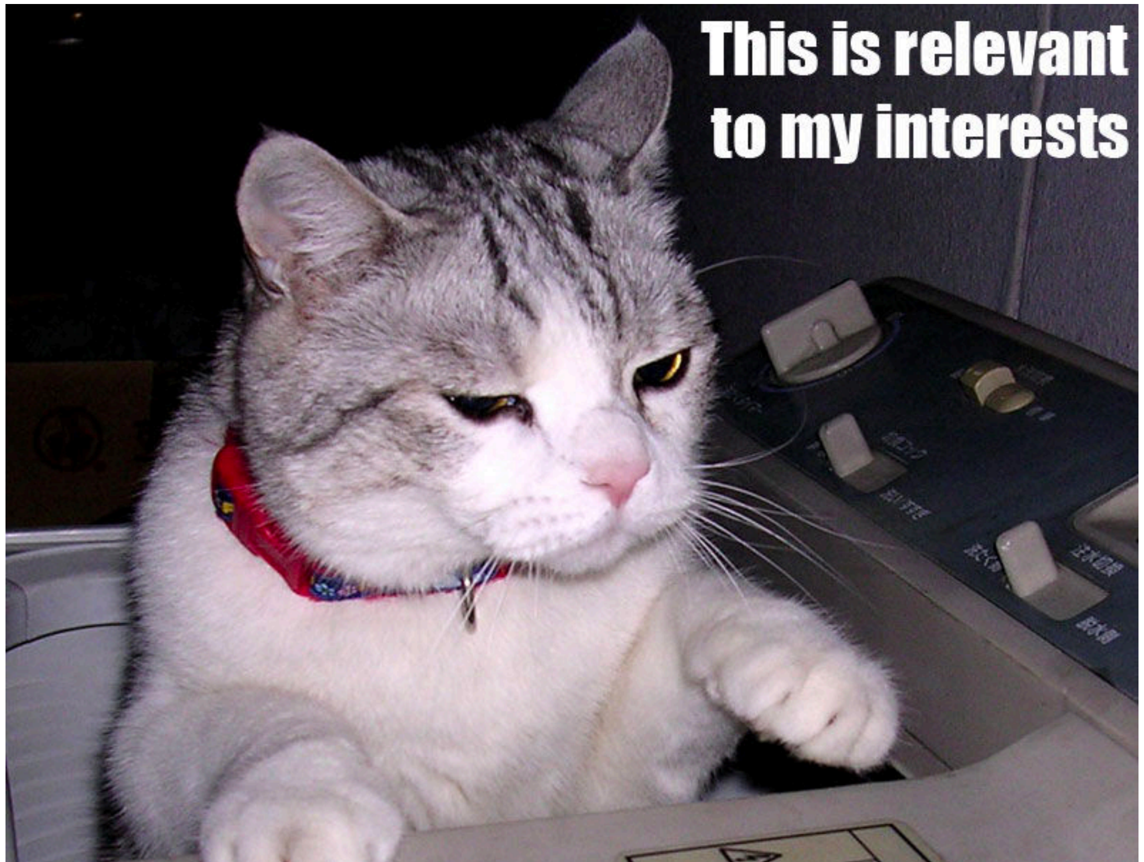
BSM Experimental Searches 1

Zach Marshall (LBNL), CERN-Fermilab HCP Summer School, 31 August 2021

A quick word about me

- Brief summer on CMS in 2005
- Working on ATLAS since 2006
- PhD on ATLAS in 2010
  - Jet shape measurements
- Share time between a few areas in ATLAS
  - SUSY (vanilla and weird searches)
  - Jets (response, SM measurements)
  - Software (simulation, generation, analysis)
- Several positions within ATLAS
  - SUSY search group convener ('16-'18)
  - Deputy computing coordinator ('20-'21)
  - Computing co-coordinator ('21-'22)

Before we get too far…



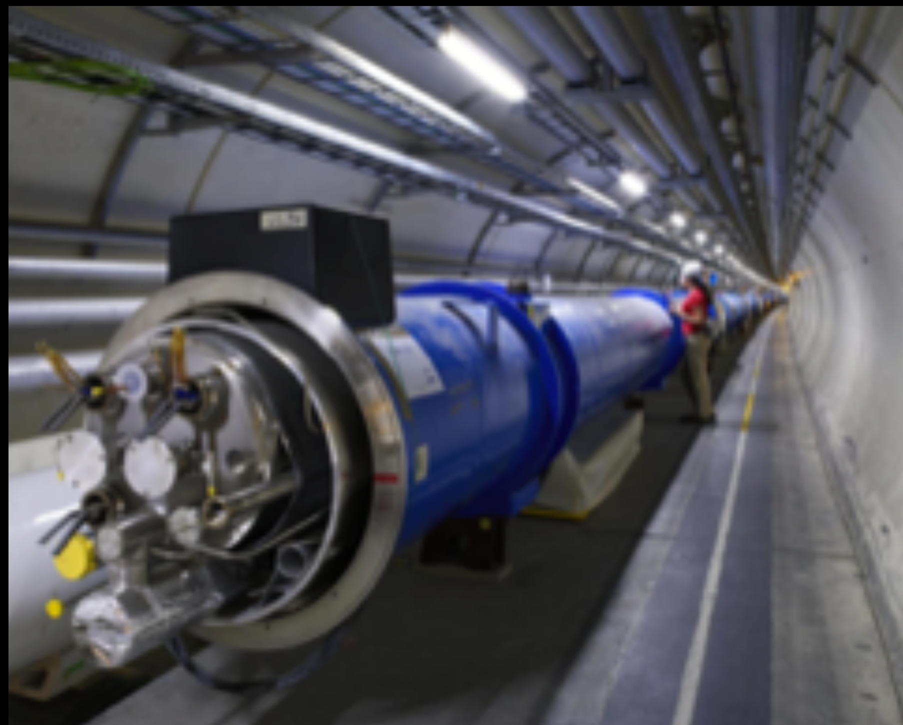
- I'm gonna talk about a whole bunch of new physics searches and techniques
- Please go ahead and send me a note or write in the chat any particular new physics searches / techniques / models that you're interested in, and I'll try to be sure they're covered in the next lectures

Outline

- Starting a search
- Designing a search
- Estimating backgrounds
- Reporting results
- LLP/Unusual searches

Disclaimer: I'm going to show mostly ATLAS results; I know those best. CMS has done much of the same work (and we share many standards)

Note: Most pictures in these talks are **links** to the paper / source

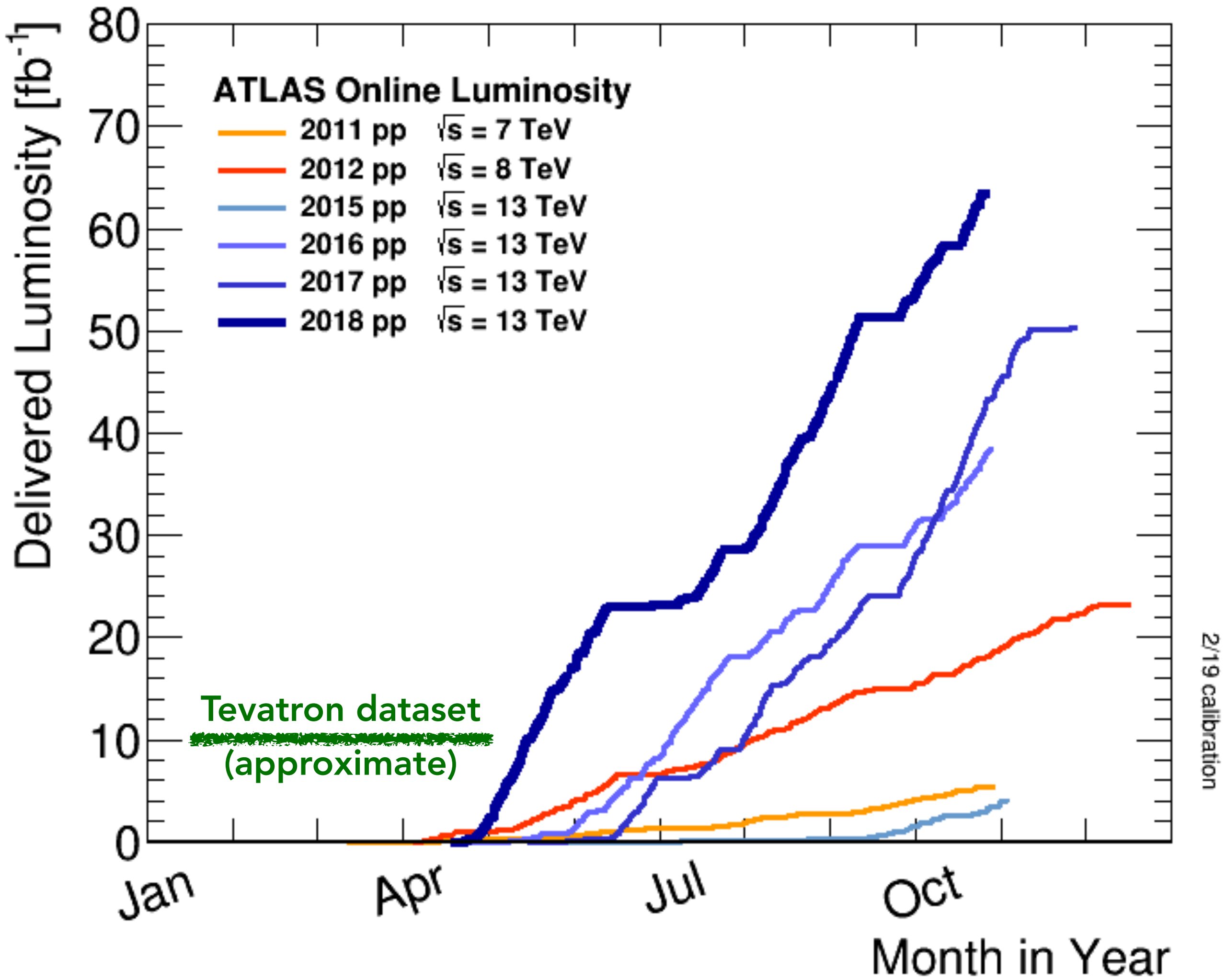


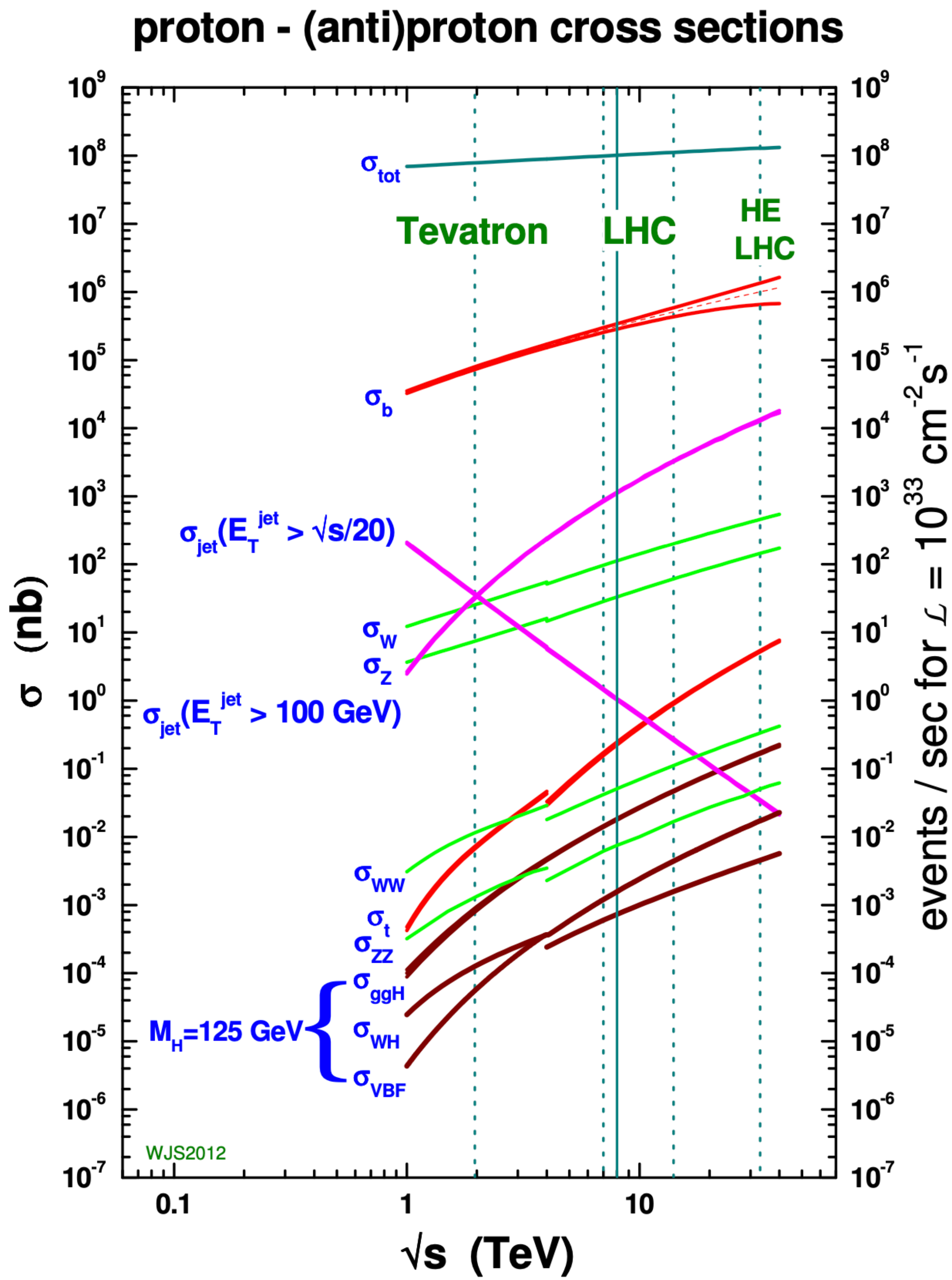

Curopean
Erganization
Ruclear
Nesearch


LHCb
ATLAS
CMS
ALICE

So Much Data!

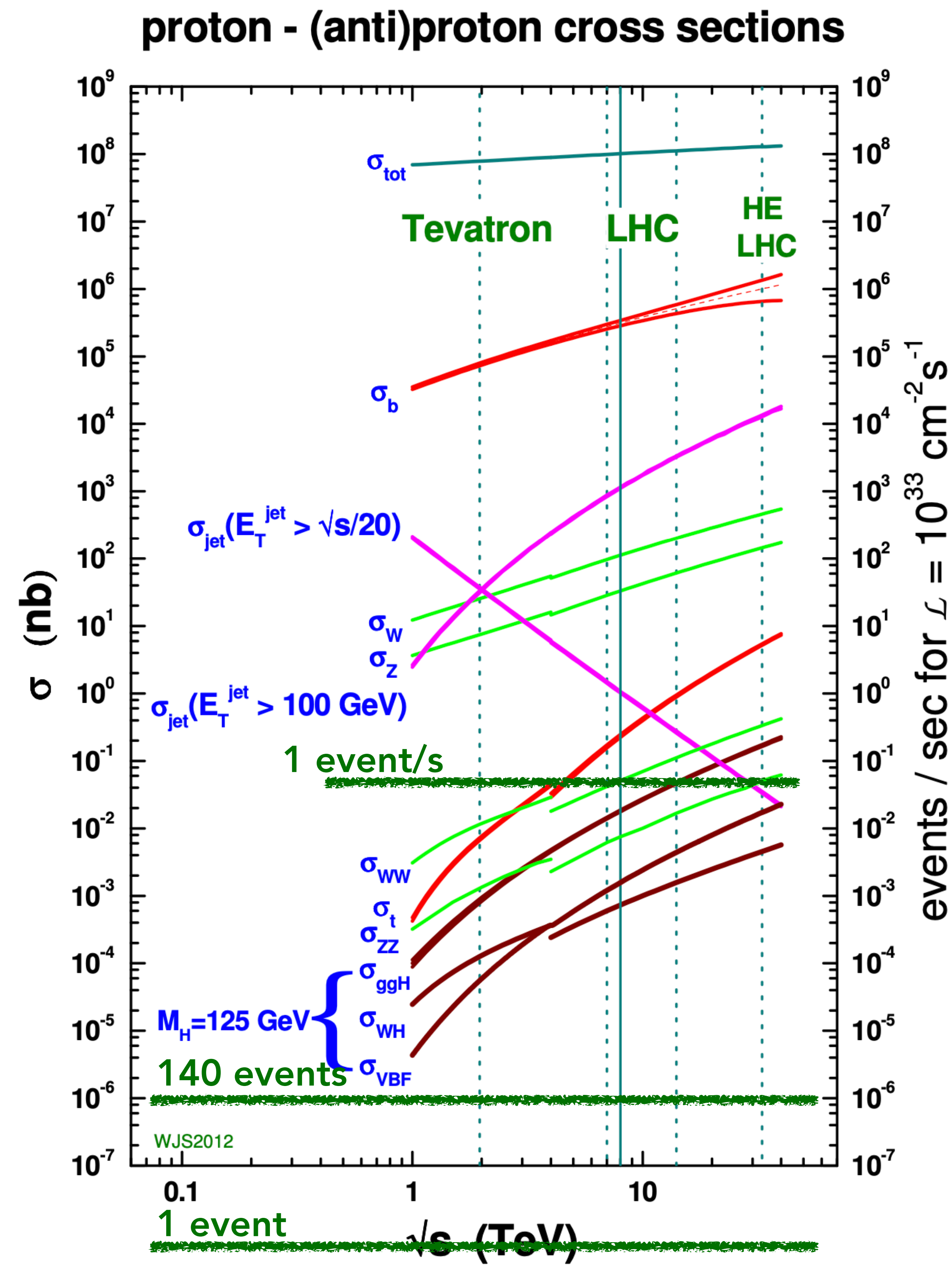
- We measure our data set in inverse cross-section
- Multiply by the cross section to get an event count (or rate)





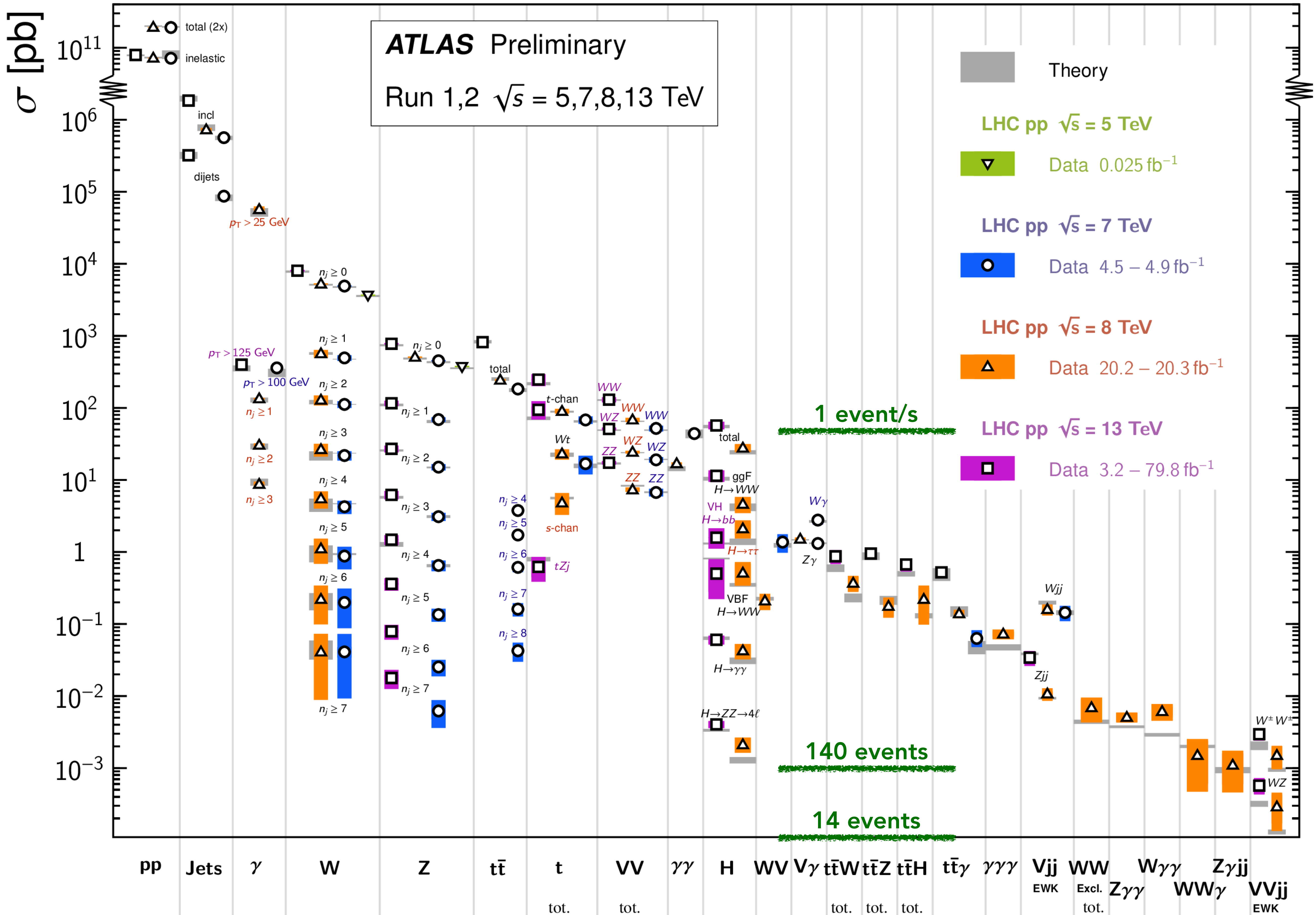
So Much Data!

