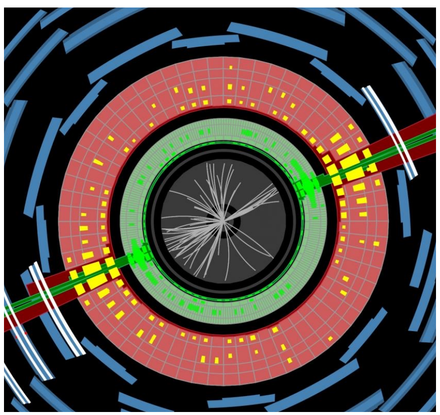
Pursuing Physics Beyond the Standard Model



…using model independent measurements.

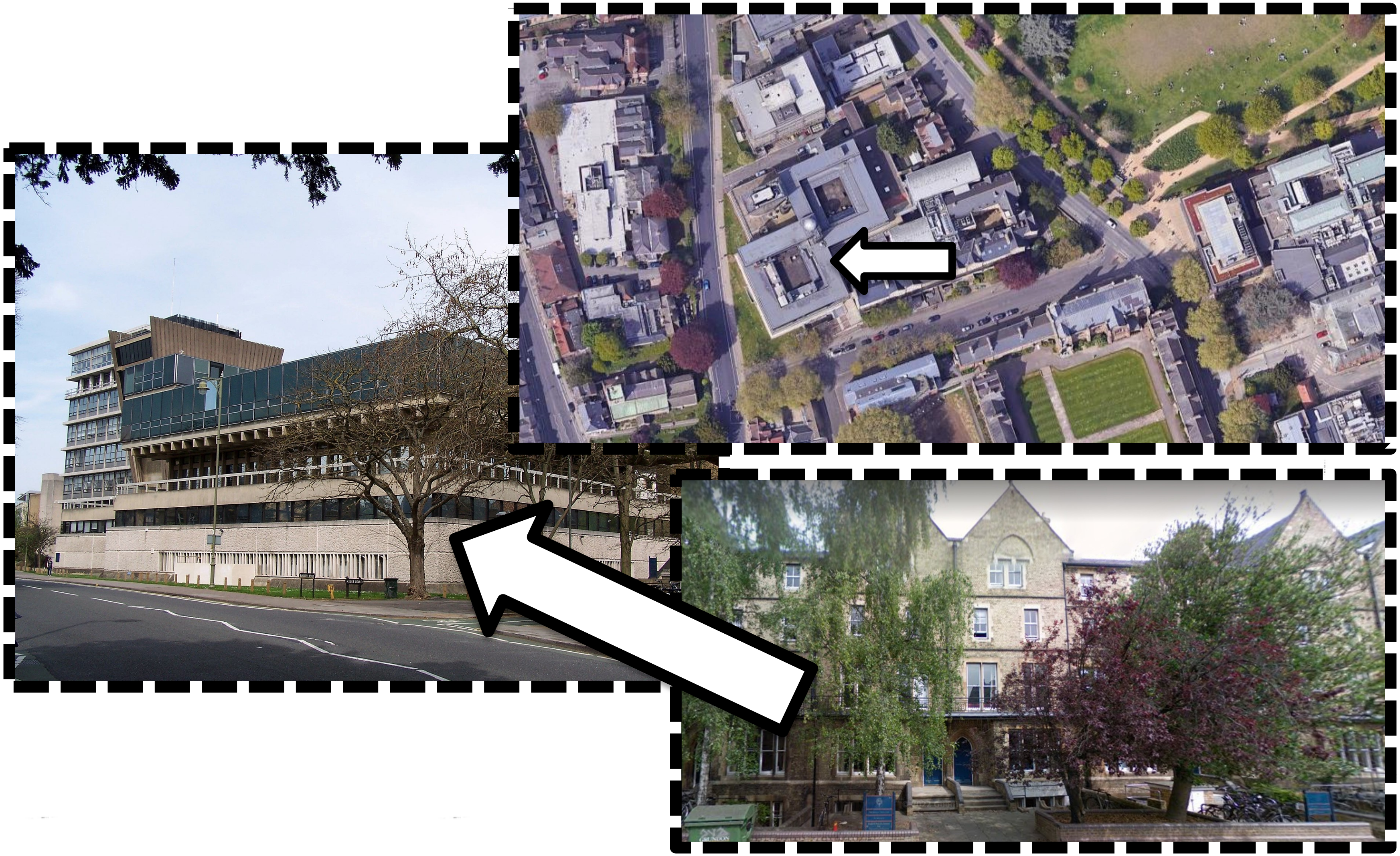
Herbifest, Bonn,

bctp

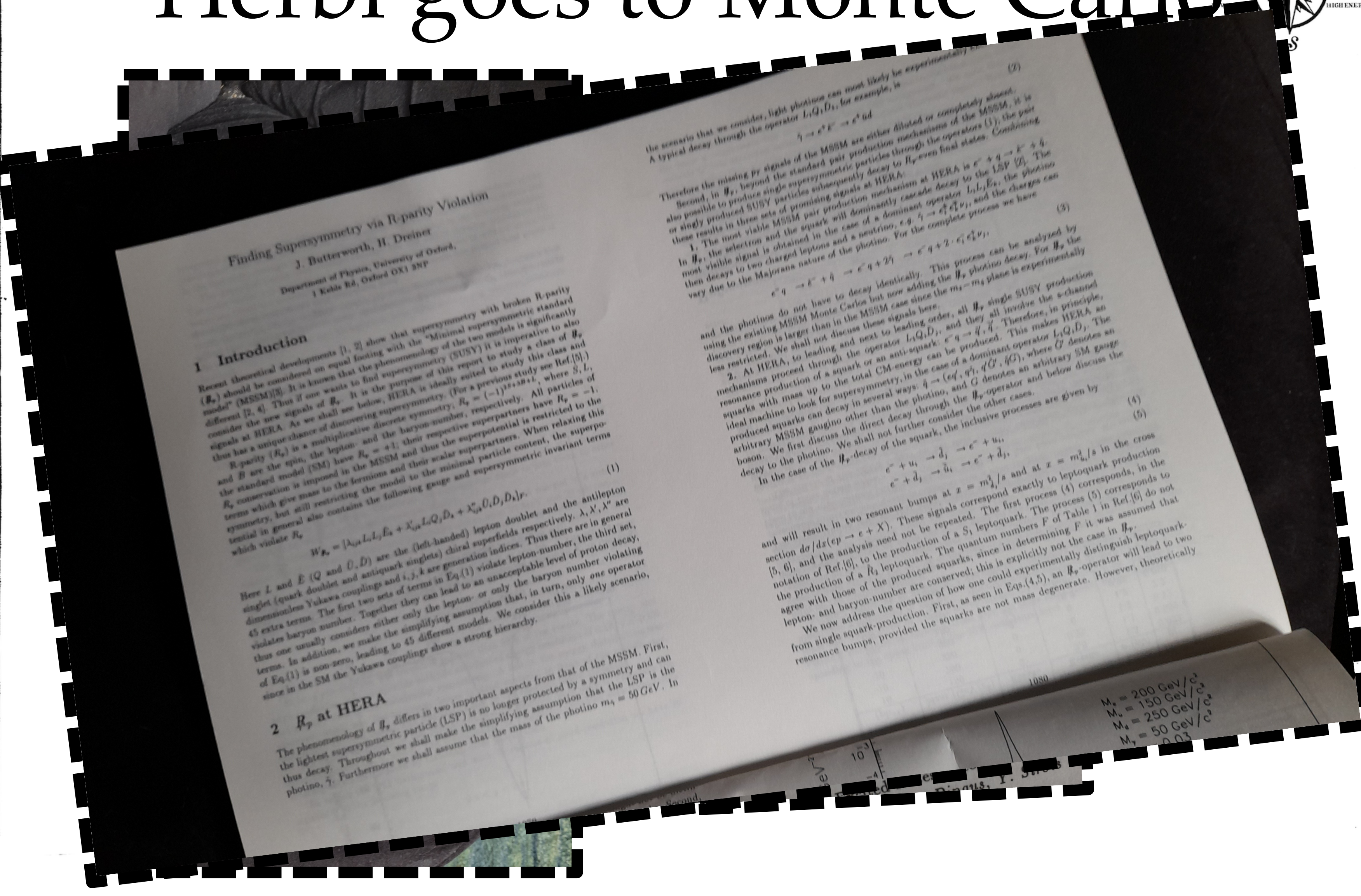
28/3/2023

Jon Butterworth UCL Physics & Astronomy

Oxford, 1990



Herbi goes to Monte Carlo



Finding Supersymmetry via R-parity Violation

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1 Introduction

Recent theoretical developments [1, 2] show that supersymmetry with broken R-parity ($\not{R}_p$) should be considered on equal footing with the "Minimal supersymmetric standard model" (MSSM)[3]. It is known that the phenomenology of the two models is significantly different [2, 4]. Thus if one wants to find supersymmetry (SUSY) it is imperative to also consider the new signals of $\not{R}_p$. It is the purpose of this report to study a class of $\not{R}_p$ signals at HERA. As we shall see below, HERA is ideally suited to study this class and thus has a unique chance of discovering supersymmetry. (For a previous study see Ref.[5].)

R-parity (R_p) is a multiplicative discrete symmetry, $R_p = (-1)^{2S+3B+L}$, where S, L, and B are the spin, the lepton- and the baryon-number, respectively. All particles of the standard model (SM) have $R_p = +1$; their respective superpartners have $R_p = -1$. R_p conservation is imposed in the MSSM and thus the superpotential is restricted to the terms which give mass to the fermions and their scalar superpartners. When relaxing this symmetry, but still restricting the model to the minimal particle content, the superpotential in general also contains the following gauge and supersymmetric invariant terms which violate R_p

$$W_{\not{R}_p} = [\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k]_F. \quad (1)$$

Here L and $\bar{E}$ (Q and $\bar{U}, \bar{D}$) are the (left-handed) lepton doublet and the antilepton singlet (quark doublet and antiquark singlets) chiral superfields respectively. $\lambda, \lambda', \lambda''$ are dimensionless Yukawa couplings and i, j, k are generation indices. Thus there are in general 45 extra terms. The first two sets of terms in Eq.(1) violate lepton-number, the third set, violates baryon number. Together they can lead to an unacceptable level of proton decay, thus one usually considers either only the lepton- or only the baryon number violating terms. In addition, we make the simplifying assumption that, in turn, only *one* operator of Eq.(1) is non-zero, leading to 45 different models. We consider this a likely scenario, since in the SM the Yukawa couplings show a strong hierarchy.

2 $\not{R}_p$ at HERA

The phenomenology of $\not{R}_p$ differs in two important aspects from that of the MSSM. First, the lightest supersymmetric particle (LSP) is no longer protected by a symmetry and can thus decay. Throughout we shall make the simplifying assumption that the LSP is the photino, $\tilde{\gamma}$. Furthermore we shall assume that the mass of the photino $m_{\tilde{\gamma}} = 50\,GeV$. In

the scenario that we consider, light photinos can most likely be experimentally ... A typical decay through the operator $L_1Q_1\bar{D}_1$, for example, is

$$\tilde{\gamma} \rightarrow e^+ \tilde{e}^- \rightarrow e^+ \bar{u} d \quad (2)$$

Therefore the missing p_T signals of the MSSM are either diluted or completely absent.

Second, in $\not{R}_p$, beyond the standard pair production mechanisms of the MSSM, it is also possible to produce single supersymmetric particles through the operators (1); the pair or singly produced SUSY particles subsequently decay to R_p-even final states. Combining these results in three sets of promising signals at HERA.

1. The most viable MSSM pair production mechanism at HERA is $e^- + q \rightarrow \tilde{e}^- + \tilde{q}$. In $\not{R}_p$, the selectron and the squark will dominantly cascade decay to the LSP [2]. The most visible signal is obtained in the case of a dominant operator $L_1L_jE_k$, the photino then decays to two charged leptons and a neutrino, e.g. $\tilde{\gamma} \rightarrow e_1^+ e_k^- \nu_j$, and the charges can vary due to the Majorana nature of the photino. For the complete process we have

$$e^- q \rightarrow \tilde{e}^- + \tilde{q} \rightarrow e^- q + 2\tilde{\gamma} \rightarrow e^- q + 2 \cdot e_1^{\mp} e_k^{\pm} \nu_j, \quad (3)$$

and the photinos do not have to decay identically. This process can be analyzed by using the existing MSSM Monte Carlos but now adding the $\not{R}_p$ photino decay. For $\not{R}_p$ the discovery region is larger than in the MSSM case since the $m_{\tilde{e}}-m_{\tilde{q}}$ plane is experimentally less restricted. We shall not discuss these signals here.

2. At HERA, to leading and next to leading order, all $\not{R}_p$ single SUSY production mechanisms proceed through the operator $L_1Q_j\bar{D}_j$, and they all involve the s-channel resonance production of a squark or an anti-squark: $e^- q \rightarrow \tilde{q}, \bar{\tilde{q}}$. Therefore, in principle, squarks with mass up to the total CM-energy can be produced. This makes HERA an ideal machine to look for supersymmetry, in the case of a dominant operator $L_1Q_j\bar{D}_j$. The produced squarks can decay in several ways: $\tilde{q} \rightarrow (eq', q\tilde{\gamma}, q'\tilde{G}', \tilde{q}G)$, where $\tilde{G}'$ denotes an arbitrary MSSM gaugino other than the photino, and G denotes an arbitrary SM gauge boson. We first discuss the direct decay through the $\not{R}_p$-operator and below discuss the decay to the photino. We shall not further consider the other cases.

In the case of the $\not{R}_p$-decay of the squark, the inclusive processes are given by

$$e^- + u_i \rightarrow \tilde{d}_j \rightarrow e^- + u_i, \quad (4)$$

$$e^- + \bar{d}_j \rightarrow \bar{\tilde{u}}_i \rightarrow e^- + \bar{d}_j, \quad (5)$$

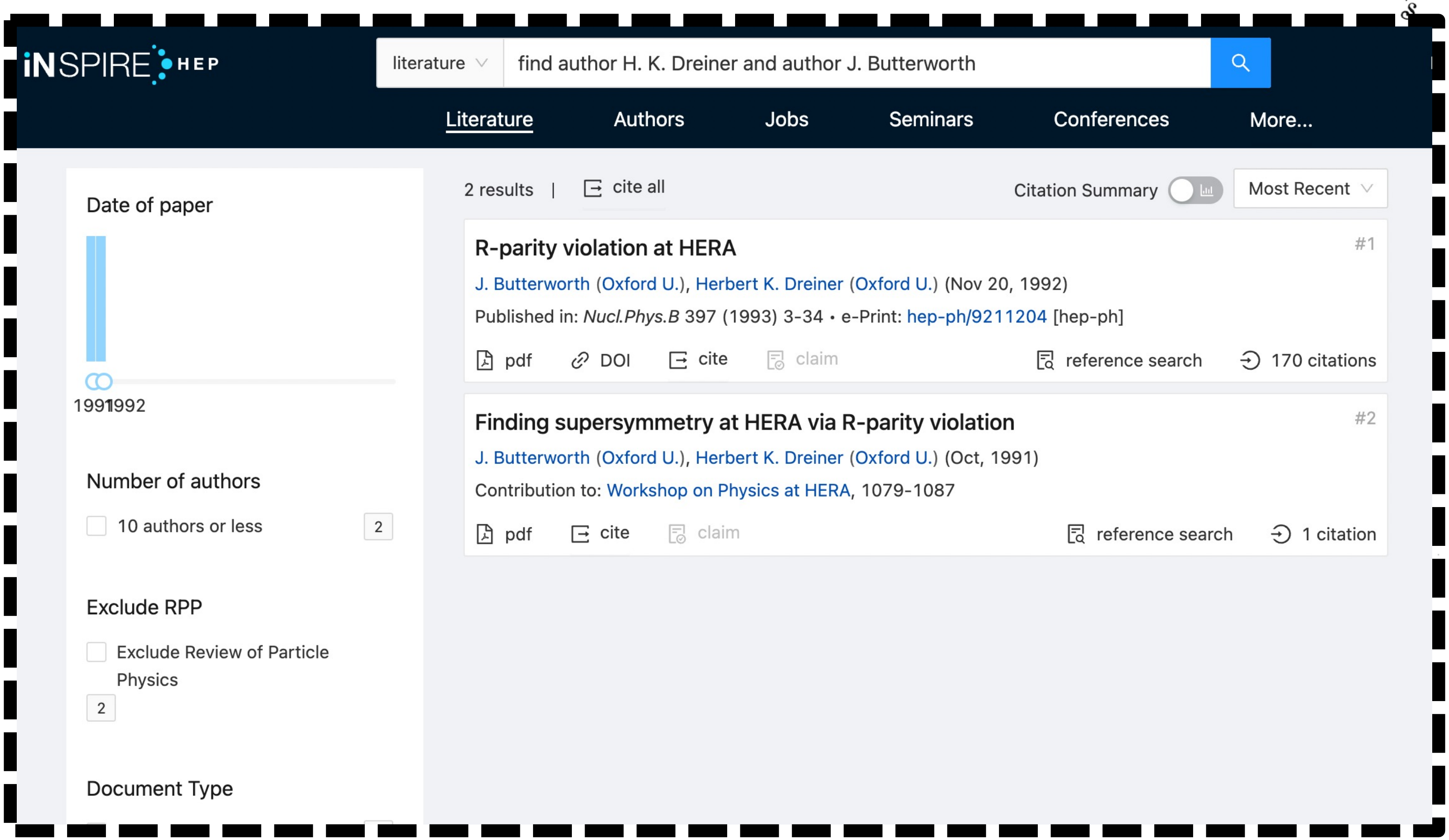
and will result in two resonant bumps at $x = m^2_{\tilde{d}_j}/s$ and at $x = m^2_{\tilde{u}_i}/s$ in the cross section $d\sigma/dx(ep \rightarrow e + X)$. These signals correspond exactly to leptoquark production [5, 6], and the analysis need not be repeated. The first process (4) corresponds, in the notation of Ref.[6], to the production of a S_1 leptoquark. The process (5) corresponds to the production of a $\tilde{R}_2$ leptoquark. The quantum numbers F of Table 1 in Ref.[6] do not agree with those of the produced squarks, since in determining F it was assumed that lepton- and baryon-number are conserved; this is explicitly not the case in $\not{R}_p$.

