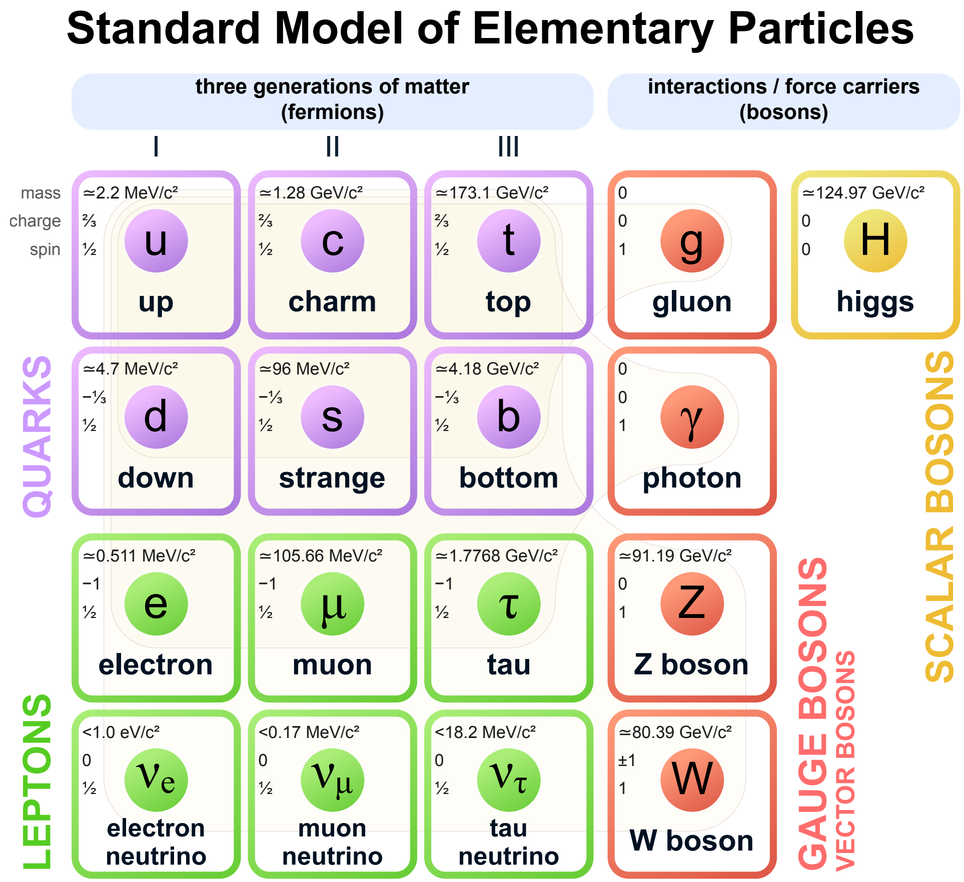
The Standard Model of Particle Physics
(and there is lots of group theory behind this)

The “particle content” of our current knowledge that describes every properly understood physical phenomenon – except gravity – together with the notion of quantum field theories is what we call the **“Standard Model of Particle Physics”** (with capital letters).



In Many ways its success is spectacular!

Anomalous magnetic dipole moment of the electron $g_e/2$
In a classical theory this quantity is zero.

The Dirac (quantum) theory predicts

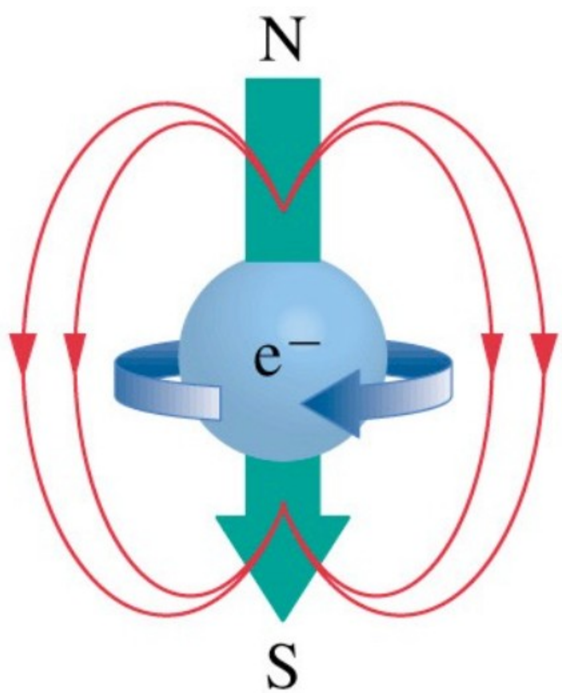
$$g_e/2 = 1$$

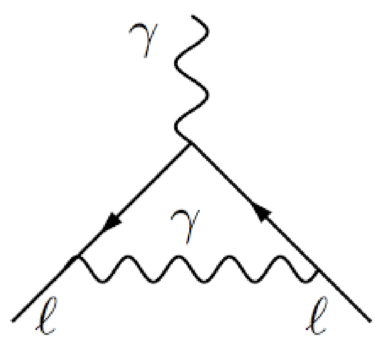
The currently most concise quantum field theoretical calculation predicts:

$$g_e/2 = 1.001\,159\,652\,181\,643\,(764)$$

The most concisely measured value is:

$$g_e/2 = 1.001\,159\,652\,180\,73\,(28)$$

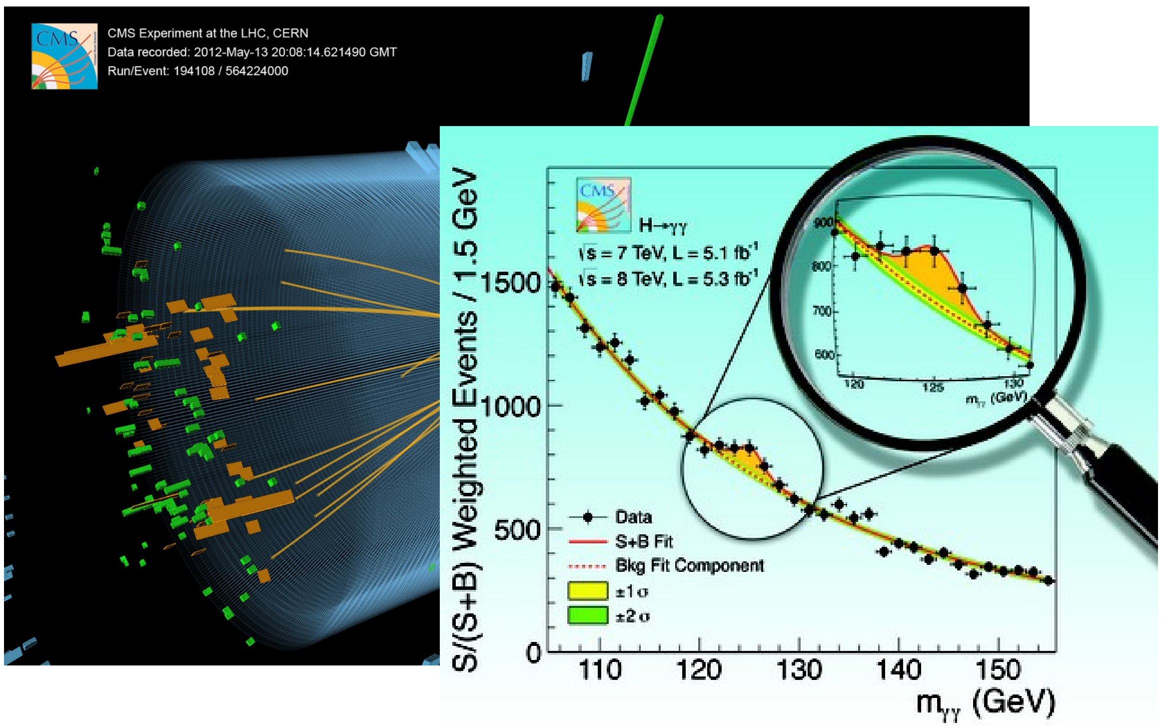


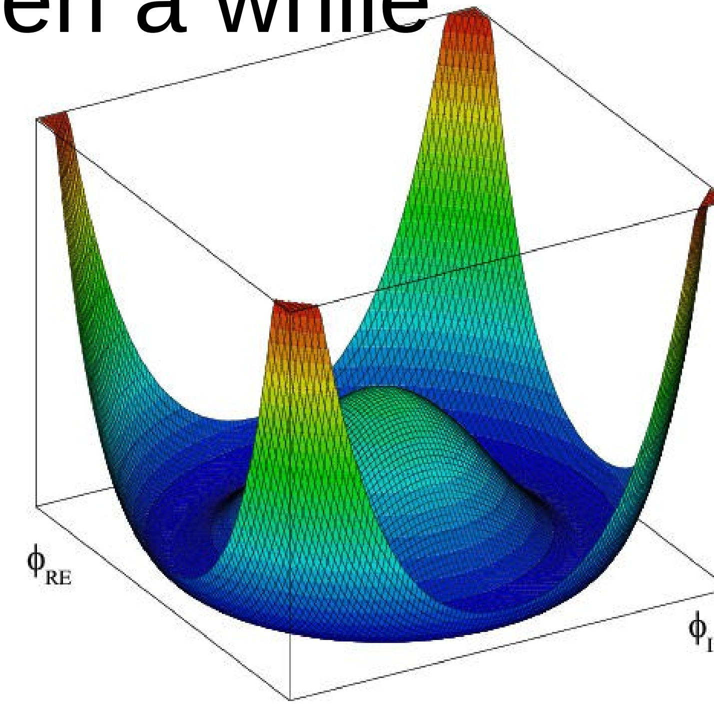


Most accurately verified prediction in all history of physics!

see e.g. arxiv:1009.4831

The latest big breakthrough in particle physics was the discovery of the Higgs boson in 2012 – it's been a while

