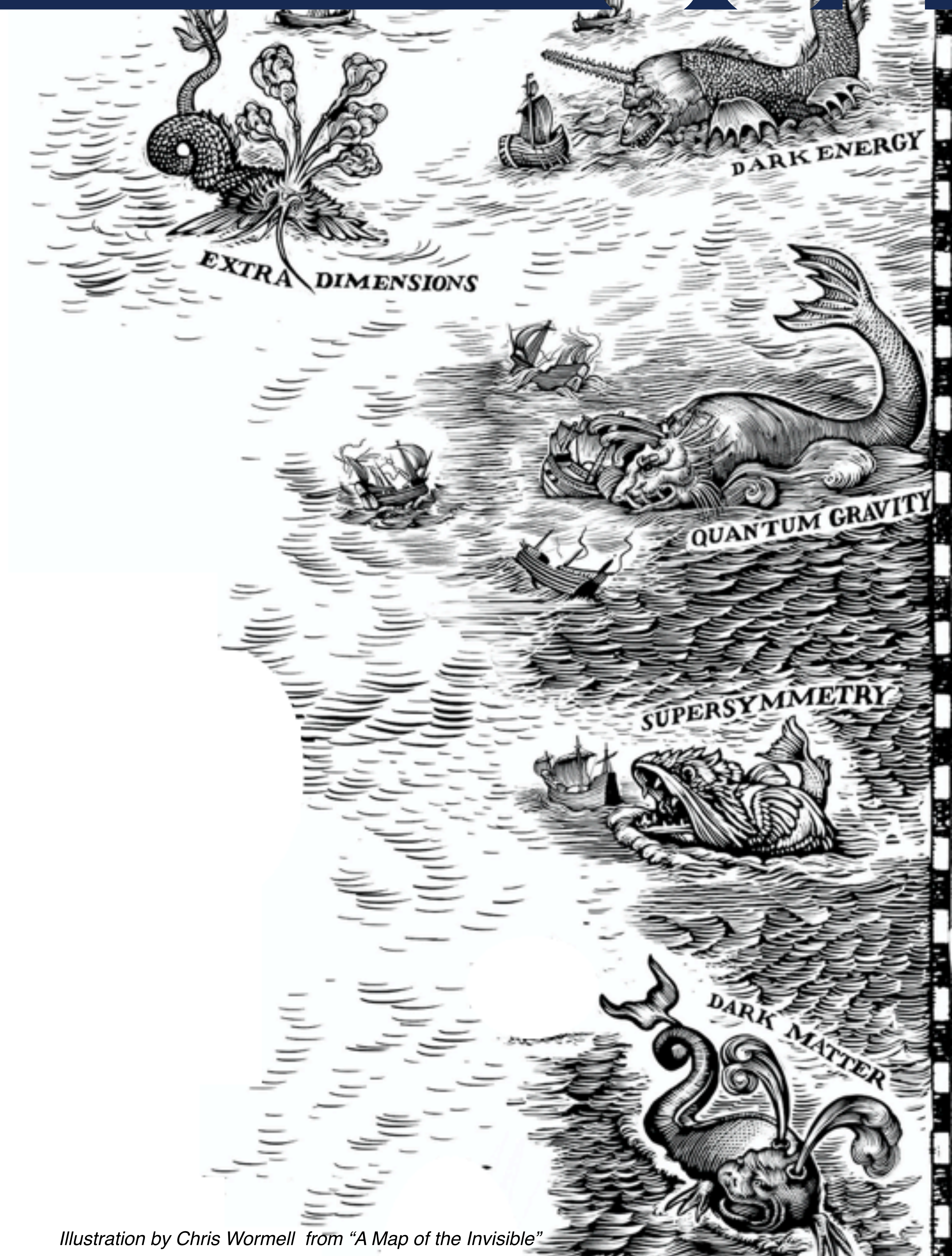
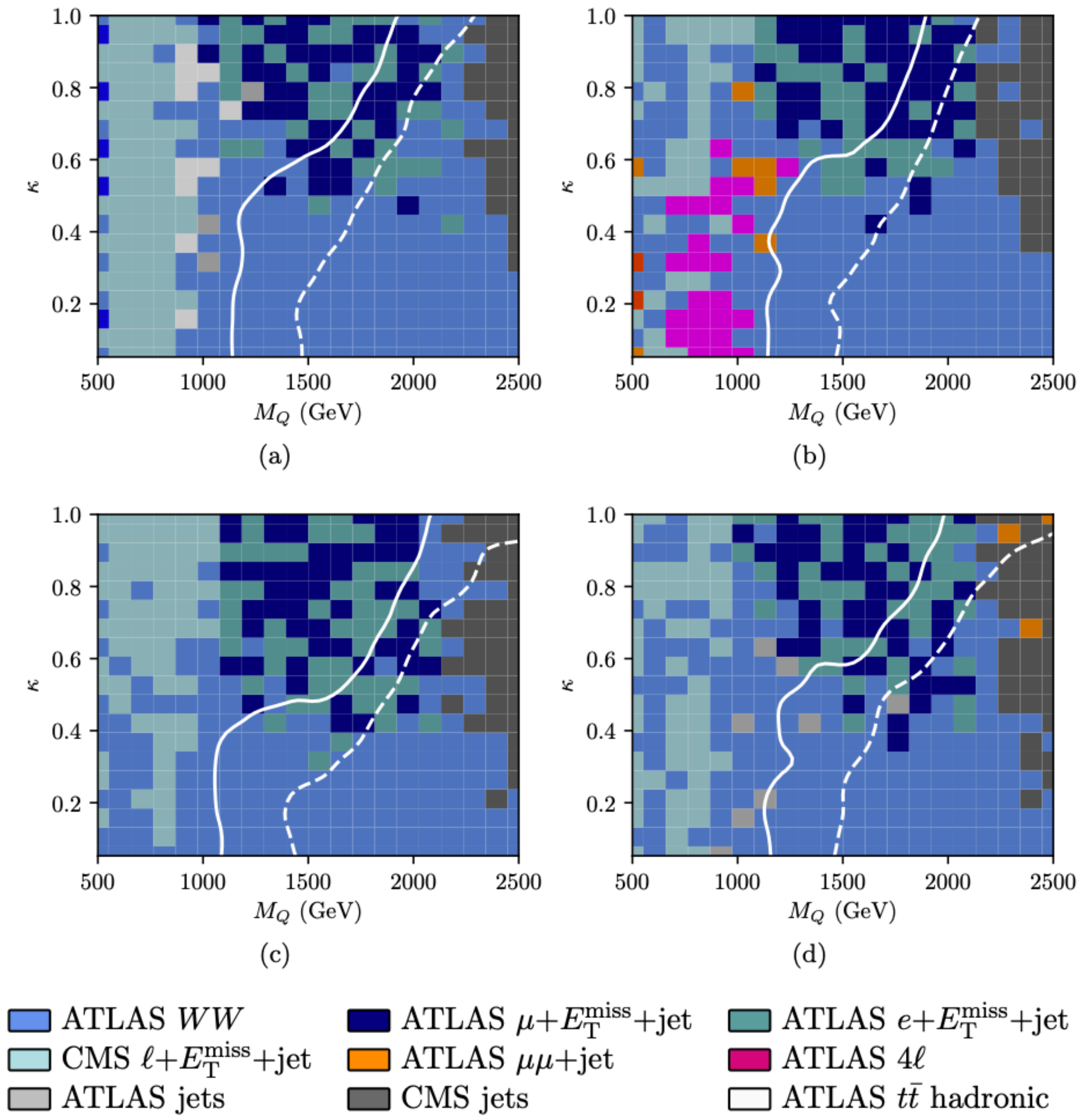