We now address the question of how one could experimentally distinguish leptoquark- from single squark-production. First, as seen in Eqs.(4,5), an $\not{R}_p$-operator will lead to two resonance bumps, provided the squarks are not mass degenerate. However, theoretically

1080

M_e = 200 GeV/c²
M_u = 150 GeV/c²
M_d = 250 GeV/c²
M_γ = 50 GeV/c²

Which led to…



But actually…

Which led to…

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World ▶ **Europe** US Americas Asia Australia Middle East Africa Inequality Global development

Life and Physics
Science

This article is mor

Can physi
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Tue 19 Jan 2016 17.24 GMT

54

Since nature is u
can reach out to
practice? And if

Life and Physics
Science

SLAM POW BANG: On Tour in England with the Bonn Physics Show

My old friend Herbi Dreiner has won awards for his classic(al) physics shows. Next week he brings a new one, with added quantum, to the UK. Here he describes the experience of trying to put the Higgs boson on stage. Plus! DEMO: The Movie

Jon Butterworth
@jonmbutterworth
Thu 13 Mar 2014 07.00 GMT

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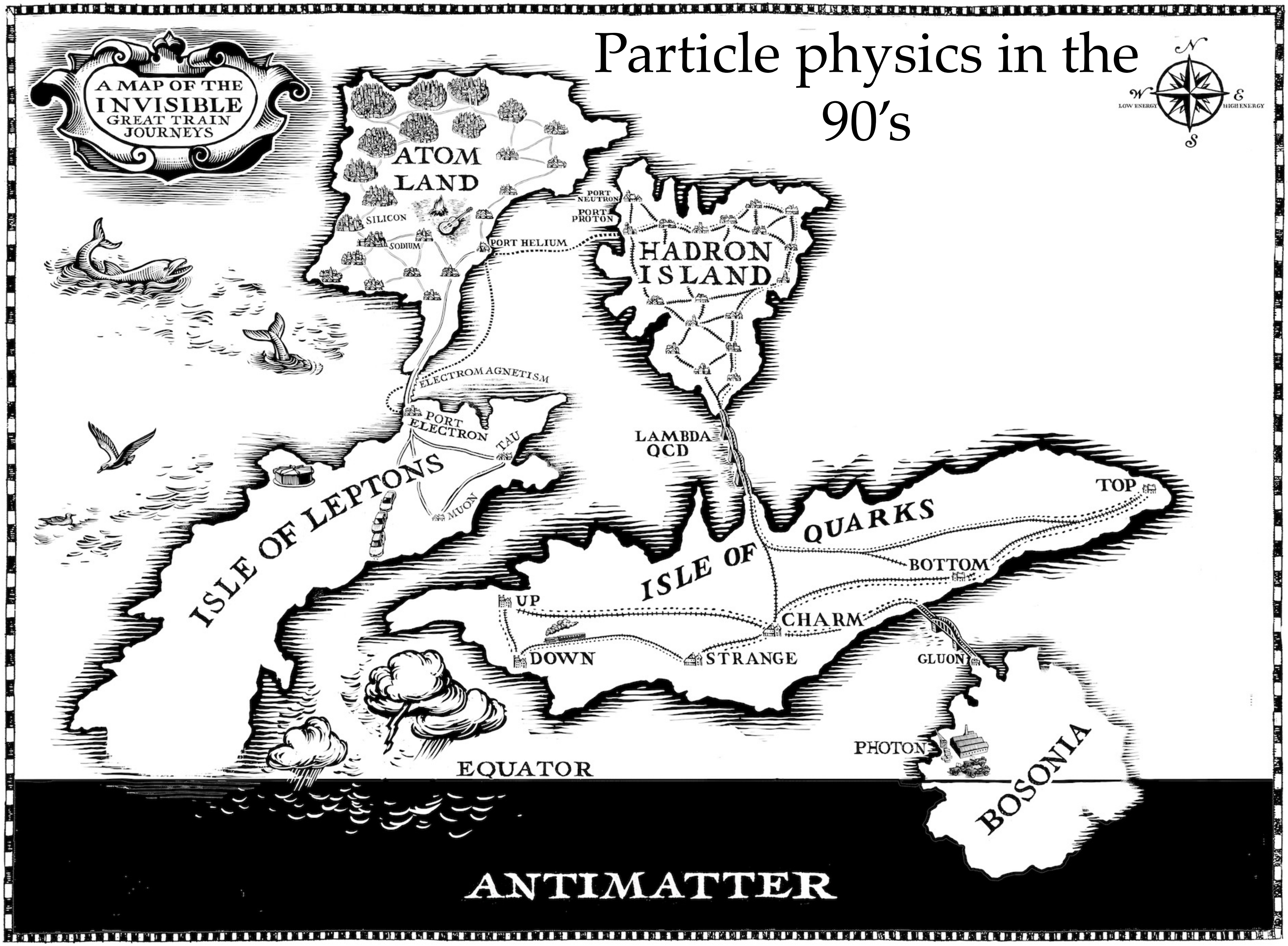
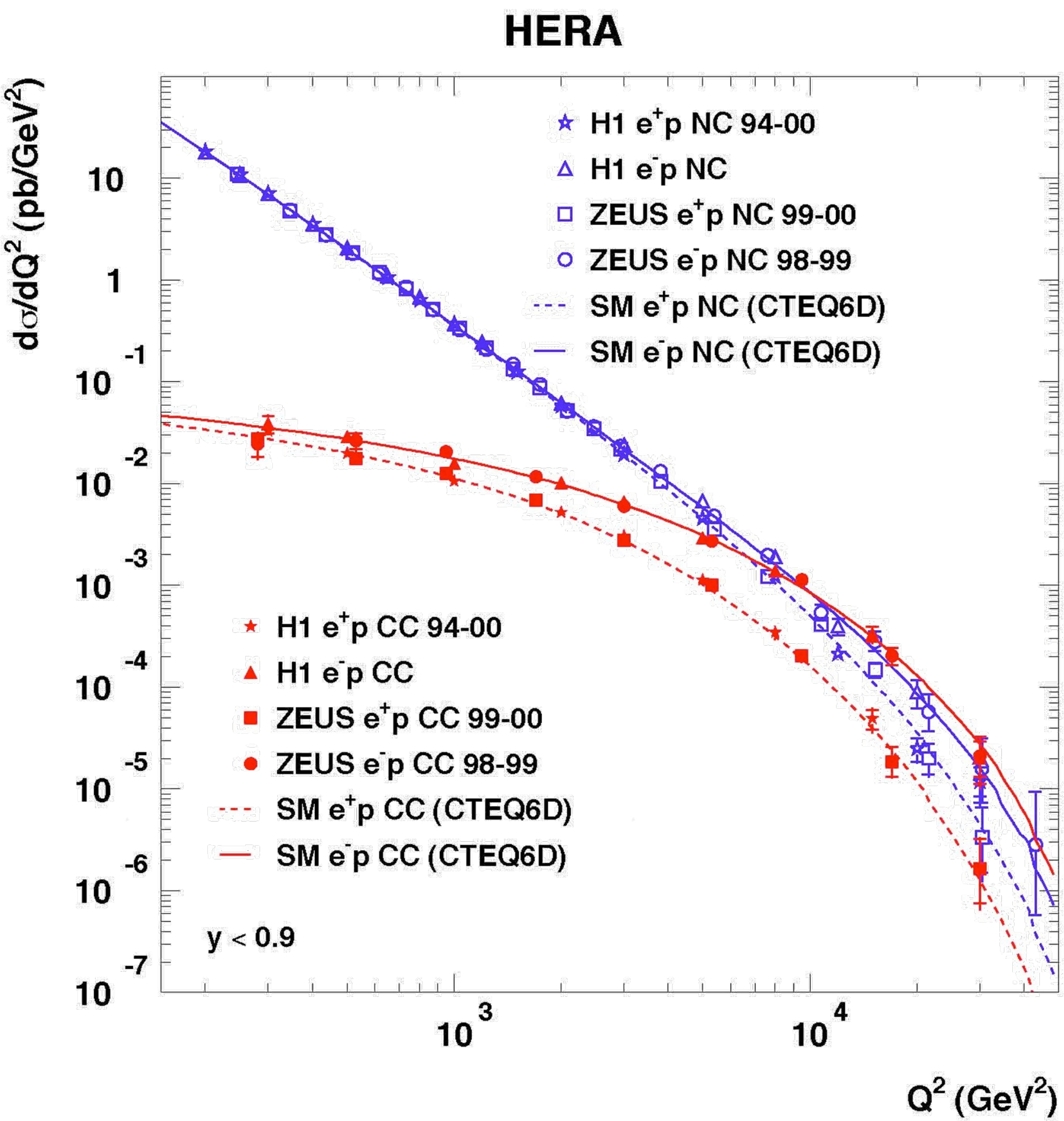
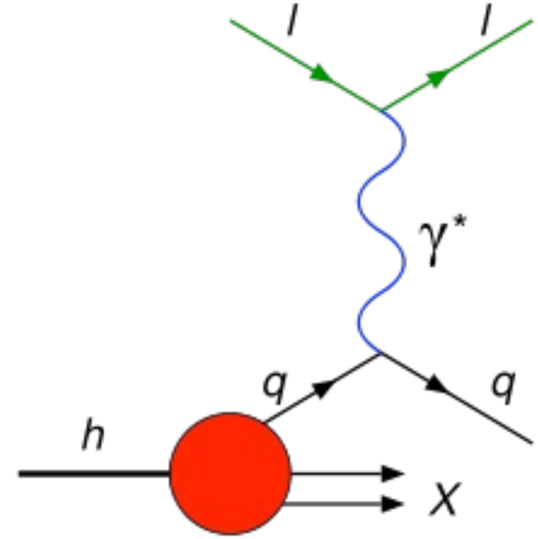
And also, indirectly, the rest of this talk…

Particle physics in the 90's





HERA
dσ/dQ² (pb/GeV²)
Q² (GeV²)
H1 e⁺p NC 94-00
H1 e⁻p NC
ZEUS e⁺p NC 99-00
ZEUS e⁻p NC 98-99
SM e⁺p NC (CTEQ6D)
SM e⁻p NC (CTEQ6D)
H1 e⁺p CC 94-00
H1 e⁻p CC
ZEUS e⁺p CC 99-00
ZEUS e⁻p CC 98-99
SM e⁺p CC (CTEQ6D)
SM e⁻p CC (CTEQ6D)
y < 0.9



l
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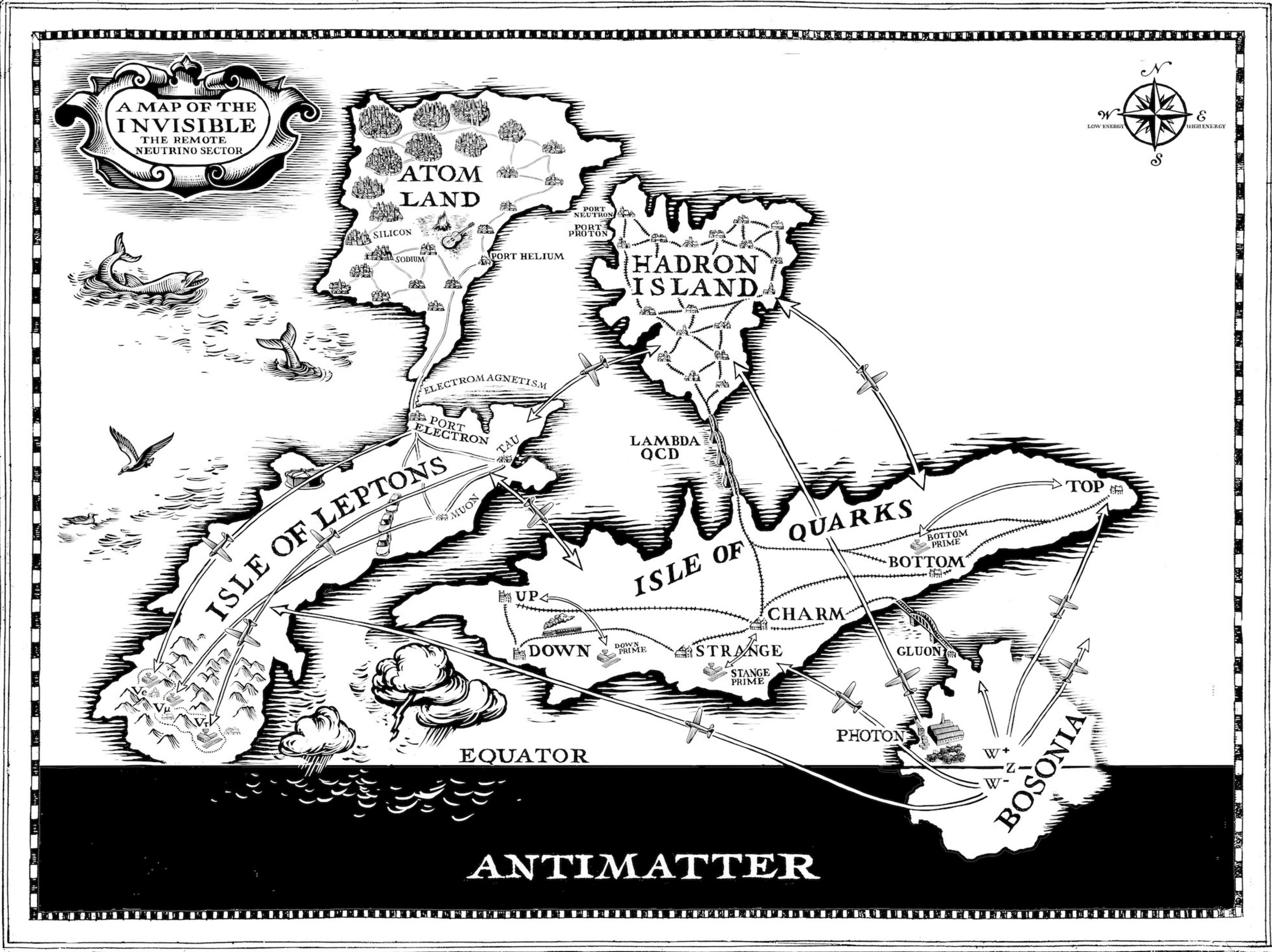
γ*
q
q
h
X


