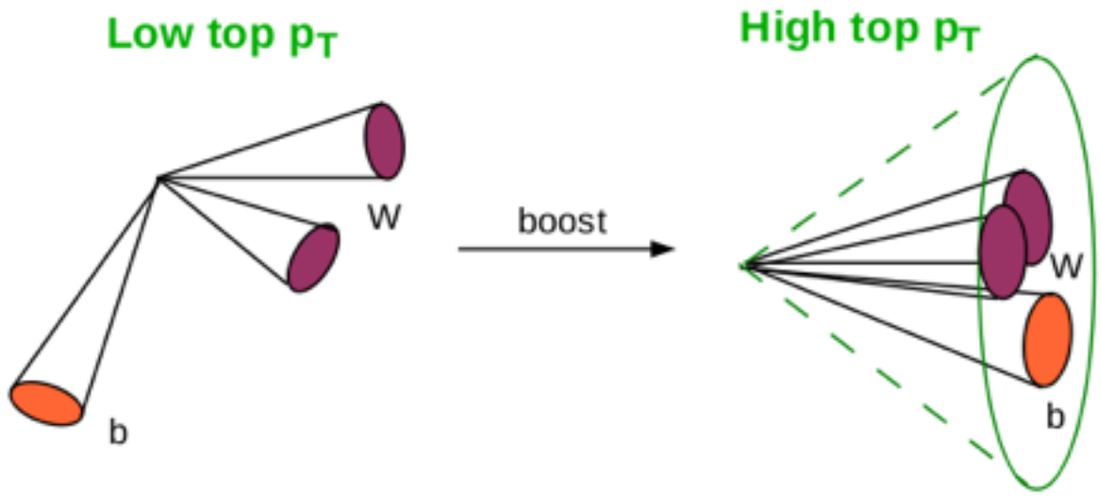
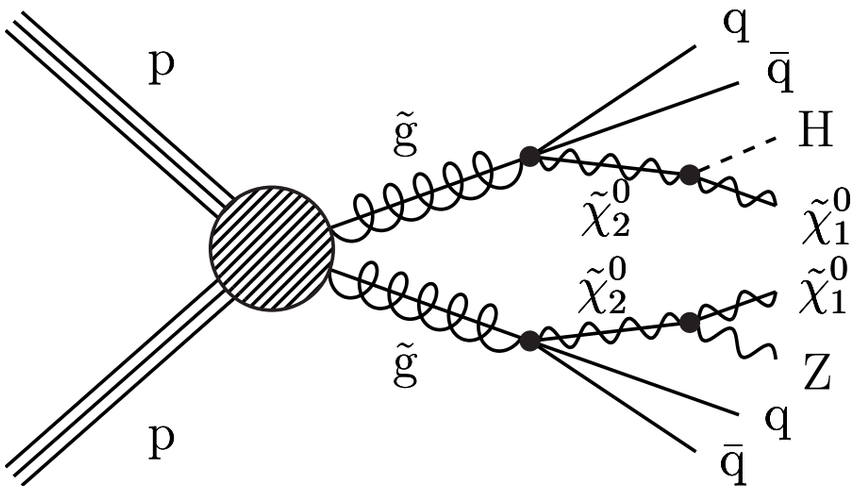
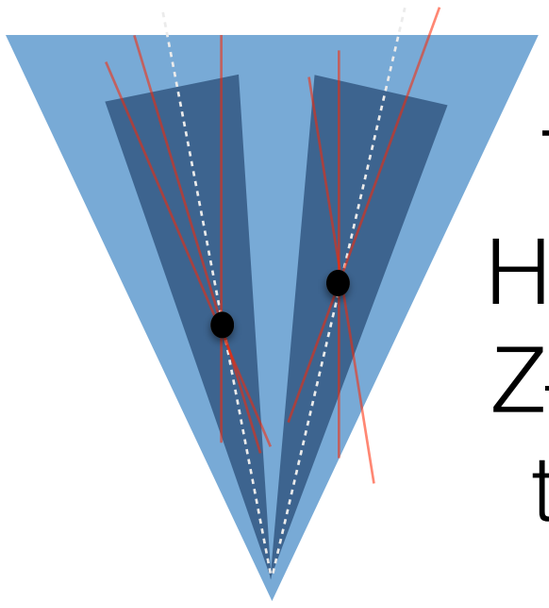


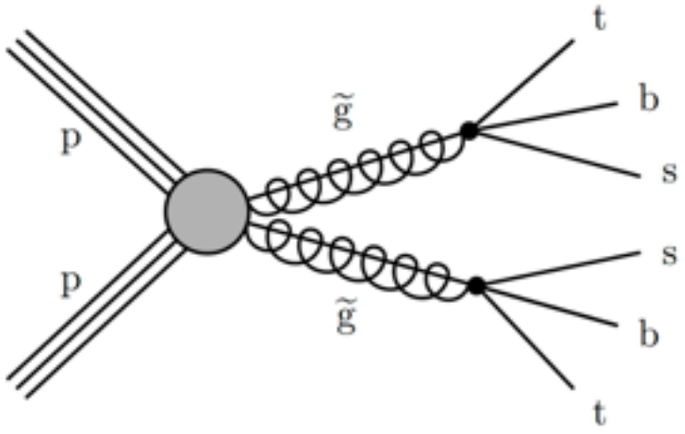
Overview: Boosted Objects in SUSY Searches

Rishi Patel





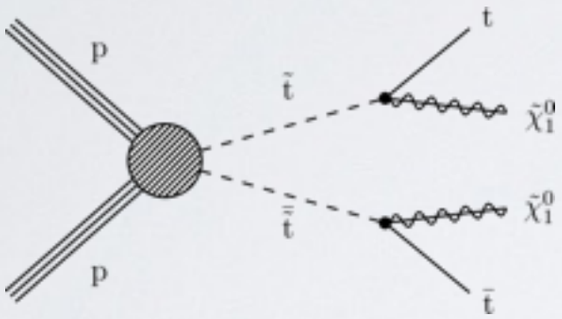
Tags:
H—>bb
Z—>bb
tb tag



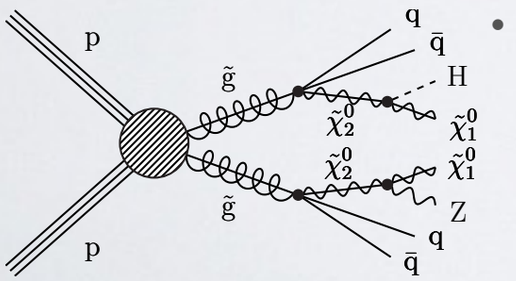
SUSY: SEARCH STRATEGIES

Strong Production

- Somewhat "natural SUSY" inspired: LHC accessible light stops and gluinos
  - Major looking-glass on these SUSY suspects are signatures with heavy flavor quarks



- For R-parity conserving scenarios rely on MET triggers
- **Tools like top-tagging take advantage of the SUSY mass scale** (high pT tops where the mass can be resolved) vs. SM Top production

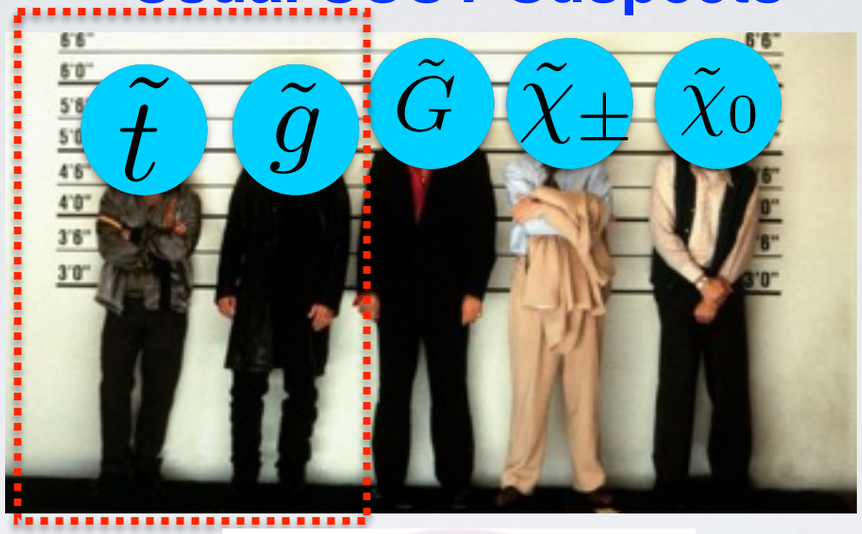


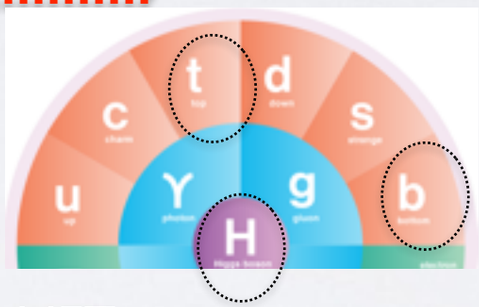
$$\Delta m = m_{\tilde{g}} - m_{\chi_2^0}$$

