Material from the ATLAS four-lepton differential cross section measurement and its use in Contur/Rivet to constrain VLQs

Joanna Huang

On behalf of the authors

RAMP #4

July 2, 2021

Overview

Measurements of differential cross-sections in four-lepton events in 13 TeV proton-proton collisions with the ATLAS detector

ATLAS Collaboration

Paper Rivet routine HEPData Twiki

New sensitivity of current LHC measurements to vector-like quarks

A. Buckley, J. M. Butterworth, L. Corpe, D. Huang, P. Sun

Paper

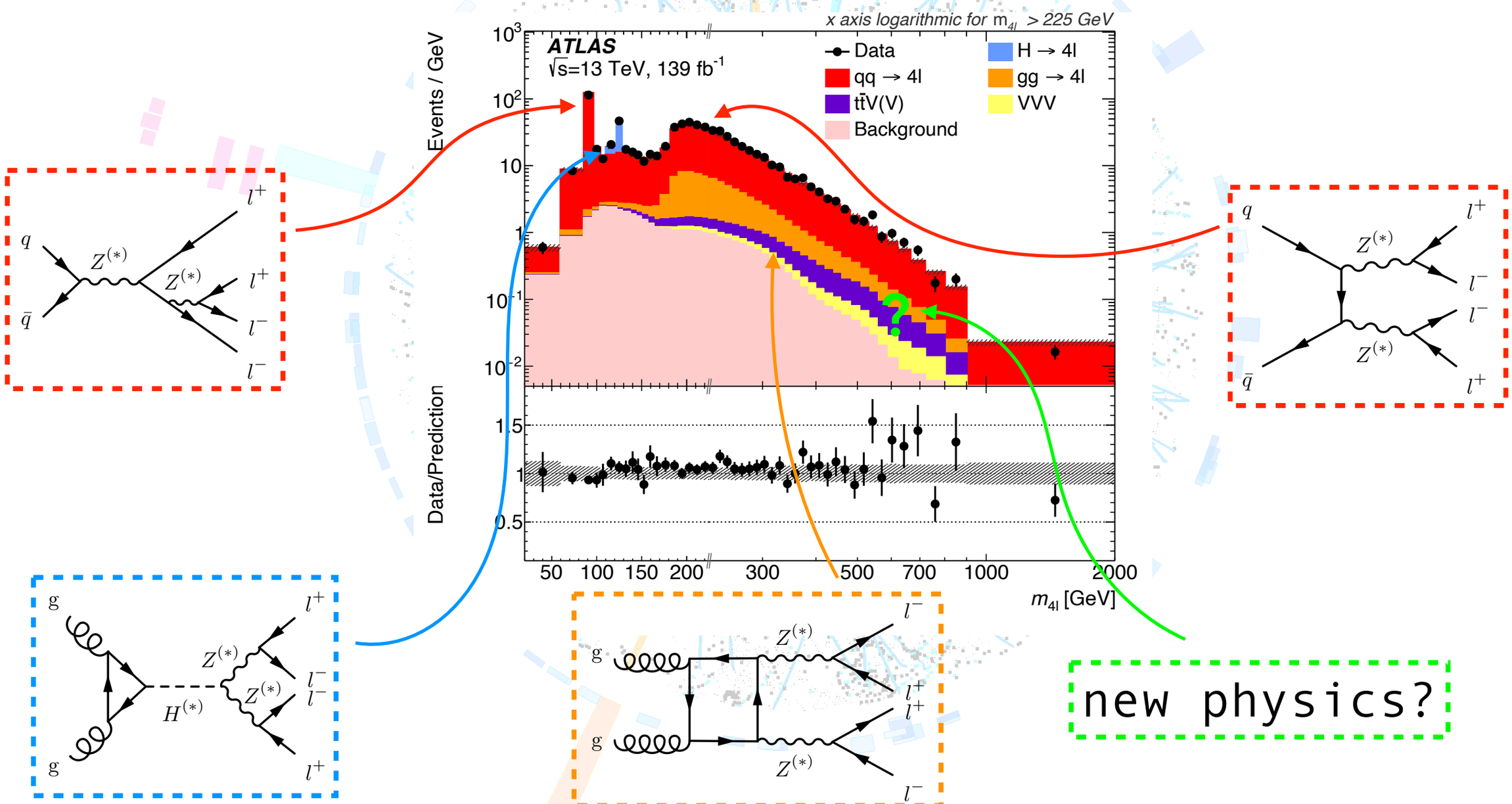
In this talk:

1. Summarize the four-lepton analysis and results
2. Reinterpretation material + an example in constraining VLQs

4 lepton invariant mass measurement

The motivation

- A measurement of the four lepton mass spectrum is a precision test of the Standard Model
  - Contains a lot of interesting physics, and potential for BSM physics
- Full Run 2 m4l analysis focuses on **maximizing inclusivity** and **reducing model dependence**
  - Measurements are corrected for detector effects, analysis workflow preserved in Rivet
  - **Re-interpretable** in the future to set **limits on new physics** scenarios



Analysis strategy

- Designed to be as inclusive as possible
- Any process leading to the production of at least four leptons in the hard scatter is considered to be part of the signal
  - Possible combinations: $e^+e^-e^+e^-$ $\mu^+\mu^-\mu^+\mu^-$ $e^+e^-\mu^+\mu^-$ $\mu^+\mu^-e^+e^-$
- **Quadruplet formation**: unique set of exactly four leptons per event is chosen
  - SFOS lepton pair with an invariant mass closest to the Z boson is the primary pair and second closest pair is the secondary pair

Table 1: Definition of the fiducial region.

Lepton selection	
Muon selection	Bare, $p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electron selection	Dressed, $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Event selection	
Four-lepton signature	At least 4 leptons, with 2 Same-Flavour, Opposite-Sign pairs
Lepton kinematics	$p_{\mathrm{T}} > 20/10$ GeV for leading two leptons
Lepton separation	$\Delta R_{ij} > 0.05$ for any leptons
J/ψ-Veto	$m_{ij} > 5$ GeVfor all SFOS pairs
Truth isolation	ptcone30/$p_{\mathrm{T}} < 0.16$

- Reducible background:
  - The subtracted background is when there are one or more “fake” leptons
  - Estimated with data-driven approach; contributes < 10% in most bins

Observables

- 4 lepton invariant mass spectrum ($m_{4\ell}$) from 20 - 2000 GeV
- Double differential $m_{4\ell}$ in slices of:
  - ➡ Transverse mass of 4 lepton system $p_T^{4\ell}$: [0, 10, 20, 50, 100]
  - ➡ Rapidity of 4 lepton system $|y_{4\ell}|$: [0, 0.3, 0.6, 0.9, 1.2, 2.5]
  - ➡ Flavour channel: $4e$ 4μ $2e2\mu/2\mu2e$
- New variables in **four slices of** $m_{4\ell}$
  - ➡ Polarization variables $\cos\theta^*_{12}$ $\cos\theta^*_{34}$
  - ➡ $|\Delta\phi_{ll}|$ between leading leptons
  - ➡ $|\Delta\phi_{\text{pairs}}|$ $|\Delta y_{\text{pairs}}|$ between lepton pairs
  - ➡ Invariant mass and transverse momenta of lepton pairs

Single Z
$60 < m_{4\ell} < 100$GeV

Higgs
$120 < m_{4\ell} < 130$GeV

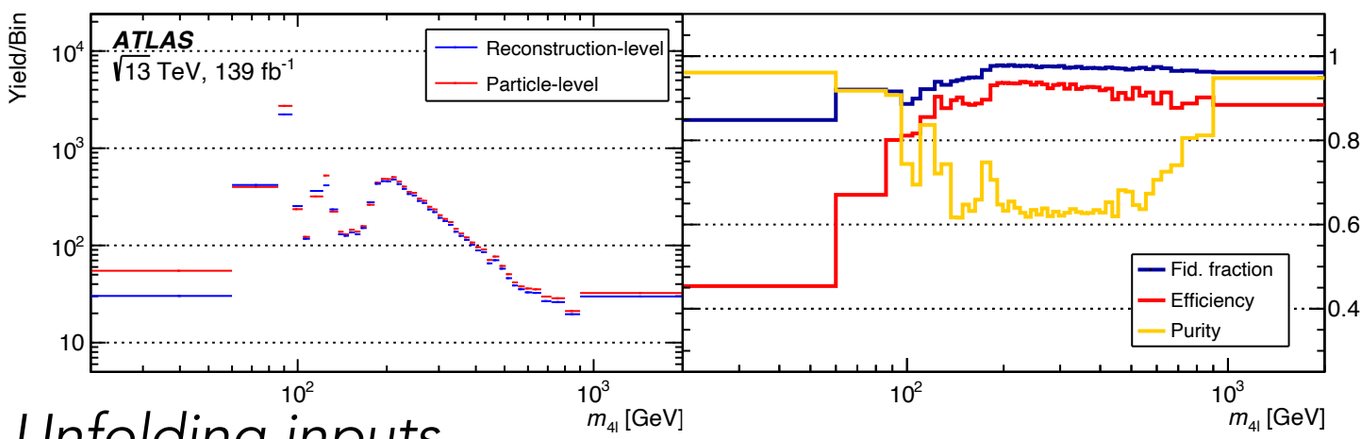
On-shell ZZ
$180 < m_{4\ell} < 2000$GeV

Off-shell ZZ
$20 < m_{4\ell} < 60$GeV,
$100 < m_{4\ell} < 120$GeV,
$130 < m_{4\ell} < 180$GeV