A MAP OF THE
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THE REMOTE
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ISLE OF
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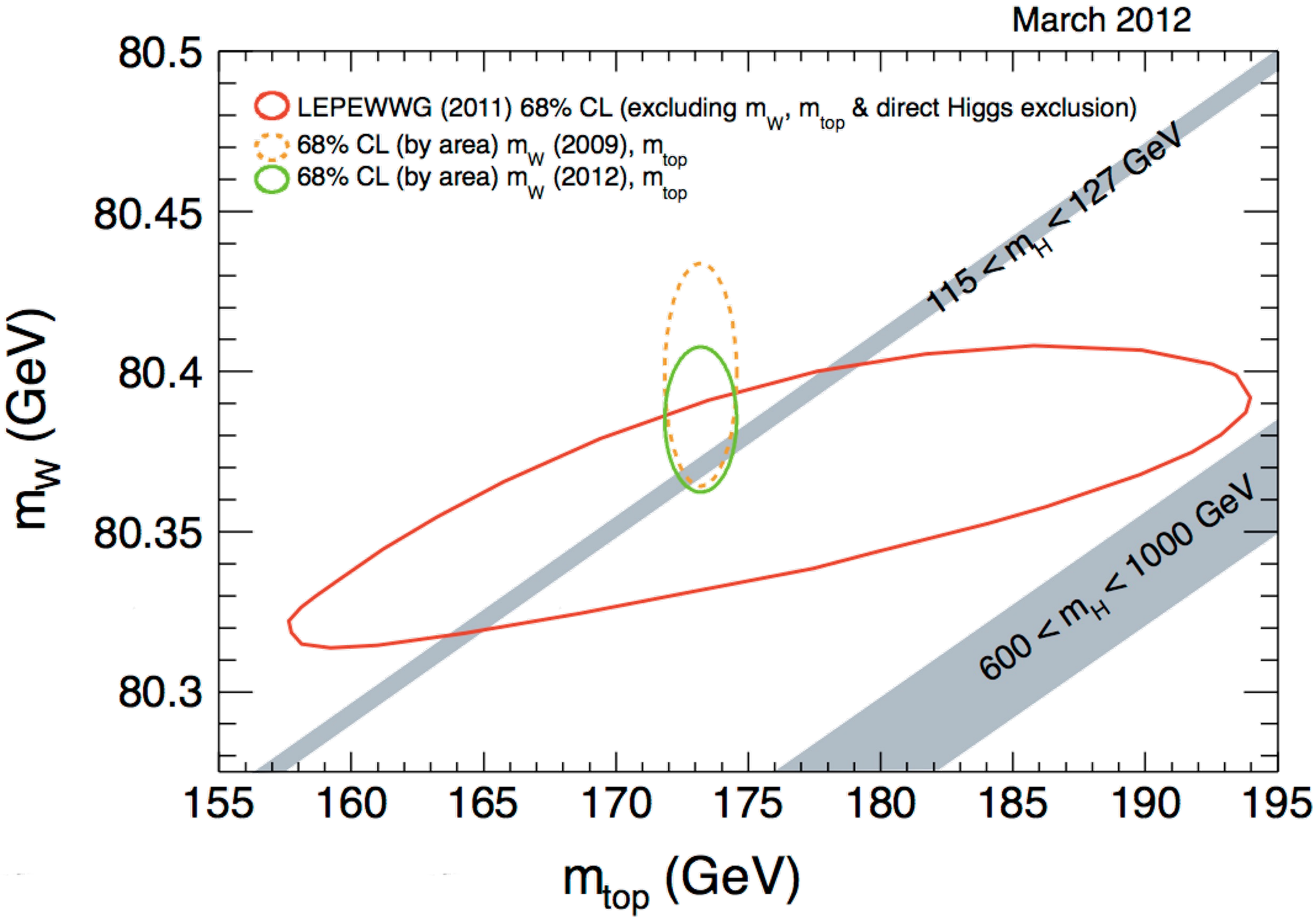
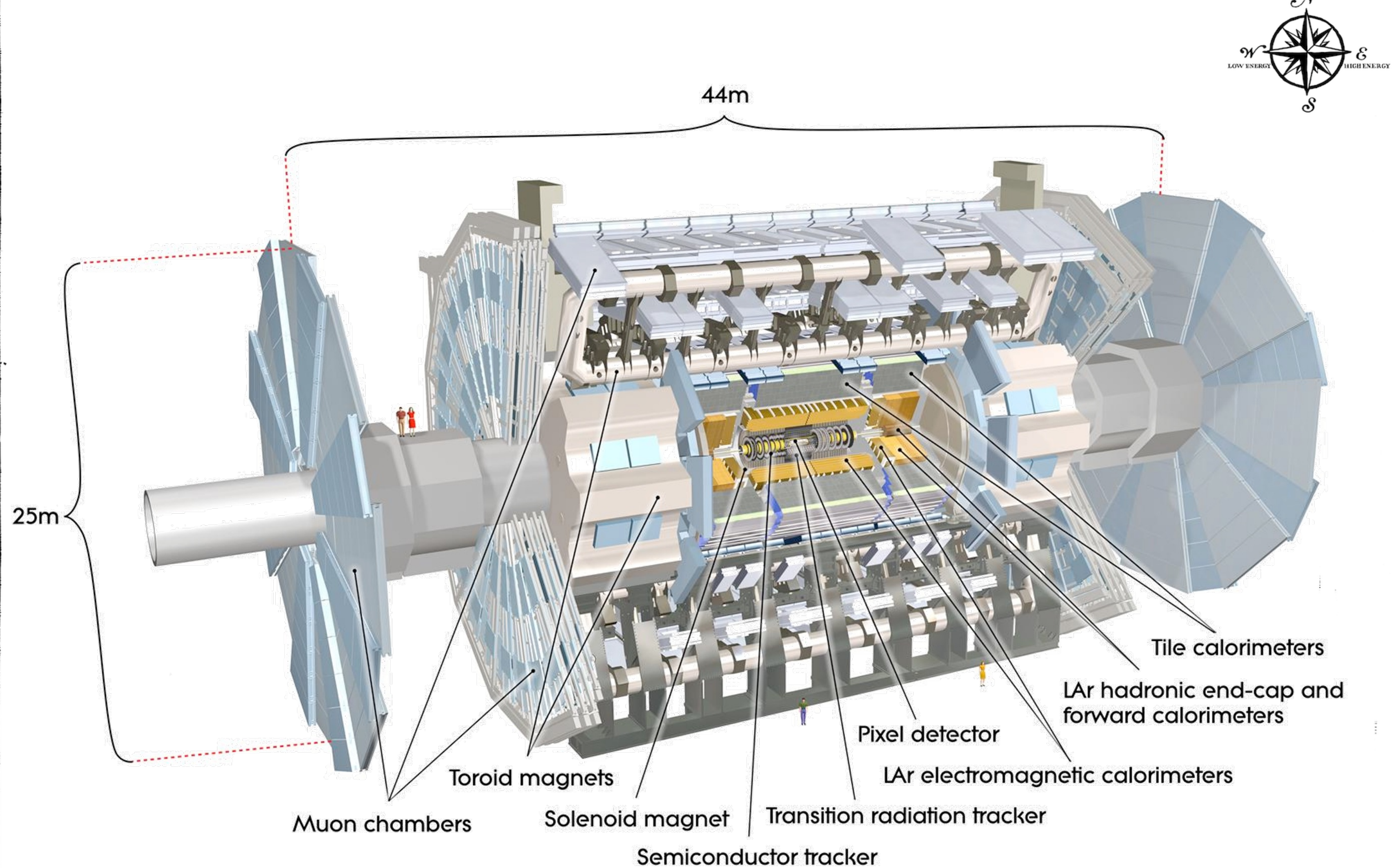
ANTIMATTER

Before the LHC




LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km



N
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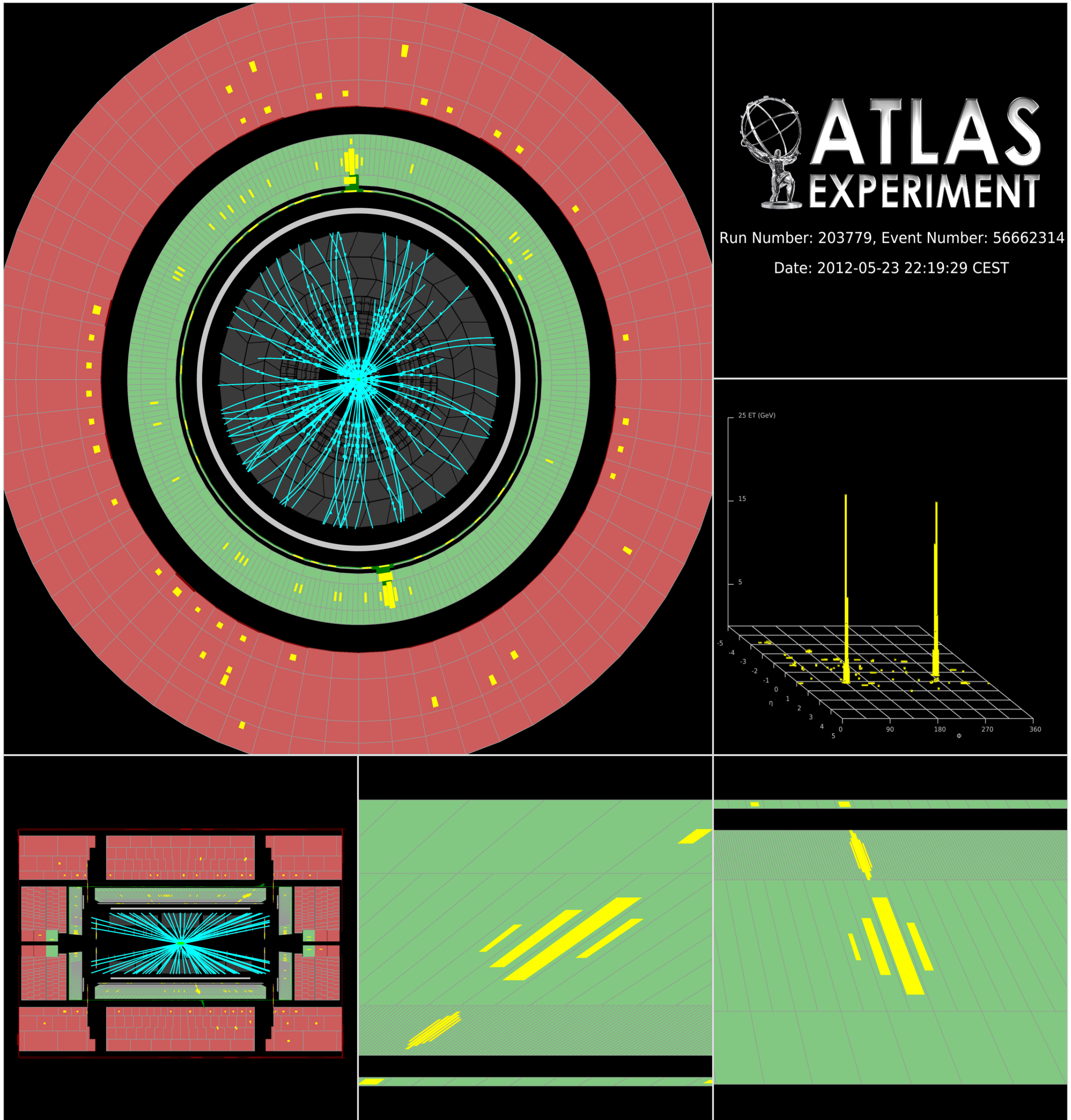
LOW ENERGY
HIGH ENERGY
44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
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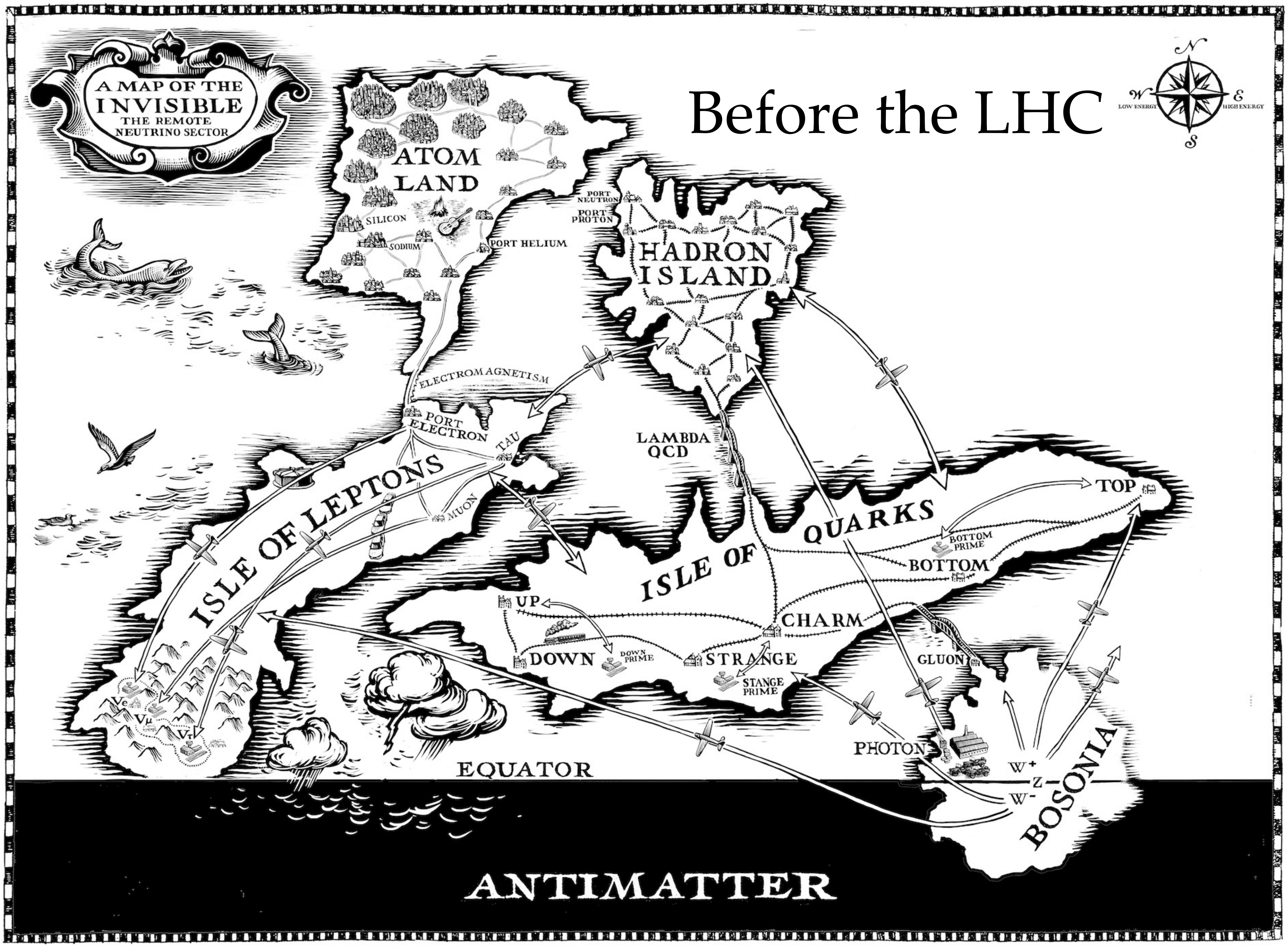
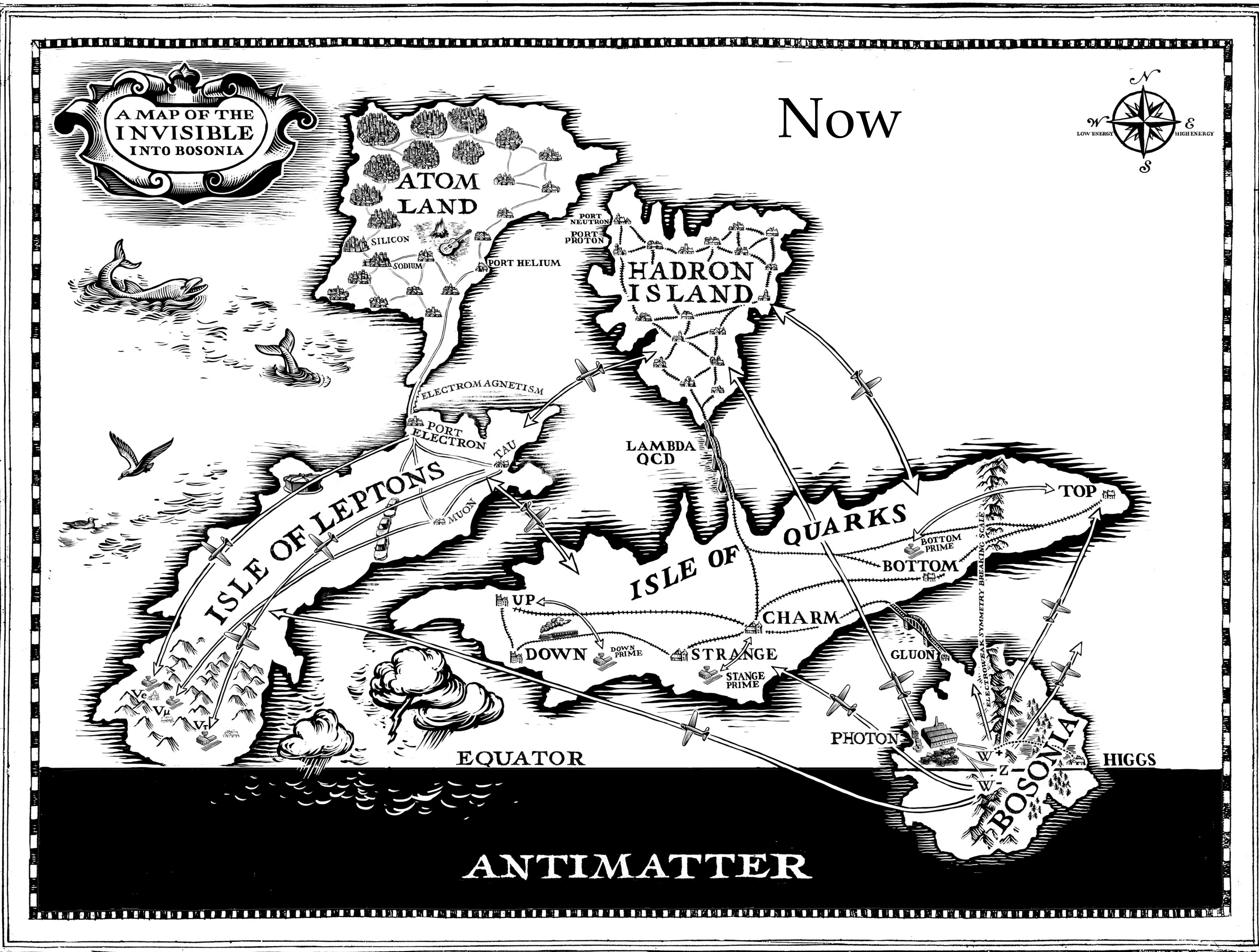
LOW ENERGY
HIGH ENERGY

