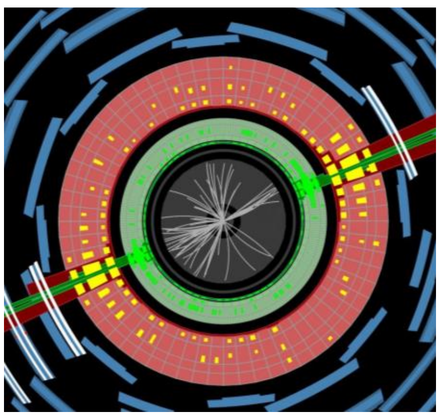
Reinterpretation of Measurements for BSM

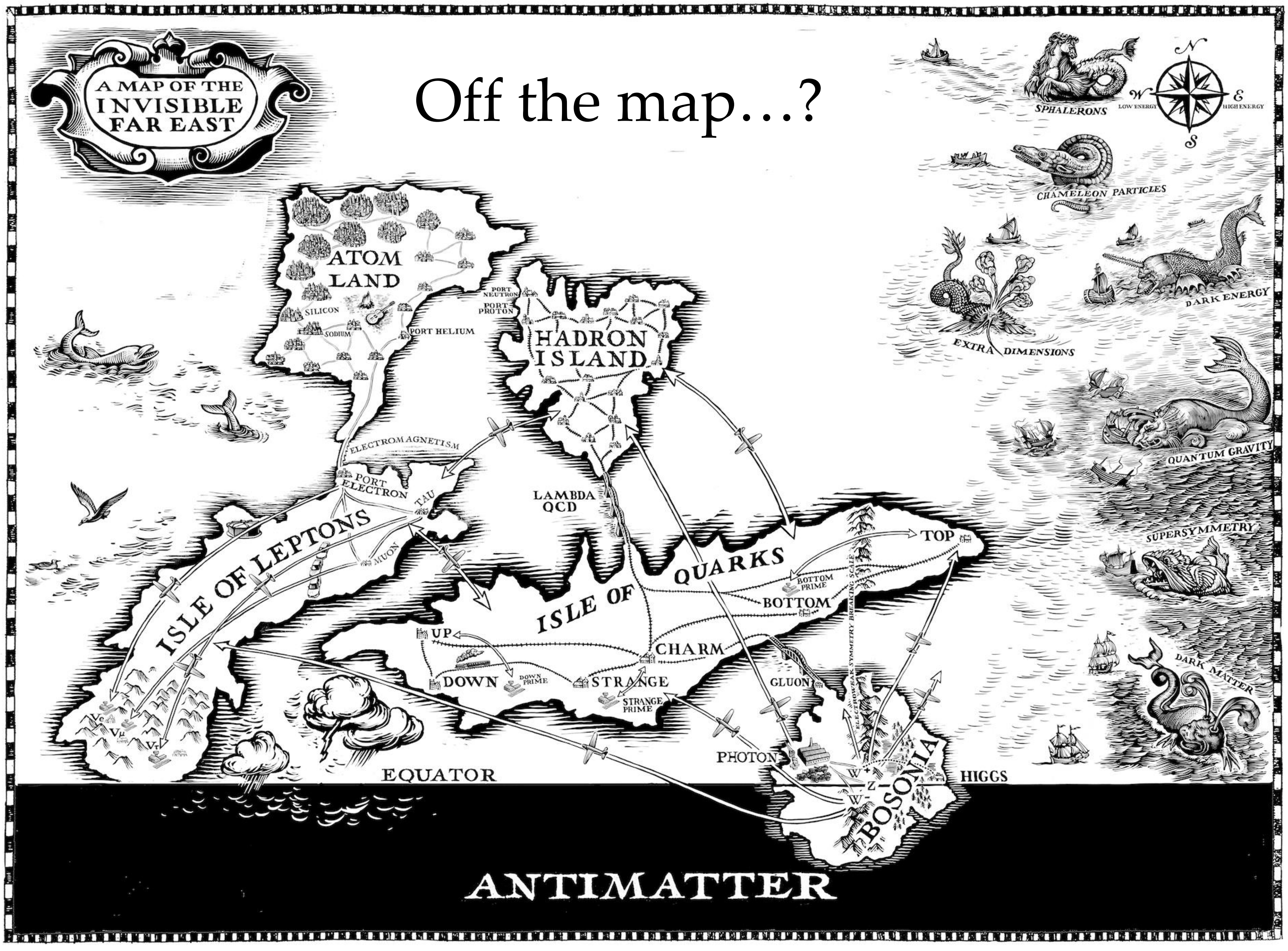


Contur in Action

Chacal, Wits, South Africa
22/1/2023

Jon Butterworth, UCL Physics & Astronomy

Off the map…?


A MAP OF THE INVISIBLE FAR EAST
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
MUON
ISLE OF LEPTONS
LAMBDA QCD
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
CHARM
UP
DOWN
DOWN PRIME
STRANGE
STRANGE PRIME
GLUON
PHOTON
ELECTROWEAK SYMMETRY BREAKING SCALE
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER
SPHALERONS
LOW ENERGY
HIGH ENERGY
CHAMELEON PARTICLES
DARK ENERGY
EXTRA DIMENSIONS
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER

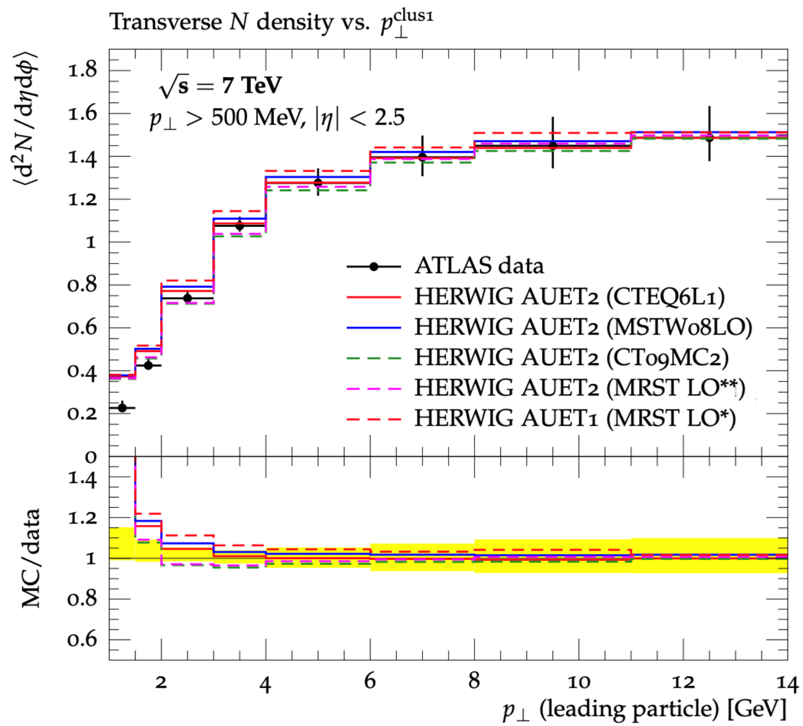

A MAP OF THE INVISIBLE FAR EAST
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
PORT ELECTRON
TAU
UON
LAMBDA QCD
ISLE OF LEPTONS
ISLE OF QUARKS
TOP
BOTTOM PRIME
BOTTOM
UP
CHARM
DOWN
PRIME
STRANGE
STRANGE PRIME
GLUON
PHOTON
ELECTROWEAK SYMMETRY BREAKING SCALE
W
Z
W-
BOSONIA
HIGGS
EQUATOR
ANTIMATTER
SPHALERONS
N
W
E
S
LOW ENERGY
HIGH ENERGY
CHAMELEON PARTICLES
DARK ENERGY
EXTRA DIMENSIONS
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER

Introducing Rivet

Robust Independent Validation of Experiment and Theory

arXiv:1003.0694, arXiv:1912.05451

- Direct legacy from HERA (*1990s, HZTOOL*)
- Developed by MCnet for tuning and validation of new MC event generators
  - e.g. What does the underlying event look like in 7 TeV pp collisions?
- Library of measurements of final state particles produced in collisions, and variables derived from them



Buckley et al, Bierlich et al

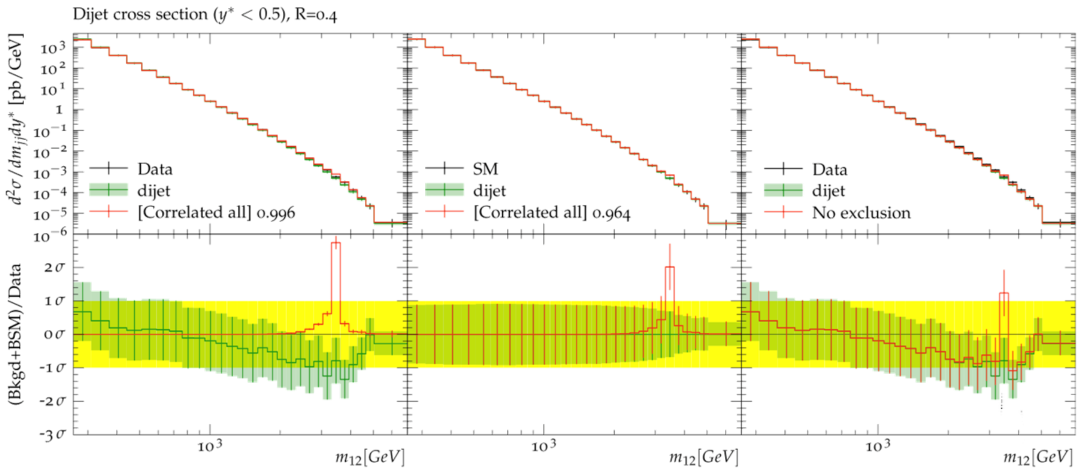
From ATL-PHYS-PUB-2011-008

Introducing Contur

Constraints On New Theories Using Rivet

arXiv:1605.05296, arXiv:2102.04377

- Extend the power of Rivet beyond the Standard Model
- Signal-injection of final-state particles from Beyond-the-SM physics events on to the measured cross sections in Rivet



(a) (b) (c)

From Altakach, JMB, Ježo, Klasen, Schienbein arXiv:2111.15406

Increasingly precise measurements and calculations together extend the reach

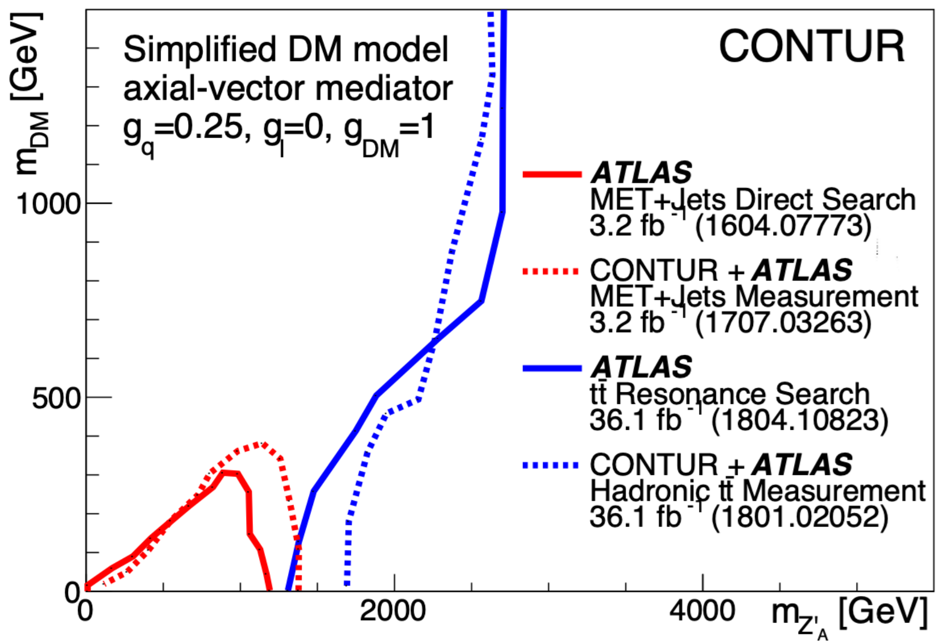
JMB, Grellscheid, Krämer, Sarrazin, Yallup; Buckley et al

Recent Developments

- New interface between Rivet+Contur and Madgraph
  - Could already drive a MG scan using Contur machinery (as with Herwig)
  - Can now access Rivet+Contur from within the MG UI and use MG scanning machinery
- Wider selection of SM predictions, move to using these only
  - no more assumption that the data ≡ SM.
- Use of correlation matrices, more Rivet analyses, other minor improvements (Contur 2.4)
- (See Yoran's talk this afternoon for more.)

