Leaving no stone unturned at the LHC in the search for new phenomena

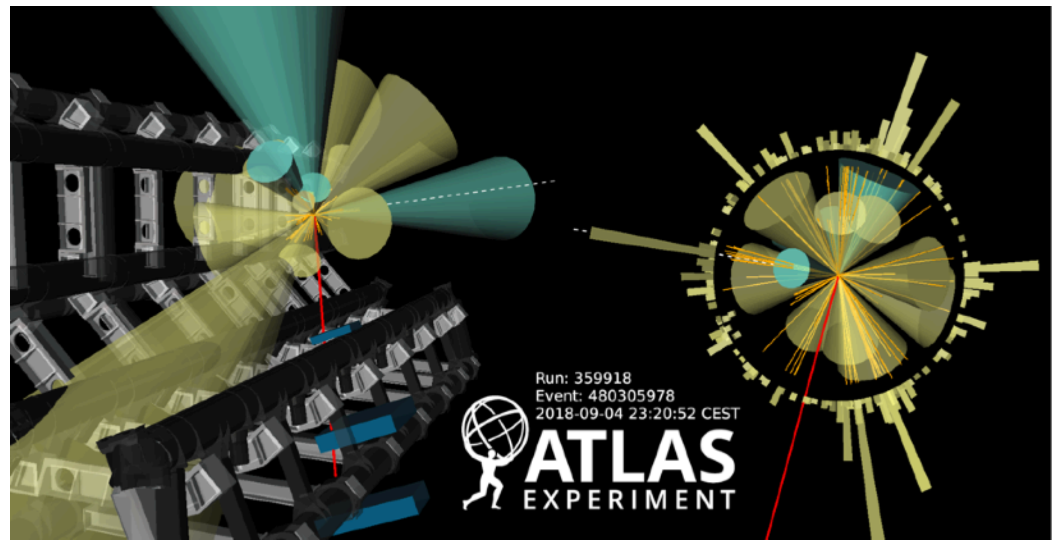
IFAE
Institut de Física d'Altes Energies

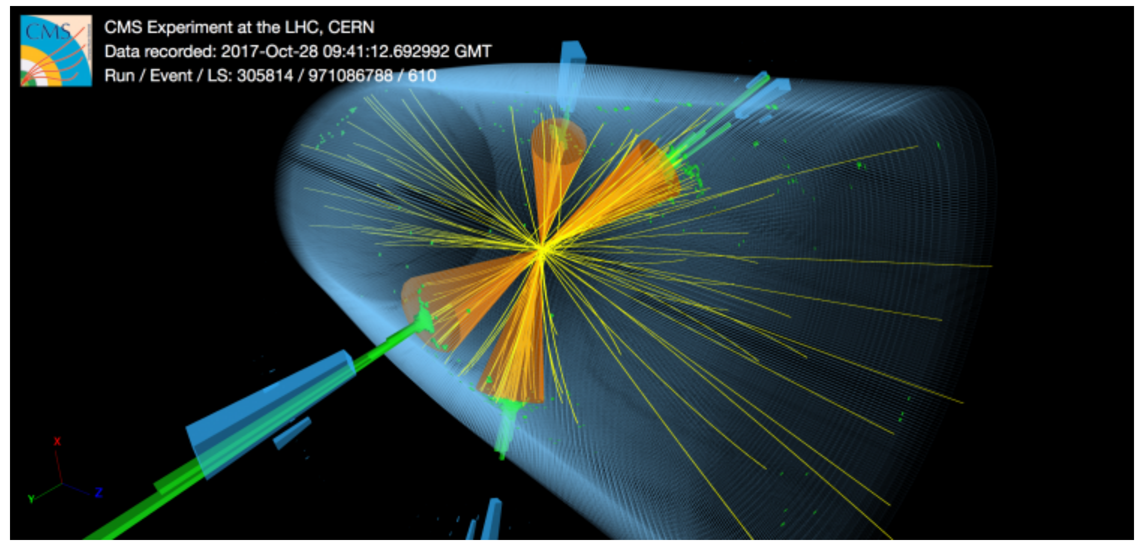
Javier Montejo Berlingen

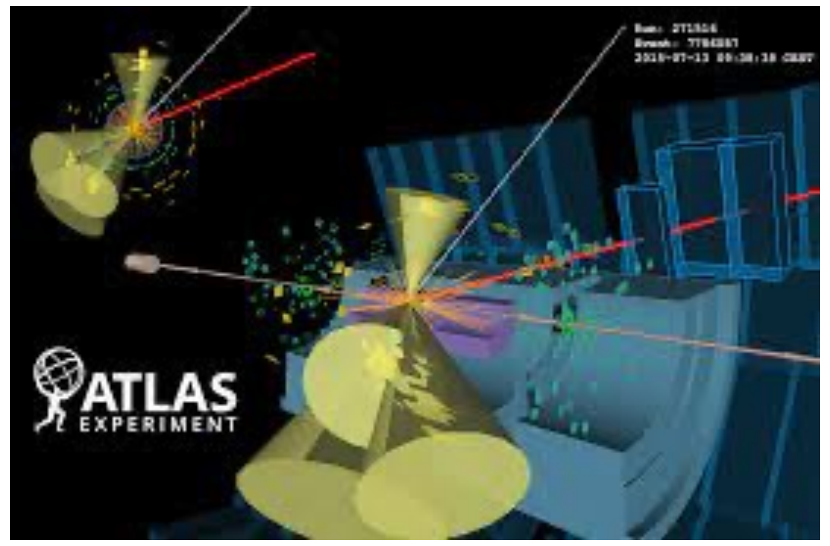
L International Meeting on Fundamental Physics and XV CPAN days

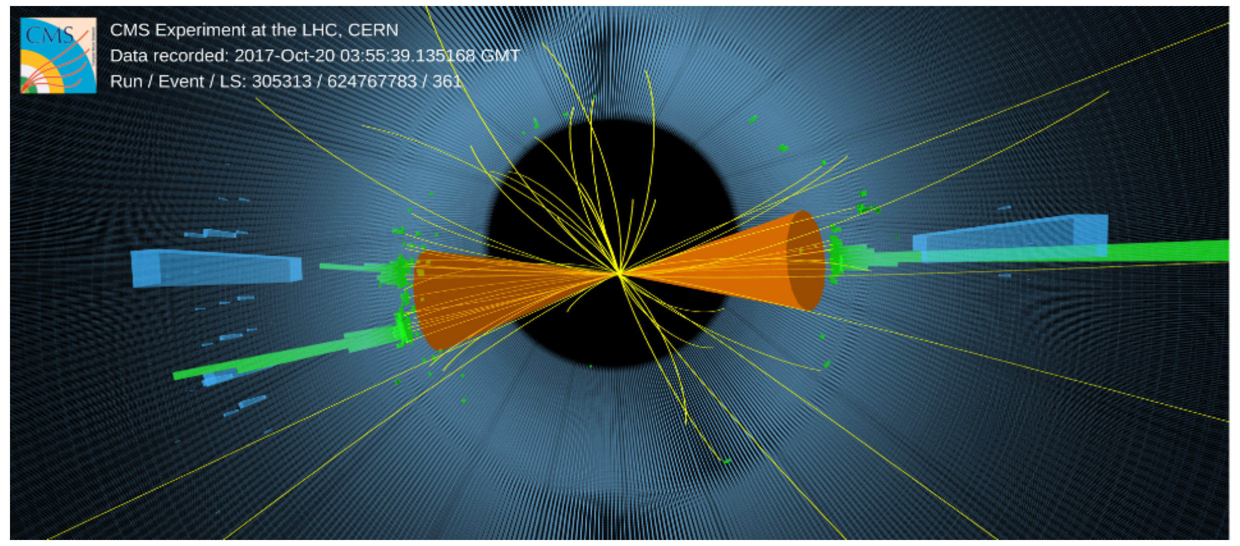
Introduction

The LHC is an incredible machine that allows us to explore the TeV scale for the first time:

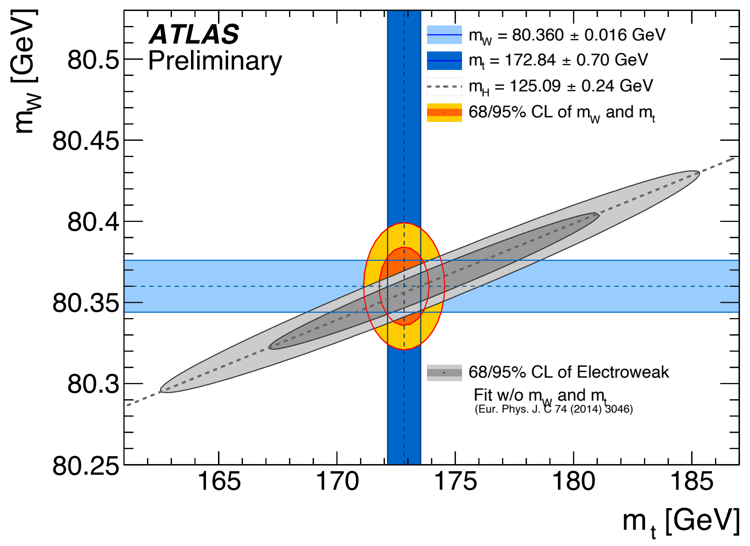


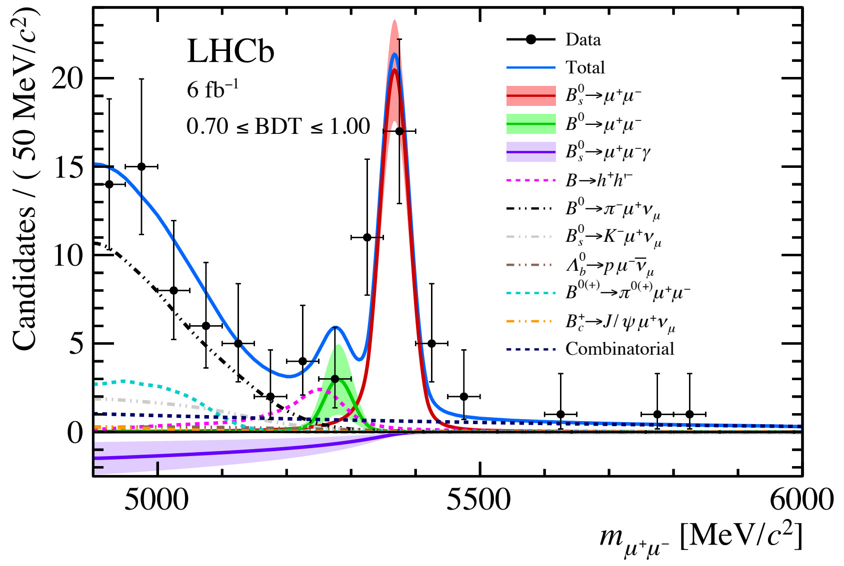


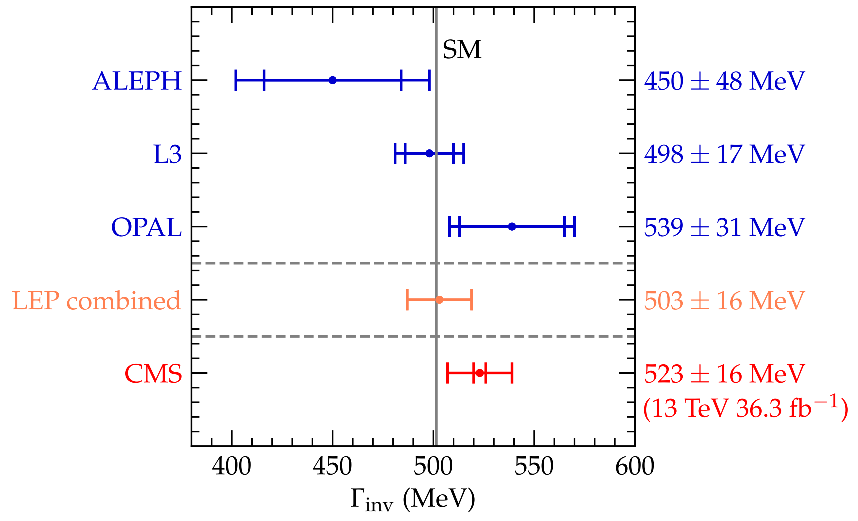


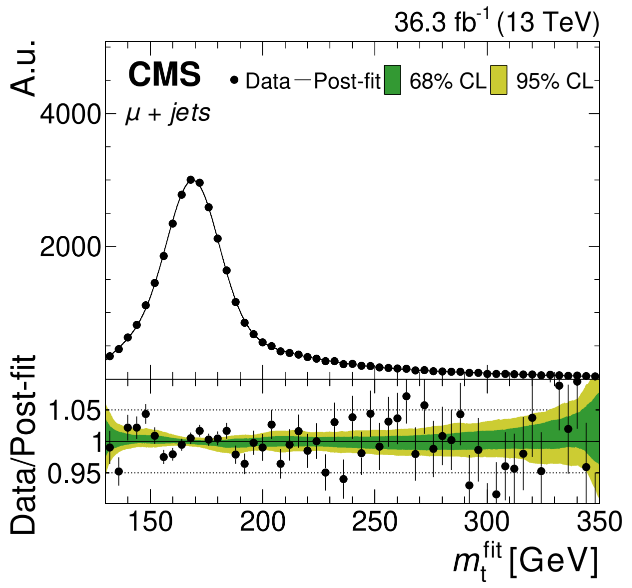


And allows us to scrutinize the electroweak scale with incredible precision:









In both cases we spend years analysing data not for the sake of it, but because we want to get insight into the **big physics questions**

- *Why is the higgs so light? what is dark matter? why is there so little antimatter? where do neutrino masses come from?*

All these questions can not be addressed within the Standard Model and require new physics

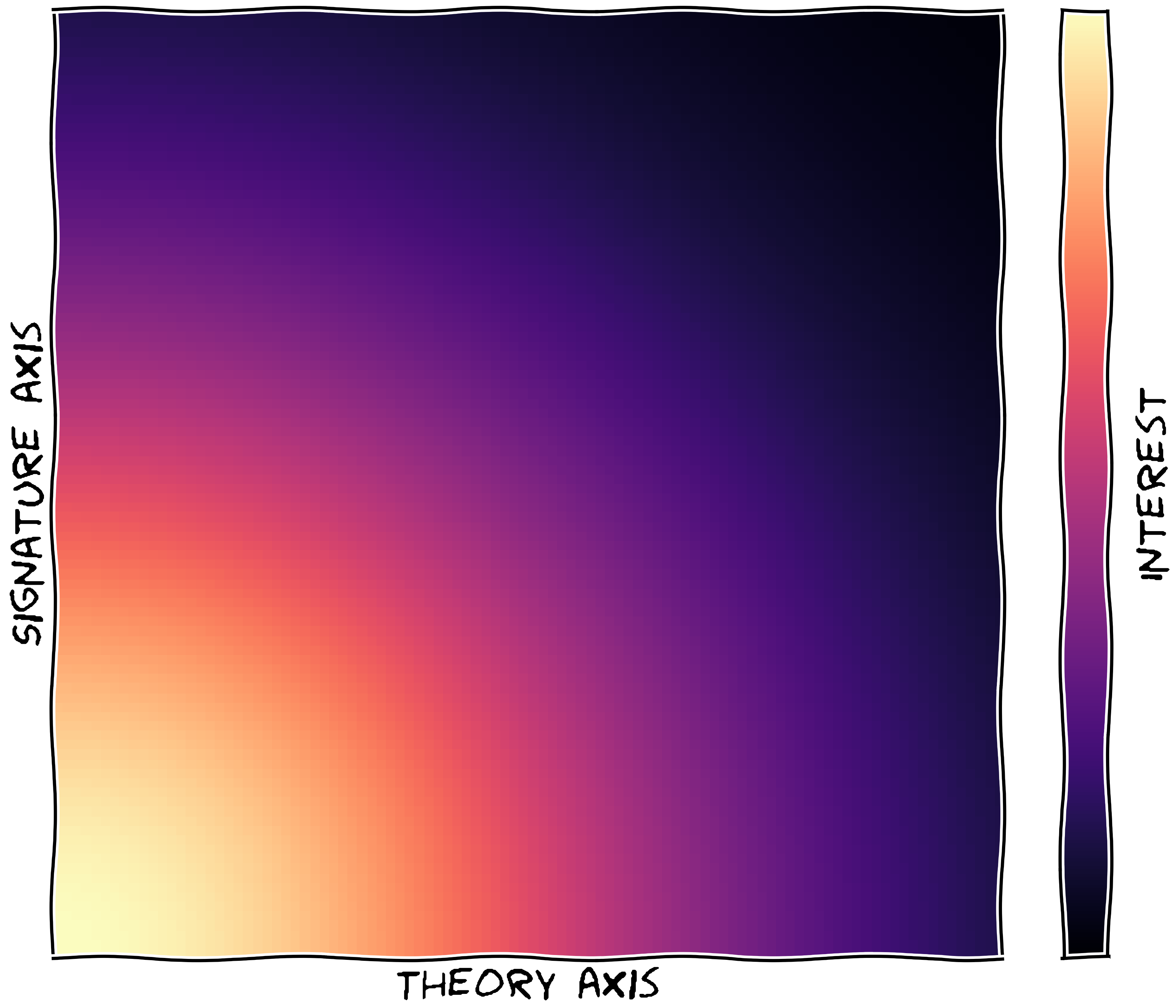
Introduction

The LHC is a **discovery** machine, and it is our (experimentalists) duty to leave no stone unturned in the search for new phenomena

But time and resources are finite, whereas BSM models are (almost) infinite! **Where should we focus?**

Choosing your work horse

Everybody has some preference/bias in this (completely subjective) theory vs signature plane



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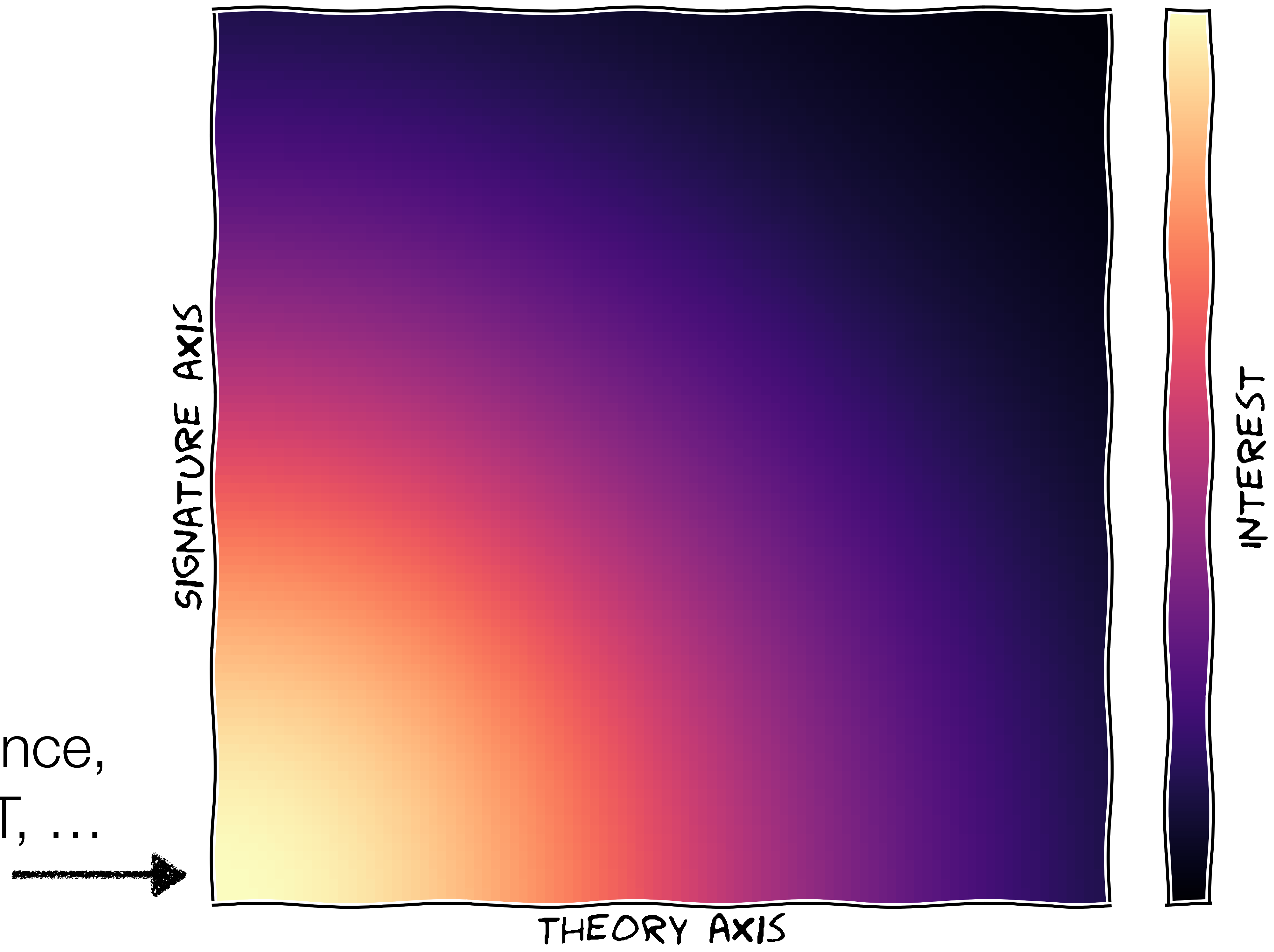
monojet, dijet/dilepton resonance, same-sign leptons, ttbar+MET, …



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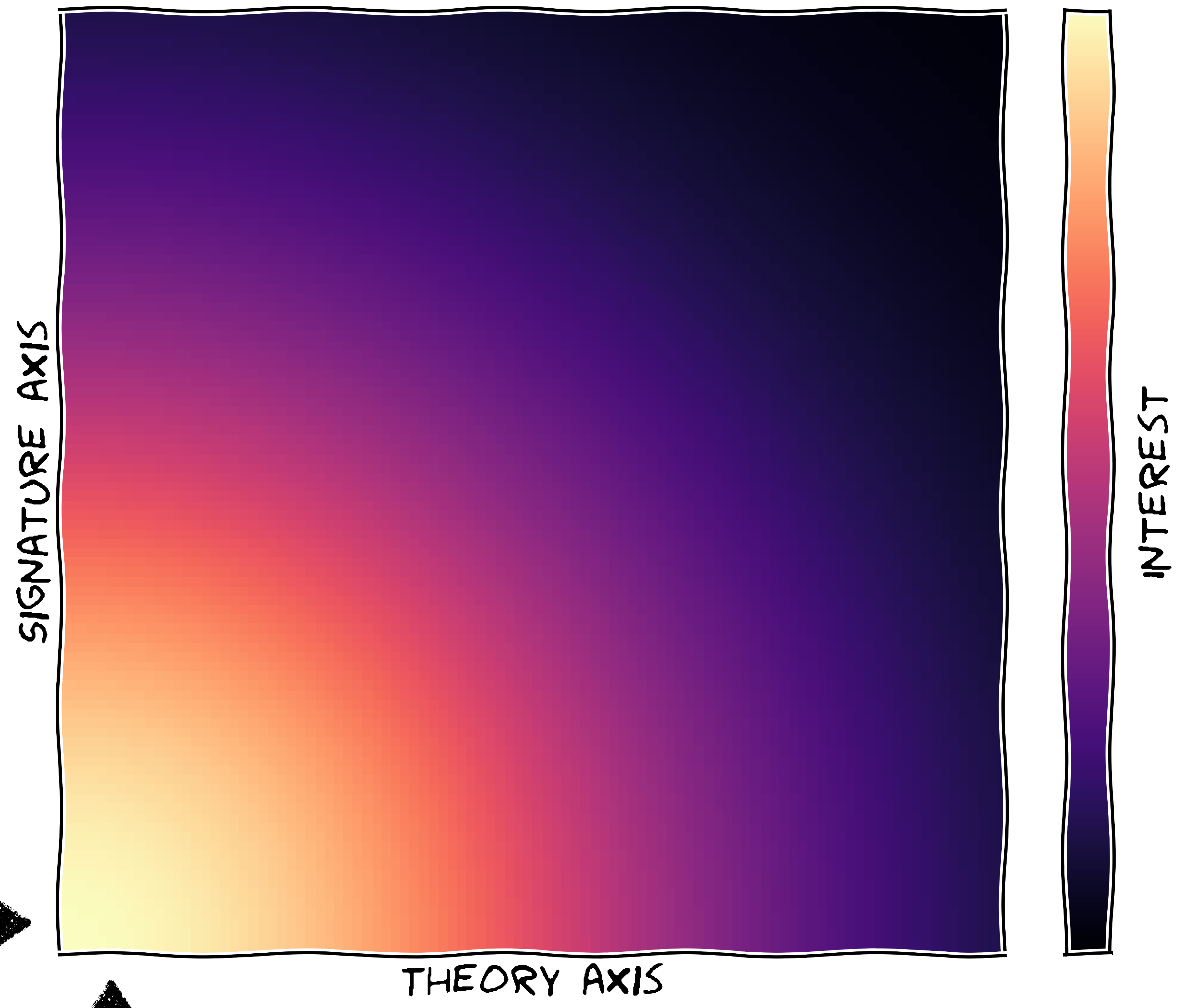

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natural SUSY, LQ, HNL, VLQs, 2HDM, …

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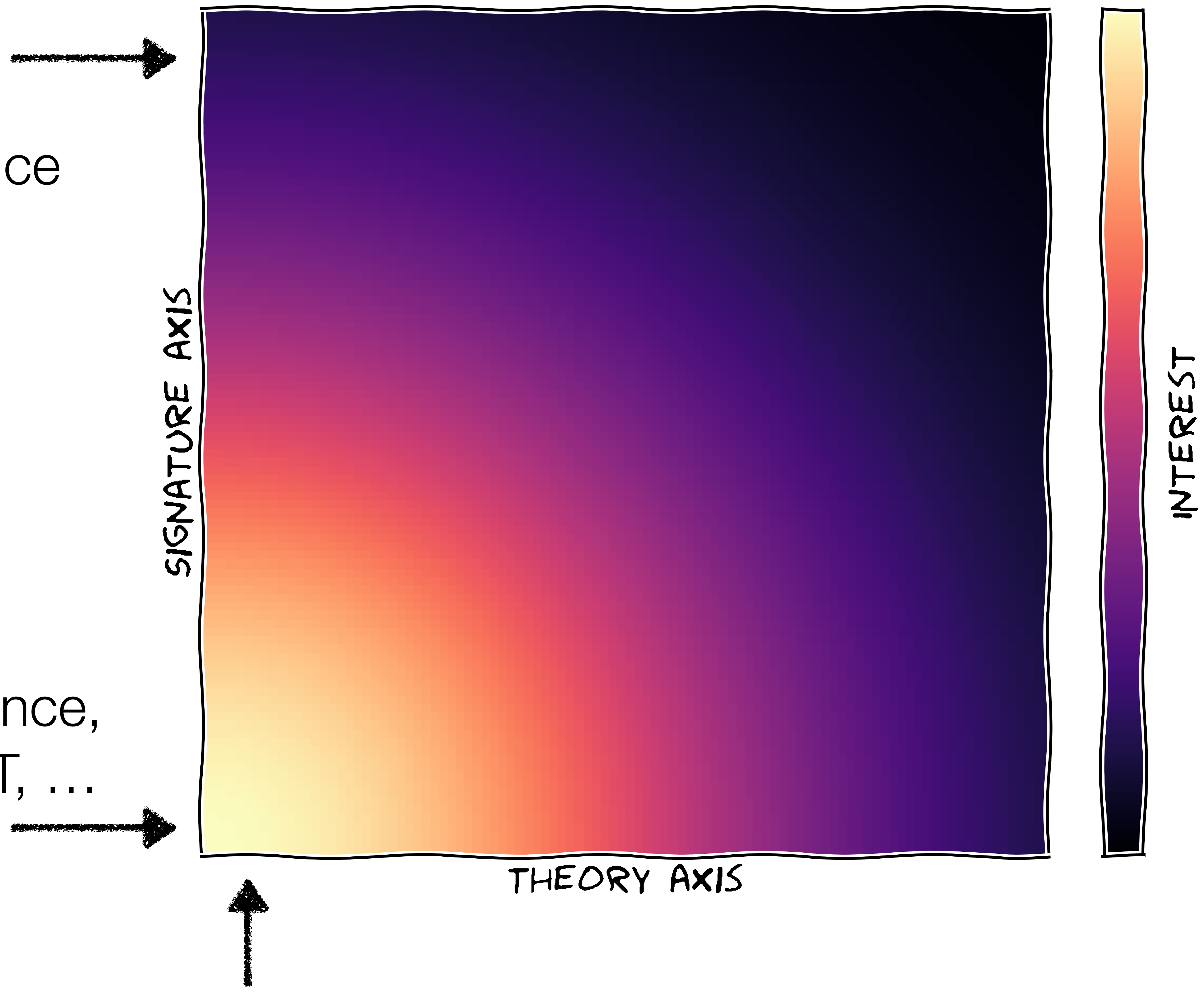
absurd signatures, like tau+photon+charm resonance with annual modulation



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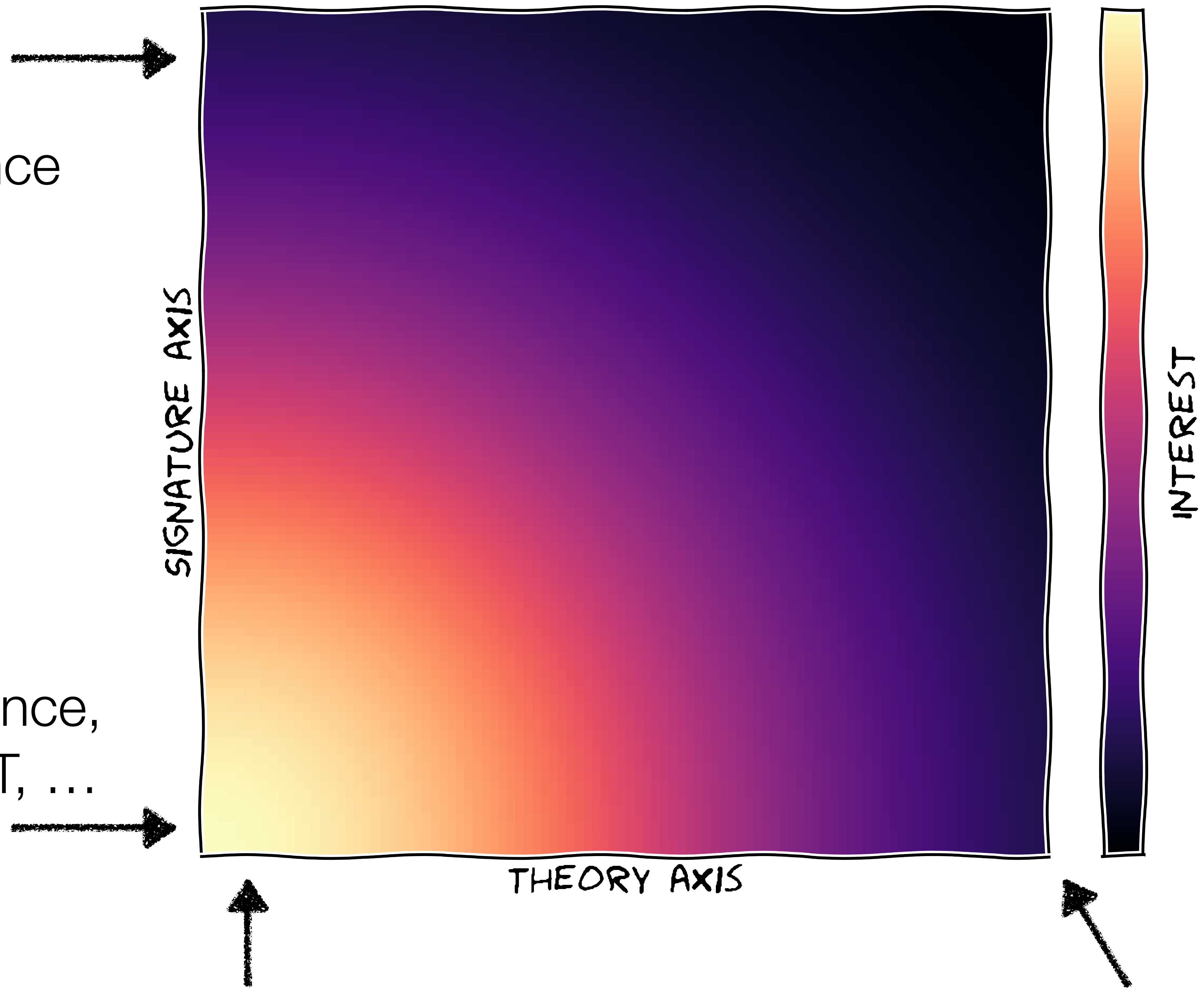

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technicolor

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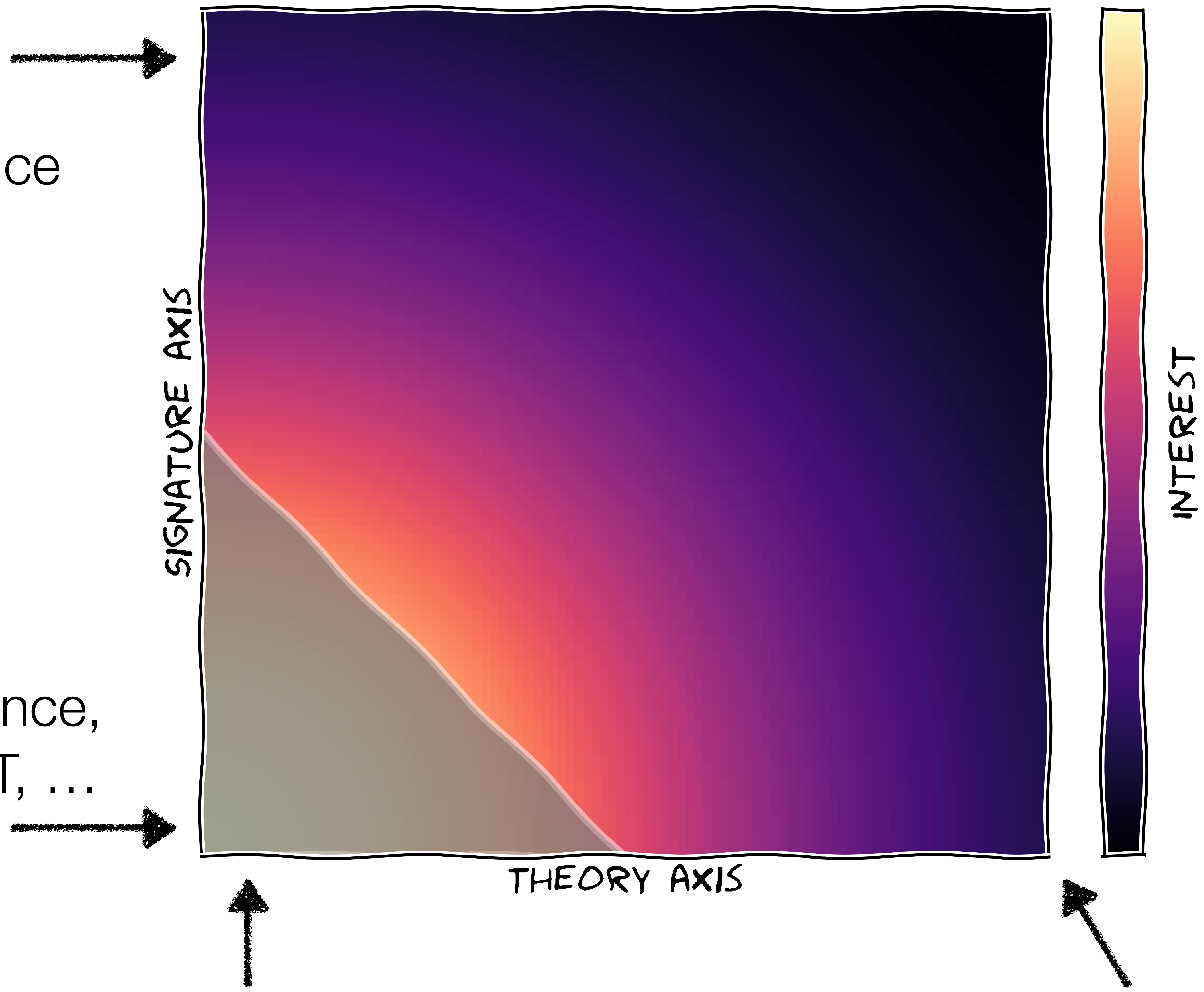

We have done hundreds of searches and set very stringent limits, now what?