Before the LHC




A MAP OF THE INVISIBLE INTO BOSONIA
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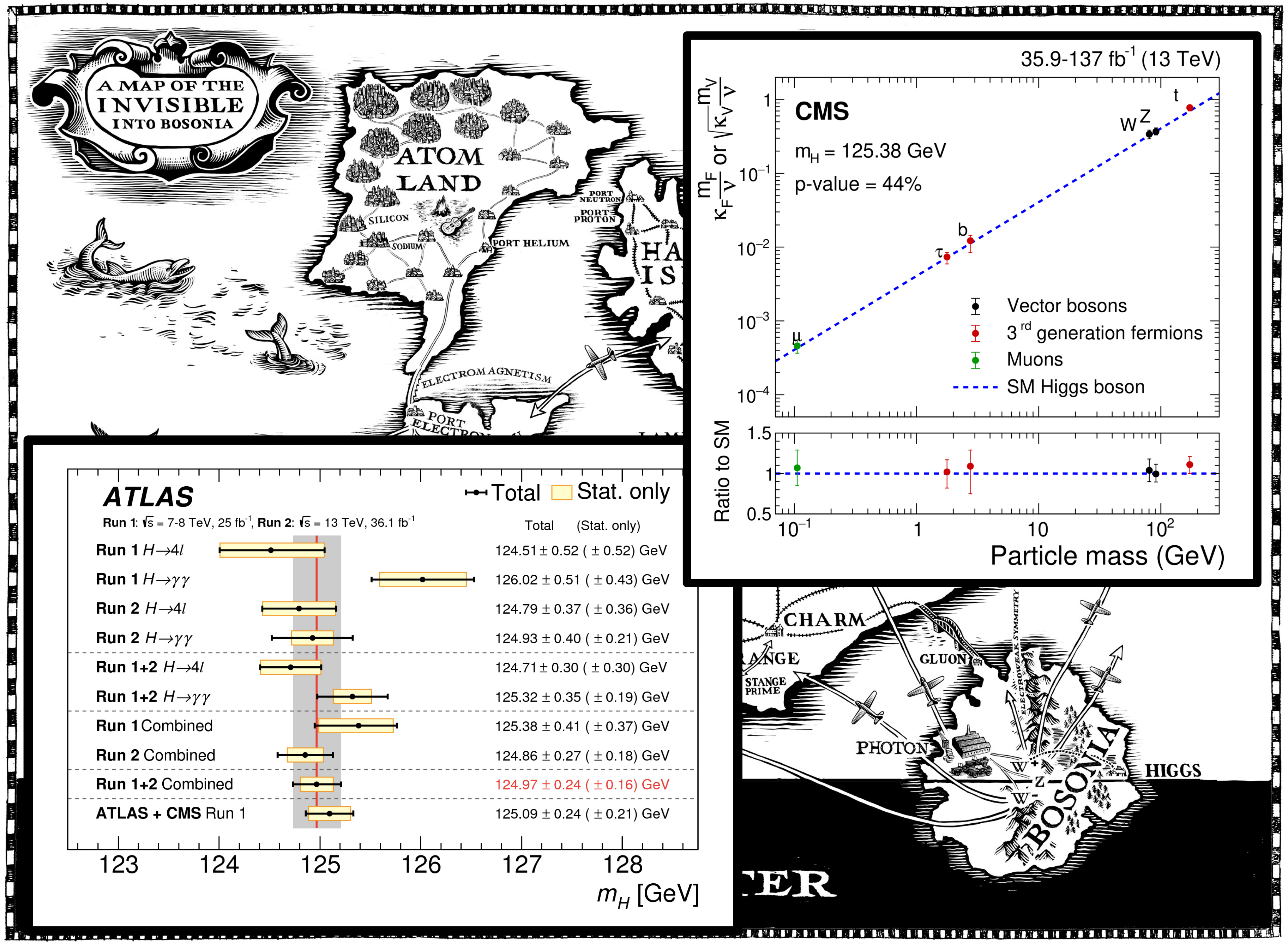
ANTIMATTER


A MAP OF THE INVISIBLE INTO BOSONIA
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STANGE PRIME
PHOTON
ELECTROWEAK SYMMETRY
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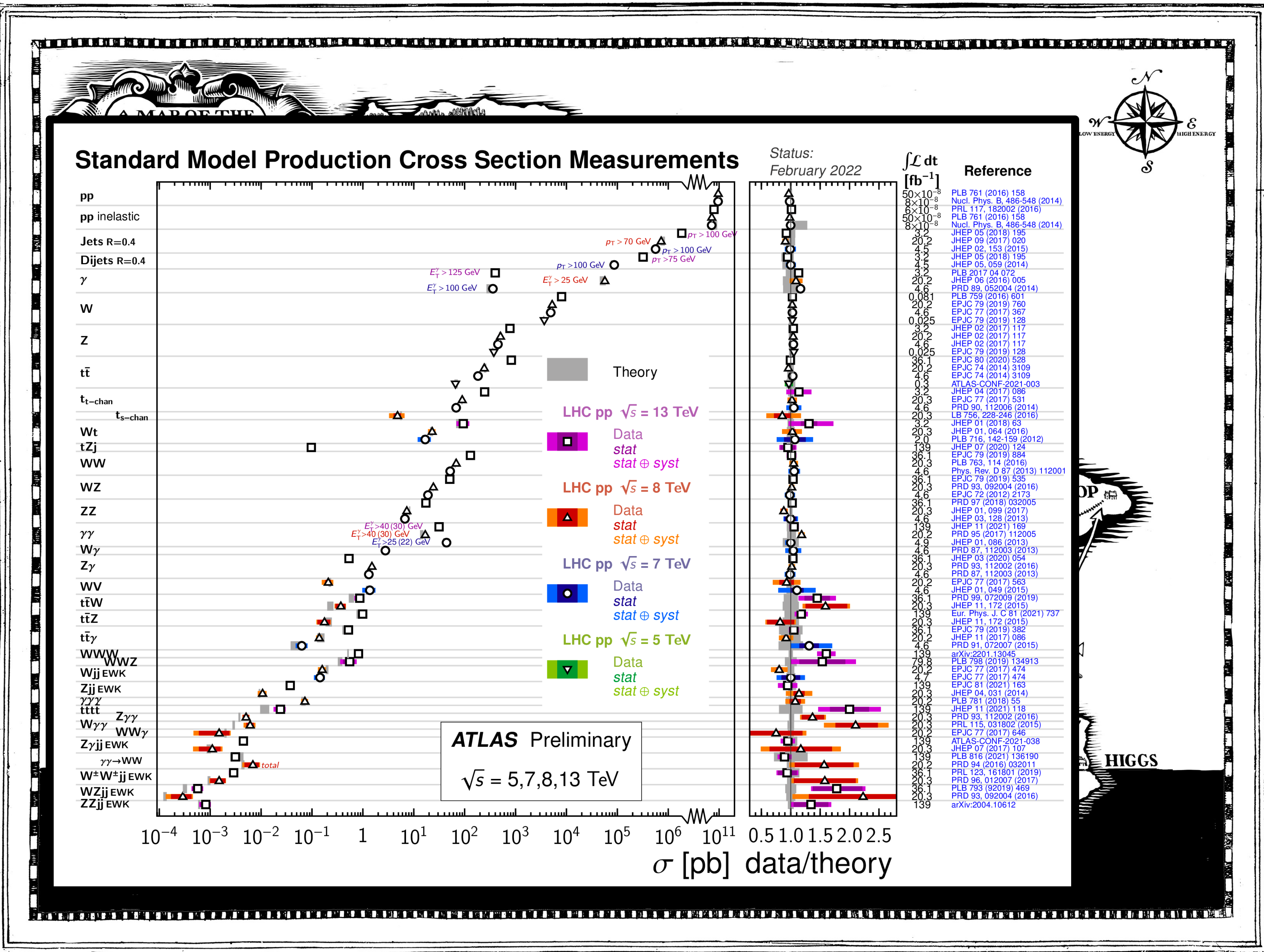
W-
BOSONIA
HIGGS
35.9-137 fb-1 (13 TeV)
CMS
mH = 125.38 GeV
p-value = 44%
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
Ratio to SM
Particle mass (GeV)
ATLAS
Total
Stat. only
Run 1: √s = 7-8 TeV, 25 fb-1, Run 2: √s = 13 TeV, 36.1 fb-1
Total (Stat. only)
Run 1 H→4l 124.51 ± 0.52 (± 0.52) GeV
Run 1 H→γγ 126.02 ± 0.51 (± 0.43) GeV
Run 2 H→4l 124.79 ± 0.37 (± 0.36) GeV
Run 2 H→γγ 124.93 ± 0.40 (± 0.21) GeV
Run 1+2 H→4l 124.71 ± 0.30 (± 0.30) GeV
Run 1+2 H→γγ 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
mH [GeV]



Standard Model Production Cross Section Measurements
Status: February 2022
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
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Z
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t t-chan
t s-chan
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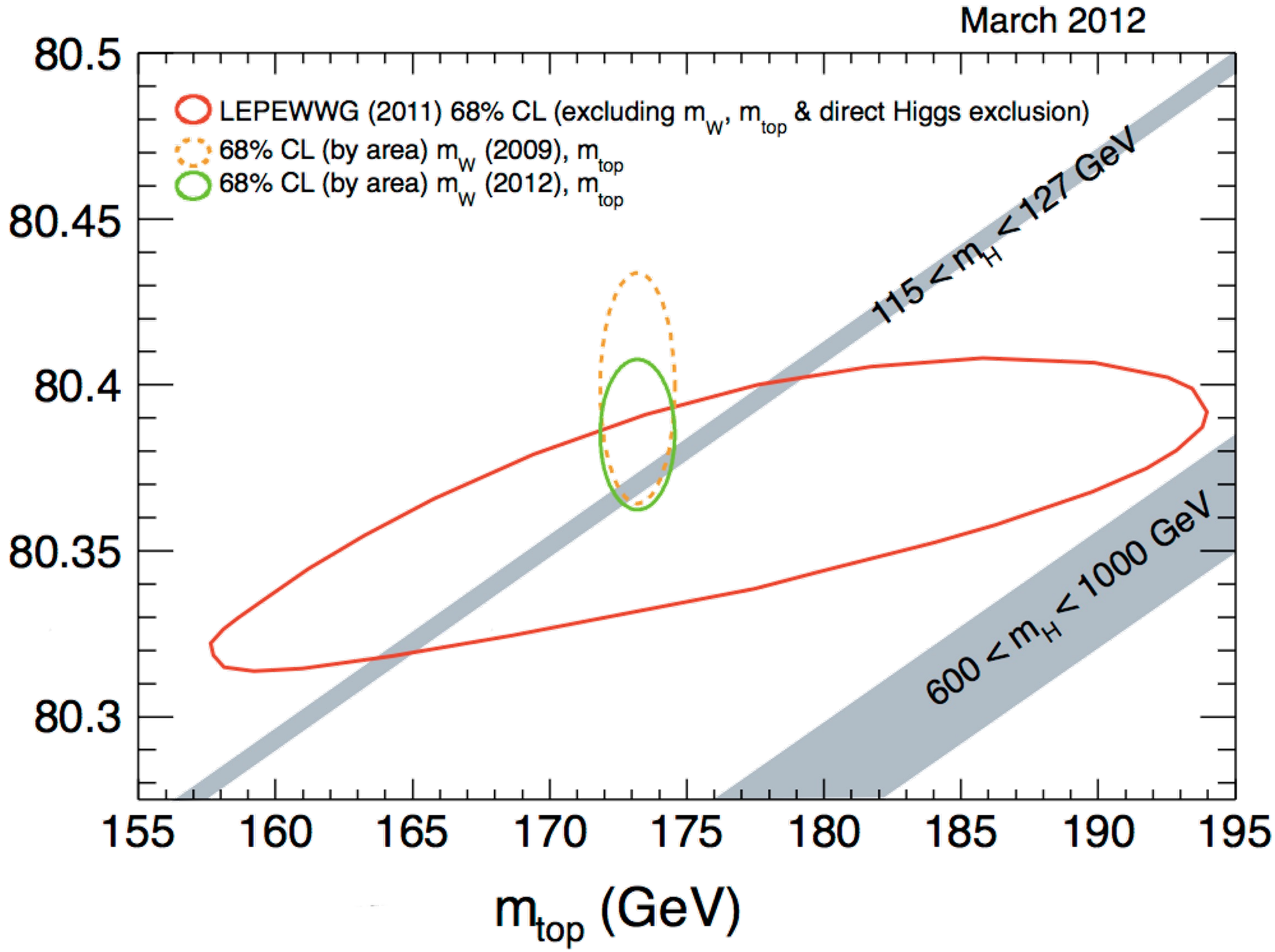
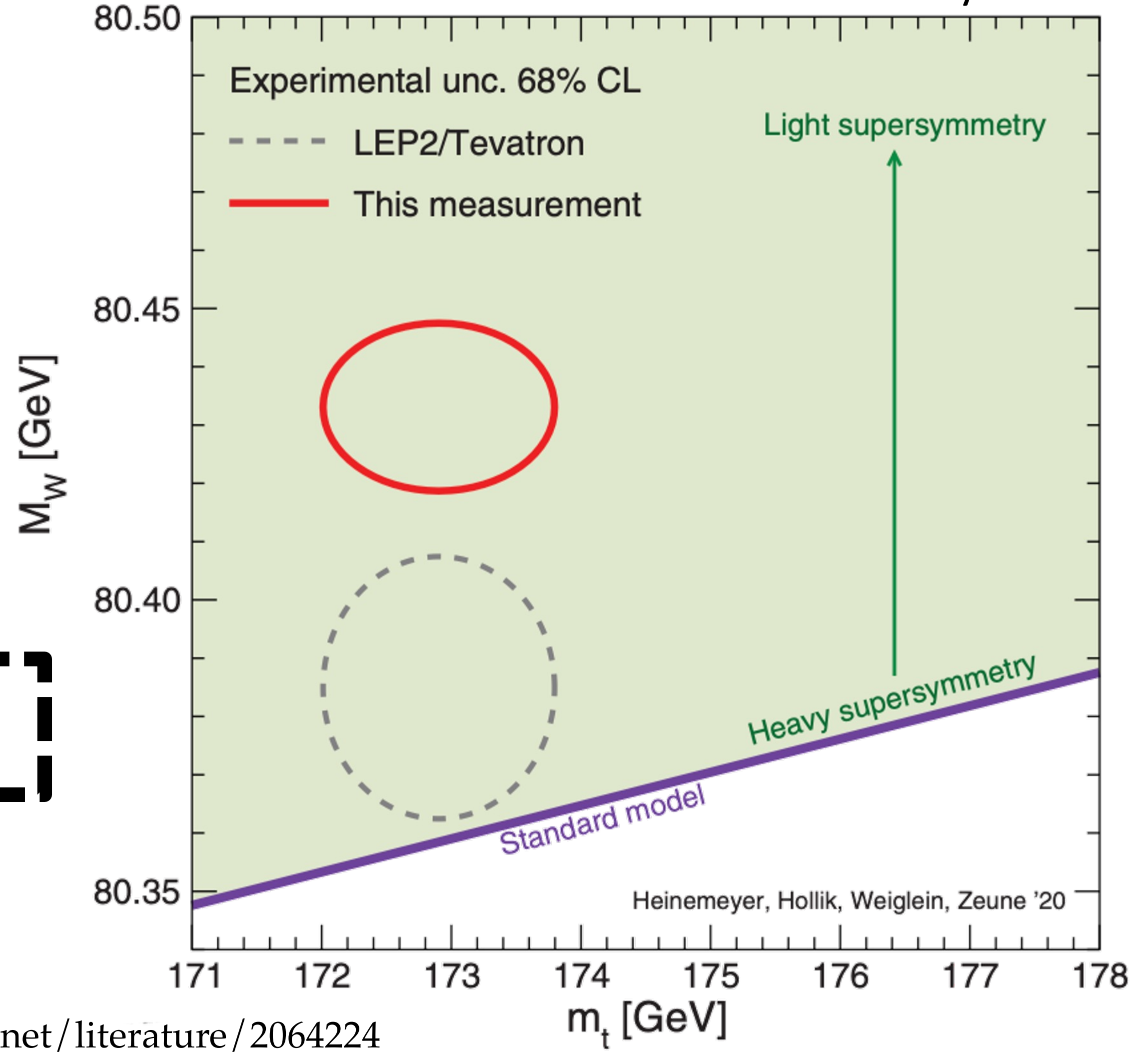
ZZ
γγ
Wγ
Zγ
WV
tt̄W
tt̄Z
tt̄γ
WWW
WWZ
Wjj EWK
Zjj EWK
γγγ
tttt
Zγγ
Wγγ
WWγ
Zγjj EWK
γγ→WW
W±W±jj EWK
WZjj EWK
ZZjj EWK
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
√s = 5,7,8,13 TeV
σ [pb]
data/theory
∫ℒ dt [fb⁻¹]
Reference
HIGGS

