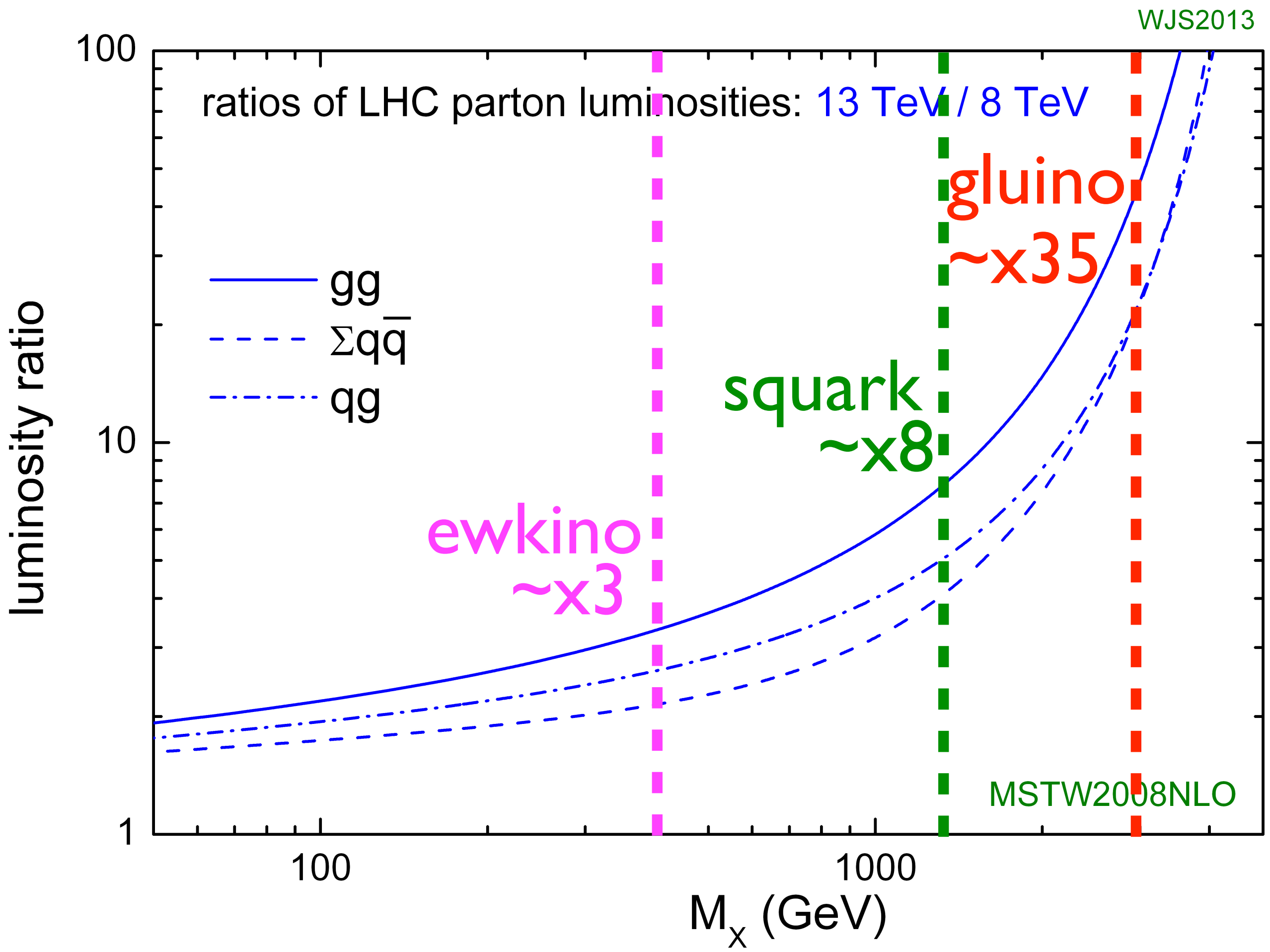
# Searching for SUSY with CMS

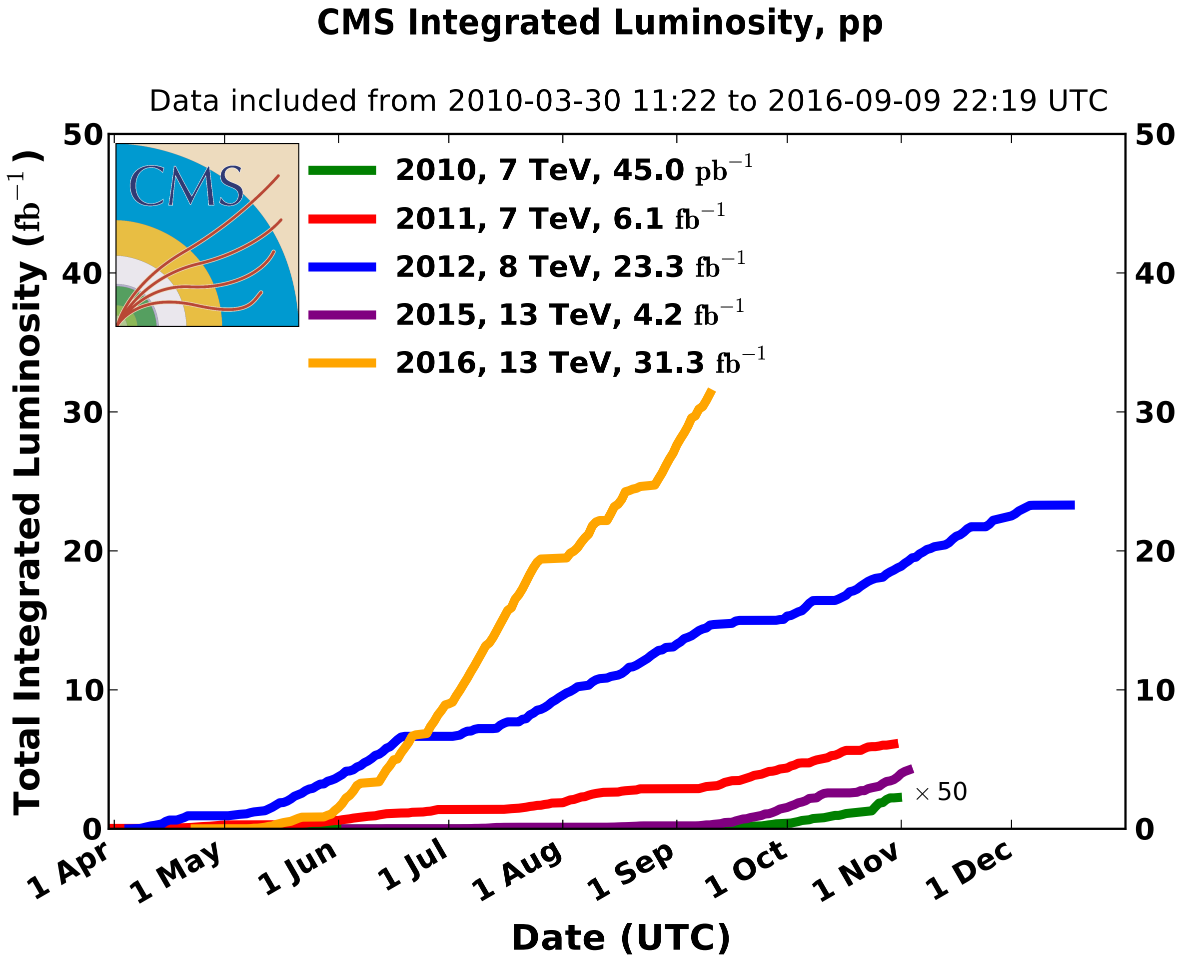
Frank Golf (UCSB)

# Outline

- Selection of searches with 13 TeV collisions
  - Inclusive searches: hadronic jets + MET
  - Searches with soft leptons (+ jets + MET)
- Some thoughts on possible future directions

# What's old is new again

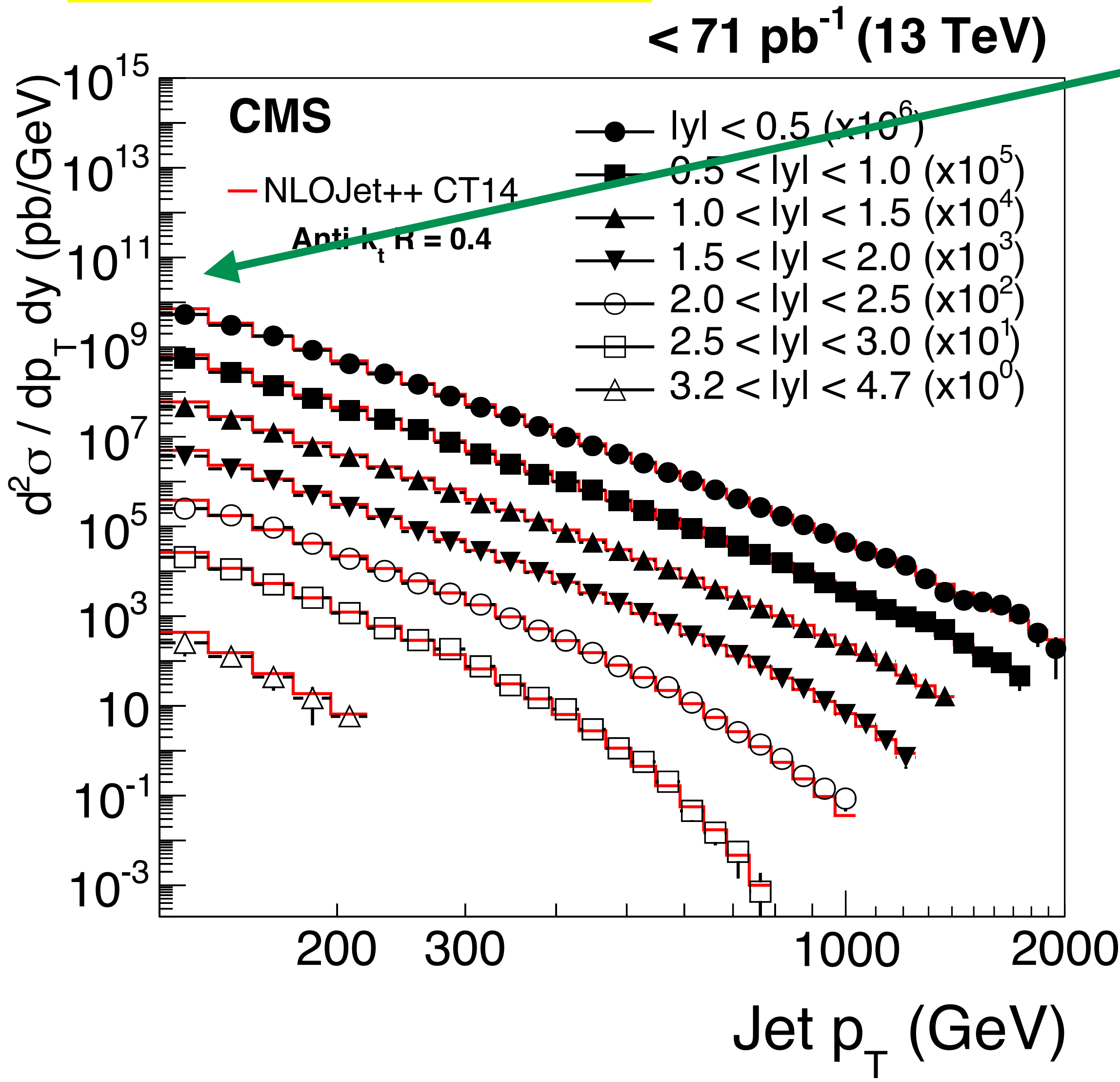


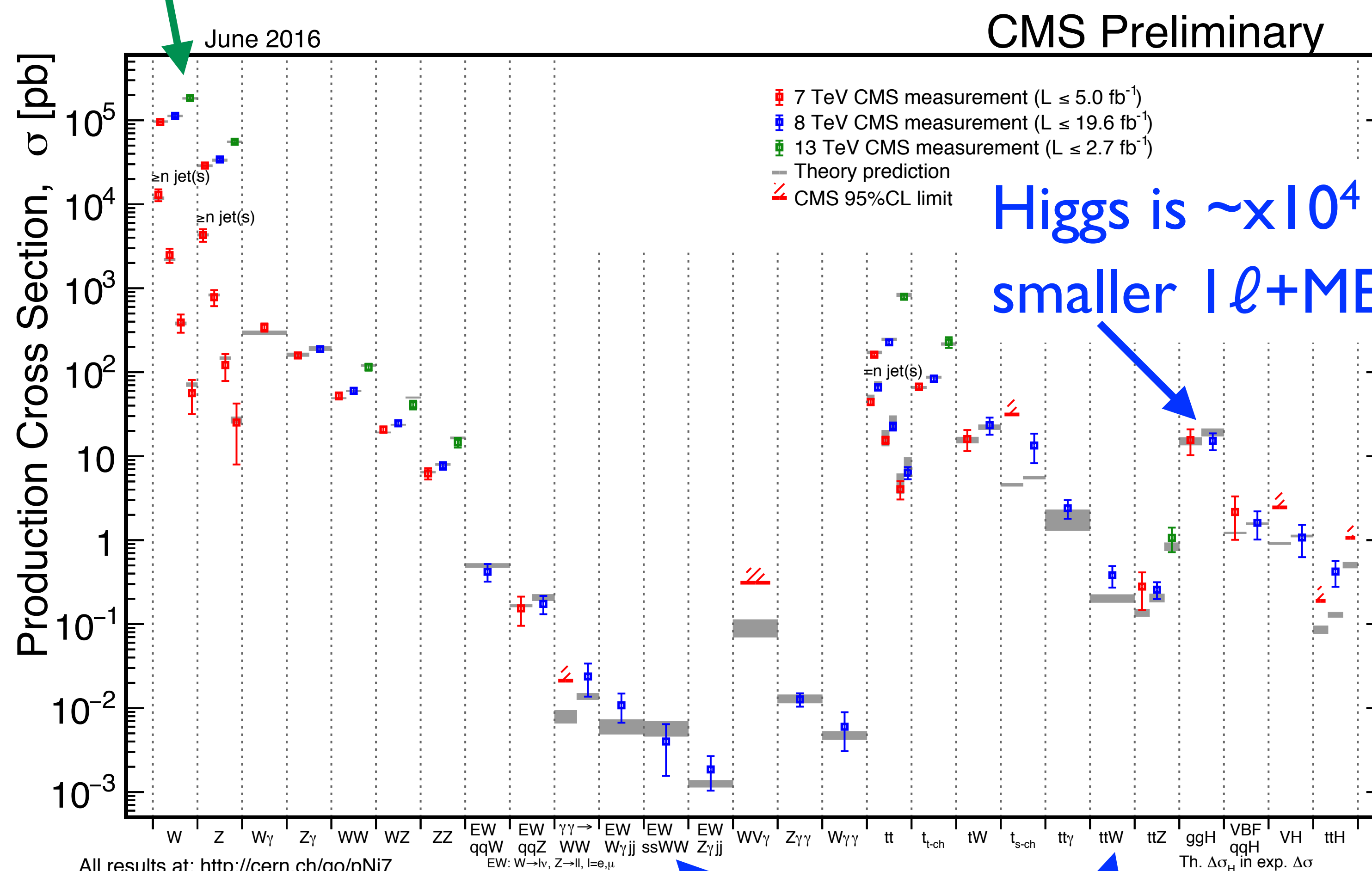

Rapidly increasing luminosity and increased collision energy have made the strategy up to now clear: probe higher mass scales by searching for "spectacular" signatures in the far tails of SM distributions.

# Standard Model @ 13 TeV

CMS-PAS-SMP-15-007




1ℓ+MET cross section many orders of magnitude smaller than all hadronic

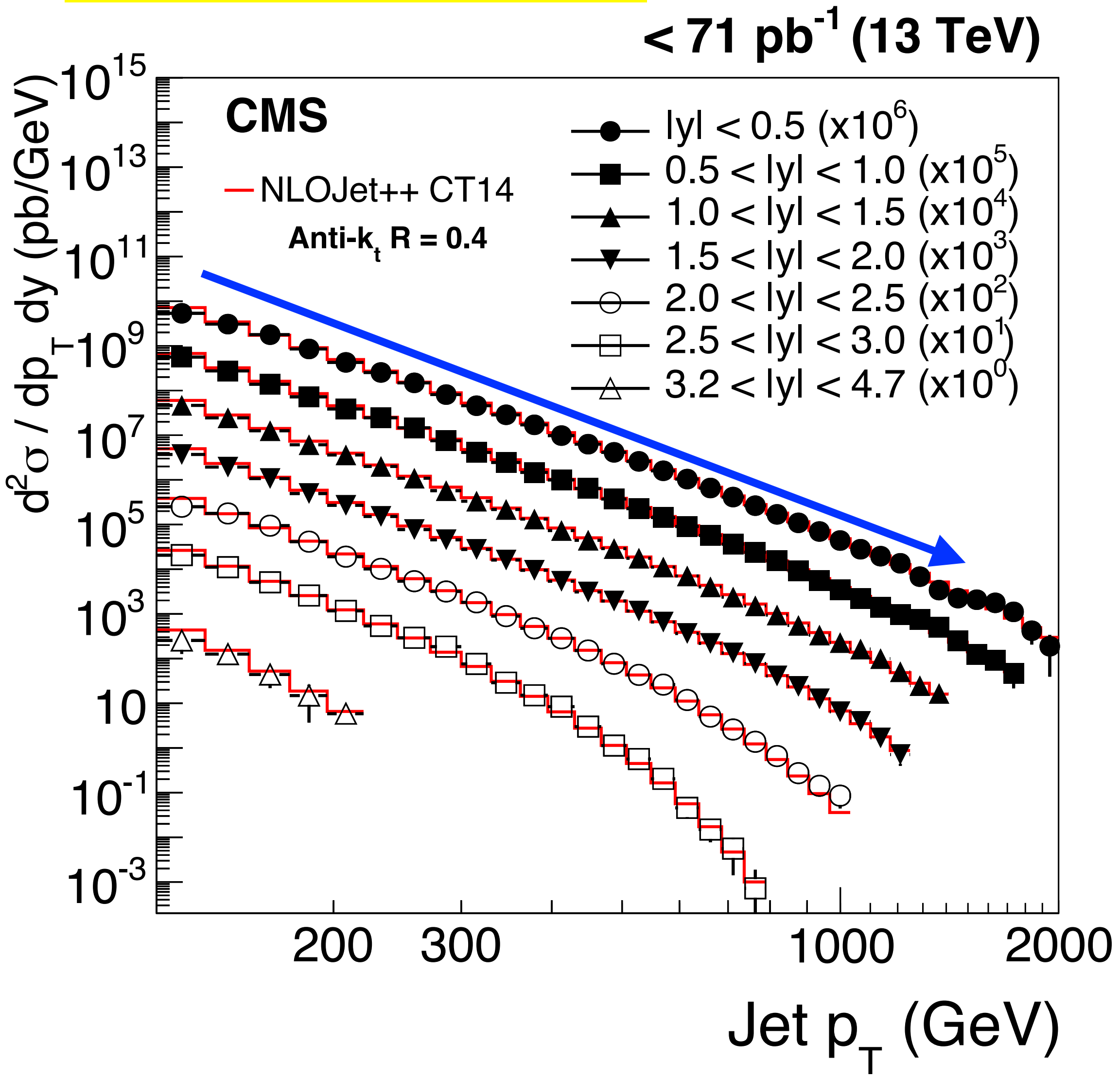



Higgs is ~x10^4 smaller 1ℓ+MET

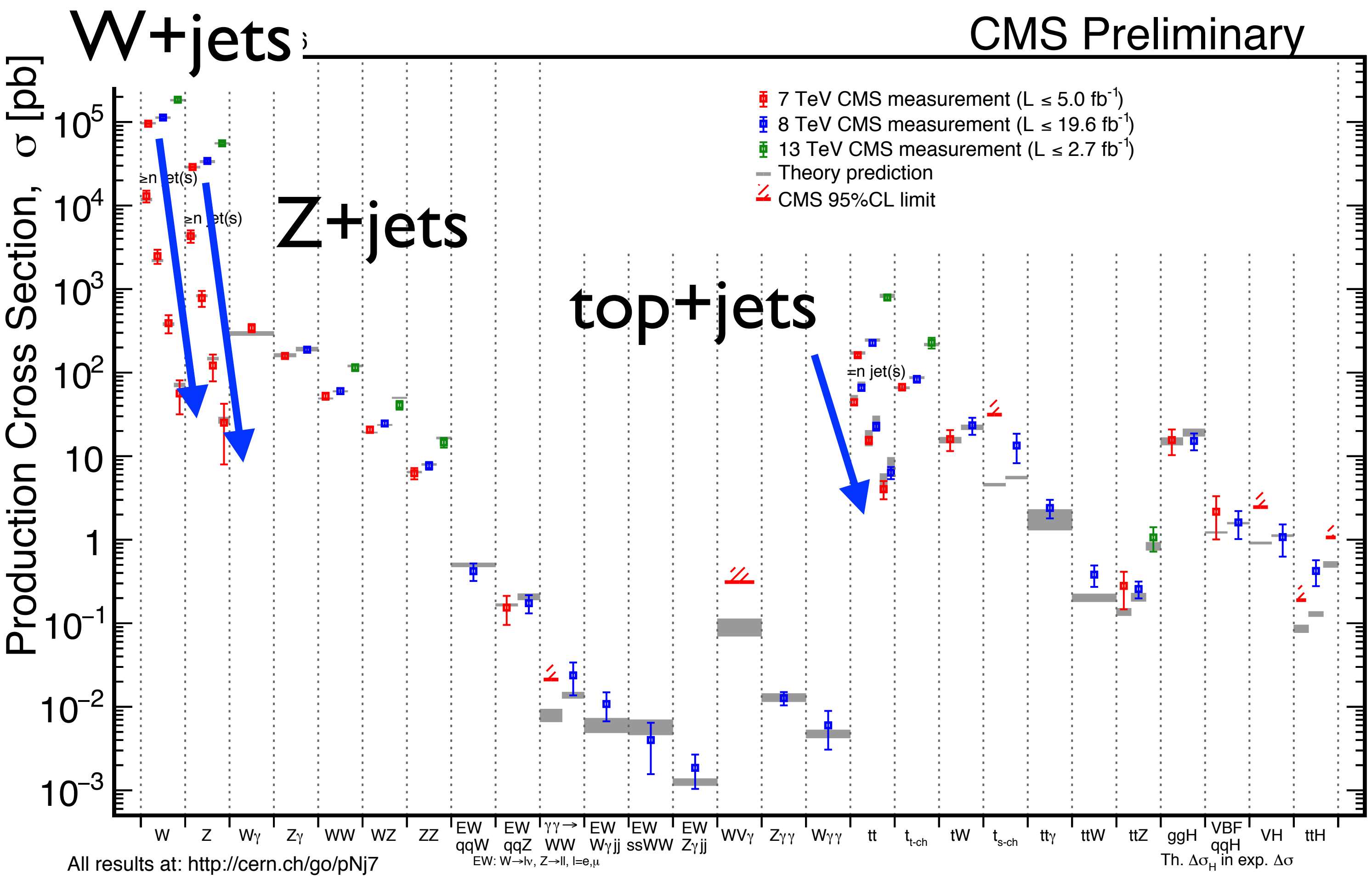
MET, leptons, resonances, etc. are powerful signatures to look for when searching for BSM physics.

Same-sign dilepton+MET are several orders of magnitude smaller still

CMS-PAS-SMP-15-007




Cross sections decrease exponentially with jet $p_T$ and number of jets.

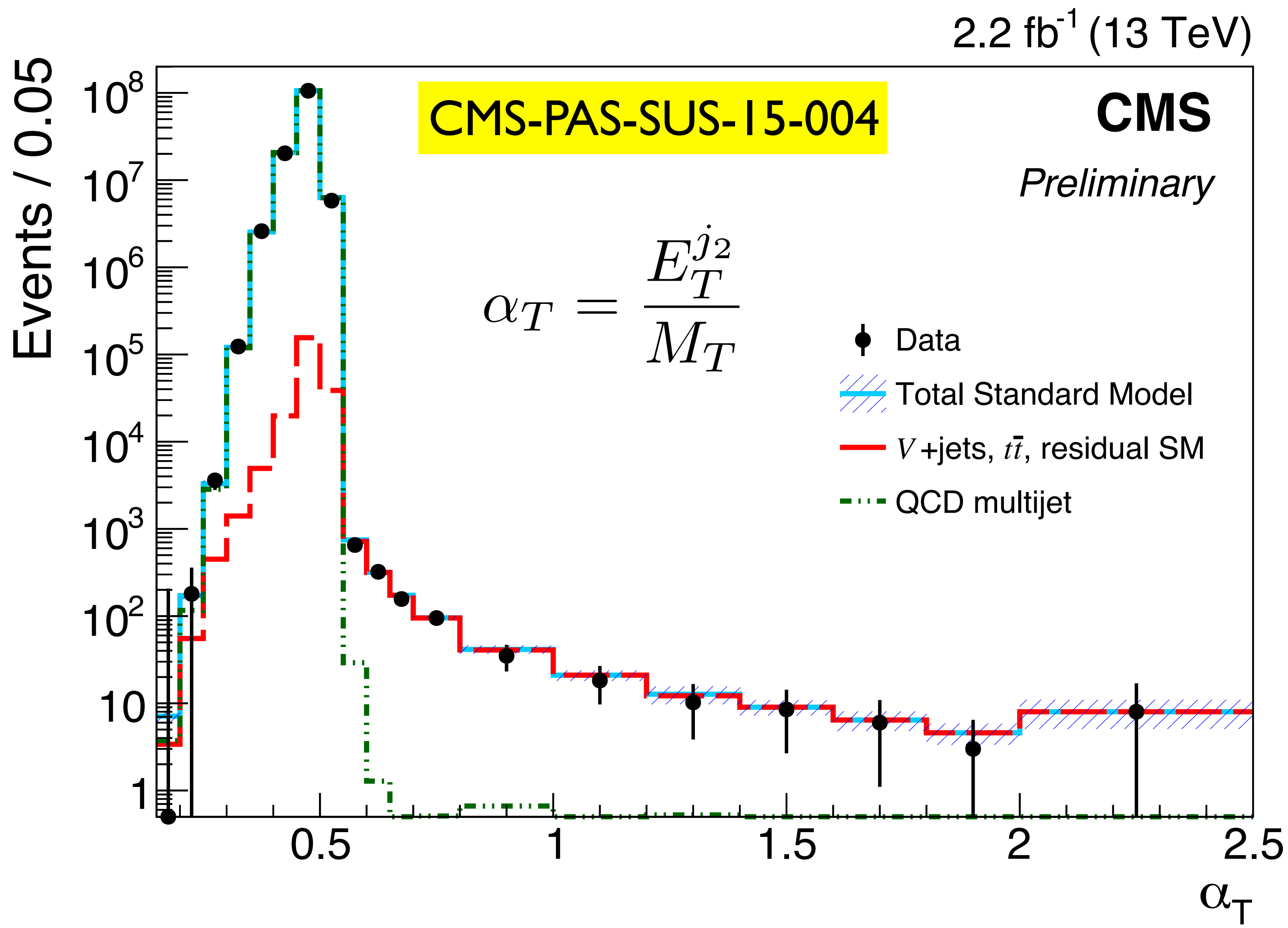


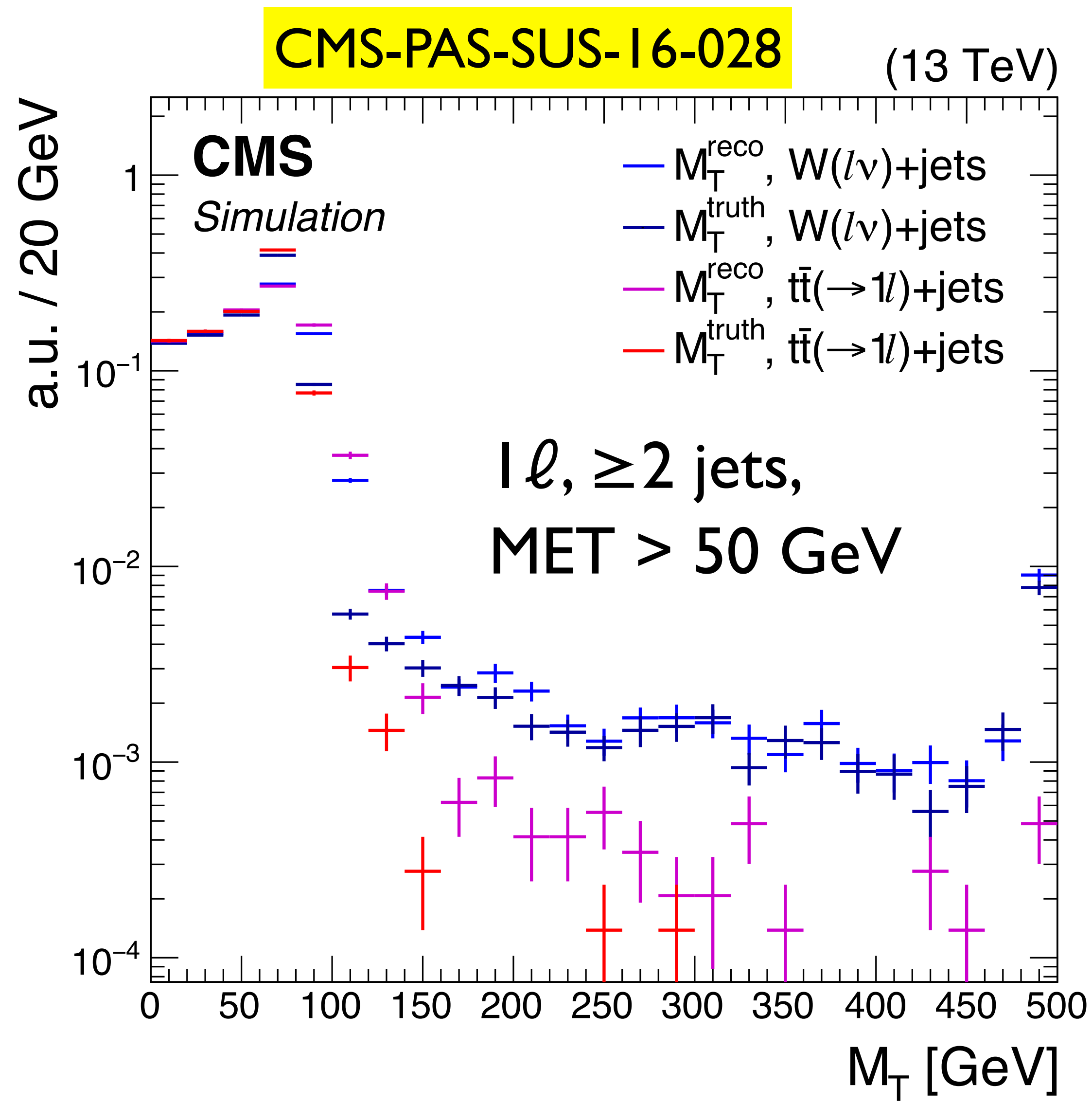

**Count number of jets above some $p_T$ threshold.**
**Define $H_T = \Sigma$ ($p_T$ of selected jets).**

# Suppress SM bkgds. using kinematic endpoints



Cluster visible energy in hadronic events into two mega-jets:



# Broad Search Strategy

- Define low bkgd. search regions using ingredients on previous slides.
- Estimate background from carefully selected bkgd-enriched control samples.
  - Extrapolation from control sample to search region using mixture of data and simulation.