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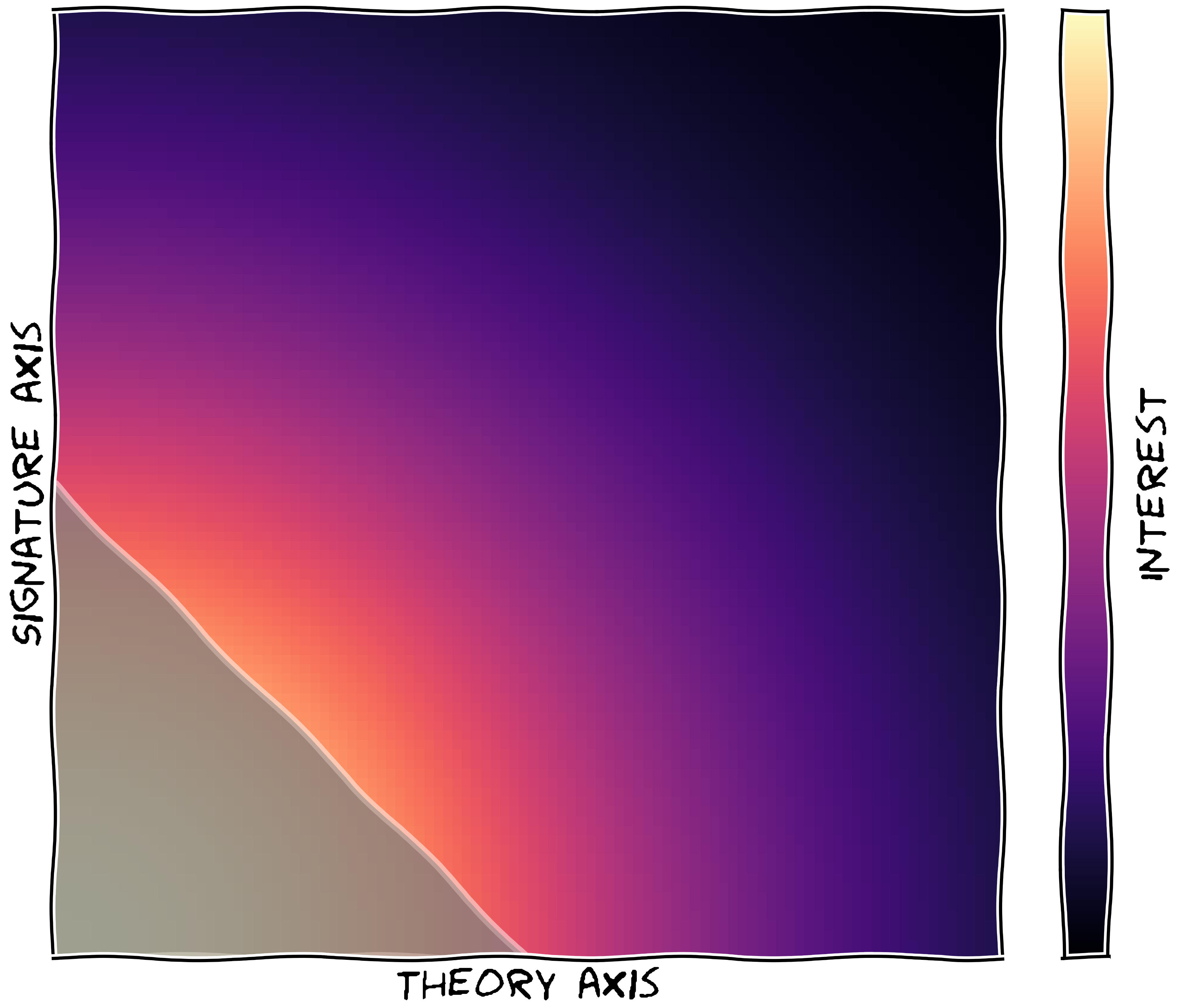
Some people become dogmatic about their choice



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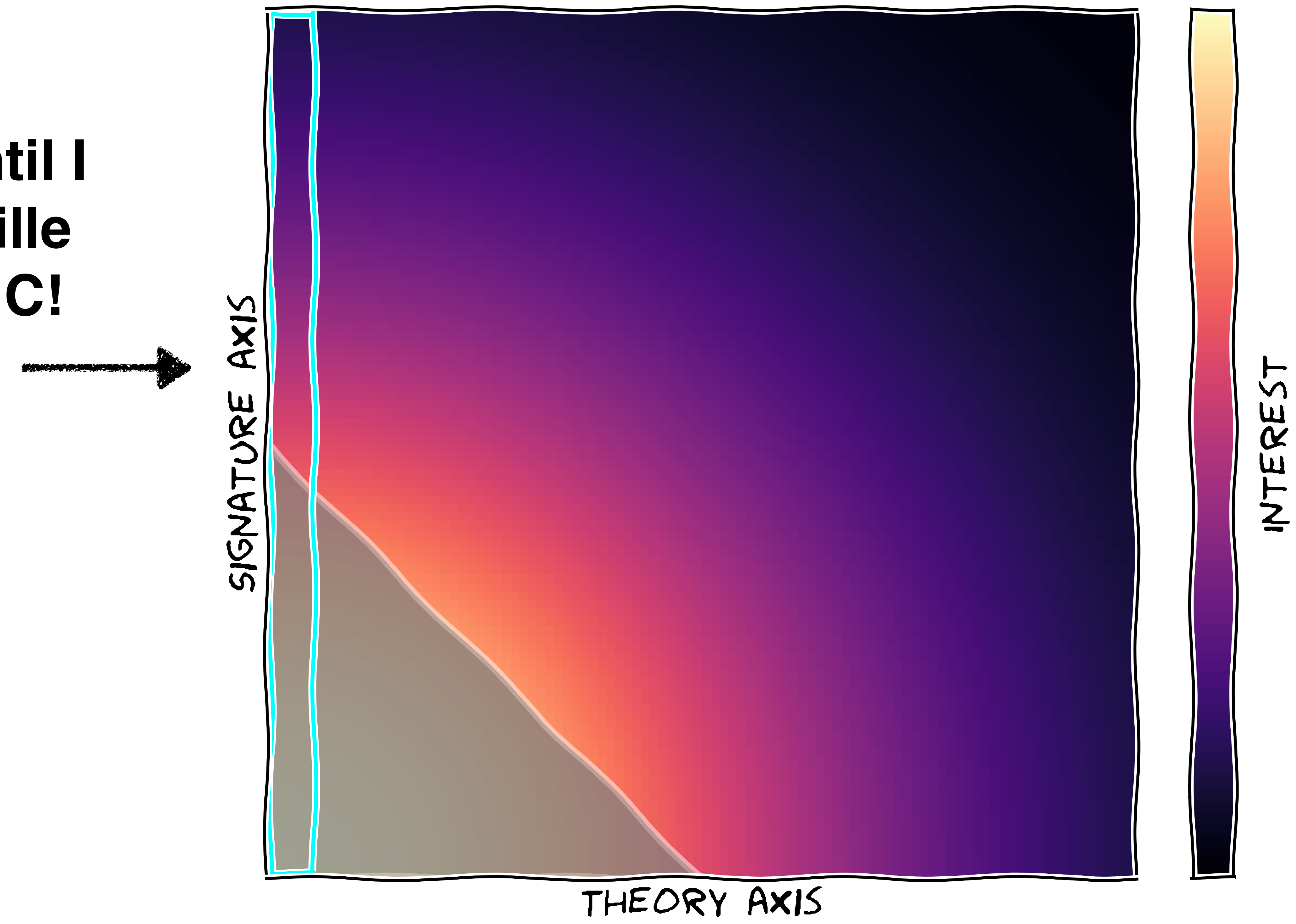
I will do monojet until I achieve sub-per-mille precision at HL-LHC!



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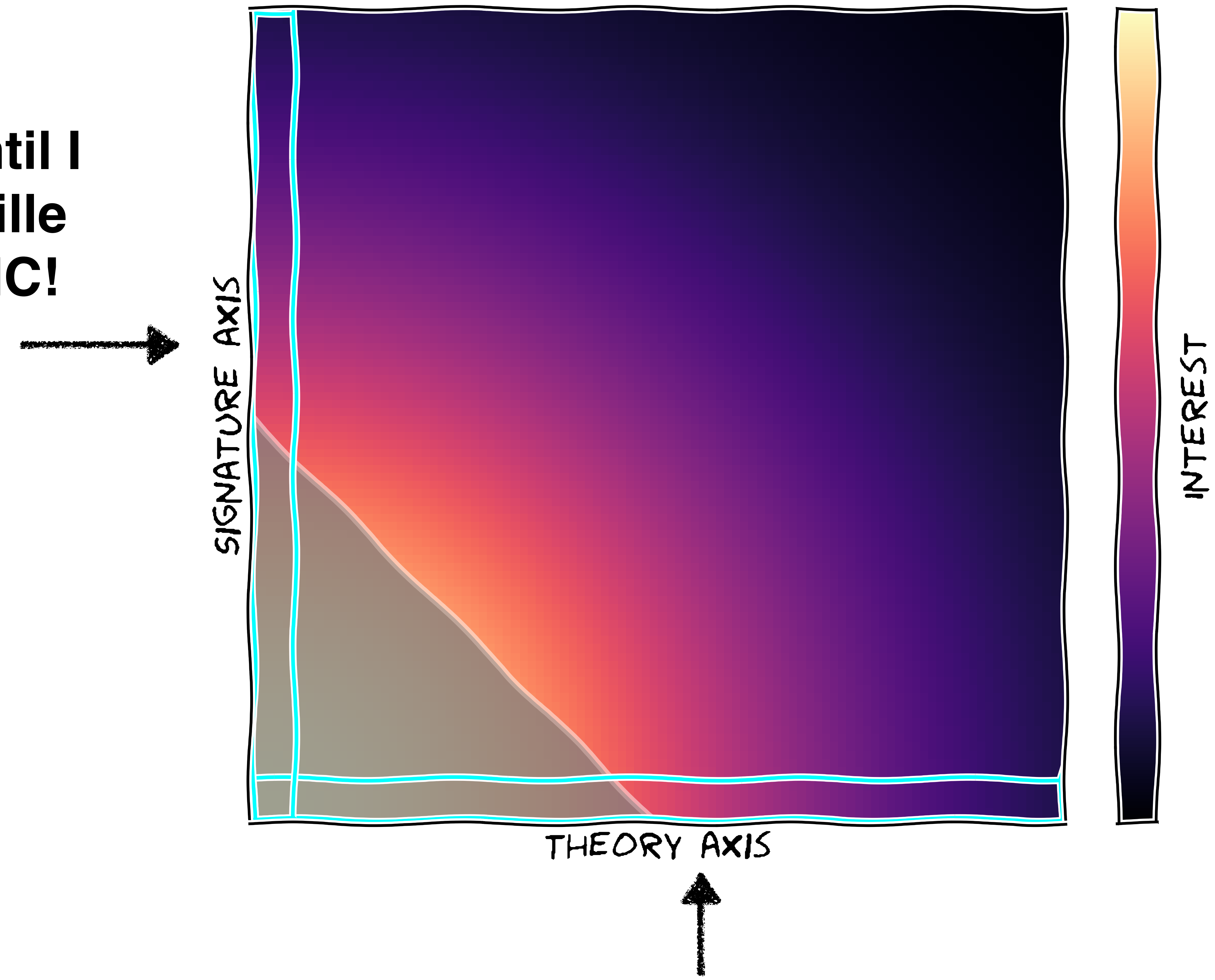

I will search for gluinos and stops until the limits reach 10 TeV (and maybe more)!

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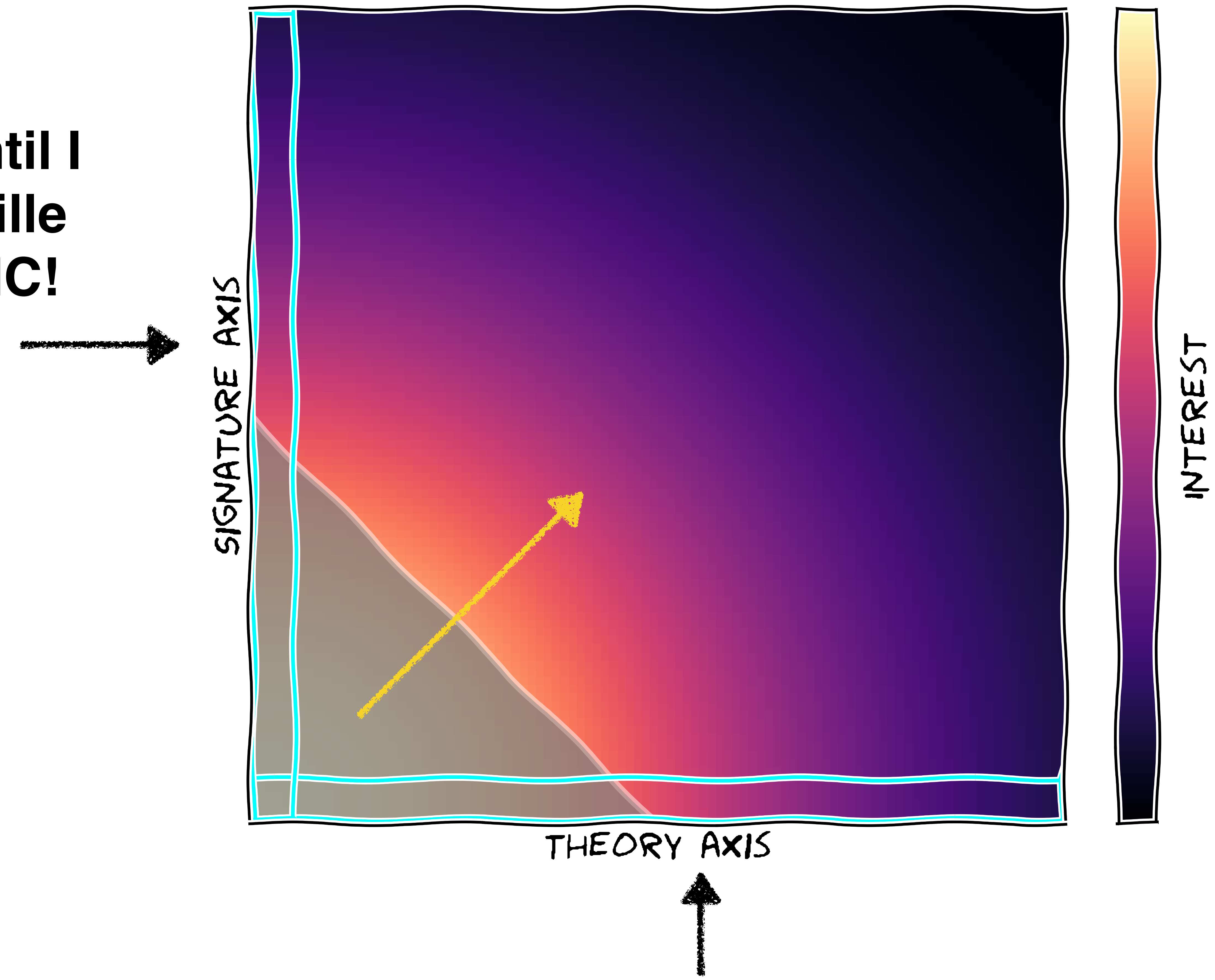


It is a great moment to think critically about our biases and leave no stone unturned

Find a balance between theoretical preference and the higher discovery potential of unexplored final states

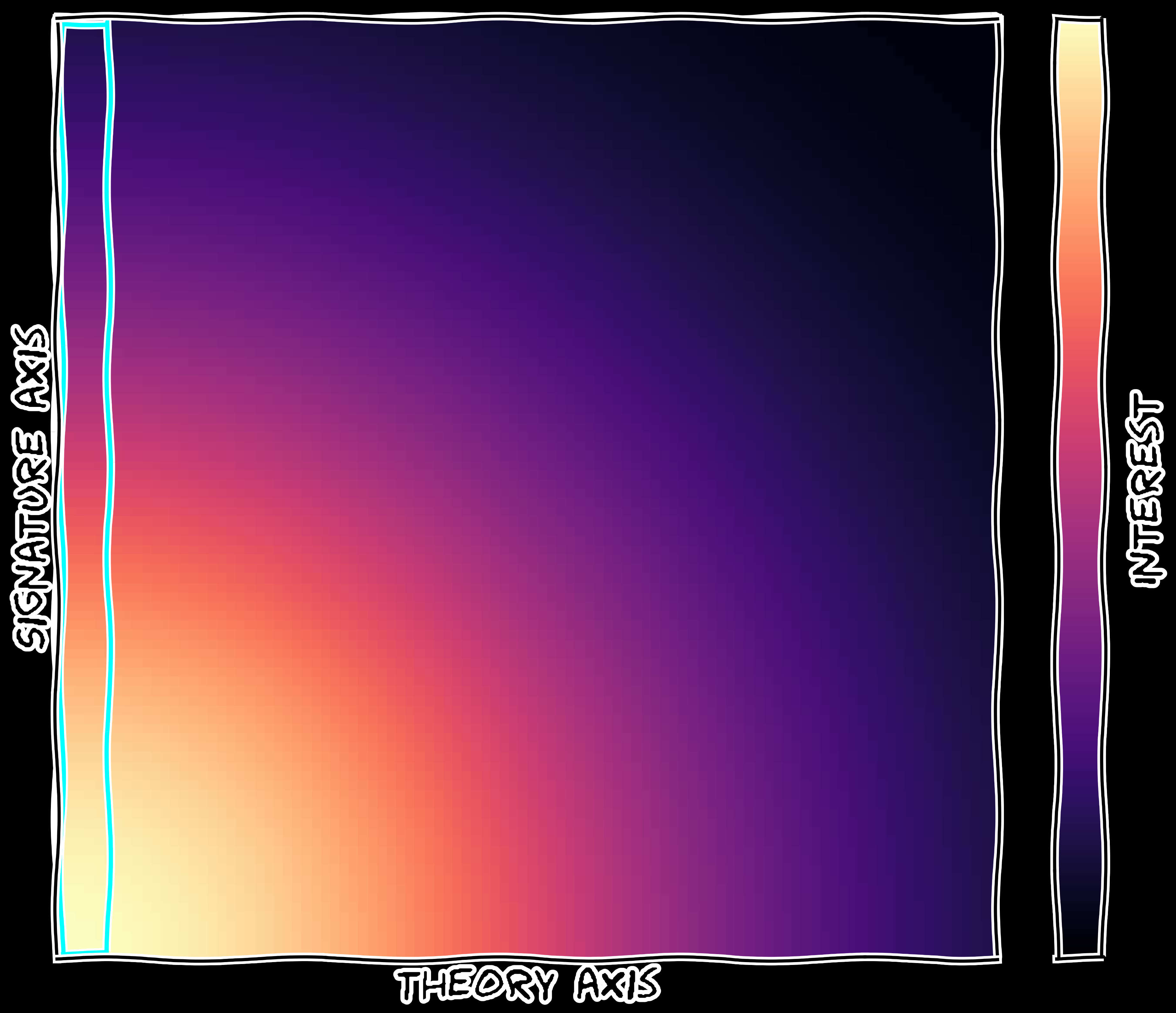
I will search for gluinos and stops until the limits reach 10 TeV (and maybe more)!

and biased

In the following I'll try to give a quick glimpse at the LHC search programme, with a focus on future directions that we should pursue

in my personal opinion

Exploring the signature axis,
the bread and butter of LHC searches



Signature-based searches

Di-object resonances are the cornerstone of the search programme and have a long history of discoveries, from J/ψ to the Higgs boson

- Search for an excess on a smoothly falling spectrum
- Usually without a reference cross-section, since a plethora of theory models can yield the same final state

for every possible object pair there is a possible resonance 1610.09392

	e	μ	τ	γ	j	b	t	W	Z	h
e	$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, e_{KK}	L^*
μ		$Z', H^{\pm\pm}$	$\not{R}, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, μ_{KK}	L^*
τ			$Z', H, H^{\pm\pm}$	L^*	$LQ, \not{R}$	$LQ, \not{R}$	$LQ, \not{R}$	L^*, ν_{KK}	L^*, τ_{KK}	L^*
γ				$H, G_{\mathrm{KK}}, \mathcal{Q}$	Q^*	Q^*	Q^*	$W_{\mathrm{KK}}, \mathcal{Q}$	$H, \mathcal{Q}$	Z_{KK}
j					$Z', \rho, G_{\mathrm{KK}}$	$W', \not{R}$	$T', \not{R}$	Q^*, Q_{KK}	Q^*, Q_{KK}	Q'
b						Z', H	$W', \not{R}, H^{\pm}$	T', Q^*, Q_{KK}	Q^*, Q_{KK}	B'
t							H, G', Z'	T'	T'	T'
W								H, G_{KK}, ρ	$W', \mathcal{Q}$	$H^{\pm}, \mathcal{Q}, \rho$
Z									H, G_{KK}, ρ	A, ρ
h										H, G_{KK}

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e	$\pm\mp$[2], $\pm\pm$[3]	$\pm\pm$[3, 4], $\pm\mp$[4, 5]	[5]	∅	∅	∅	∅	∅	∅	∅
μ		$\pm\mp$[2], $\pm\pm$[3]	[5]	∅	∅	∅	∅	∅	∅	∅
τ			[6]	∅	∅	∅	[7]	∅	∅	∅
γ				[8]	[9–11]	∅	∅	[12]	[12]	∅
j					[13]	[14]	[15]	[16]	[16]	∅
b						[14]	[17]	∅	∅	∅
t							[18]	[19]	∅	∅
W								[20–23]	[21, 22, 24, 25]	[26–28]
Z									[21, 23, 29]	[26, 28, 30, 31]
h										[32–35]

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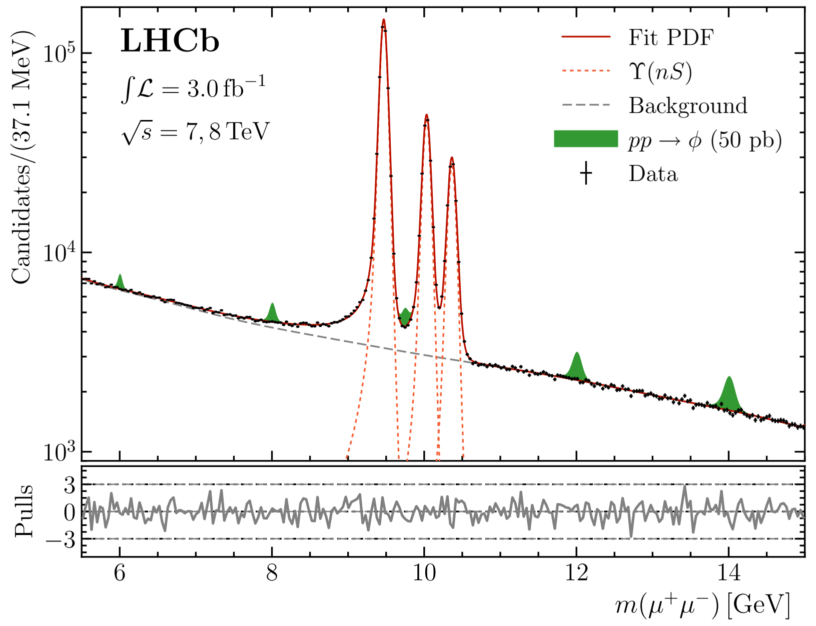

by now many of the missing signatures have been analysed 1610.09392

	e	μ	τ	γ	j	b	t	W	Z	h
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μ		$\pm\mp$[2], $\pm\pm$[3]	[5]	∅	∅	∅	∅	∅	∅	∅
τ			[6]	∅	∅	∅	[7]	∅	∅	∅
γ				[8]	[9–11]	∅	∅	[12]	[12]	∅
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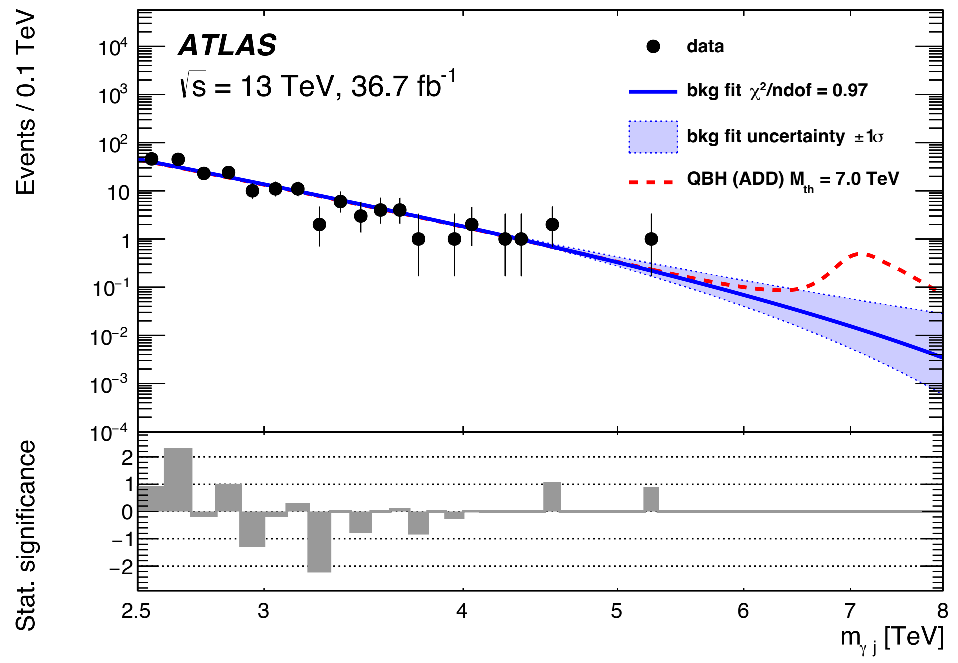
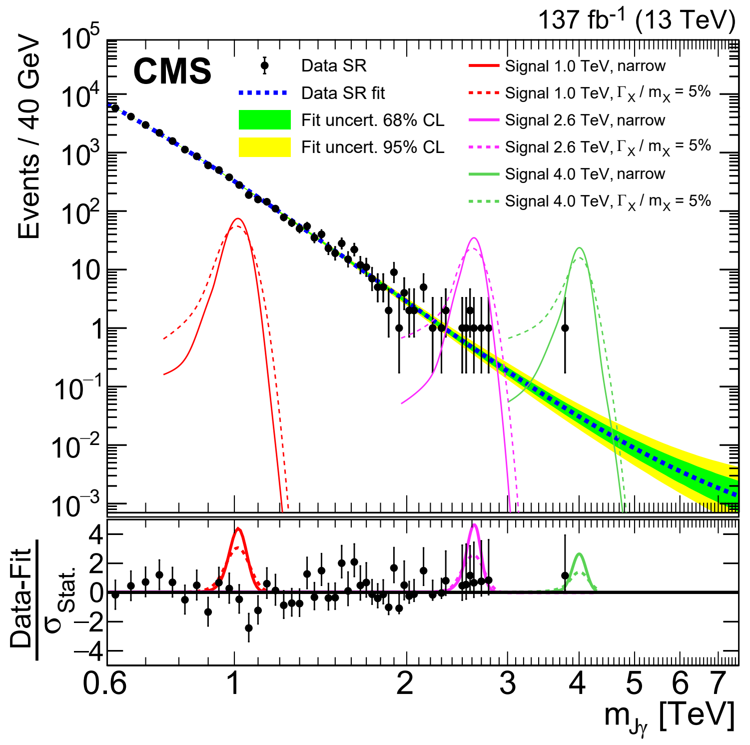
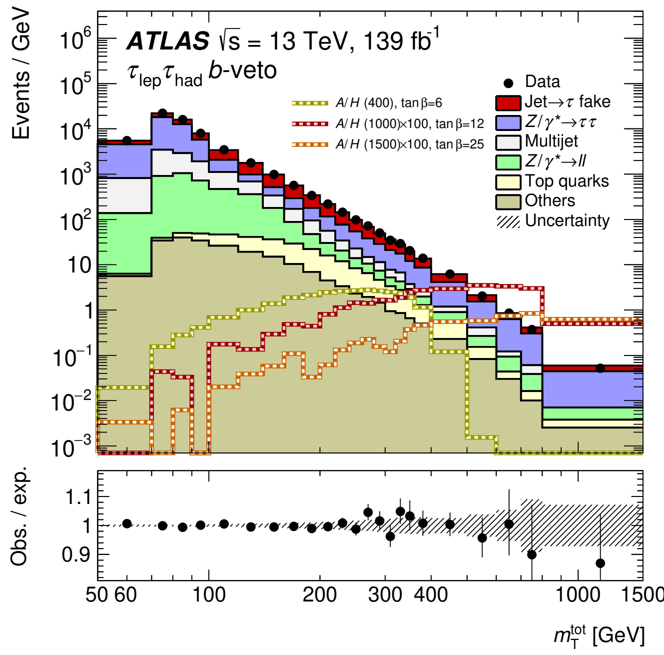
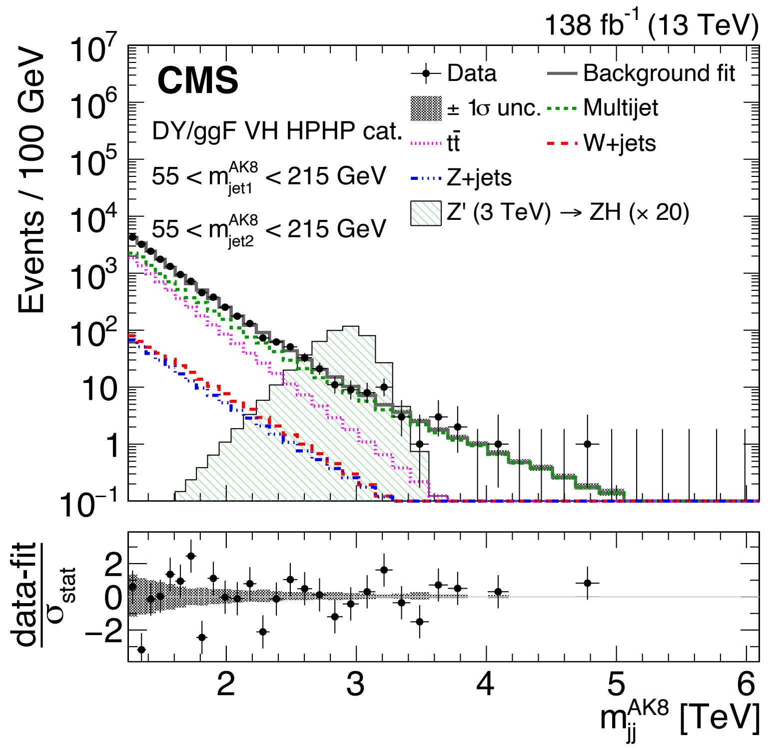
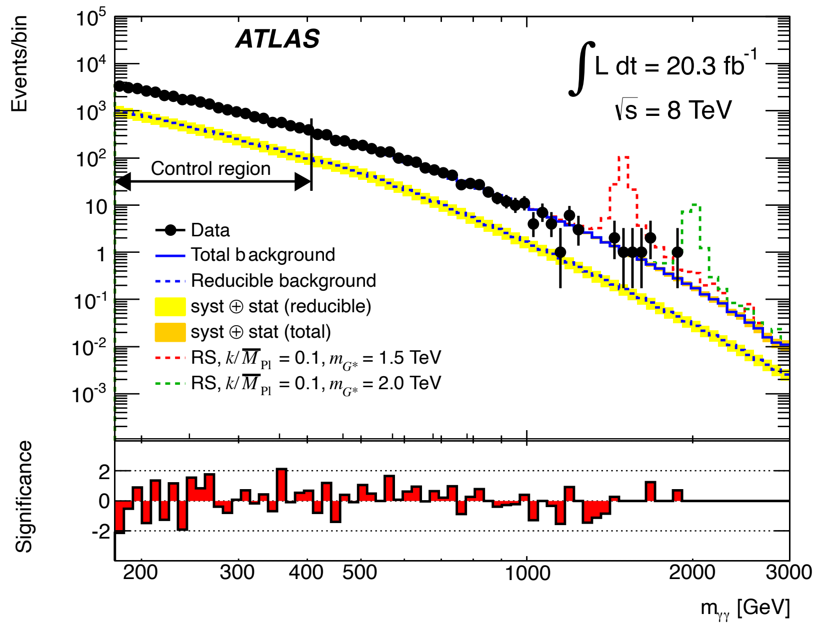
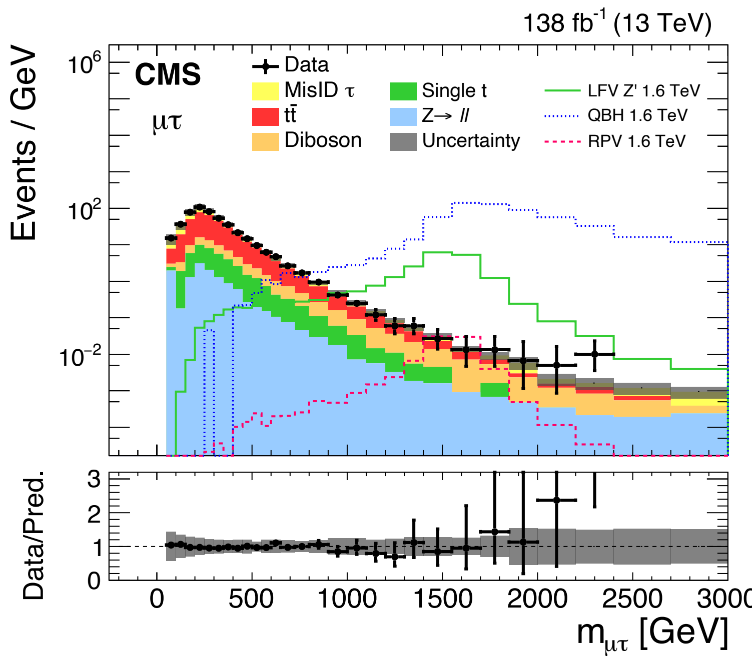


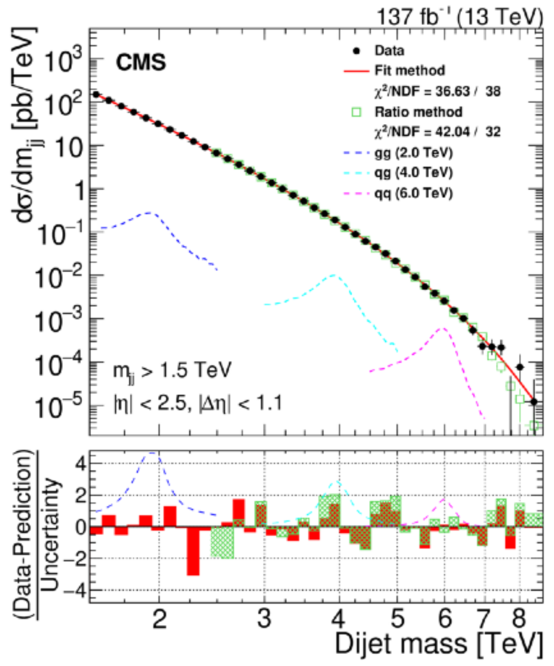








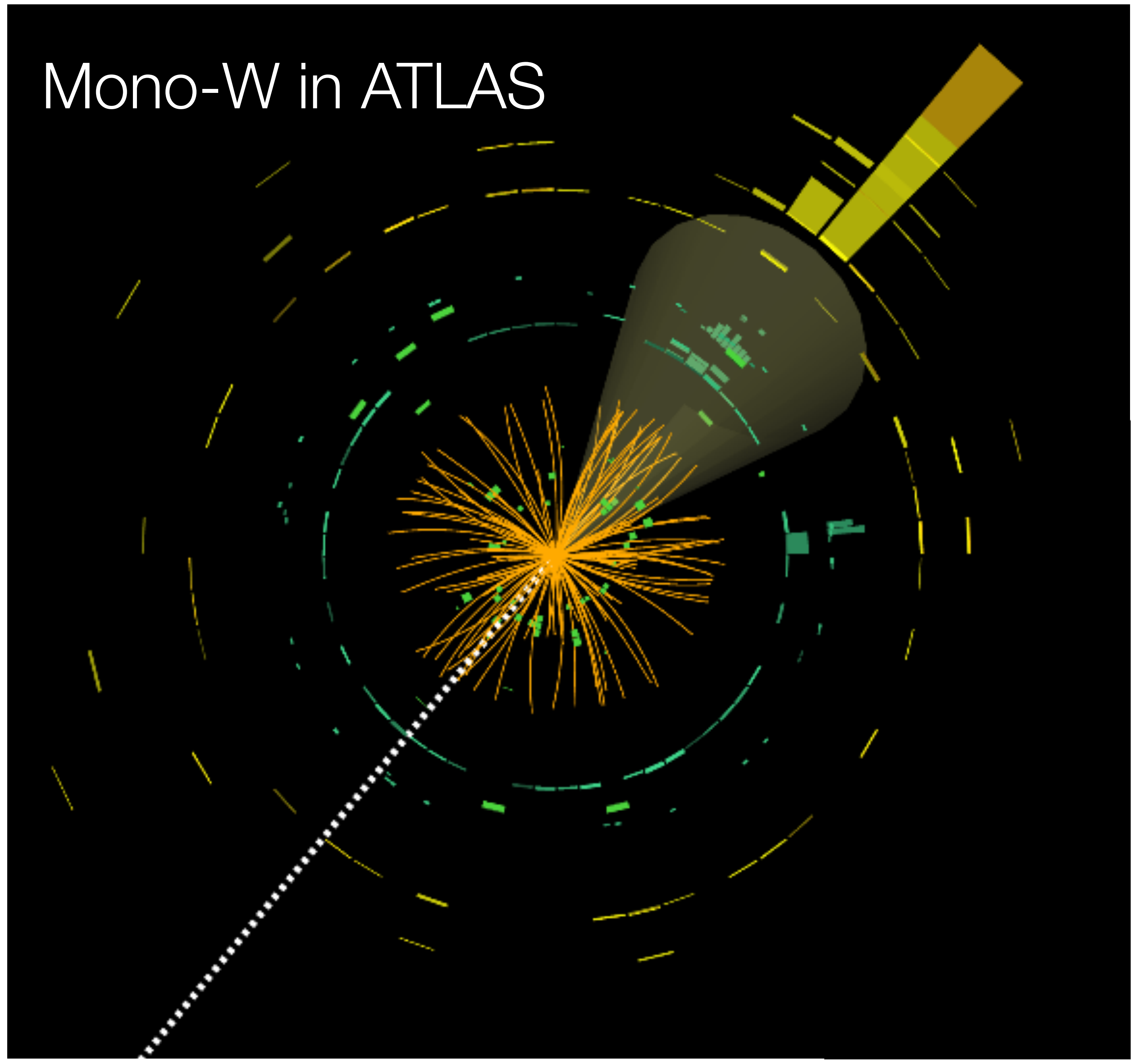




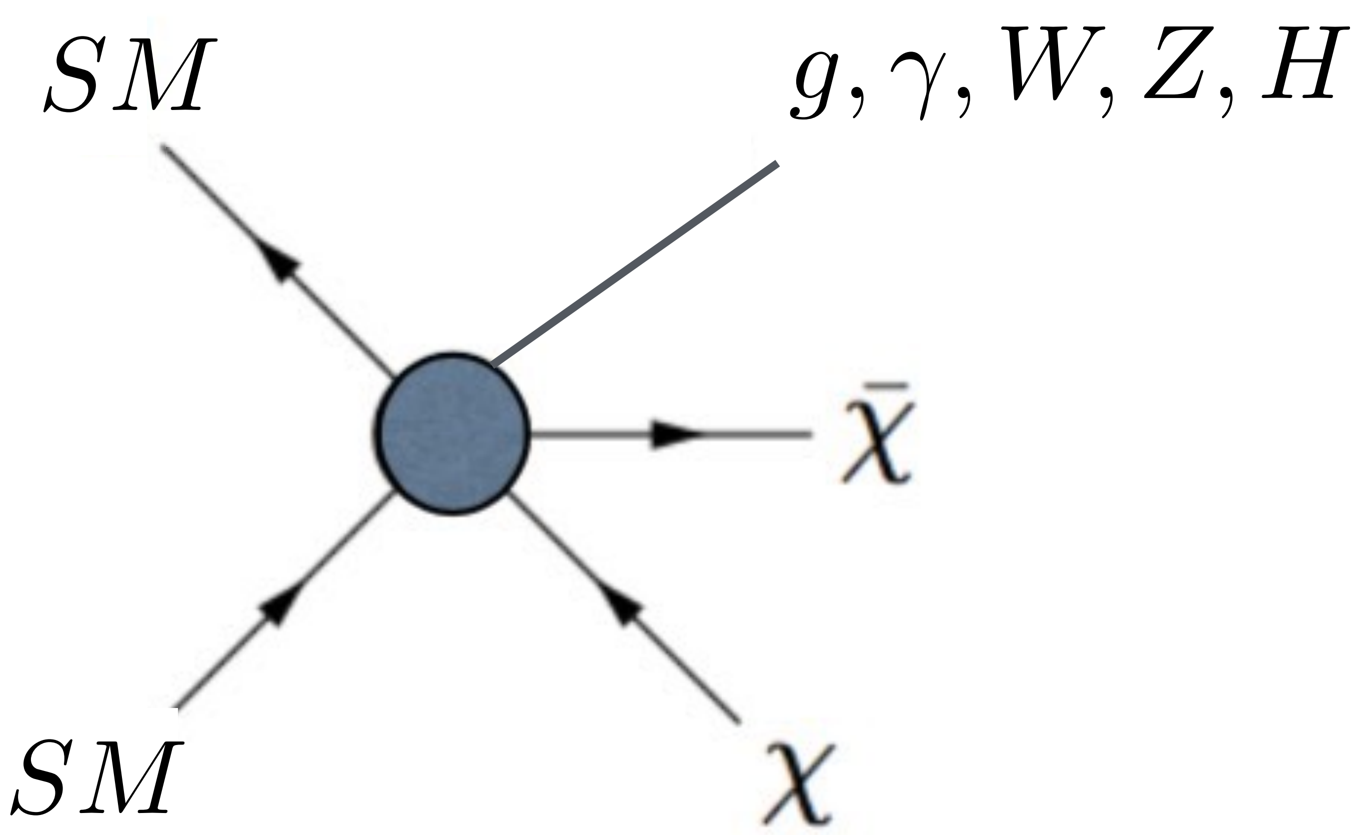
Signature-based searches

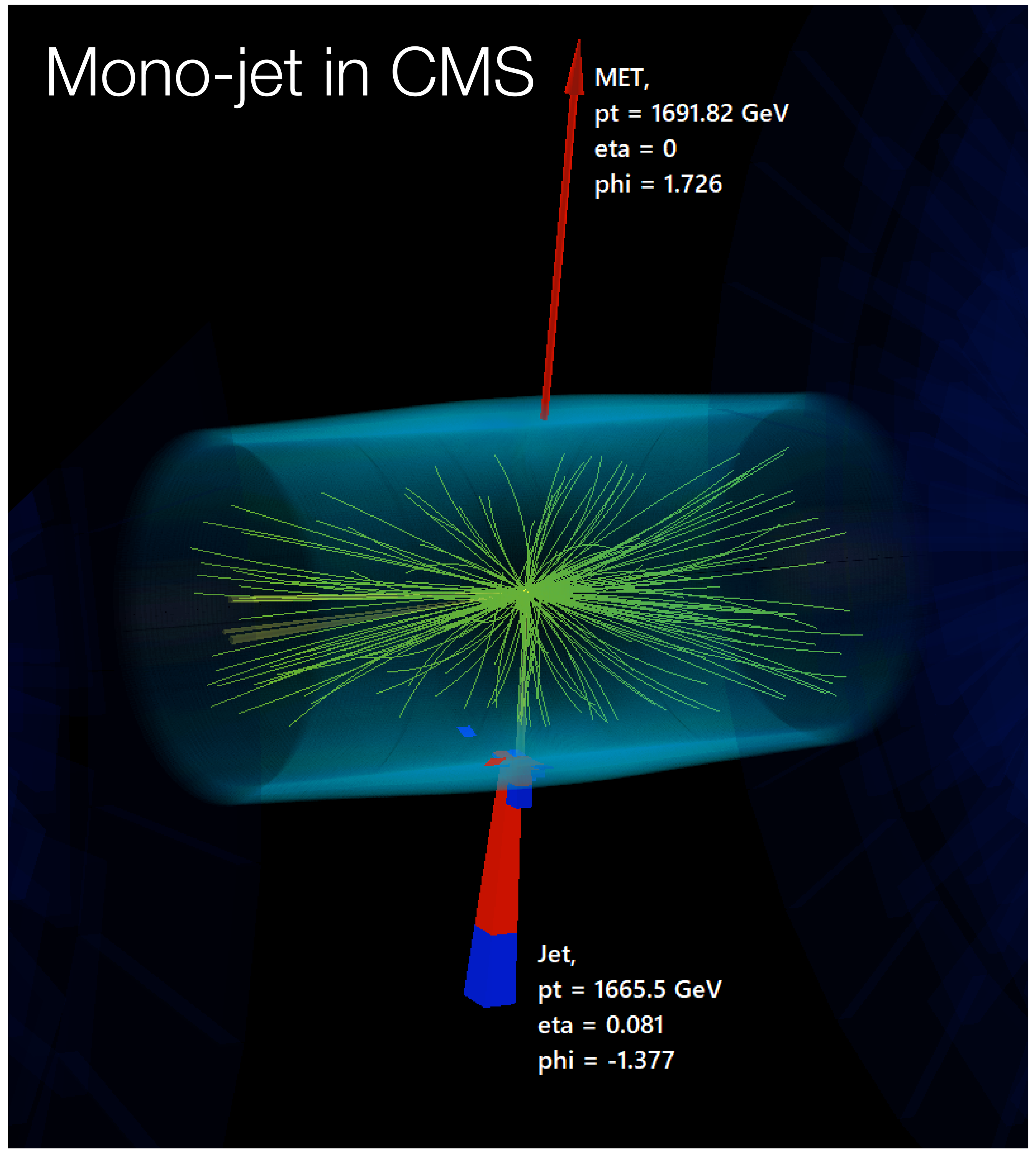
One of the big open questions we try to address is the nature of **dark matter**