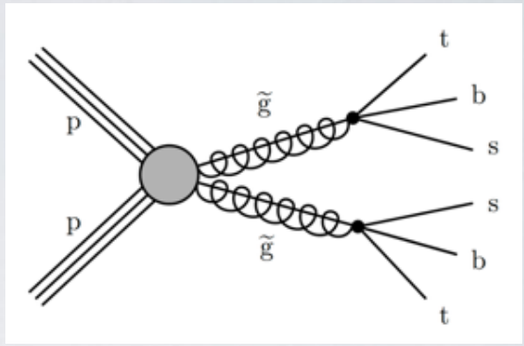
- **Boosted Higgs or Vector boson tagging** can play a role in cascade decays from high mass gluinos:

  at low values gives both high MET and high pT bosons

Usual SUSY Suspects

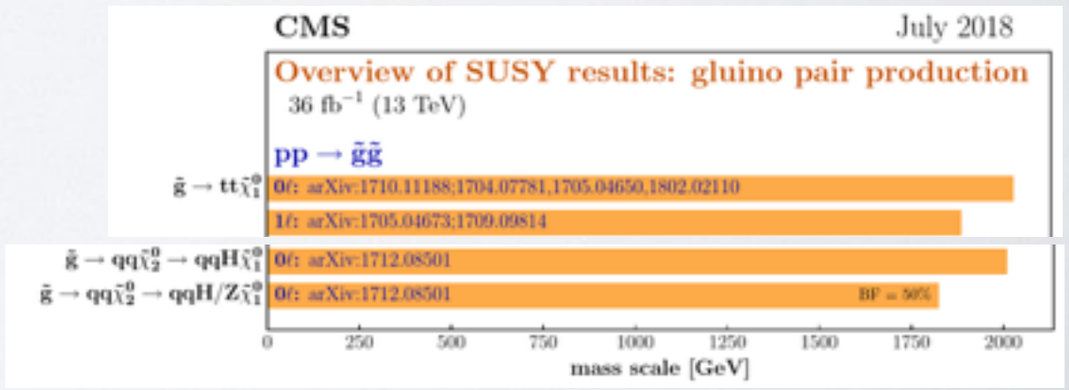






For searches at low MET with RPV violation can trigger on high HT:

- Rely on high b-multiplicity and clumps of jets with large mass to discriminate against SM top production
- Squeezing sensitivity in all scenarios constrains gluino masses up to ~2TeV (small xsecs)



SUSY: SEARCH STRATEGIES

- Given the high mass constraints on gluinos and stops, one can also focus on another part of the SUSY spectrum that is LHC accessible

Electroweakinos

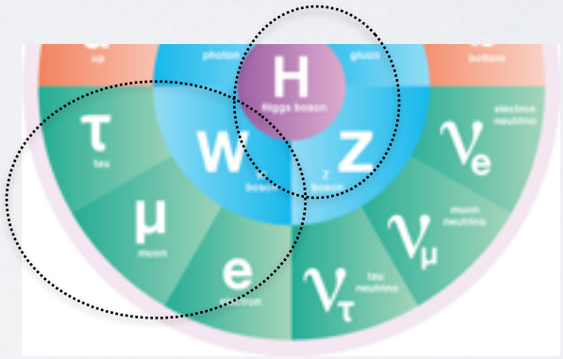
What is their mass spectrum?

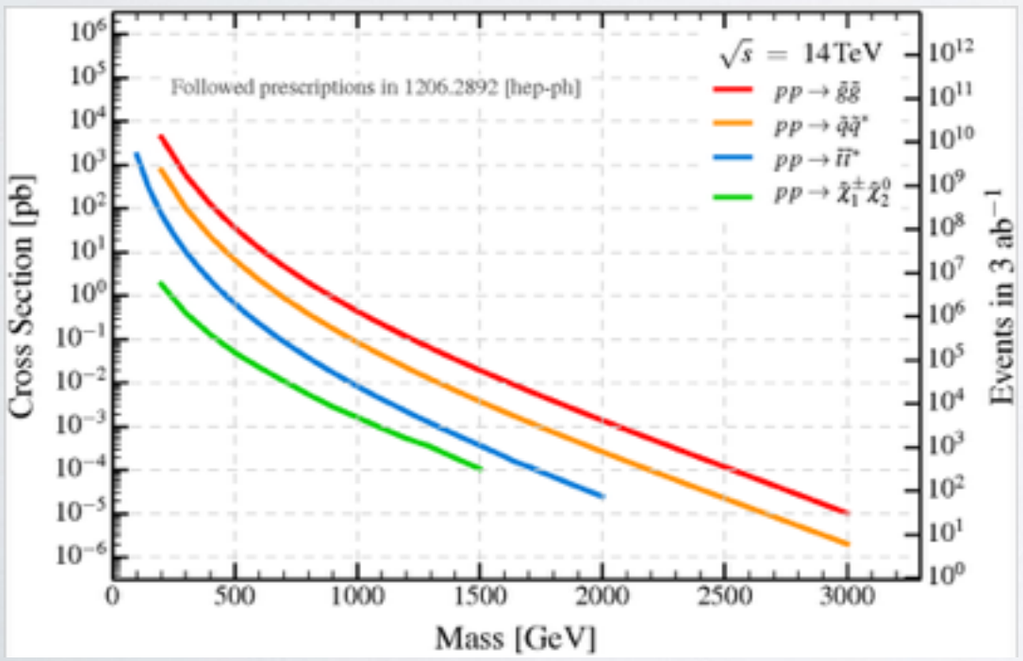
Usual SUSY Suspects

An interesting case **arxiv: 1809.02097** GAMBIT fit shows what searches can drive a full model for EWMSSM where EWKinos

- Squarks and sleptons are decoupled from neutralinos and charginos. So that the main parameters are M1, M2, μ, tan β

- Weakly produced sparticles have lower production cross-sections compared to strong production
- Lower mass range with high xsec can result in more moderate MET, can trigger on one or more leptons from Vector bosons





Current searches that drive this model fit:

- WH-final states with 1-letpon: SUS-16-043
- On-Z search OSSF Leptons: SUS-16-034
- Ewkino Multi-lepton : SUS-16-039
- ATLAS Higgsino search hh(4b)+MET

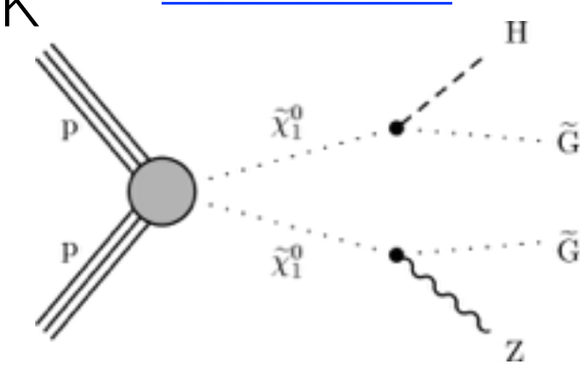
BIG QUESTIONs with Boosted Objects:

Can we take advantage of the hadronic parts of the W/Z decays?
Can we squeeze Higgs tagging for the above searches with sub-structure?