- Generic searches for NP: signature-based, probe tails of SM processes.
  - classic signatures: $0\ell$, $1\ell$, SS $2\ell$, $\geq 3\ell$ with hadronic activity and significant MET.
- Targeted searches when there is strong theory motivation.
  - Searches for third generation partners continue to be one of the top priorities.

**Basics of strategy common to all searches in this final state:**

- cut tight on some kinematics until QCD bkgd. is small.
- categorize events by multiplicity, flavor, visible & invisible energy
- search for excess yield above data-driven bkgd. estimate

Count (b-tagged) jets with $p_T$ > (20) 30 GeV

Veto events with e,μ or isolated track to suppress top & W background

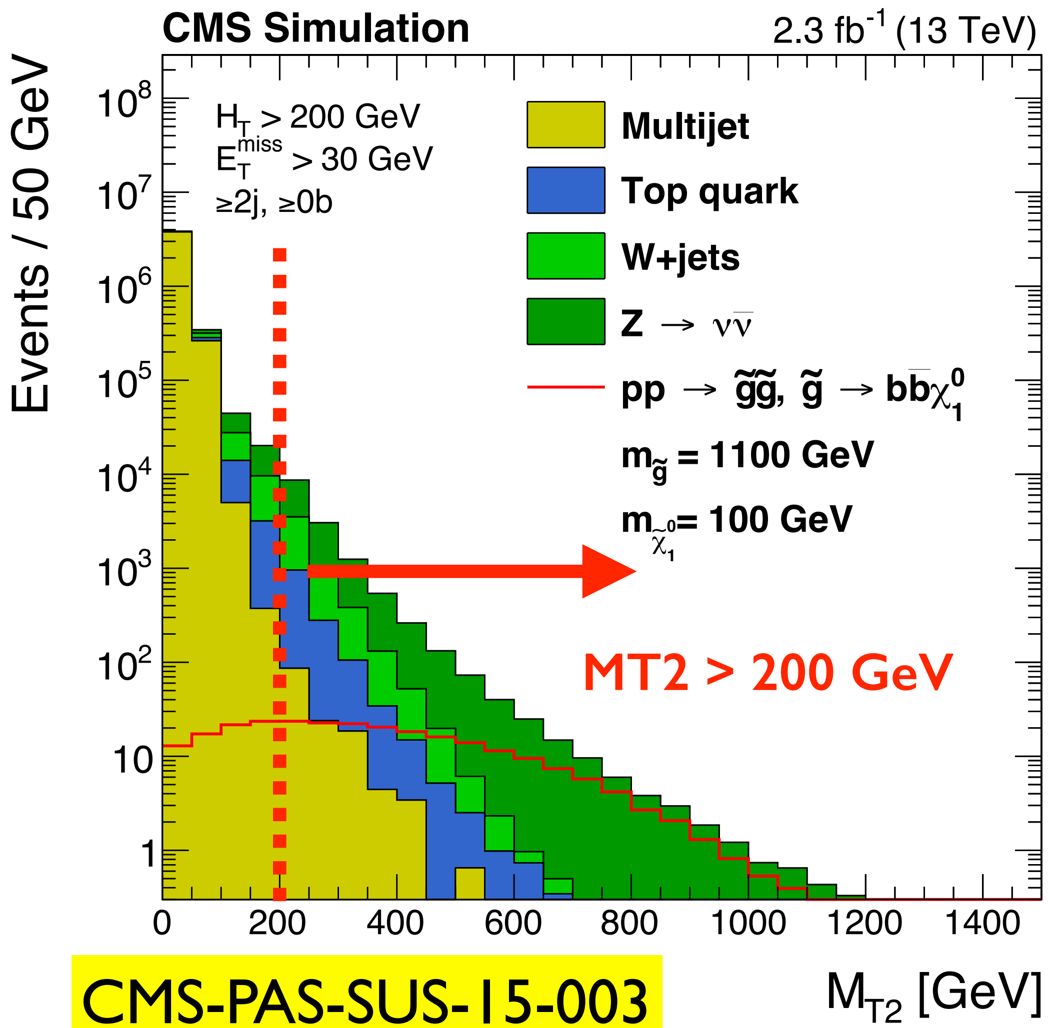
Suppress QCD by requiring:

- MET $\Delta\varphi > 0.3$ with 4 leading jets
- minimum MT2 of 200 GeV

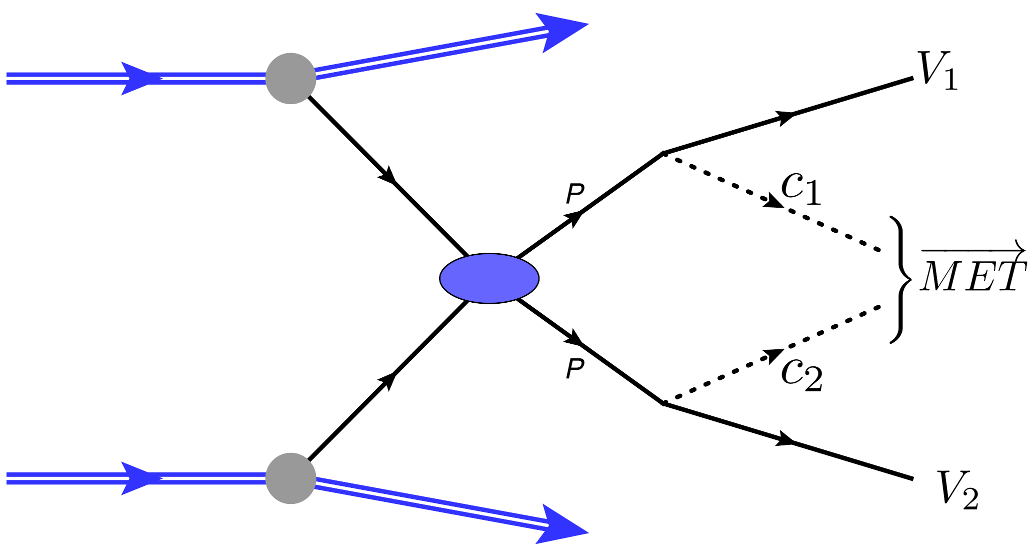
# Generic searches for NP in jets + MET

- CMS has several generic searches for NP in jets + MET. They differ primarily in how they use information about the invisible energy in the event. Also some differences in details of binning and background treatment.

- One version makes use of MT2, a generalization of transverse mass ($M_T$) to scenarios with two decay chains each with one or more invisible particles.




CMS-PAS-SUS-15-003



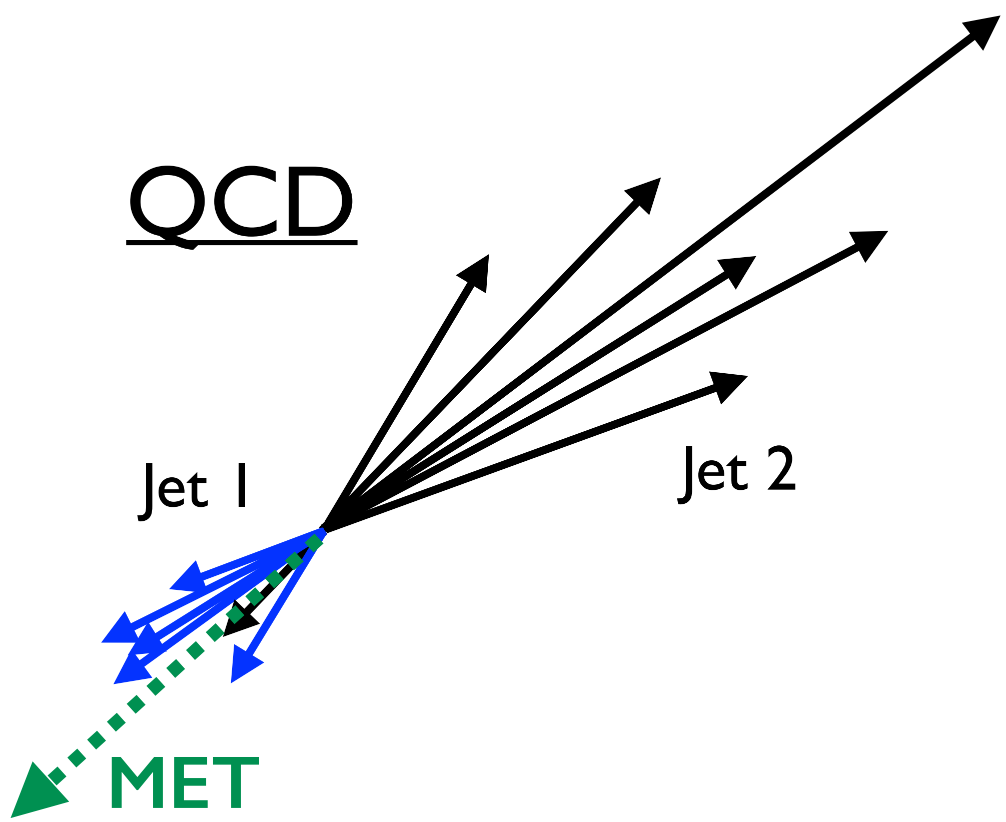

$$M_{T2}(m_c) = \min_{\vec{p}_T^{c(1)} + \vec{p}_T^{c(2)} = \vec{p}_T^{miss}} \left[ \max\left( M_T^{(1)}, M_T^{(2)} \right) \right]$$

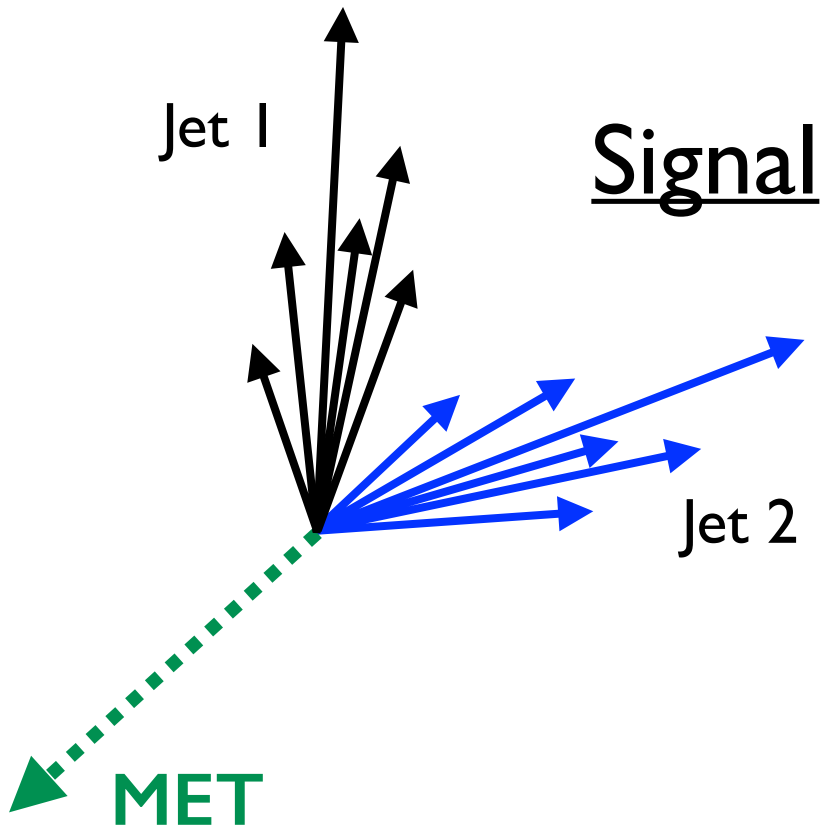
MT2 for dijet events:

$$M_{T2}^2 = 2 p_T^{V(1)} p_T^{V(2)} (1 + \cos\phi_{1,2})$$

MT2 ≈ MET for X pair production with X→Y + LSP.

MT2 ≪ MET for topologies that are nearly back-to-back.



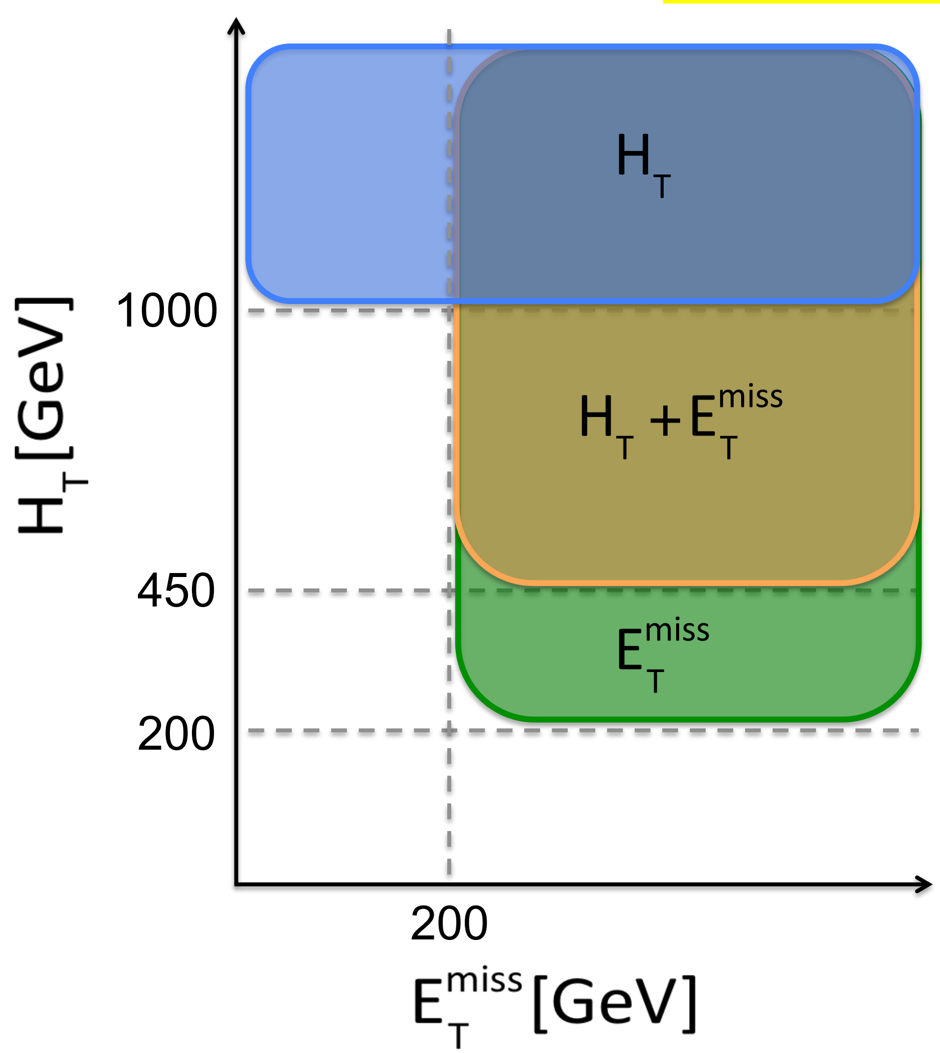



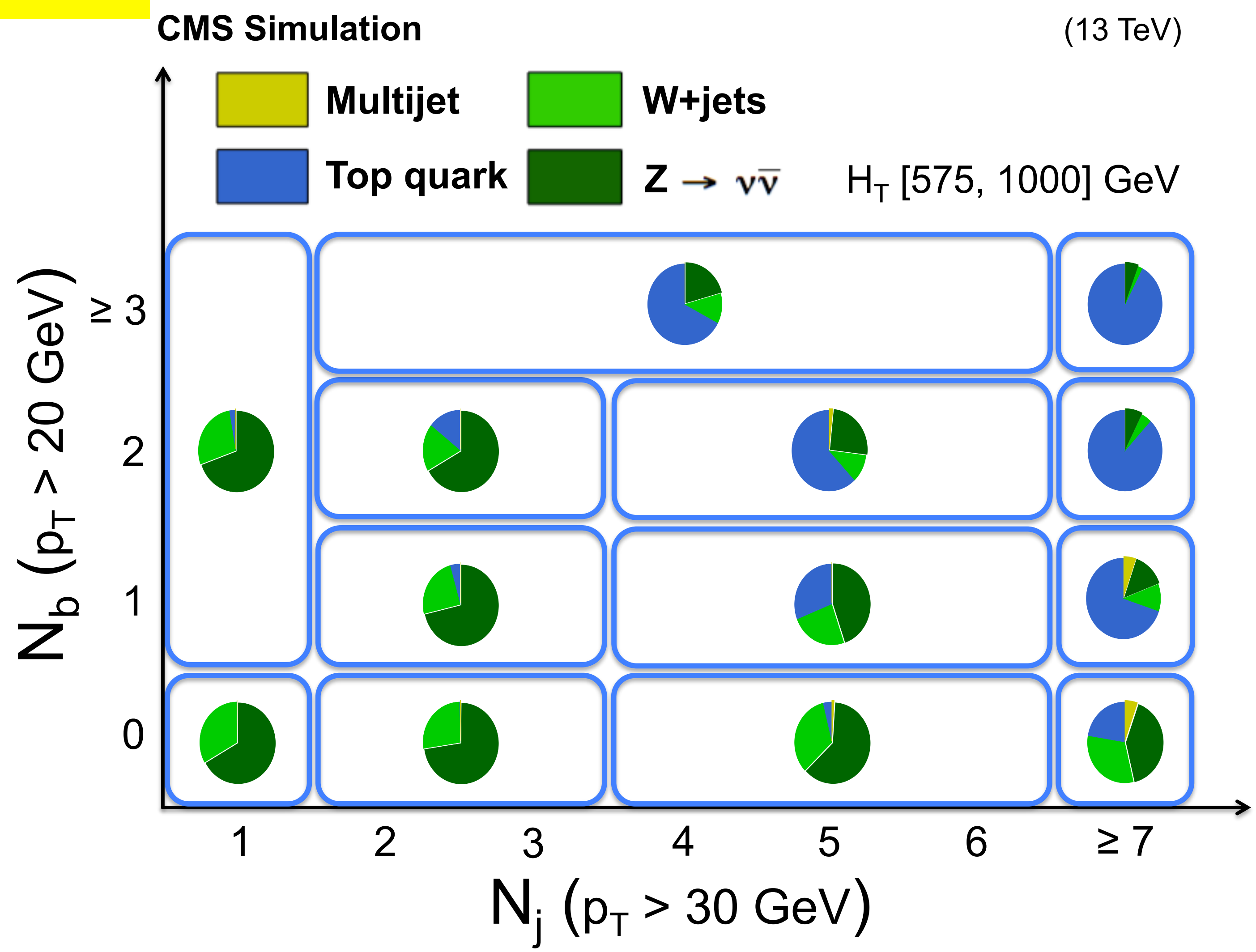

MT2 << MET

MT2 ~ MET

Design search to cover the full phase space permitted by the trigger.

CMS-PAS-SUS-16-015

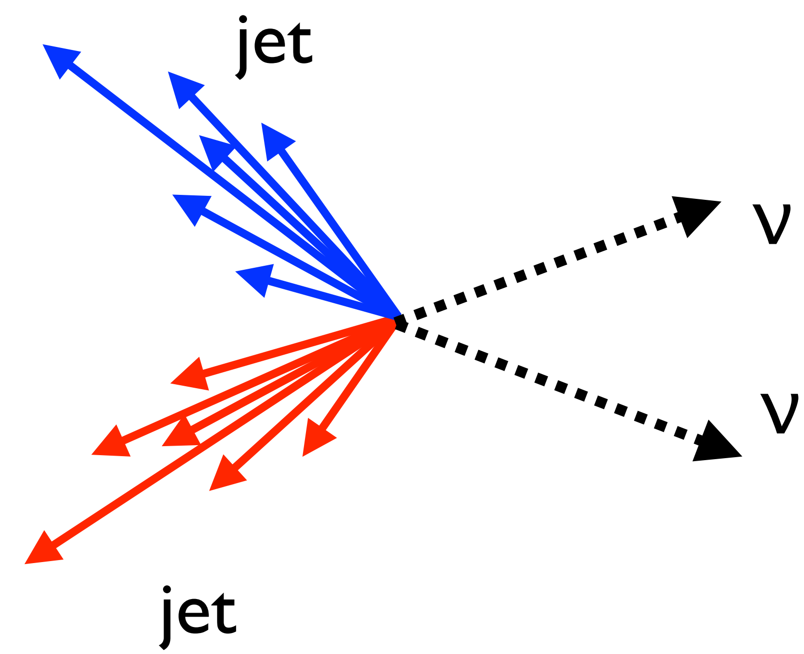


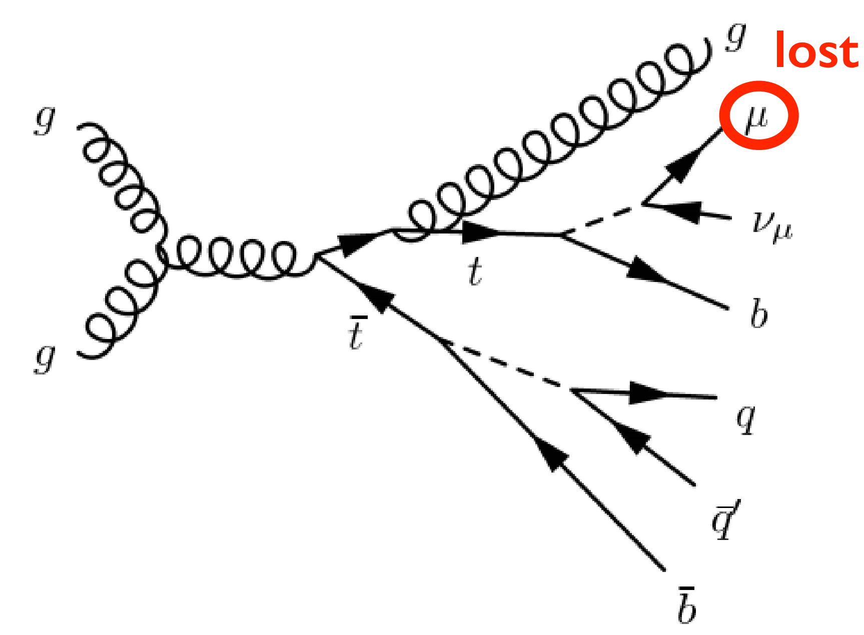

Search based on MT2 has 174 search regions in bins of $H_T$,$N_j$,$N_b$,$MT_2$.

