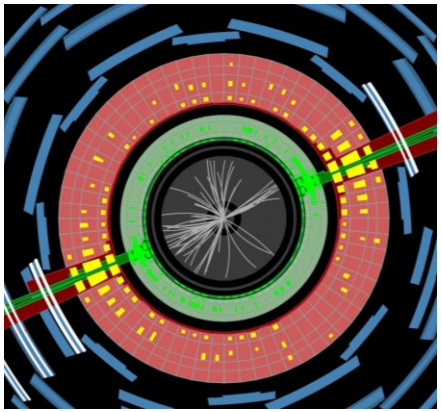
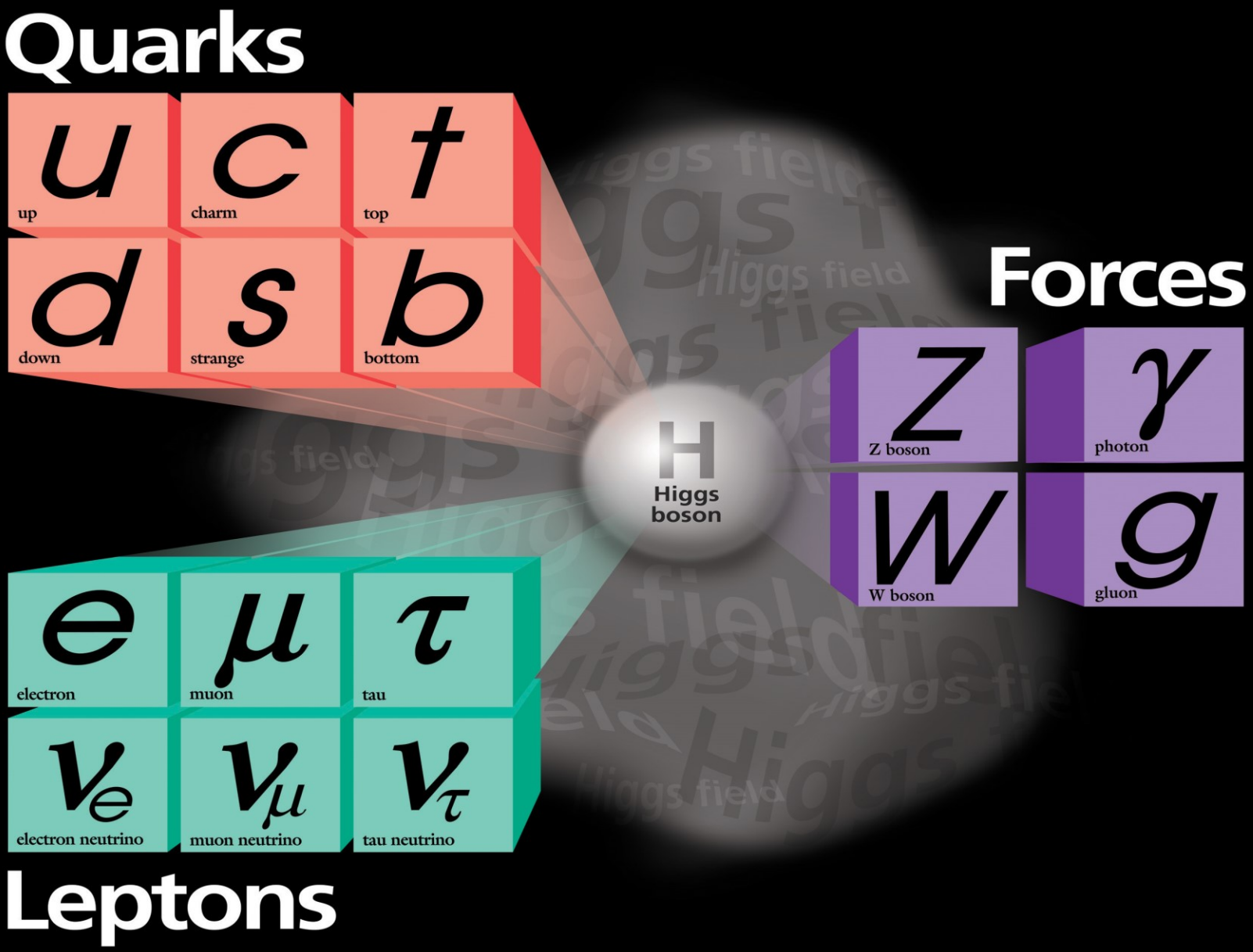
New physics and model independent measurements at the LHC



Jon Butterworth

University College Londc

DESY, June 2019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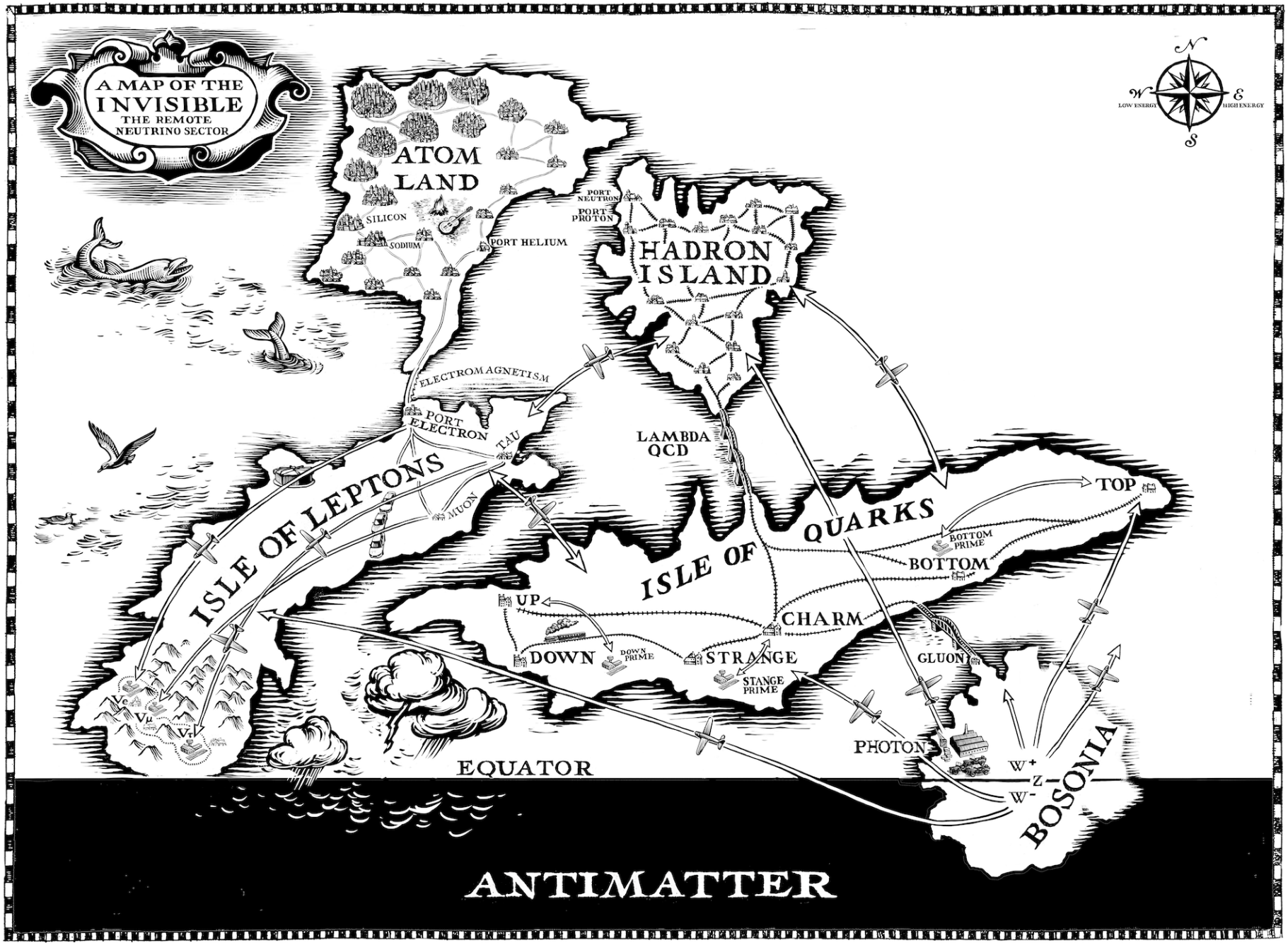
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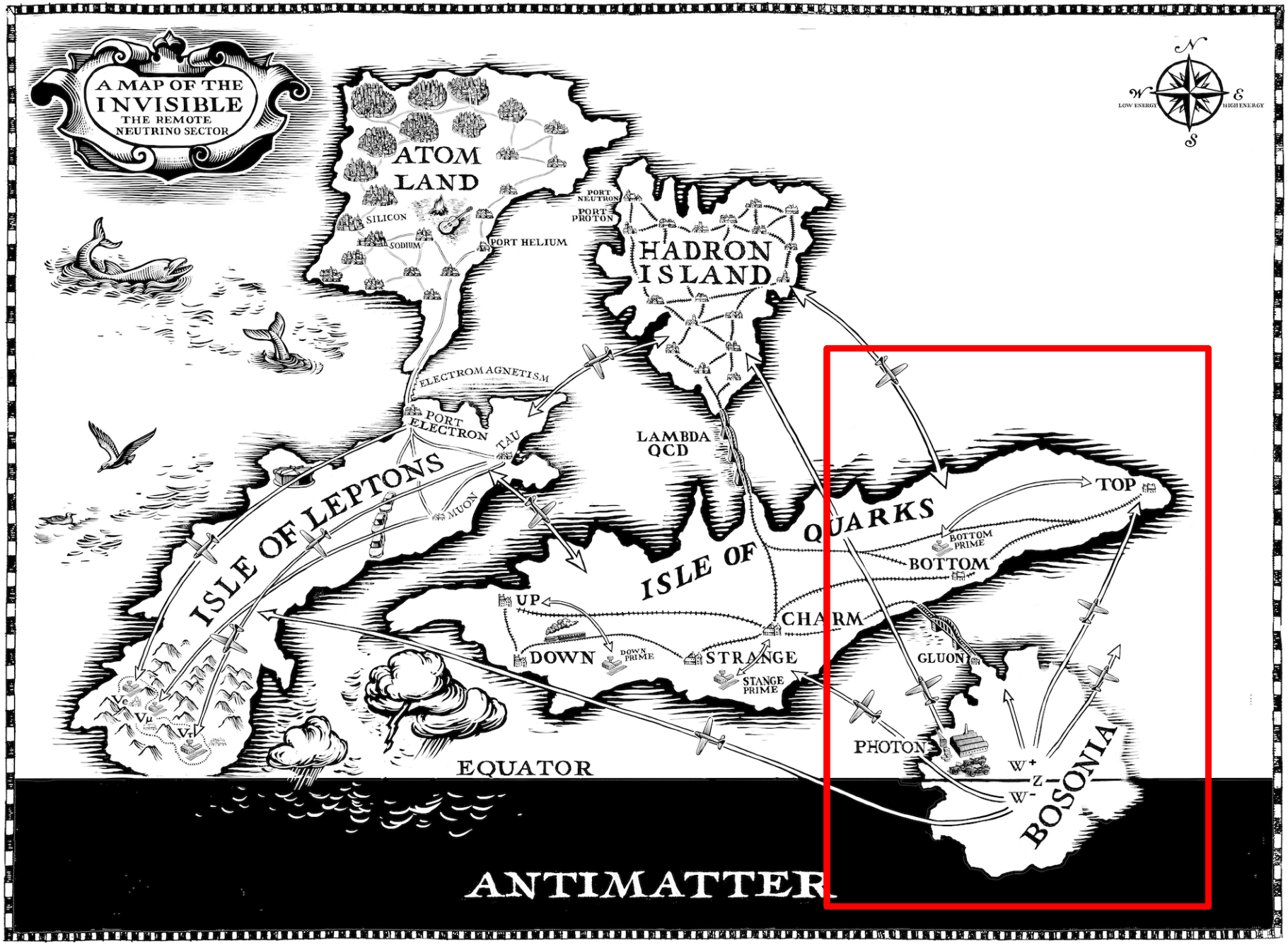
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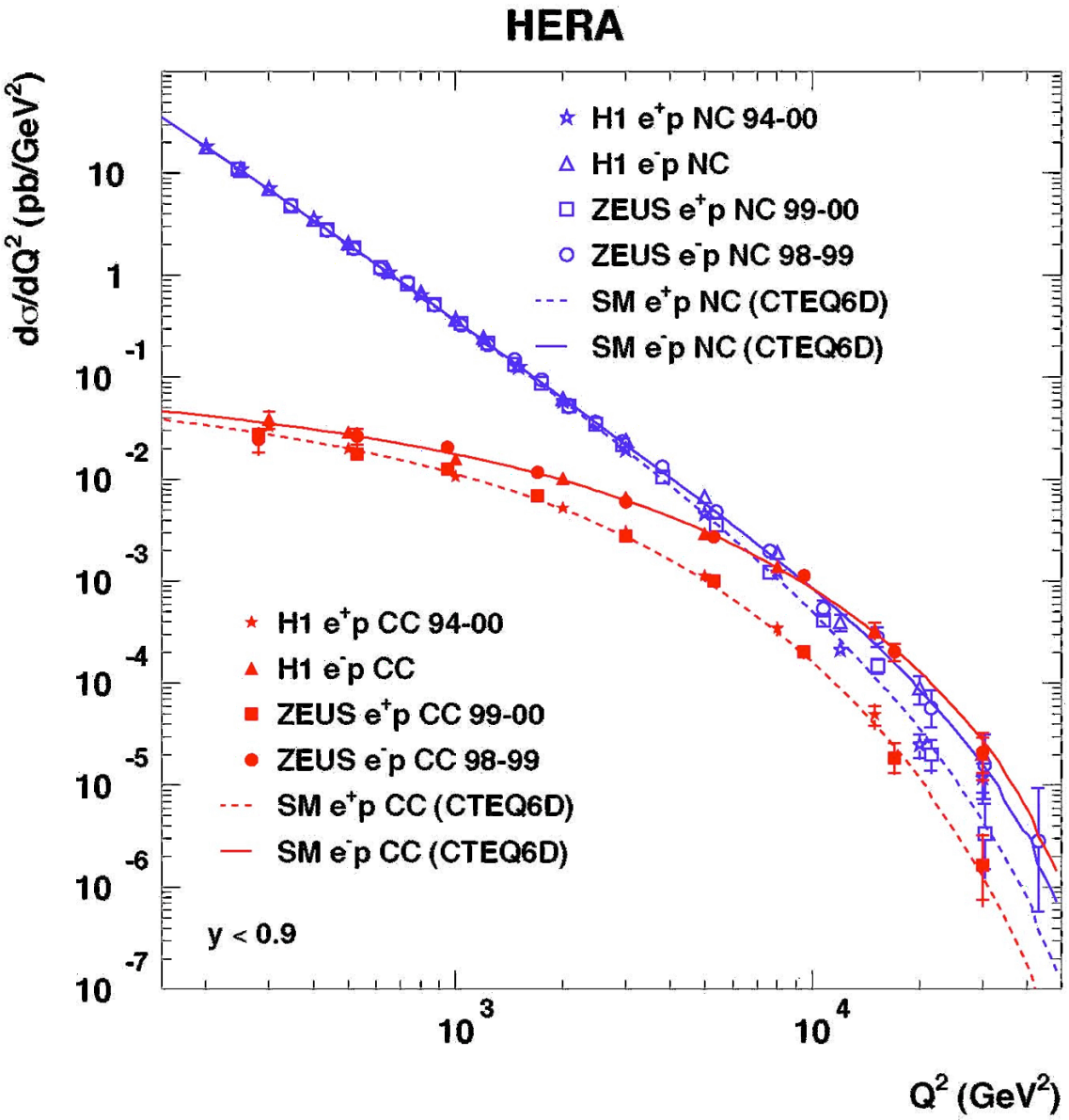
HERA
$d\sigma/dQ^2$ (pb/GeV^2)
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ZEUS e^+p NC 99-00
ZEUS e^-p NC 98-99
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SM e^-p NC (CTEQ6D)
H1 e^+p CC 94-00
H1 e^-p CC
ZEUS e^+p CC 99-00
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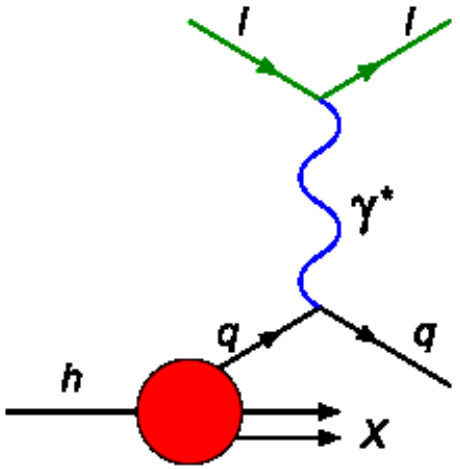
y < 0.9
Q^2 (GeV^2)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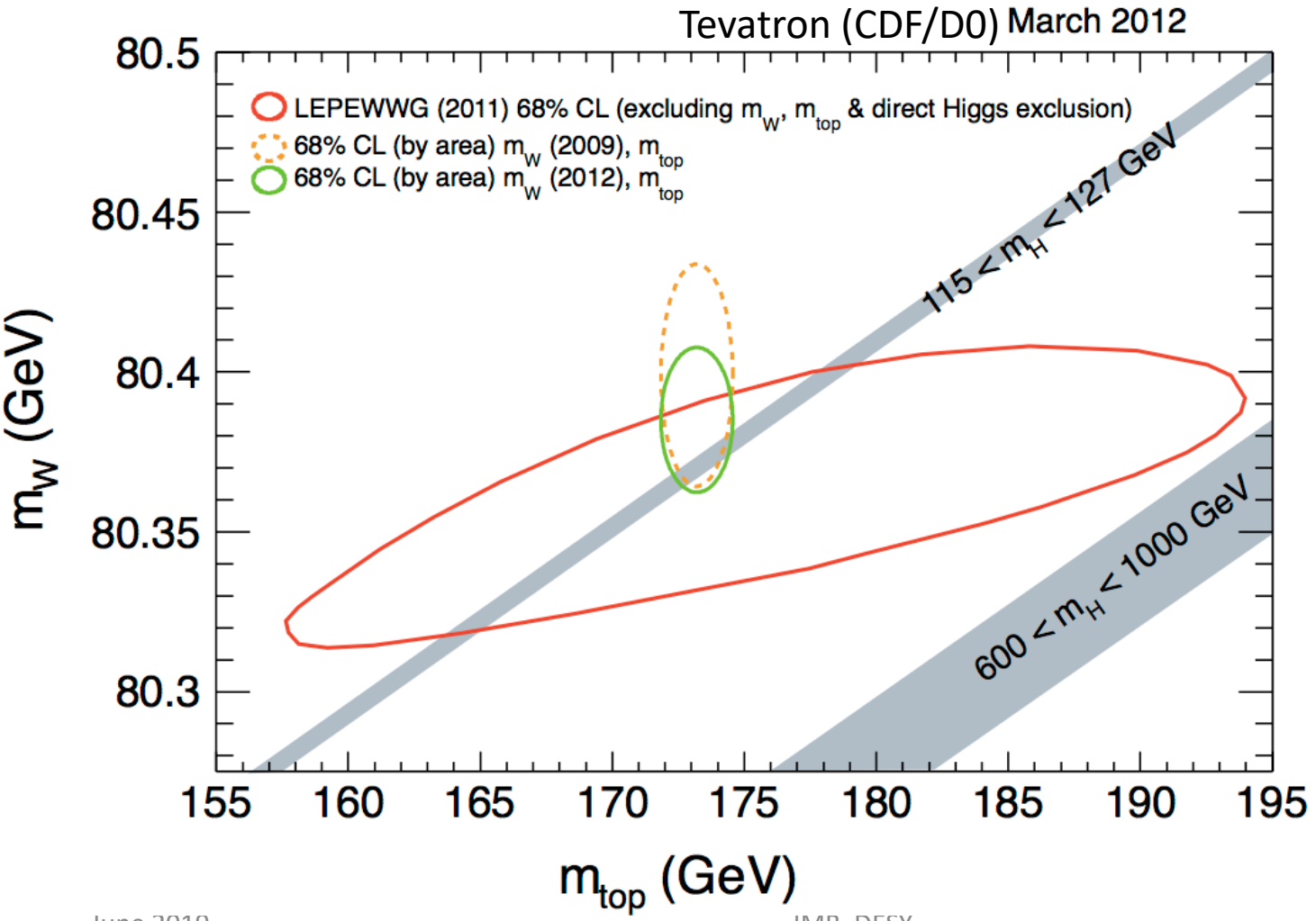
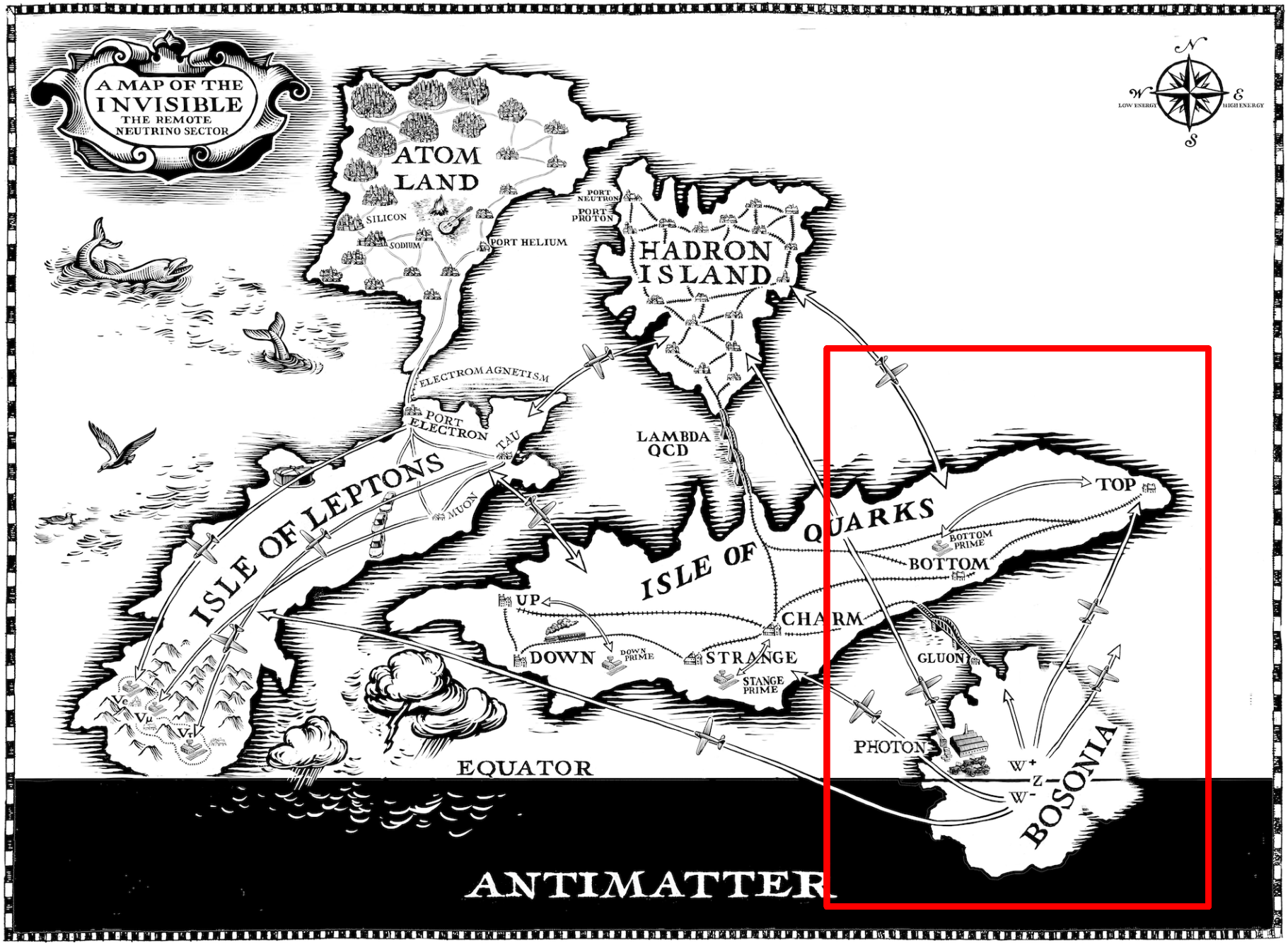
Electroweak symmetry breaking