- Peak:1 Higgs boson per second
  - Higgs production is an important background for searches!
- Approx. 67k top quark pairs from the Tevatron; we collect more than that every hour
- Sensitive down to quite small cross sections and rare processes with our full Run 2 dataset (about 140/fb)



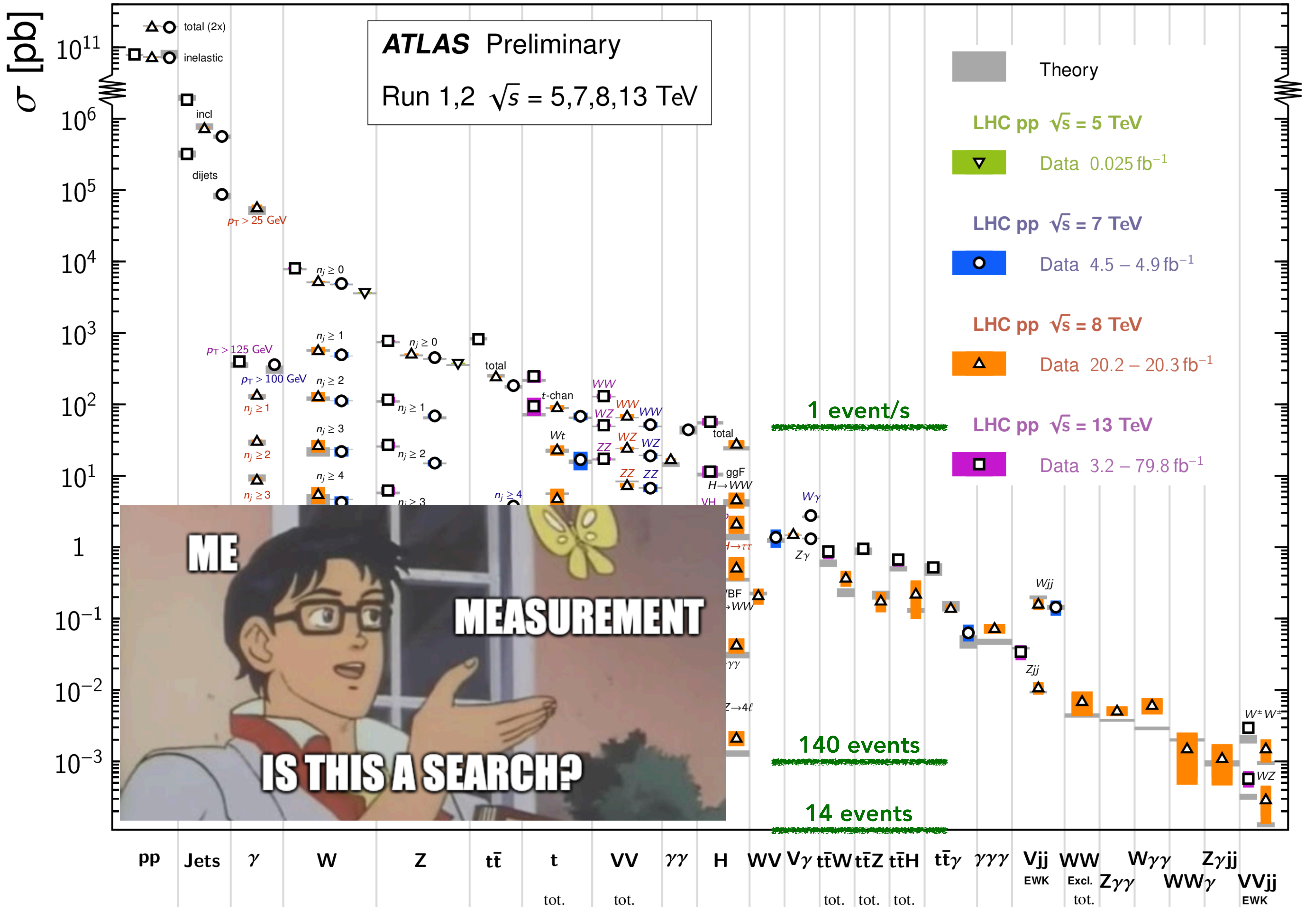
Standard Model Production Cross Section Measurements

Status: November 2019



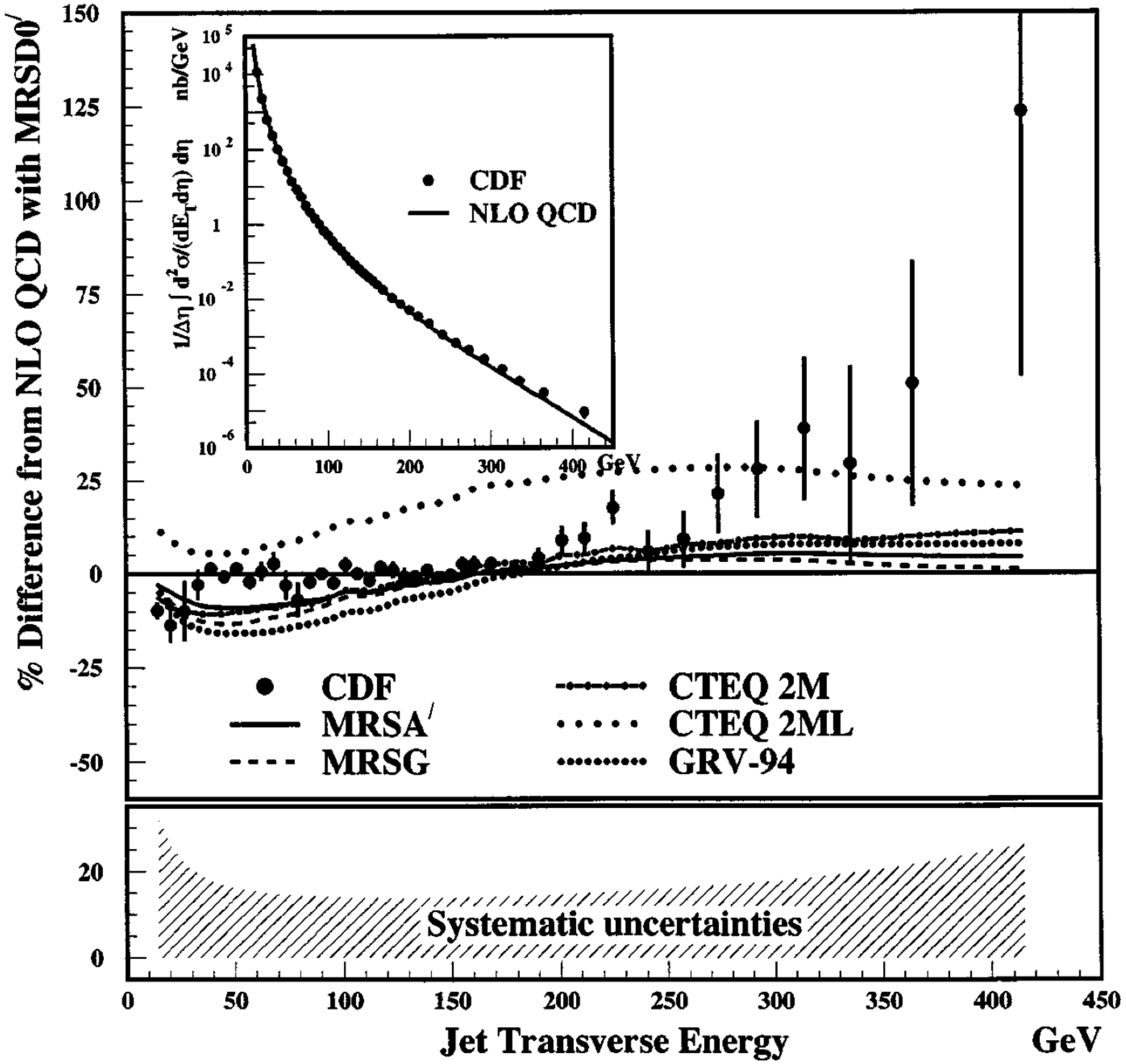
Standard Model Production Cross Section Measurements

Status: November 2019



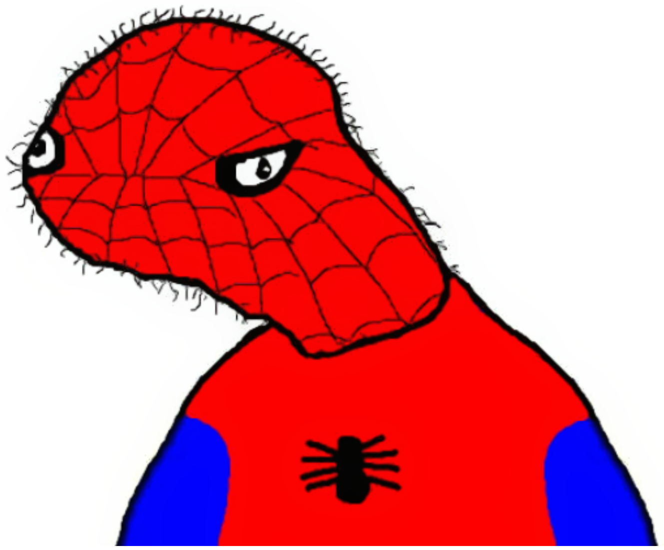
What is a search?

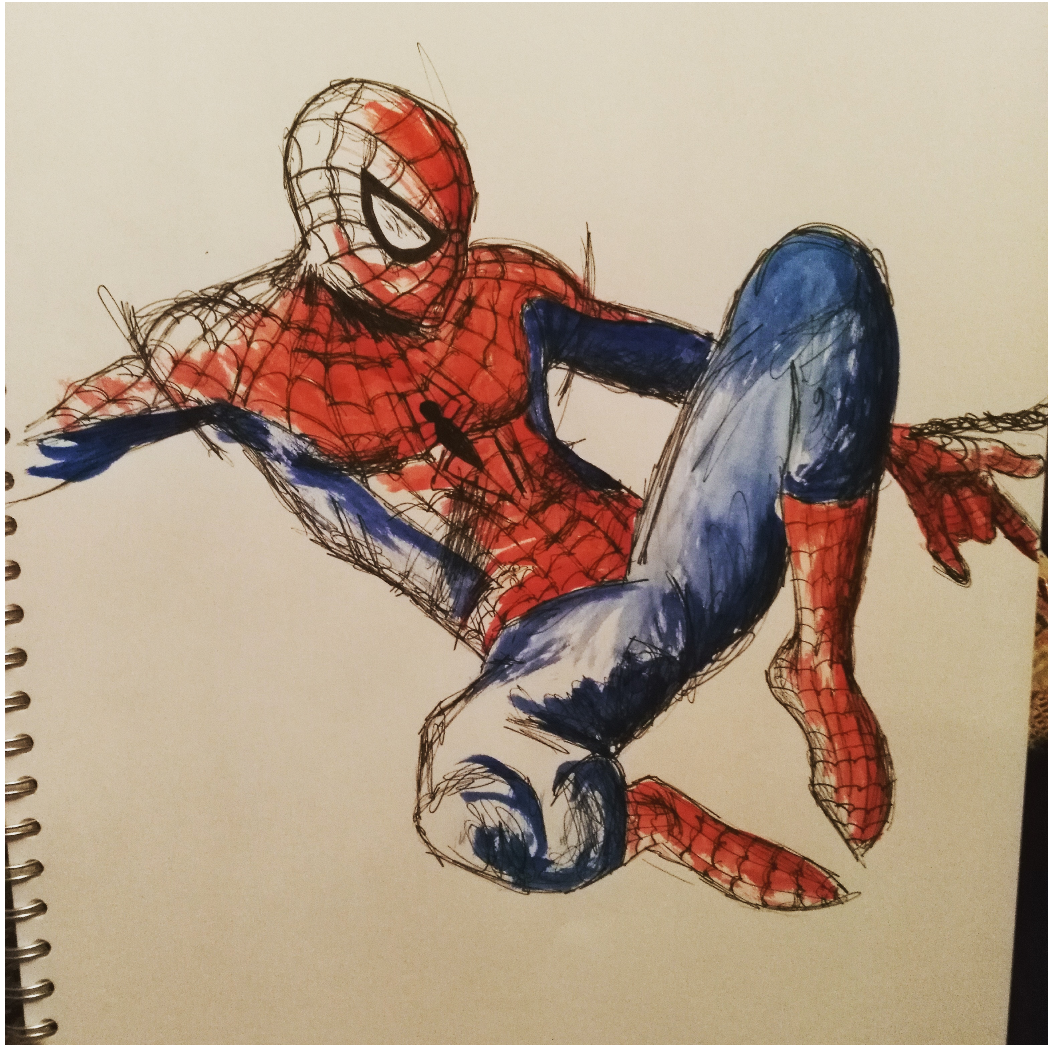
- Measurements are searches too!
- "Above 160 GeV… a probability of 1% that the excess is due to a fluctuation."
- "The best agreement with our data is for $\Lambda_C < 1.6\,\text{TeV}$"
- Unfortunately, we didn't find quark compositeness, we found the gluon in the proton…
- Small industry now devoted to reinterpretation
- But for now, we'll talk about *intentional* searches



Phys. Rev. Lett. 77 (1996) 438

Starting a search



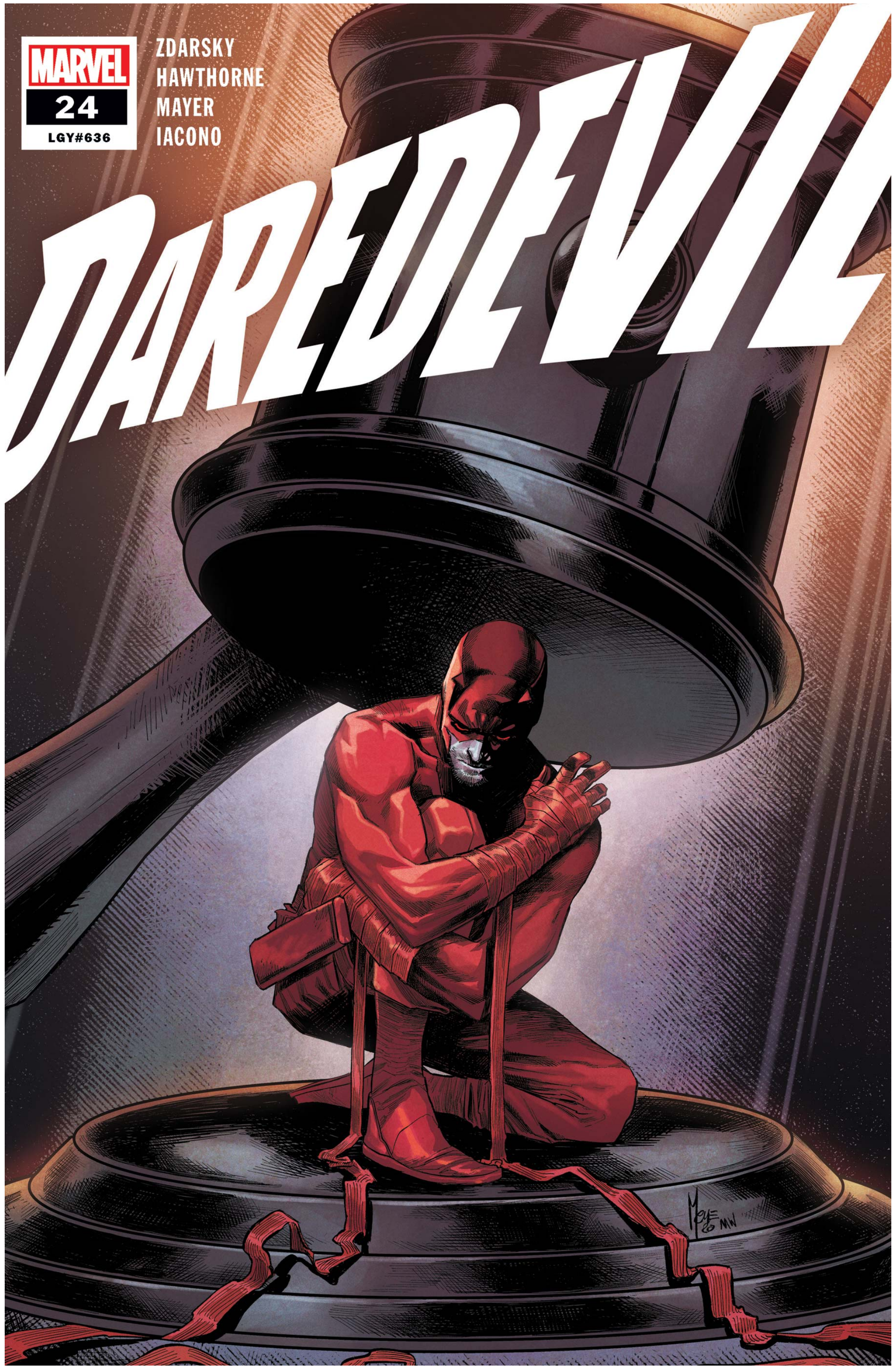


- My favorite way to think about a new project is to think about the **paper**
- What is the **title** of the paper?
- What are the sections of the paper?
- What are the **main plots** in the paper?

- Once I can draw those plots with a crayon, I am ready
  - Different people have different ideas of how much prep to do…

Blinding

- Blinding is one of the biggest philosophical discussions in searches
  - Many measurements are not blind
- What it usually means is "don't look at your signal region data until your background estimation is finalized."
- In some cases it is *very hard to do.*
- It is not strictly necessary, and usually is not strictly required, to do good physics
- It is **very** helpful to avoid biases
  - **ALWAYS COMPARE EXPECTED LIMITS**
- Do not take blinding as a religion
  - If you look in your SR and see something stupid, go back and try again.



Searching Step 0: What am I Looking For?

- Identifying a ***model*** or ***signature*** of interest is a great starting point

Why a signature? Why a model?

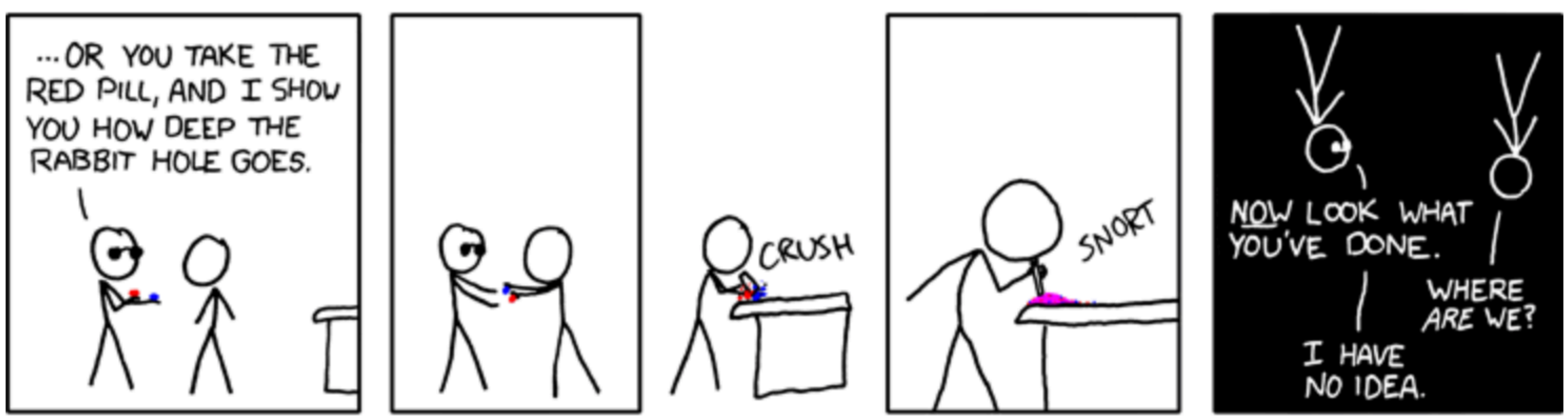
- Signatures are ***general***
- They don't rely on **biases** of the pheno community
- They let you **explore** interesting detector / detection problems
- **Extremely hard** for 'vanilla' signatures (jets+MET)

- Models are (usually) ***physical***
- Someone has worked out the **implications** in the real world
- They allow **comparisons** between searches and other experiments
- May allow **detailed optimization** (also **bad**)

- Signatures don't necessarily have fewer or more parameters than models
- A search for a signature doesn't necessarily mean interpretation is easier or harder

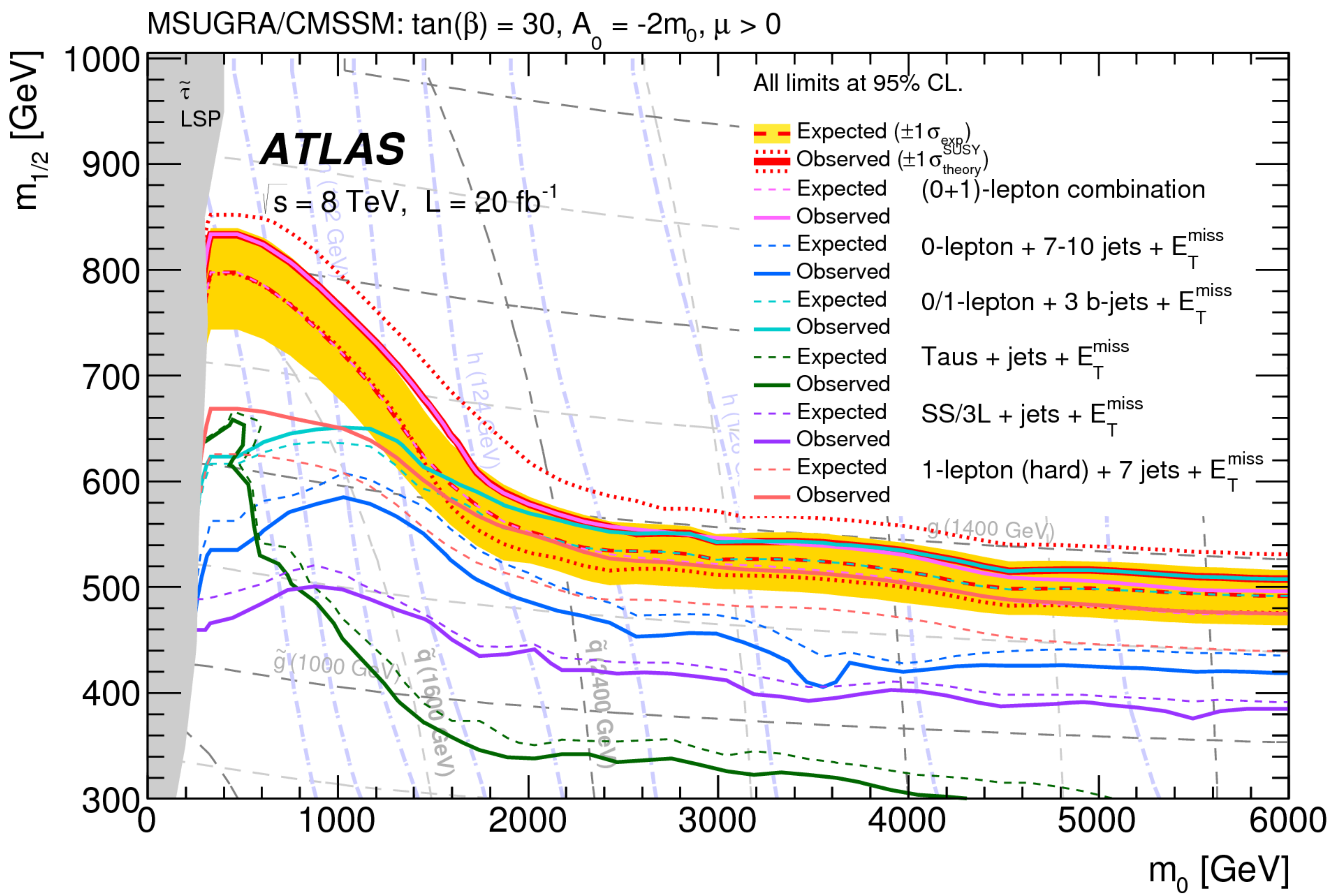
My Opinion

- Let a good ***model*** guide you to an interesting ***signature***
- Then generalize your search based on that ***signature***