# Data-driven background estimates

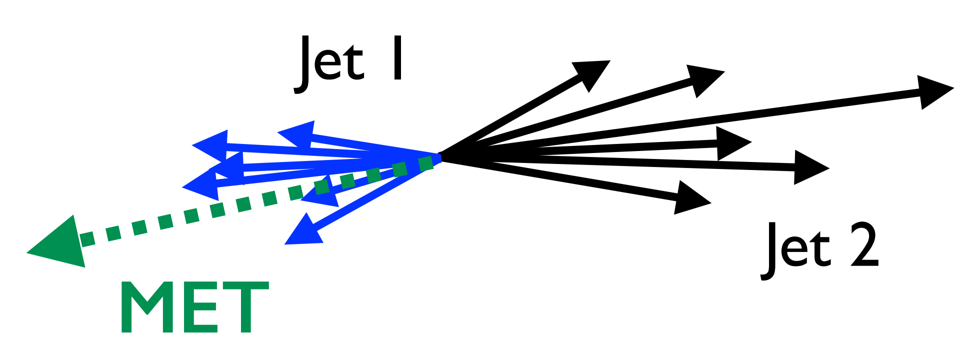
- **Invisible Z ($Z \to \nu\bar{\nu}$)**
  - Irreducible background: real MET from neutrinos
  - Data-driven estimate based on γ+jets control region




- **Lost lepton (top, W+jets)**
  - Real MET from leptonic W decay
  - Data-driven estimate based on 1 lepton control region




- **QCD multijet**
  - MET from jet mis-measurement
  - Data-driven estimate using low Δφ, MT2 sidebands



# General Idea

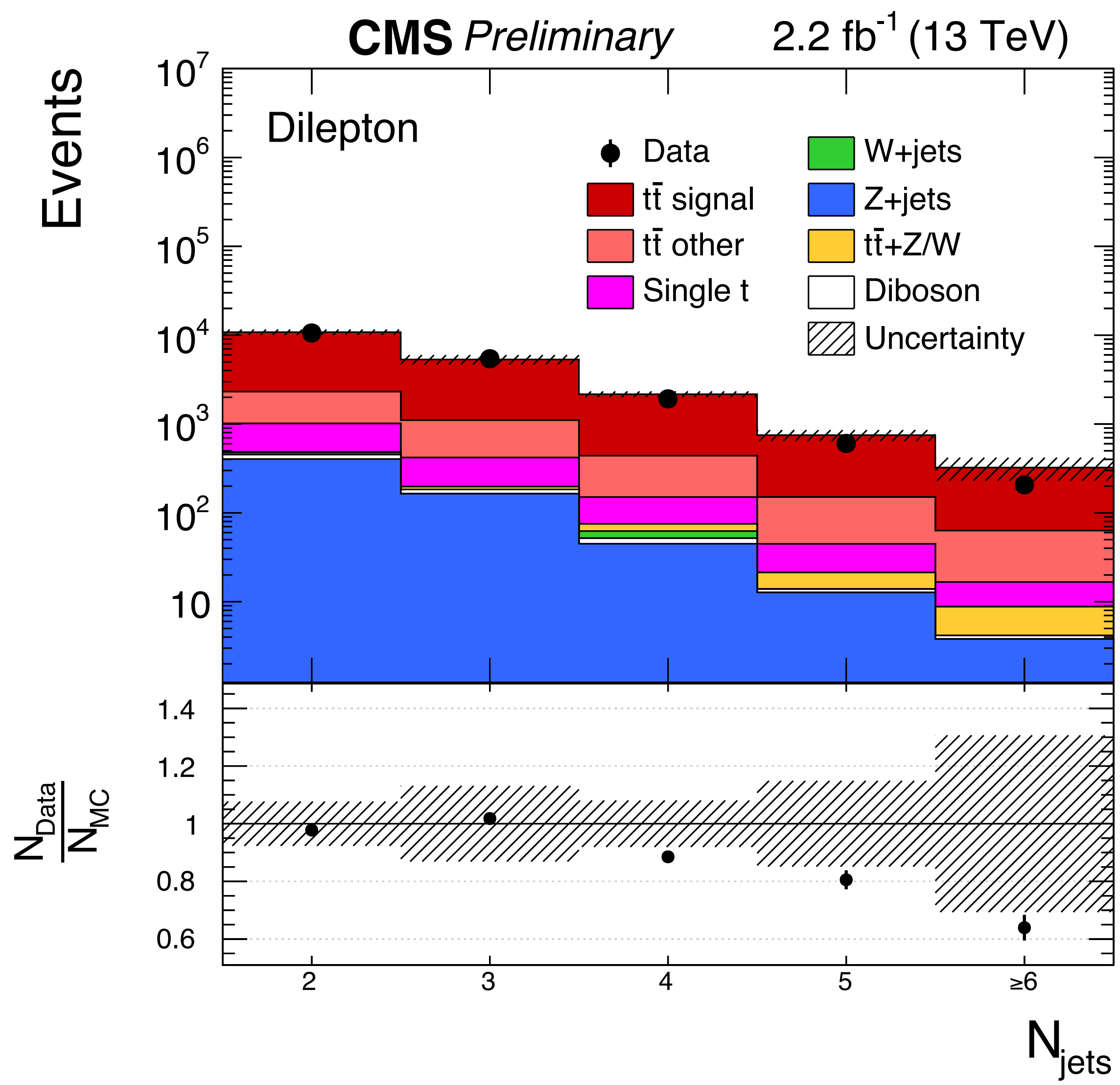
CMS-PAS-TOP-16-011

Define control regions (CR) orthogonal to but with similar kinematics as signal regions (SR), e.g.

$$N_{LL}^{SR}(H_T, N_j, N_b, MT_2) = \kappa \times N_{1\ell}^{CR}(H_T, N_j, N_b, MT_2)$$

where κ is a CR → SR transfer factor (TF) taken mostly from simulation.

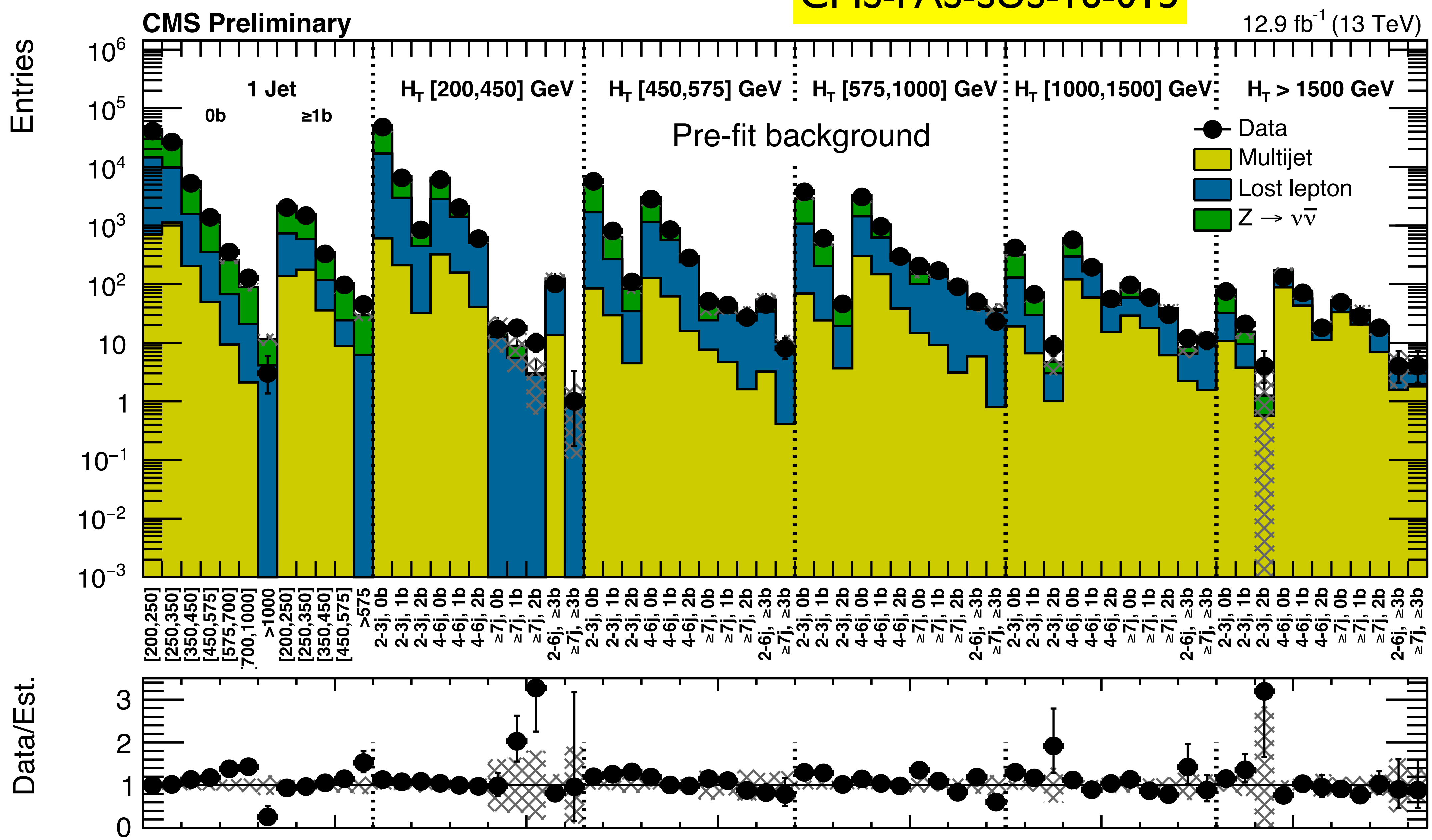
In some cases, the TF may include an extrapolation in one or more of the kinematic variables in which the search is binned.




When possible, minimize reliance on MC, which is good but not perfect.

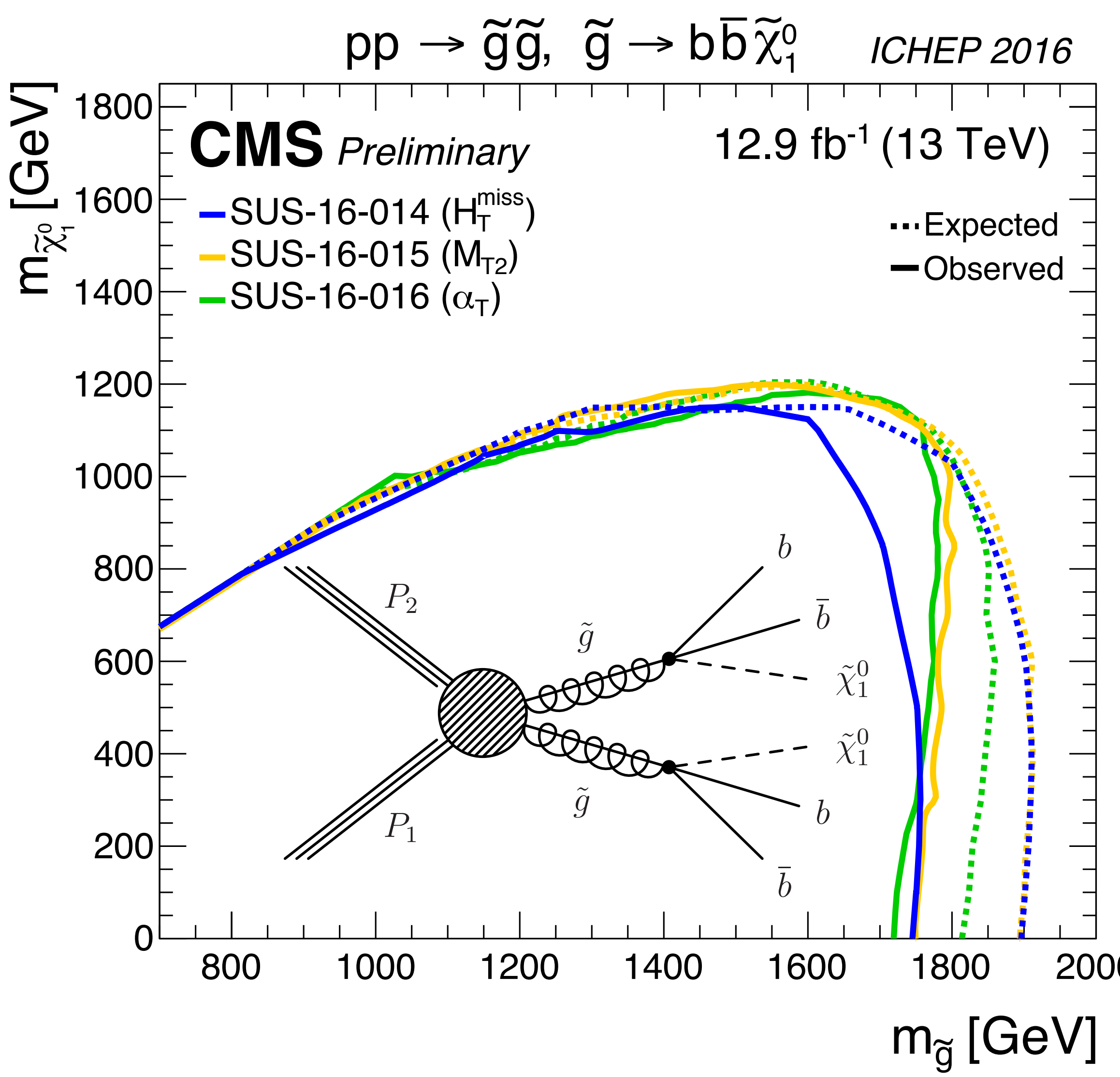
# Results of jets+MET search with MT2

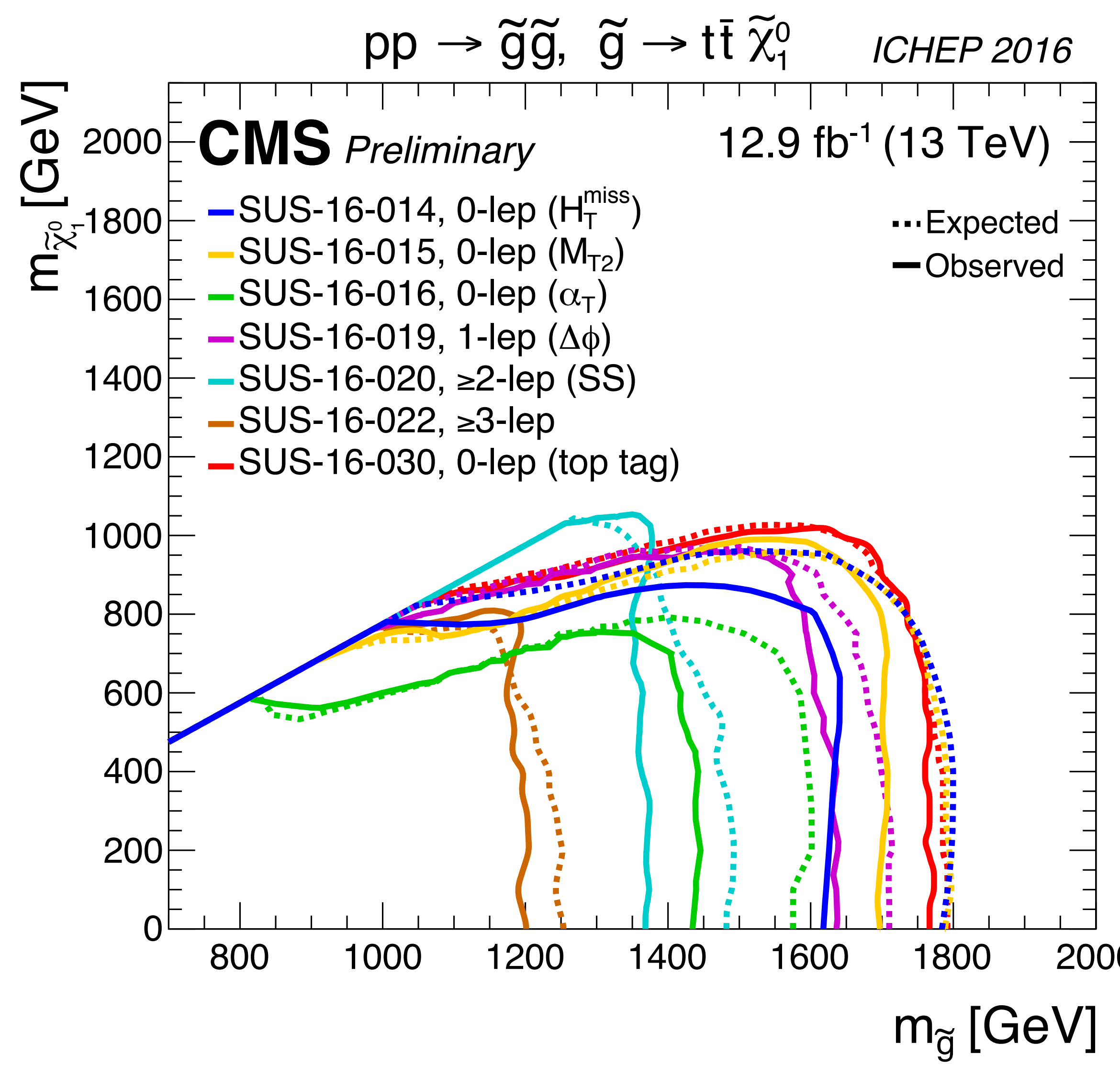
CMS-PAS-SUS-16-015




No evidence for non-SM physics, here, or in any other SUSY search with 13 TeV data.

# Interpreting results with simplified models

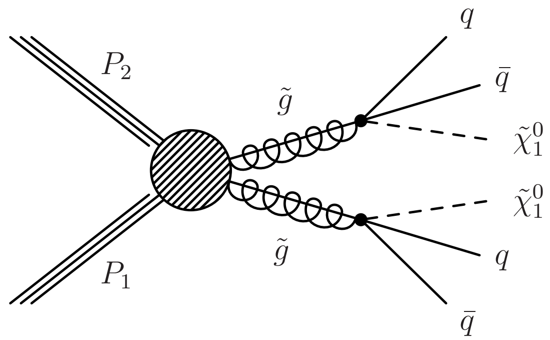


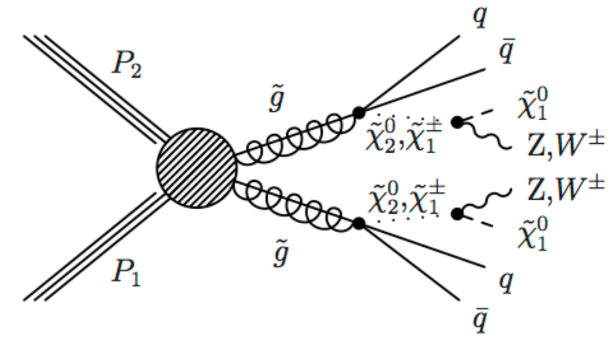

Probe gluino masses up to ~1.8 TeV. If fine-tuning is our guide, these are the results that may leave us most anxious…

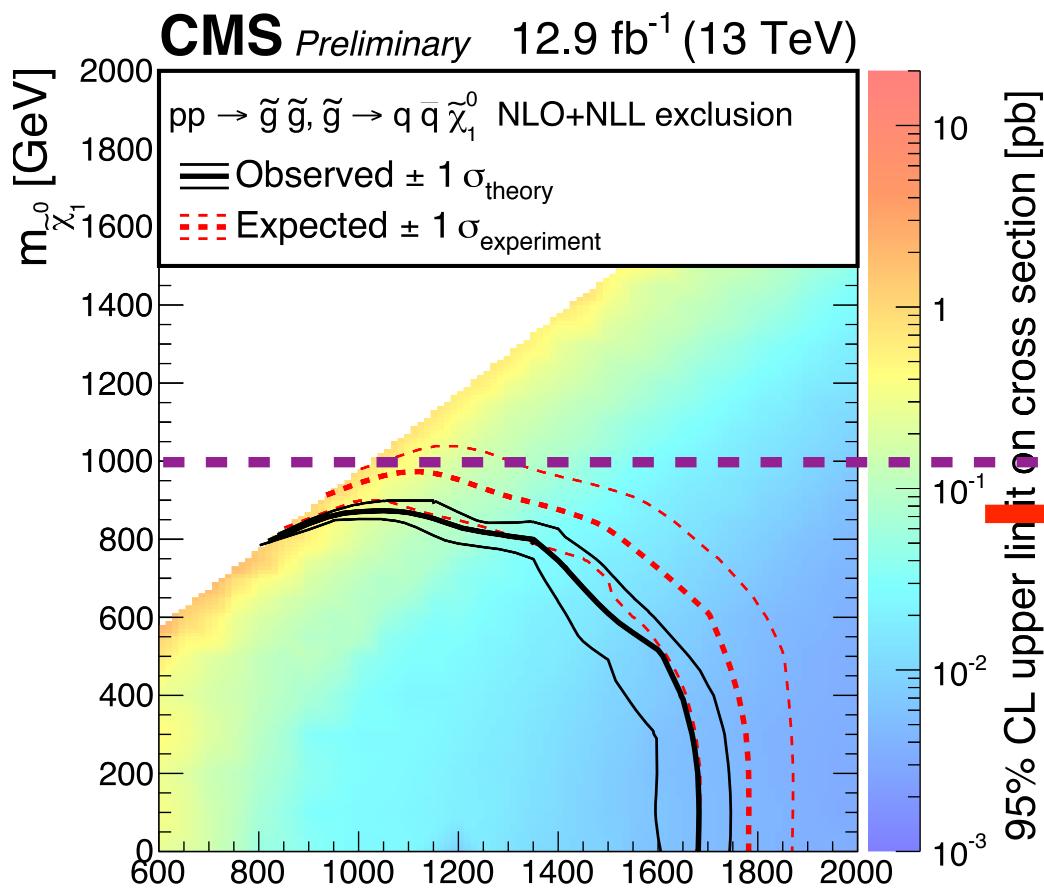
Of course, these are simplified models, they don't necessarily tell the whole story.

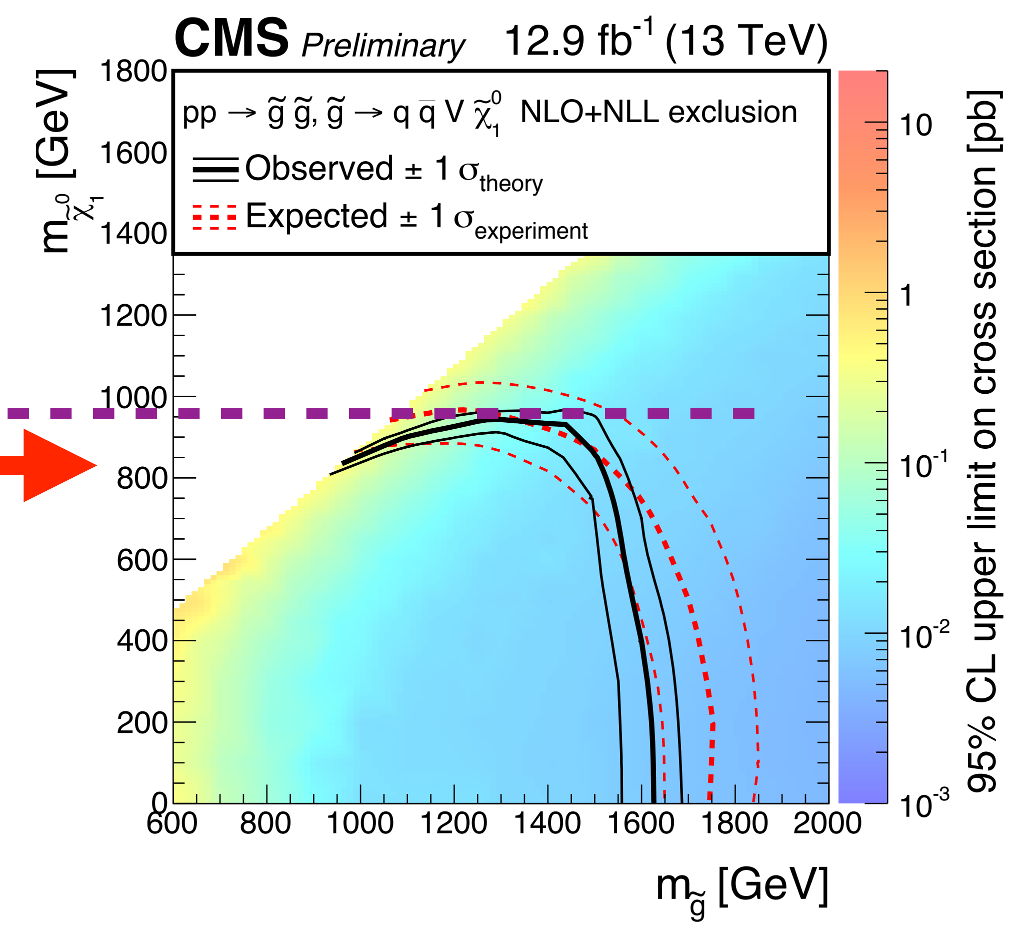
# Tradeoff between kinematics and multiplicity




4 jets → 8 jets



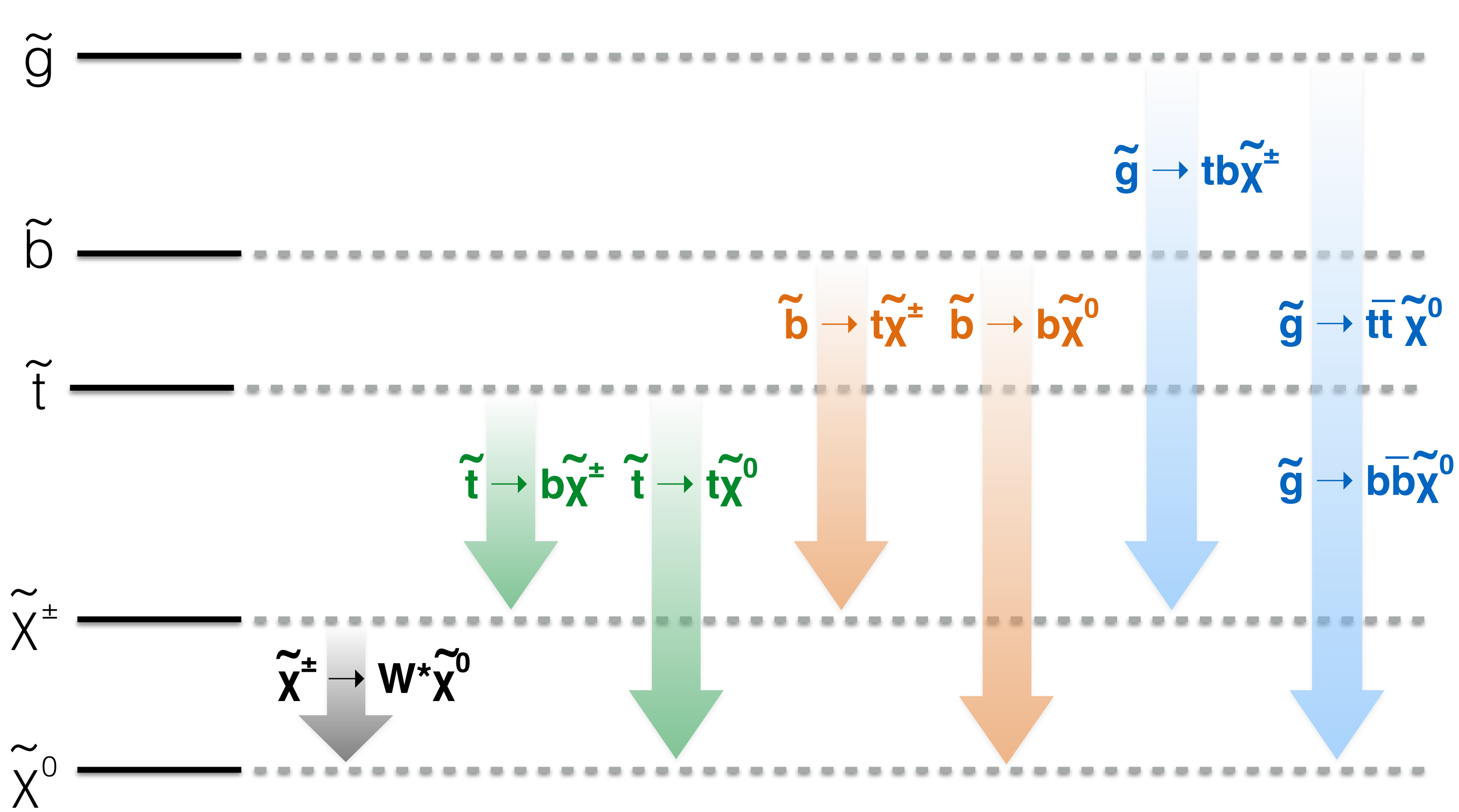




CMS-PAS-SUS-15-002

For the same mass, adding intermediate states leads to more, but softer jets and less MET. We probe similar mass scale by being broad with our search strategy.