Unleashing the power of high luminosity LHC data
(example case studies)

- A heavy scalar triplet and the W mass
- Composite Dark Matter
- Vector-like Quarks
- The future?



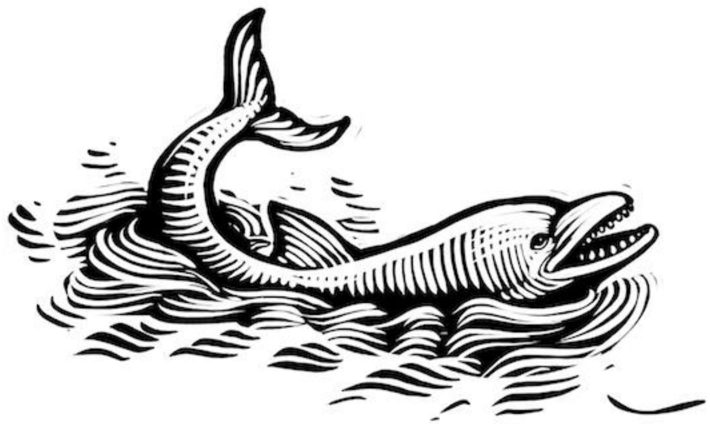
Louie Corpe

A Heavy Scalar Triplet and the W mass

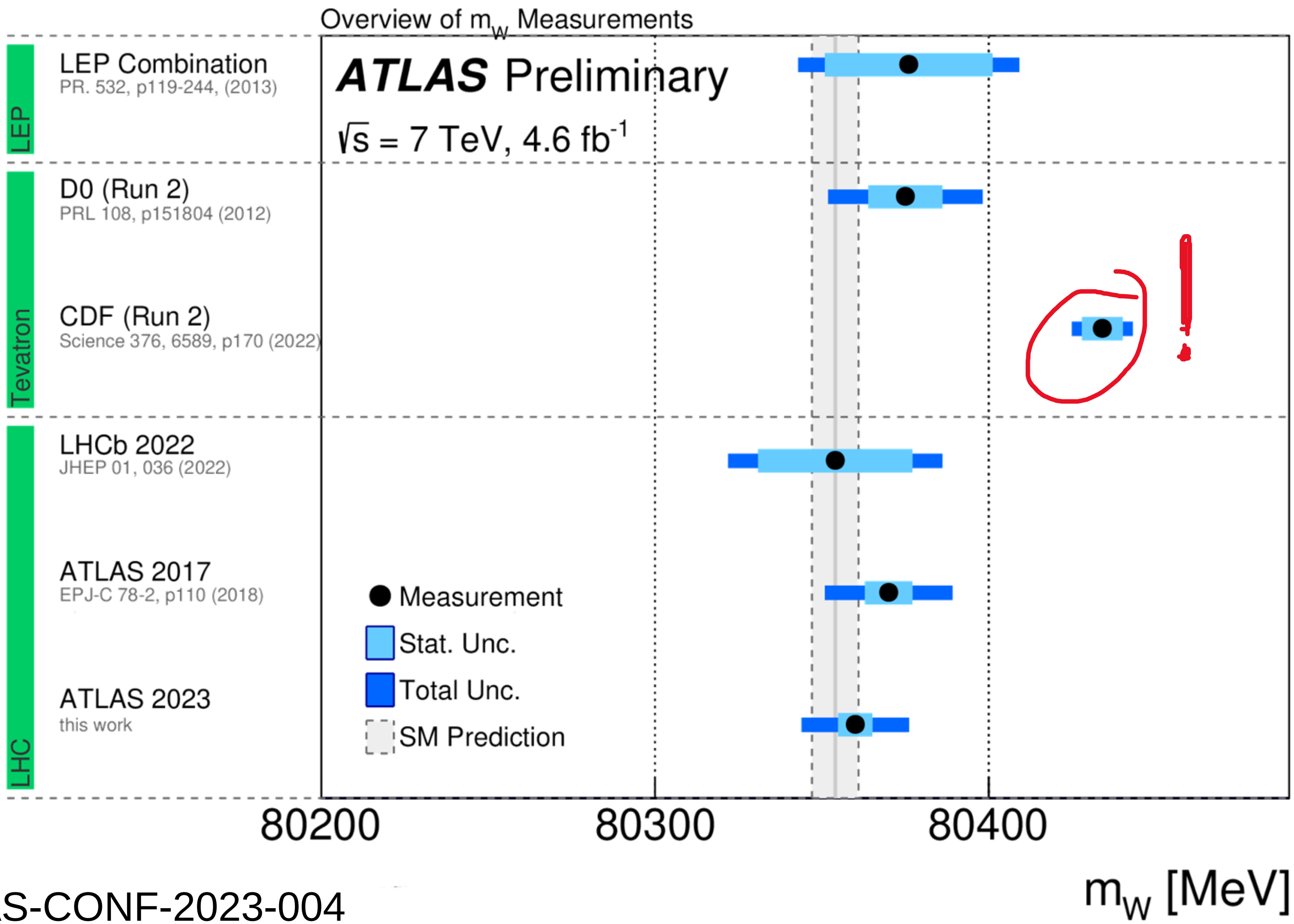
- Motivation
  - The W mass: CDF and custodial symmetry
  - The Type II Seesaw model
  - Bringing them together
- Method
  - Rivet, Contur and, the LHC measurement library and SM predictions
- Results and conclusions

JMB, Julian Heeck, Sihyun Jeon, Olivier Mattelaer, Richard Ruiz
Phys.Rev.D 107 (2023) 7, 075020
2210.13496 [hep-ph]

Motivation

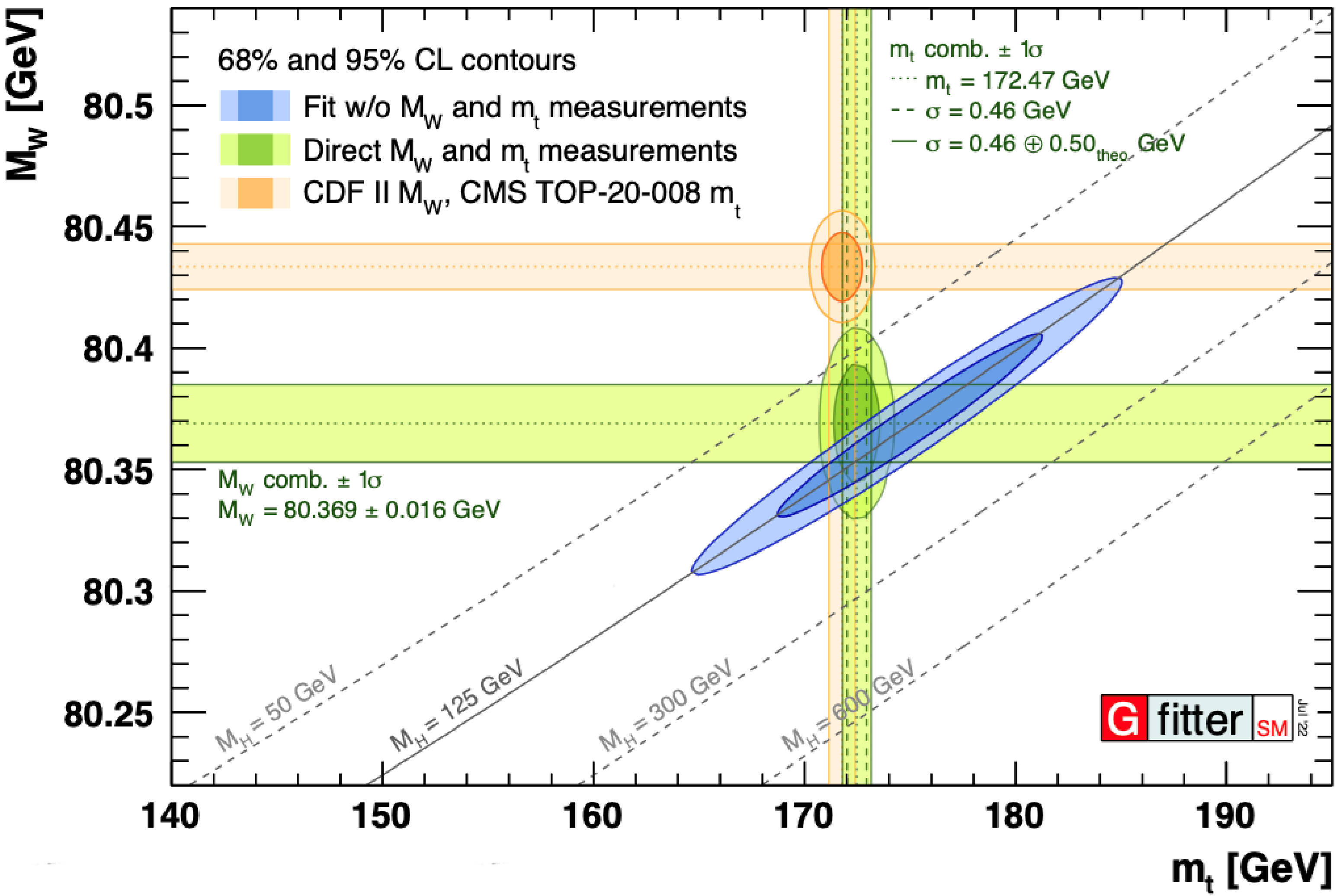


The W mass



ATLAS-CONF-2023-004

The W mass


68% and 95% CL contours
Fit w/o M_W and m_t measurements
Direct M_W and m_t measurements
CDF II M_W, CMS TOP-20-008 m_t
m_t comb. ± 1σ
m_t = 172.47 GeV
σ = 0.46 GeV
σ = 0.46 ⊕ 0.50_{theo} GeV
M_W comb. ± 1σ
M_W = 80.369 ± 0.016 GeV
M_H = 50 GeV
M_H = 125 GeV
M_H = 300 GeV
M_H = 600 GeV
G fitter SM
Jul '22
M_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
m_t [GeV]

Custodial Symmetry

- Residual SU(2) symmetry after spontaneous symmetry breaking
  - Invariance under rotations among (W^1, W^2, W^3) i.e. $M(W^{+/-}) = M(W^3)$
  - After mixing with U(1):

$$\rho_0 \equiv M_W^2 / M_Z^2 \cos^2\theta_W = 1$$

  - Obviously must be broken (but only slightly!) if CDF are even approximately right
  - Many BSM models build in $\rho_0 = 1$
  - But not all…

Type II Seesaw Model

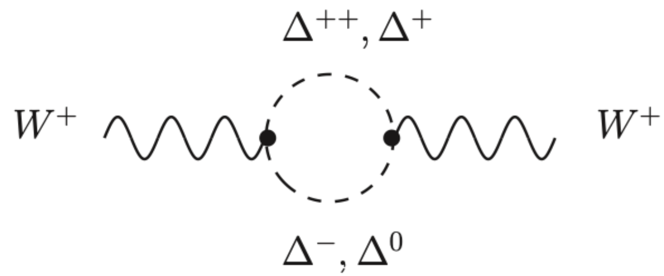
- Add a complex scalar triplet with a vev to the SM

