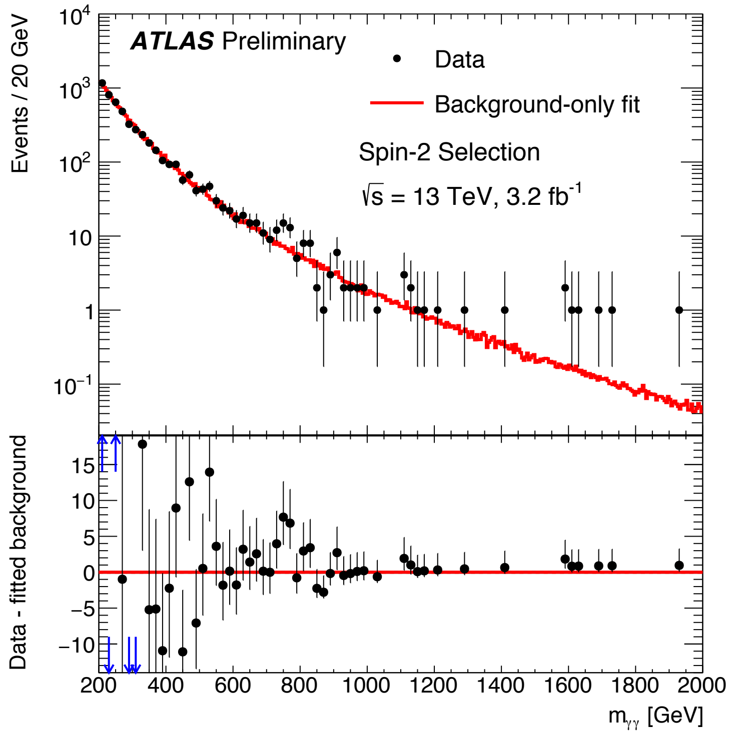
BSM Results from Run 2 of the LHC

Frank Golf
UC Santa Barbara

The bump du jour



Who ordered that?

N. Craig

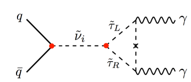
Supersymmetry

Not obvious out of the box, but necessity is the mother of invention…

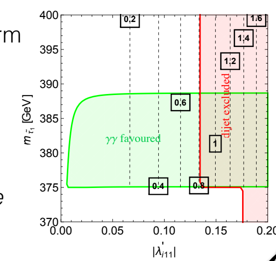
RPV sneutrino

[Allanach, Bhupal Dev, Renner, Sakurai 1512.07645]

W=QLD + LLE A-term



8 TeV tension since qq initiated?



"Sgoldstino"

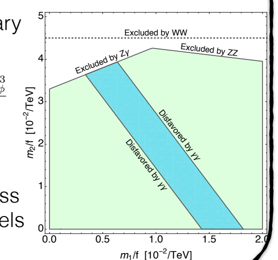
[Petersson, Torre 1512.05333]

(Not sgoldstino of primary SUSY breaking)

$$\Gamma(\phi \to \gamma\gamma) = \frac{(m_1^2 c_W^2 + m_2^2 s_W^2) M_\phi^3}{32\pi F^2}$$

$$\Gamma(\phi \to gg) = \frac{m_3^2 M_\phi^3}{4\pi F^2}$$

Ruled out by gluino mass limits in calculable models



Sbino in supersoft SUSY / dirac gauginos

[Carpenter, Colburn, Goodman 1512.06107]

$$\begin{pmatrix} & A_\mu & \\ \psi & & \lambda \\ & \Phi & \end{pmatrix}$$

Scalar adjoint of $U(1)_Y$, couples to sfermions via D-term

Fitting signal requires m_D~ 10 TeV, enormous splitting in multiplet

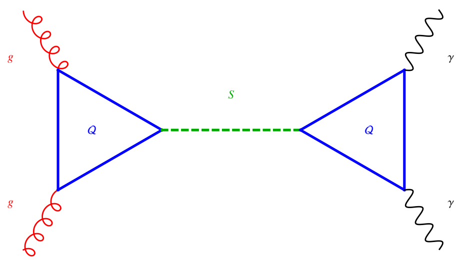
Many thought that when the LHC turned on, NP in some form of SUSY would be waiting just around the corner. Could this be it? If so, not the SUSY most were expecting…

Does the bump have friends?

- In many discussions about the bump, variations on one scenario that frequently pops up requires some new heavy charged/colored particles through running the loops.

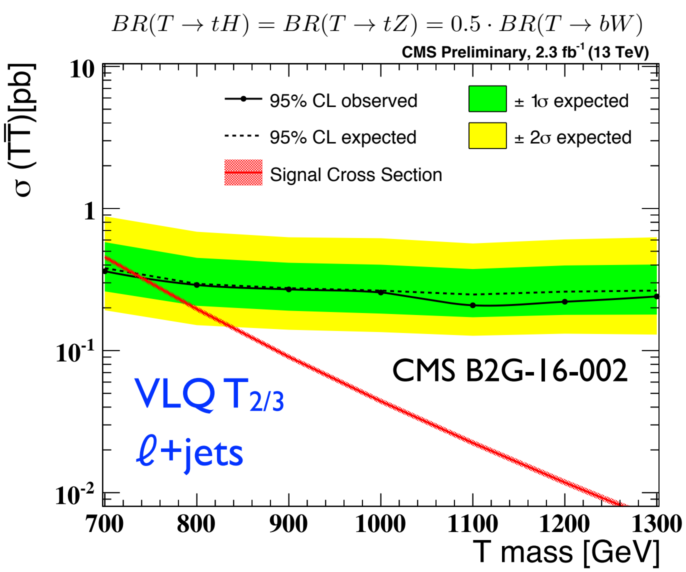
Volksmodell (the everybody's model)

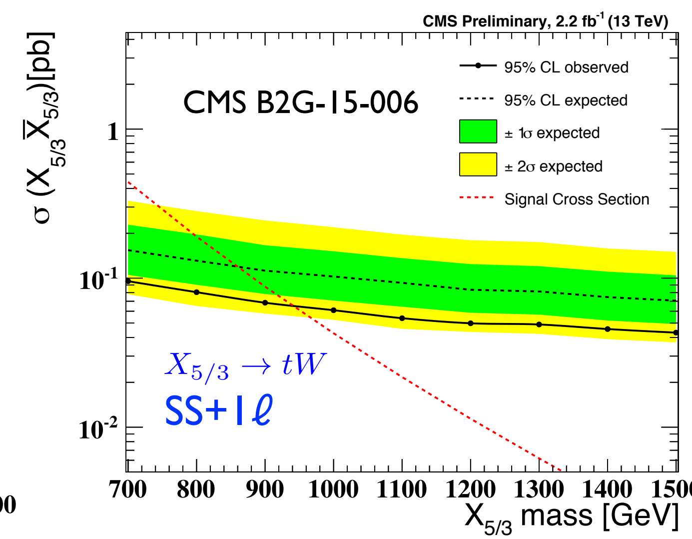
A. Strumia



Extra fermions Q or scalars $\tilde{Q}$ needed

SM loop excluded: the tree level decay would be too large e.g. $\frac{\Gamma_{t\bar{t}}}{\Gamma_{\gamma\gamma}} \approx 10^5$.





No evidence for BSM physics. Extend range of mass probed by ~50-150 GeV.

It has certainly been a social phenomenon

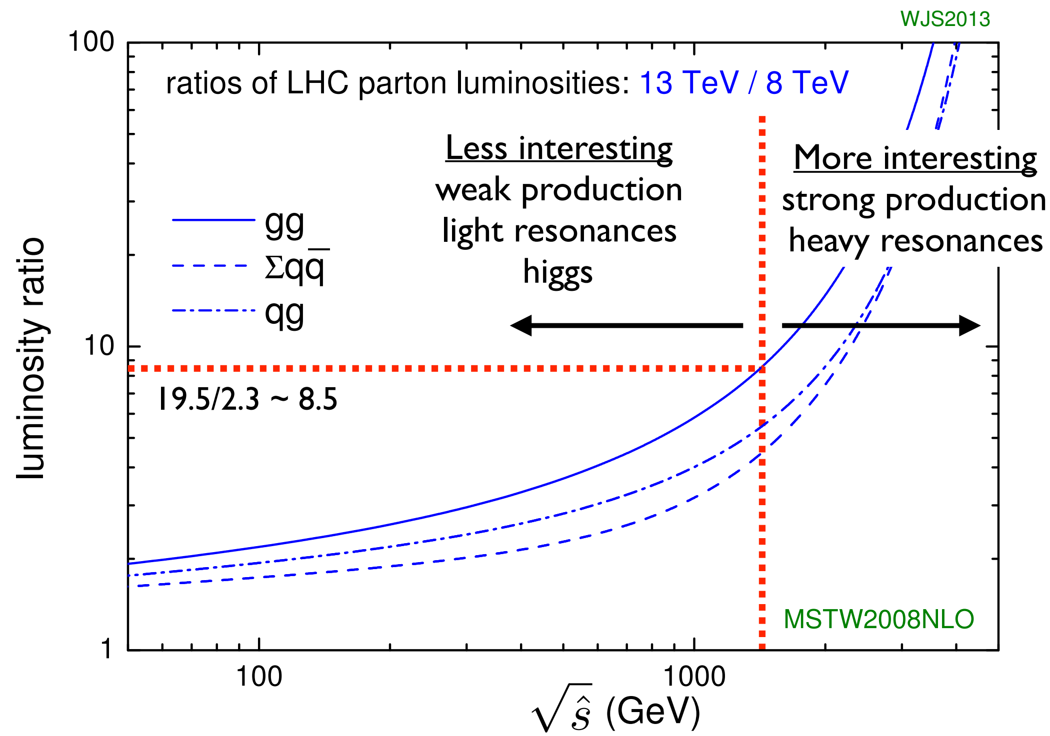
A. Strumia

Date	papers
16 Dec	10
25 Dec	101
1 Jan	137
1 Feb	212
1 Mar	263
1 Apr	?
26 May	>380***

- Much time and creativity devoted to trying to explain what this might be.
- So far more than 380 publications related to the topic, surpassing the prediction (310) in arXiv: 1603.01204***. Is this the first victim to fall? There will surely be more by summers end…

What I will and won't cover today

- Guided to target ~30 minutes. Can't possibly cover everything (even poorly) in that time, so instead I'll try to highlight a few things that might be interesting.
- Types of things I won't talk much about: higgs, other light resonances, weak production, etc.
- Types of things I will talk about: heavy, colored objects → this will mostly be a talk about SUSY.

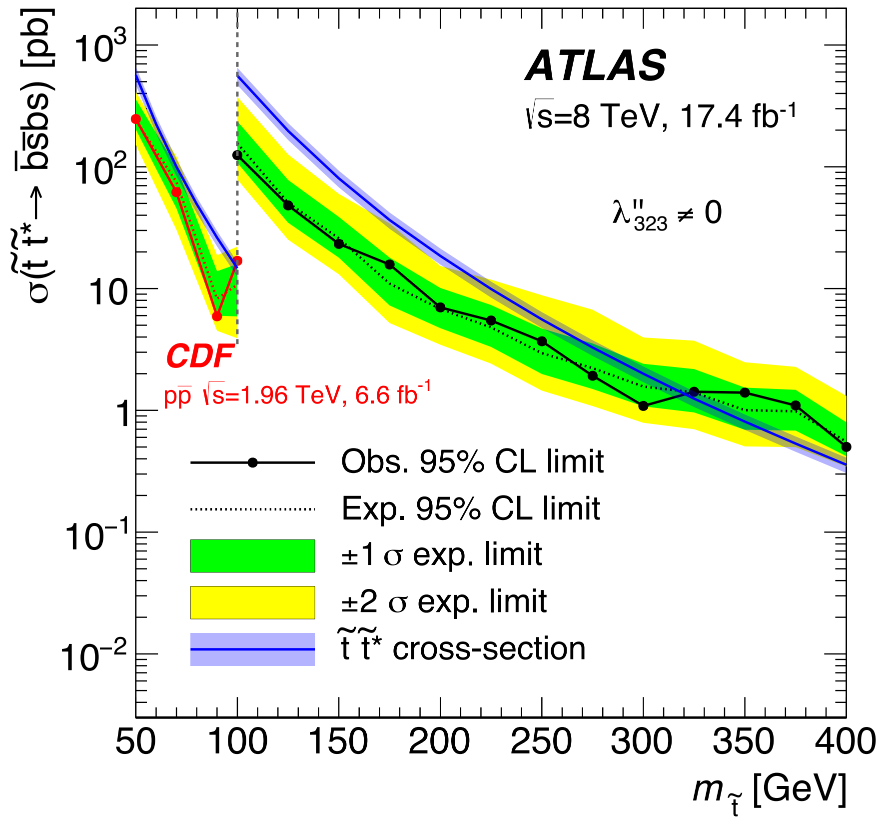


SUSY: Caveats and disclaimers

- Disclosure of personal bias: From here on we're going to talk about searches for SUSY. When I say SUSY here, what I mean is **new physics searches where MET is a primary distinguishing characteristic**.