Illustration by Chris Wormell from "A Map of the Invisible"

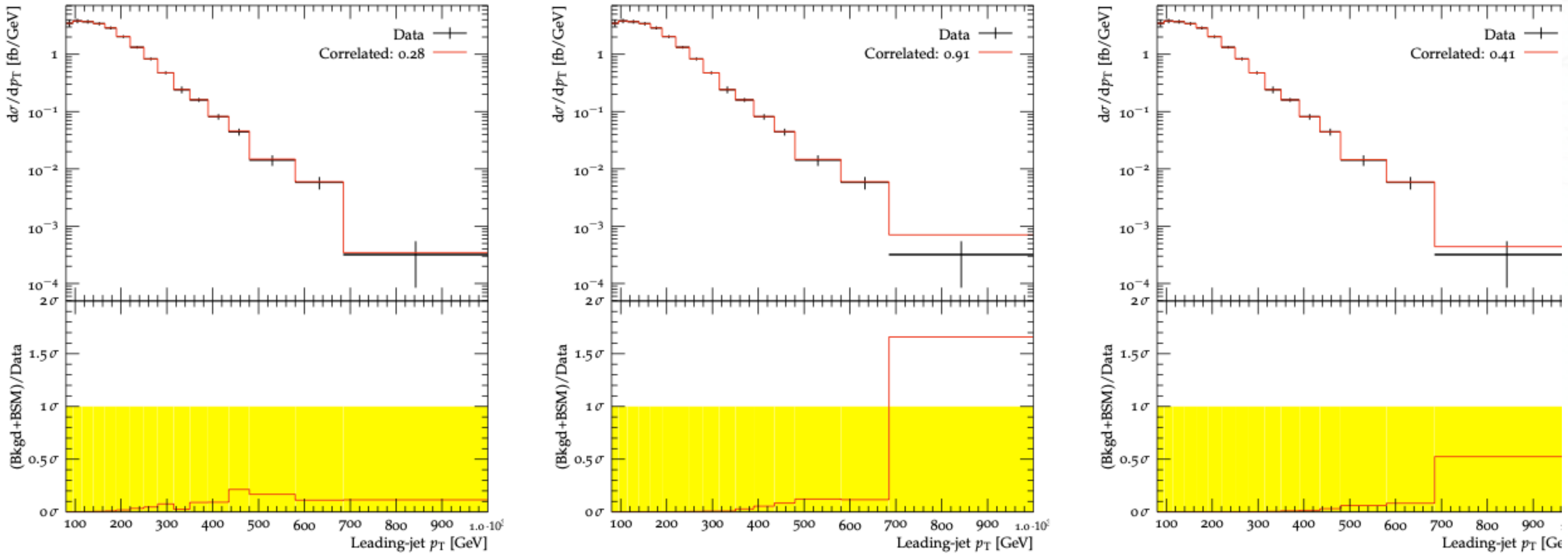
Louie Corpe, UCL (l.corpe@ucl.ac.uk)