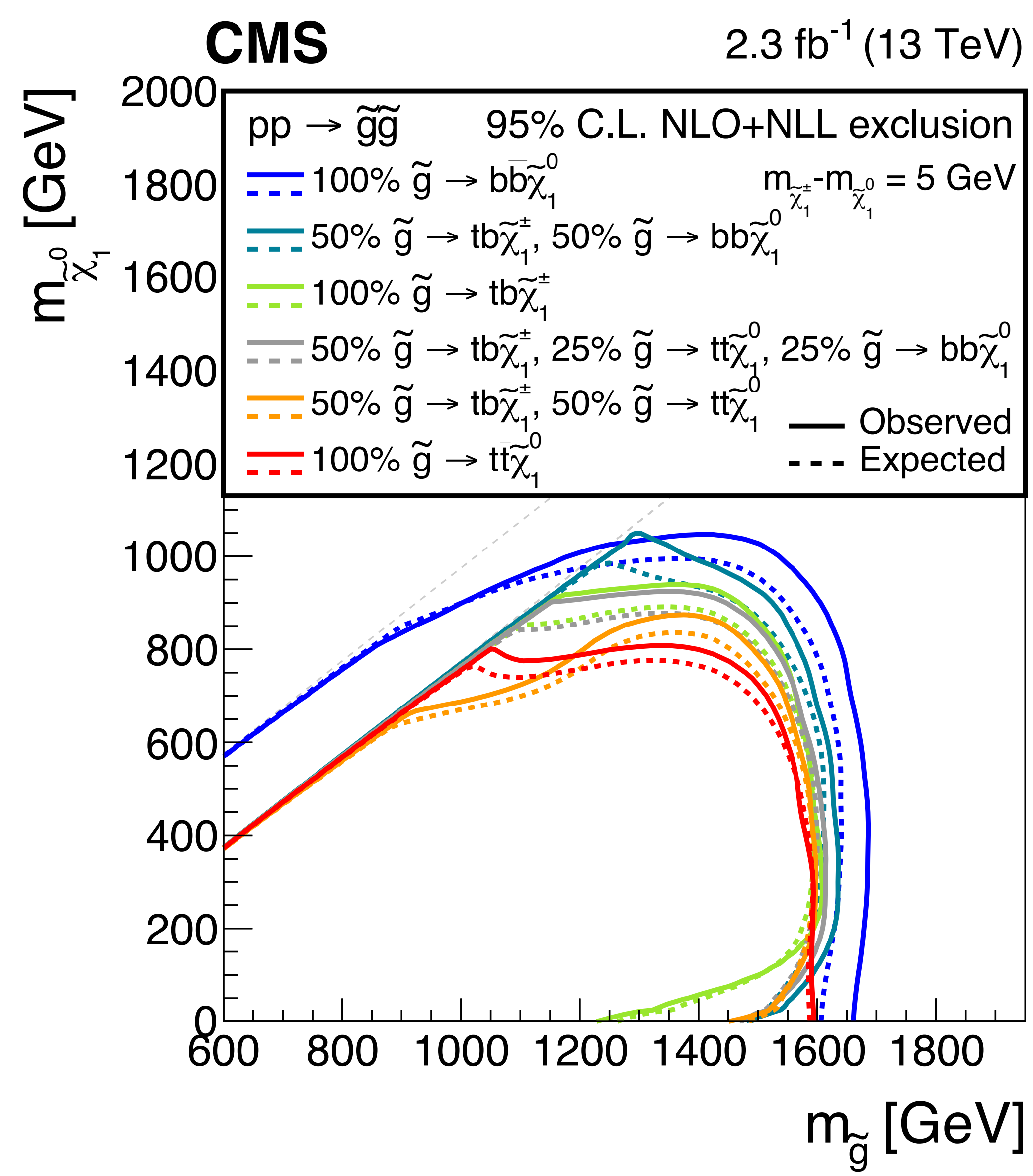
# BR need not be 1, but gluinos need to decay to something

An example of a "natural" spectrum?



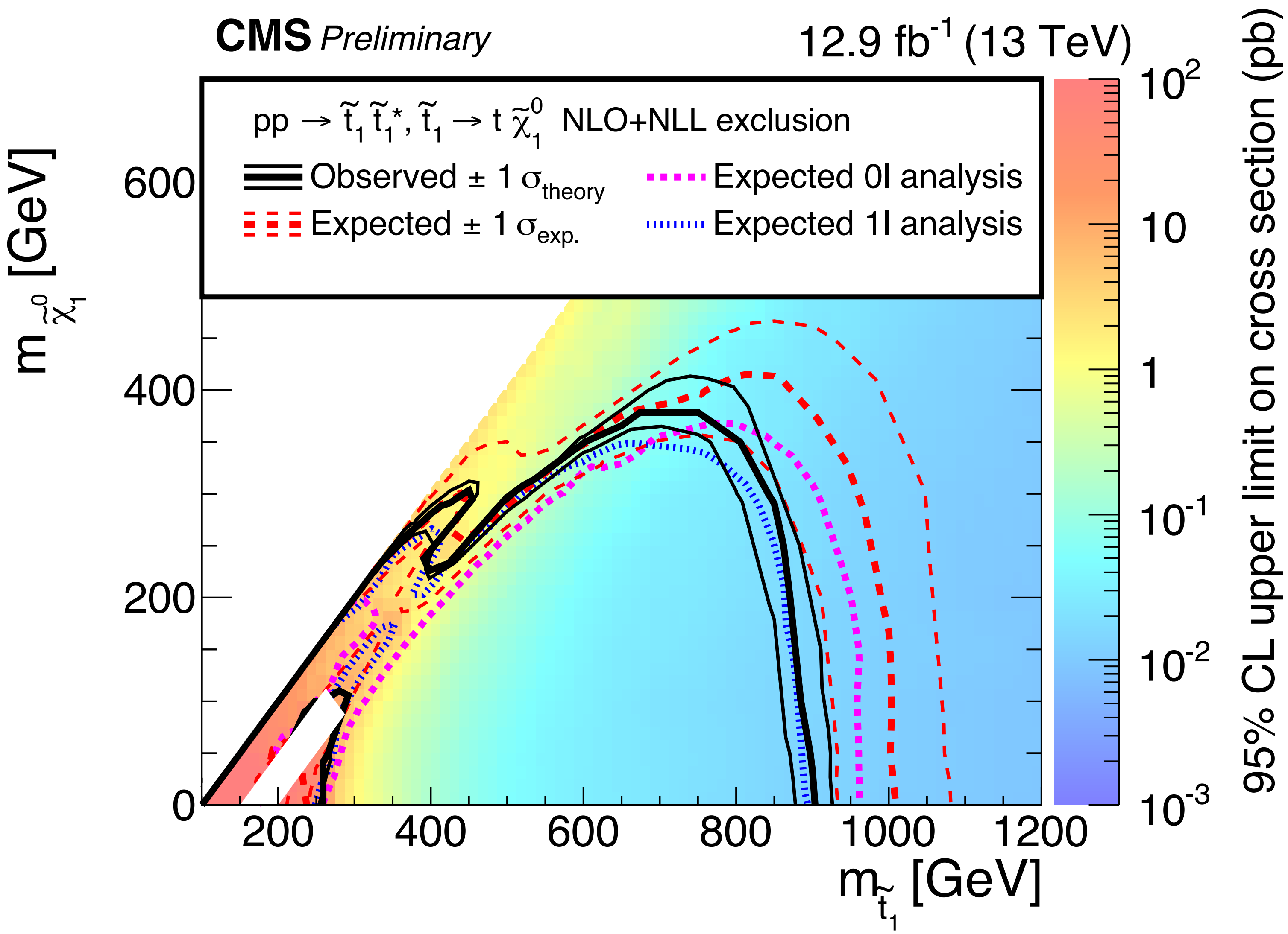

CMS-PAS-SUS-14-011

CMS-PAS-SUS-15-004




Studies after Run 1(arXiv: 1310.5758) found it was difficult to accommodate gluinos below ~1 TeV regardless of the decay modes and Run II data has allowed the LHC to extend sensitivity to gluino mass by ~500 GeV.

# Similar situation for squarks as gluinos

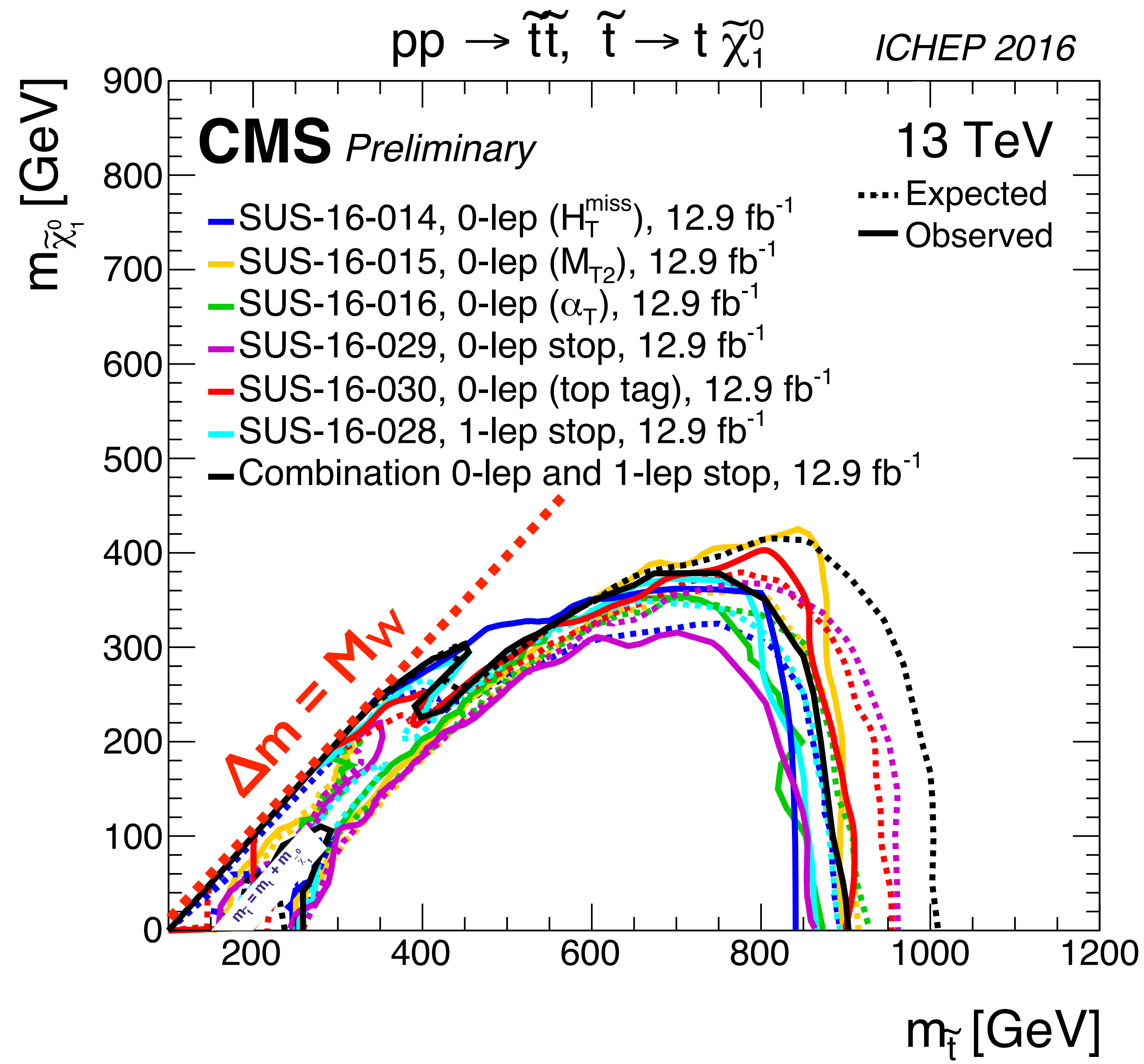



But conclusions aren't as drastic.

We're beginning to probe stop masses near ~1 TeV, although only for relatively light LSPs. Both 0L and 1L searches see a slight excesses at high stop and low LSP masses. A hint?

The difference in sensitivity between the inclusive and targeted searches isn't so big.

At least for setting limits.



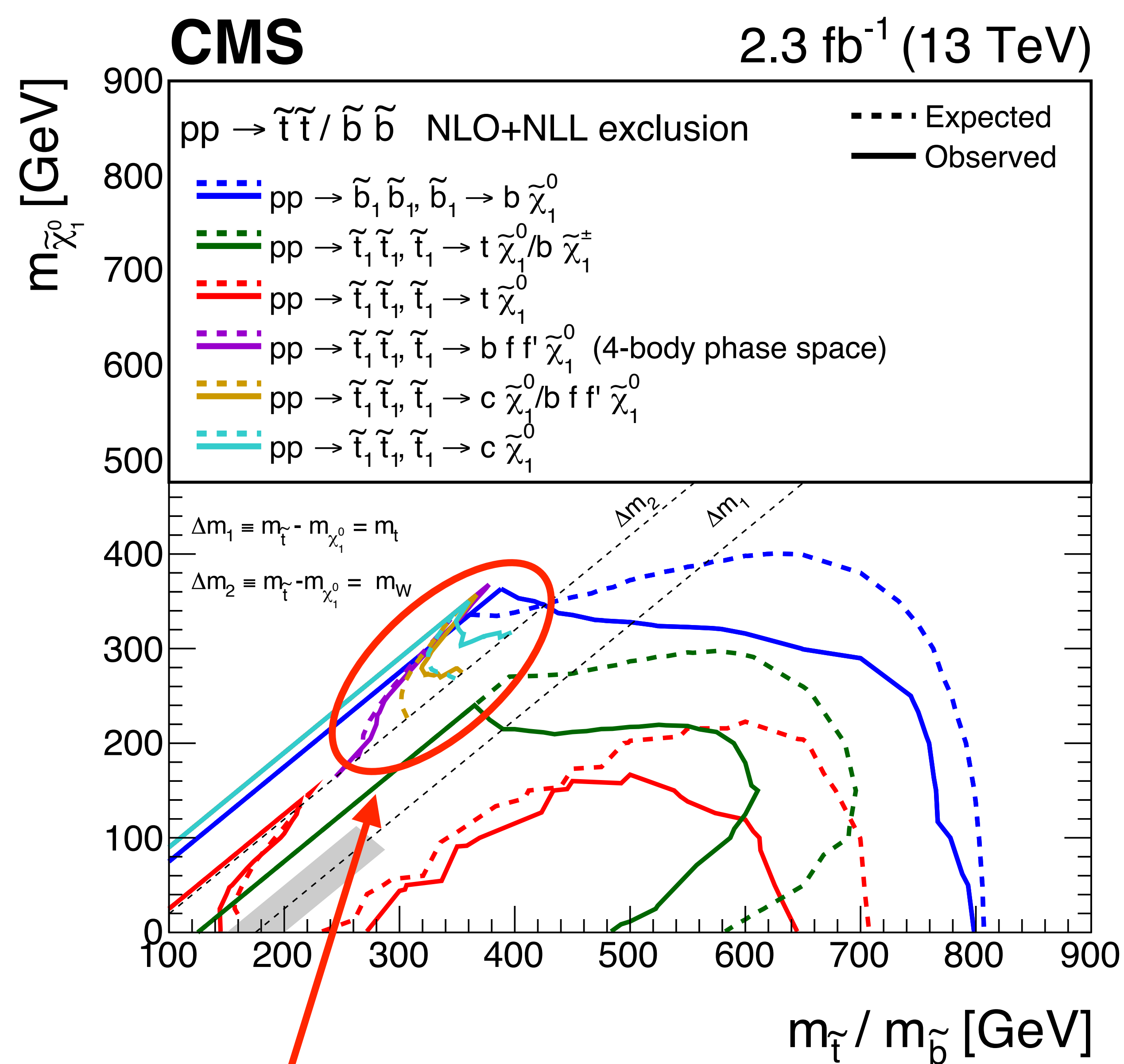
# Results of generic searches are versatile

CMS-PAS-SUS-15-005

The difference in sensitivity between the inclusive and targeted searches isn't so big.

At least for setting limits.

And inclusive searches are sensitive to many different decay modes, including scenarios with a compressed mass spectrum.




Sensitivity depends more on final state as we approach the diagonal. Leptonic decays have enough momentum to be found by our vetoes while hadronic decays are still too soft to enhance sensitivity. Can we fill this gap with other searches?

# Inclusive soft lepton + MET (SUS-16-011)

Trigger with MET, efficient above 200 GeV
- require $MT_2$ > 200 GeV to suppress QCD

Select events with 1 soft lepton: 5 < $p_T$ < 20 GeV
- veto events with 2nd lepton or isolated track

Categorize events in bins of $H_T$,$N_j$,$N_b$,MET,$M_T$
- count (b-tagged) jets with $p_T$ > (20) 30 GeV
- classify b-tags with $p_T$ </> 50 GeV as soft/hard
- search for excess yield above data-driven bkgd. estimate

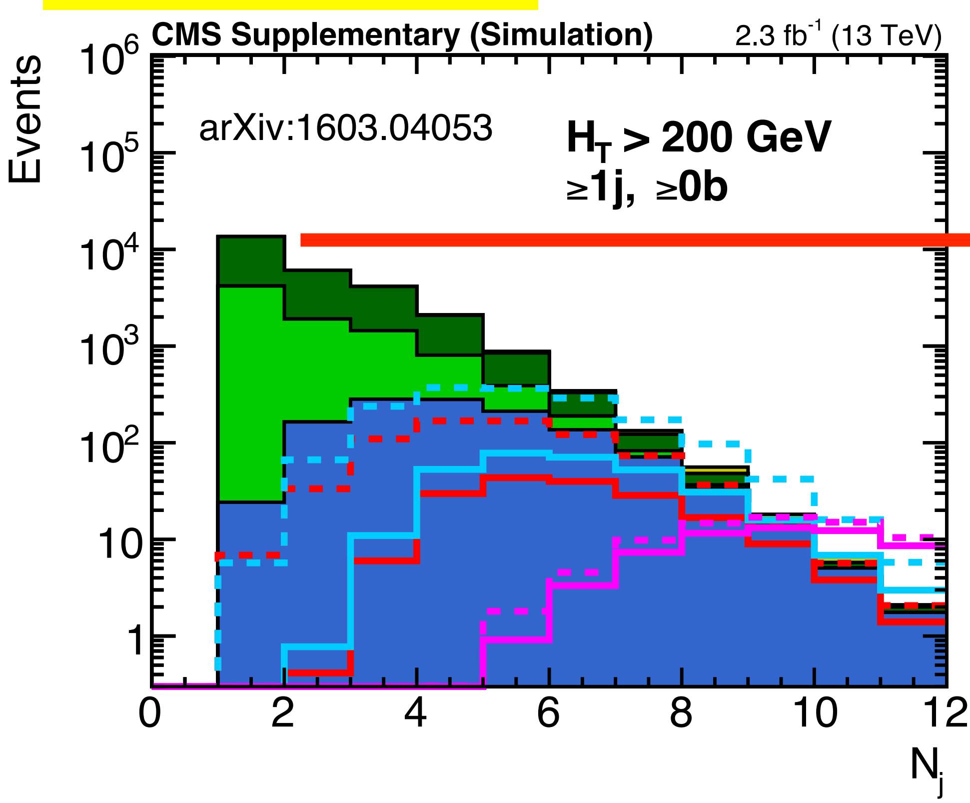
## Reduce significantly the irreducible background in jets+MET searches

- $Z(\nu\bar{\nu})$ bkgd. dominates at low $N_j, N_b$ → negligible after requiring a lepton
- Events with single $W(\ell\nu)$ reduced by requiring a soft lepton and can be further suppressed by requiring that $M_T(\ell, MET)$ is large

## Provide sensitivity to scenarios with new particles of similar masses

- Not uncommon in natural SUSY spectra. Even in the SM, $\Delta m(W,Z) \sim O(10)$ GeV
- If allowed, decays between such particles may lead to final states with soft leptons

CMS-PAS-SUS-15-003

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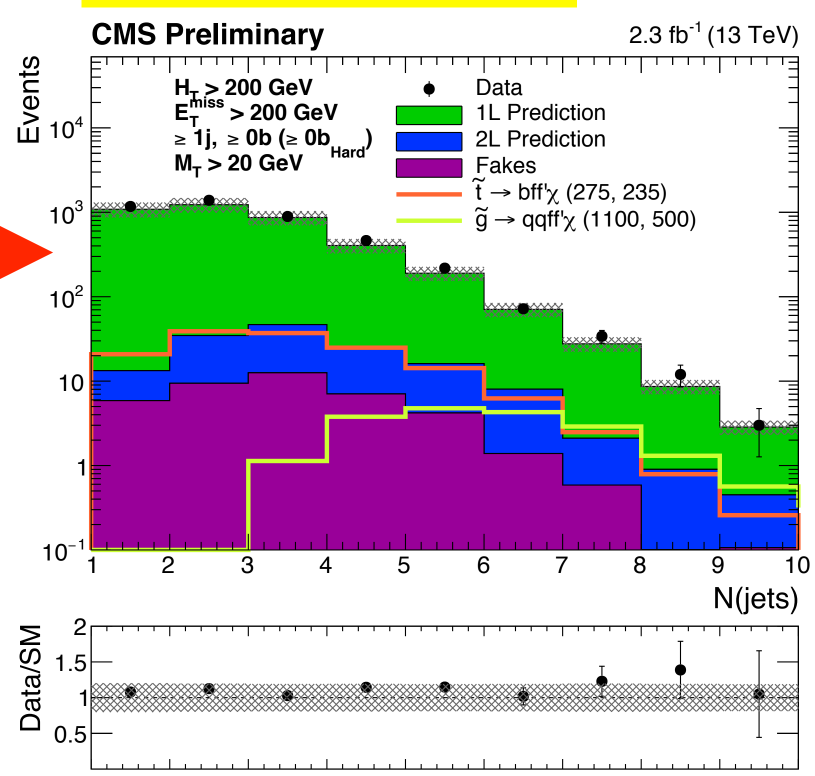
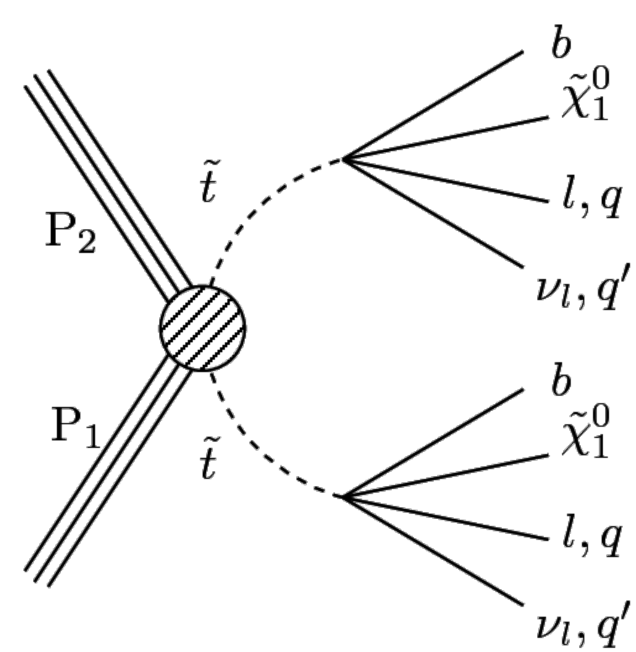


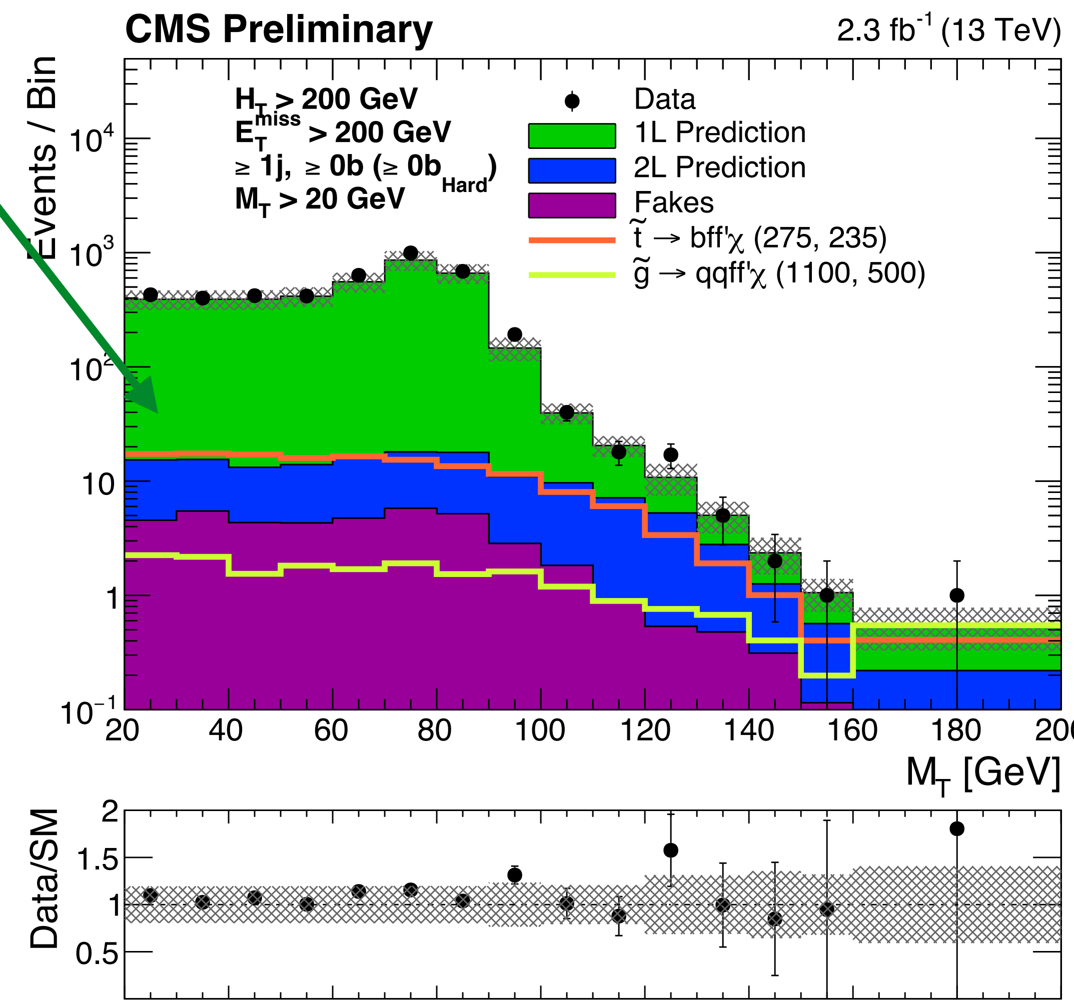



# Data-driven background estimates

## 1 lepton backgrounds

- W and Top(1L) with 1 soft lepton and a hard neutrino
- Control Region
  - reverse *W decay kinematics* (hard lep., low MET)
  - maintain similar *event kinematics* ($p_T$(W))
- Uncertainties: W polarization, W/tt fraction, lep. eff.