Benchmark Strategy: Opposite Sign Leptons

- This search is "inclusive" and meant to cover both strong and EWK scenarios with Z decays to OSSF leptons **(no boosted Objects)**

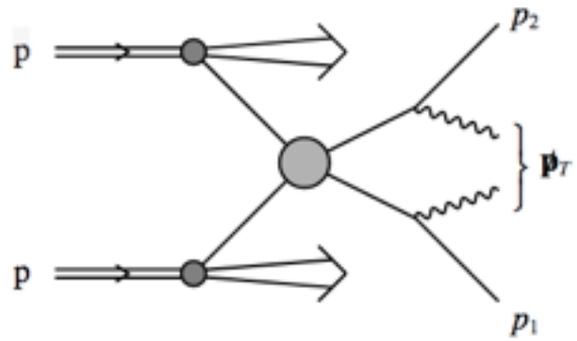
SUS-16-034



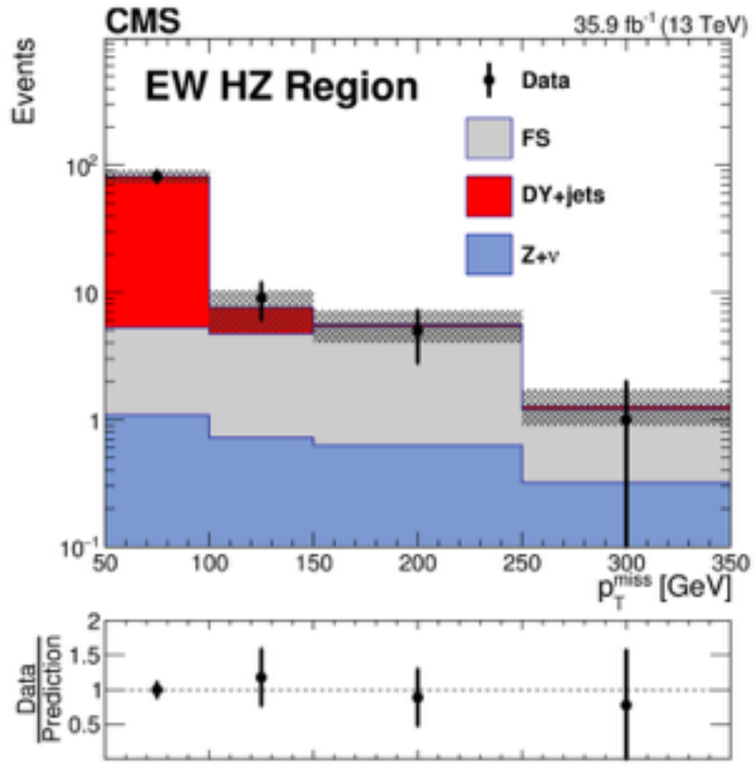
- A model of interest in Gauge mediated SUSY are neutralino production with near mass degenerate higgsinos (boost production xsec) BF=50% for H/Z. These results are recast in models like EwkMSSM in the previous slide.

Signal Cut Flow for HZ signal events

Electroweak HZ Region	
HZ model, higgsino mass: 350 GeV	Events in 35.9 fb^{-1}
Expected events	324.77
$\geq$ 2 Leptons ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) with (sub)leading $p_T > 25(20)$ GeV	76.15
Extra lepton vetos	70.31
Dilepton mass $\in$ Z mass window (86,96) GeV	54.04
$\geq$ 2 Jets	46.52
$\Delta\Phi$ between MET and two highest p_T jets > 0.4 rad	39.68
Exactly 2 btags	12.57
$M_{T2}(\ell b \ell b) > 200$ GeV	11.50
$M_{bb} < 150$ GeV	11.04
$E_T^{miss} > 100$ GeV	9.46
$E_T^{miss} > 150$ GeV	7.74
$E_T^{miss} > 250$ GeV	3.71



Sensitivity up to 400 GeV in higgsino mass

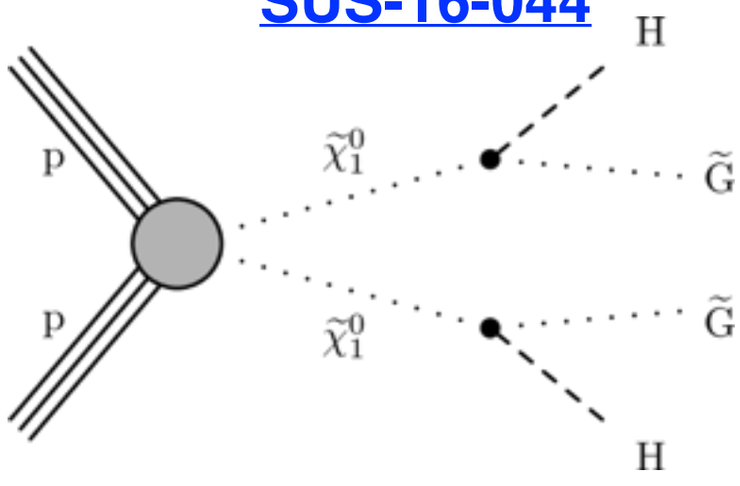


- Biggest reduction in signal is in requiring 2-leptons on-Z and also in requiring two b-tags
- For bkg rejection the search uses a general SUSY strategy of using a variable with an endpoint in SUSY signal (MT2) which is designed to reject top production (flavor symmetric bkg). The mass constraint on the Higgs is then fairly loose Mbb<150
- **What happens if we consider this picture with only jets?**

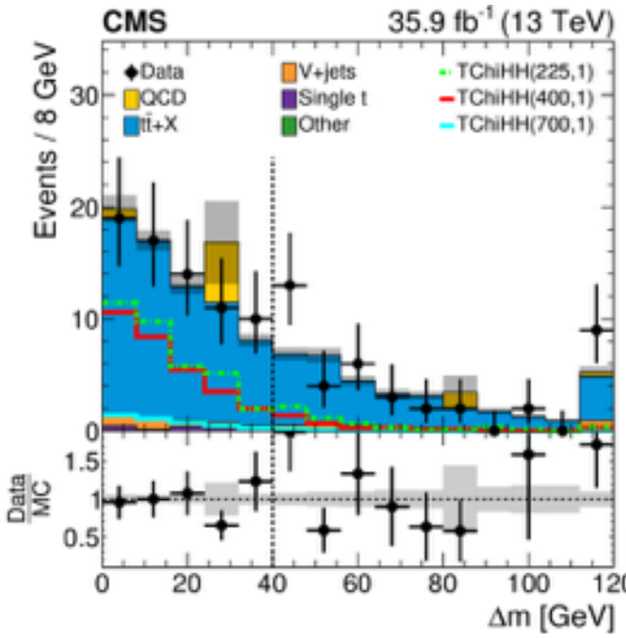
Target Higgsino Search with b-jets

- Target 4b events from higgsino production resulting in decays with 2 Higgs
  - 1-Higgs with 2-b is swamped by top-production
- Use low MET thresholds in the L1 trigger starting at ~100GeV allowing for sensitivity to even low higgsino masses
- The two Higgs masses are resolved from the 4-highest ranked b-jets

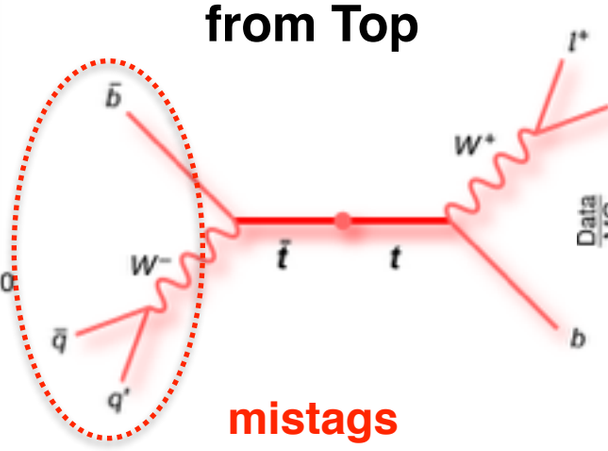
SUS-16-044



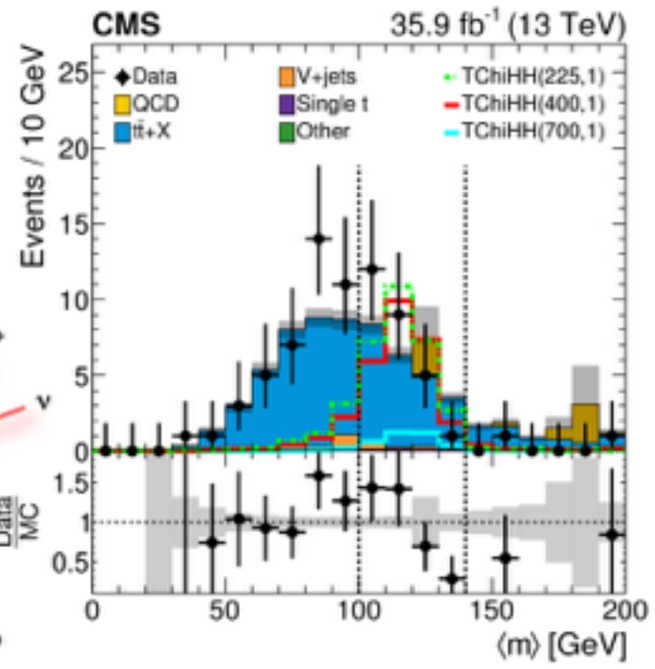
4-highest deep CSV value jets give 3 bb-pair combinations:
Choose the pair with the smallest bb-mass difference



Cut on mass window based on the avg of the two Higgs candidates:
Higgs bump on top of bad combinations from Top



mistags



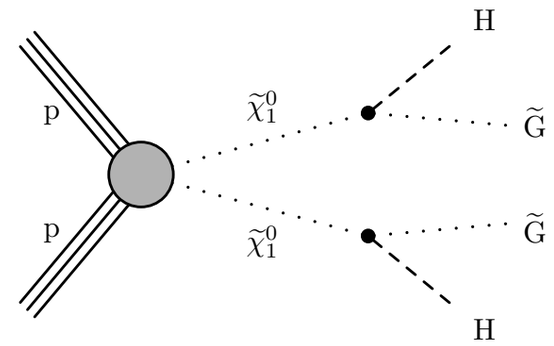
H—>bb mass constraint does suppress TTbar here

What happens if we consider this picture with only jets?