Extra Material

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

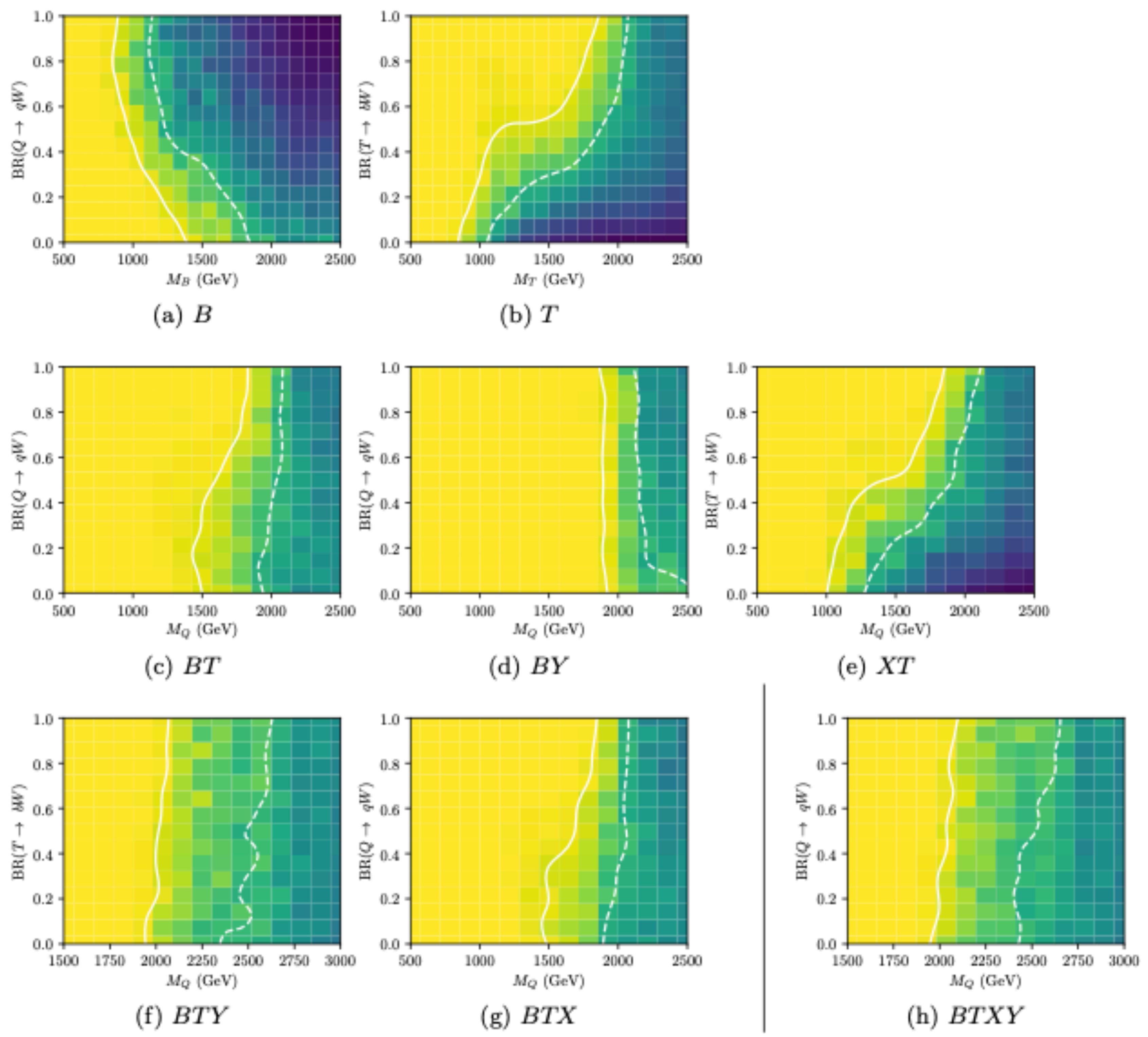
