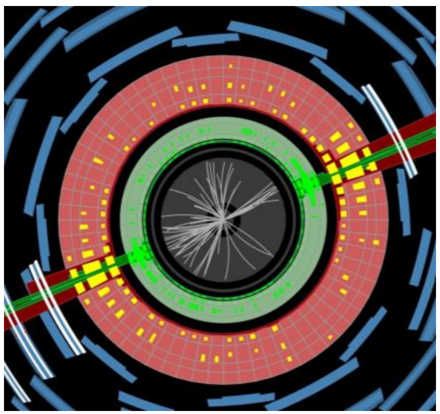
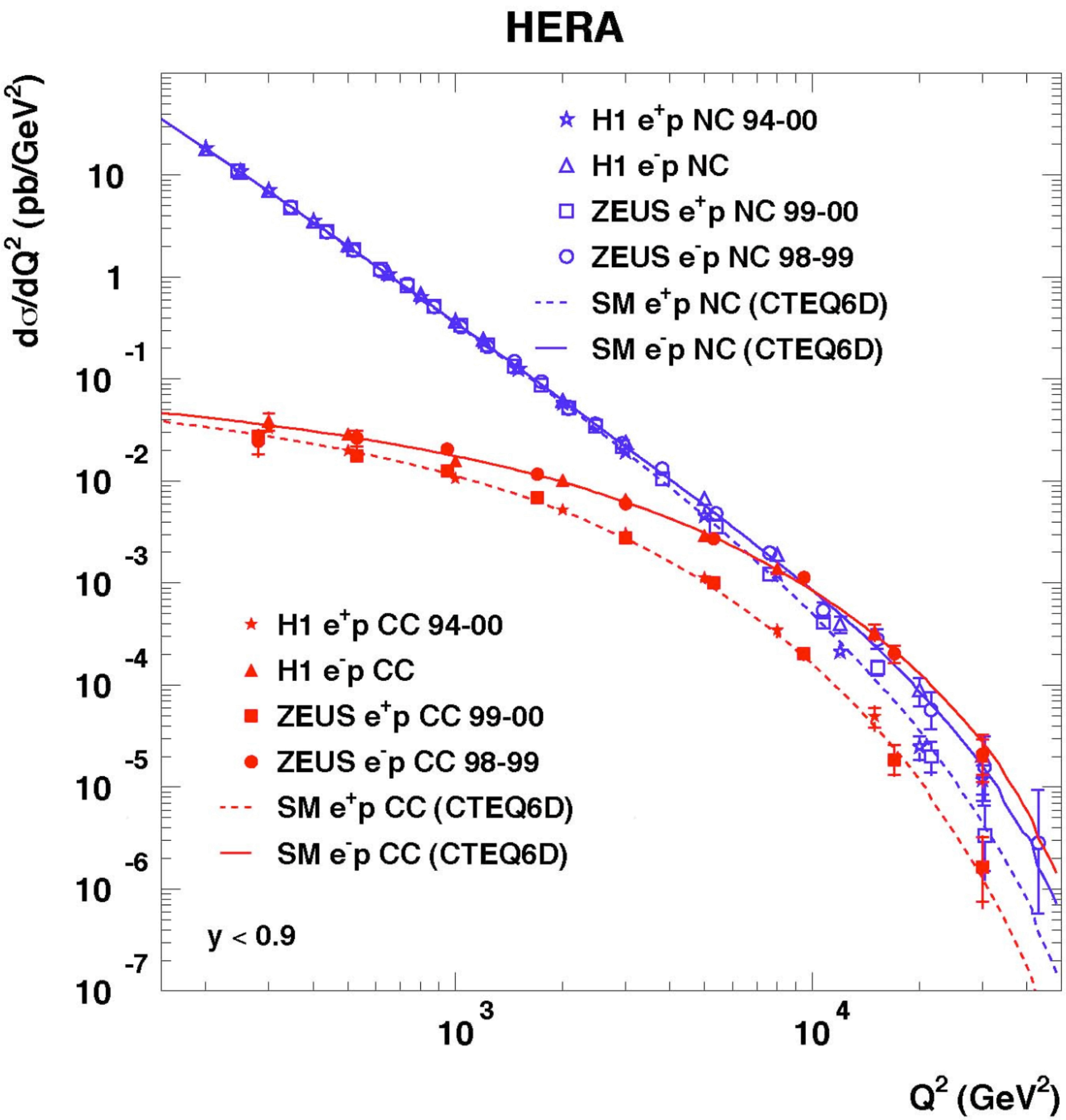
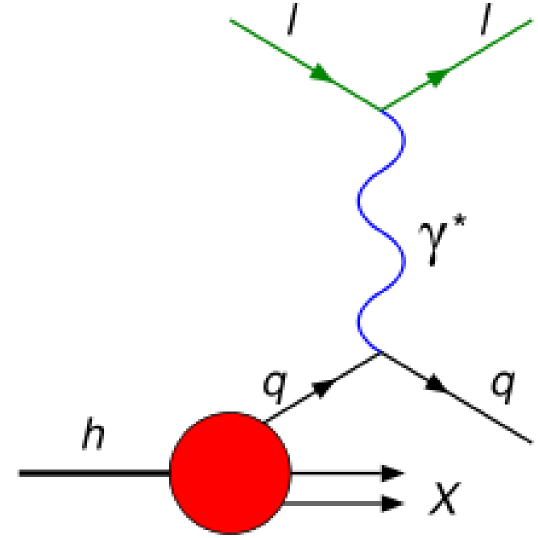
# *Overview, and Contur*



IoP Halfday, Sussex
14/6/2022
Jon Butterworth, UCL Physics & Astronomy



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*
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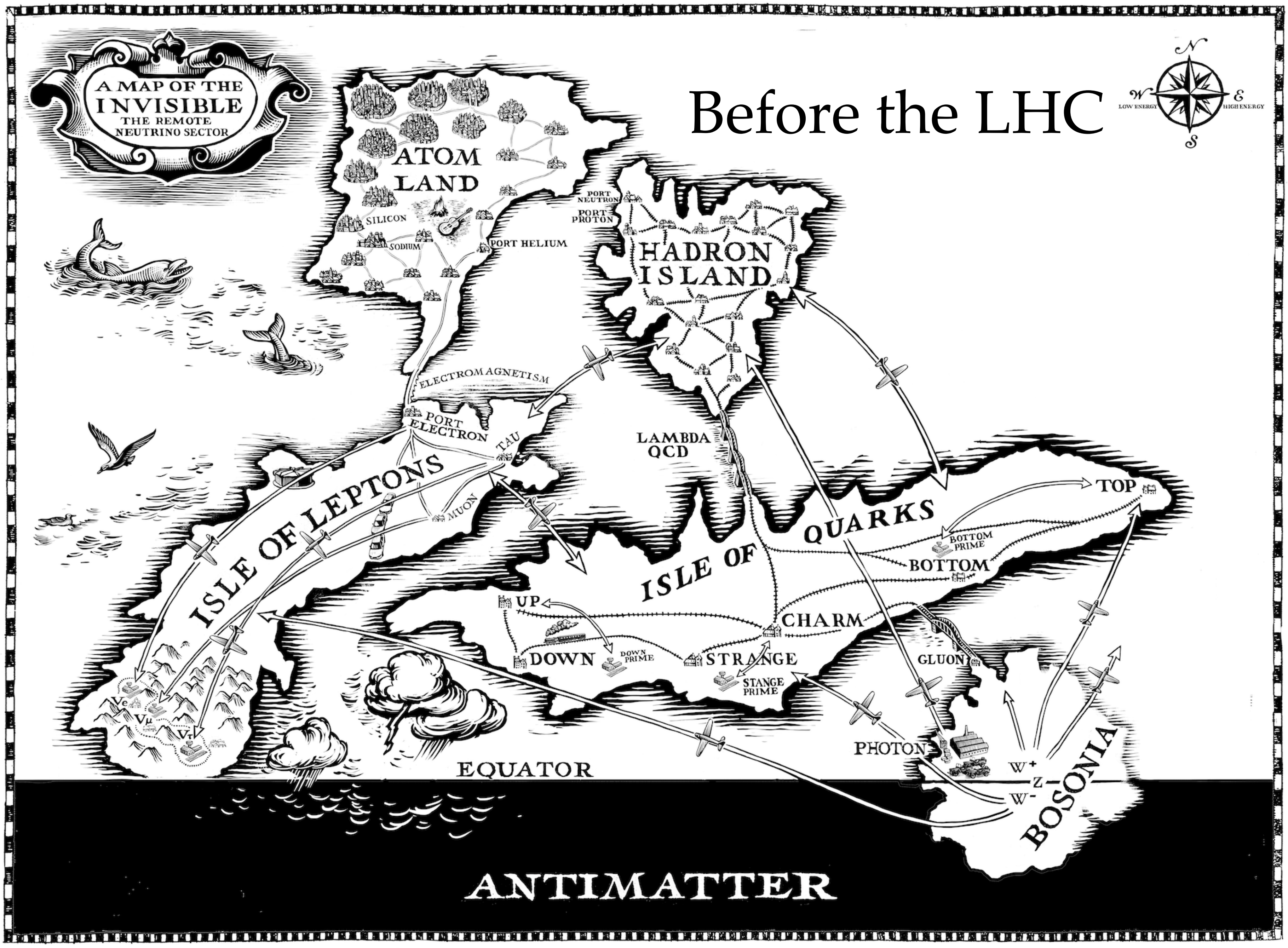
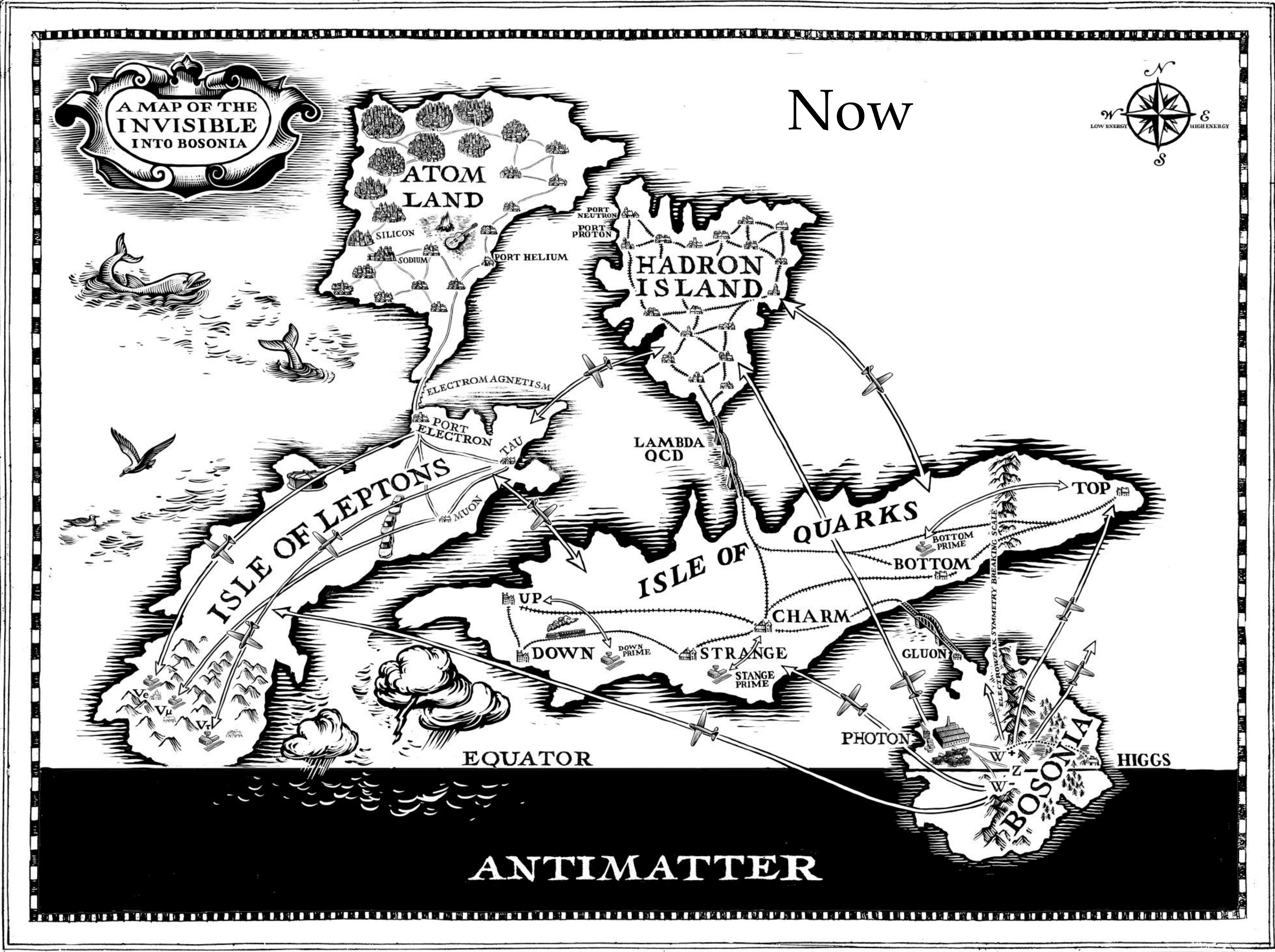
h
X

# Before the LHC




Now
A MAP OF THE
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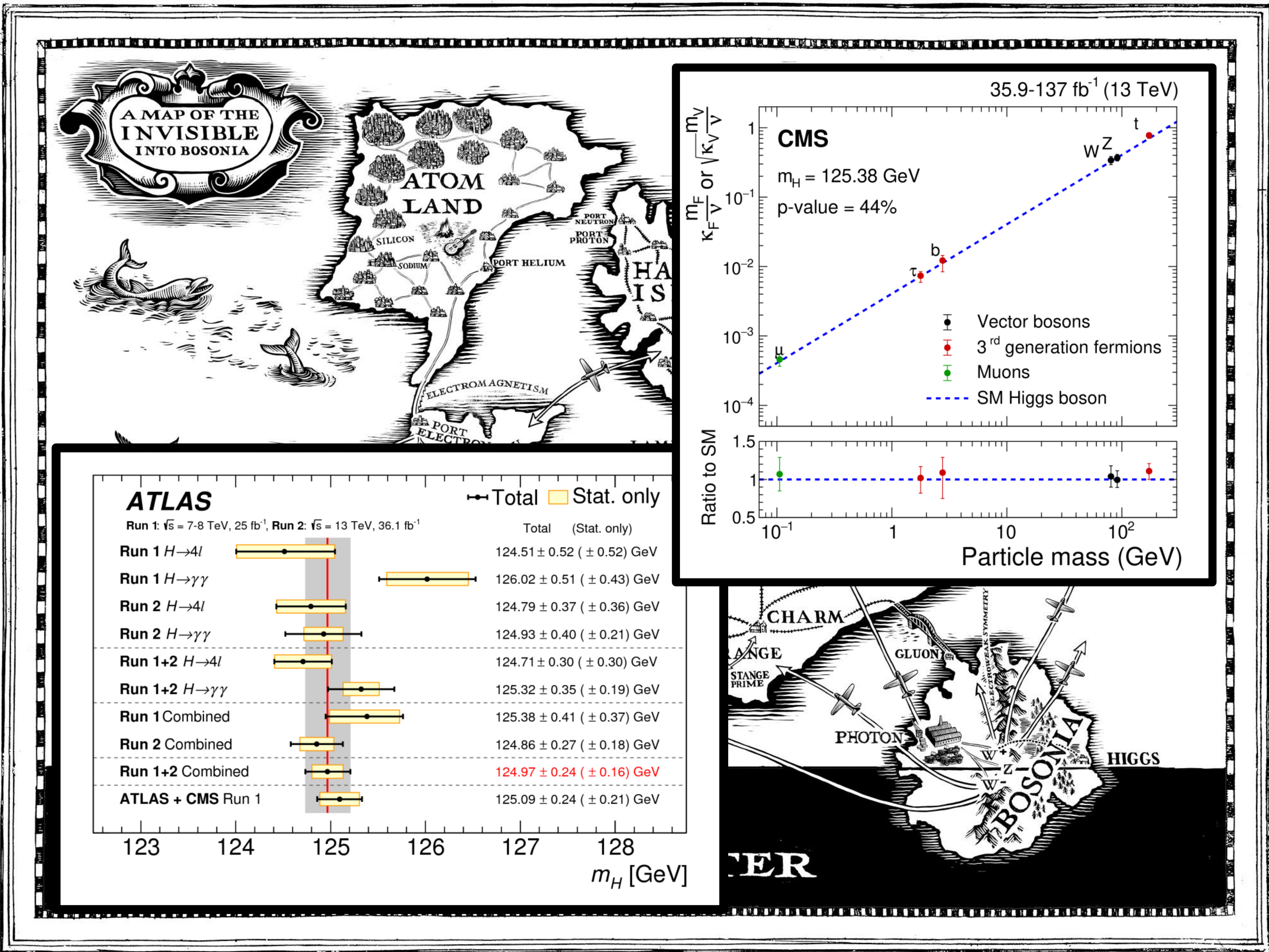
A MAP OF THE
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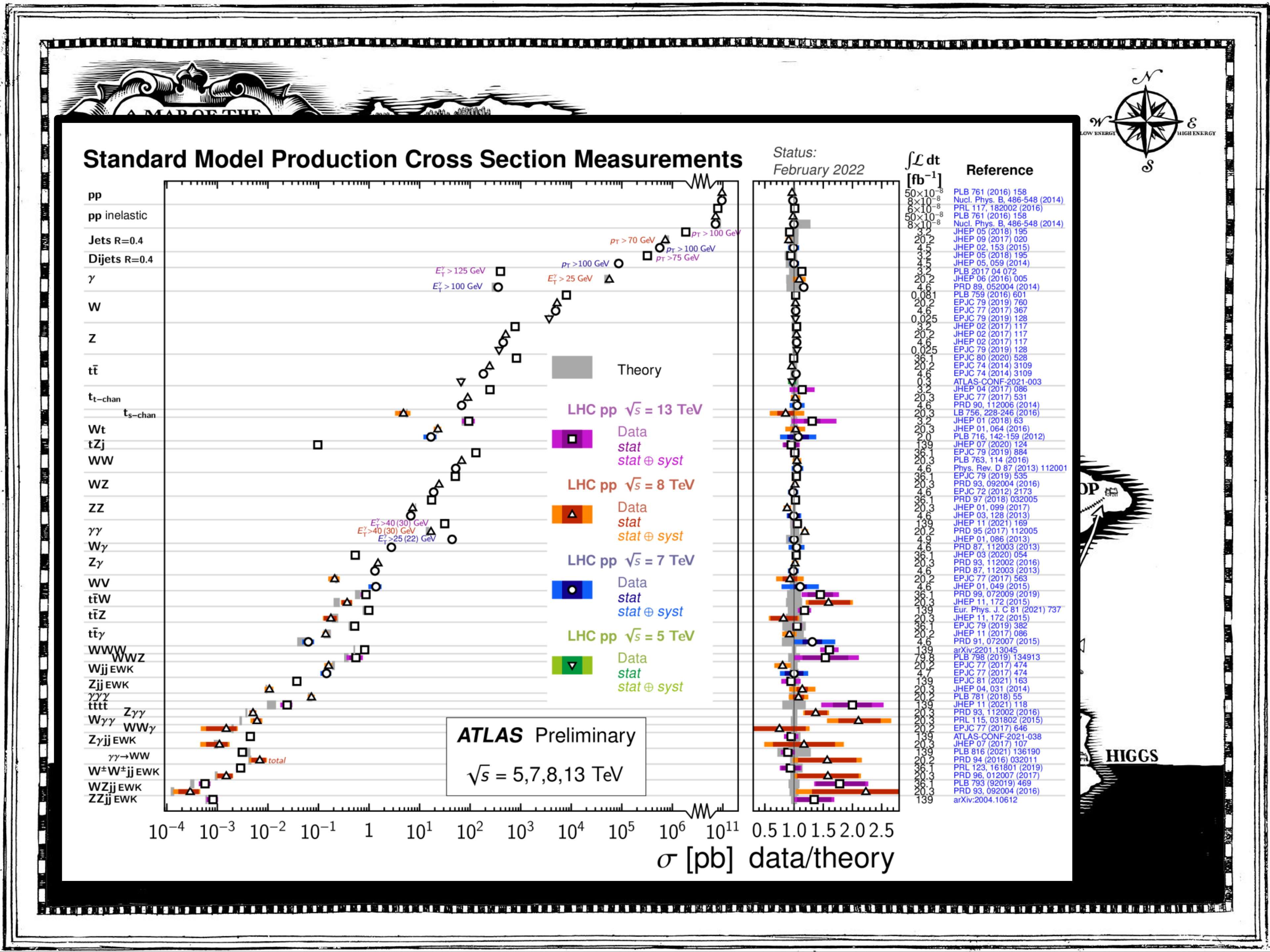
GLUON
STANGE PRIME
PHOTON
HIGGS
BOSONIA
W+
Z
W-
ELECTROWEAK SYMMETRY
35.9-137 fb$^{-1}$ (13 TeV)
CMS
$m_H$ = 125.38 GeV
p-value = 44%
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
Vector bosons
3$^{rd}$ generation fermions
Muons
SM Higgs boson
μ τ b W Z t
Ratio to SM
Particle mass (GeV)
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
$m_H$ [GeV]