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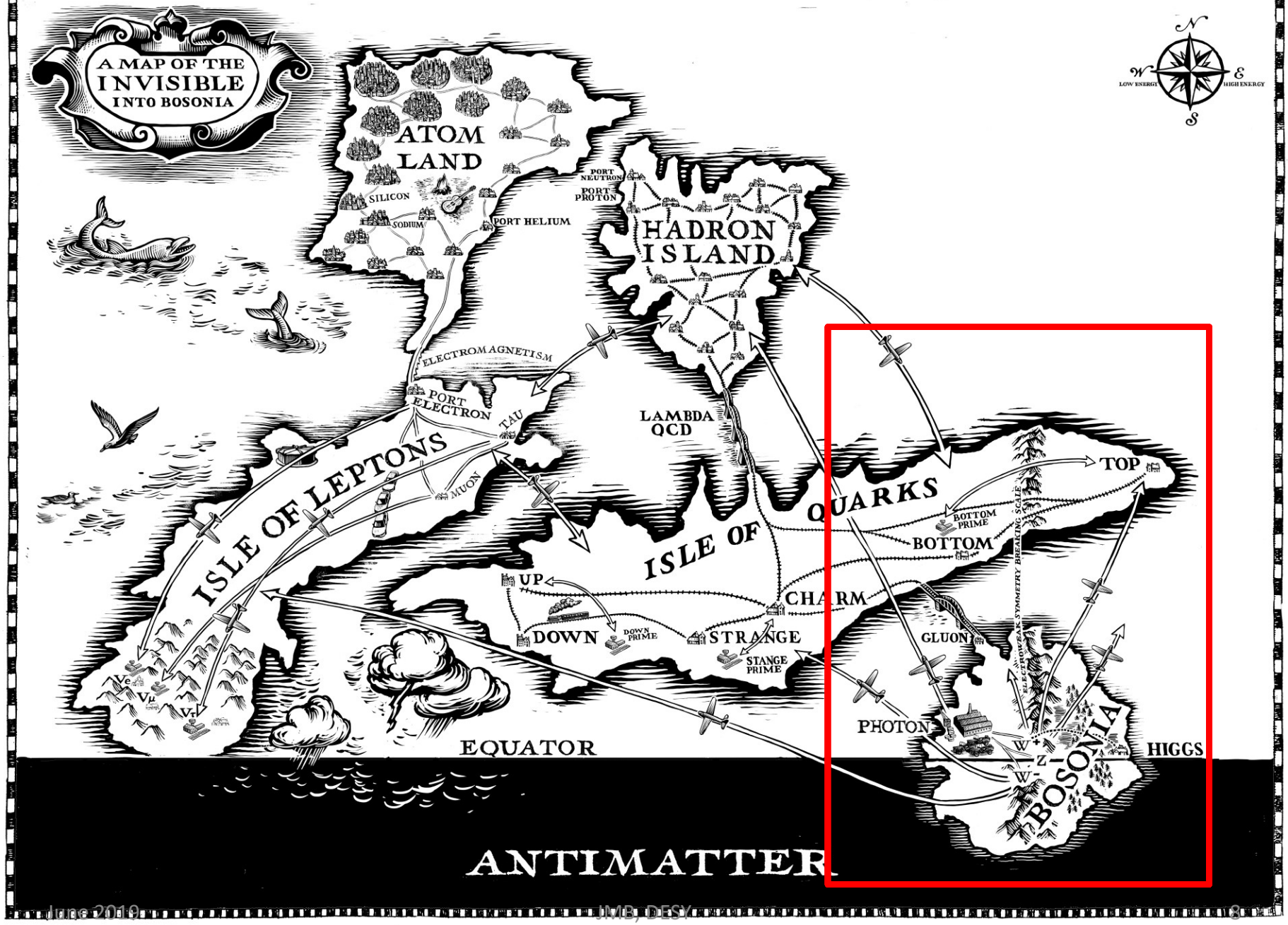
A MAP OF THE INVISIBLE INTO BOSONIA
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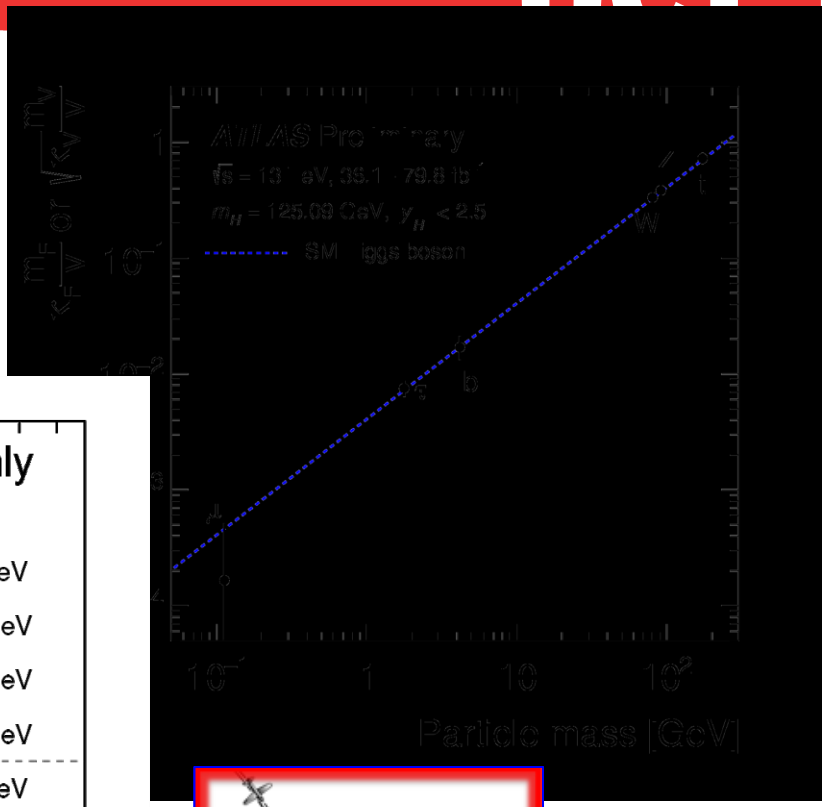
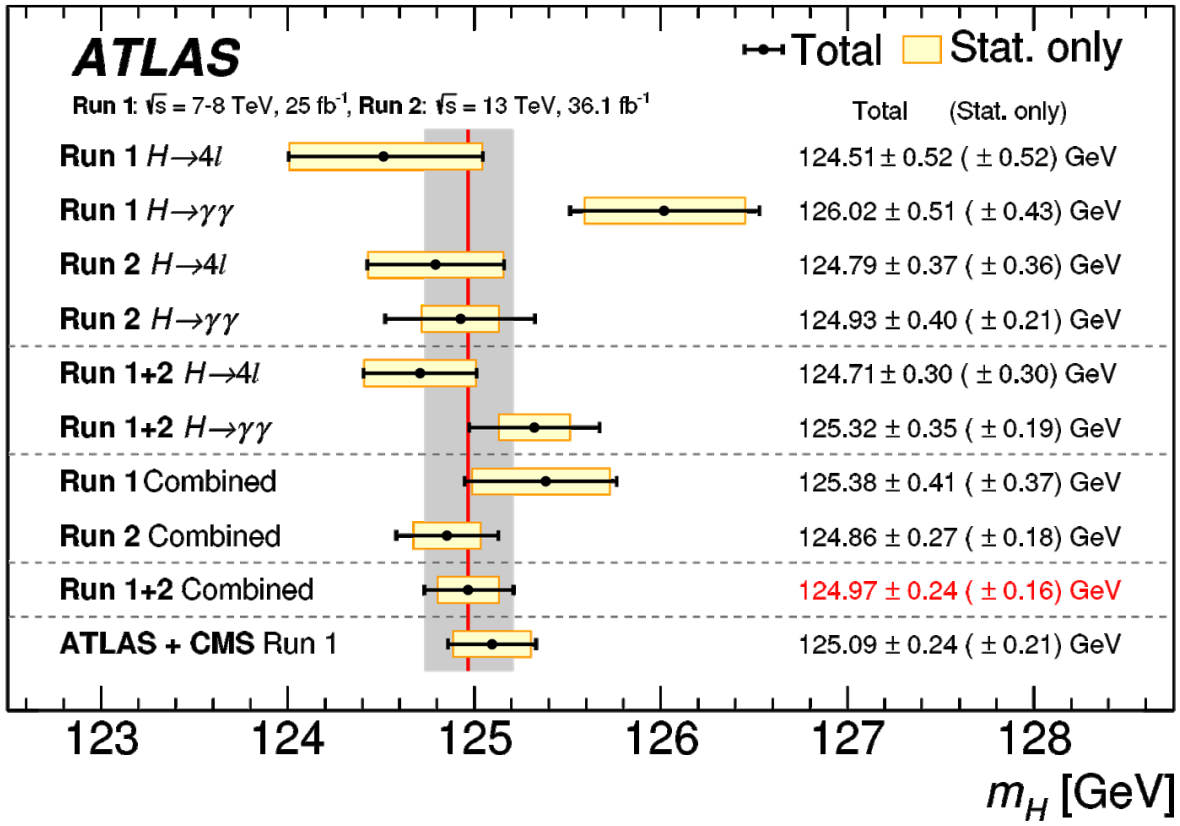
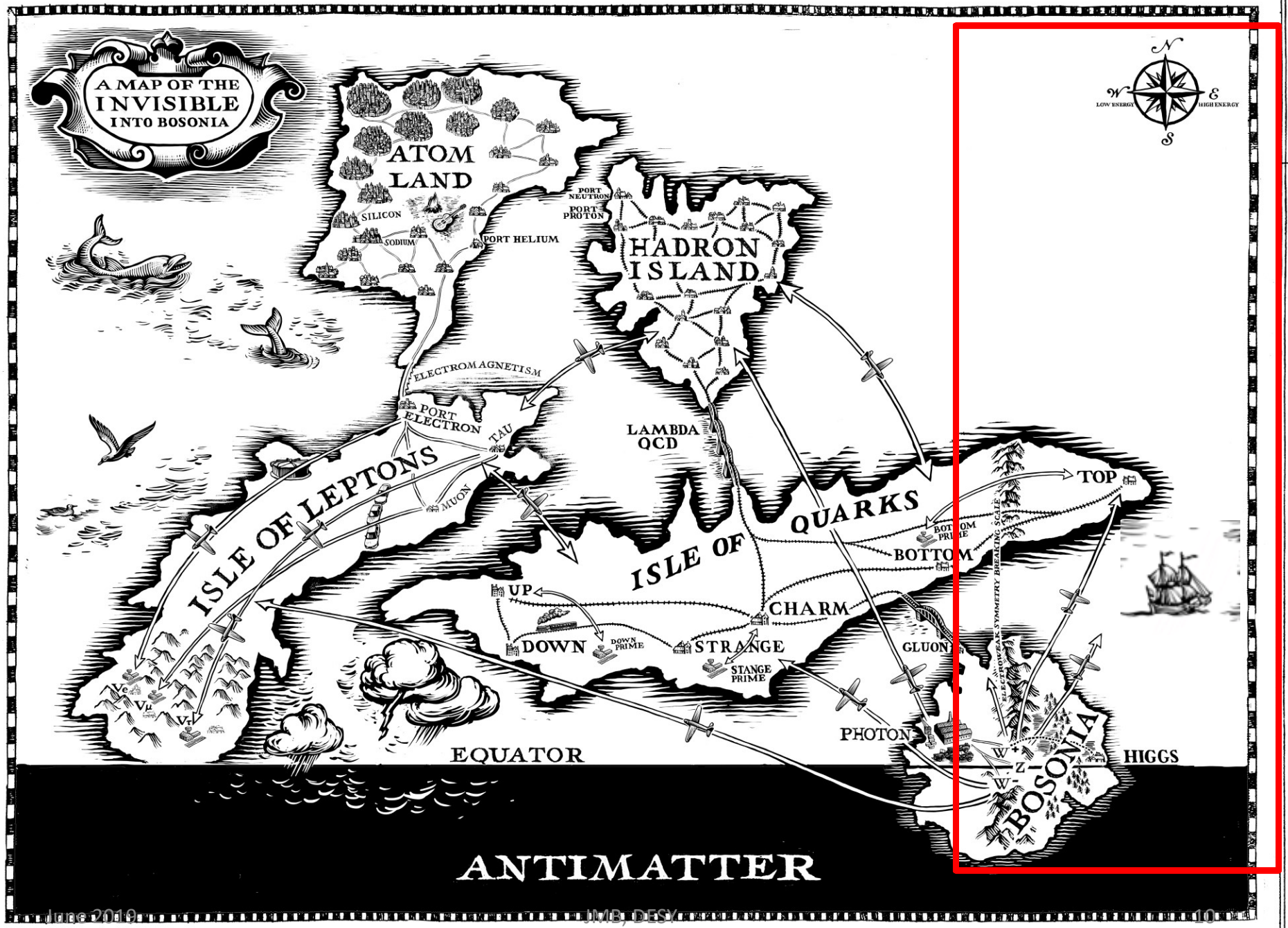
Precision Higgs



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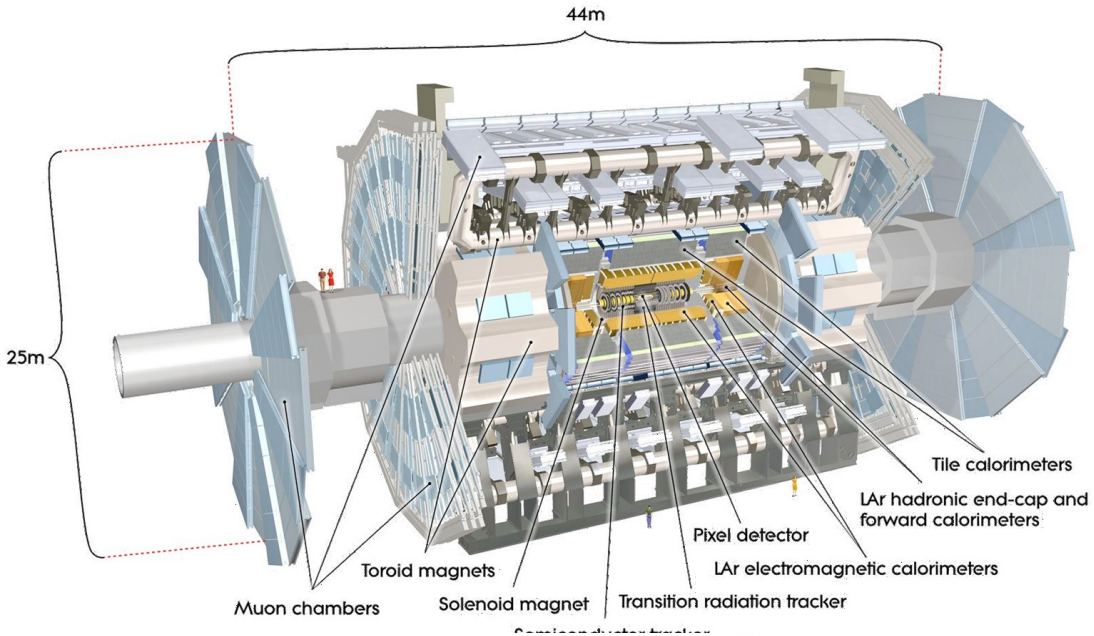
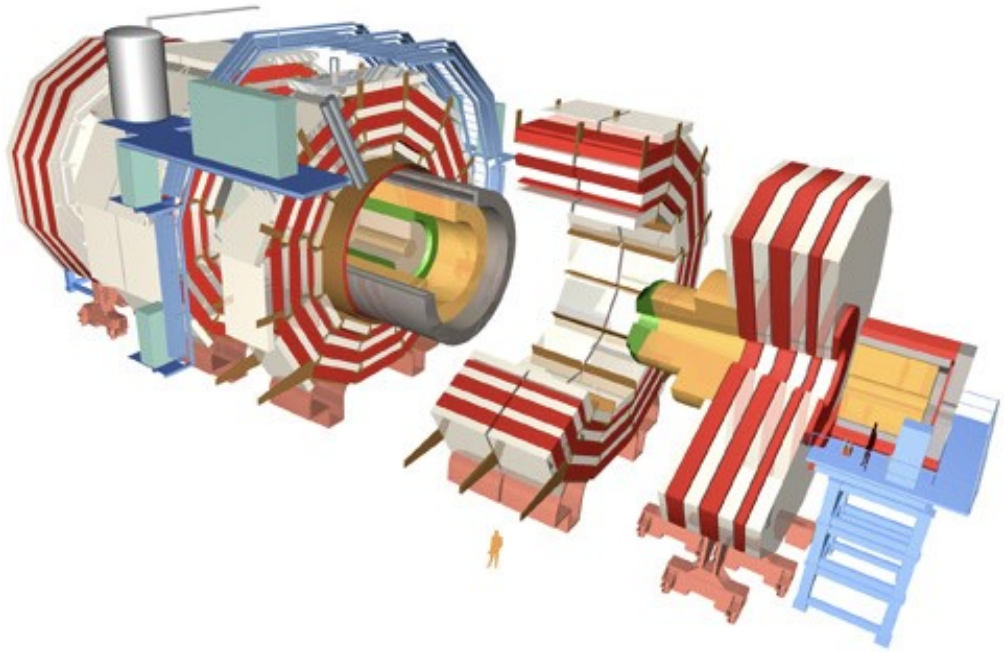
LHC 27 km


TOP
BOSONIA
HIGGS

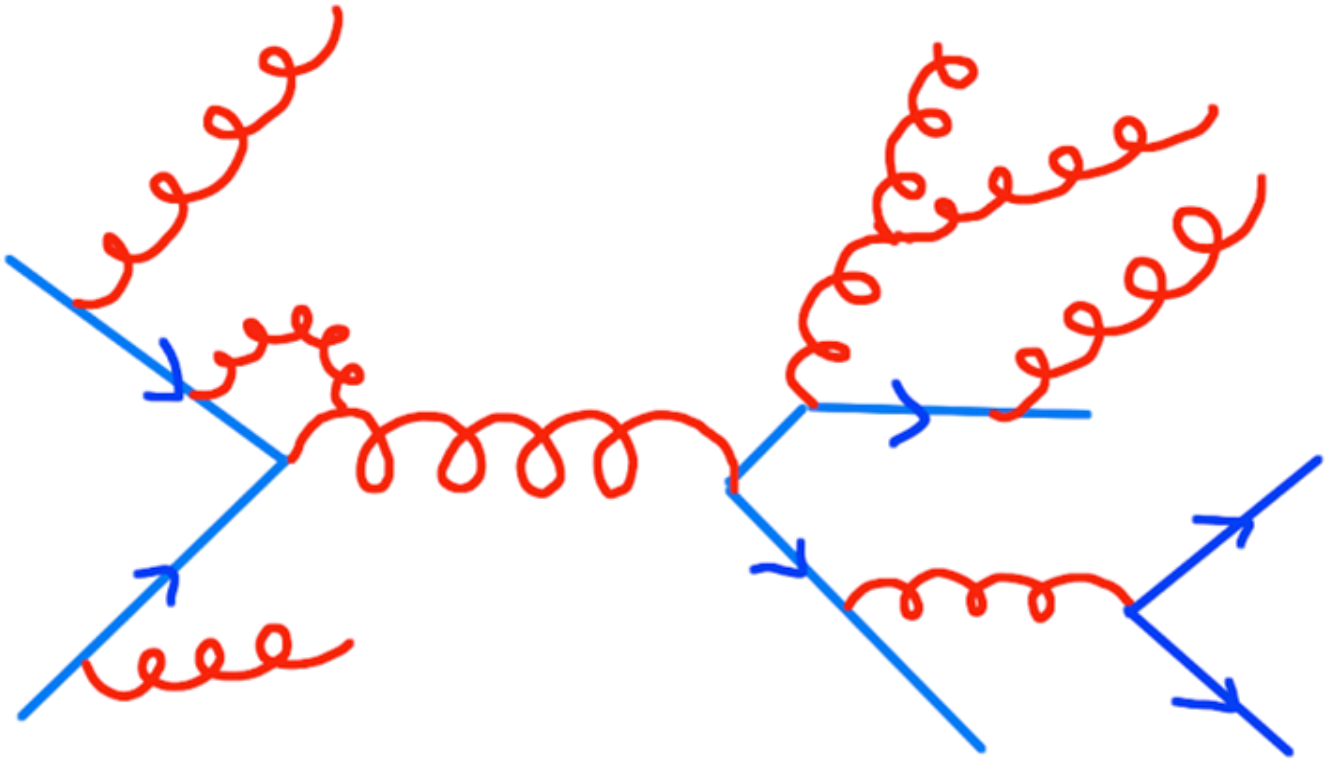

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker




TOP
BOSONIA
HIGGS

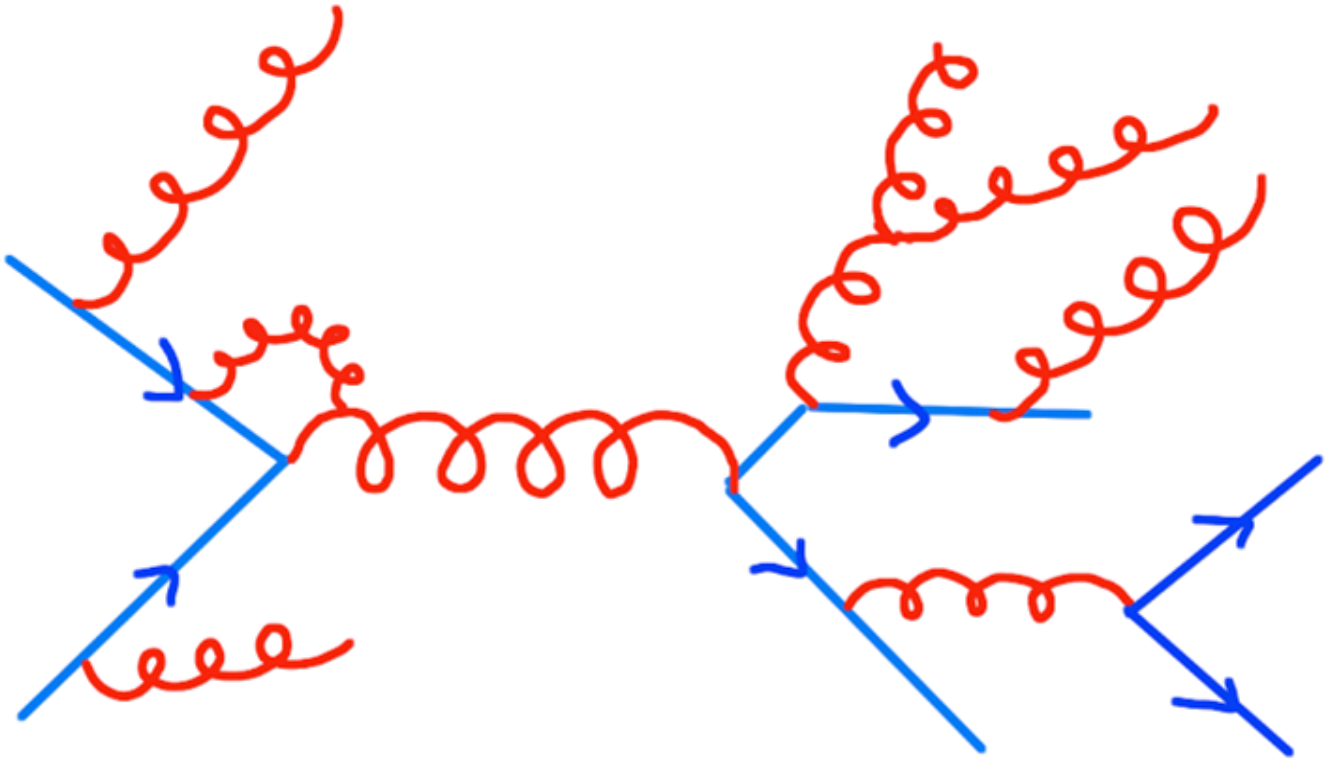
To the TeV scale and beyond…

- Precision theory, exclusive calculations, fixed orders & resummed & matched



To the TeV scale and beyond…

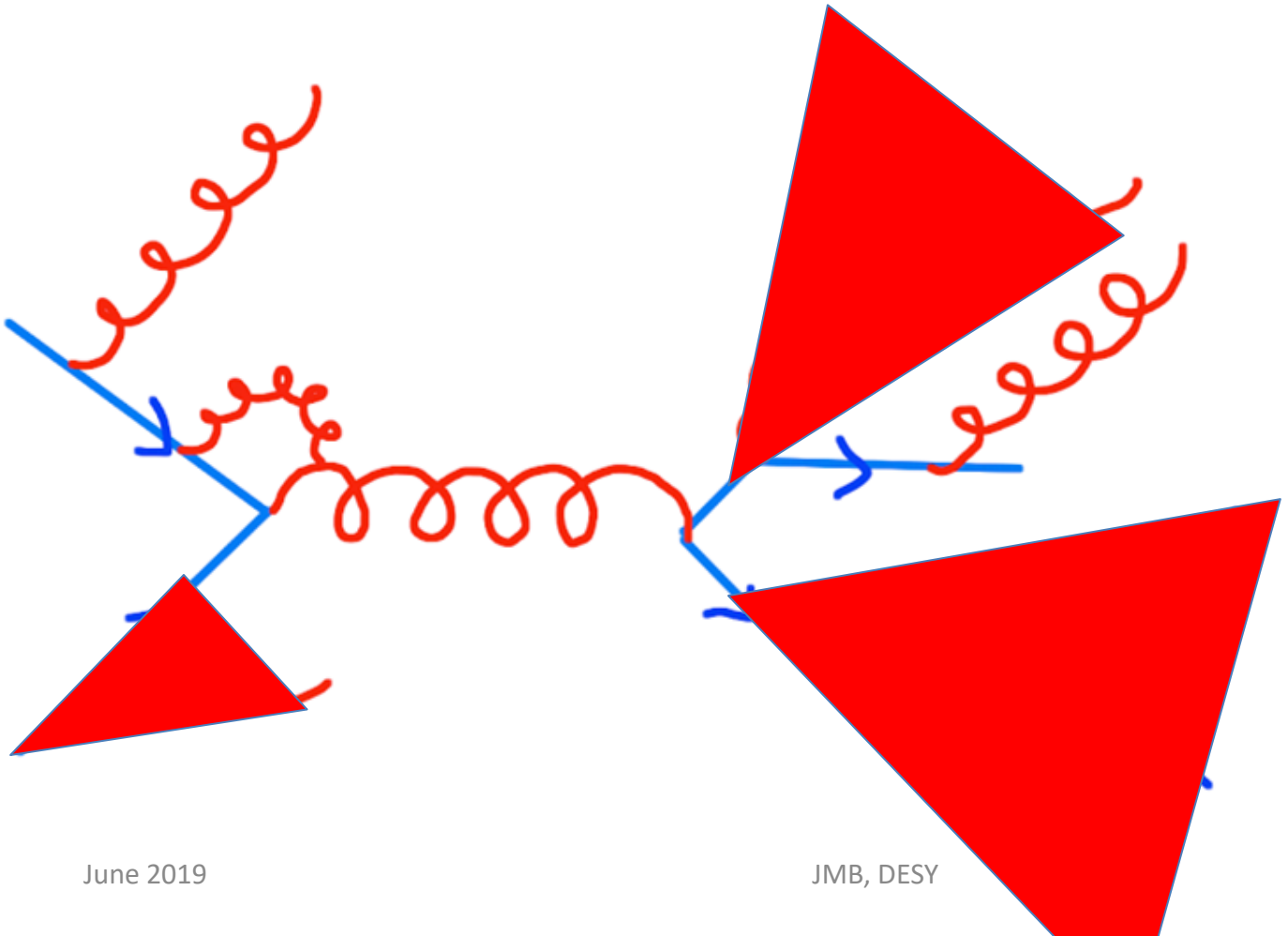
- Precision theory, exclusive calculations, fixed orders & resummed & matched



Vertices → α_s, O(0.1)

To the TeV scale and beyond…

- Precision theory, exclusive calculations, fixed orders & resummed & matched

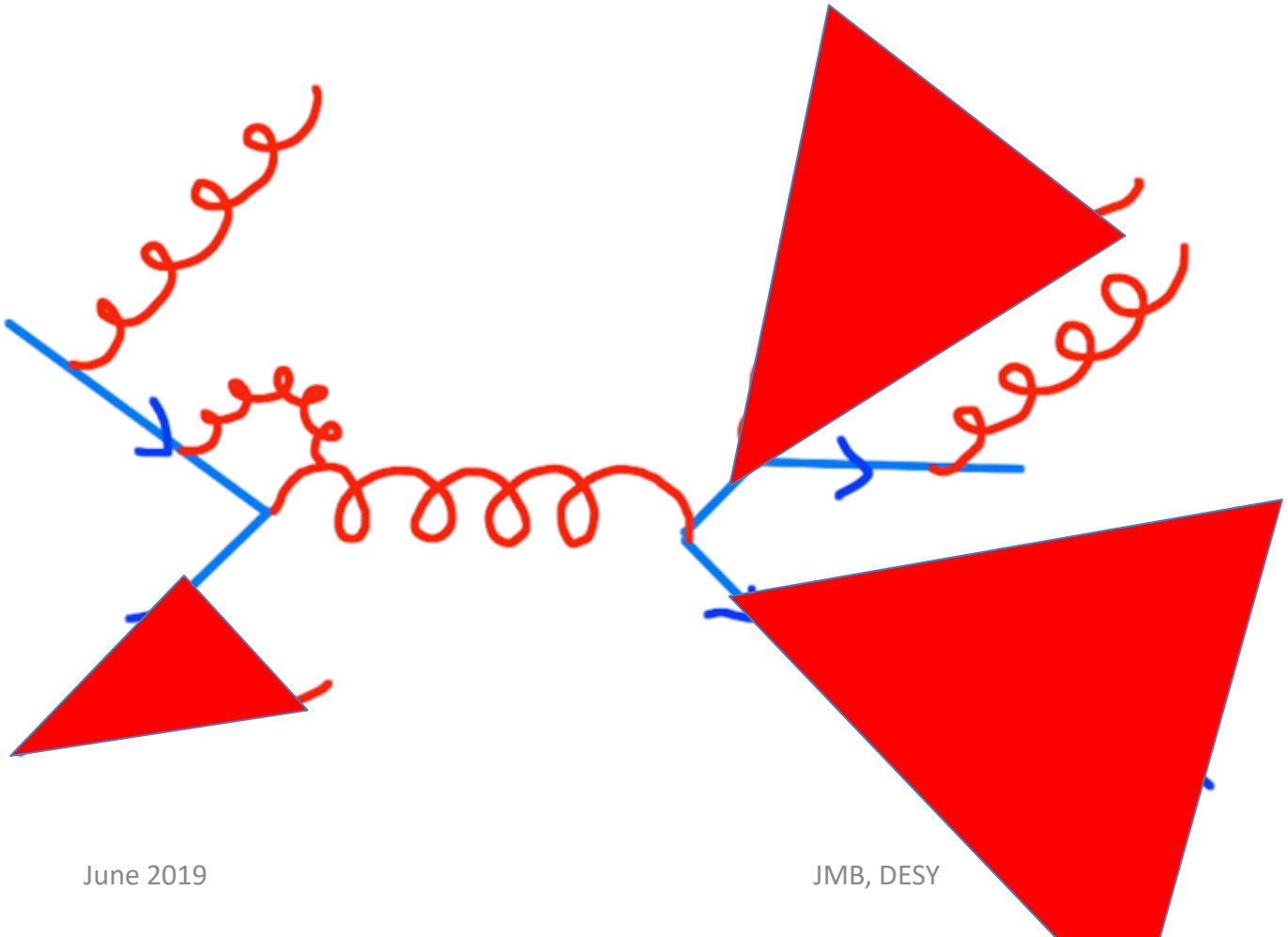


Vertices → α_s, O(0.1)

Soft or collinear kinematics → *log*(scales) O(10)

To the TeV scale and beyond…

- Precision theory, exclusive calculations, fixed orders & resummed & matched



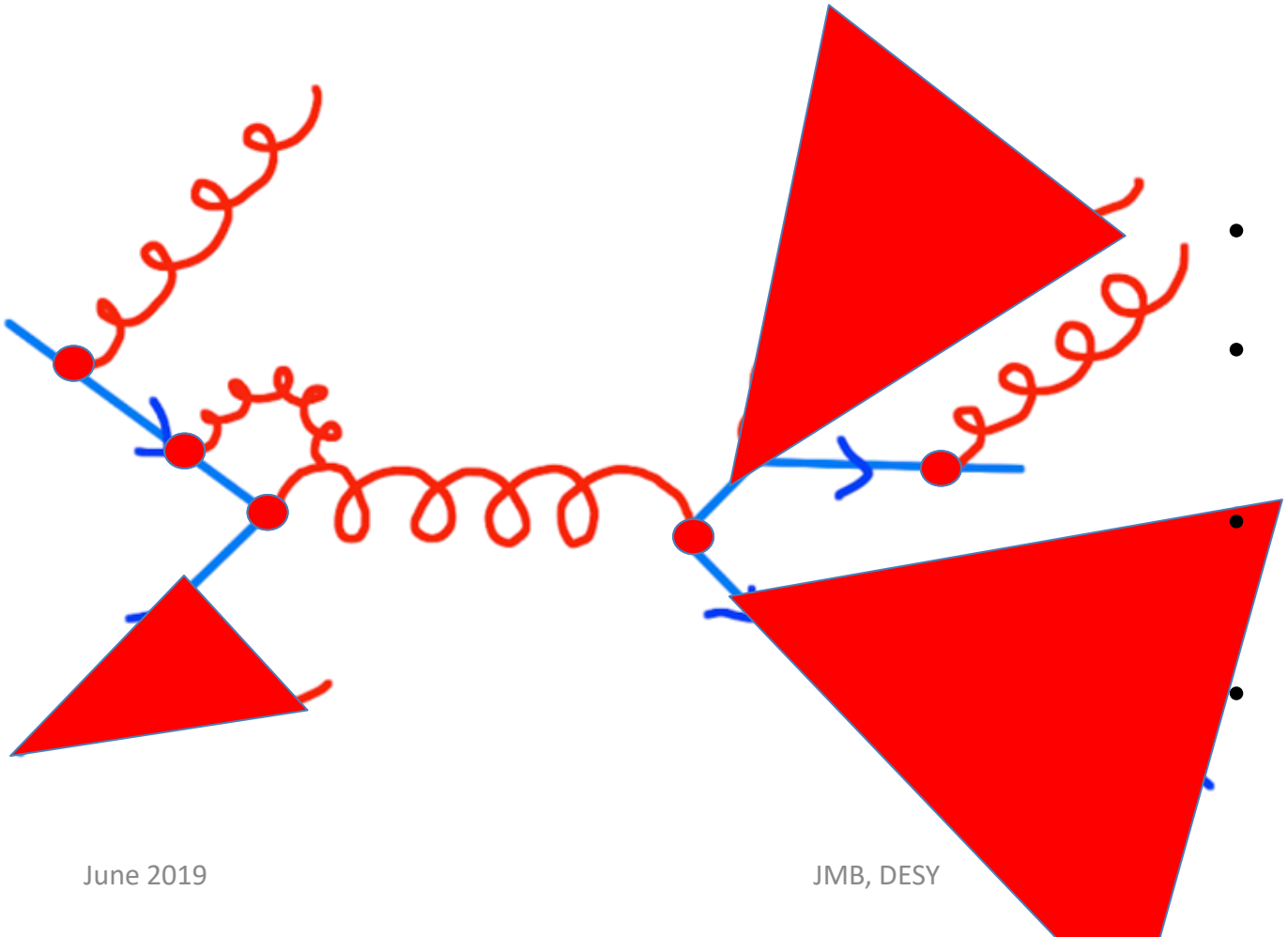
Vertices → α_s, O(0.1)