Sensitivity from 200 to 800 GeV in Higgsino mass

Targeted Higgs+MET searches

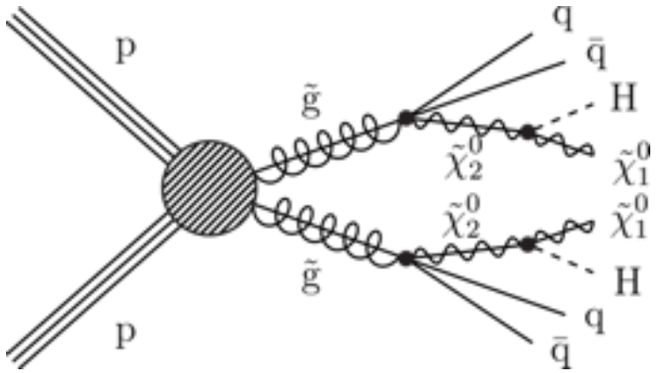
SUS-16-044: Resolved Higgs Search for Higgsinos



- **Use AK4 jets with deep CSV b-tagging** to resolve the higgs based on the top 4 b-like jets: (4 choose 2)/2 =3 combinations
- All events have two Higgs candidates resolved from 4 b-jets

Sensitive to Higgsino masses out to 800GeV

SUS-17-006: Boosted Higgs Search for Gluinos



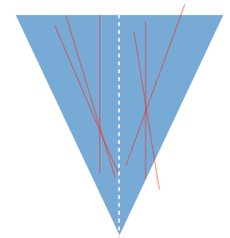
- **Use sub-structure of AK8 jets:** Use the same double-b tagger as in **B2G-16-026** at high MET (use a high MET L1 trigger)
- This allows an additional handle to suppress TTBar (2b content vs. 1b)
- Get a single Higgs Object: AK8 jet that passes double-b tag. Can have a category with just 1-Higgs for H(Z/W) +MET Final states

Sensitive to gluino masses out to 2TeV

- **Two signals are clearly related so that the analyses can be combined to cover a broad Higgs pT range**
  - SUSY analogy would be top-tagging: Divide events into Boosted and Resolved H categories and try to make an intermediate region to cover any intermediate pT that is missed

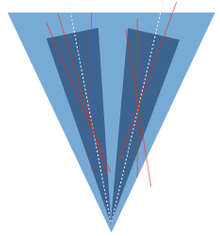
Double-b Tag for Higgs

- Want a measure of the heavy flavor content of a wide cone jet
  - **Loose tag:** use b-tagging on the large cone jets. This will have no rejection power against jets from top
  - **Tight tag:** Decluster the jet into two sub-jets and require each subjet to be b-tagged. This will reject top jets, but can be too tight given the number of tracks in each subjet (require a SIP)
  - **Double-b tag:** Use the subjets for the b-direction and check for SV's that you can find along that direction. Also make use of the opening angle for a heavy particle decay

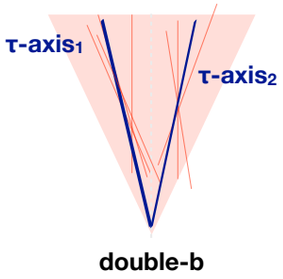


BTV-15-002

Too loose

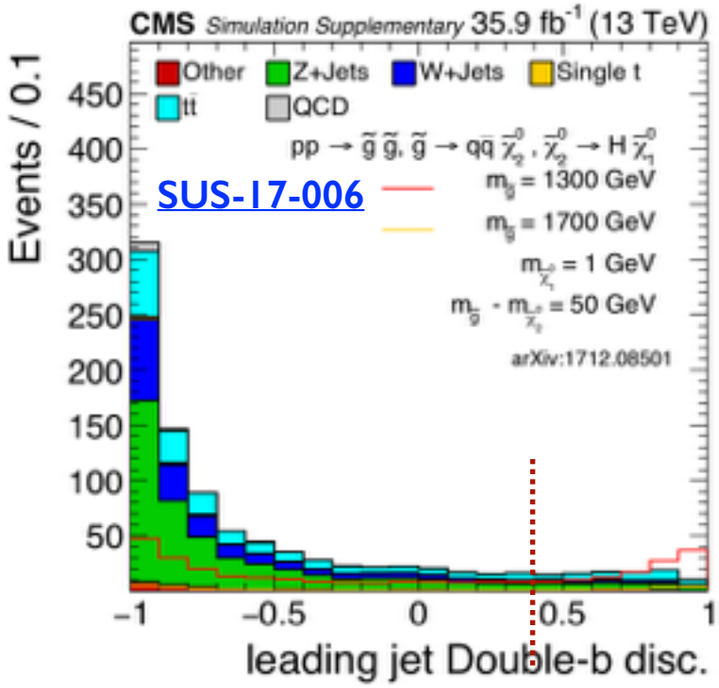


Too tight



Just right!

- **Search for Higgs production at large missing energy**;
  - Low MET searches are dominated by the bulk of QCD-multijets.
  - For SUSY we we are dominated by mistags and single-b background from top



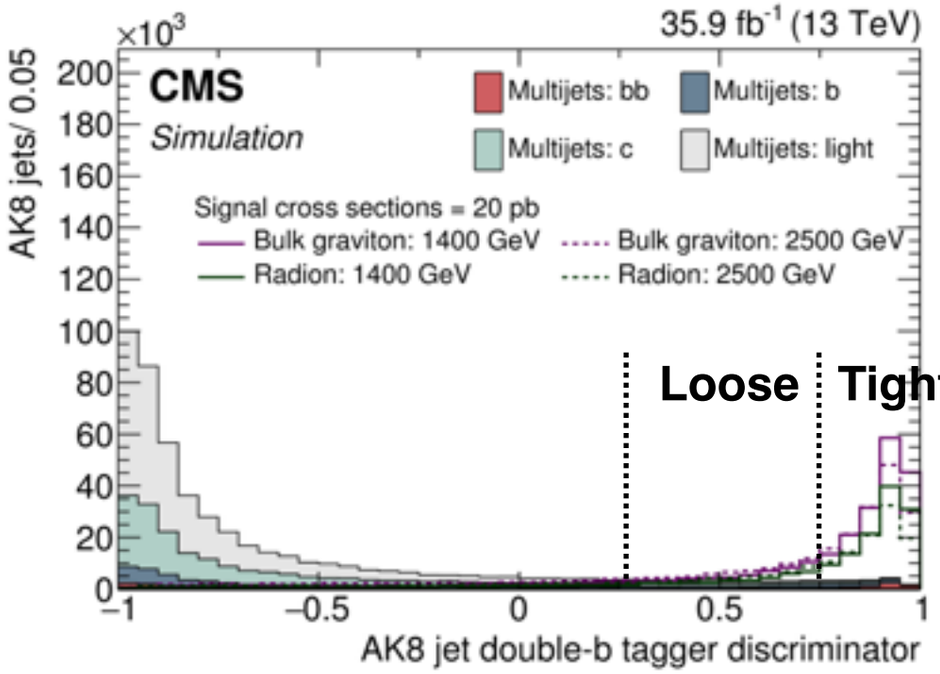
Radion/Graviton vs. Gluino search with the same Higgs tag: Both look for Higgs as decay products of massive particles