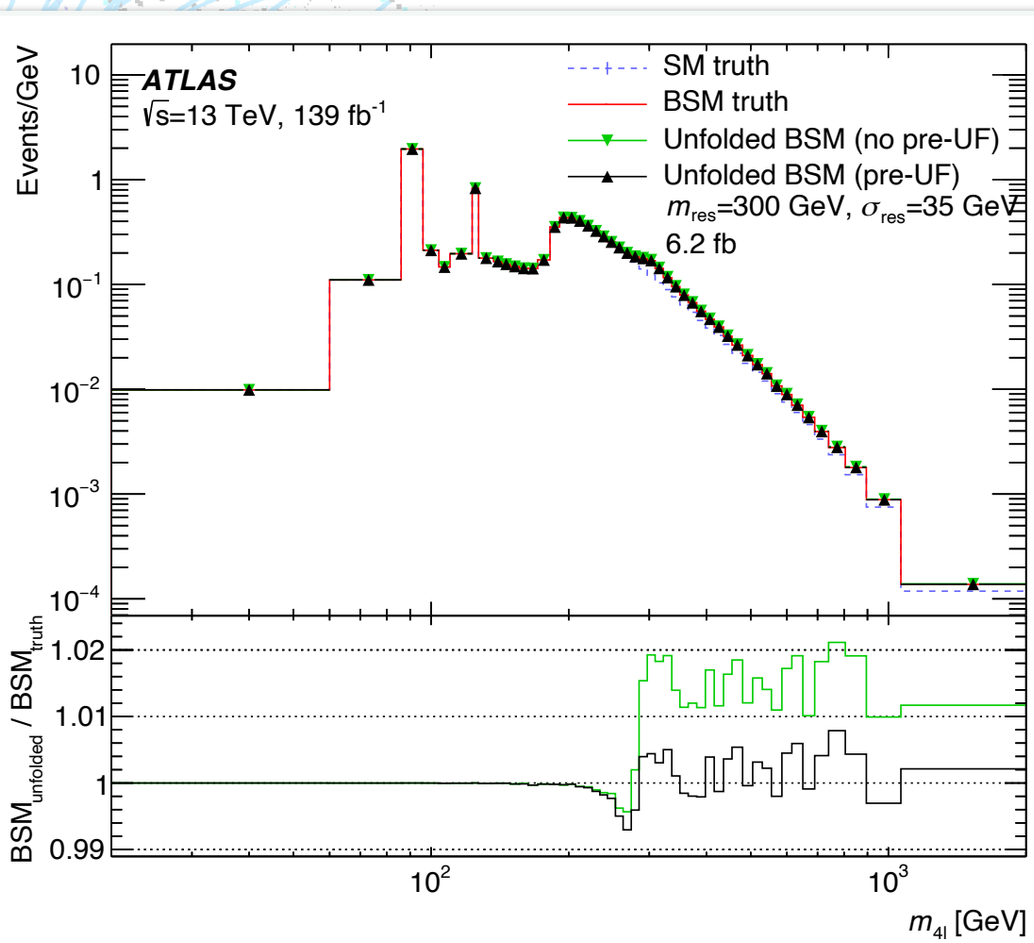
Unfolding optimization

- Binning of distributions optimize for number of reconstructed events and purity
- **Iterative Bayesian unfolding** with either 2/3 iterations, optimized based on the bias and statistical uncertainty
- Monte Carlo and data-driven closure tests show good agreement
- **Injection studies unfold Pseudo-data of SM+BSM using nominal SM simulation** and the result is compared to the particle-level SM+BSM simulation
  - Important as a demonstration that the measurement remains valid in the presence of BSM contributions, and the data can be safely used for re-interpretation

Binning requirements	
# Reco events	**Purity**
[14,20)	80%
[20,25)	70%
≥25	60%



Unfolding inputs



Injection test

Unfolded results

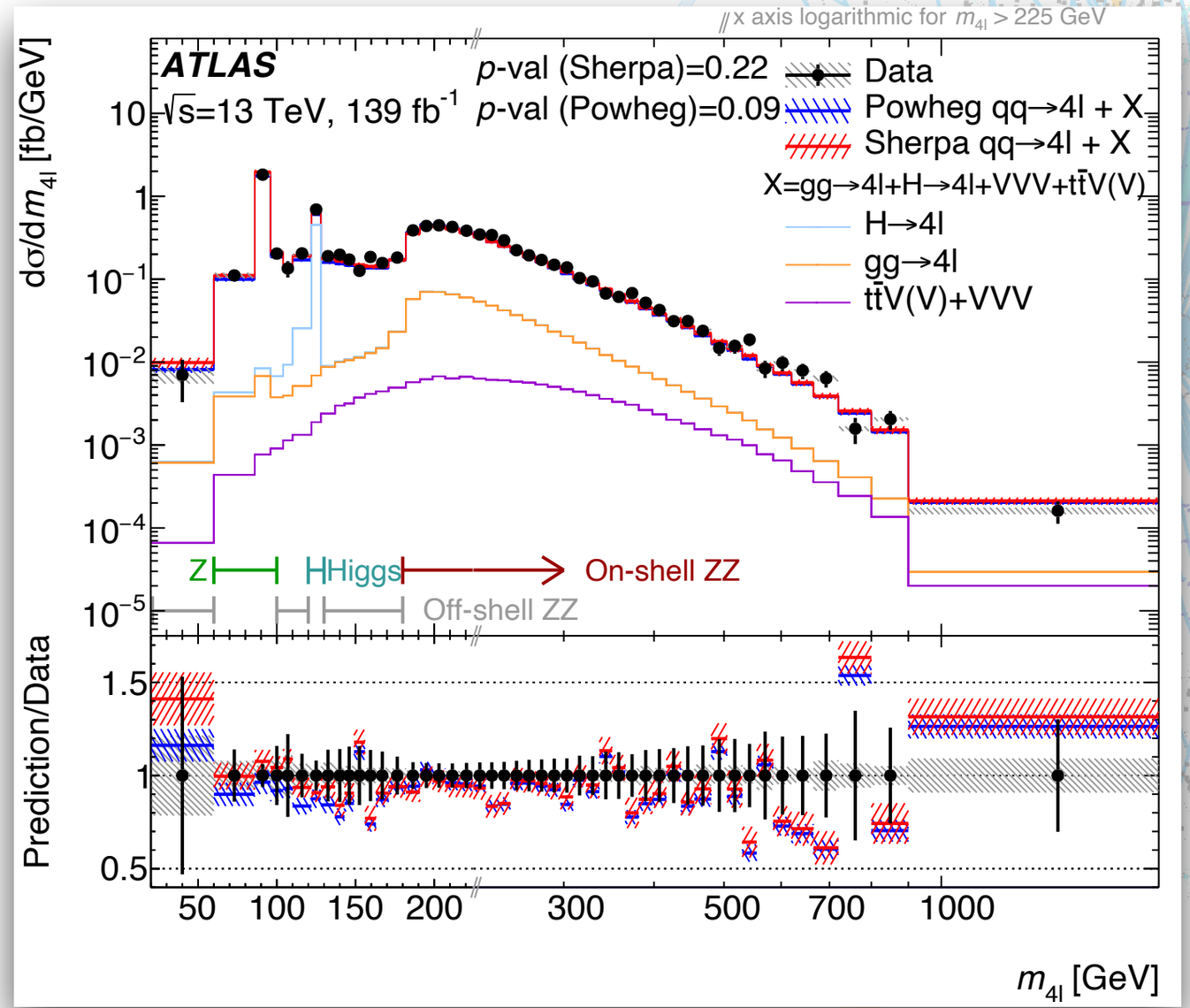
	Region				
	Inclusive	$Z \to 4\ell$	$H \to 4\ell$	Off-shell ZZ	On-shell ZZ
Measured cross-section [fb]	88.9 ±1.1 (stat.) ±2.3 (syst.) ±1.5 (lumi.) ±3.0 (total)	22.1 ±0.7 (stat.) ±1.1 (syst.) ±0.4 (lumi.) ±1.3 (total)	4.76 ±0.29 (stat.) ±0.18 (syst.) ±0.08 (lumi.) ±0.35 (total)	12.4 ±0.5 (stat.) ±0.6 (syst.) ±0.2 (lumi.) ±0.8 (total)	49.3 ±0.8 (stat.) ±0.8 (syst.) ±0.8 (lumi.) ±1.3 (total)
SHERPA	86±5	23.6±1.5	4.57±0.21	11.5±0.7	46.0±2.9
POWHEG + PYTHIA8	83±5	21.2±1.3	4.38±0.20	10.7±0.7	46.4±3.0