Soft or collinear kinematics → *log*(scales) O(10)

α_s*log* terms O(1), must be resummed (exponentiated)

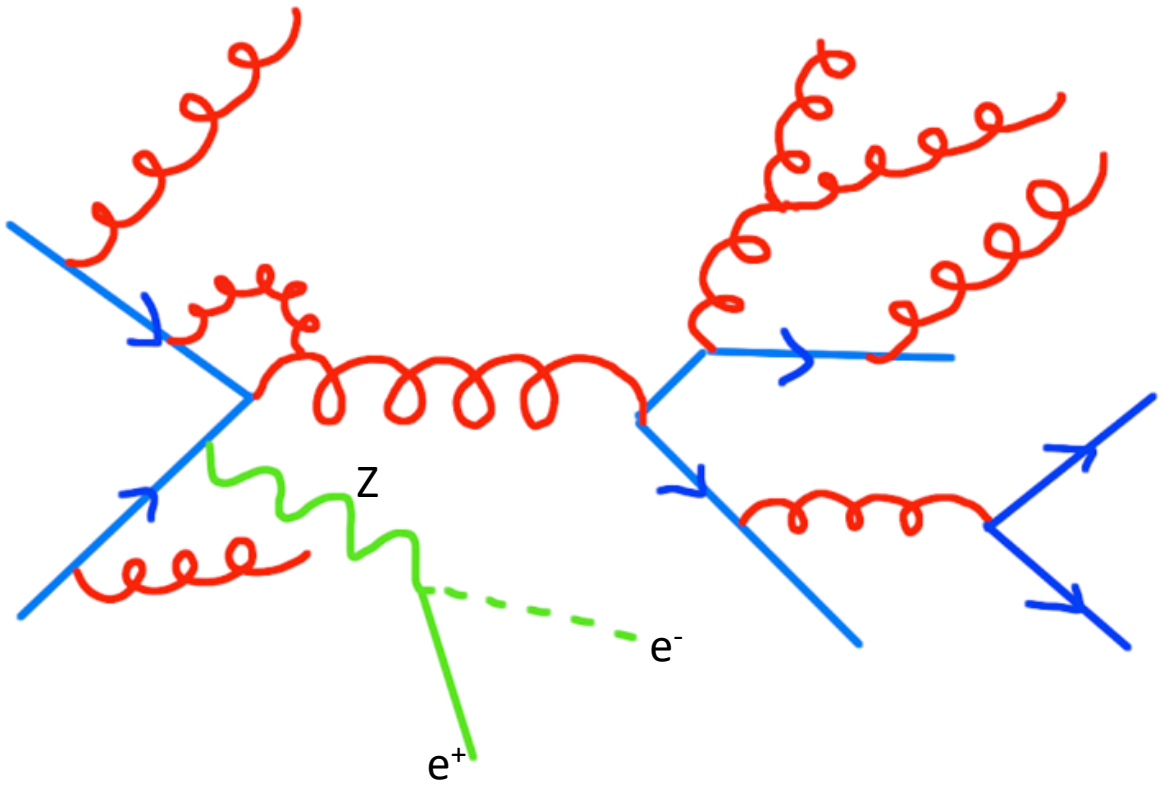
To the TeV scale and beyond…

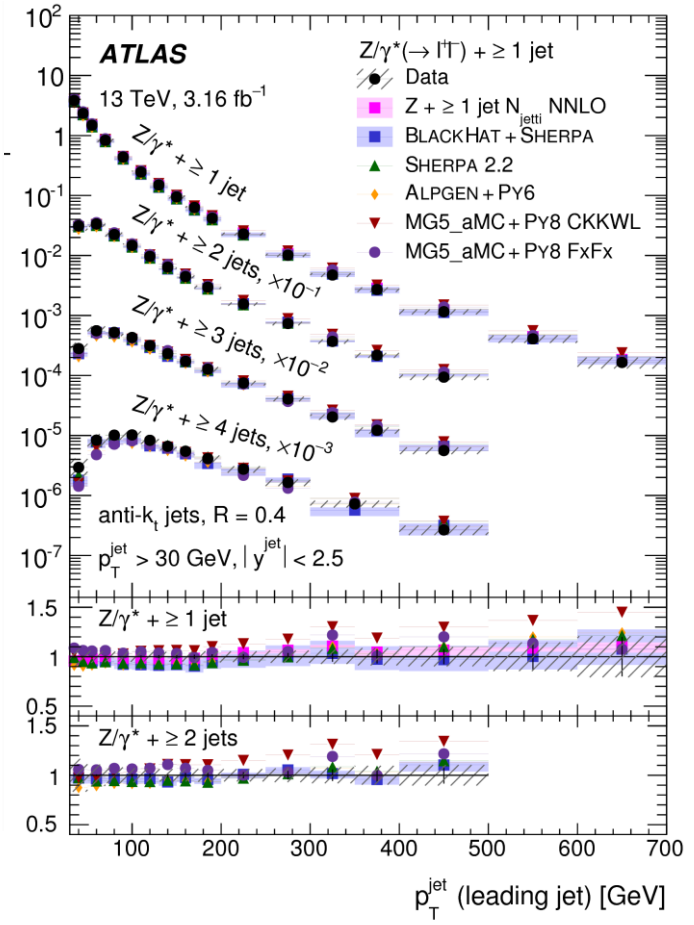
- Precision theory, exclusive calculations, fixed orders & resummed & matched



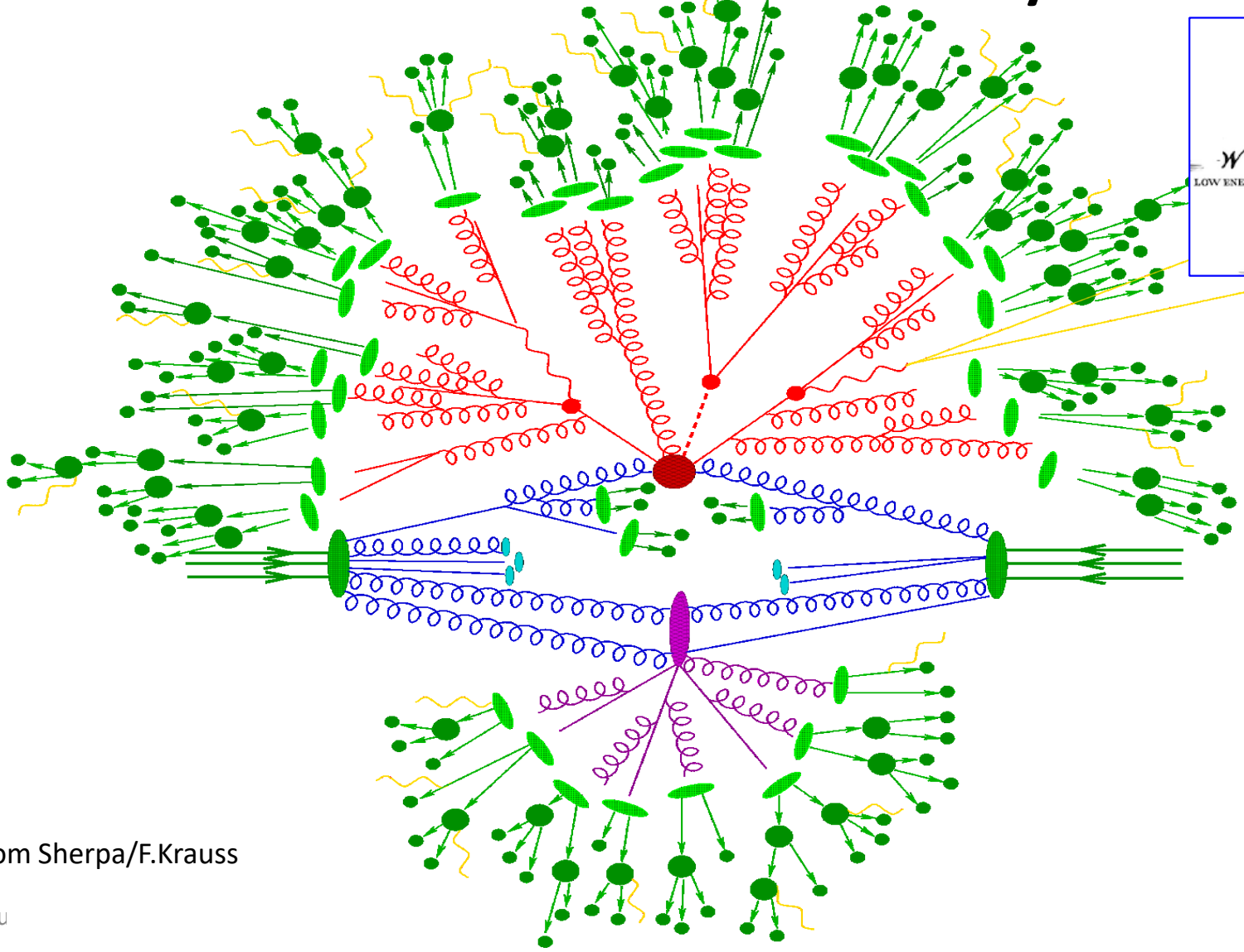
- Vertices → α_s, O(0.1)
- Soft or collinear kinematics → *log*(scales) O(10)
- α_s*log* terms O(1), must be resummed (exponentiated)
- Still need fixed-order α_s outside these enhanced regions

To the TeV scale and beyond…



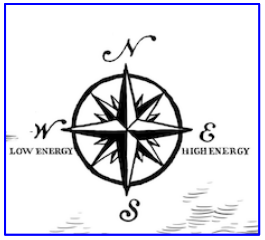


To the TeV scale and beyond…

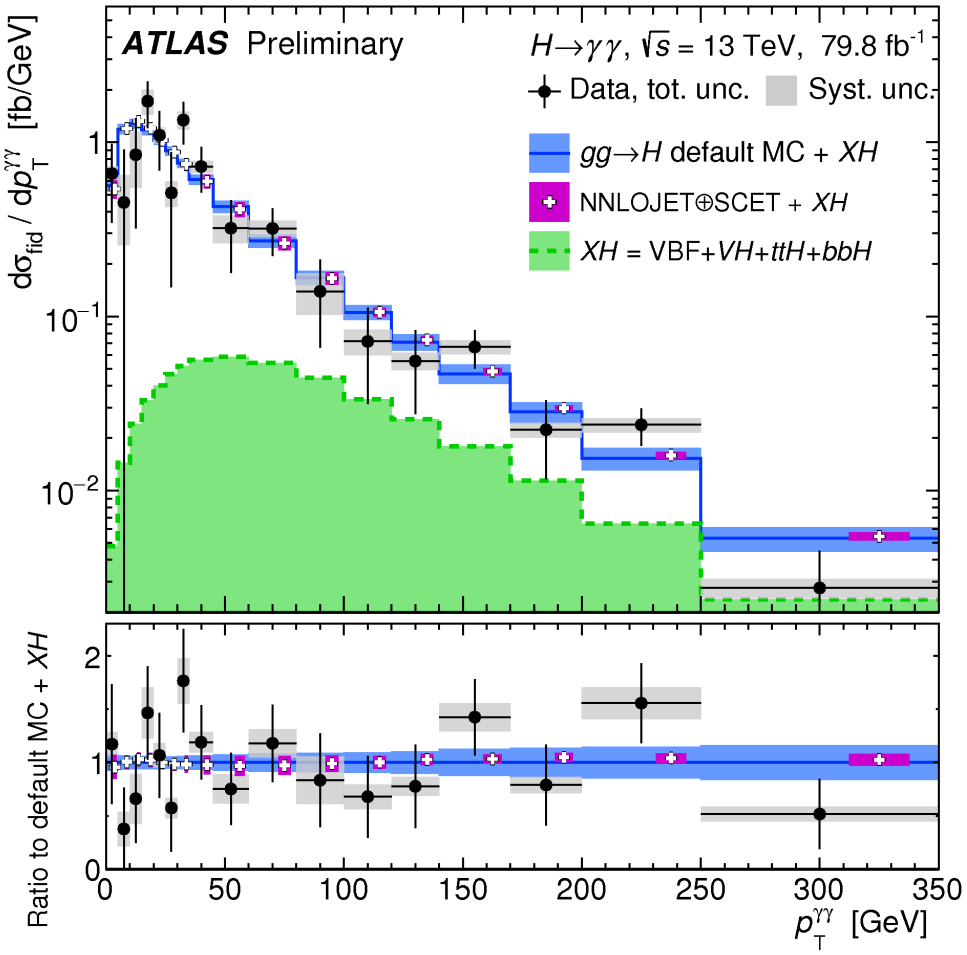


Pic from Sherpa/F.Krauss

To the TeV scale and beyond…

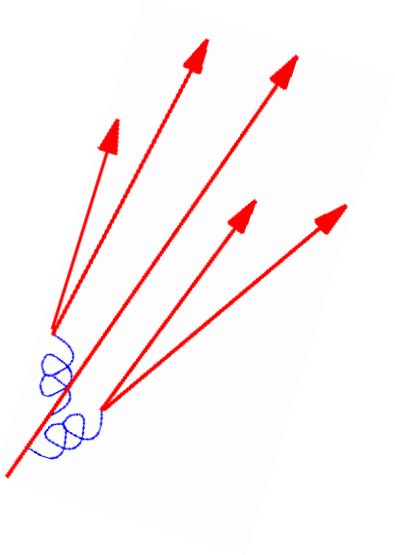


- Into the unknown…
  - Well-defined, precise measurements and calculations.
  - High multiplicities
  - High boosts, even for electroweak-scale objects



To the TeV scale and beyond…

- New feature… the boost
- Perturbative QCD between about 1 GeV (hadronisation) and LHC kinematic limit (highest p_T jet formation)

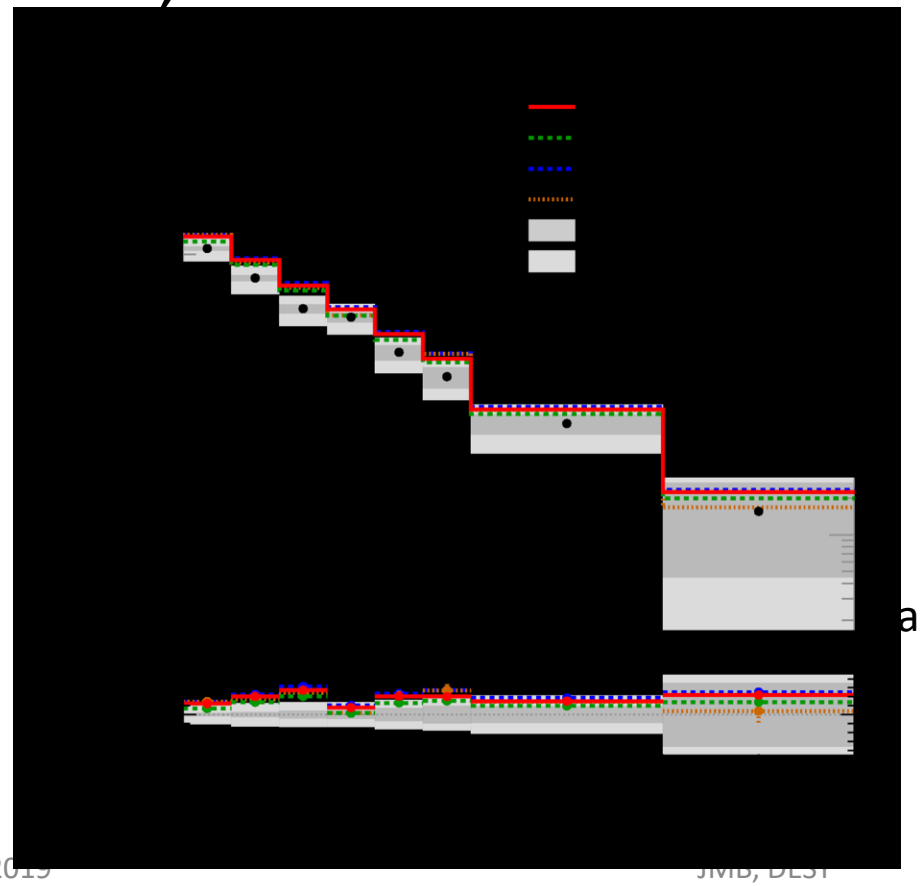


To the TeV scale and beyond…

- New feature… the boost
- Perturbative QCD between about 1 GeV (hadronisation) and LHC kinematic limit (highest p_T jet formation)
- Electroweak symmetry breaking scale lies between these scales →
- Electroweak physics “inside” jets (H,W,Z,t – collimated decay products).
- Need to account for this in measurments and searches

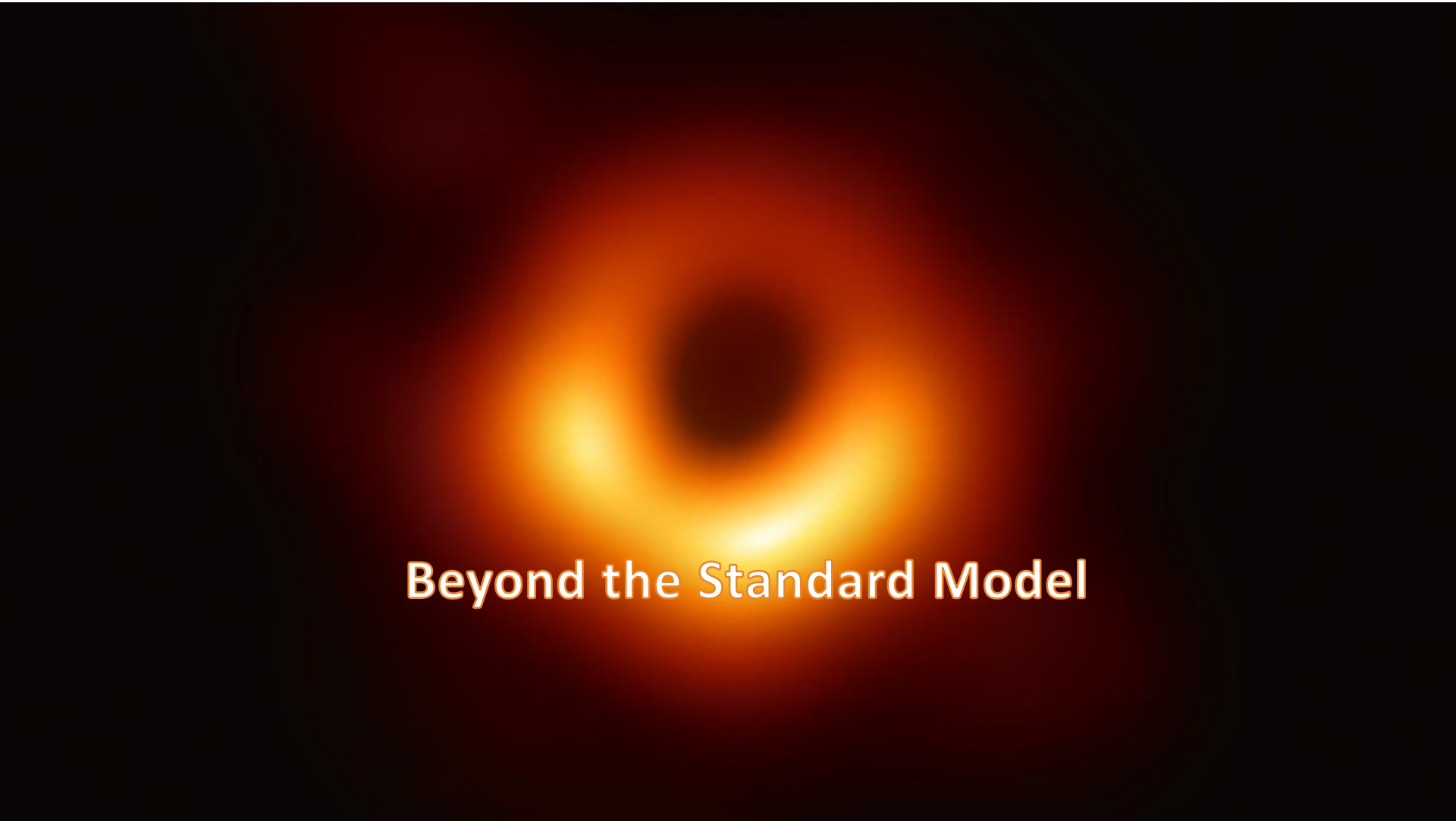
To the TeV scale and beyond…

- Example: Boosted top differential cross section, built from final-state particles



arXiv:1801.02052

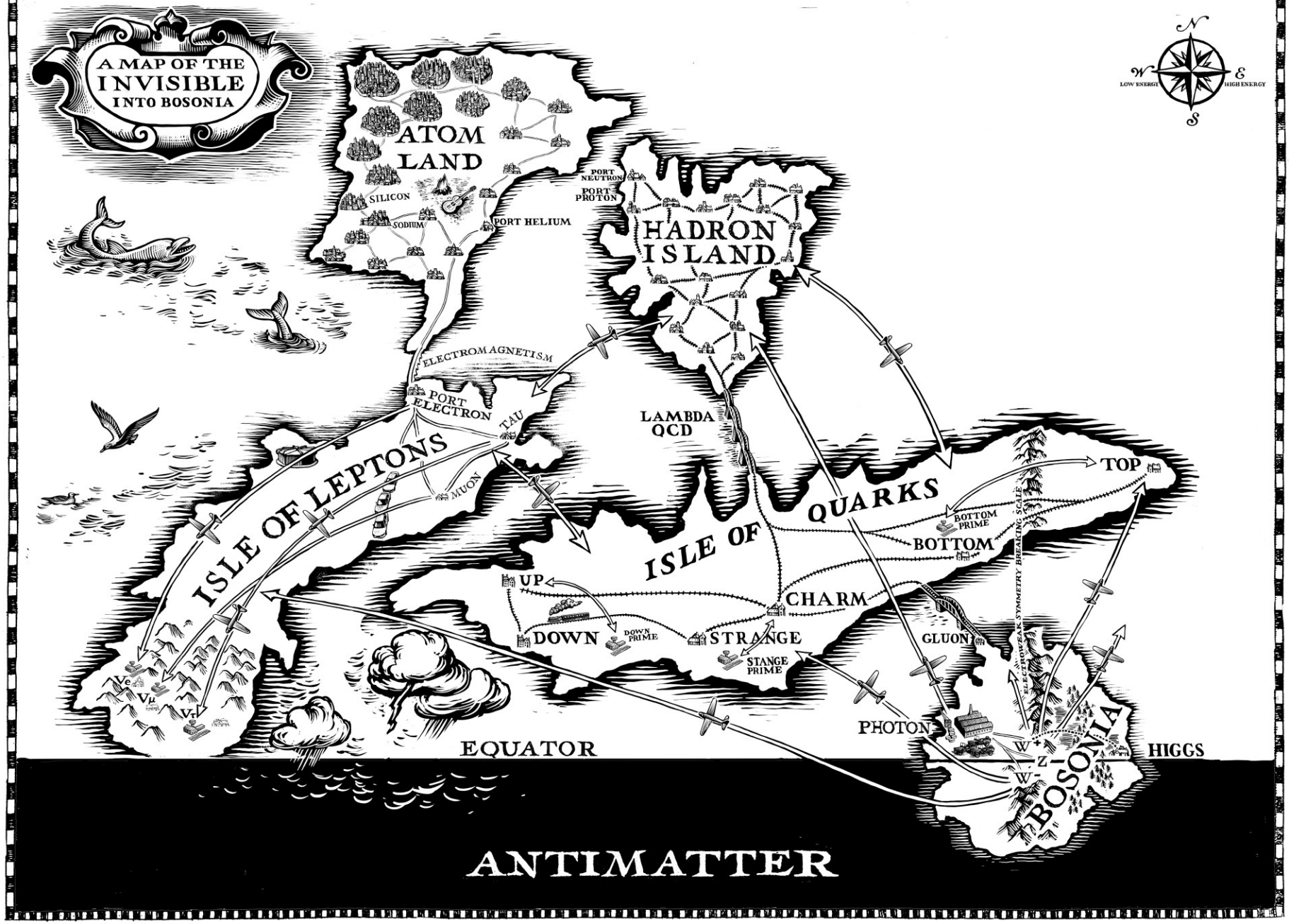
Before we get too pleased with ourselves…



And before we get too pleased with ourselves…

Beyond the Standard Model

Beyond the Standard Model *and* General Relativity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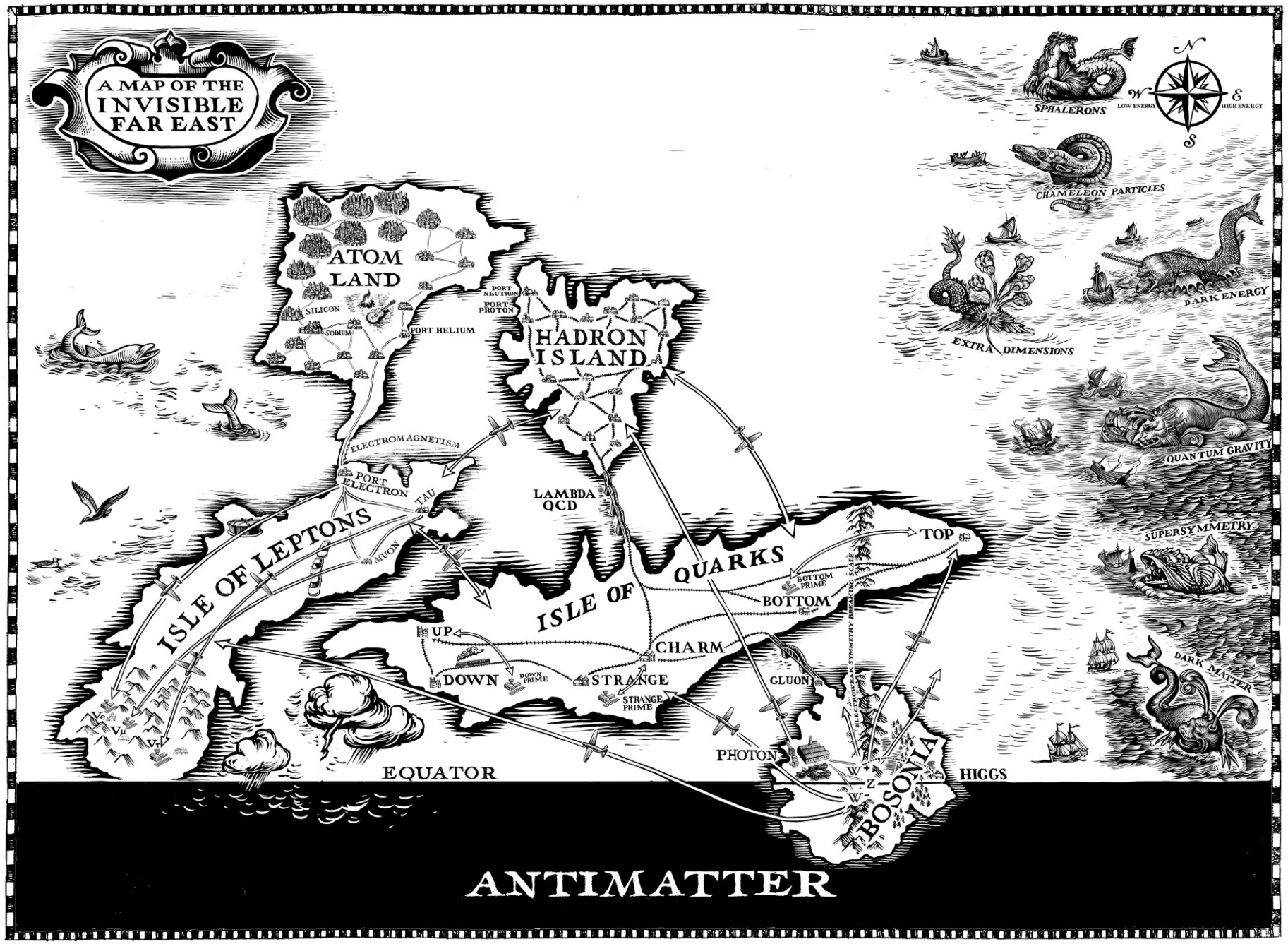
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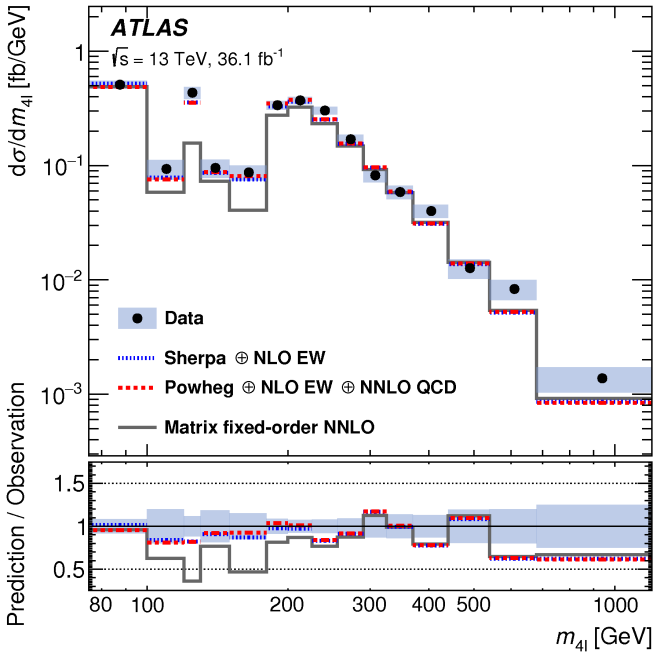
SUPERSYMMETRY
DARK MATTER
ANTIMATTER