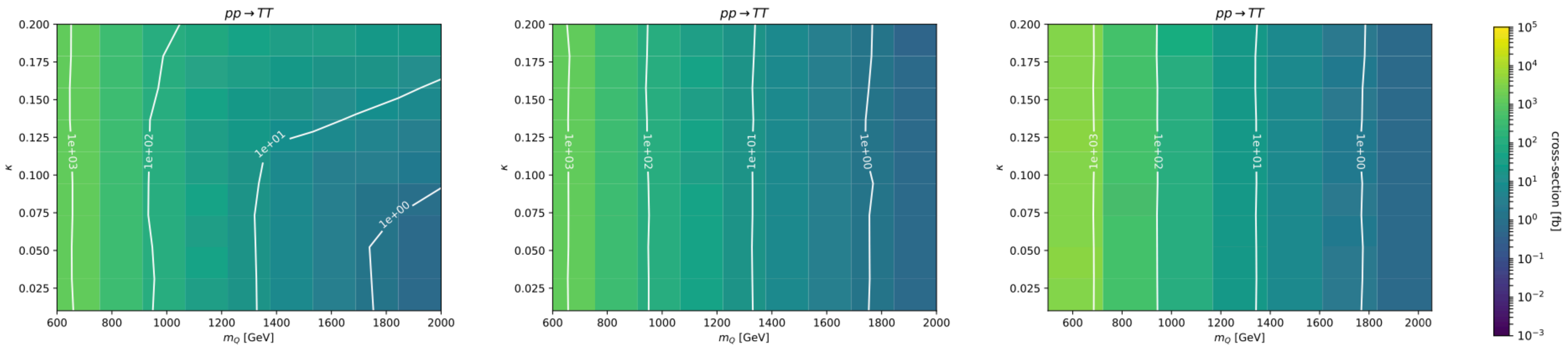
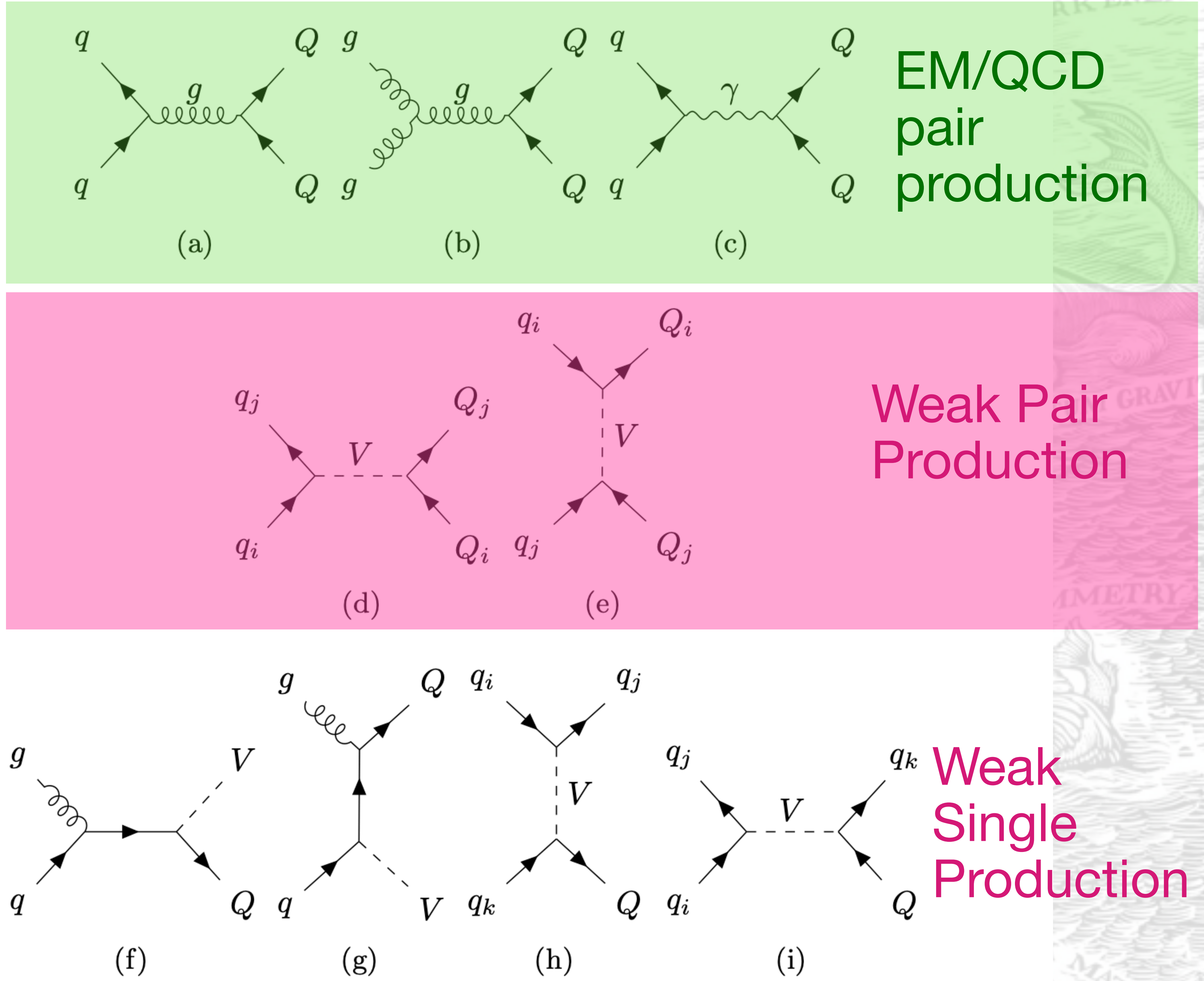