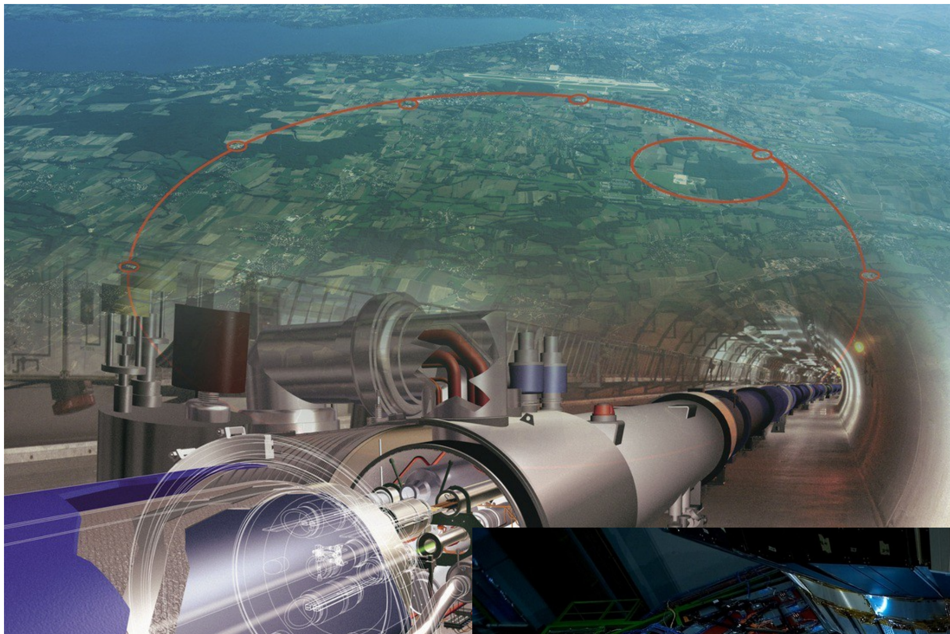


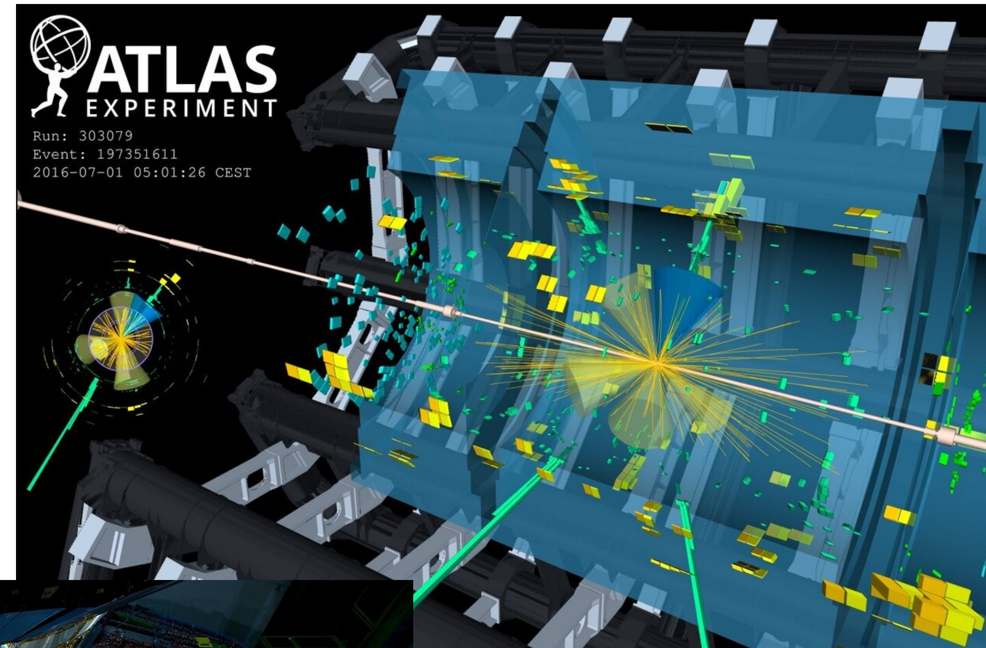


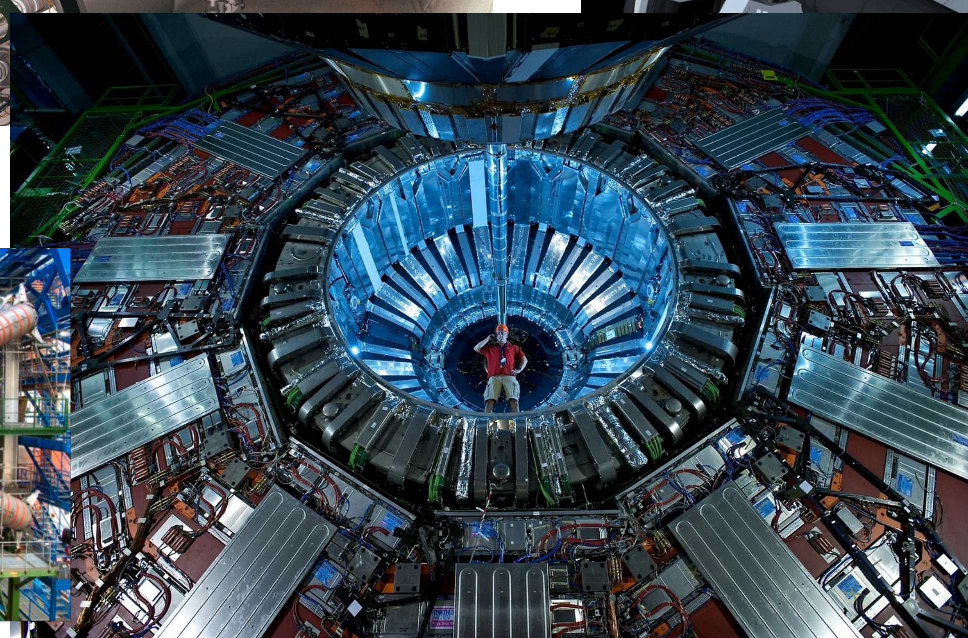
$$V(z,\phi) = \lambda(|z|^2 - \phi^2)^2$$

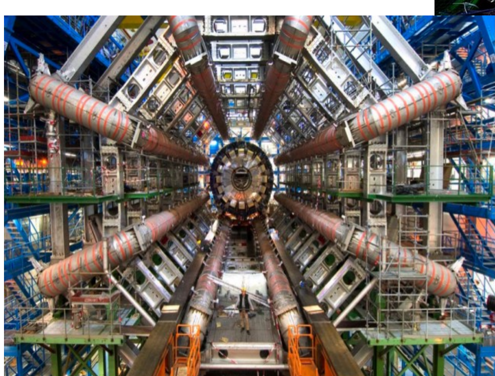
Its prediction was awarded the Nobel prize of physics 2013. The theory came with one and only one free parameter. The mass of the Higgs particle. **In terms of statistics, all we had to do was a simple, frequentist hypothesis test with a single parameter of interest**. [Except with the largest scientific experiment ever built, based on O(100 Petabytes) of data and having O(1000) different sources of "uncertainties" in our statistical model]

And here are some impressions of the hardware needed for this discovery









At the end of the day, the discovery of the Higgs boson was a likelihood ratio test (for a theory without the Higgs), but alpha was taken to be 0.0000003 – 5 sigmas from both big experiments CMS and ATLAS!
The statistical model behind the test looked like this:

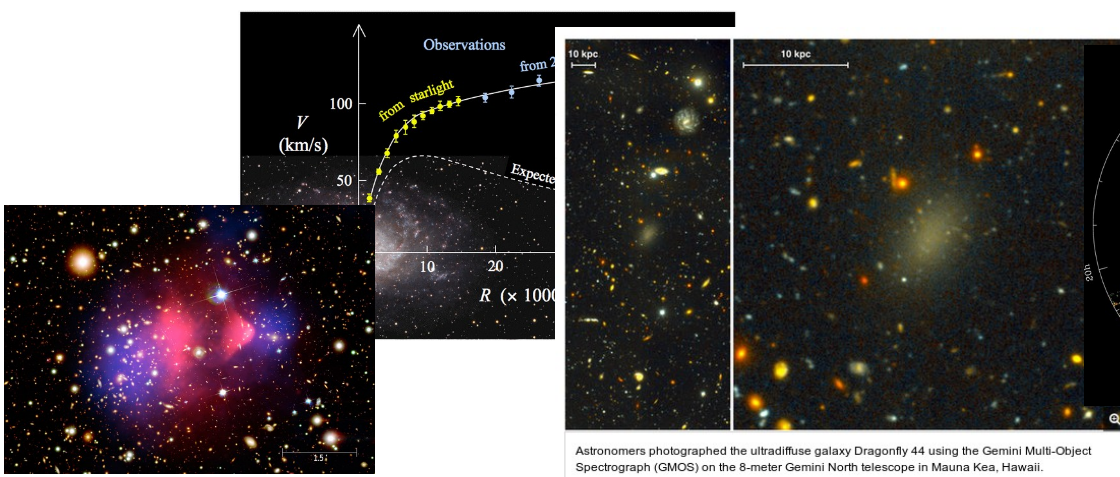
computational graph of a Higgs combination workspace

this graphic was stolen from Wouter Verkerke

But the Standard Model, in a few senses also fails spectacularly!

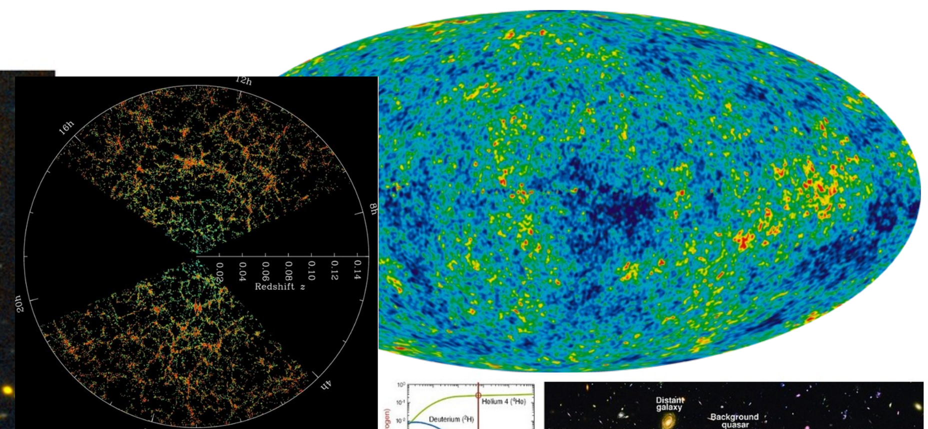
We know that it cannot be the end of the story. To name just the biggest problem that we face:

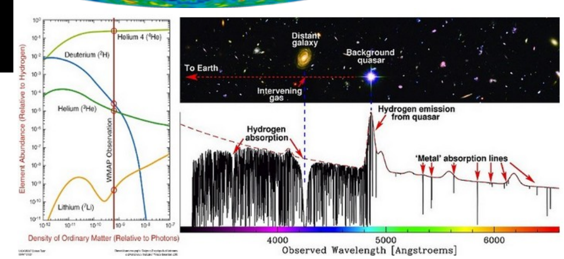
we know that 80% of the matter content and 95% of the matter-energy content of the universe is made up of stuff that we know is not accounted for within the Standard Model!



Astronomers photographed the ultradiffuse galaxy Dragonfly 44 using the Gemini Multi-Object Spectrograph (GMOS) on the 8-meter Gemini North telescope in Mauna Kea, Hawaii.

Credit: Pieter van Dokkum, Roberto Abraham, Gemini Observatory/AURA





Images credit: NASA / WMAP science team, Gary Steigman (L), of Big Bang Nucleosynthesis and the baryon-to-photon ratio; Michael Murphy, Swinburne U.; HUDF: NASA, ESA, S. Beckwith (STScI) et al. (R), of the Lyman-alpha forest from intervening intergalactic clumps of non-luminous matter.

Every one of these plots stands for a slew of solid evidence
For the statements raised above. Many of these plots came with
Nobel and breakthrough prizes in physics.

But the Standard Model, in a few senses also fails spectacularly!

(There are many more questions left unanswered by the Standard Model, but let's not go there)

And similar negative or positive terms for all (unknown) particles, all the way up to the *Planck scale!* The mass of the Higgs boson would then be

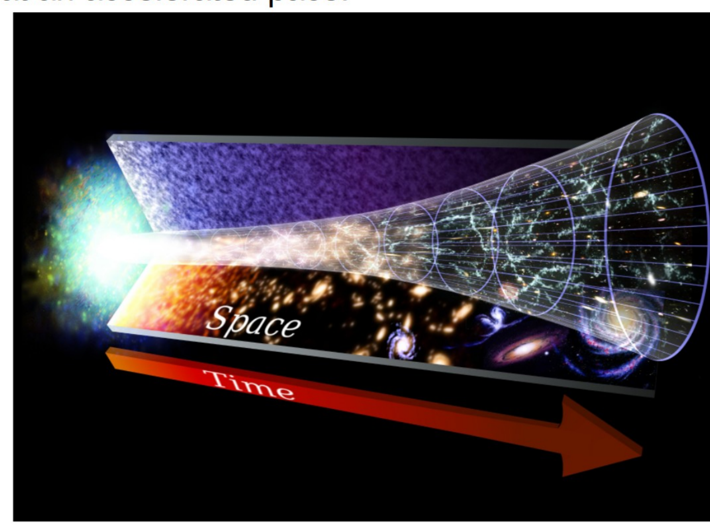
$$m_H^2 = m_{0H}^2 + \sum_{i:particles} \delta m_i^2$$

the physical, "real" Higgs mass: 125 GeV

Contributions from the heaviest hypothesized particles: $O(10^{19}$ GeV)?

- **Baryon asymmetry:** the whole universe seems to consist almost entirely of matter, not anti-matter. None of the known physics can explain this asymmetry.
- **Dark energy:** not only is the universe expanding (that's well accounted for within the Big Bang theory), but it is accelerating at an accelerated pace! Interpreted as a "dark" energy, it would account for almost 70% of the matter-energy content of the universe!

While current observations can be well described with a non-zero cosmological constant, a deeper understanding of the origin of this dark energy remains elusive.