CMS-PAS-SUS-16-011




## 2 lepton backgrounds

- Top(2L) with 1 soft lepton, 1 lost lepton, 2 neutrinos
  - 2 or 3 missing objects, producing an $m_T$ tail
- Control Region = SR + 1 extra lepton
- Uncertainties: lepton efficiency, acceptance

$$N^{SR}_{bkgd} = \left(N^{CR}_{data} - N^{CR}_{MC,other}\right) \times \frac{N^{SR}_{MC}}{N^{CR}_{MC}}$$

## Fakes

- Small background (very tight ID/ISO requirement)
- Use MC for $m_T$ < 120 GeV (negligible)
- Use Tight/Loose ("fake rate") method > 120 GeV

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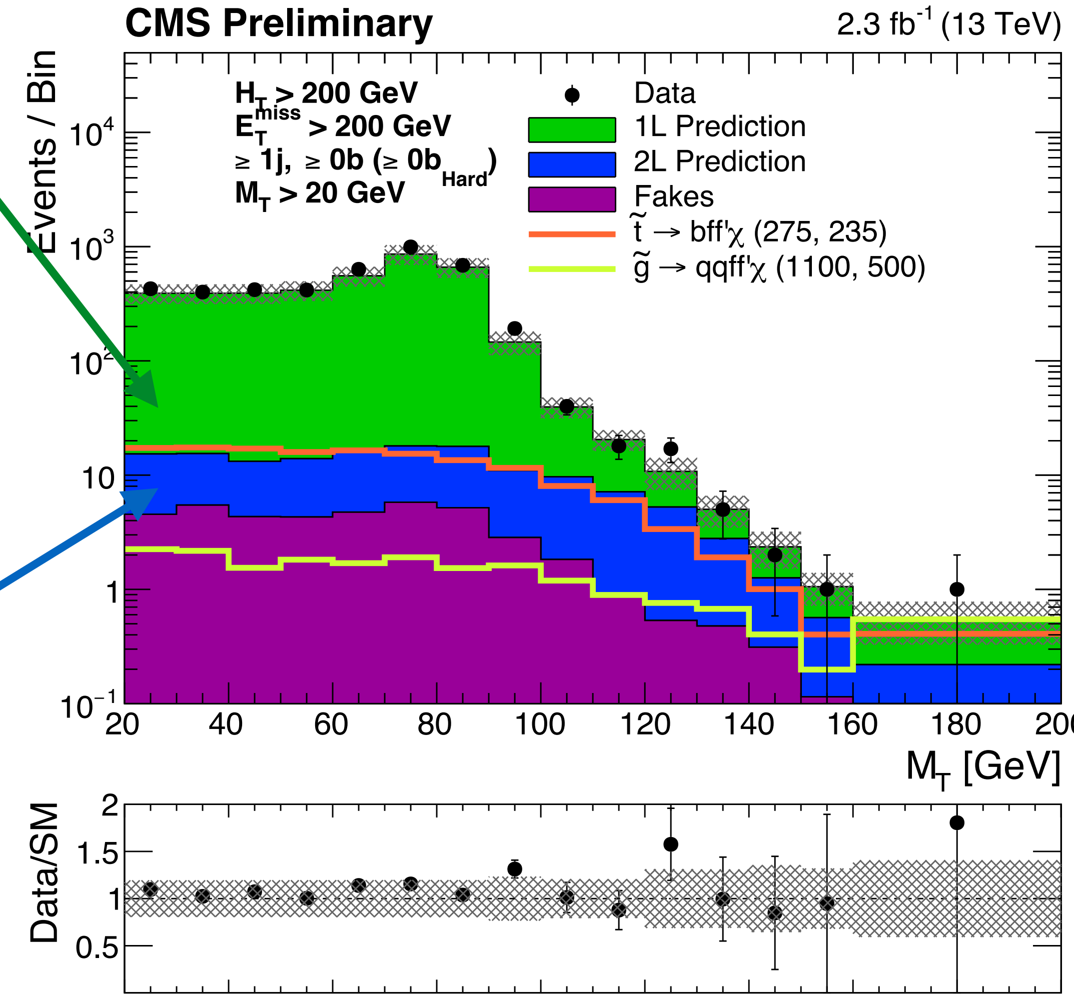


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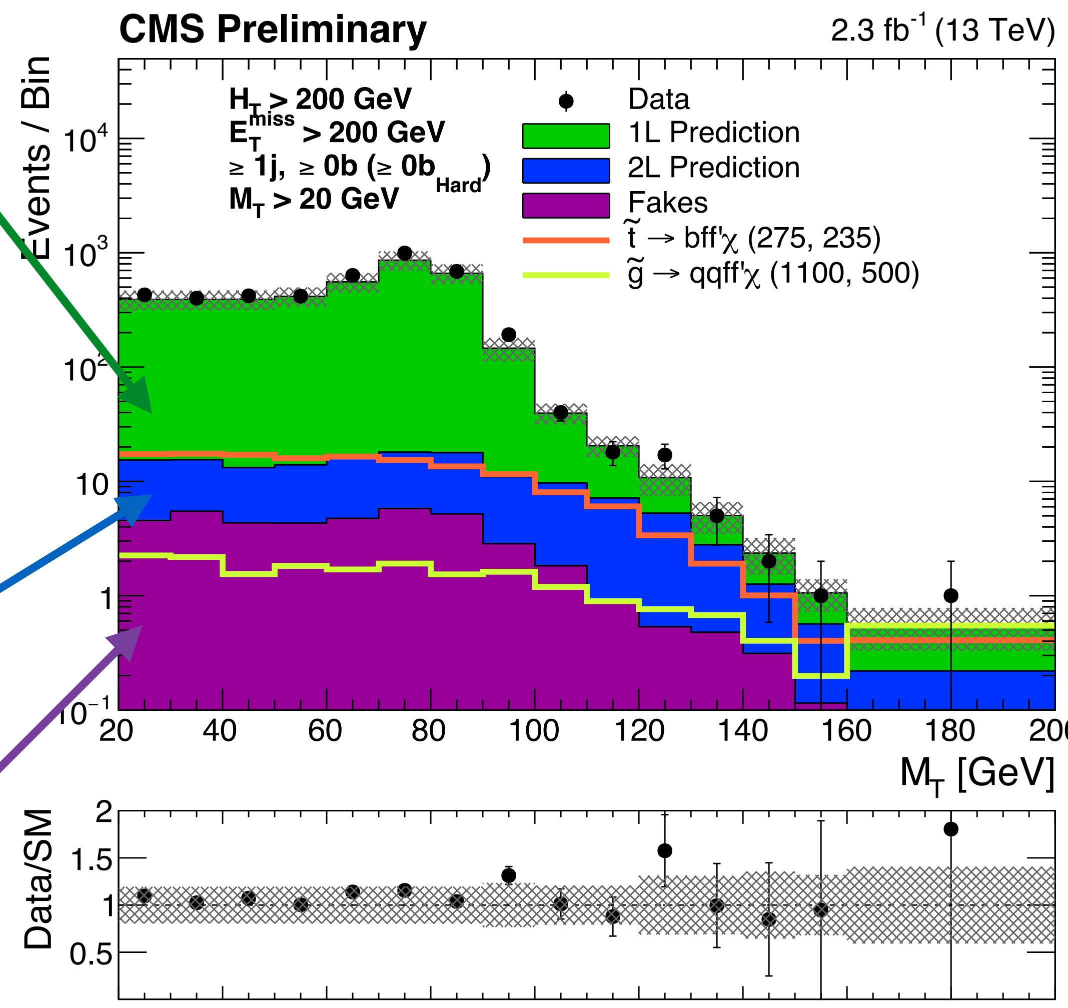


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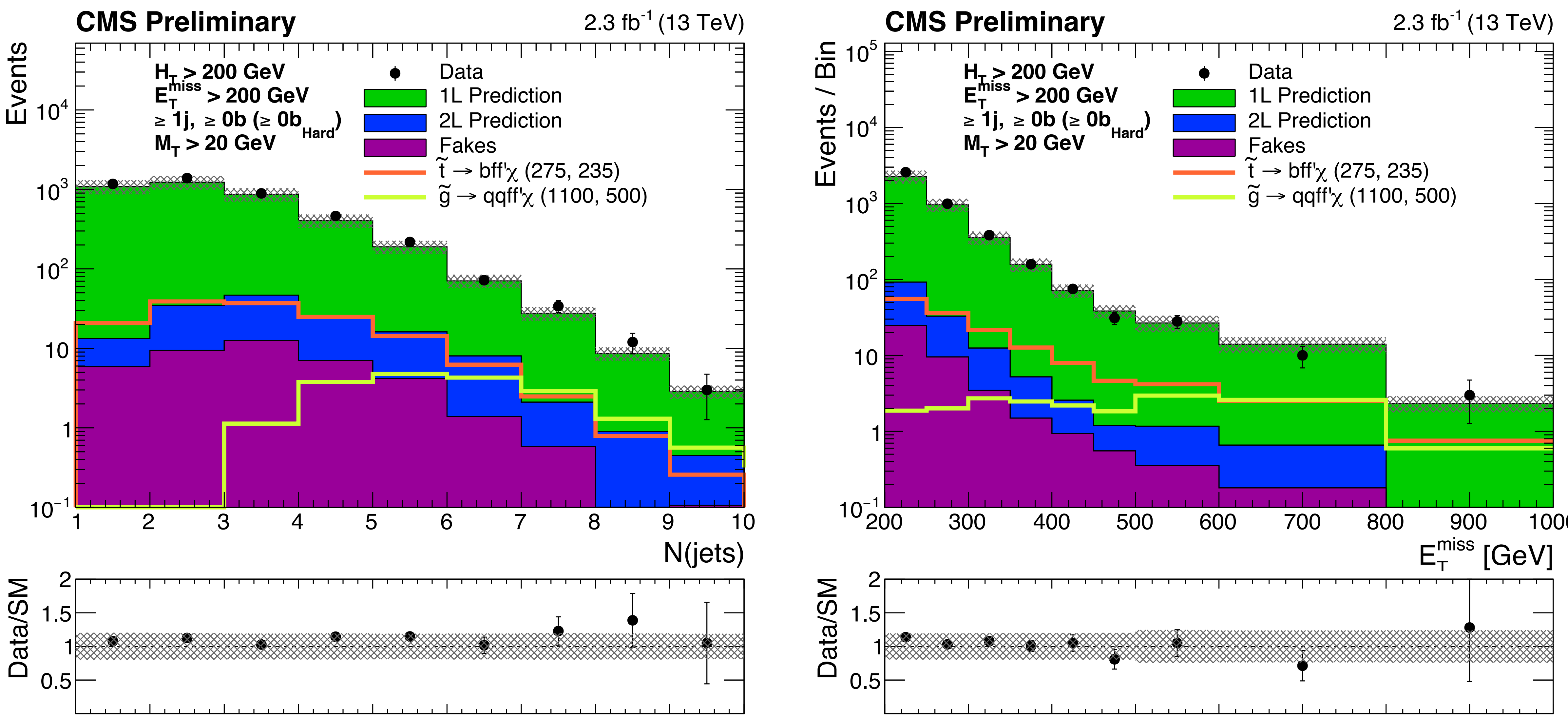
# Soft lepton + MET results

CMS-PAS-SUS-16-011



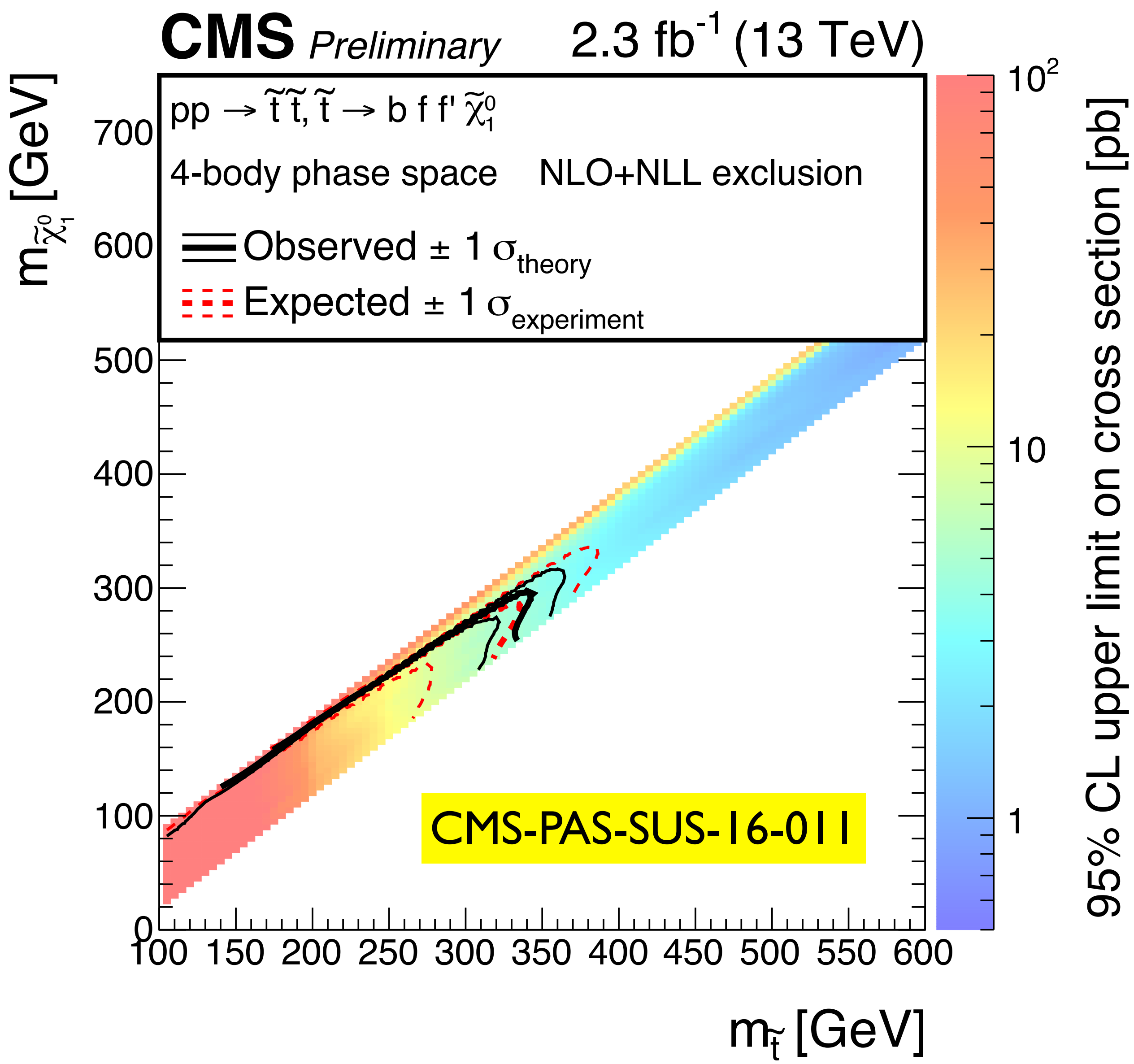

No excess above expected SM backgrounds.
Good agreement across a broad kinematic range.

# Compressed stop interpretation

With a soft lepton, can probe larger Δm region of 4-body decay.

Together with hadronic searches, most stringent limits on this scenario prior to ICHEP.

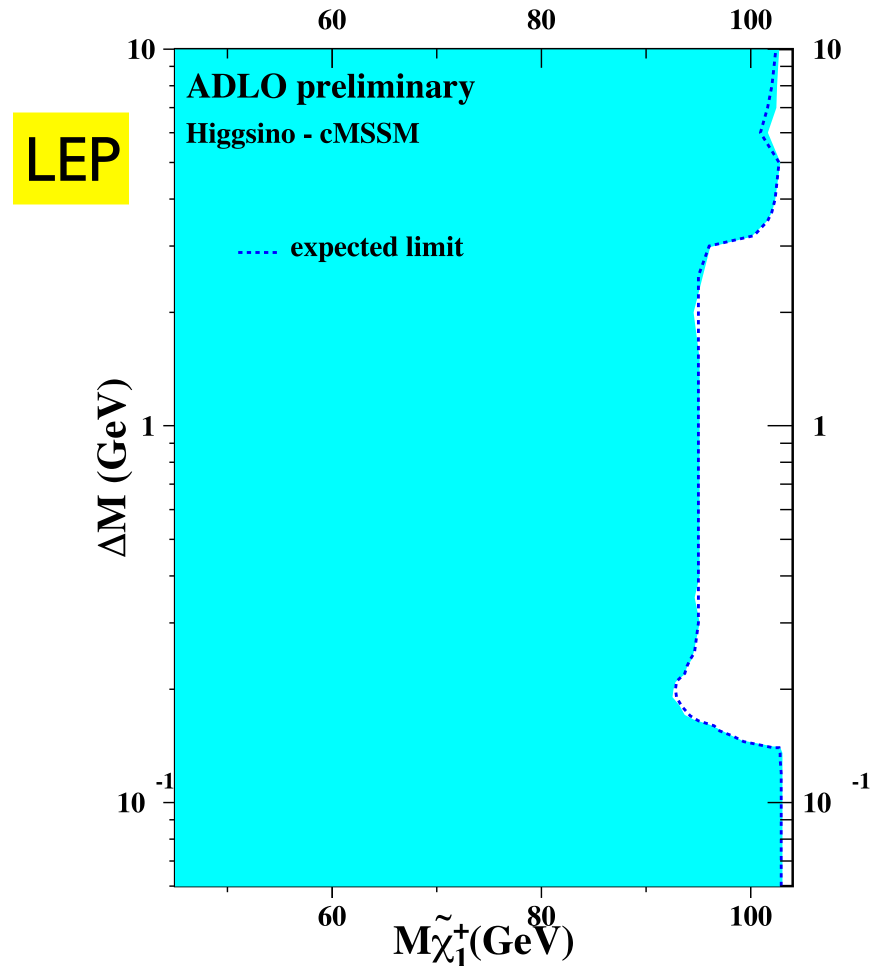
With the limited dataset recorded in 2015, only strong production scenarios were within reach.  Expect more from this strategy as accumulated luminosity grows.

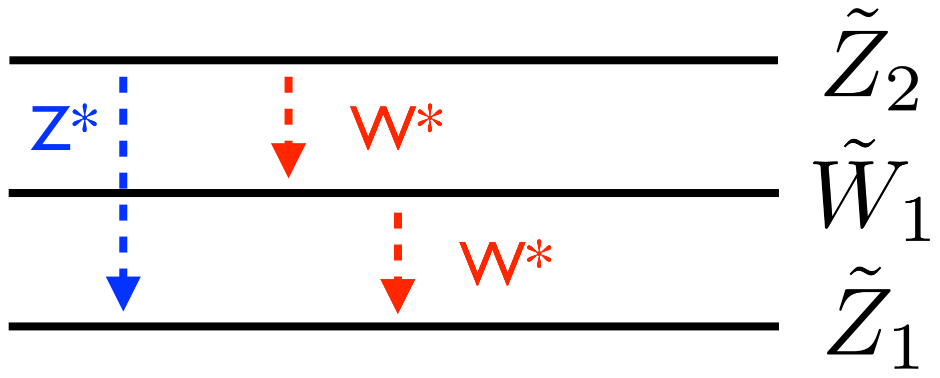


# From strong to weak production

First set of results already presented at ICHEP with initial focus on:
- slepton mediated decays resulting in final states with many leptons
- large mass splittings leading to on-shell W/Z/h + large MET

With more data, can begin to go after compressed gauginos (e.g. higgsinos):
- last component of "natural SUSY" that the LHC has yet to test
- most stringent limits still from LEP




Δm ~ O(0.1-10) GeV

Mono-X signatures very challenging (e.g. 1401.1162). Large W/Z+MET background → soft leptons can provide additional handles, improving mono-X prospects (e.g. 1004.4902).

## Trigger with MET, dimuon+MET

- pure MET trigger fully efficient above 200 GeV
- dimuon+MET trigger allows access to MET as low as 125 GeV

## Select events with soft lepton pair with opposite charge

- require leptons have $5 < p_T < 30$ GeV
- veto hadronic resonances: $M_{\ell\ell} > 4$ && $9 < M_{\ell\ell} < 10.5$ GeV
- veto events consistent with $0 < M_{\tau\tau} < 160$ GeV

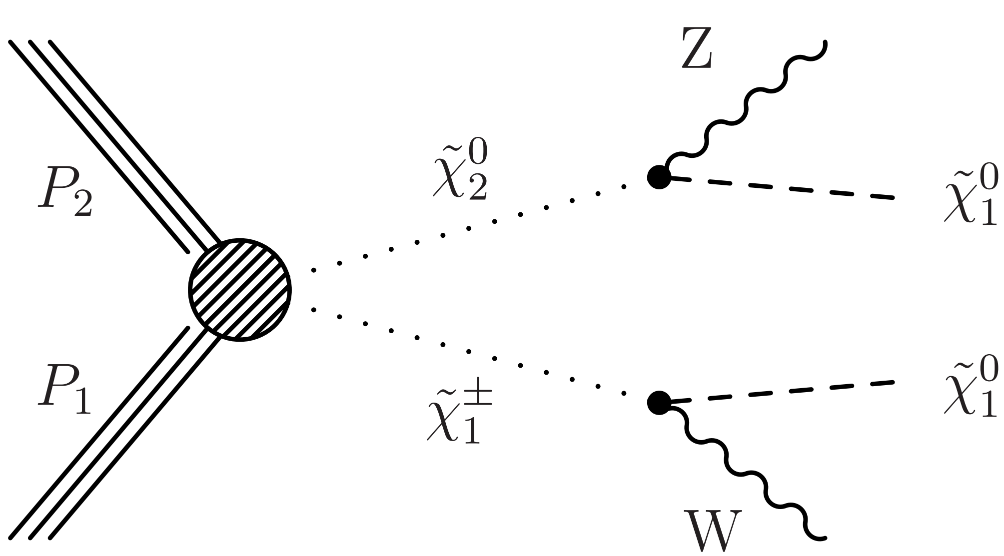
## Categorize events in bins of MET and $M_{\ell\ell}$ or $p_T(\ell\ell)$

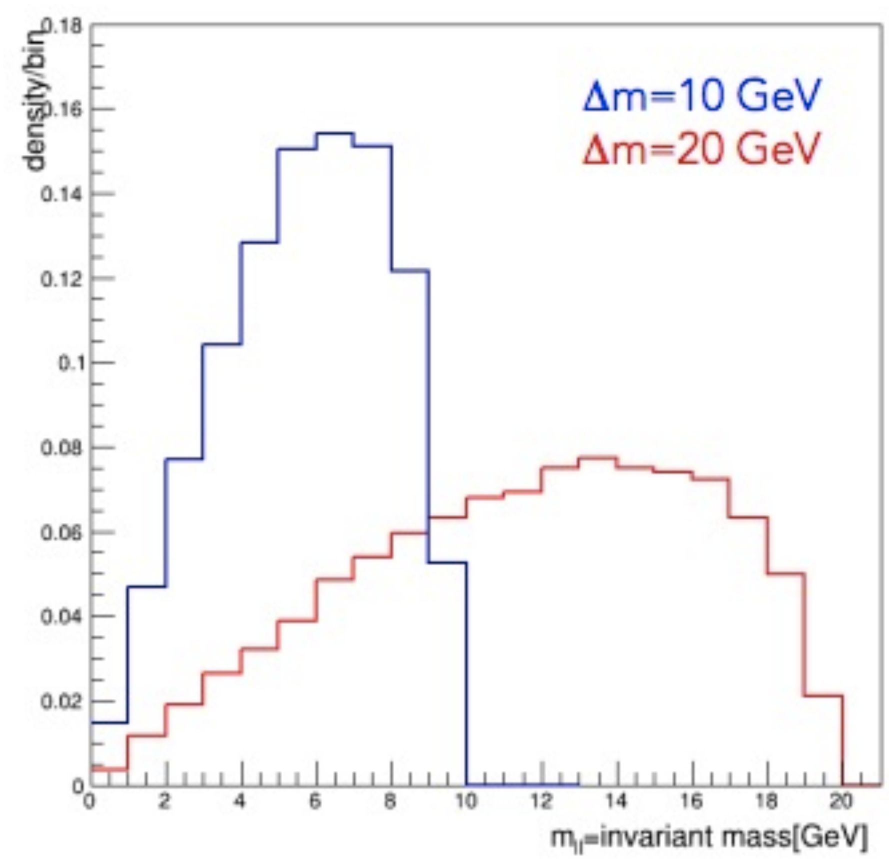
- $H_T > 100$ GeV, need hadronic recoil to get MET
- otherwise inclusive in number of jets
- veto events with a b-tagged jet to suppress ttbar

# Motivation and Strategy

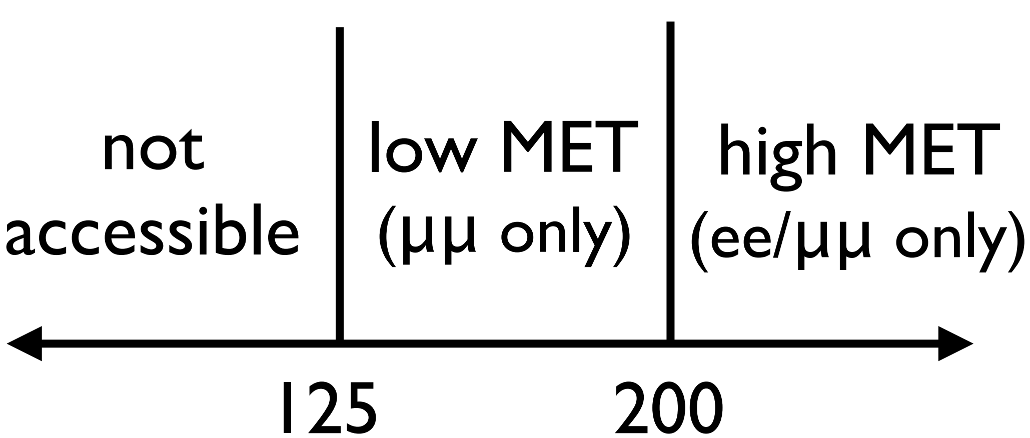
## Resonant search (e.g. 1401.1235)

"compressed gaugino search"

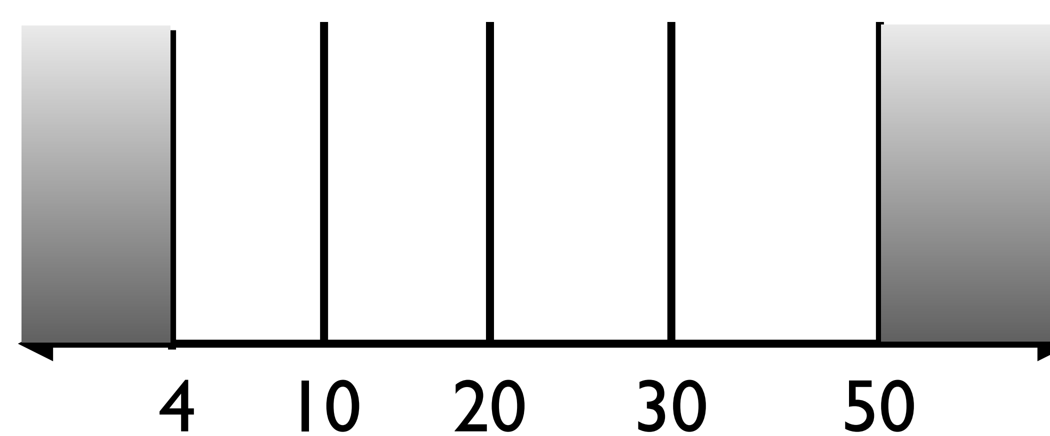



### MET binning (from trigger)



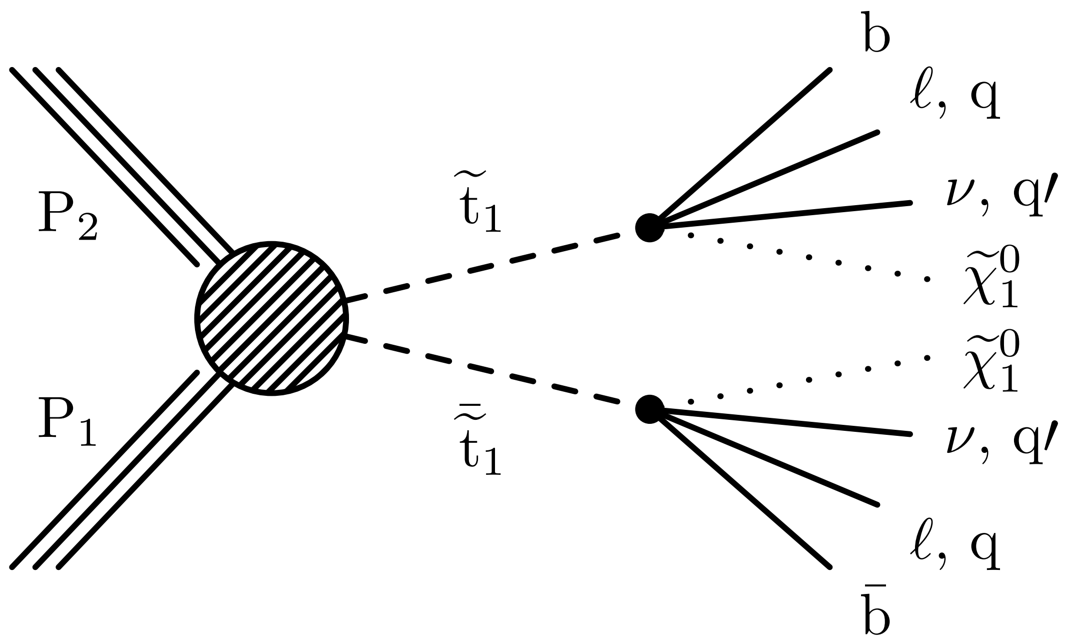

### $M_{\ell\ell}$ binning (from physics)



# Motivation and Strategy

## Non-resonant search

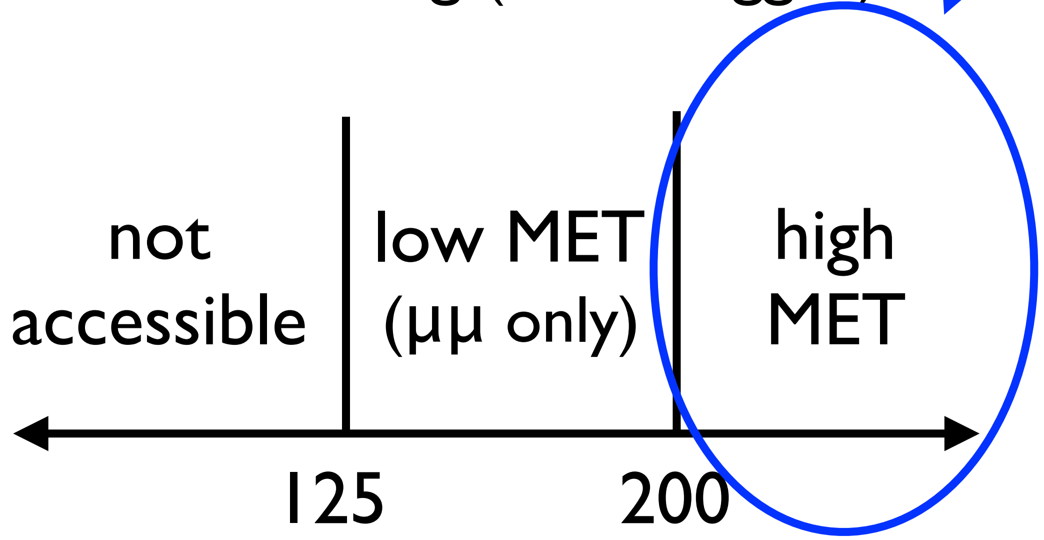
"compressed stop search"



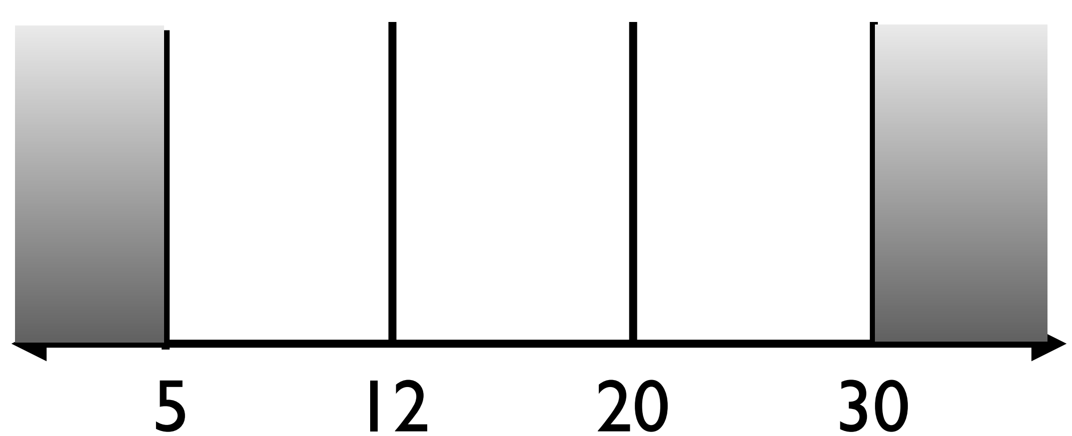

In high MET region, lower threshold on second lepton to 3.5 GeV if it is a muon.