Figure 6: Sensitivity of LHC measurements to VLQ production when B, T, X, Y are degenerate in mass. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed white) exclusion contours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

Assuming ξ such that W:Z:H=1:1:1



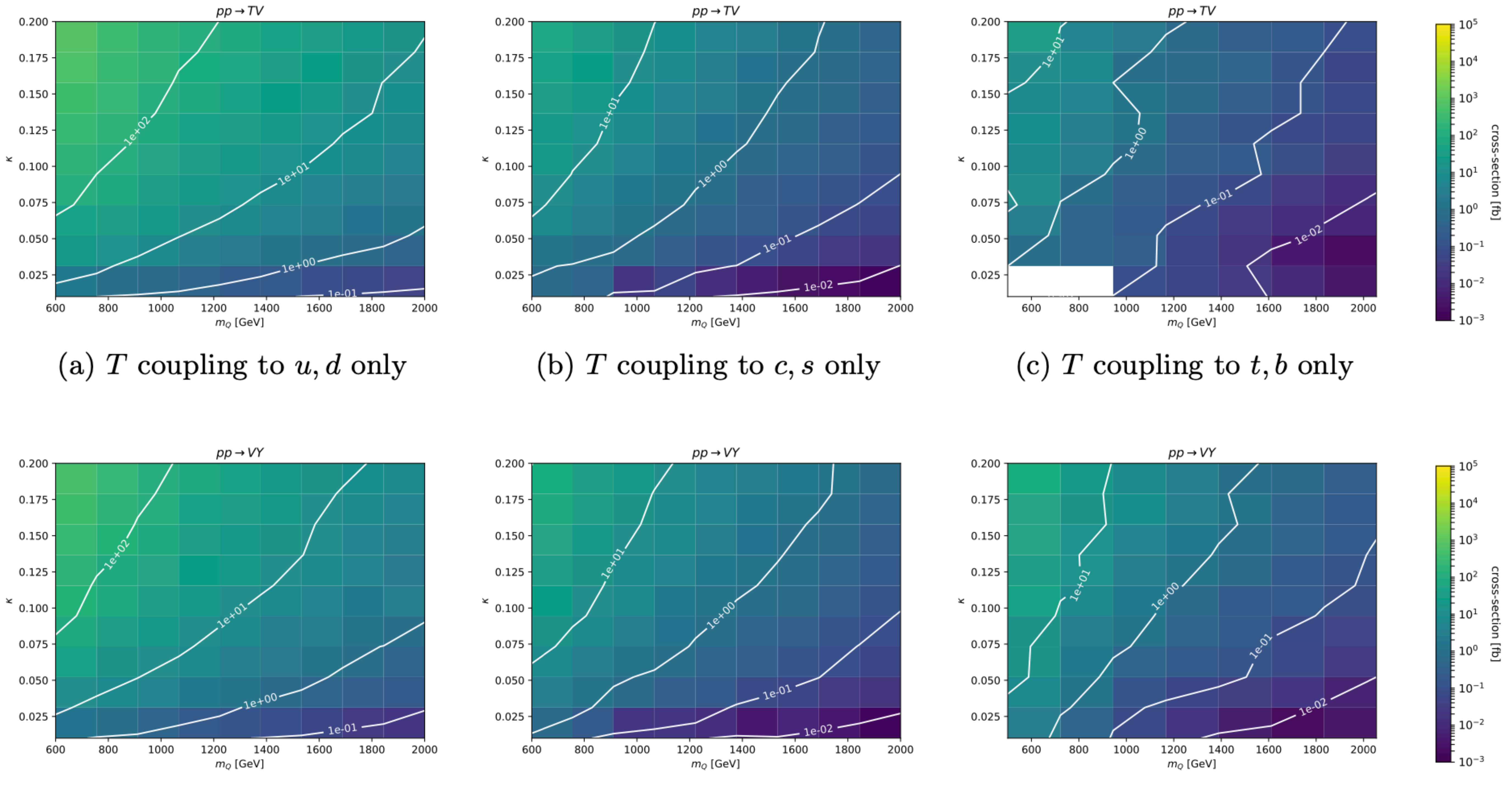
(a) T coupling to u, d only (b) T coupling to c, s only (c) T coupling to t, b only