MET>300GeV

B2G-16-026
Resonance

SUS-17-006
Counting

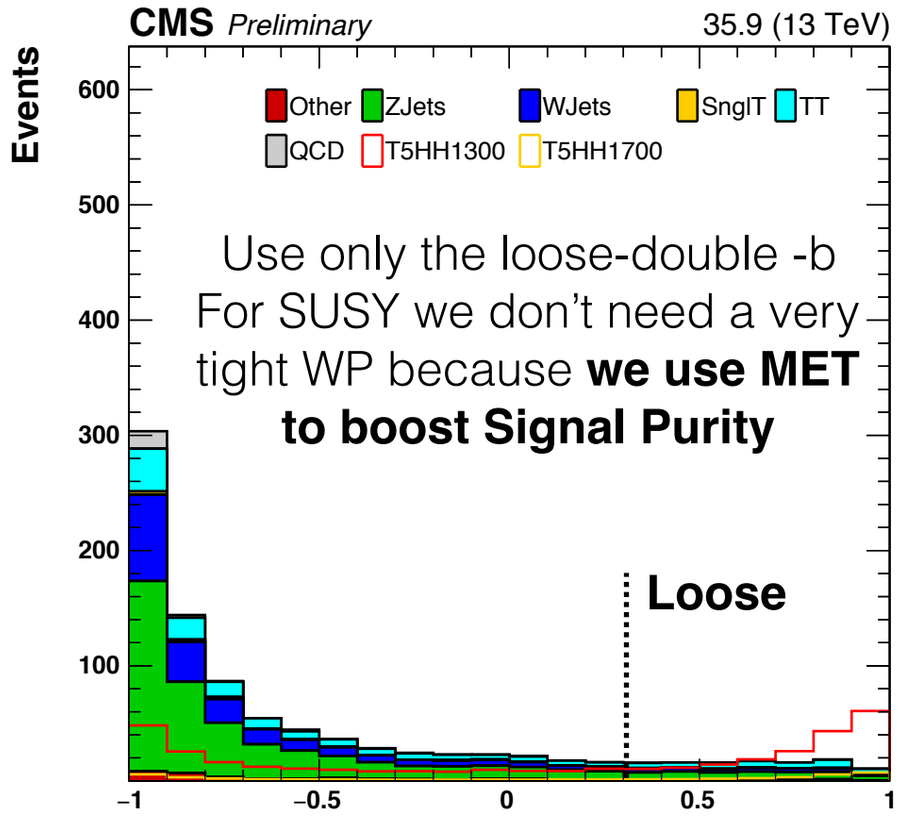
Bkg: QCD Multijet



g—>bb is particularly tough the main difference with signal is the opening angle between sub-jet axes
Make Tight/Loose category based on double-b

Event category	Jet	Soft-drop mass (GeV)	Double-b tagger discriminator
Signal (LL)	j_1	105–135	>0.3, but not both >0.8
	j_2		
Signal (TT)	j_1		>0.8
	j_2		

Bkg: mis-tags in VJets and single b in TTbar



Loosening the cut even further, would help to model the background in the Signal region

Radion/Graviton vs. Gluino search both use the mass sideband for a data-driven mass estimate

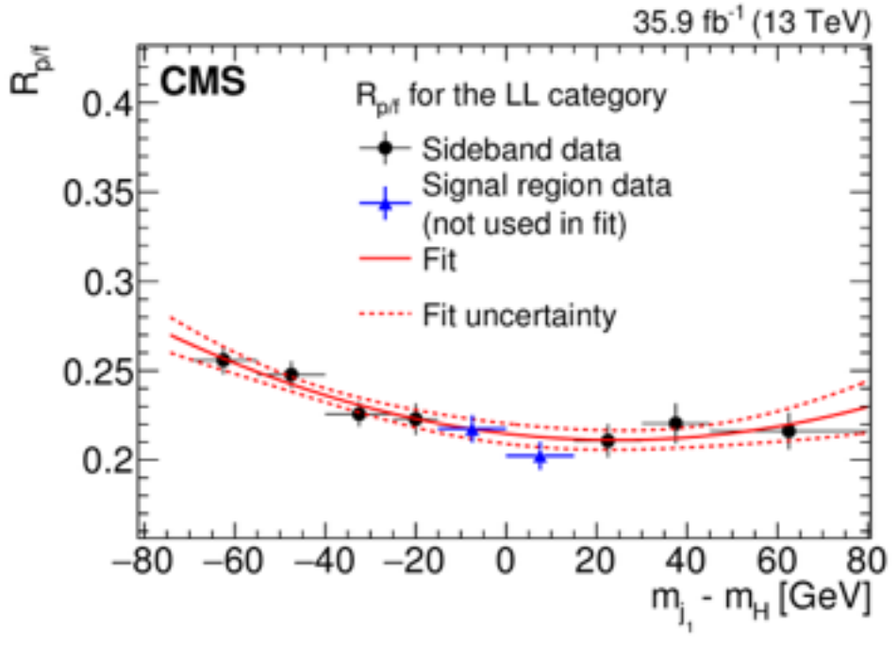
B2G-16-026

Resonance

Antitag LL (0-H tags) here is a signal region for the SUSY search

Signal (LL)	j_1 j_2	105–135	0.3–0.8
Signal (TT)	j_1 j_2		>0.8
Antitag (LL)	j_1 j_2	105–135	<0.3 0.3–0.8
Antitag (TT)	j_1 j_2		<0.3 >0.8

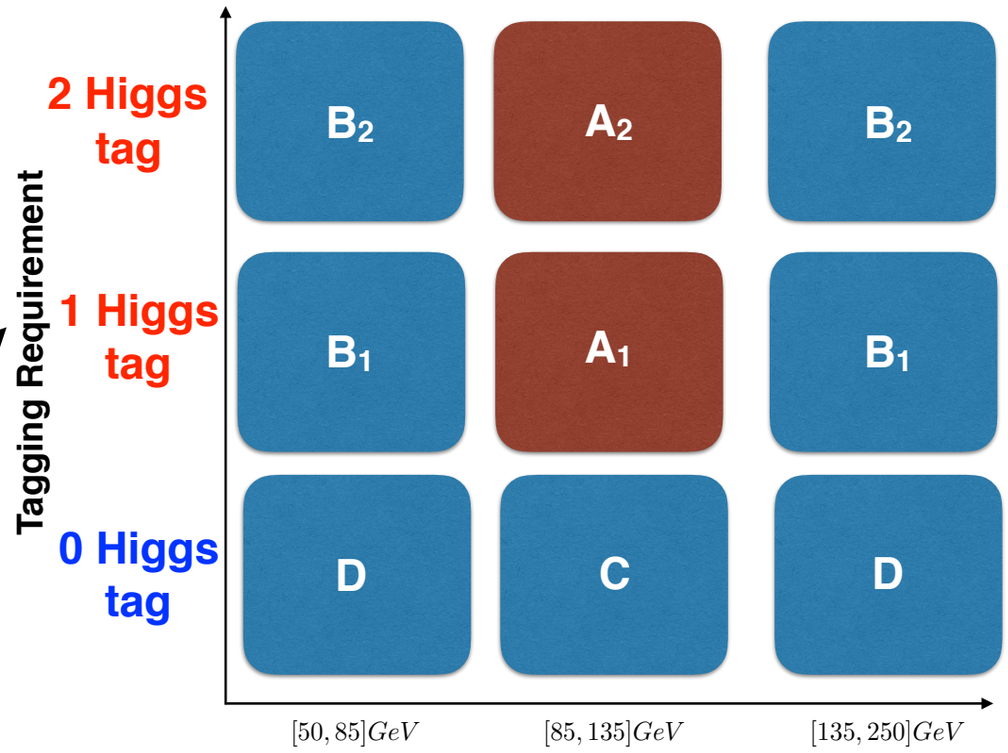
For the high bkg SB stats in B2G you can fully parameterize the B/D ratio in the sidebands



MET>300GeV

SUS-17-006

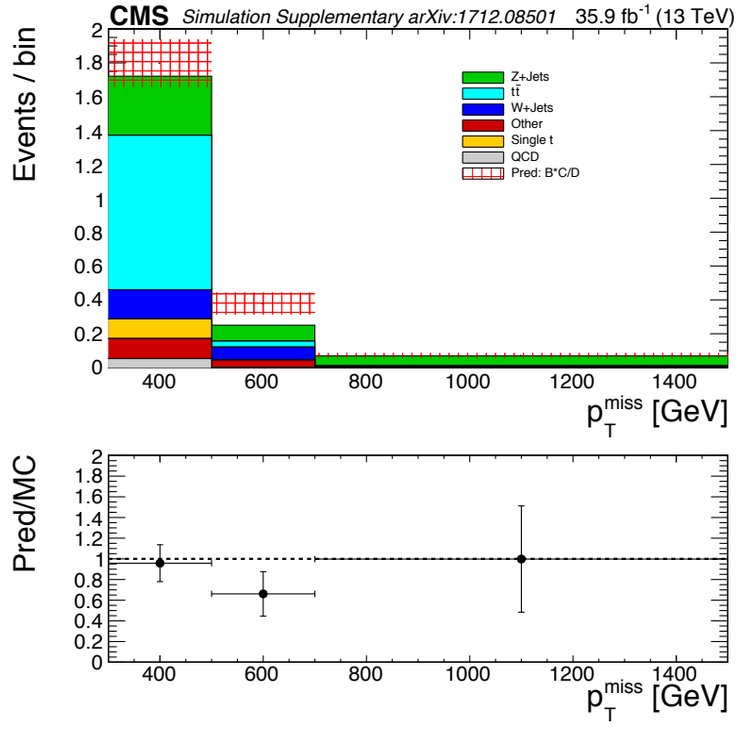
Counting



Here we have to use MC scaled by Data/MC to test correlations in double-b and Jet mass