Increase sensitivity to very low Δm region.

MET binning (from trigger)

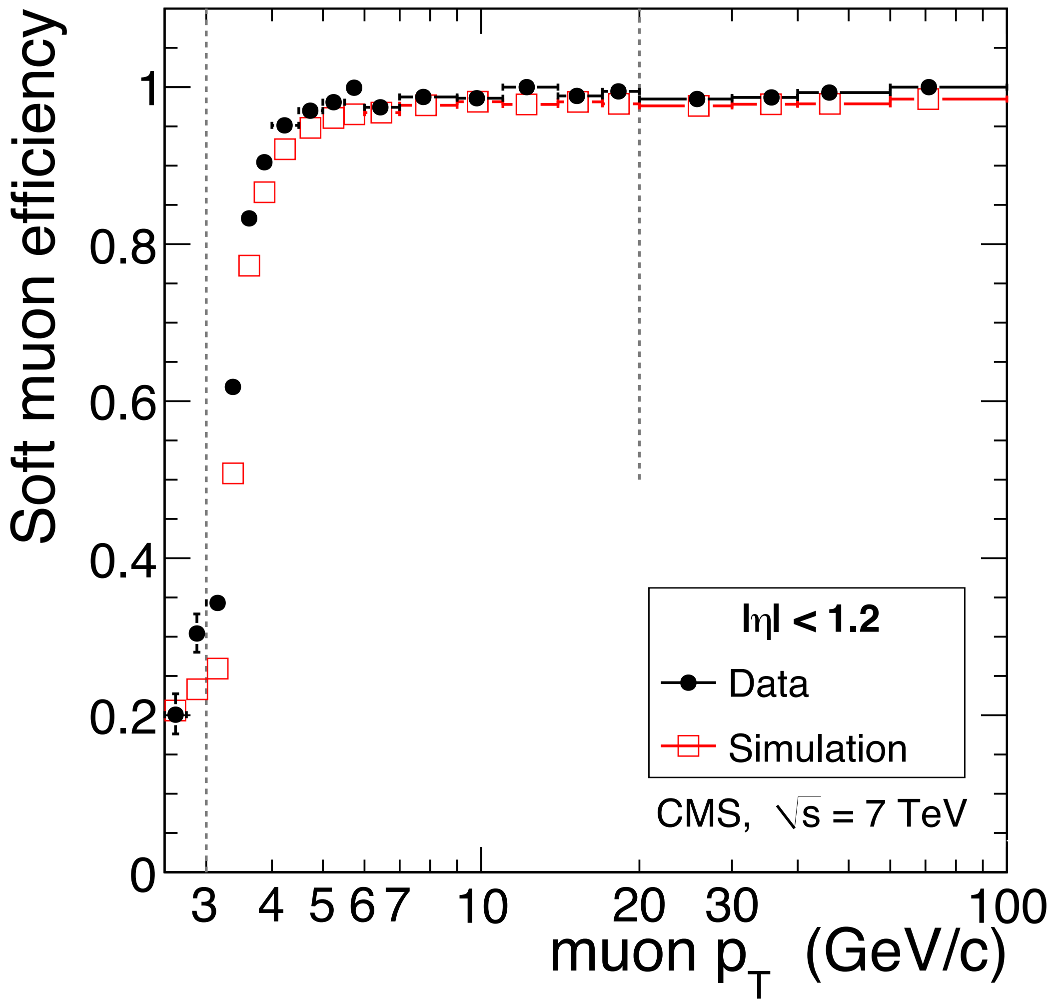



$p_T(\ell_1)$ binning (from physics)

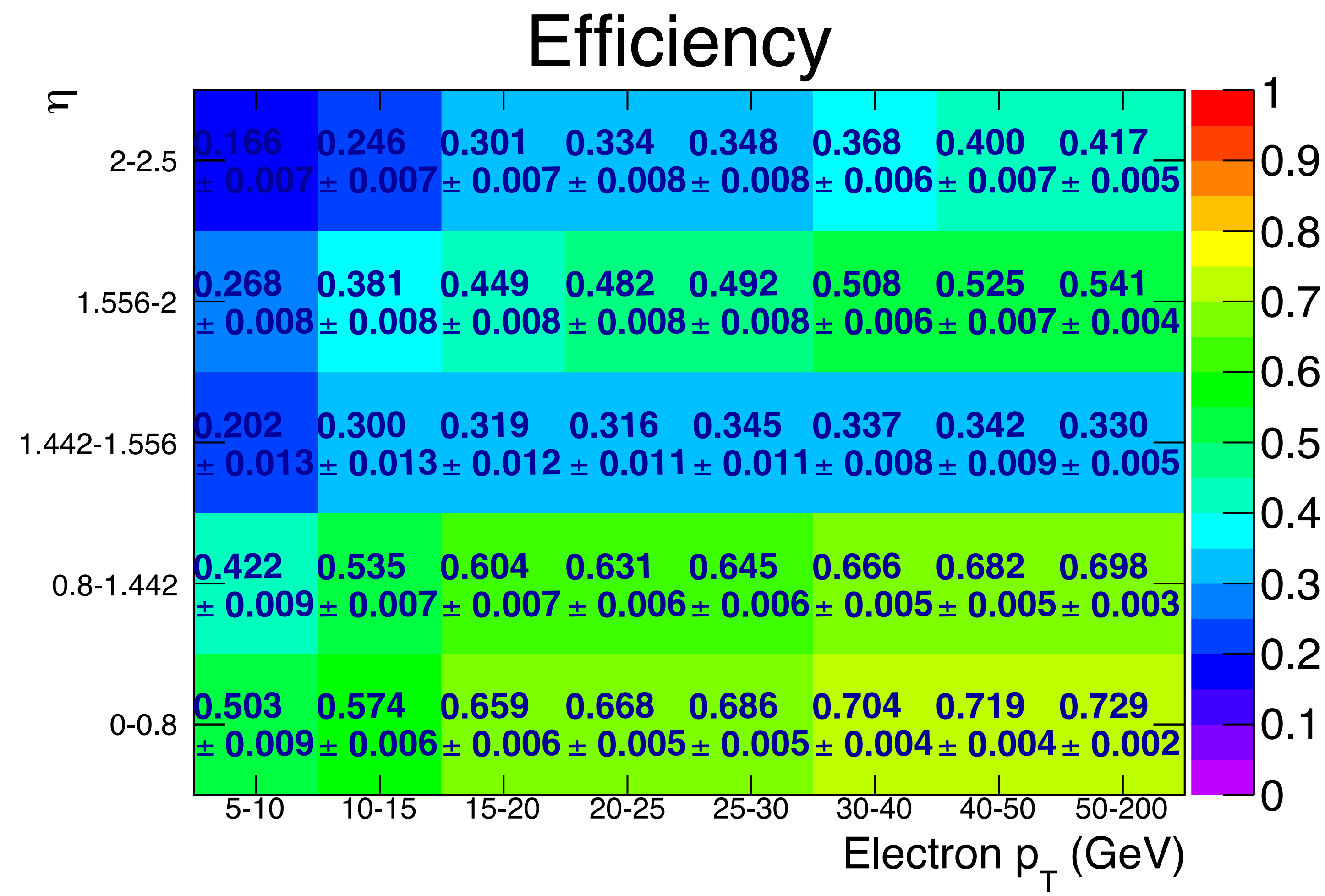


# Soft lepton efficiency

arXiv:1206.4071



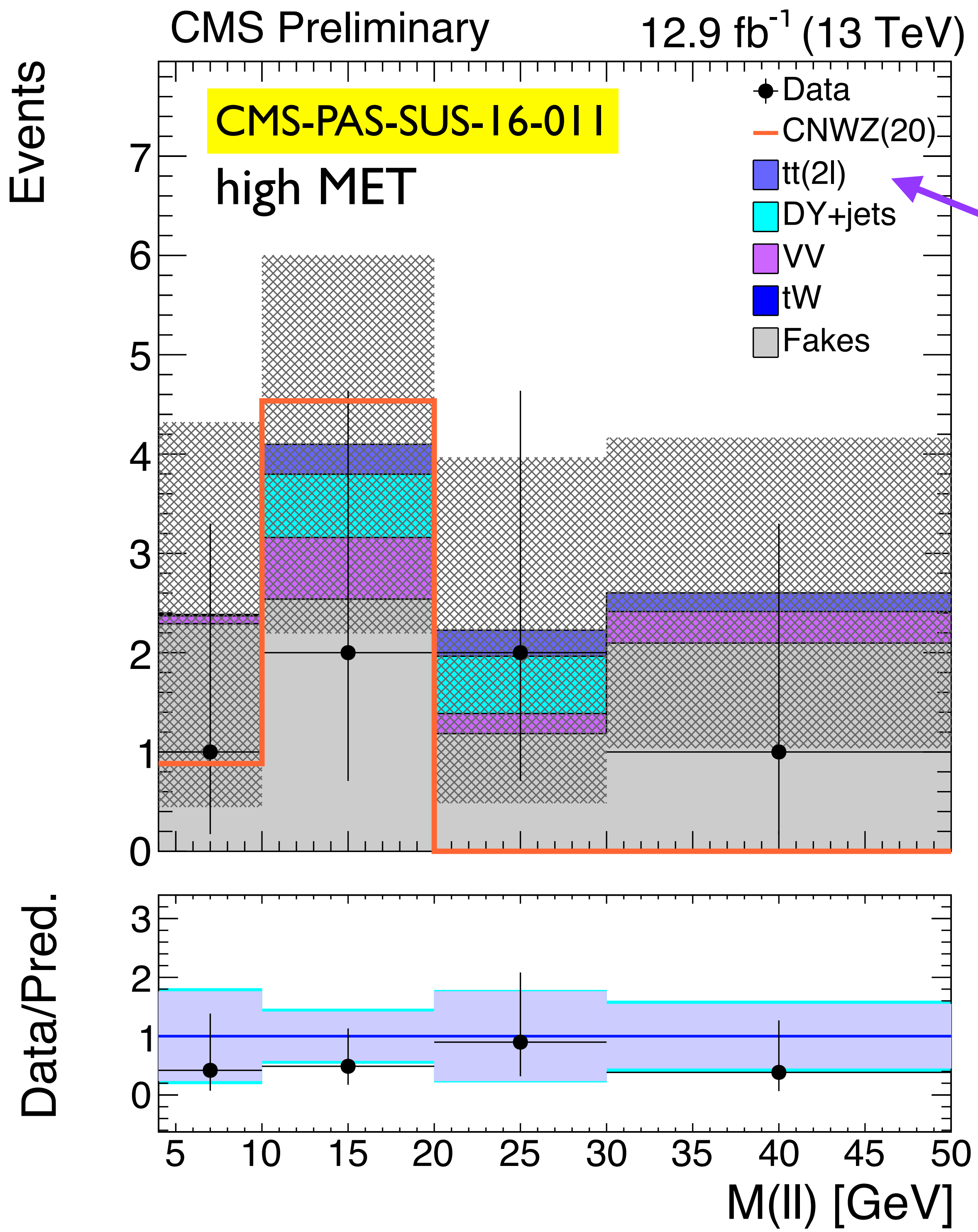

SUS ICHEP16 Object Efficiency Twiki




Must obtain large background reduction to gain with soft leptons.

# Backgrounds to soft 2l search

$$N^{SR}_{bkgd} = (N^{CR}_{data} - N^{CR}_{MC,other}) \times \frac{N^{SR}_{MC}}{N^{CR}_{MC}}$$




**For all CR:**

- remove $p_T(\ell)$ < 30 GeV (except fakes)
- bin in MET, but not $M_{\ell\ell}$ or $p_T(\ell\ell)$

**top background**

- CR: ≥ 1 b-tag with $p_T$ > 40 GeV

**DY→ττ background**

- CR: 0 ≤ $M_{\tau\tau}$ ≤ 160 GeV

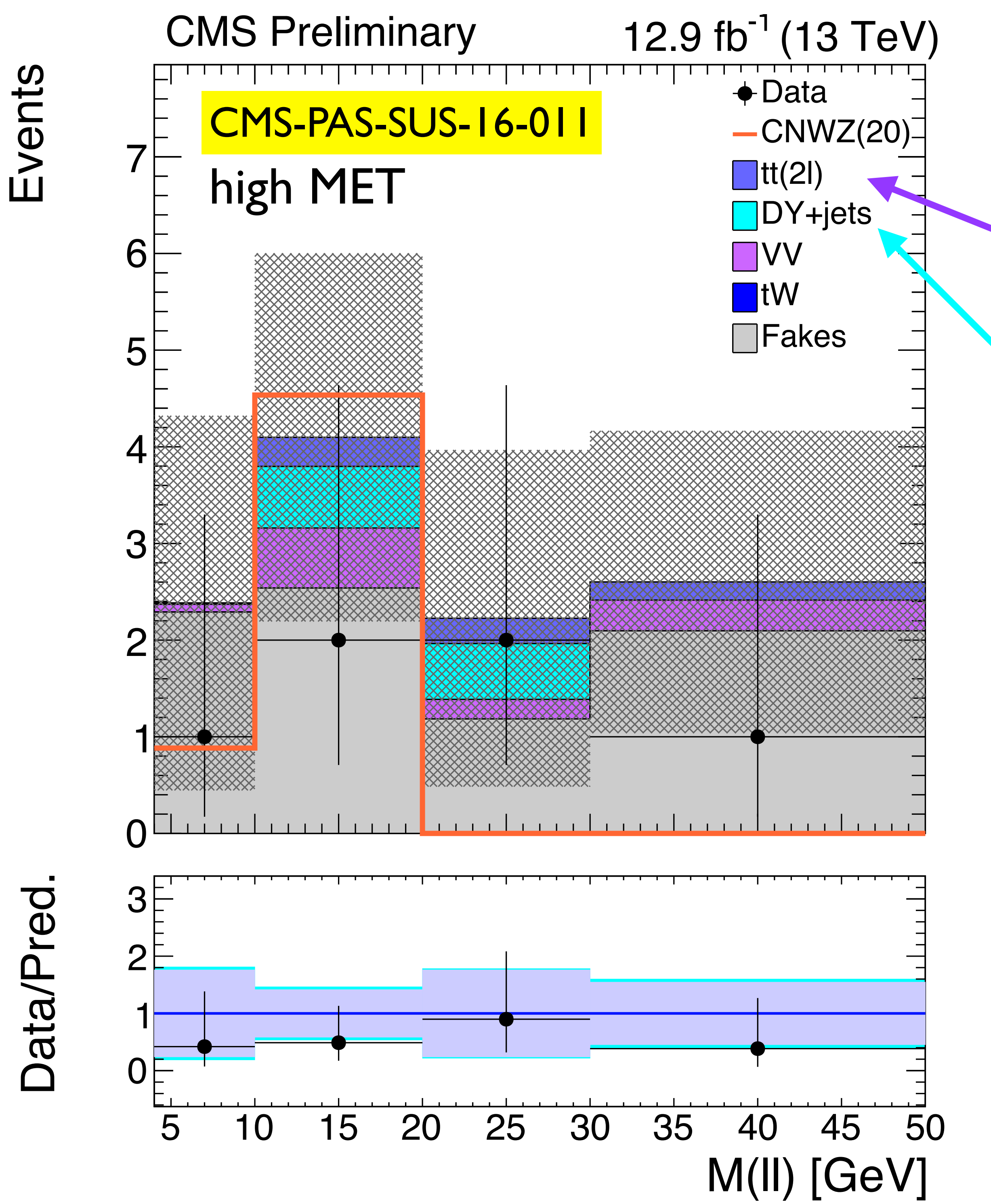
**VV (from MC)**

- validation region: $p_T(\ell_1)$ > 20 GeV, $M_T(\ell$,MET) > 90 GeV, Z-veto

**Fakes**

- Use Tight/Loose (“fake rate”) method

$$N^{SR}_{bkgd} = (N^{CR}_{data} - N^{CR}_{MC,other}) \times \frac{N^{SR}_{MC}}{N^{CR}_{MC}}$$




**For all CR:**

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- bin in MET, but not $M_{\ell\ell}$ or $p_T(\ell\ell)$

**top background**

- CR: ≥ 1 b-tag with $p_T > 40$ GeV

**DY→ττ background**

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**VV (from MC)**

- validation region: $p_T(\ell_1) > 20$ GeV, $M_T(\ell,MET) > 90$ GeV, Z-veto

**Fakes**

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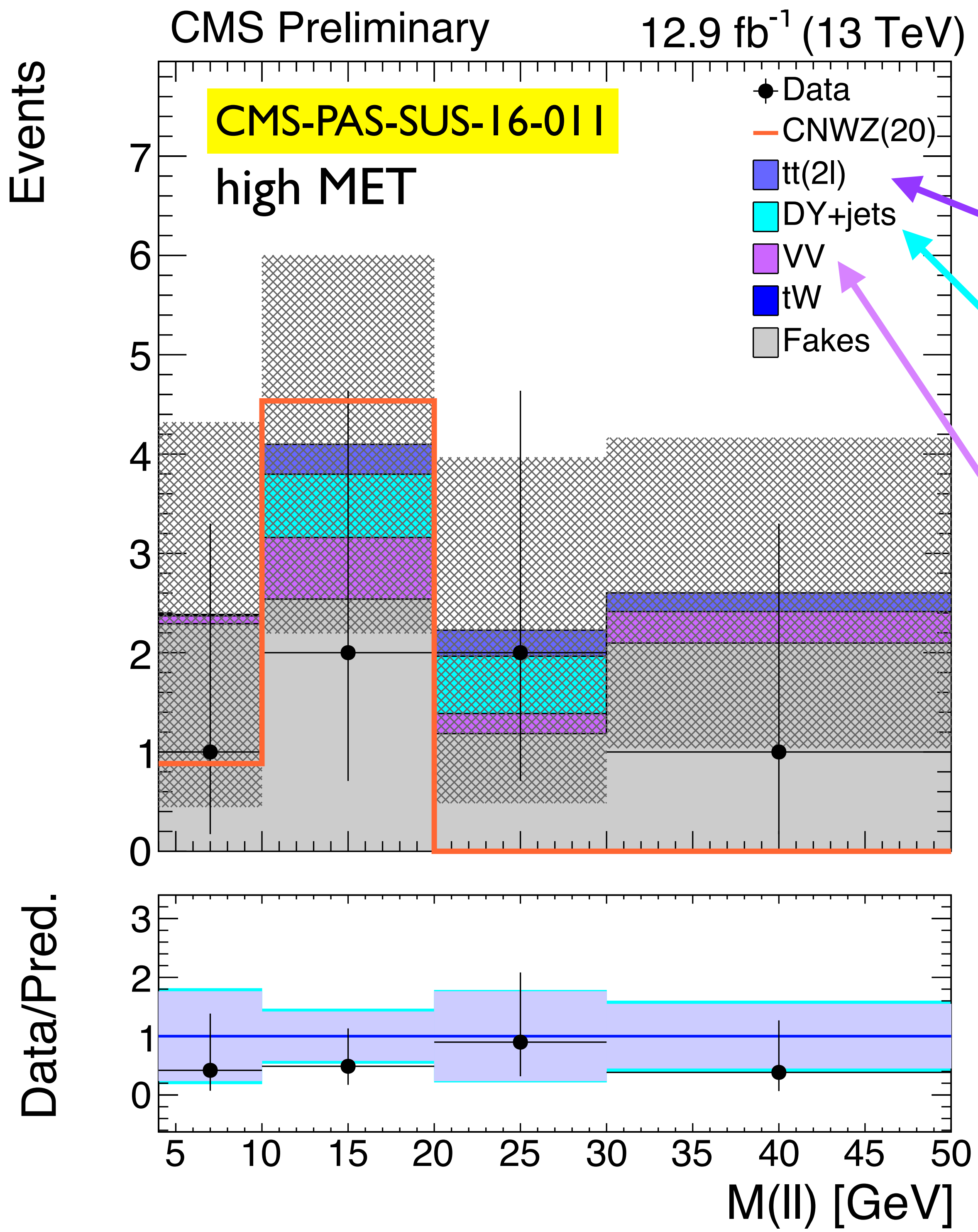
# Backgrounds to soft 2l search

$$N^{SR}_{bkgd} = (N^{CR}_{data} - N^{CR}_{MC,other}) \times \frac{N^{SR}_{MC}}{N^{CR}_{MC}}$$




**For all CR:**

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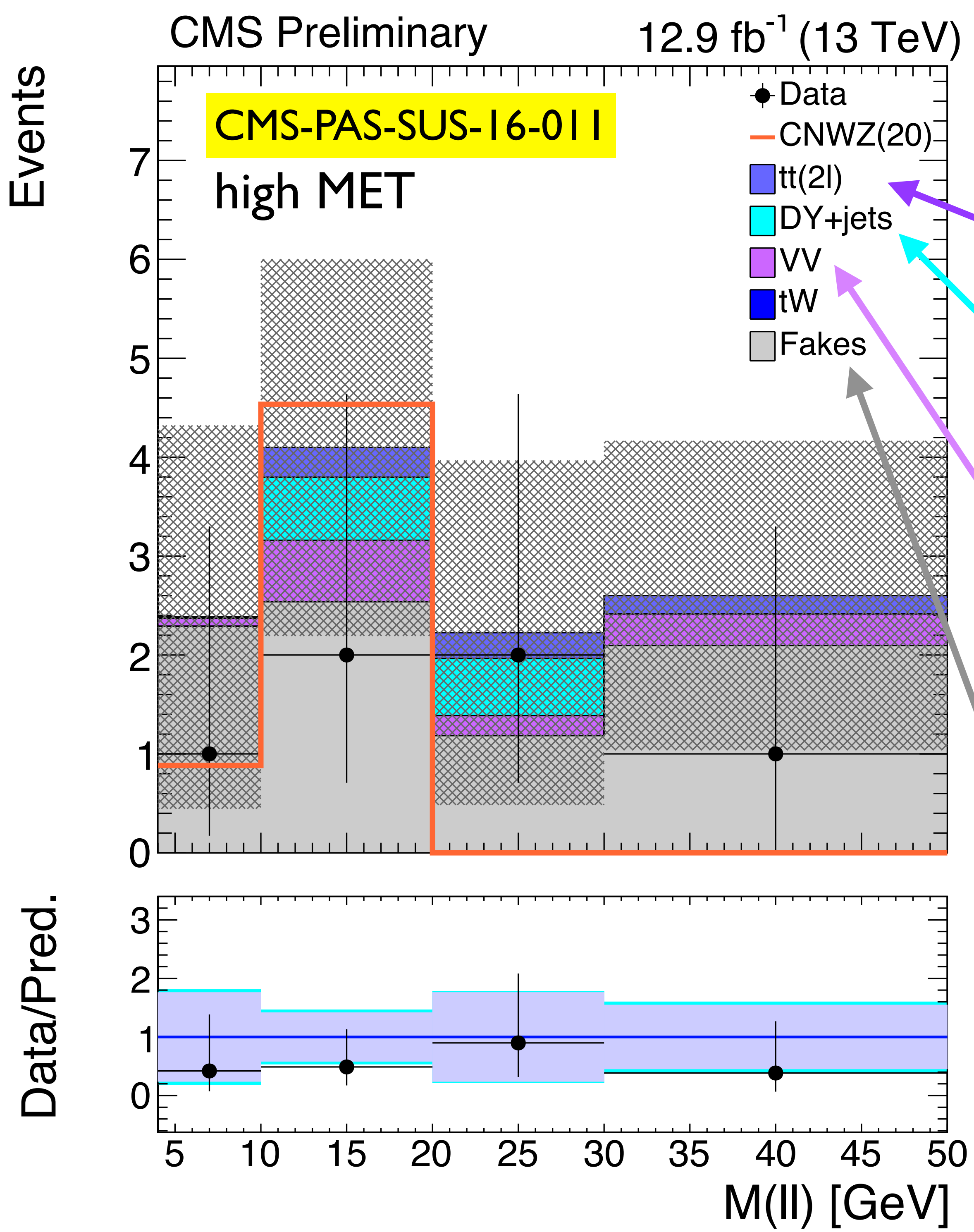
# Backgrounds to soft 2l search

$$N_{bkgd}^{SR} = (N_{data}^{CR} - N_{MC,other}^{CR}) \times \frac{N_{MC}^{SR}}{N_{MC}^{CR}}$$