- This ignores RPV scenarios, for which lately there have been some very interesting results, but tend to have more in common with what is often traditionally thought of as "exotics", such as searches for hadronic resonances, multi-jet final states without significant MET, etc. Daniel will tell us all about searches for resonances in the next talk.

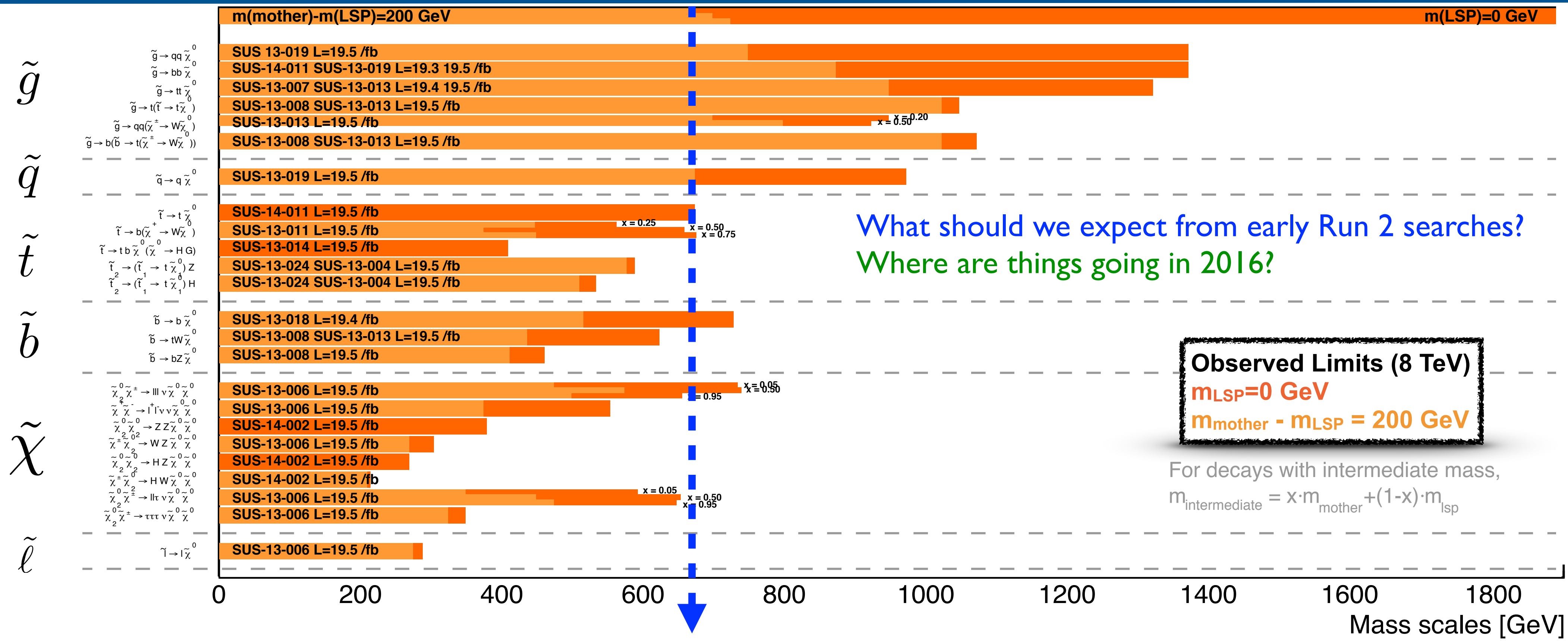
ATLAS-CONF-2016-022



SUSY: Caveats and disclaimers

- Before moving on, I should also note that there is a whole class of searches that have MET as the defining characteristic that I am ignoring here — i.e. dark matter searches.
- Why? Because fundamentally they have the same signature as SUSY searches, and thus confront many of the same backgrounds and challenges, i.e. **at a basic level, searches for SUSY (gluinos, squarks, ewkinos) were already searches for dark matter**.
- Disclaimer: Most of the results I'll talk about today are available from both the ATLAS and CMS experiments. I'll mostly show CMS results, not because they are necessarily any better, but because they are the results with which I am most familiar.

SUSY searches at the dawn of Run 2

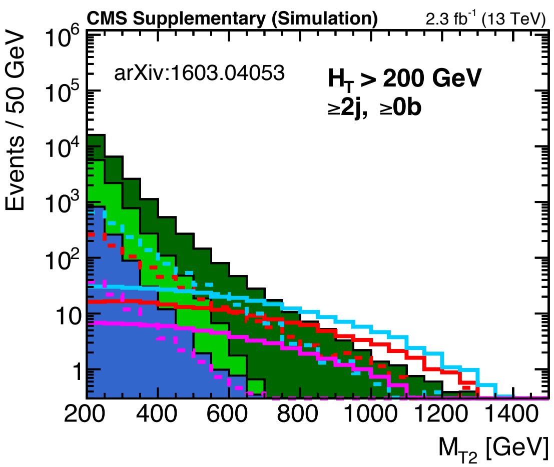


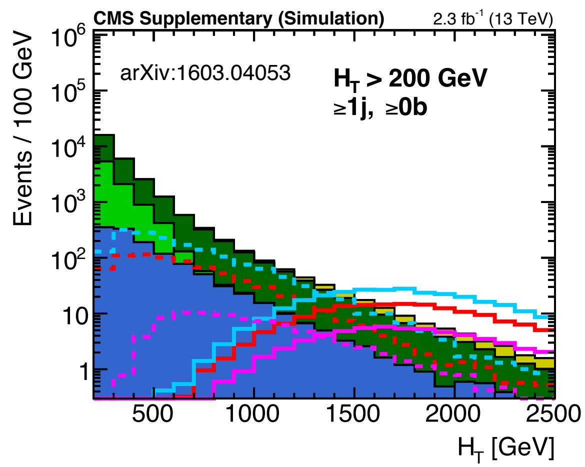
Inclusive searches organized by signature (0L, 1L, SS, ≥3L) probing high mass colored partners.

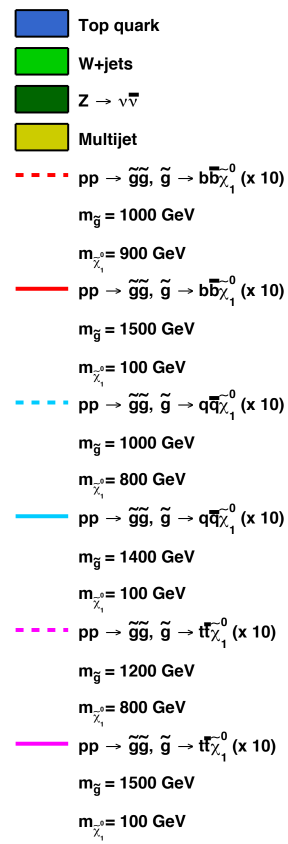
Targeted searches for 3rd generation squarks.

Anatomy of an inclusive search: jets+MET

Selections are chosen to cover a broad range of signatures.

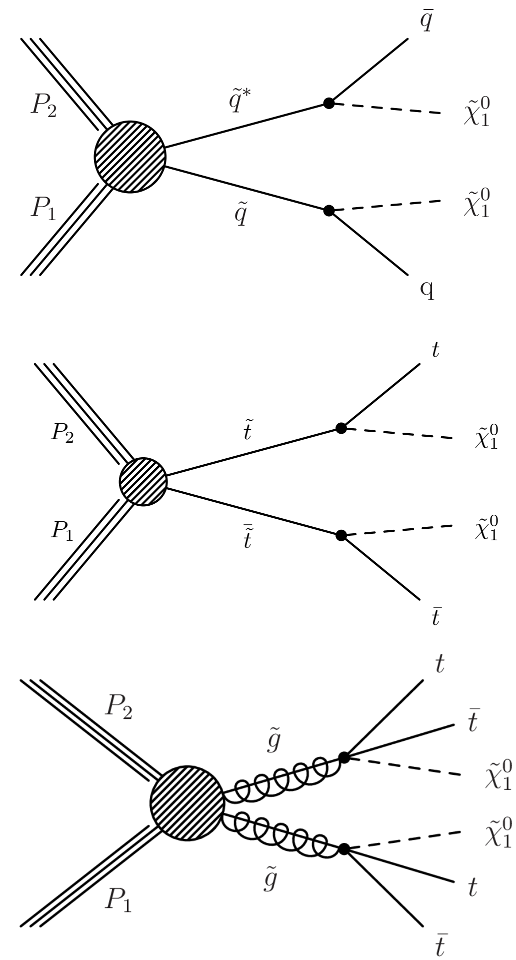






invisible energy scale:
MET, MHT, M_{T2}, R^2

visible energy scale:
H_T, M_R, jet p_T

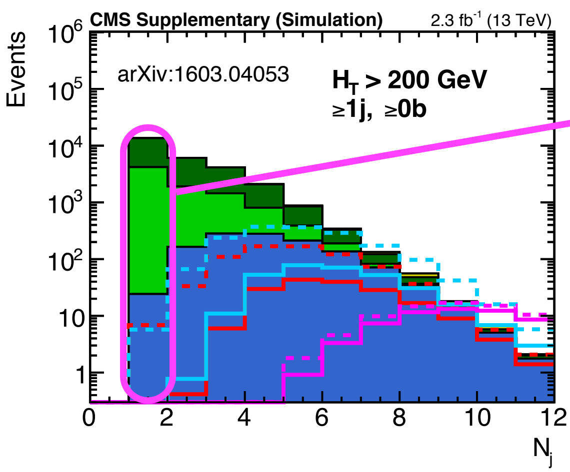


Unknown mass scale and mass splittings for new physics.

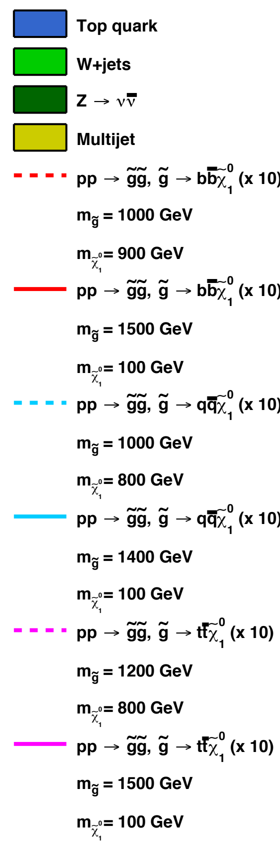
Anatomy of an inclusive search: jets+MET

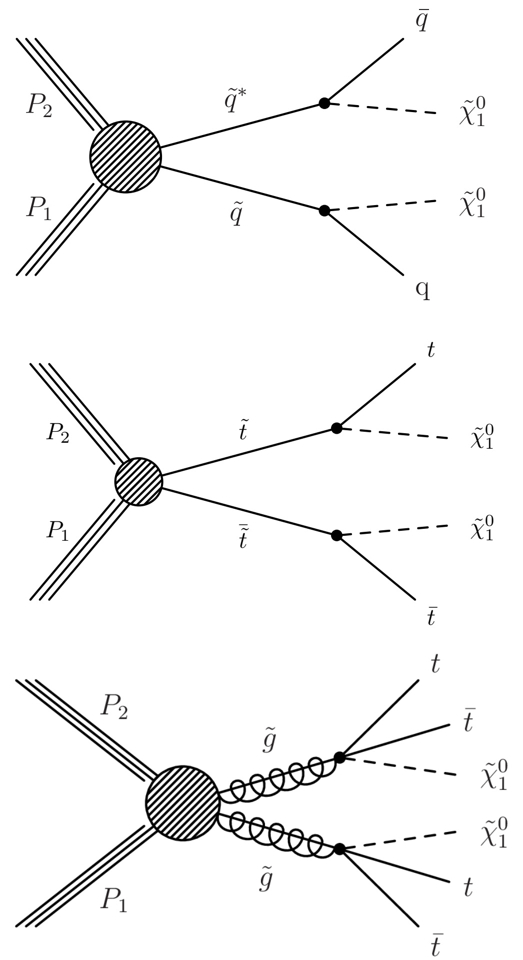
Selections are chosen to cover a broad range of signatures.

Unknown parton multiplicity.



CMS inclusive analyses (M_{T2},α_T) now also including monojet regions.