Standard Model Production Cross Section Measurements
Status: February 2022
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t t-chan
t s-chan
Wt
tZj
WW
WZ
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
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
∫L dt [fb−1]
Reference
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)
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139 JHEP 11 (2021) 169
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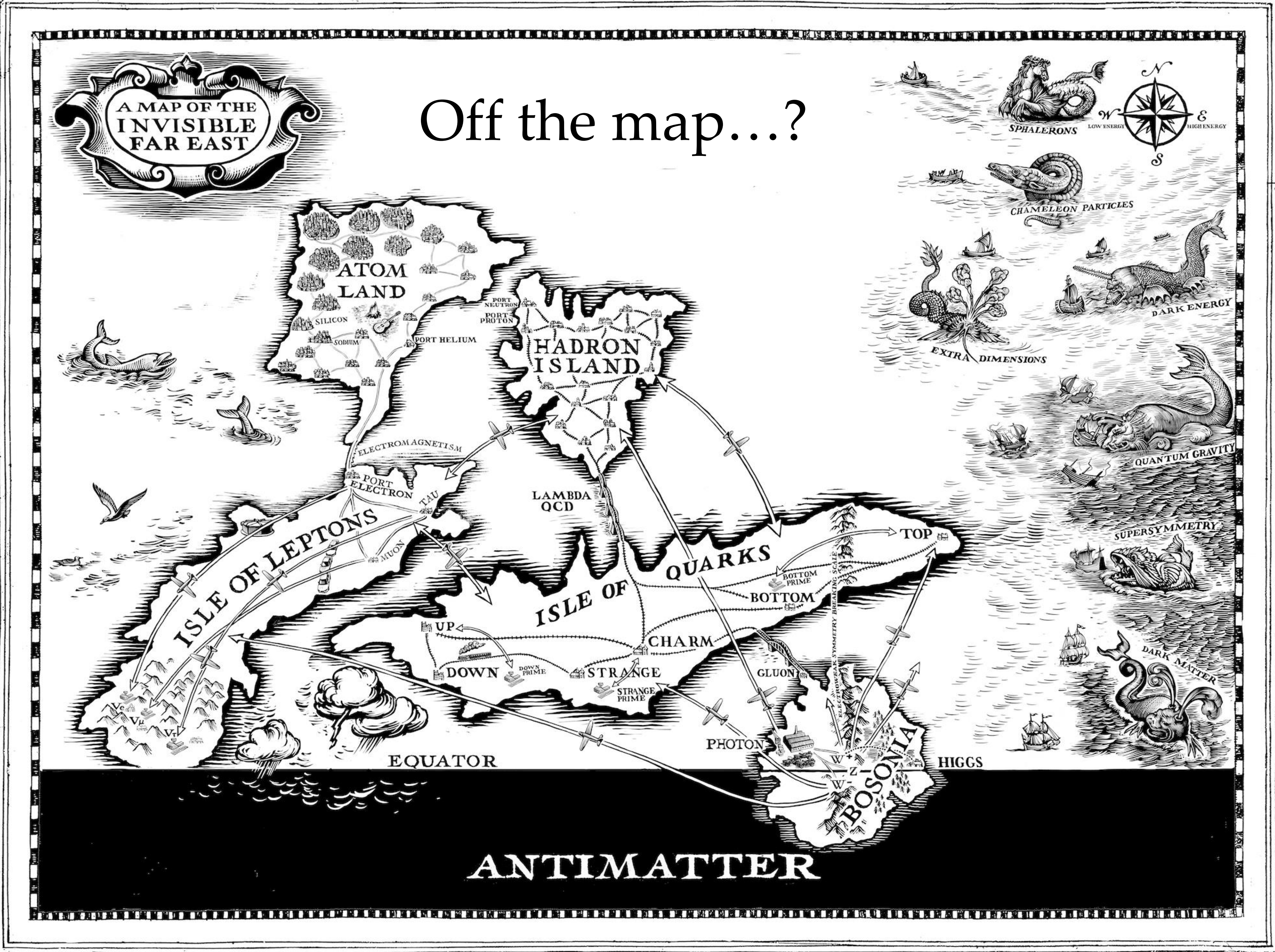
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
139 Eur. Phys. J. C 81 (2021) 737
20.3 JHEP 11, 172 (2015)
36.1 EPJC 79 (2019) 382
20.2 JHEP 11 (2017) 086
4.6 PRD 91, 072007 (2015)
139 arXiv:2201.13045
79.8 PLB 798 (2019) 134913
20.2 EPJC 77 (2017) 474
4.7 EPJC 77 (2017) 474
139 EPJC 81 (2021) 163
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 (2015)
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

# 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
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EQUATOR
ANTIMATTER
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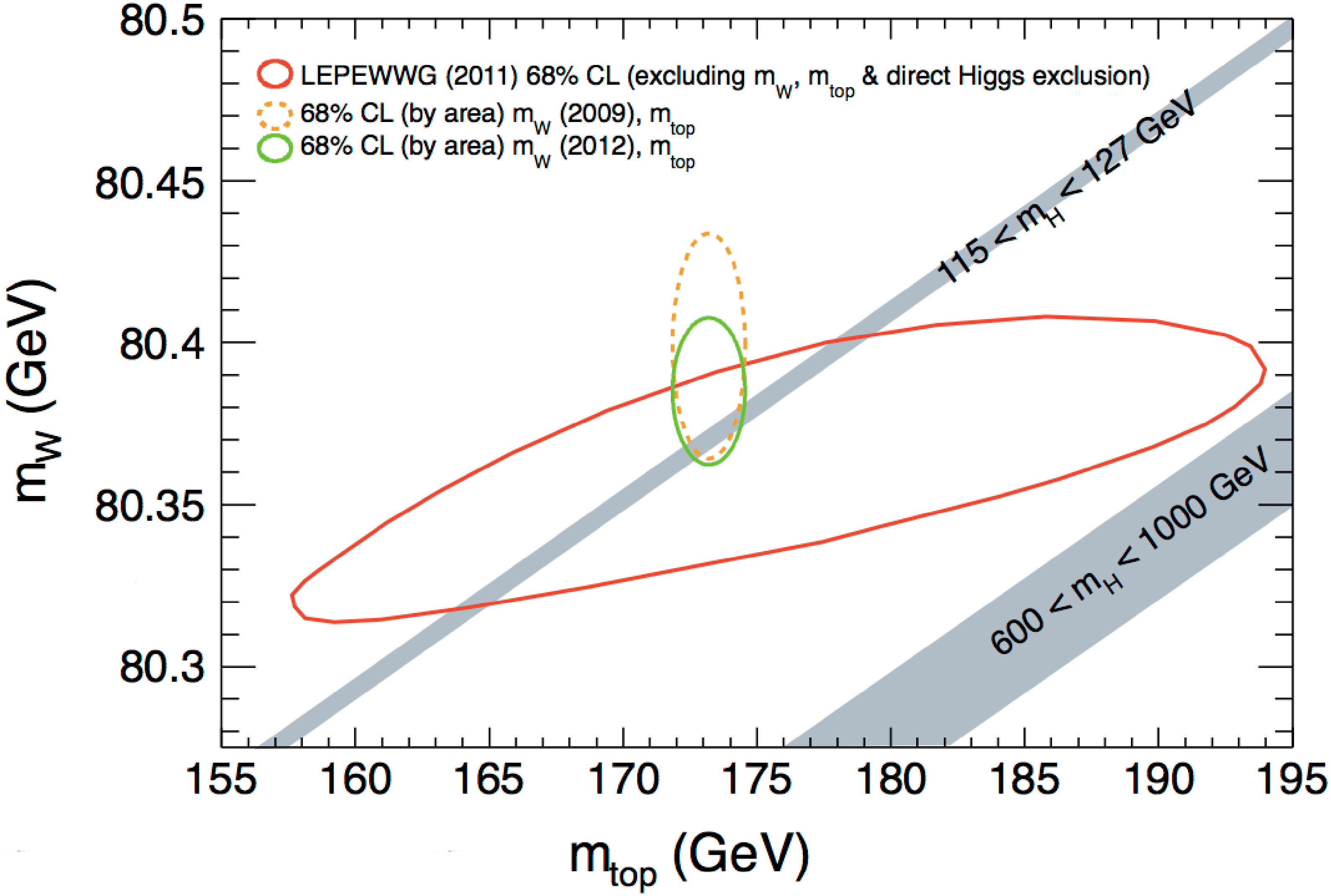
HIGH ENERGY
CHAMELEON PARTICLES
DARK ENERGY
EXTRA DIMENSIONS
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER