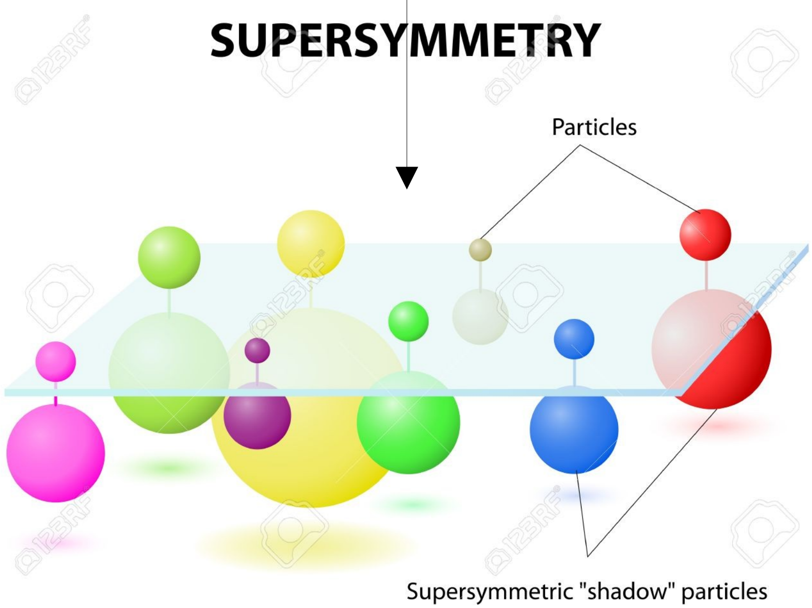


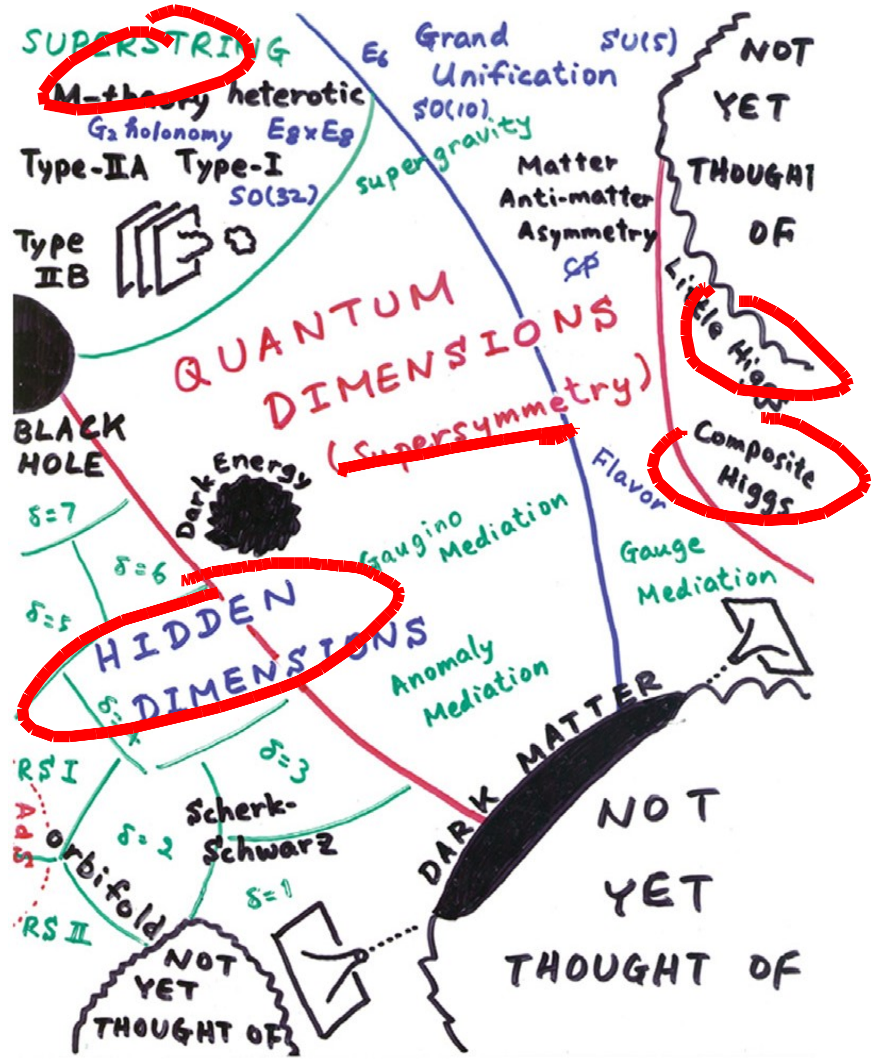
- **Strong CP Problem:** why does quantum chromodynamics (QCD) not violate CP invariance? Is the solution to this problem also the solution to the dark matter problem?

The Standard Model cannot be the end of the story

We obviously do not actually know what the more fundamental theory will look like. But suffices to say that:

-) we actually have quite a slew of ideas
-) many of these ideas predict that there exists a “clone” of some or all the Standard Model particles, e.g. the “supersymmetric partner particles” in supersymmetry





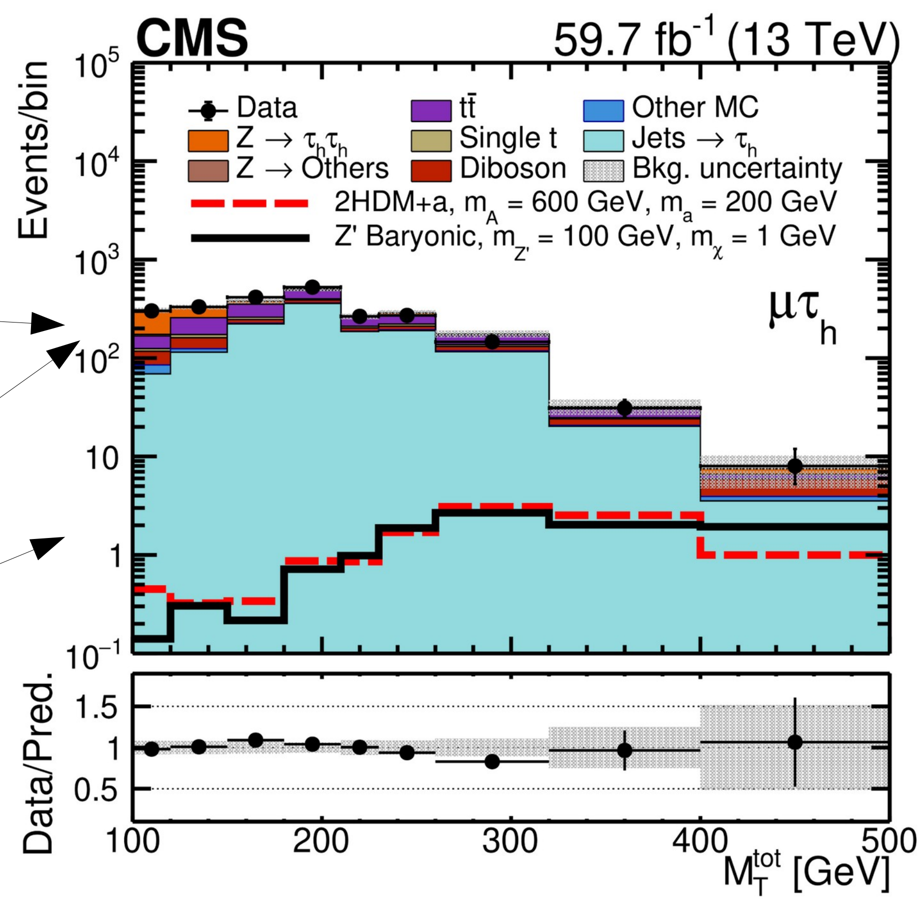
So, we have been searching for hints of new physics

-) Of all the events ("pictures") produced and stored at the LHC, **select** the ones that have some characteristics indicative of new physics. **Count** them. **Compare** with the Standard Model Prediction. Compute how many more you would expect, if you new physics model was realized in nature. Make a statistical statement about your physics model.

filled histograms: your expected count from the Standard Model

Black dots: your observed counts

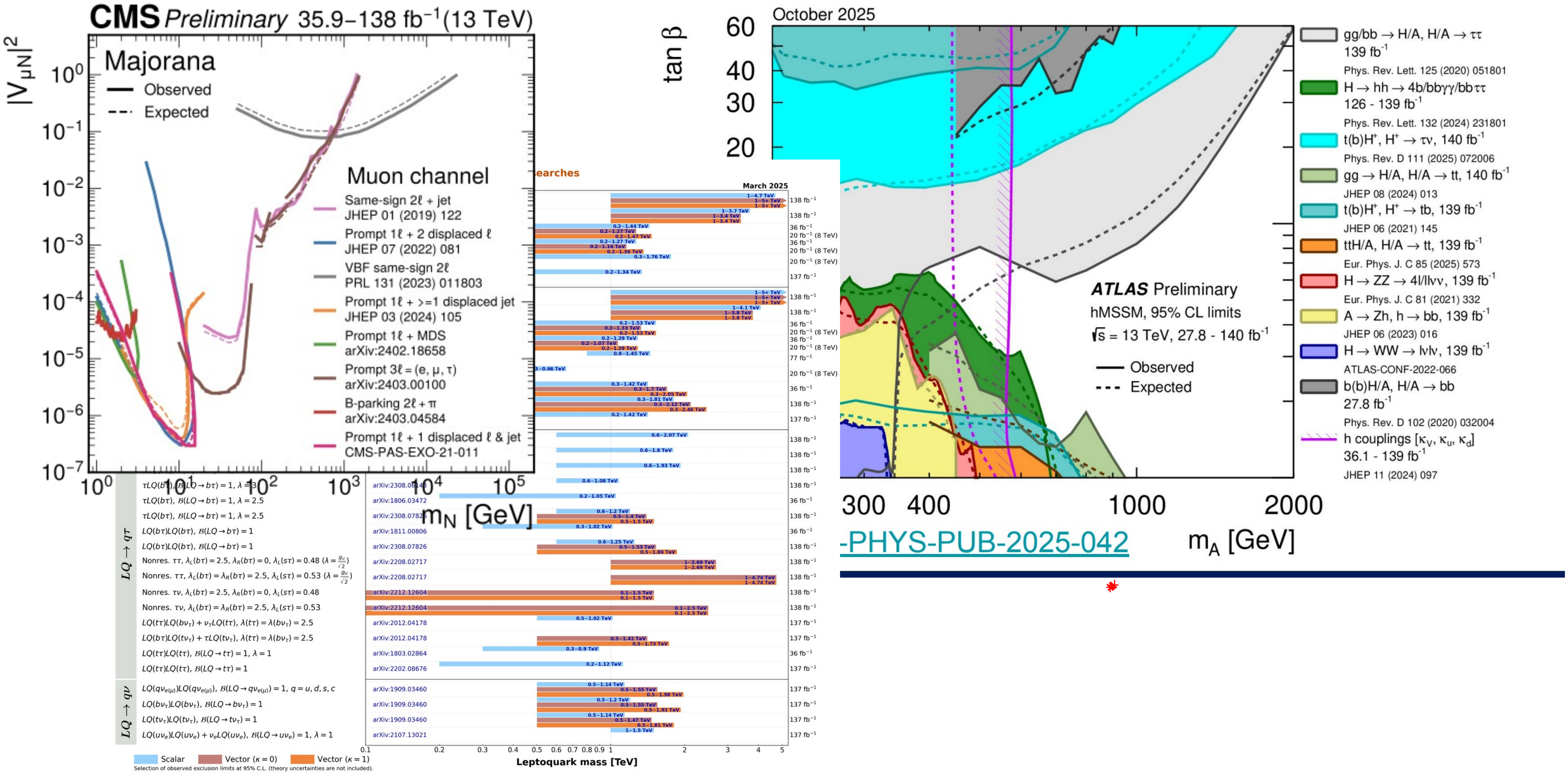
Red dashed line: your predicted additional count **from a specific new physics model**