If it is produced at collider experiments it will not interact with the detector, and manifest as **missing transverse energy** as it recoils against some visible objects



Mono-X production





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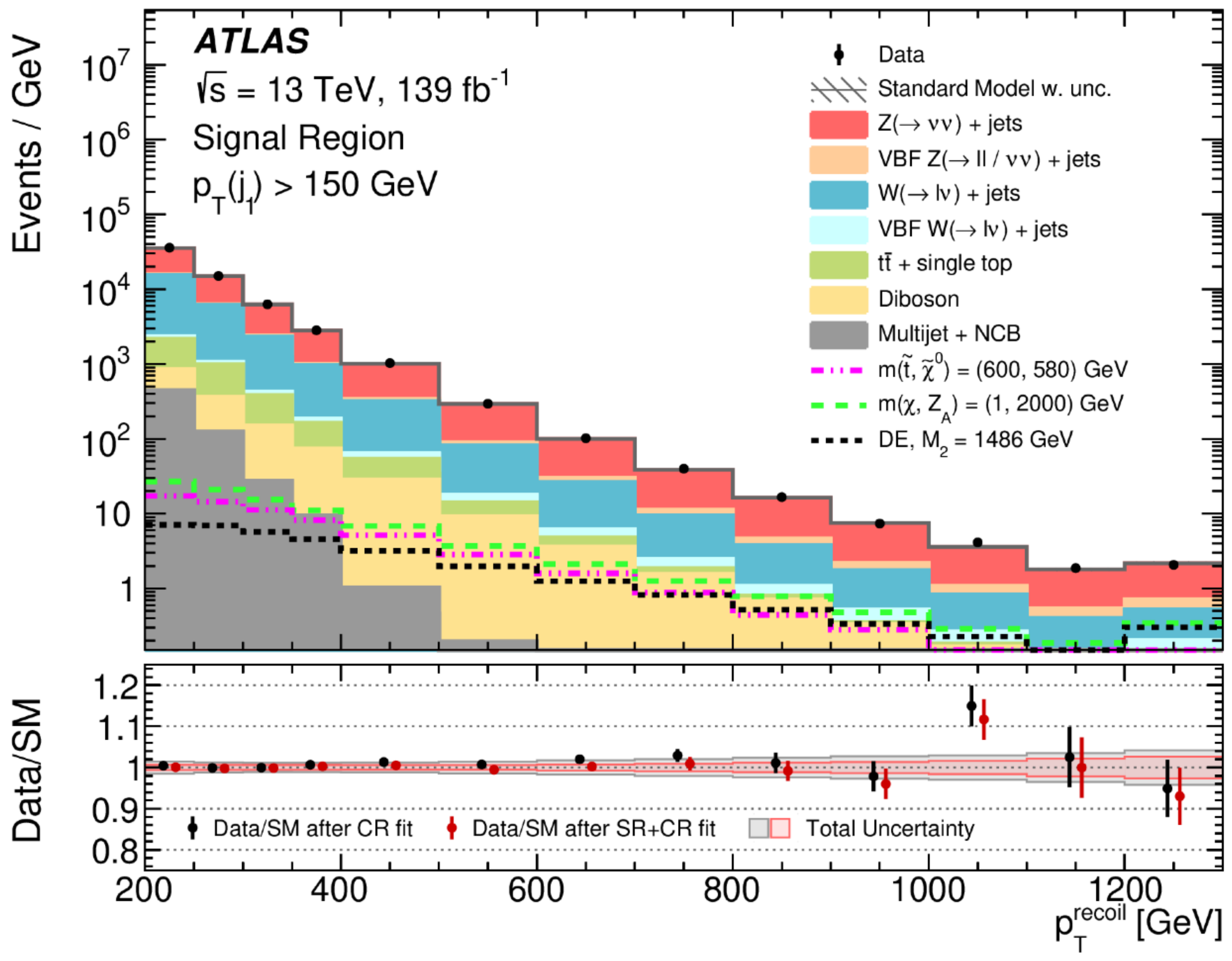

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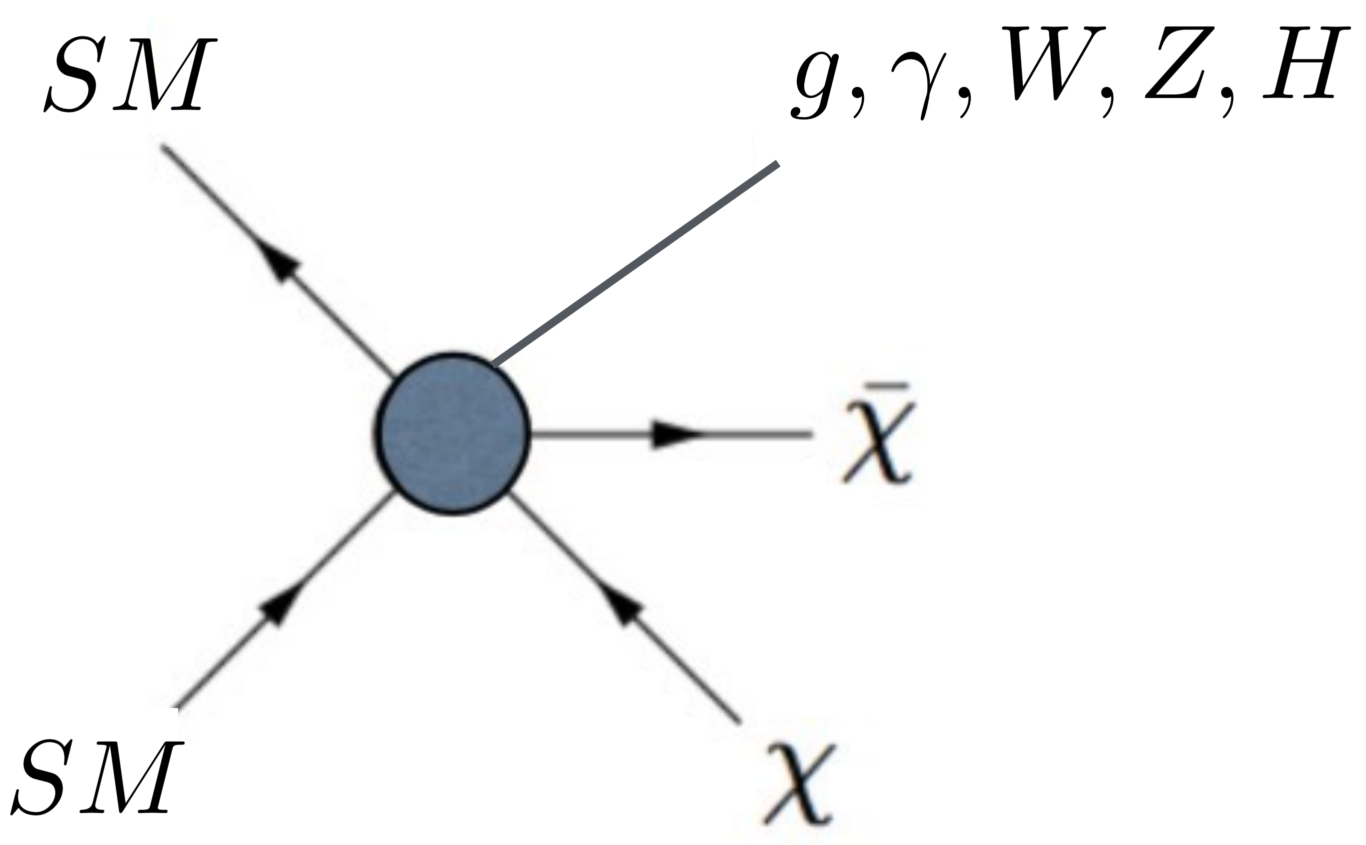
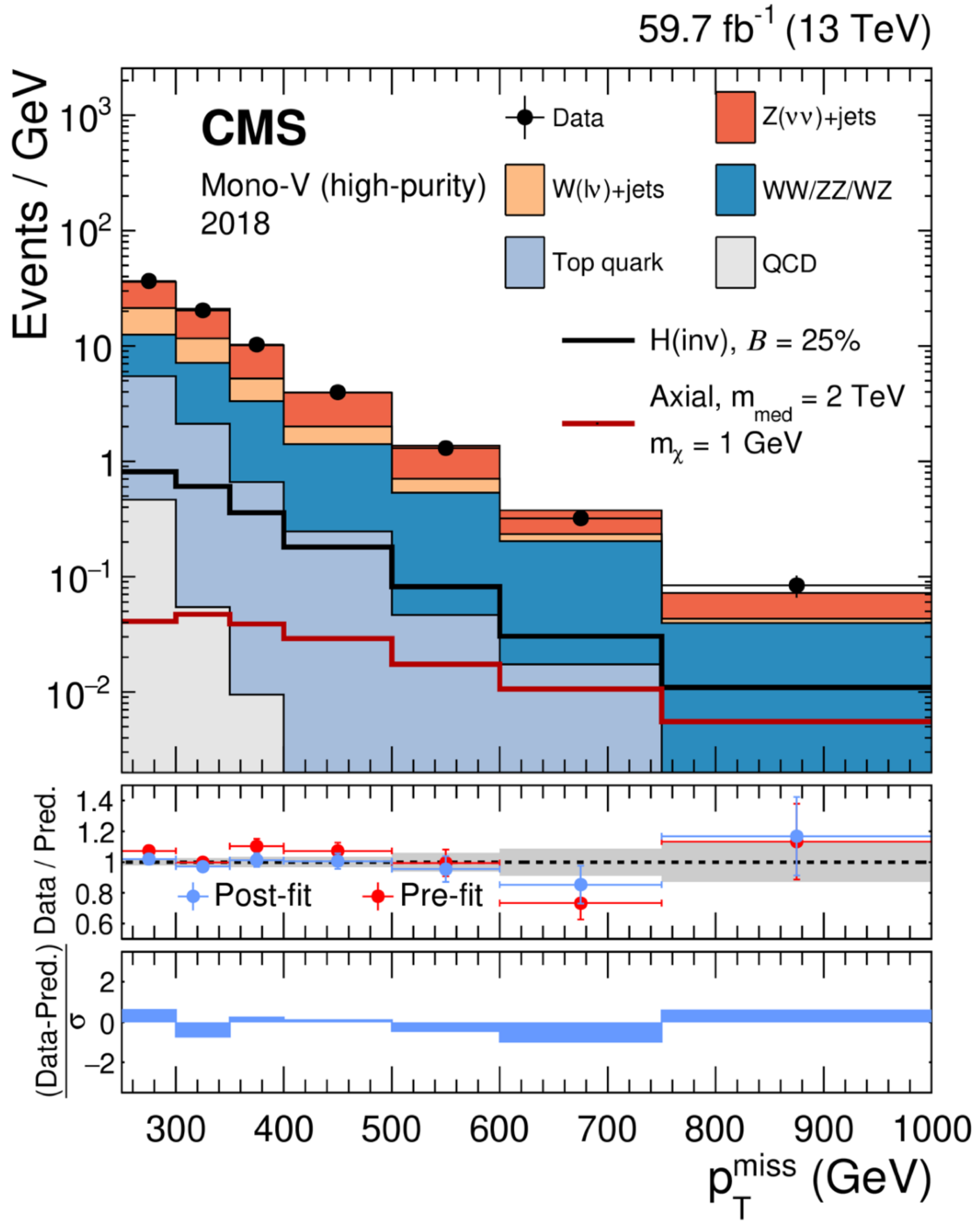
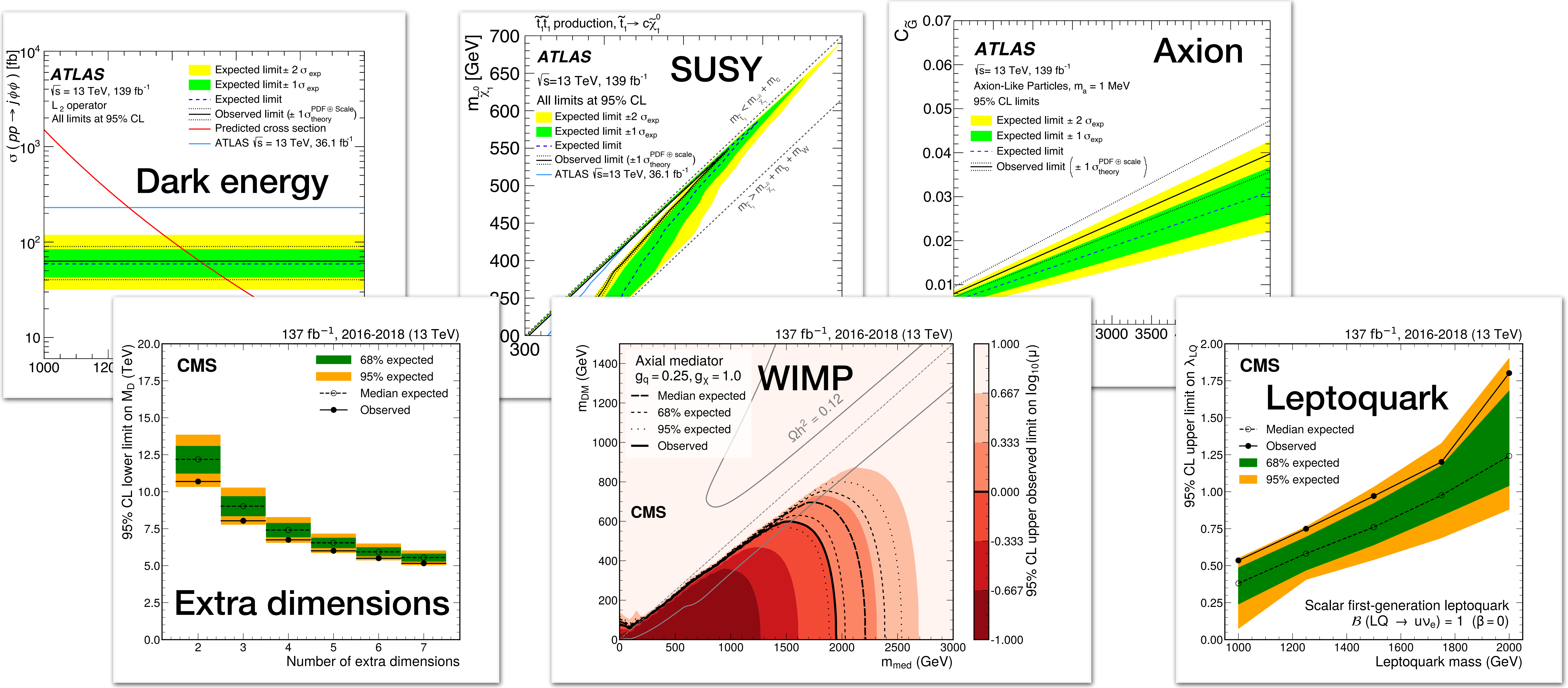




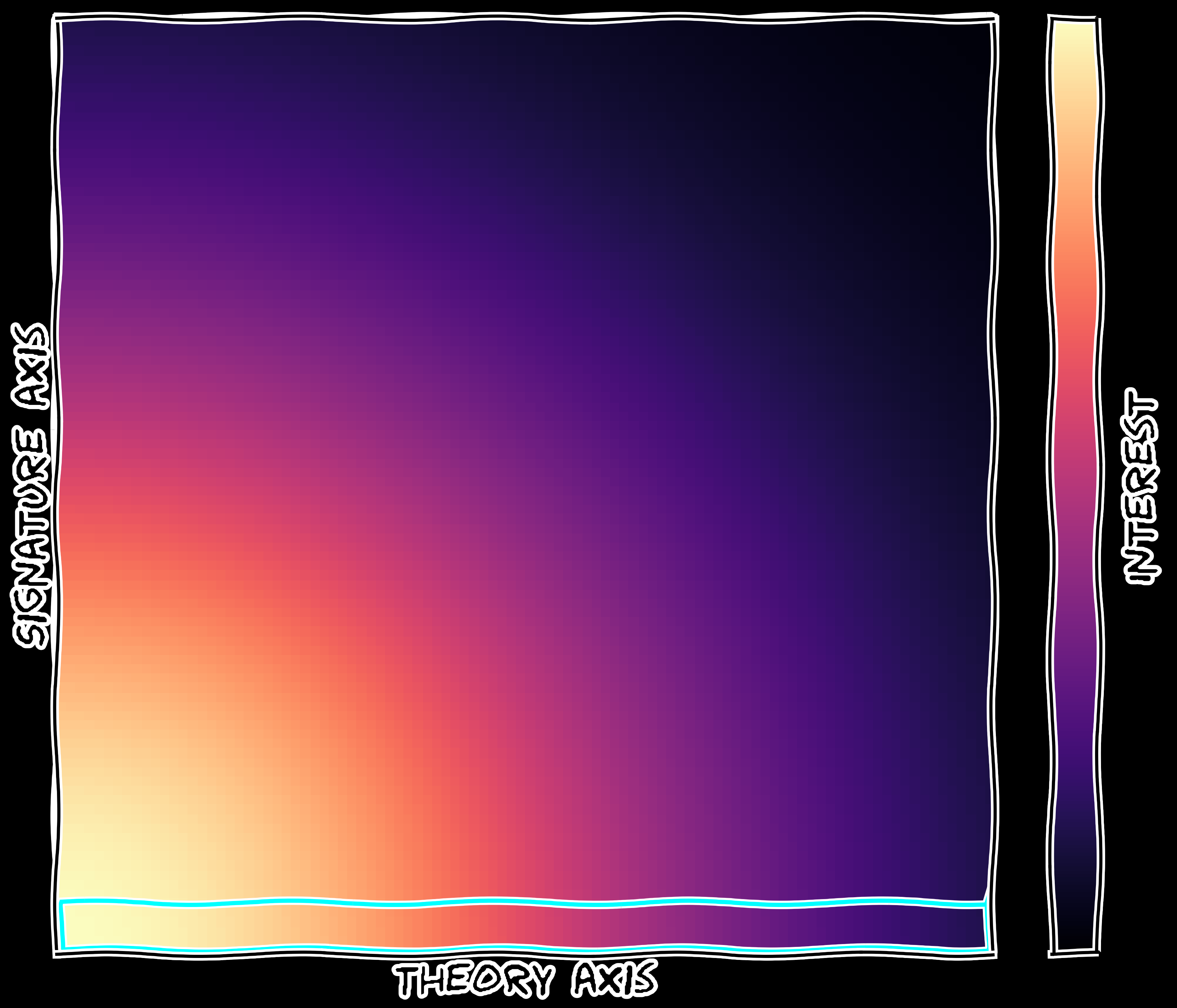
Signature-based searches

The monojet search is a perfect example of the signature-based approach: one signature, many model interpretations



Exploring the theory axis,

the LHC dream (before hitting null results)



Theory-based searches

Many models propose elegant solutions to SM problems, we then tailor searches to the predicted final states

Heavy neutral leptons, provide an explanation for neutrino masses

- N → $\ell\ell\nu$, possibly displaced

Leptoquarks, connect lepton and quark sector, arise in grand unified theories

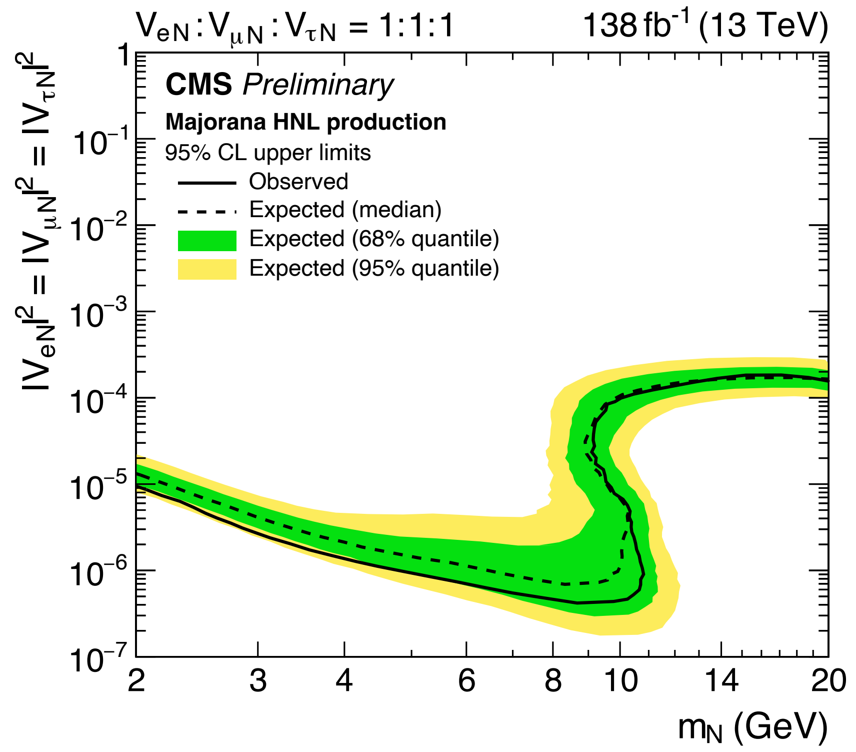
- LQ pair → ℓq ℓq, also νq νq (SUSY-like) and mixed decays

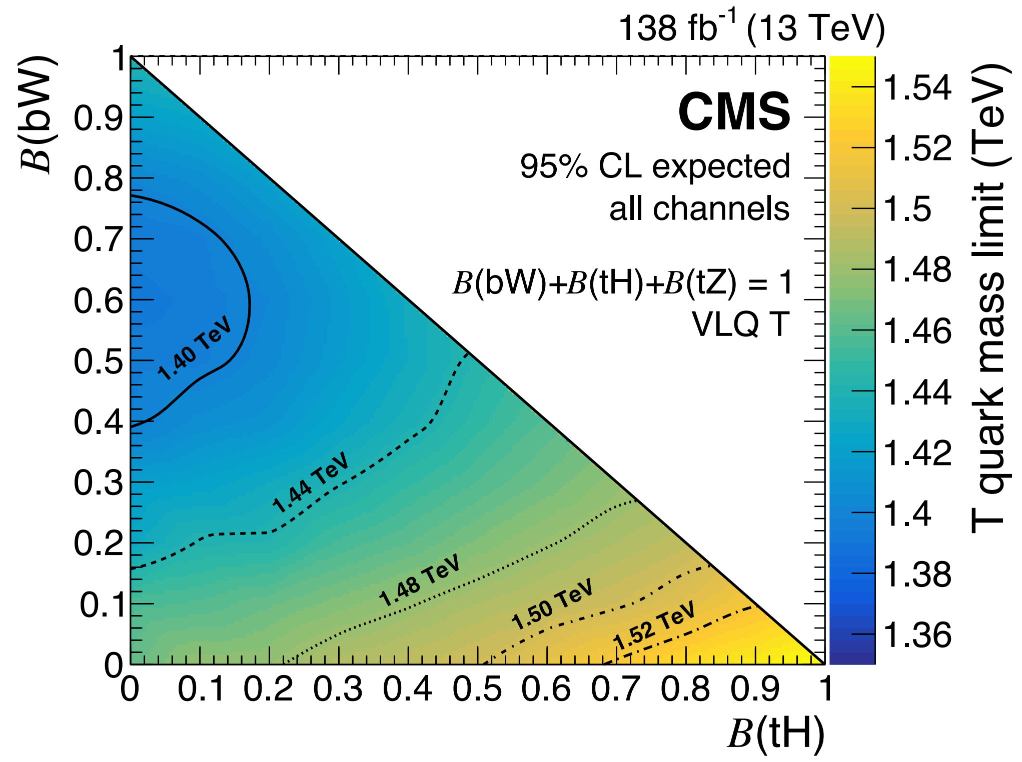
Vector-like quarks, arise in composite Higgs models addressing the hierarchy problem

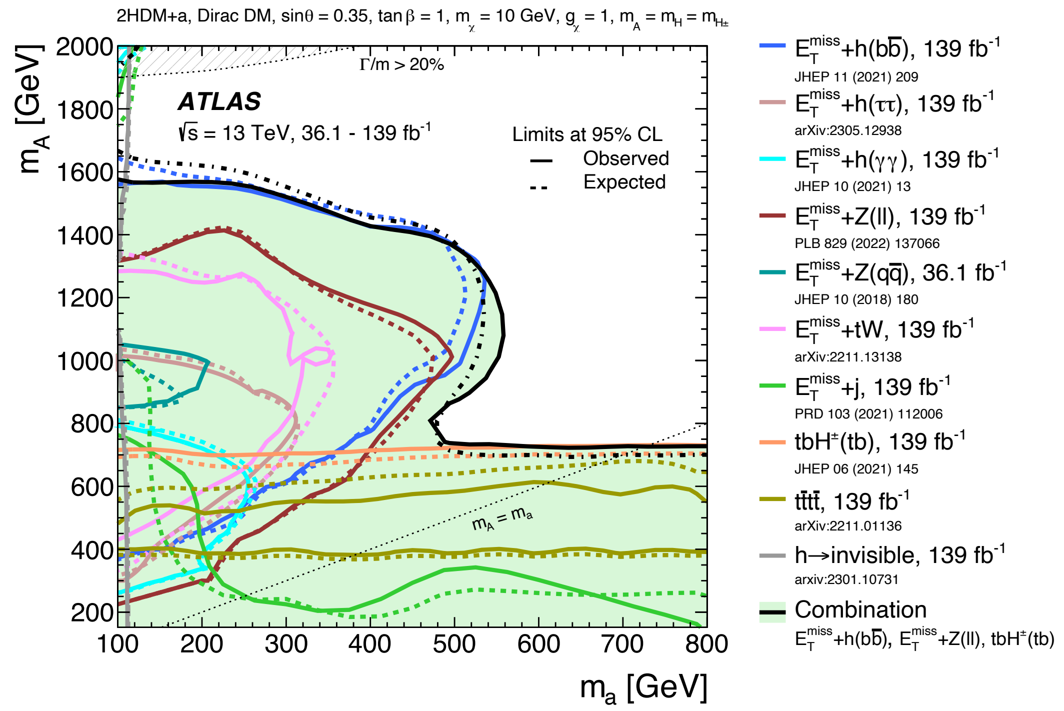
- T → tH/tZ/bW

2HDM(+s), source of additional CP violation, dark matter mediator

- Predict a rich phenomenology mono-H/Z/j, tt+MET, tbH+, four-top
- A great example of the theory-based approach: one model, many complementary signatures





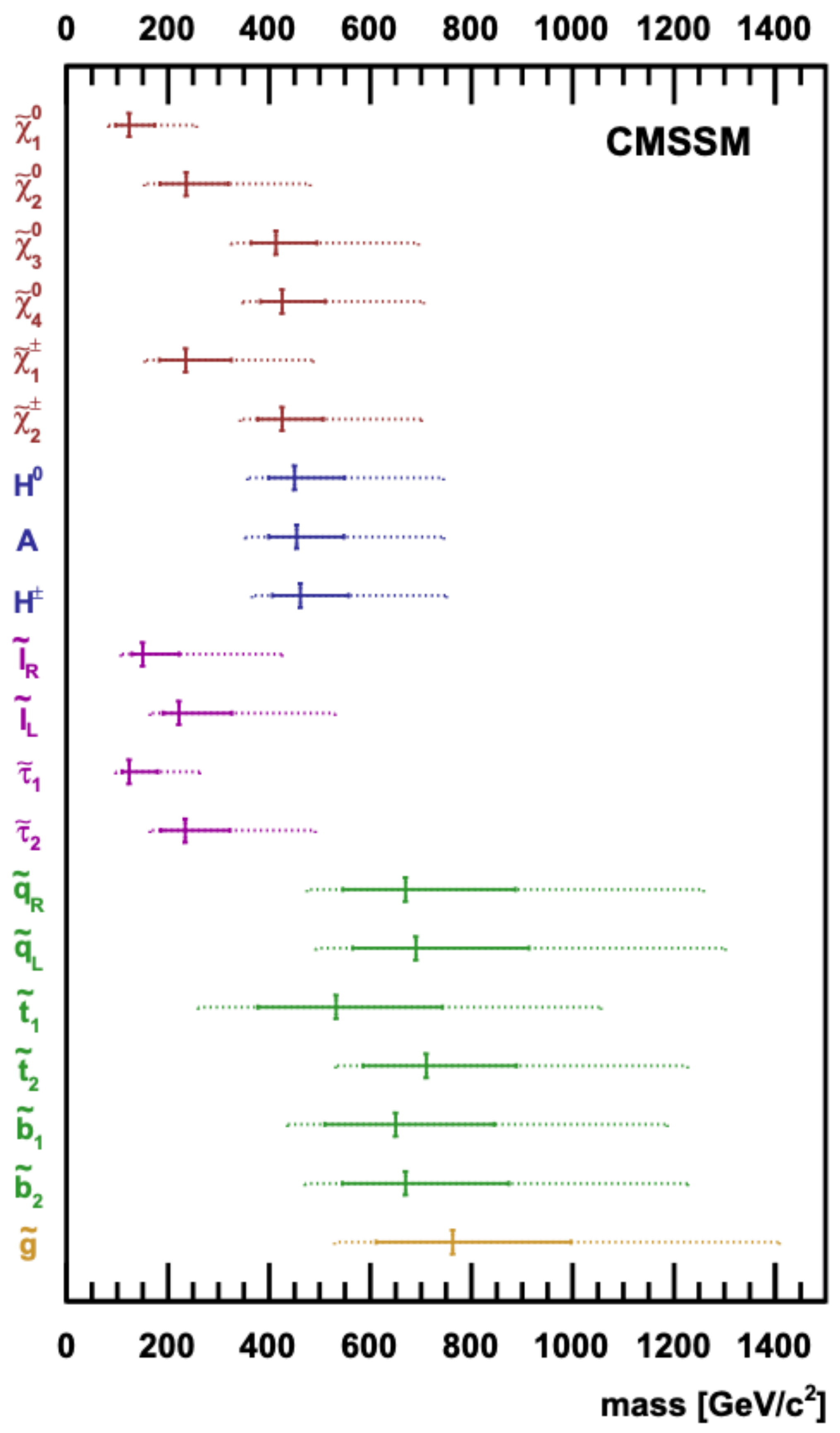


Theory-based searches

Supersymmetry, an overly simplified history of hopes and frustration running behind a moving target:

- Supersymmetry provides solutions to many problems simultaneously: hierarchy problem, dark matter, gauge coupling unification
- In its minimal version (MSSM) requires 105 new parameters, which we reduced to 5 (cMSSM) with some hand-wavy arguments

0909.4662



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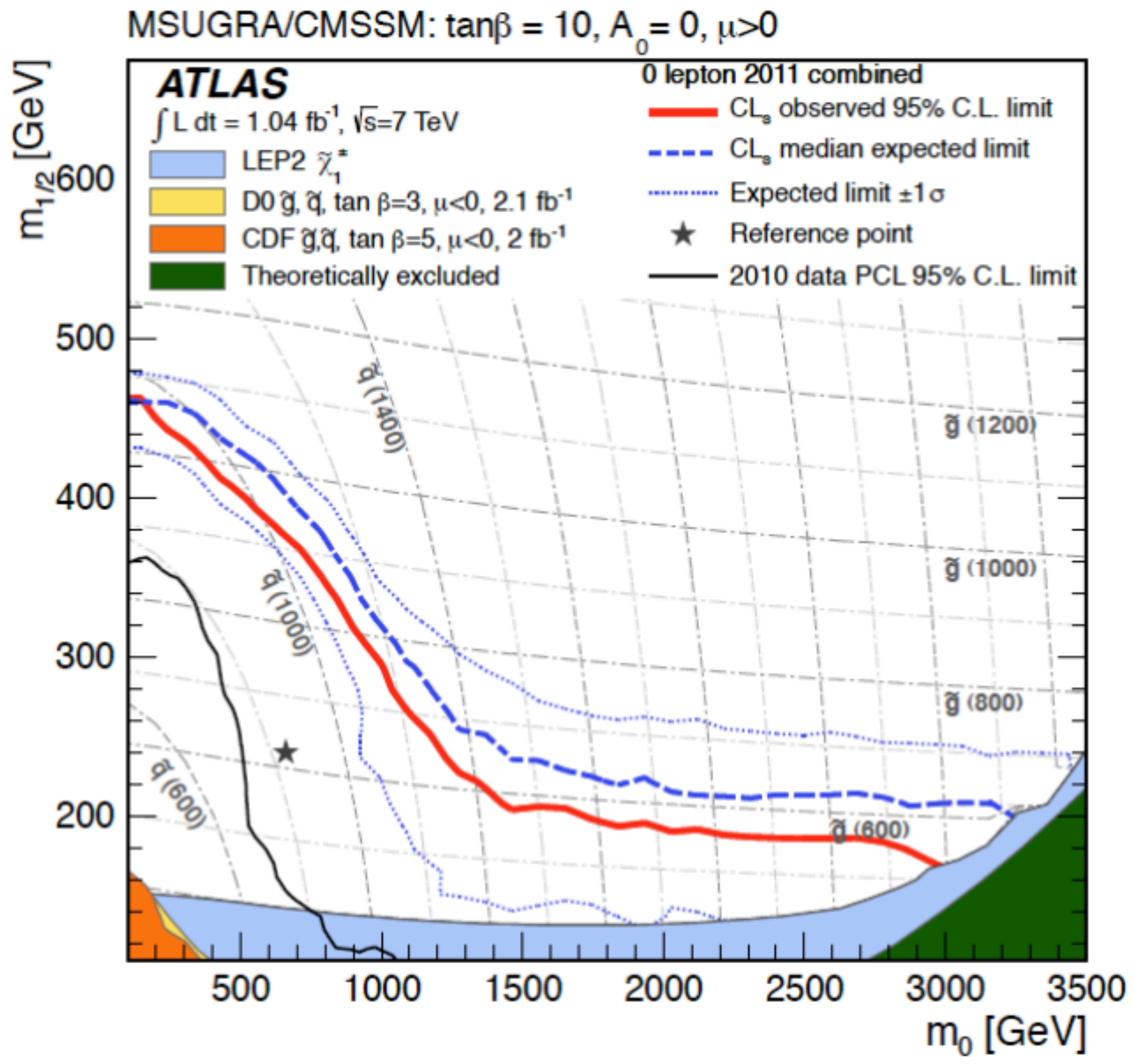