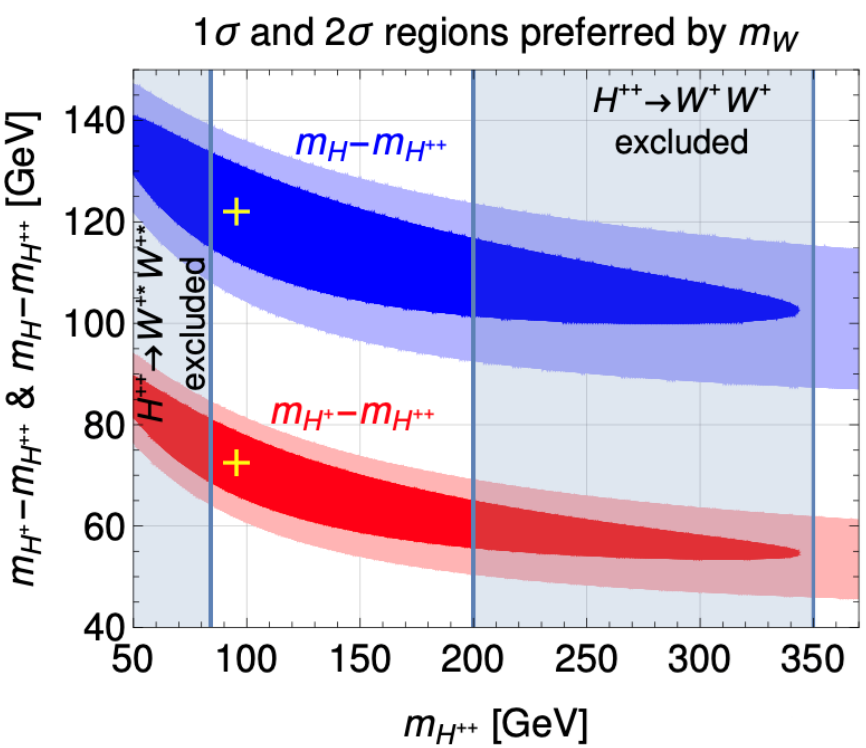
$$\hat{\Delta} = \begin{pmatrix} \frac{1}{\sqrt{2}}\hat{\Delta}^{+} & \hat{\Delta}^{++} \\ \hat{\Delta}^{0} & -\frac{1}{\sqrt{2}}\hat{\Delta}^{+} \end{pmatrix} \qquad \langle\hat{\Delta}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ v_{\Delta} & 0 \end{pmatrix}$$

- Introduces Majorana mass terms for neutrinos
- Direct connection between neutrino oscillation parameters and Yukawa couplings implies correlations between collider signatures (D decays to leptons) and neutrino sector
- Breaks custodial symmetry at tree level… ☺
- … but *reduces* ρ_0 , and thus M_W 😟

Two problems solved?

- Low vev ($\lesssim 1$ GeV) means the tree-level effect is small
- One-loop contributions can be large and opposite in sign
- Low Yukawa couplings/vev evades many searches
  - $Y \ll 1$, MeV $< v_\Delta <$ GeV
- A CDF-like shift in M_W implies *upper* bounds on mass states

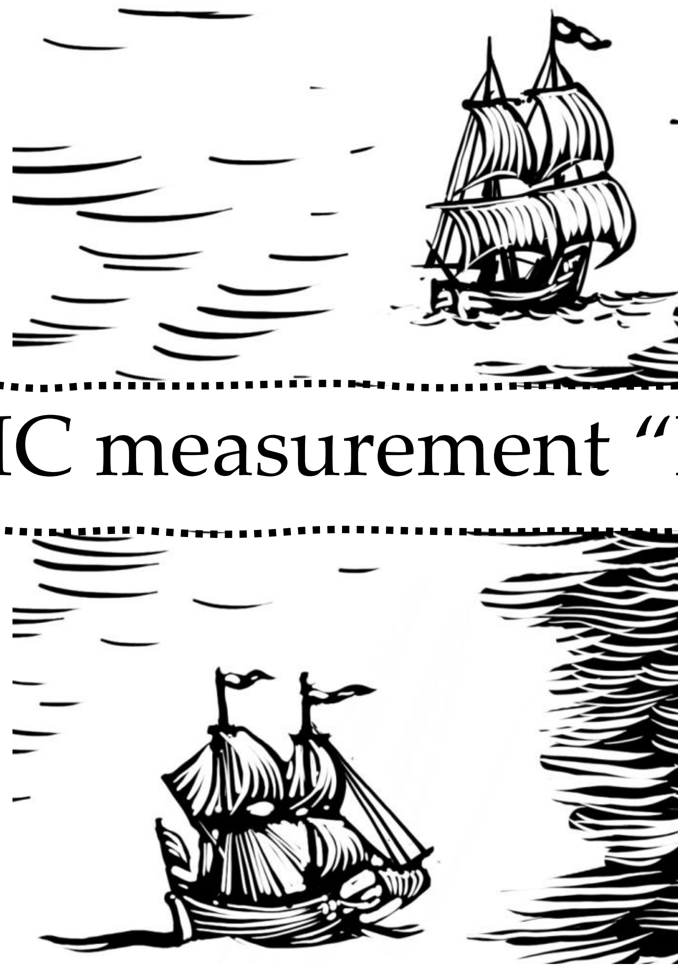




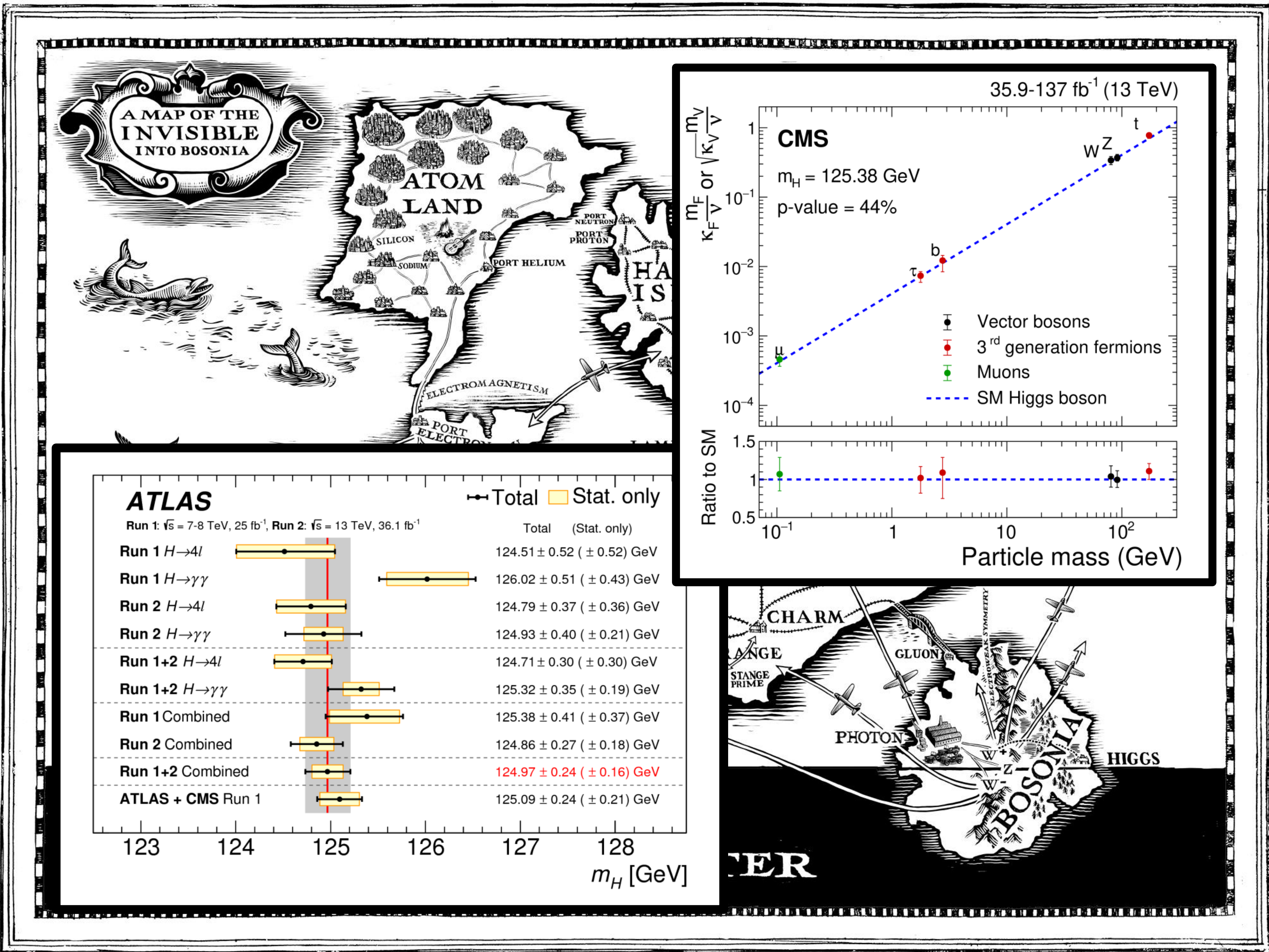
J Heeck, Phys.Rev.D 106 (2022) 1, 015004

[2204.10274](2204.10274)

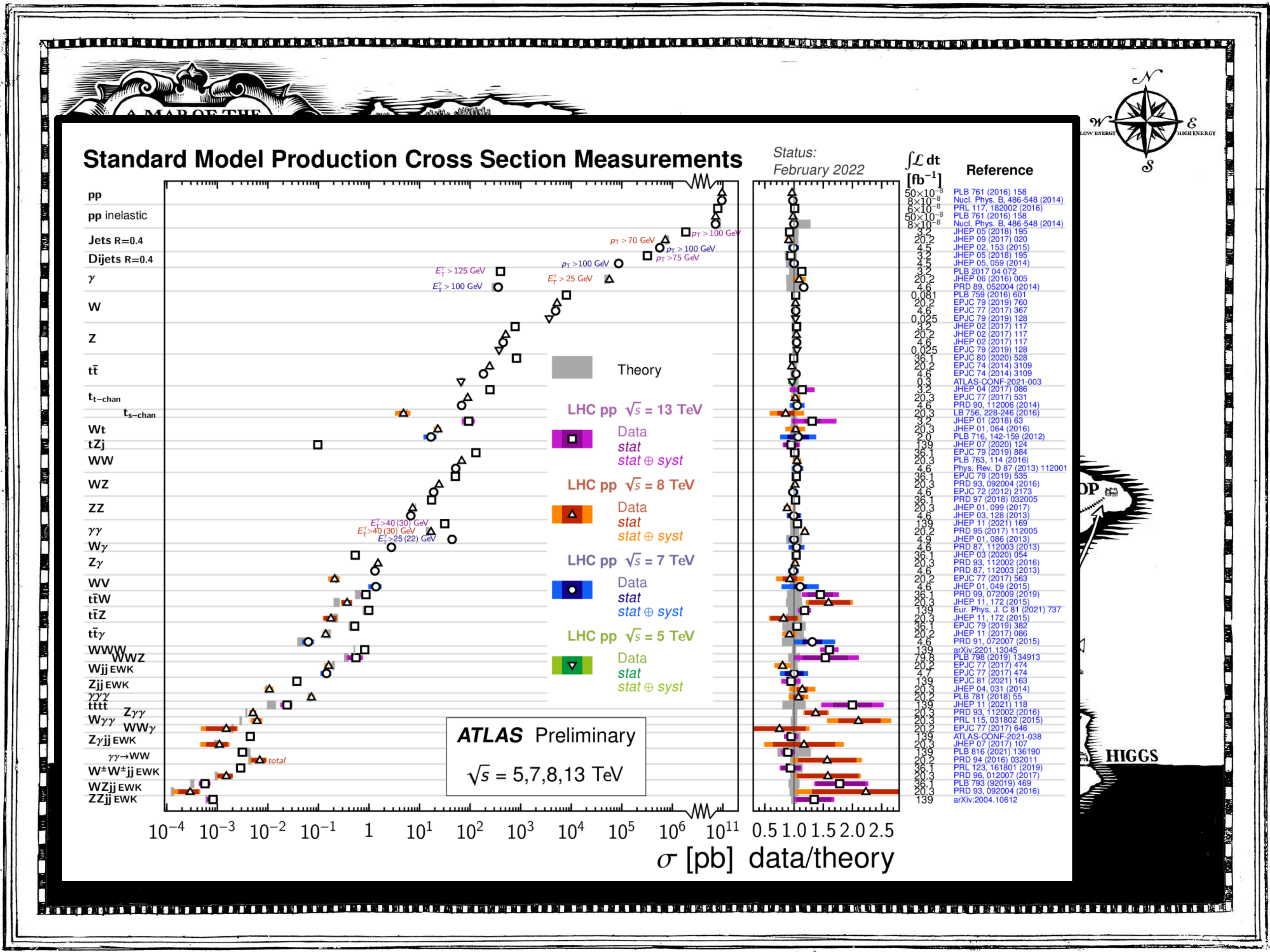
Method



The LHC measurement “library”