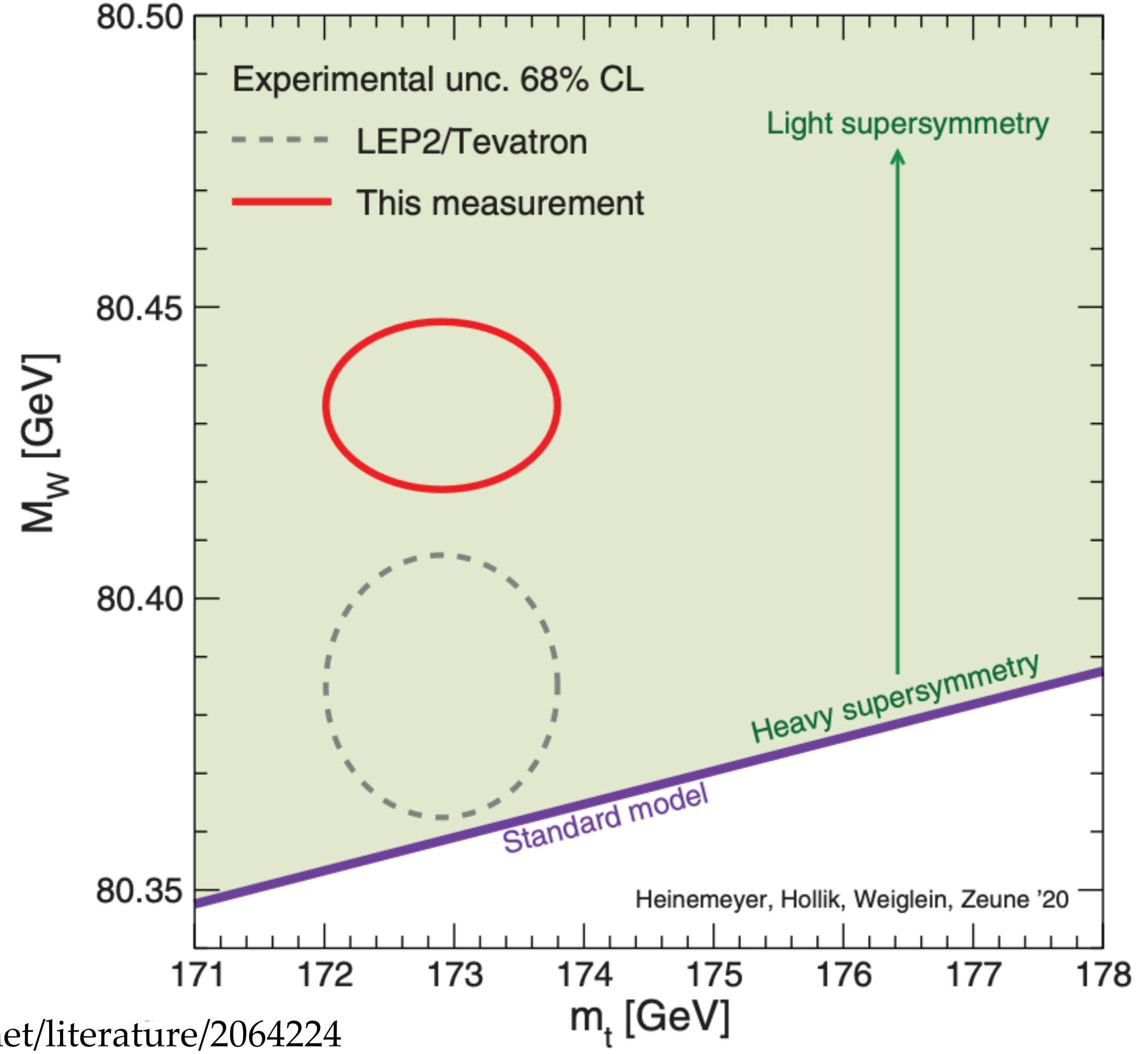
# Before the LHC

March 2012

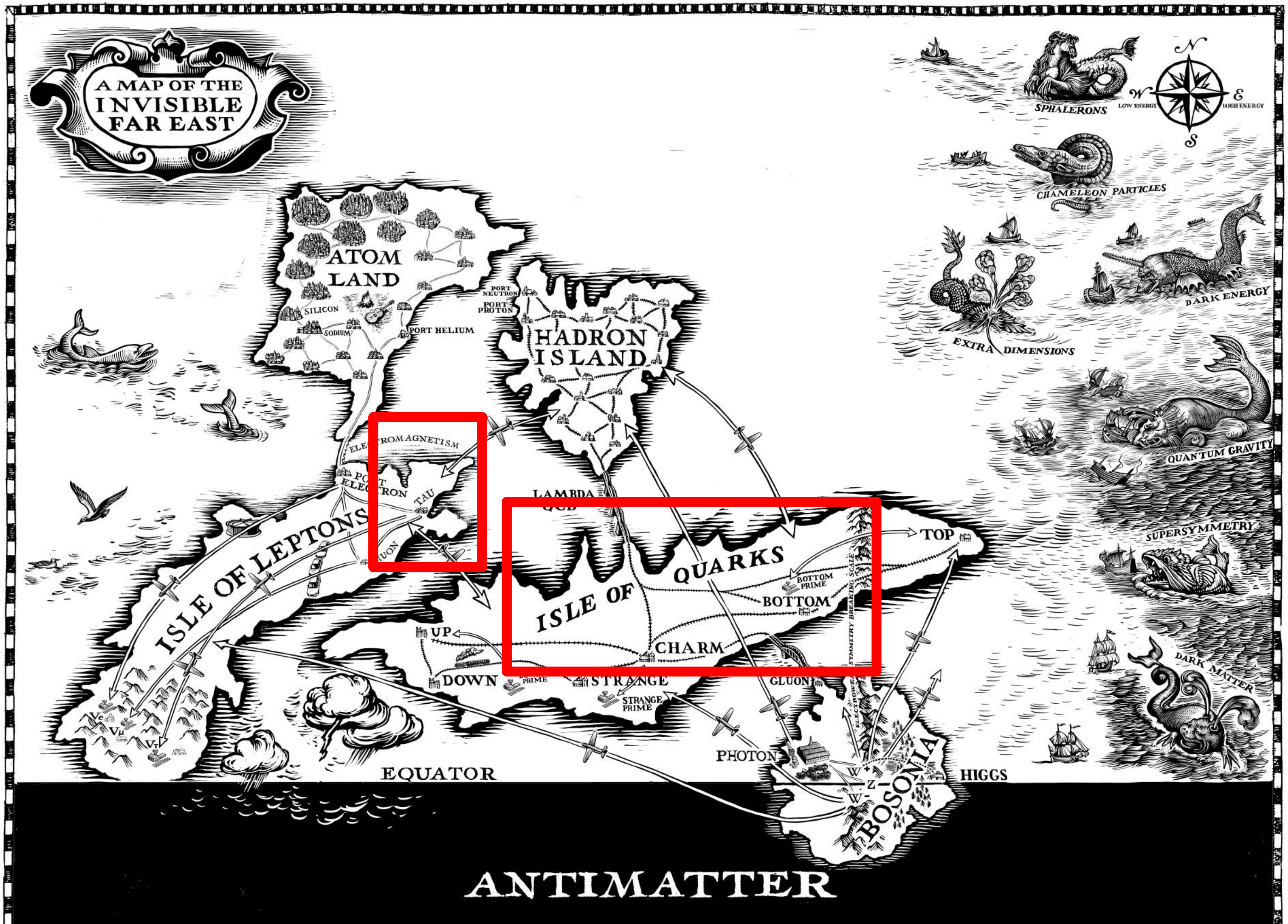


# Update from CDF

Last month




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



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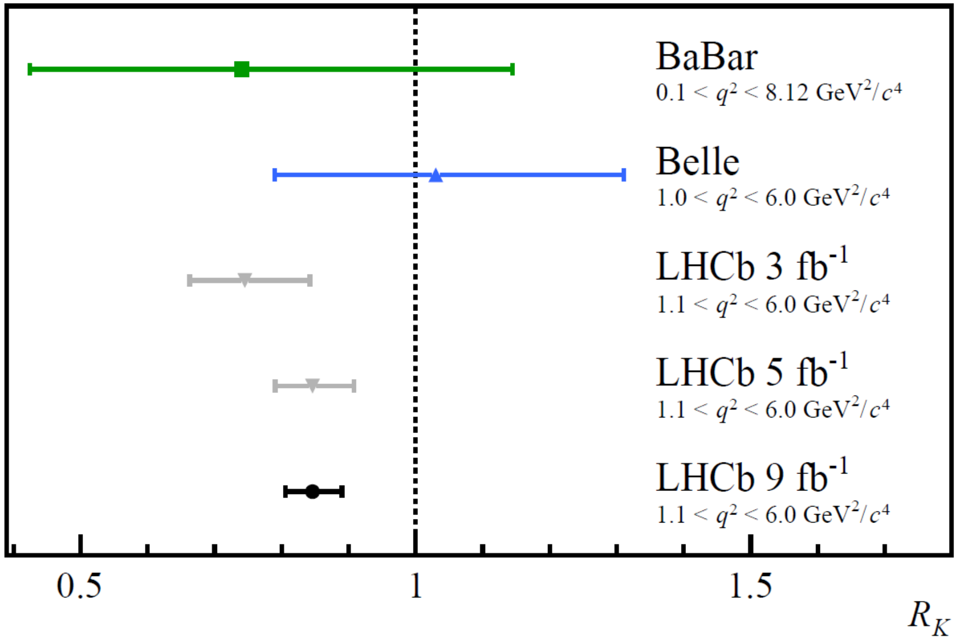
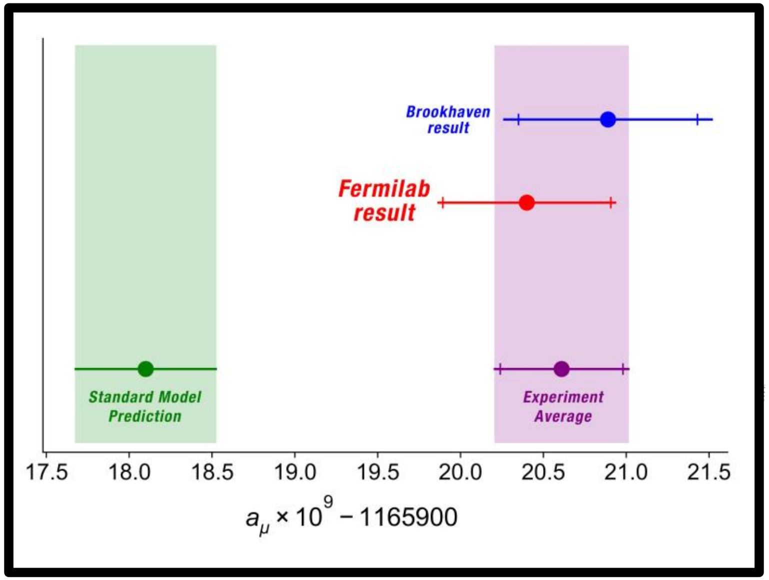
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER

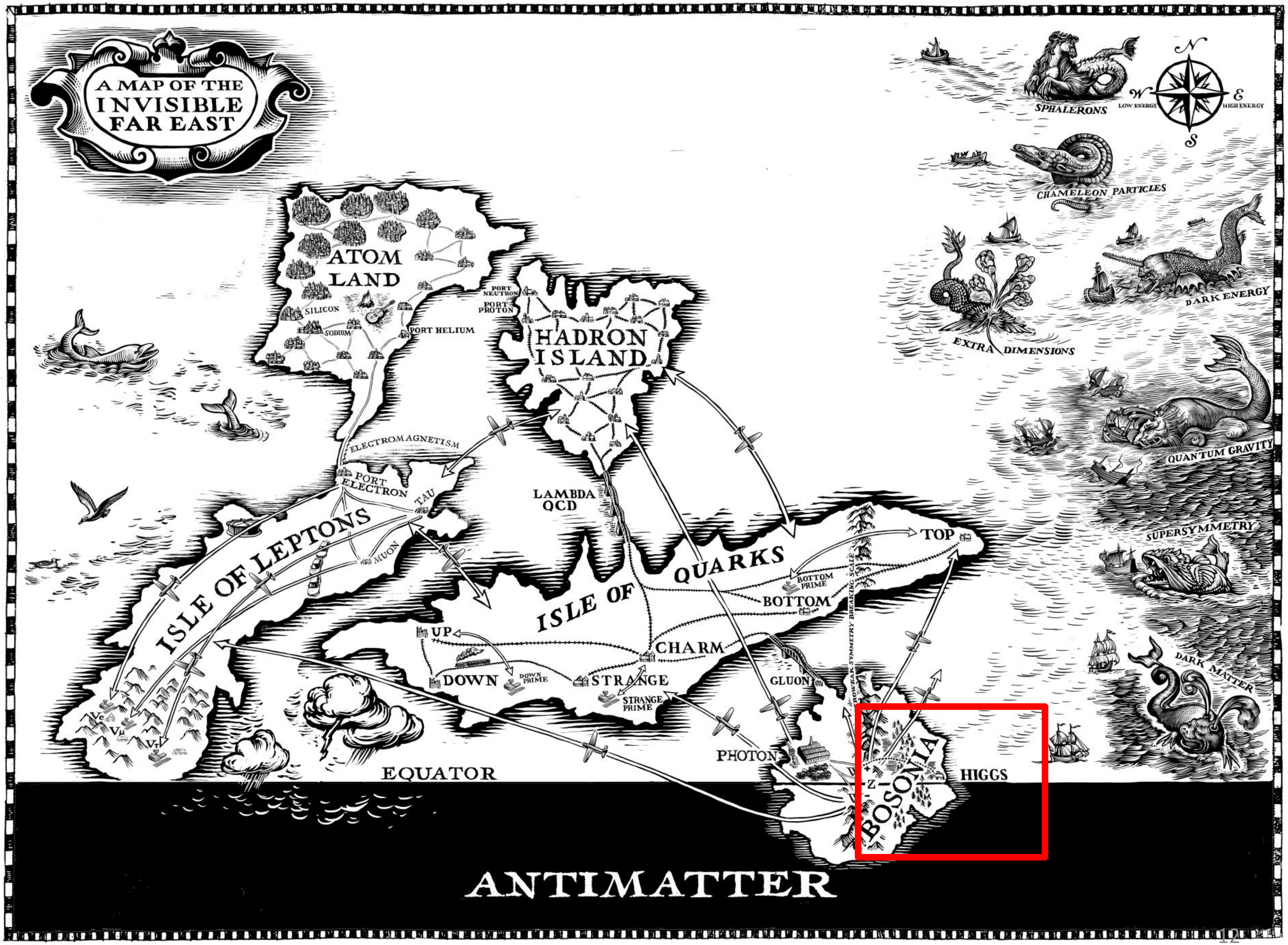
# It's not just $M_W$




LHCb, arXiv:2103.11769




g-2 arXiv:2104.03281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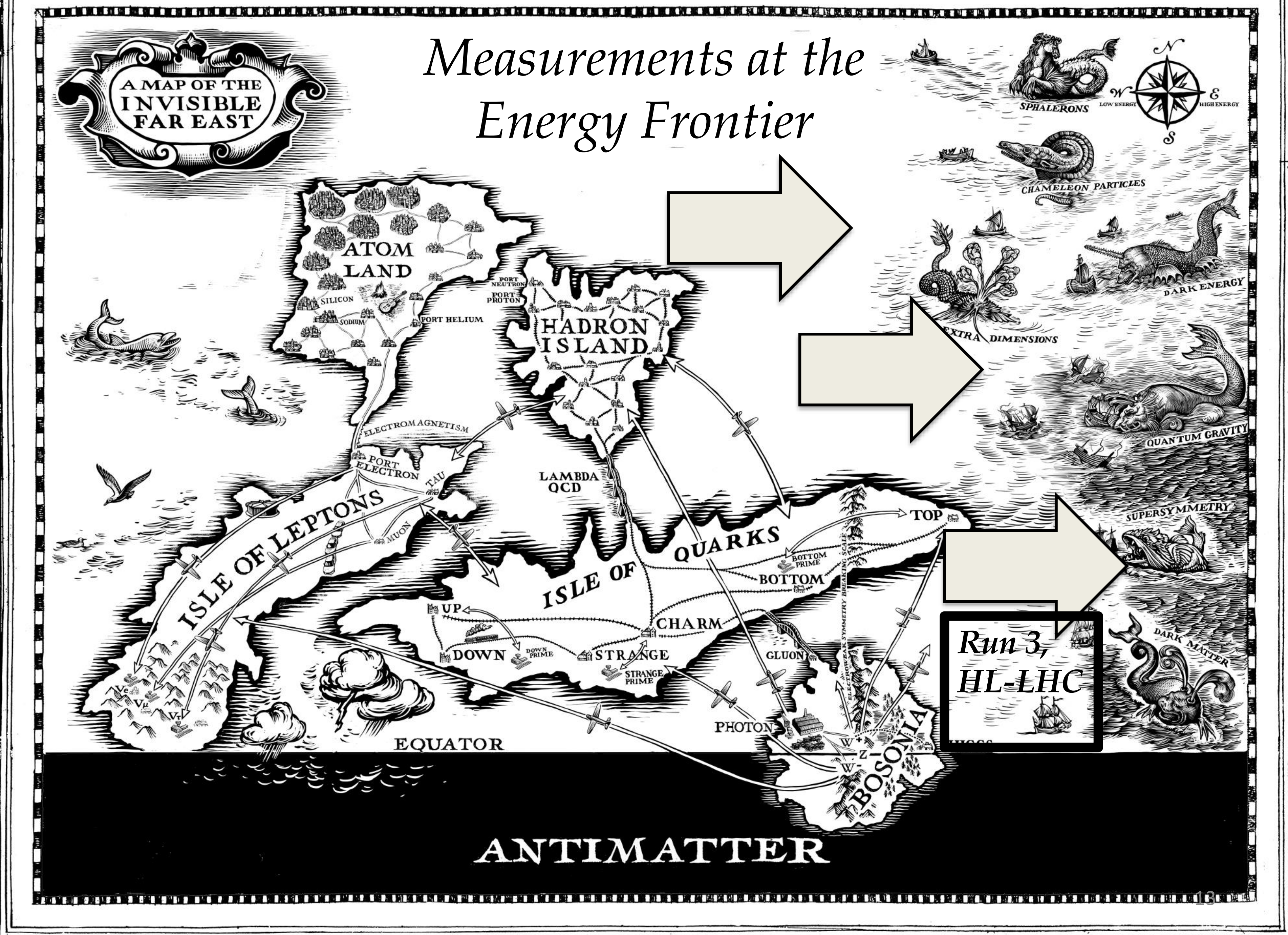
# *Measurements at the Energy Frontier*




***Run 3, HL-LHC***

# *Particle Level Measurements*

- If you
  - Have already calibrated the detector/reconstruction
  - Define the **final state** carefully
  - Use this to define a fiducial phase space
  - Use a simulated prior that describes all relevant distributions
- … then “unfolding” is not a big final step
- Several standard techniques and implementations available