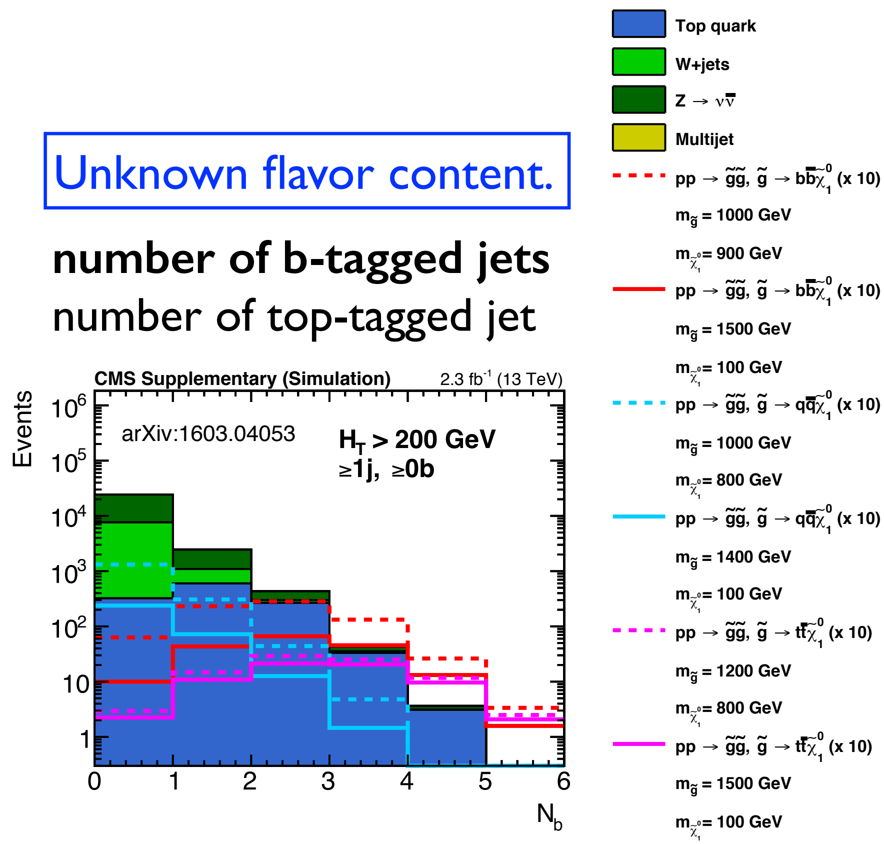
Anatomy of an inclusive search: jets+MET

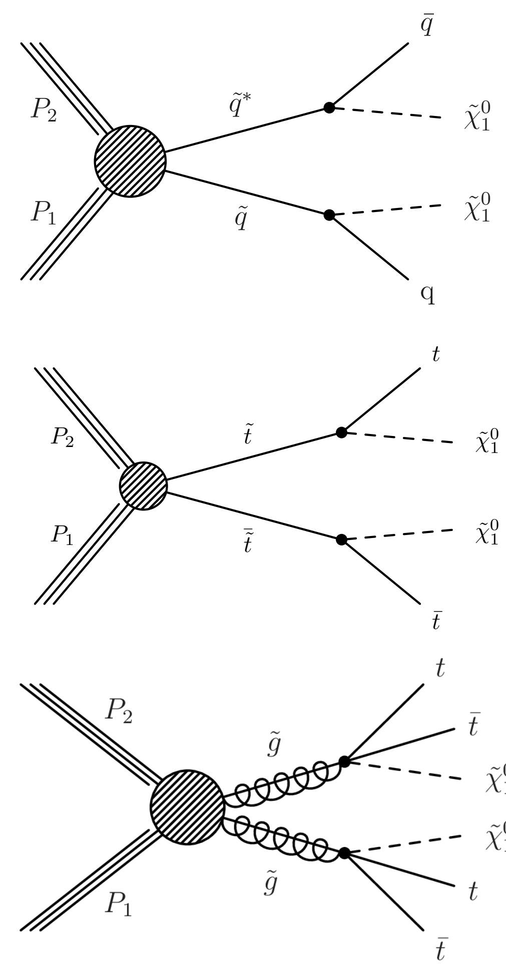
Selections are chosen to cover a broad range of signatures.

Unknown flavor content.

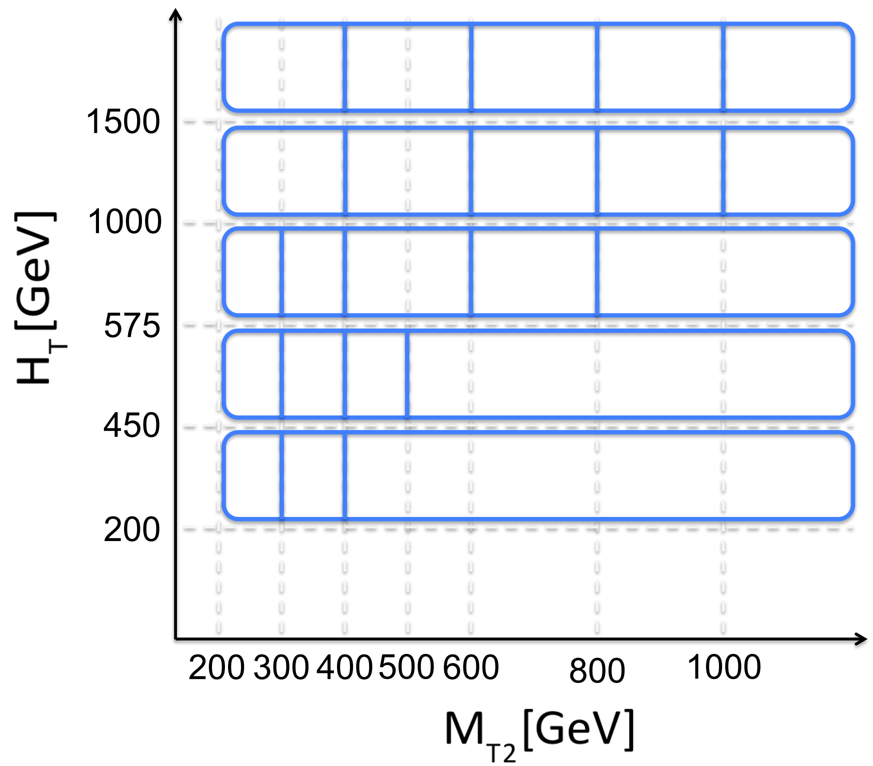
number of b-tagged jets

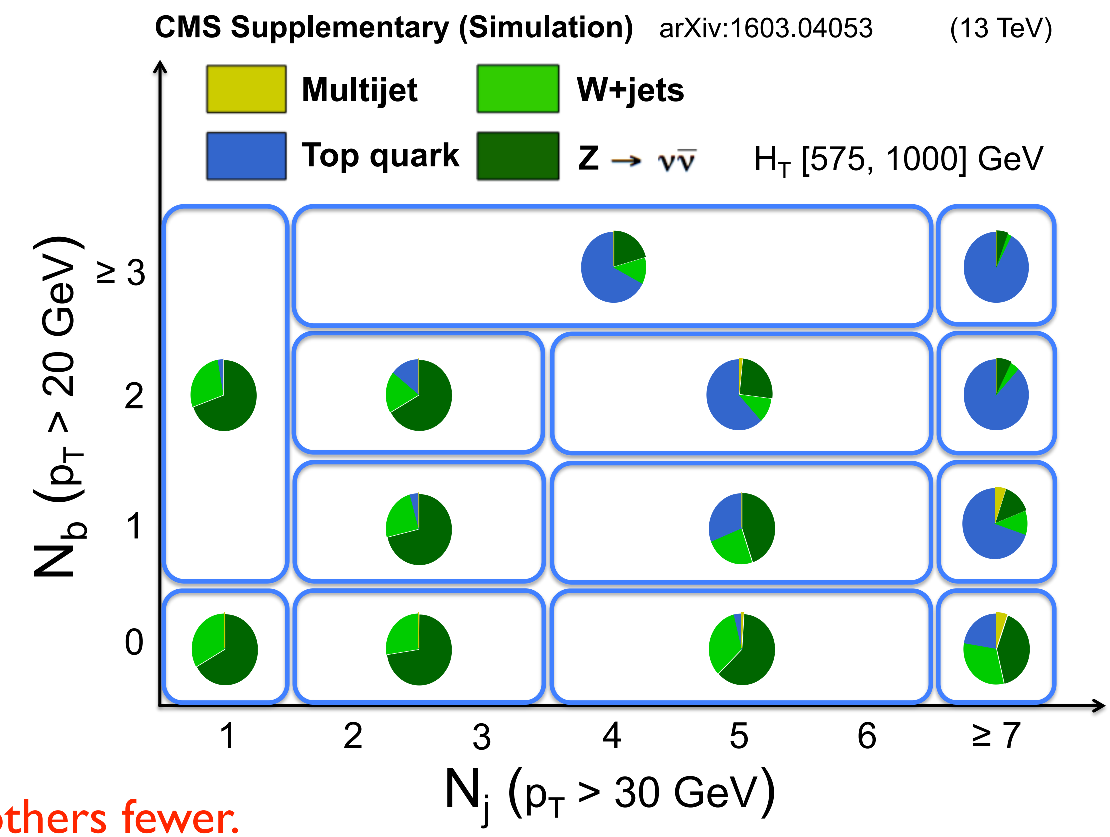
number of top-tagged jet





Searches, such as MT2, aim to cover the full phase space permitted by the CMS trigger.

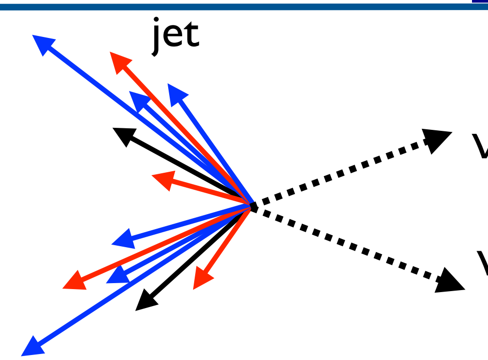


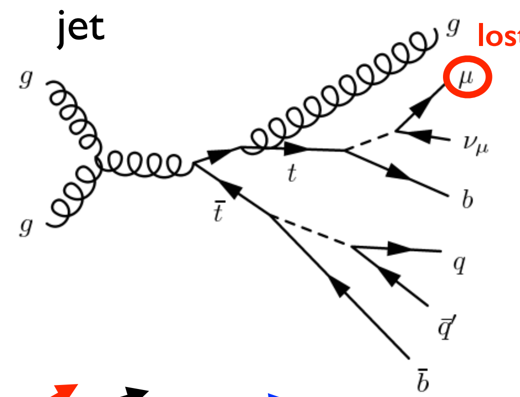


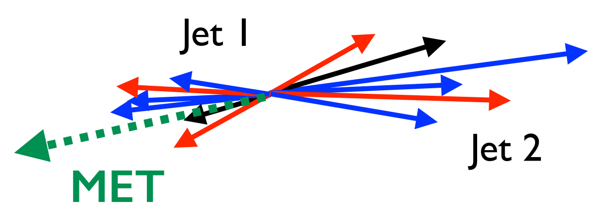
MT2 has172 search regions. Some have more, others fewer.

All jets+MET searches face similar background processes

- **<u>Invisible Z ($Z \to \nu\bar{\nu}$)</u>**
  - Most signal-like: real MET from neutrinos
  - Data-driven estimate using γ+jets (and/or W,Z) control region
- **<u>Lost lepton (top, W+jets)</u>**
  - Real MET from leptonic W decay
  - Data-driven estimate based on 1 lepton control region
- **<u>QCD multijet</u>**
  - MET from jet mis-measurement
  - Data-driven estimate using sideband (e.g. low Δφ, MT2)

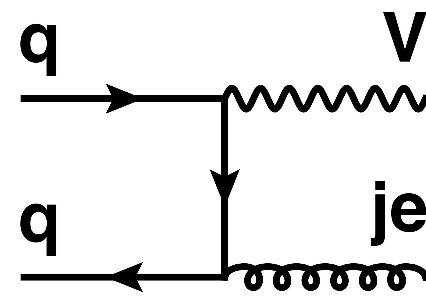




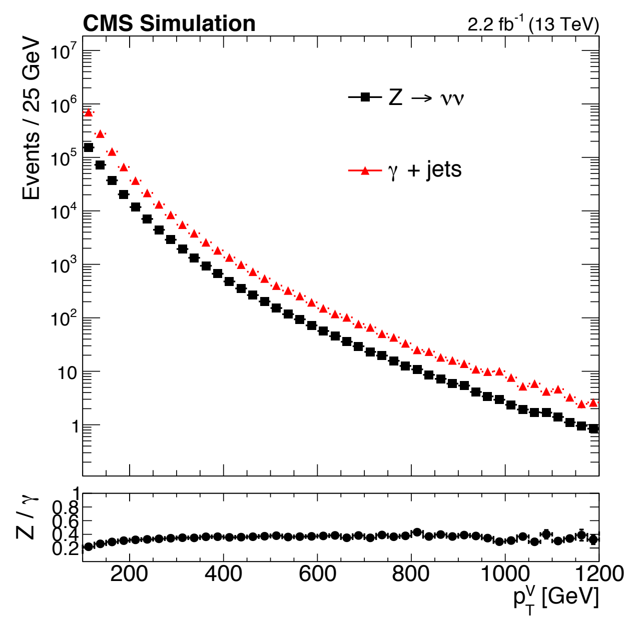


Invisible Z: Basic Idea

Useful to look at an example of how a background estimate we're all familiar with is performed.