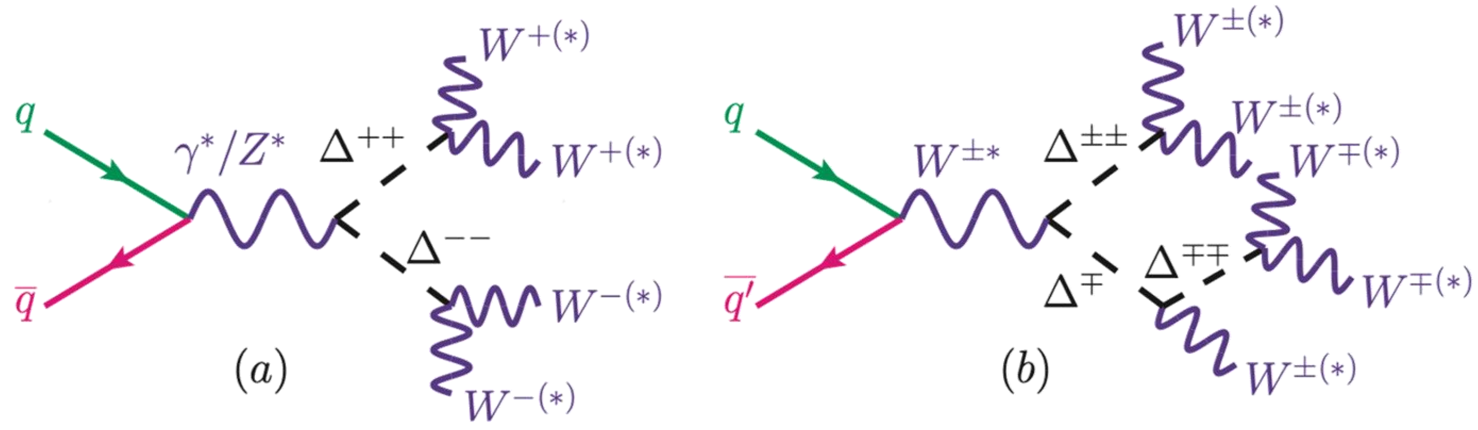


A MAP OF THE INVISIBLE INTO BOSONIA
ATOM LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
ELECTROMAGNETISM
PORT ELECTRON
CHARM
STANGE PRIME
GLUON
ELECTROWEAK SYMMETRY
PHOTON
W+
Z
W-
HIGGS
BOSONIA
35.9-137 fb^{-1} (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
Ratio to SM
Particle mass (GeV)
ATLAS
Total
Stat. only
Run 1: $\sqrt{s}$ = 7-8 TeV, 25 fb^{-1}, Run 2: $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Total (Stat. only)
Run 1 $H\rightarrow 4l$ 124.51 ± 0.52 (± 0.52) GeV
Run 1 $H\rightarrow\gamma\gamma$ 126.02 ± 0.51 (± 0.43) GeV
Run 2 $H\rightarrow 4l$ 124.79 ± 0.37 (± 0.36) GeV
Run 2 $H\rightarrow\gamma\gamma$ 124.93 ± 0.40 (± 0.21) GeV
Run 1+2 $H\rightarrow 4l$ 124.71 ± 0.30 (± 0.30) GeV
Run 1+2 $H\rightarrow\gamma\gamma$ 125.32 ± 0.35 (± 0.19) GeV
Run 1 Combined 125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined 124.86 ± 0.27 (± 0.18) GeV
Run 1+2 Combined 124.97 ± 0.24 (± 0.16) GeV
ATLAS + CMS Run 1 125.09 ± 0.24 (± 0.21) GeV
m_H [GeV]


Standard Model Production Cross Section Measurements
Status: February 2022
∫ℒ dt [fb⁻¹]
Reference
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
tt−chan
ts−chan
Wt
tZj
WW
WZ
ZZ
γγ
Wγ
Zγ
WV
tt̄W
tt̄Z
tt̄γ
WWW
WWZ
Wjj EWK
Zjj EWK
γγγ
tt̄tt̄
Zγγ
Wγγ
WWγ
Zγjj EWK
γγ→WW
W±W±jj EWK
WZjj EWK
ZZjj EWK
pT > 70 GeV
pT > 100 GeV
pT > 100 GeV
pT >75 GeV
pT >100 GeV
ET > 125 GeV
ET > 100 GeV
ET > 25 GeV
ET>40 (30) GeV
ET>40 (30) GeV
ET>25 (22) GeV
total
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
√s = 5,7,8,13 TeV
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory
50×10⁻⁸ PLB 761 (2016) 158
8×10⁻⁸ Nucl. Phys. B, 486-548 (2014)
6×10⁻⁸ PRL 117, 182002 (2016)
50×10⁻⁸ PLB 761 (2016) 158
8×10⁻⁸ Nucl. Phys. B, 486-548 (2014)
3.2 JHEP 05 (2018) 195
20.2 JHEP 09 (2017) 020
4.5 JHEP 02, 153 (2015)
3.2 JHEP 05 (2018) 195
4.5 JHEP 05, 059 (2014)
3.2 PLB 2017 04 072
20.2 JHEP 06 (2016) 005
4.6 PRD 89, 052004 (2014)
0.081 PLB 759 (2016) 601
20.2 EPJC 79 (2019) 760
4.6 EPJC 77 (2017) 367
0.025 EPJC 79 (2019) 128
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
0.025 EPJC 79 (2019) 128
36.1 EPJC 80 (2020) 528
20.2 EPJC 74 (2014) 3109
4.6 EPJC 74 (2014) 3109
0.3 ATLAS-CONF-2021-003
3.2 JHEP 04 (2017) 086
20.3 EPJC 77 (2017) 531
4.6 PRD 90, 112006 (2014)
20.3 LB 756, 228-246 (2016)
3.2 JHEP 01 (2018) 63
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
139 JHEP 07 (2020) 124
36.1 EPJC 79 (2019) 884
20.3 PLB 763, 114 (2016)
4.6 Phys. Rev. D 87 (2013) 112001
36.1 EPJC 79 (2019) 535
20.3 PRD 93, 092004 (2016)
4.6 EPJC 72 (2012) 2173
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013)
139 JHEP 11 (2021) 169
20.2 PRD 95 (2017) 112005
4.9 JHEP 01, 086 (2013)
4.6 PRD 87, 112003 (2013)
36.1 JHEP 03 (2020) 054
20.3 PRD 93, 112002 (2016)
4.6 PRD 87, 112003 (2013)
20.2 EPJC 77 (2017) 563
4.6 JHEP 01, 049 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
139 Eur. Phys. J. C 81 (2021) 737
20.3 JHEP 11, 172 (2015)
36.1 EPJC 79 (2019) 382
20.2 JHEP 11 (2017) 086
4.6 PRD 91, 072007 (2015)
139 arXiv:2201.13045
79.8 PLB 798 (2019) 134913
20.2 EPJC 77 (2017) 474
4.7 EPJC 77 (2017) 474
139 EPJC 81 (2021) 163
20.3 JHEP 04, 031 (2014)
20.2 PLB 781 (2018) 55
139 JHEP 11 (2021) 118
20.3 PRD 93, 112002 (2016)
20.3 PRL 115, 031802 (2016)
20.2 EPJC 77 (2017) 646
139 ATLAS-CONF-2021-038
20.3 JHEP 07 (2017) 107
139 PLB 816 (2021) 136190
20.2 PRD 94 (2016) 032011
36.1 PRL 123, 161801 (2019)
20.3 PRD 96, 012007 (2017)
36.1 PLB 793 (92019) 469
20.3 PRD 93, 092004 (2016)
139 arXiv:2004.10612
HIGGS

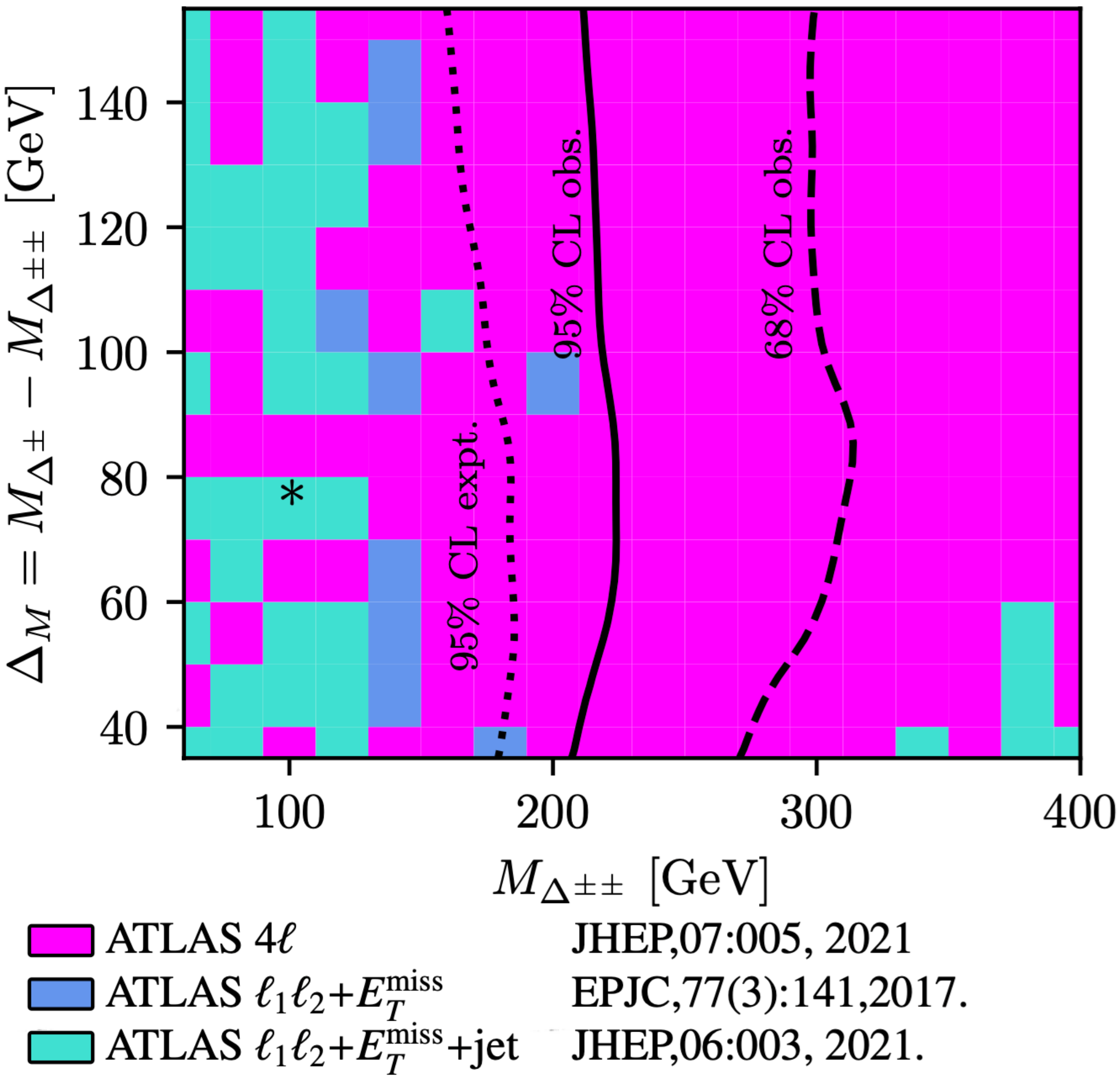
Analysis

- Feynrules[1] → UFO → Madgraph → Pythia → Rivet → Contur (over 130 LHC measurement papers)
- vev = 1 GeV
  - High enough that Δ decays are prompt. At very low values (~0.1 MeV for $M_{\Delta^{++}}$ = 200 GeV) may not be true
  - Little effect on collider phenomenology otherwise



[1] Pich, Santamaria, Bernabeu, Phys. Lett. B 148 (1984) 229–233.