bins: different selections

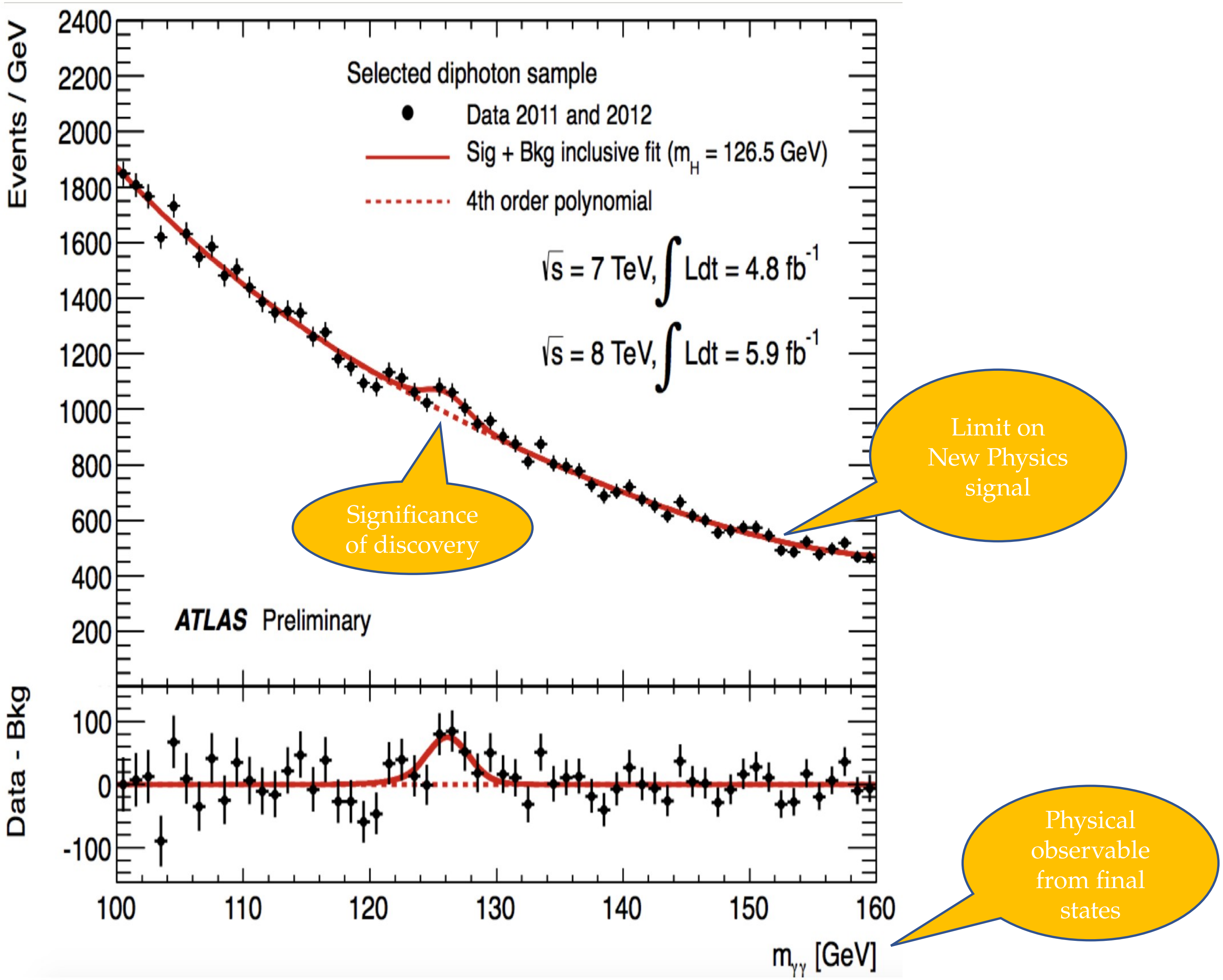
CMS-SUS-23-012

And we have performed and published quite the collections of such searches

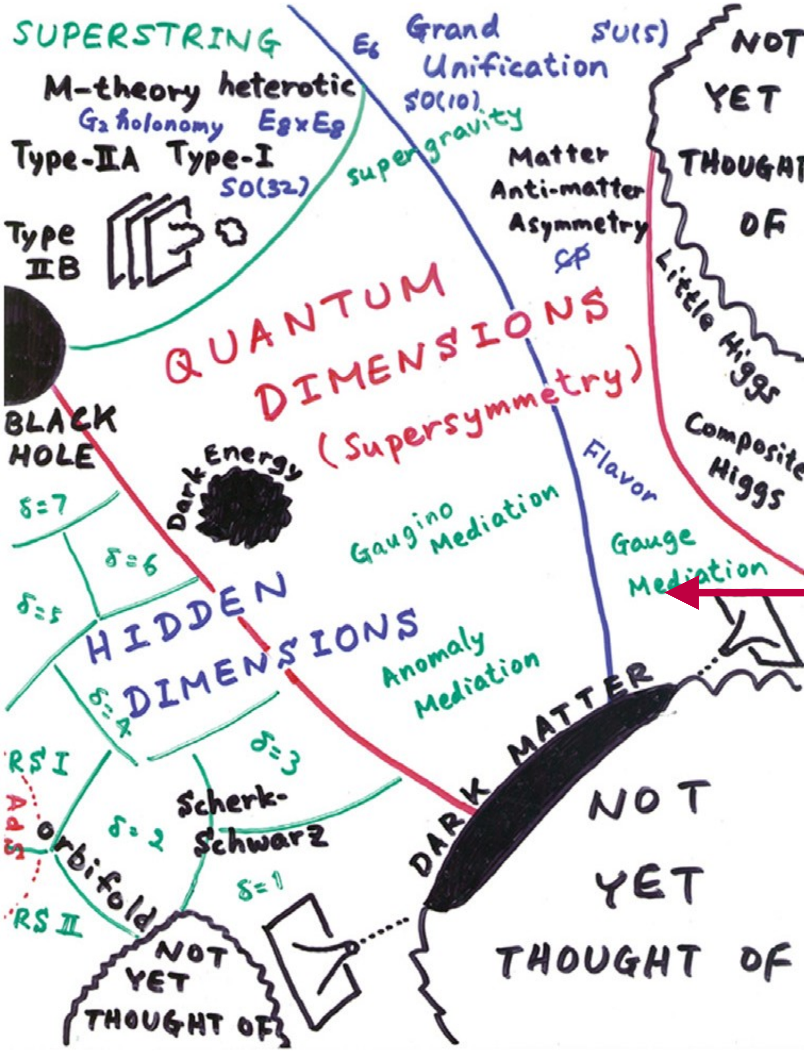


We have literally! thousands of publications of searches for new physics at the LHC alone. Let alone all satellite-based experiments, dark matter experiments, non-LHC collider experiments, and so on.

Exercise 6.3-6.5



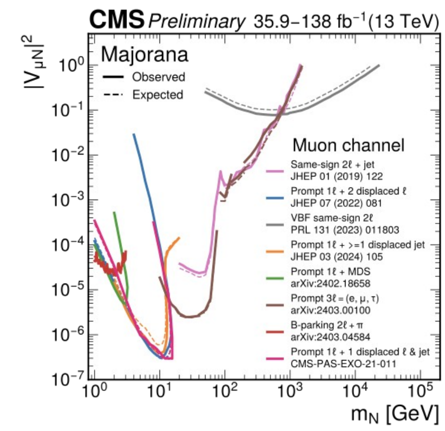
Problem statement:

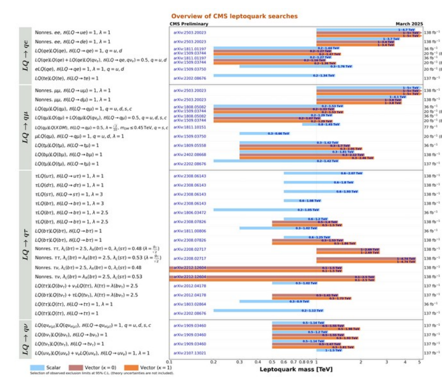


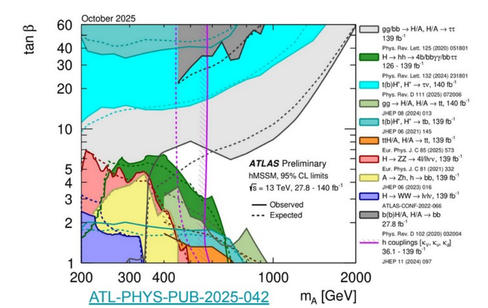
How shall we confront this

with this

?







In a small, ~ 20 people in a few countries, collaboration called SModelS we made it our job to collect as many results of searches of new physics as we can.

What can we do with this collection of many Individual results? **Meta Statistics!!**

https://smodels.github.io/docs/ListOfAnalyses310

If no new physics is in the data, the significances of all these searches should follow a Standard Normal distribution

Stats by run, experiment, type

Run 2 - 13 TeV

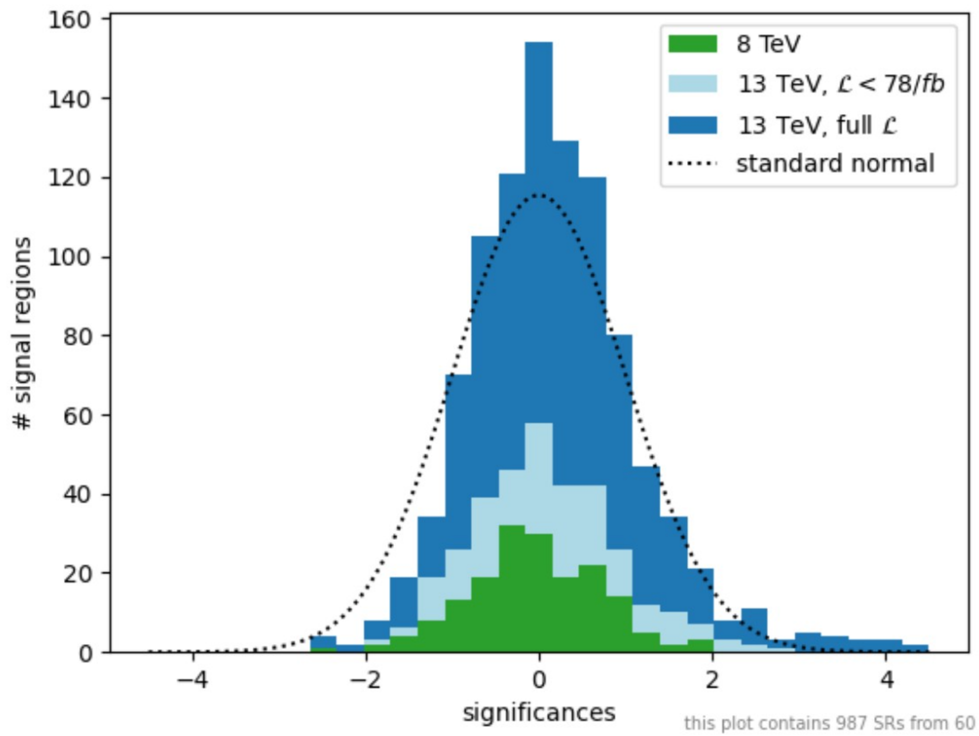
In total, we have results from 45 ATLAS and 44 CMS 13 TeV searches.

- ATLAS efficiency maps: 29 analyses, 100 (of which 14 LLP) results, 1353 individual maps
- ATLAS upper limits: 40 analyses, 97 (of which 4 LLP) results
- CMS efficiency maps: 11 analyses, 67 results, 3885 individual maps
- CMS upper limits: 40 analyses, 153 (of which 3 LLP) results

Run 1 - 8 TeV

In total, we have results from 16 ATLAS and 20 CMS 8 TeV searches.