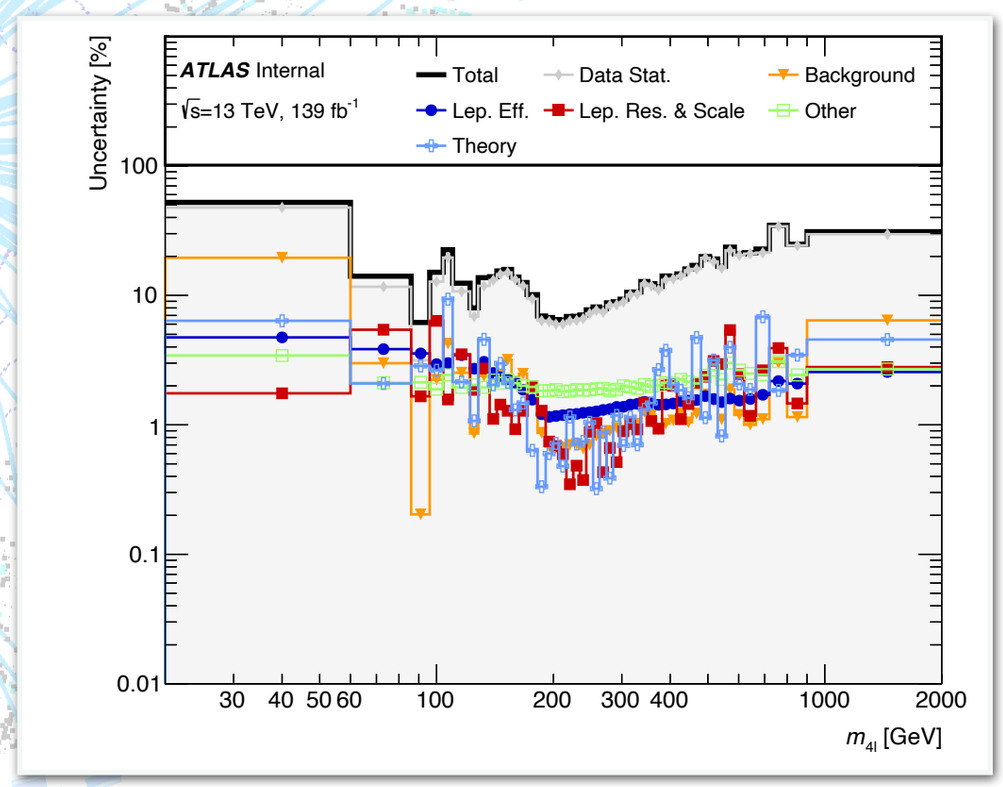
Single Z
60< $m_{4\ell}$ <100GeV

Off-shell ZZ
20< <60GeV,
100< $m_{4\ell}$ <120GeV,
130< $m_{4\ell}$ <180GeV

Higgs
120< $m_{4\ell}$ <130GeV

On-shell ZZ
180< $m_{4\ell}$ <2000GeV





Z → 4l branching fraction

Measured XS in Z→4l region

Predicted fid. XS from non-qqZZ sources

Fraction of qq→4l coming from single Z production

$$\mathcal{B}_{Z\to 4\ell} = \frac{\left(\sigma^{\text{meas}} - \sigma^{\text{pred}}_{\text{non-}q\bar{q}\to 4\ell}\right) \times f_{Z} \times f_{\text{non-}\tau}}{\sigma_{Z} \times A_{\text{fid}}}$$

Total XS from single Z production

From arXiv 1603.09222

Acceptance factor

Fraction of events where no leptons originate from tau decays

$$\begin{aligned} \mathrm{B}_{Z\to 4\ell} &= \left(4.41 \pm 0.13(\text{stat.}) \pm 0.23(\text{syst.}) \pm 0.09(\text{theory}) \pm 0.12(\text{lumi.})\right) \times 10^{-6} \\ &= (4.41 \pm 0.30) \times 10^{-6} \end{aligned}$$

➡ *Most precise measurement to date*

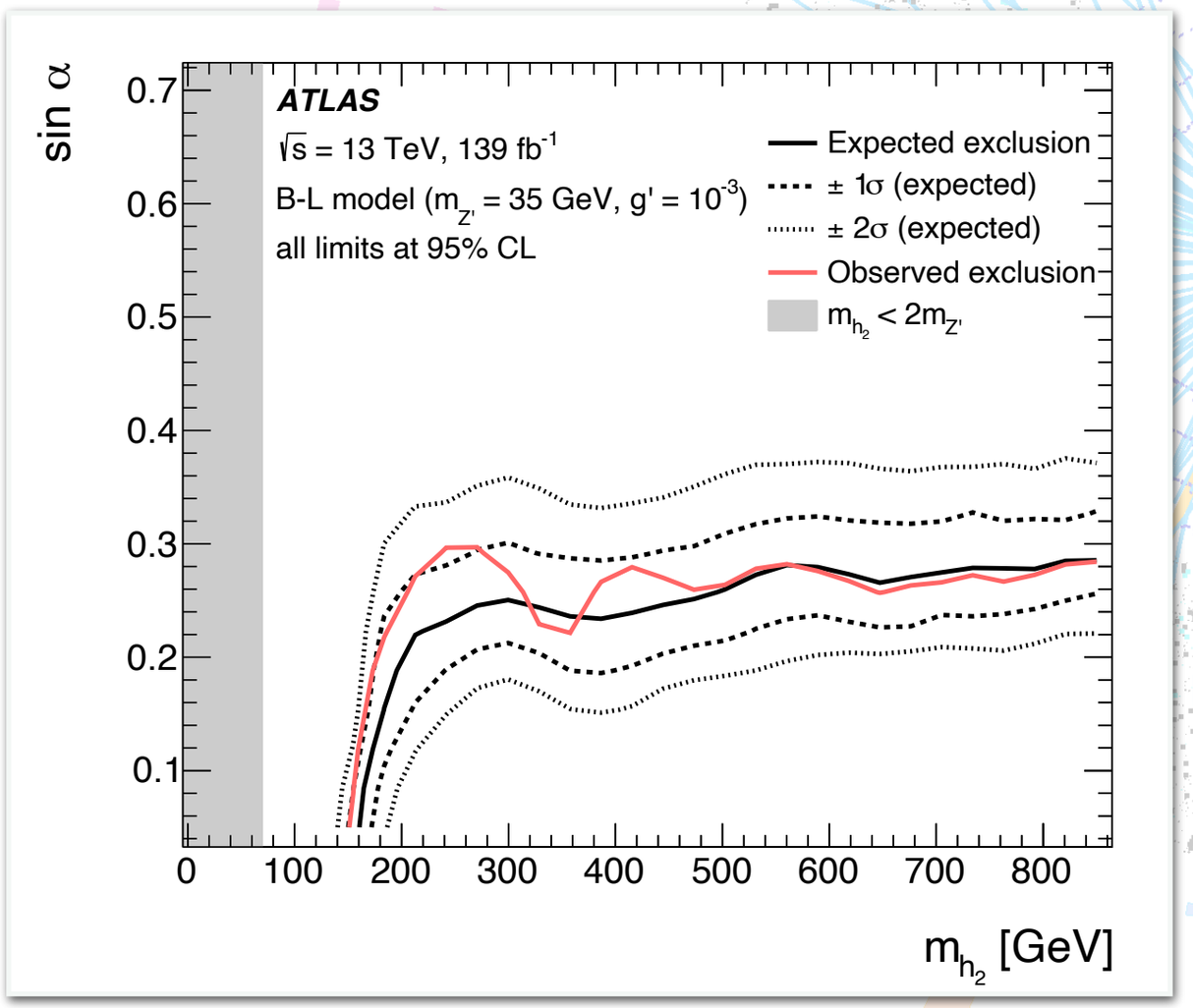
BSM interpretations

- **Variable providing the best expected sensitivity used to set limits** with likelihood function

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k\,|C|}} \exp\left\{-\frac{1}{2}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]^T C^{-1}\left[\vec{\sigma}^{\text{meas}} - \vec{\sigma}^{\text{pred}}\left(\vec{\theta}\right)\right]\right\} \times \prod_i \mathcal{G}\left(\theta_i, 0, 1\right)$$

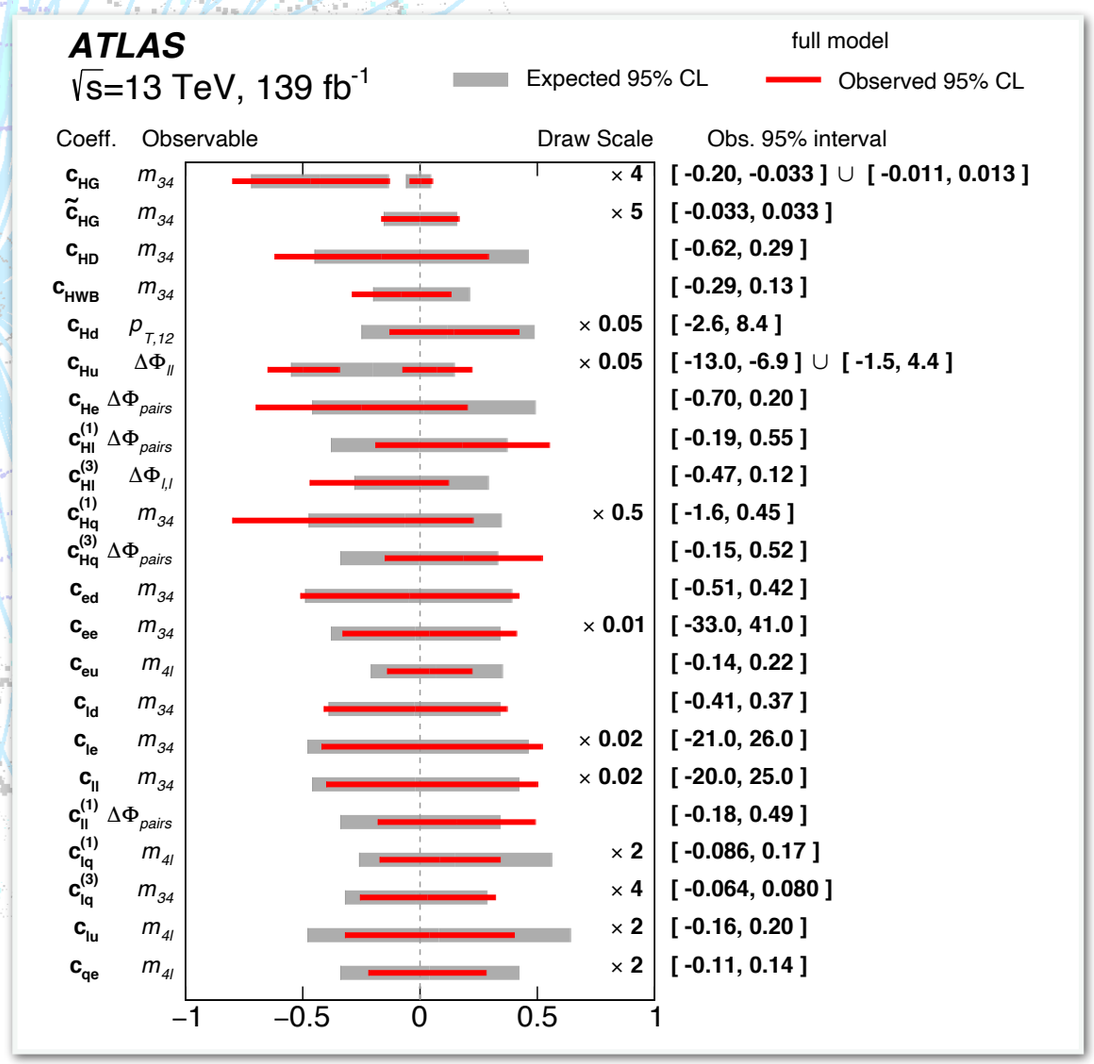
1. B-L gauge model

- Spontaneously B-L gauge symmetry breaking
- Particles introduced: Z', exotic Higgs h_2, with mixing angle α