Analysis



The ($M\Delta^{\pm\pm}$,ΔM) parameter space overlaid with the 95% (solid) and 68% (long-dash) exclusion limits as obtained from MGaMC + Contur.

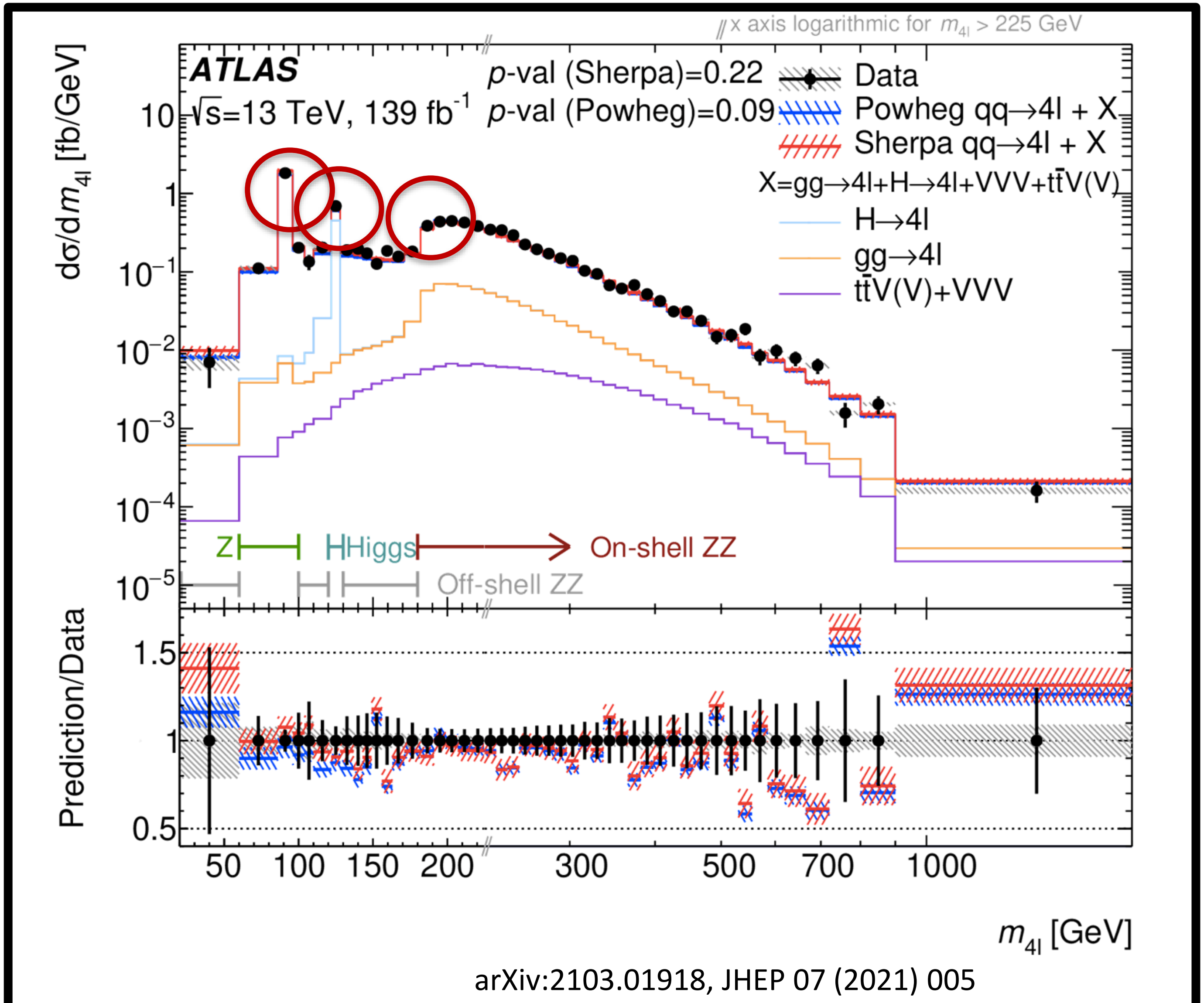
Values to the left of the lines are excluded.

Also shown is the 95% expected exclusion (dotted).

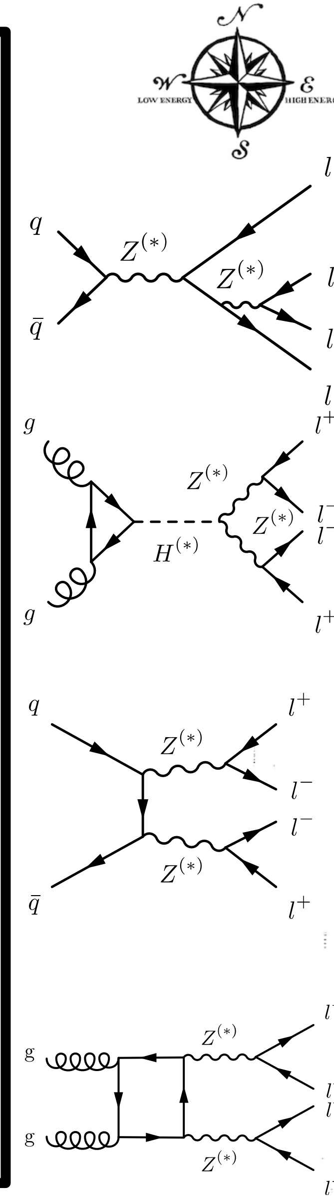
The colour-shading scheme indicates which SM measurement provides the dominant exclusion.

The black asterisk indicates the best fit value from *Heeck (2022)*

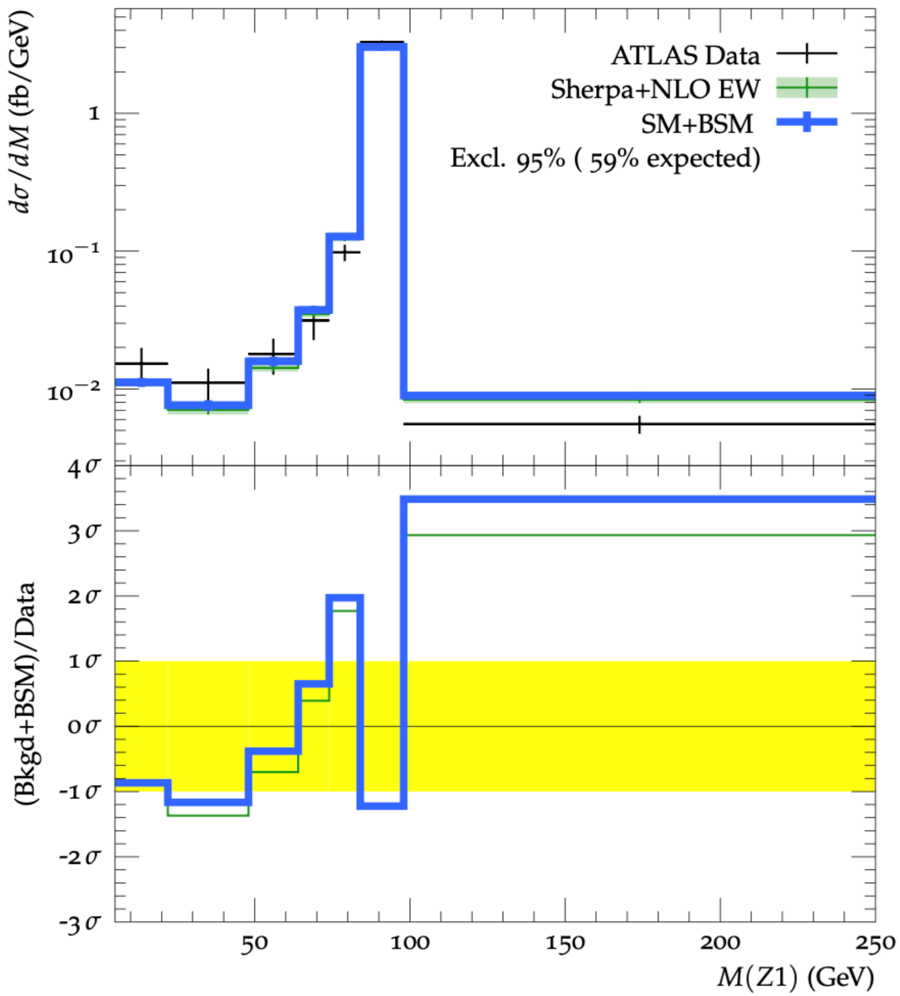
All possible final states were scanned



arXiv:2103.01918, JHEP 07 (2021) 005



Example of Impact



Upper panel: Representative differential cross section as a function of the highest-mass dilepton pair in 4-lepton measurements used in this study showing:

- ATLAS data (crosses) JHEP 07 (2021) 005
- Predicted SM yields (green) Sherpa, SciPost Phys. 7 (3) (2019) 034
- Predicted SM+BSM yields for ($M\Delta^{\pm\pm}$, $M\Delta^{\pm}$) = (180 GeV, 255 GeV) (blue).

Lower panel: bin-by-bin significance of expected theory yields relative to data with combined data and theory uncertainties (band).

Conclusion

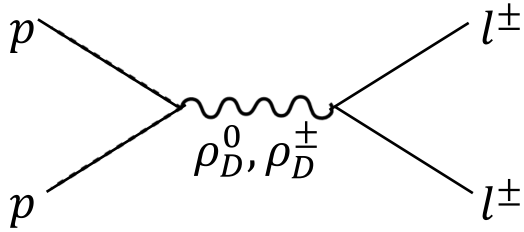
- Previously "unconstrained" best fit point is actually already excluded by LHC measurements, for promptly-decaying Δ^{++}
- Still a worth looking for in LLP searches, but not otherwise

Composite Dark Matter Models

- What if Dark Matter is a composite particle arising from e.g. an SU(4) symmetry which confines at some scale Λ_{dark}?
- Lead to bound states "dark" mesons and baryons.
  - Kribs et al. arXiv:1809.10183
- Dark fermions transform under electroweak part of the Standard Model: communication with SM
- There are **no direct searches** for this model by ATLAS or CMS:
  instead to constrain this model using the bank of existing LHC measurements using Contur
- Dynamics of the theory depend a lot on $\eta = m(\pi_D)/m(\rho_D)$

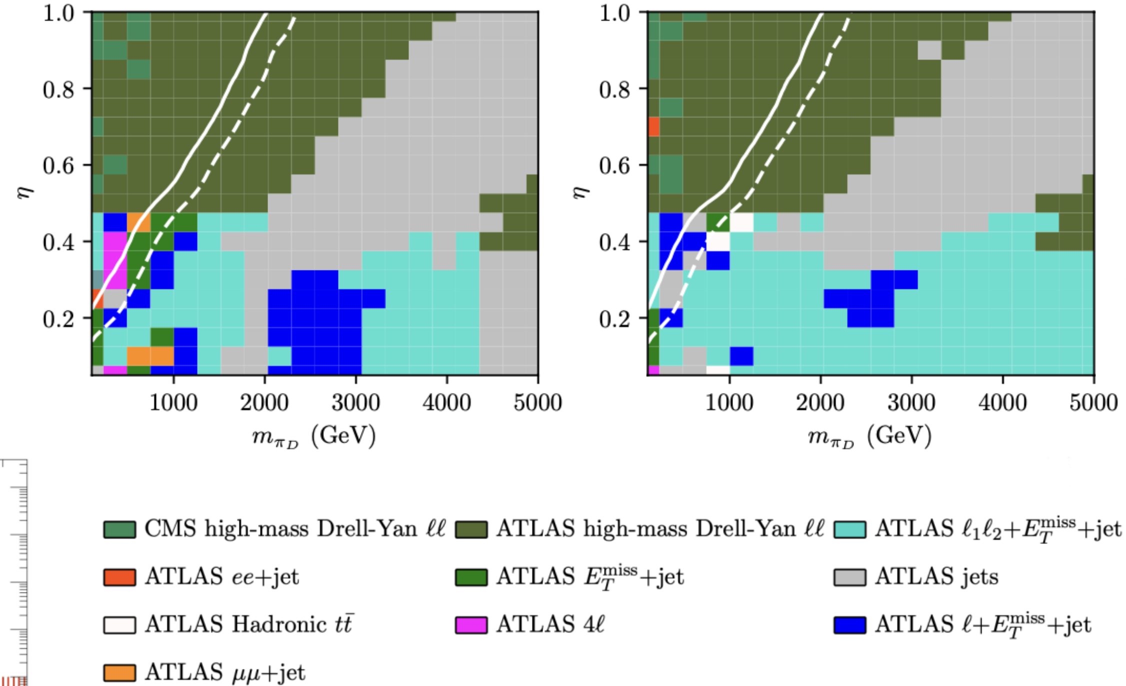
JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