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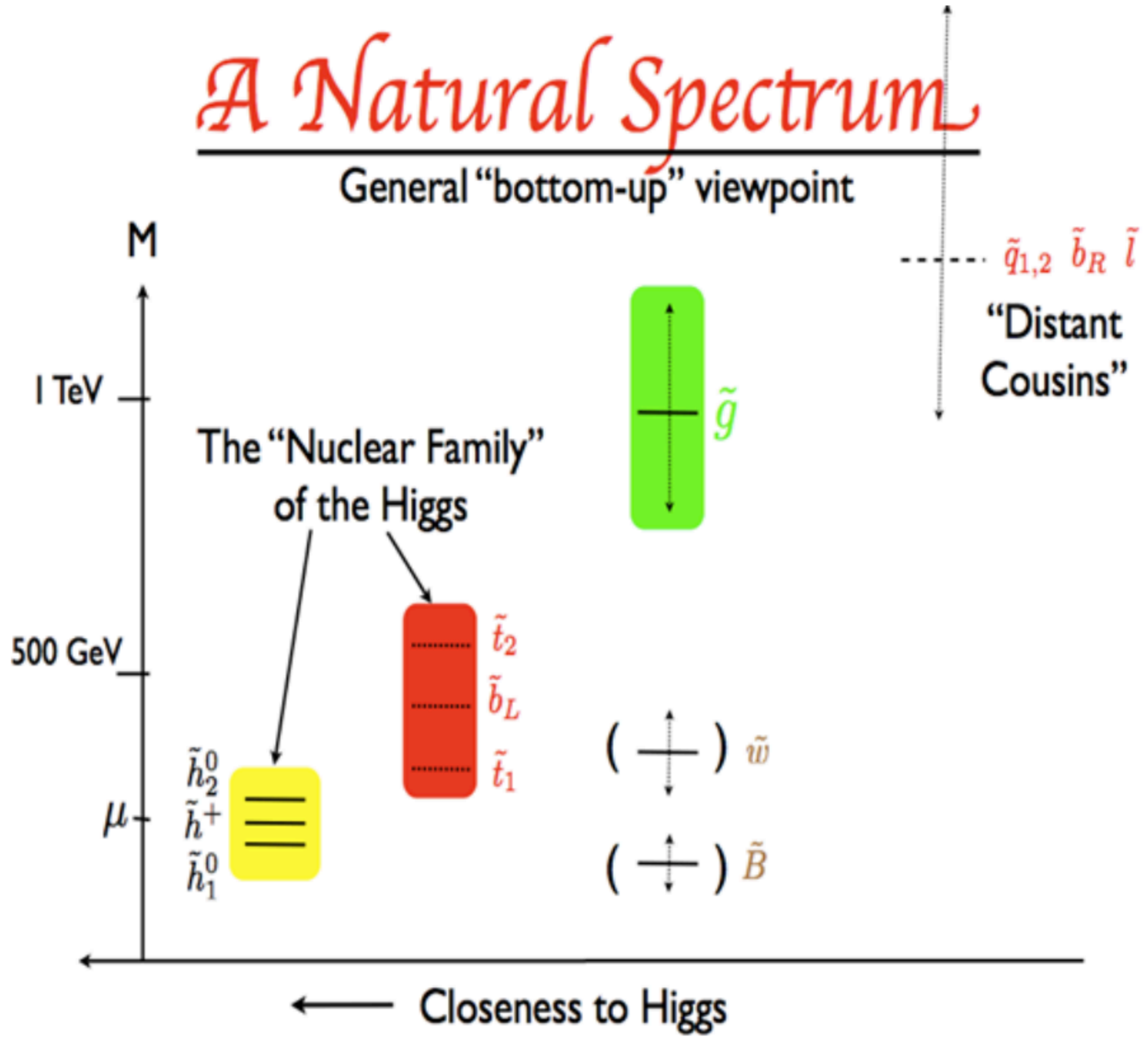
  - Natural supersymmetry requires three sparticles to be "light": higgsinos, stops, gluinos



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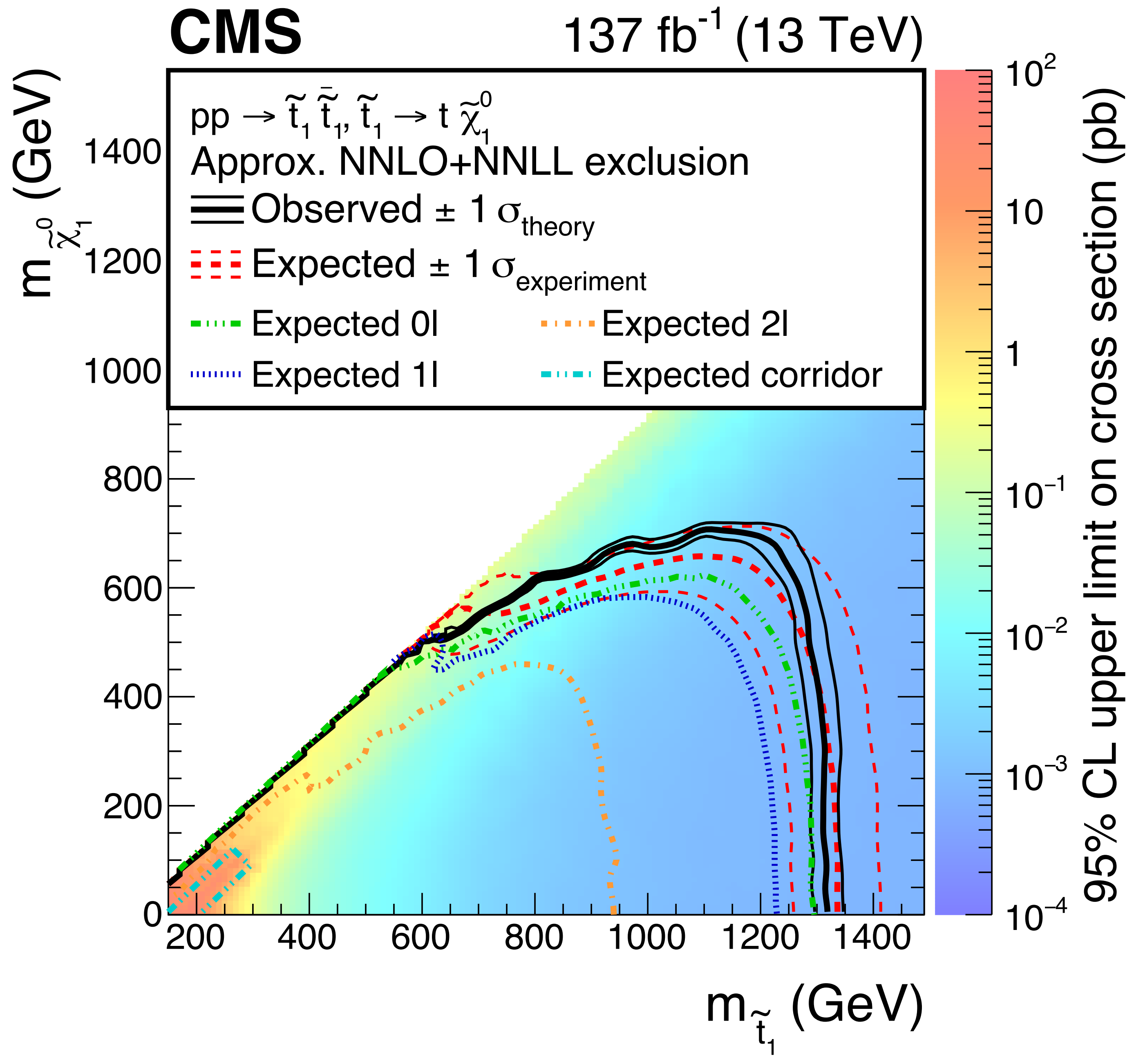

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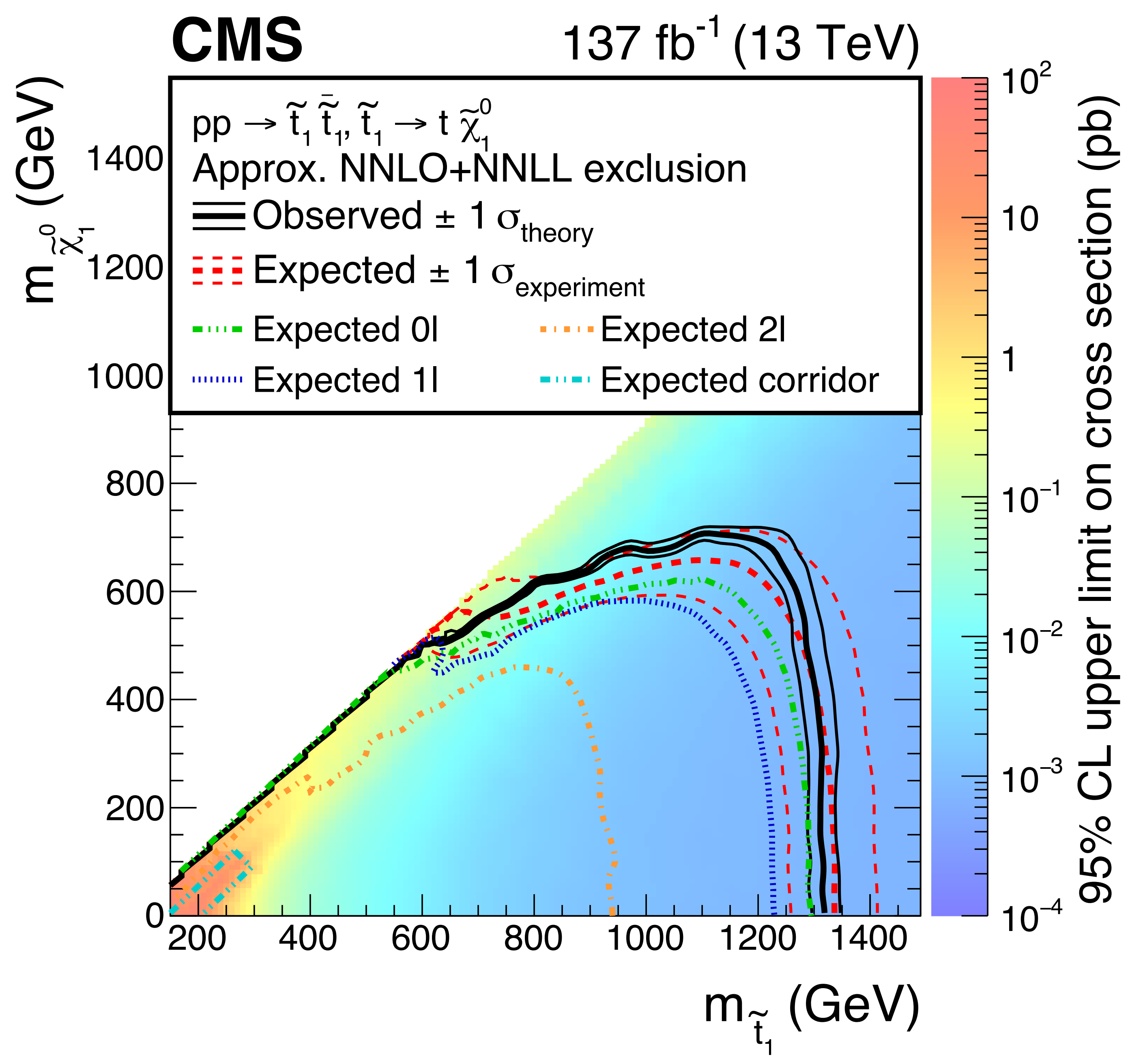
  - Only higgsinos need to be light (≲350 GeV), stops and gluinos can be multi-TeV



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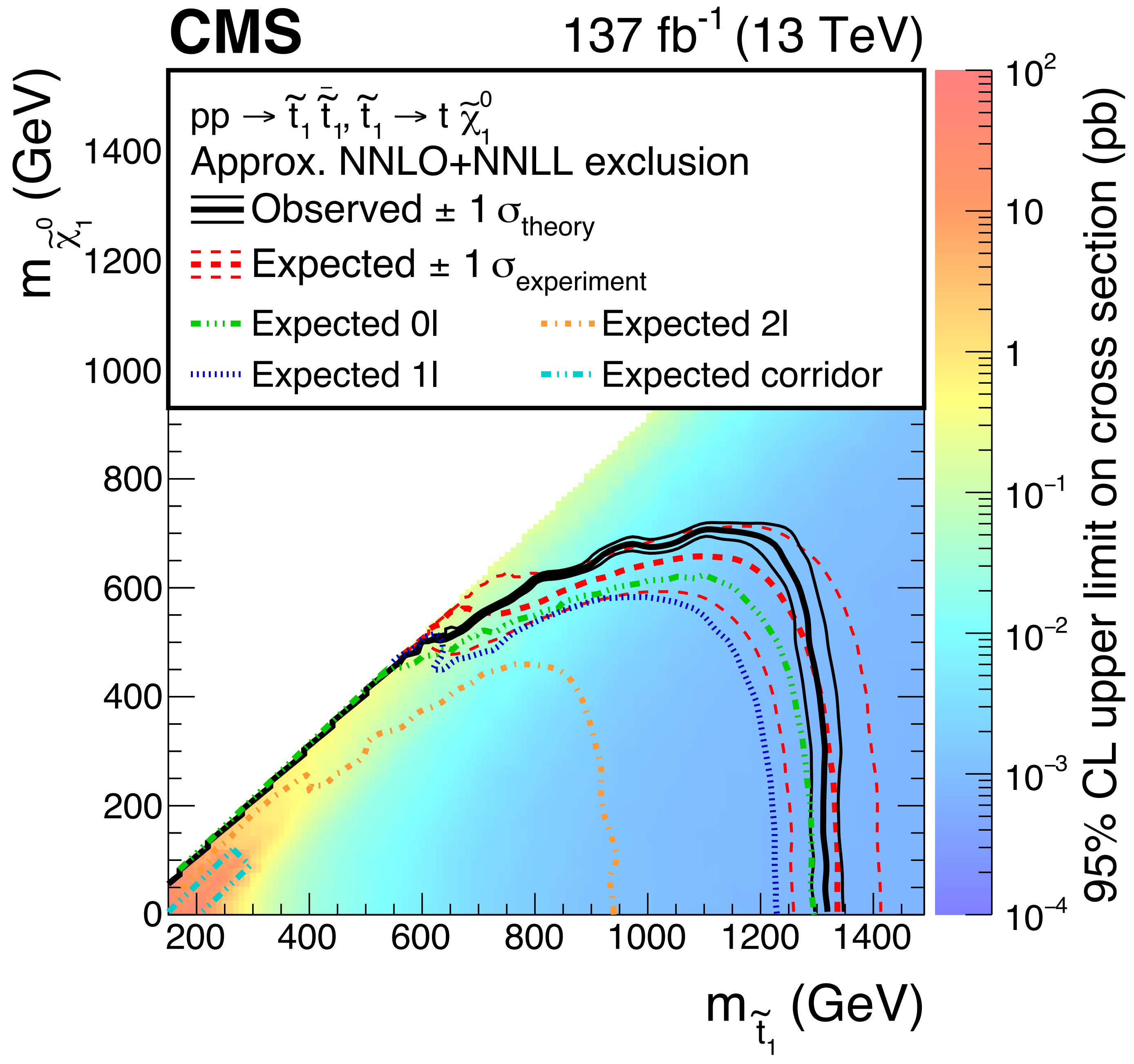

Do you trust we picked the right assumptions and metrics? **Then SUSY is dead**

Are there still vast parameter regions that still provide good solutions to all the original SM problems? **Absolutely**

Theory-based searches

SUSY hater:

- Limits on stops have reached the TeV scale, gluinos above 2 TeV, natural SUSY is dead!

SUSY lover:

- No! Light stops are still possible in RPV, non-MFV, NMSSM, stealth

Theory-based searches

SUSY hater:

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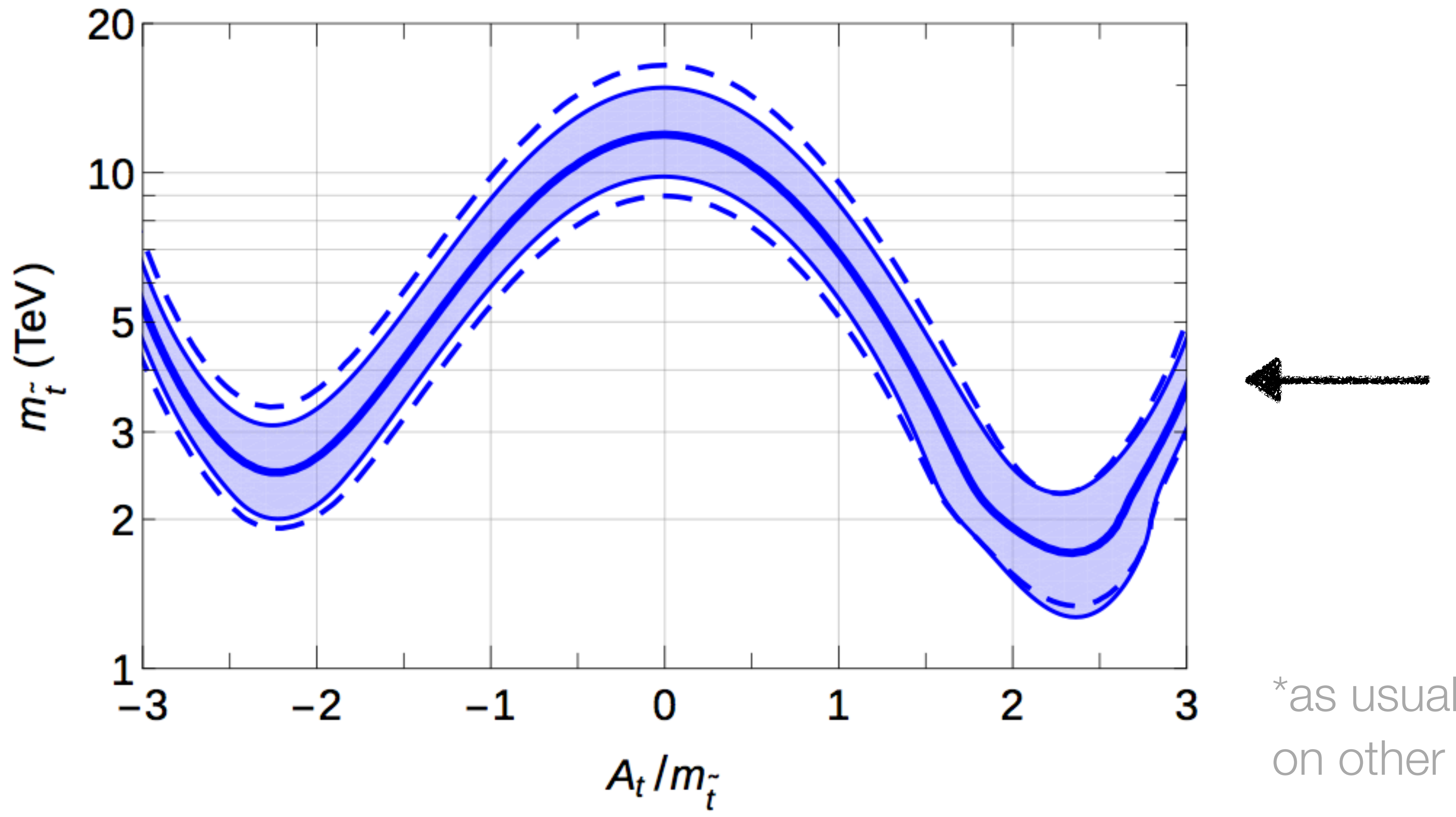
SUSY lover:

- No! Light stops are still possible in RPV, non-MFV, NMSSM, stealth

It seems we trust more our theory priors than the data, the higgs mass measurement **requires SUSY above the TeV scale**, regardless of our naturalness prior



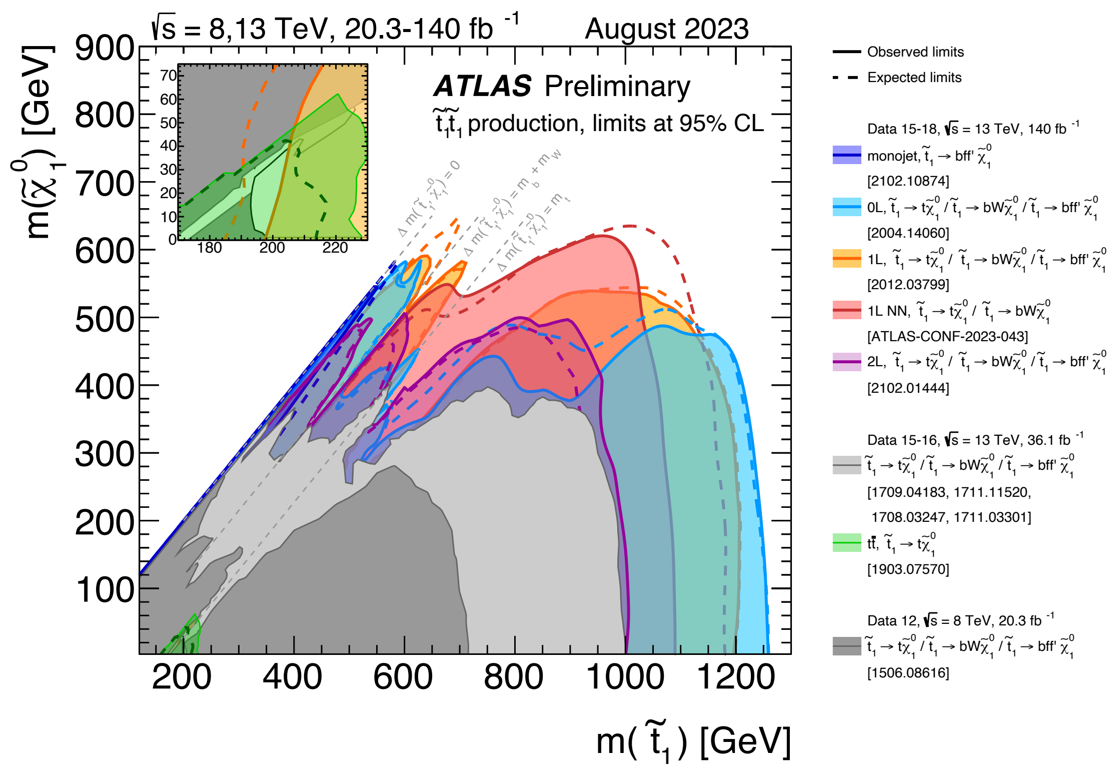
band compatible with higgs mass

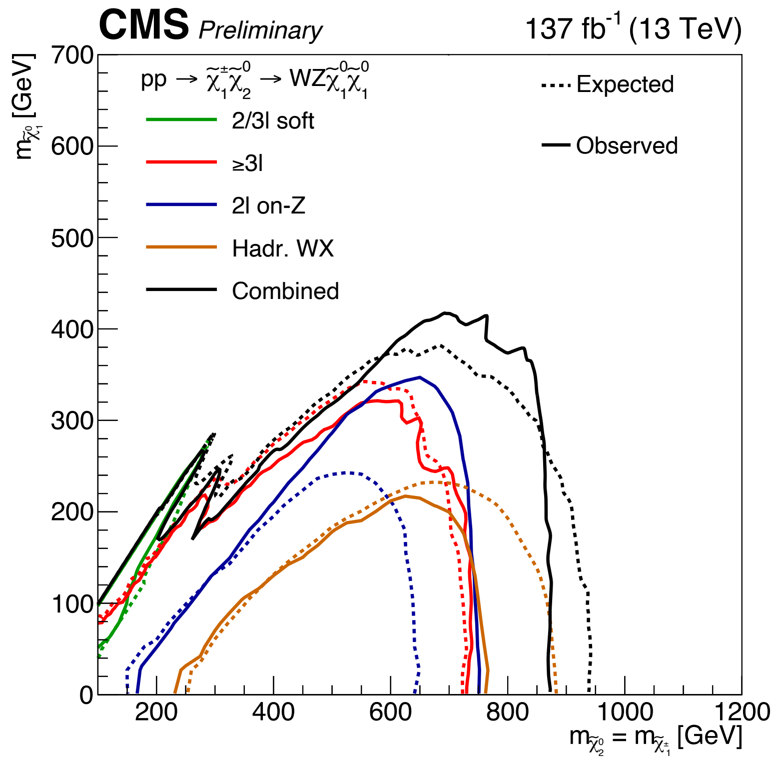
*as usual, caveats apply, some dependence on other parameters such as tan ß

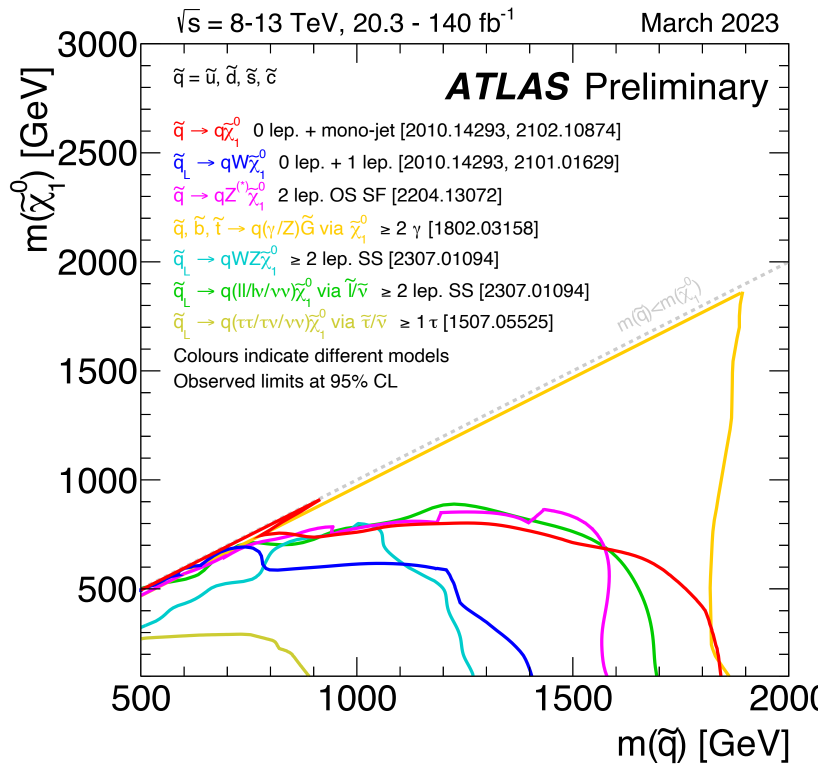
SUSY, are we there yet?

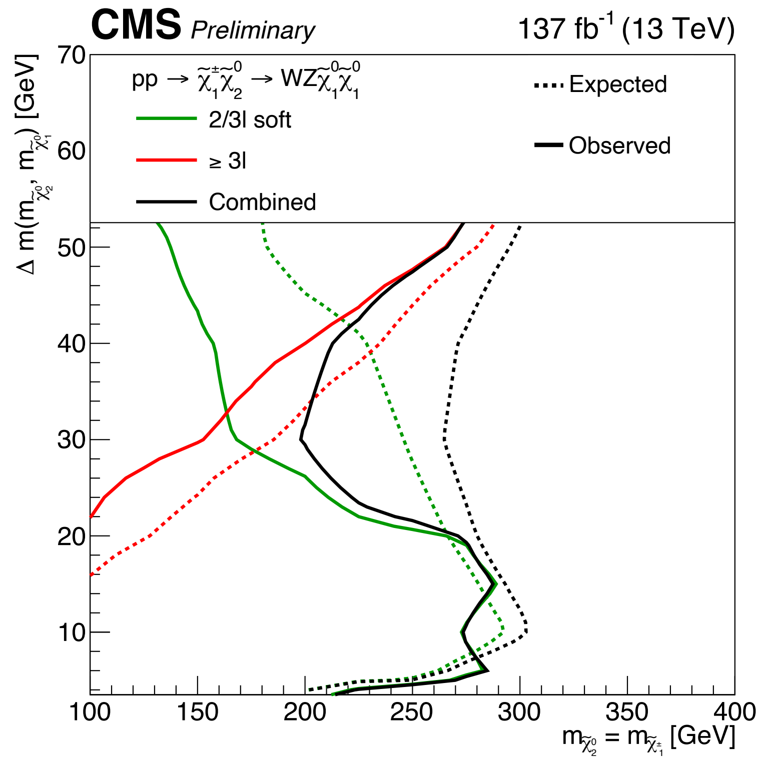
The MSSM is another example of the theory-based approach: one model, many complementary signatures

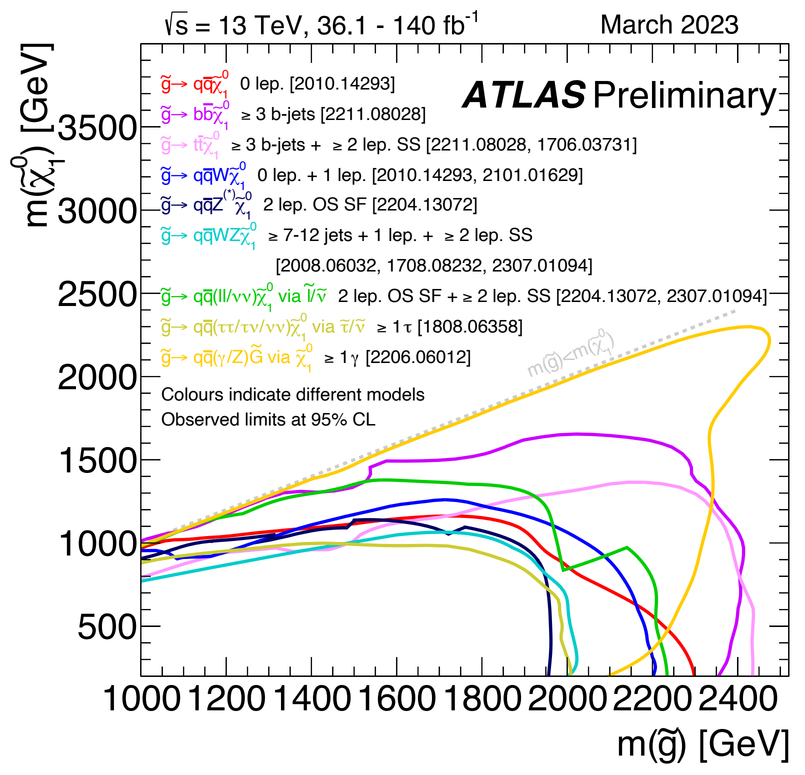
But after many years of work and results looking for every signature, no evidence for SUSY