# Simulation and Experiment

- MC Event Generator

Particle Four-Vectors

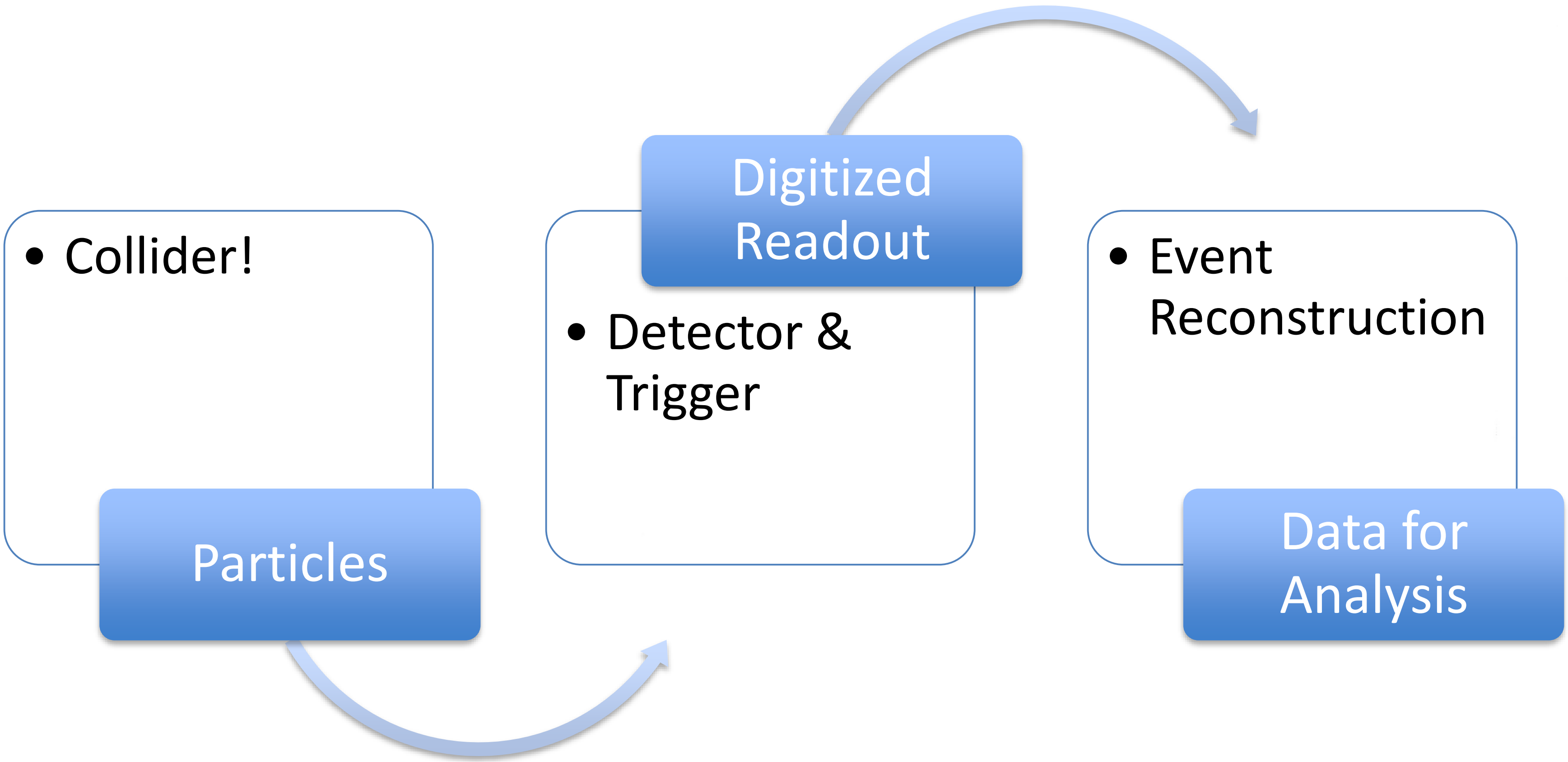
Digitized Readout

- Detector & Trigger Simulation

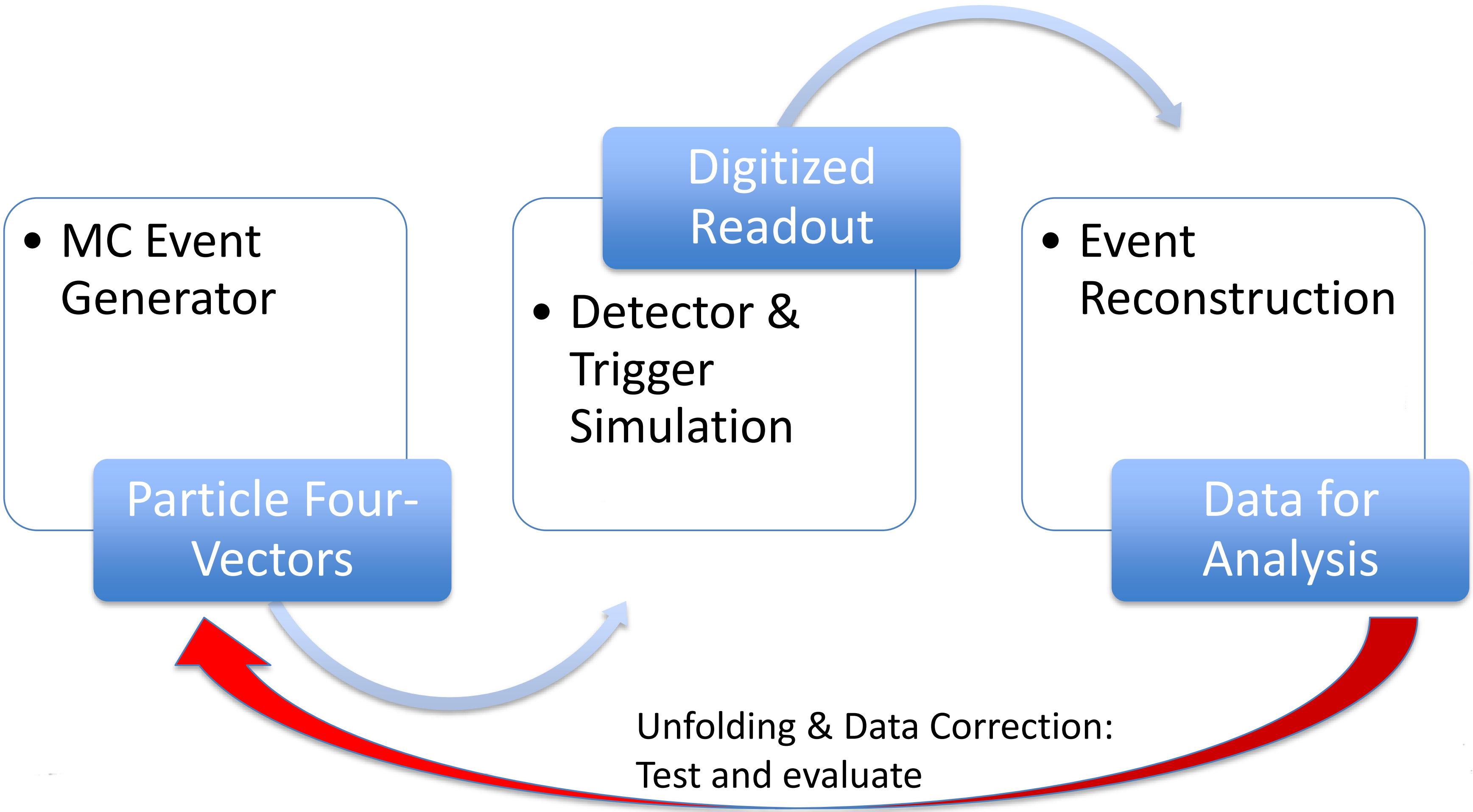
- Event Reconstruction

Data for Analysis

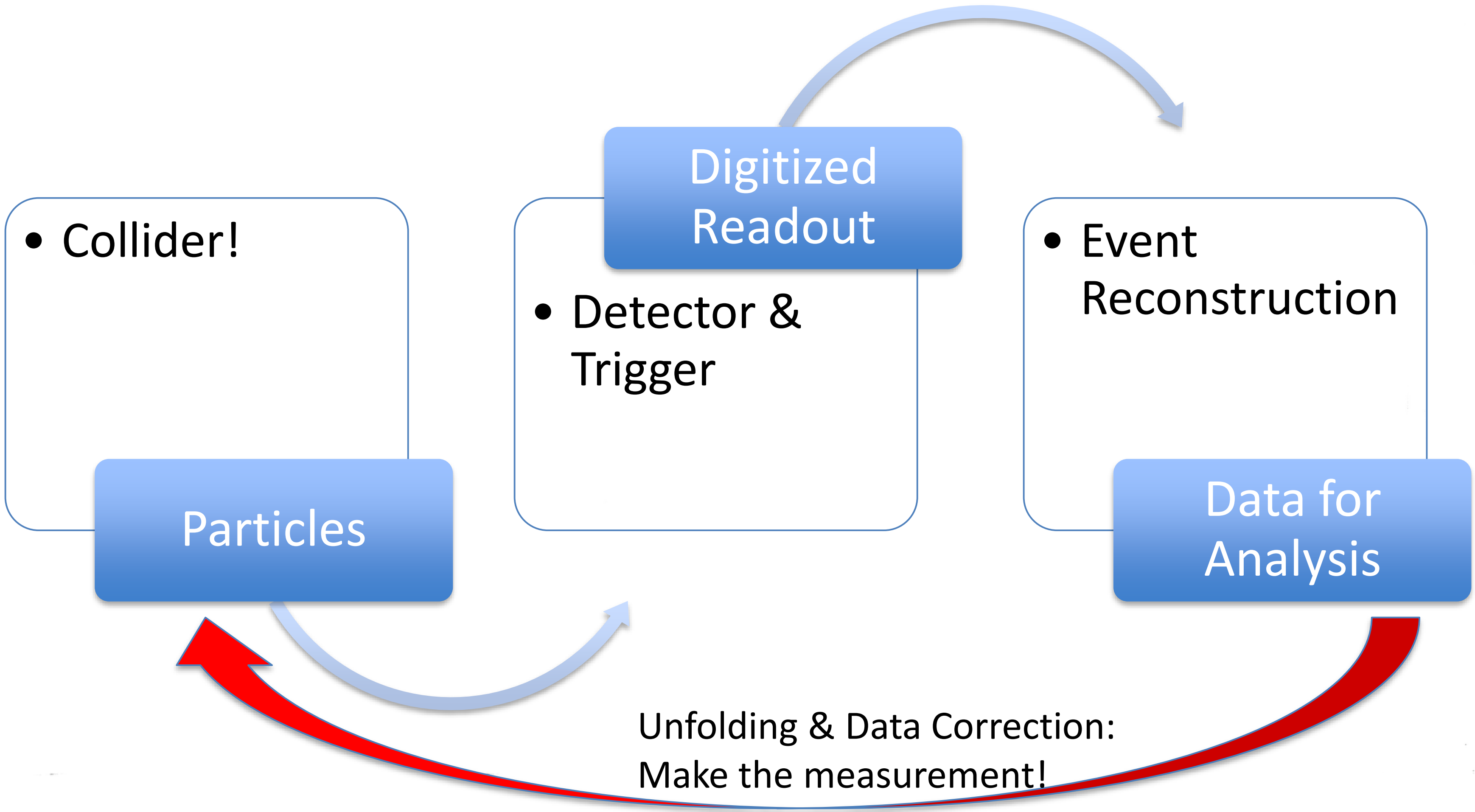
# Simulation and Experiment



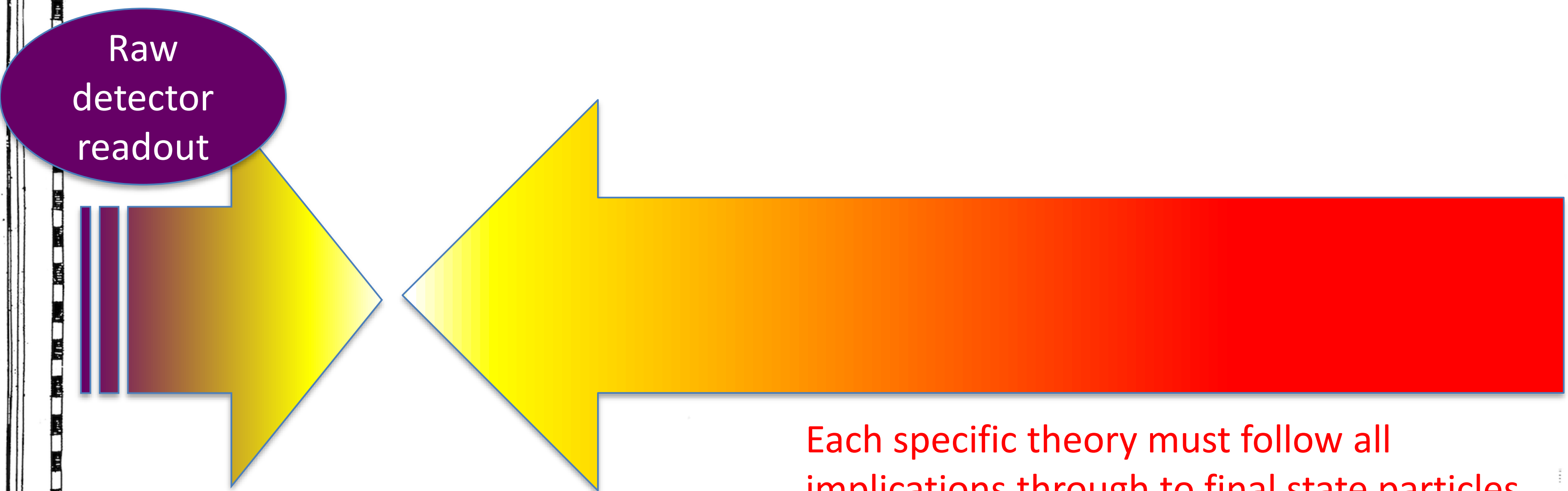
# Simulation and Experiment



# Simulation and Experiment



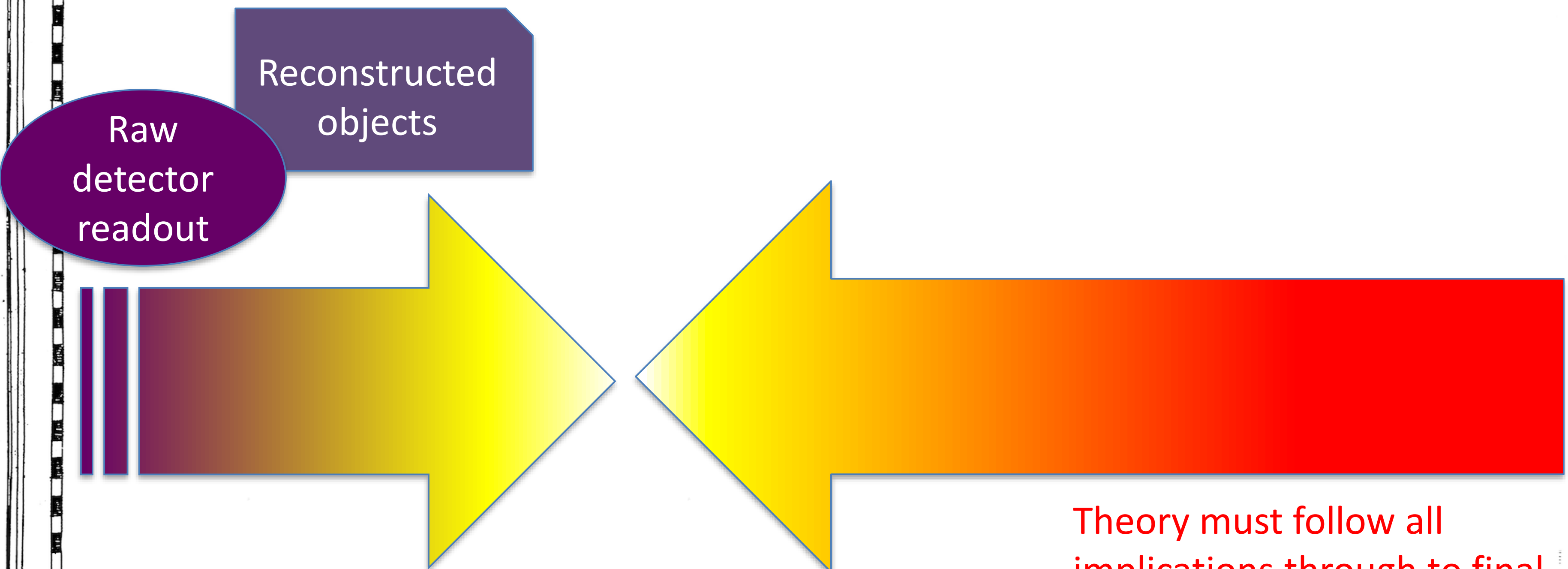
# Where to compare nature to our ideas?




Zero model dependence.

Each specific theory must follow all implications through to final state particles and full detector simulation, including specific run conditions and time-dependent calibrations.

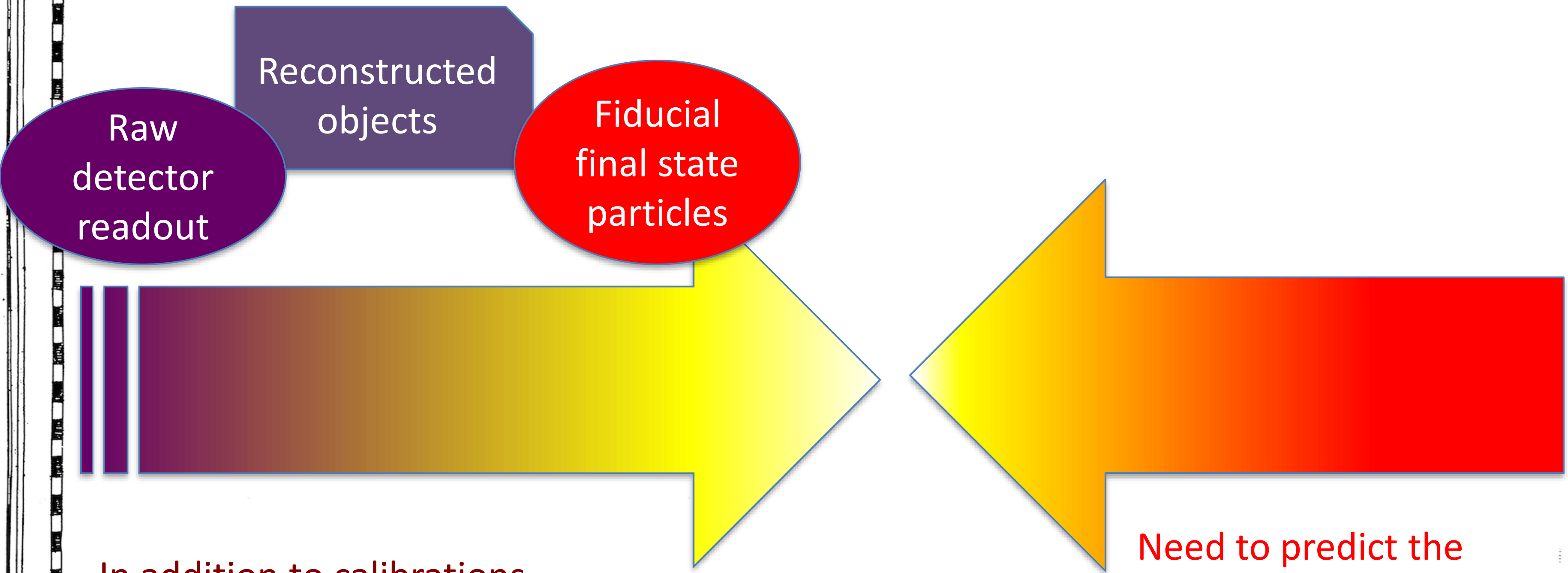
# Where to compare nature to our ideas?




Calibrations applied which may have some dependence on models, but minimal and dependence can be controlled.

Theory must follow all implications through to final state and at least some parameterised approximation of detector resolution and efficiency.