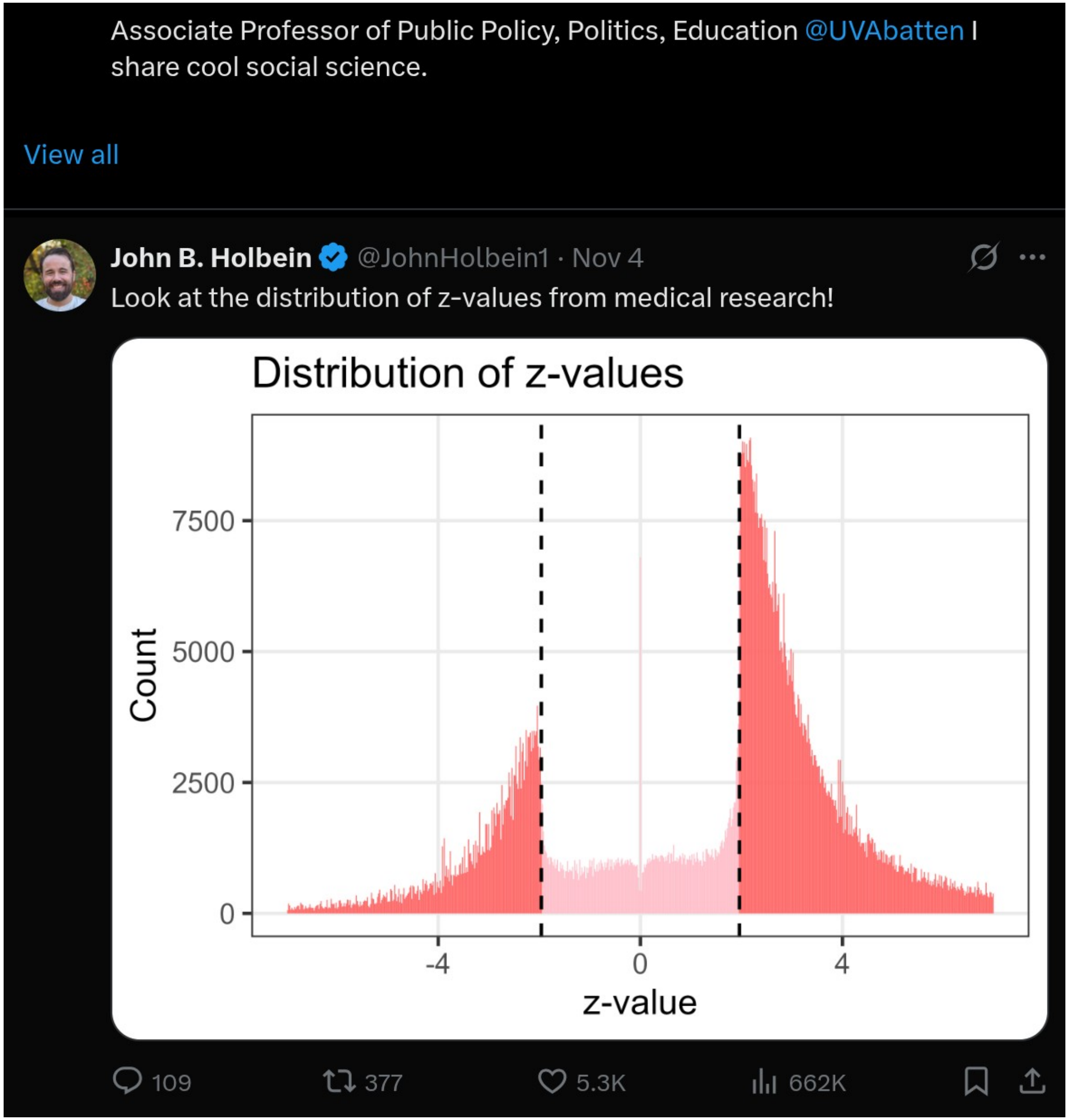
- ATLAS efficiency maps: 11 analyses, 36 results, 274 individual maps
- ATLAS upper limits: 14 analyses, 35 results
- CMS efficiency maps: 9 analyses, 47 (of which 9 LLP) results, 980 individual maps
- CMS upper limits: 18 analyses, 58 (of which 3 LLP) results

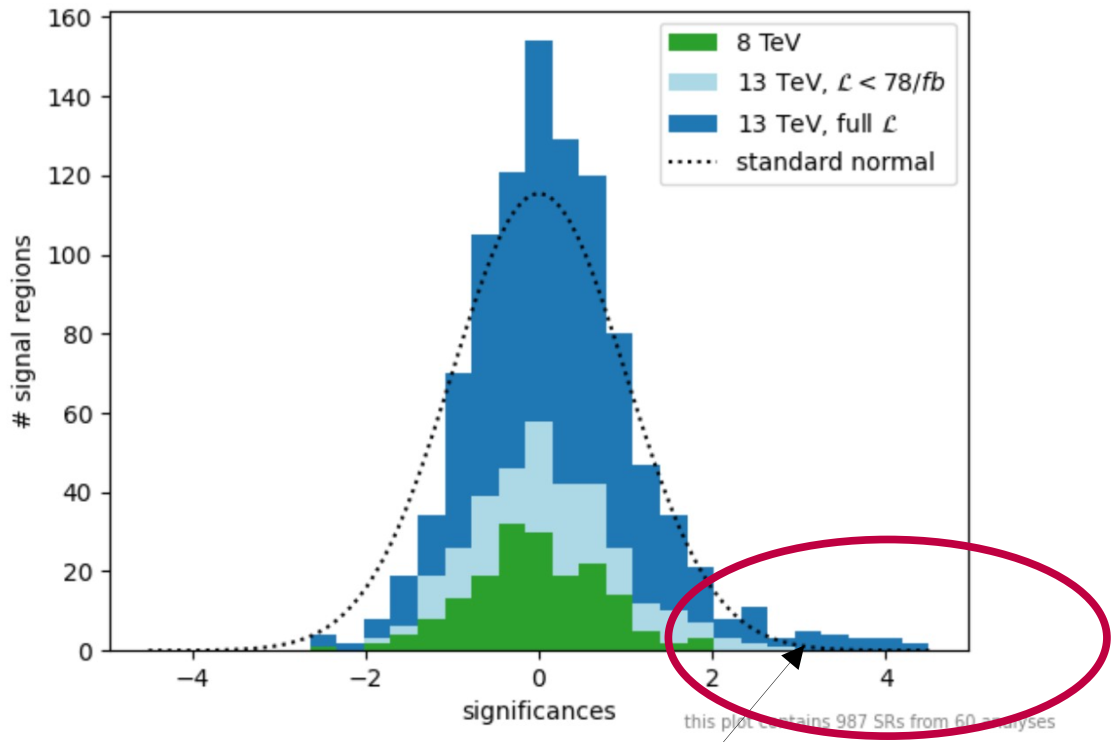


this plot contains 987 SRs from 60 analyses

Plot: Significances with respect to the Standard Model hypothesis, for all signal regions (1). A standard normal distribution is expected if no new physics is in the data. New physics would manifest itself as an overabundance of large (positive) significances.

Interlude: Meta Statistics in Medical research

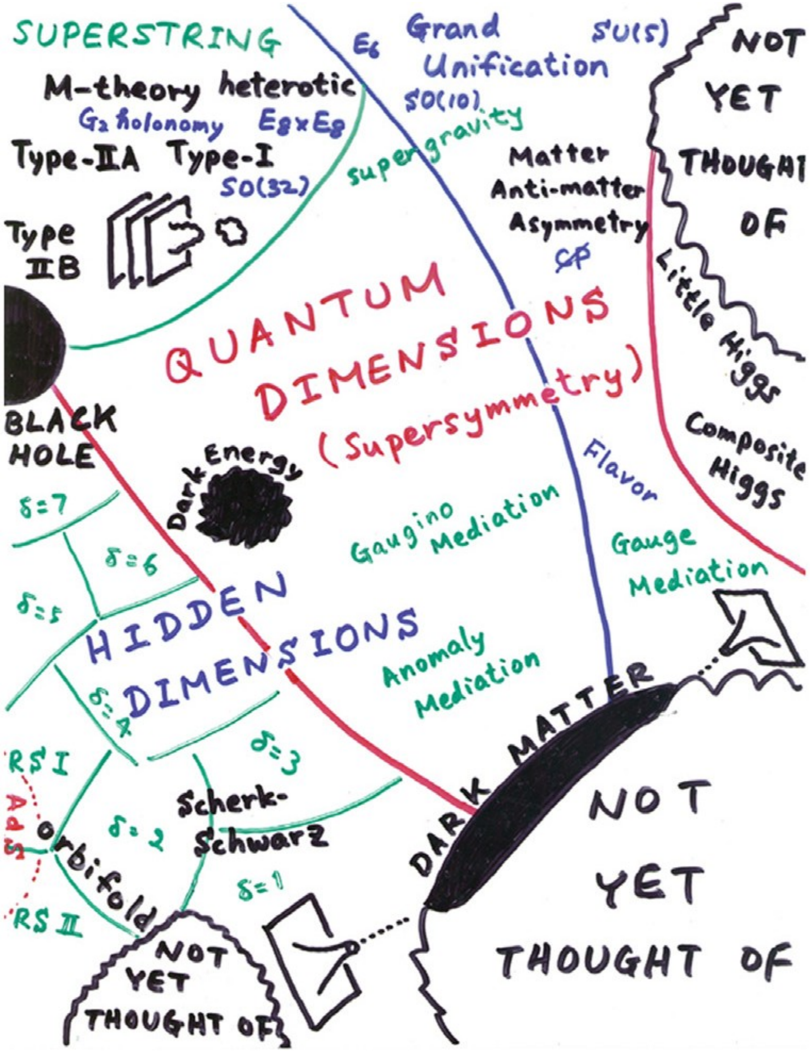




Plot: Significances with respect to the Standard Model hypothesis, for all signal regions (1). A standard normal distribution is expected if no new physics is in the data. New physics would manifest itself as an overabundance of large (positive) significances.

If new physics were to slowly seep into our publications, it would manifest as an overabudance of too large significances

But how find which part of this landscape best matches the excess?



Top-Down Approach

Bottom-Up Approach

Construct a NP Lagrangian

↓

Compute physical observables such as masses, cross sections,..

↓

Compare with data -> get significance/ limits on observables

Infer NP Lagrangian

↑

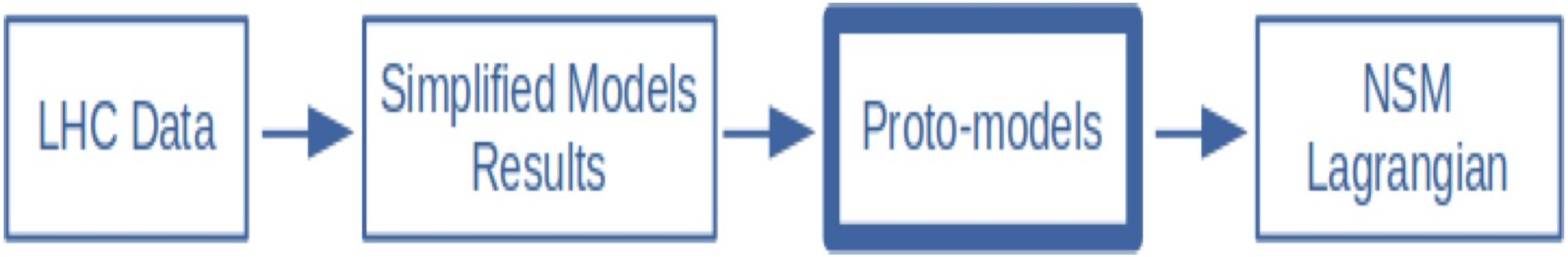
Fit (learn) physical observables - masses ,cross sections, ….

↑

Take data

Bottom-up Approach

Given the data, can we build the next Lagrangian?



- Develop a statistical learning algorithm that identifies **potential excesses** amongst the published LHC data.
- Build candidate **'proto-models'** from them

Bayesian Inference

The goal is to calculate the posterior distribution of our theory parameter space:

$$L(\theta_{NP}|x) = \frac{p(x|\theta_{NP})\pi(\theta_{NP})}{\int p(x|\theta_{NP})\pi(\theta_{NP})\, d\theta_{NP}}$$

Calculation in high dimension parameter spaces becomes tedious

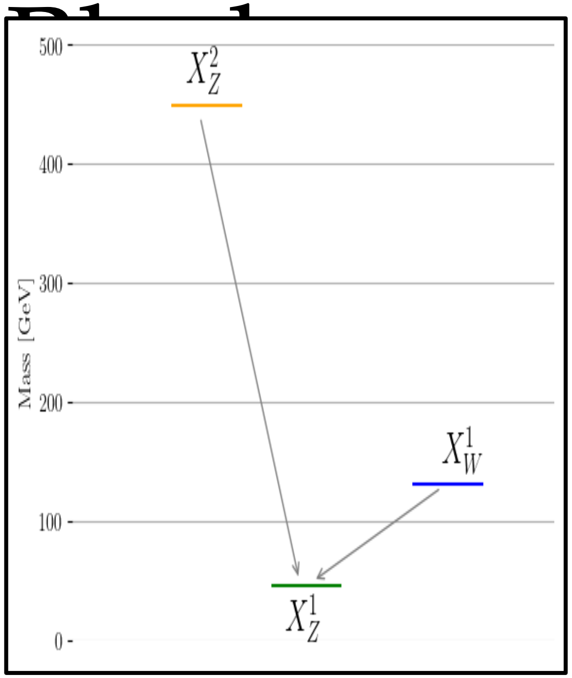
In MCMC methods, we do not need to know the explicit form of the denominator, as we are only interested in calculating the ratio of likelihoods in different time steps -> acceptance probability