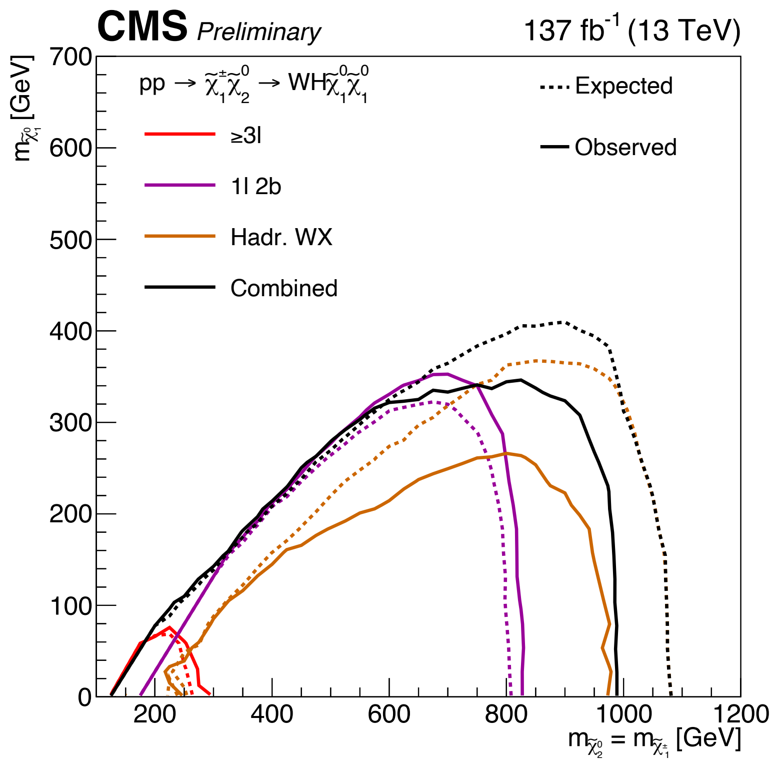


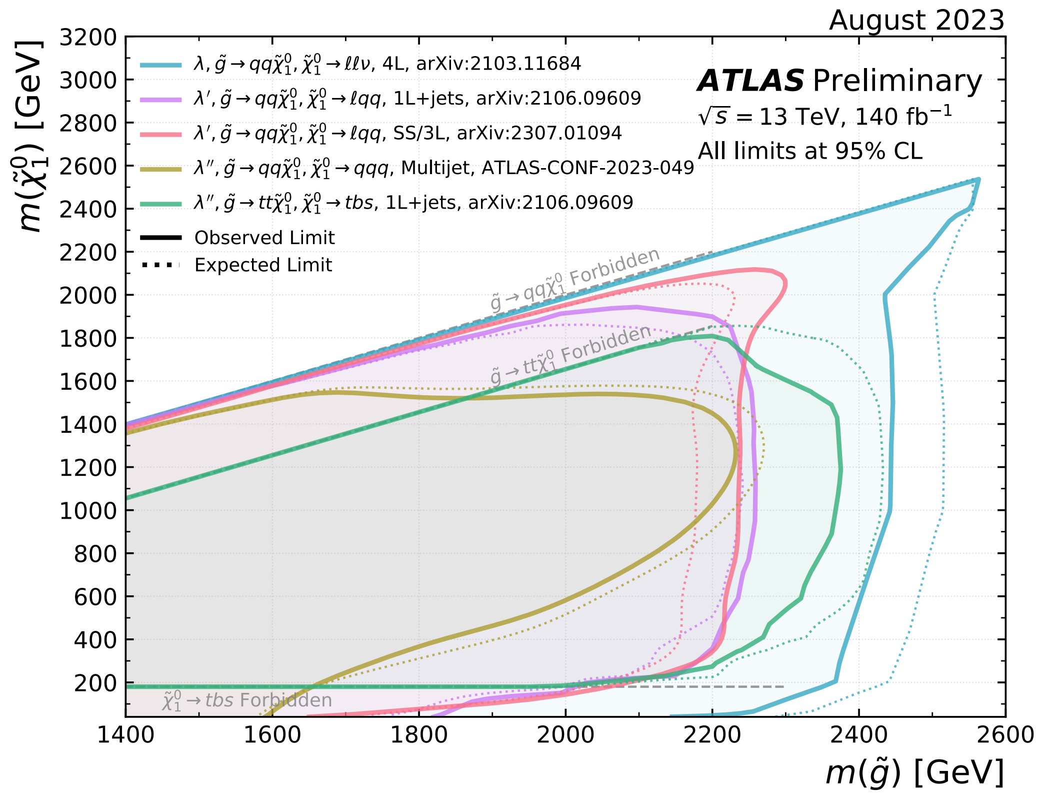


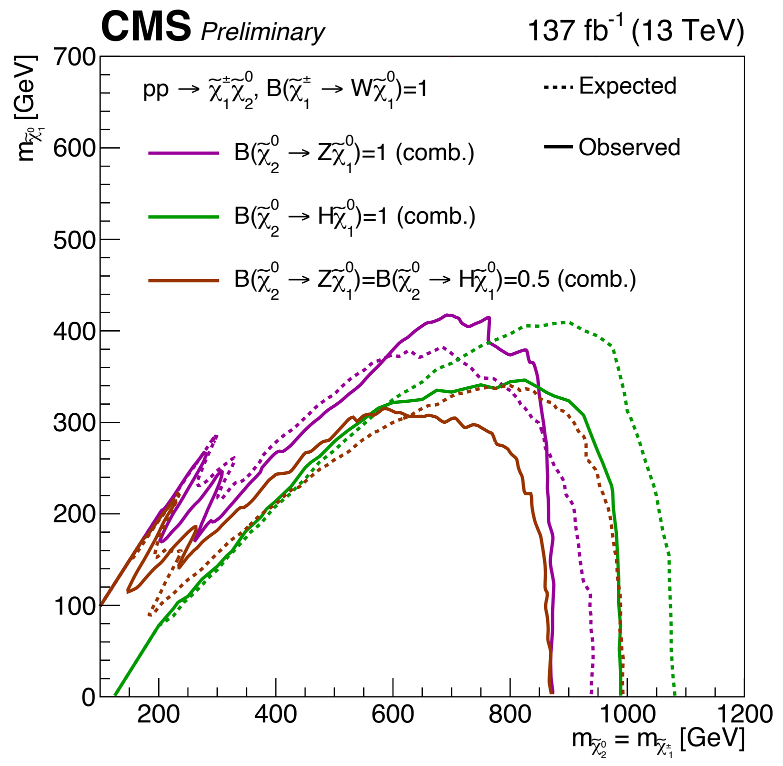


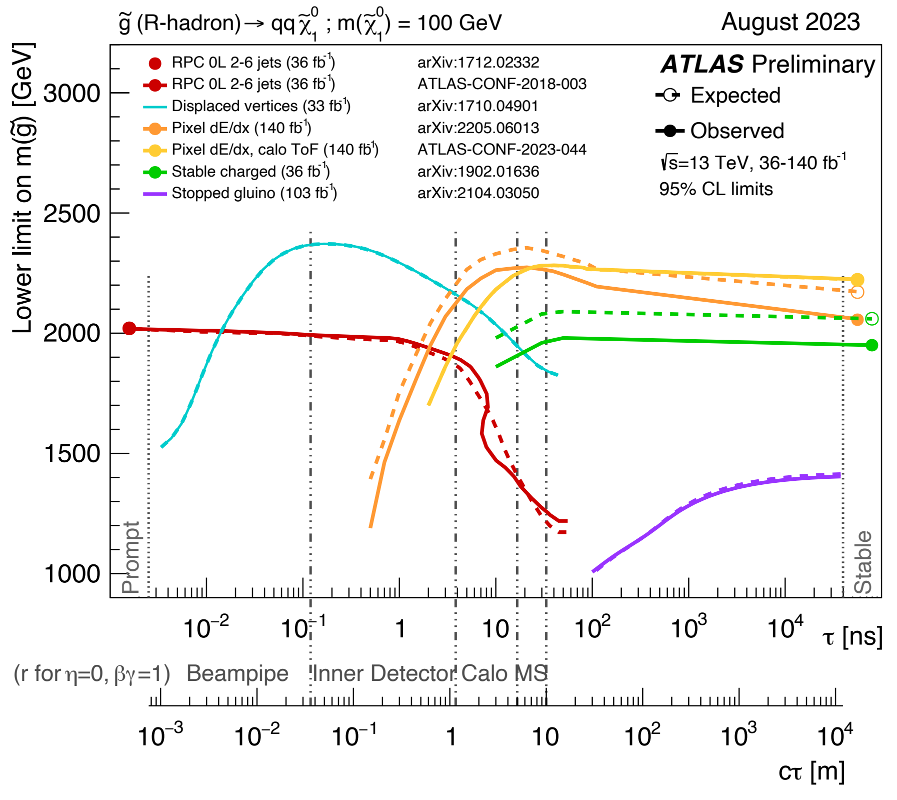


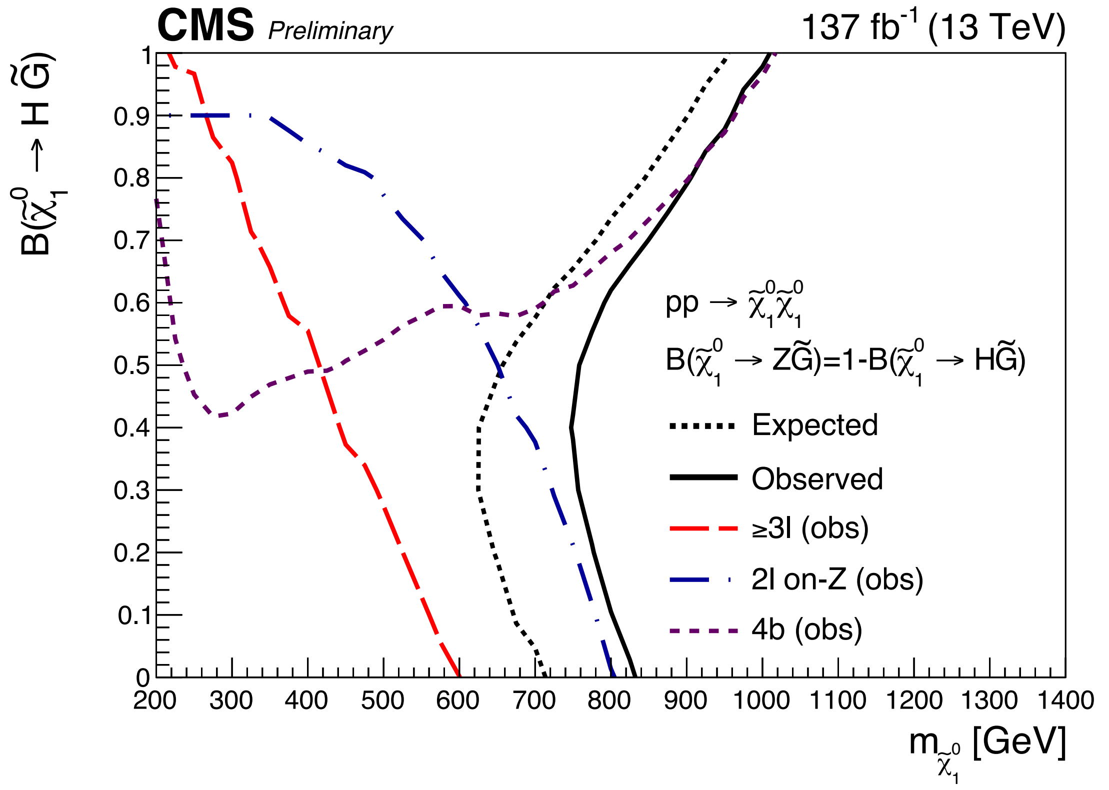






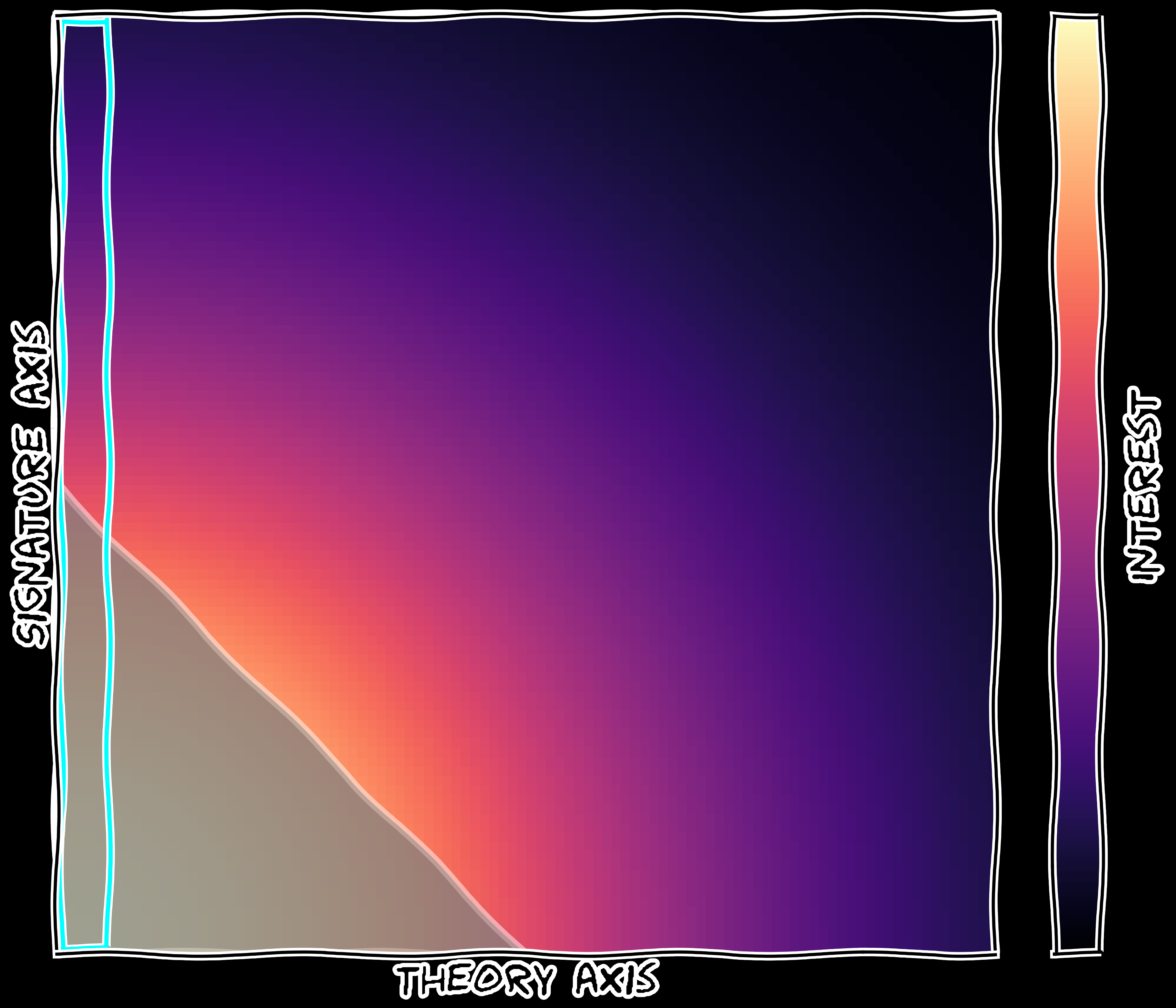






Exhausting the signature axis,

getting creative and squeezing sensitivity



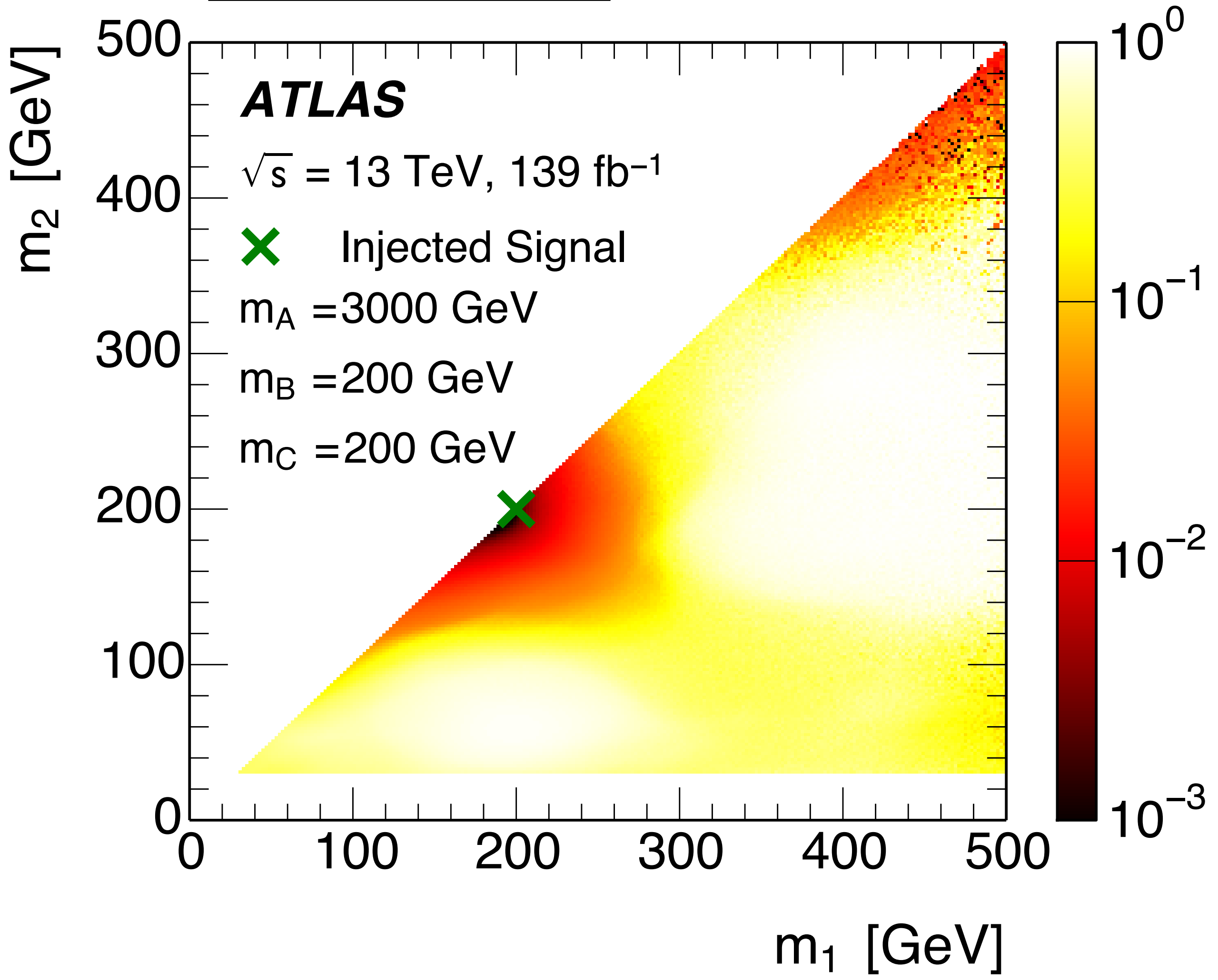
Upgrading signature-based searches

For all signatures, fine-tuning for a model and being more specific in the selection will always improve the sensitivity at the cost of reducing the inclusive-ness of the search

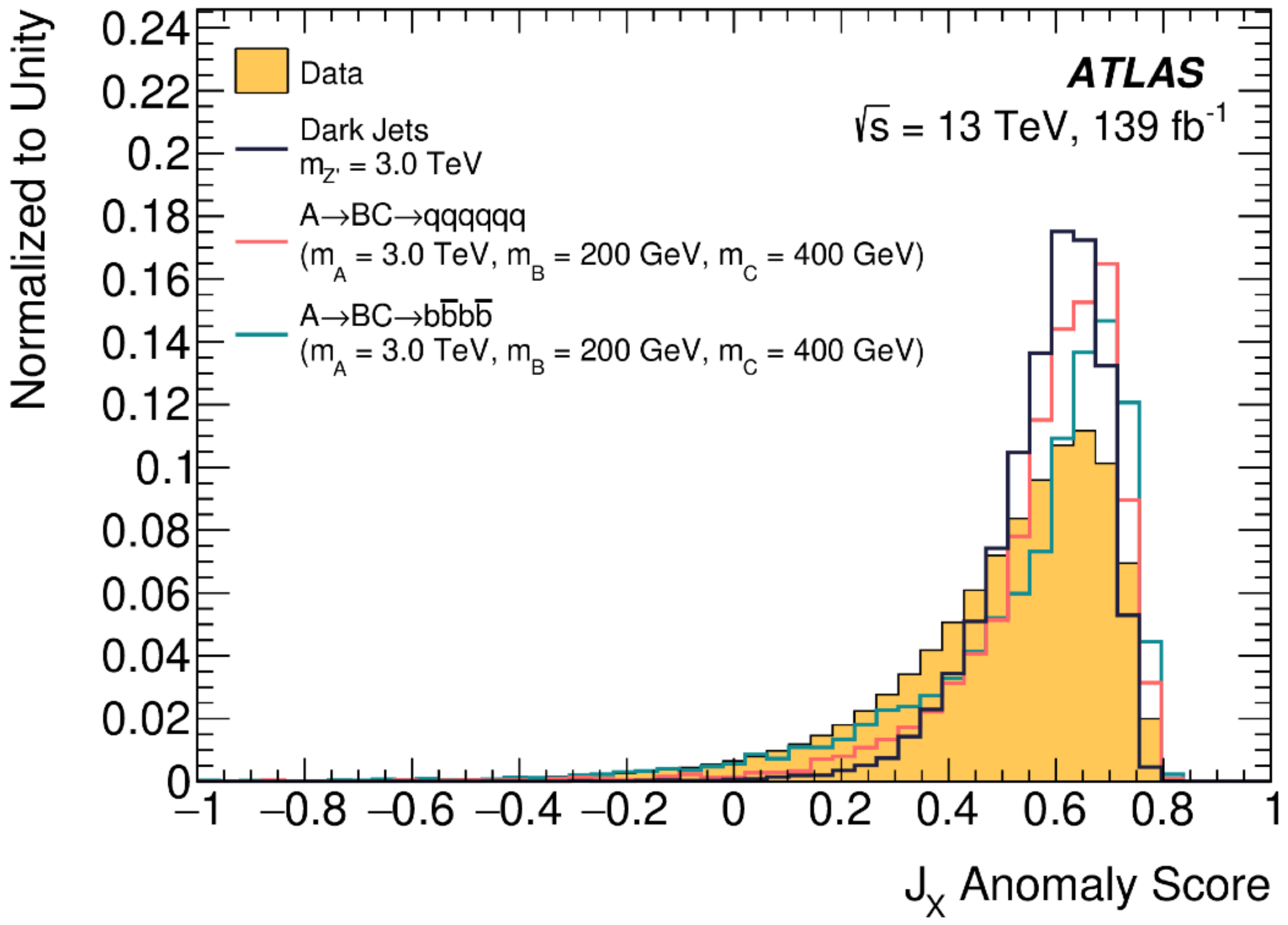
Can we improve the sensitivity and still be model agnostic? look for **anomalies** without a signal hypothesis

- Classification without labels, train a classifier to distinguish events in the SR from the sidebands
- Run an autoencoder to identify anomalous jets, use them to perform a bump-hunt
- Run an autoencoder to identify anomalous events, perform bump-hunt on many possible di-object pairs

2005.02983



2306.03637



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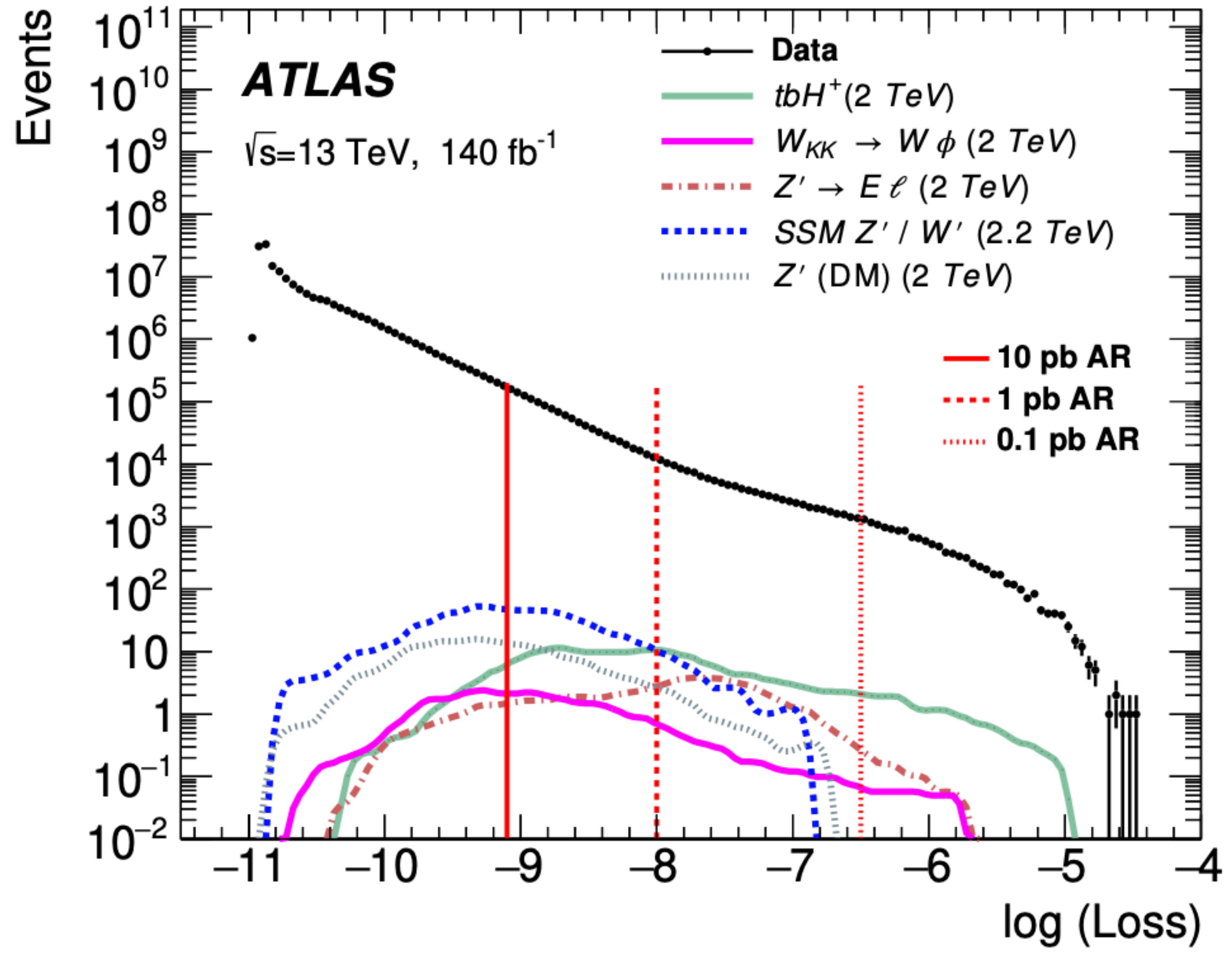
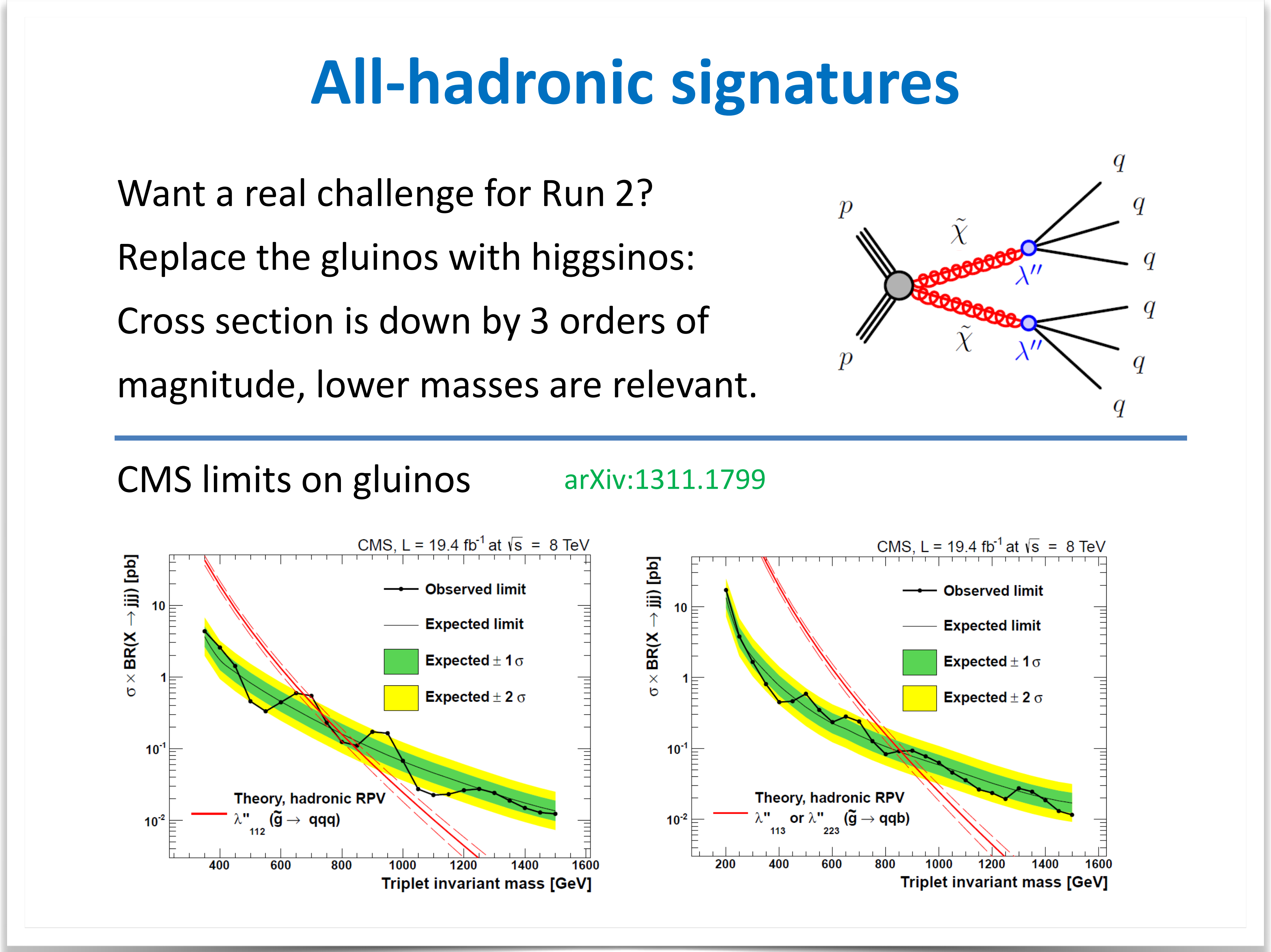


Complex signatures

Some signatures are incredibly hard at a hadron collider, borderline impossible

- Pair-production of an electroweak-scale particle with decay to three jets
- But if you really want a sensitivity boost, just challenge us!

LHCP 2015



Complex signatures

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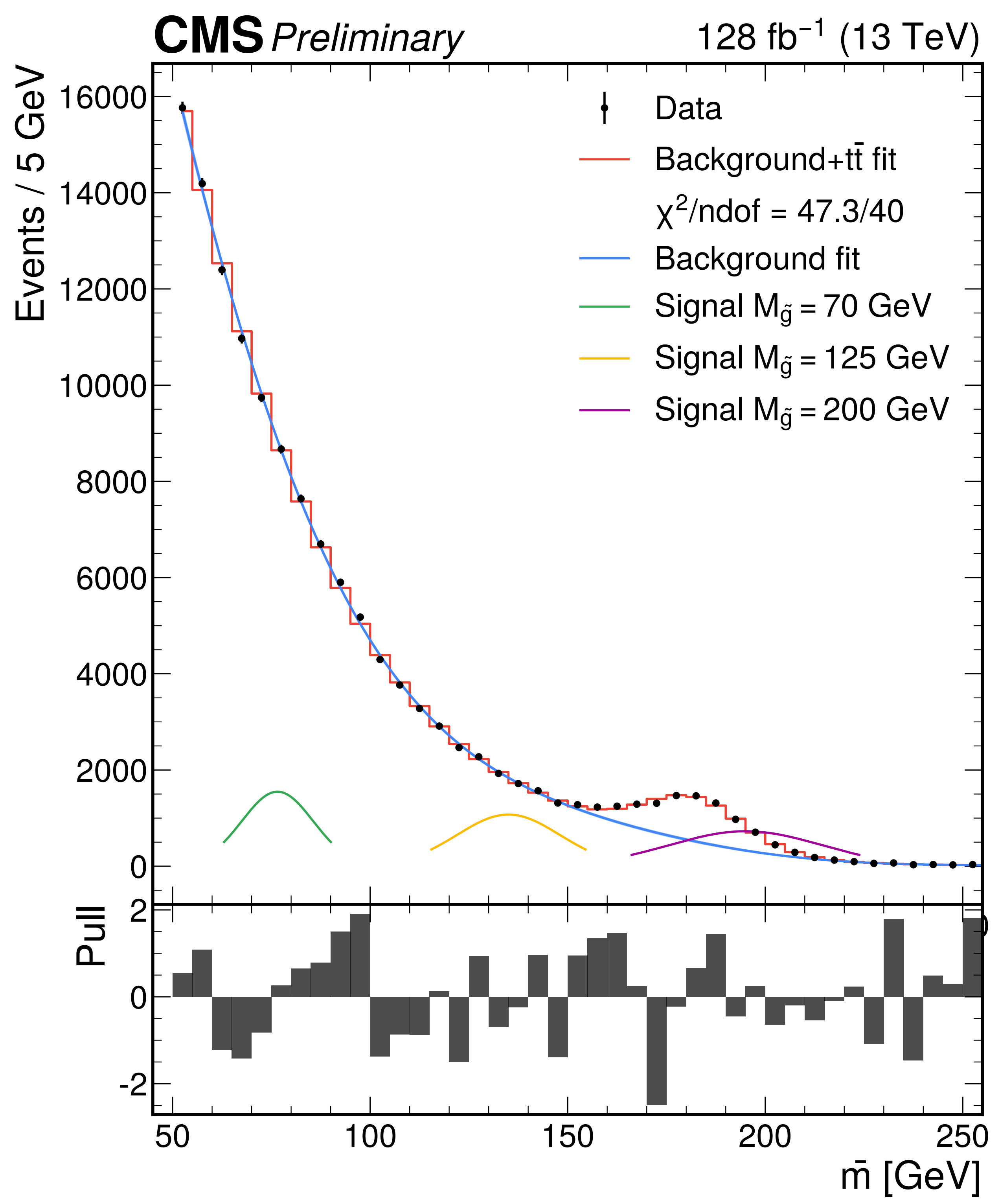
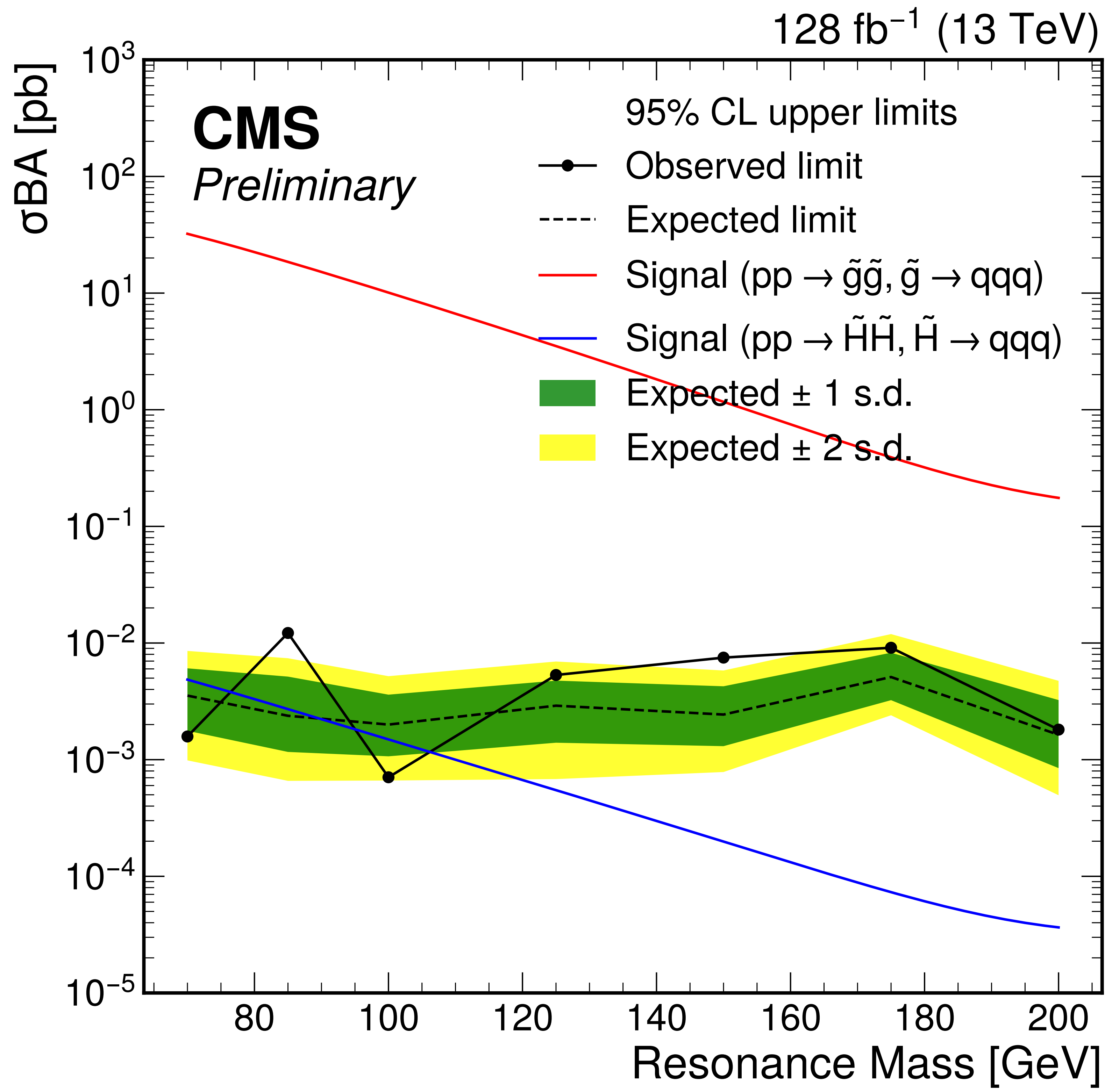
- Pair-production of an electroweak-scale particle with decay to three jets
- But if you really want a sensitivity boost, just challenge us!

Search for tri-jet pairs

- Data scouting: overcome trigger limitation by storing only the objects that were already reconstructed by the trigger
- Use large-radius jet substructure to find 3-prong decays





Complex signatures

We have also expanded our search programme towards much more involved and complex signatures, in many cases making novel uses of our detectors:

Non-resonant production of **semivisible jets**

- Dark quarks decay and hadronize in the dark sector where part of the shower is stable and escapes the detector
- Semi-visible jets are experimentally similar to mismeasured jets

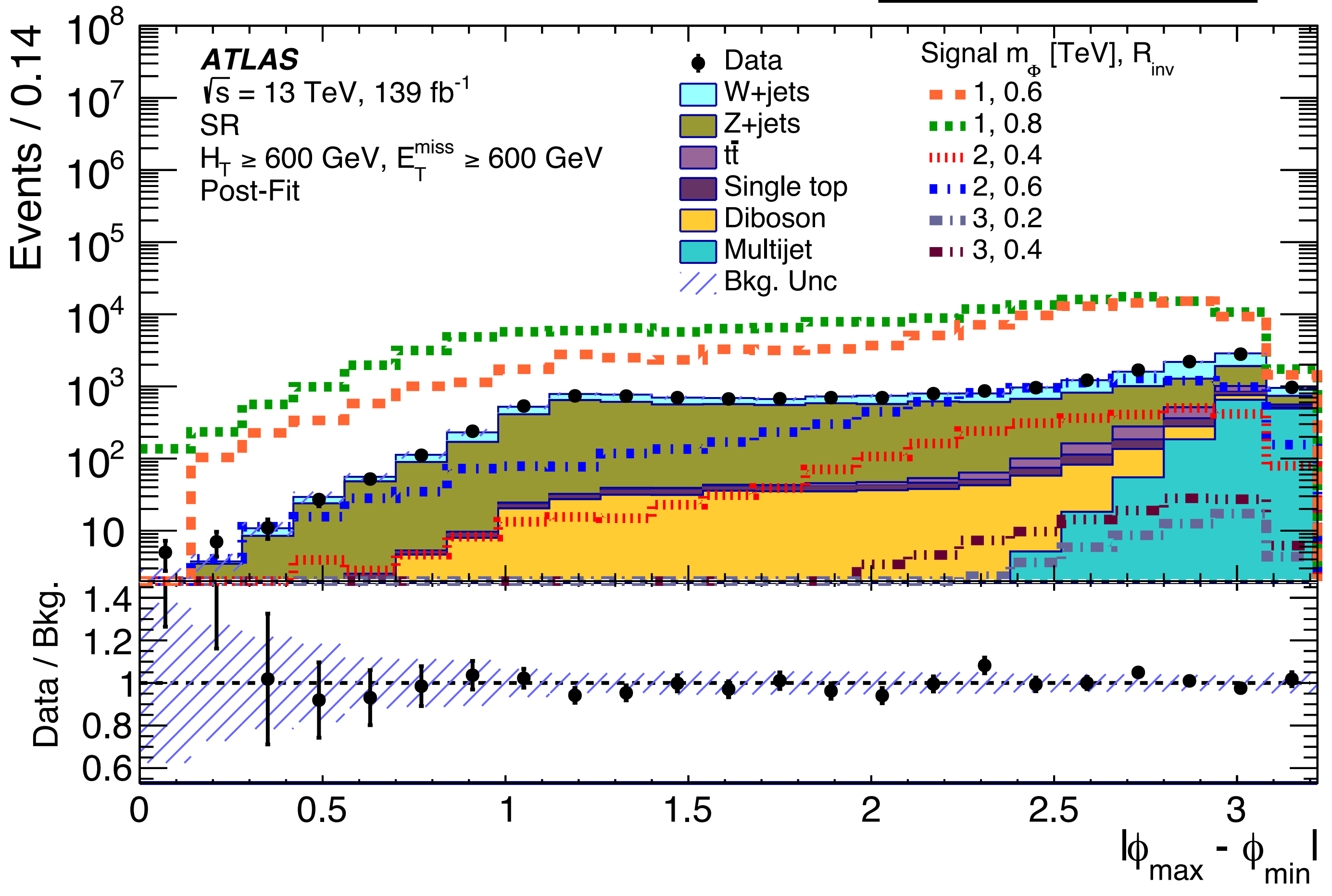
Periodic signals as predicted by clockwork models

- The analysis is performed in the frequency domain!