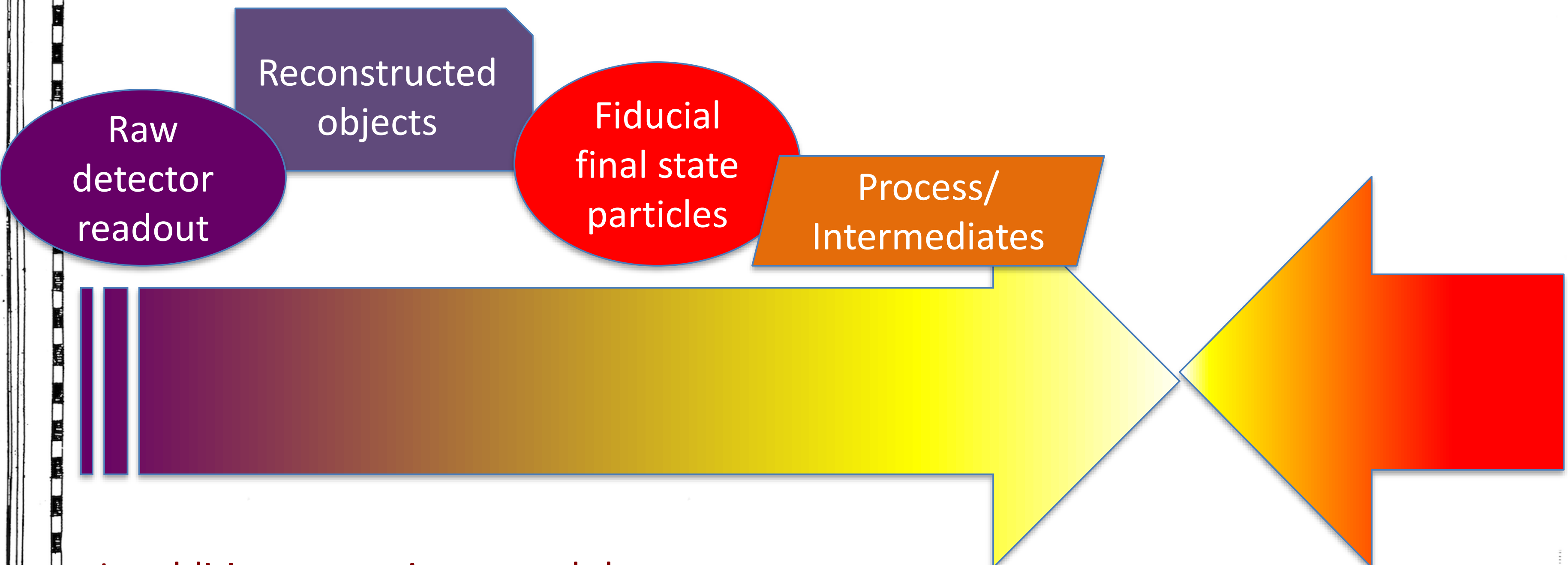
# Where to compare nature to our ideas?




Need to predict the exclusive final state.

In addition to calibrations, need unfolding for resolution and efficiency, though uncertainties can generally be controlled.

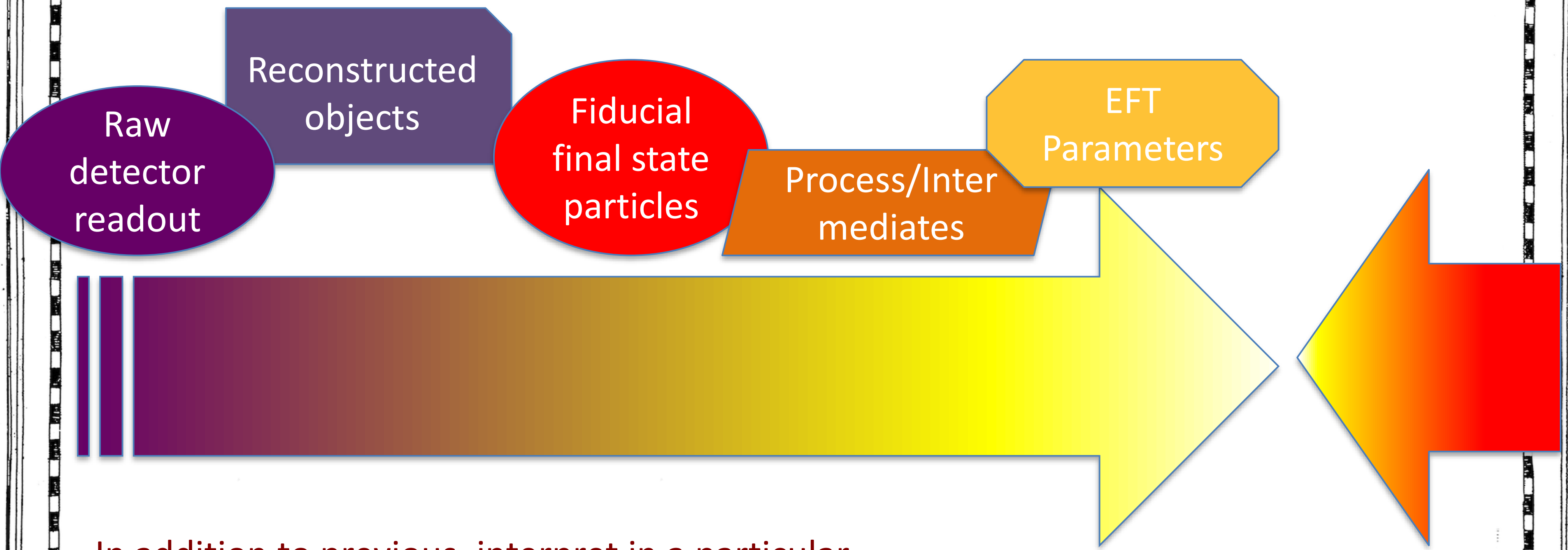
# Where to compare nature to our ideas?




In addition to previous, need theory extrapolations into unobserved regions, theory background subtractions, and corrections for soft/long distance physics.

Can integrate over inclusive phase spaces and ignore soft/long distance physics.

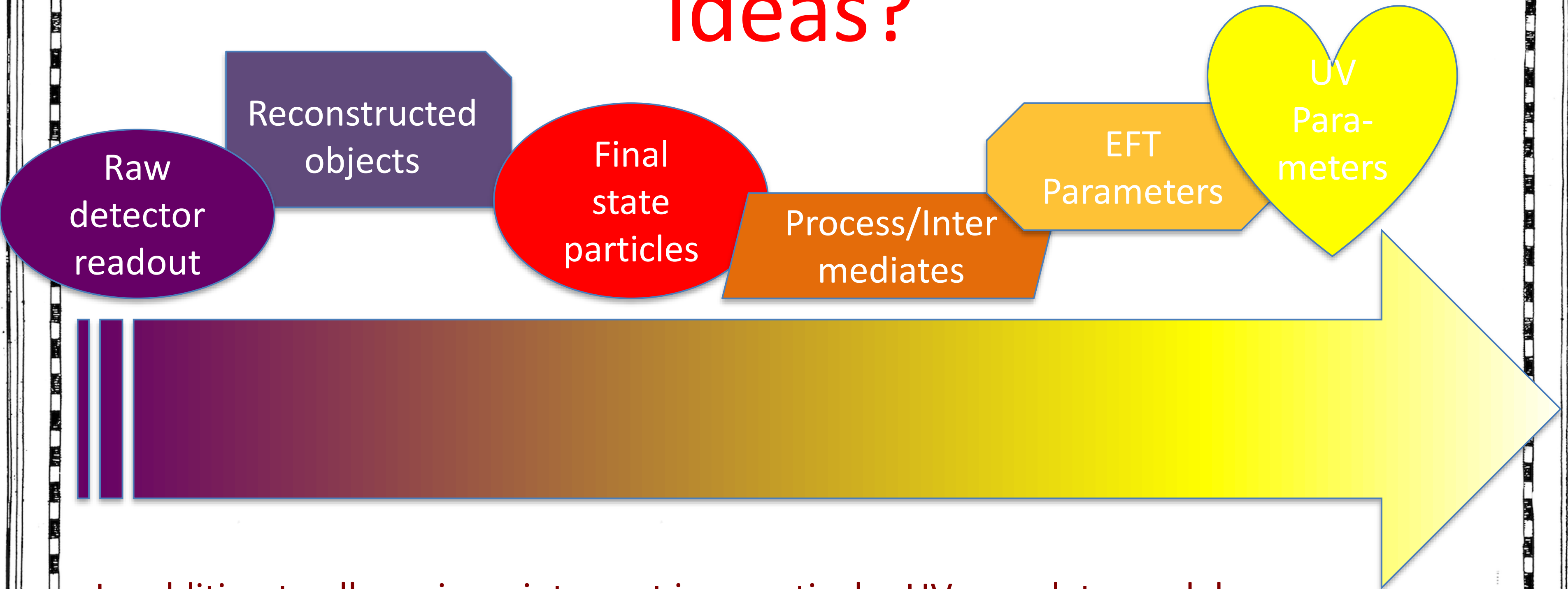
# Where to compare nature to our ideas?




In addition to previous, interpret in a particular (simplified?) model.

Need to think about running from high energies, but not much else…

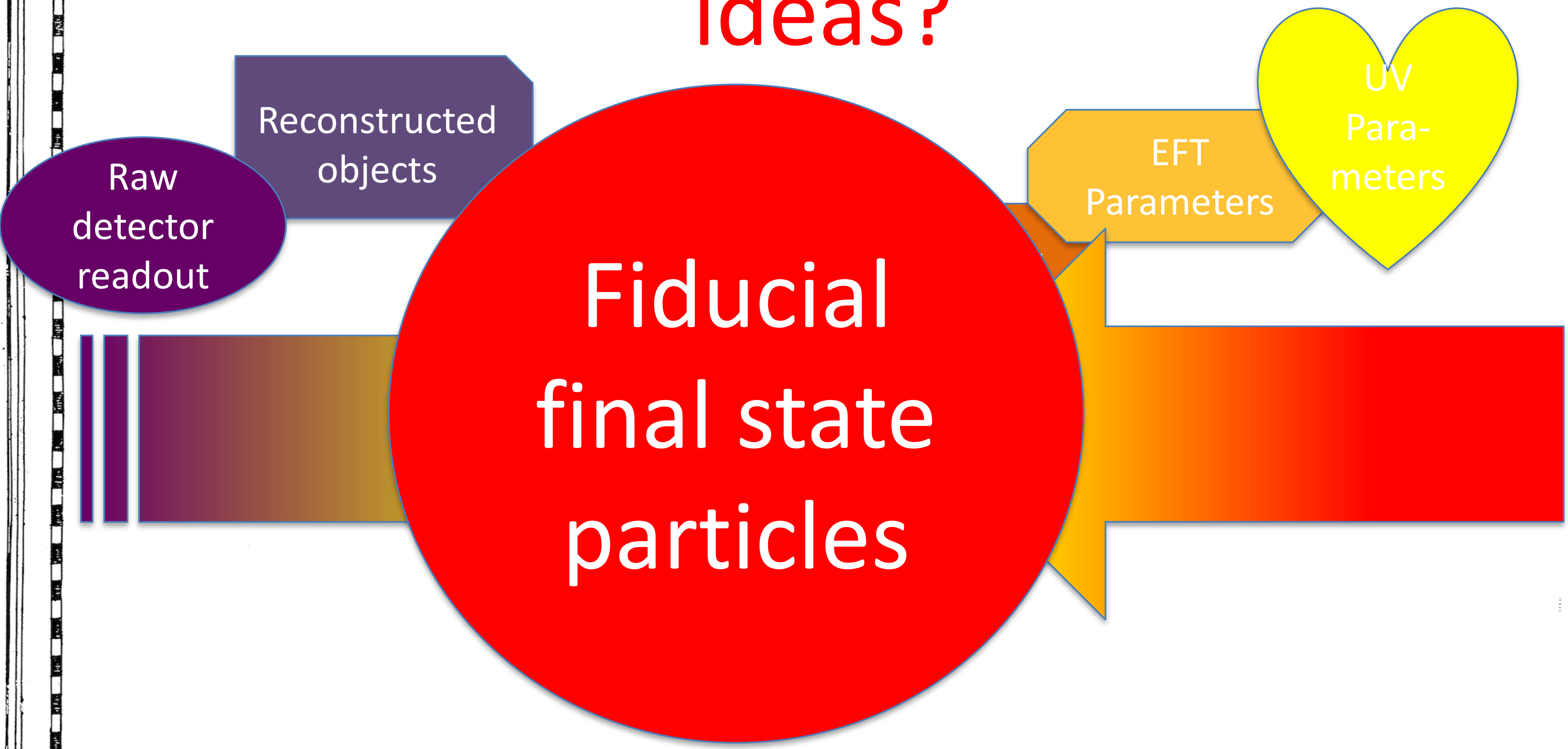
# Where to compare nature to our ideas?

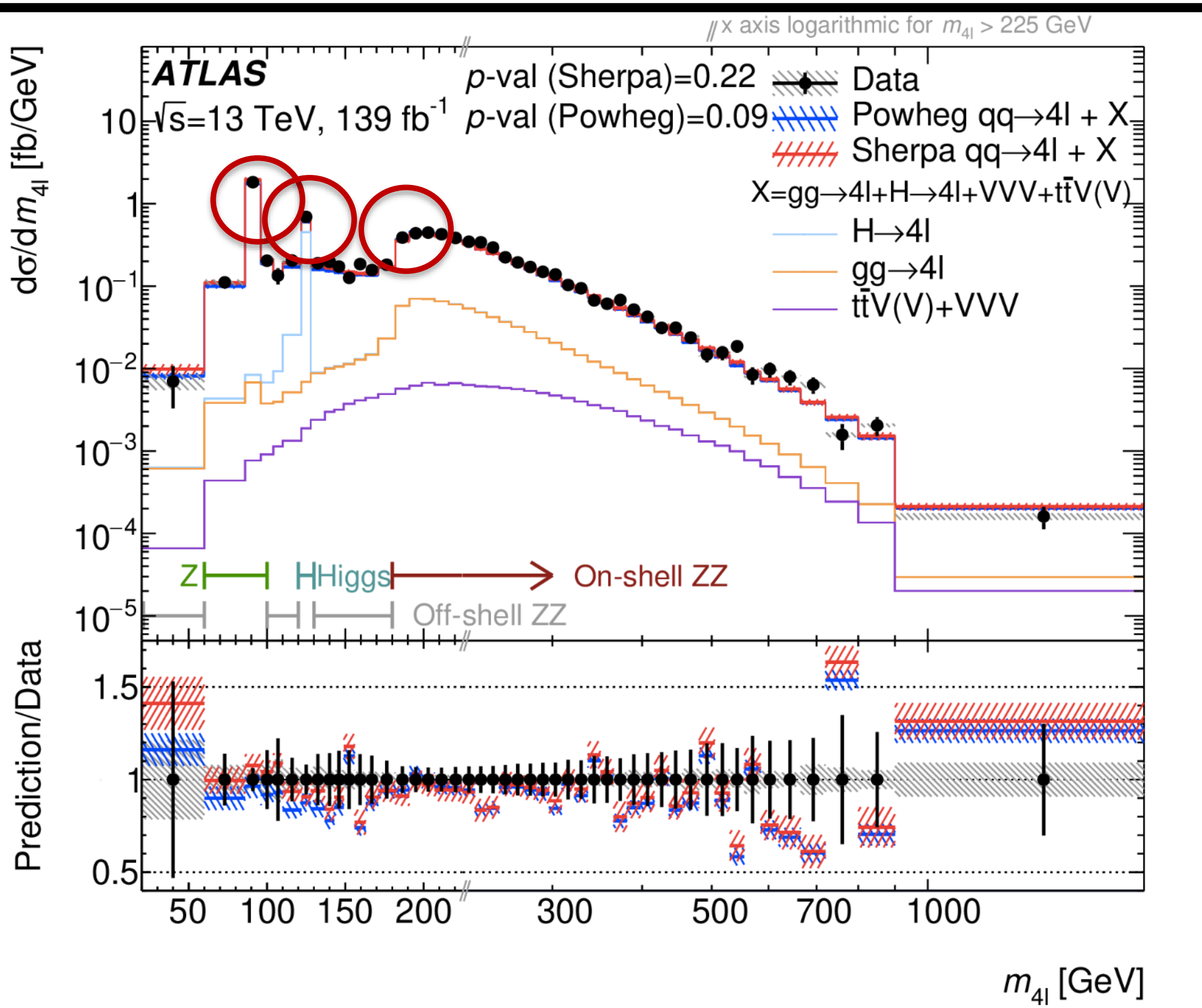



In addition to all previous, interpret in a particular UV complete model.

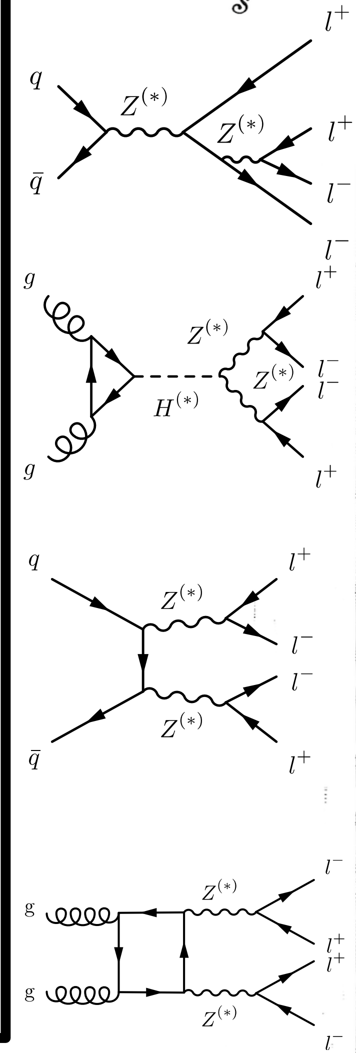
Have a good idea, then play golf.