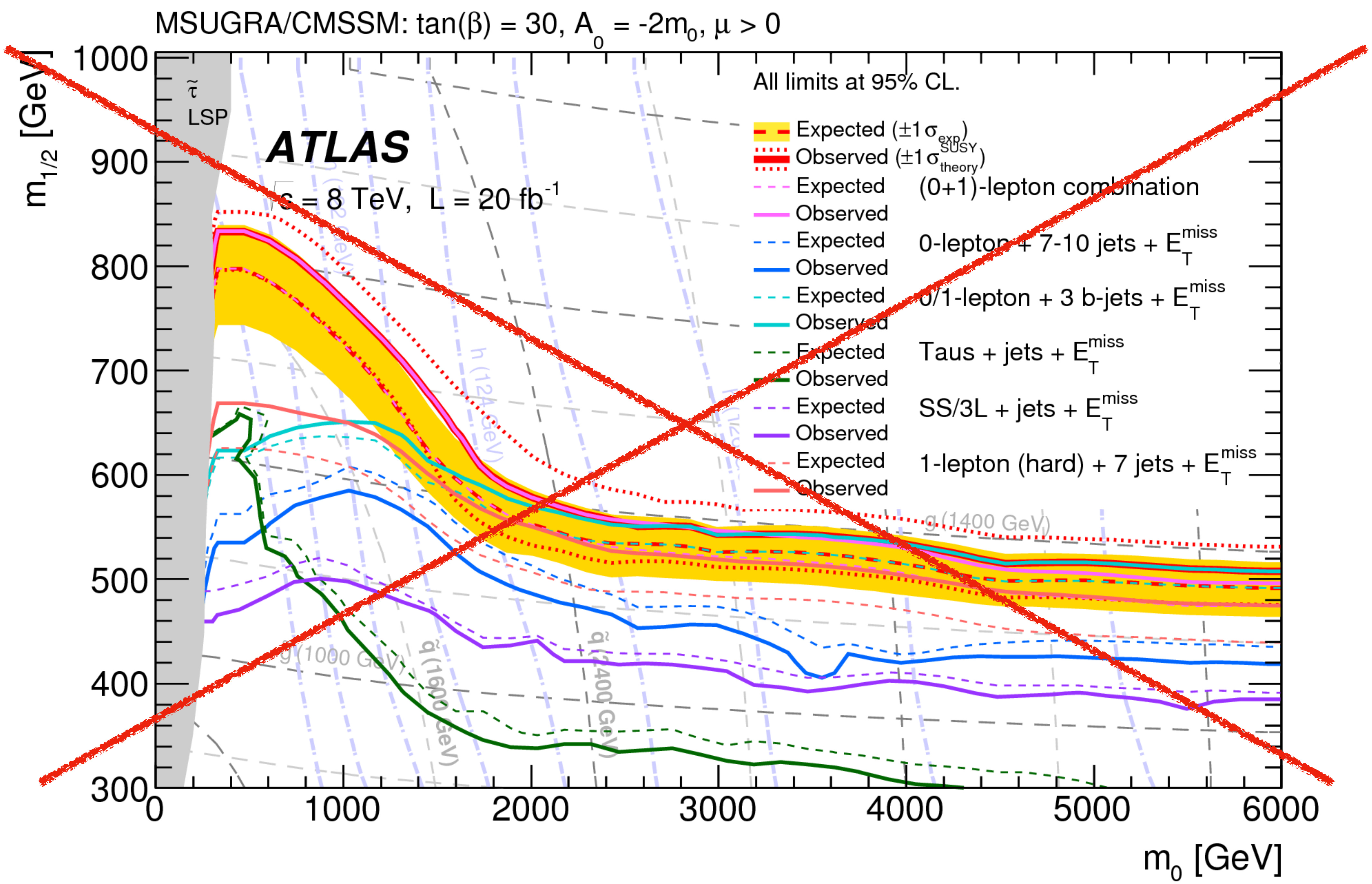
Dealing with a model

- This is a(n example of a) simplified model



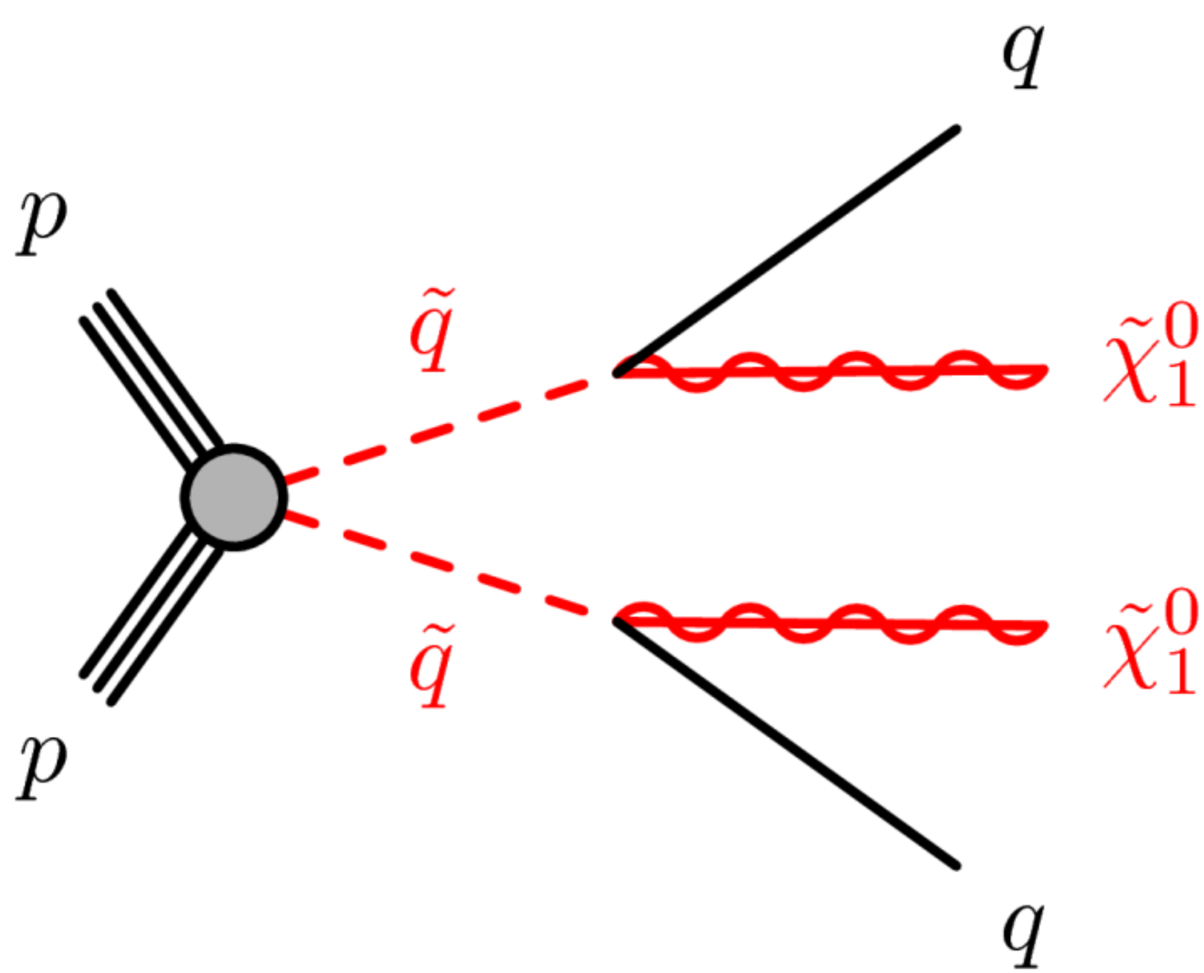
Dealing with a model

- This is a(n example of a) annoying simplified model



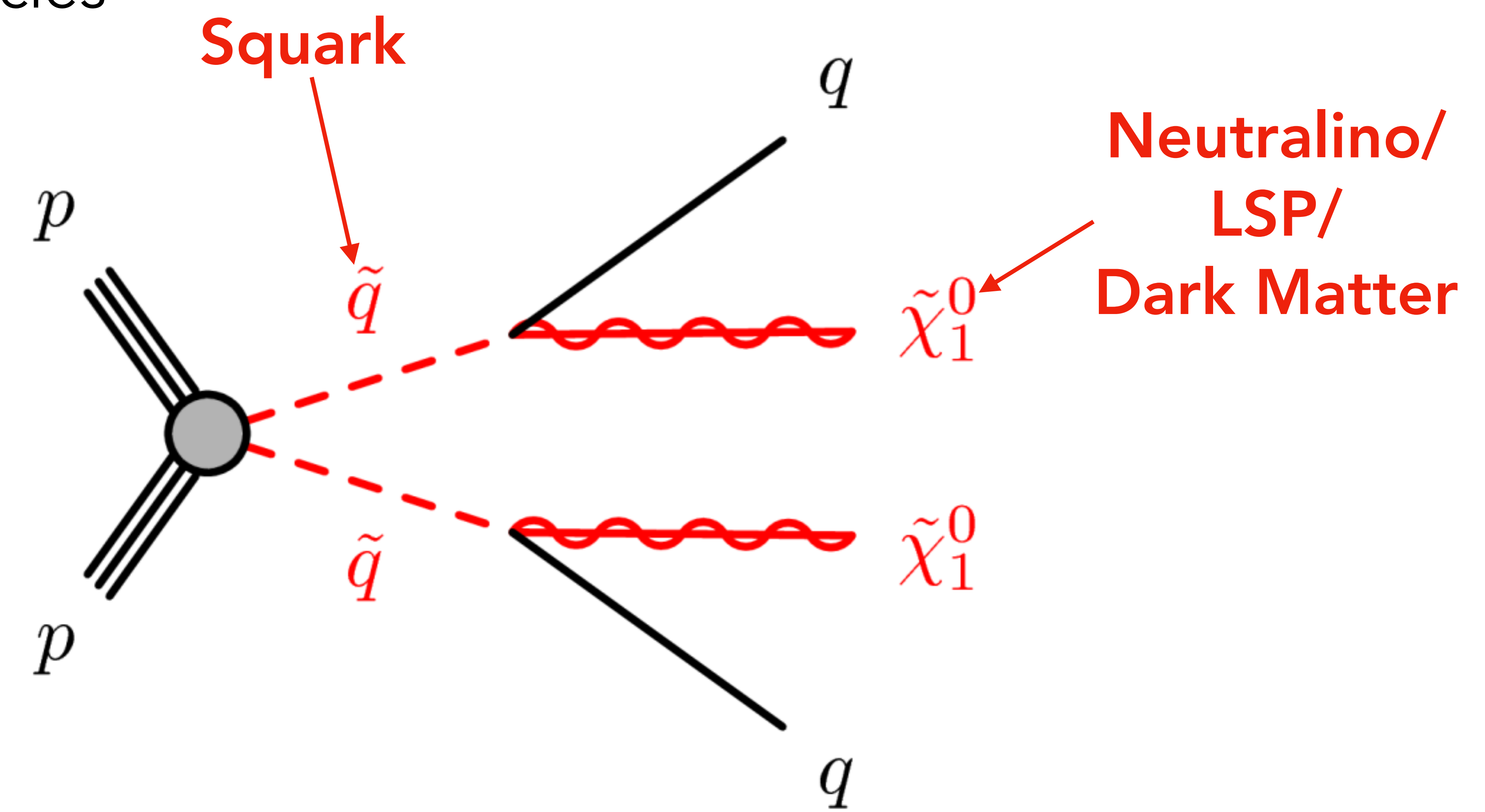
Dealing with a model

- This is a(n example of a) simplified model



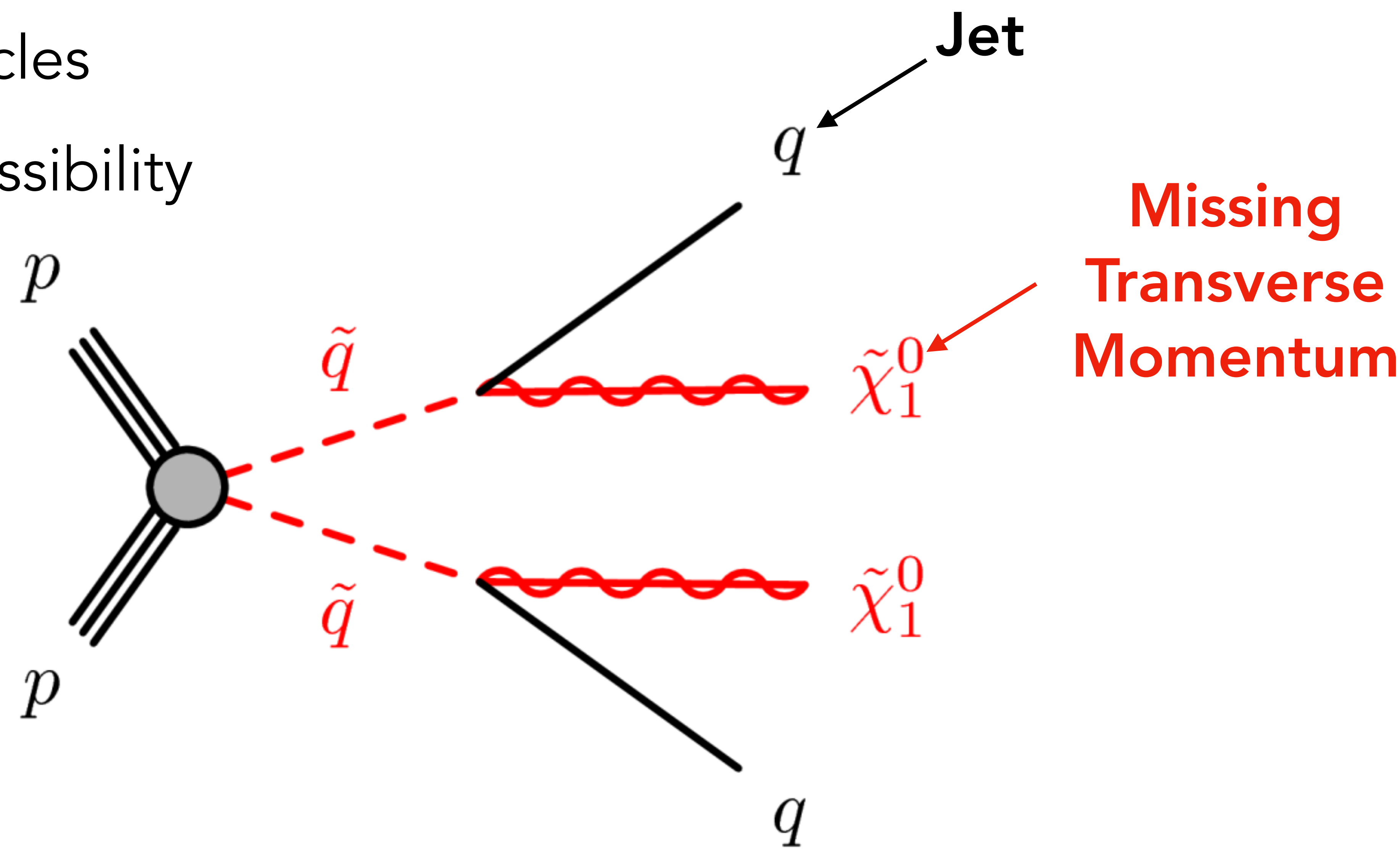
Dealing with a model

- This is a(n example of a) simplified model
- Two new particles



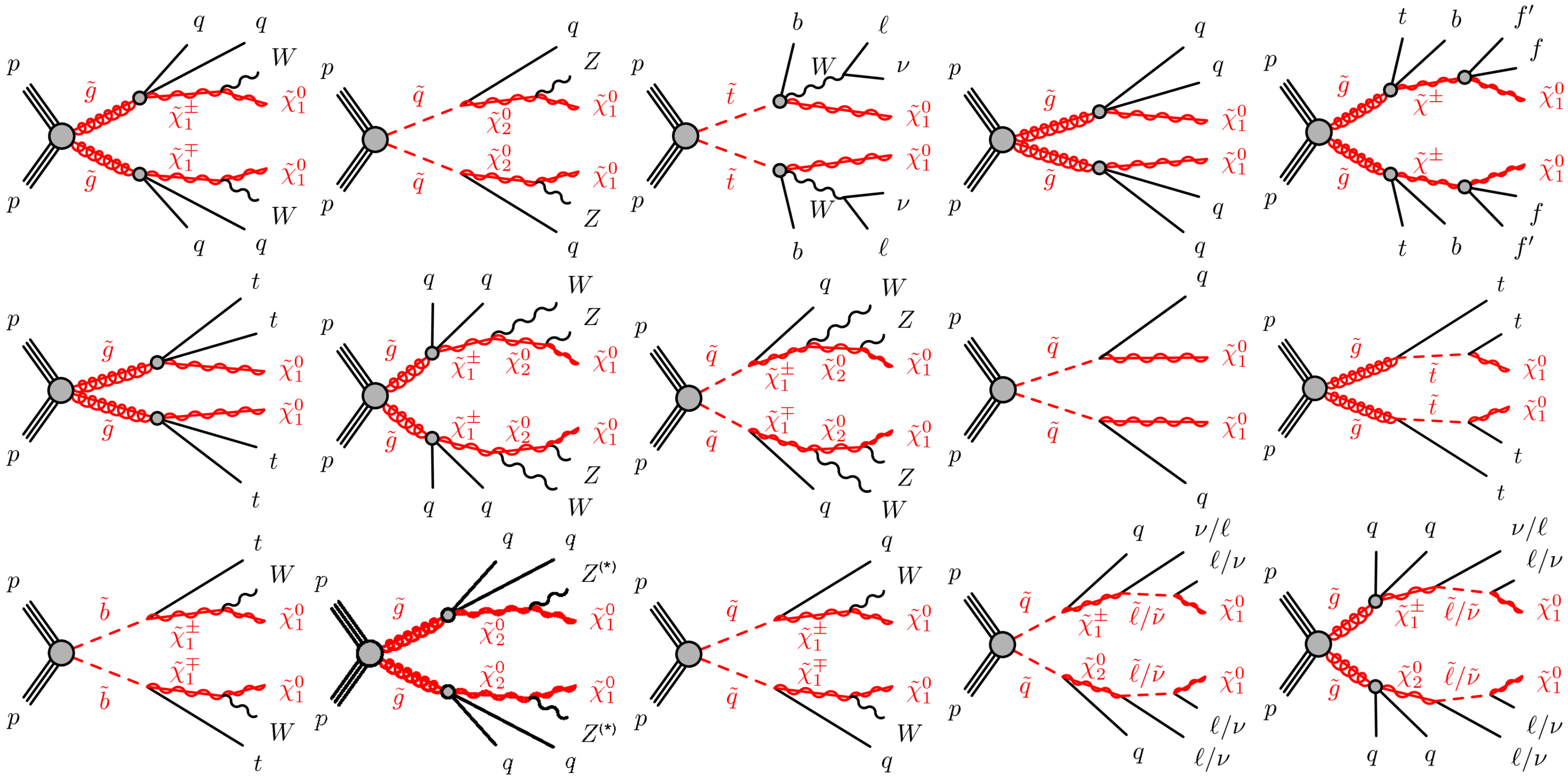
Dealing with a model

- This is a(n example of a) simplified model
- Two new particles
- One decay possibility

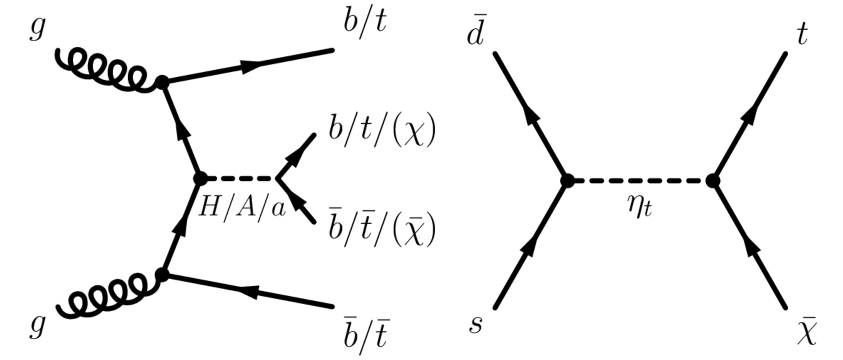


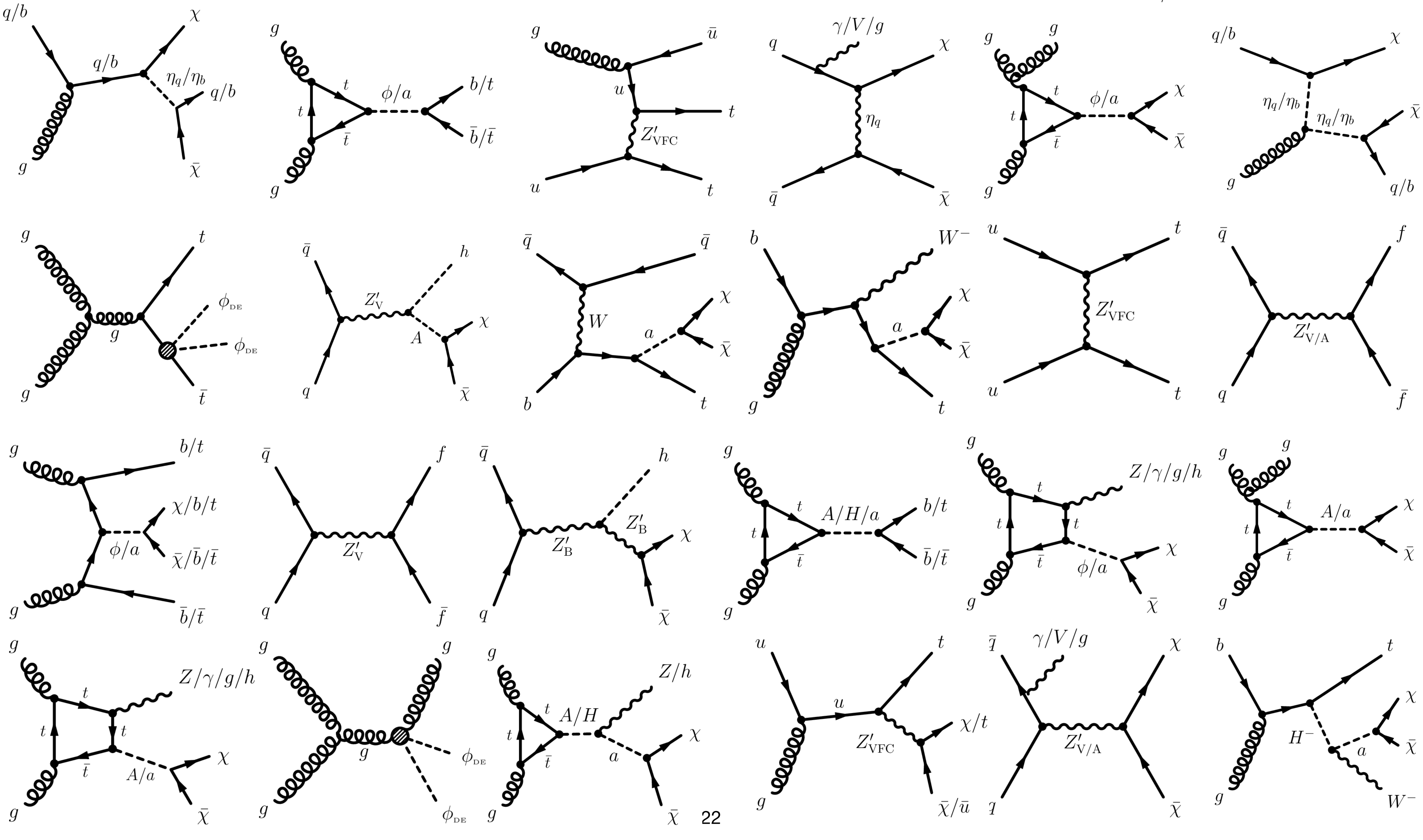
I can search for that ☺

So many options!



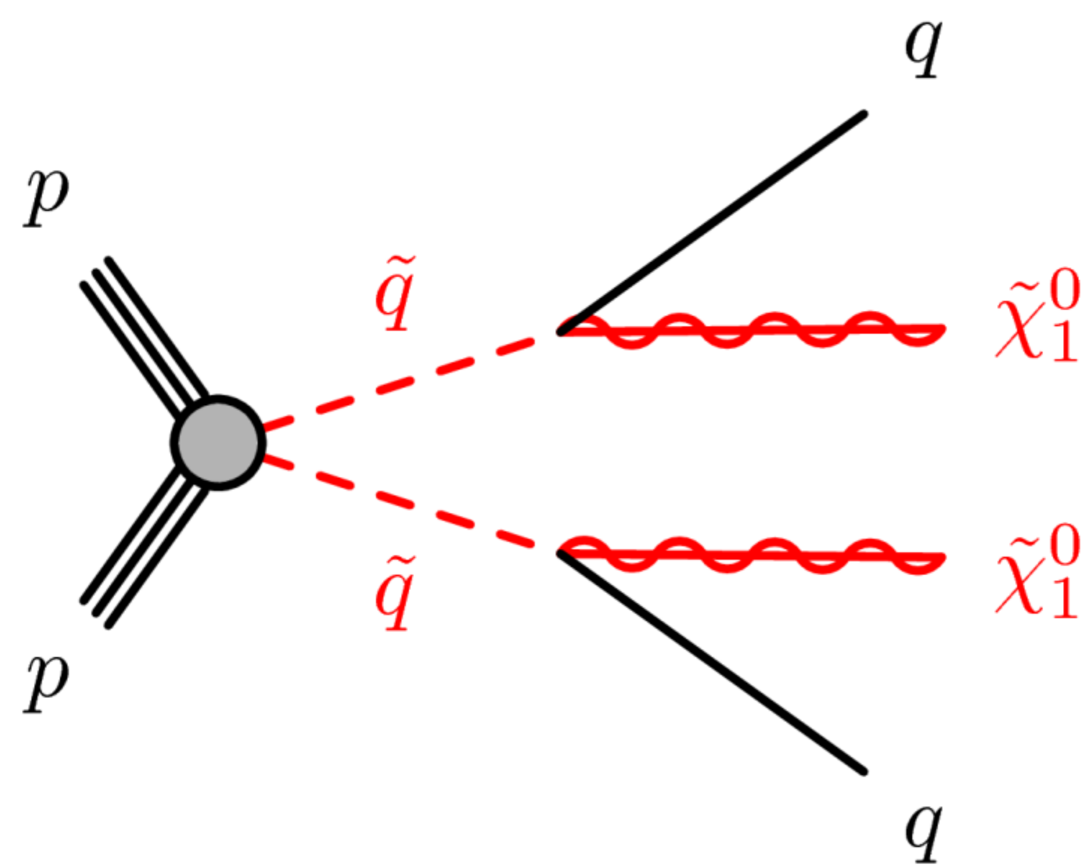
So many options!