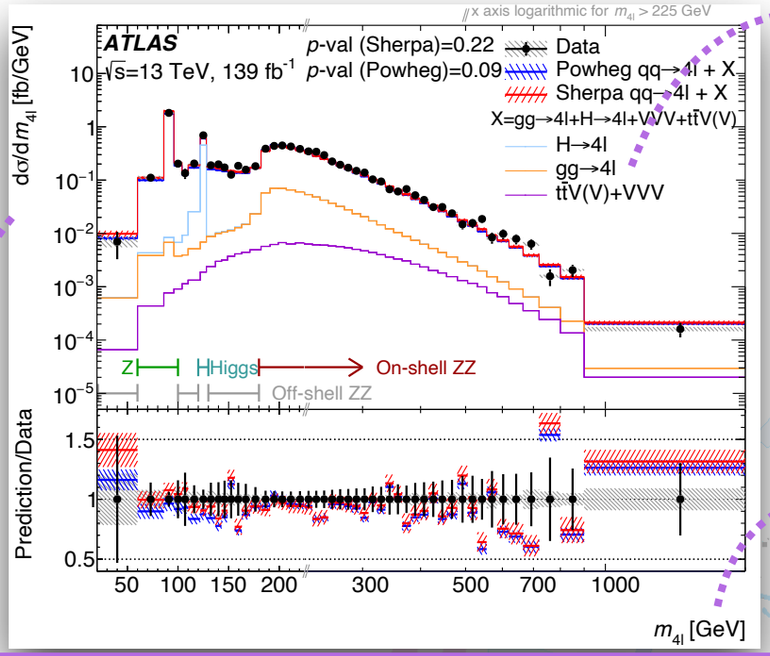
2. EFT

- SM effective field theory formalism
- Independent constraints on 22 coefficients



Re-interpretation

Is it re-interpretable?



No subtraction of irreducible background

Analysis is defined in terms of final state

Data is corrected for detector effects

Source code: `ATLAS_2021_I1849535.cc`

Rivet routine

```
// -*- C++ -*-
#include "Rivet/Analysis.hh"
#include "Rivet/Projections/FinalState.hh"
#include "Rivet/Projections/PromptFinalState.hh"
#include "Rivet/Projections/VetoedFinalState.hh"
#include "Rivet/Projections/ChargedFinalState.hh"
#include "Rivet/Projections/DressedLeptons.hh"

namespace Rivet {

  /// @name M4lLineshape analysis
  class ATLAS_2021_I1849535 : public Analysis {
    public:

      /// Constructor
      DEFAULT_RIVET_ANALYSIS_CTOR(ATLAS_2021_I1849535);

      void init() {

        // Selection
        Cut el_fid_sel = (Cuts::abseta < 2.47) && (Cuts::pT > 7*GeV);
        Cut mu_fid_sel = (Cuts::abseta < 2.7) && (Cuts::pT > 5*GeV);

        PromptFinalState photons(Cuts::abspid == PID::PHOTON);
        PromptFinalState elecs(Cuts::abspid == PID::ELECTRON);
        PromptFinalState muons(Cuts::abspid == PID::MUON && mu_fid_sel);
        elecs.acceptTauDecays(true);
        muons.acceptTauDecays(true);


        // Final state including all charged particles
        declare(ChargedFinalState(), "CFS");

        DressedLeptons dressed_elecs(photons, elecs, 0.1, el_fid_sel, false);
        declare(dressed_elecs, "elecs");

        declare(muons, "muons");
```

HEPData

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Rivet Analysis **Measurements of differential cross-sections in four-lepton events in 13 TeV proton-proton collisions with the ATLAS detector**

The ATLAS collaboration Aad, Georges ; Abbott, Brad ; Abbott, Dale Charles ; *et al.*

CERN-EP-2021-019, 2021.

Inspire Record 1849535 DOI 10.17182/hepdata.94413

Measurements of four-lepton differential and integrated fiducial cross-sections in events with two same-flavour, opposite-charge electron or muon pairs are presented. The data correspond to 139 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collisions, collected by the ATLAS detector during…

65 data tables match query

m4l	Inclusive differential cross section for four leptons (Max = 1710~GeV).
m4l_4mu	Inclusive differential cross section for four muons (Max = 1320~GeV)
m4l_4e	Inclusive differential cross section for four electrons (Max = 887~GeV).

More…

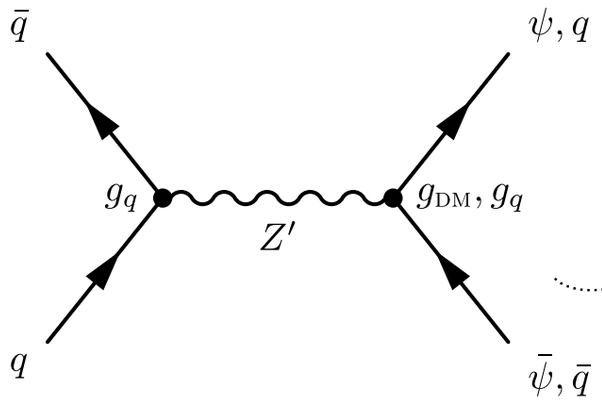
HEPData

Analysis workflow is preserved in Rivet

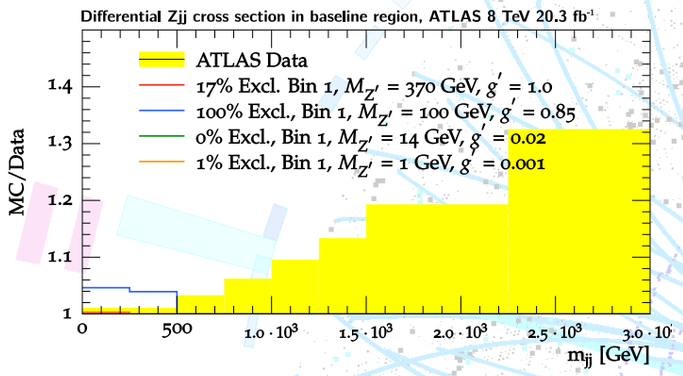
All data, uncertainties, & predictions are published on HEPData

Re-interpretation with Contur

[Contur talk at (re)interpretation forum]
[Contur manual]



$$\{g_{\rm DM}, g_q, m_{Z'}, m_\phi\}$$

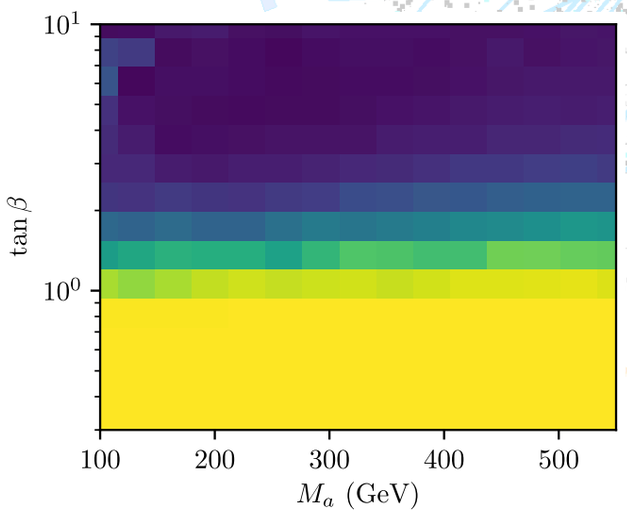


Sampling model parameters
contur-batch

Calculate observables
event generators, Rivet, ...

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

Evaluating the likelihood for a model
contur



Visualisation of parameter space
contur-plot, contur-mkhtml, ...