# Where to compare nature to our ideas?

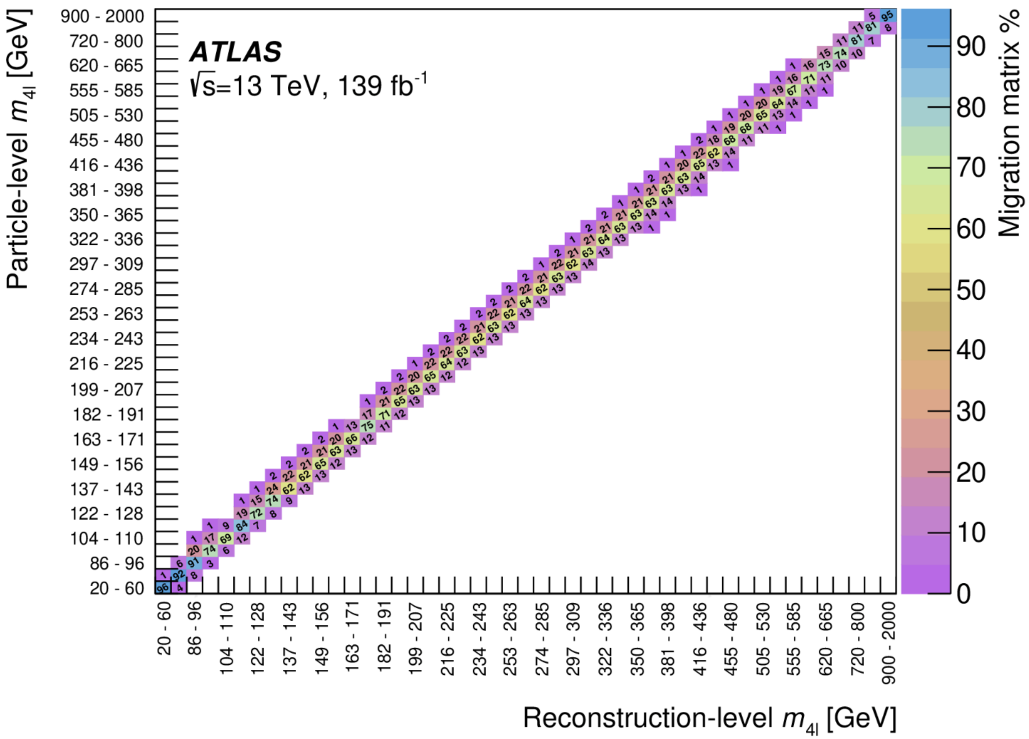


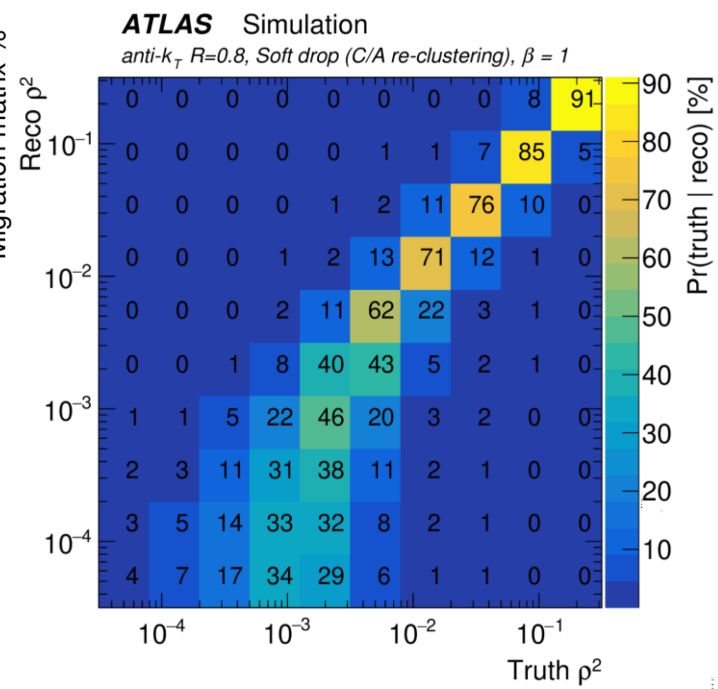



arXiv:2103.01918

# Unfolding Matrices (Examples)




[arXiv:1711.08341](https://arxiv.org/abs/1711.08341)

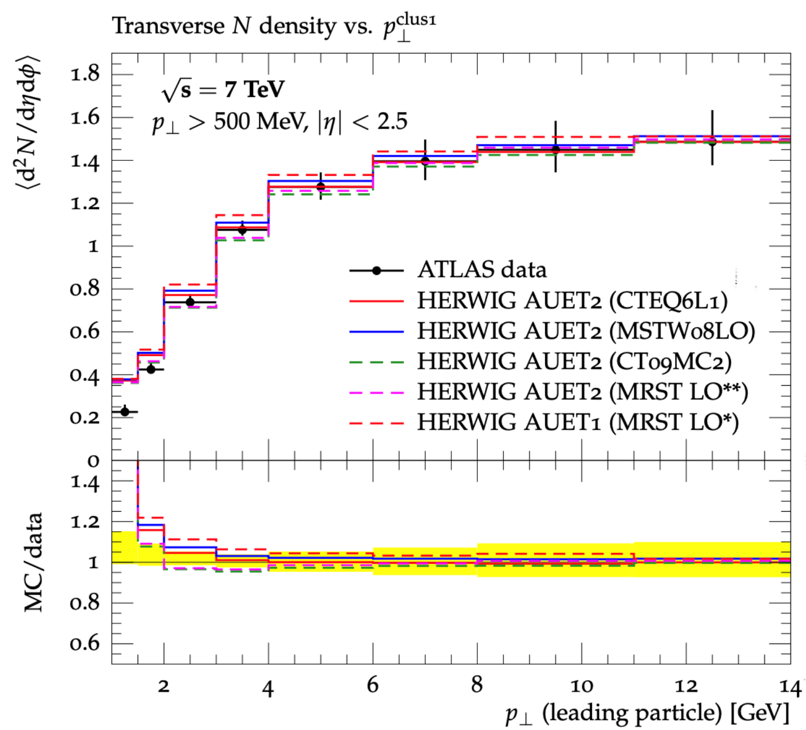
arXiv:2103.01918

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




Buckley et al, Bierlich et al: **Talk from Chris Gütschow next**

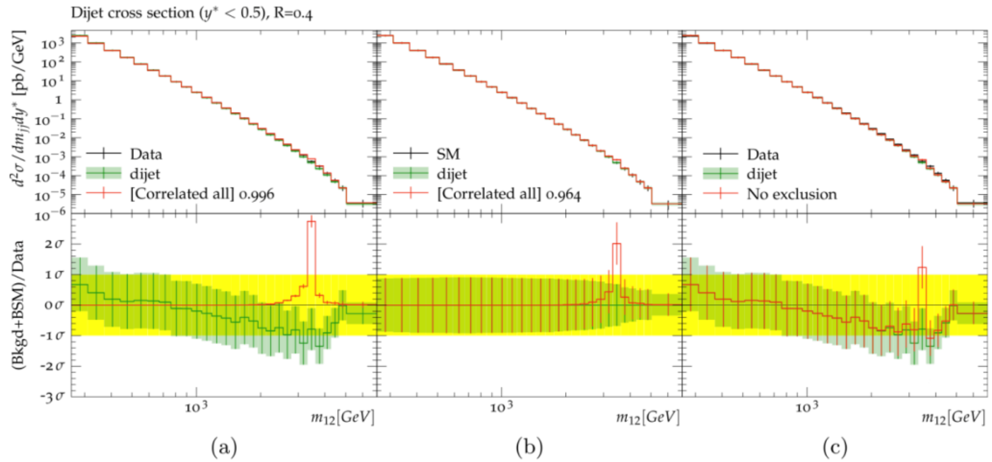
From ATL-PHYS-PUB-2011-008

# 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




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

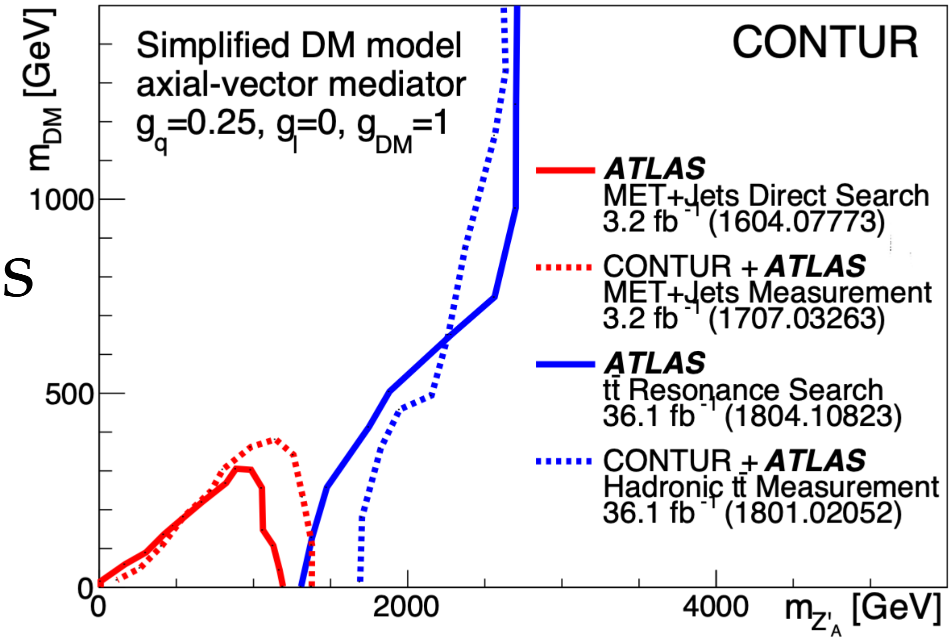
- Increasingly precise measurements and calculations together extend the reach

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

# Unleashing the power of high luminosity LHC data

*(example case studies)*

- Z′ models motivated by Lepton Flavour Violation anomalies
- Composite Dark Matter
- Vector-like Quarks




Louie Corpe

# Z′ models motivated by Lepton Flavour Violation anomalies

- Muon deficit in $R_{K^*}$ may be explained by introducing a new gauge boson (Z′) with non-trivial flavour coupling structure
- Fit to LHCb data gives favoured parameter values away from SM
- Take these parameter points and see whether other measurements still allow them

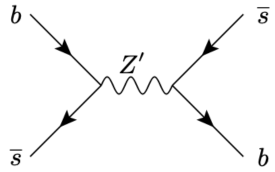
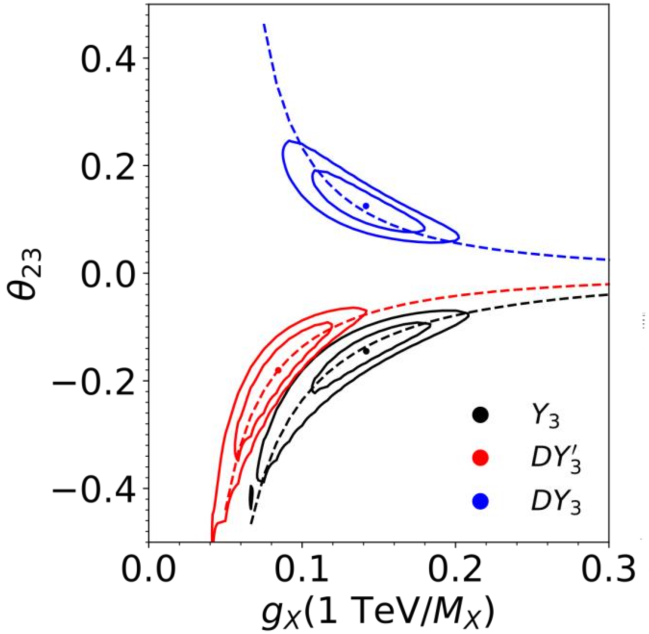
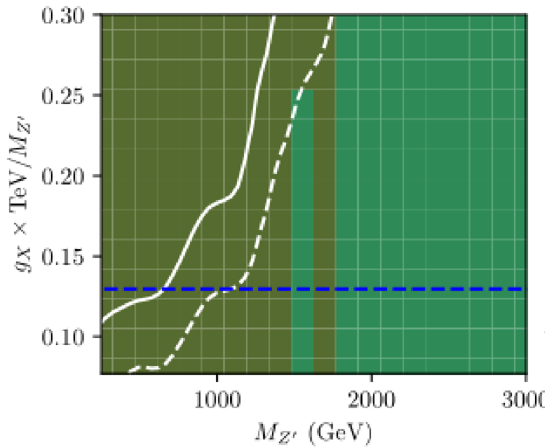



Fig. 2: Tree-level Feynman diagram of a $Z'$-mediated process which contributes to $B_s - \overline{B_s}$ mixing.

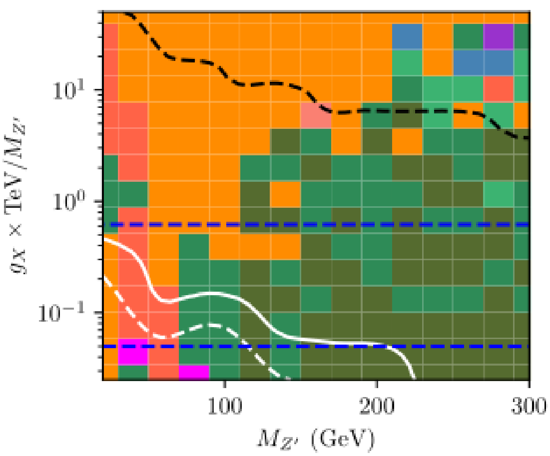



Allanach, JMB, Corbett . arXiv:2110.13518

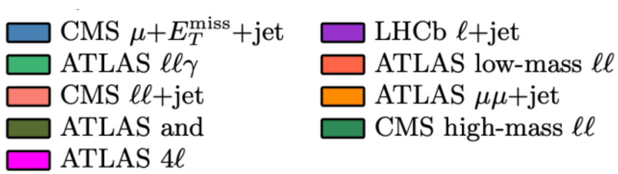
- Main signature is dimuons.
- In the high Z′ mass regions, what sensitivity there is comes from the ATLAS dimuon search. For Third Family Hypercharge Models models that's all there is.
- In the $B_3$-$L_2$ model, the "window" at low mass largely is closed by low mass Drell Yan and Z →leptons measurements




**Deformed 3[rd] Family Hypercharge Model (DY3′).**
Favoured region is below blue line. Above white line, 95% exclusion.




**$B_3$-$L_2$ Model.**
Favoured region is between blue lines. Above black line, Z′ width >30% of mass. Below white line, 95% exclusion.



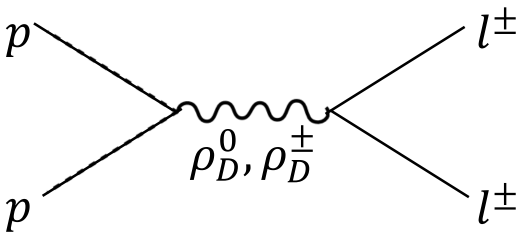

Allanach, JMB, Corbett . arXiv:2110.13518

# 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 $\Lambda_{dark}$?
- 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
  $\eta = m(\pi_D)/m(\rho_D)$

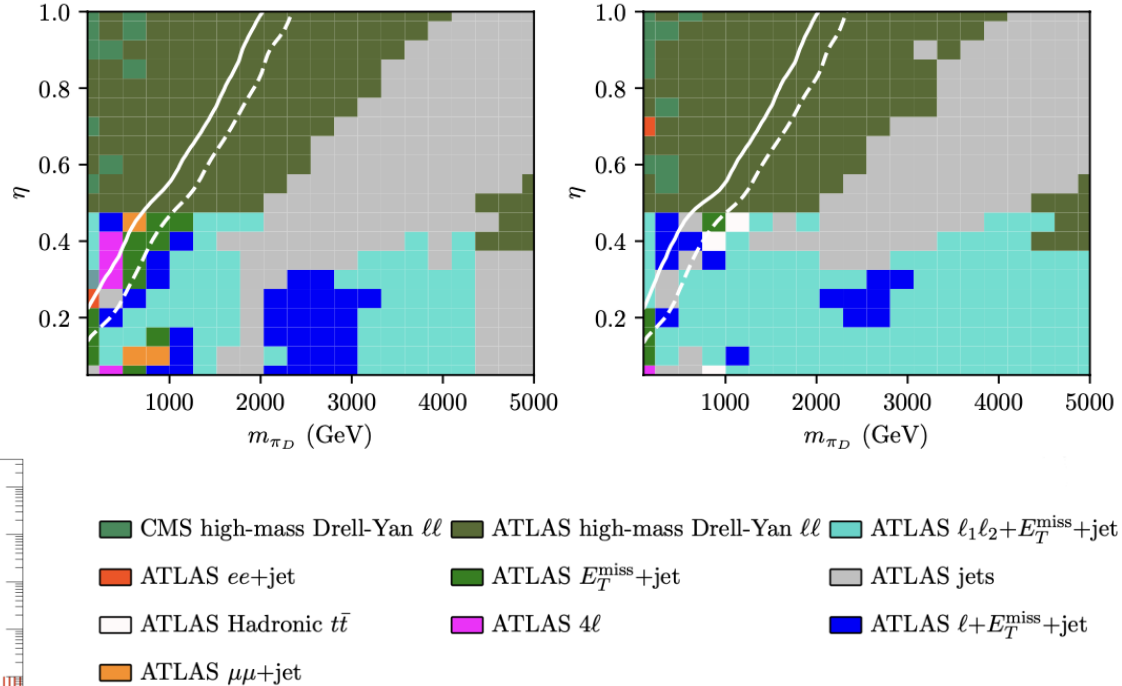
JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