Dual/overlapping role of the LHC

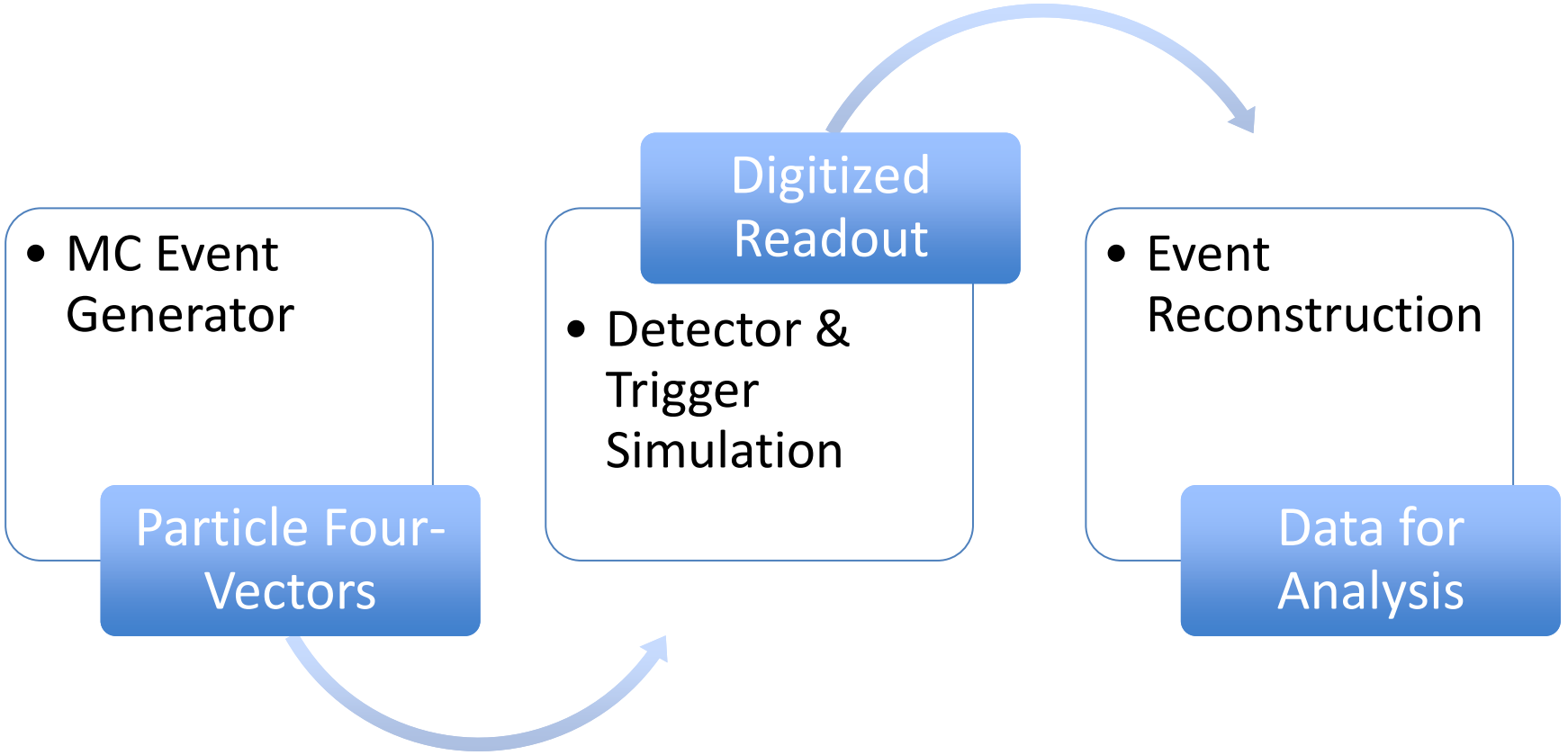
- Searching for Physics Beyond the SM
  - Well motivated
- ~~Measure the Standard Model~~

arXiv:1902.05892

Measure what happens, and compare to the predictions of the Standard Model



Simulation and Experiment



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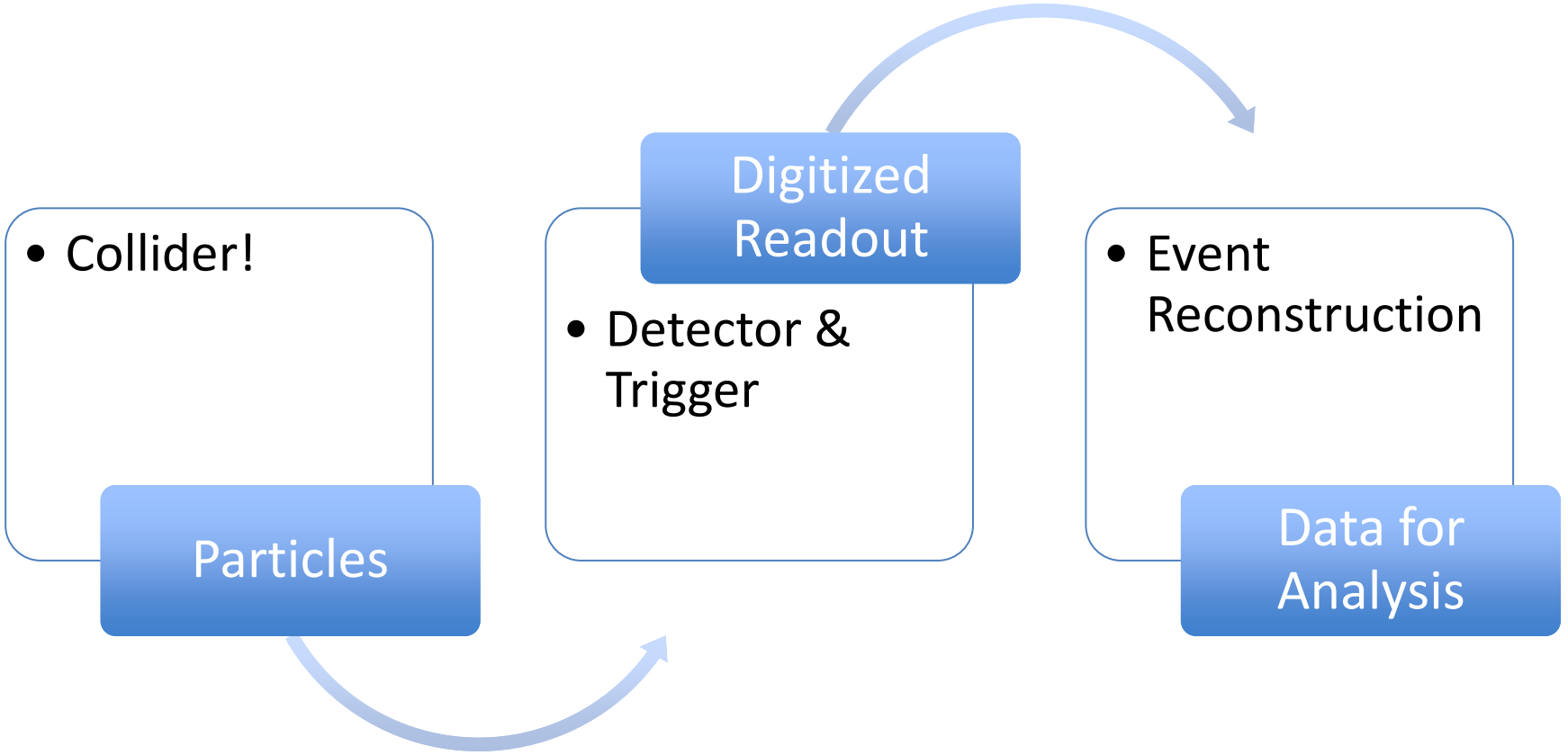

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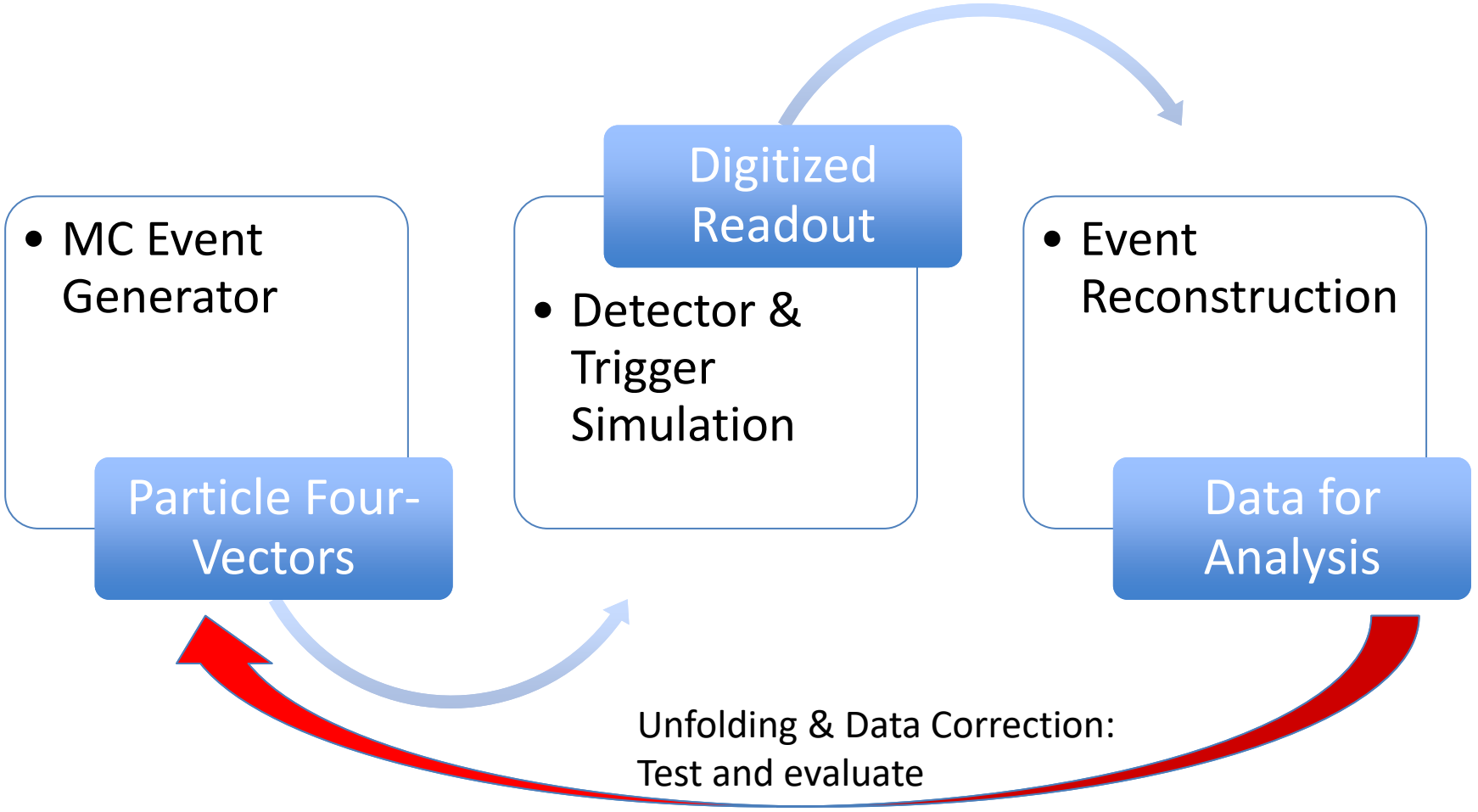

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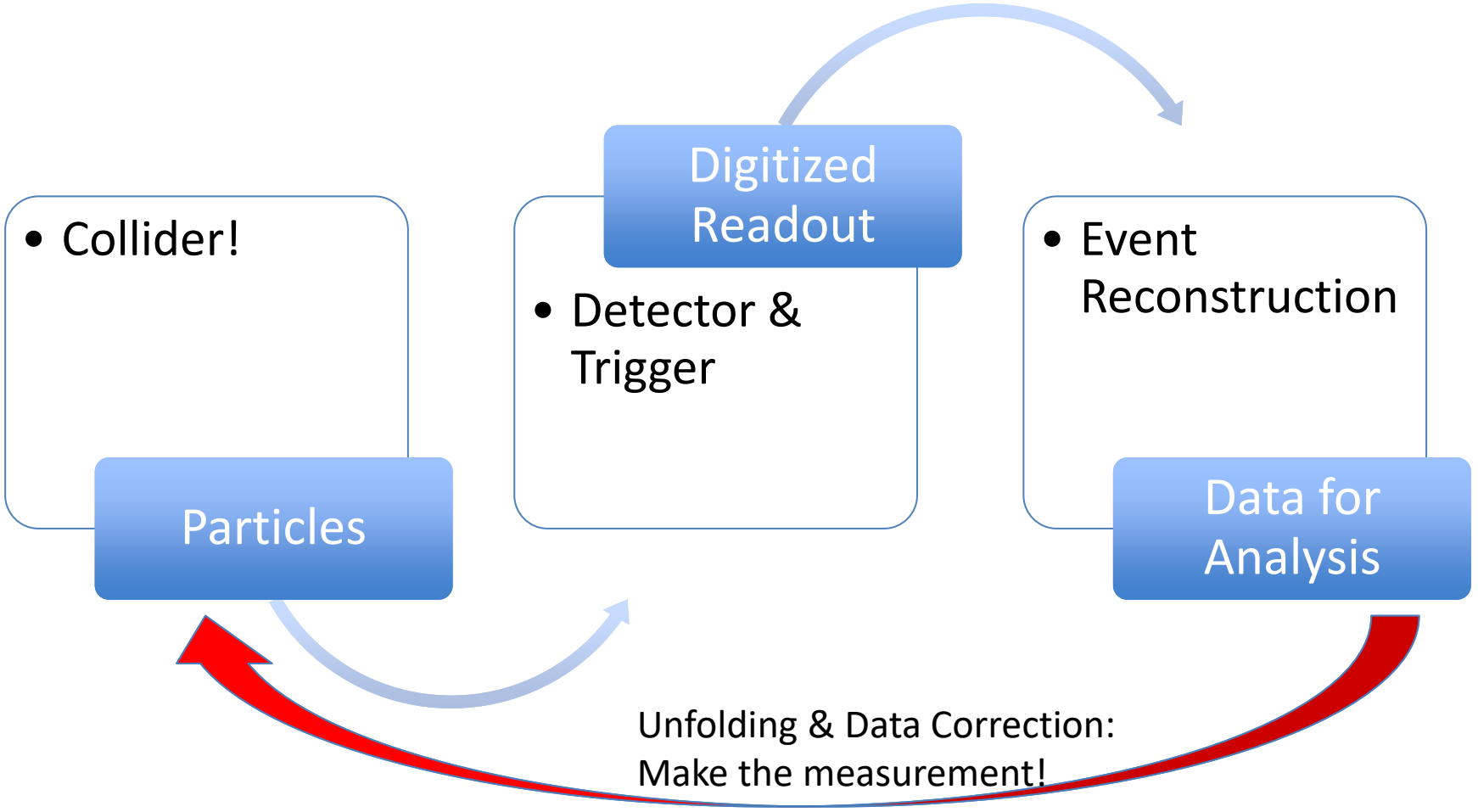
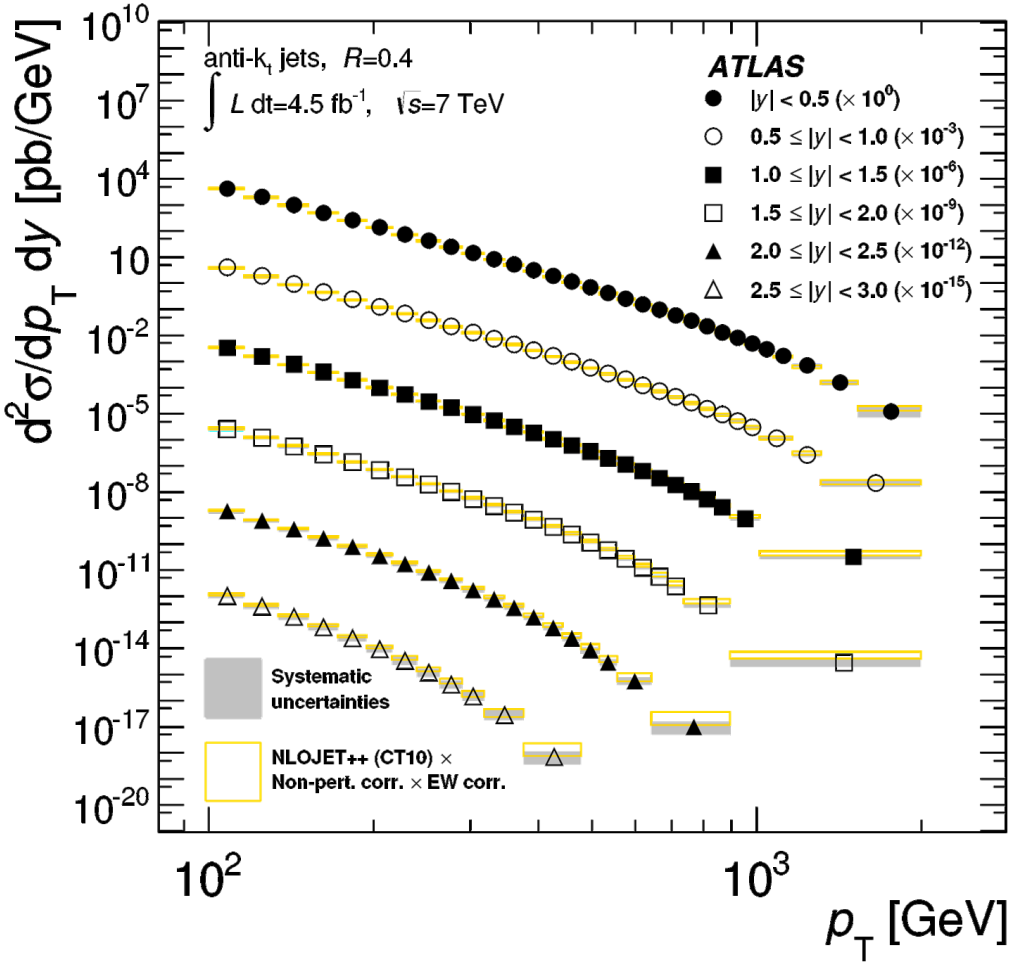


“Unfolding”

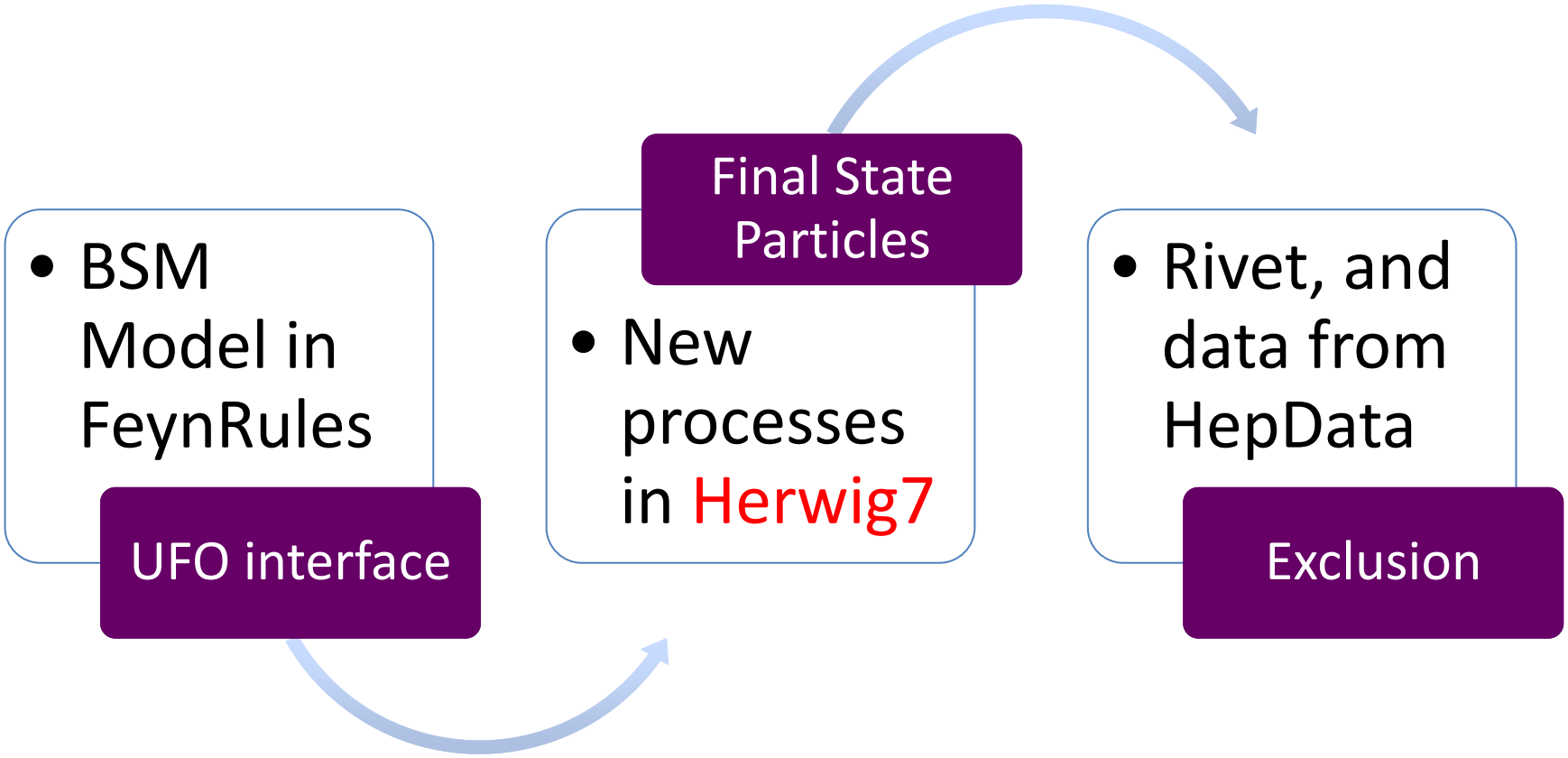
- If the cross section is well-defined, unfolding and its uncertainties can be well-defined
  - Fiducial region, matches the experimental acceptance well
  - “True” final-state objects
  - Can iteratively adapt to the unfolded distribution but eventually need to model all important variables reasonably well
- To compare to the measurement requires simulation of the full final state
  - Inclusive calculation is not enough on its own
  - MC generator are key tools
- In the end, we “count the particles”, removing the imperfections of the detector within some known uncertainty

Precision ‘Standard Model’ Measurements

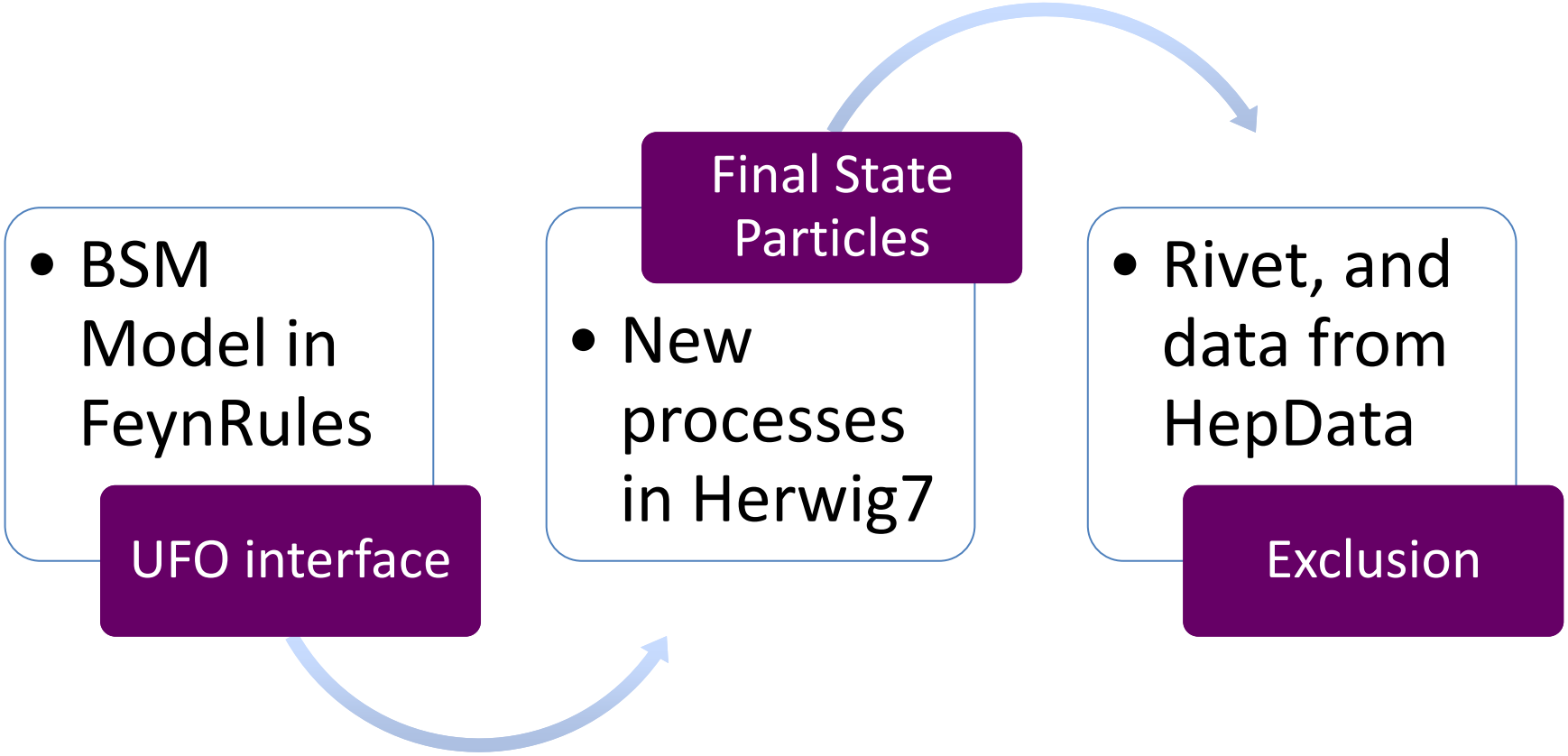
- Measurements of final-state particles in well-defined fiducial regions
- Generally differential cross sections
- Should not (and mostly do not) assume the SM
- Agree with the SM (so far)
- Thus they can potentially exclude extensions



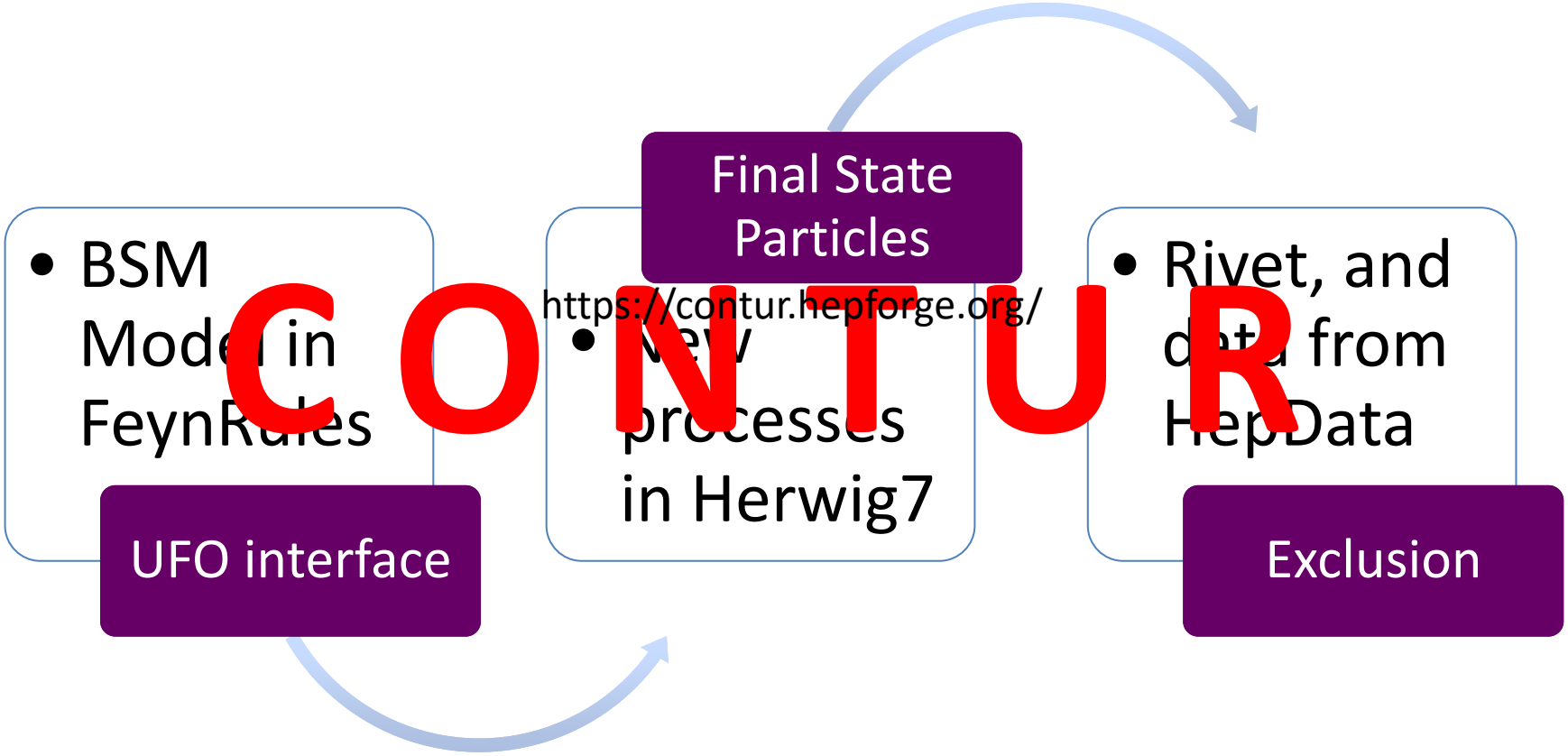
Key tools:


• BSM Model in FeynRules
UFO interface
Final State Particles
• New processes in Herwig7
• Rivet, and data from HepData
Exclusion

Key tools: Constraints On New Theories Using Rivet



Key tools: Constraints On New Theories Using Rivet



https://contur.hepforge.org/

Strategy

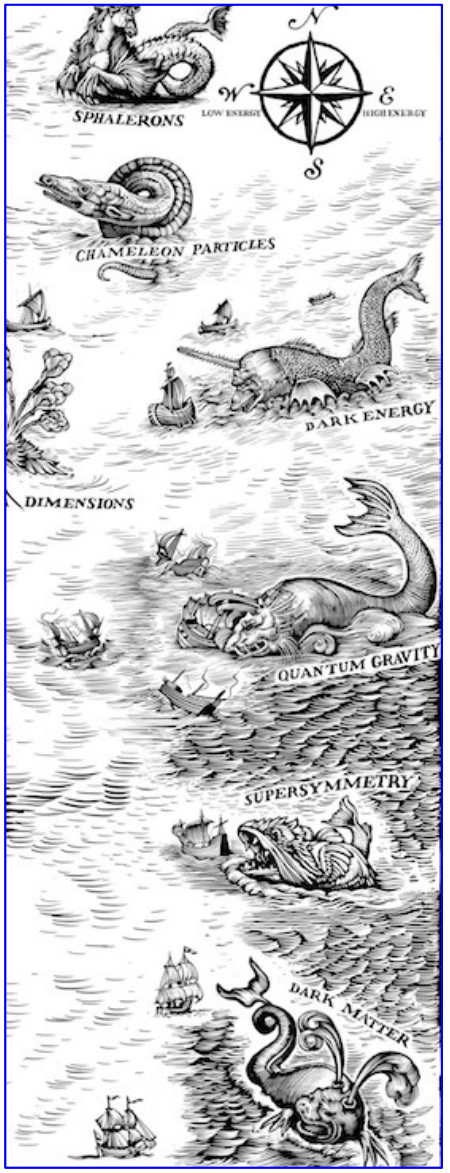
- Use measurements shown to agree with the Standard Model
  - (Currently) assume the data = the background, as in a typical search control region.
  - Excellent for quick sensitivity/limit scans of new models
- Key for constraining new models if there is a signal (unintended consequences)
- Key for constraining scale of new physics if there is no signal

Dynamic data selection

- Measurements of fiducial, particle-level differential cross sections, with existing Rivet routines
- Classify according to data set (7, 8, 13 TeV) and into non-overlapping signatures
- Use only one plot from each given statistically correlated sample
  - *e.g.* Jets, lν+jets, ll+jets, γ (+jets), γγ, 4l, etc □.
- "Most sensitive measurement" will vary with model and model parameters

Some examples

- Spontaneously-broken B-L gauge theory
- Generic Light Scalar Model
- Dark Matter models
- Dark Energy
- Flavour anomalies



Some examples

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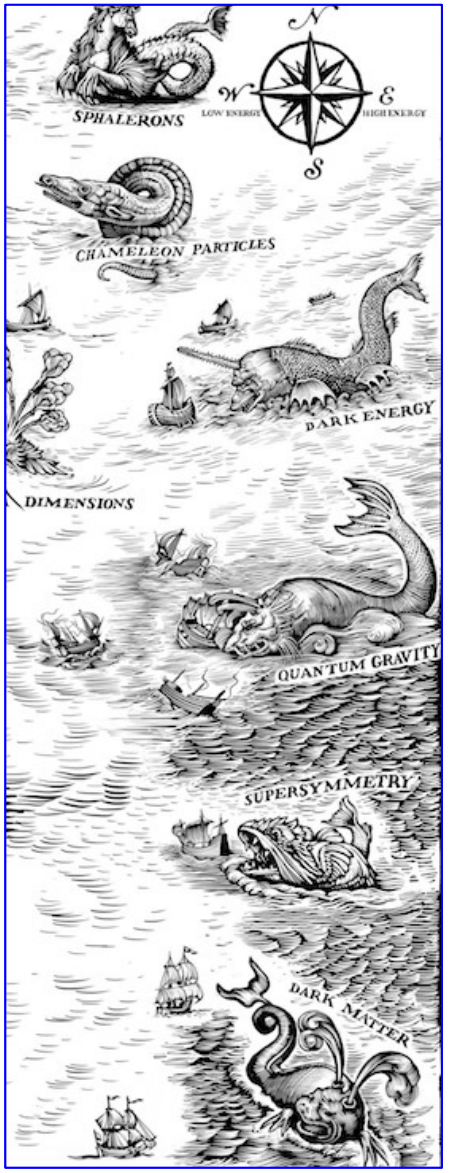


Spontaneously-broken B-L gauge theory

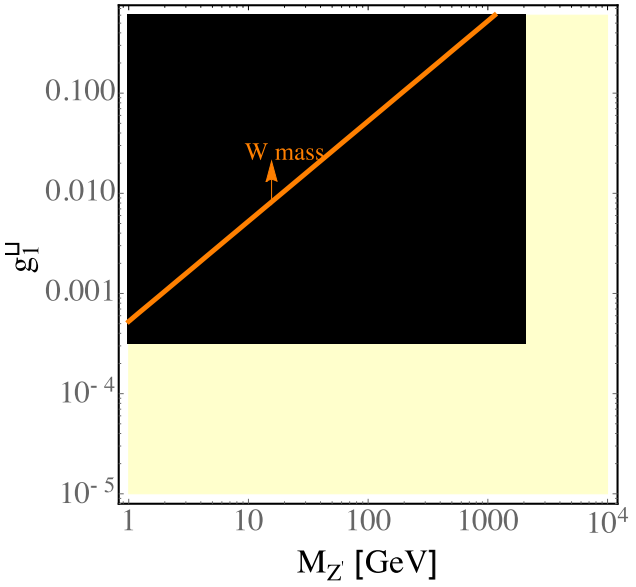
S. Amrith, JMB, F.F.Deppisch, W. Liu, A.Varma, D.Yallup
1811.11452, JHEP 1905 (2019) 154

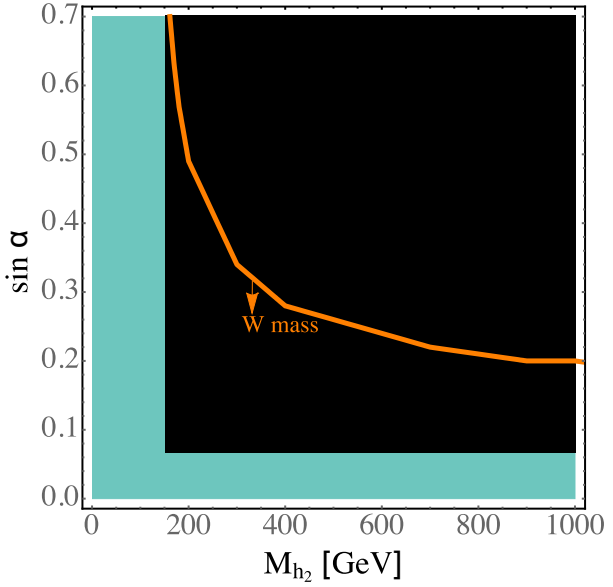
- UV complete
- Three pairs of parameters which interplay to give quite a rich phenomenology
  - New U(1) gauge symmetry from B-L
    - New gauge boson Z', coupling g_1'
  - Spontaneously broken
    - New Higgs boson, h_2, can mix with SM Higgs: $\sin\alpha$
  - RH neutrinos with Majorana masses, natural explanation of light neutrino masses (seesaw mechanism)
    - Lifetime of neutrino may lead to prompt decays, (far-)displaced-vertex, or effective stability for collider signatures

Spontaneously broken B-L gauge theory

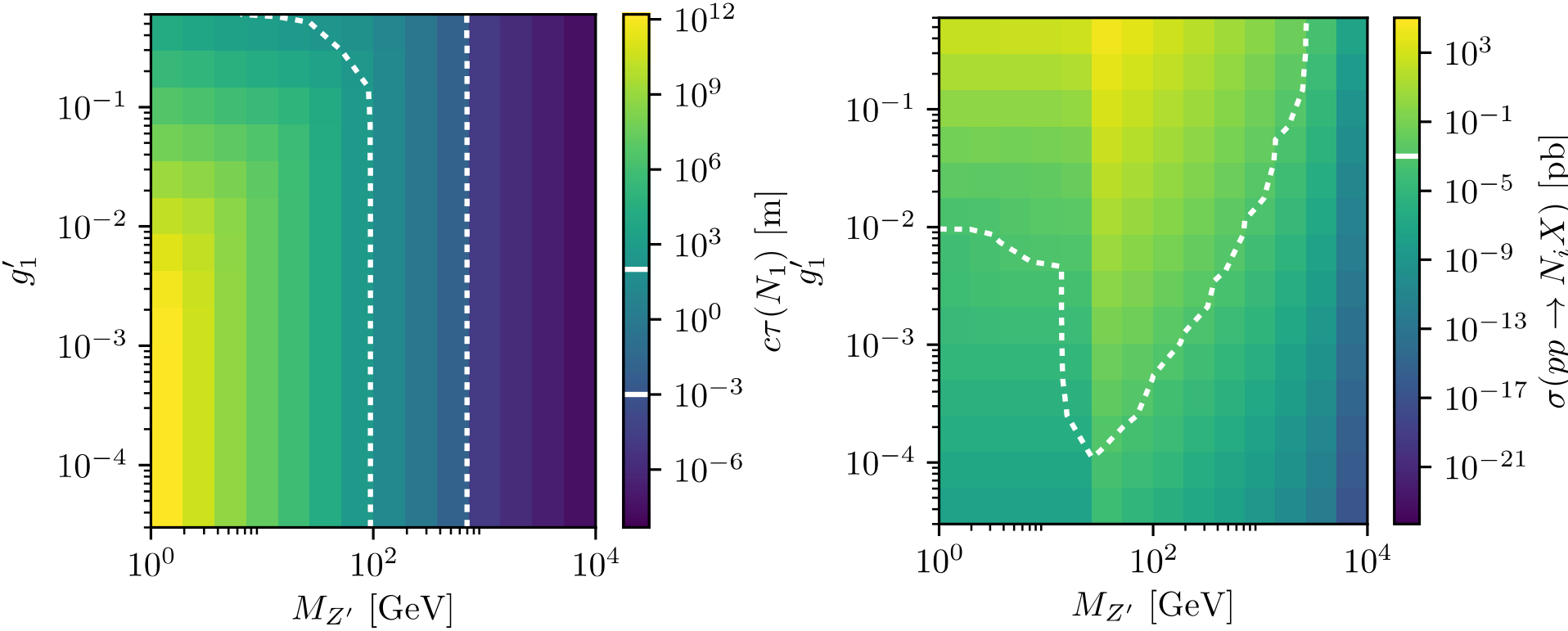
Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
B	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0.2	$M_{Z'}/5$
C	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	200 GeV	0.2	$M_{Z'}/5$
D	7000	0.2	[0, 800] GeV	[0, 0.7]	$M_{Z'}/5$
E	35	10^{-3}	[0, 800] GeV	[0, 0.7]	$M_{Z'}/5$

Table 1: Benchmark scenarios used in our analysis. In addition, the active-sterile neutrino mixing is fixed as $V_{lN} = \sqrt{0.1\text{ eV}/M_N}$, independent of the generation of the heavy neutrino.





Spontaneously-broken B-L gauge theory



Contur approach is not well-suited for long-lived-particle signatures: most measurements demand prompt particles attached to primary vertex, or else known SM particle (B, τ□). See Deppisch, Liu, Mitra arXiv:1804.04075 for a study of this model

Case A

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
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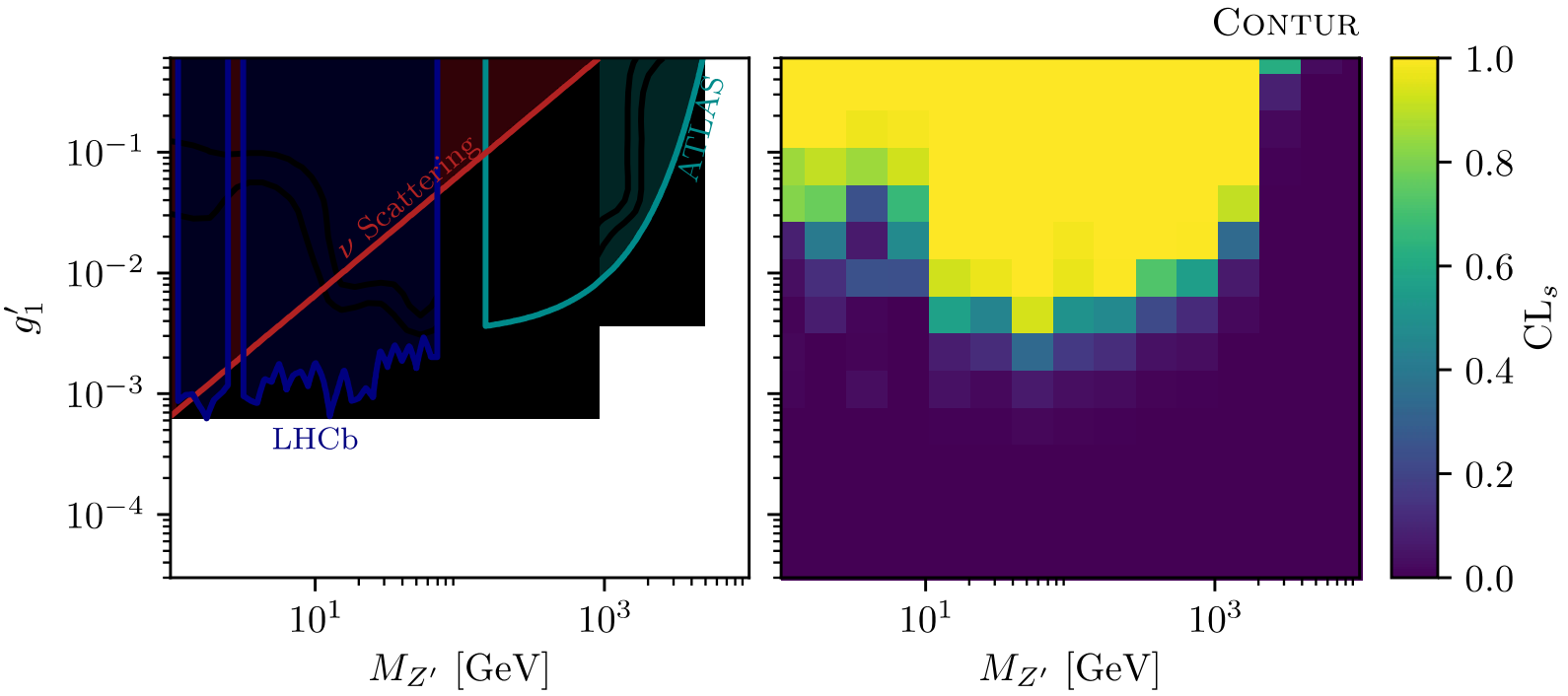

Case B

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
B	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0.2	$M_{Z'}/5$
C	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	200 GeV	0.2	$M_{Z'}/5$
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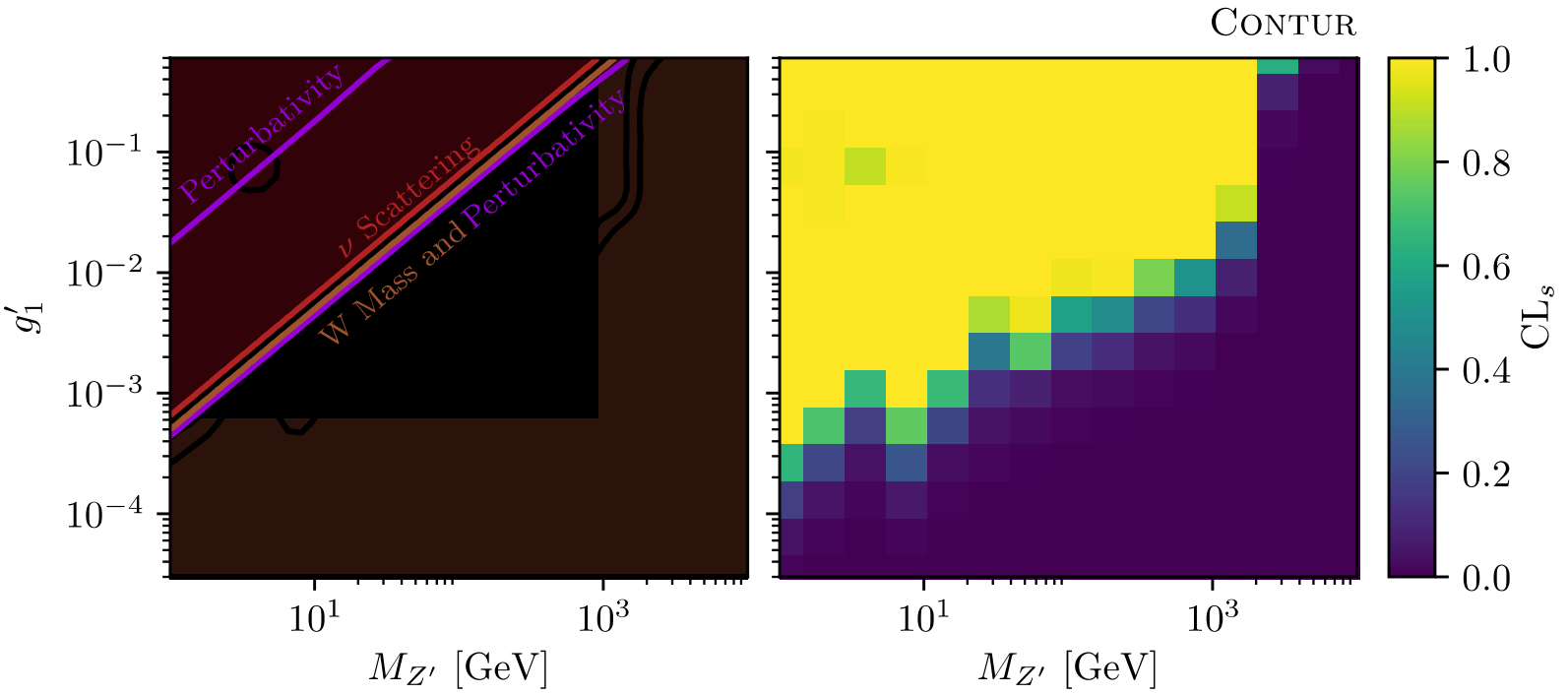
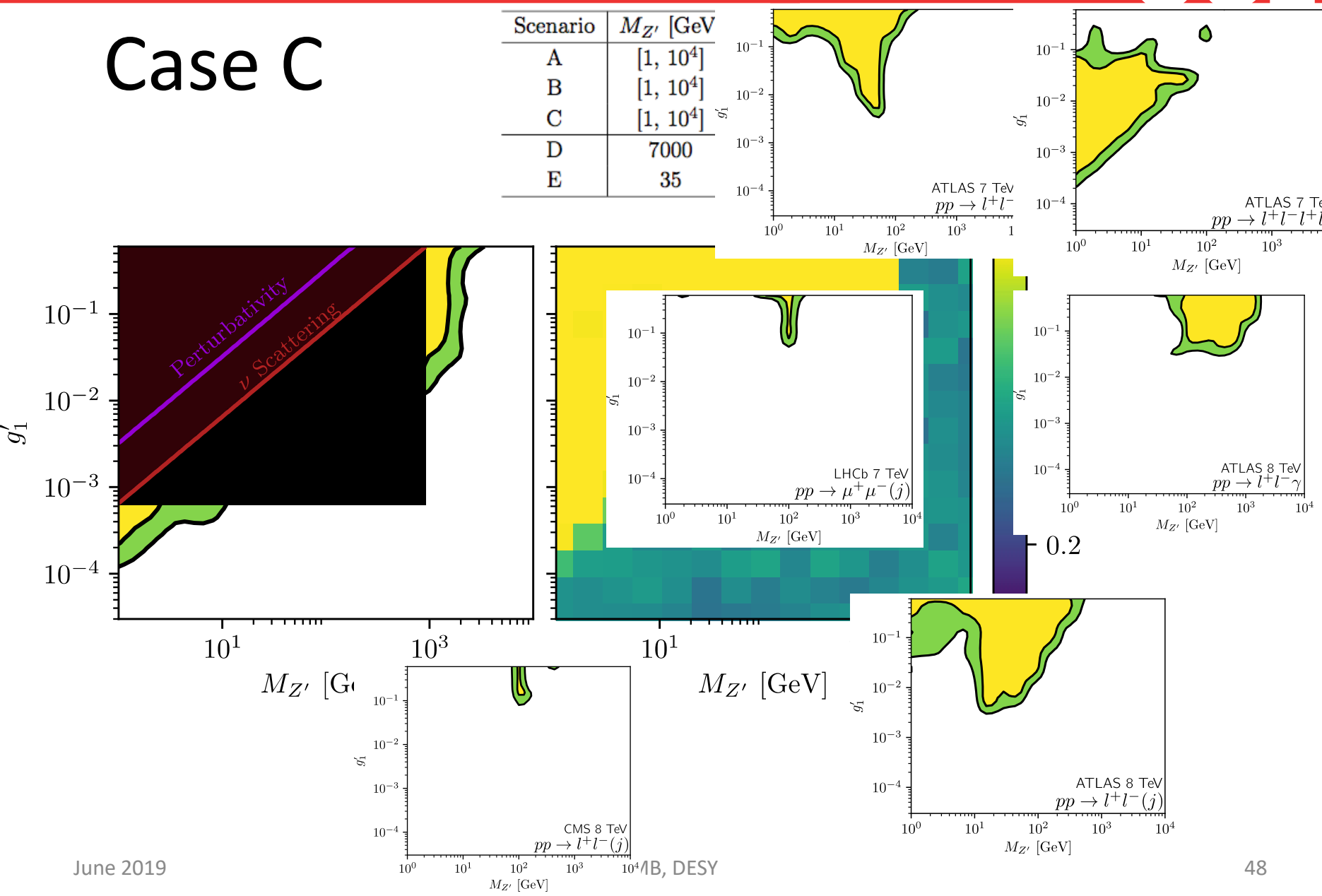


Case C

Scenario	$M_{Z'}$ [GeV
A	$[1, 10^4]$
B	$[1, 10^4]$
C	$[1, 10^4]$
D	7000
E	35



Case C

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
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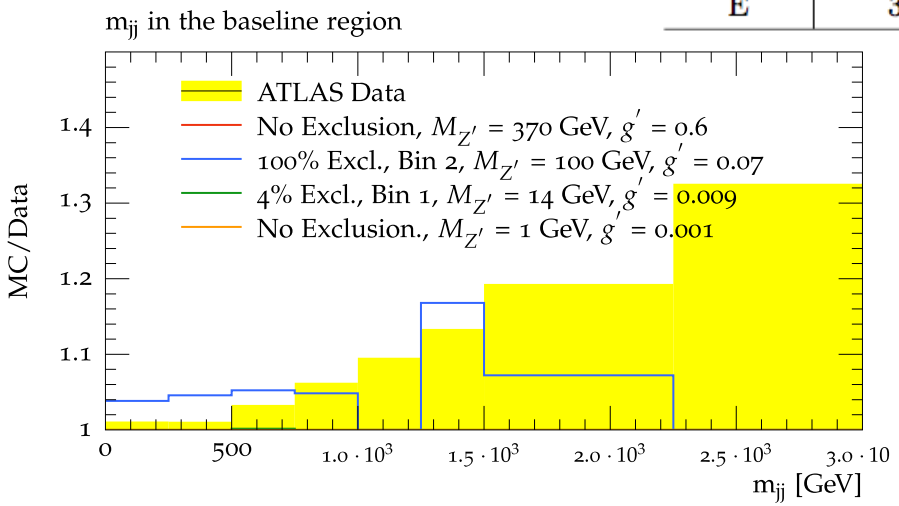