Before the LHC



Update from CDF

Last year

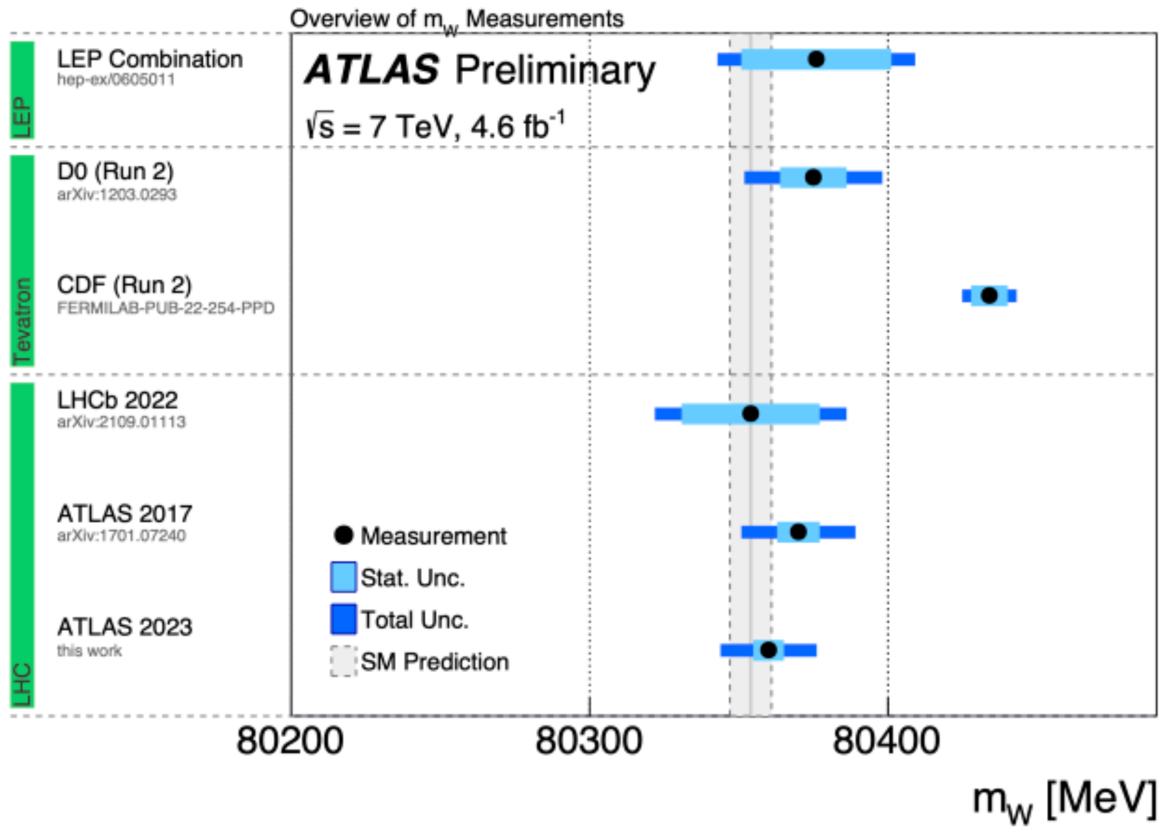


Plot ©GW et al, caveats noted

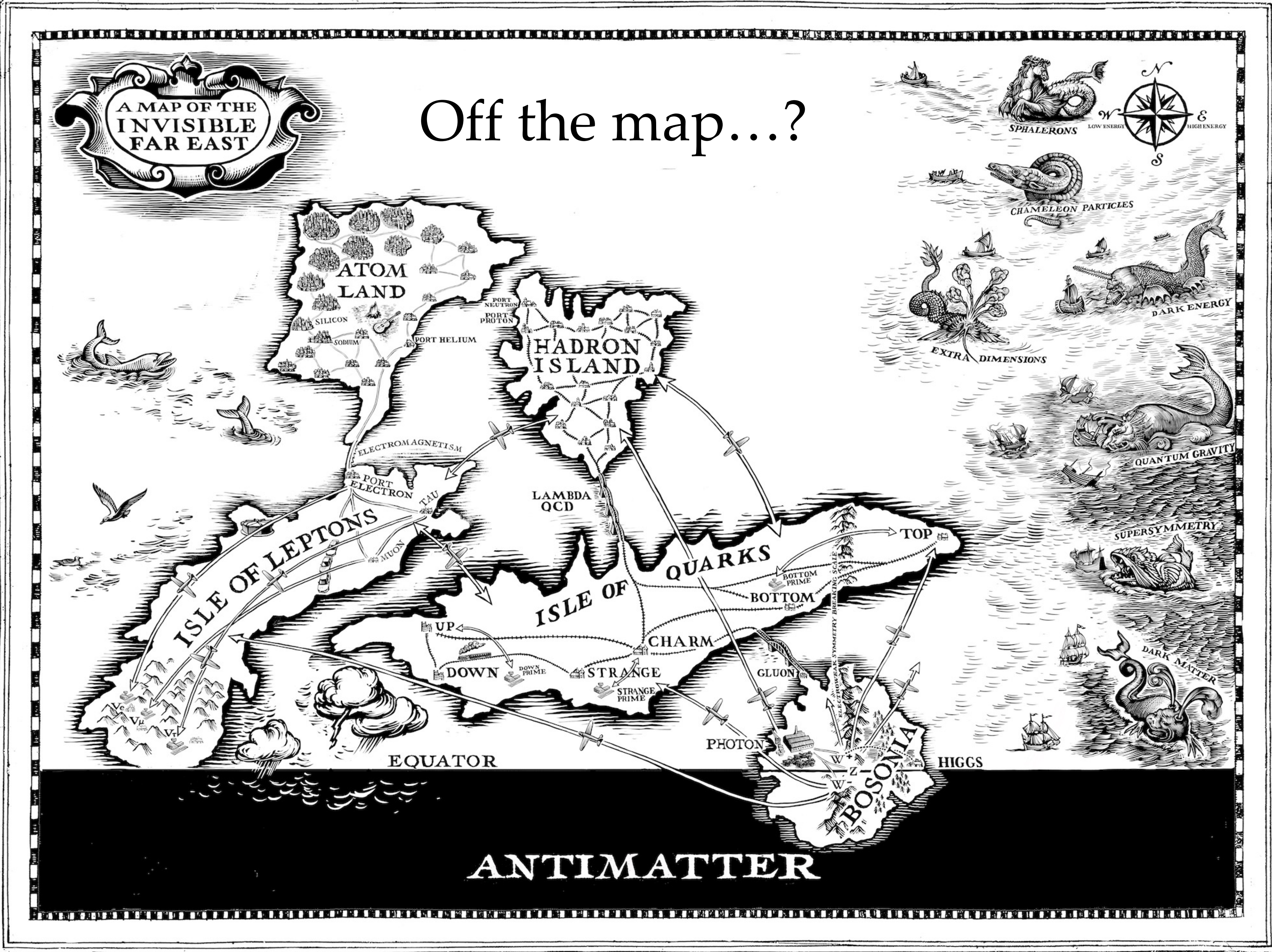
CDF https://inspirehep.net/literature/2064224

Update from ATLAS

Last week



Off the map…?


A MAP OF THE INVISIBLE FAR EAST
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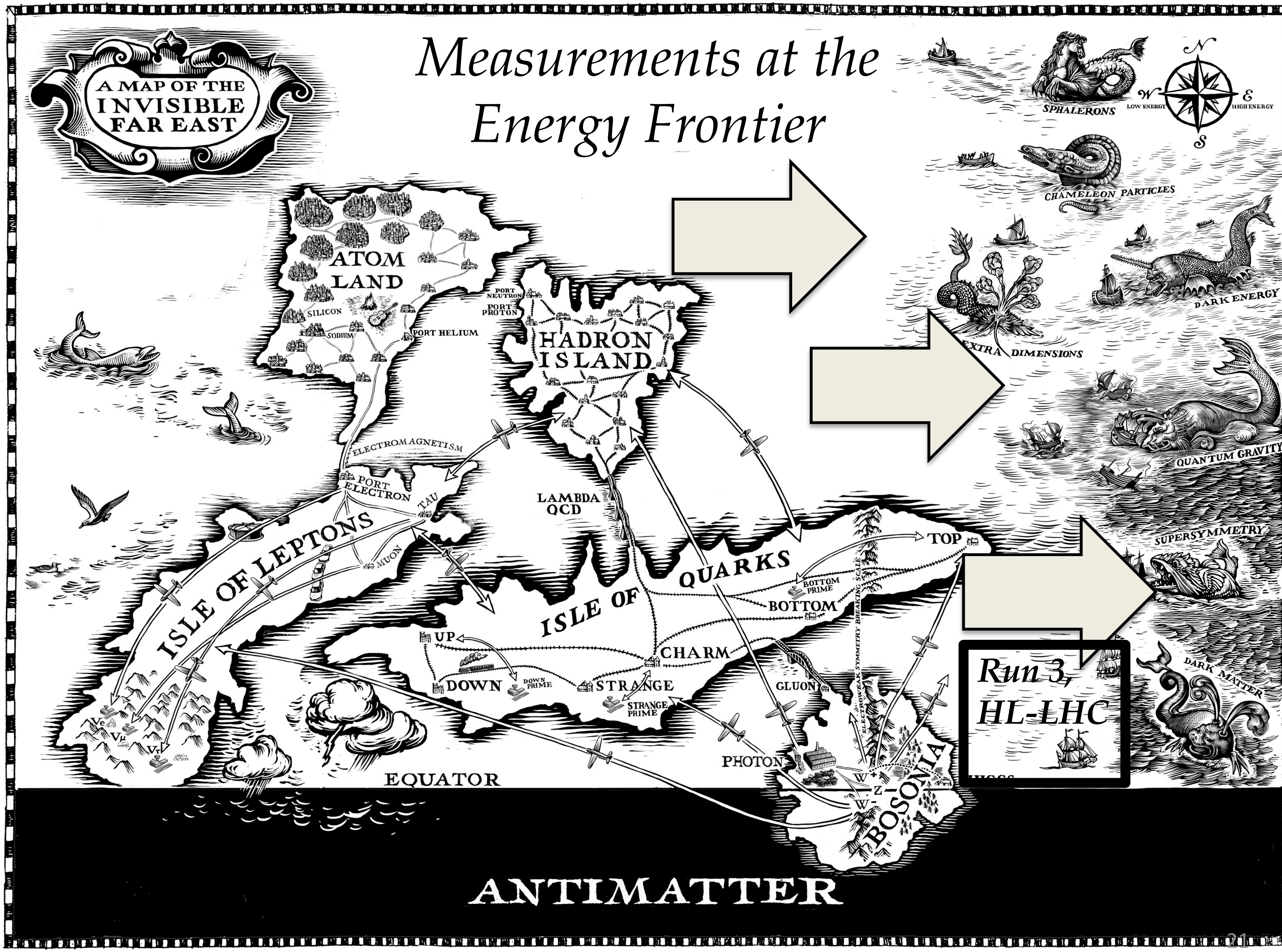
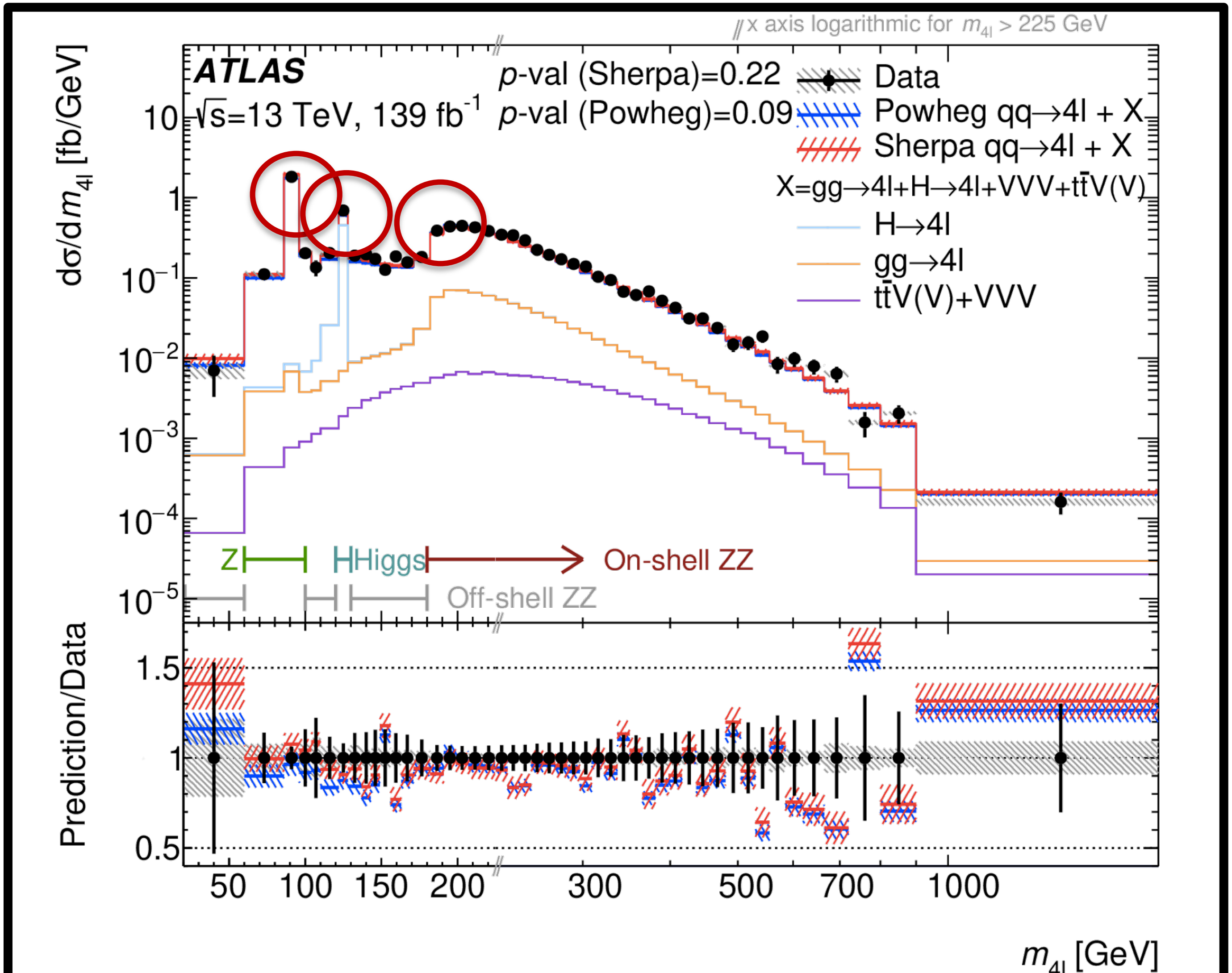
SUPERSYMMETRY
DARK MATTER