- Jets in $Z \rightarrow \nu\bar{\nu}$ from initial state radiation, would rather not rely entirely on MC to model this correctly.
- Production properties of $pp \rightarrow Z$+jets and $pp \rightarrow \gamma$+jets are very similar.
- Idea: Use γ+jets events, remove the photon from the event and apply some well understood corrections to predict $Z(\nu\bar{\nu})$+jets.
- Once the momentum becomes sufficiently large, the difference in boson mass becomes a small effect and $R(Z/\gamma)$ becomes relatively flat.



Invisible Z background estimate in MT2 search

Estimate $Z(\nu\bar{\nu})$ background in each (HT,NJ,NB) region using γ+jets yield in corresponding (HT,NJ,NB) CR:

$$N^{\mathrm{SR}}_{Z\to\nu\bar{\nu}} = \underline{N^{\mathrm{CR}}_{\gamma} \times P_{\gamma} \times R^{Z/\gamma}_{\mathrm{MC}}} \times \underline{k_{\mathrm{MC}}}$$

- **N_{γ}^{CR}**: γ+jet yield in control region
- **P_{γ}**: purity of photon control region
  - ~0.95, measured in data, accounts for π^0 and fakes
- **R(Z/γ)**: $Z\to\nu\bar{\nu}$ to γ+jets ratio, ~0.4-0.5 from MC
  - Validated using $Z\to\ell\ell$: $R(Z\ell\ell/\gamma)^{\mathrm{data}}$ vs $R(Z\ell\ell/\gamma)^{\mathrm{MC}}$

Used to obtain estimate of $Z\to\nu\bar{\nu}$ in each (HT,NJ,NB) region, integrated over MT2.

Q: How sensitive is R(Z/γ) to higher order corrections?

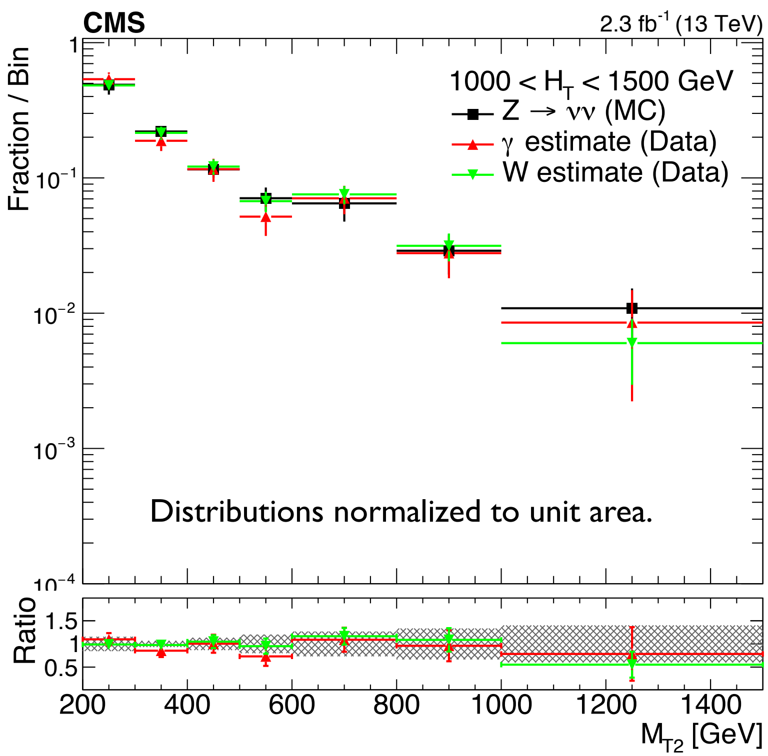
- In each (HT,NJ,NB) region, use Z MC to get fraction in each MT2 bin, **k_{MC}**
  - No MT2 binning for monojet regions, CR binning is same as SR (i.e. no MC shape used)

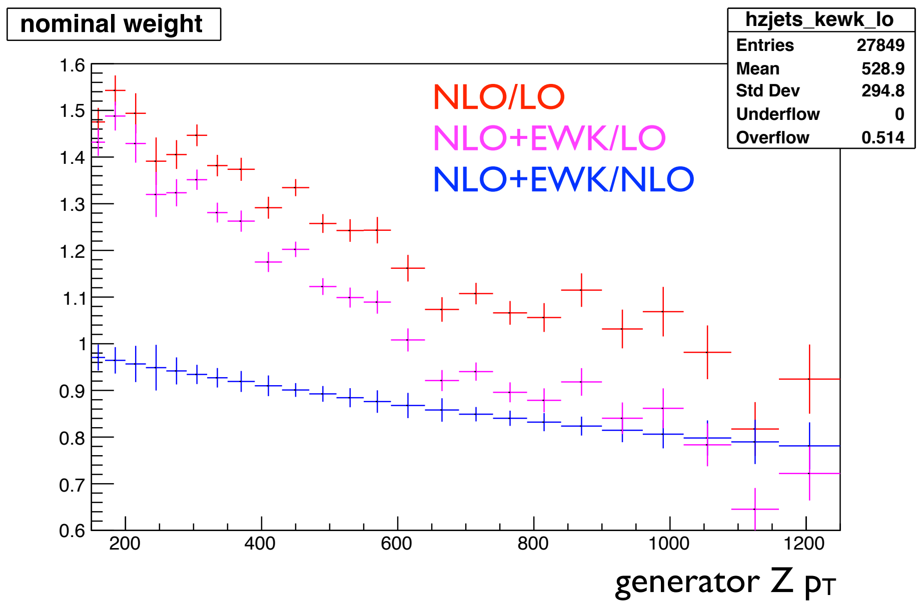
Extrapolate estimate of $Z\to\nu\bar{\nu}$ in a given (HT,NJ,NB) region to a particular bin of MT2.

Q: How well is MT2 modeled?
Related Q: How well do we know the Z p_T?

Invisible Z: MT2 shape

- Compare MT2 shape in LO Z MC to γ+jets, W→ℓν data, uncertainty from theory+reco MC variations.
- Additional cross-check by comparing extrapolation with bin-by-bin estimate.

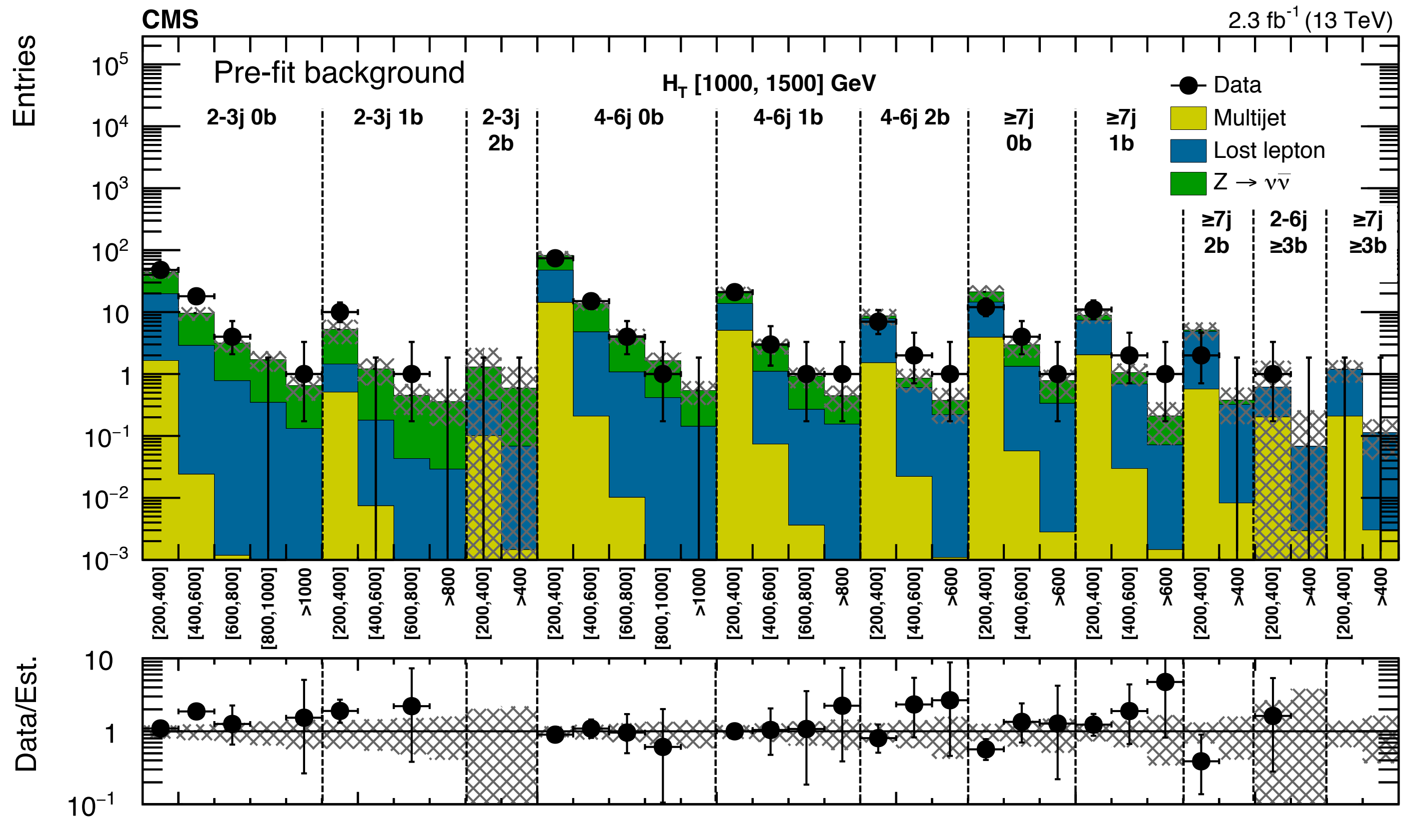




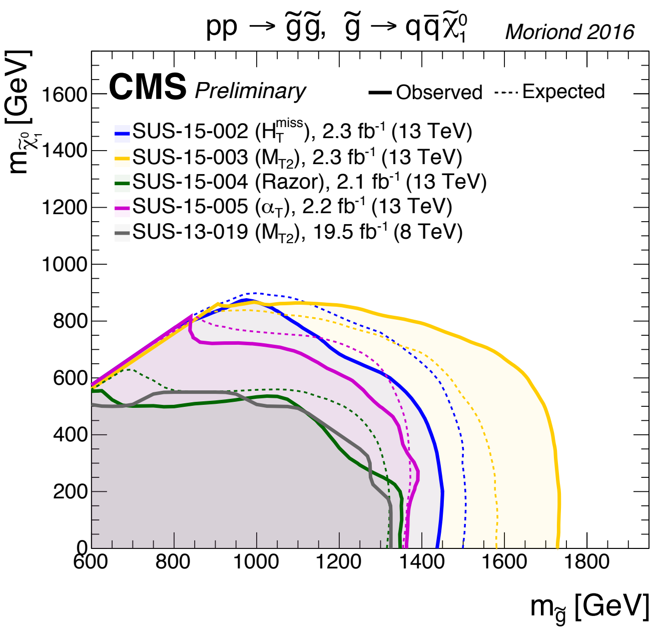
Some evidence for data falling faster than MC (left)?
Is this a result of missing higher order corrections?

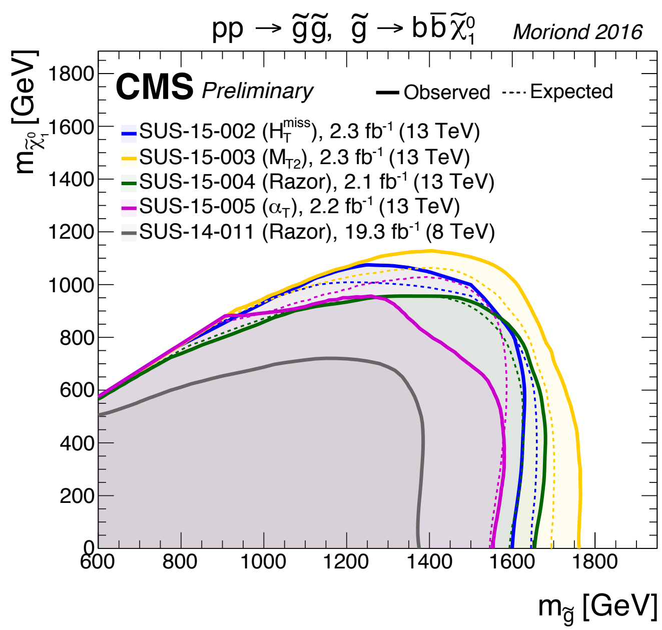
MT2 results: high HT search regions

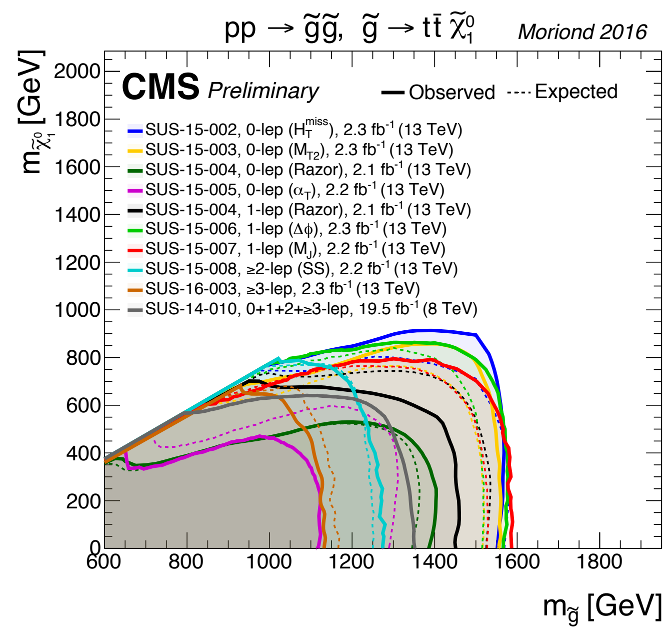
No evidence for non-SM physics, here, or in any other SUSY search with 2015 data.