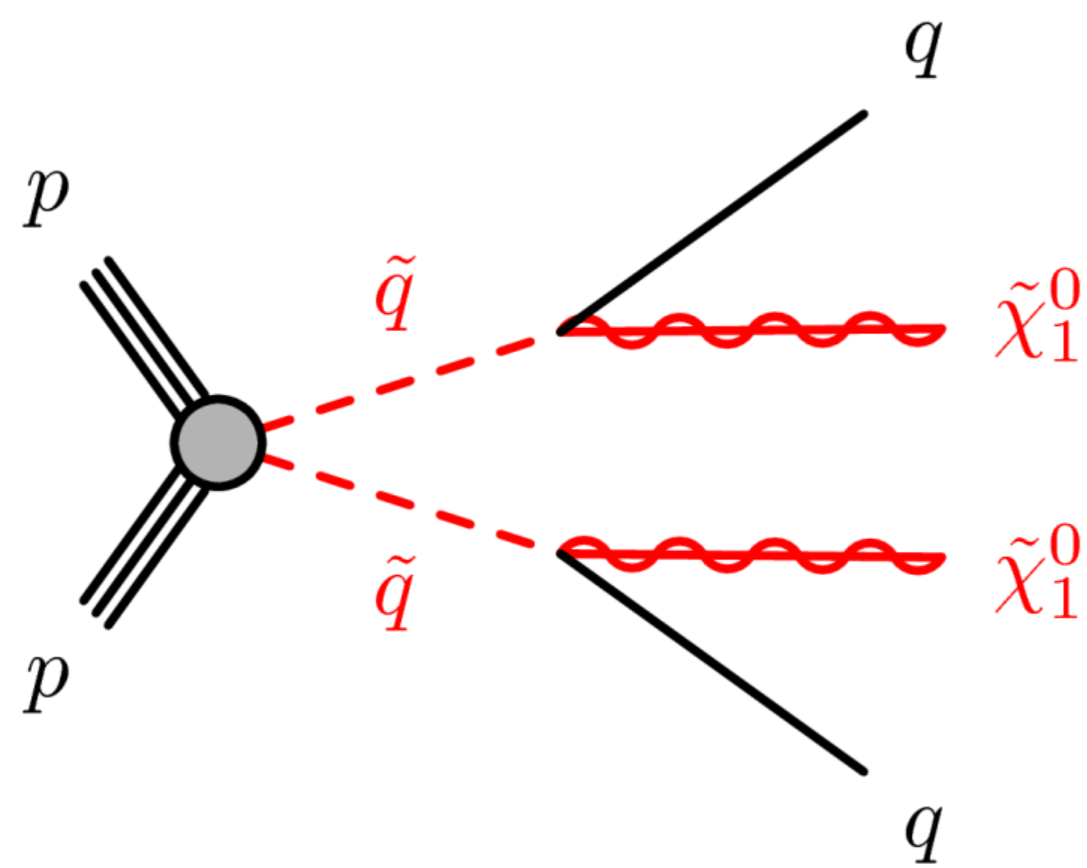
Back to our model…

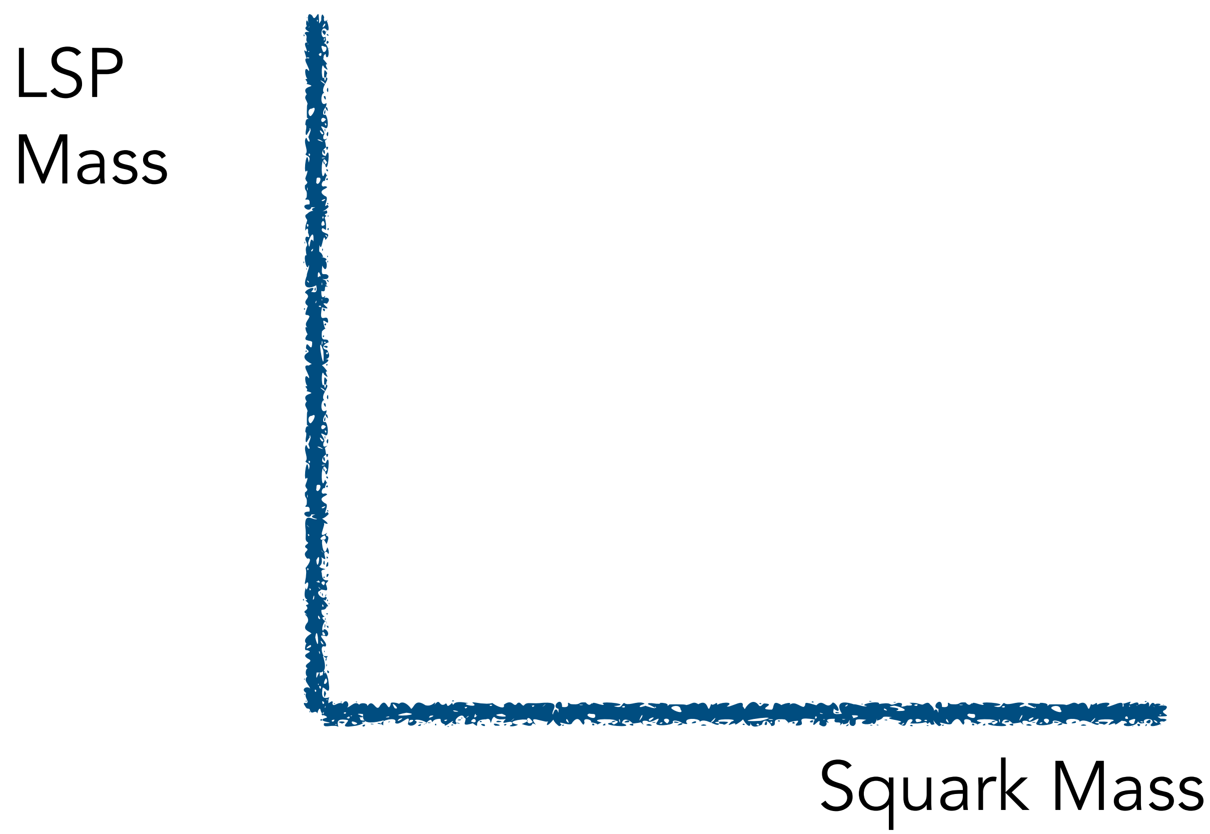
- What are the ***free parameters*** of our model?
  - We have to make the thing: there's a production cross section.
  - Two new particles mean two new masses.



Back to our model…

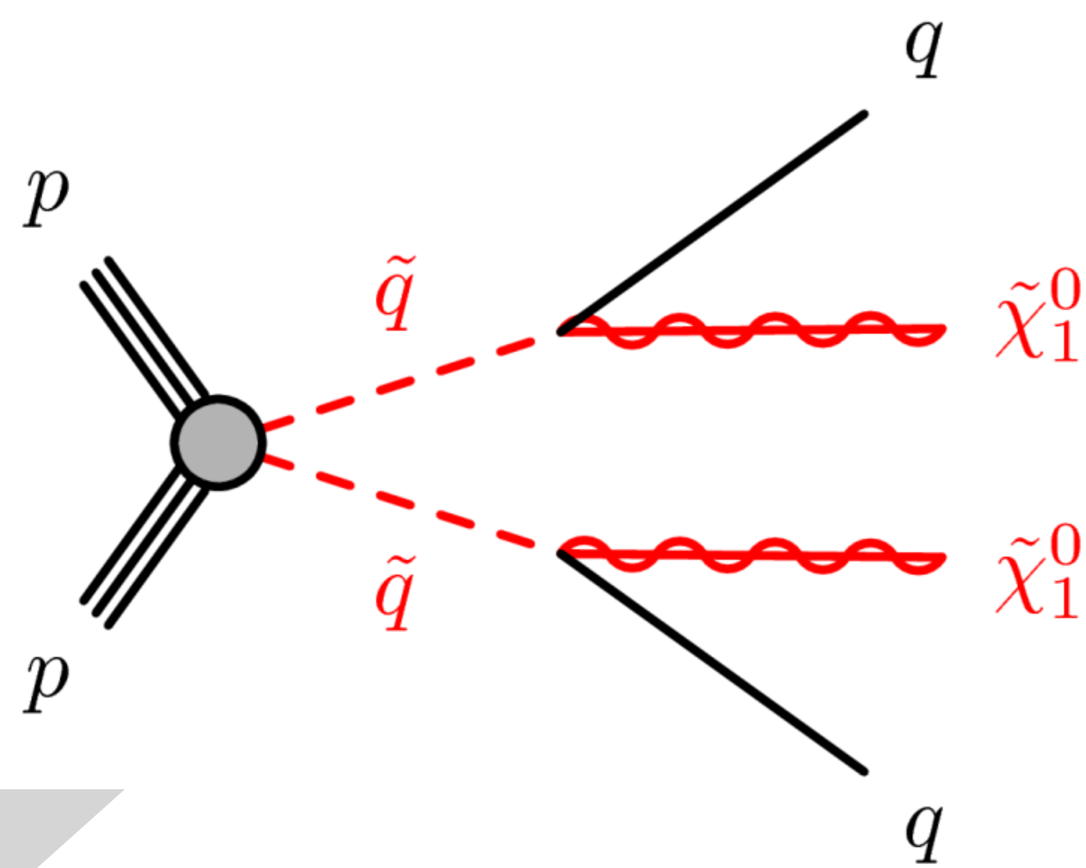
- What are the ***free parameters*** of our model?
  - We have to make the thing: there's a production cross section.
  - Two new particles mean two new masses.

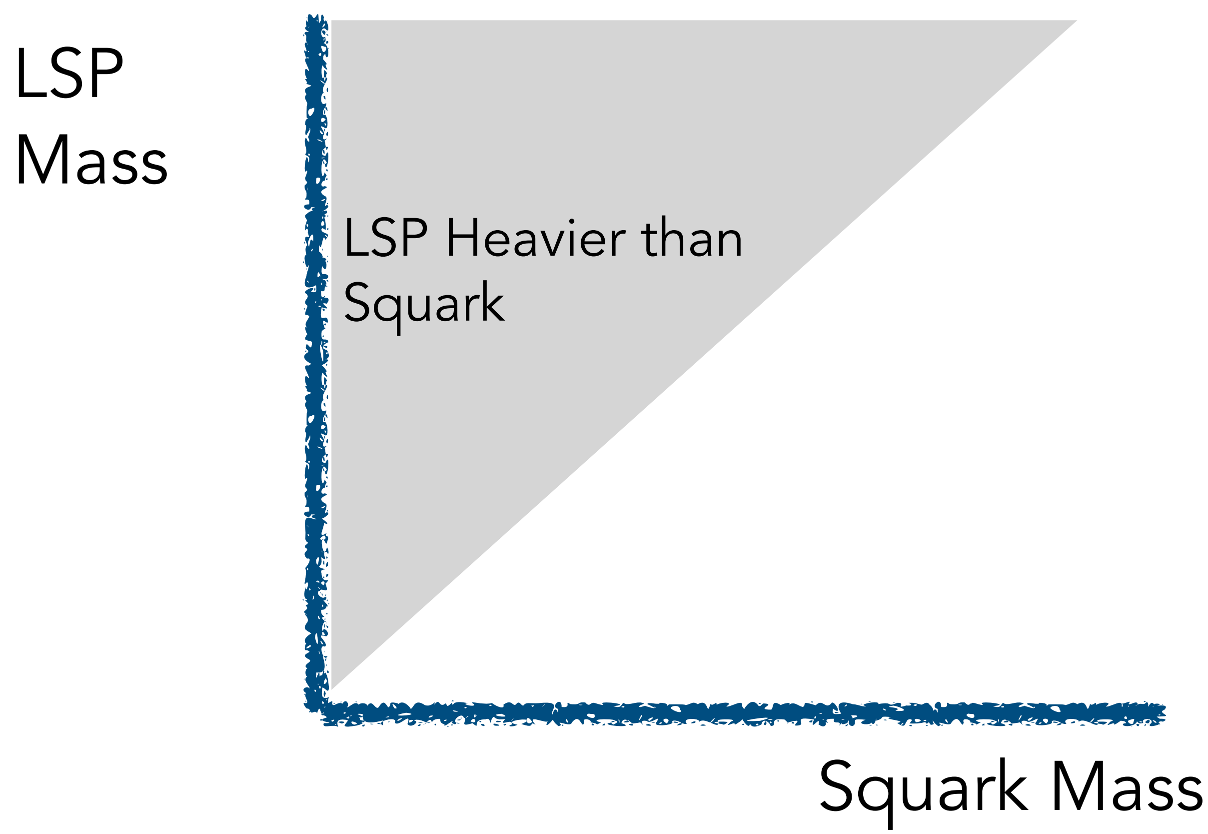




Back to our model…

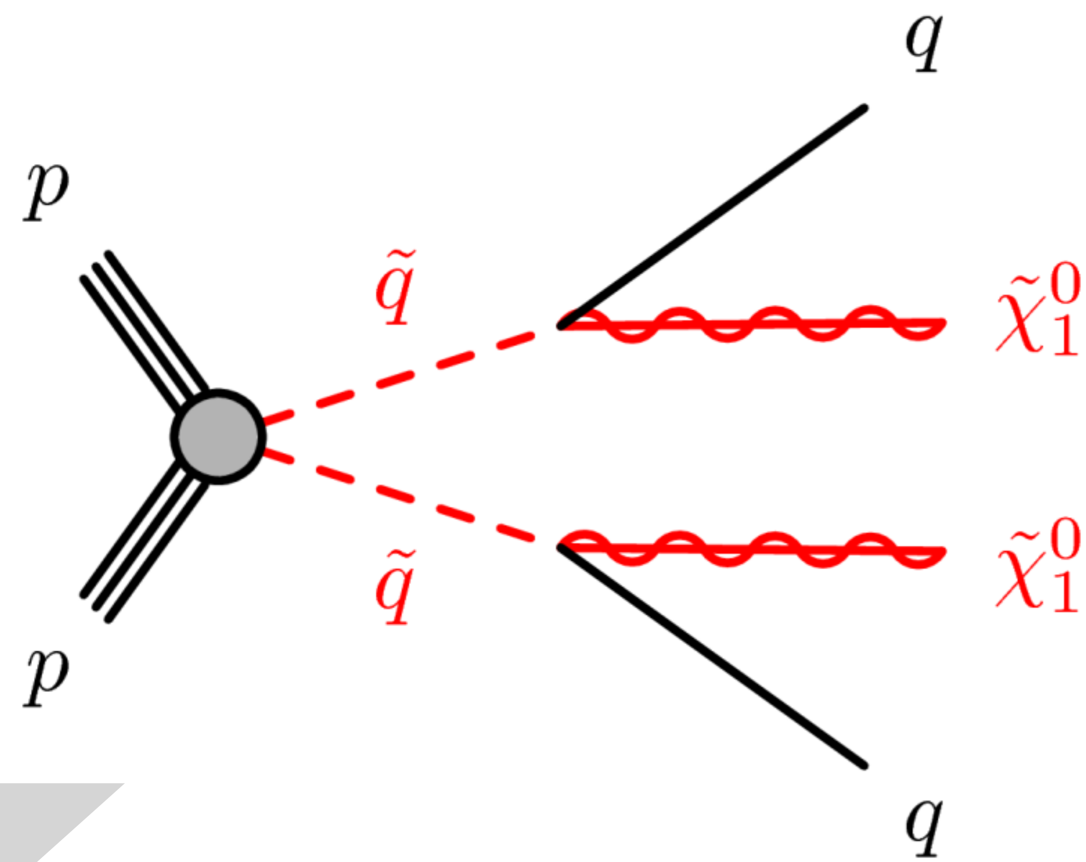
- What are the ***free parameters*** of our model?
  - We have to make the thing: there's a production cross section.
  - Two new particles mean two new masses.

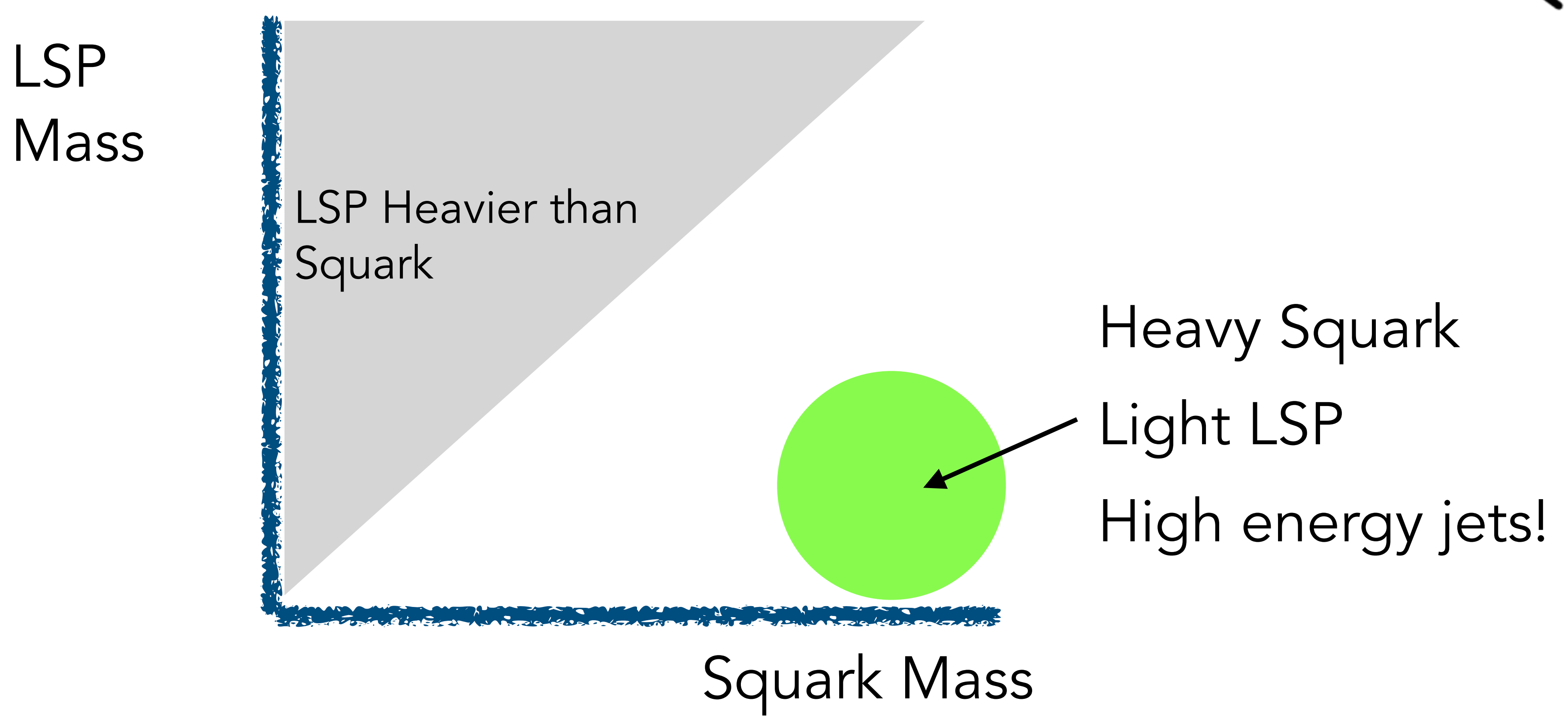




Back to our model…

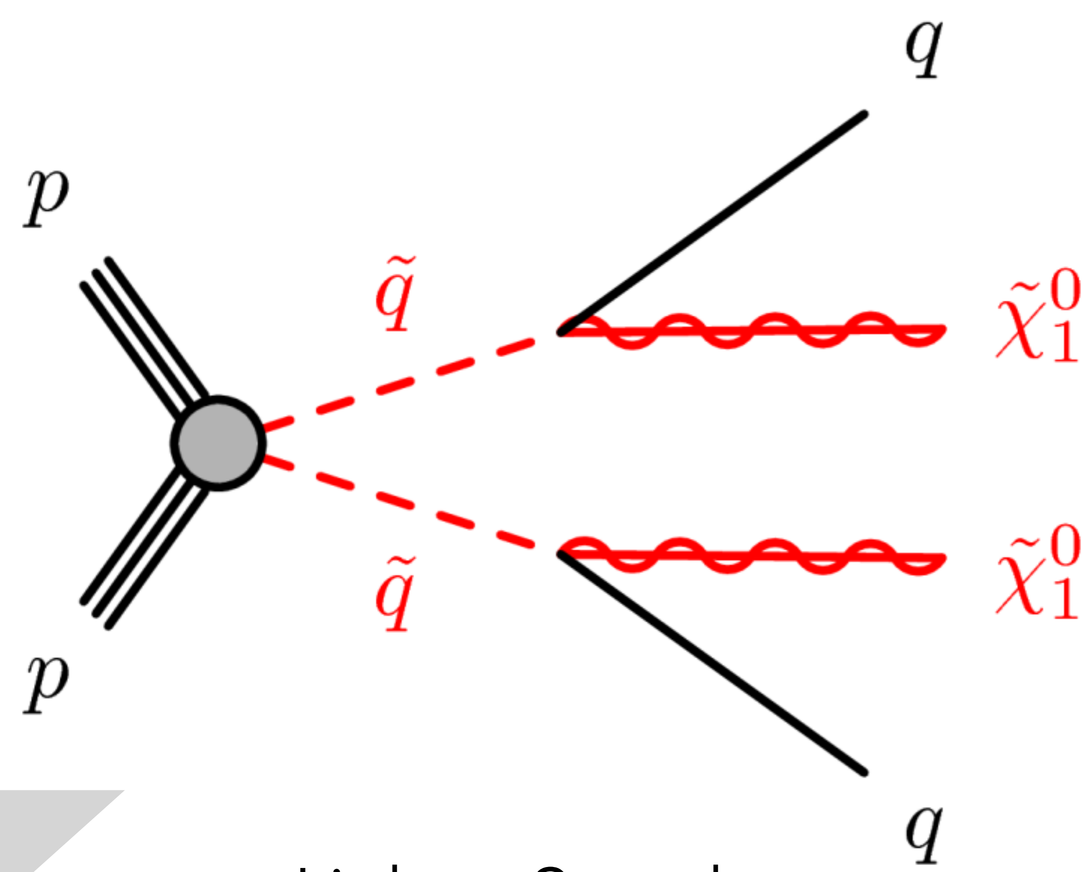
- What are the ***free parameters*** of our model?
  - We have to make the thing: there's a production cross section.
  - Two new particles mean two new masses.