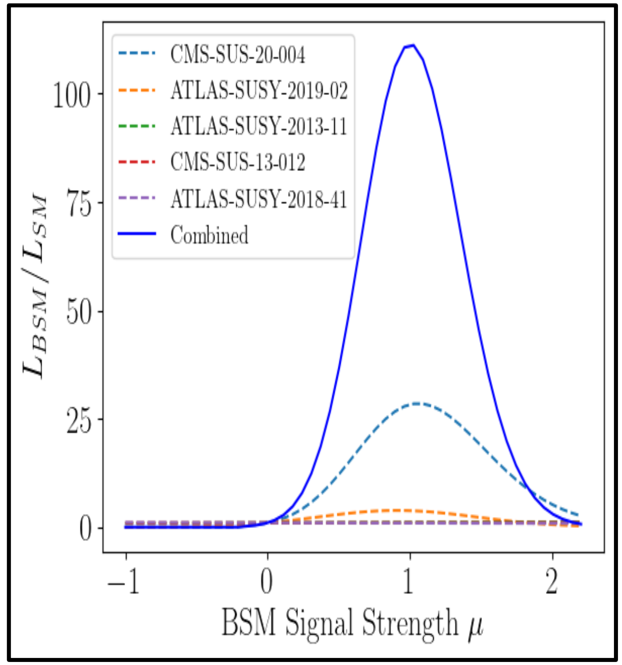
Our Method

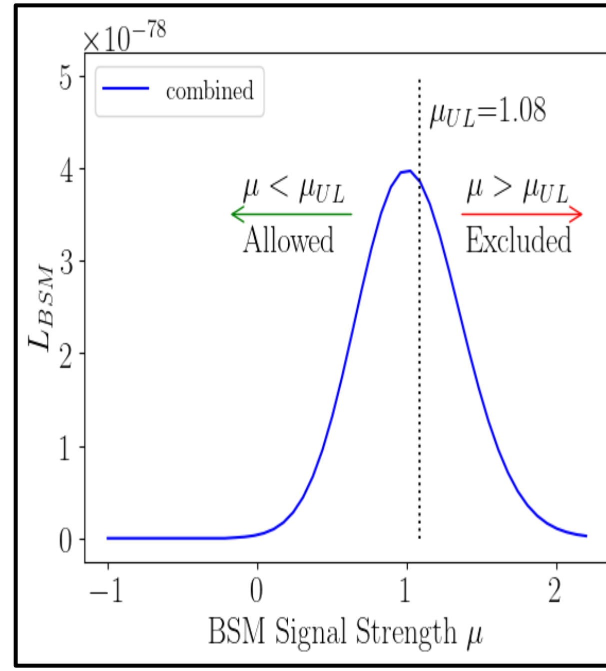
algorithm (the ***walker***) combs through proto-model parameter
order to identify the models that best fit the data.

Parameter space:

- Number of NP particle content
- Masses of particles
- Production-cross sections
- Decay Branching ratios







Builder

Creates proto-models, randomly adding or removing new particles and changing any of the proto-model parameters.

Combiner

Identifies possible combinations of experimental results and constructs a combined likelihood for the proto-model

Critic

Checks the compatibility of the proto-model against the database of results

Test Statistic

Since we are walking with varying dimensions, we need the acceptance probability i.e the probability to accept the new step to take into account the degrees of freedom at each step

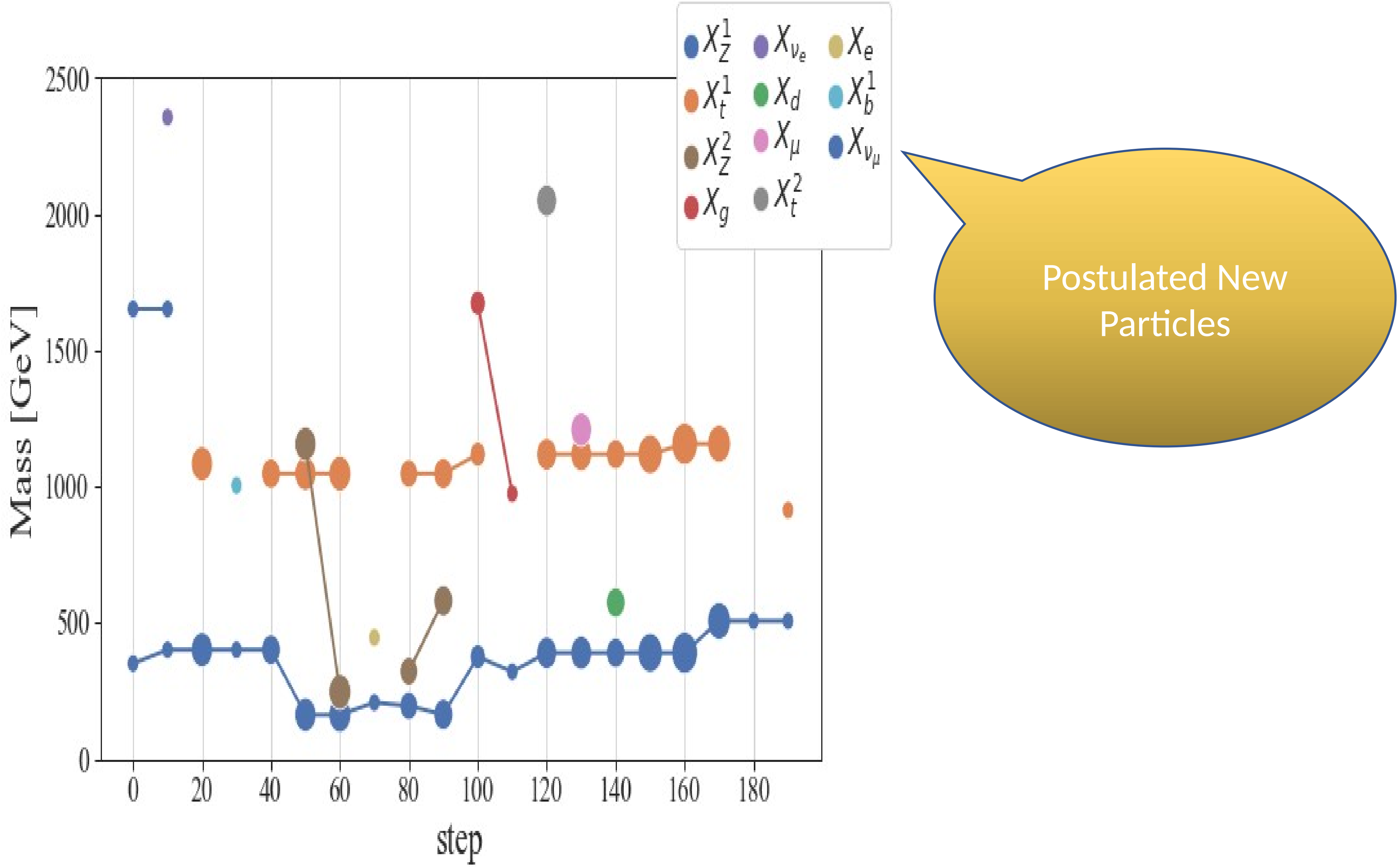
⇒ Compute a test statistic K which is defined as:

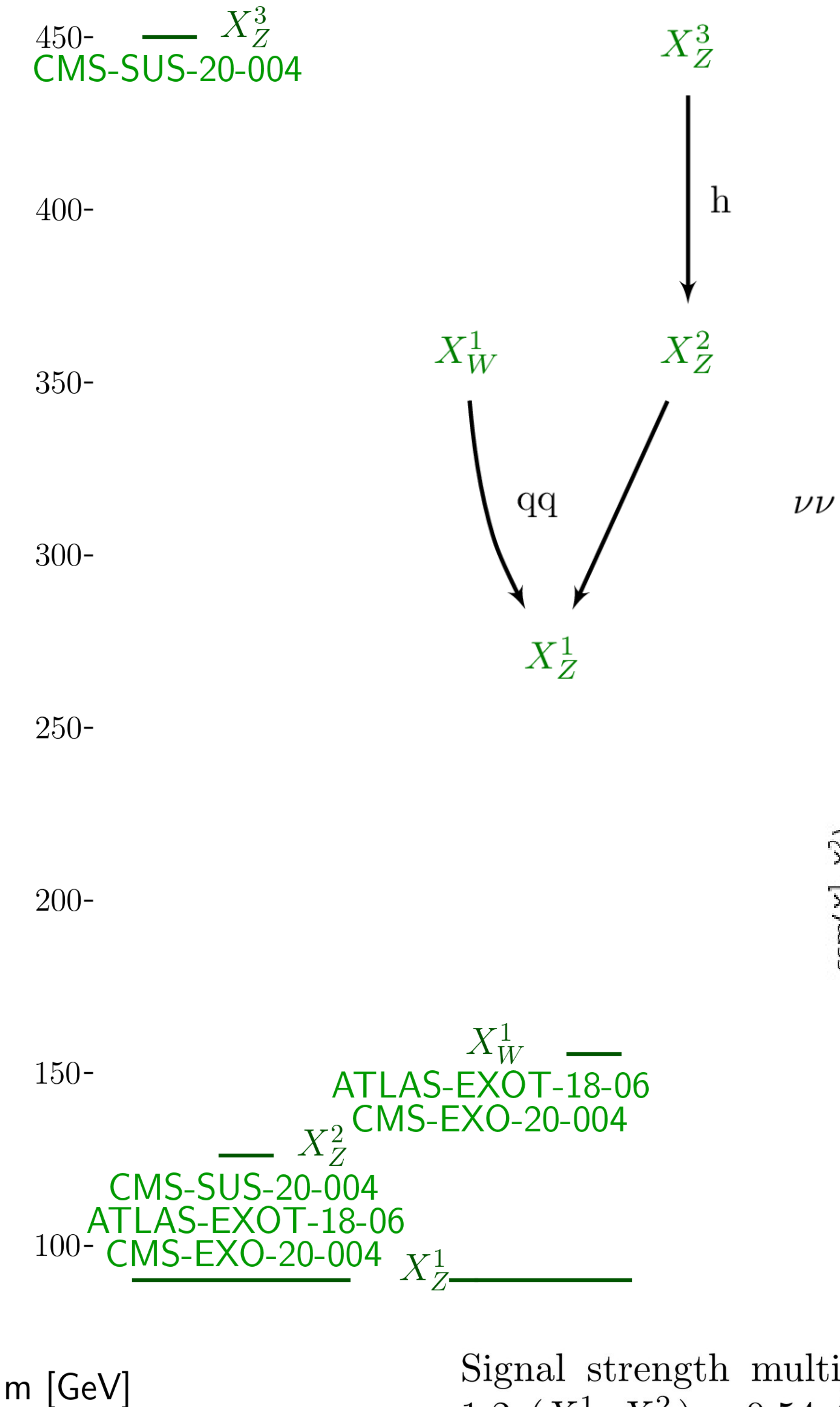
$$K \propto \log\frac{L_{BSM}}{L_{SM}} + \text{penalty\_term(d.o.f)}$$

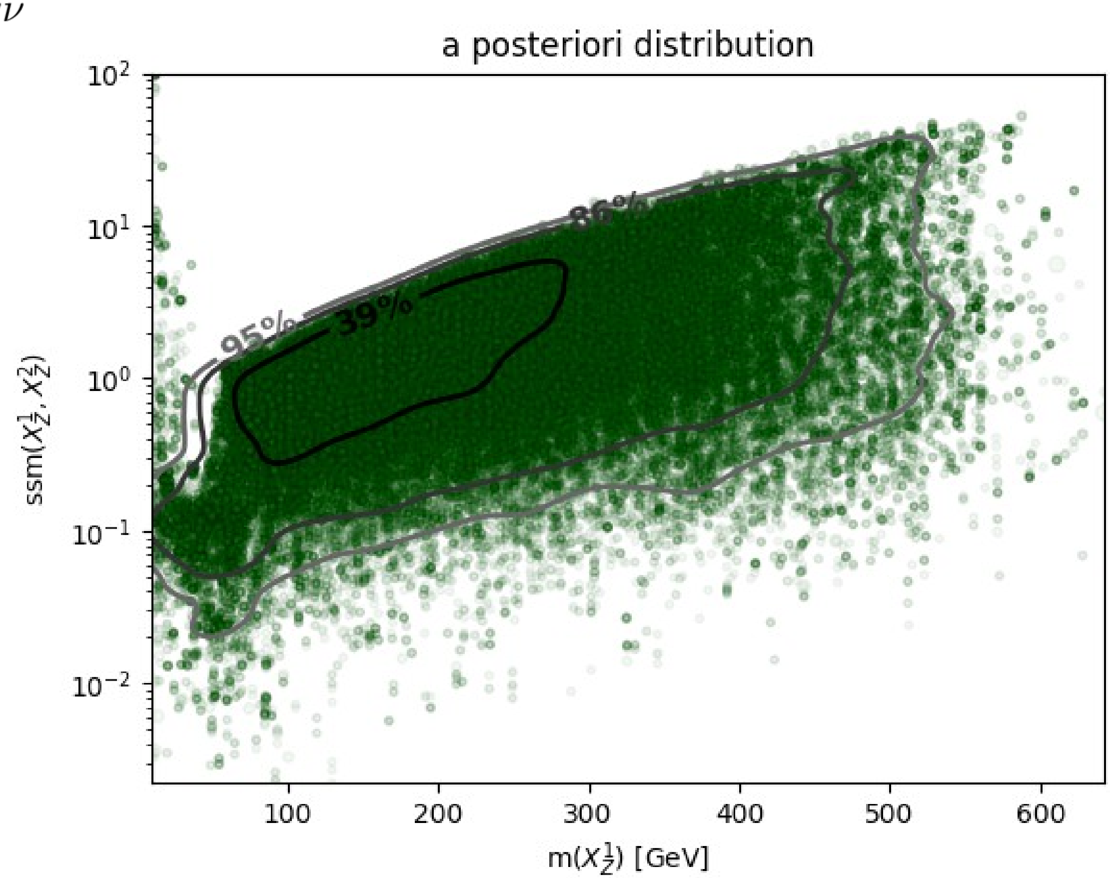
where we penalize for extra degrees of freedom

If K is larger than the previous step, we accept the protomodel, otherwise we revert back to the previous proto-model with a certain probability.