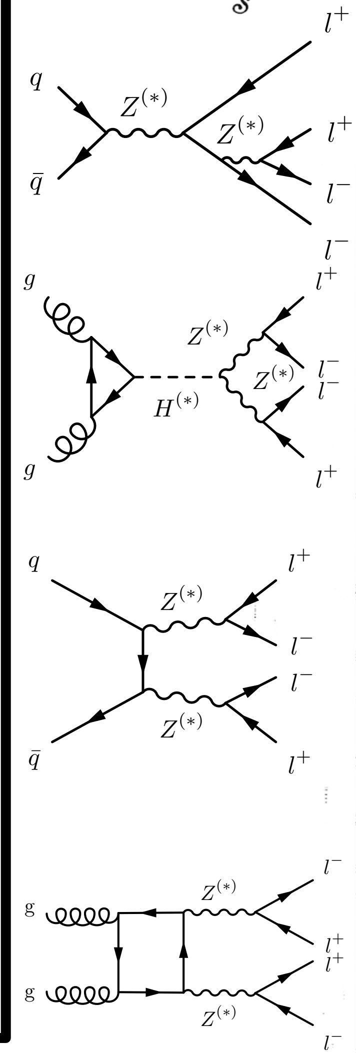
Measurements at the Energy Frontier



Run 3, HL-LHC



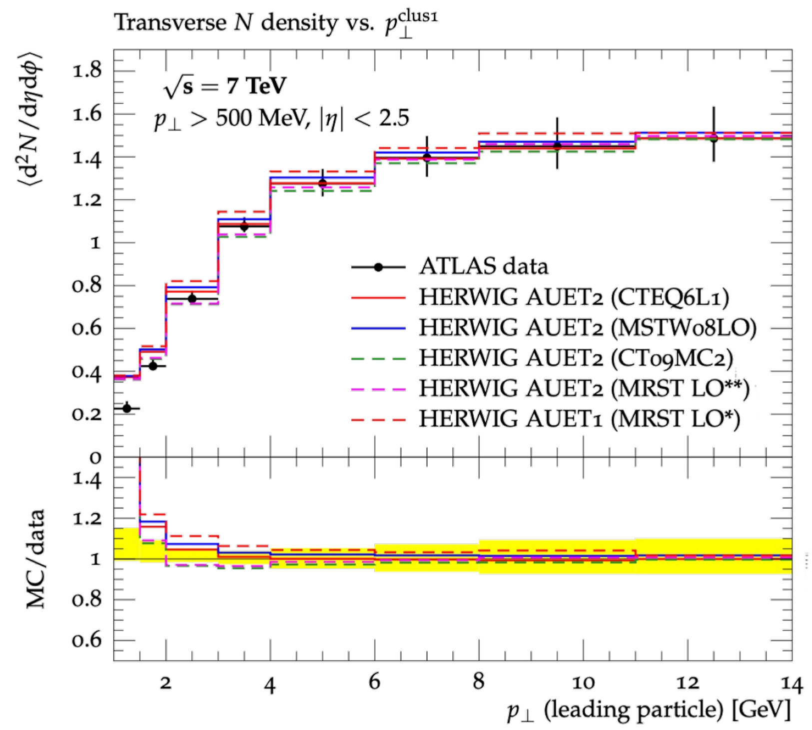
arXiv:2103.01918 (JHEP)



Introducing Rivet

"Robust Independent Validation of Experiment and Theory"

- 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?
- Vast library of measurements of final state particles produced in collisions, and variables derived from them



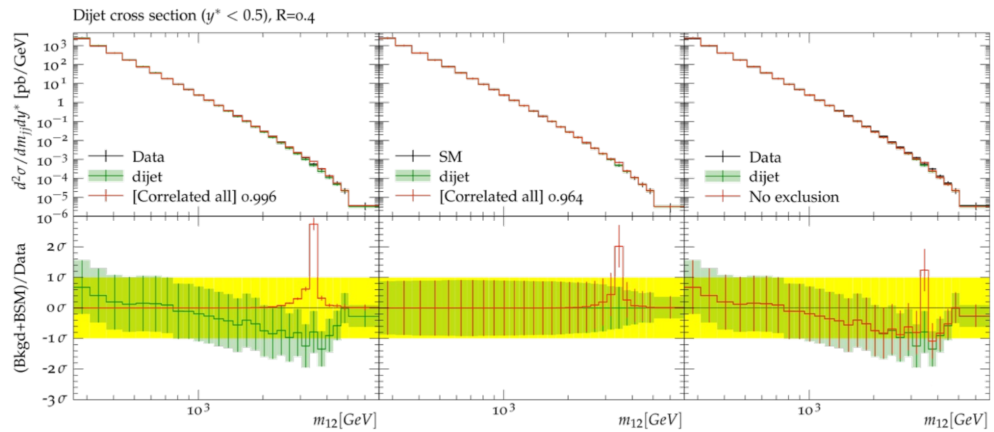
From ATL-PHYS-PUB-2011-008

Buckley et al, Bierlich et al arXiv:1003.0694 (CPC), arXiv:1912.05451 (SciPost)

Introducing Contur

“Constraints On New Theories Using Rivet”

- 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



From Altak
arXiv:2111.

Importance of of reinterpretability. See also **CheckMate** for searches

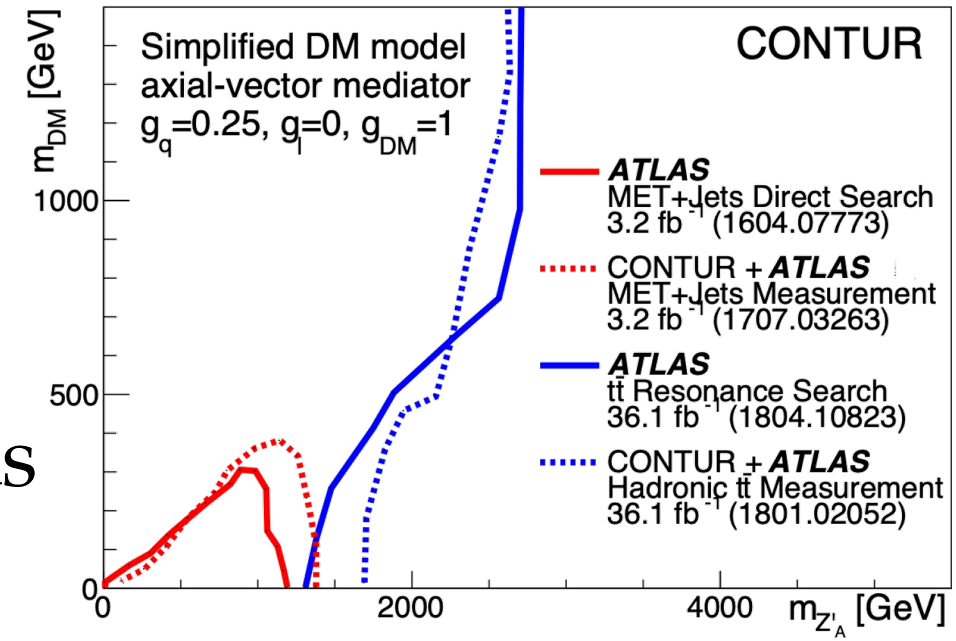
- Increasingly precise measurer calculations together extend t

JMB, Grellscheid, Krämer, Sarrazin, Yallup; Buckley et al
arXiv:1606.05296 (JHEP), arXiv:2102.04377 (SciPost)

Unleashing the power of high luminosity LHC data

(example case studies)

- Composite Dark Matter
- Back to the W mass
- Vector-like Quarks
- Back to SUSY



Louie Corpe

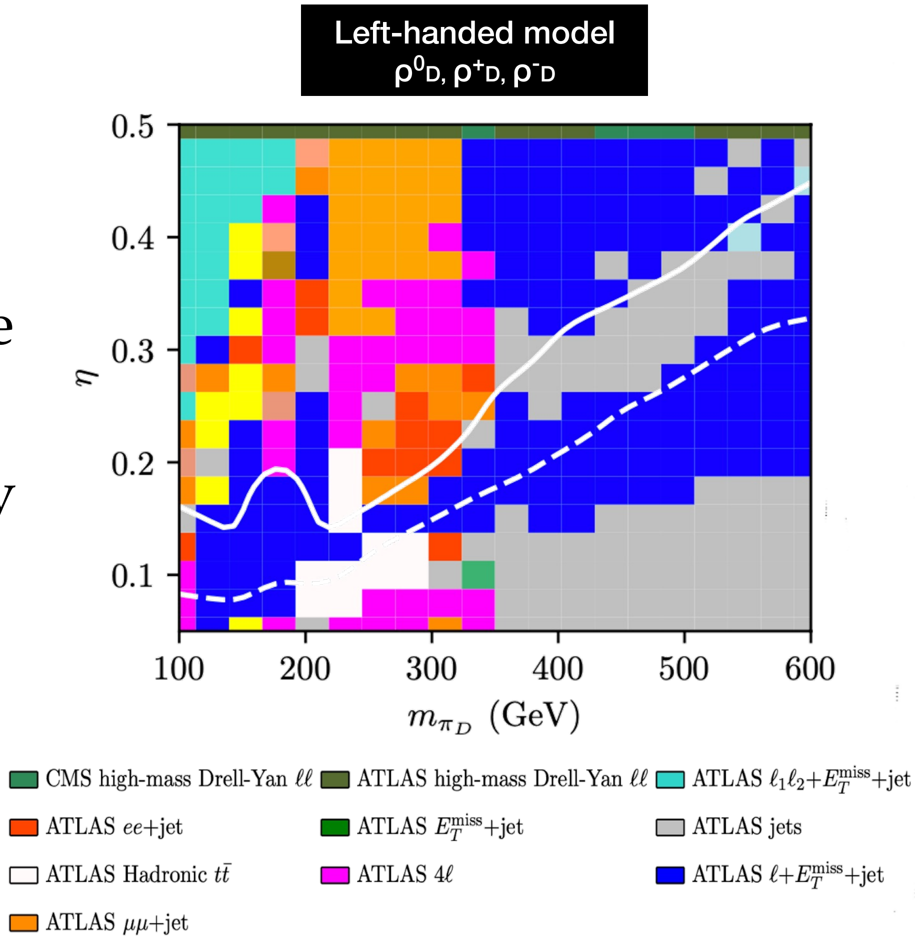
Composite Dark Matter Models

- 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 (JHEP)
- 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 (PRD)

Composite Dark Matter Models

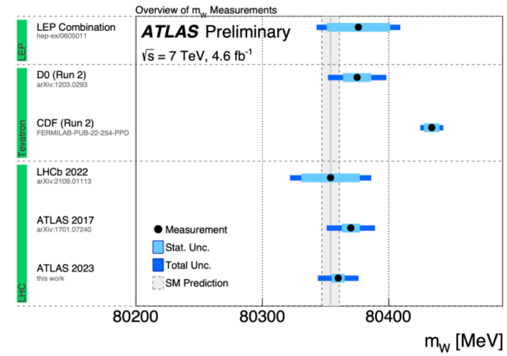
- Large areas excluded:
  - When pion mass is close to Higgs mass, H→gg analysis contributes
  - Boosted hadron "top" measurements contribute when pion mass ~200 GeV: Pions decay to tb and are boost from heavy r.
  - Other sensitivity from Z-pole dileptons, and lepton+missing energy (Z, top, W production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

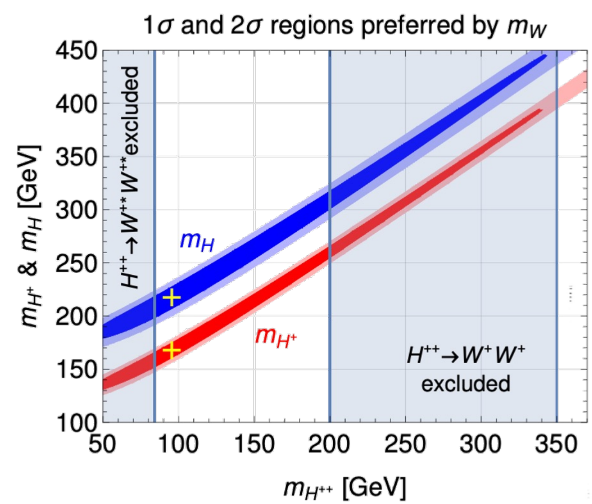


JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494 (PRD)

Back to the W mass

- Numerous possible explanations (not all BSM!)
- *Type-II seesaw* model is well-motivated by other physics (neutrino masses)
  - New scalars $\Delta^{\pm\pm}, \Delta^{\pm}, \Delta^{0}, \xi^{0}$
  - Predicts shifts in W/Z mass ratio
  - Shift can be negative or positive depending on scalar mass splittings
  - Region around $100 < M_{\Delta} < 300$ GeV explains M_W, and evades LFV constraints and LHC searches
- Does it survive our "SM" measurements?

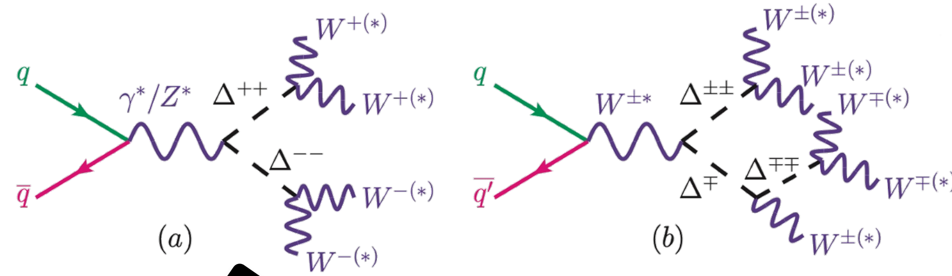


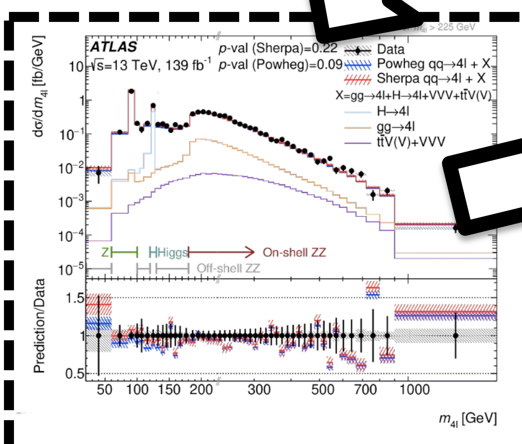


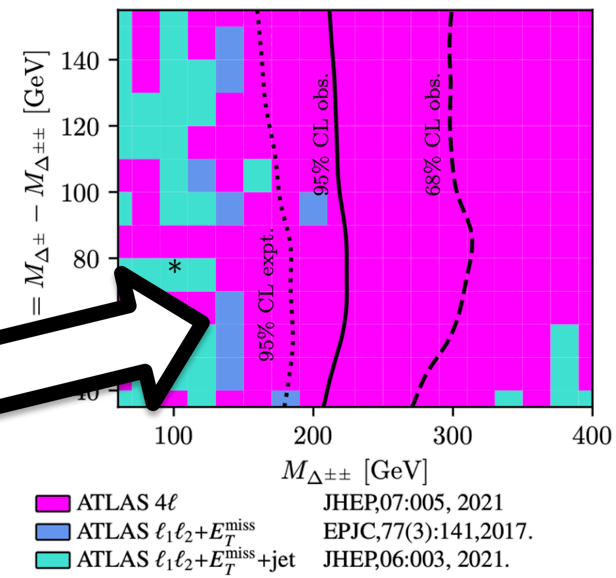
J. Heeck, 2204.10274 , PRD

Does it survive our "SM" measurements?