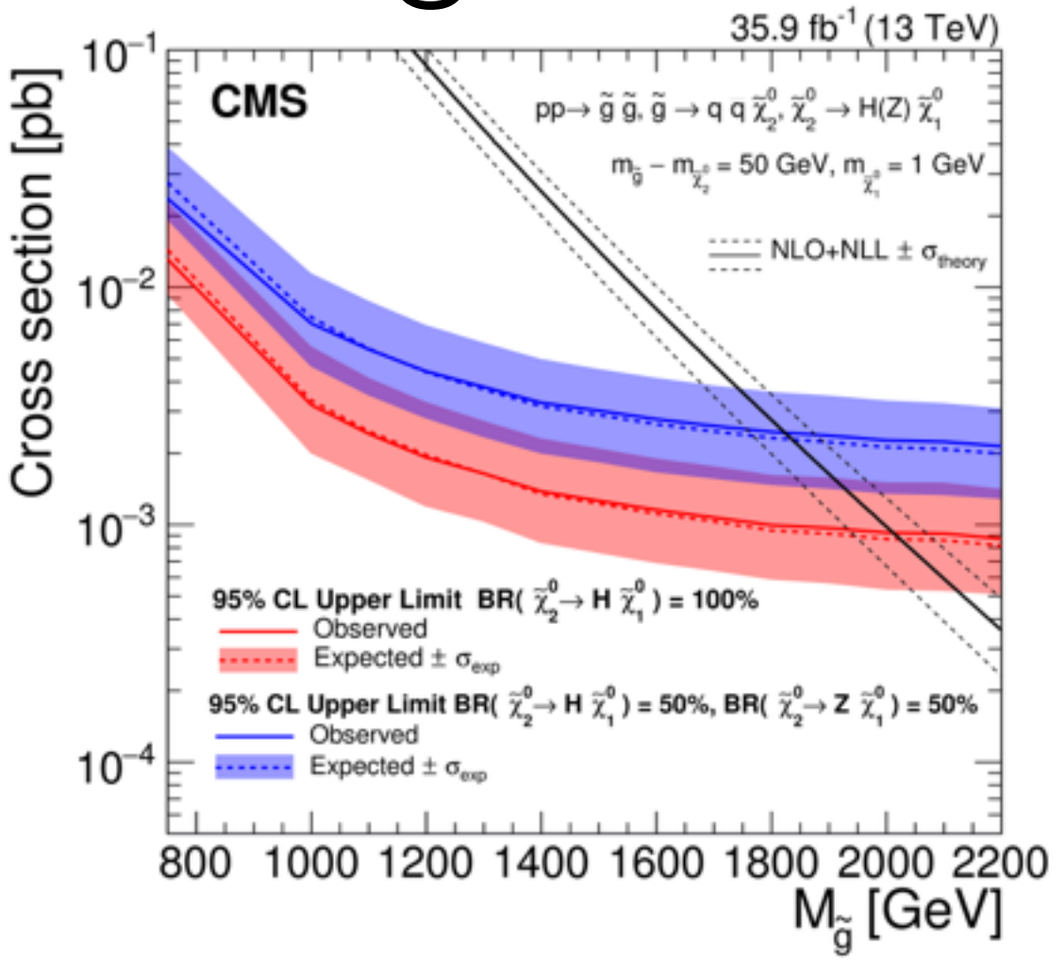
Assign κ correction based on closure in each MET bin

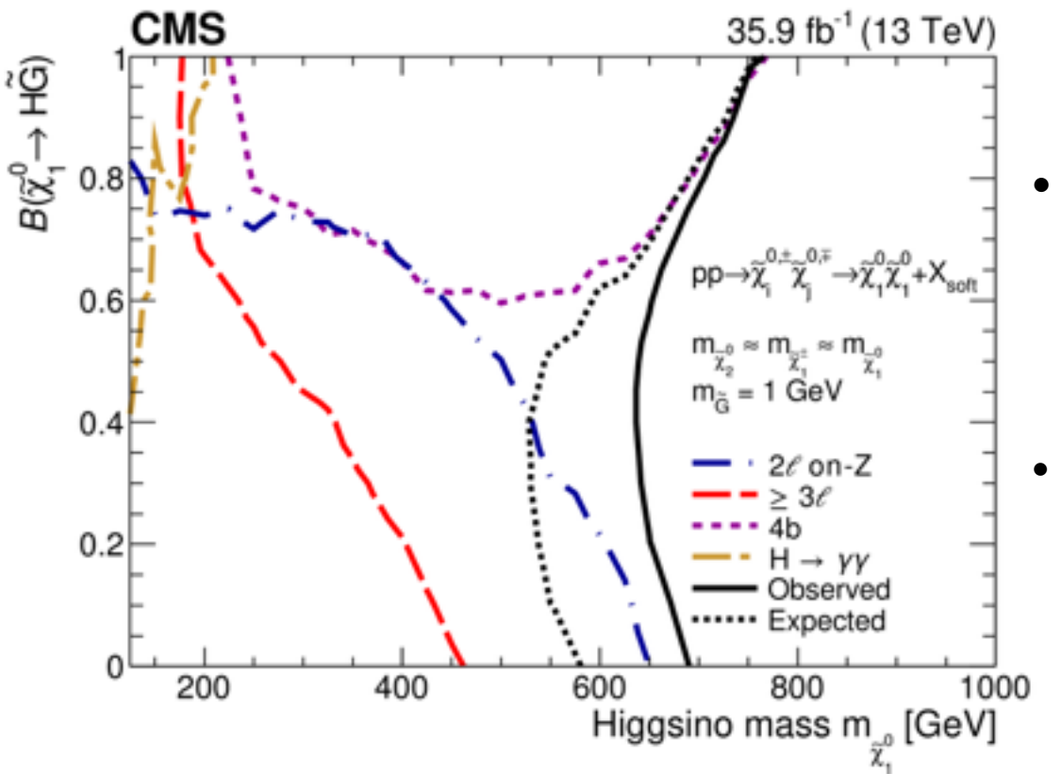
Jet Mass



Results for HH+MET signal

- **For the boosted case:** We look at two cases of gluino decay:
  - 2 Higgs final states
  - 1 Higgs Final states with a Z
- Limits shown exclude a wide range of heavy gluino masses, which can translate to sensitivity to high mass Higgsino decays to HH and HZ

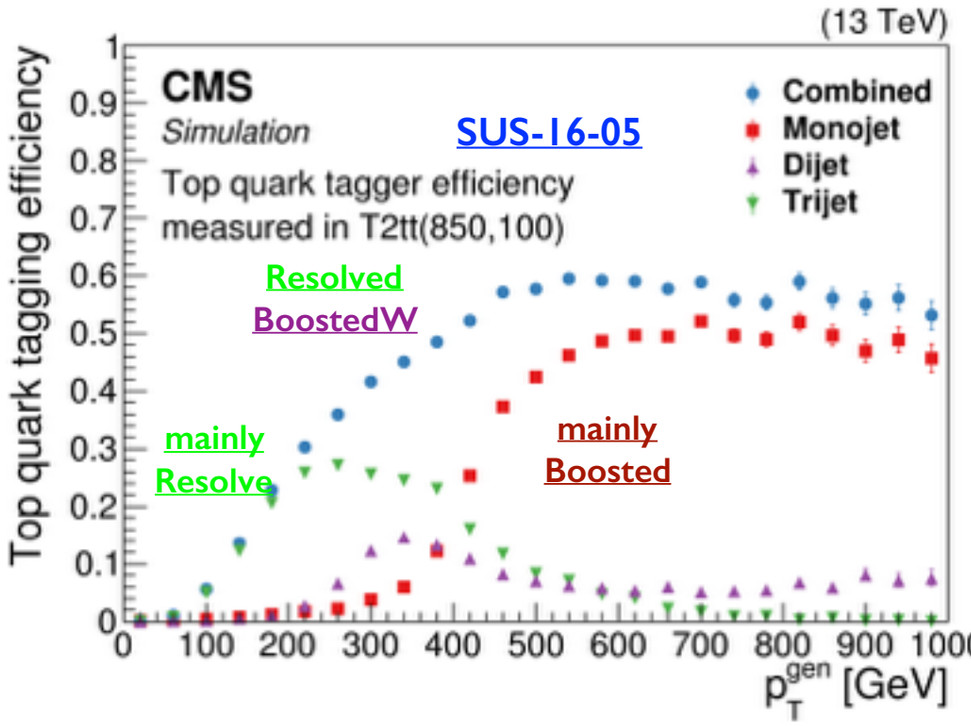




- There are many nice features of complementarity between the **resolved** and **boosted** searches:
  - Can separate events based on the presence of AK8 jets (signal and control samples then are independent)
- **Resolved** search looks for HH events (2b is a control region) **boosted** search has sensitivity to HZ models (lower BF in the Higgsino plot)