**For all CR:**

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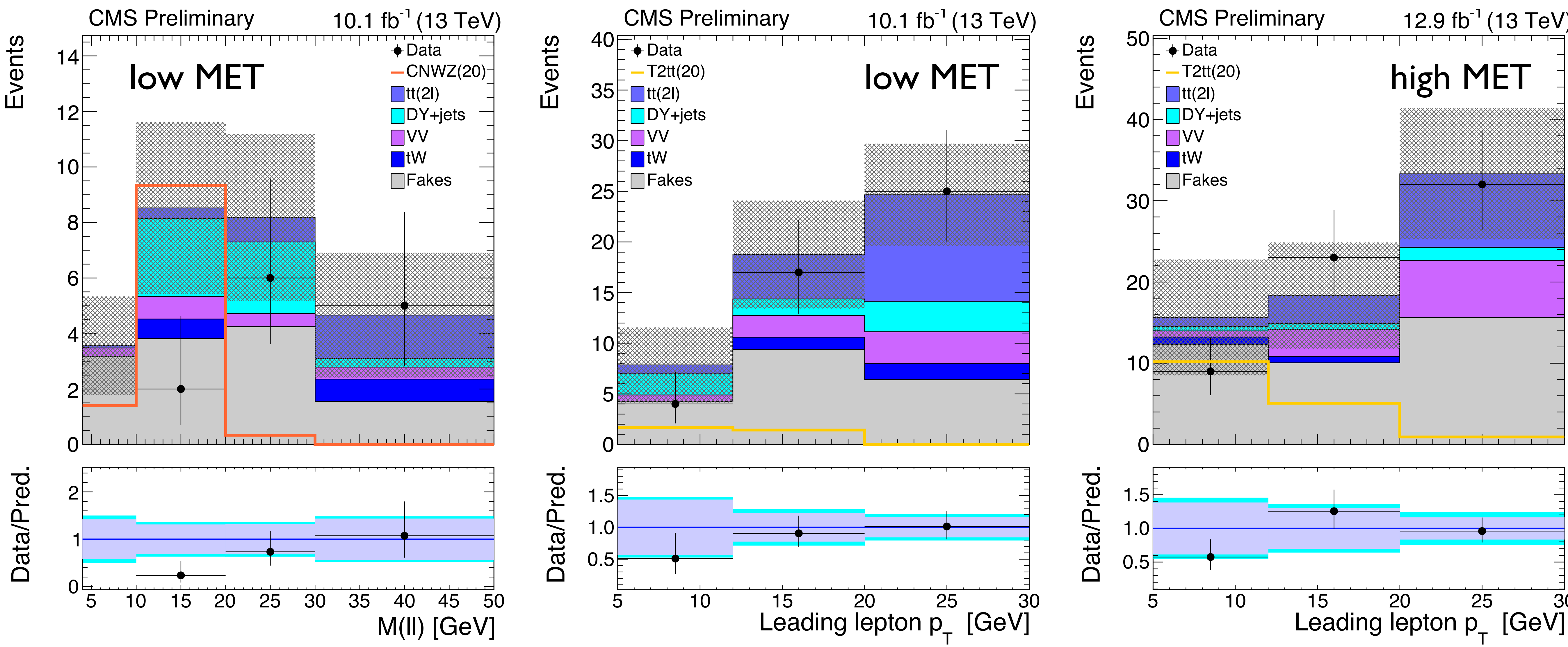
# Results of soft 2l search

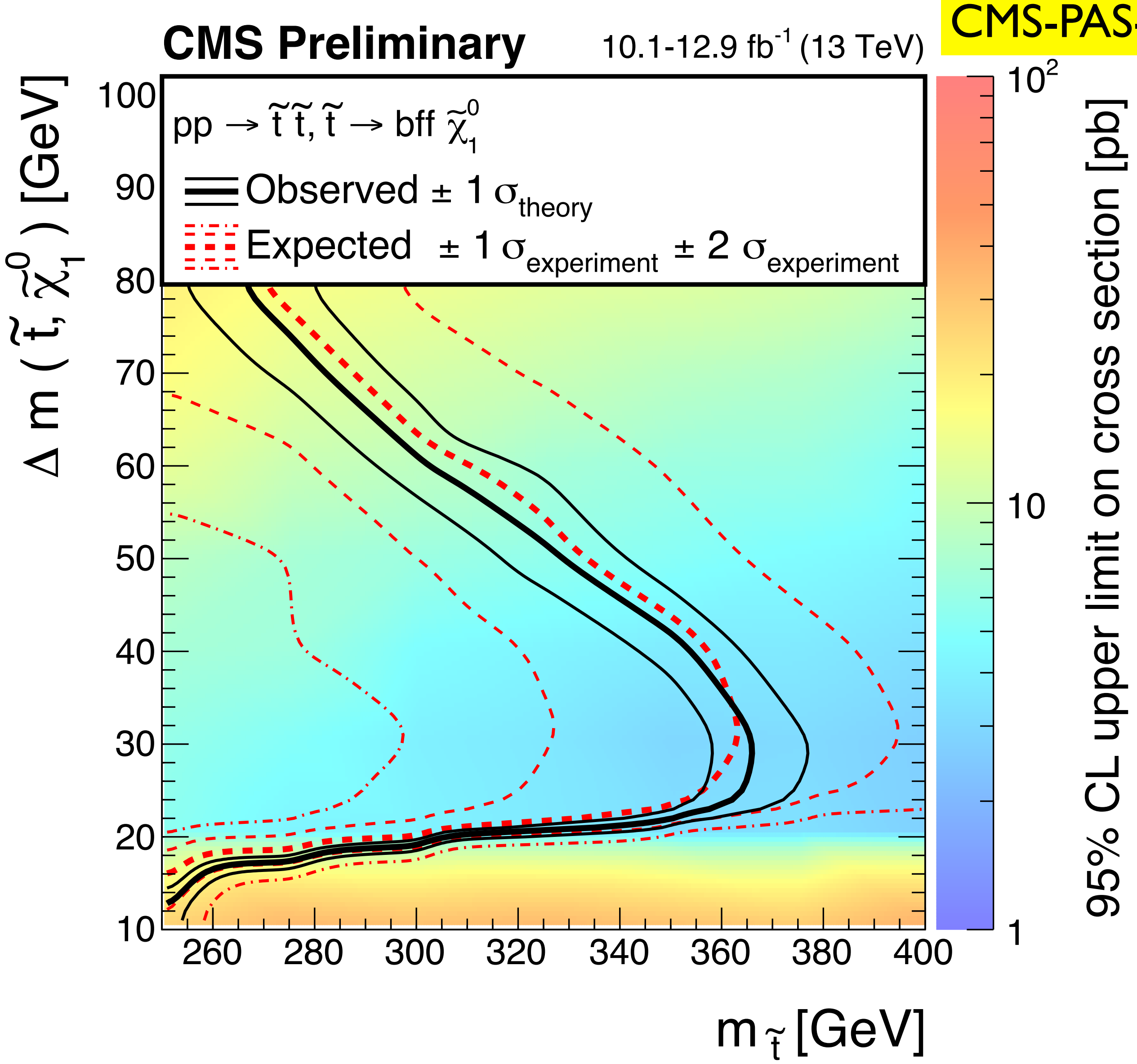
CMS-PAS-SUS-16-011

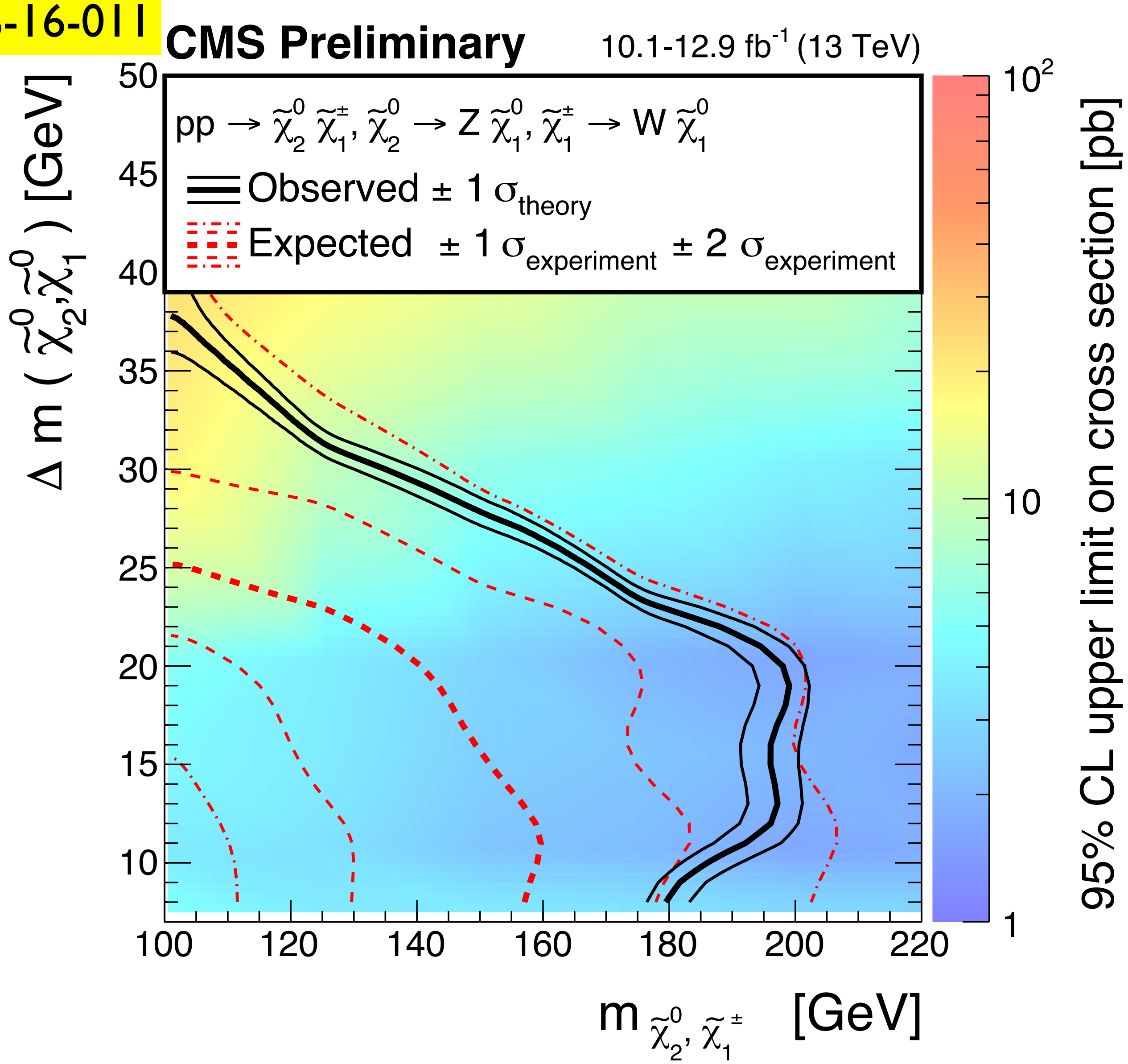



No evidence for BSM physics.

# Interpretations of soft 2l search

CMS-PAS-SUS-16-011




Probe similar stop mass as soft 1ℓ, but with larger dataset. Expect significant gains in compressed stop sensitivity with end-of-year combination of hadronic and soft lepton searches.

Probe compressed gauginos up to ~200 GeV, assuming pure Wino cross section (factor few larger than higgsino). May begin to probe region unexplored by LEP as early as this year, stay tuned!

# Where do we go from here?

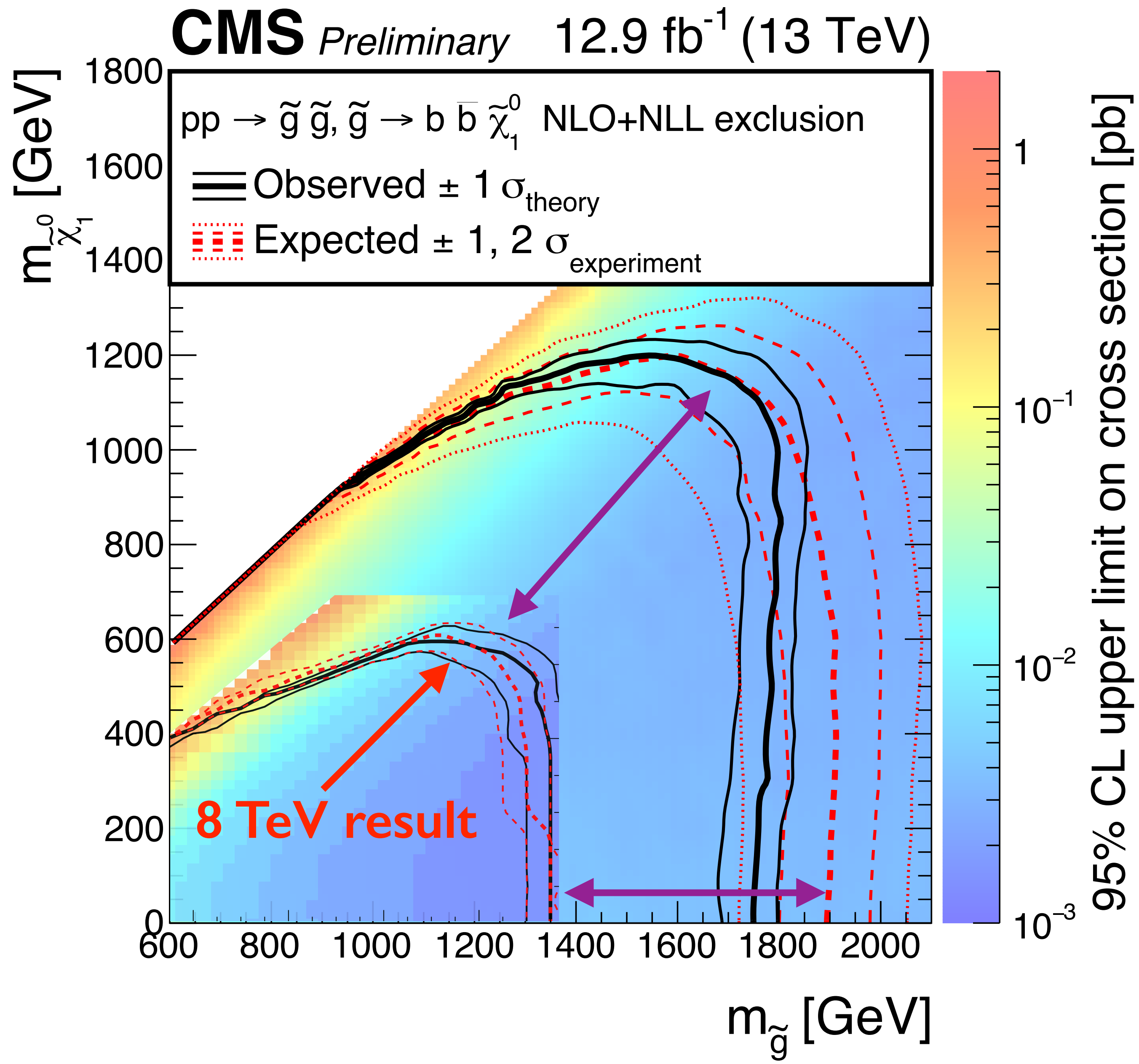
CMS-PAS-SUS-16-015

Path ahead for exploring weakly produced scenarios seems clear, at least for the next year or two. What about strong production?

SUSY could have been waiting just around the corner for us. If it was, we should have begun to see a hint of it.

optimistic: maybe we are?

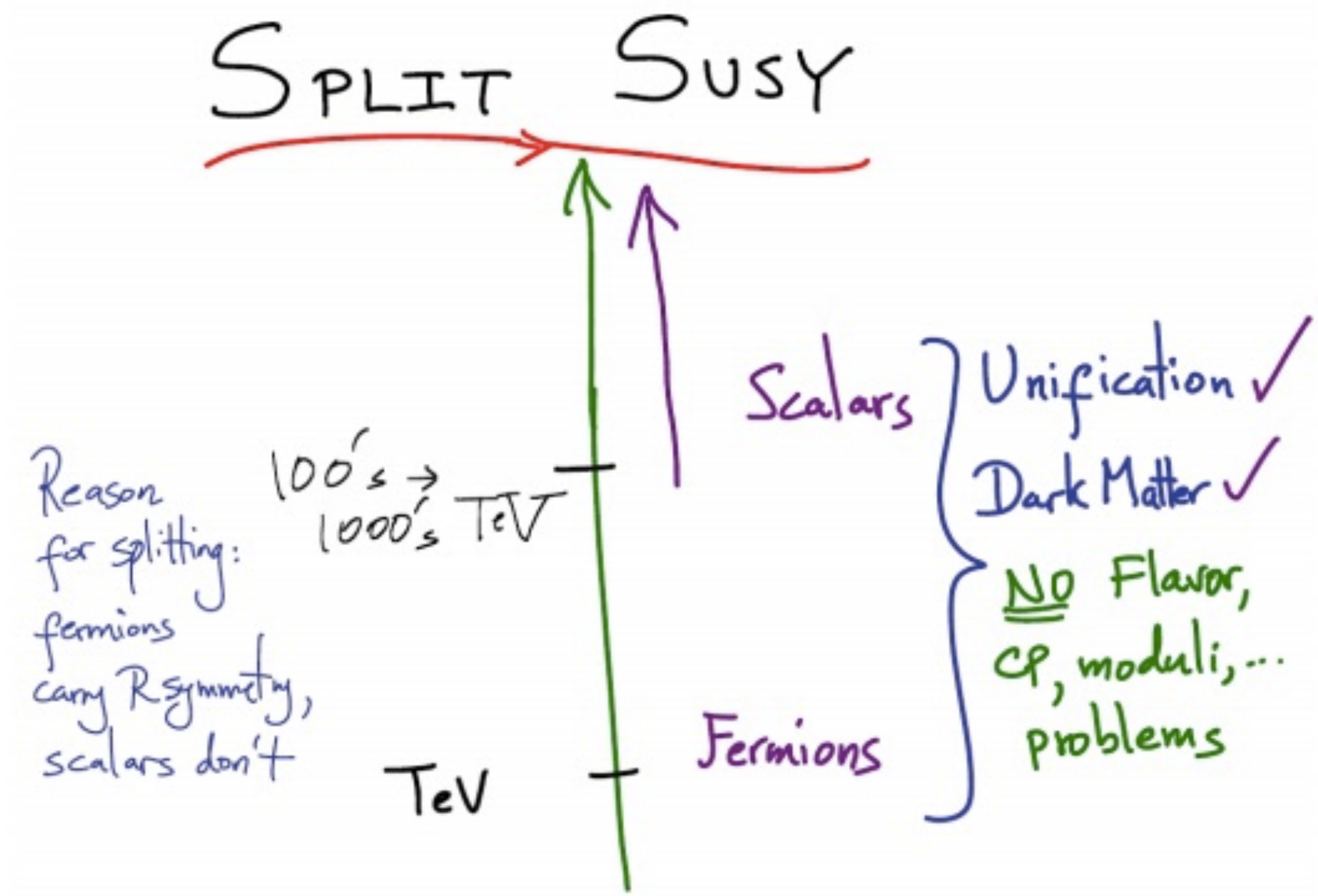
pessimistic: put these searches in a drawer and dust them off at the end of each run? or give up all together?




Gain in reach of ~550 GeV driven by O($10^2$) gain in cross section going from 8→13 TeV. It will take another ~decade to extend our reach by that amount again.

# Oft-repeated myths about naturalness

- requires m(t1,t2,b1)<500 GeV
- requires small At parameter
- requires m(gluino)<1500 GeV



# One experimentalist's perspective

If only it were as easy for experimentalists to increase beam energy as it is for theorists to move the goalpost by increasing particle masses…

# One experimentalist's perspective

If only it were as easy for experimentalists to increase beam energy as it is for theorists to move the goalpost by increasing particle masses…

…but I share some of the optimism.
It's not yet time to raise the white flag.

Up to now, we've mostly just recycled the program of Run 1. And this was expected as we have been living through a similar time of increased collision energy and rapidly increasing luminosity.

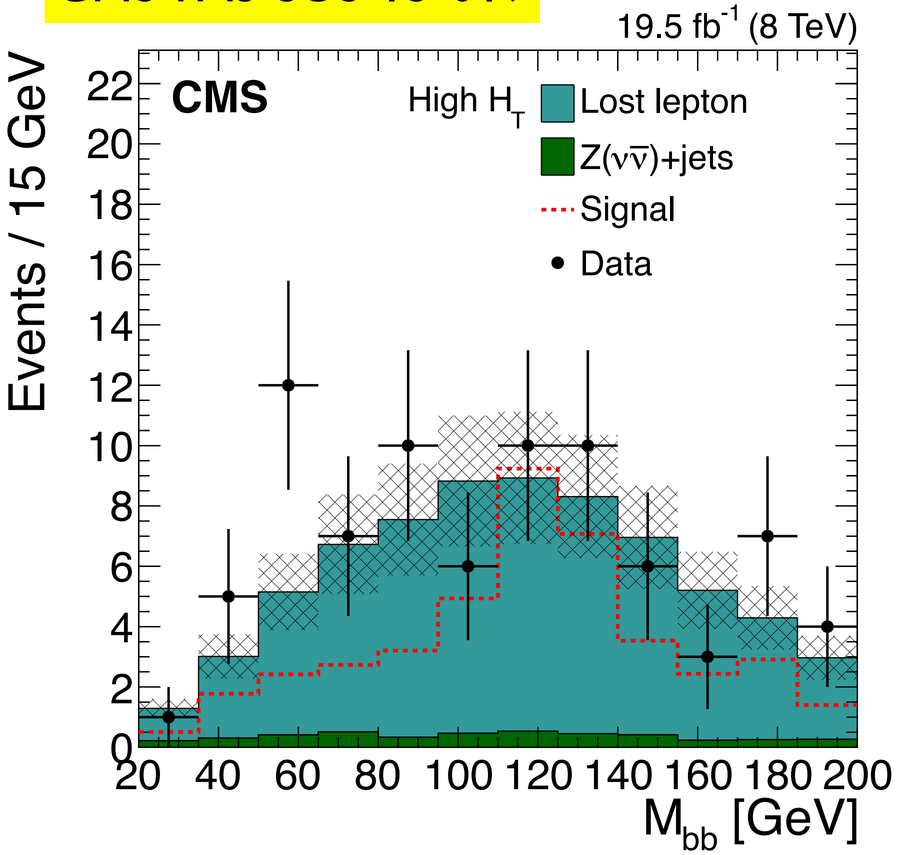
Moving forward, there is an opportunity for more creativity.

The lack of evidence so far may, for example, actually lead to a greater number and diversity of jets+MET (or 1L, SS, etc.), not fewer…