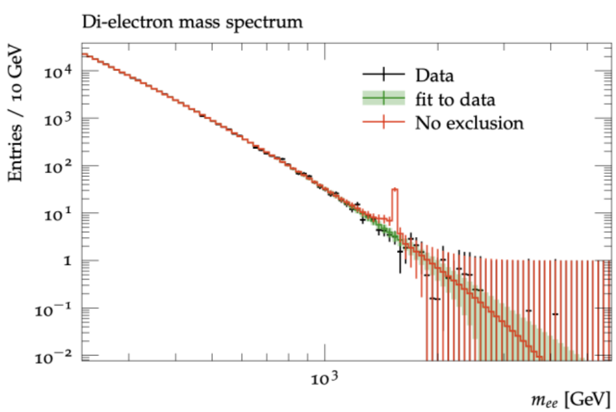
Composite Dark Matter Models



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

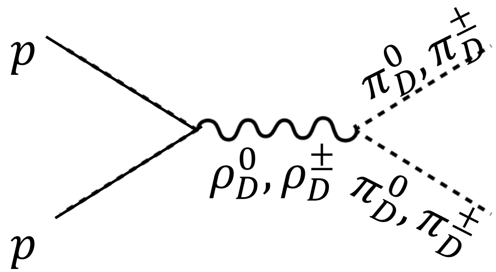
Right-handed model
$\rho^0{}_D$ only

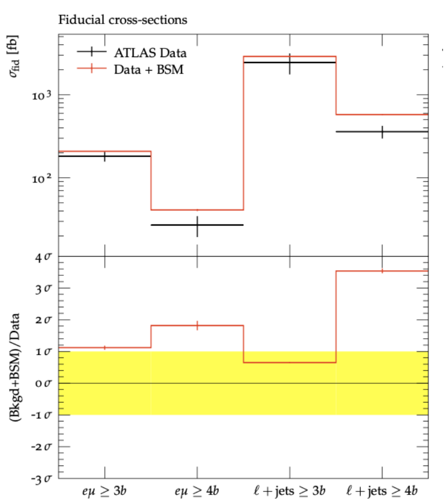




JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

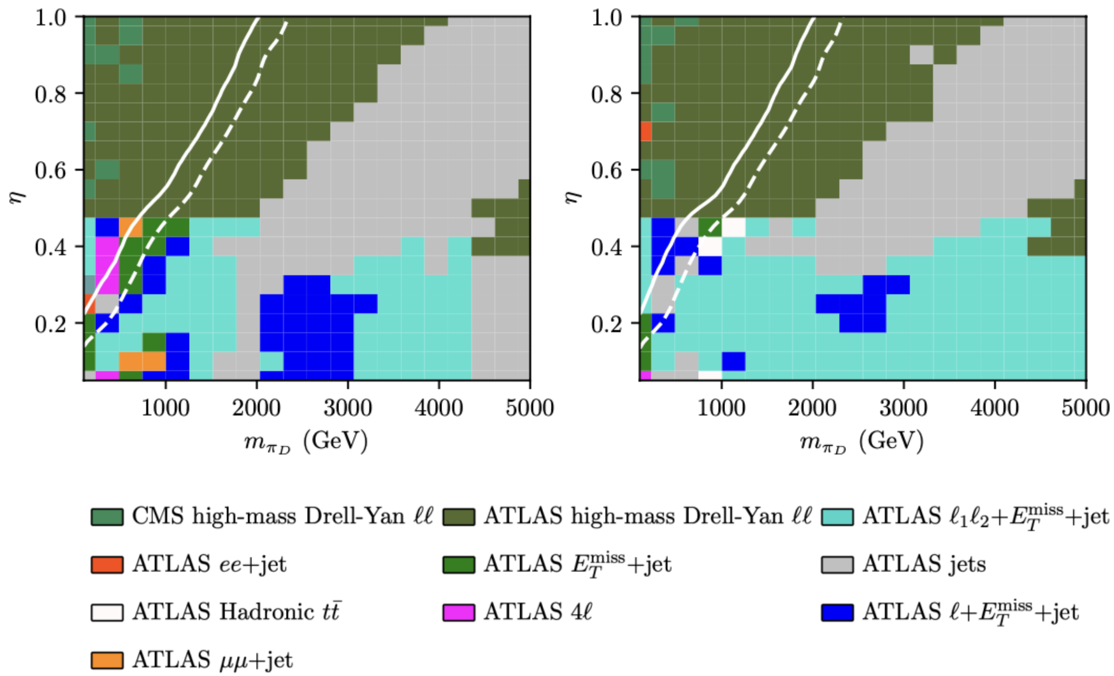
Composite Dark Matter Models





Left-handed model
ρ^0_D, ρ^+_D, ρ^-_D

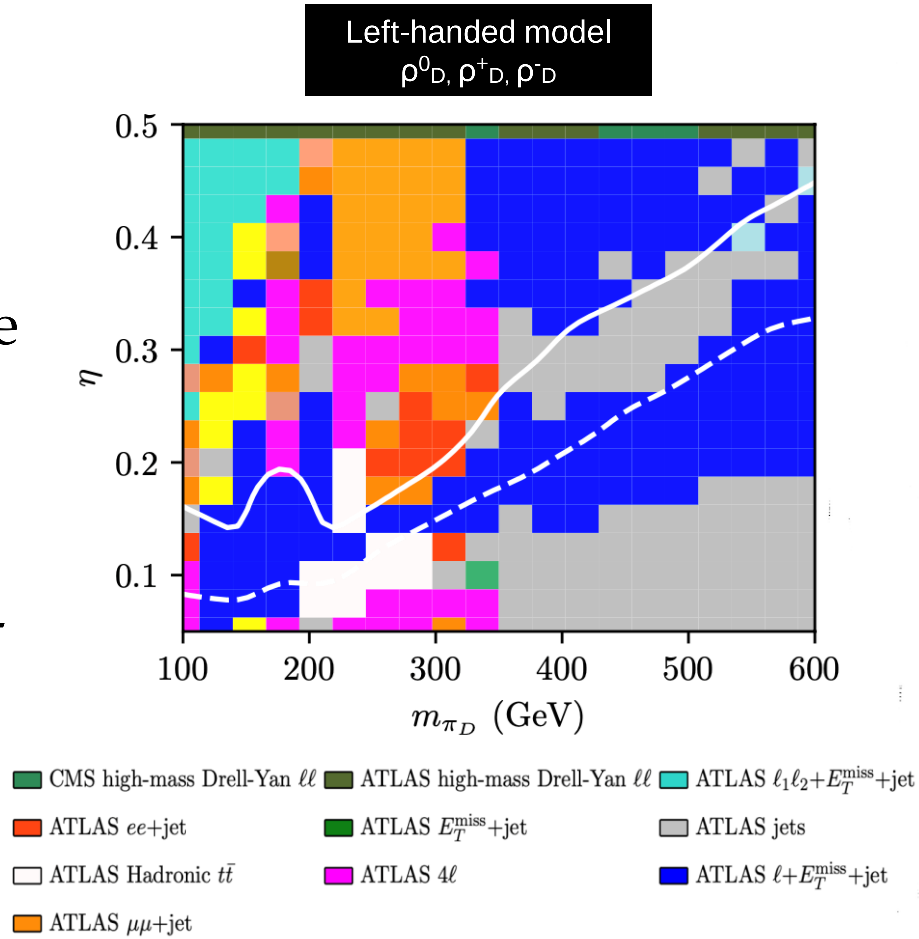
Right-handed model
ρ^0_D only



JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

Composite Dark Matter Models

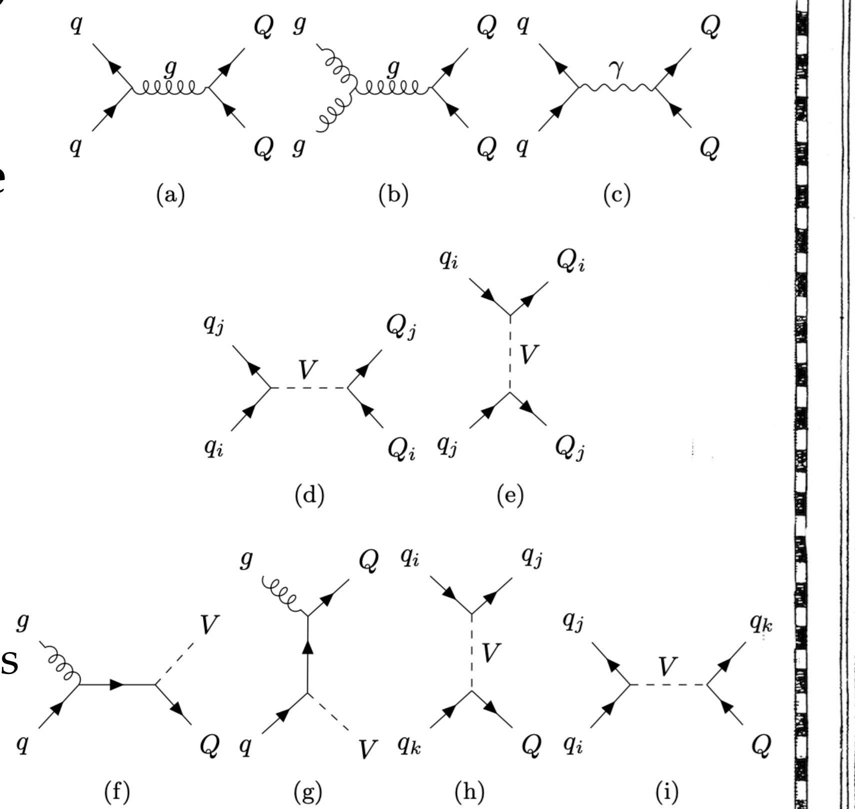
- Large areas excluded:
  - When pion mass is close to Higgs mass, H→gg analysis contributes
  - Boosted hadron "top" measurements contribute when pion mass ~200 GeV: Pions decay to tb and are boost from heavy r.
  - Other sensitivity from Z-pole dileptons, and lepton+missing energy (Z, top, W production in decay chains)



JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

Vector-like Quarks

- Very common extension to SM, general model by Buchkremer et al (arXiv:1305.4172). Introduces up to four quark partners, B, T, X, Y.
  - Usual strong couplings to SM
  - Evade bounds from Higgs because they are vectors
  - B, T interact with with W, Z, H with modfied weak couplings
  - X, Y interact with W (only) similarly
- Three sets of parameters (in additon to masses)
  - 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}**



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

- Compare to (quite limited) direct searches: ATLAS limits from arXiv:1808.02343
- Assumes 3rd generation coupling only, and X, Y are decoupled.
- Only include pair production