Combining Resolved and Boosted

- Also try to catch the in between cases with one boosted and one resolved H->bb candidate
- Simplest possibility: use mutually exclusive signal bins
  - Start from purest case of 2 boosted H->bb candidates (a la SUS-17-006)
  - Then consider 1 boosted + 1 resolved
  - End with 2 resolved case (a la SUS-16-044)



Combine Exclusive Categories of Higgs pT → **Decreasing pT**

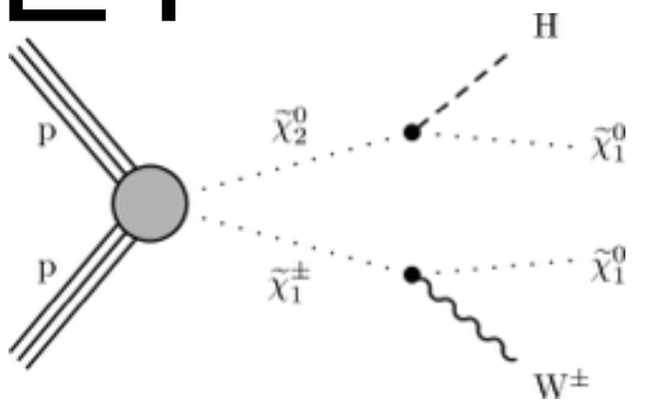
2 boosted H	**1 boosted H +1 Resolved**	**2 resolved H**
2 AK8 Jets in pruned Mass window [85,135]GeV	**1 boosted H + 1 AK4 bjet**	**4-5 AK4 Jets 3 or 4 deep CSV b-tags**
2 Categories: 1 or 2 double-b tags		
SUS-17-006		**SUS-16-044**

- This is pretty analogous to the top tagging categories: Fully Merged, boosted W (partially merged) fully resolved
- Use resolved case to catch the events that aren't caught by the boosted H tag. And look for blind spots between publications
- 1 H-tag is still exclusive from these categories

SUSY: WH +MET

- Consider boosted techniques for the wino-like Ewkinos: **SUS-16-043**

- These are complementary 1-Lepton events to the searches with only jets, used in GAMBIT recasting for constraining the wino-like component



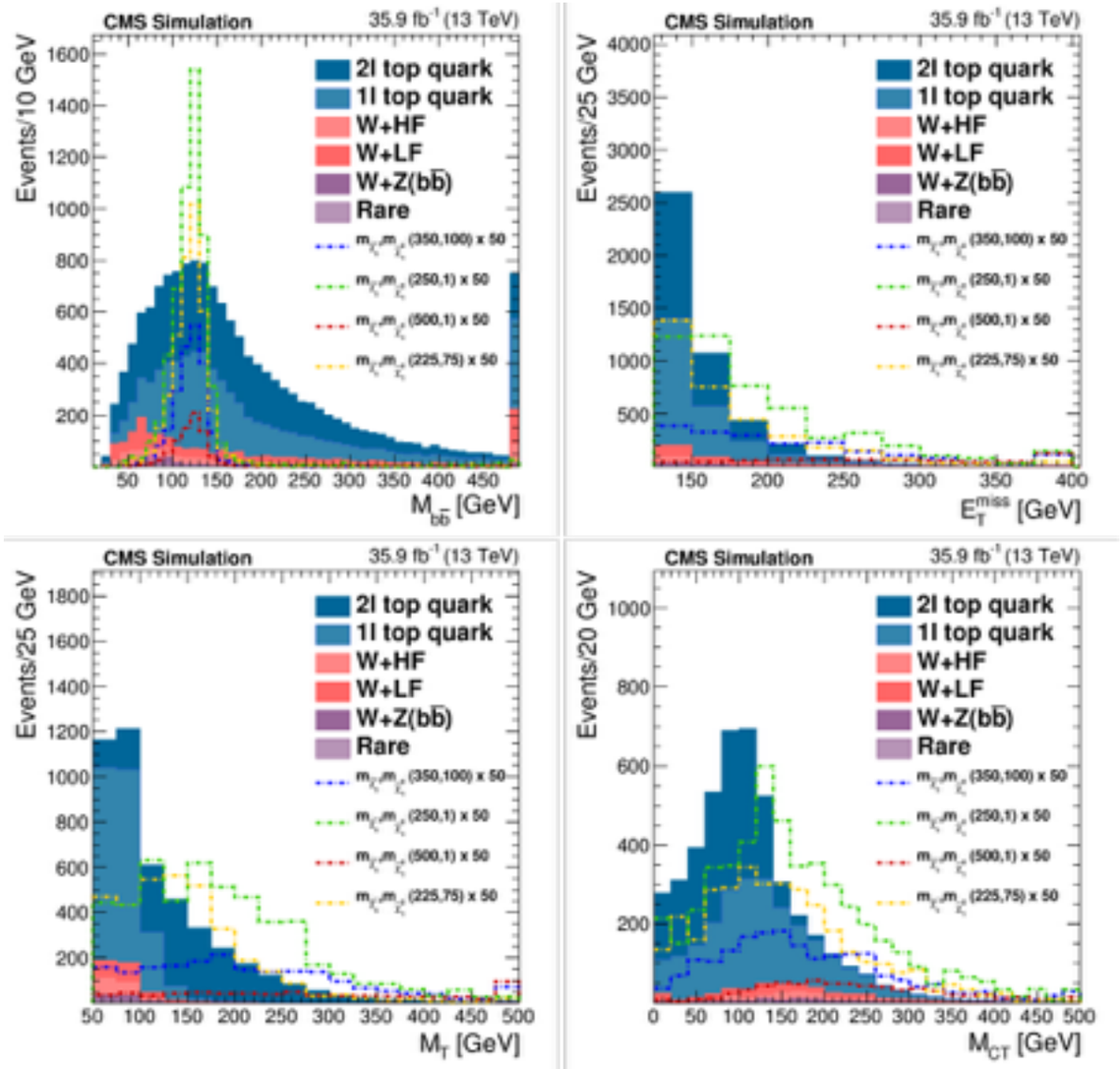
- 1-Lepton requirement along with 2-btags also makes this a H bump hunt on top of SM Top production (mainly di-leptonic)

  - 2-btags no problem of choosing combinations

- Use standard endpoint variables to suppress top: MT, MCT (cotransverse mass)

  - Can the MCT cut be loosened when you have a boosted Higgs tag? Double-b tag also suppresses top production

  - Current high mass exclusion here is up to ~500GeV. Higher mass neutralinos can start to give a larger H pT

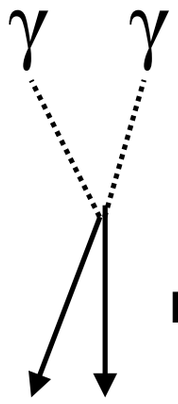


Interlude: Low Mass Scales at L1

- A key feature of all searches is that some phase-space is clipped by the L1-Trigger: e.g. RPV searches in Abhijith's talk and also those in published in SUSY