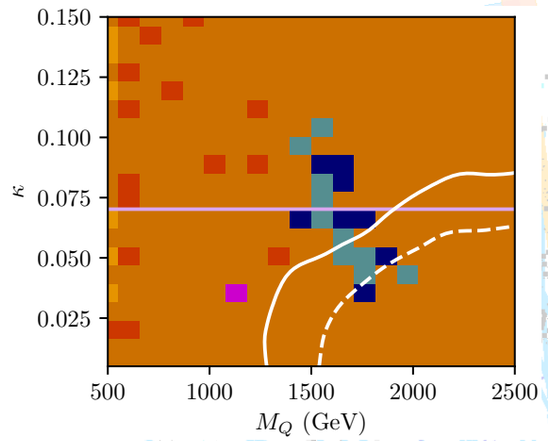
Contur limits on VLQs

arXiv 2006.07172

- Consider VLQs coupling to each of the SM quark generations, in different W:H:Z coupling scenarios
- Colours show which final state signature gave the dominant exclusion at each parameter point

First gen

W:H:Z = 0:0:1

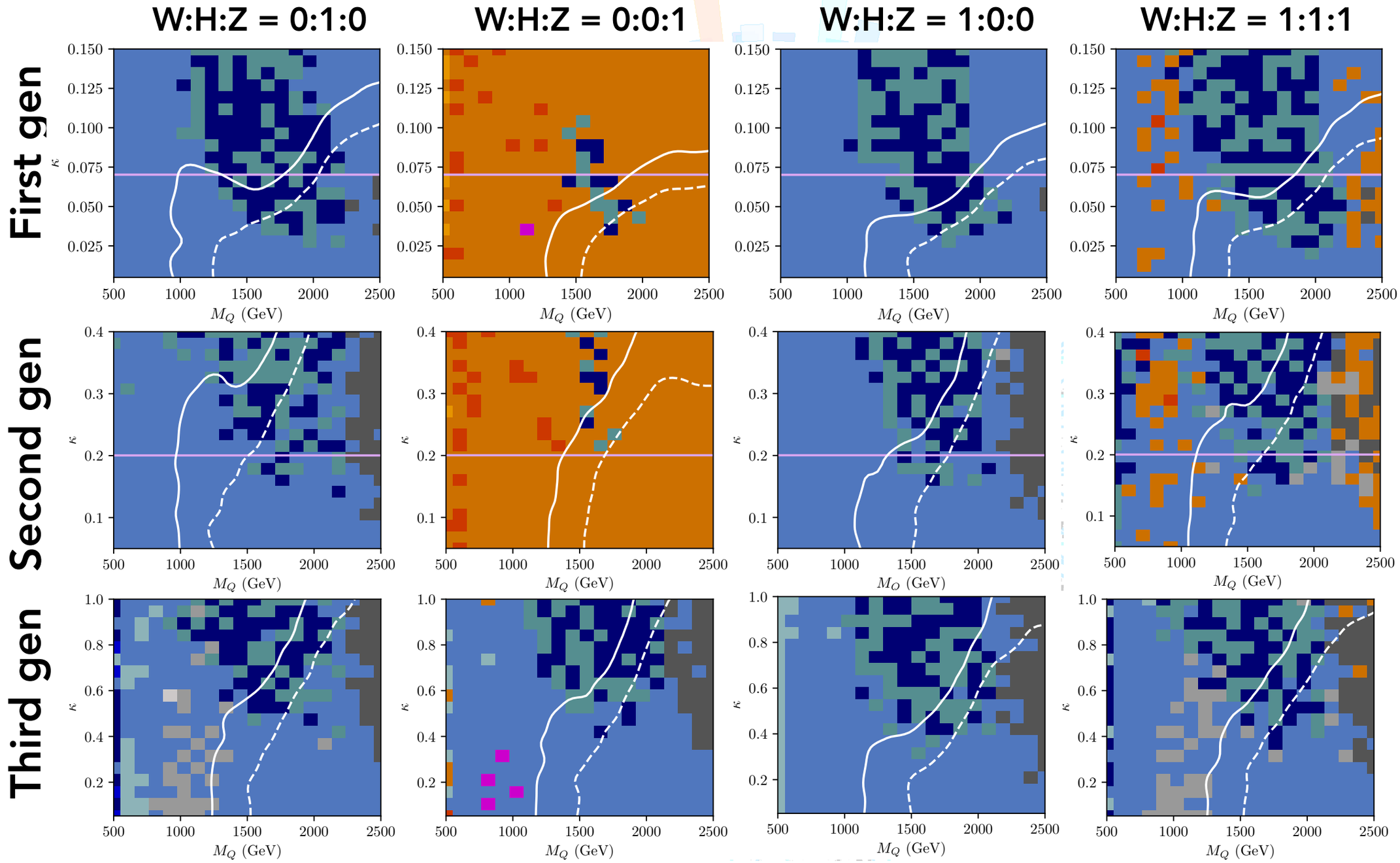


ATLAS ℓ+MET+jet
ATLAS WW
ATLAS ee+jet
ATLAS ℓ+MET+jet
ATLAS μ+$E_{\mathrm{T}}^{\mathrm{miss}}$+jet
ATLAS $\mu\mu$+jet
ATLAS $t\bar{t}$ hadr
ATLAS e+$E_{\mathrm{T}}^{\mathrm{miss}}$+jet
ATLAS $\ell\ell$+jet
ATLAS 4ℓ
ATLAS jets
CMS jets

Contur limits on VLQs

arXiv 2006.07172

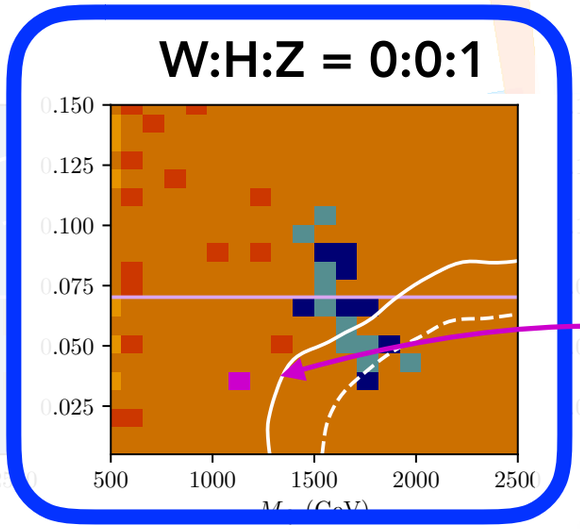
- Consider VLQs coupling to each of the SM quark generations, in different W:H:Z coupling scenarios
- Colours show which final state signature gave the dominant exclusion at each parameter point