Many inclusive searches all tell the same story



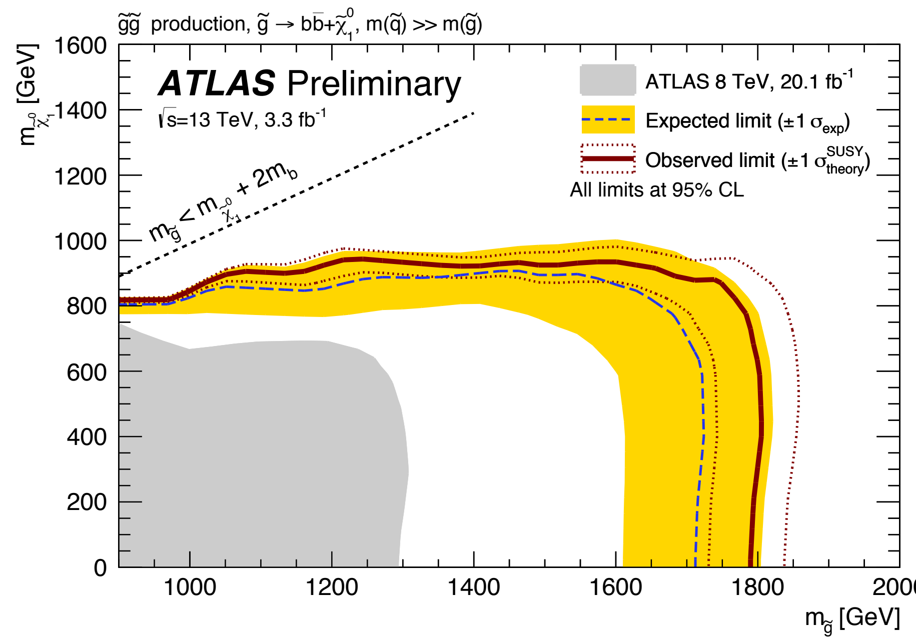




- Different approaches perform ~same, probe gluino mass in range ~1.5-1.75 TeV depending on decay.
- For massless LSP, expected xsec reach for T1bbbb is ~2 (3) times smaller than for T1qqqq (T1tttt).
- For large LSP mass, probe much closer to diagonal for T1bbbb than for T1qqqq and T1tttt.

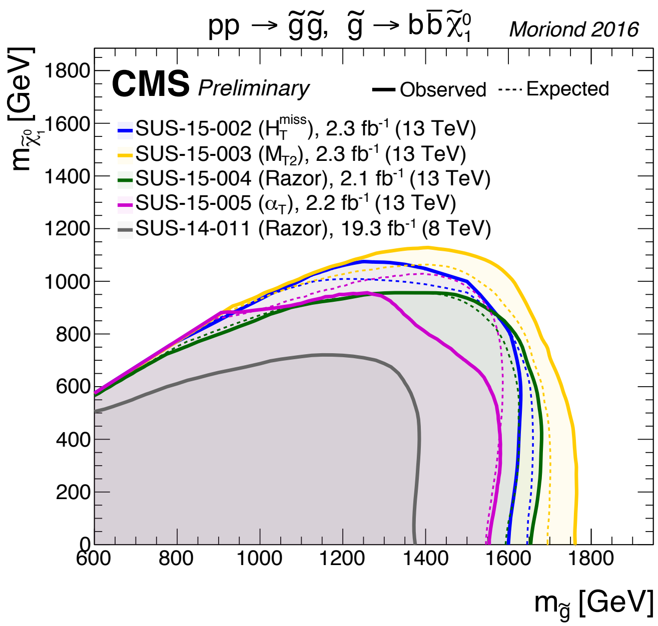
ATLAS searches tend to employ a different strategy

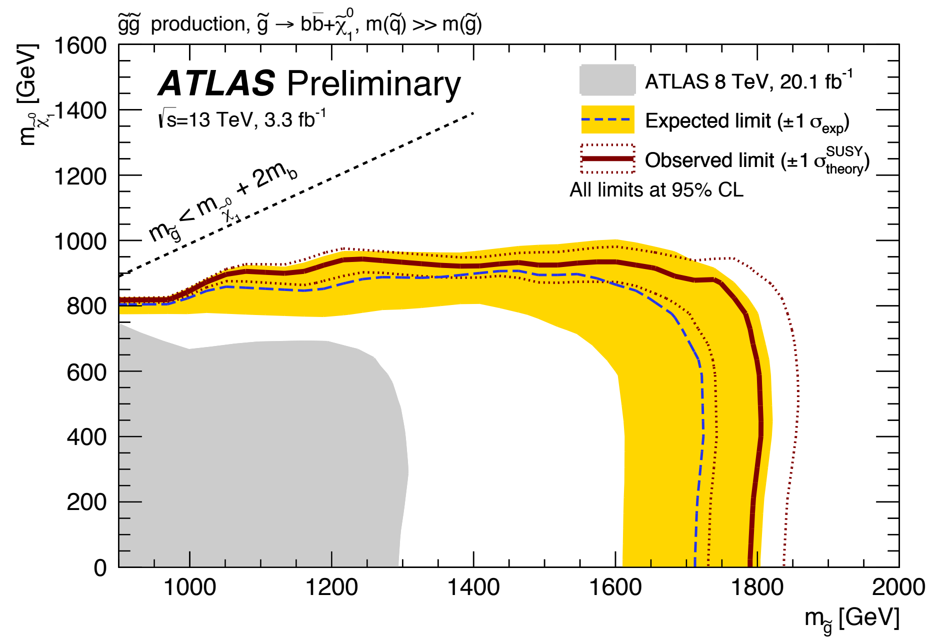
	SR-Gbb-A	SR-Gbb-B	SR-Gbb-C
Observed events	0	1	5
Fitted background events	1.4 ± 0.7	1.5 ± 0.5	7.5 ± 1.4
$t\bar{t}$	0.7 ± 0.5	0.83 ± 0.32	3.9 ± 1.0
Z+jets	0.25 ± 0.26	0.25 ± 0.22	1.4 ± 0.6
W+jets	0.19 ± 0.10	0.15 ± 0.06	0.95 ± 0.34
Single-top	0.22 ± 0.10	0.16 ± 0.15	0.67 ± 0.33
$t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}t\bar{t}$	< 0.1	< 0.1	0.18 ± 0.10
Diboson	–	< 0.1	0.43 ± 0.25
MC-only prediction	1.7	1.6	7.1
$\mu_{t\bar{t}}$	0.7 ± 0.3	0.9 ± 0.4	1.1 ± 0.4



- In contrast to CMS, ATLAS typically defines a small number of (potentially overlapping) search regions and interprets the results using the region that gives the best expected limit at each point for a SMS.

Different approaches leading to a similar result

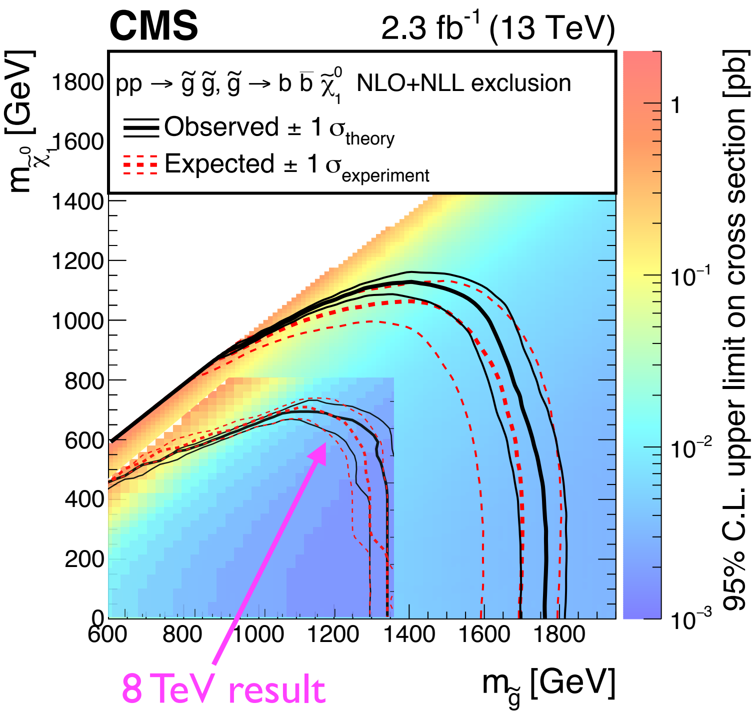


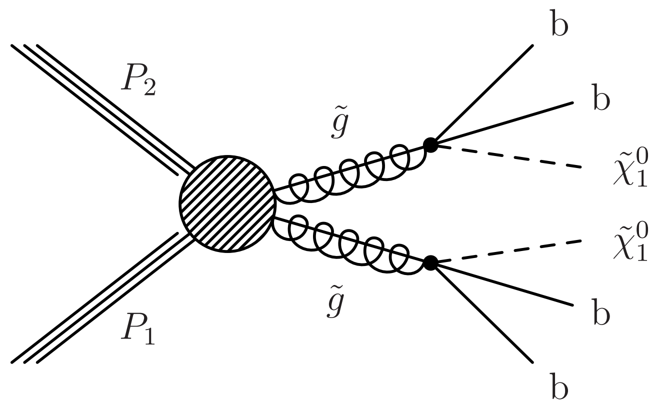


- In contrast to CMS, ATLAS typically defines a small number of (potentially overlapping) search regions and interprets the results using the region that gives the best expected limit at each point for a SMS.

- ATLAS searches probe a similar mass range for large Δm(g̃,LSP), flatten out sooner at high LSP mass.

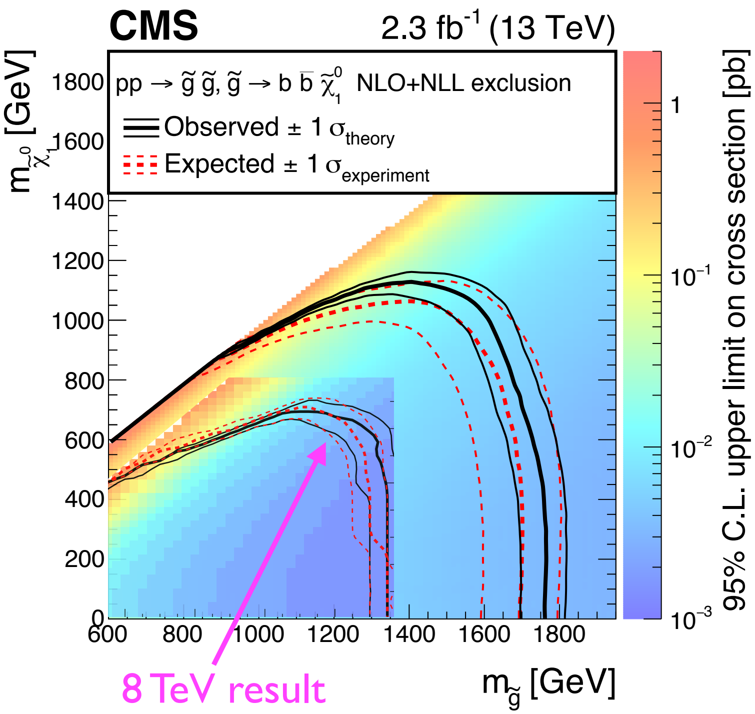
How did our sensitivity change from 8 TeV?