Example of a walk







Signal strength multipliers: $(X_Z^2, X_Z^3) = 13; (X_Z^2, X_W^1) = 12; (X_Z^1, X_W^1) = 1.2; (X_Z^1, X_Z^2) = 0.54; (X_Z^2, X_Z^2), (X_W^1, X_Z^3) = 0.36; (X_Z^3, X_Z^3) = 0.35$

“Artificial Proto-Modelling:

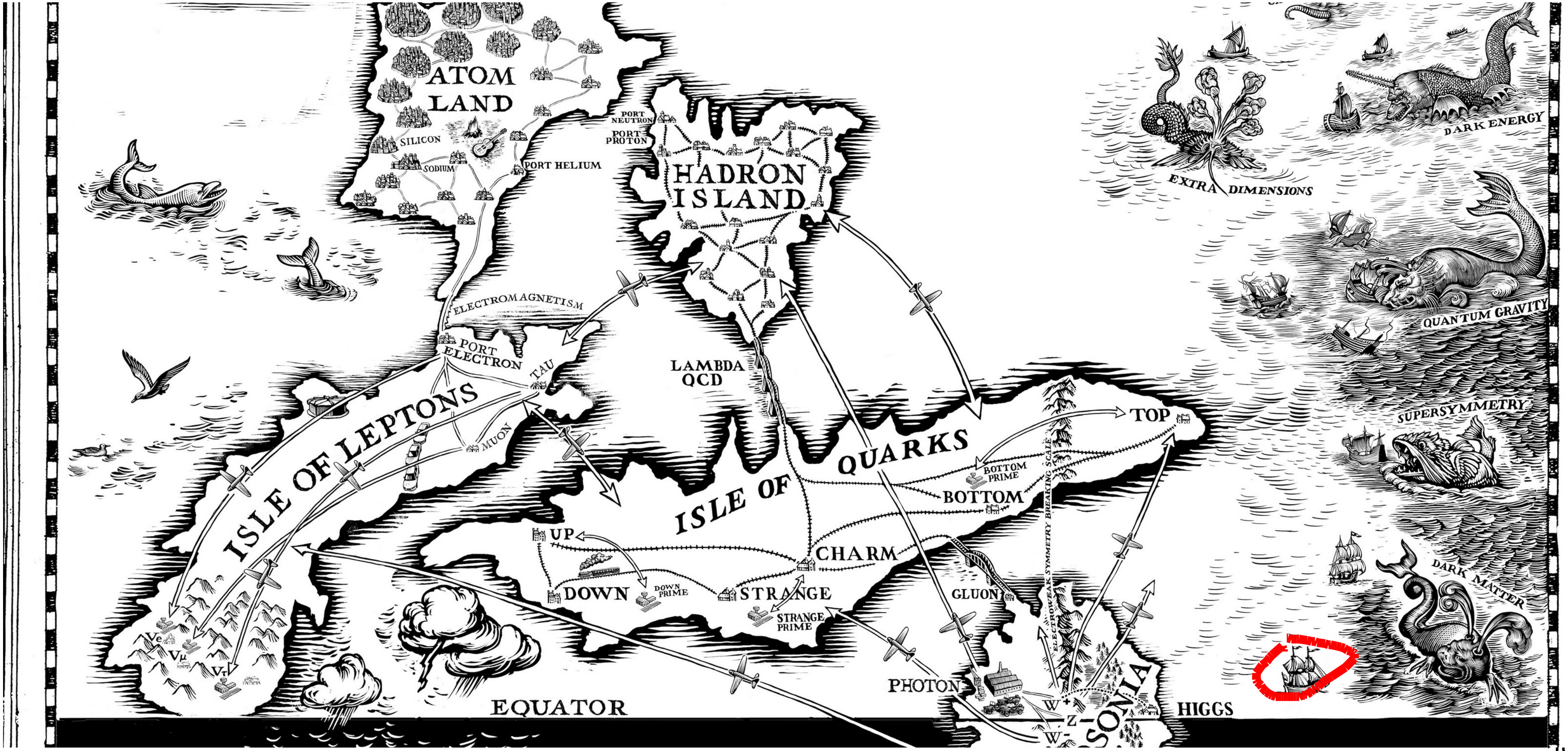
Building Precursors of a Next Standard Model from LHC Data”

(plot taken from the book “atomland”
by my colleague Jon Butterworth)

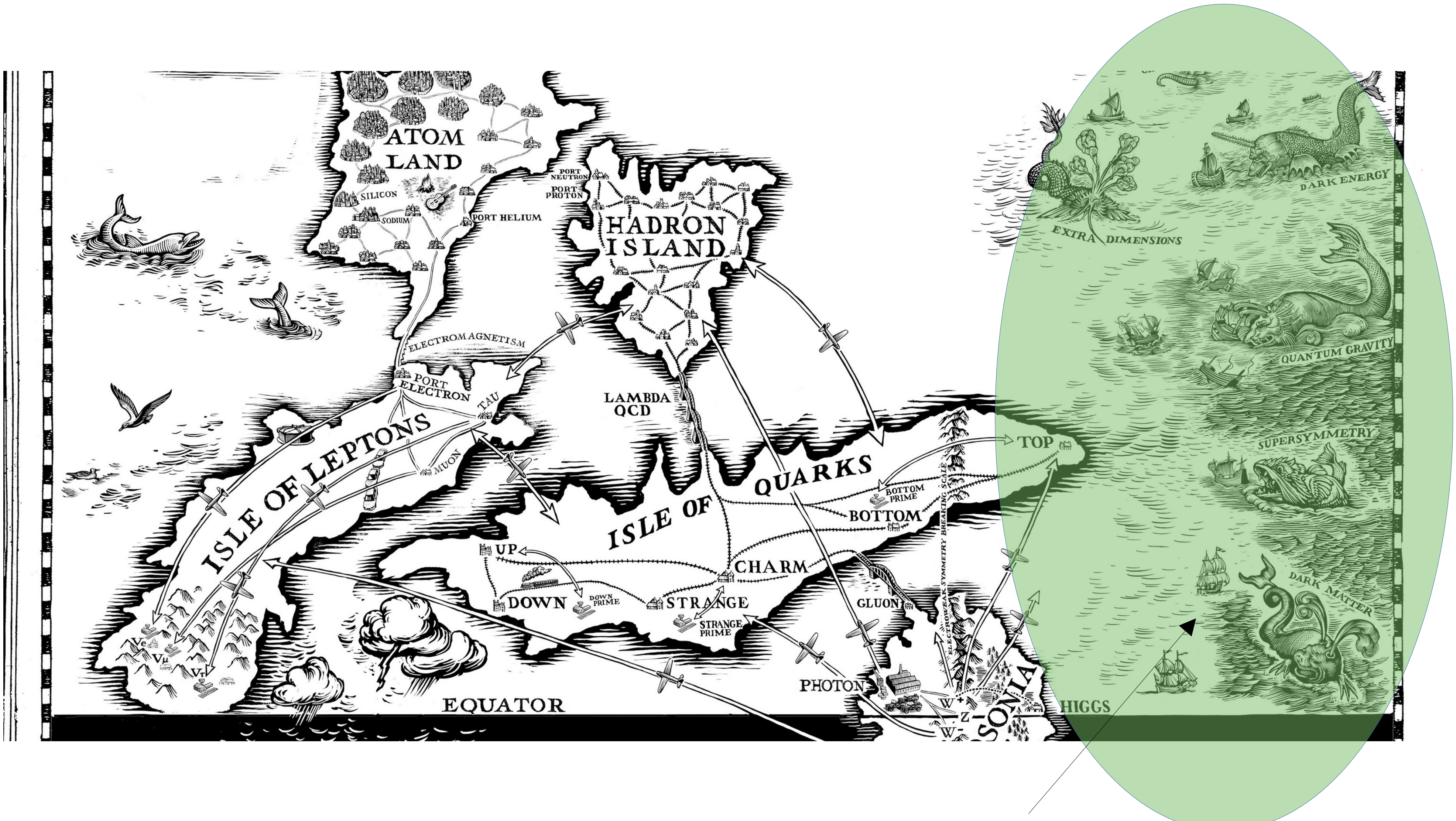
HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

Kontext: theoretische Teilchenphysik

Fragestellung: Aufbauend auf den veröffentlichten Suchen nach neuer Physik am LHC, können wir die fundamentalen physikalischen Gesetzmäßigkeiten aus diesen Daten lernen?

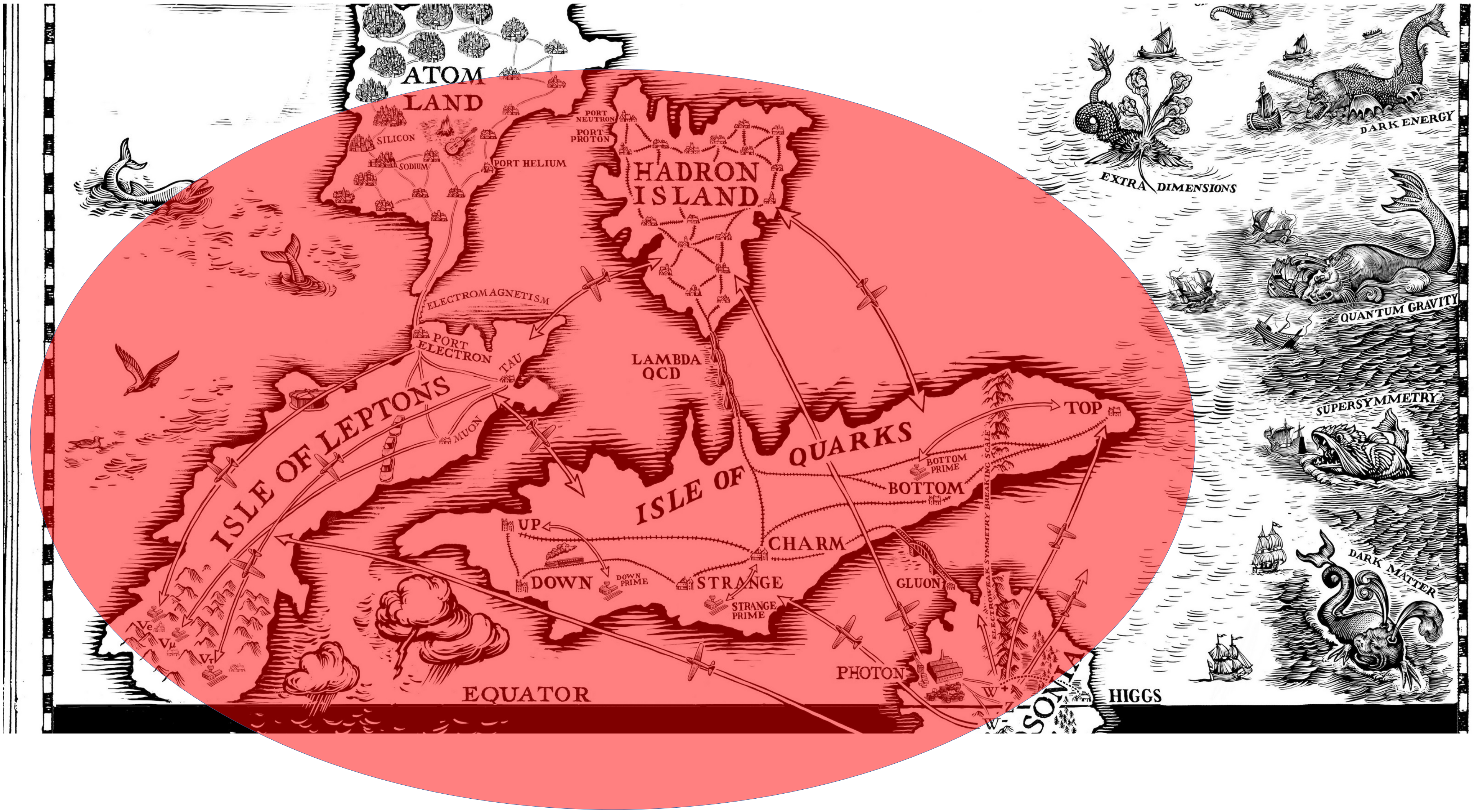


Eine Landkarte als Metapher für die Suche nach neuer Physik:



Der Osten in dieser Karte repräsentiert das Unbekannte (und ist kein politisches Statement). Unsere Aufgabe ist es herauszufinden, welches dieser Fantastischen Wesen echt ist.