Contur limits on VLQs

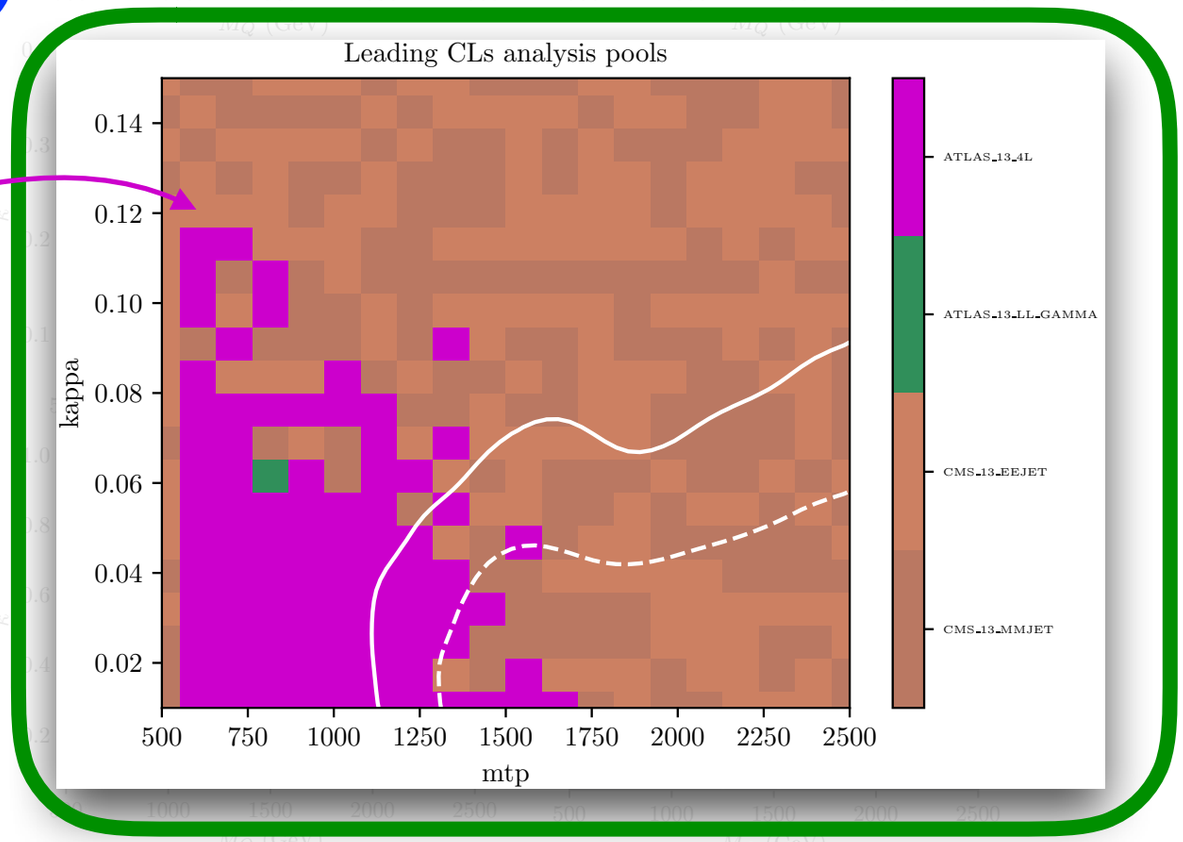
arXiv 2006.07172

Result from paper using
Contur 1.2.2 and Rivet 3.1.1



Here the ATLAS 4l pool is sub-dominant

Updated scan using
Contur 2.0.x and Rivet 3.1.4

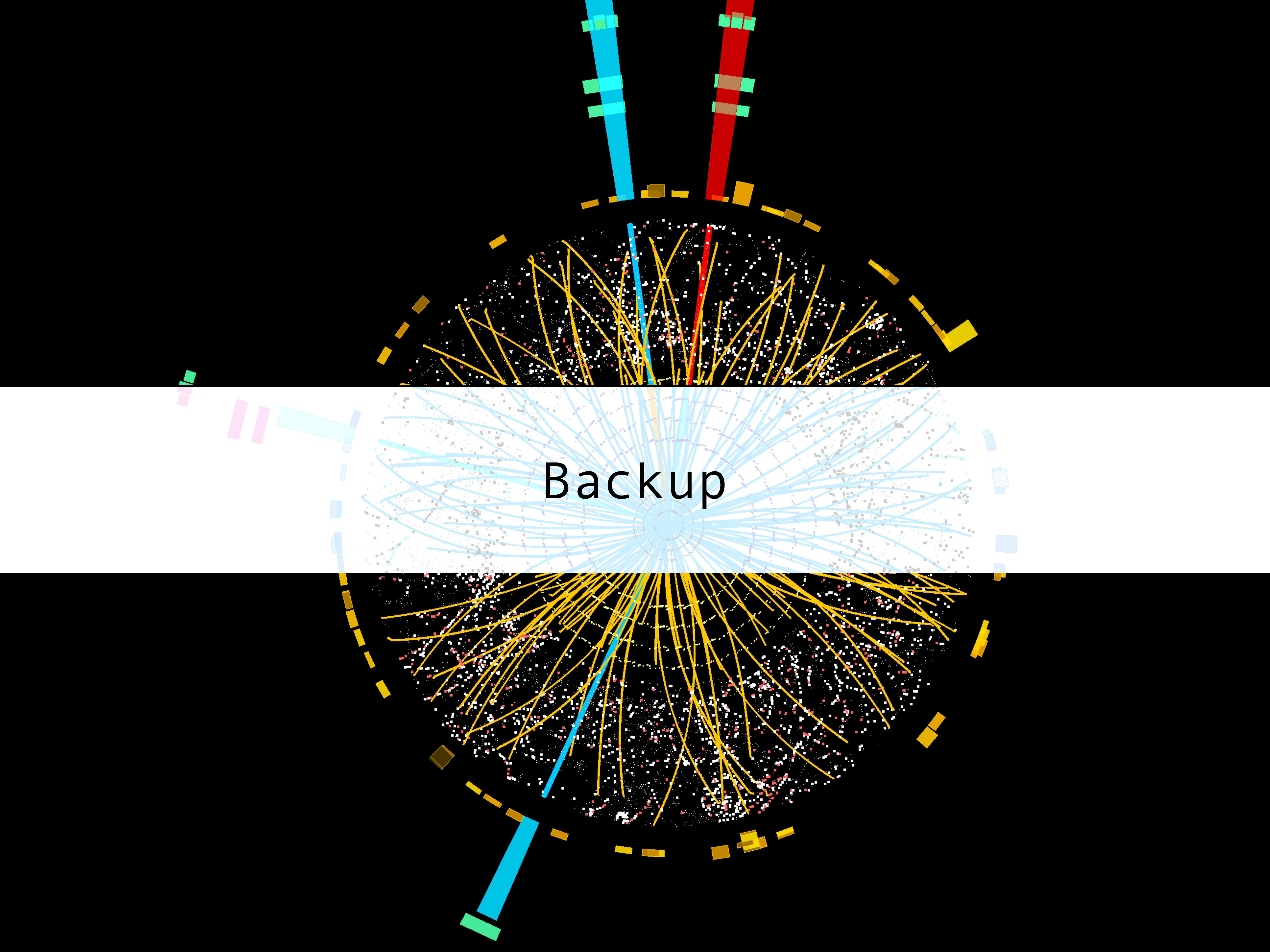


… but the addition of the new m4l measurement gives it more exclusion power!

ATLAS ℓ+MET+jet
ATLAS WW
ATLAS ee+jet
ATLAS ℓ+MET+jet
ATLAS μ+$E_{\mathrm{T}}^{\mathrm{miss}}$+jet
ATLAS $\mu\mu$+jet
ATLAS $t\bar{t}$ hadr
ATLAS e+$E_{\mathrm{T}}^{\mathrm{miss}}$+jet
ATLAS $\ell\ell$+jet
ATLAS 4ℓ
ATLAS jets
CMS jets

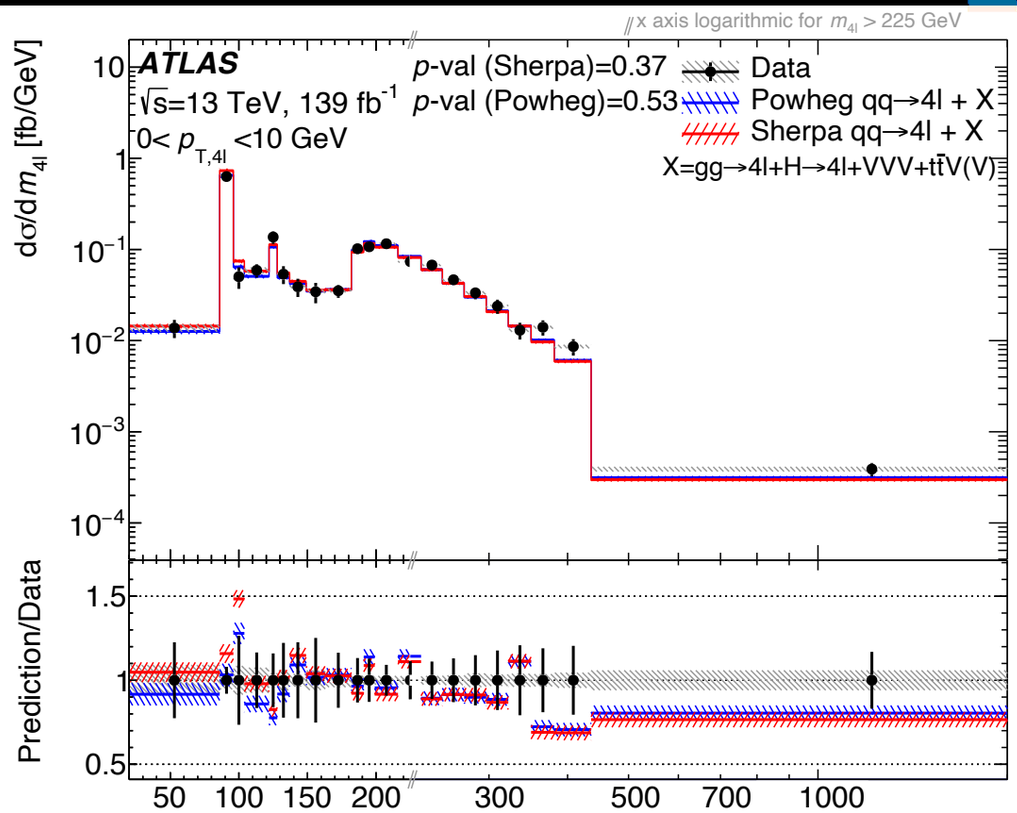
Summary

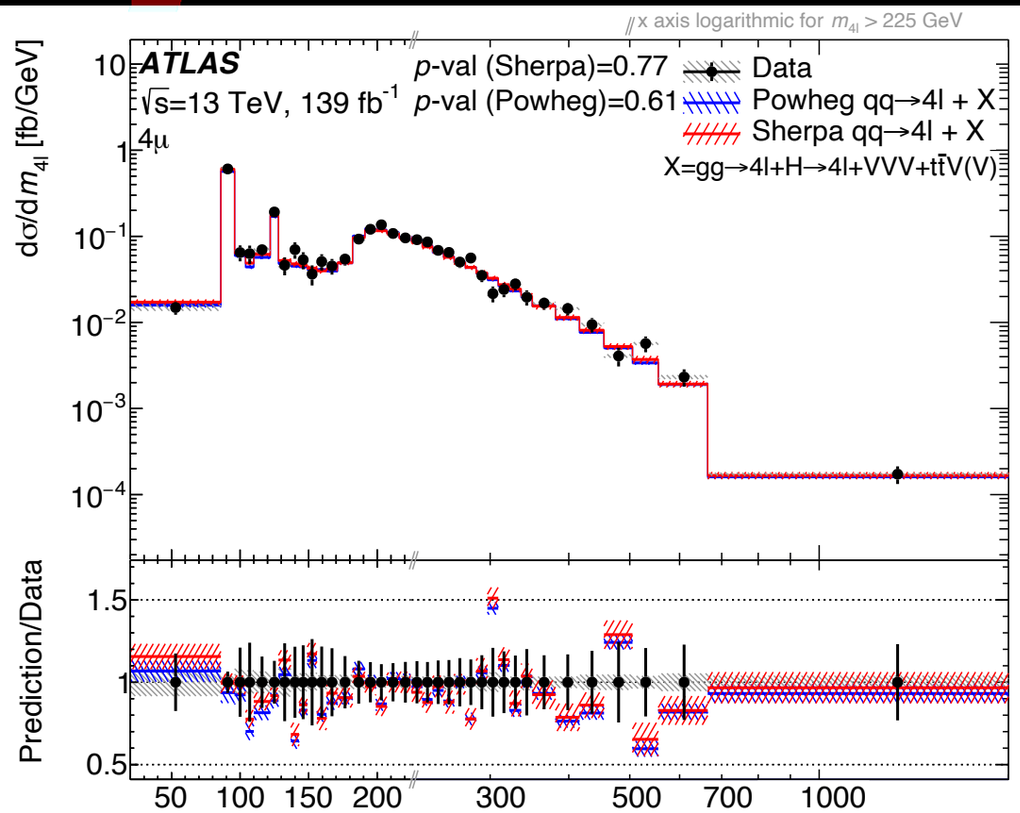
- ATLAS measurements of four-lepton invariant mass was designed with re-interprebility in mind!
  - Clean final state, low background, wide acceptance, and minimal model dependence
- Unfolded data are used to extract **Z → 4l branching fraction**, **constrain SMEFT coefficients** and set **constraints on gauged B-L model**
- Data, covariance matrices, and SM predictions made available in **HEPData**, and **Rivet** routine will be provided for **future reinterpretation**
- The m4l measurement plays a role in constraining VLQs, and has the potential to constrain other BSM models
  - Quick and easy to do using **Contur**