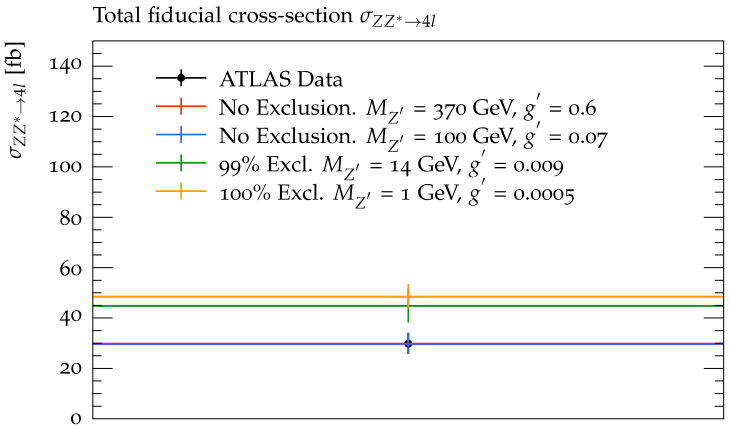

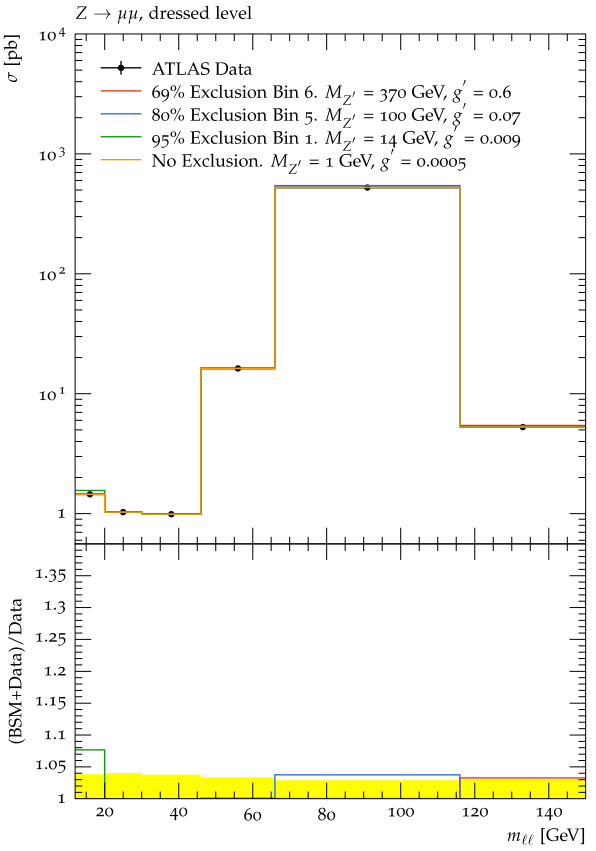

Case D

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
B	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0.2	$M_{Z'}/5$
C	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	200 GeV	0.2	$M_{Z'}/5$
D	7000	0.2	[0, 800] GeV	[0, 0.7]	$M_{Z'}/5$
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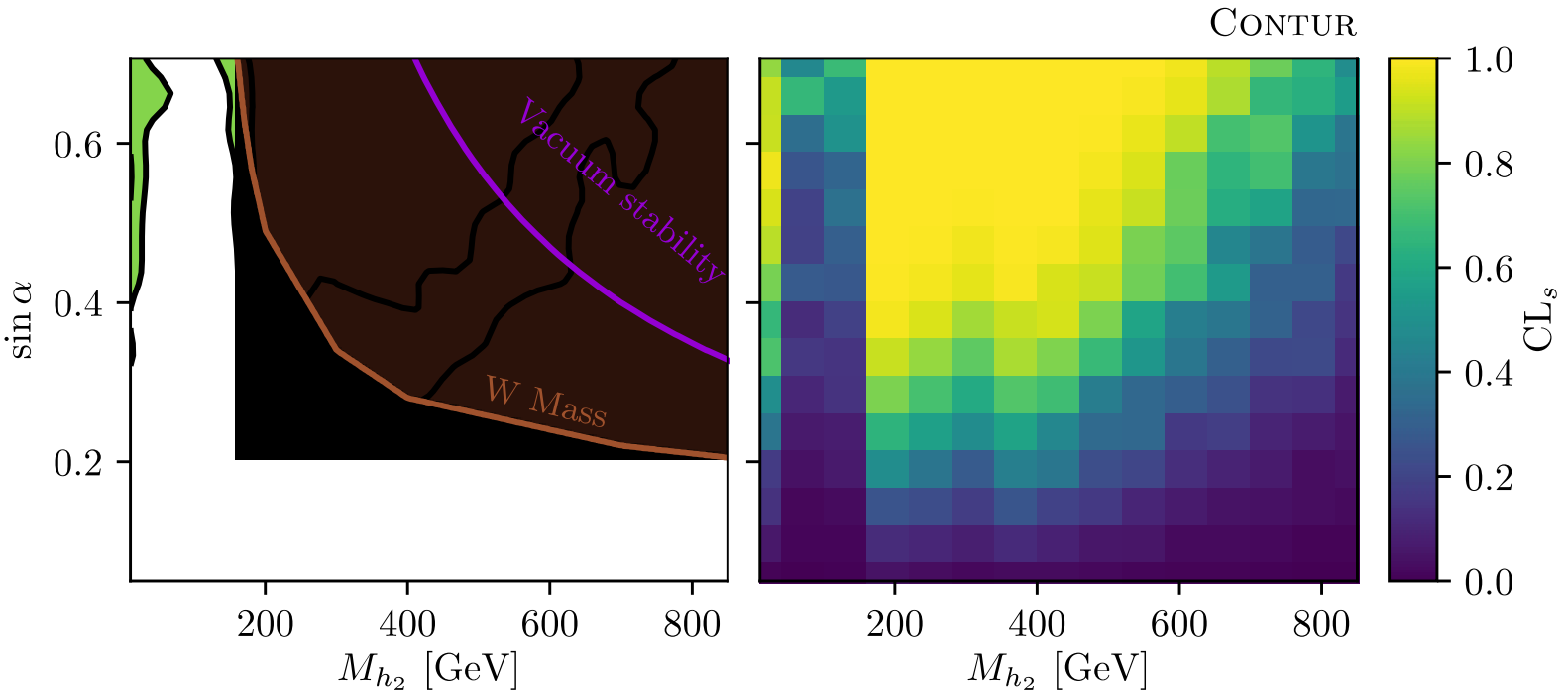
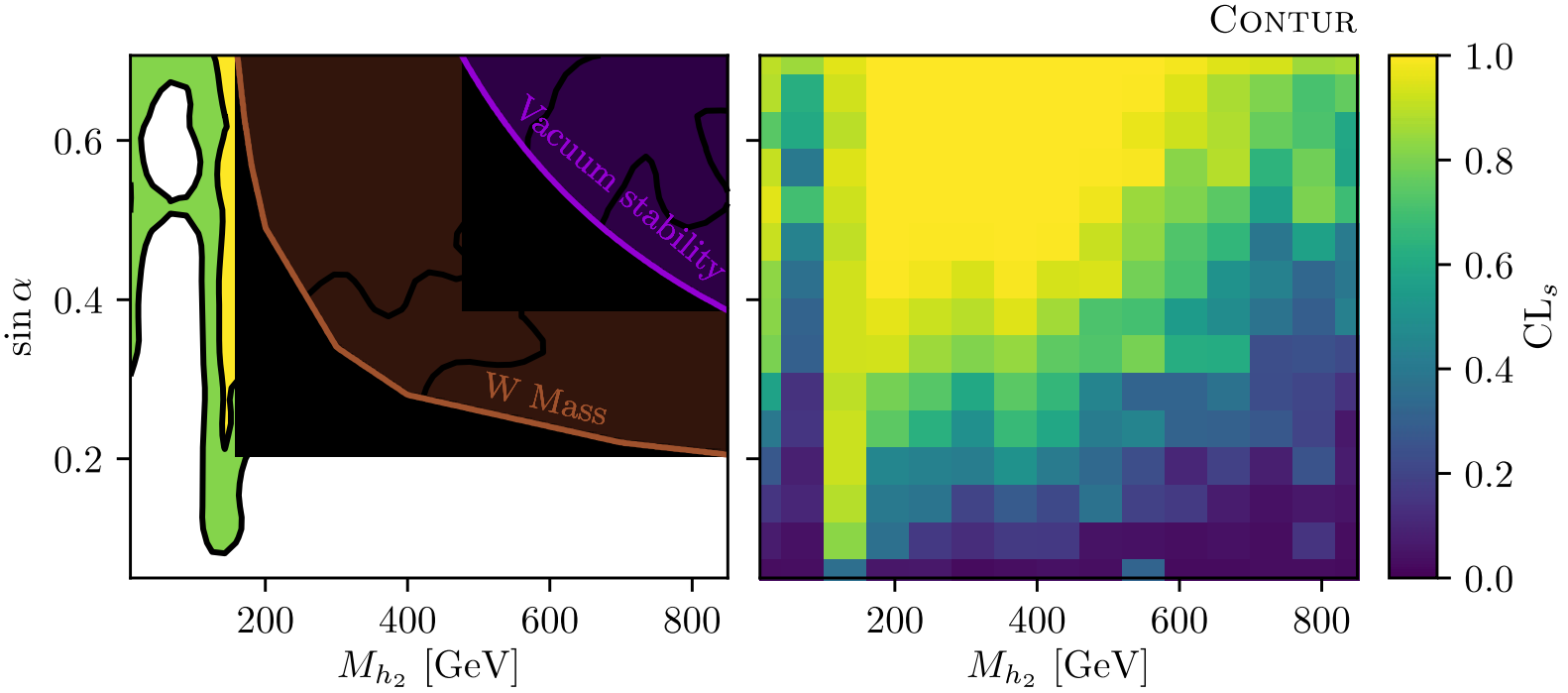


Case E

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
B	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0.2	$M_{Z'}/5$
C	$[1, 10^4]$	$[3 \times 10^{-5}, 0.6]$	200 GeV	0.2	$M_{Z'}/5$
D	7000	0.2	[0, 800] GeV	[0, 0.7]	$M_{Z'}/5$
E	35	10^{-3}	[0, 800] GeV	[0, 0.7]	$M_{Z'}/5$



Case D

Scenario	$M_{Z'}$ [GeV]	g'_1	M_{h_2}	$\sin\alpha$	M_{N_i}
A	$[1, 10^4]$	$[3\times10^{-5}, 0.6]$	$M_{Z'}/(2g'_1)$	0	$M_{Z'}/5$
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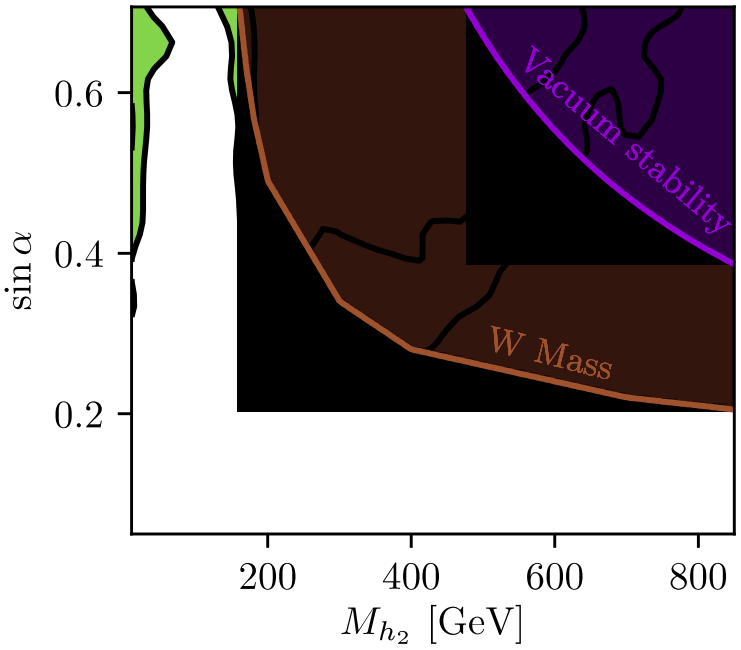


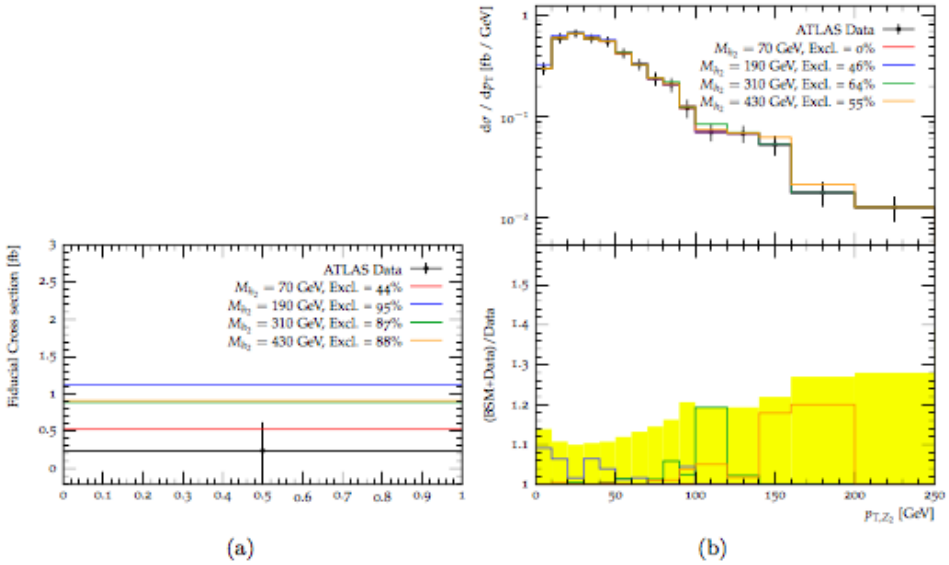
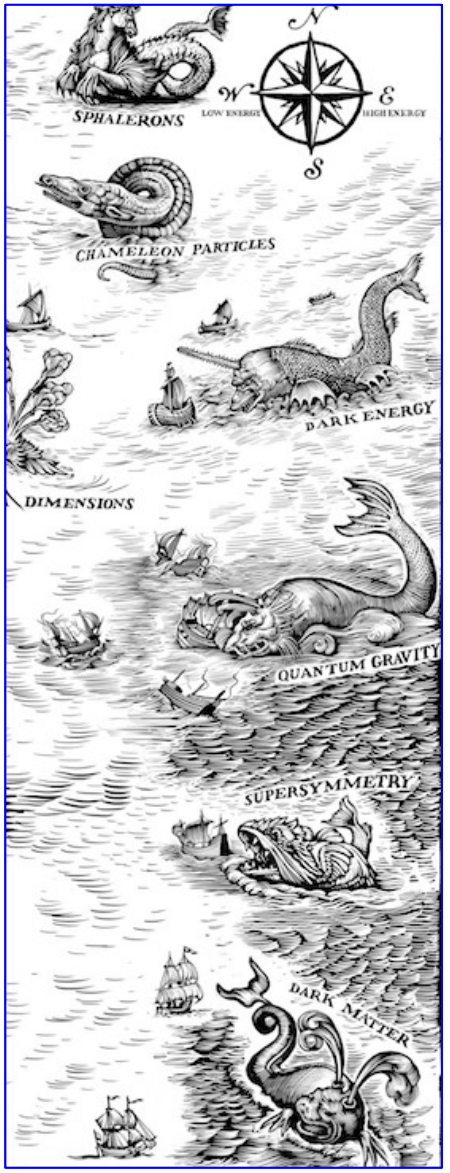


Figure 7: Examples of the exclusion from four points in the parameter space moving along the lower edge of the theoretically allowed region of Fig.6a. (a) The dilepton plus dijet measurement from [32], (b) The ZZ^* (four lepton) measurement from [35], The legend indicates the parameter point in $M_{Z'} = 7$ TeV, $g'_1 = 0.2$, $\sin\alpha = 0.42$

Some examples

- Spontaneously-broken B-L gauge theory
- Generic Light Scalar Model
- Dark Matter models
- Dark Energy
- Flavour anomalies



Generic Light scalars

- Effective couplings to gauge bosons.
  - Dominant decay to photons → sensitivity in inclusive, diphoton and V+photon measurements
  - Model from S. Fichet, G. Moreau. See Les Houches 2017 proceedings arXiv:1803.10379, *Contribution 20*

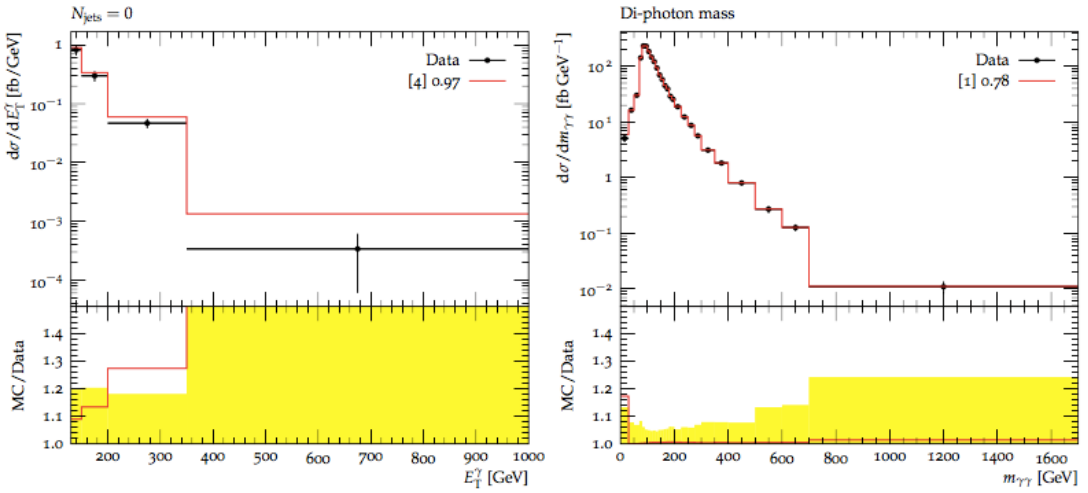
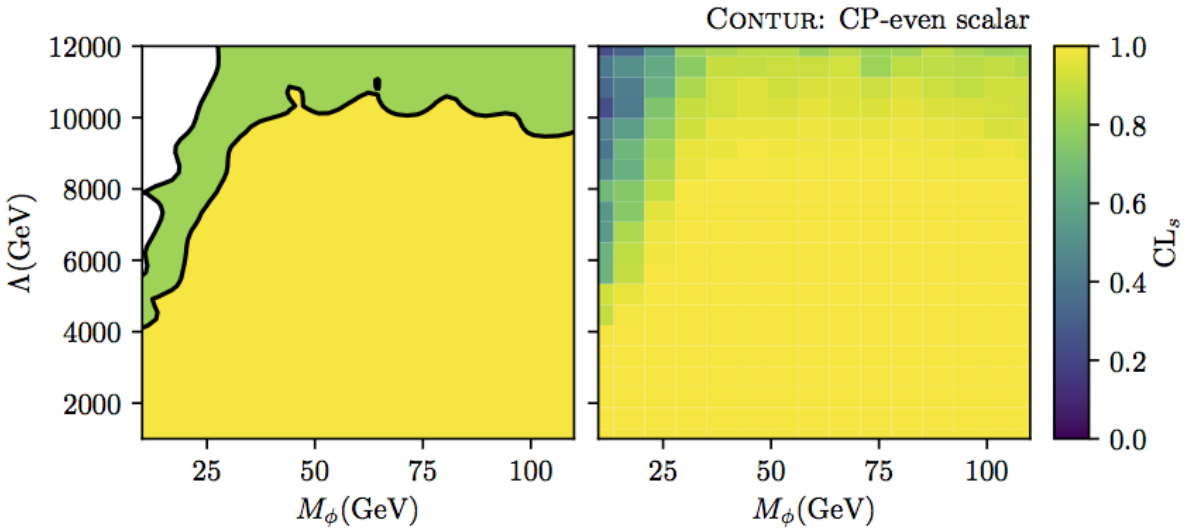
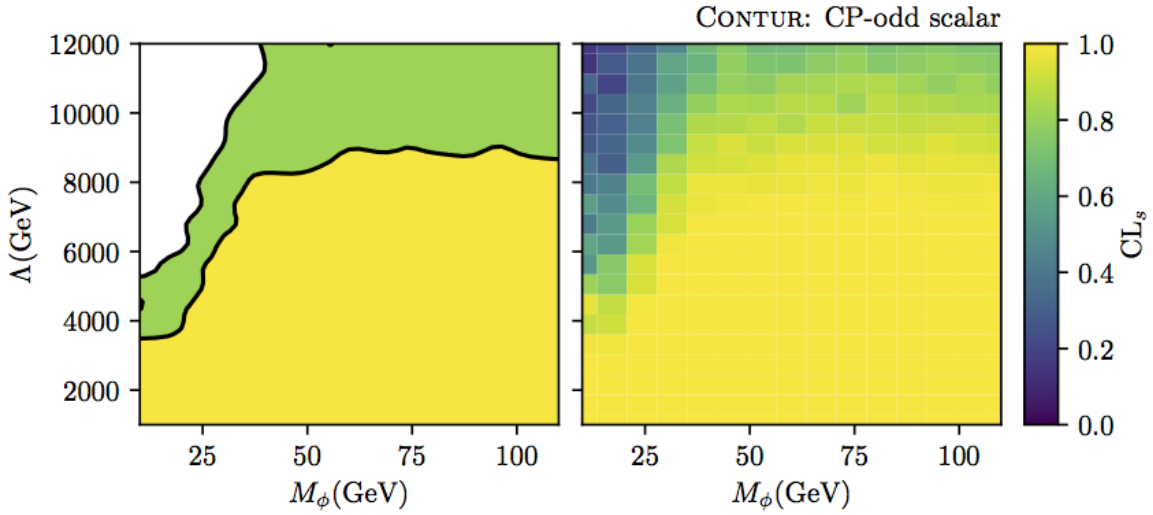


Figure 1: Projection of the contribution of the CP-odd model, (left) for $M_\varphi = 10$ GeV and $\Lambda = 3500$ TeV, on to the 8 TeV ATLAS $\gamma + E_T^{\text{miss}}$ differential E_T^γ cross-section measurement and (right) on the diphoton mass measurement, now with $M_\varphi = 20$ GeV – which brings the mass peak from the φ within the range of the measurement. Black points indicate the data, the red upper histogram is the data+BSM. The lower sections of the plots show the ratio of (data+BSM)/data, with the yellow band indicating the uncertainty in the measurement. The numbers in the legend show the bin number of the most powerful bin, and the exclusion from that bin expressed as a probability.


CONTUR: CP-even scalar
12000
10000
8000
6000
4000
2000
Λ(GeV)
25
50
75
100
M_ϕ(GeV)
1.0
0.8
0.6
0.4
0.2
0.0
CL_s


CONTUR: CP-odd scalar
12000
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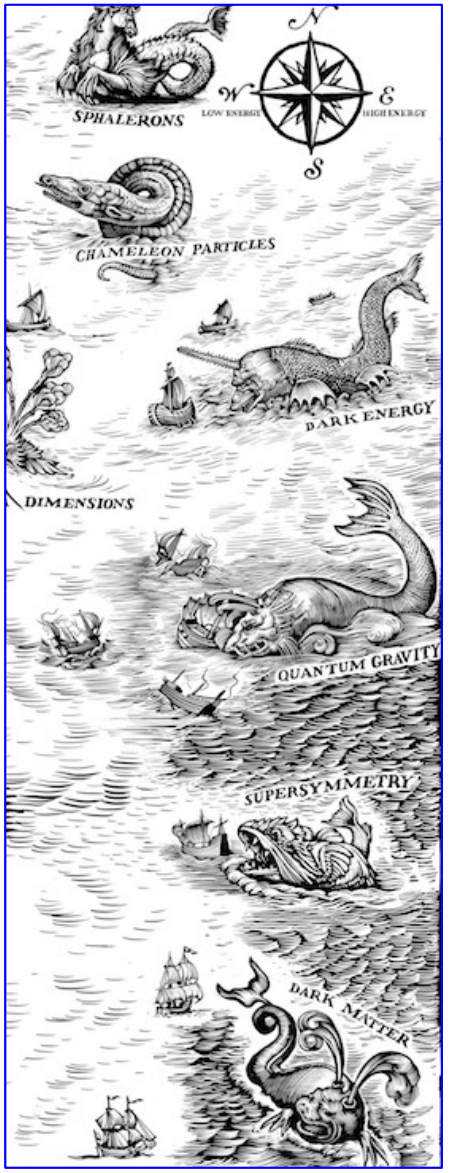
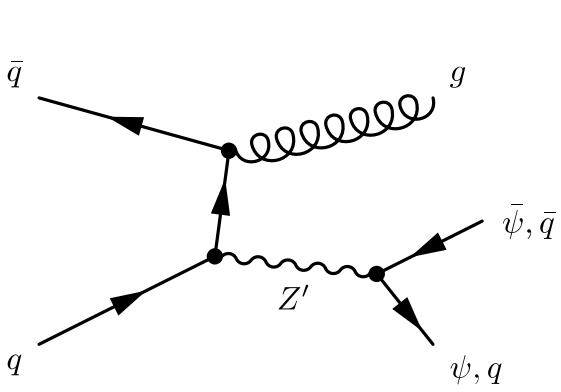


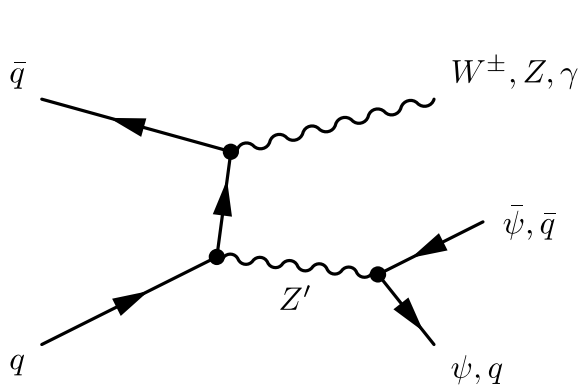
Simplified Dark Matter Model

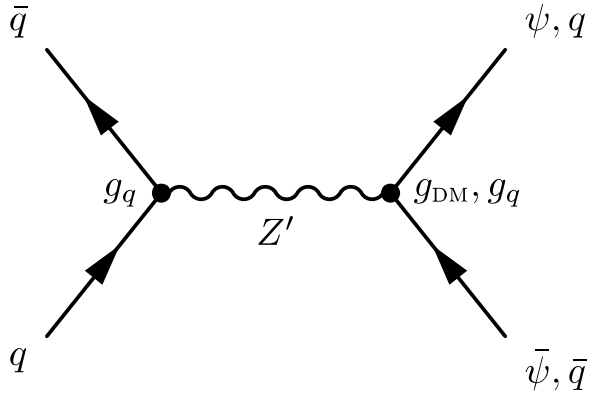
- Introduce Z' mediator, a Majorana fermion DM candidate, and two couplings

$$\mathcal{L} \supset g_{\mathrm{DM}}\,\overline{\psi}\gamma_\mu\gamma_5\psi\,Z'^\mu + g_q \sum_q \bar{q}\gamma_\mu q\,Z'^\mu$$

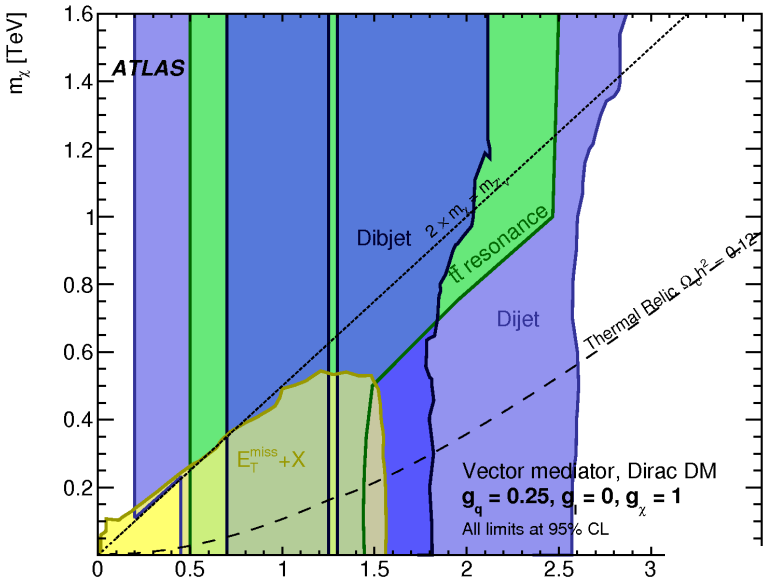
- Variant considered in Z' which couples only to first generation quarks
  - JMB, D. Grellscheid, M.Krämer, B.Sarrazin, D.Yallup , arXiv:1606.05296
- Have since also looked at coupling to all generations



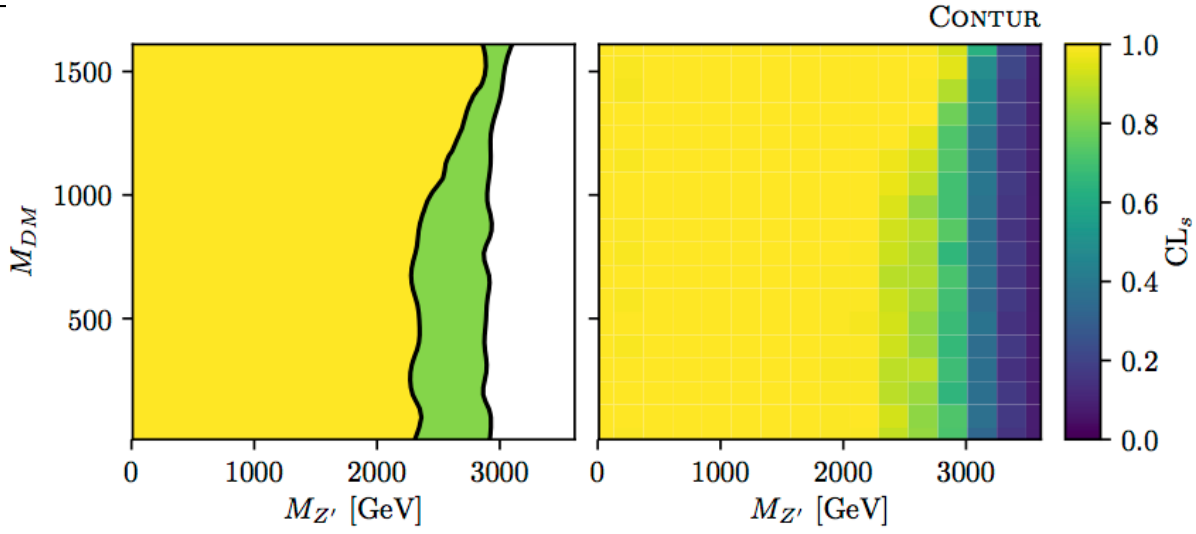




Comparison to ATLAS search benchmarks



arXiv:1903.01400



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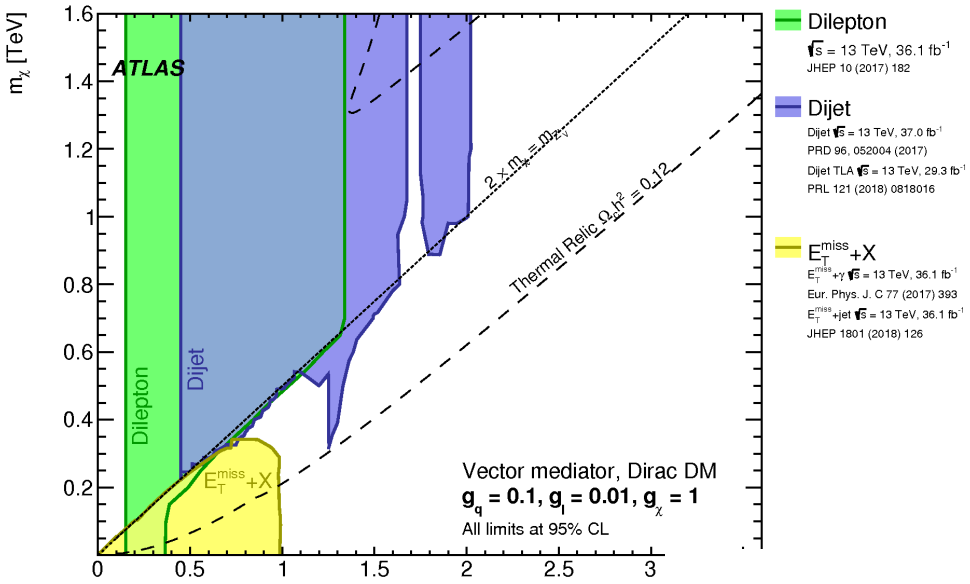
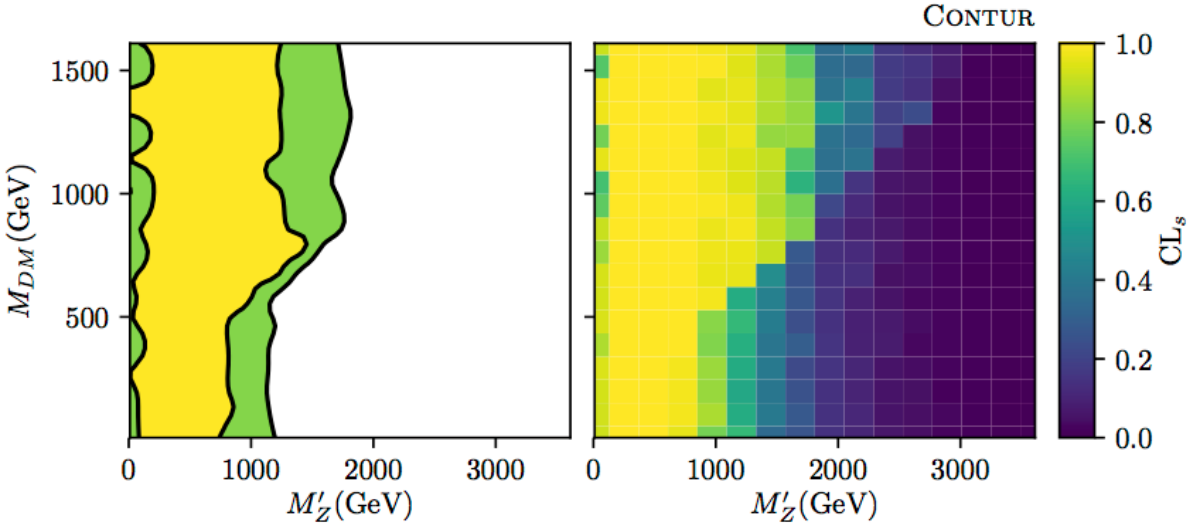
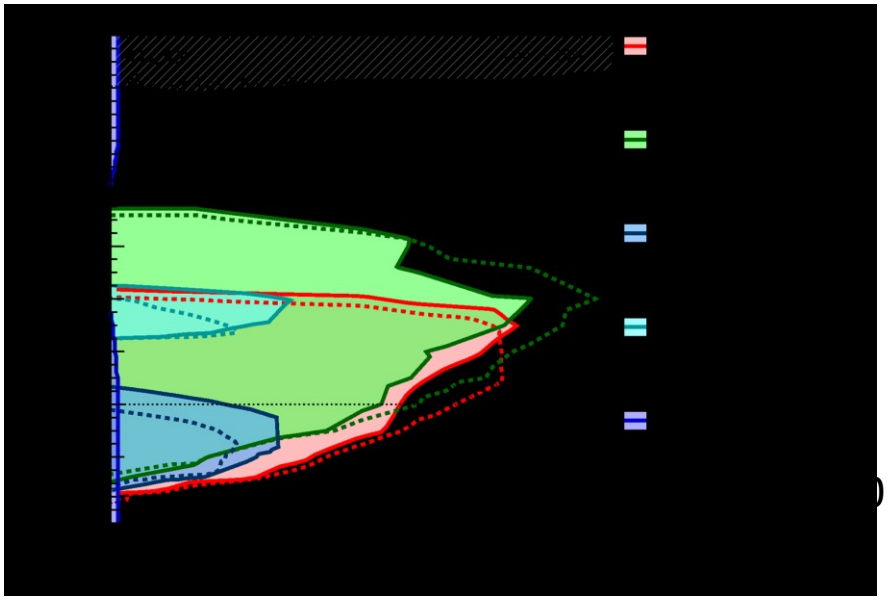
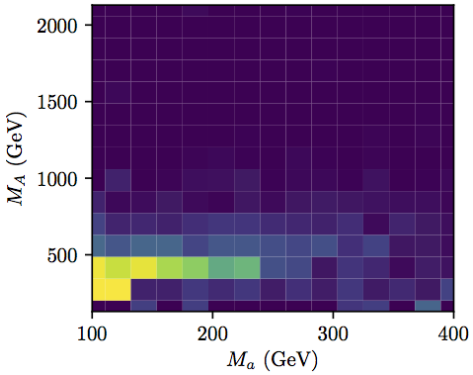