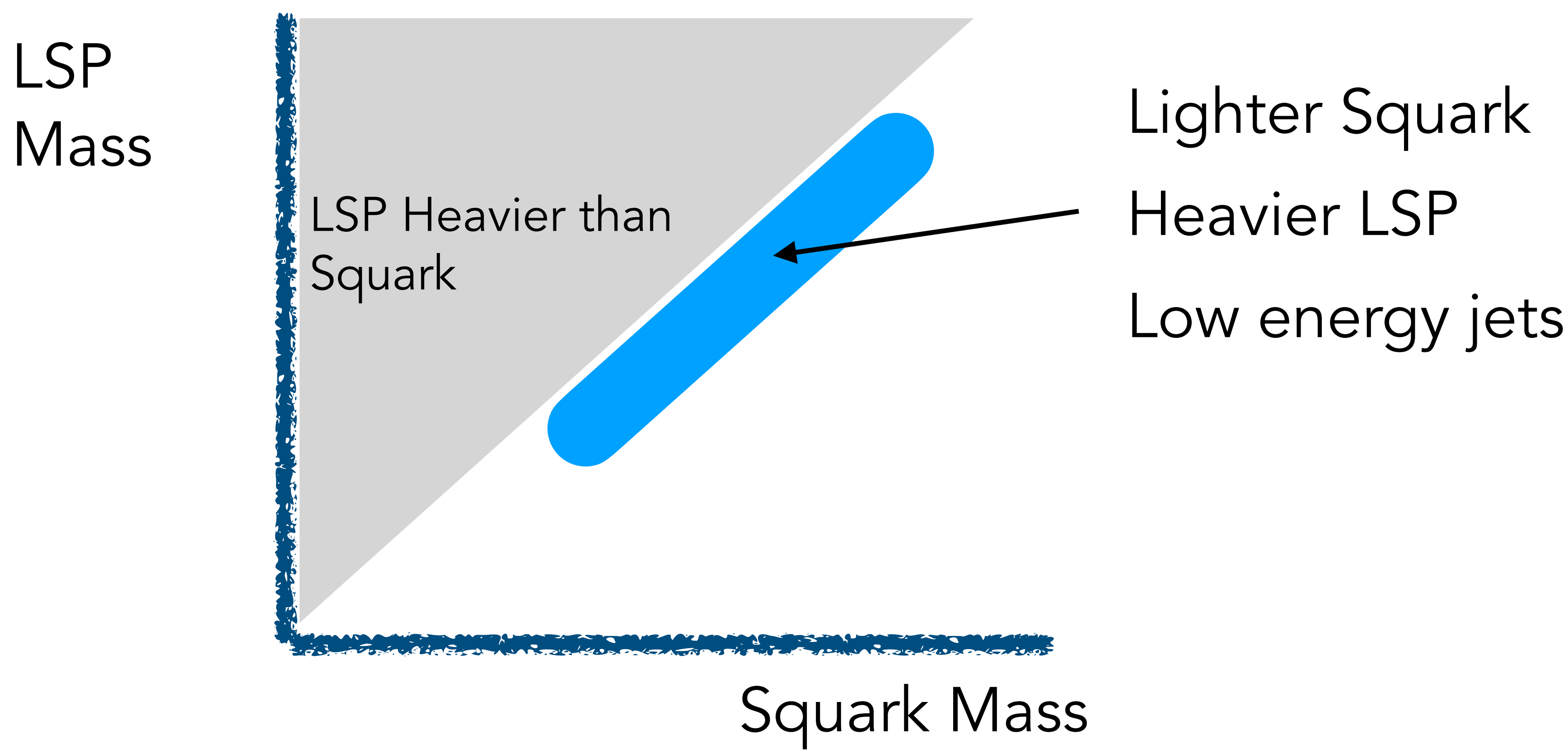




Back to our model…

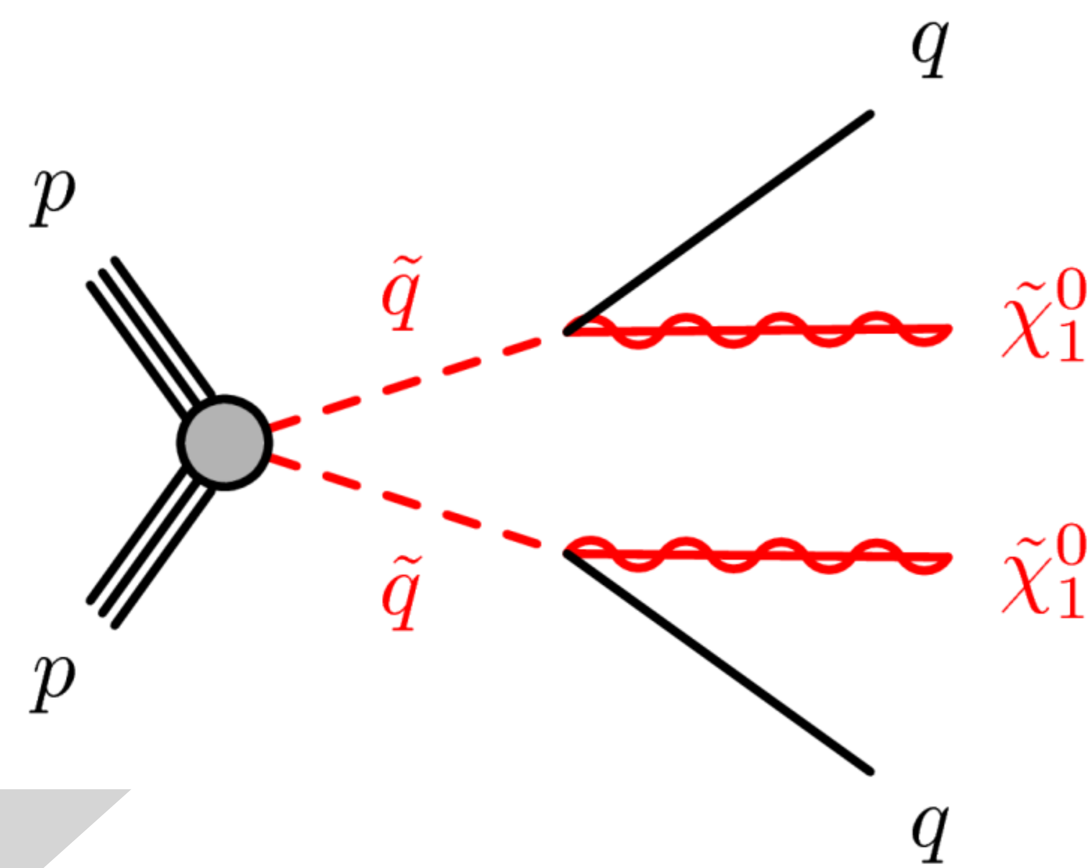
- What are the ***free parameters*** of our model?
  - We have to make the thing: there’s a production cross section.
  - Two new particles mean two new masses.

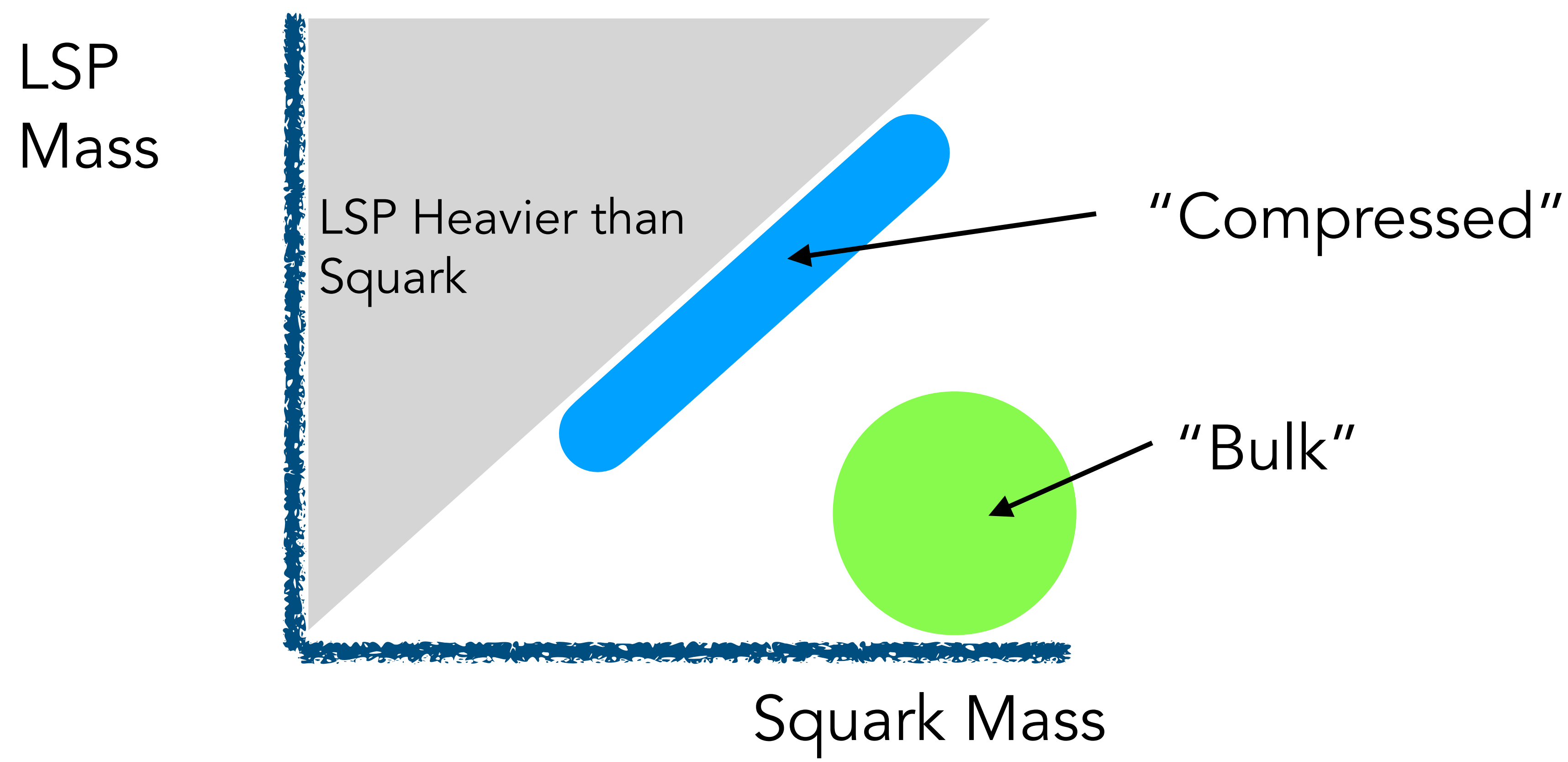




Back to our model…

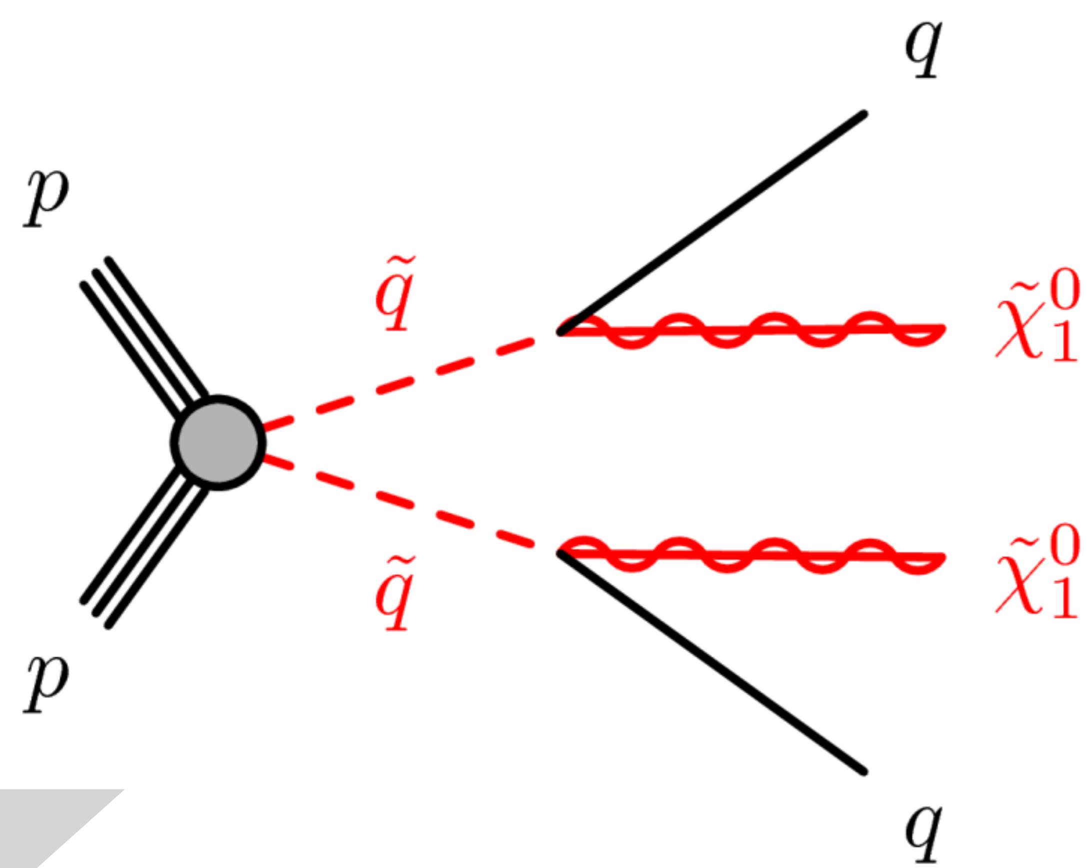
- What are the ***free parameters*** of our model?
  - We have to make the thing: there's a production cross section.
  - Two new particles mean two new masses.

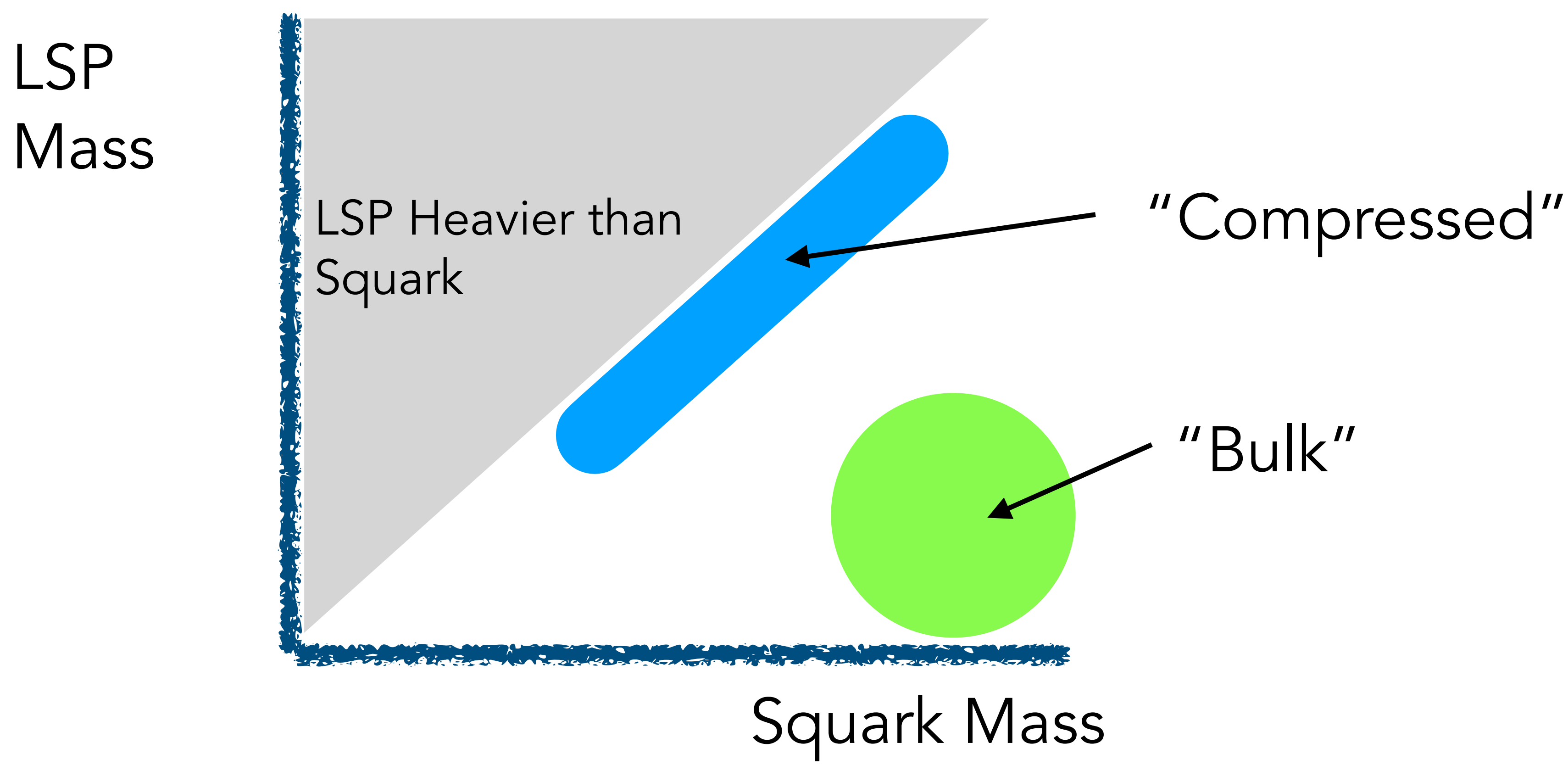




Back to our model…

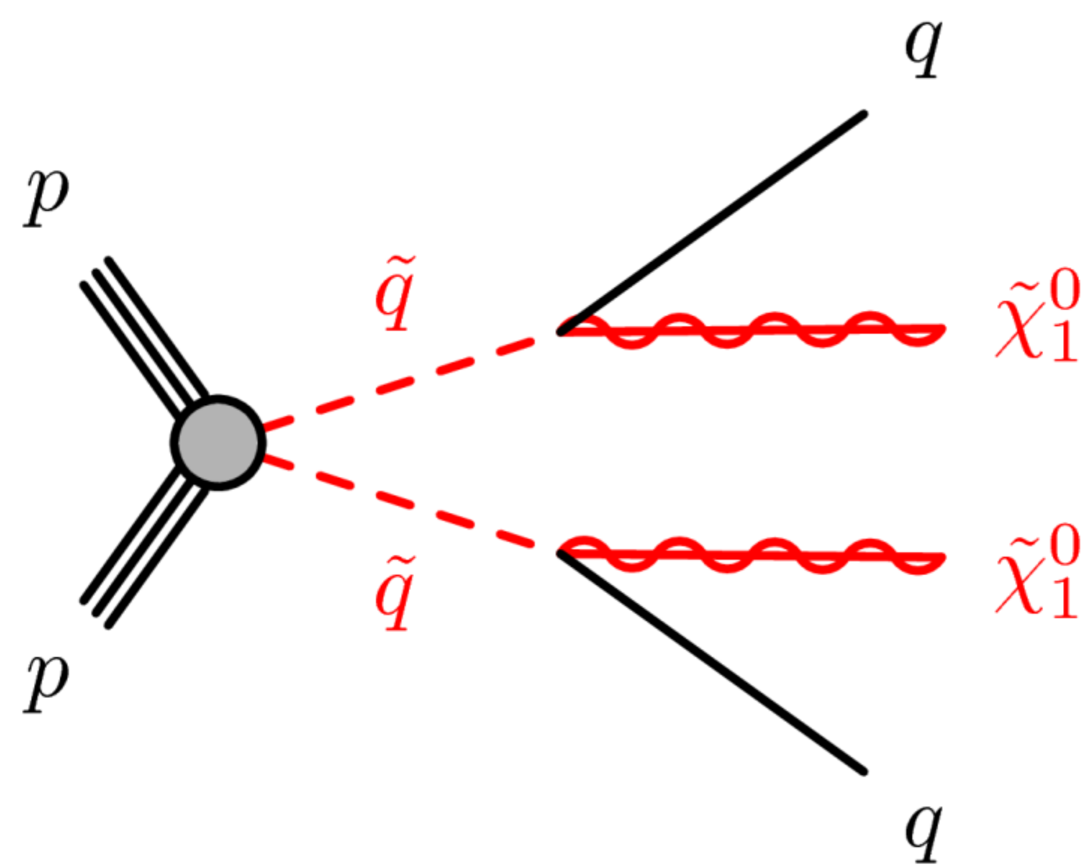
- What is our ***signature?***
  - Jets with MET, but how much of each depends on where we are in the **parameter space**





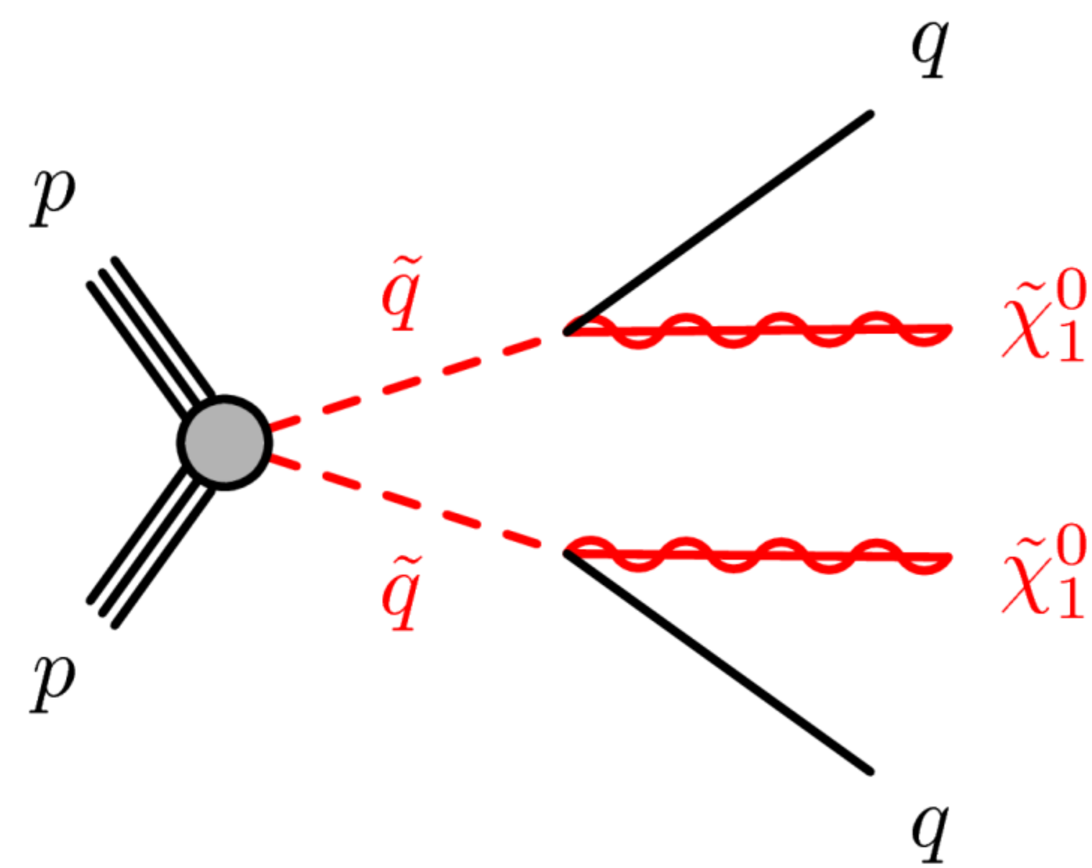
Back to our model…

- What are our ***assumptions?***
  - Is this SUSY, so that we know the production cross section?
  - What about the other particles?
    - Do we *really* know the cross section?
    - Could there be other decays?
    - Would they help us or hurt us?
  - Do the squarks have a lifetime?