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

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

CERN-EP-2018-205
November 26, 2018

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

The ATLAS Collaboration

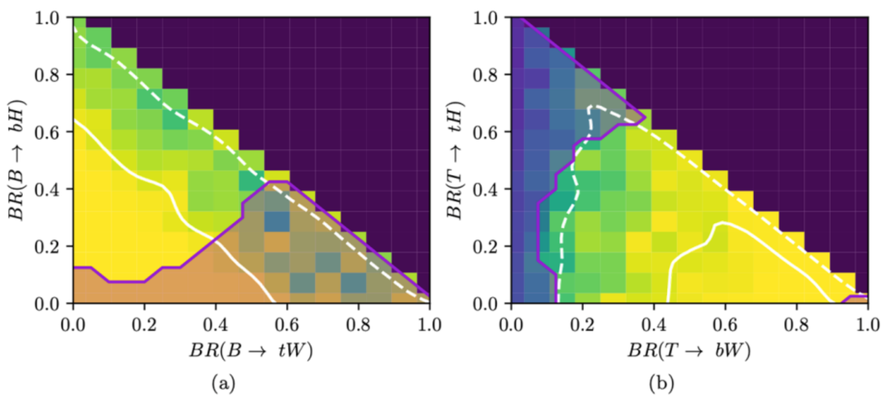
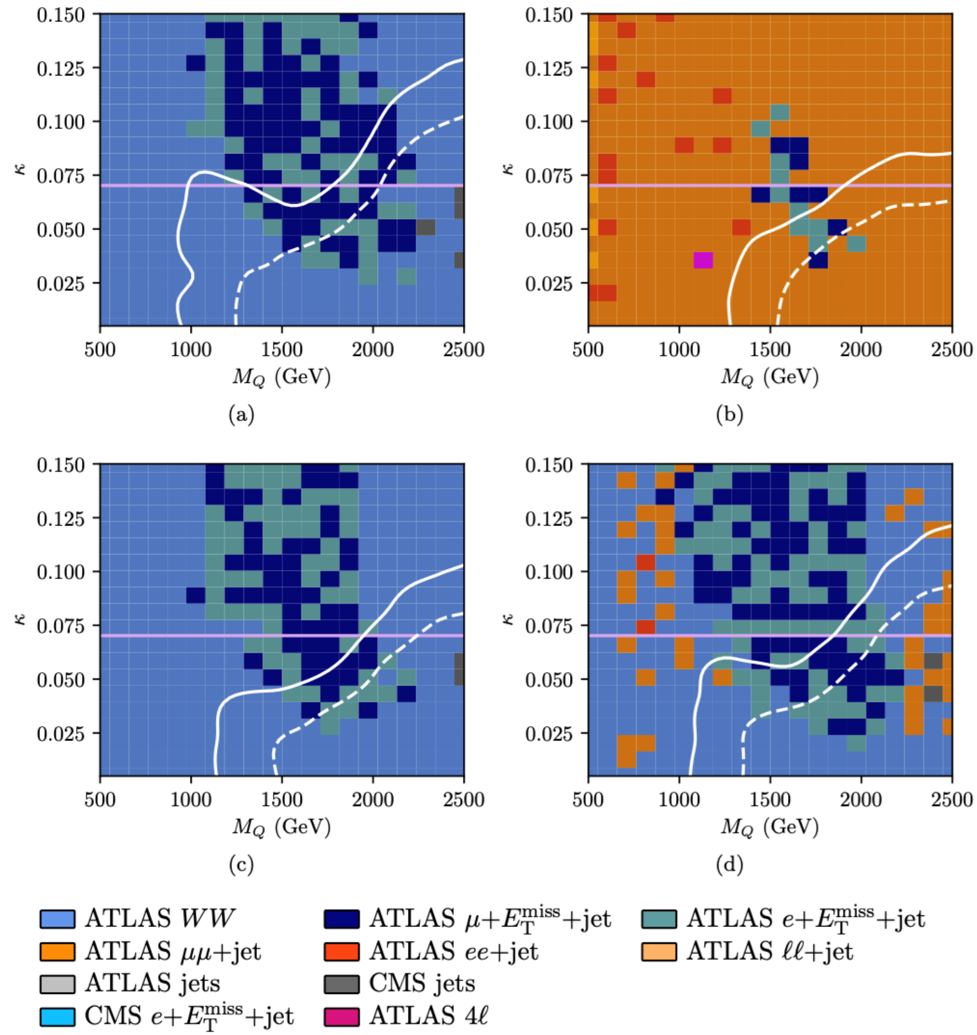


Figure 5: Sensitivity of LHC measurements to (a) B-production for M_B = 1200 GeV and (b) T-production for M_T = 1350 GeV. The CONTUR exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL (dashed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

Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

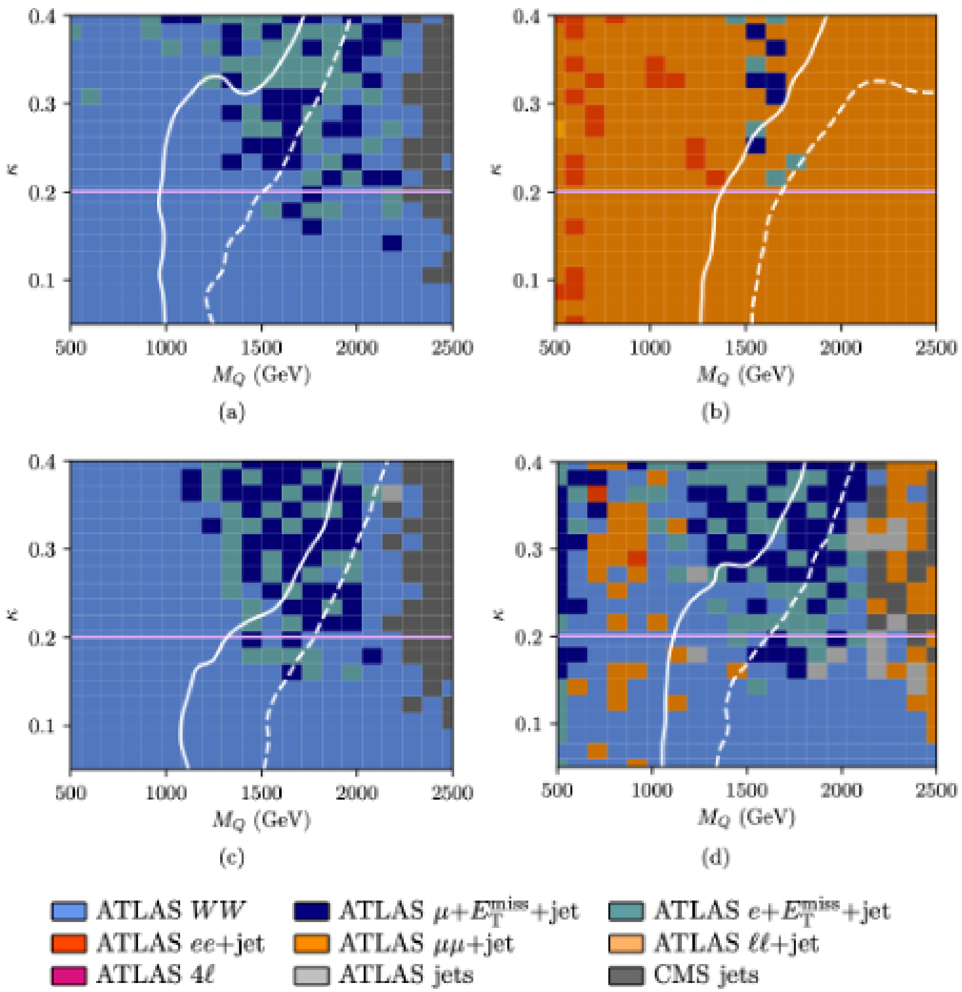
- Coupling to 1st generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude most of the plane.
- Single VLQ production very important at highest masses



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

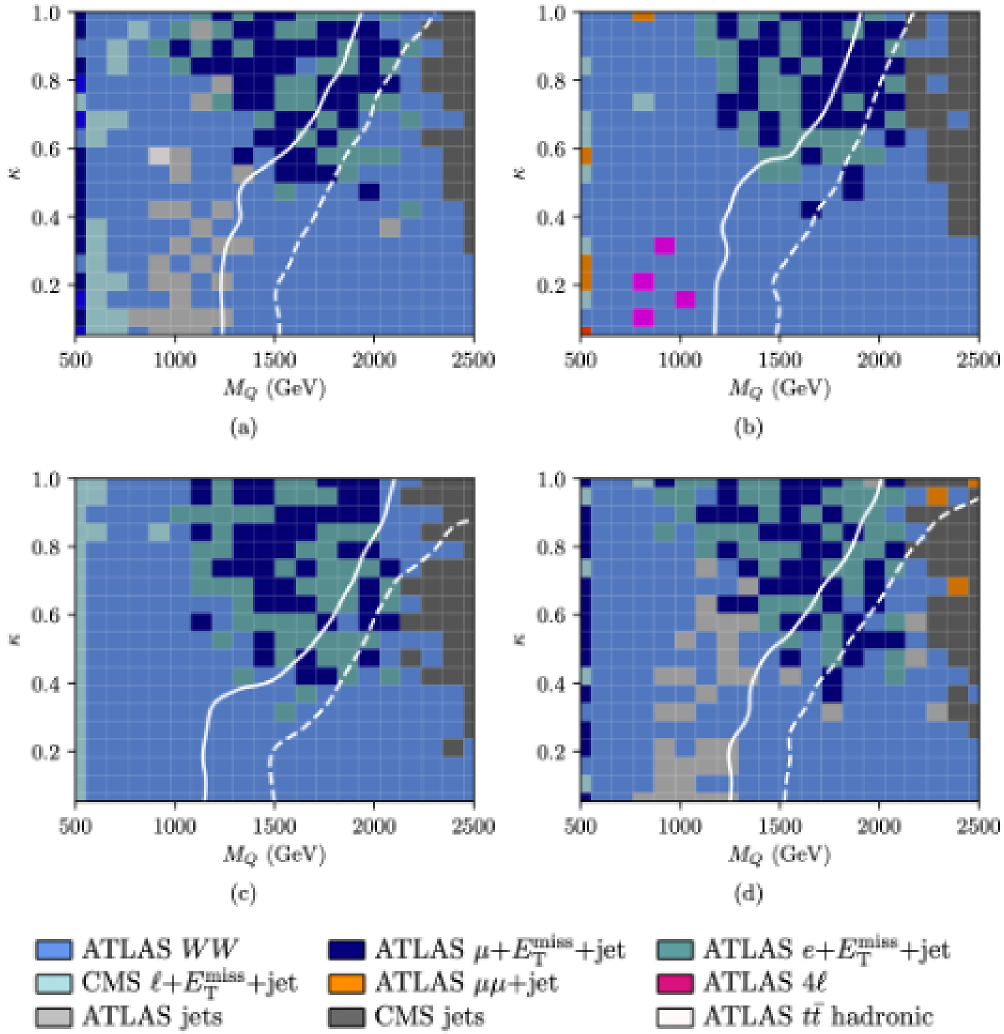
- Coupling to 2nd generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude significant part of the plane.
- Single VLQ production again very important at highest masses



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

- Coupling to 3rd generation.
- No exclusion from non-collider, but there are several LHC searches
- Measurements also exclude significant part of the plane.
- Single VLQ production still significant at highest masses



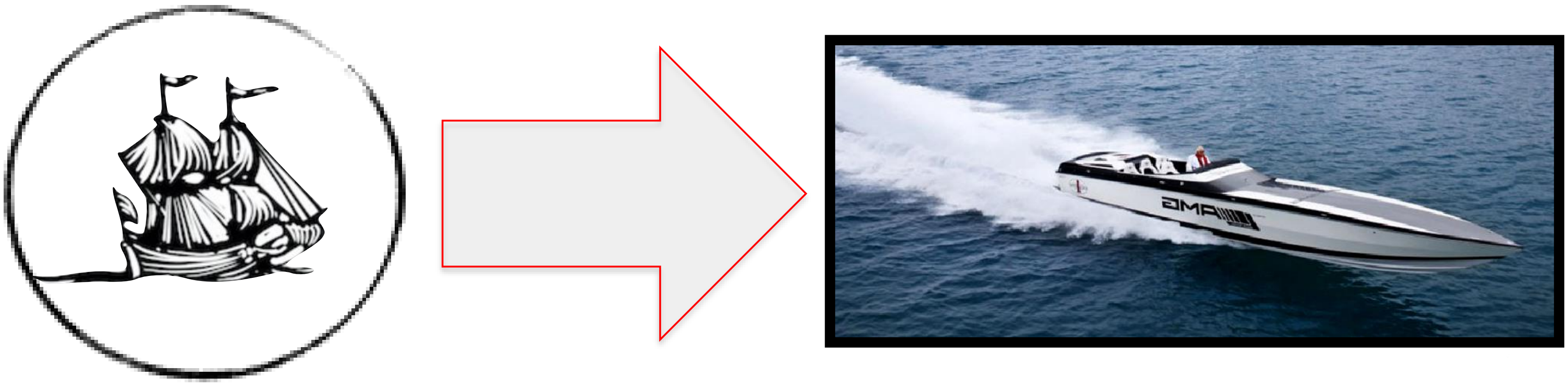
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

- Addendum: During journal review for this paper, it was pointed put that we'd missed some of the most compelling scenarios, and should instead consider:
  - B, T singlets
  - BT, XT, TY doublets
  - BYX, BTY triplets
- … for each generational coupling scenario and for four different decay branching benchmarks to W, Z, H.
- i.e. 7 x 3 x 4 two dimensional parameter scans
- Hmm. A challenge for Contur?