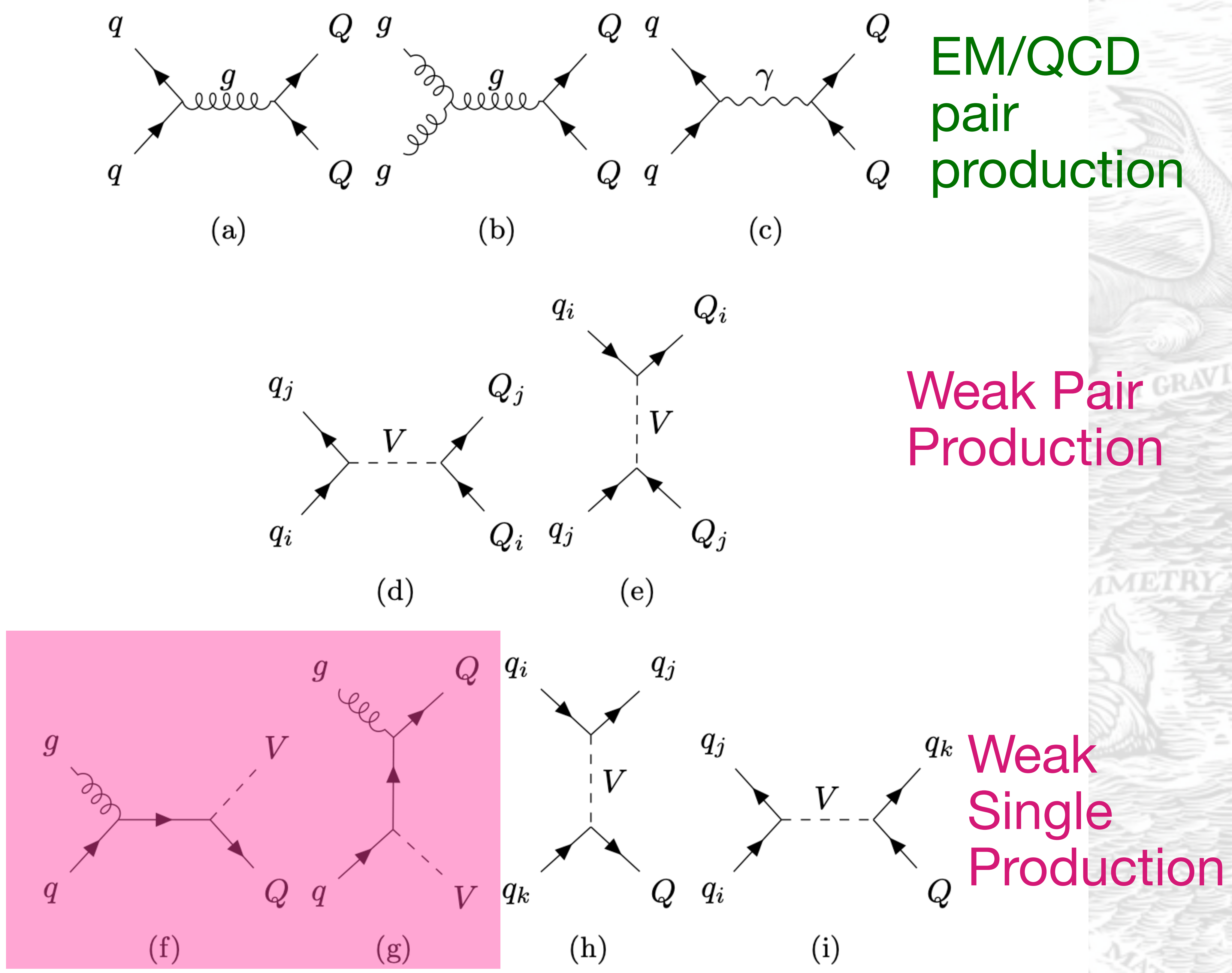
1st-gen couplings: even pair-production has κ-dependence due to weak production initiated by valence quarks