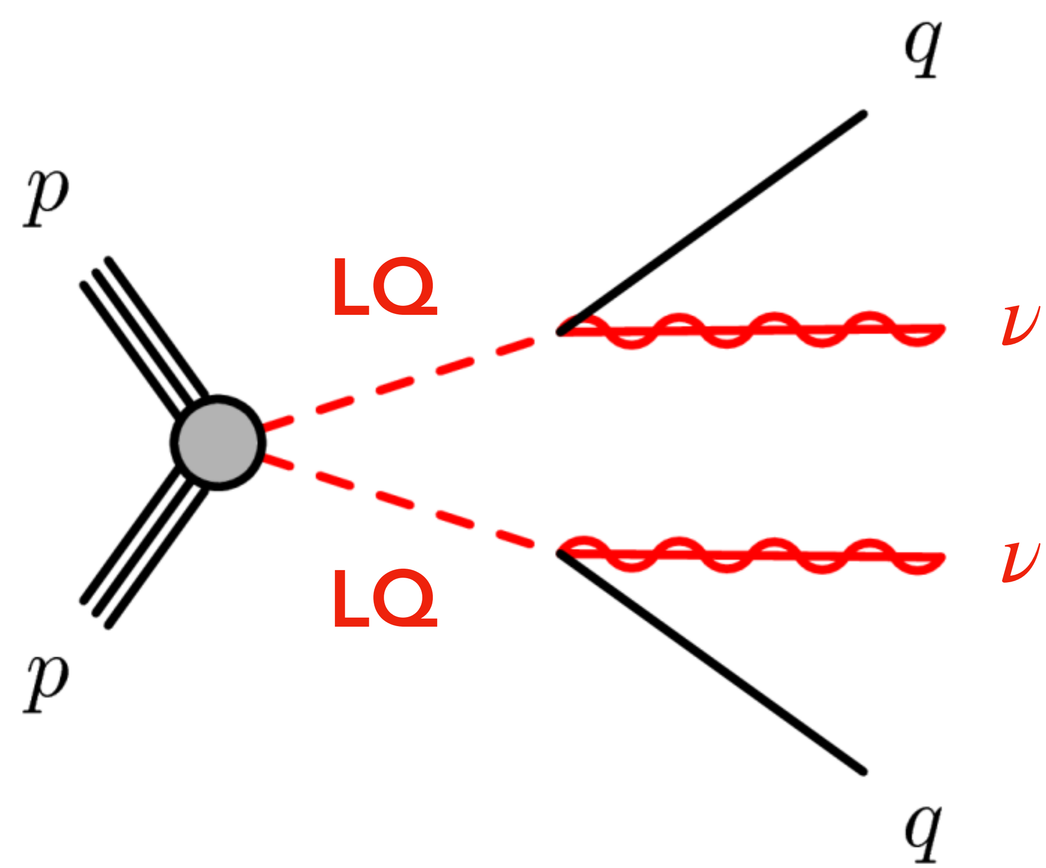
Those Assumptions

- Always keep an eye on those assumptions you're making!
- Remember, the goal is to ***find new physics***, not to search for a diagram.
- A change to your search might make you a bit more sensitive to your particular model, but ***at what cost***?
- When reading papers, be very careful with assuming that they *have* or *do not have* sensitivity to a slightly different model
  - Especially when the slight difference is something like a lifetime



Those Assumptions

- Always keep an eye on those assumptions you're making!
- Remember, the goal is to ***find new physics***, not to search for a diagram.
- A change to your search might make you a bit more sensitive to your particular model, but ***at what cost***?
- When reading papers, be very careful with assuming that they *have* or *do not have* sensitivity to a slightly different model
  - Especially when the slight difference is something like a lifetime

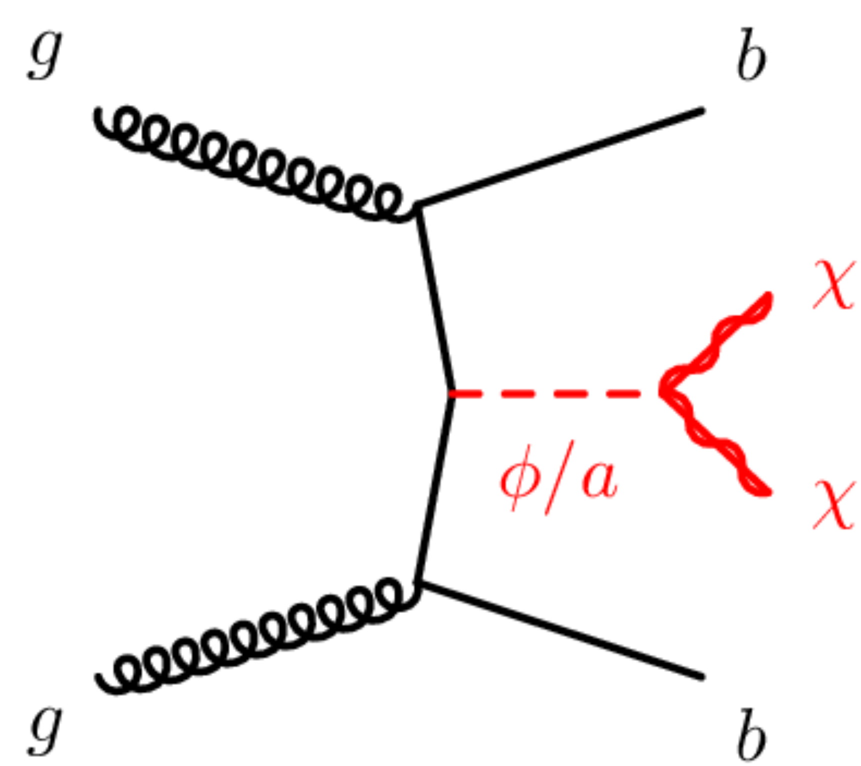


SURPRISE!

It was a leptoquark search the whole time!

Those Assumptions

- Always keep an eye on those assumptions you're making!
- Remember, the goal is to ***find new physics***, not to search for a diagram.
- A change to your search might make you a bit more sensitive to your particular model, but ***at what cost***?
- When reading papers, be very careful with assuming that they *have* or *do not have* sensitivity to a slightly different model
  - Especially when the slight difference is something like a lifetime

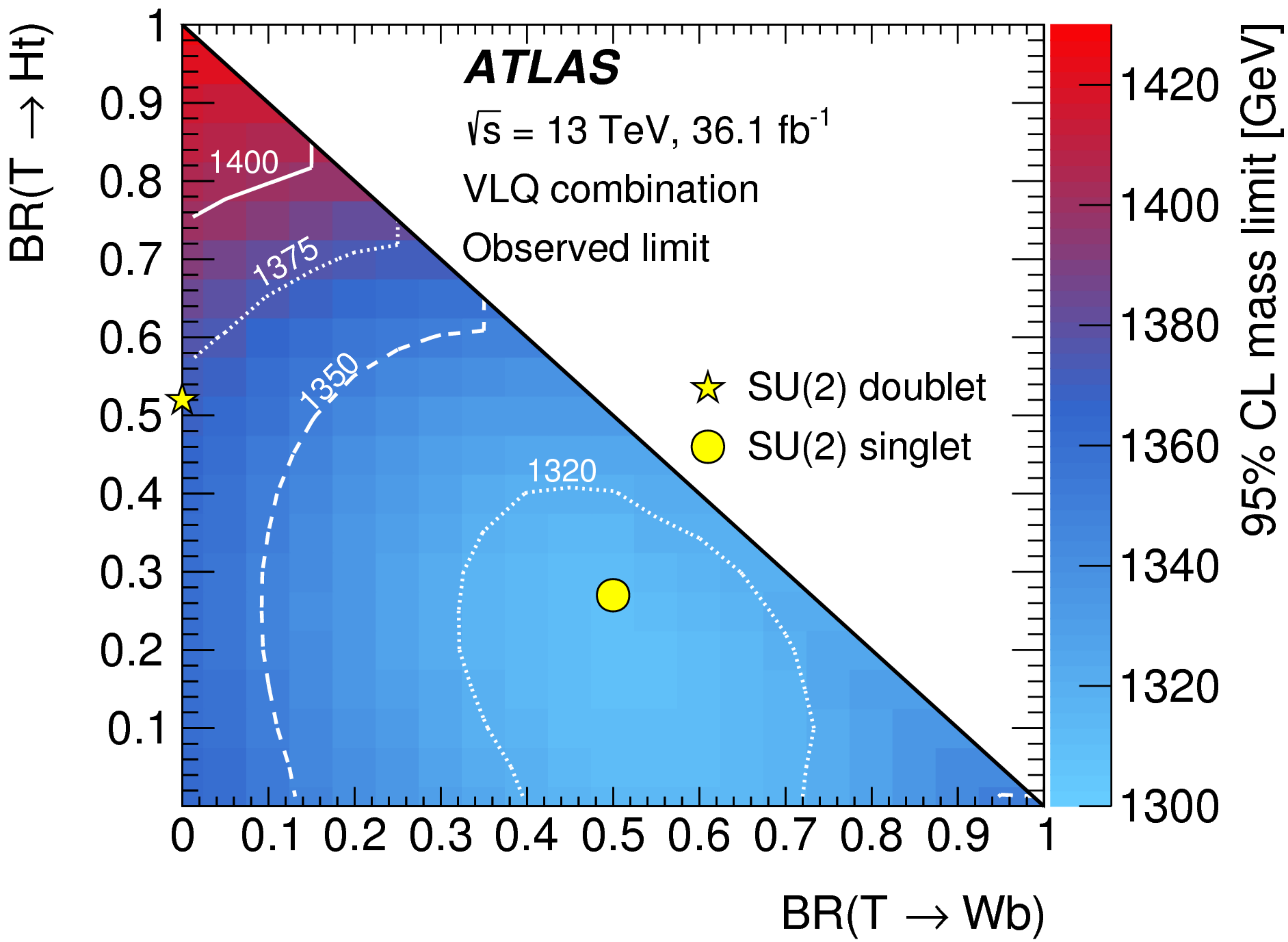


SURPRISE!

It was a dark matter search the whole time!

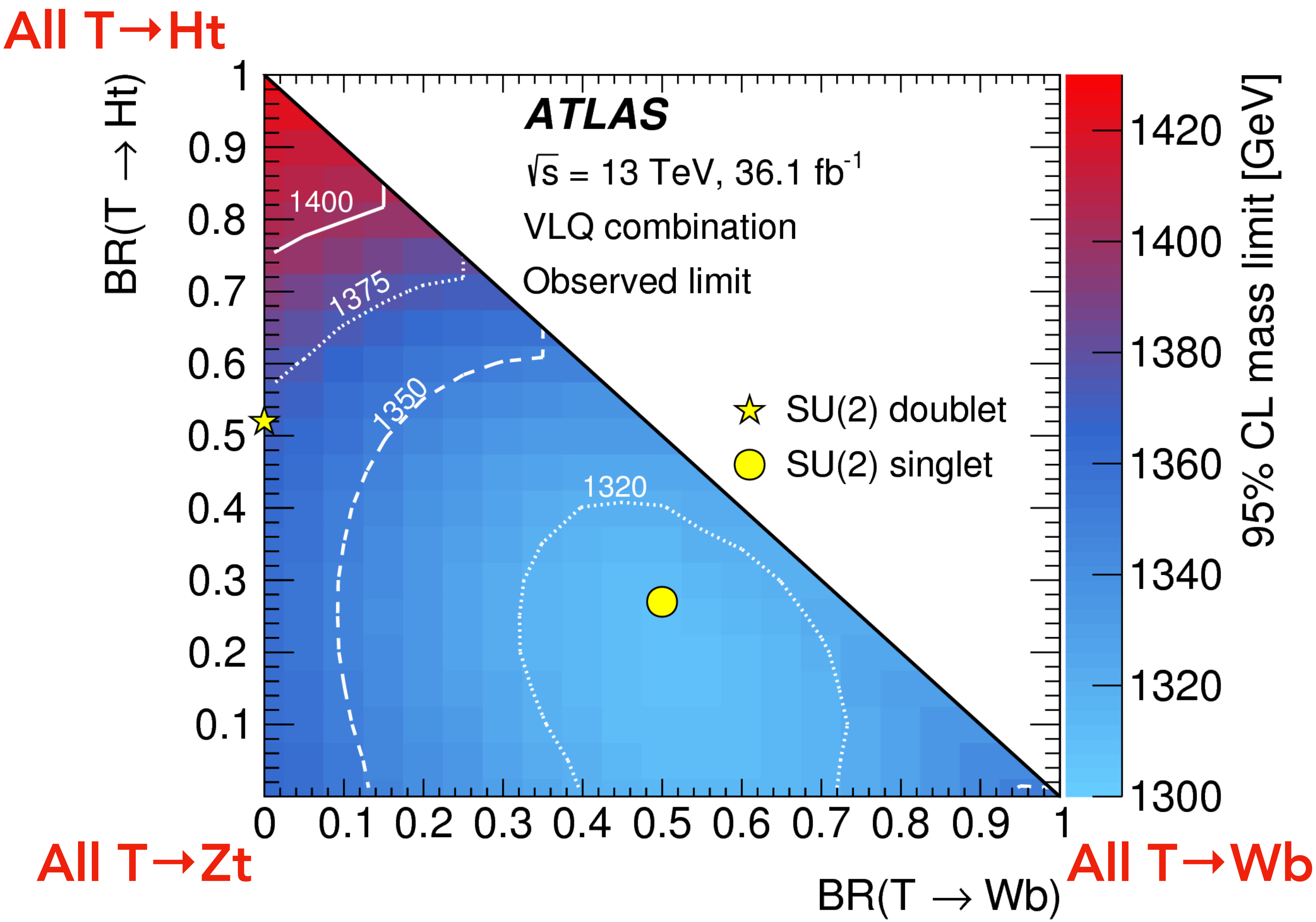
Those Assumptions

- This becomes a big issue when thinking about **backgrounds**



Those Assumptions

- This becomes a big issue when thinking about **backgrounds**



Those Assumptions

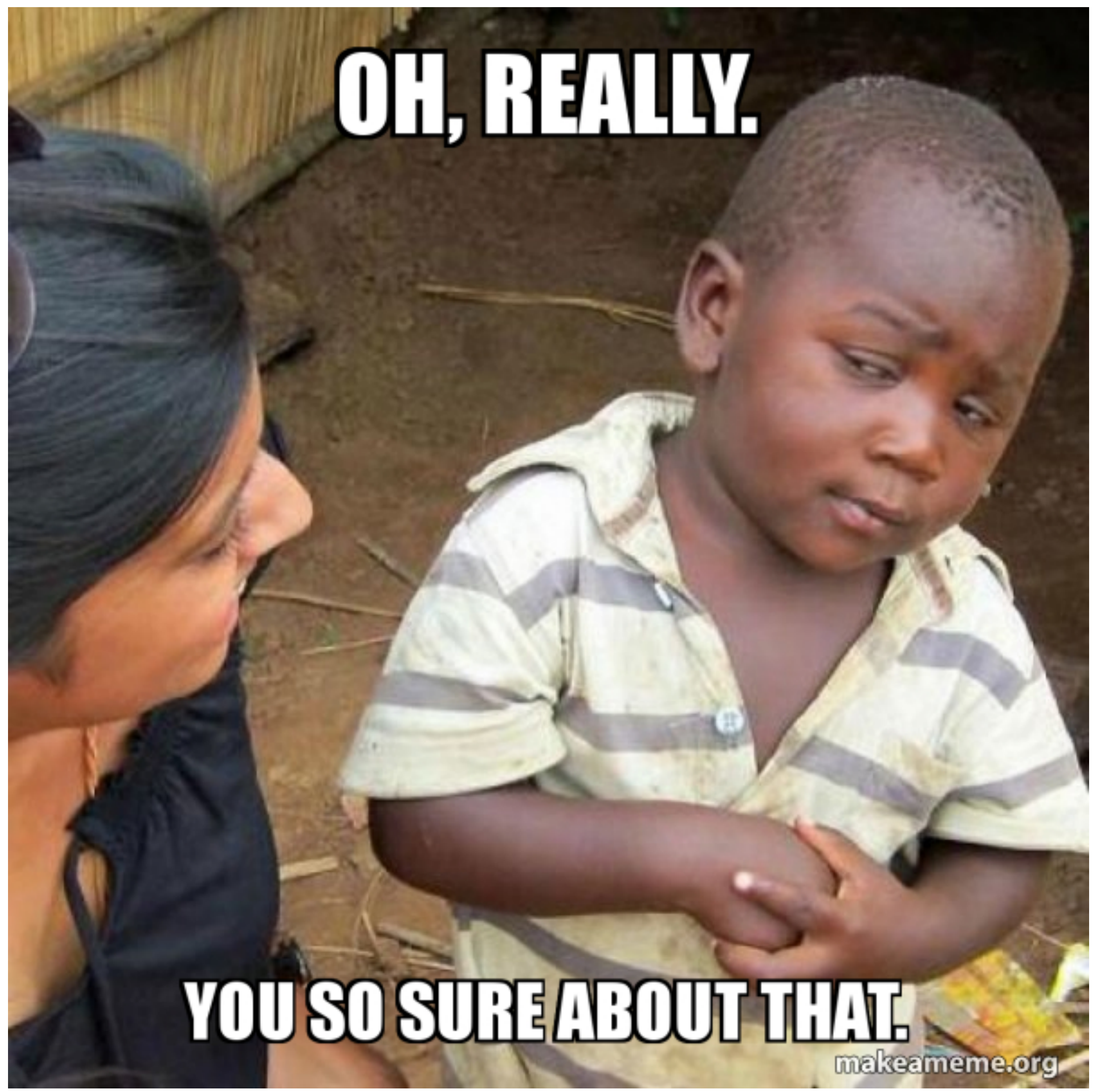
- This becomes a big issue when thinking about **backgrounds**

- **Be extremely careful!**
  - Can you use photon+jets to estimate Z+jets? W+jets?
  - Can you use different flavor leptons to estimate same-flavor leptons?

- Very clever data-driven estimates often suffer from model-dependent signal contamination

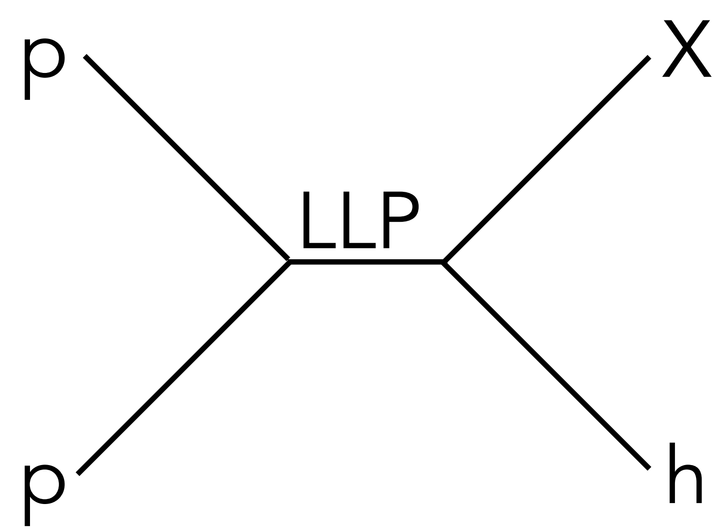
But what about a signature?

- Commonly overheard: "But I'm searching for a signature, so this is fully general! I have no assumptions!"



But what about a signature?

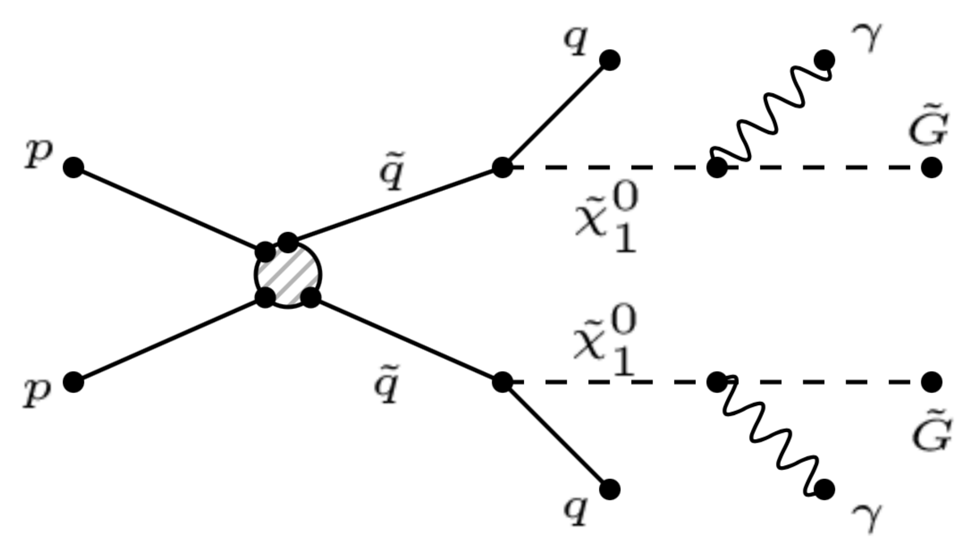
- If your signal is far easier to find in other ways, your search probably isn't the right one
- If I want **displaced photons**, this model works:



- But Higgs bosons *don't like to decay to photons*. Gonna be way easier to find other ways.
- This *doesn't mean* you shouldn't look for displaced photons!
- It just means you should optimize with a different signal.

But what about a signature?

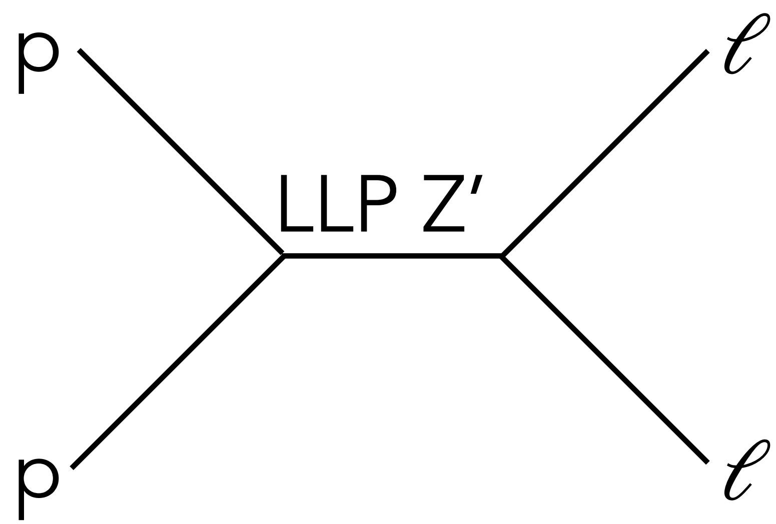
- If your signal is far easier to find in other ways, your search probably isn't the right one
- If I want **displaced photons**, this model ***actually*** works:



- But Higgs bosons *don't like to decay to photons*. Gonna be way easier to find other ways.
- This *doesn't mean* you shouldn't look for displaced photons!
- It just means you should optimize with a different signal.

But what about a signature?

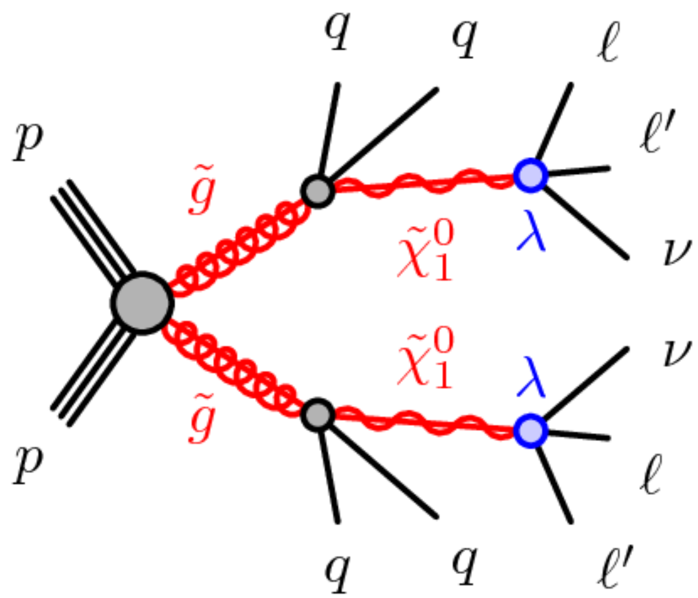
- If your signal is far easier to find in other ways, your search probably isn't the right one
- If I want **displaced leptons**, this model works:



- But to avoid the Z' decay to quarks (and a dijet search), I have to reduce the coupling to quarks, *which changes the production cross section for the model*
- Doesn't mean this isn't worth searching for! Just have to be careful that the model makes sense.