arXiv:1903.01400



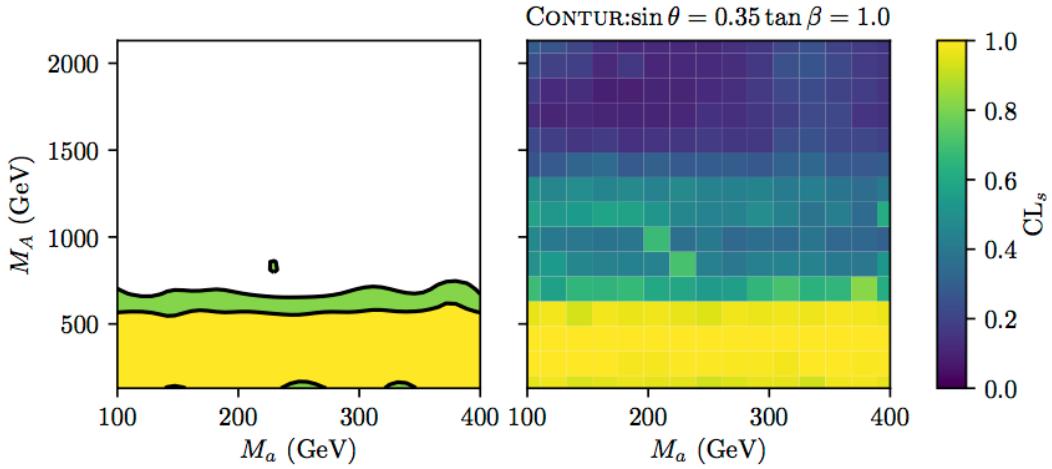
Two Higgs-doublet model, with the pseudoscalar Higgs acting as mediator to Dark Matter

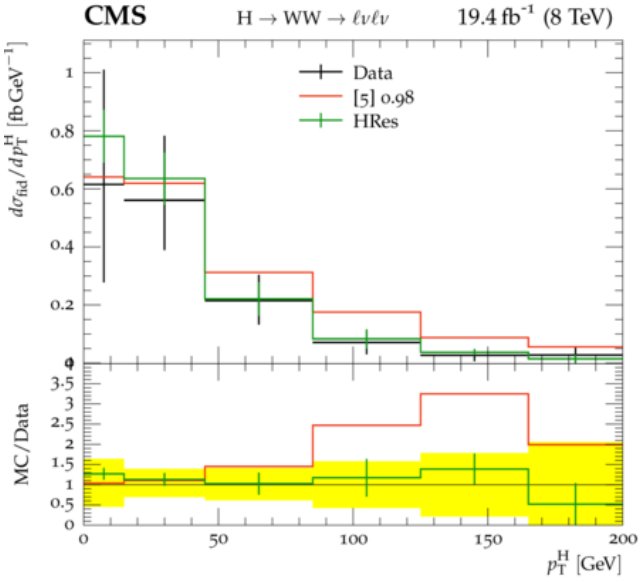




ATLAS
arXiv:1707.03263

01400





CMS arXiv:1606.01522,

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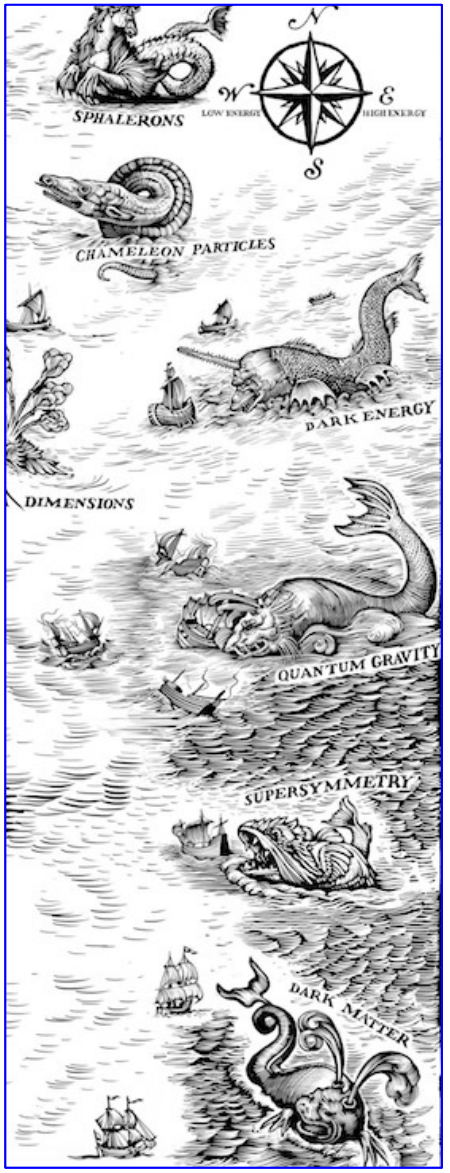
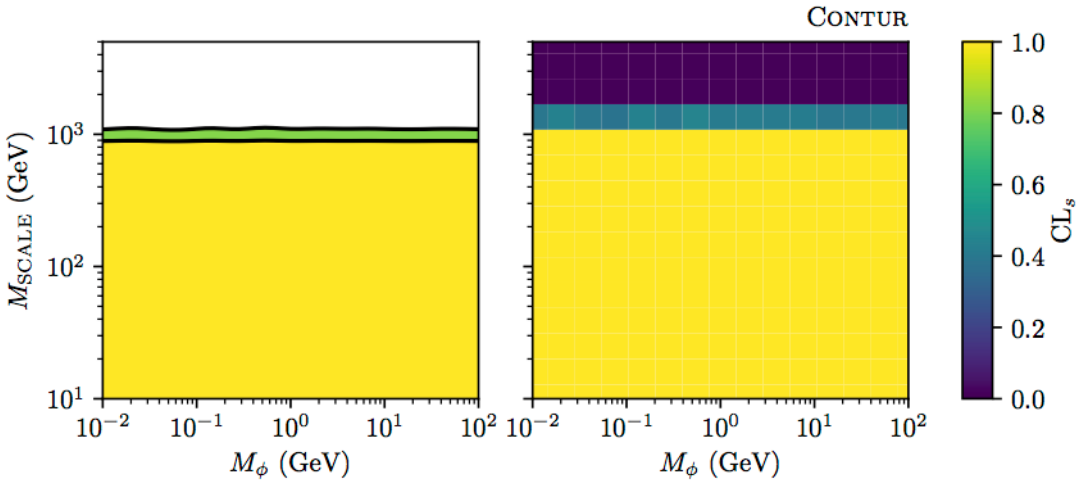


Scalar Dark Energy Field coupling to SM

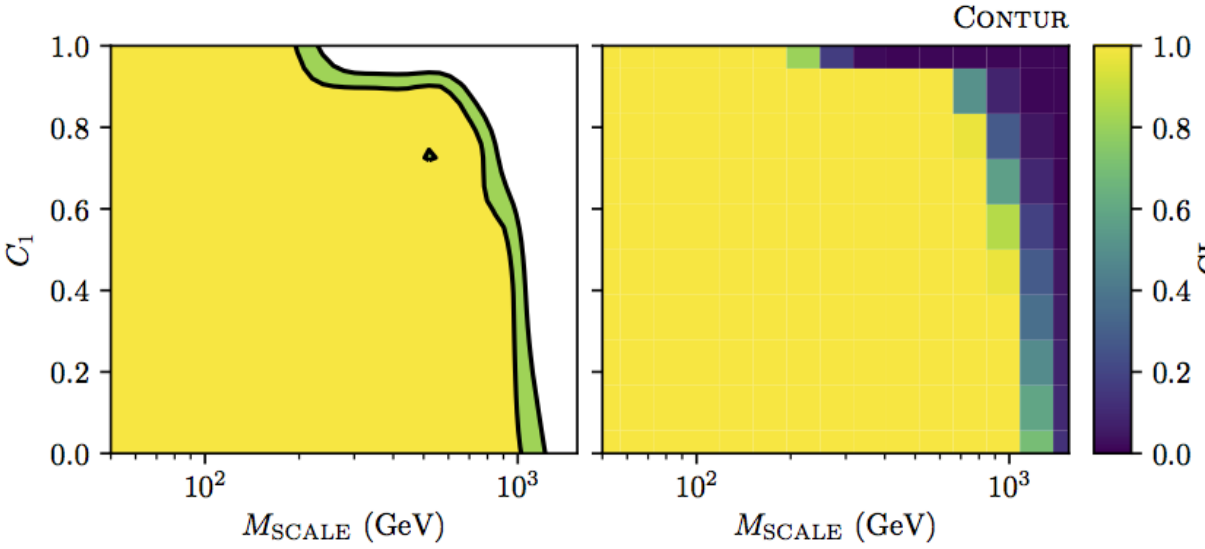
- Mode introduced by Brax, Burrage, Englert & Spannowsky in arXiv:1604.04299
- Neutral scalar dark energy field of mass M_ϕ couples to Standard Model particles via various Effective Field Theory (EFT) operators which are suppressed by powers of a scale parameter M_{SCALE}.
- Concentrate on couplings C_1 & C_2 which appear in front on the leading EFT operators, setting others to zero.
  - This means that ϕ is pair-produced and stable, so dominant signatures are expected to involve missing transverse energy

Setting C_1=C_2=1 scan in M_ϕ and M_{SCALE}



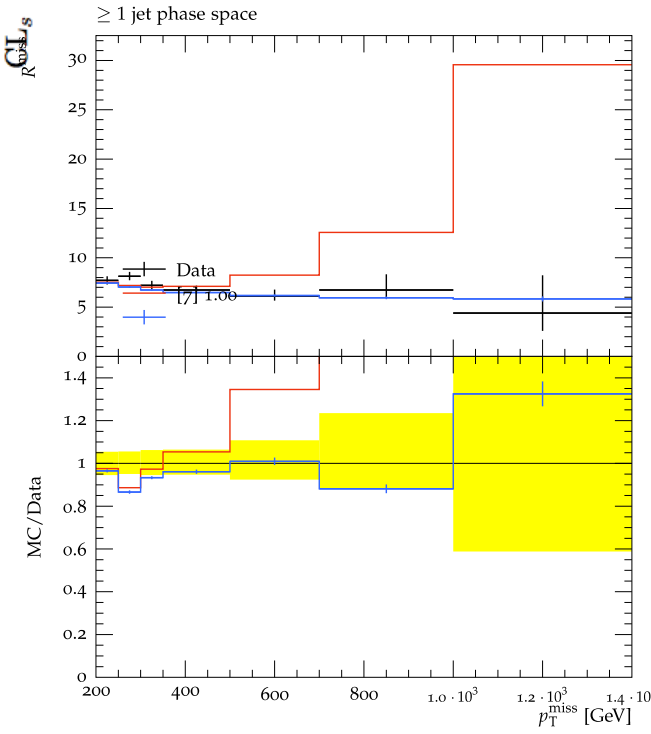
Scalar Dark Energy Field coupling to SM

- Now set M_ϕ=0.1 GeV, and setting C_2=1−C_1, scan in C_1 and M_{SCALE}.



Limits similar to but stronger than reinterpreted searches in the original paper (which used 8 TeV data)

Most sensitive measure, ATLAS 13 TeV jets + missing energy. arXiv:1707.03263



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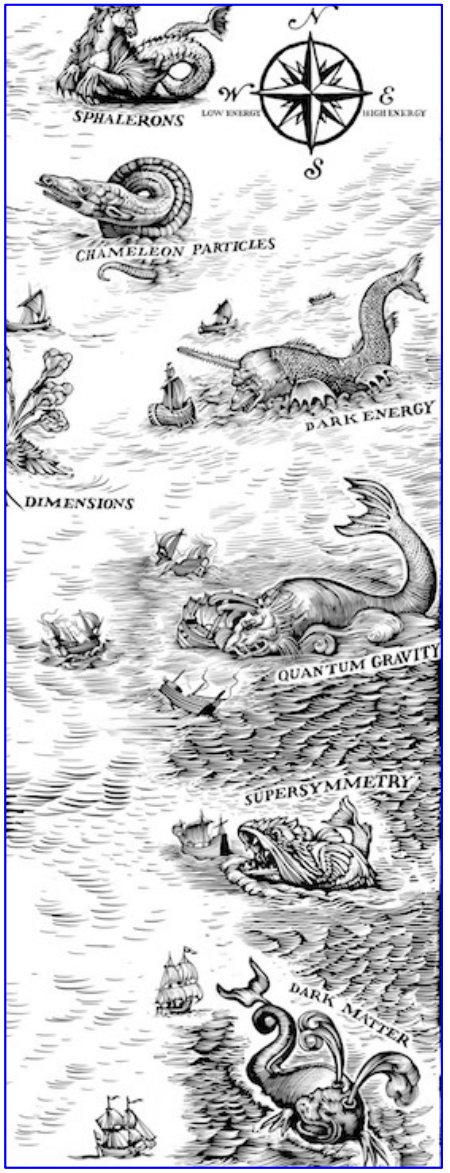
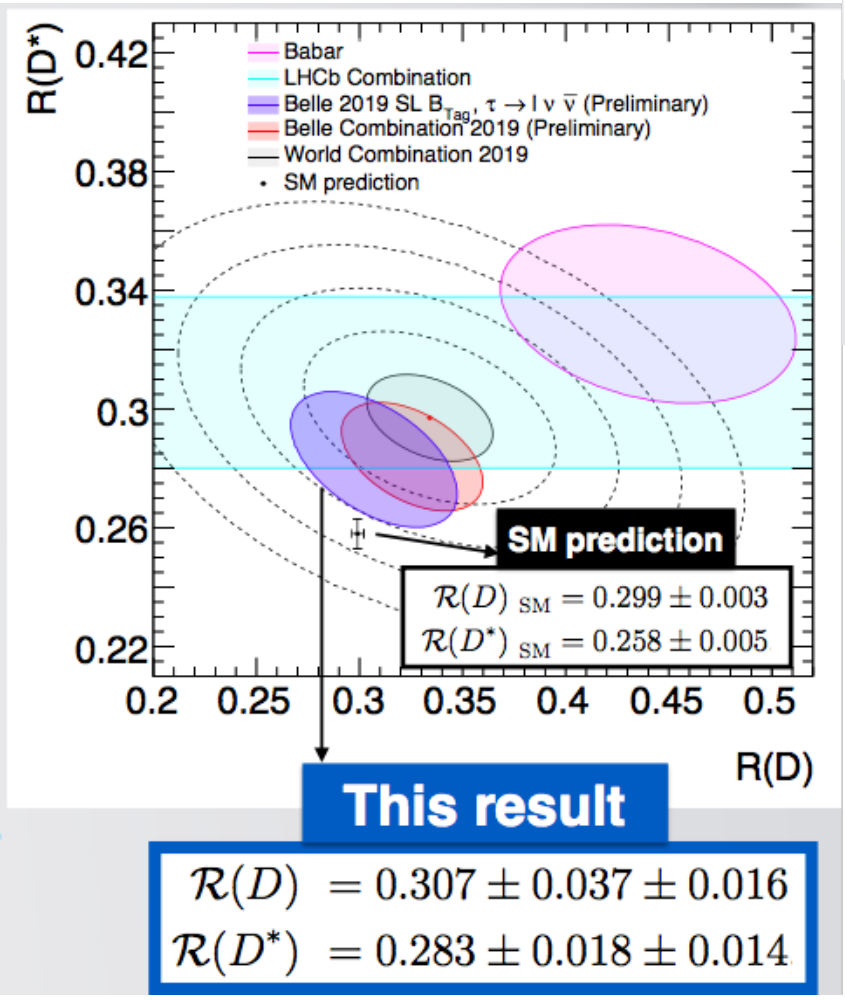
- Flavour anomalies



Flavour Anomalies



This result

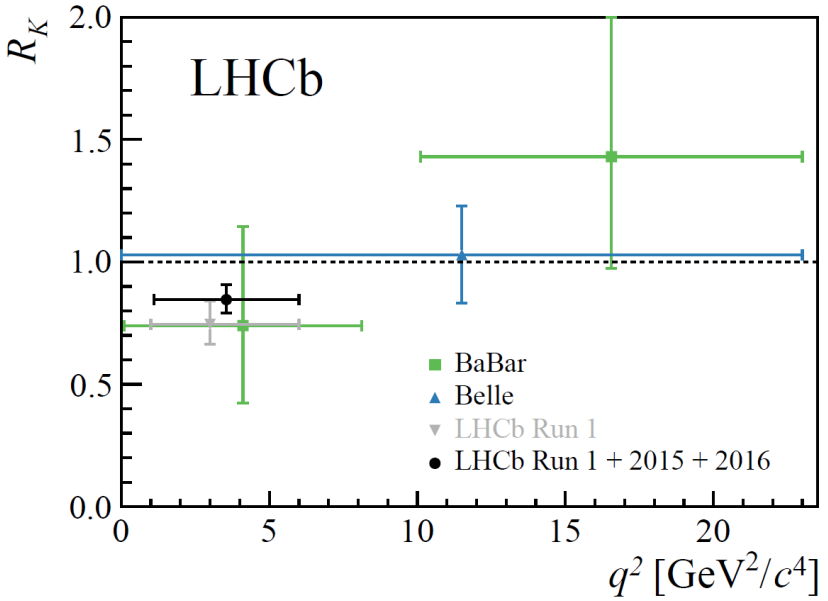
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)}$$

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)}$$

where ℓ = e,μ

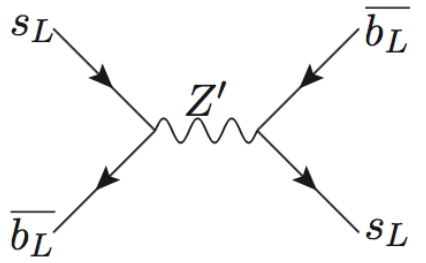
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)} \overset{\rm SM}{=} 1.0$$

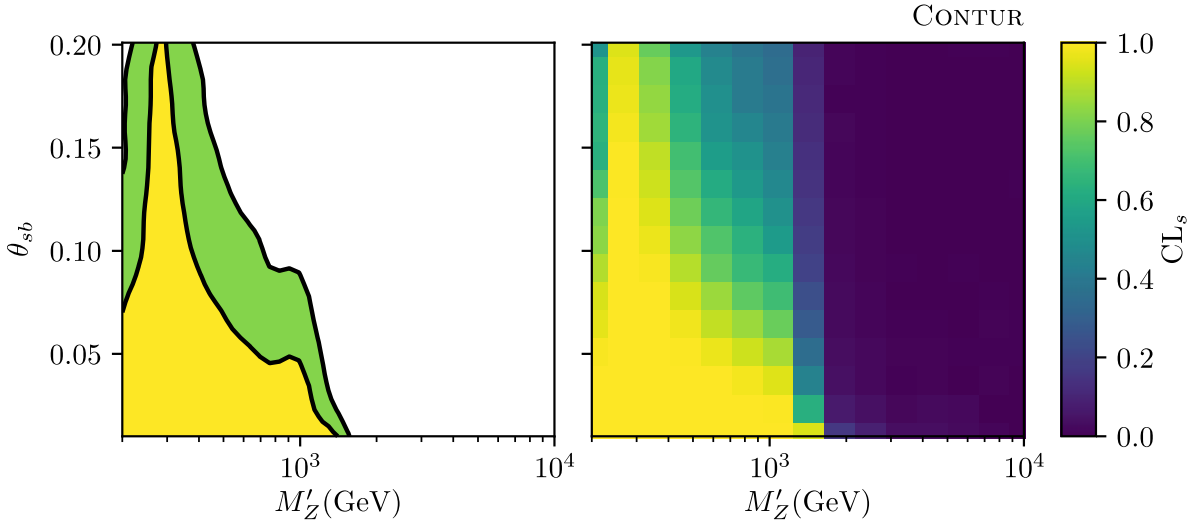


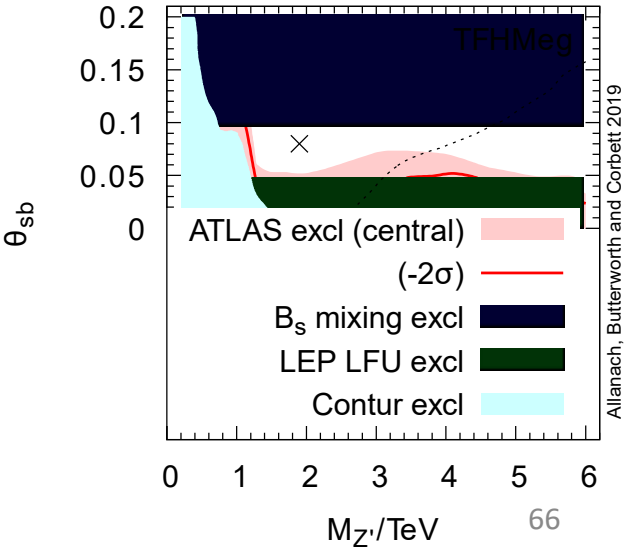
Moriond 2019

Flavour Anomalies

- Introduce a new particle/interaction to explain this:
- Look at the impact of direct searches and measurements for such a particle
  - e.g. *Allanach, JMB, Corbett arXiv:1904.10954*

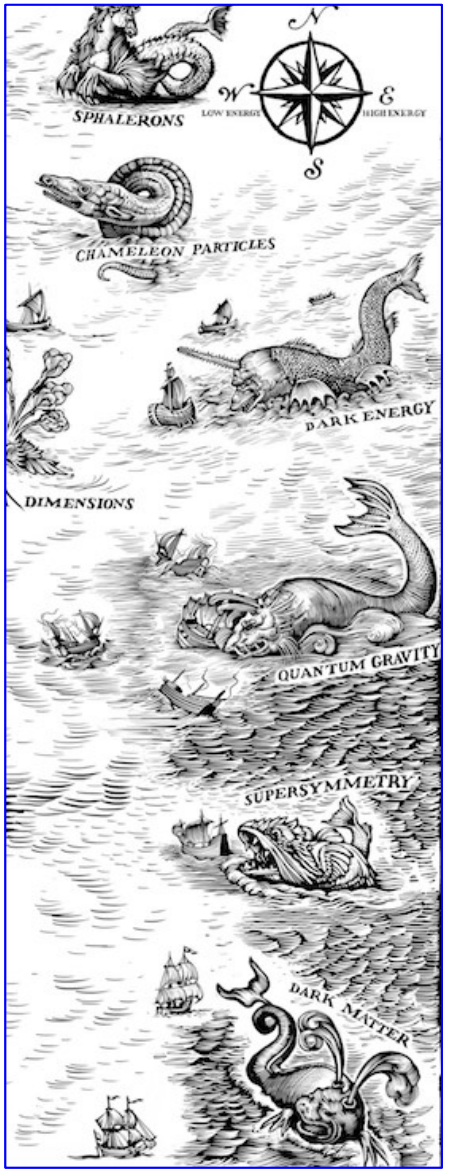






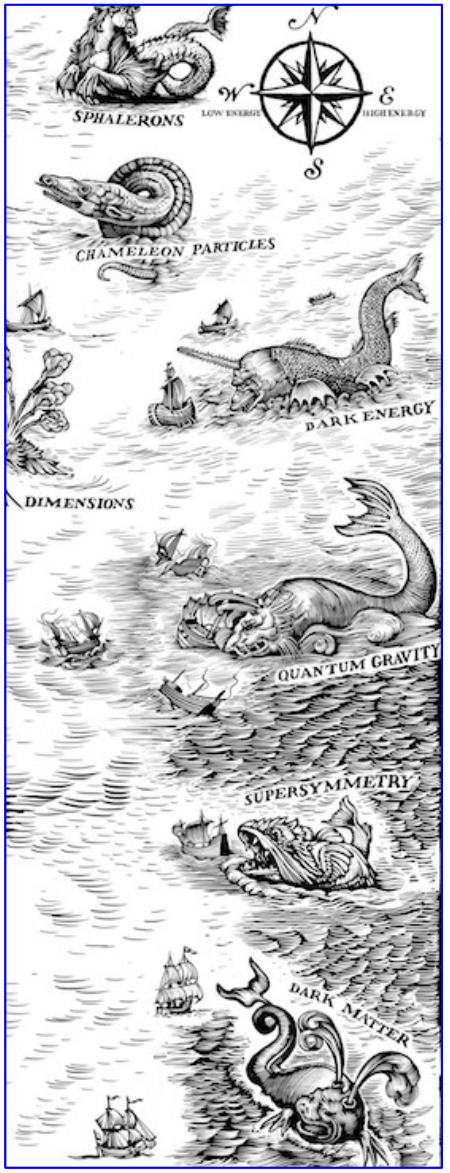
Summary…

- With the Higgs, the Standard Model could work well above the Electroweak symmetry breaking scale.
- Take its predictions seriously!
- Model independent measurements stored in HepData and Rivet are a powerful and flexible resource
  - Already used more MC tuning and validation, comparison to precision SM measurements
  - Can now be used to constrain BSM physics (several examples shown, more available)



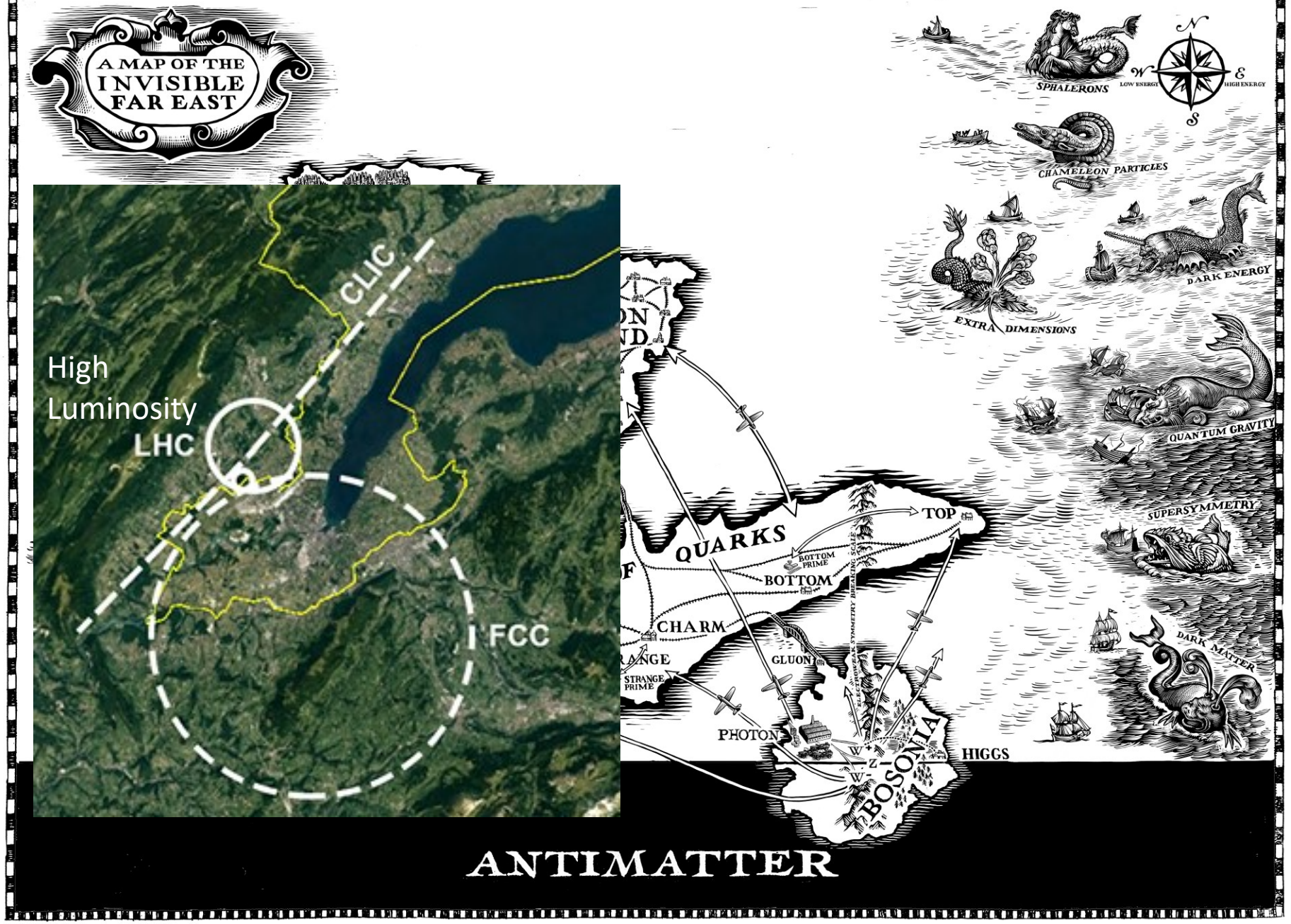
Summary…

- Complementary approaches
  - EFT fits when new states are out of reach
  - Truly “exotic” signatures (e.g. long lived/(dis)appearing particles etc) require dedicated searches
- Future
  - Keep adding more data. Hopefully the priority of these kind of measurements at LHC will increase
  - Treat correlations better, where available
  - Use precision SM theory where available: Could then also become a discovery tool



New colliders?