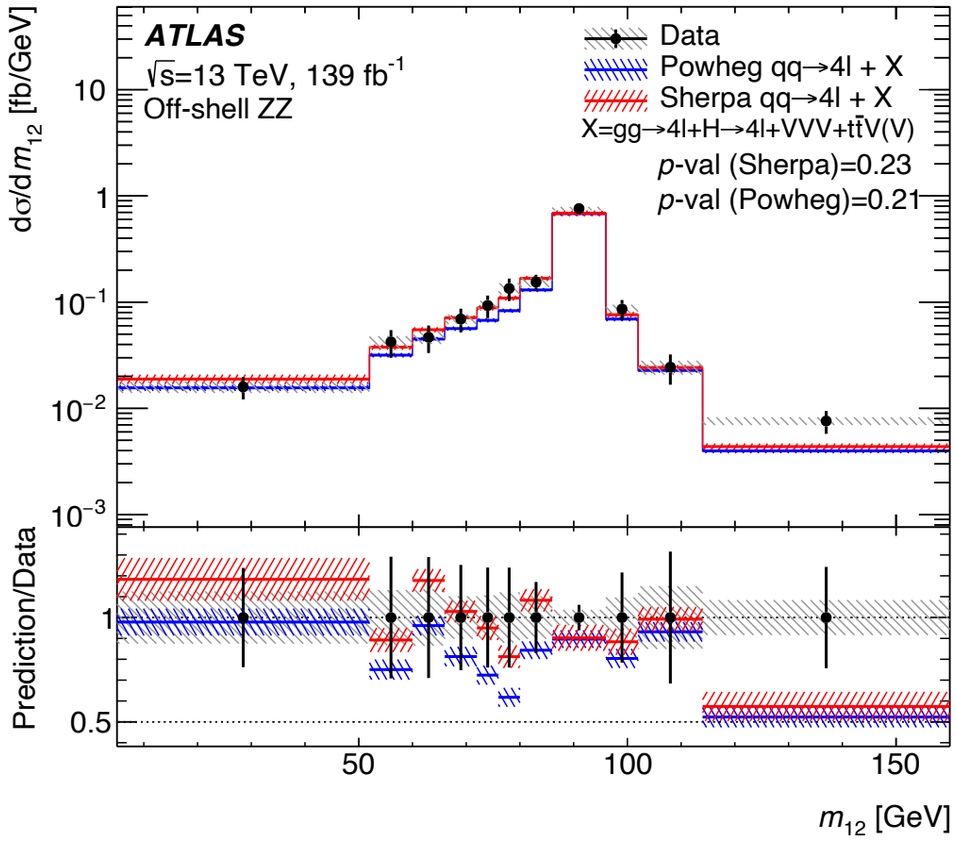


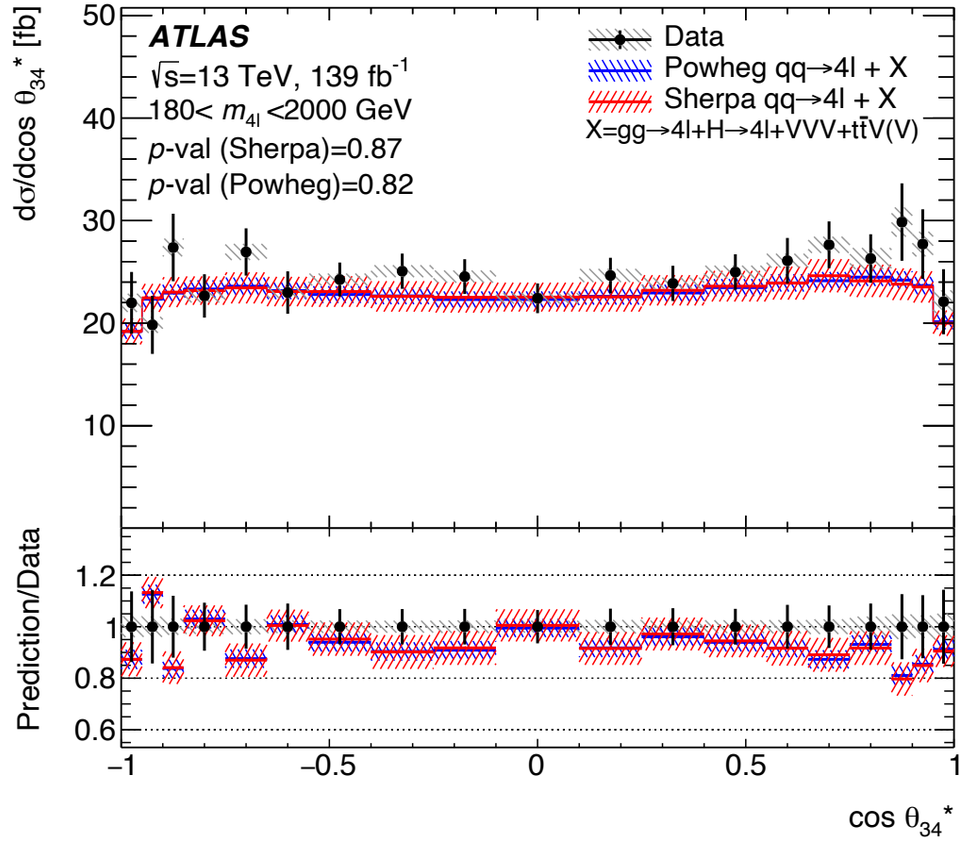
Backup

Unfolded results

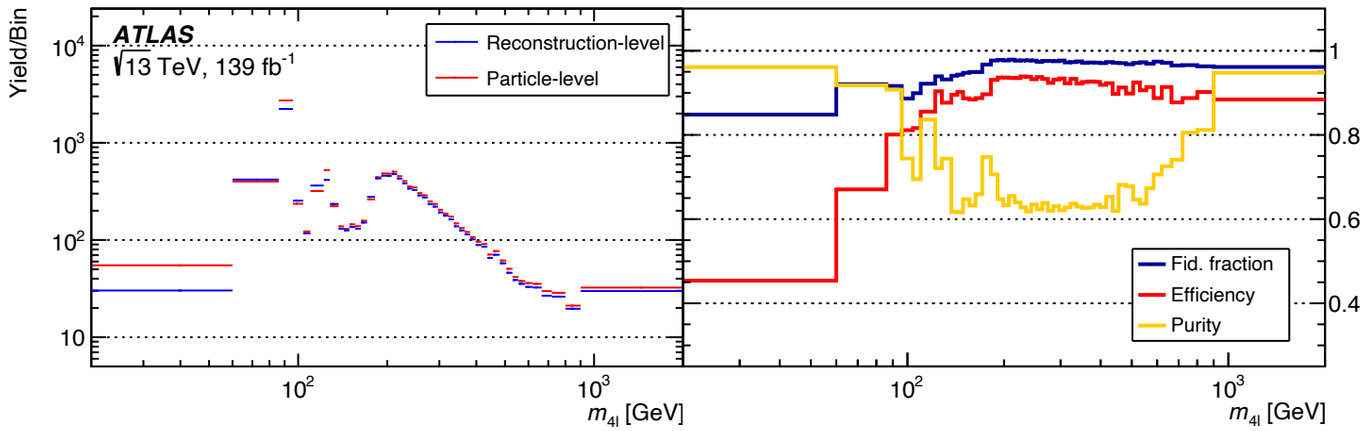


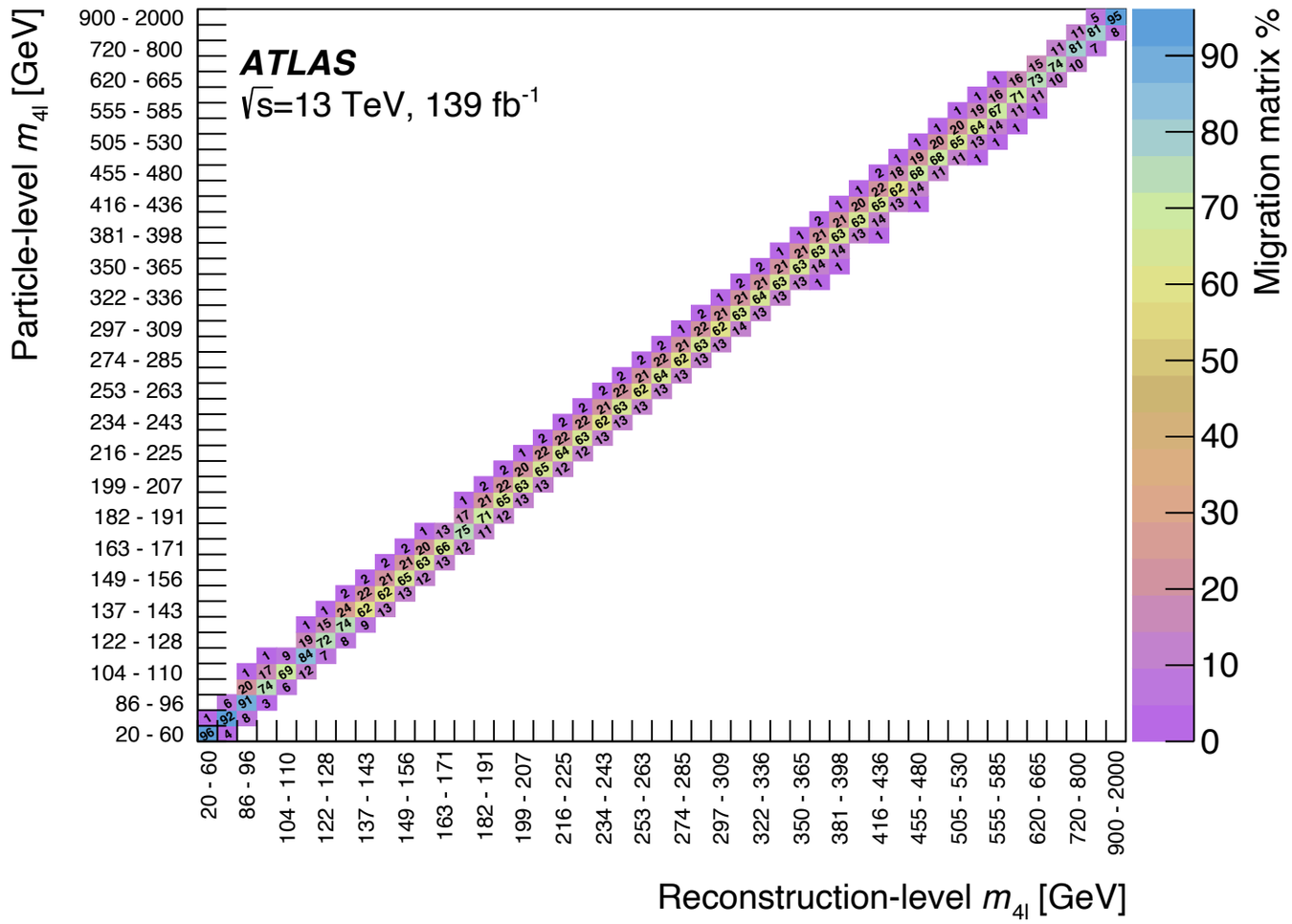






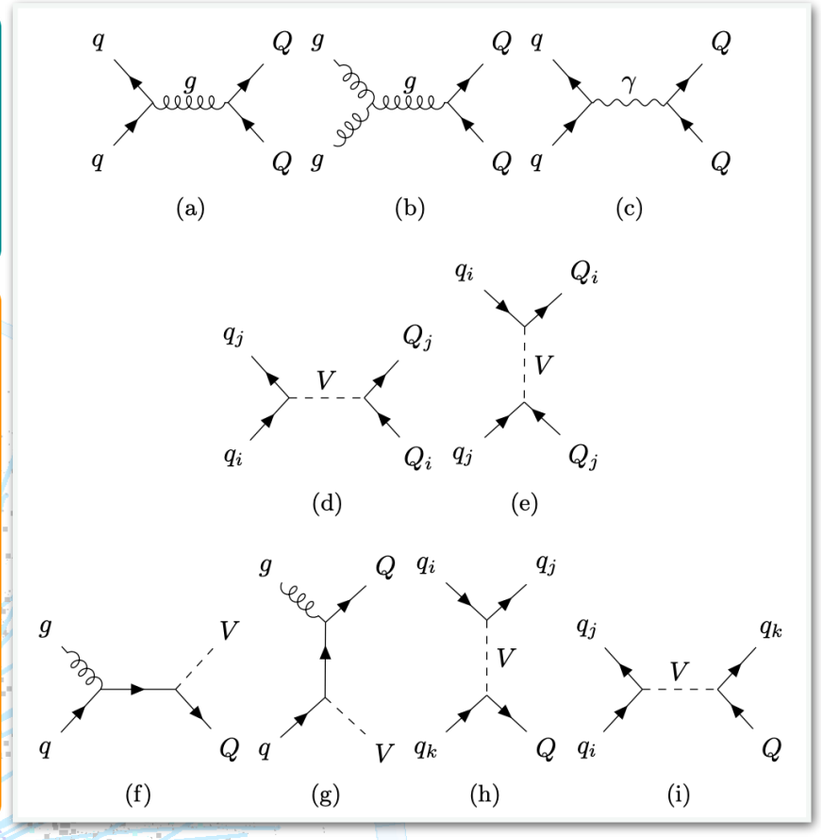
Unfolding inputs





VLQ introduction

- Vector-like quarks (VLQ) are the simplest type of coloured fermions still allowed by experimental data
- Typically, LHC searches assume coupling only to third-generation SM quarks
- We use **existing particle level measurements** to set more **general limits on novel scenarios**, such as mixing only with first or second generation



Coupling to SM quark generations ζ_i

$$\mathcal{L} = \kappa_T \left[\sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_{L/R} Z_\mu \gamma^\mu u_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M_T}{v} [\bar{T}_{R/L} H u_{L/R}^i] \right]$$