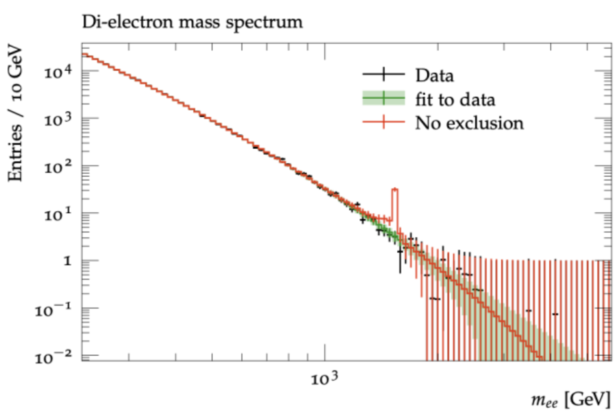
# Composite Dark Matter Models




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

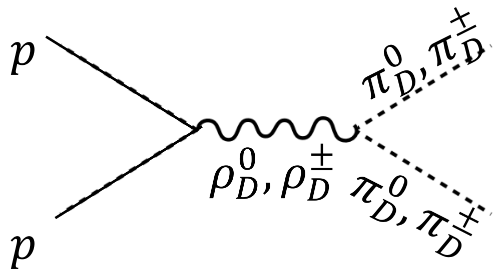
Right-handed model
$\rho^0_D$ only

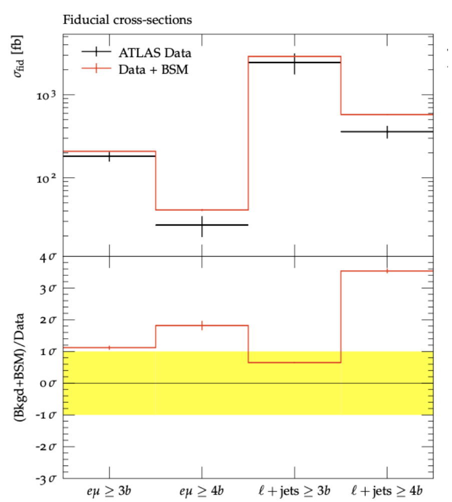



JMB, Corpe, Kong, Kulkarni, Thomas. arXiv:2105.08494

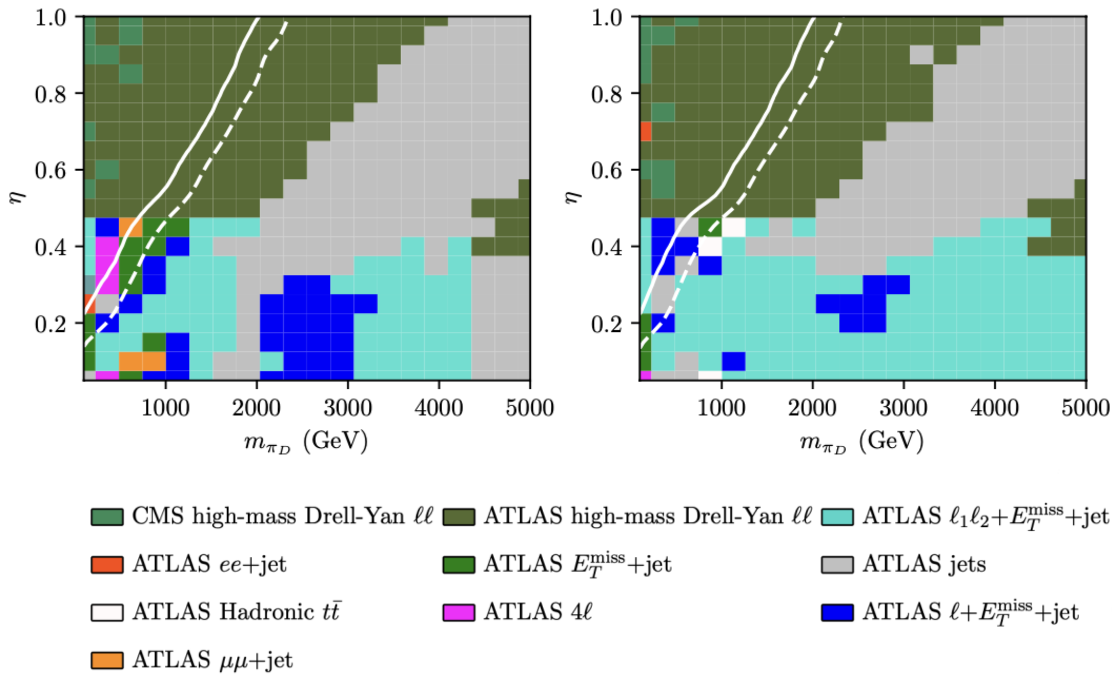
# Composite Dark Matter Models




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

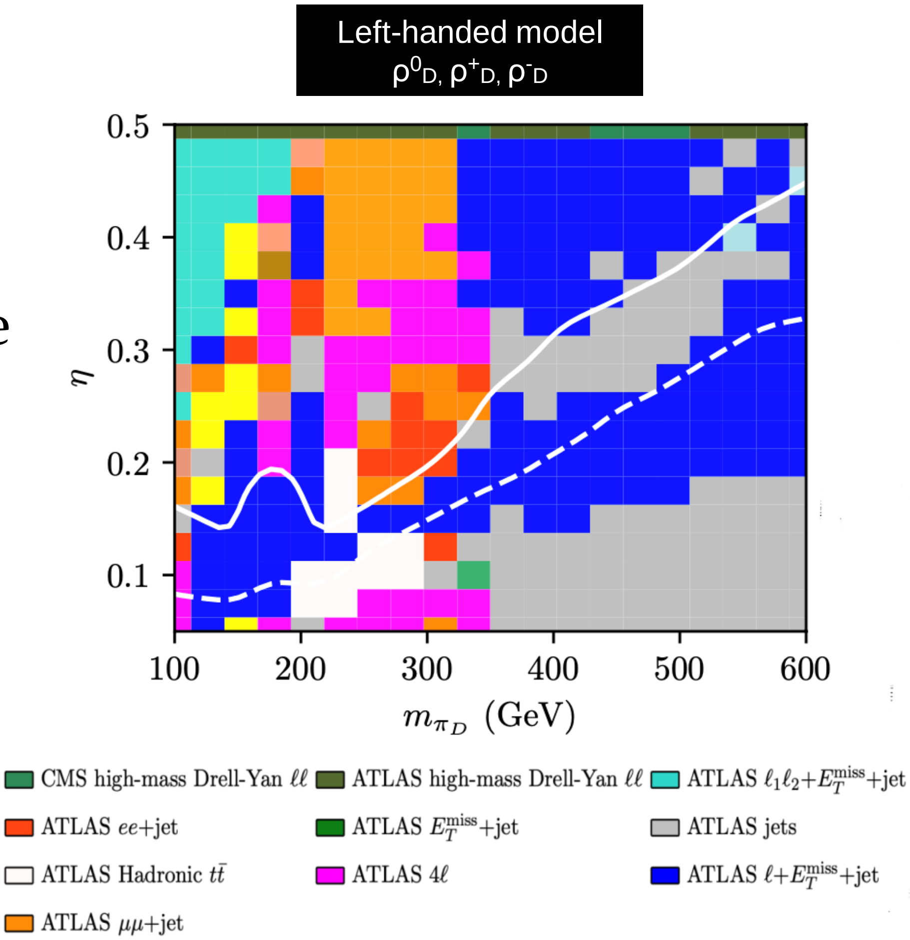
Right-handed model
$\rho^0_D$ only




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

# Composite Dark Matter Models

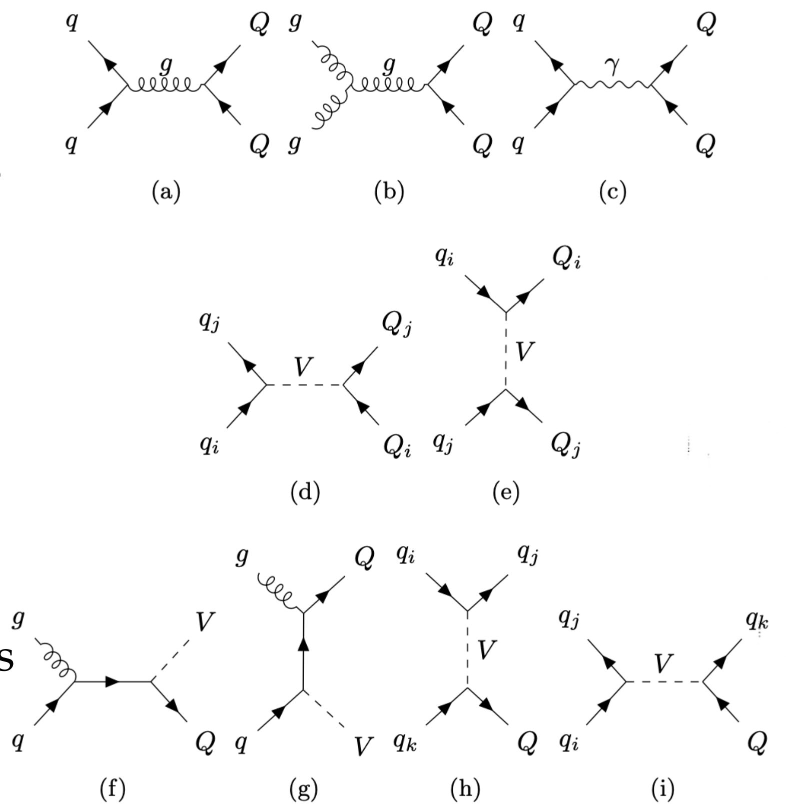
- Large areas excluded:
  - When pion mass is close to Higgs mass, H→gg analysis contributes
  - Boosted hadron "top" measurements contribute when pion mass ~200 GeV: Pions decay to tb and are boost from heavy r.
  - Other sensitivity from Z-pole dileptons, and lepton+missing energy (Z, top, W production 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)
  - $\kappa$: **absolute coupling** of VLQs to SM quarks
  - $\zeta_i$: relative **coupling of VLQs to i$^{th}$ generation**
  - $\xi_V$: 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

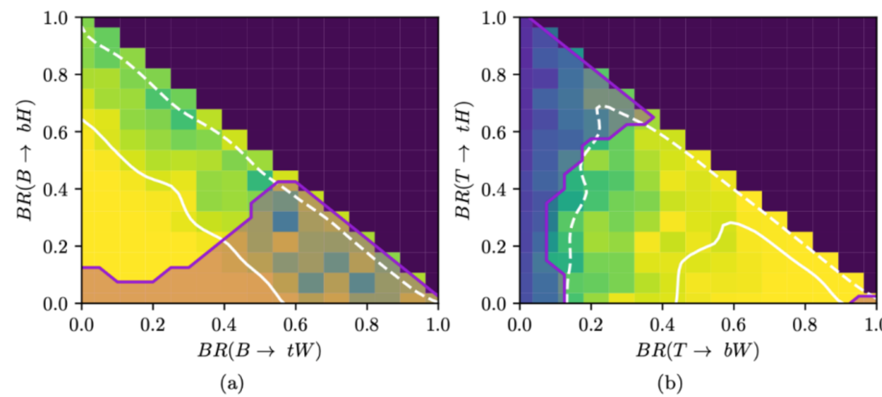
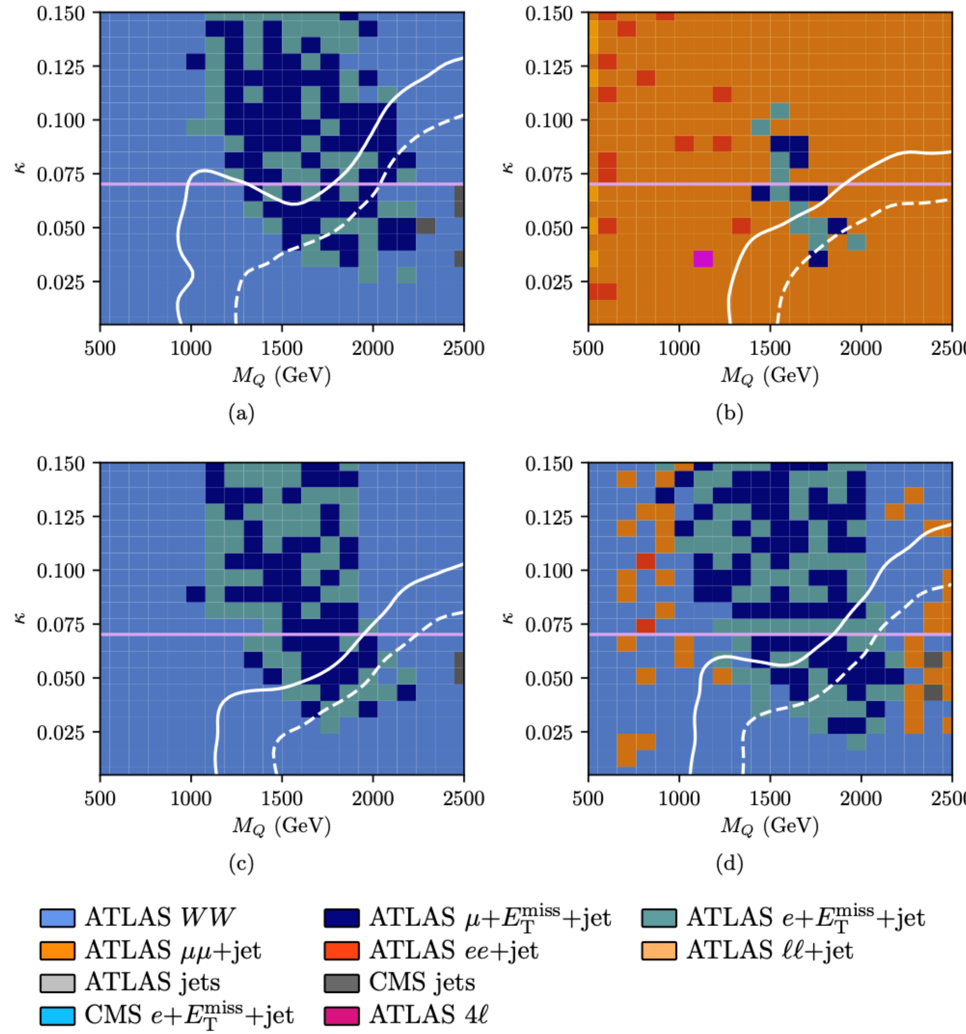



Figure 5: Sensitivity of LHC measurements to (a) $B$-production for $M_B = 1200$ GeV and (b) $T$-production for $M_T = 1350$ GeV. The Contur exclusion is shown in the bins in which it is evaluated, graduated from yellow through green to black on a linear scale, with the 95% CL (solid white) and 68% CL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

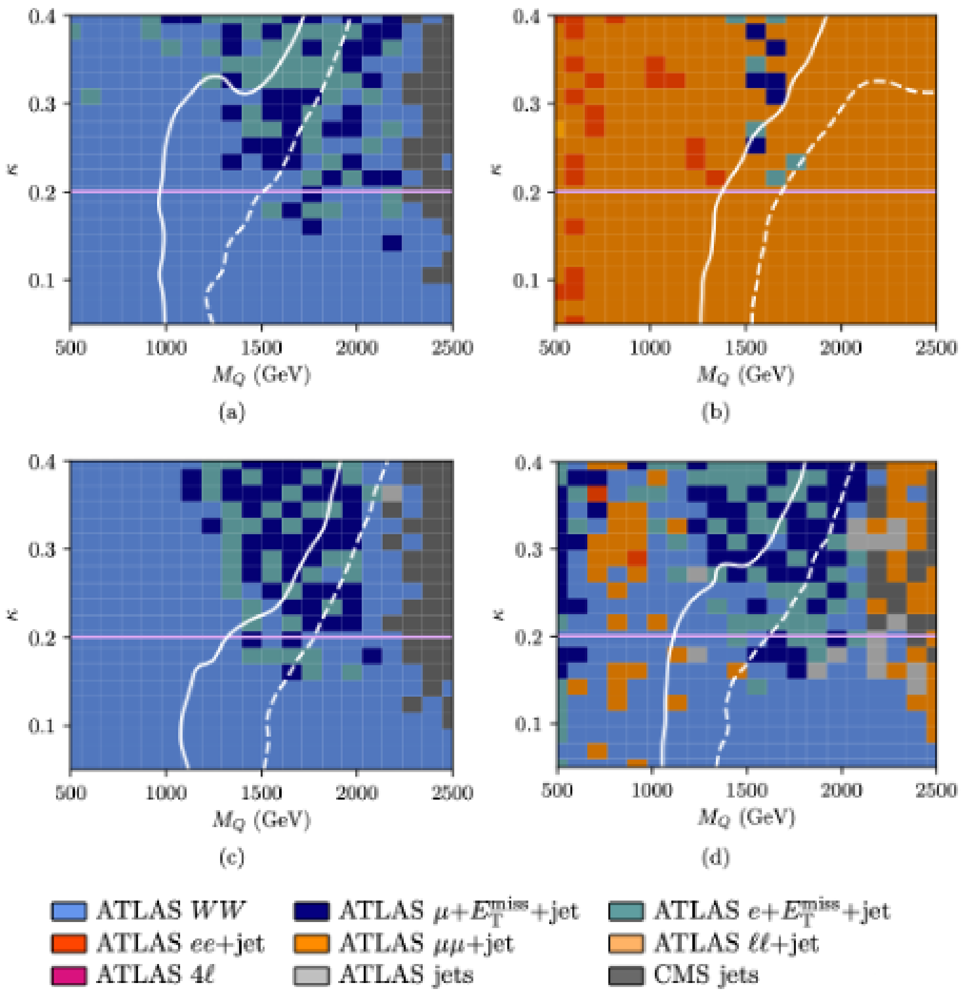
- Coupling to 1st generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude most of the plane.
- Single VLQ production very important at highest masses