Eine Landkarte als Metapher für die Suche nach neuer Physik:



All of “the west” is what we know. We know that the universe at the smallest scales, its tinies structures, are correctly described by a mathematical framework called “quantum field theories”.

A multi-level Bayesian optimization algorithm that
“digs into the data”,
tries to find hints for new physics
dispersed in the slew of papers.

While doing so it builds precursor theories
(“protomodels”) that would contextualize, explain,
the hints, while not being in violation with
anything else we know (= “negative results”).

a walker

We wrote a random walk algorithm – similar to MCMC-walks – that “builds” the theories and sees if it can find evidence for these theories in the plethora of results.

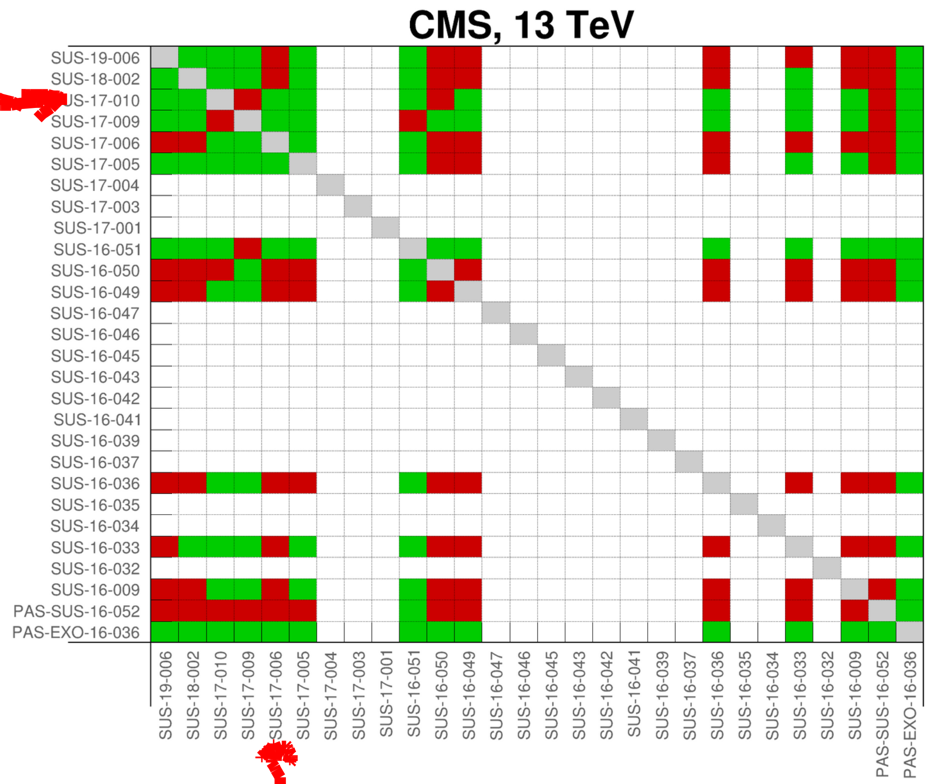
a combiner

For reasons that I do not wish to go into, the algorithm is allowed to statistically combine some of the results, but not all. In each step, the algorithm has to find the most interesting combination of these results.
If we think of the random walk as an optimization problem (as we are currently concerned only with the most interesting theory it finds), we can think of finding the best combination of experimental results as an optimization problem within an optimization problem – multi-level optimization.
Below you see to most interesting combination of results that it found.
You see that “observed” is always above “expected”.

Analysis Name	Type	Dataset	Observed	Expected	Approx σ	Particles
ATLAS-SUSY-2013-02	em	SR6jtp	6	4.9 +/- 1.6	0.4 σ	X_d
ATLAS-SUSY-2013-15	em	tNboost	5	3.3 +/- 0.7	0.9 σ	X_t
ATLAS-SUSY-2016-07	em	2j_Meff_1200	611	526 +/- 31	2.2 σ	X_d
ATLAS-SUSY-2016-16	em	tN_med	50	36.3 +/- 6.6	1.5 σ	X_t
CMS-SUS-13-012	ul	-	29.4 fb	18.3 fb	1.2 σ	X_d
CMS-SUS-16-050	ul	-	106.0 fb	49.3 fb	2.3 σ	X_t

a critic

But the results that do not make it into the combination should not be forgotten! They can still “veto” on a specific proto-model!
Thus, we do not build theories that are in contradiction with any results
In the database!



a test statistic

The walker needs a test statistic “K”. The construction is a bit involved, but essentially for a given combination of results it boils down to a chi2 criterion minus twice the number of new particles introduced. This is similar to an Akaike information criterion (except we actually motivate it in a Bayesian framework).

$$K^c := -2 \ln \frac{\mathrm{L}^c_{\mathbf{SM}} \cdot \pi(\mathbf{SM})}{\mathrm{L}^c_{\mathbf{BSM}}(\hat{\mu}) \cdot \pi(\mathbf{BSM})}$$

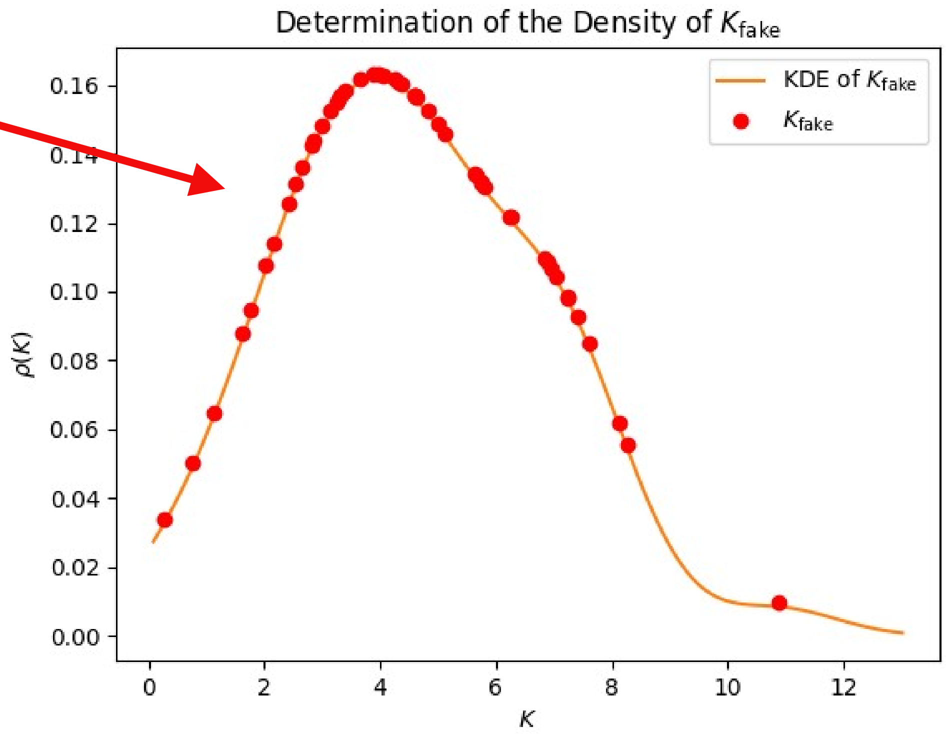
$$\pi(\mathbf{M}) = \exp\left[-\left(\frac{n_{\text{particles}}}{a} + \frac{n_{\text{branchings}}}{b} + \frac{n_{\text{ssm}}}{c}\right)\right]$$

$$K := \max_{\forall c \in C} K^c$$

a global p-value

We of course cannot employ Neyman-Pearson's Lemma for our test statistic.
But if you remember, we have statistical models for all our measurements.
So we can create "fake databases" of all our results assuming the null hypothesis, assuming no new physics, by sampling from these models. We can then run our protomodel builder, and see what *K* values it finds based on the null-hypothesis.

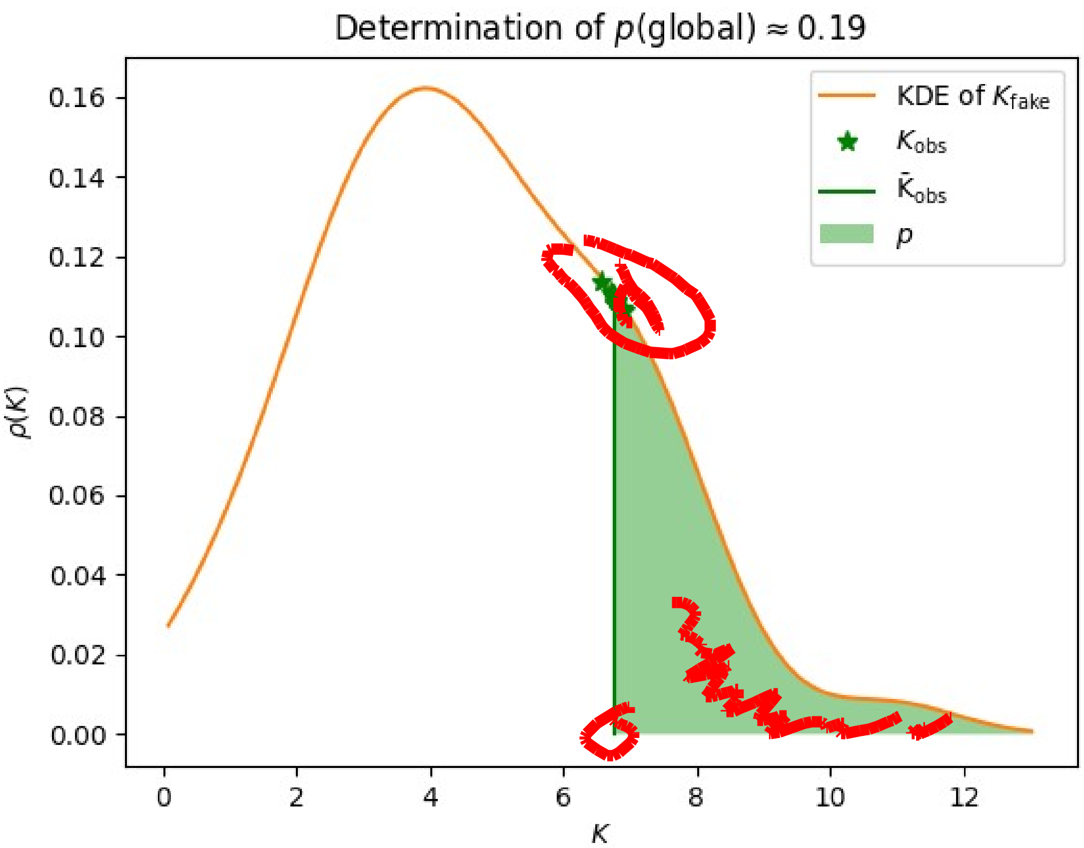
Here is the estimated density of *K* under the null hypothesis.



Million dollar question: where do we land in this plot based on a run with the actual, real data?

(And let me remind you, the estimate will be conservative, because the experimentalists are conservative)

a result



With the real data we land at a (conservatively estimated) p ≈ 0.19. A fluctuation?
First very mild signs of new physics?

As always: more data is needed.

Material:

- https://smodels.github.io/protomodels
- https://smodels.github.io/protomodels/videos