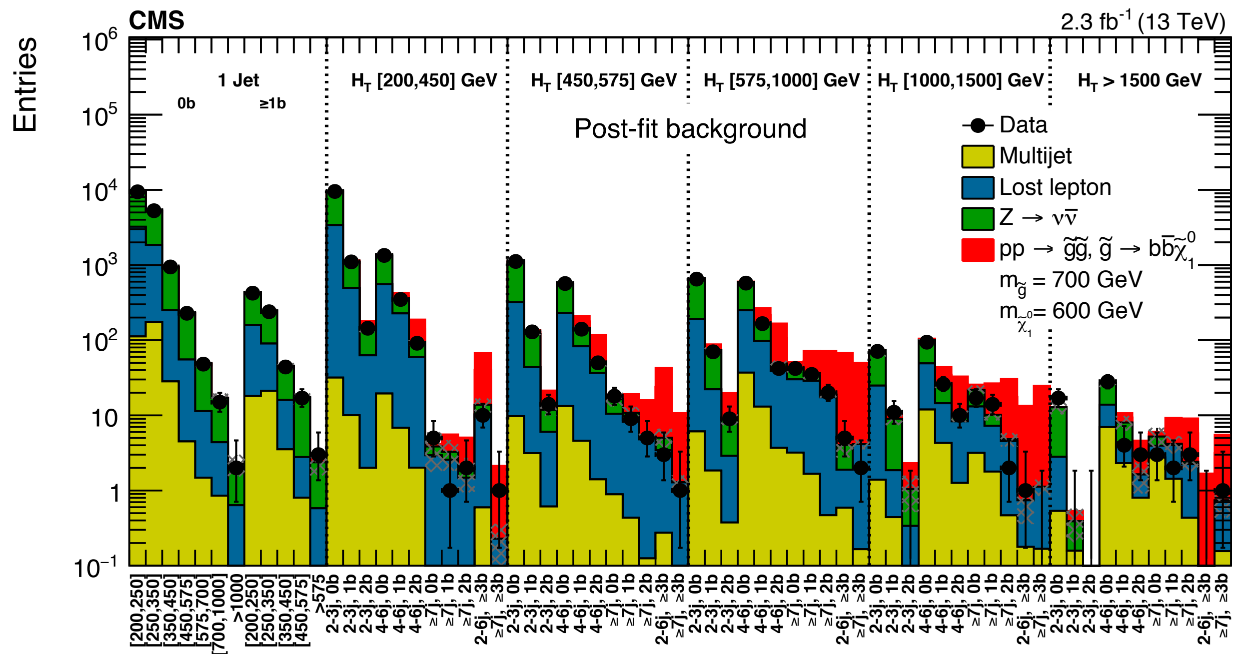




Extend reach in m(lsp) ~same as m(g̃).
Where does this come from?

It's the effective $\sqrt{\hat{s}}$ that matters

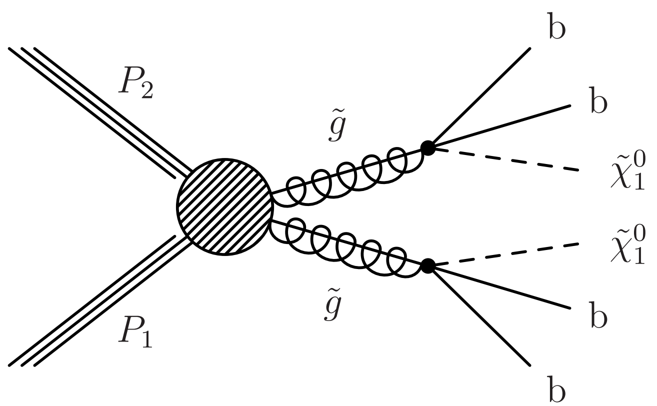


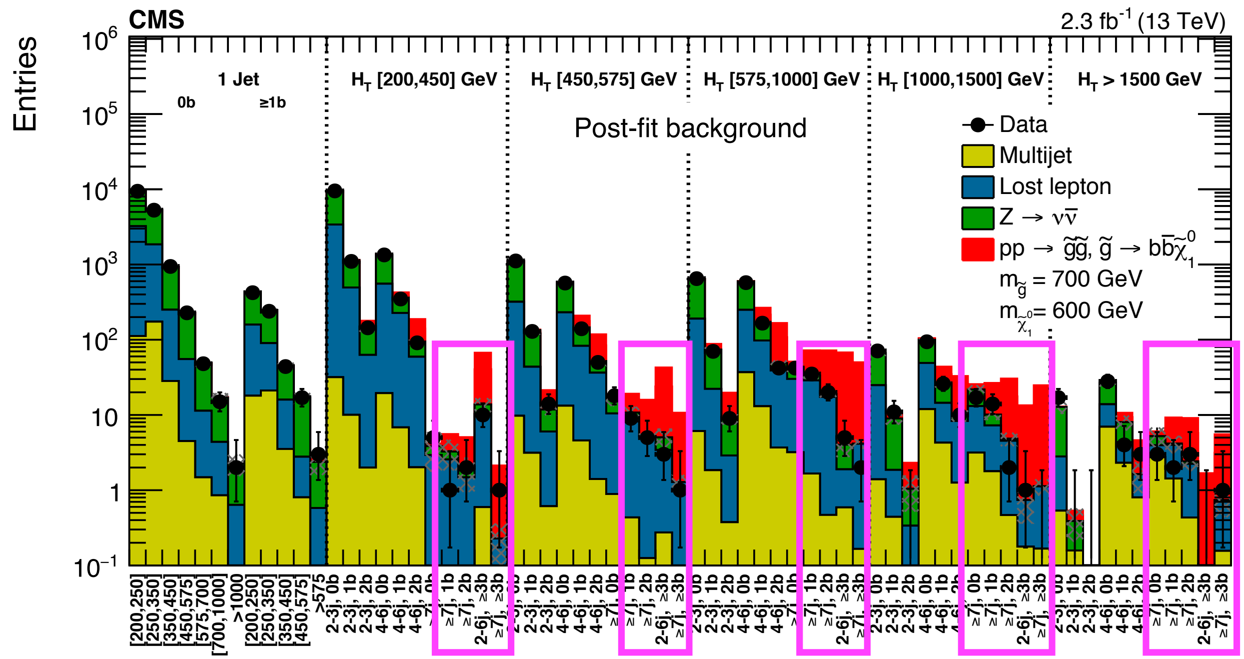


Extend reach in m(lsp) ~same as m($\tilde{g}$). Where does this come from?

Sensitivity from moderate to high HT bins. The only way to get this is if there is significant ISR → higher $\sqrt{\hat{s}}$ and thus larger effective cross section enhancement.

Higher H_T isn't the only thing going on here…





It's interesting to note that some of our sensitivity is coming from bins requiring at least 7 jets. This means that, at best, we're probably requiring at least 3 additional jets from radiation in these regions.

No obvious cause for concern, but something to keep in mind

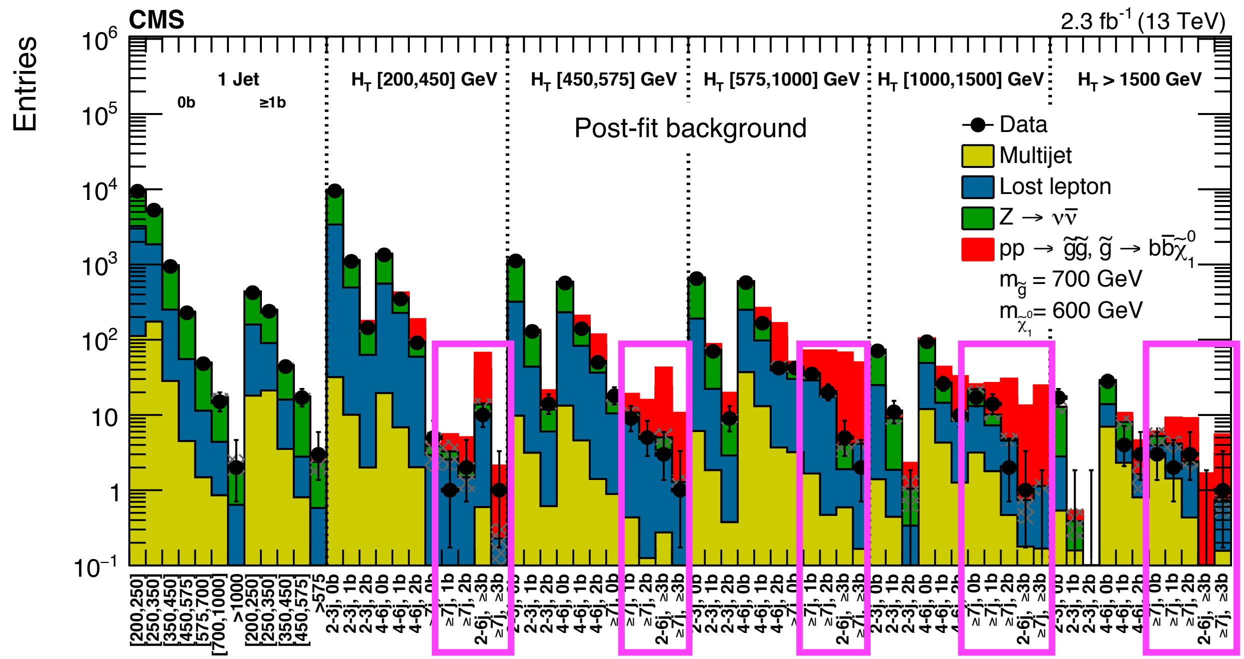
Ranking of SRs by expected UL, T1bbbb(900,850)

HT575to1000 j4to6 b2
HT575to1000 j4to6 b1
HT1000to1500 j4to6 b1
HT575to1000 j2to6 b3toInf
HT1000to1500 j4to6 b2
HT575to1000 j2to3 b1
HT575to1000 j2to3 b2
HT575to1000 j7toInf b2
HT200toInf j1 b1toInf
HT450to575 j4to6 b2

Looking at the most sensitive regions for a related point is somewhat reassuring.

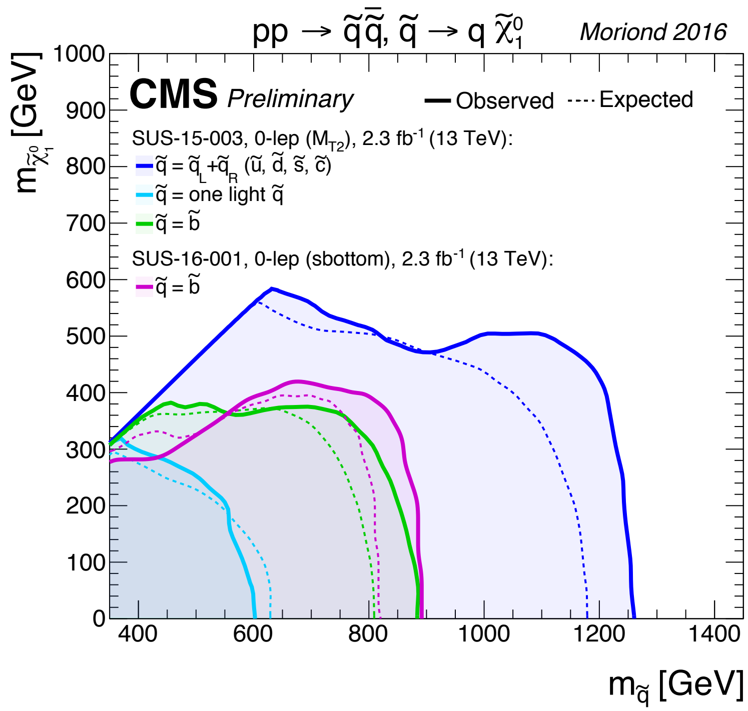
Most of our sensitivity comes from moderate HT and NJ with a few b-tags.

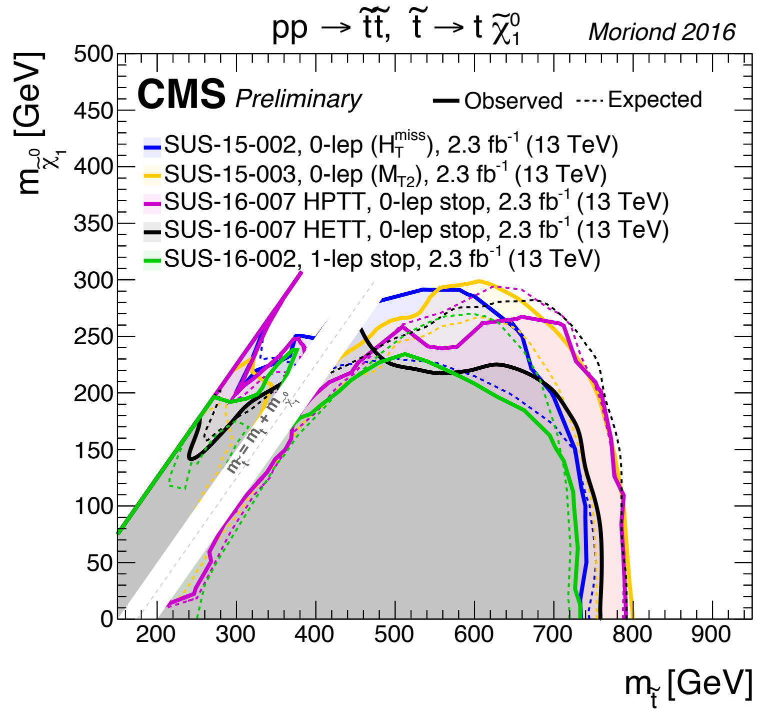
Only 1 of the 10 most sensitive regions requires at least 7 jets.