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

# Vector-like Quarks

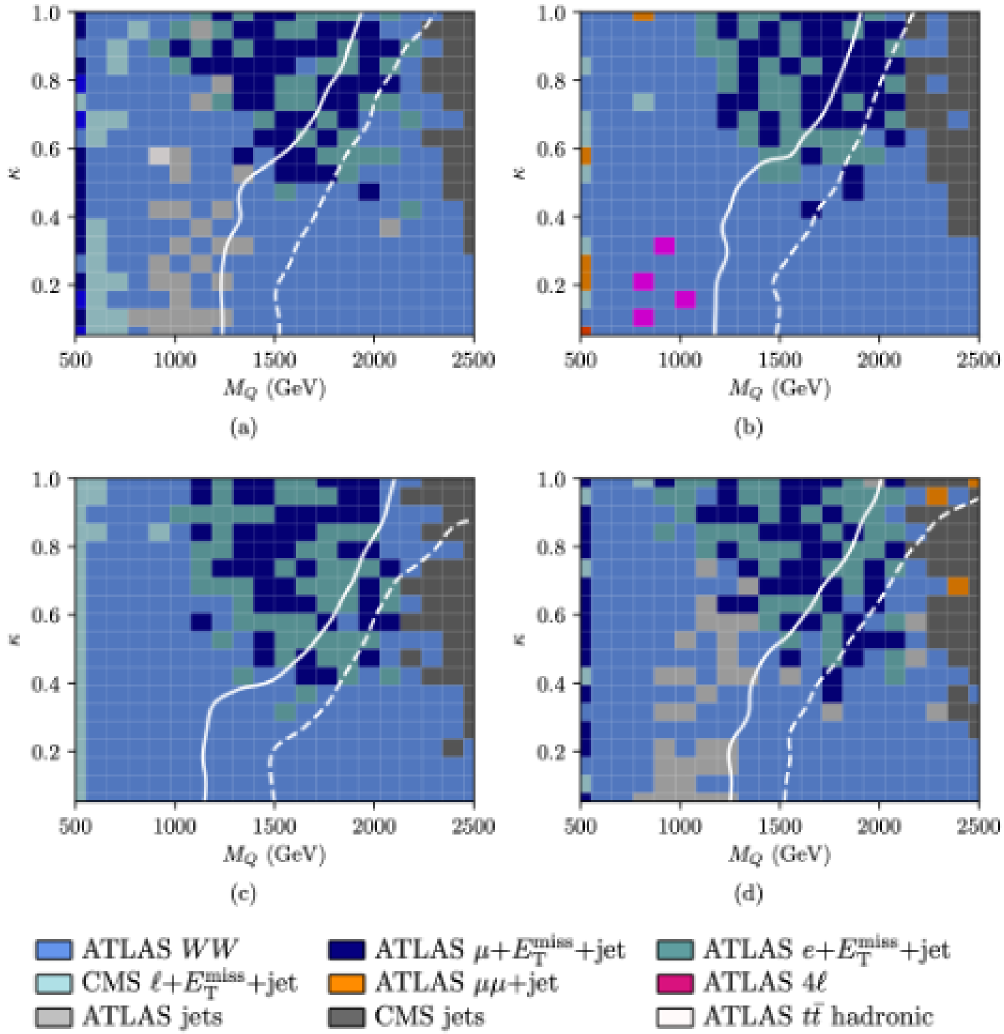
- Coupling to 2nd generation.
- Region above line excluded by non-collider constraints
- No LHC search analyses exist
- Measurements exclude significant part of the plane.
- Single VLQ production again very important at highest masses




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

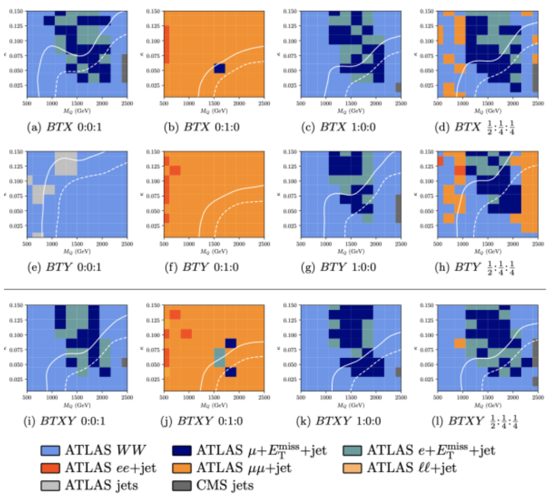
- Addendum: During journal review for this paper, it was pointed put that we'd missed some of the most compelling scenarios, and should instead consider:
  - B, T singlets
  - BT, XT, TY doublets
  - BYX, BTY triplets
- … for each generational coupling scenario and for four different decay branching 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

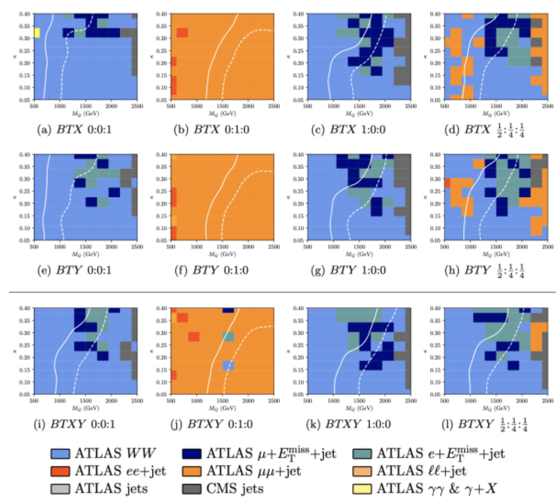
# Vector-like Quarks


# Vector-like Quarks

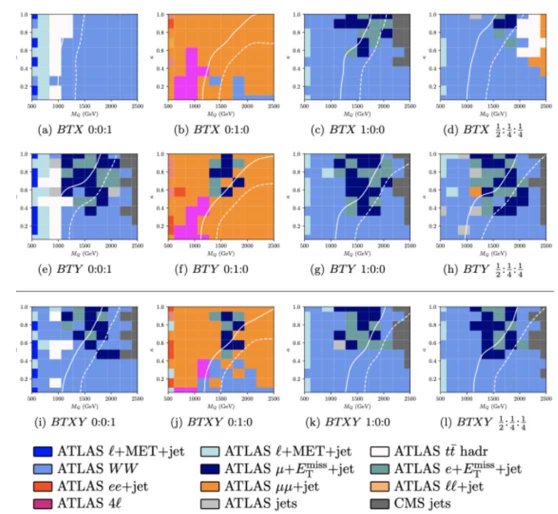
## 1st Generation




## 2nd Generation



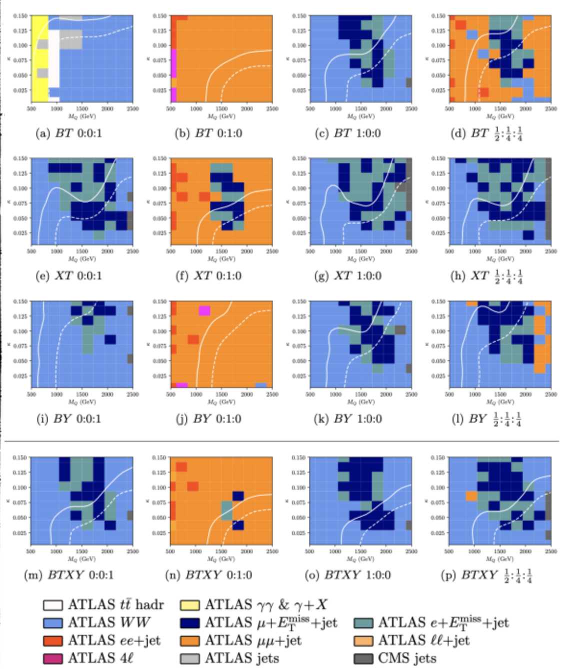

## 3rd Generation



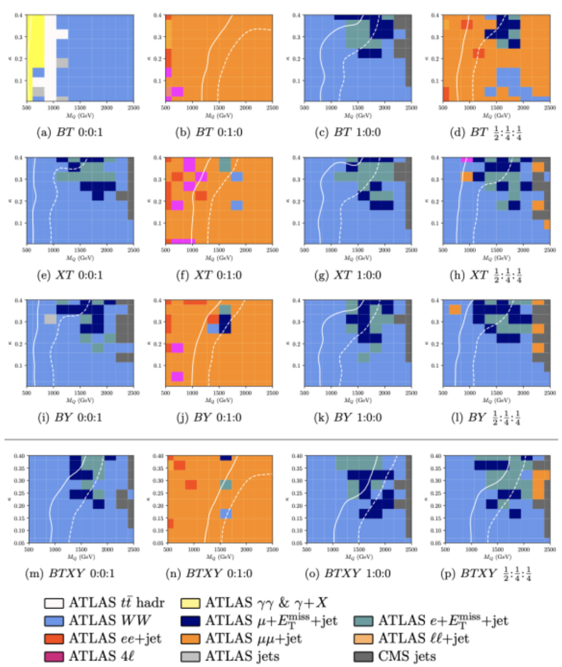

Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

# Vector-like Quarks

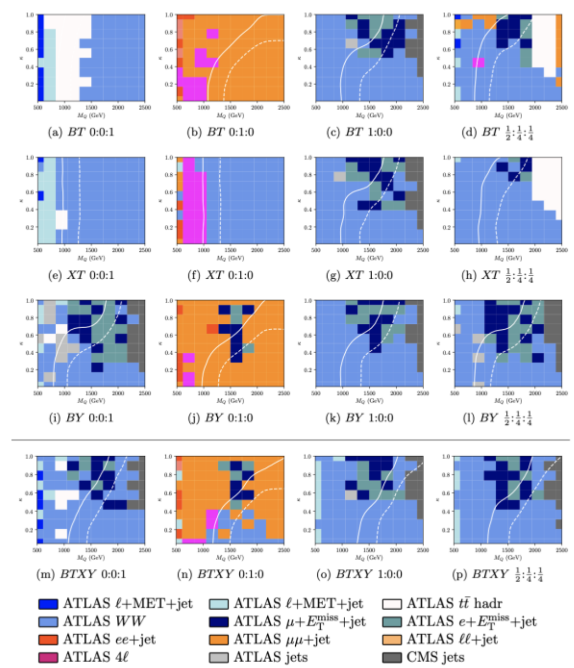
## 1st Generation




## 2nd Generation



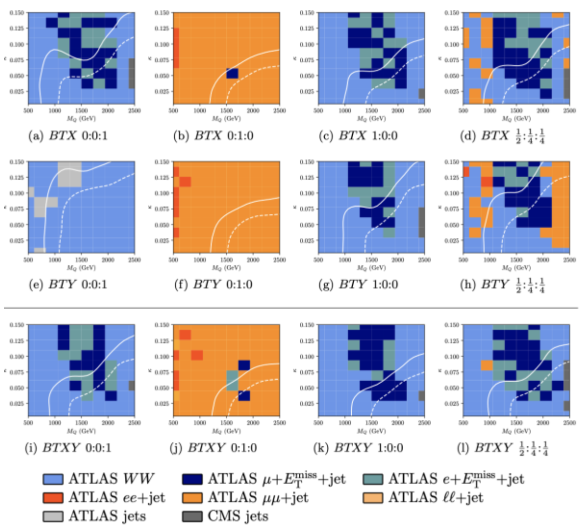

## 3rd Generation



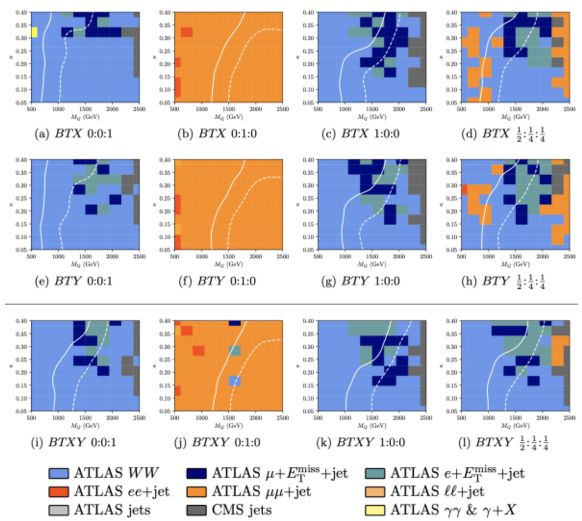

Buckley, JMB, Corpe, Huang, Sun arXiv:2006.07172

# Vector-like Quarks

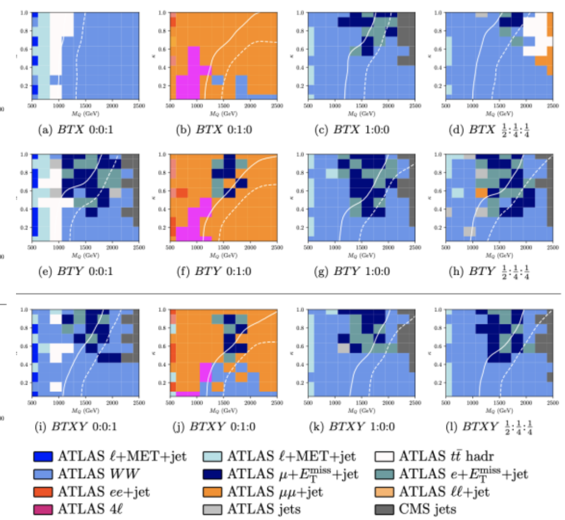
## 1st Generation




## 2nd Generation



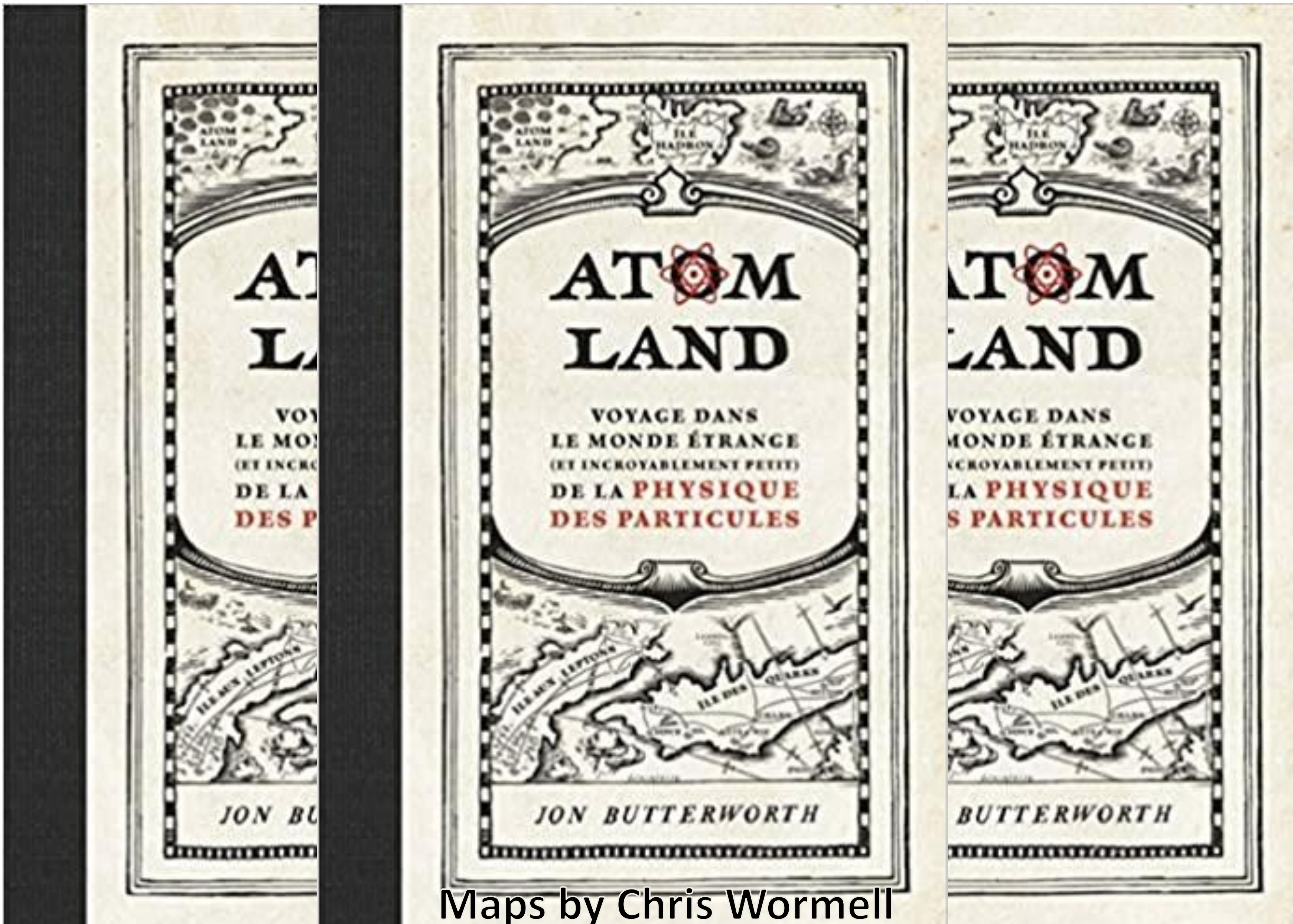

## 3rd Generation




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

# So where are we now?

- *No agreed "fave" extensions to the Standard Model*
- *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*
- *Not enough to say "we looked for everything we could think of"*
  - ***Quantify** whether or not the Standard Model continues to apply, well beyond the region in which it was developed, and to extreme precision*
  - *Need precise, theory-independent **measurements**, and comparable calculations in Standard Model & beyond.*
- *Into the future (new models, more precise calculations) this requires particle-level measurements*




Maps by Chris Wormell