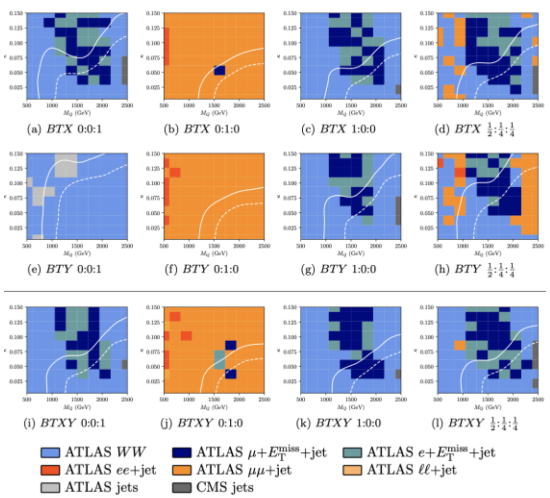
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

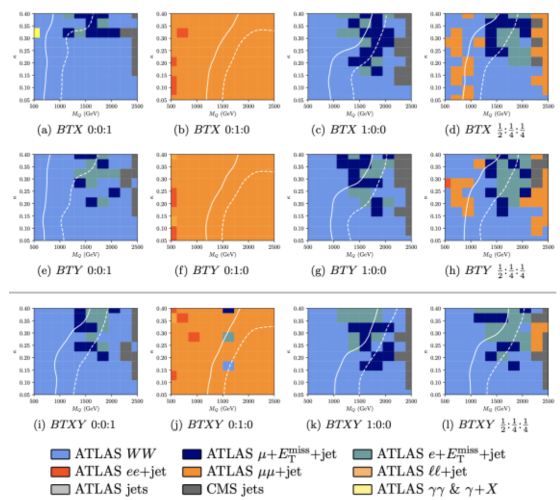


Vector-like Quarks

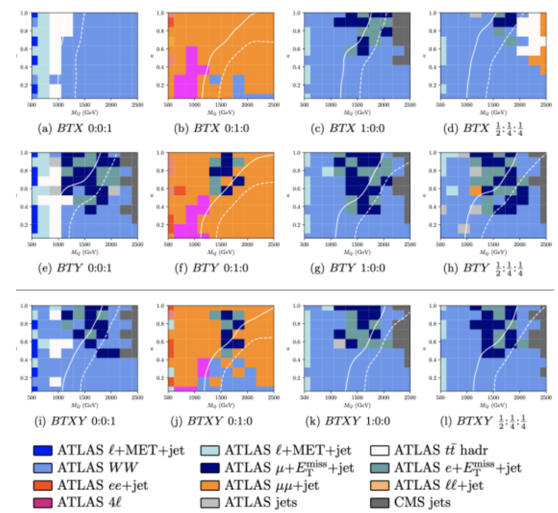
1st Generation



2nd Generation



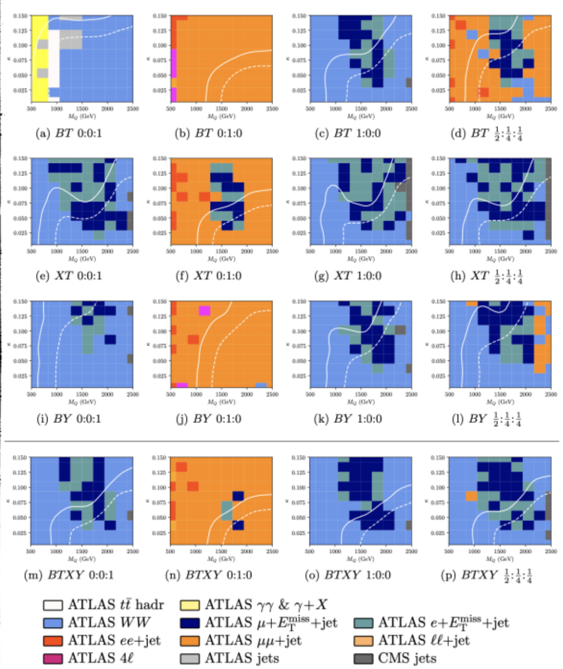
3rd Generation

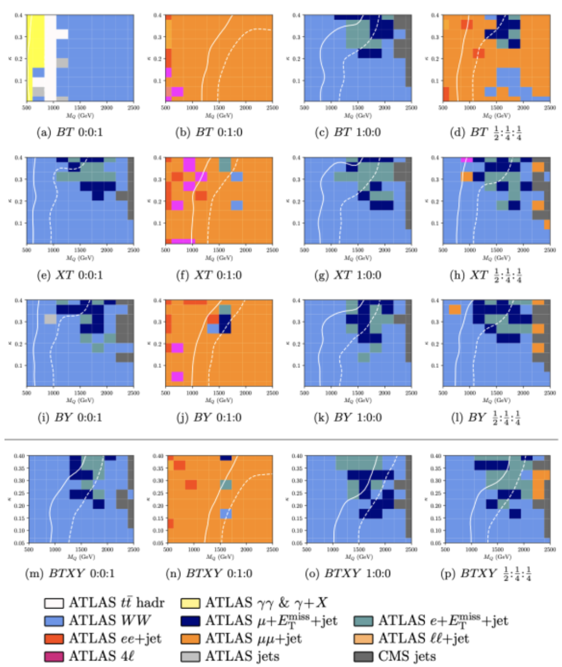


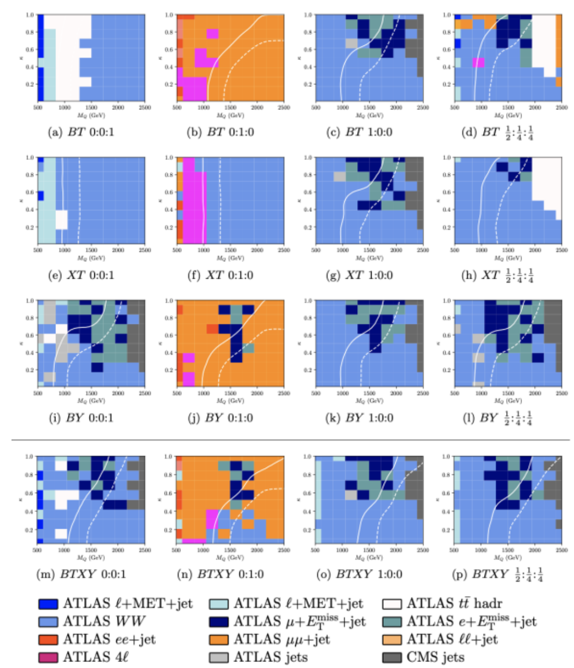
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

1st Generation 2nd Generation 3rd Generation



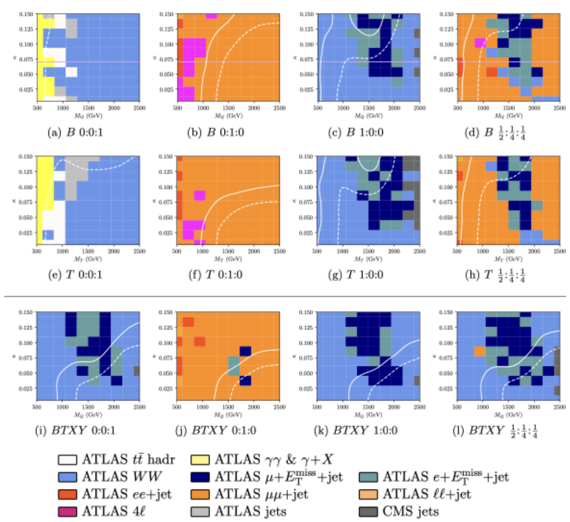




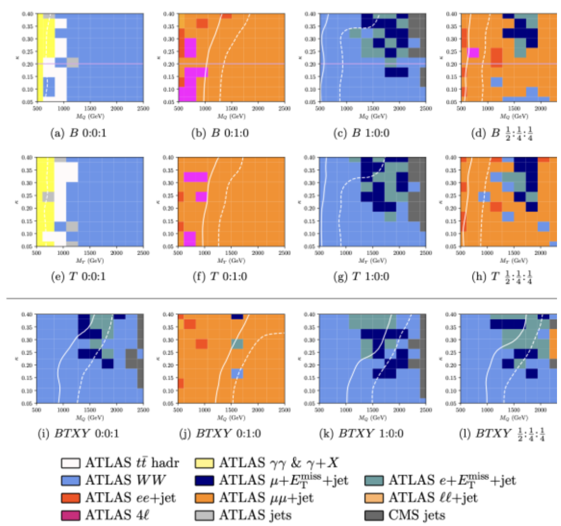
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Vector-like Quarks

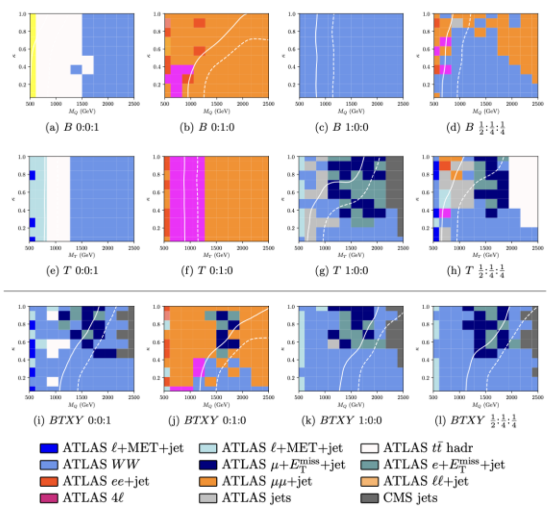
1st Generation



2nd Generation



3rd Generation



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

Summary

From Benjamin

Picking up an experimental publication

- Reading
- Understanding

✅ Relatively easy

Writing the analysis code in the tool internal language

Accurate information for proper validation

- Efficiencies (trigger, $e^{\pm}$, $\mu^{\pm}$, *b*-tagging, JES, *etc.*)
  → including p_T/η dependence
- Detailed cutflows for well-defined benchmarks
  → Region per region information
  → Exact definition of benchmarks (spectra)
  → Event generation information (cards, tunes)
- Digitised histograms (e.g. on HEPDATA)

⚠ Essential
✕ Often difficult!

In many cases, best to let the experimentalists do this once-and-for-all) → particle-level measurements

Summary

Contur (and the software stack it sits on) provides a very efficient way of extracting *additional* BSM information from "SM" measurements (if they are made properly – see previous lectures!)

Once you have the BSM HepMC file…

- mkdir /Work
- cd /Work
- rivet -a $CONTUR_RA13TeV /Events/chacal2024_events_vnoweights.hepmc.gz
- contur Rivet.yoda
- contur-rivetplots --cls 0.3 -–nomultip

Then copy the ANALYSIS directory to somewhere visible outside of docker, and view ANALYSIS/plots/index.html in your browser.