$$+ \kappa_B \left[\sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_{L/R} W_\mu^- \gamma^\mu u_{L/R}^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_{L/R} Z_\mu \gamma^\mu d_{L/R}^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M_B}{v} [\bar{B}_{R/L} H d_{L/R}^i] \right]$$
$$+ \kappa_X \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_{L/R} W_\mu^+ \gamma^\mu u_{L/R}^i] \right] + \kappa_Y \left[\sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_{L/R} W_\mu^- \gamma^\mu d_{L/R}^i] \right] + \text{h.c.}, \quad (1)$$

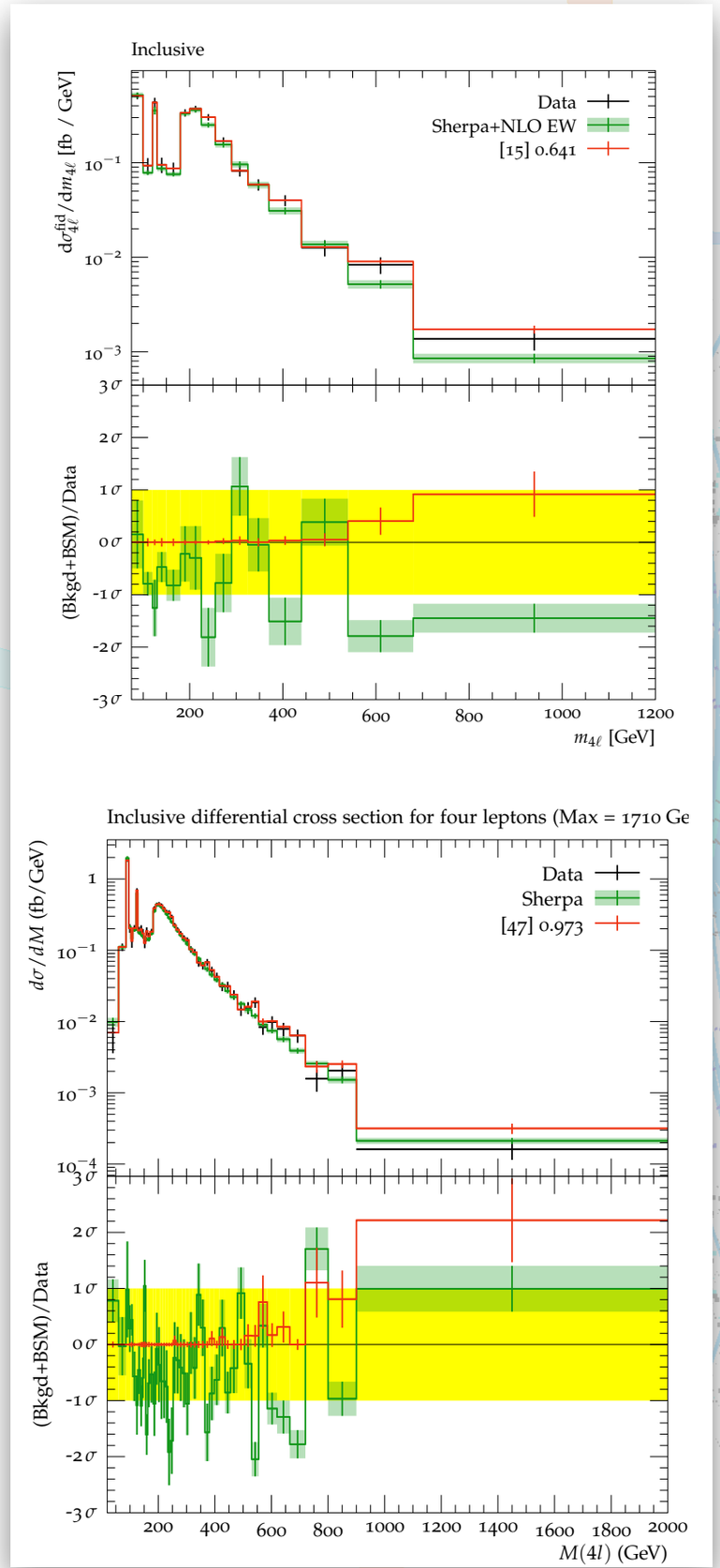
Overall coupling κ

Coupling to weak bosons ξ_V

- $BR(Q \to V q_i) = \xi_V \, \zeta_i$ where $\sum_{V=W,Z,H} \xi_V = 1$, $\sum_{i=1}^{3} \zeta_i = 1$;
- **T**$^{2/3}$ and **B**$^{-1/3}$ couple to W, Z, and H; **X**$^{5/3}$ and **Y**$^{-4/3}$ couple only to W boson

Contur limits on VLQs

Previous
m4l measurement



Full Run 2
m4l measurement

Updated scan using
Contur 2.0.x and Rivet 3.1.4