VLQs

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



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

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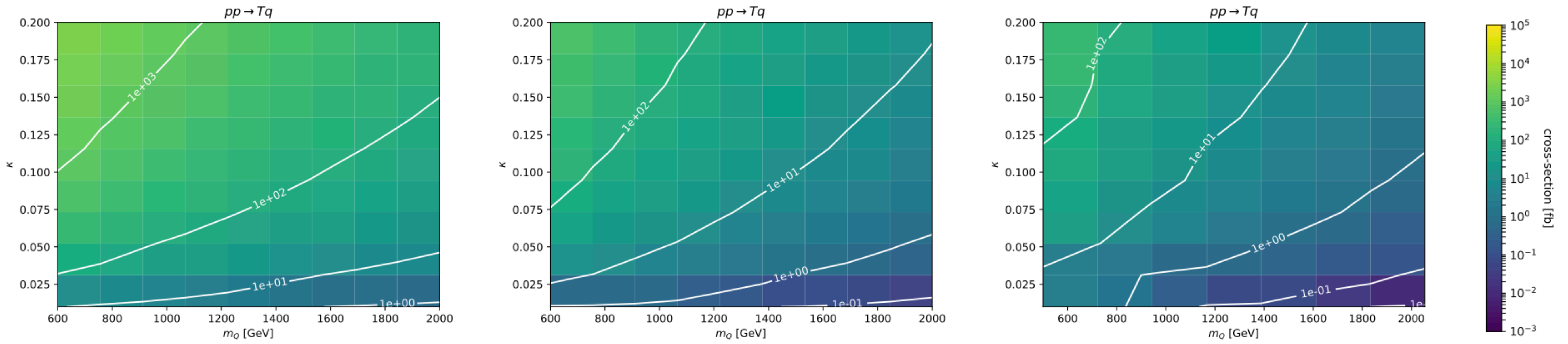
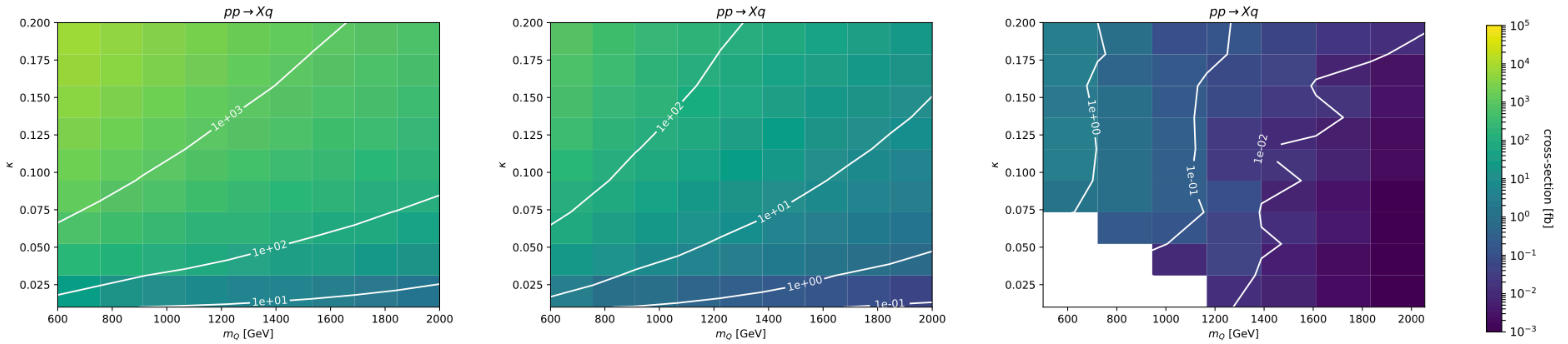
VLQs