# Go forth and multiply

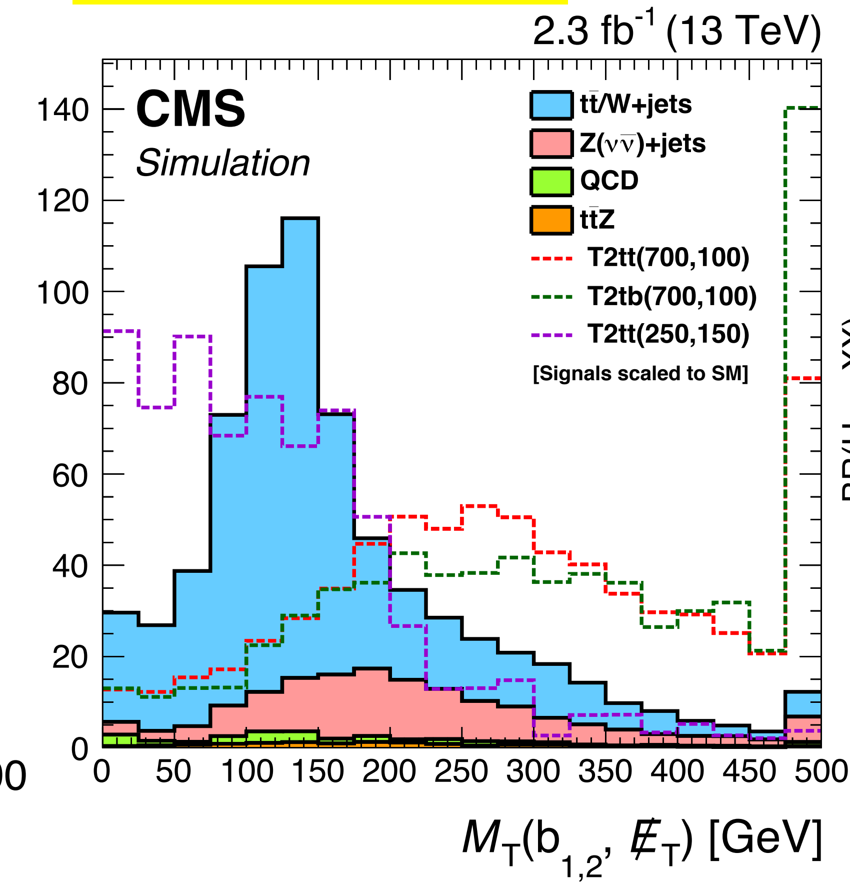
## known resonances

CMS-PAS-SUS-13-019

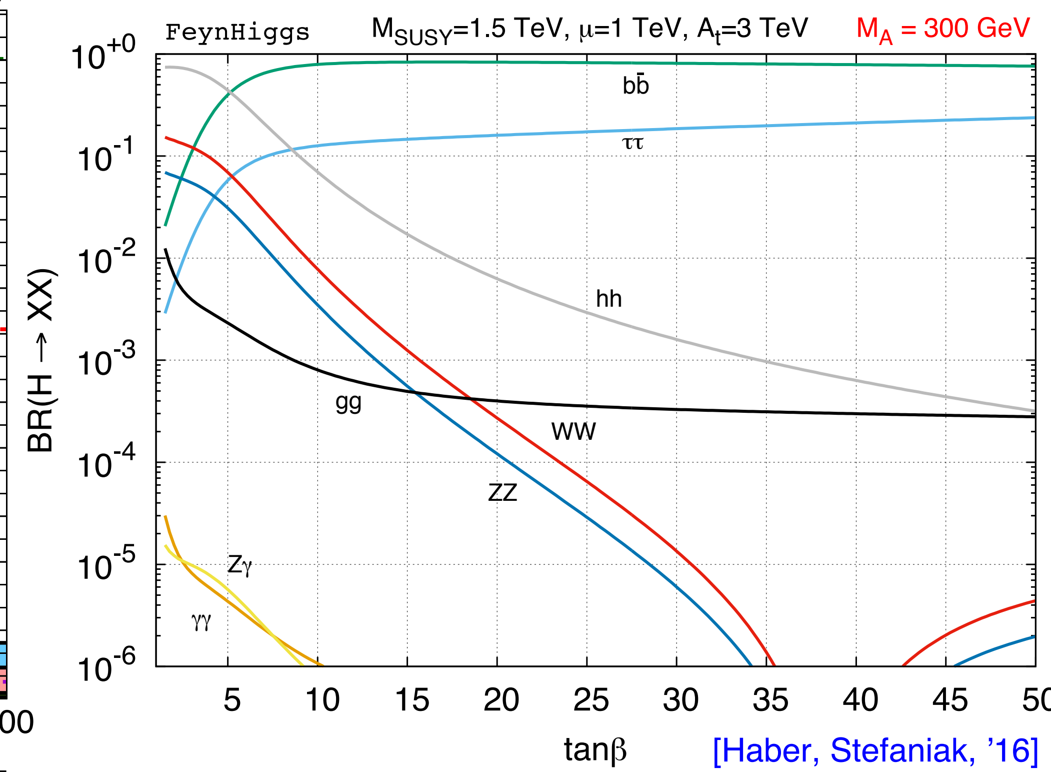



## kinematic edges

CMS-PAS-SUS-16-007

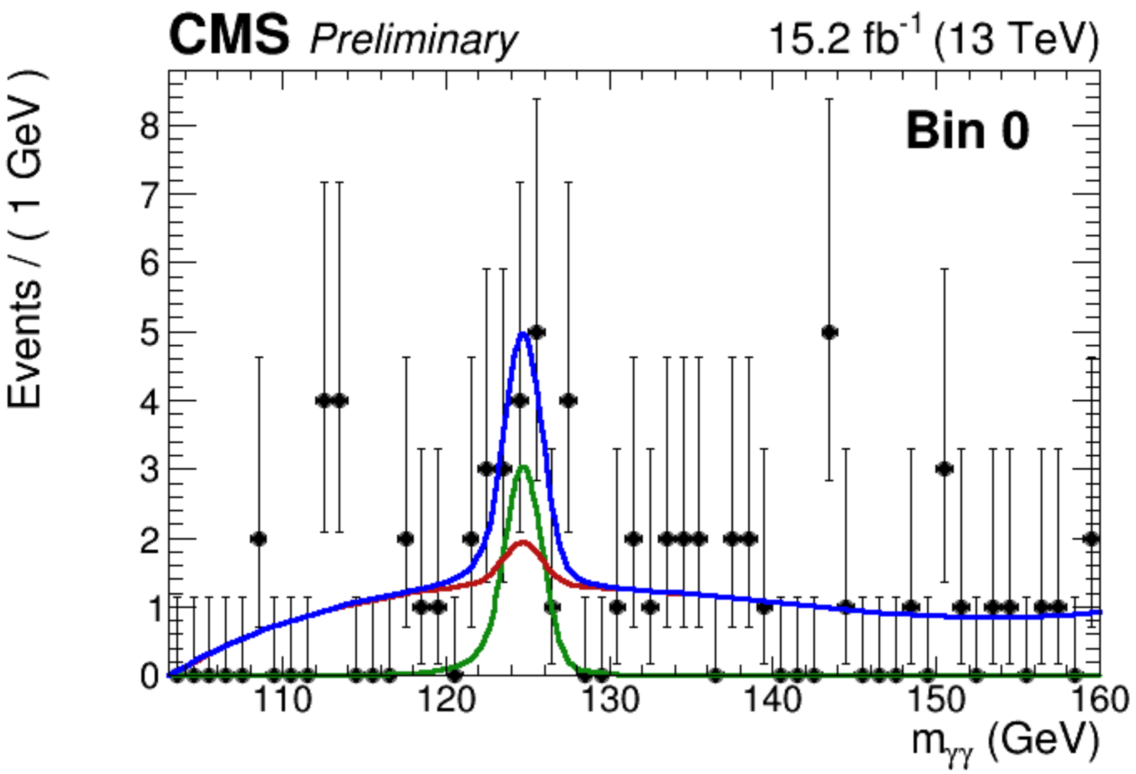


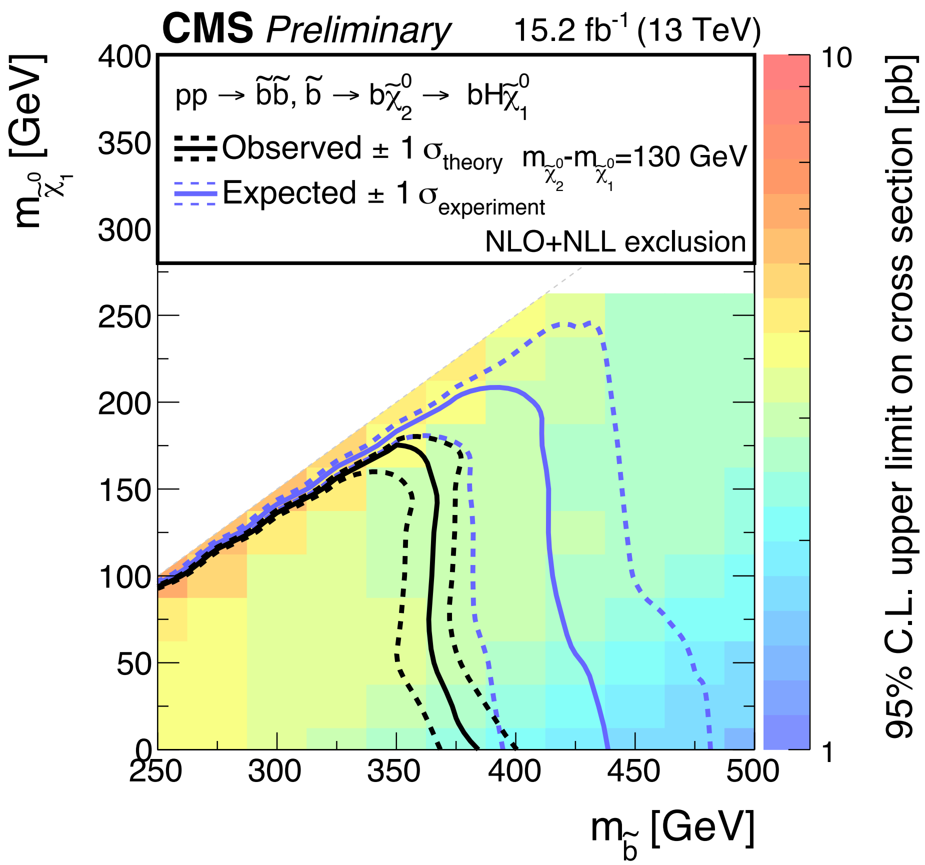

## new resonances?

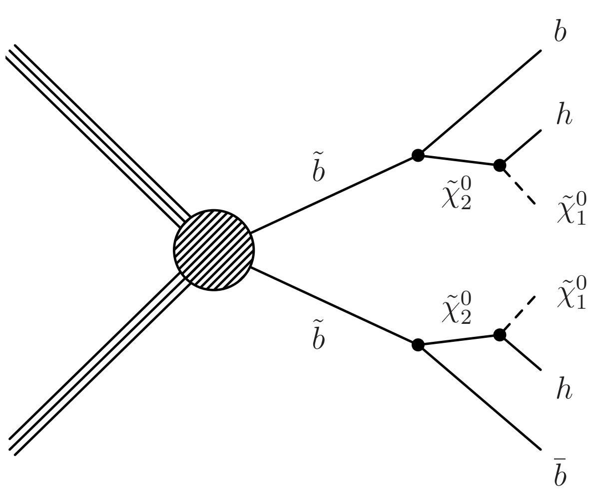



As we accumulate more and more luminosity we can afford to search for rare signatures of NP as long as they provide striking enough signatures to substantially suppress SM backgrounds.

# A hint in h(γγ)-tagged events?



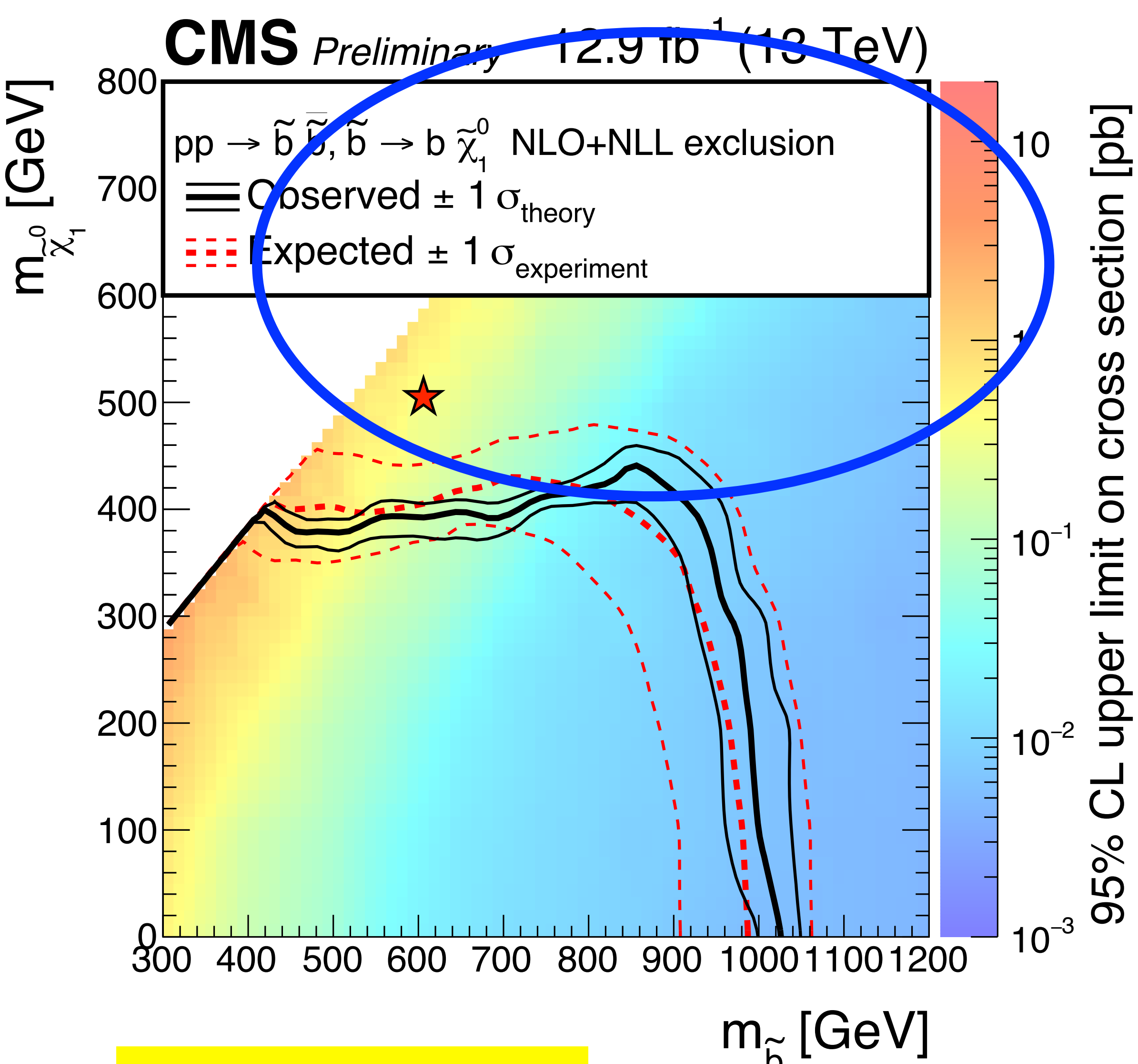



New ICHEP result: small excess seen in search for events with h(γγ) using razor variables. How easy would it be to hide from hadronic searches?

The xsec for m($\tilde{b}$)=450 GeV is ~1 pb. 0L searches for $\tilde{b}$→b+LSP have xsec UL ~100 fb, so we would not see if BR($\tilde{b}$→b+LSP) is O(1%). Of course, this decay would lead to many events with 6 b-quarks+moderate MET. Opportunity for new search? How do we trigger on such events?

# Still a lot of unexplored territory

There are many corners of phase space where SM backgrounds can easily hide NP at large cross sections - e.g. expect O(2000) squark pairs with m=600 GeV in current data.



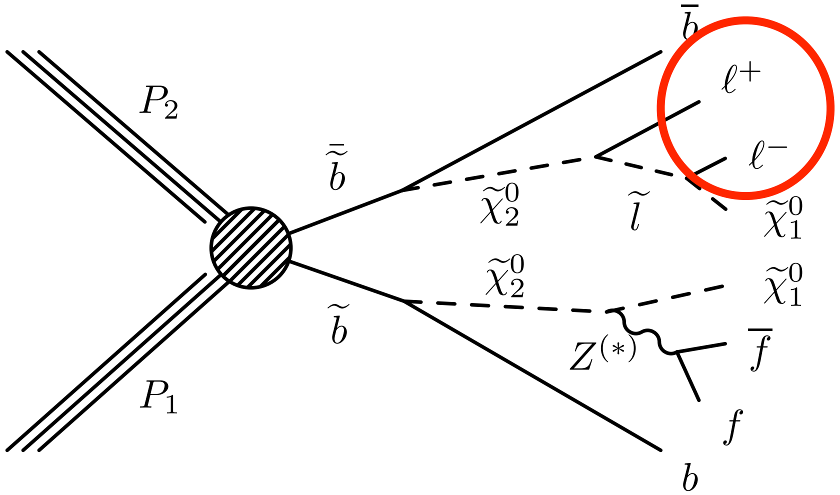

CMS-PAS-SUS-16-015

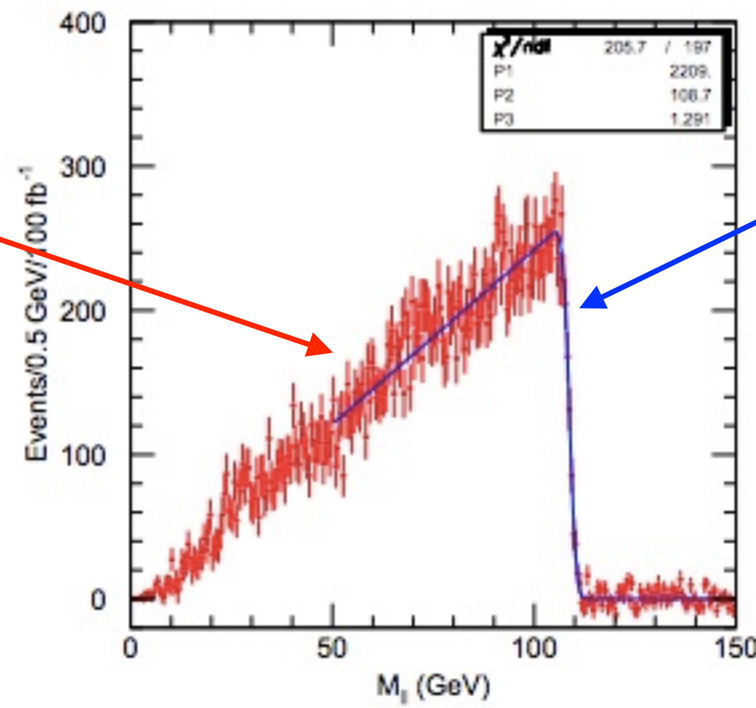
We can afford to search for rare decay modes of NP as long as they provide striking enough signatures to substantially suppress SM backgrounds even for a lowish MET selection.

Possible examples:
- dilepton edge
- soft lepton(s)
- things we haven't thought of yet…

# Can we get an “edge” on squarks

arXiv:9907518



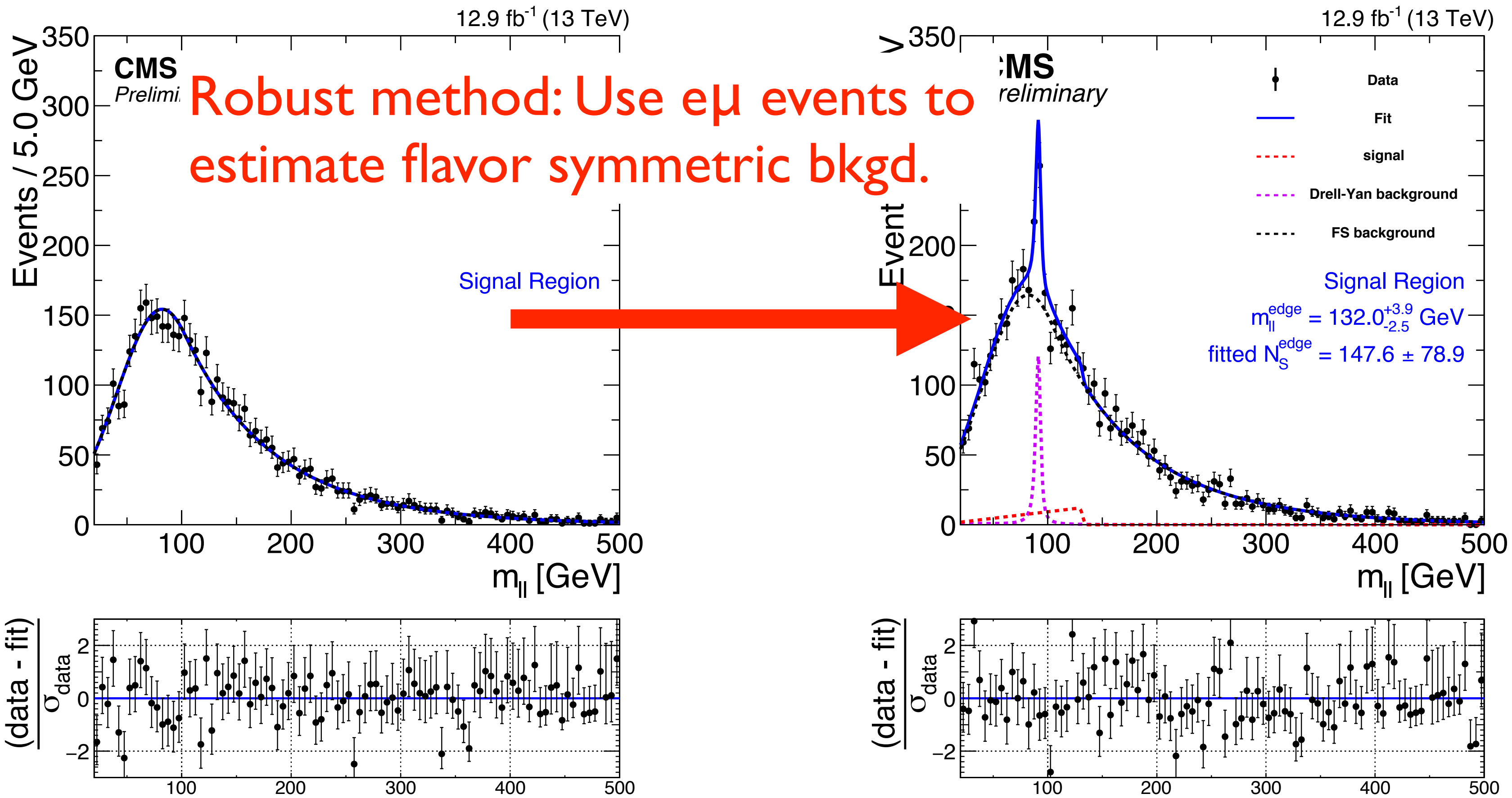

$$M(\tilde\chi_2^0)\sqrt{1-\frac{M(\tilde\ell)}{M(\tilde\chi_2^0)}}\sqrt{1-\frac{M(\tilde\chi_1^0)}{M(\tilde\ell)}}$$

If the BR to leptons is large enough, can probe with searches requiring $\geq 3\ell$.

If the BR is small enough, we won’t get enough events with $\geq 3\ell$, but may still get enough events with two leptons to reconstruct a dilepton edge.

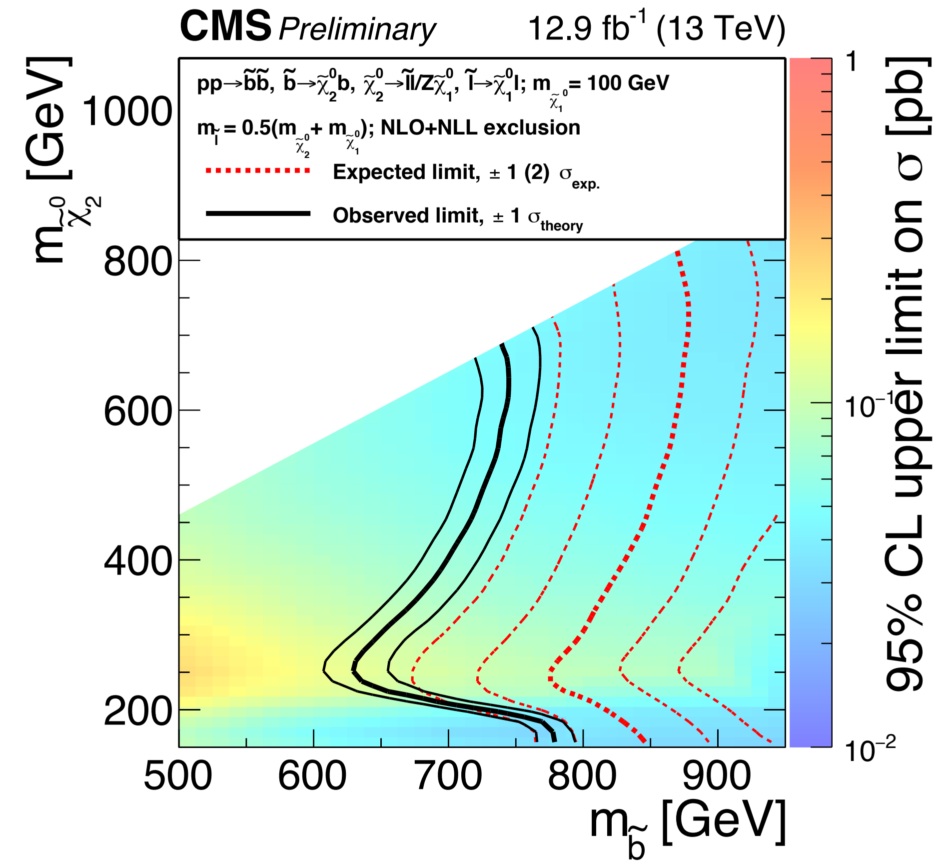
Events with these signatures can be selected with lepton triggers → this **allows searches to probe low MET final states**.

# Pushing existing searches to more difficult regimes




Robust method: Use eμ events to estimate flavor symmetric bkgd.

CMS-PAS-SUS-16-021



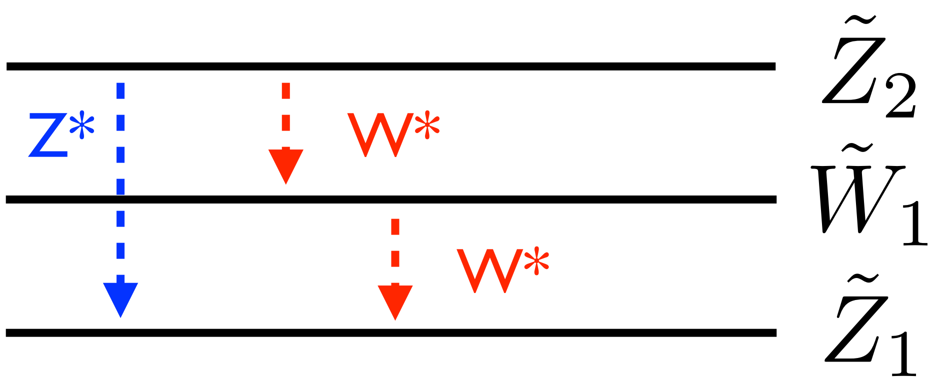

CMS-PAS-SUS-16-021 searches in regions with at least 2 jets, MET > 150 GeV. Looks for an excess above the expected background, mostly top.

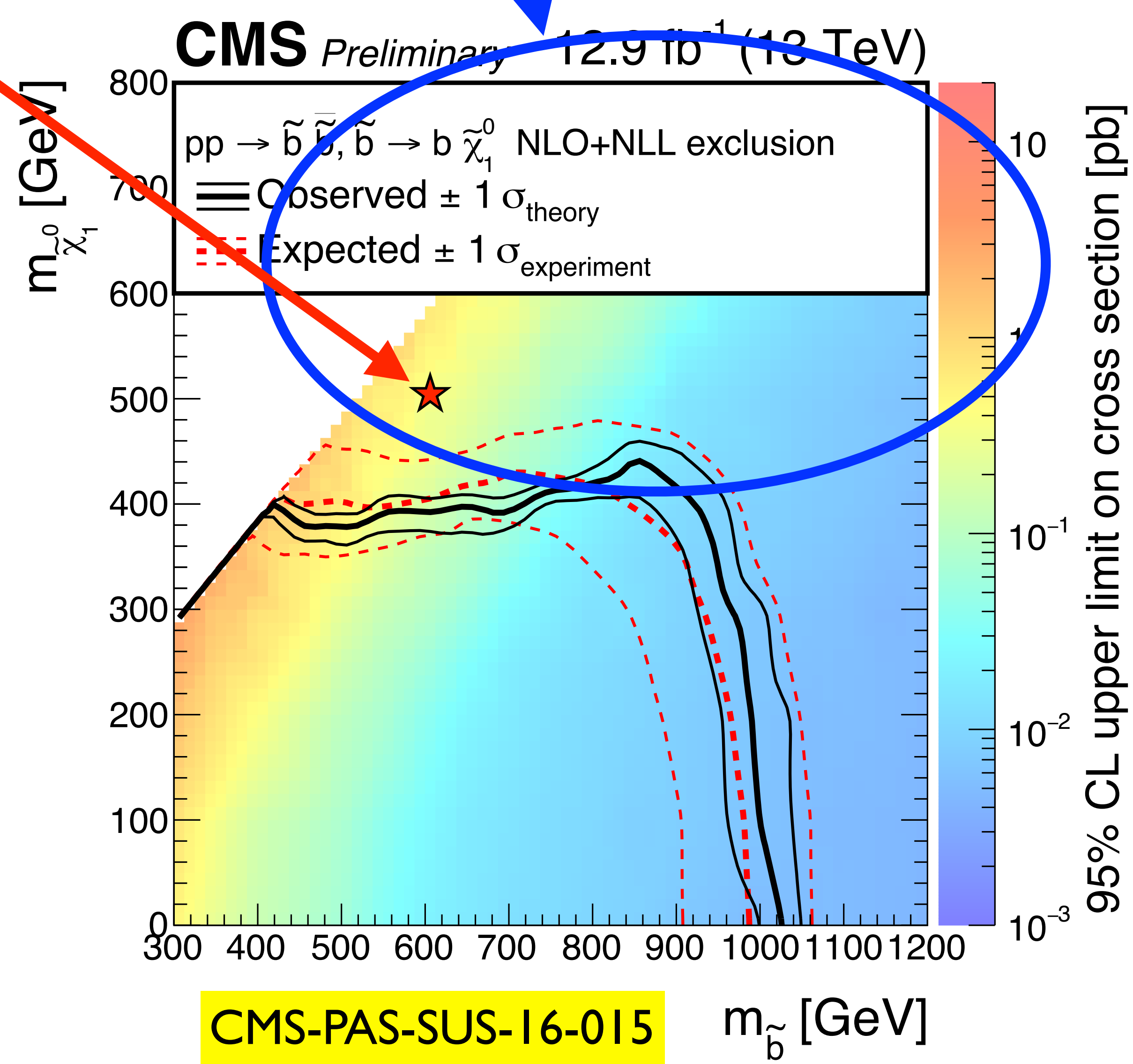
Can this method be pushed towards lower MET in order to be sensitive to more kinematically compressed new physics final states?

# Making a discovery via rare decays of NP

Would we be able to discover NP in this kinematic range via rare decays to soft lepton(s)?

Large regions of unexplored territory for gluino and squark production at large LSP mass.




Is 1 soft lepton sufficient to suppress bkgd?
Also, what do we trigger on?

What about 2 same flavor leptons and small $m_{\ell\ell}$?

- recall current search has a b-veto

# Final thoughts

Run 2 has started off successfully, in that we've probed much higher mass scales than before. Unfortunately, NP wasn't waiting around the corner for us.

With the expectation to double the amount of data this year and double it again by the end of this run, expect exciting times ahead in the search for new physics.

With larger datasets, there are opportunities for more targeted searches, to explore new signatures in the context of inclusive ones, and to make the search for rare signatures in decay chains worthwhile.

# Still the future we aspire to

**2017?**

~~2016~~: Discover excess in multiple final states

jets + MET + b-tags with or without leptons

2018: First evidence for WIMP new physics

multileptons + MET with distinctive dilepton mass spectrum

2020-30: Discover additional states & measure features of earlier discoveries in detail.

production & decay rates & kinematics in all final states