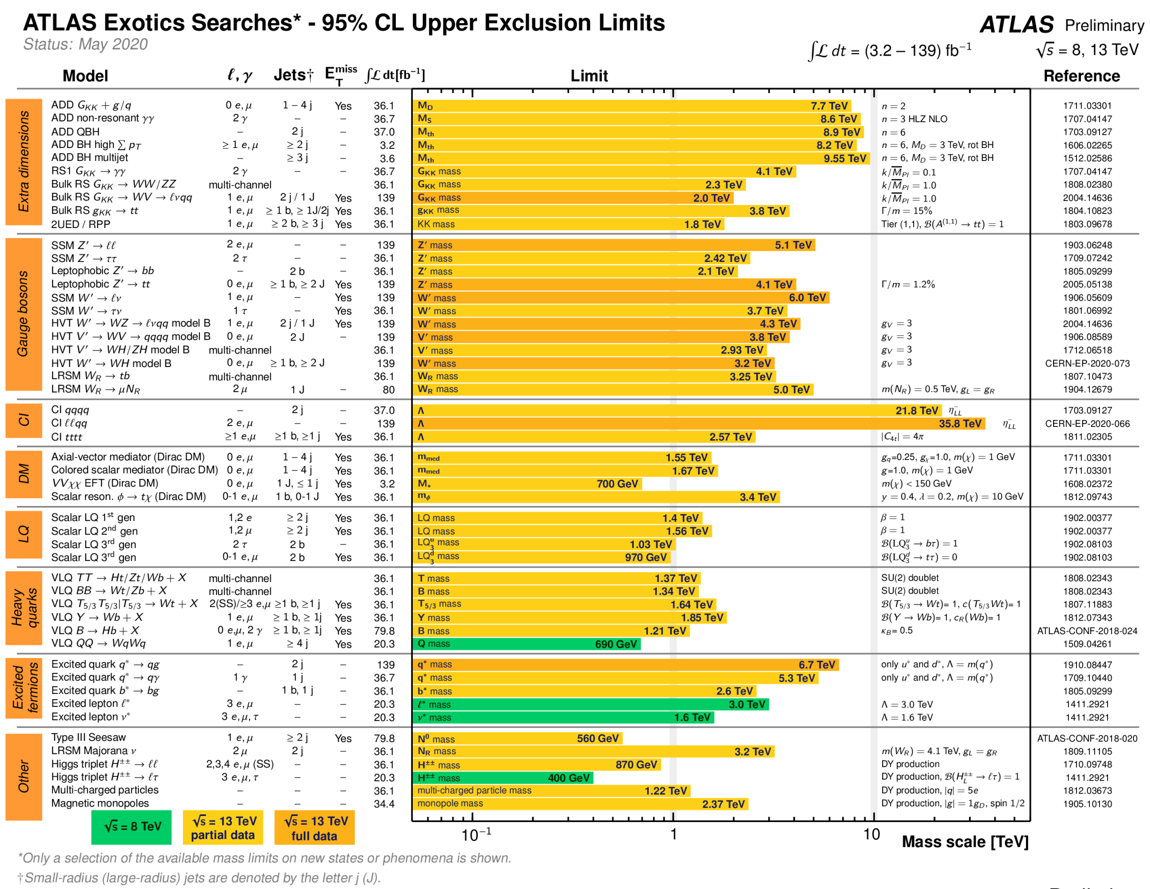
But what about a signature?

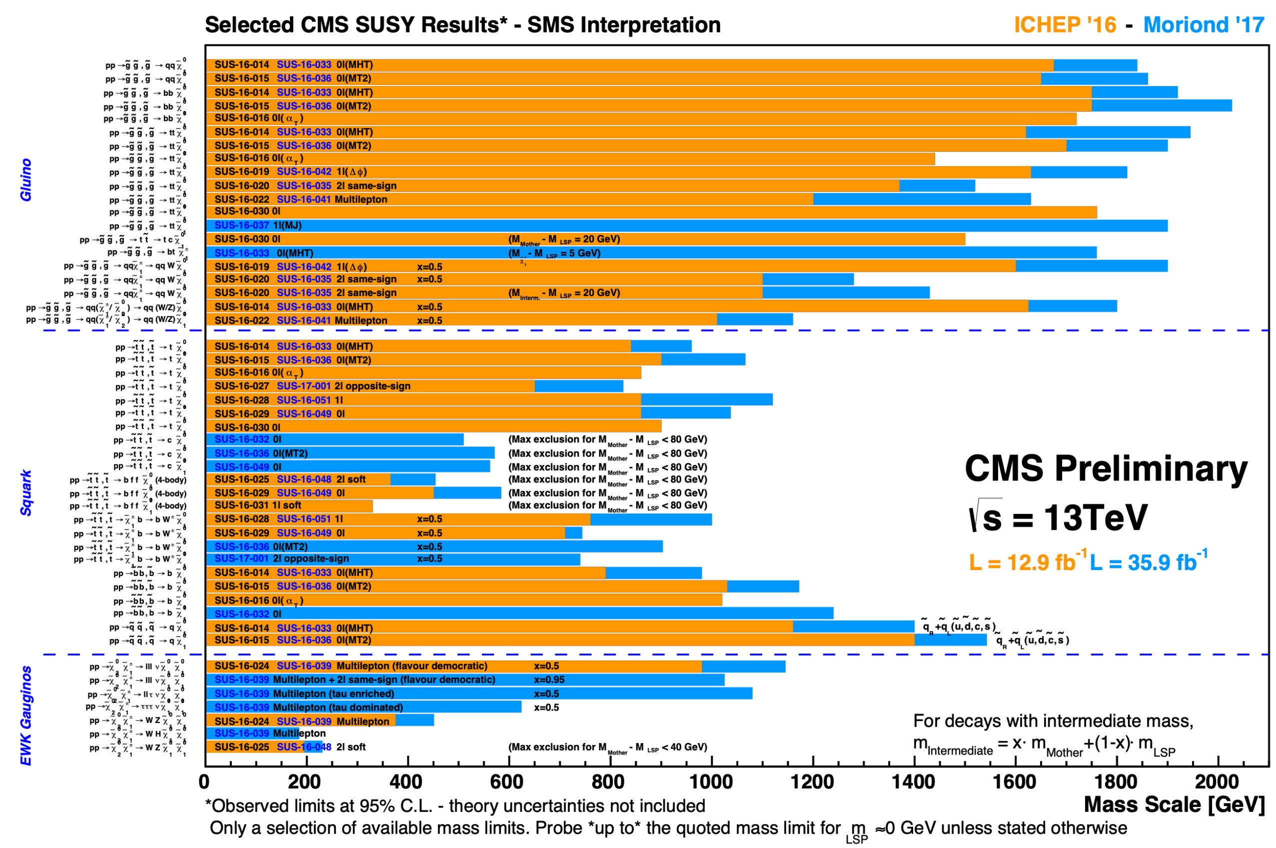
- If your signal is far easier to find in other ways, your search probably isn't the right one
- If I want **displaced leptons**, this model ***actually*** works:

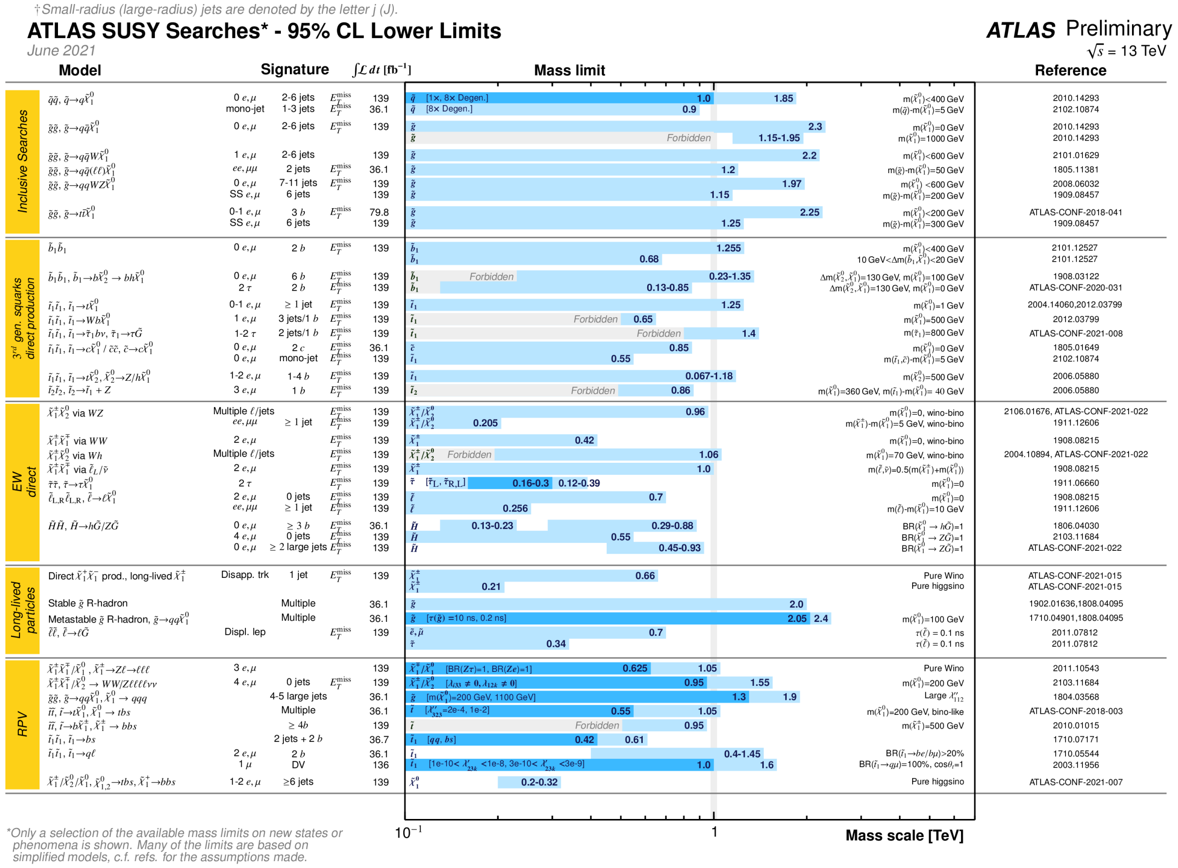


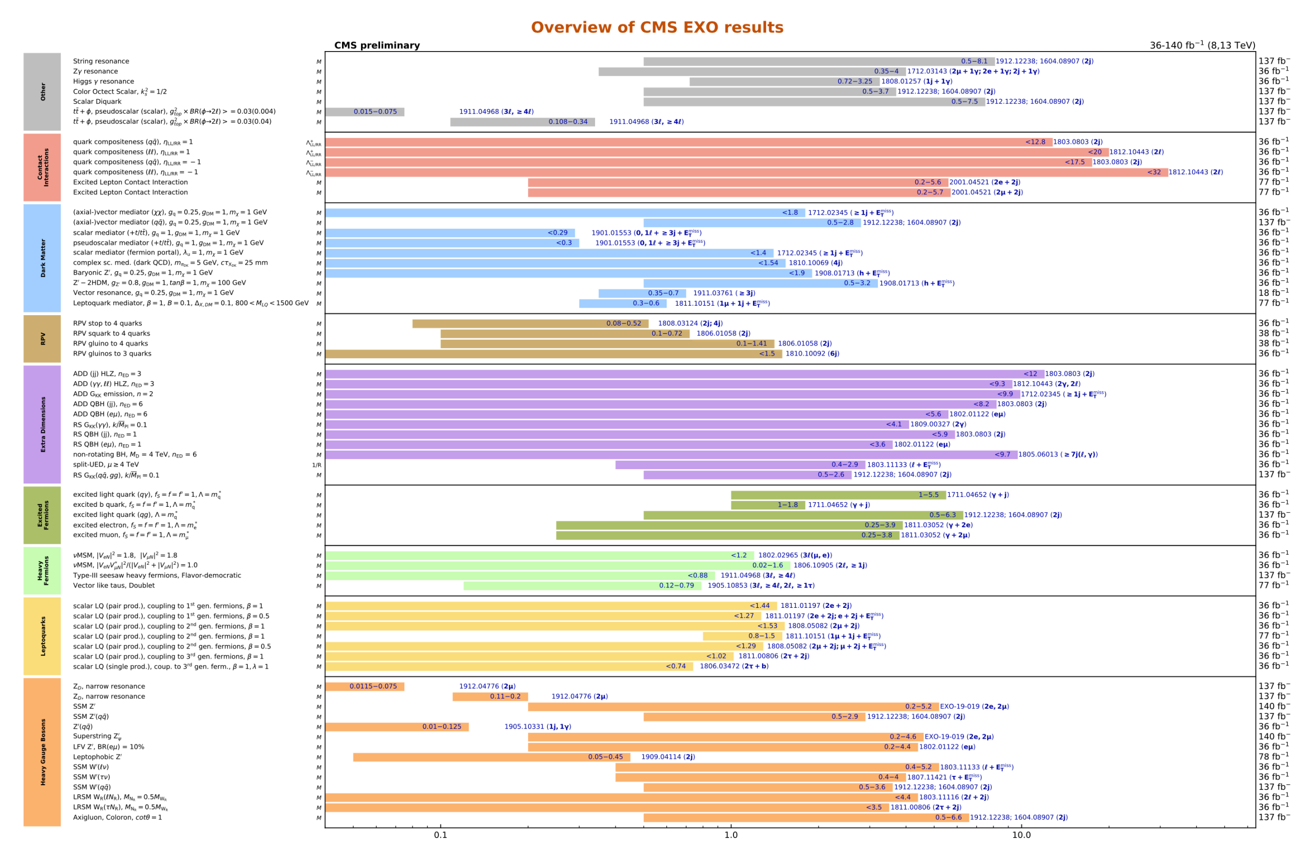
- But to avoid the Z' decay to quarks (and a dijet search), I have to reduce the coupling to quarks, *which changes the production cross section for the model*
- Doesn't mean this isn't worth searching for! Just have to be careful that the model makes sense.

We’ve done a few searches







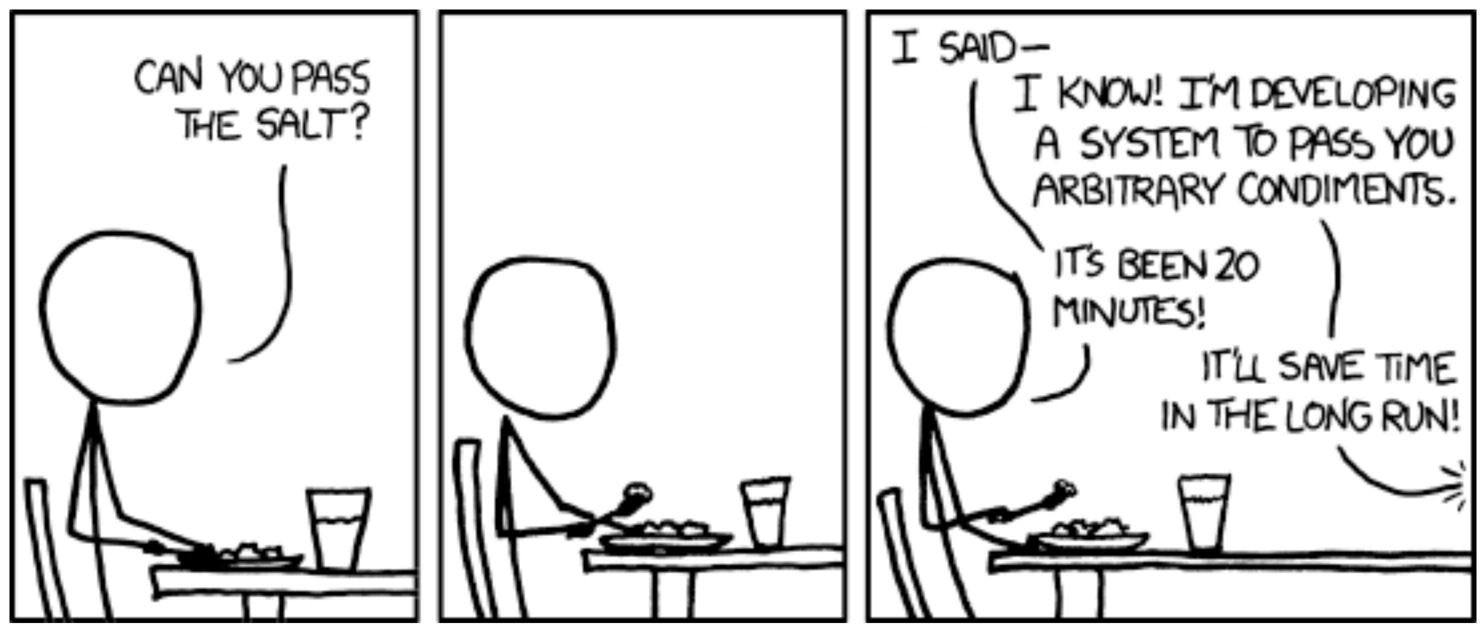


Splitting Things Up

- A search can be sensitive to **many** signals
- ATLAS divides searches into
  - SUSY: *primarily* SUSY-motivated models
  - HDBS: *primarily* Higgs BSM models
  - Exotics: everything else
- CMS divides searches into
  - SUSY: *primarily* light-flavor SUSY
  - B2G: *primarily* models with heavy flavor
  - Exotica: everything else, including ~*all* LLPs
- LHCb has one group with most searches
- ALICE has no search group that I know of

Searching Step 1: Designing a Search

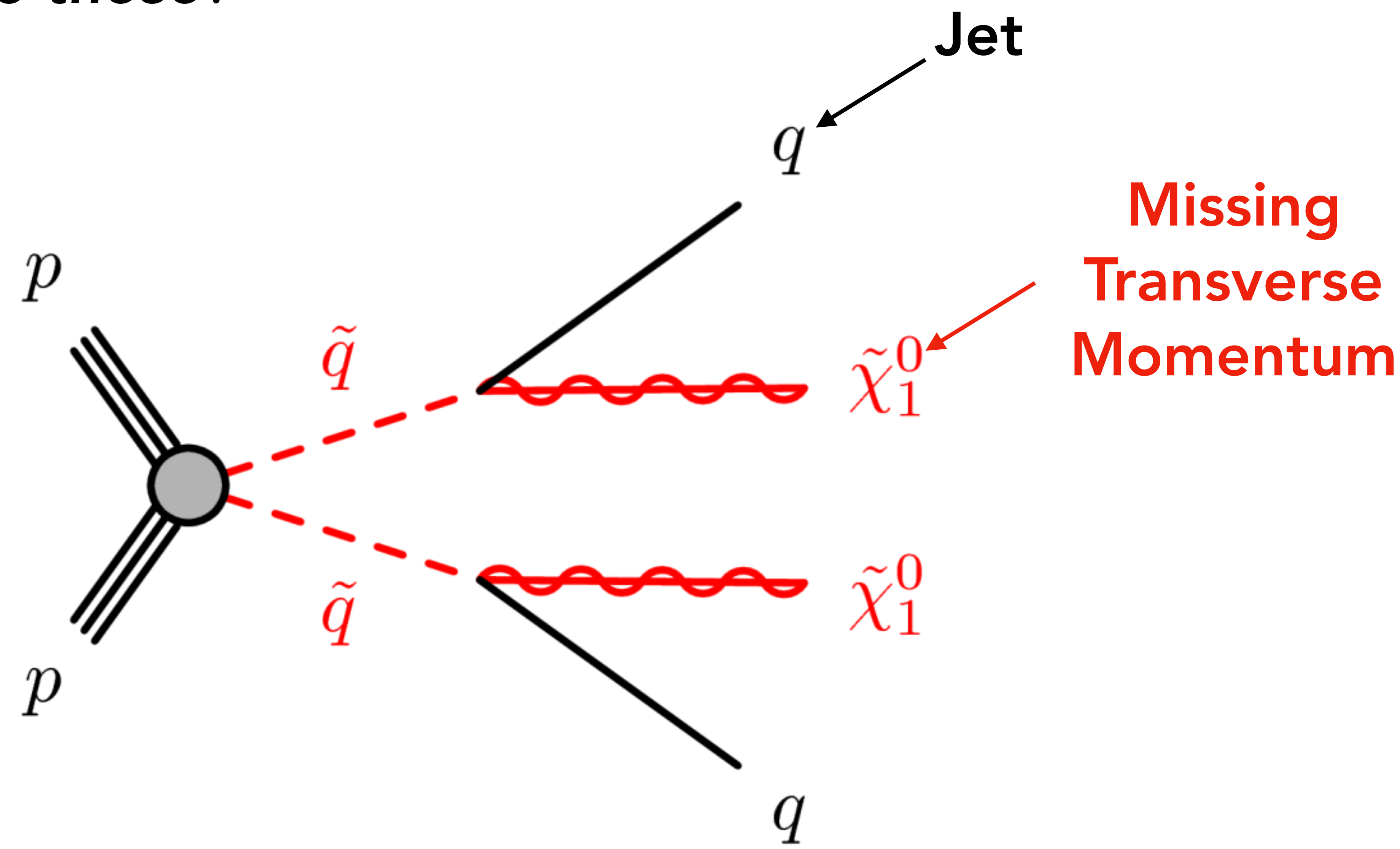
- Now that we have a model, we have to go look for it!



- Pro Tip: For most searches, aim to do *one or two difficult things*.
  - If you're a phenomenologist: find that difficult thing they did.
  - If you're watching a talk: ask about that difficult thing they did.

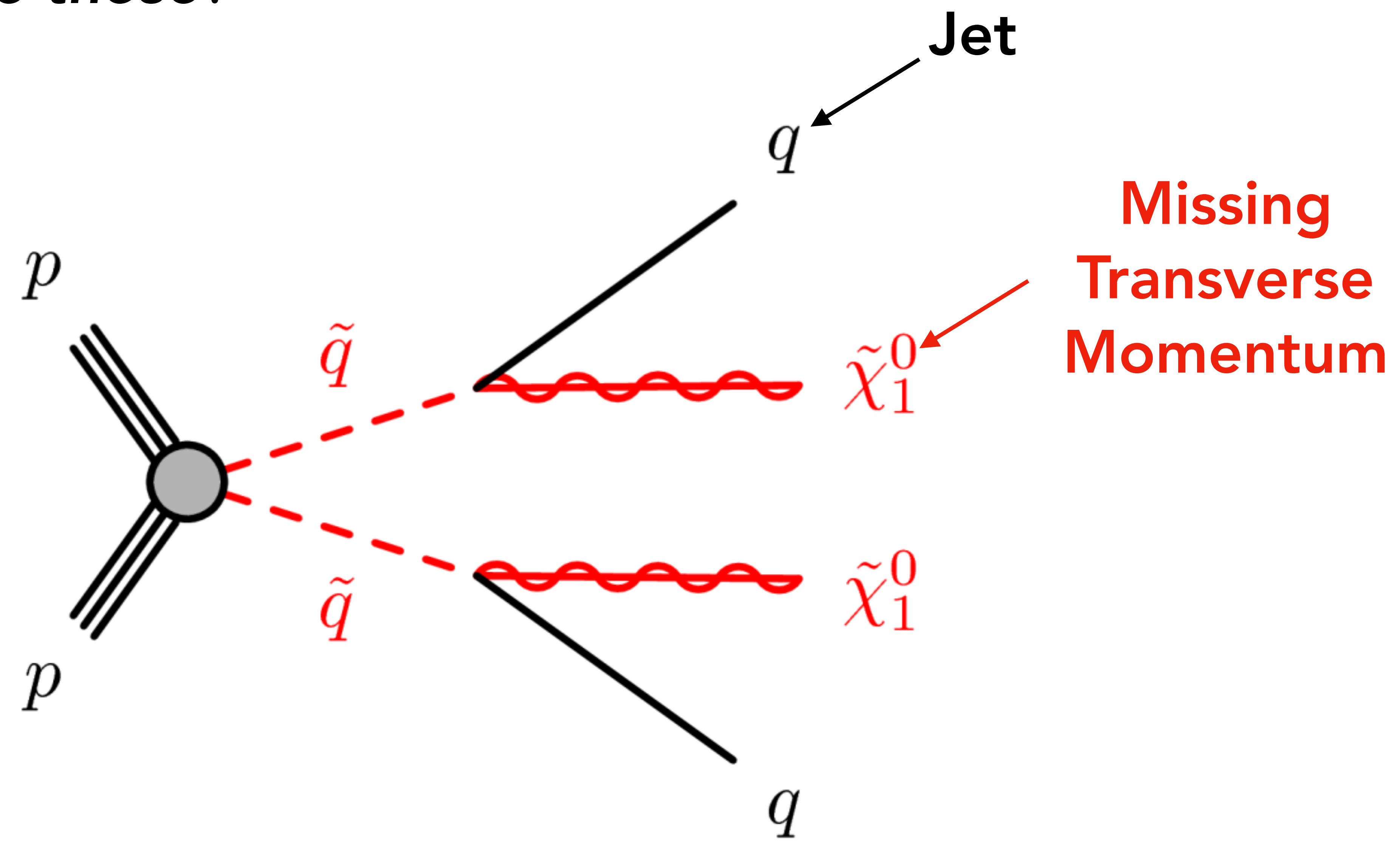
Back to our model

- What are the ***characteristics of your signature***?
- What makes this ***different from the Standard Model*** and how can you ***isolate those***?