Emerging jets

- Dark QCD sector that leads to a long-lived neutral particle showering into SM particles. A jet that “emerges” and starts to have tracks after some distance

2305.18037



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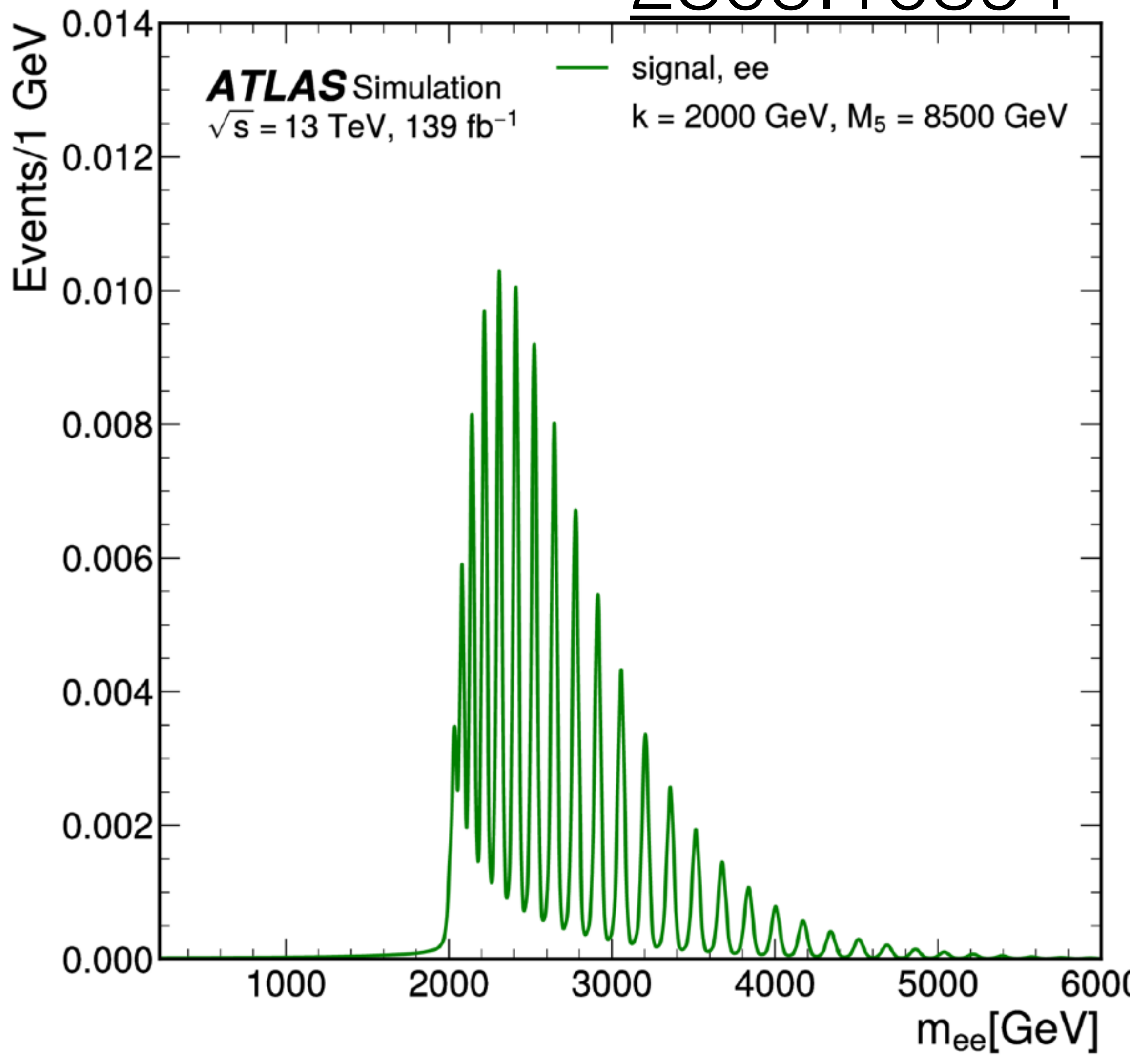
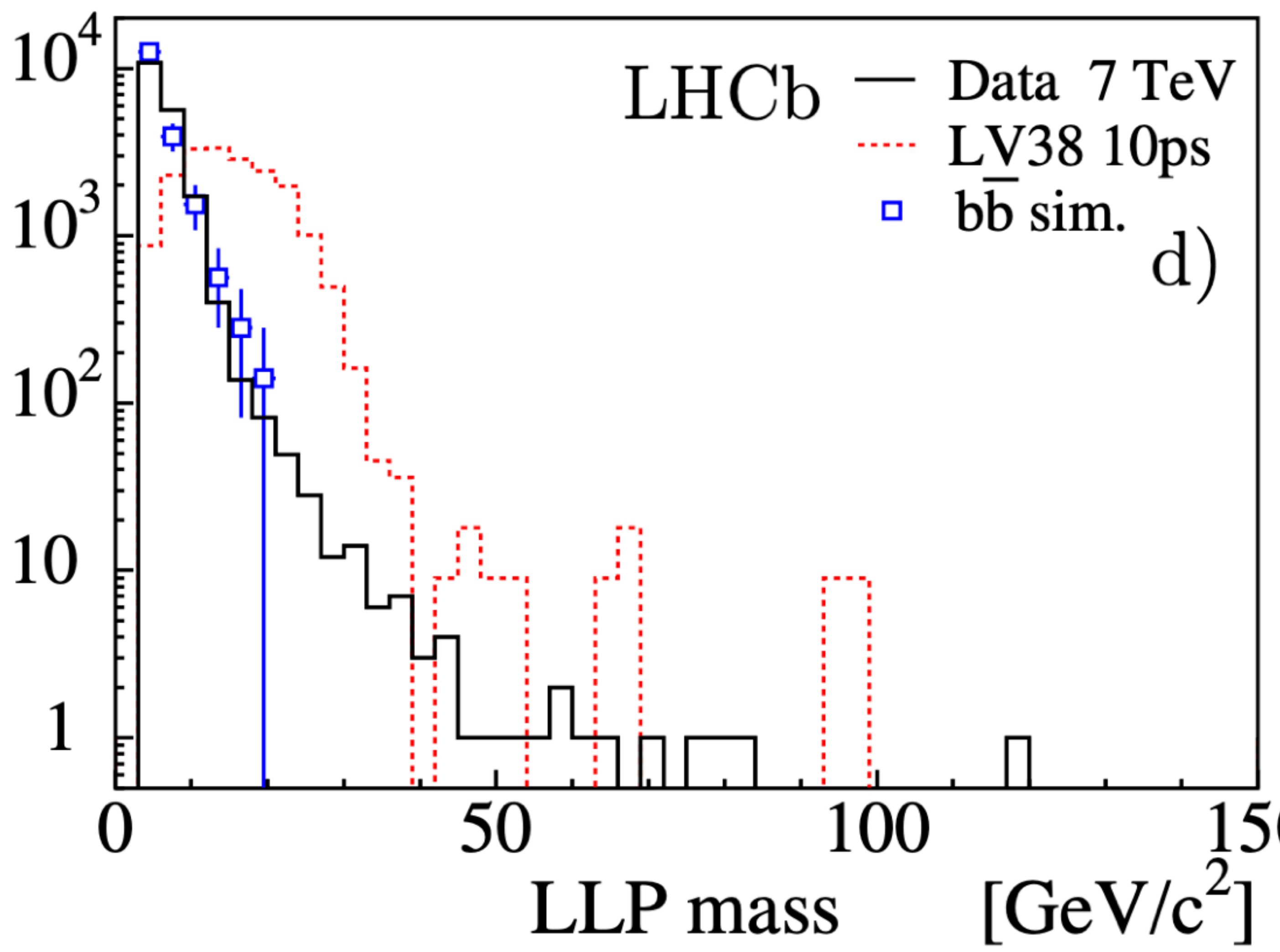
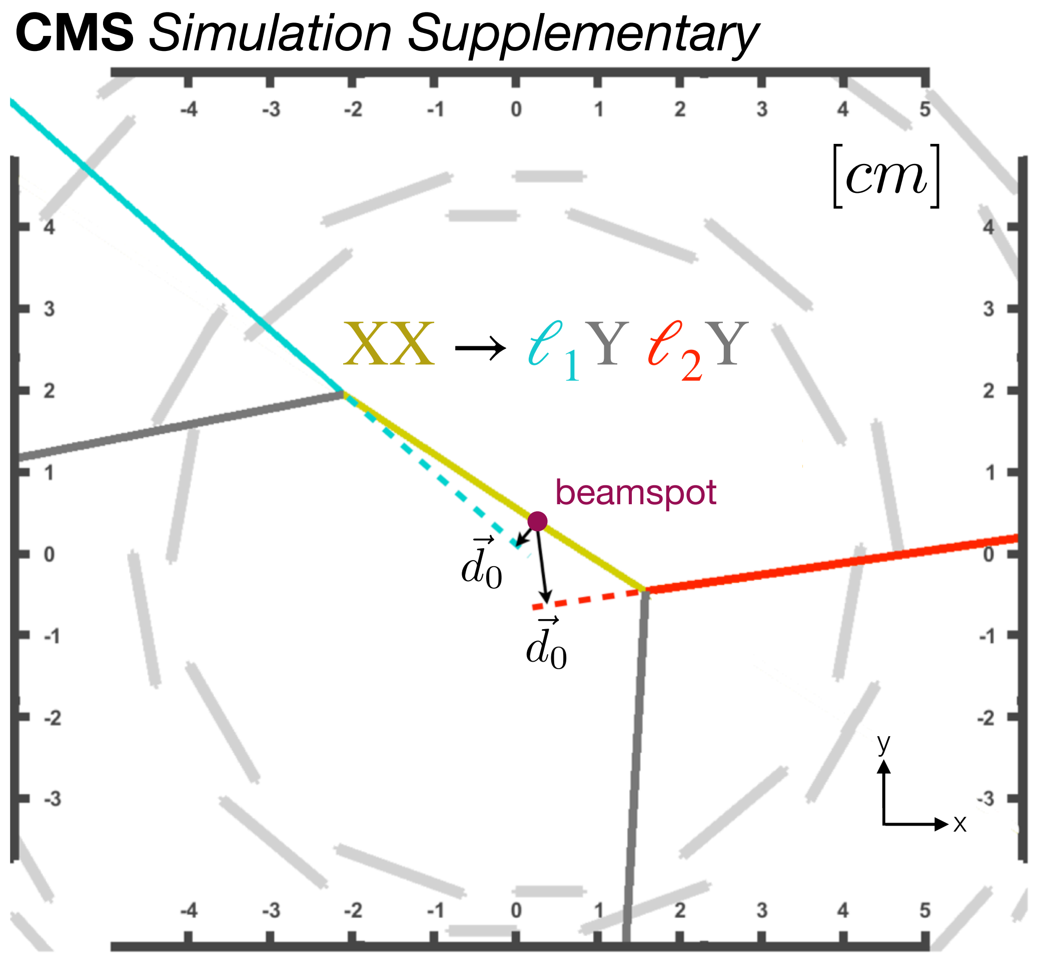


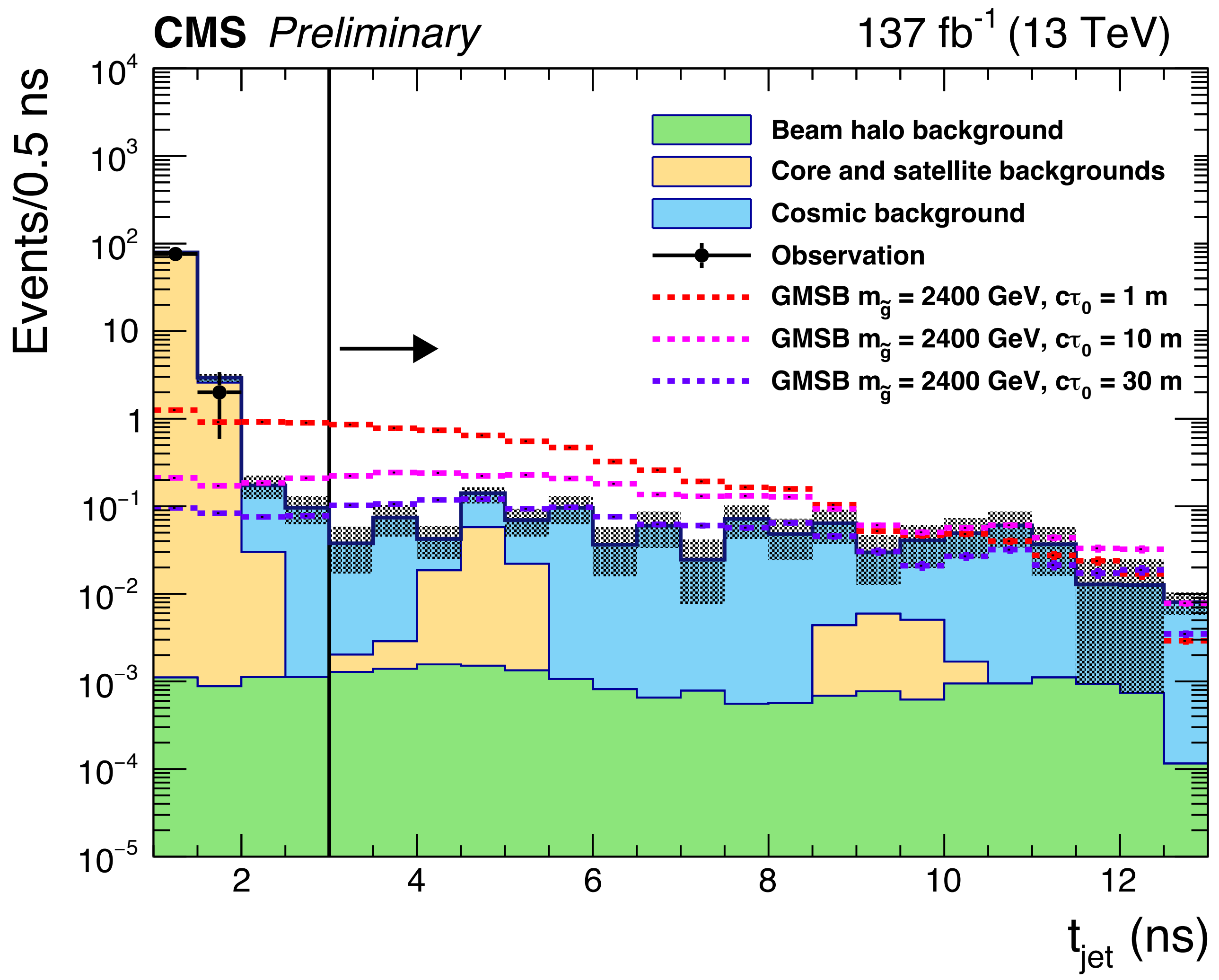
Complex signatures

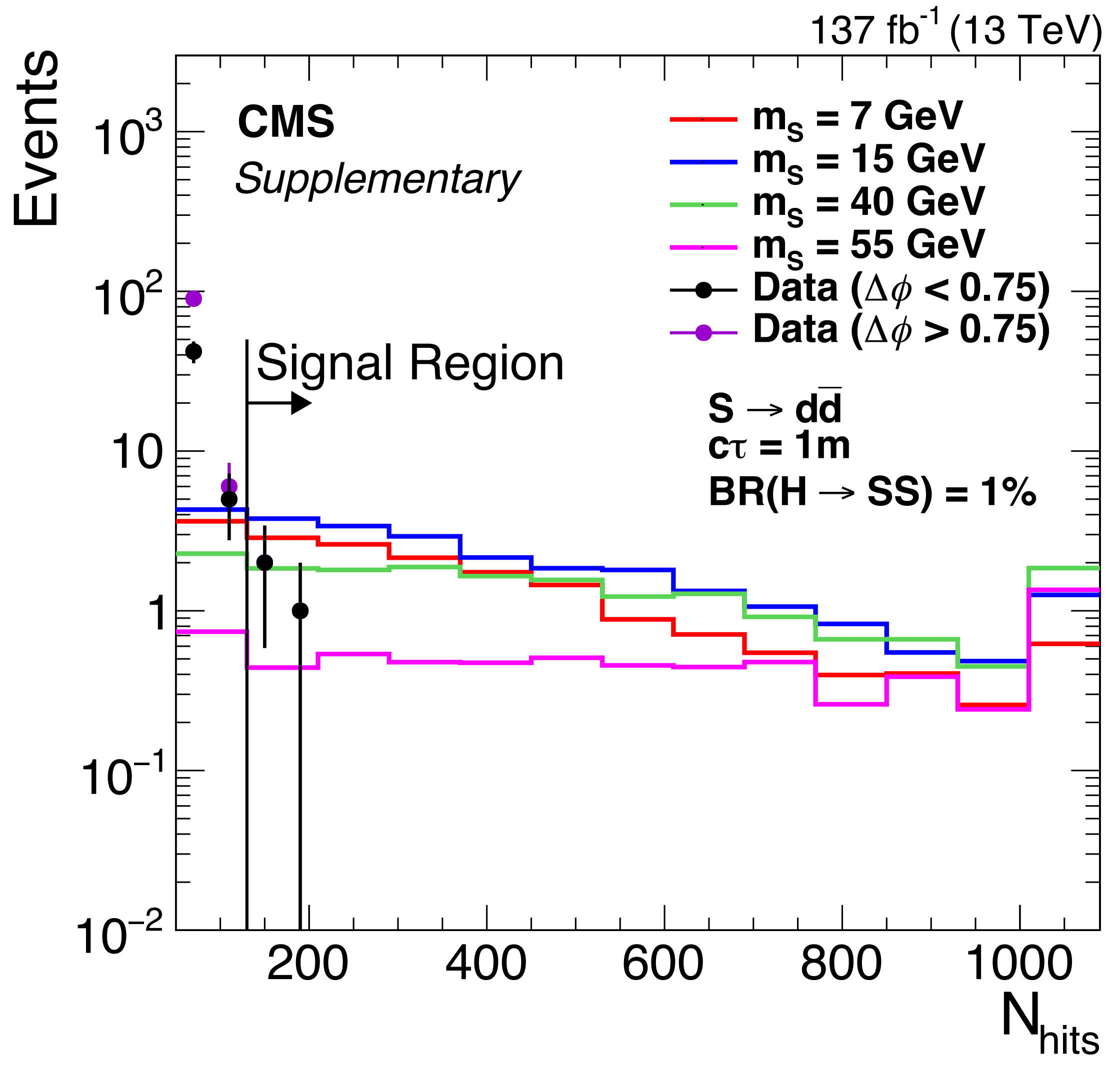
Long-lived particles (LLP) were once the weirdos of searches, but are by now increasingly common

- Displaced diphoton vertex, exploit ATLAS LAr pointing capabilities to find photons from a common displaced vertex
- Exploit LHCb superb vertexing to search for LLPs decaying to muon plus quarks
- Displaced leptons, search for leptons with large impact parameter without vertex requirement
- Search for out-of-time jets from slow-moving particles
- Search for showers in the muon detector





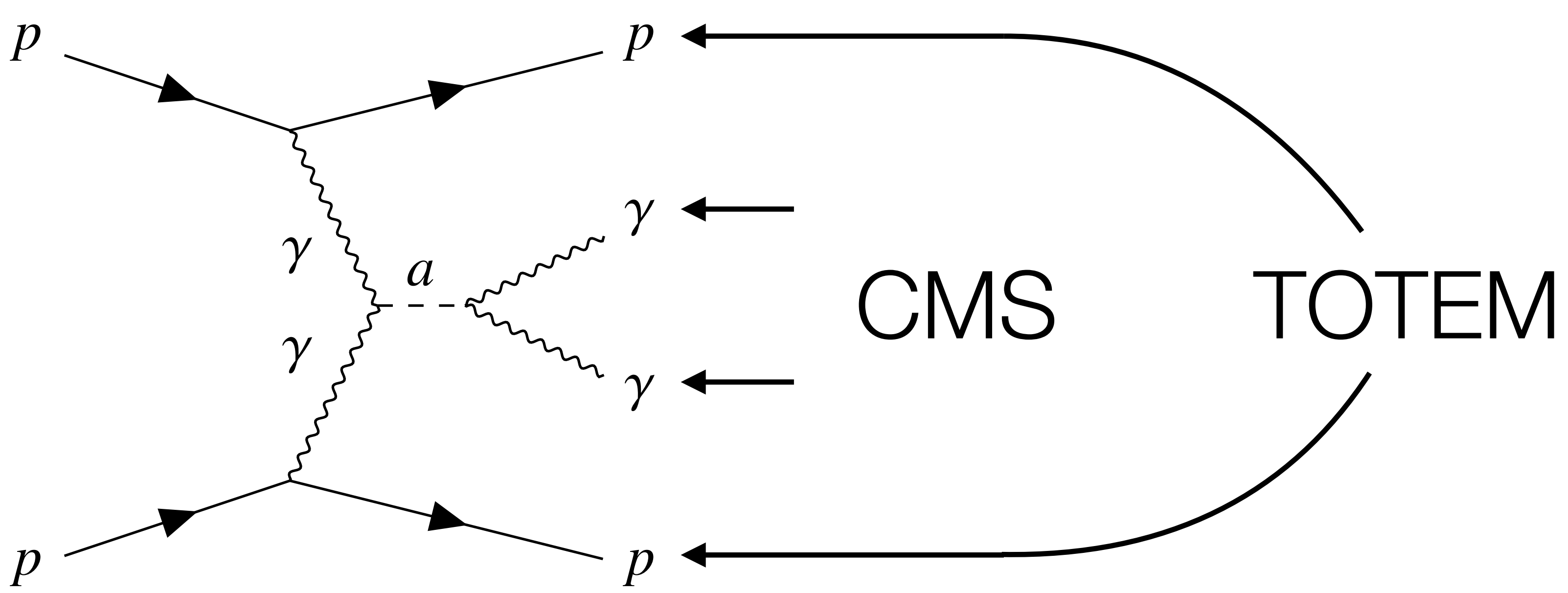




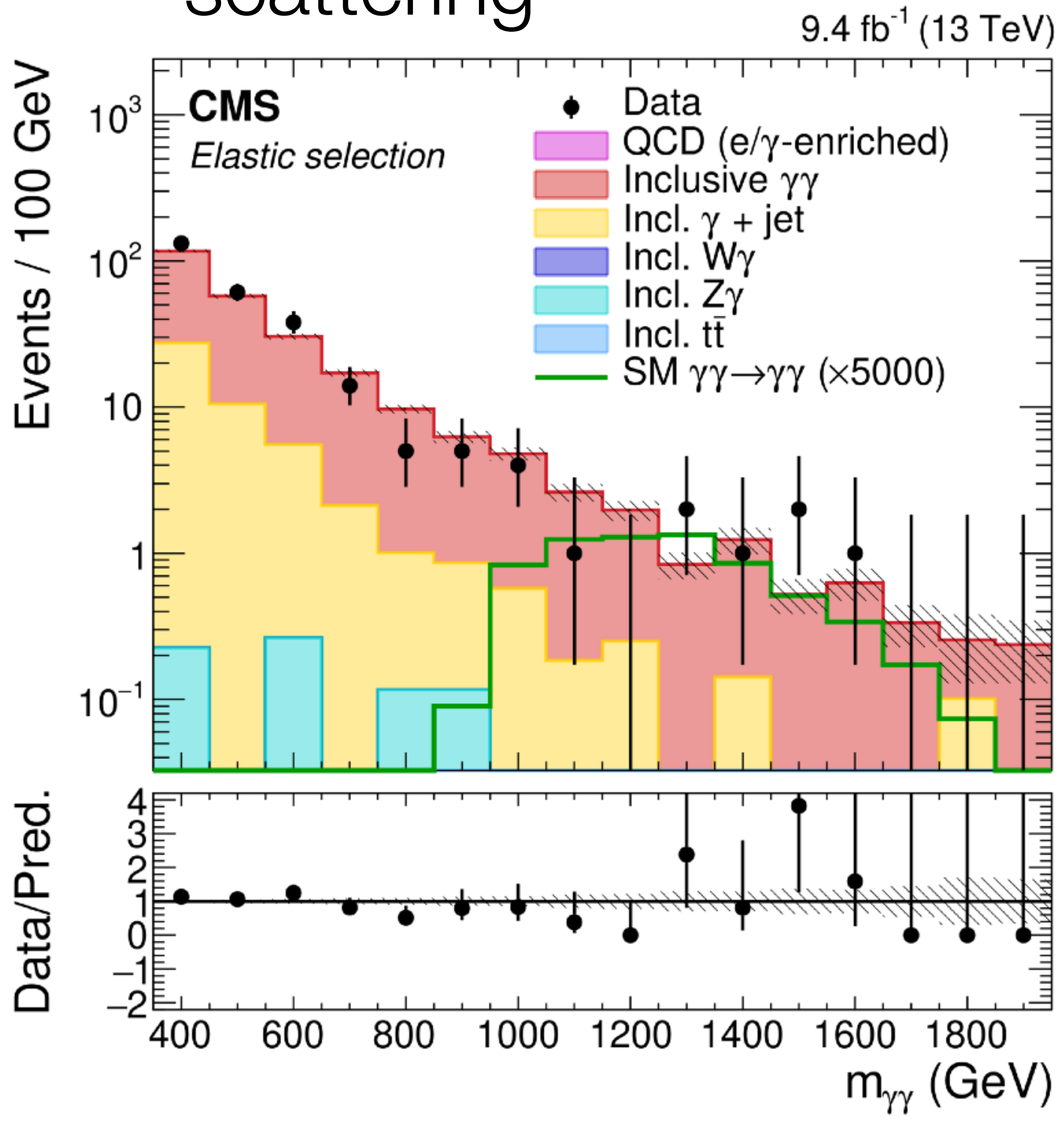
Exploiting forward detectors

TOTEM and AFP are **forward detectors** at ~200m from the CMS/ATLAS interaction point respectively

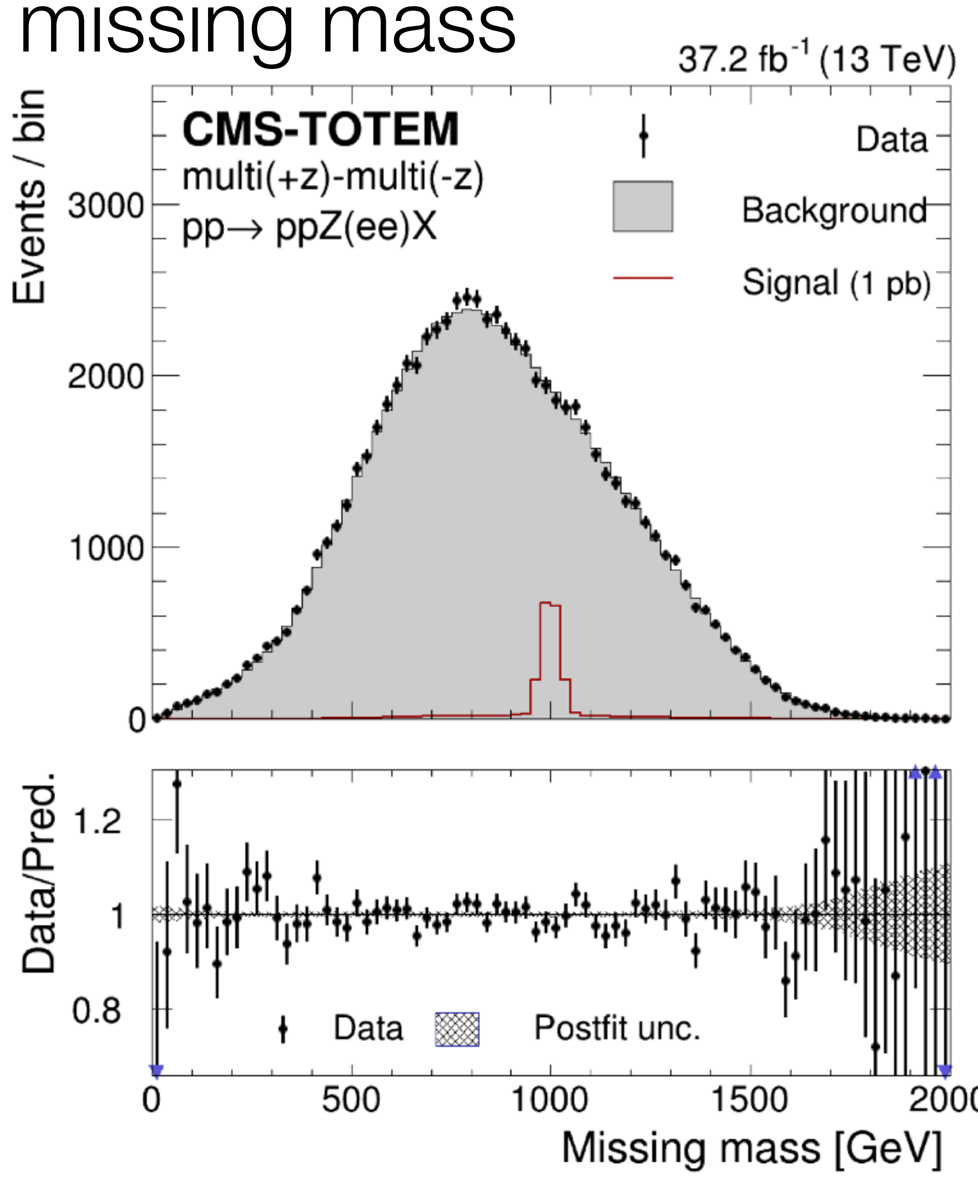
- They are instrumented to tag protons that are deflected in elastic scattering
- If both protons are tagged we can measure the full energy transfer, including the longitudinal component



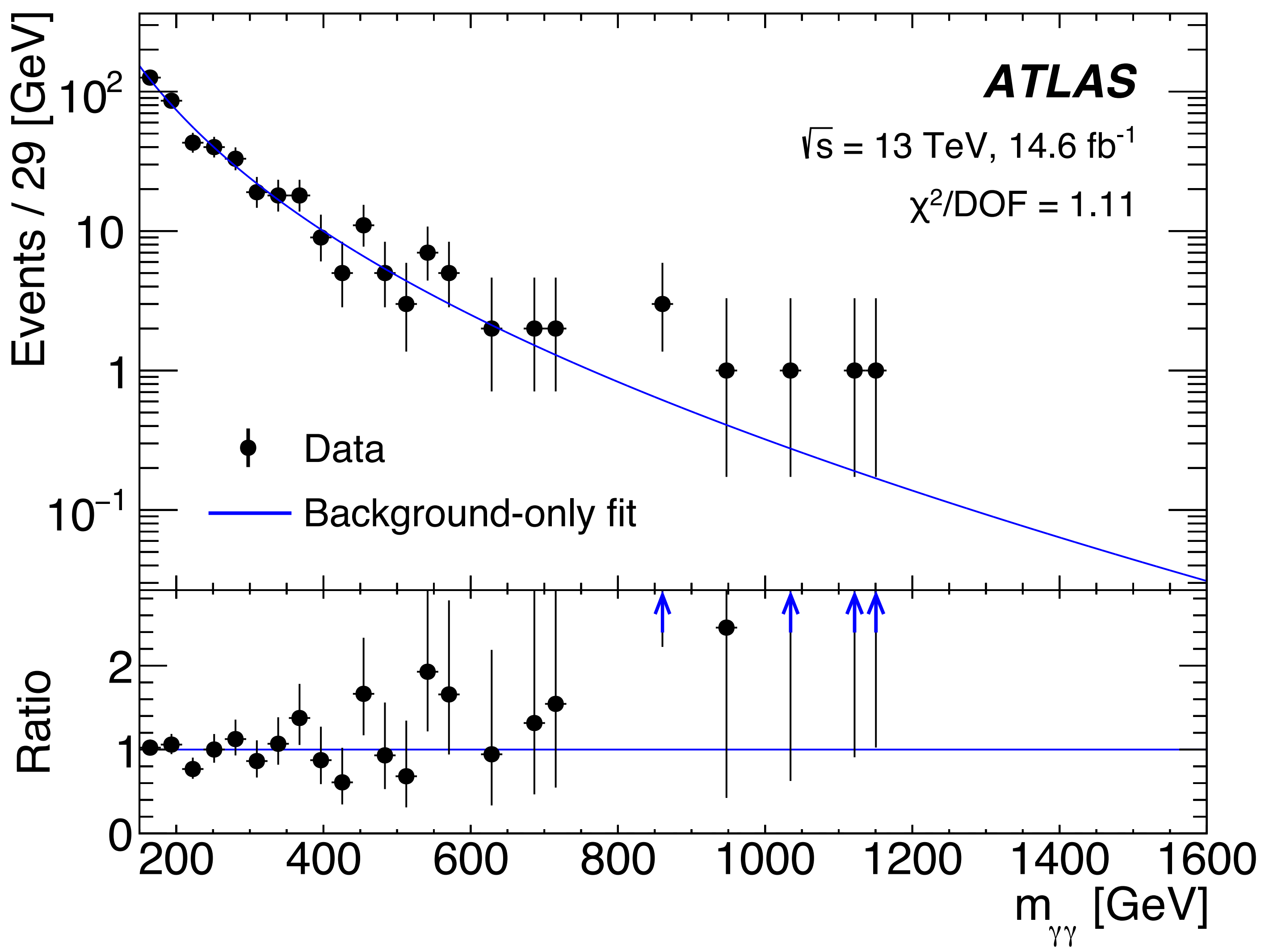
Search for light-by-light scattering



Search for new particles via missing mass

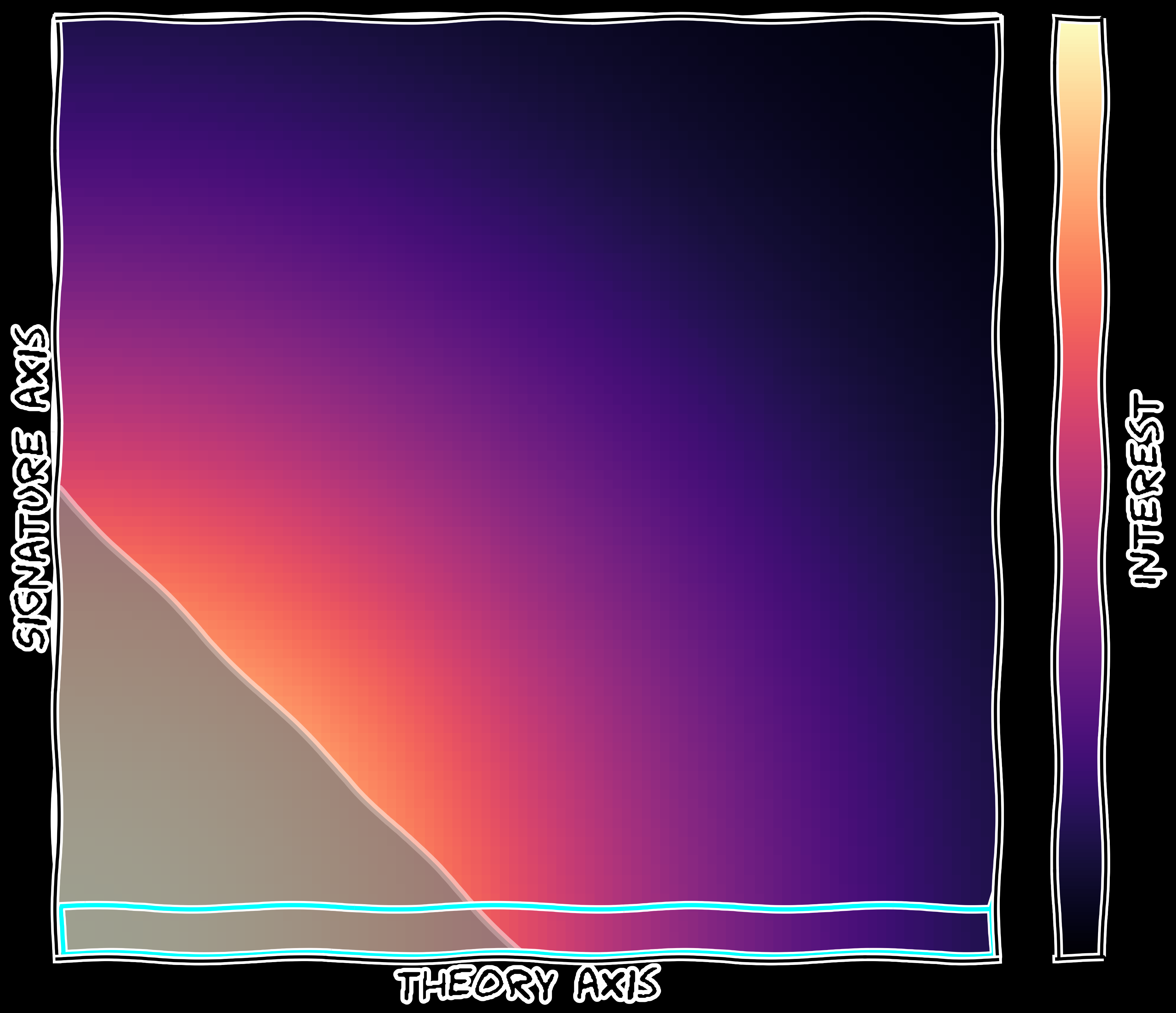


Search for diphoton resonance with forward proton tag



Exhausting the theory axis,

great theories and incredibly hard signatures

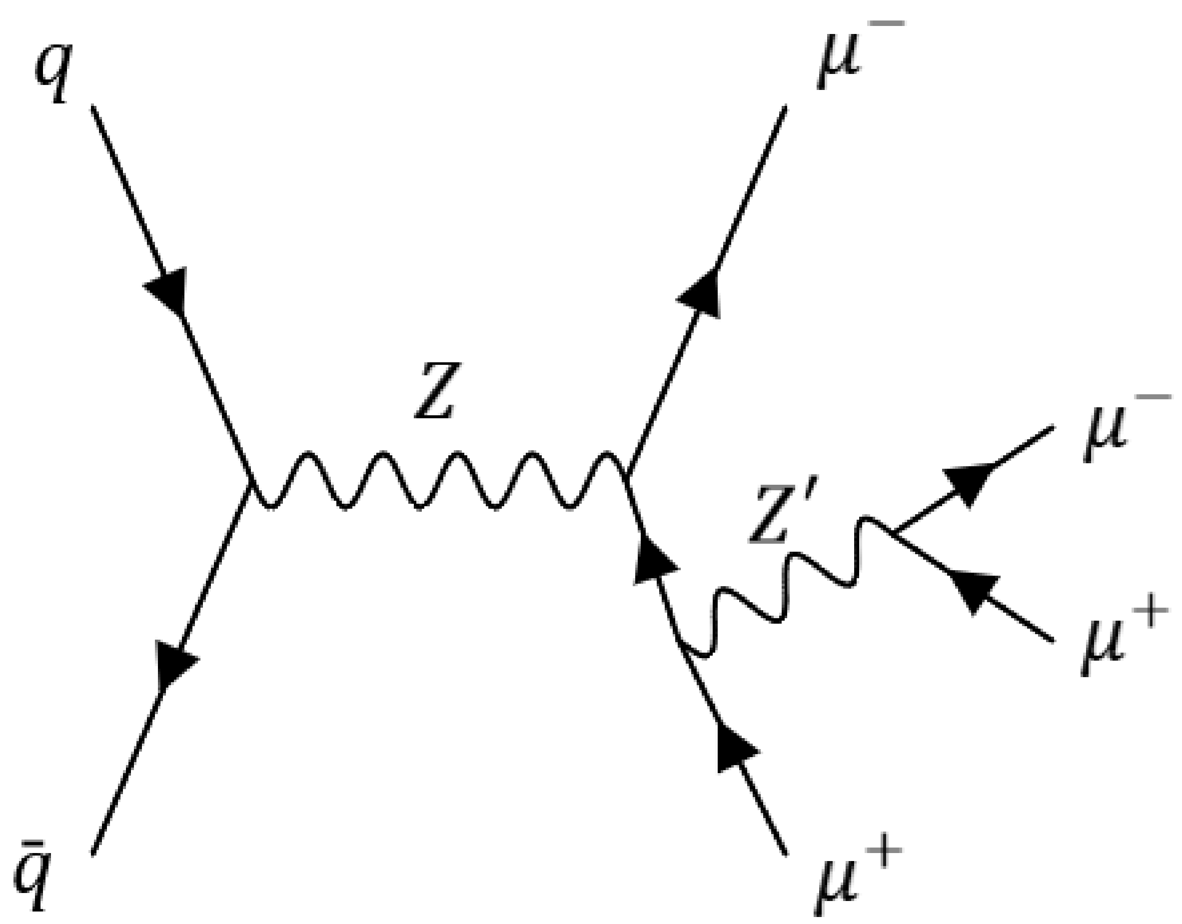


The hard regions of theory-based searches

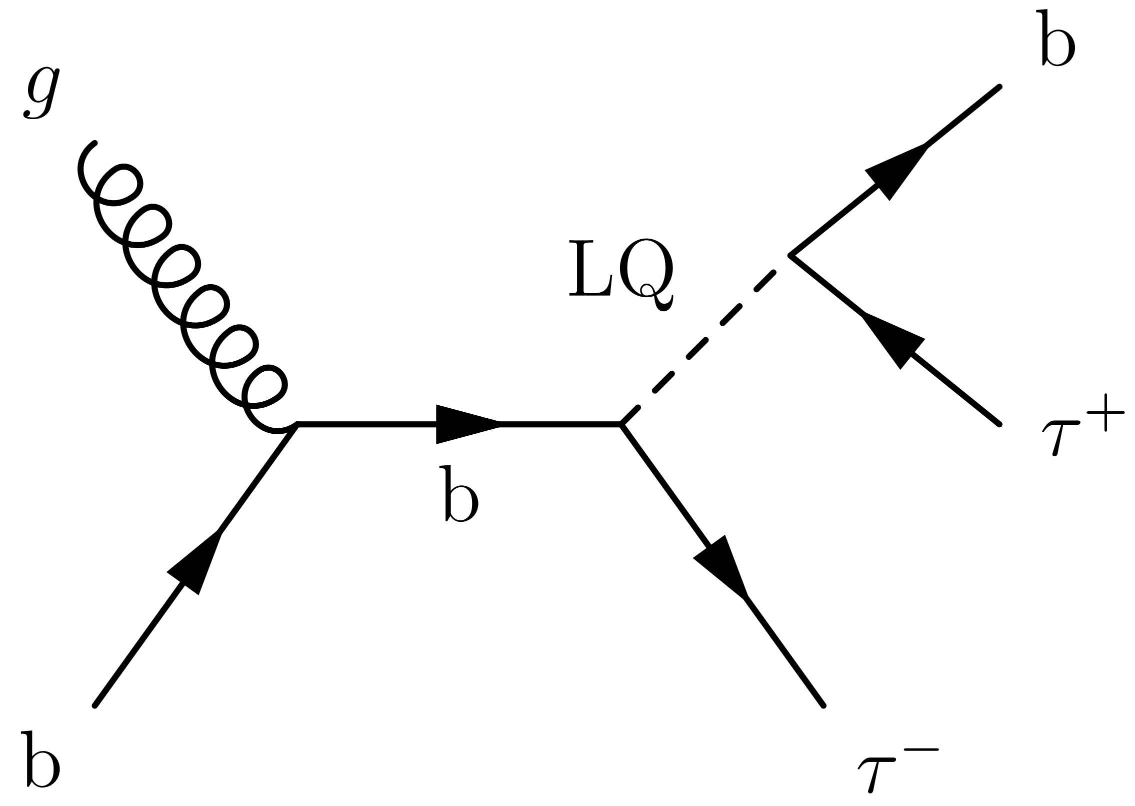
In many cases, we have a strong motivation to insist on some external theory guidance:

- Observed discrepancies in other experiments like $(g\text{-}2)_\mu$ or flavour anomalies
- Nothing like an excess to get the creativity flowing and force ourselves to look into less-common final states