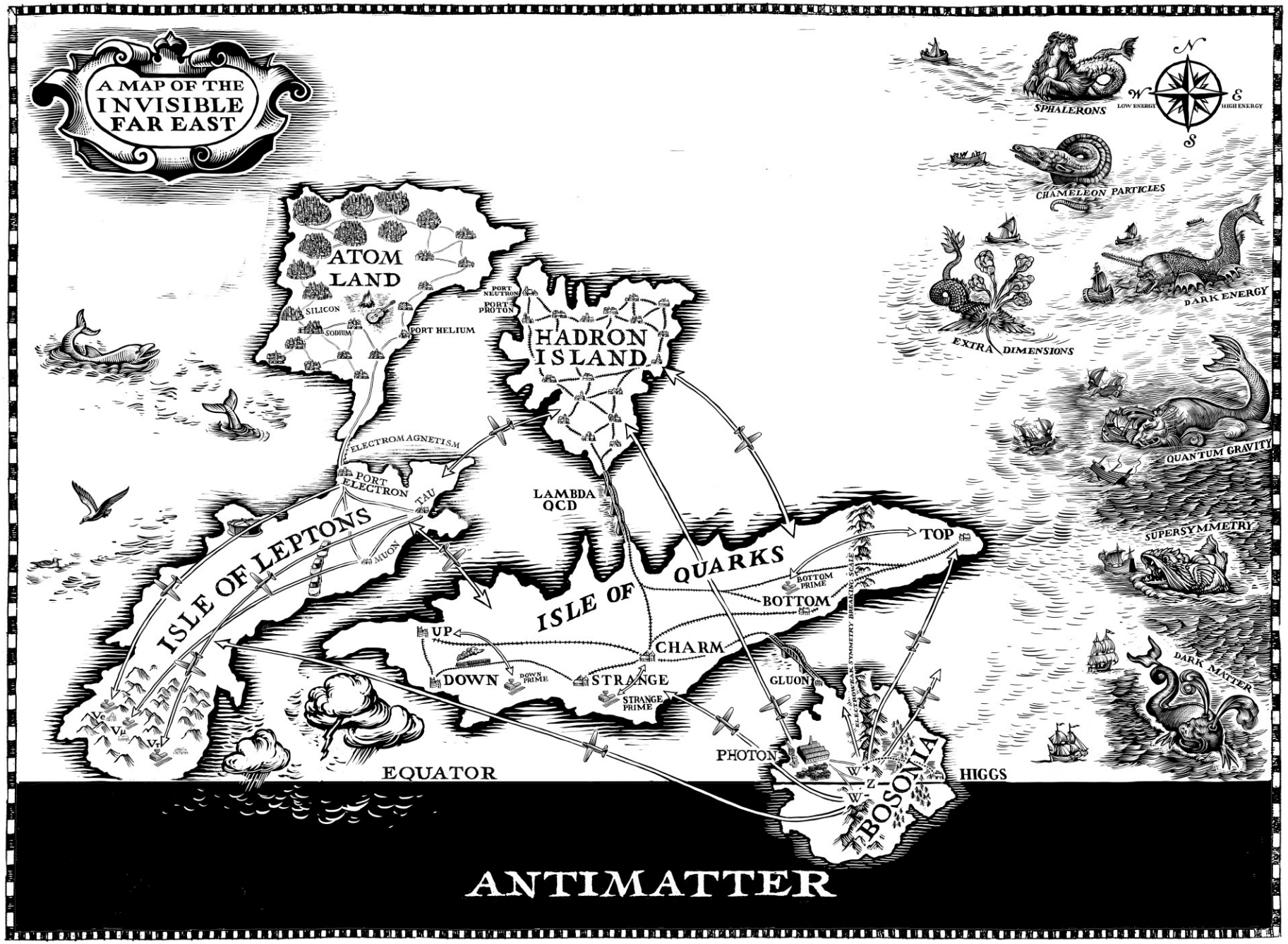
- Study the Higgs more carefully/precisely
  - 250 GeV "Higgs factory" e^+e^-, linear or circular (FCC-ee, CEPC, CLIC stage 1, ILC)
  - Other precision precision measurements e.g. top threshold at 350 GeV, or "GigaZ"
- Explore the energy frontier
  - Circular proton collider (FCC-hh/eh)
  - Circular muon collider?
- Target a specific new particle/energy
  - Linear e^+e^- collider (CLIC)


A MAP OF THE
INVISIBLE
FAR EAST
CLIC
High
Luminosity
LHC
FCC
SPHALERONS
LOW ENERGY
HIGH ENERGY
N
W
E
S
CHAMELEON PARTICLES
DARK ENERGY
EXTRA DIMENSIONS
QUANTUM GRAVITY
SUPERSYMMETRY
DARK MATTER
QUARKS
TOP
BOTTOM
BOTTOM PRIME
CHARM
GLUON
STRANGE PRIME
PHOTON
W
Z
W
BOSONIA
HIGGS
ANTIMATTER

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain


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
UP
CHARM
DOWN
DOWN PRIME
STRANGE
STRANGE PRIME
GLUON
ELECTROWEAK SYMMETRY BREAKING SCALE
PHOTON
W+
Z
W-
BOSONIA
HIGGS
EQUATOR
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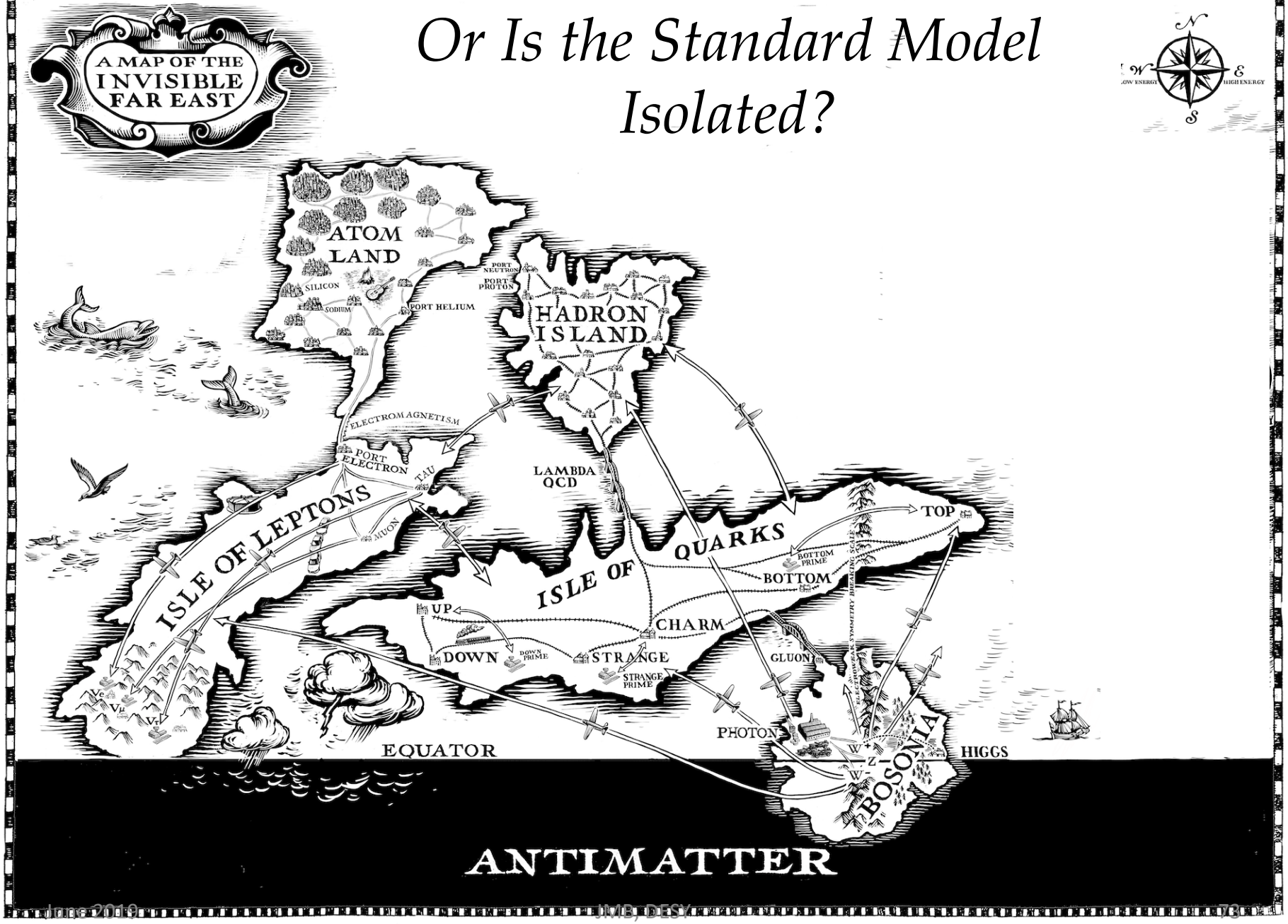
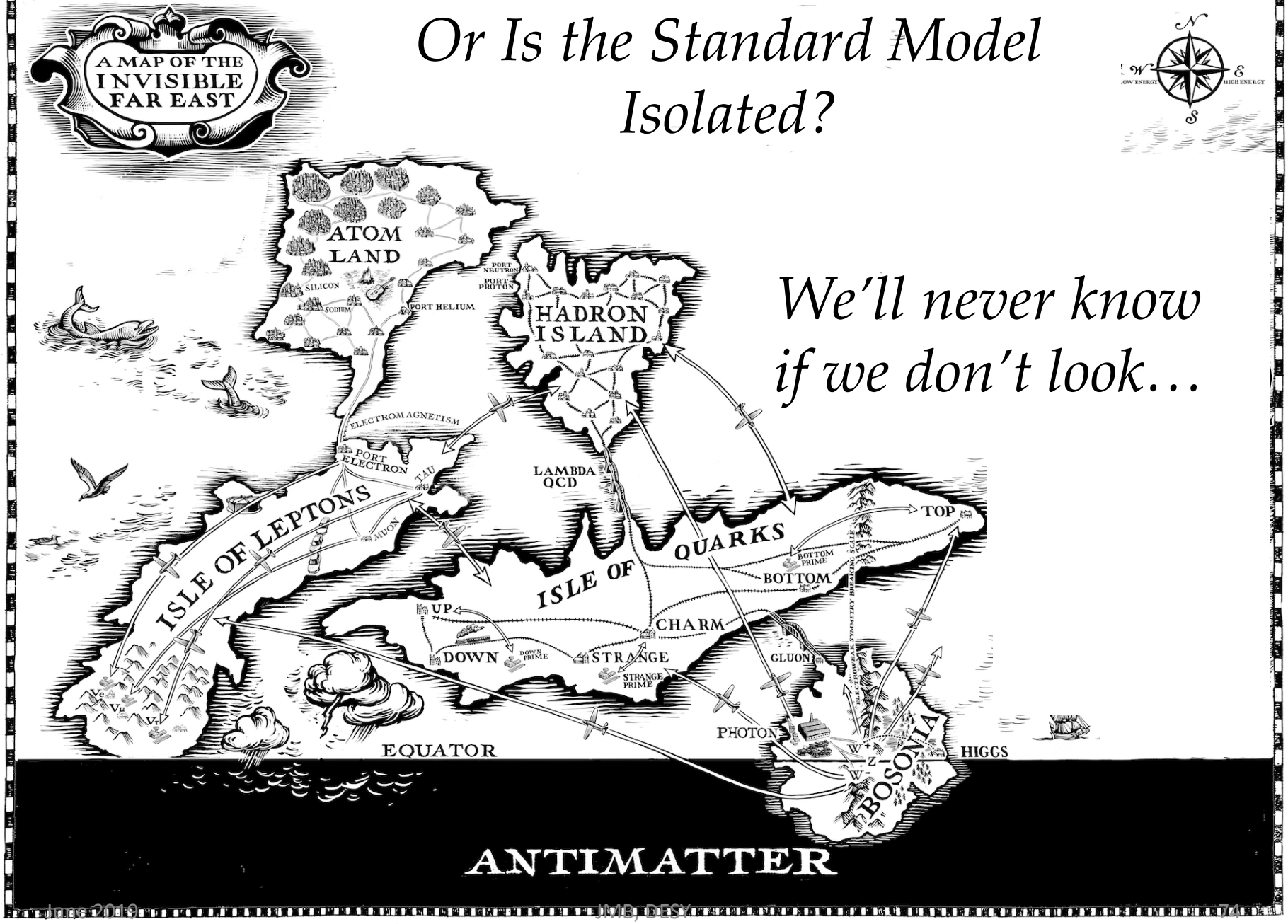
SUPERSYMMETRY
DARK MATTER
ANTIMATTER

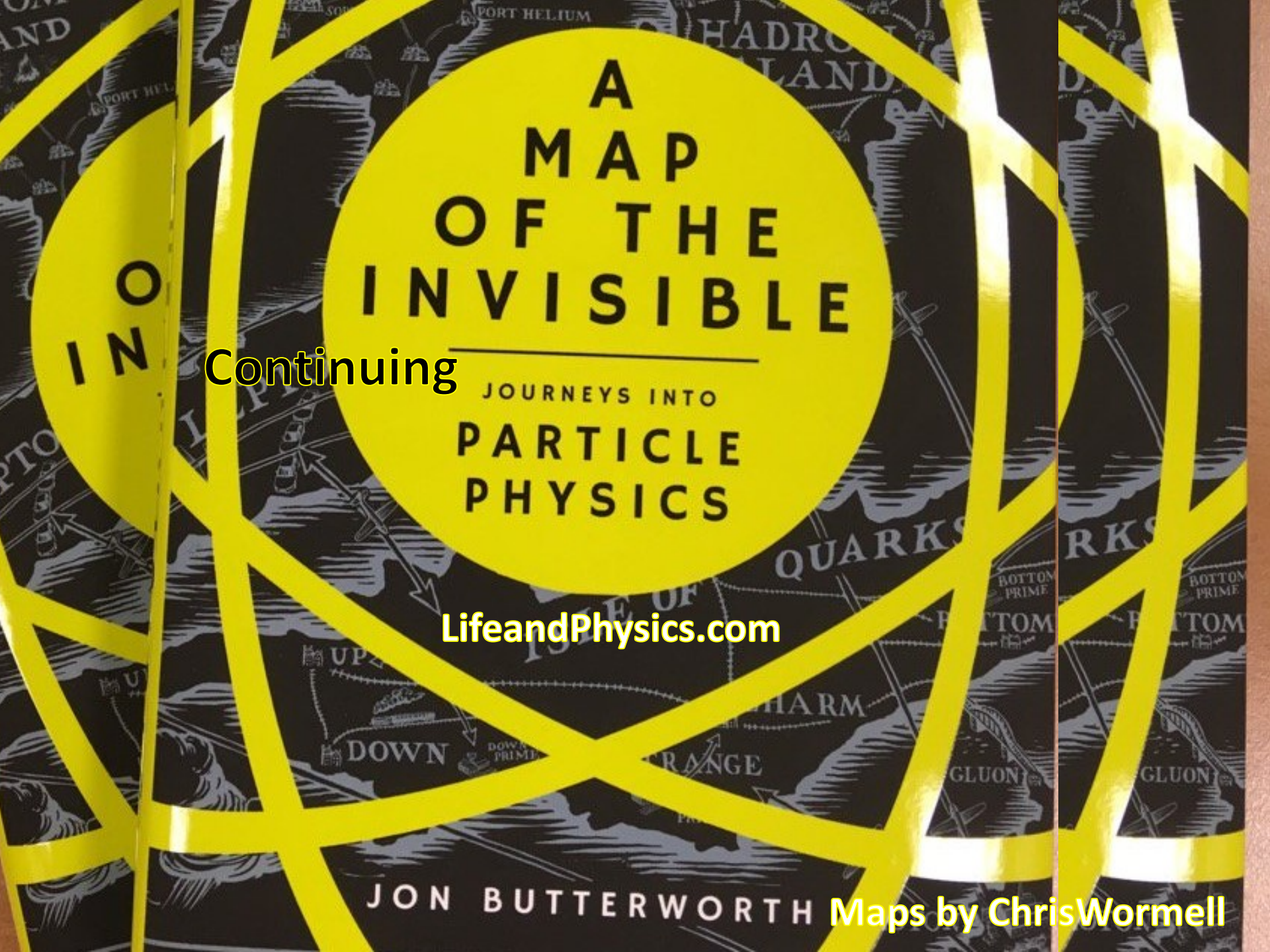
Or Is the Standard Model Isolated?



Or Is the Standard Model Isolated?



We'll never know if we don't look…



Continuing

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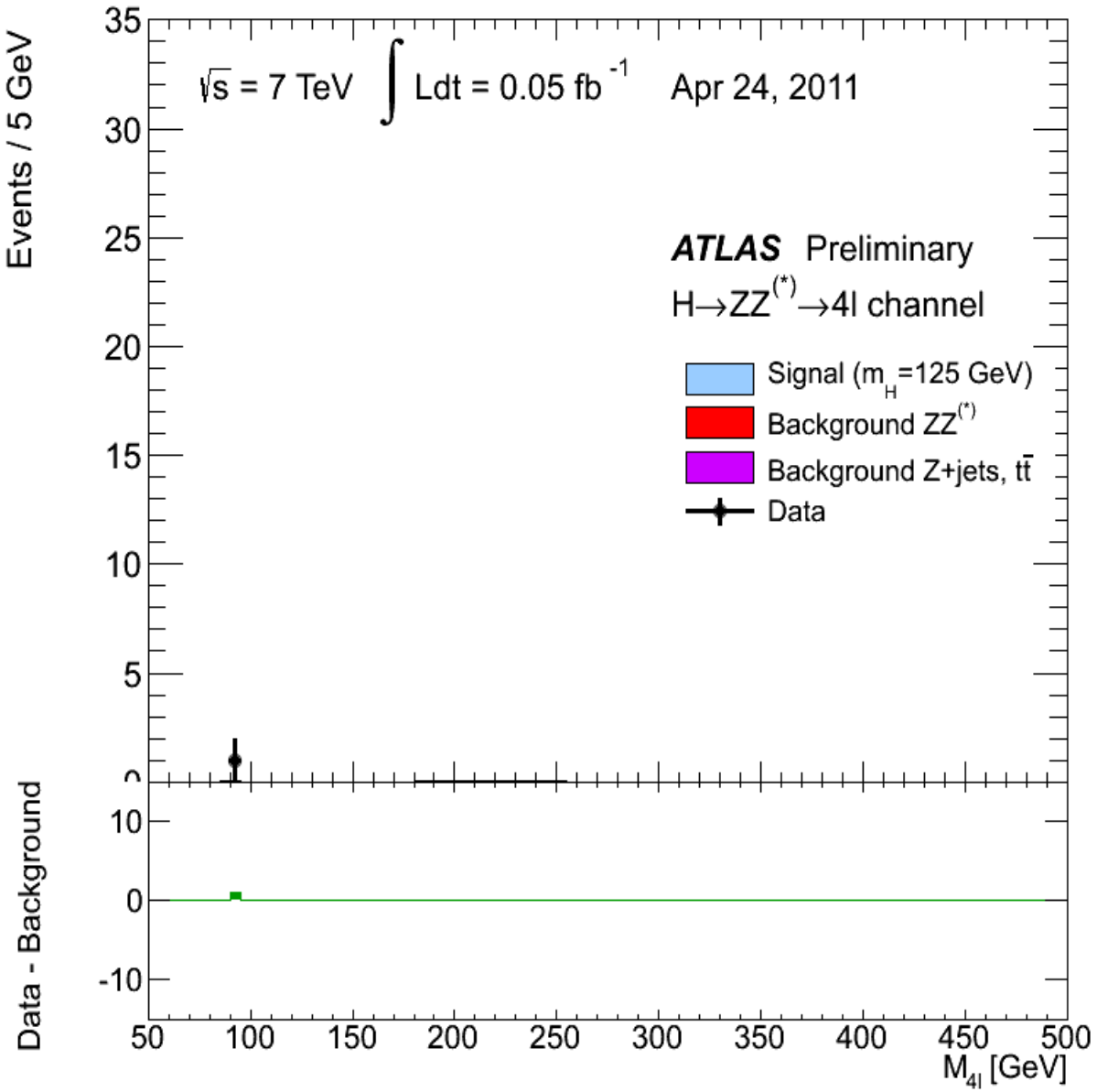
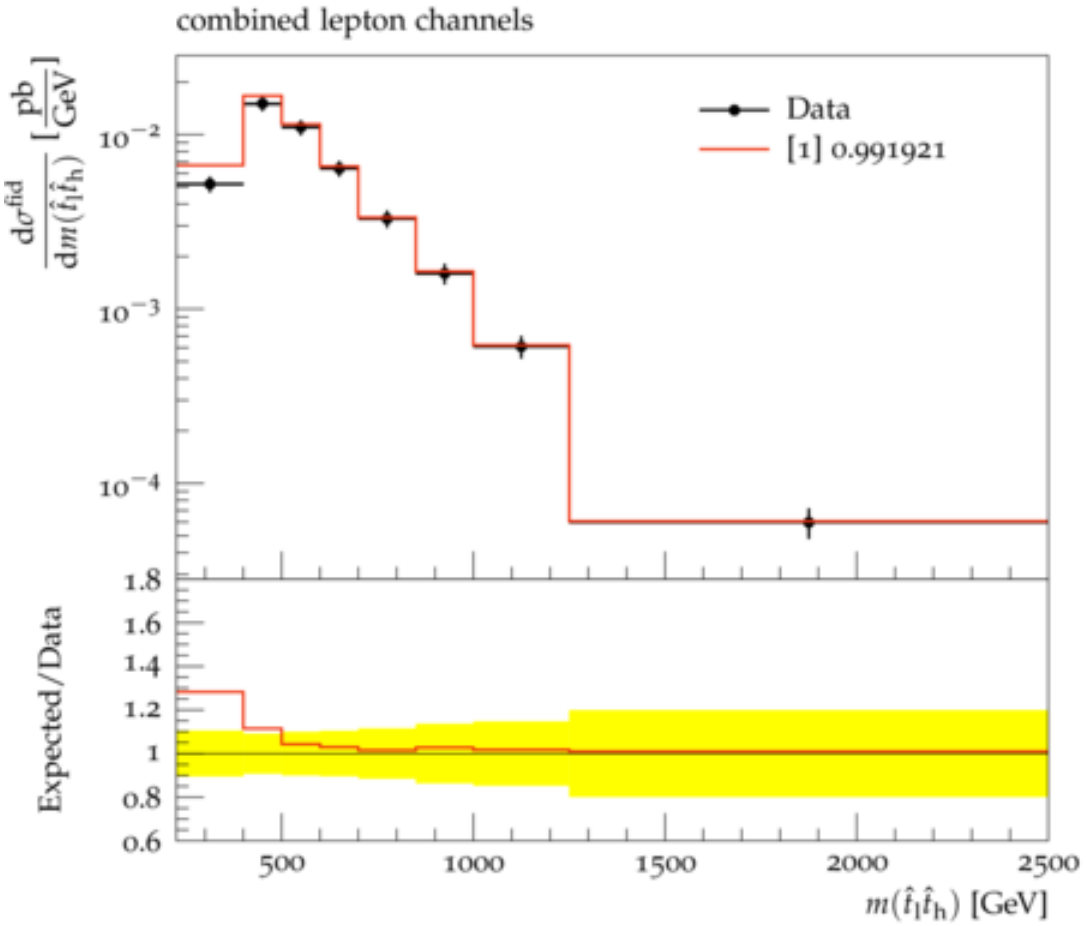

Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

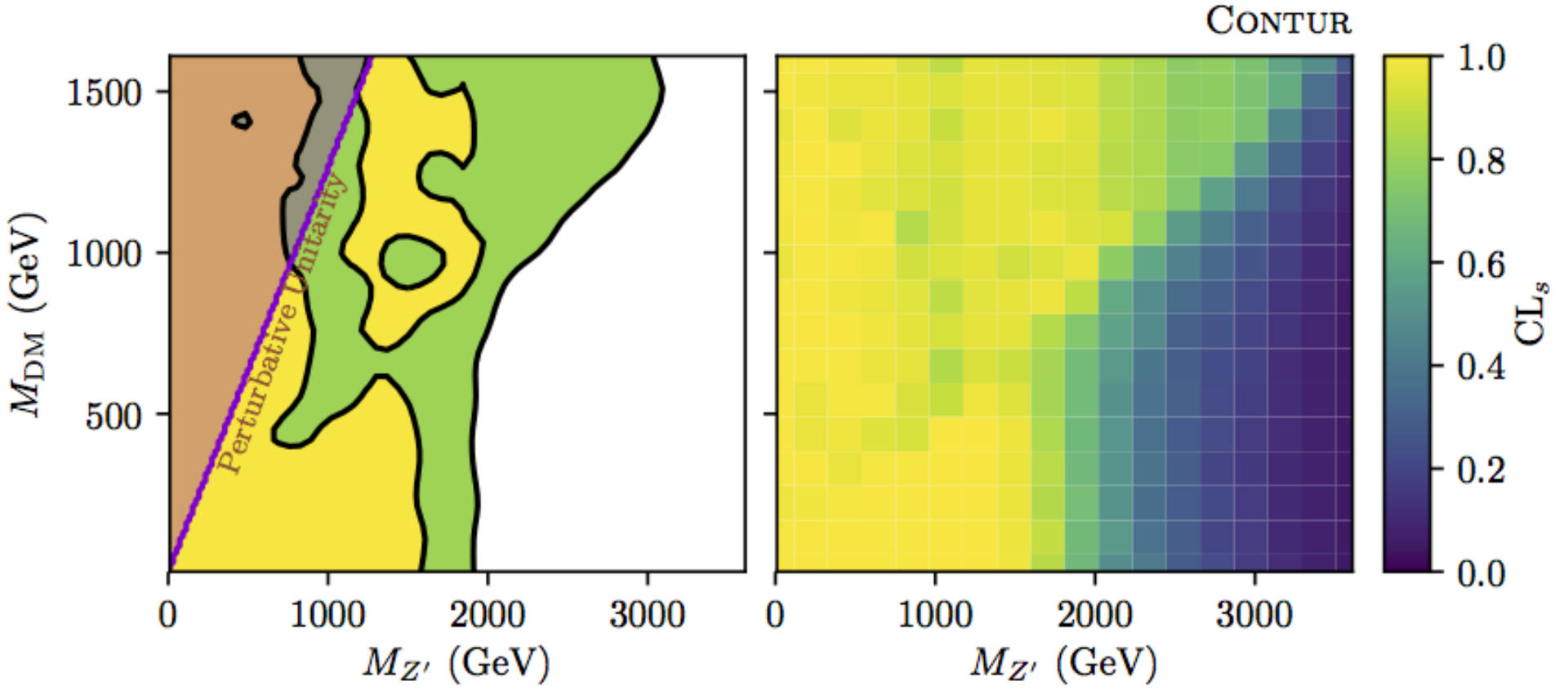

TOP
QUARKS
BOTTOM
GLUON
PHOTON
W+
Z
W-
BOSONIA

Simplified DM model coupling to all flavours



ATLAS, arXiv:1502.05923

Simplified DM model coupling to first generation quarks



Simplified DM model coupling to all quark flavours