Back to our model

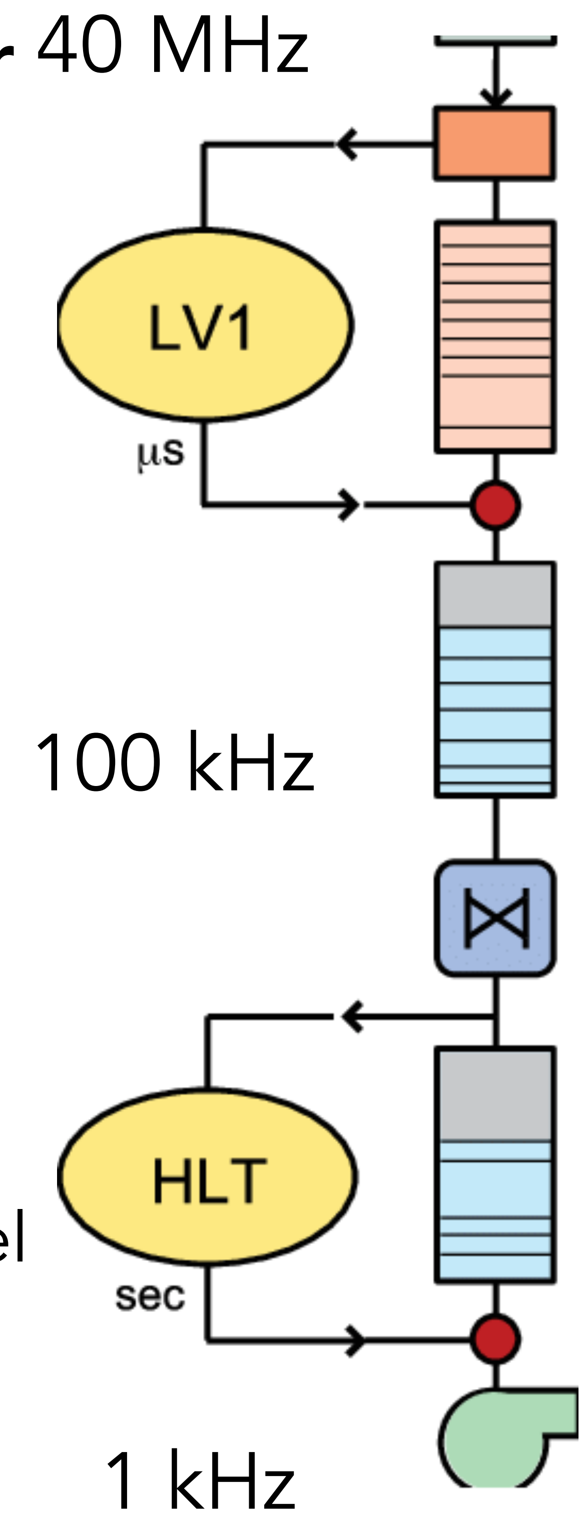
- What are the ***characteristics of your signature***?
- What makes this ***different from the Standard Model*** and how can you ***isolate those***?



(Now would be a good time to run off and generate some events to play with)

First and Foremost: The Trigger

- All experiments have a complex, multi-level **trigger system** to identify events to read out
- If it doesn't pass the trigger, it's gone forever
- Two stages:
    - Coarse, fast (μs), hardware-based (Level 1)
    - Detailed, slow (s), software-based (HLT)
    - For most searches, the Level 1 trigger is the hard part
- In a nutshell: there had better be something interesting / different about your signal!
    - There is a cottage industry devoted to pointing out novel signatures that could be missed, and then finding other cool ways to pick out the events



Trigger: Keep it Simple

Trigger	Typical offline selection	Trigger Selection		L1 Peak Rate [kHz]	HLT Peak Rate [Hz]
		L1 [GeV]	HLT [GeV]	L=2.0×10^{34} $cm^{-2}s^{-1}$	
Single leptons	Single isolated μ, $p_T > 27$ GeV	20	26 (i)	16	218
	Single isolated tight e, $p_T > 27$ GeV	22 (i)	26 (i)	31	195
	Single μ, $p_T > 52$ GeV	20	50	16	70
	Single e, $p_T > 61$ GeV	22 (i)	60	28	20
	Single τ, $p_T > 170$ GeV	100	160	1.4	42
Two leptons	Two μ, each $p_T > 15$ GeV	2×10	2×14	2.2	30
	Two μ, $p_T > 23, 9$ GeV	20	22, 8	16	47
	Two very loose e, each $p_T > 18$ GeV	2×15 (i)	2×17	2.0	13
	One e & one μ, $p_T > 8, 25$ GeV	20 (μ)	7, 24	16	6
	One loose e & one μ, $p_T > 18, 15$ GeV	15, 10	17, 14	2.6	5
	One e & one μ, $p_T > 27, 9$ GeV	22 (e, i)	26, 8	21	4
	Two τ, $p_T > 40, 30$ GeV	20 (i), 12 (i) (+jets, topo)	35, 25	5.7	93
	One τ & one isolated μ, $p_T > 30, 15$ GeV	12 (i), 10 (+jets)	25, 14 (i)	2.4	17
	One τ & one isolated e, $p_T > 30, 18$ GeV	12 (i), 15 (i) (+jets)	25, 17 (i)	4.6	19
Three leptons	Three very loose e, $p_T > 25, 13, 13$ GeV	20, 2×10	24, 2×12	1.6	0.1
	Three μ, each $p_T > 7$ GeV	3×6	3×6	0.2	7
	Three μ, $p_T > 21, 2 \times 5$ GeV	20	20, 2×4	16	9
	Two μ & one loose e, $p_T > 2 \times 11, 13$ GeV	2×10 (μ)	2×10, 12	2.2	0.5
	Two loose e & one μ, $p_T > 2 \times 13, 11$ GeV	2×8, 10	2×12, 10	2.3	0.1
Signle photon	One loose γ, $p_T > 145$ GeV	24 (i)	140	24	47
Two photons	Two loose γ, each $p_T > 55$ GeV	2×20	2×50	3.0	7
	Two γ, $p_T > 40, 30$ GeV	2×20	35, 25	3.0	21
	Two isolated tight γ, each $p_T > 25$ GeV	2×15 (i)	2×20 (i)	2.0	15
Single jet	Jet ($R = 0.4$), $p_T > 435$ GeV	100	420	3.7	35
	Jet ($R = 1.0$), $p_T > 480$ GeV	111 (topo: $R = 1.0$)	460	2.6	42
	Jet ($R = 1.0$), $p_T > 450$ GeV, $m_{jet} > 45$ GeV	111 (topo: $R = 1.0$)	420, $m_{jet} > 35$	2.6	36
b−jets	One b ($\epsilon = 60\%$), $p_T > 285$ GeV	100	275	3.6	15
	Two b ($\epsilon = 60\%$), $p_T > 185, 70$ GeV	100	175, 60	3.6	11
	One b ($\epsilon = 40\%$) & three jets, each $p_T > 85$ GeV	4×15	4×75	1.5	14
	Two b ($\epsilon = 70\%$) & one jet, $p_T > 65, 65, 160$ GeV	2×30, 85	2×55, 150	1.3	17
	Two b ($\epsilon = 60\%$) & two jets, each $p_T > 65$ GeV	4×15, $\lvert\eta\rvert < 2.5$	4×55	3.2	15
Multijets	Four jets, each $p_T > 125$ GeV	3×50	4×115	0.5	16
	Five jets, each $p_T > 95$ GeV	4×15	5×85	4.8	10
	Six jets, each $p_T > 80$ GeV	4×15	6×70	4.8	4
	Six jets, each $p_T > 60$ GeV, $\lvert\eta\rvert < 2.0$	4×15	6×55, $\lvert\eta\rvert < 2.4$	4.8	15
E_T^{miss}	$E_T^{miss} > 200$ GeV	50	110	5.1	94
B-physics	Two μ, $p_T > 11, 6$ GeV, $0.1 < m(\mu,\mu) < 14$ GeV	11, 6	11, 6 (di-μ)	2.9	55
	Two μ, $p_T > 6, 6$ GeV, $2.5 < m(\mu,\mu) < 4.0$ GeV	2×6 (J/ψ, topo)	2×6 (J/ψ)	1.4	55
	Two μ, $p_T > 6, 6$ GeV, $4.7 < m(\mu,\mu) < 5.9$ GeV	2×6 (B, topo)	2×6 (B)	1.4	6
	Two μ, $p_T > 6, 6$ GeV, $7 < m(\mu,\mu) < 12$ GeV	2×6 (Υ, topo)	2×6 (Υ)	1.2	12
Main Rate				86	1750
B-physics and Light States Rate					200

Trigger: Keep it Simple

- Most searches rely on *simple triggers* like MET or single-lepton
- Complexity is an enemy in the trigger! Require ≤ what you have
    - For multi-lepton signals: can you require only *one* lepton in the trigger?
    - Do you *need to* require a b-tagged jet? If not, then don't!
- Very high *efficiency* is the name of the game here
    - You can always remove it later, if you *want to*, but keep as much as possible in the recorded data!

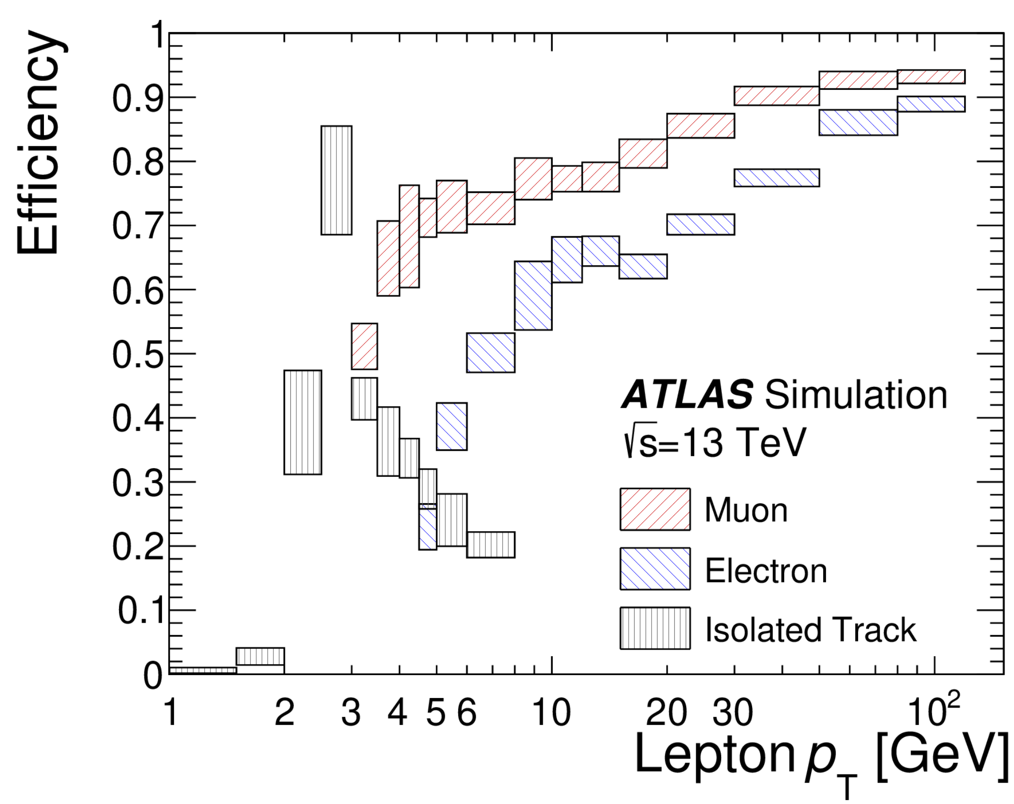
Type	Rate (Hz)
Single Lepton	545 (mostly e/μ)
Multi-lepton	251 (mostly tau)
Photon(s)	90 (half 1 photon)
Jet(s)	158 (75% 1 jet)
b-Jets	72
MET	94
Total	1750

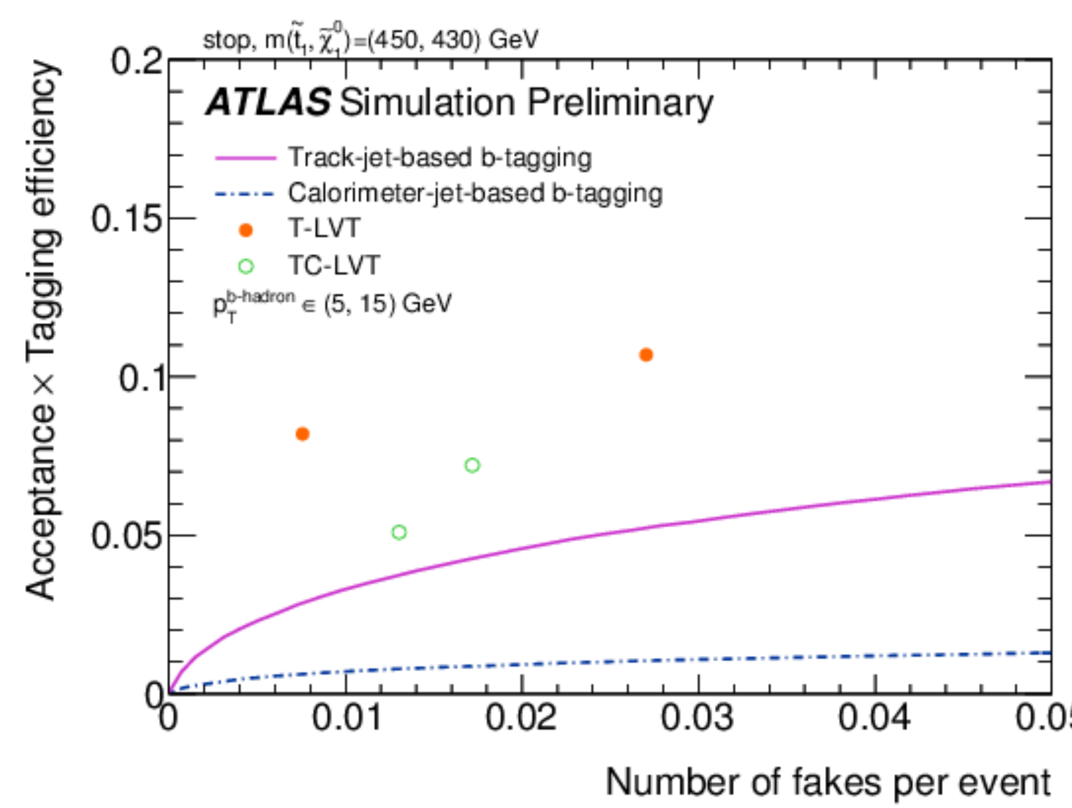
Trigger: It's there when you need it

- When you *can't* keep it simple, the trigger can quickly get very complex
- There are many one-analysis triggers out there!
  - Triggers with very unusual configurations of objects
  - Triggers for large energy deposits in the muon system or inner detector
  - Triggers for late particles
- This can get **extremely sticky**
  - Befriend someone who built the hardware if you want something really complicated!
- Lots of talk of track-based triggers for LHC Run 3 – let's see what happens!

Reconstruction

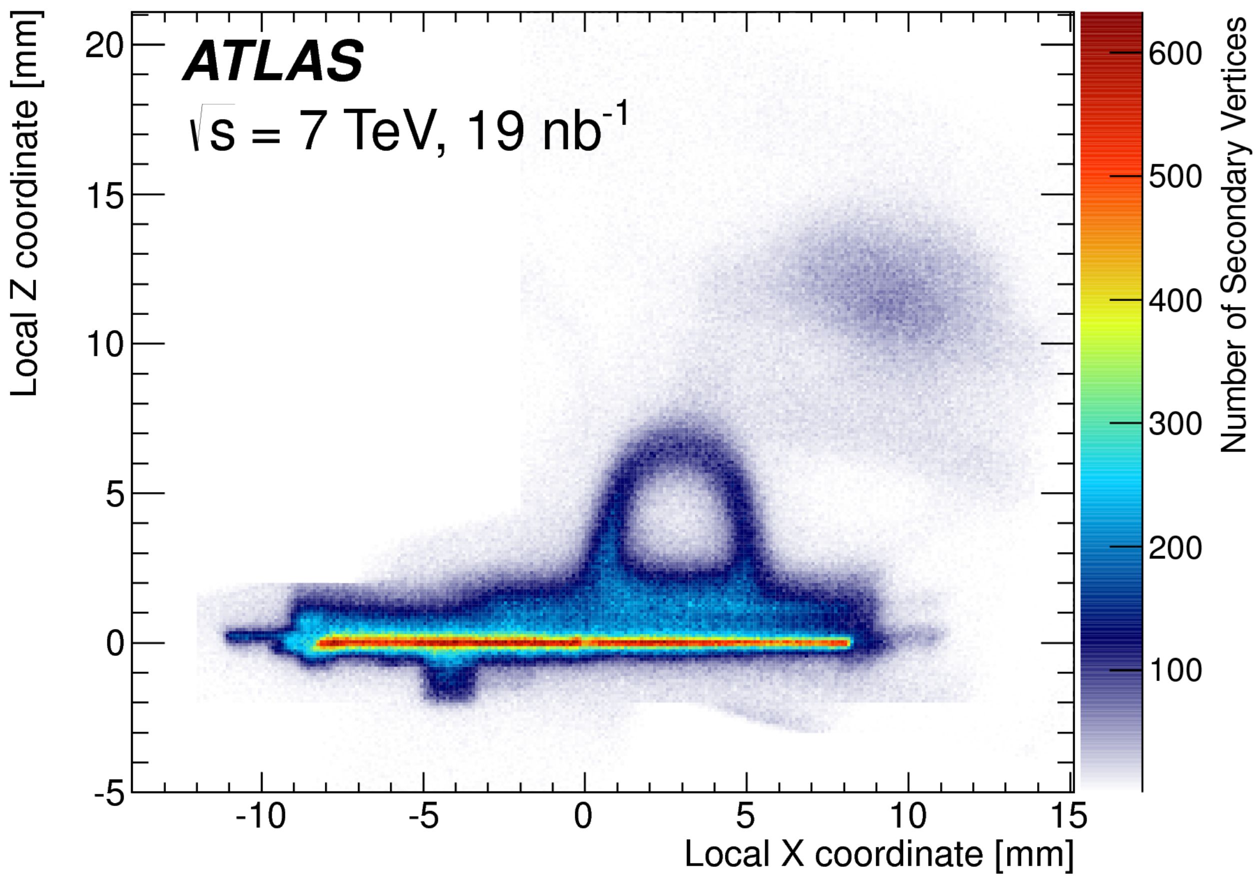
- After we **record** the data, we need to **reconstruct** the objects
- Searches often push objects to their limits in every direction
  - Low momentum, high momentum, far forward, disappearing, re-appearing, displaced, delayed, non-pointing…
  - There's not a lot to say about this except: 1) this is a **lot of hard work**; 2) this is best done **for the experiment**; 3) we can go **much further than we thought**.

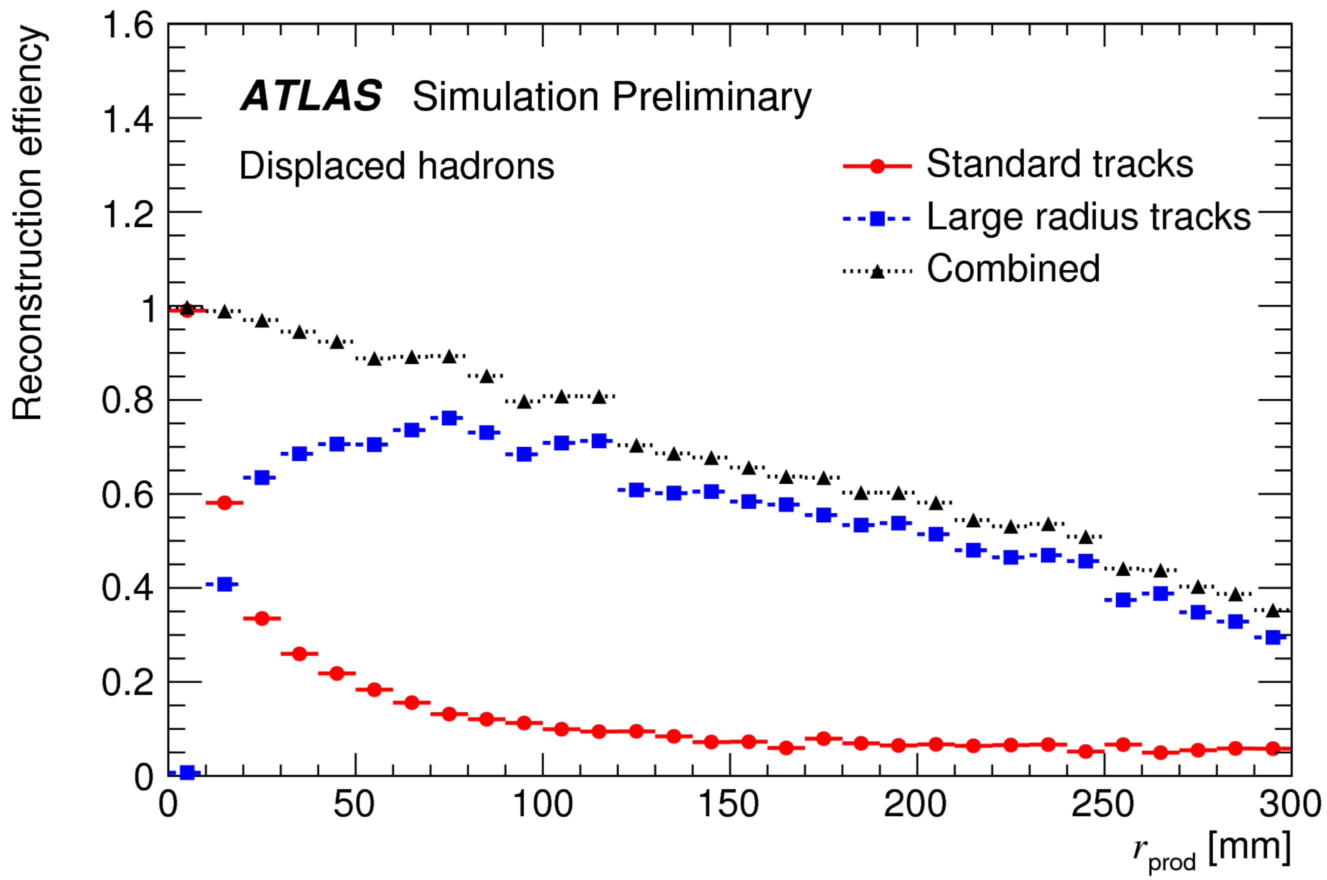




Reconstruction

- One of the big pushes in recent years has been for *large radius tracking*, for long-lived particles
- Tracking is very CPU-hungry, but both experiments work on neat tricks to keep it feasible
- The other key ingredient for many of these searches is *detailed understanding of the detector* – we're able to do more than we could at the start up!





Non-Reconstruction

- Remember that sometimes you *needn't reconstruct everything*.
- If I can't reconstruct the quarks on the left, then the diagram is the same as the Dark Matter search on the right
- If I can't reconstruct a long-lived (/weirdly behaving) particle, then often it "appears" as missing transverse momentum and I can still set a limit on the process!