- In a word, **no.**
- $\Delta^{\pm\pm}$ production leads to multilepton production
- Would have been visible in several ATLAS measurements, most notably inclusive four-leptons



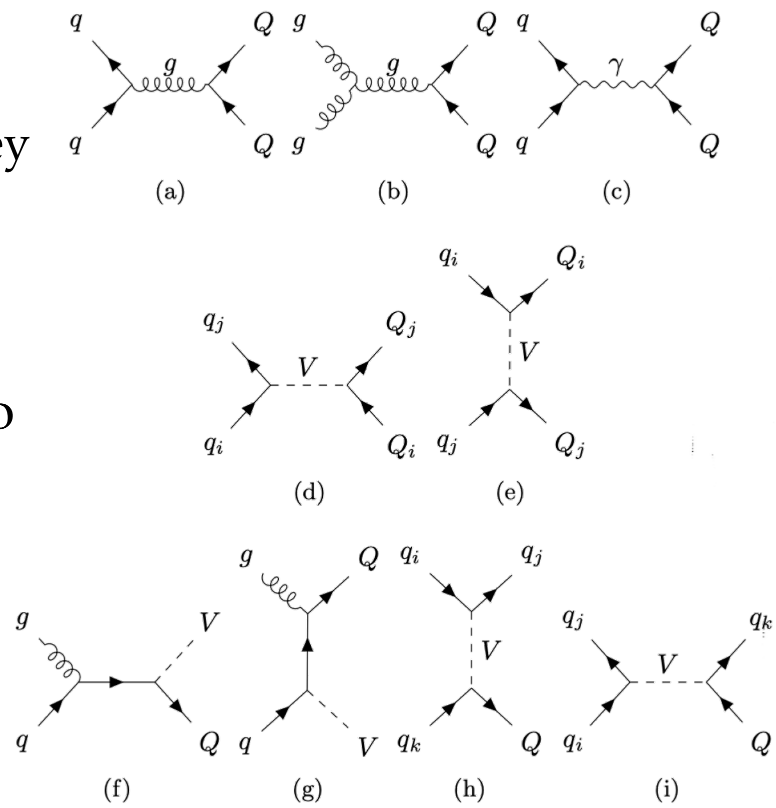




JMB, J. Heeck, S. Jeon, O. Matteler, R. Ruiz 2210.13496 (PRD, accepted)

Vector-like Quarks

- Very common extension to SM, general model by *Buchkremer et al arXiv:1305.4172 (NPB).* 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 i^th^ generation**
  - ξ_V: relative **coupling of B,T to V in {W, H, Z}**



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

Vector-like Quarks

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

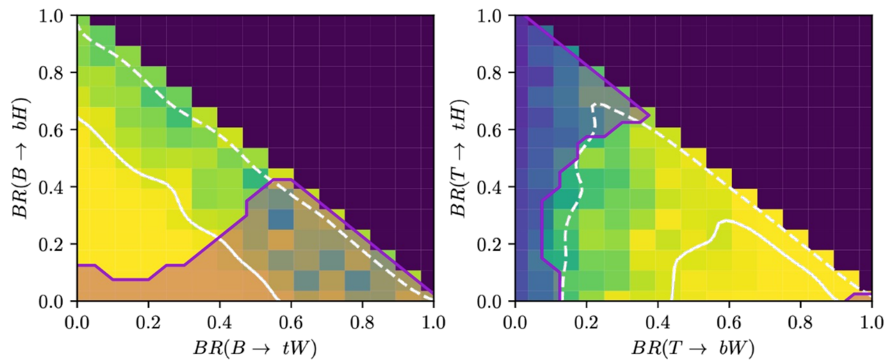
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

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



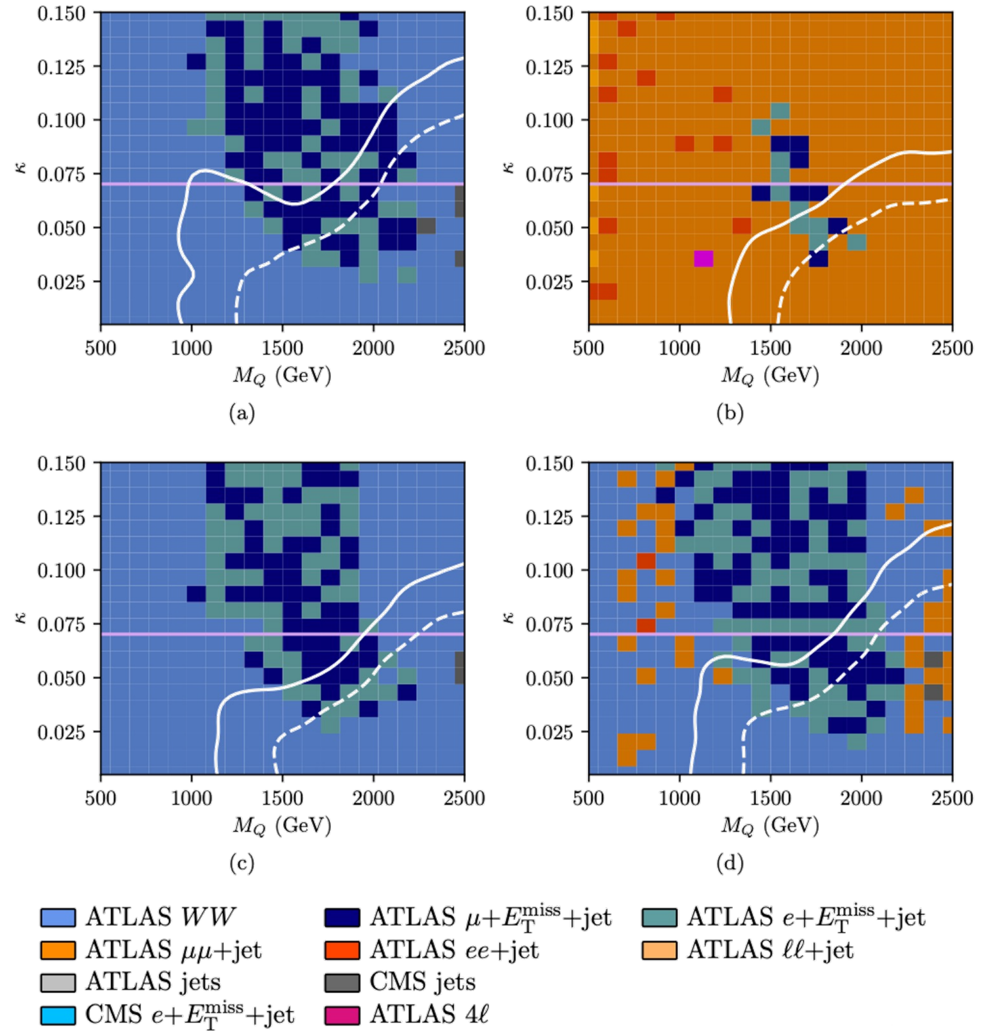
(a) (b)

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 (SciPost)

Vector-like Quarks

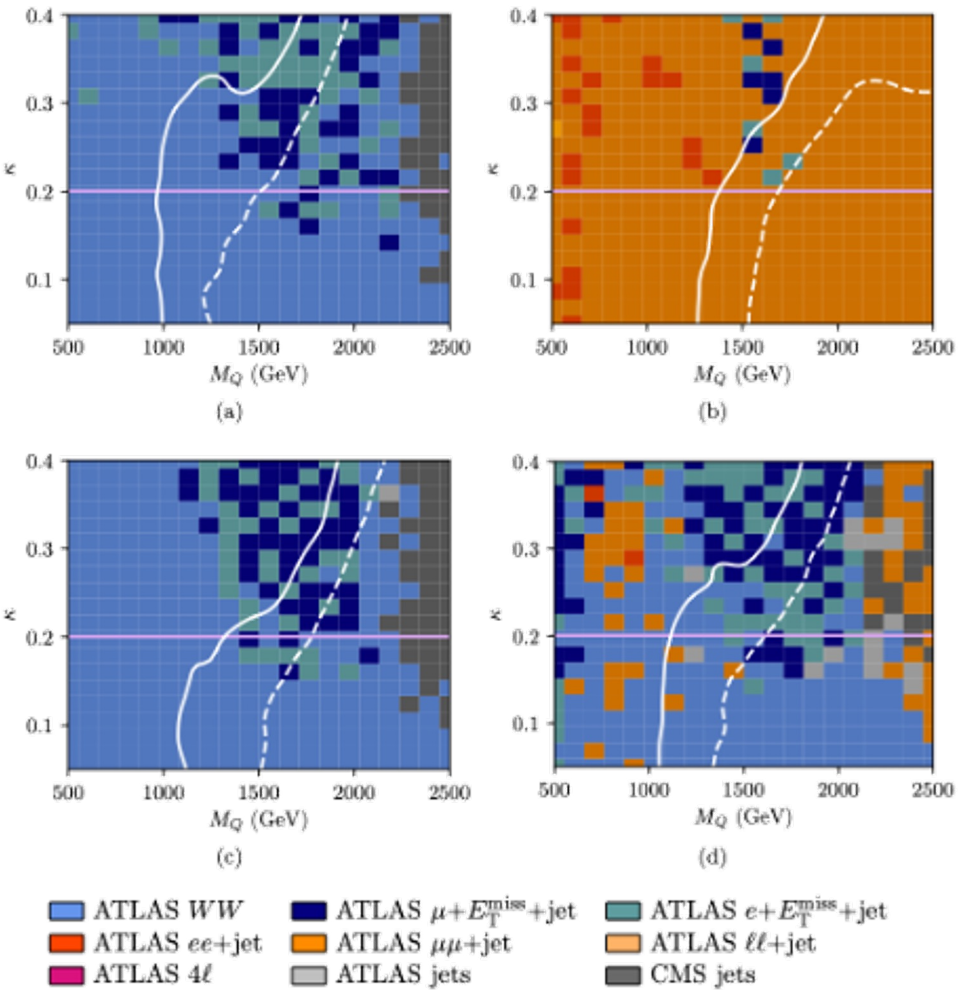
- Coupling to 1st generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude most of the plane.
- Single VLQ production very important at highest masses



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

Vector-like Quarks

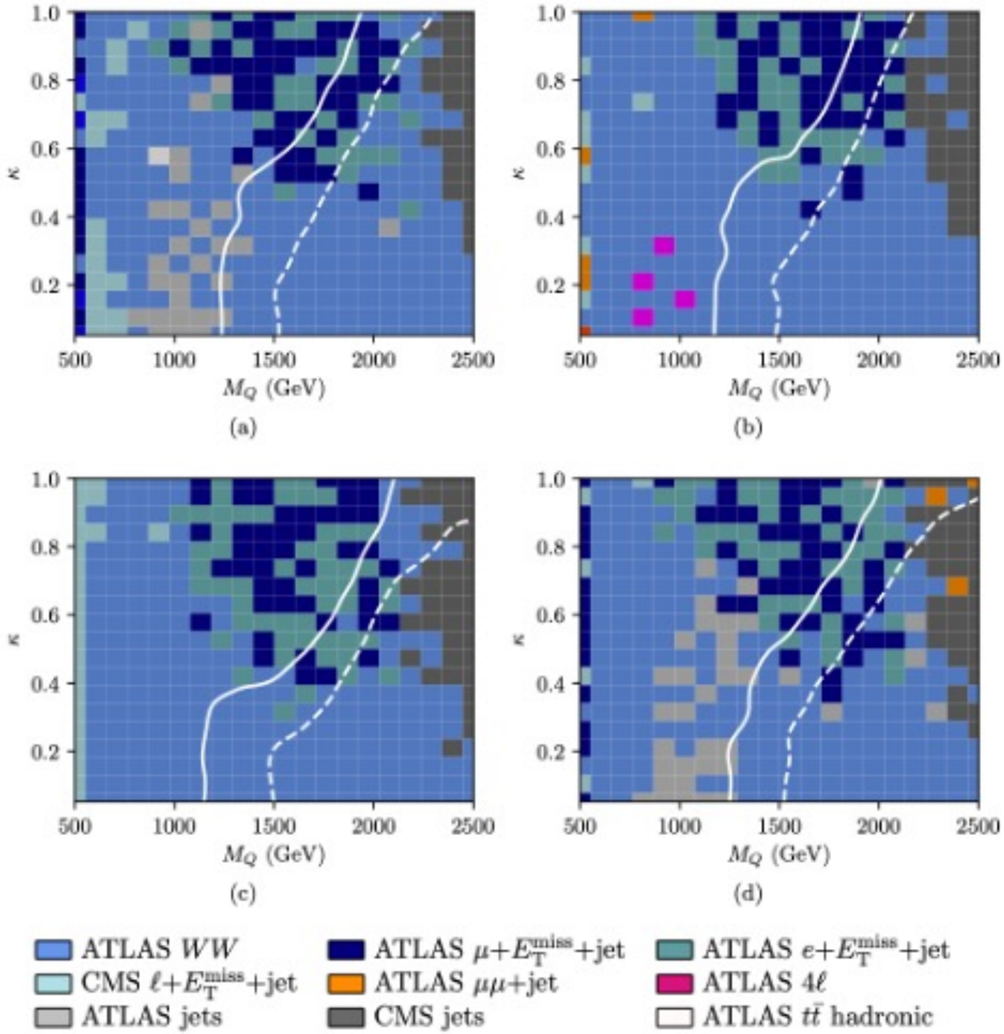
- Coupling to 2nd generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude significant part of the plane.
- Single VLQ production again very important at highest masses



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

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



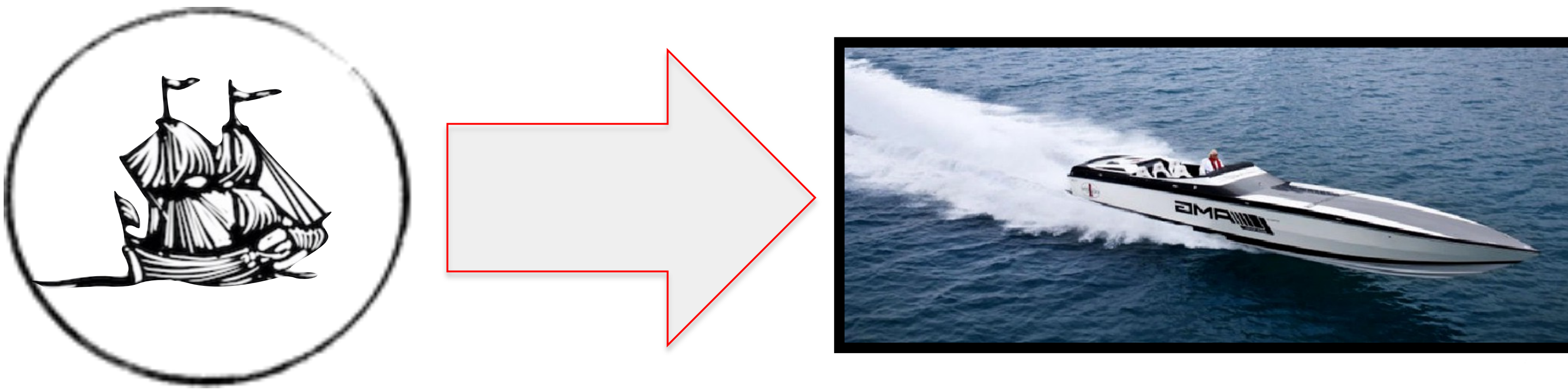
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

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?

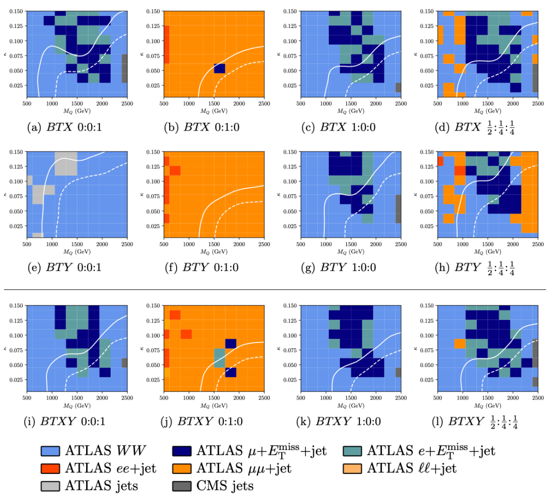
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

Vector-like Quarks

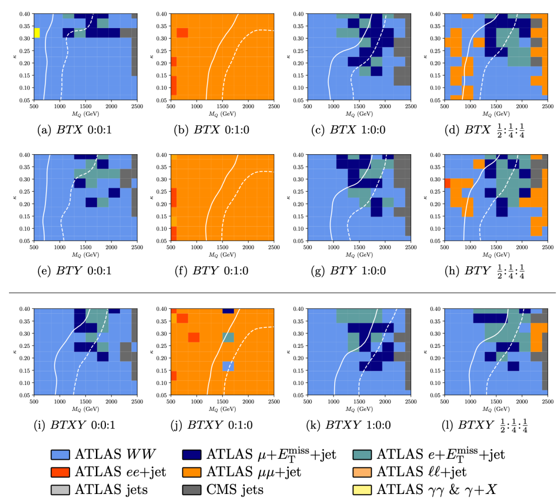


Vector-like Quarks

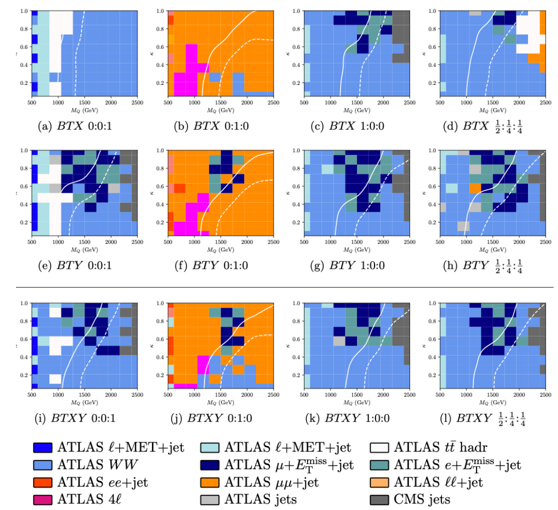
1st Generation



2nd Generation



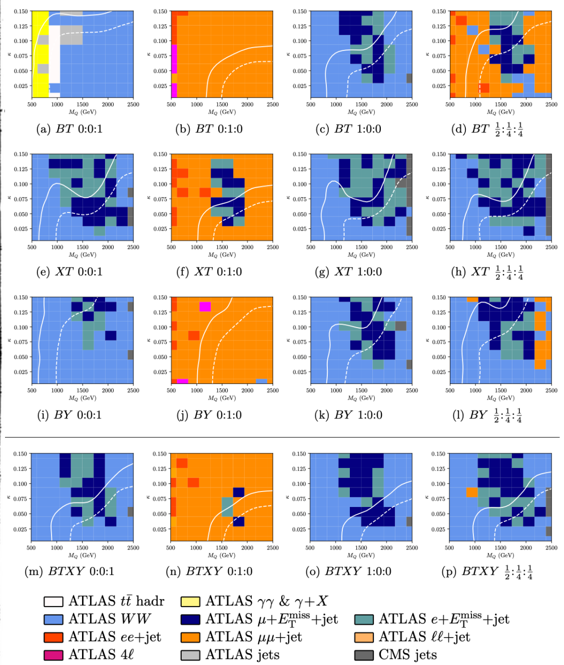
3rd Generation



Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

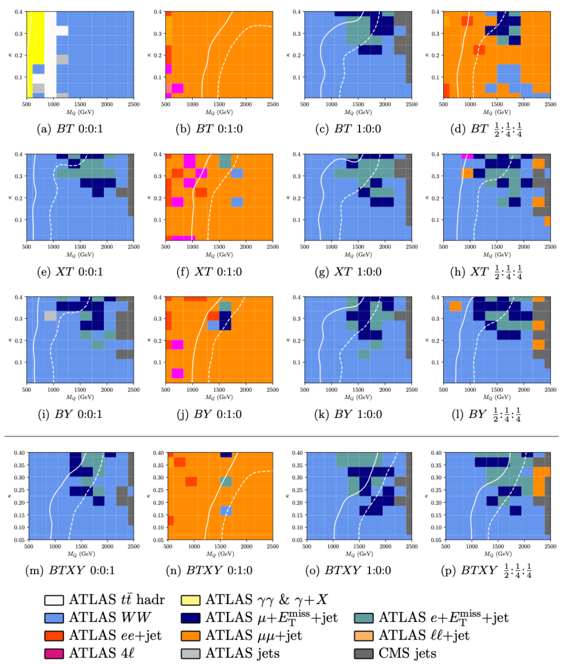
Vector-like Quarks

1st Generation



(a) BT 0:0:1 (b) BT 0:1:0 (c) BT 1:0:0 (d) BT $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(e) XT 0:0:1 (f) XT 0:1:0 (g) XT 1:0:0 (h) XT $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(i) BY 0:0:1 (j) BY 0:1:0 (k) BY 1:0:0 (l) BY $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(m) BTXY 0:0:1 (n) BTXY 0:1:0 (o) BTXY 1:0:0 (p) BTXY $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$