It's interesting to note that some of our sensitivity is coming from bins requiring at least 7 jets. This means that, at best, we're probably requiring at least 3 additional jets from radiation in these regions.

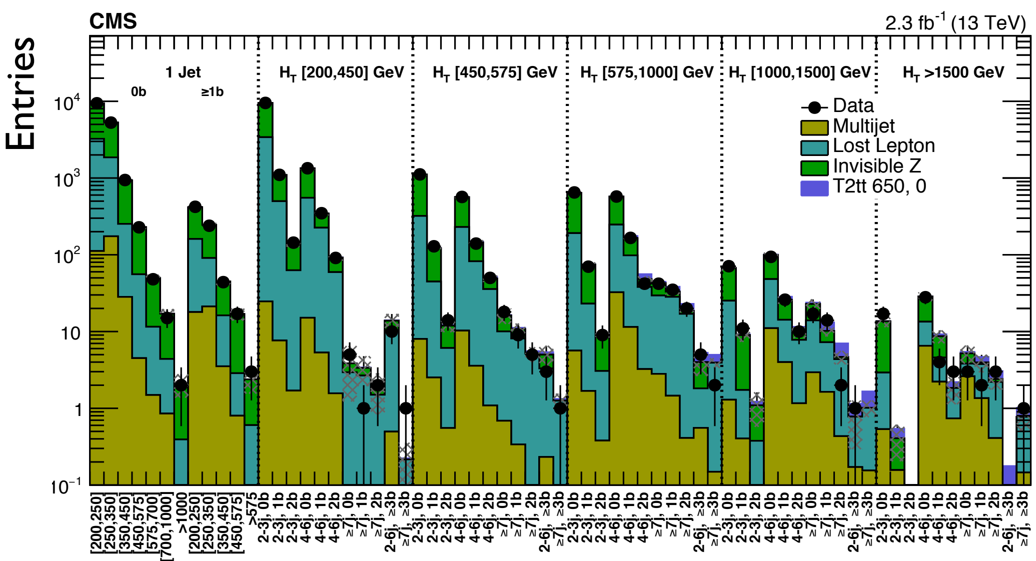
The picture for squarks is not so different

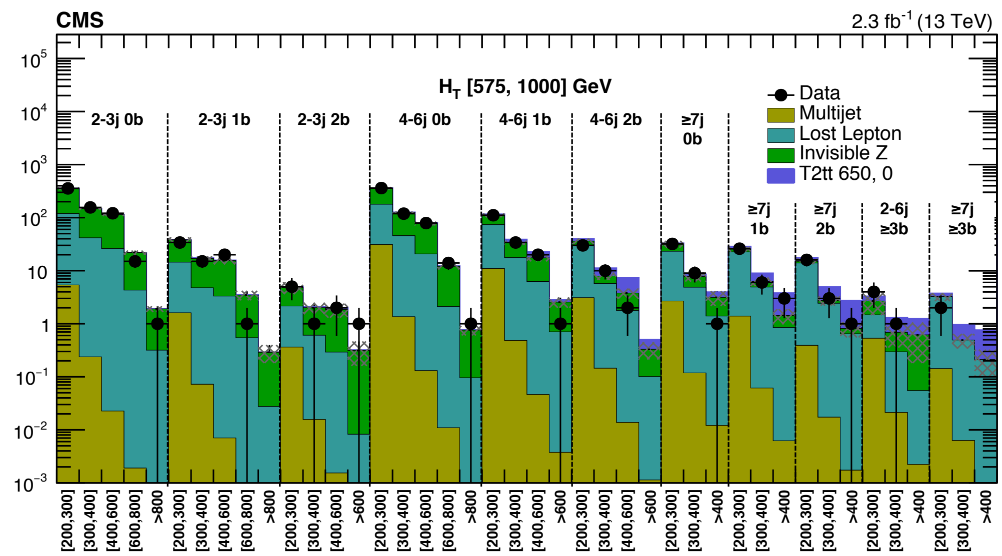




- Multiple searches perform ~same, better sensitivity when b-quarks are present.
- Interesting to note that targeted searches do only slightly better than generic ones. Whats going on?

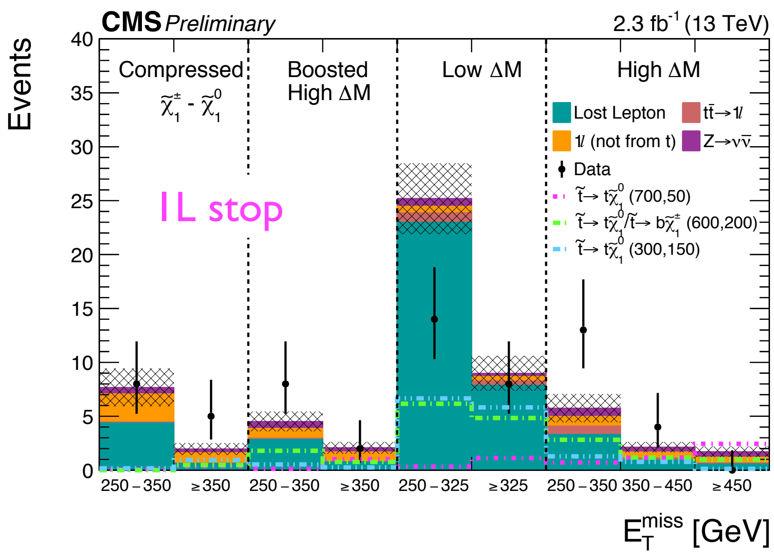
Inclusive searches aren't so generic

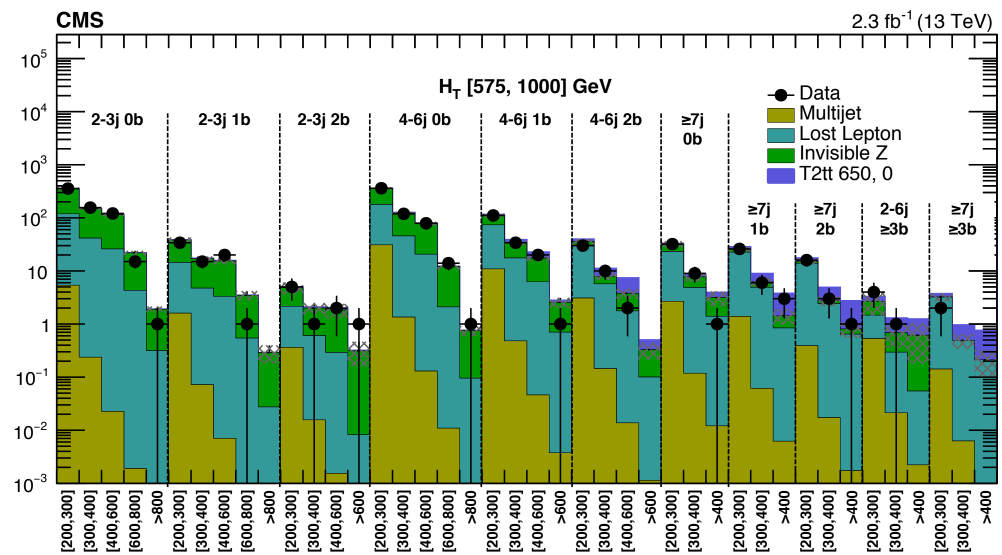




Inclusive searches have become quite sophisticated. The large number of bins collects signal over a broad range of multiplicities and visible and invisible energies.

Comparing inclusive and targeted searches





Targeted searches not yet so targeted, (in part) because of the limited luminosity. Two lines of thinking here:

1. Targeted searches need to be more aggressive in future to significantly improve on the inclusive searches.

2. It will be difficult to convince people that an excess seen in the inclusive searches is real when it's spread across so many regions — simplicity here is a virtue!

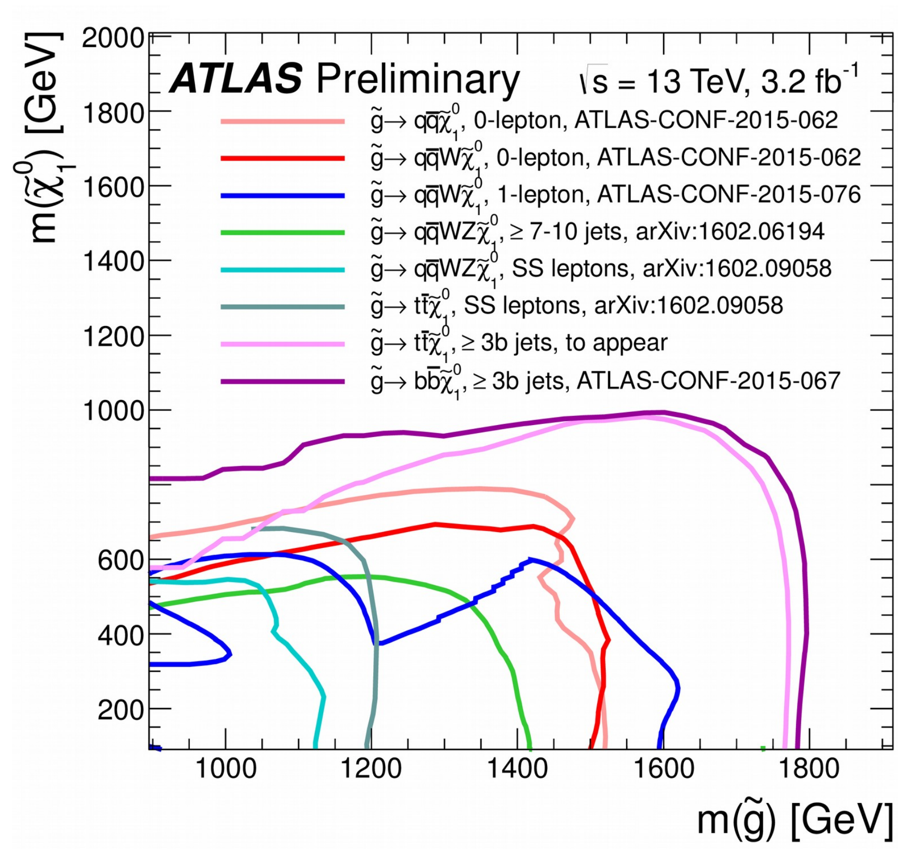
Inclusive searches have become quite sophisticated. The large number of bins collects signal over a broad range of multiplicities and visible and invisible energies.

What does the future look like?

- Much of the gain from going to higher beam energy will soon be realized. As this happens, expect that the focus will transition to lower cross sections, less spectacular signatures:
  - weak production OR
  - more specific signatures OR
  - compressed spectra
  - OR some combination of these.
- Weak production gained less from the increase in beam energy and thus will proceed down a well-worn path, extending reach to higher mass, at least for a while.

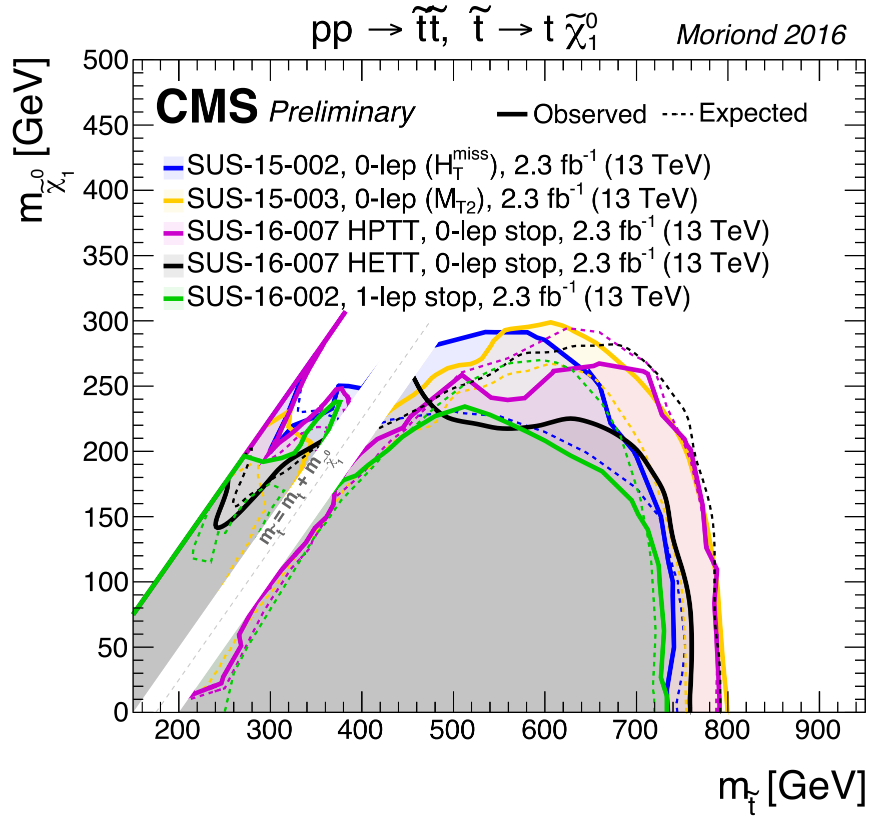
What if nature is more complicated than a simplified model?