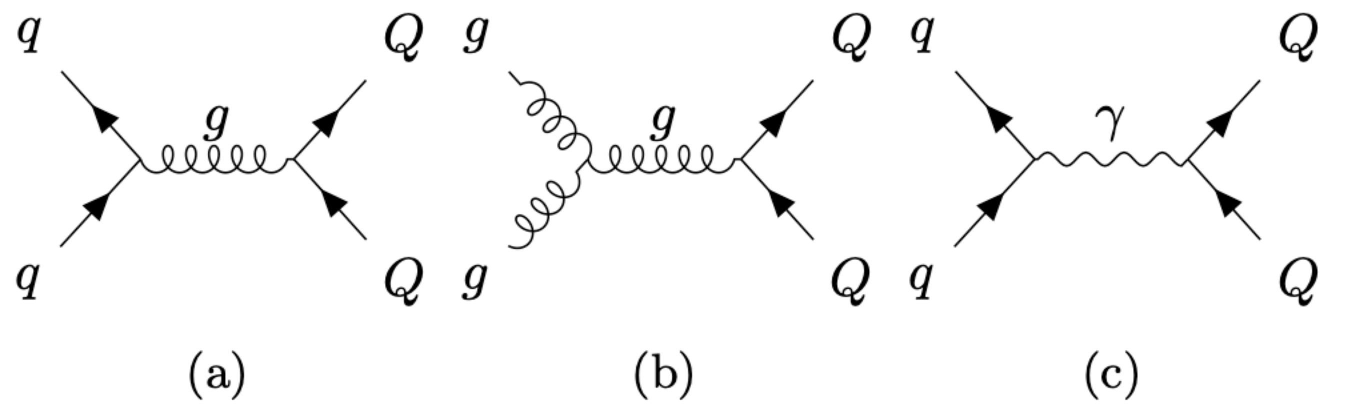
Assuming ξ such that W:Z:H=1:1:1



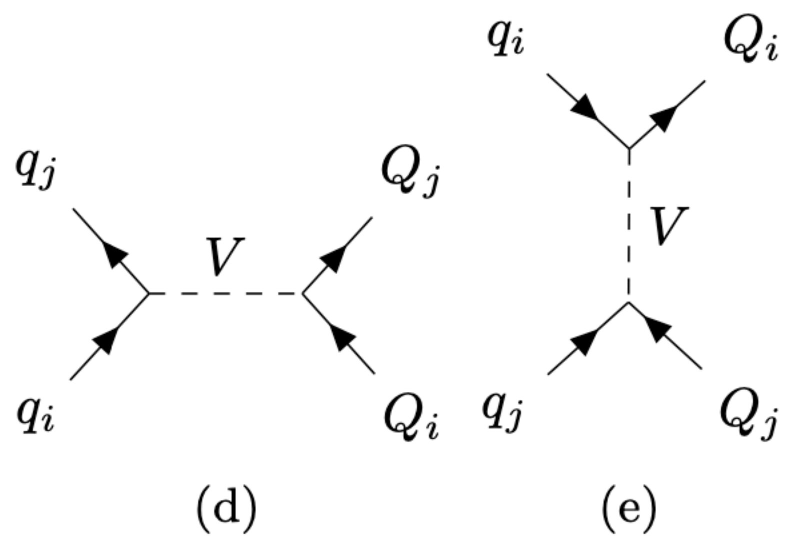
(a) T coupling to u, d only (b) T coupling to c, s only (c) T coupling to t, b only



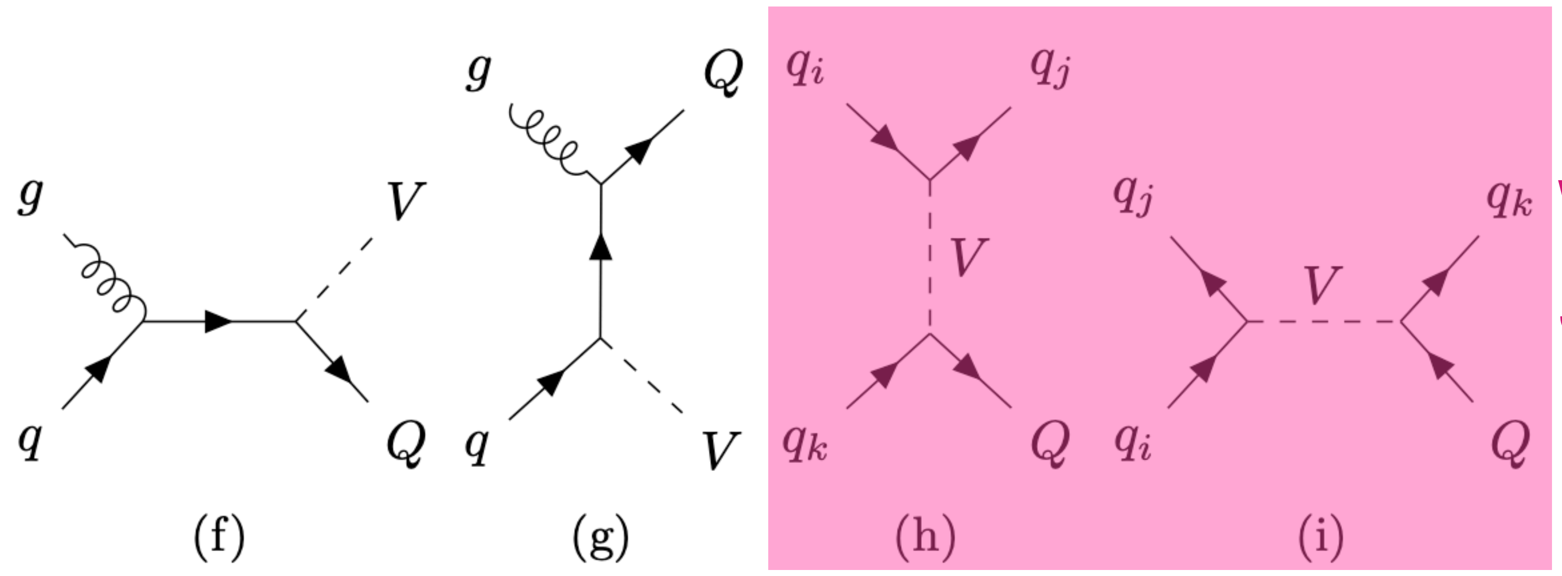
(d) X coupling to u, d only (e) X coupling to c, s only (f) X coupling to t, b only



EM/QCD pair production



Weak Pair Production



Weak Single Production

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

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