2nd Generation



(a) BT 0:0:1 (b) BT 0:1:0 (c) BT 1:0:0 (d) BT $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
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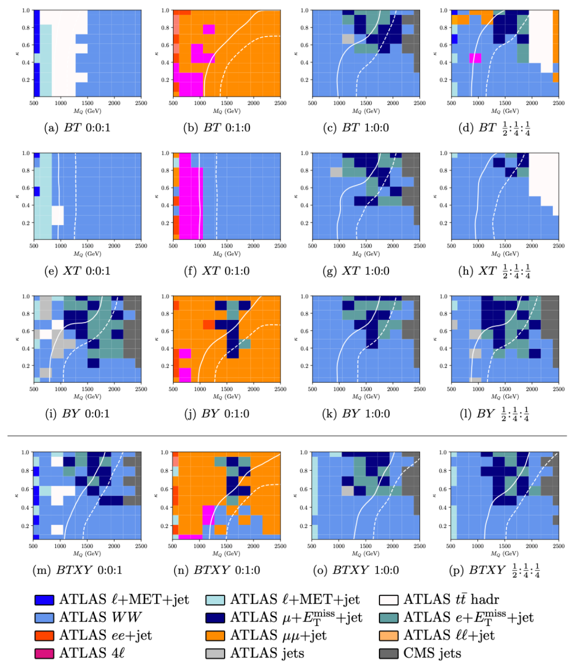
(m) BTXY 0:0:1 (n) BTXY 0:1:0 (o) BTXY 1:0:0 (p) BTXY $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$

3rd Generation

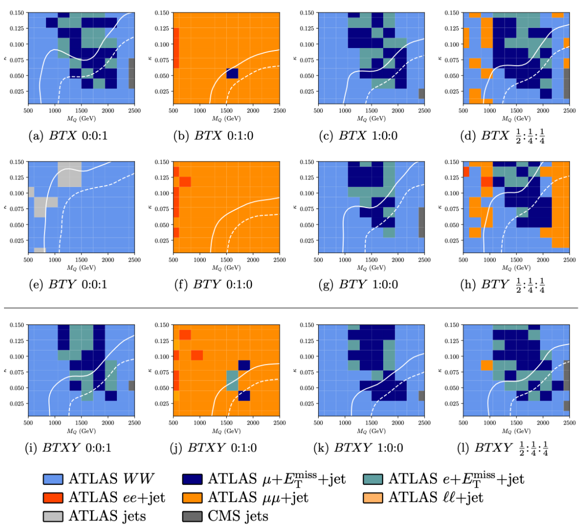


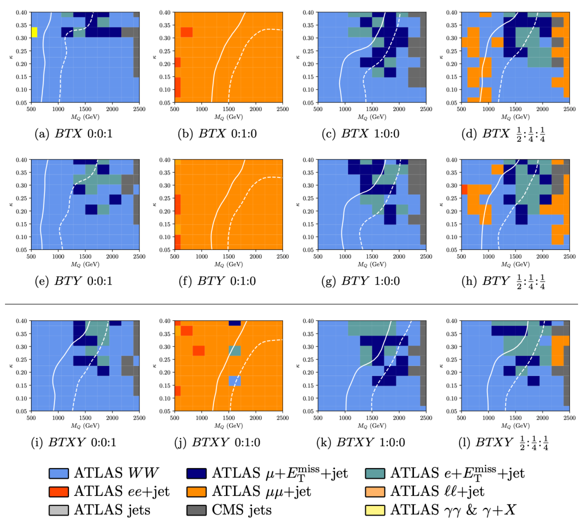
(a) BT 0:0:1 (b) BT 0:1:0 (c) BT 1:0:0 (d) BT $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(e) XT 0:0:1 (f) XT 0:1:0 (g) XT 1:0:0 (h) XT $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(i) BY 0:0:1 (j) BY 0:1:0 (k) BY 1:0:0 (l) BY $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$
(m) BTXY 0:0:1 (n) BTXY 0:1:0 (o) BTXY 1:0:0 (p) BTXY $\frac{1}{2}$:$\frac{1}{4}$:$\frac{1}{4}$

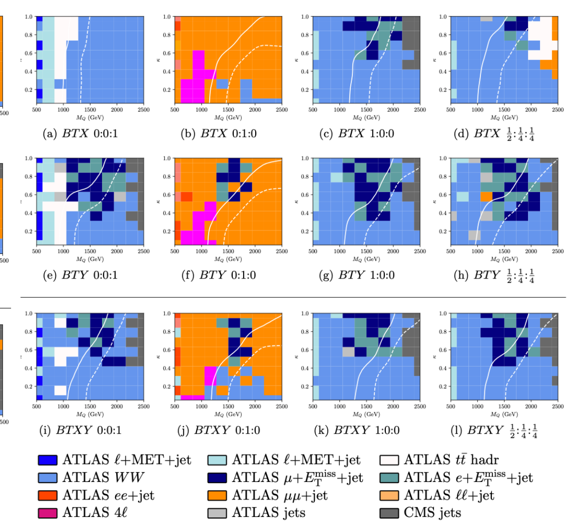
Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

Vector-like Quarks

1st Generation 2nd Generation 3rd Generation







Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172 (SciPost)

Back to SUSY?

TTP23-009, KCL-PH-TH/2023-21, gambit-physics-23, MCnet-23-05, ADP-23-08/T1217, CERN-TH-2023-043

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Received: date / Accepted: date

Abstract Using the GAMBIT global fitting framework, we constrain the MSSM with an eV-scale gravitino as the lightest supersymmetric particle, and the six electroweakinos (neutralinos and charginos) as the only other light new states. We combine 15 ATLAS and 12 CMS searches at 13 TeV, along with a large collection of ATLAS and CMS measurements of Standard Model signatures. This model, which we refer to as the $\tilde{G}$-EWMSSM, exhibits quite varied collider phenomenology due to its many permitted electroweakino production processes and decay modes. Characteristic $\tilde{G}$-EWMSSM signal events have two or more Standard Model bosons and missing energy due to the escaping gravitinos. While much of the $\tilde{G}$-EWMSSM parameter space is excluded, we find several viable parameter regions that predict phenomenologically rich scenarios with multiple neutralinos and charginos within the kinematic reach of the LHC during Run 3, or the High Luminosity LHC. In particular, we identify scenarios with Higgsino-dominated electroweakinos as light as 140 GeV that are consistent with our combined set of collider searches and measurements. The full set of $\tilde{G}$-EWMSSM parameter samples and GAMBIT input files generated for this work is available via Zenodo.

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Contents

So where are we now?

- *No agreed extensions to the Standard Model*
  - *But many ideas, connecting various anomalous phenomena*
- *Change of approach required*
  - *This is about exploration of new physics territory*
  - *No guarantee that Dark Matter, Supersymmetry, or indeed anything else beyond the Standard Model will be within reach*
- *Need precise, theory-independent measurements, and comparable calculations, in Standard Model & beyond. (As well as looking for "outliers".)*

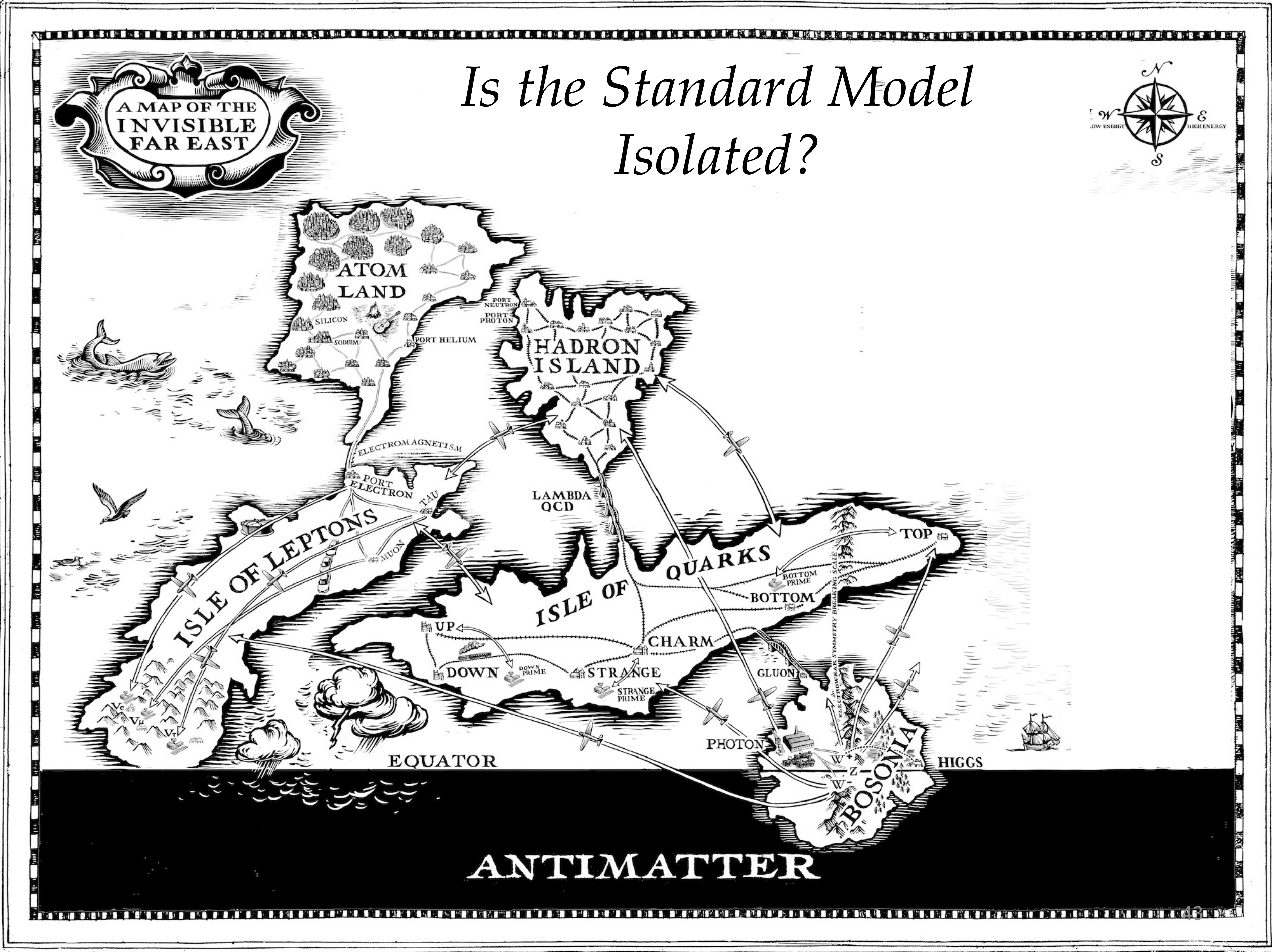
So where are we now?

The guarantee is we will find out

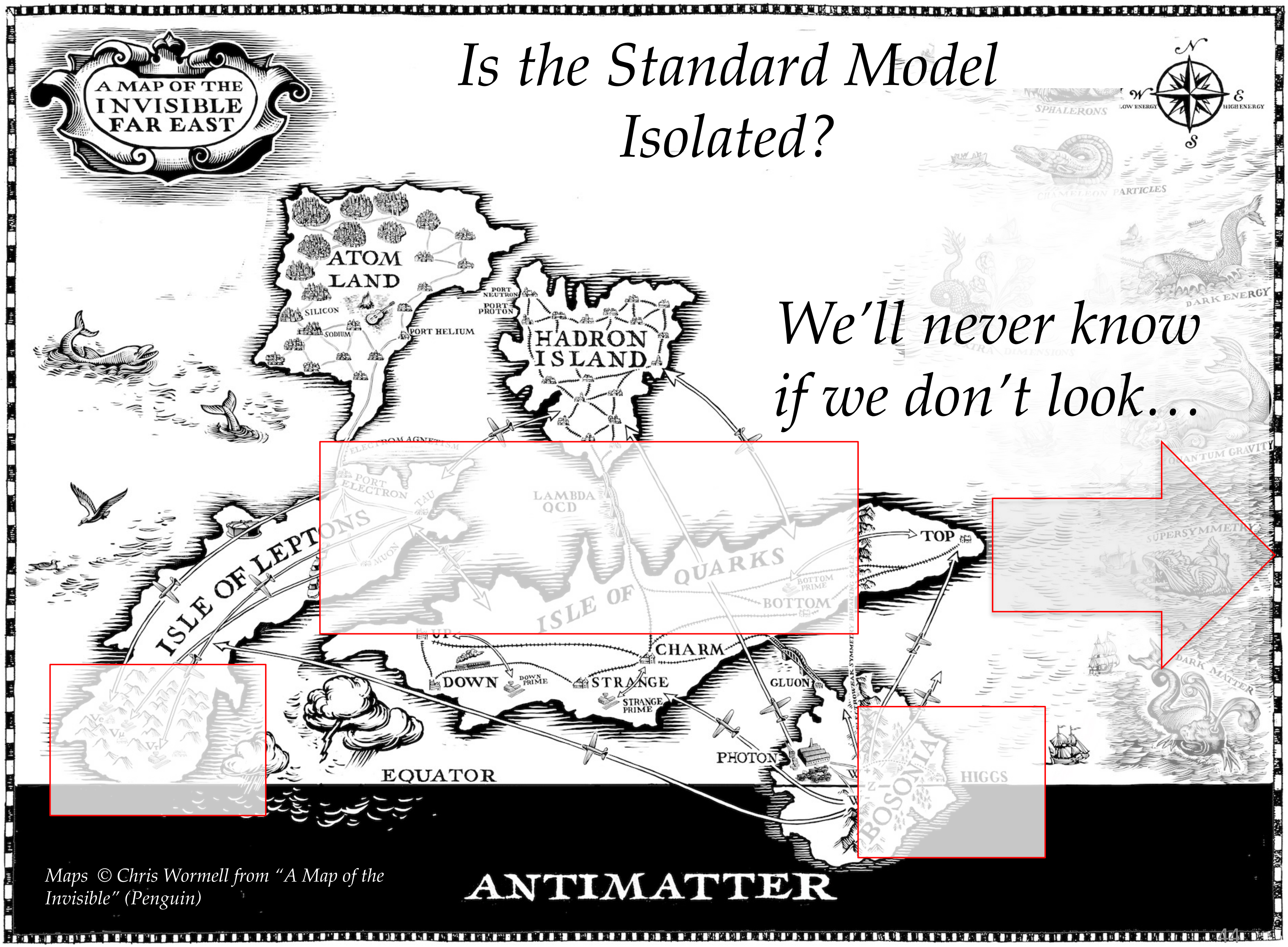
- *Whether the Higgs-self coupling is as the Standard Model predicts*
- *Whether or not the Standard Model continues to apply, well beyond the region in which it was developed, and to what precision*
- *We will also push some amazing technologies, with likely benefits elsewhere*

- *And there may be big surprises!*

Is the Standard Model Isolated?



Is the Standard Model Isolated?



We'll never know if we don't look…

Maps © Chris Wormell from "A Map of the Invisible" (Penguin)


Happy New Decade, Herbi!
'A magnificent, compelling and insightful voyage'
BRIAN COX
QUARKS
JON BUTTERWORTH
JON BUTTERWORTH
Maps by Chris Wormell