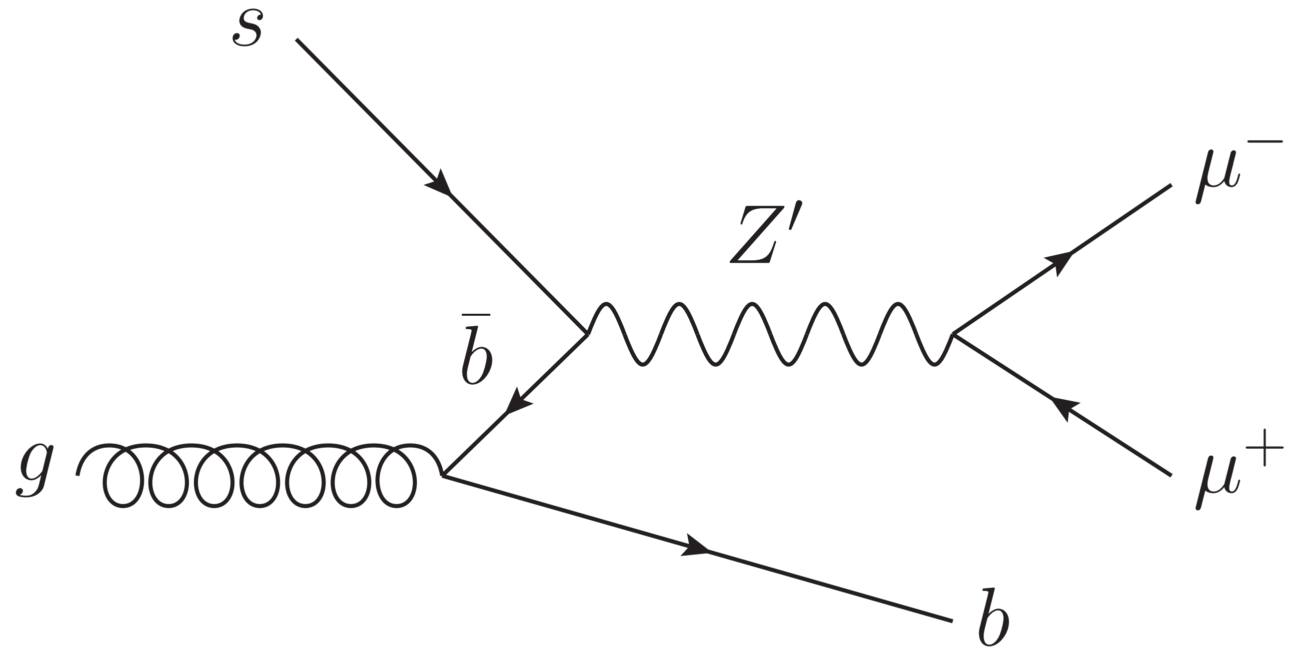
Light Z' in Z decays



Single LQ production



Heavy Z' with single b-jet



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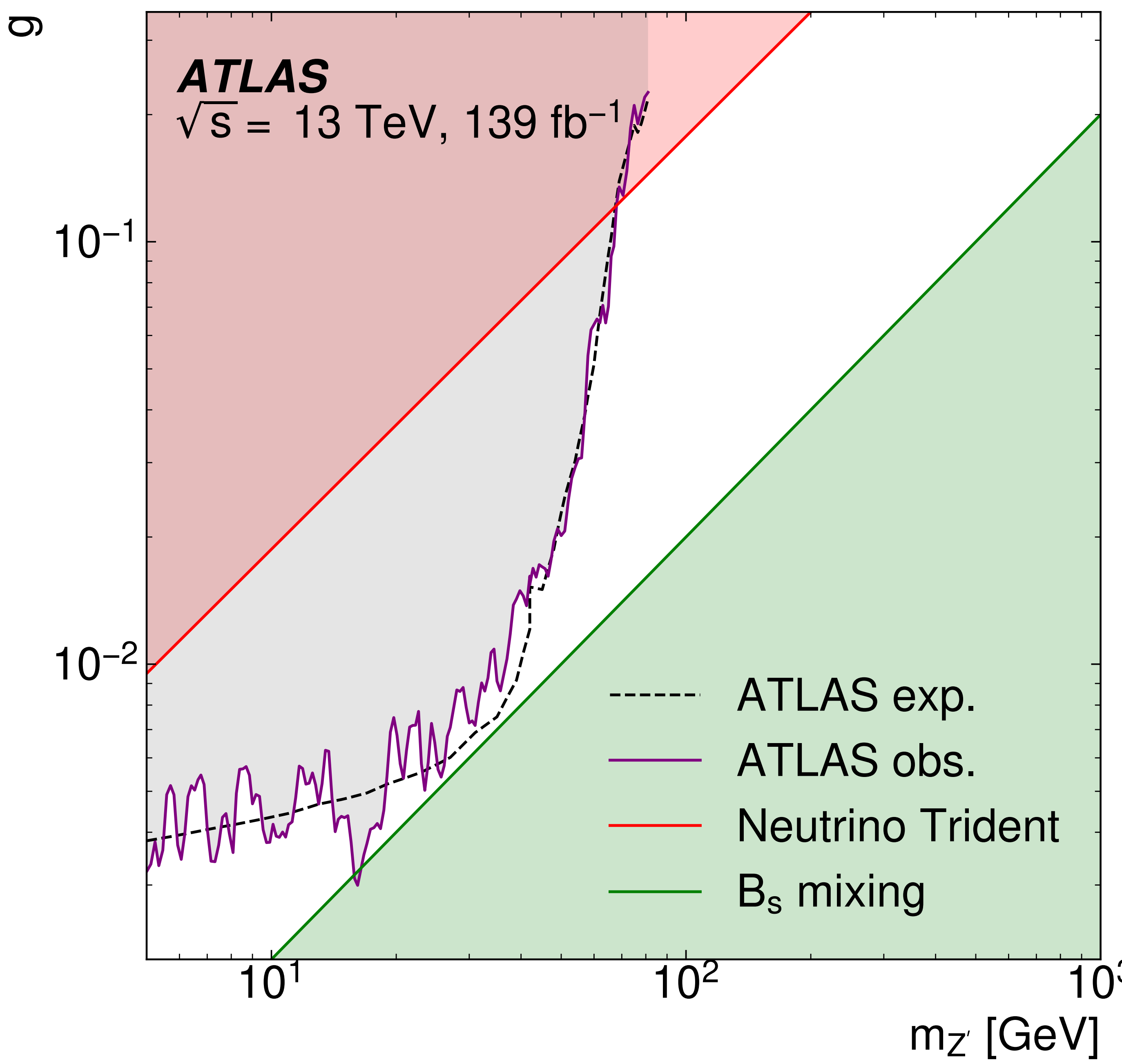

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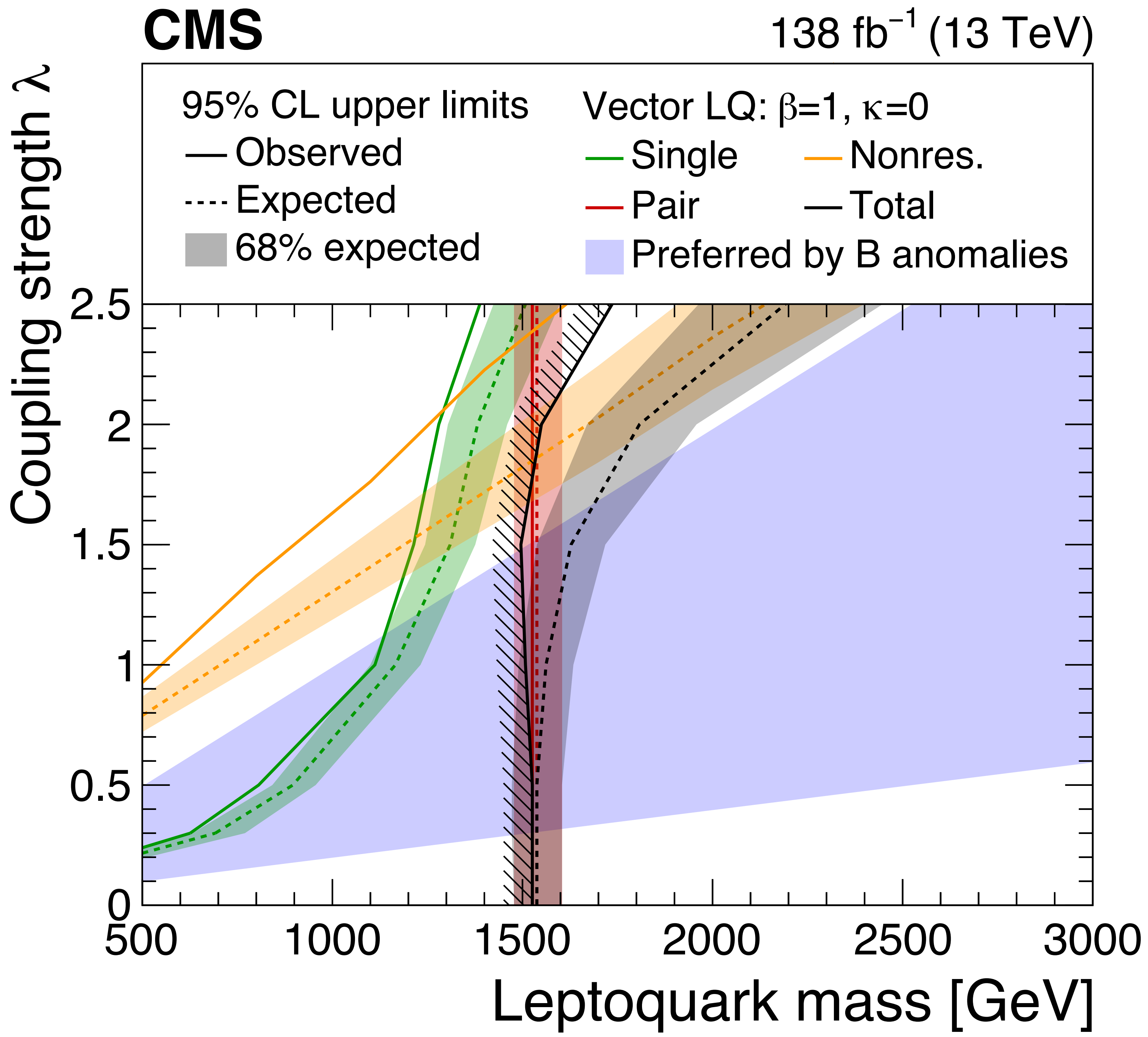

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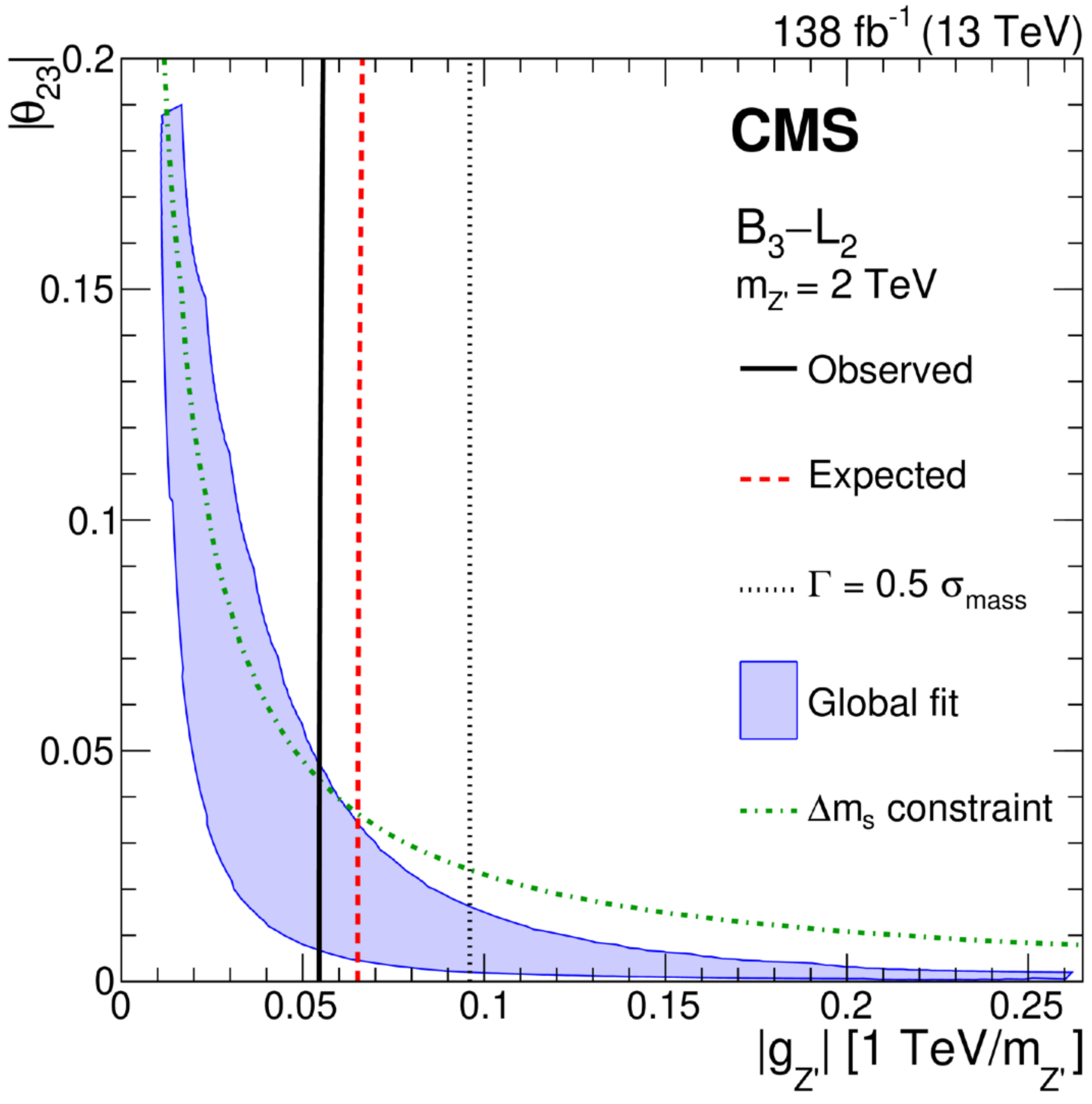


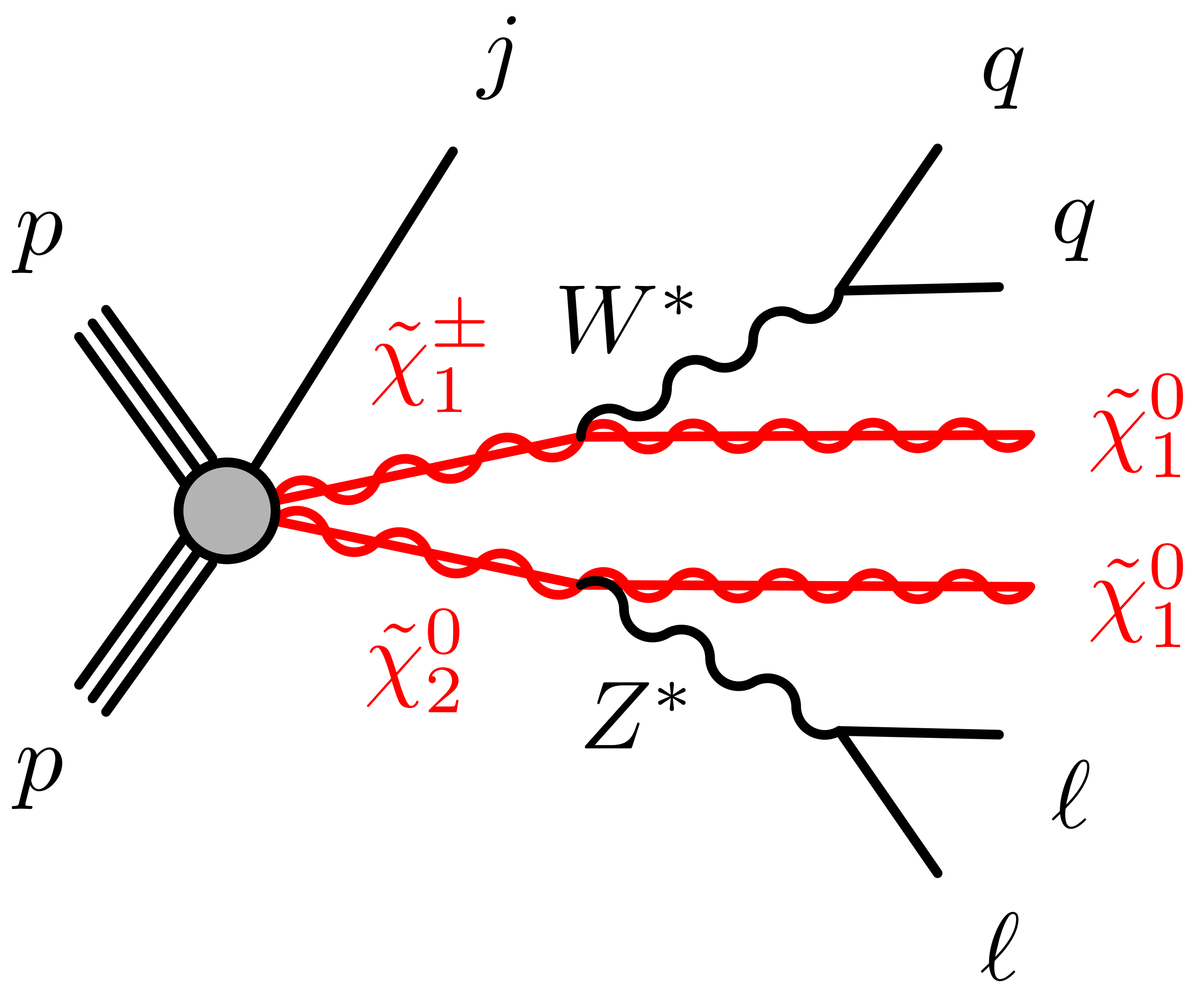
The hard regions of theory-based searches

In other cases we insist on our theory prior because the basic predictions are really challenging to test

One of the key predictions of natural supersymmetry is that **higgsinos** have to be light

- Higgsinos form a triplet $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ with a mass splitting of 300 MeV < Δm < O(1-10) GeV depending on the mixing
- Very hard to trigger, that mass splitting is the only visible energy the decay will leave on the detector
- Have a very small cross section

Yet we will do everything that is on our hands to look for them!



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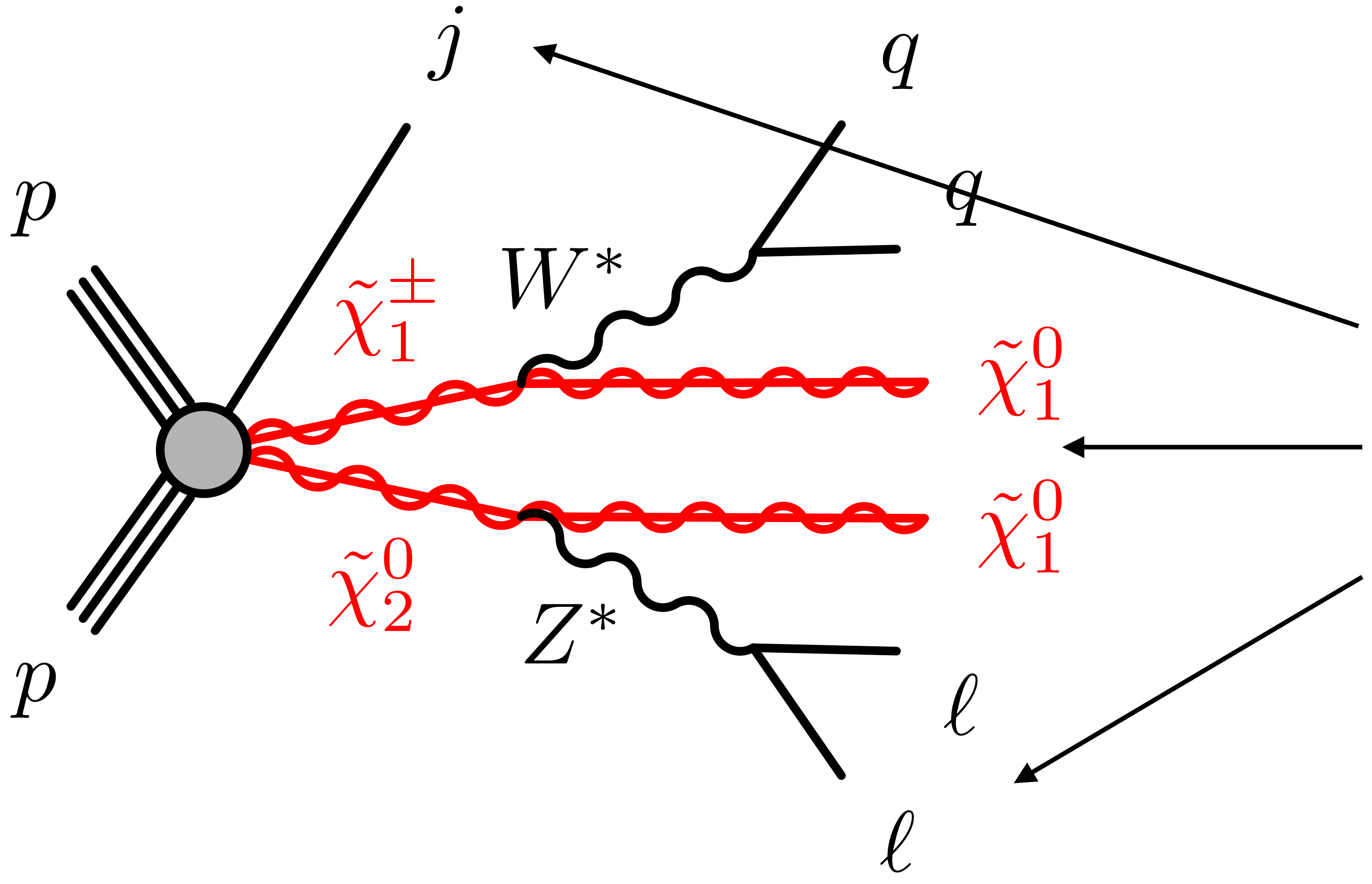

Trigger on jets, missing energy and leptons

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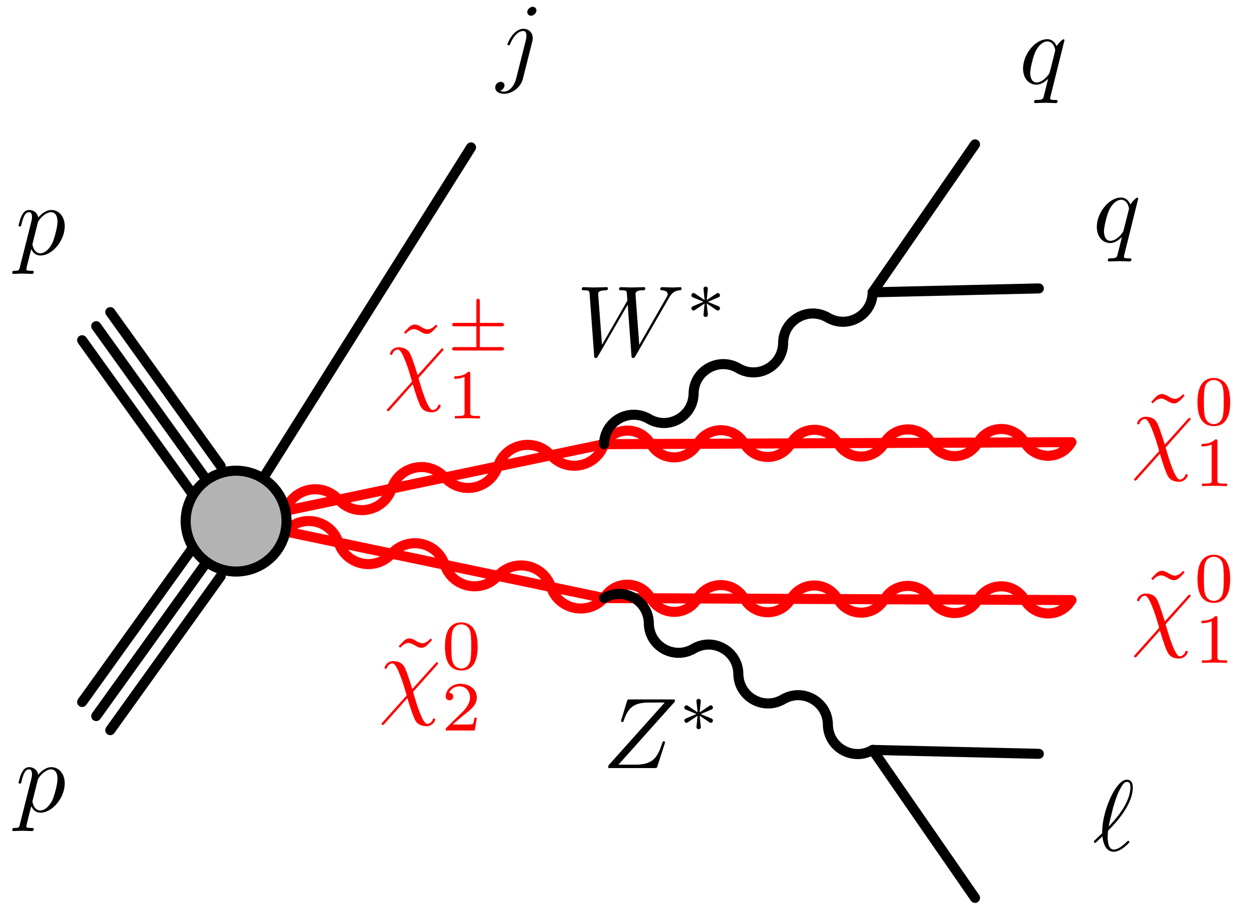

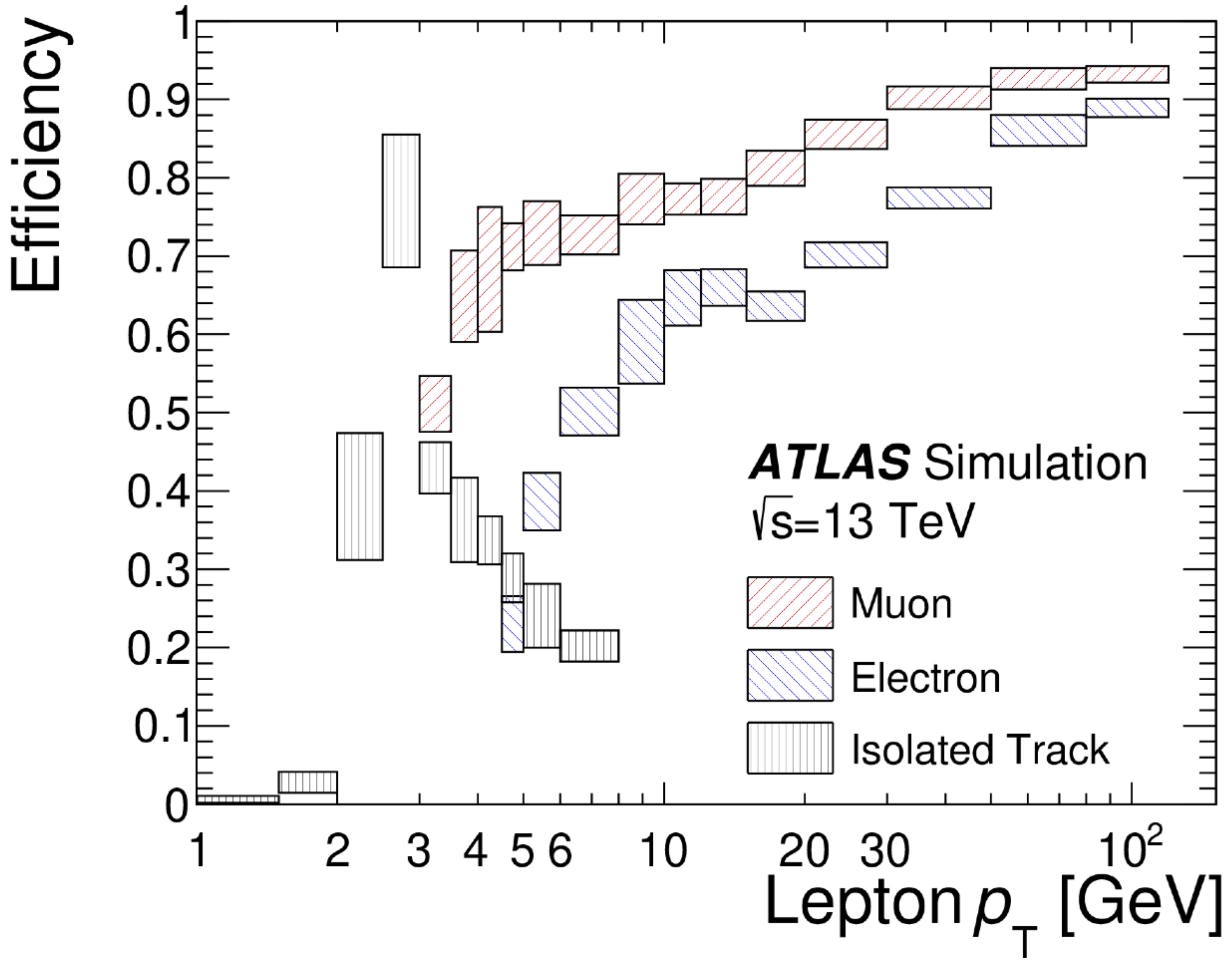

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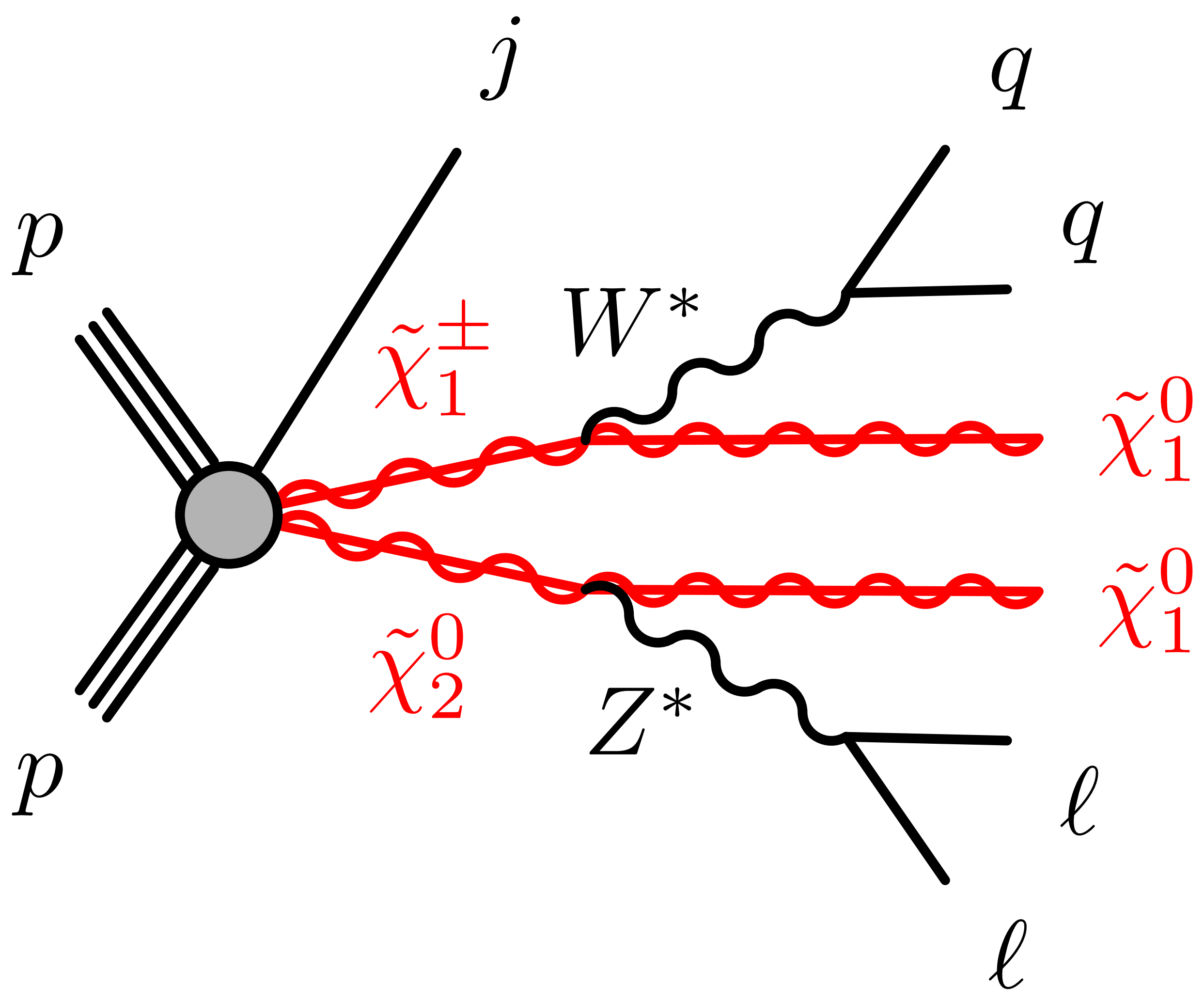
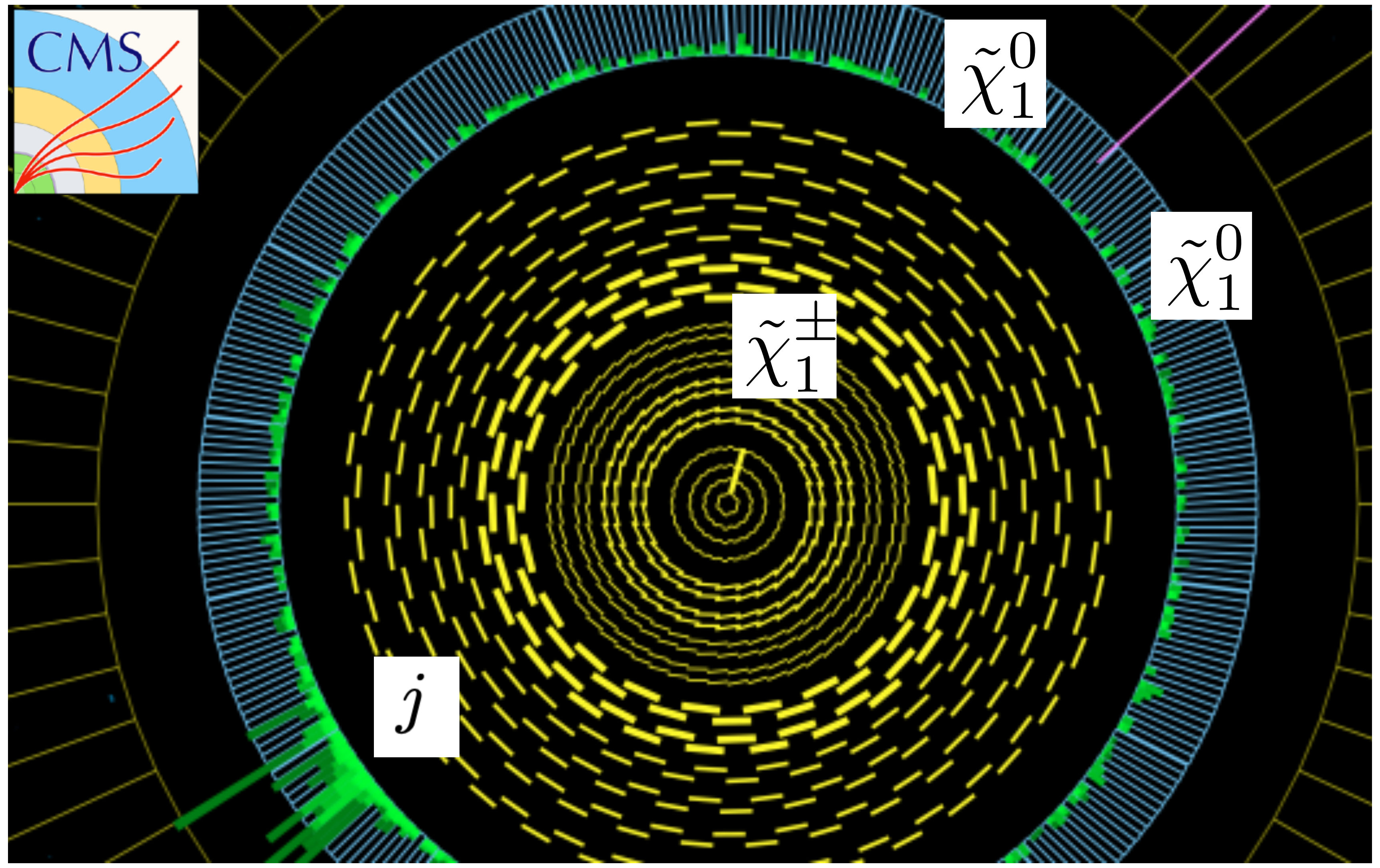
Yet we will do everything that is on our hands to look for them!