- Sensitivity depends strongly on the mass spectrum.
- The presence of additional resonances in the decay chain may increase the multiplicity, but at the expense of softer kinematics and less MET.
- One direction searches are already moving in 2016 is to try to exploit the presence of these resonances:
  - count number of reconstructed H(bb), W(jj)/Z(jj), hadronic top
- These tools have been widely used in "exotics" searches, but are relatively new to SUSY. What do we need to be aware of to make use of these tools?



Compressed spectra: are we ready for the future?

- Scenarios with a compressed mass spectrum are already a subject of interest, and are likely to become more so in the future.
- For now at least, CMS is "whiting out" at least one region with a compressed mass spectrum — the Δm(stop,lsp) = m(top) corridor.
- What questions do we need to answer before we are prepared to make statements about these regions?



Compressed spectra questions, a partial list

1. As we try to push what we can say about compressed spectra, we become sensitive to the far tails of distributions, often those related to ISR. What do we need to understand about how well our background MC works to reasonably trust it for the determination of transfer factors or the actual background estimate itself?

2. Where does sensitivity to compressed spectra come from? How much of it derives from the far tails of kinematic or multiplicity distributions — e.g. high ISR recoil, high ISR multiplicity, high b-jet multiplicity (how often do regions requiring $\geq$3 b-tagged jets contribute to our sensitivity to signals with 2 or fewer b-quarks in the decay?). How do we convince ourselves that we trust our signal MC in these regimes?

3. Where does the signal yield come from? For example, in a jets+MET search, what fraction of the yield is from genuine all-hadronic events and how much from events with $\geq$1L?

4. How important is signal contamination and how is it handled?

5. How important are differences in how we generate signal and background samples? Fullsim vs Fastsim?

6. How can we use other production mechanisms (e.g. VBF) or decays (e.g. soft leptons) to probe these scenarios?

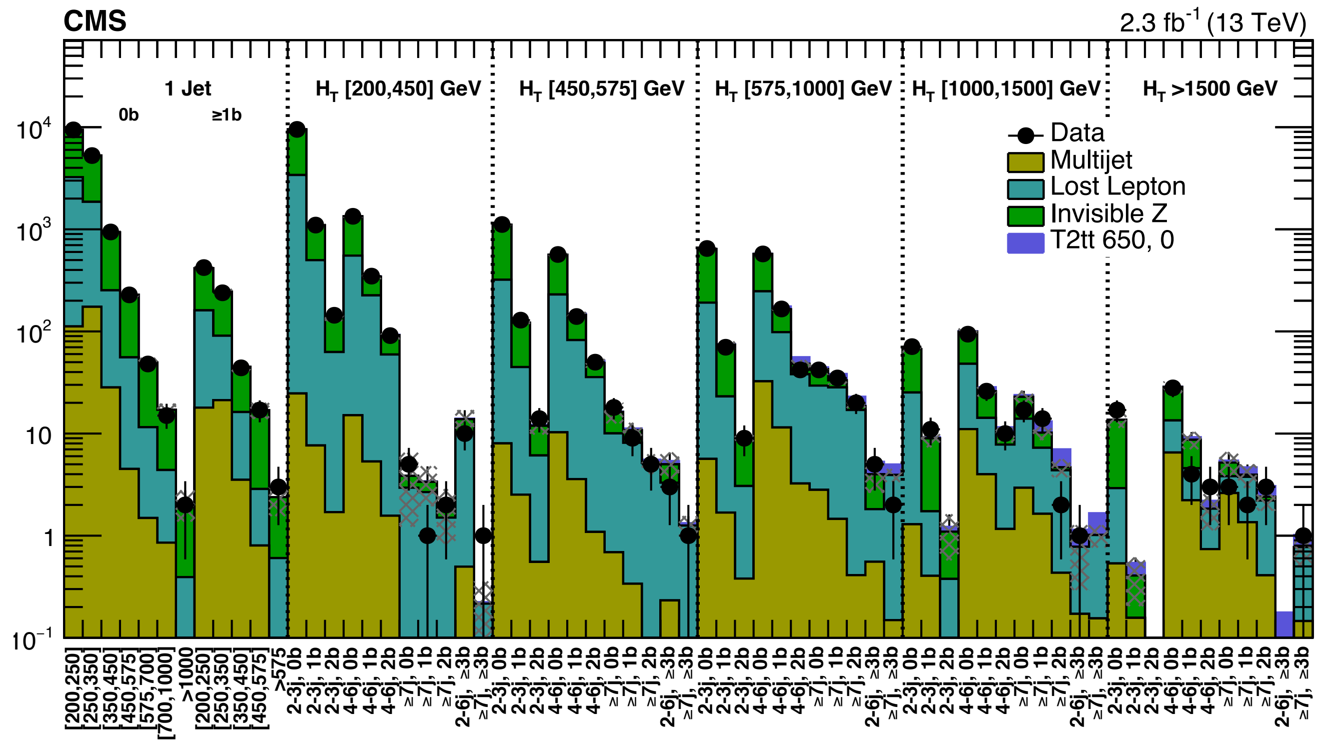
Exciting times ahead, much work to do to get there

- Run 2 of the LHC has just begun. This run is about exploration and discovery.
- The increase in beam energy and the promise of large luminosity datasets gives reason to hope for an exciting future. Perhaps we're already glimpsing the first signs of it?
- As the 2016 run begins, this workshop comes at a perfect time. There are many questions and challenges to address to take full advantage of it, only a small number of them mentioned here.

Backup

What should we do if we see an excess?

Suppose instead of this…

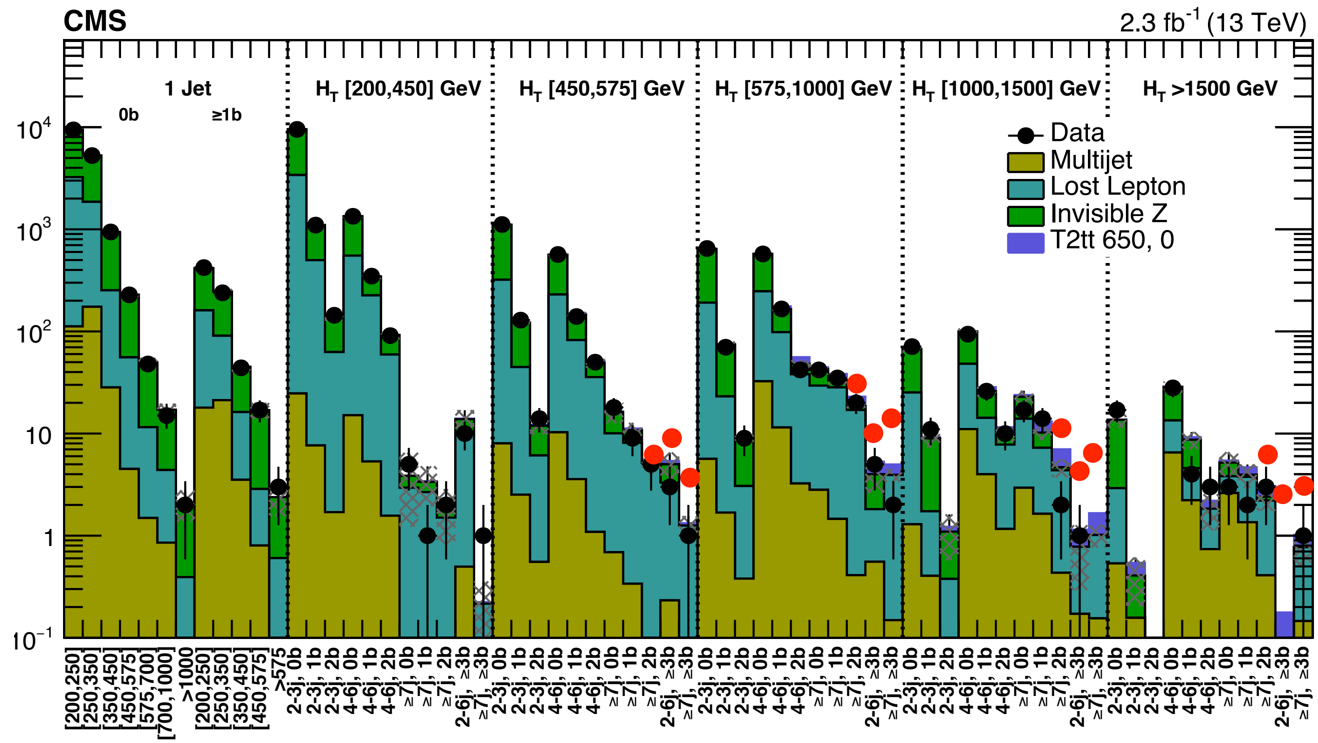


What should we do if we see an excess?

Suppose instead of this…we saw something like this.

The significance of an excess such as this would be severely reduced, if not wiped out, by LEE effects.

What can we do about this?



What should we do if we see an excess?

Suppose instead of this…we saw something like this.

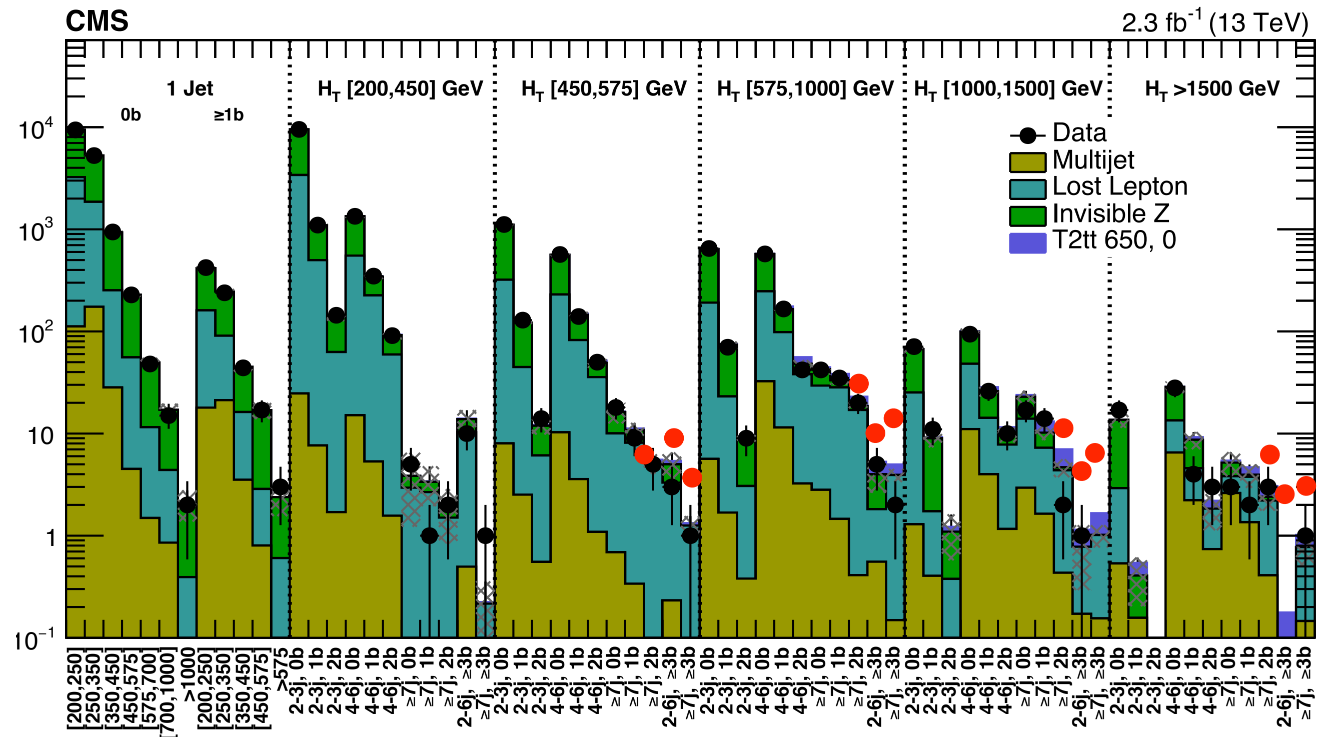
The significance of an excess such as this would be severely reduced, if not wiped out, by LEE effects.

What can we do about this?

Proposal: **Draw a box around the regions characterizing the excess and start over.**

Use just this subset of regions to define a new search. The old data can't be be used to quantify the excess, but the next N/fb can be used LEE-free.

This works as long as we're in an era of rapidly aggregating luminosity.



New search bins: HT > 450, NJ >= 2, NB >=2.