- Develop dedicated triggers combining all objects to gain acceptance
- Reconstruct and calibrate leptons down to 3 GeV, and work with tracks below that
- Train BDTs to find the track of a long-lived chargino before it “disappears”

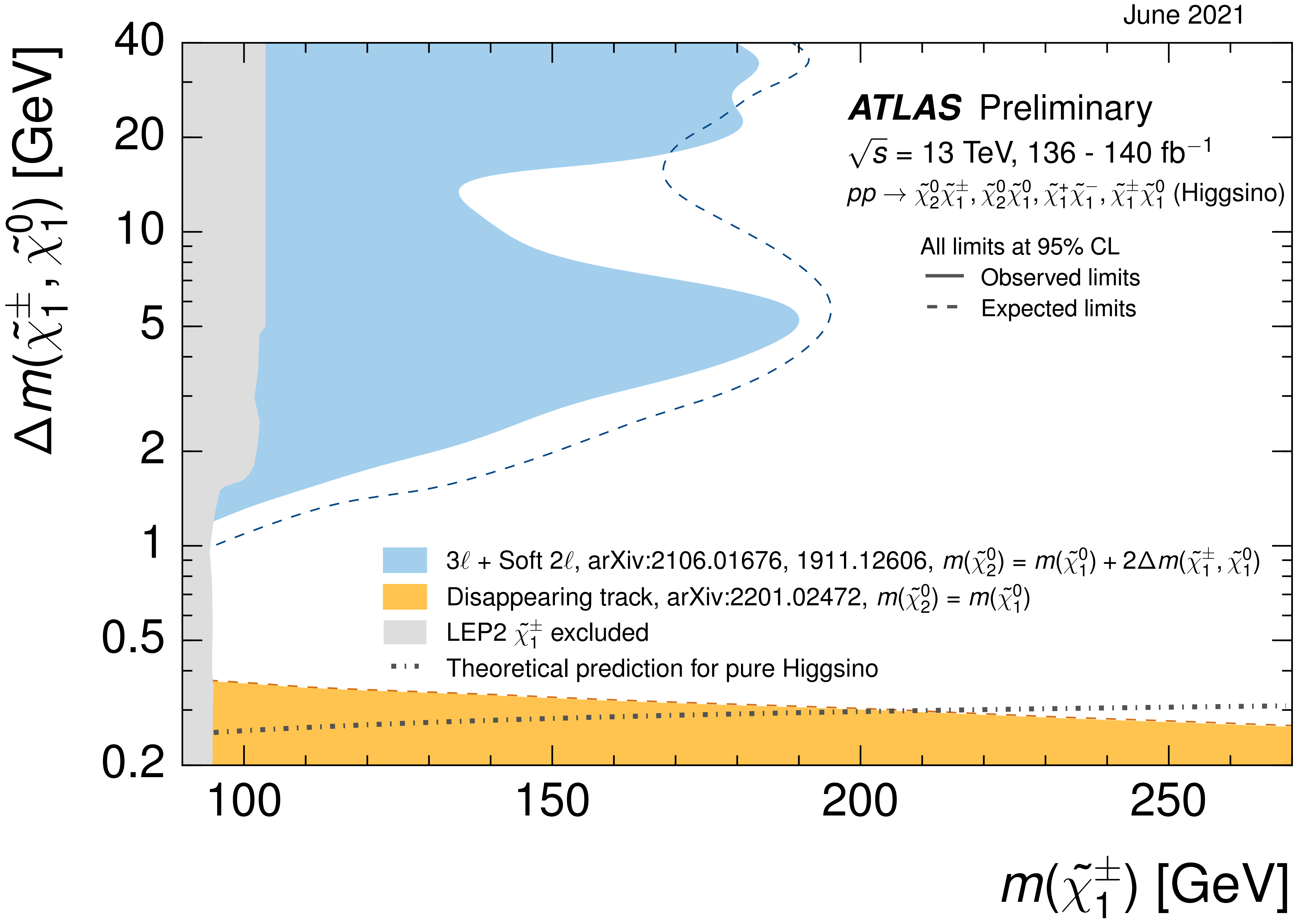




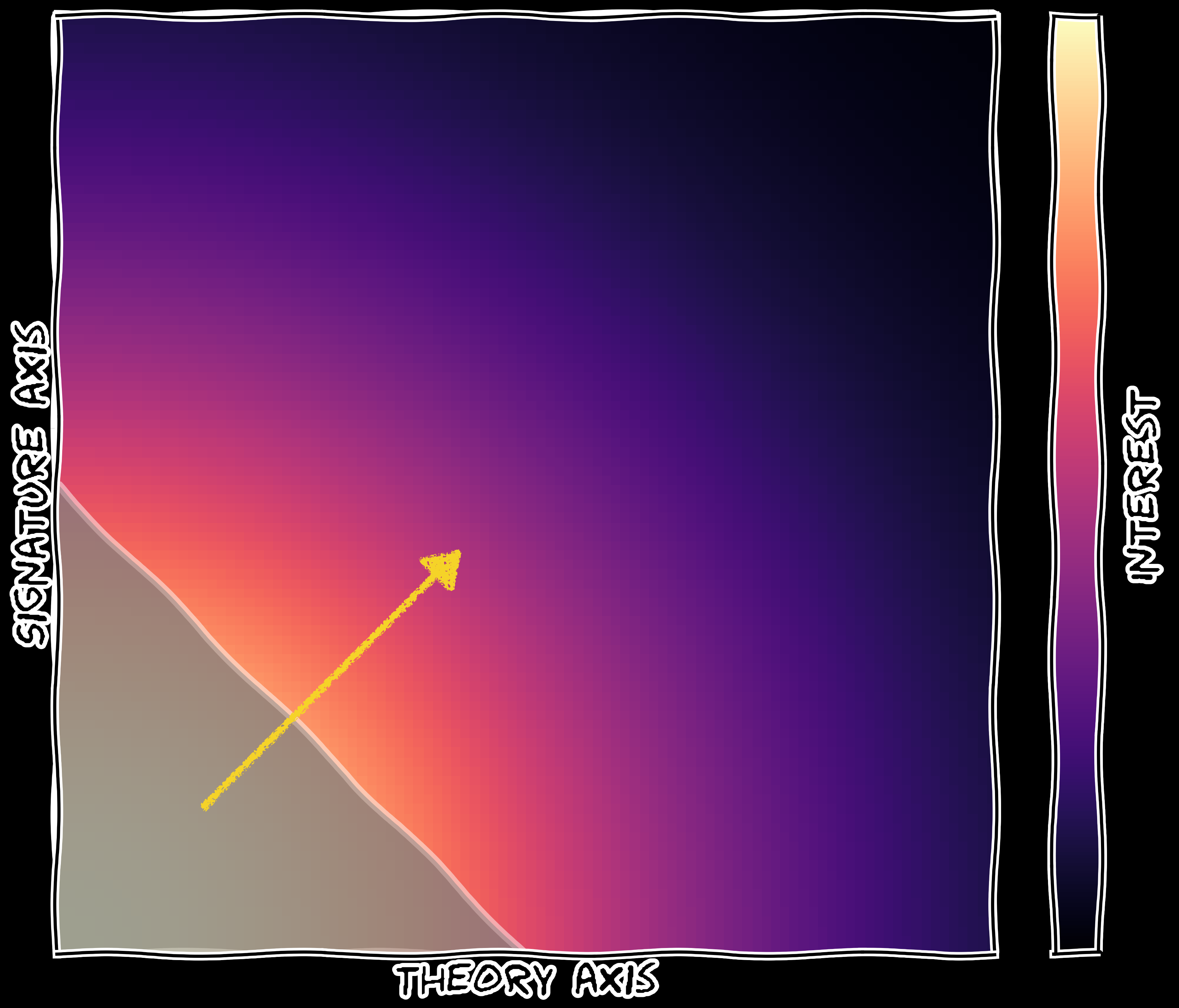
The hard regions of theory-based searches

We are starting to surpass LEP results, but not by a great margin

For some particular regions, 500 MeV < Δm < 1 GeV, the LEP results still hold (though there are ideas)



Leave no stone unturned,
beyond minimal theories as signature generators



Leave no stone unturned

No doubt there are good reasons to:

- keep improving the sensitivity of model-agnostic searches
- access larger regions of mass/parameter space in theory-motivated searches

But both have to be balanced against **discovery potential**

- ATLAS/CMS have 30/20 BSM searches with same-sign leptons in the title (surely more in general)
- This is a very sensitive signature, but do we really think we will suddenly get 5 sigma with a slightly different selection?

Many searches start looking into non-minimal models that **predict new signatures**

- Especially important over the next years, where the luminosity doubling time is much slower than before

Theories as signature generators

We are still interested in answering the big questions and BSM theories are still the basis to address them, but:

- What happens when we start questioning the assumptions that we introduced to simplify theories?
- What if we give up on addressing all shortcomings of the SM at once?
- What if we simply look into theories that are more complex than usual but equally consistent?

If the **experimental final state changes significantly** and we haven't tested it, it is worth exploring

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2HDM

- Off-diagonal Yukawa couplings
- Extend to 3HDM

Supersymmetry

- Drop R-parity conservation
- Drop minimal flavour violation
- Drop naturalness
- Drop WIMP dark matter

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2HDM

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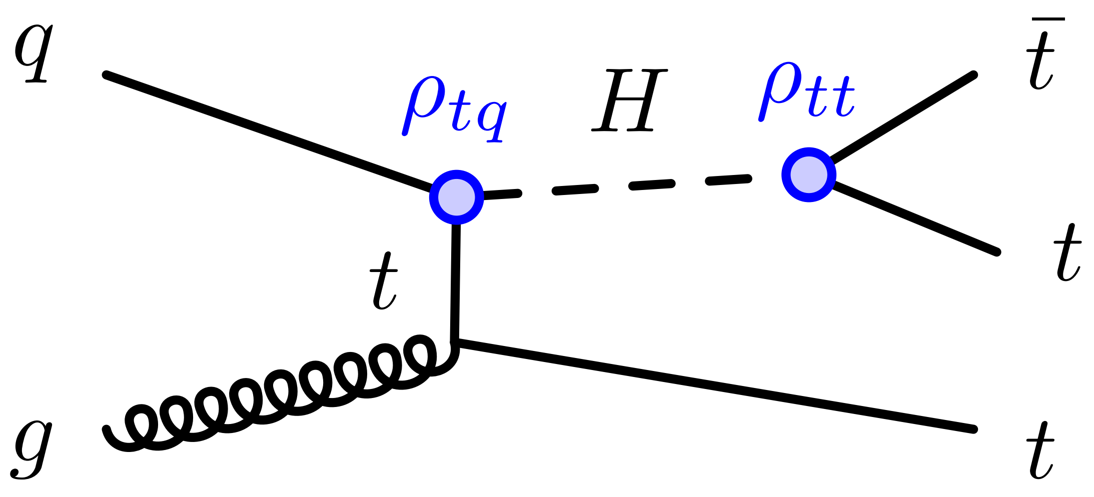
Supersymmetry

- Drop R-parity conservation ⟶ No $\not{E}_T$, single production possible
- Drop minimal flavour violation ⟶ Mixing across squarks, mixed decays
- Drop naturalness ⟶ Split-SUSY, long-lived gluinos
- Drop WIMP dark matter ⟶ Interplay with axion/axino

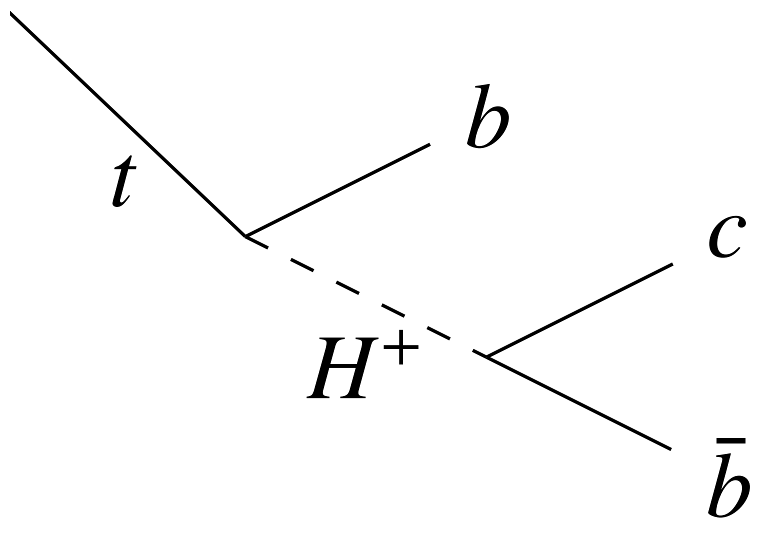
Theories as signature generators

Are these the most beautiful theories? Maybe not, but they lead us to **novel signatures** that we need to test, understand and sometimes build new tools to analyze them

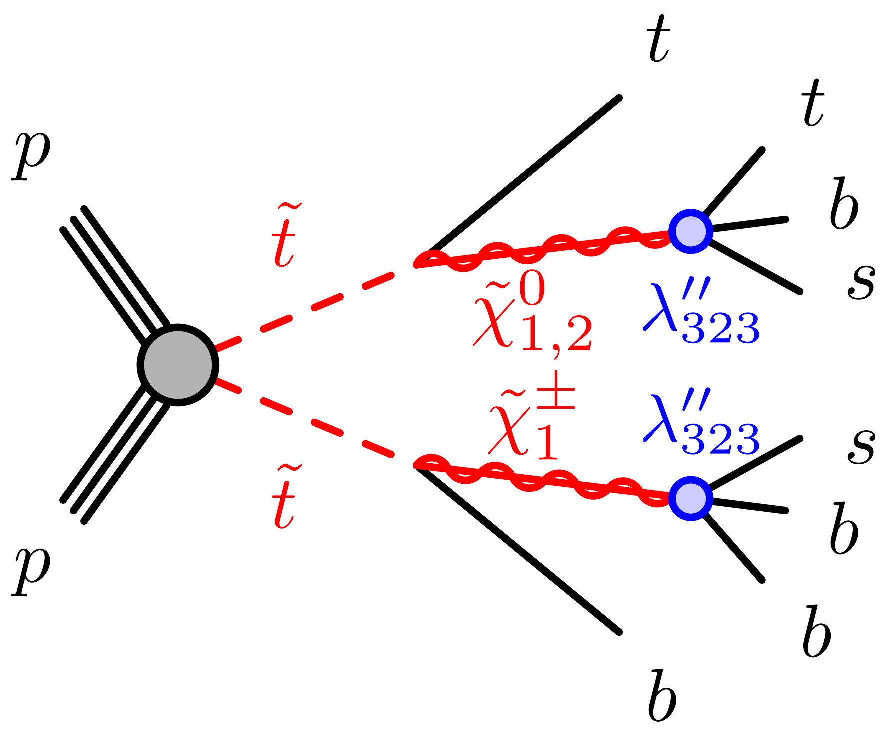
3-top production



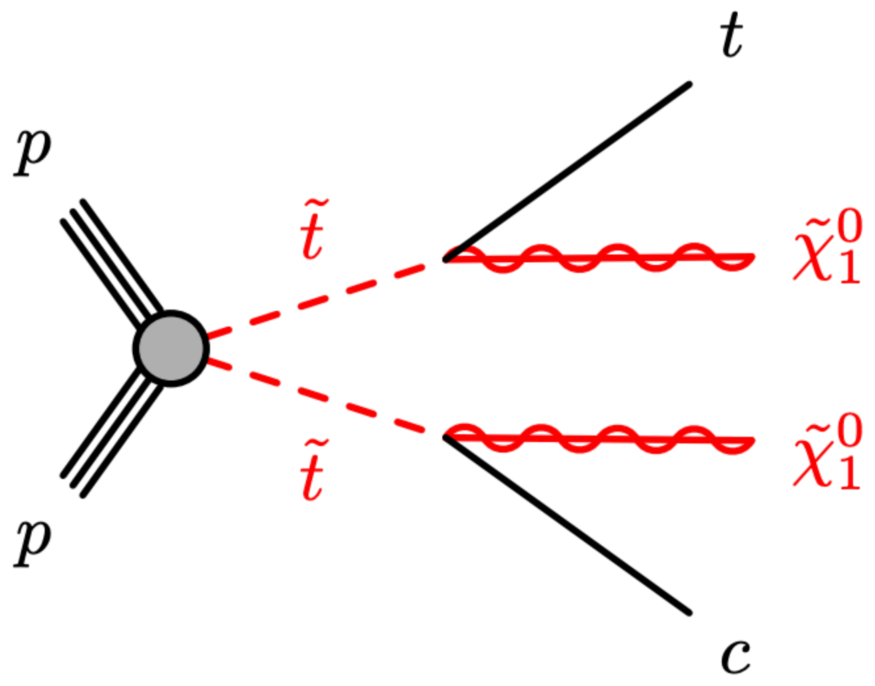
New top decays



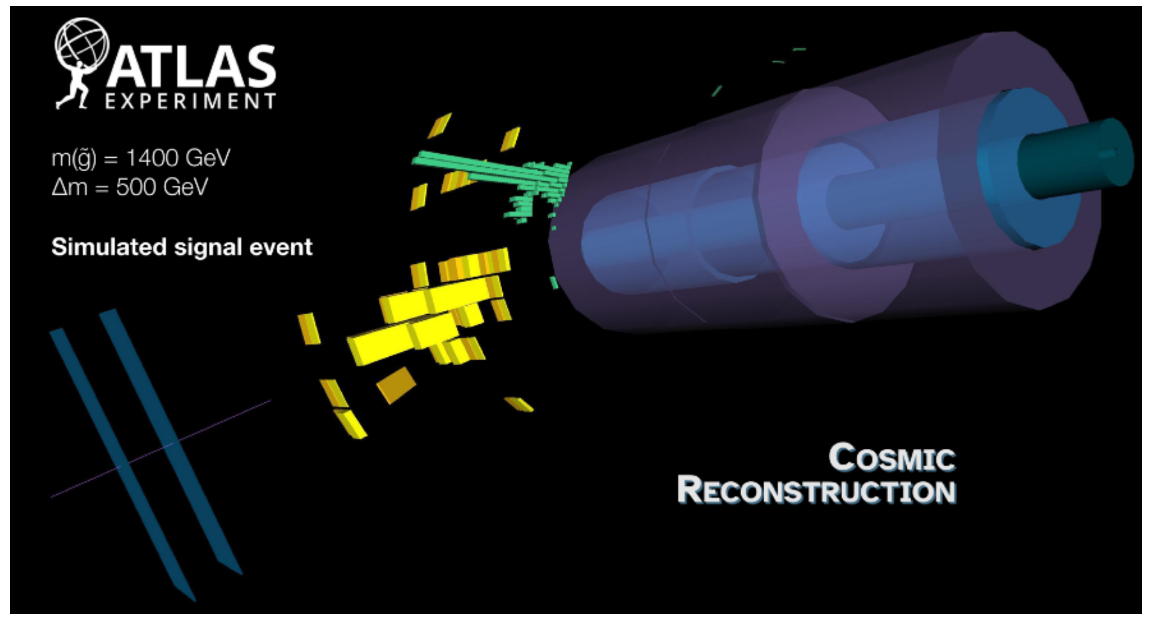
Lepton plus many (>10) jets



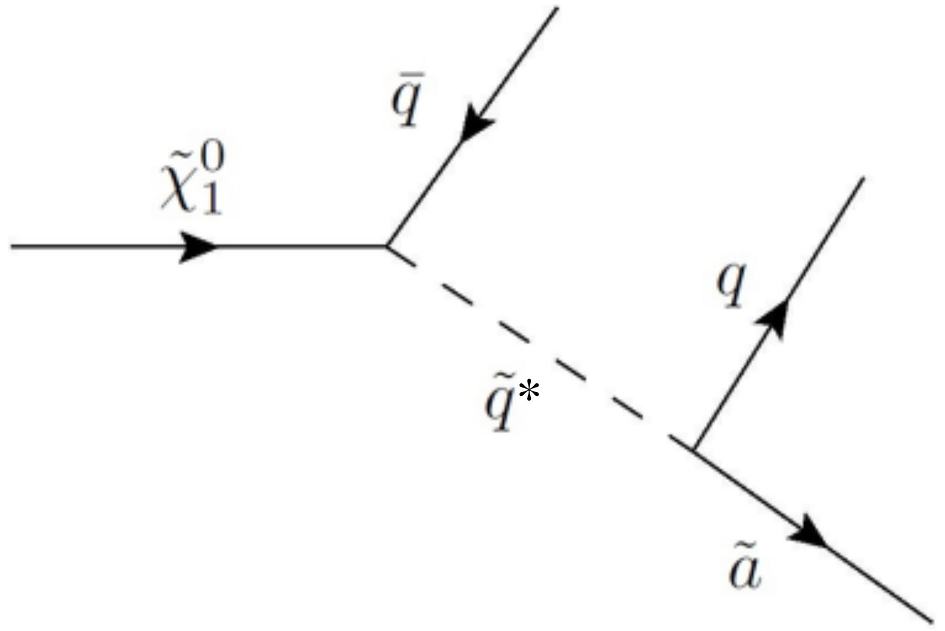
top + charm + E_T (missing)



LLPs decaying after days



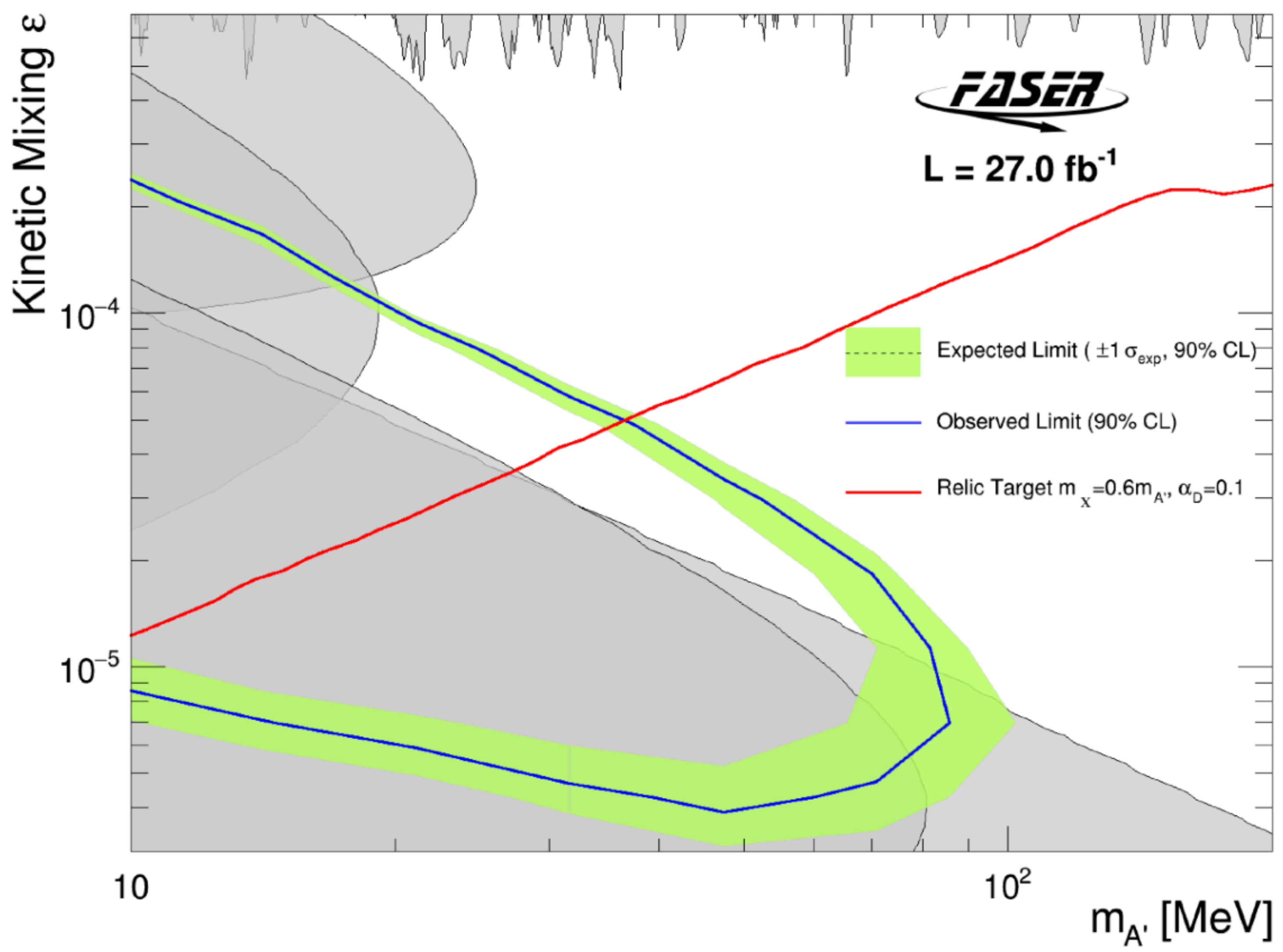
Non-resonant neutralino decays



Searches at the LHC and beyond

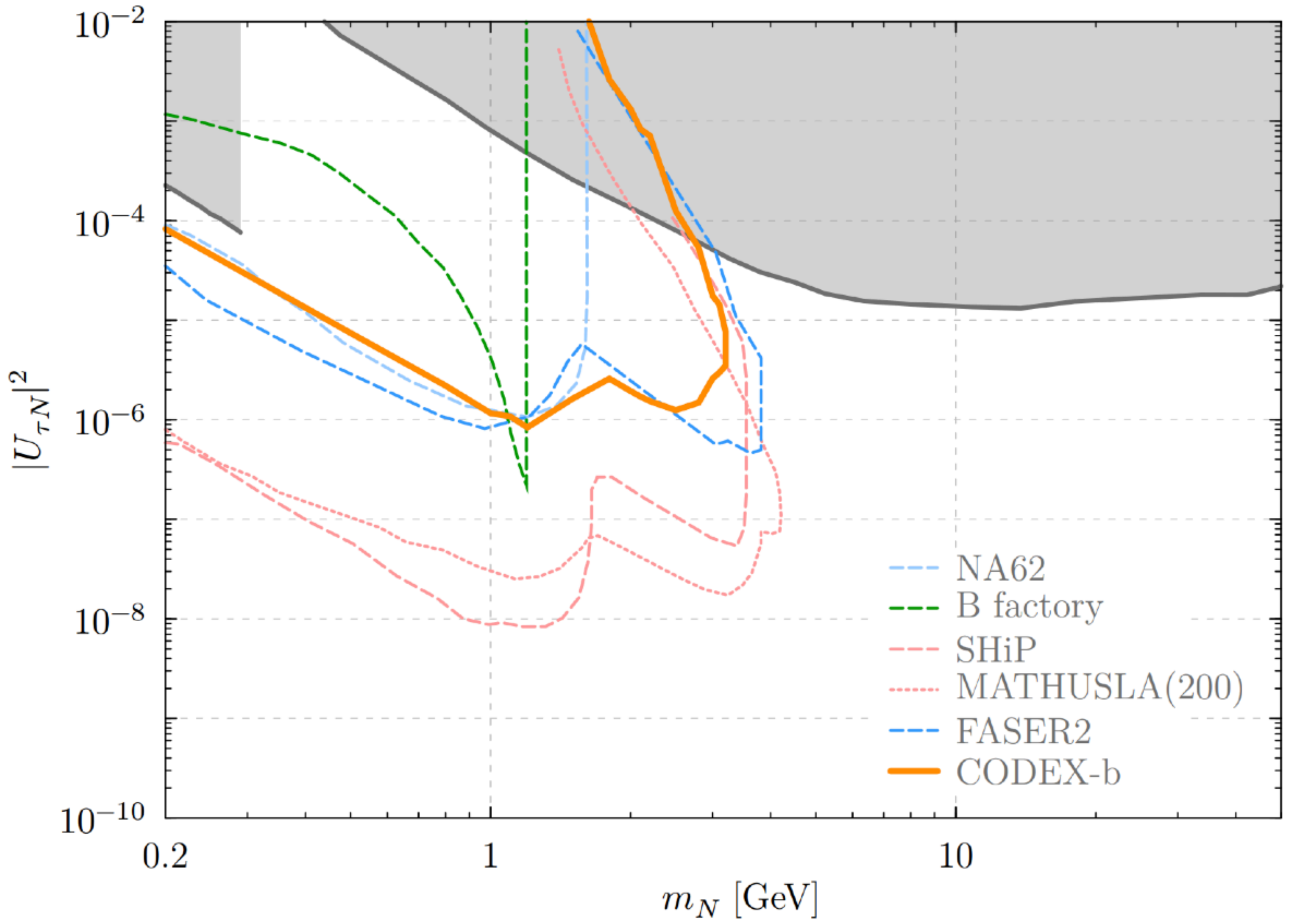
We tend to identify LHC searches = ATLAS/CMS searches (sometimes LHCb), but there is much more!

- FASER is producing first results on dark photons
- Many LLP experiments have been proposed, and some have already prototypes installed
  - ANUBIS, CODEX-b, MATHUSLA

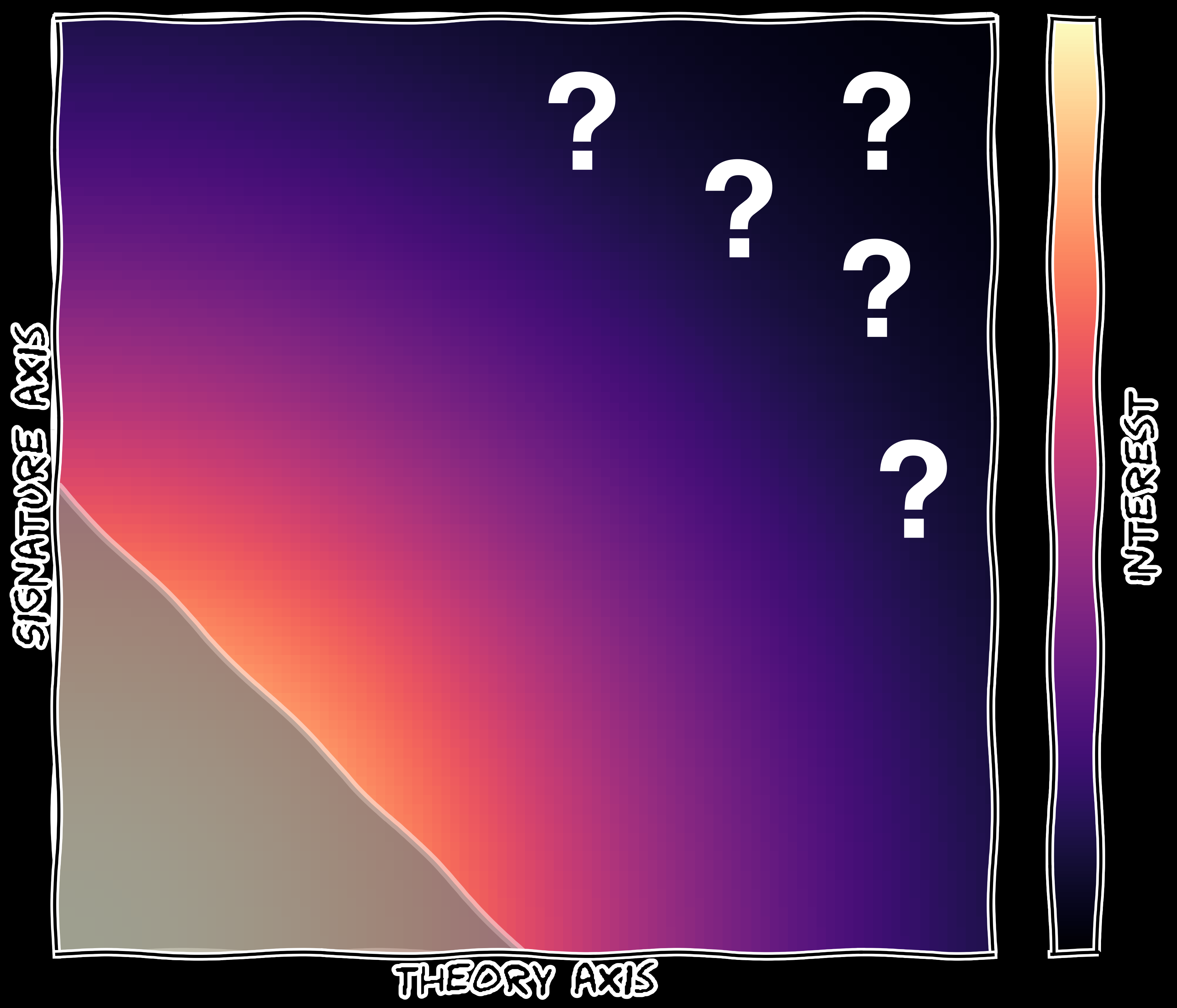


And going slightly beyond scope, there are other (proposed) searches and **physics beyond colliders**

- E.g. NA64, HIKE, SHADOWS, SHIP, MilliQan and experiments at FPF



It's getting dark,
can we first find a flashlight?



The nightmare scenario

"Higgs and nothing else" has often been referred to as the nightmare scenario at the LHC

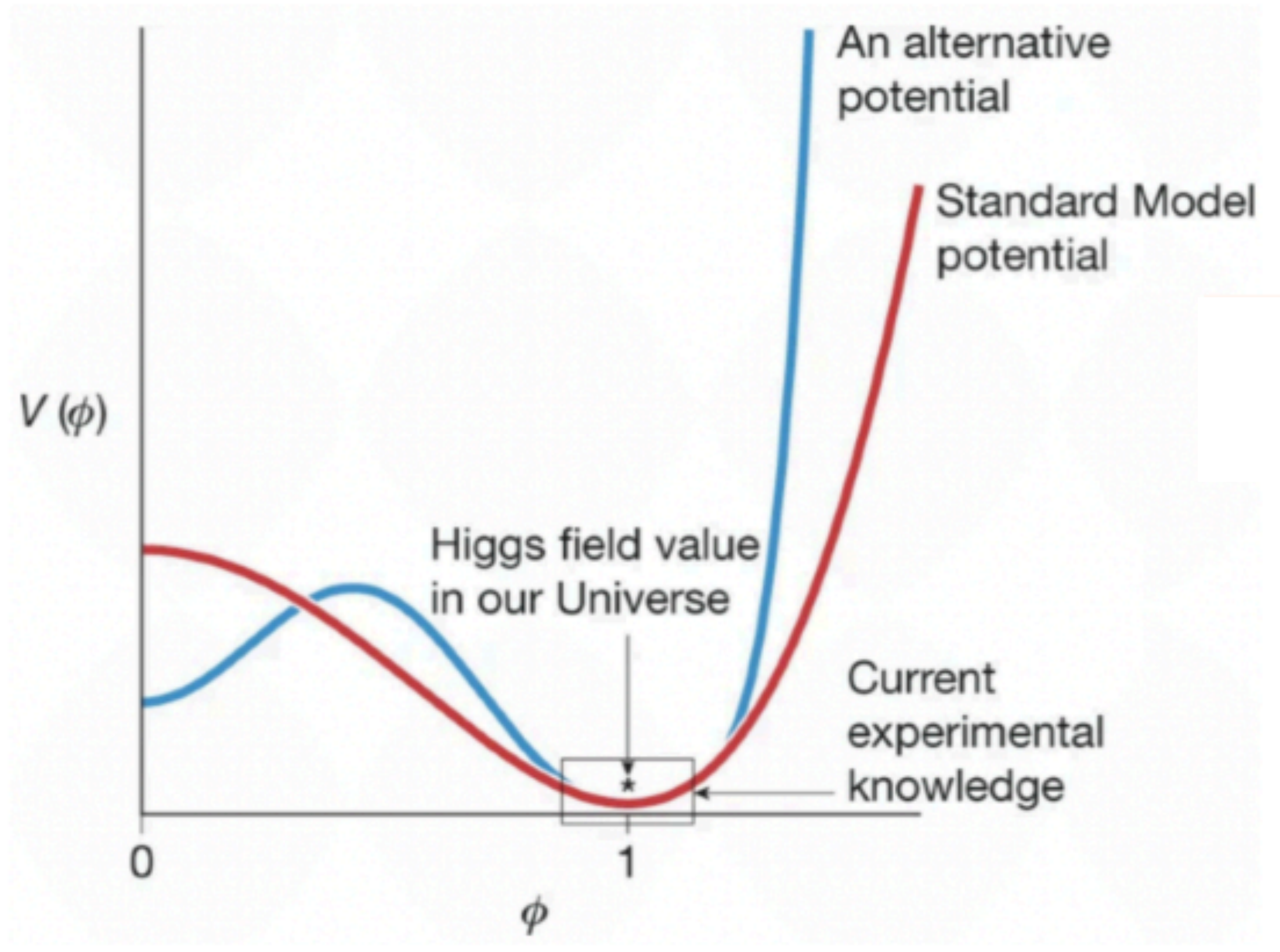
- Flavour anomalies are vanishing, $(g\text{-}2)_{\mu}$ tension is now disputed
- We have plenty of new ideas for Run 3 and improved detectors, but what if nothing shows up?

We are exploring in detail for the first time many SM processes that are sensitive to new physics

- Four-top production cross section has been measured for the first time, and it's high in both ATLAS and CMS
- ttW cross section is high in both ATLAS and CMS
- The higgs to invisible branching ratio can still be ~10%
- Most higgs couplings have still 5-10% uncertainties
- In general we have still very little idea about the higgs potential!

There are still a lot of unexplored signatures and models, but eventually we will enter a phase of diminishing returns, and we should step back and look at our understanding of the SM, especially the Higgs boson

[G. Salam, Nature 607, 41–47 (2022)]



Conclusions

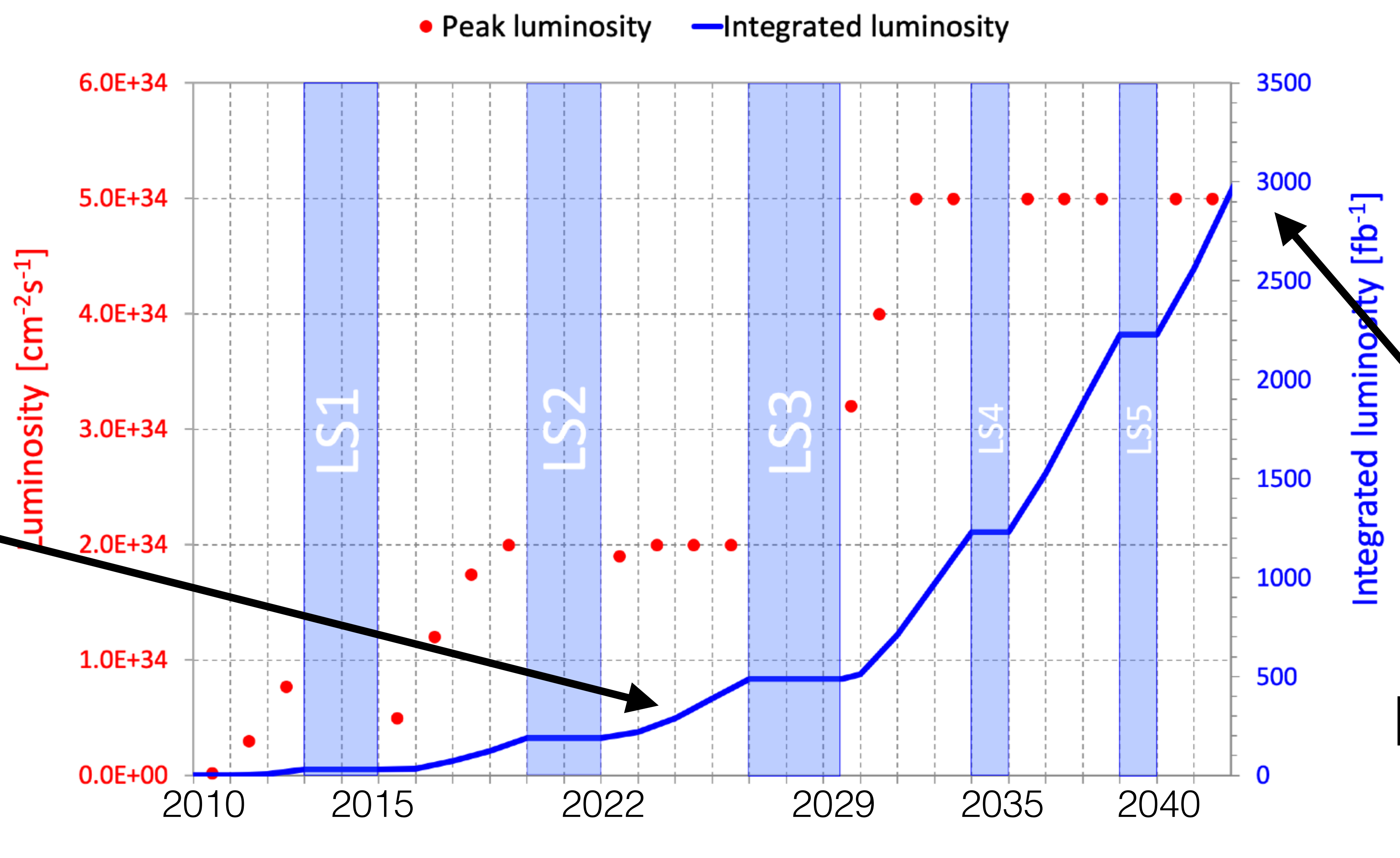
I have presented a (very) brief overview of the broad and diverse LHC search programme

- After more than a decade of searches and with the slow down of the luminosity doubling time, it is critical to revise our preferences and biases to **maximize the discovery potential**

The real nightmare scenario: there is BSM physics in reach and we don't find it because it doesn't match our expectations

Let's do our part and **leave no stone unturned**

And remember, we are here



and we are heading here

lots of fun and challenges ahead!

Leave no stone unturned!