- **Can low HT signals be saved by substructure??**

Consider very low resonances from axion-like particles: **arxiv: 1710.01743**

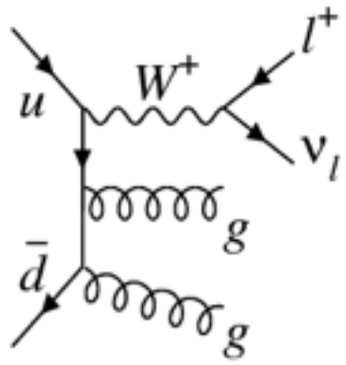


low mass diphoton peak

kick ISR jets

These jets have similar features to the boosted H bkg

V+Jets bkg at high MET

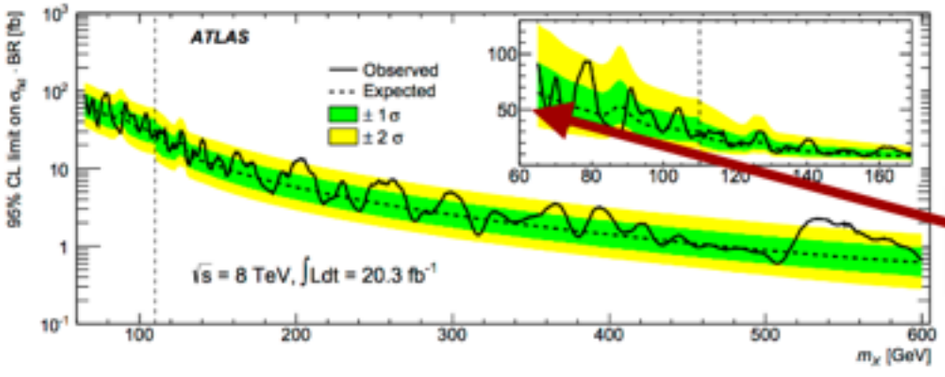


- There might be some structure to these gluons that causes them to be double-b tagged in V +Jets events:
  - This is what you want to consider in an HT +substructure trigger to have lower HT thresholds for all searches with jets

For this phase-space there is hole between 10-65GeV

Talk from HL-LHC Workshop

diphoton :



Can we go *below* that?

In Run2, SUSY made a L1 optimization using soft-leptons to lower the L1 MET threshold.

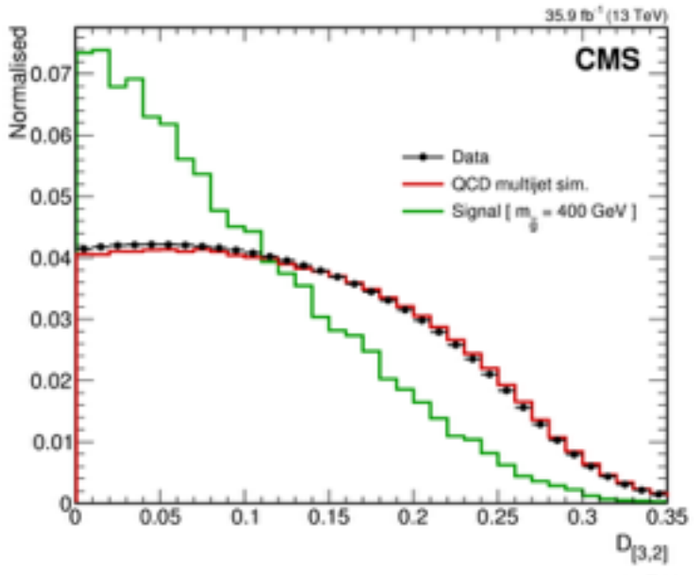
This is a substructure could be a similar optimization for HT: Other exciting signals are Exotic h decays

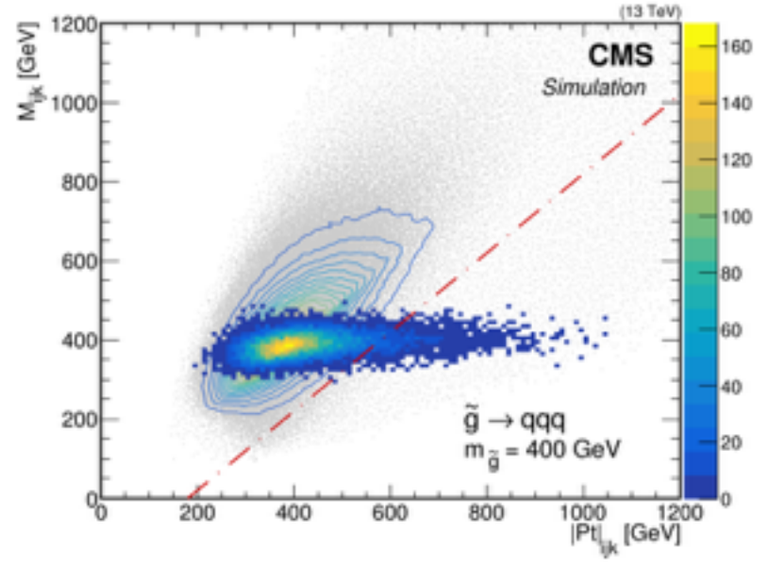
Abhijith is working on this, but who else?

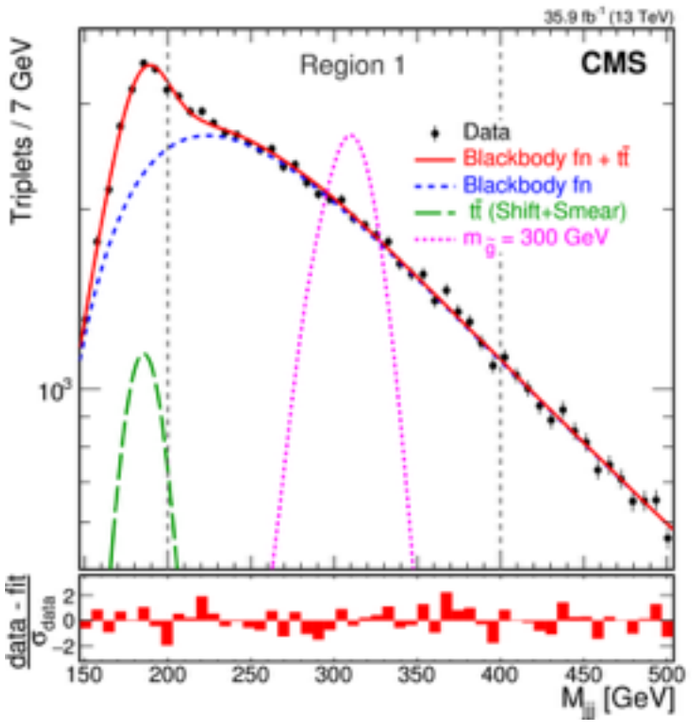
EXO: RPV Trijet Searches

EXO-17-030

- **<u>Bump hunt in three quark jets on the QCD bulk background</u>**:
  - Lots of 3-jet combinations in events with at least six jets: **20 triplets per event!** Choose the best 2
  - Even signal events can have bad combinations!
  - **To choose good combinations** use angular spread of jets in a triplet and Dalitz variables originally used for Kaon decays, make dijet pairs inside the triplet)
- **Once you have triplet candidates:**
  - Cut on mass asymmetry of the two triplets
  - Diagonal cut on triplet vs. scalar sum pT of jets in the combination





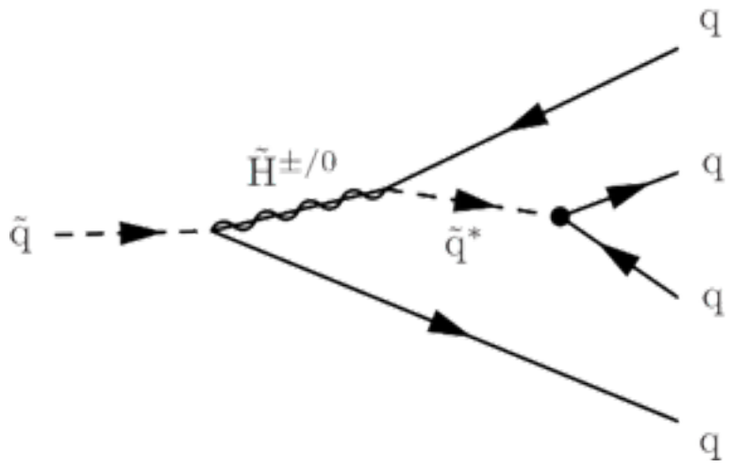


- Jet HT triggers used (HT>800 jet pT>40GeV) collected for high mass search region
- **Lower mass range down to 200 GeV use PF scouting trigger (HT>410 with jet pT >20GeV) CAN GO EVEN FURTHER Down with sub-structure**
- Combinatorial QCD background follows black-body radiation formula for dN/dM(jjj) for the turn on at 6 jets. Top is just a low mass tri-jet peak

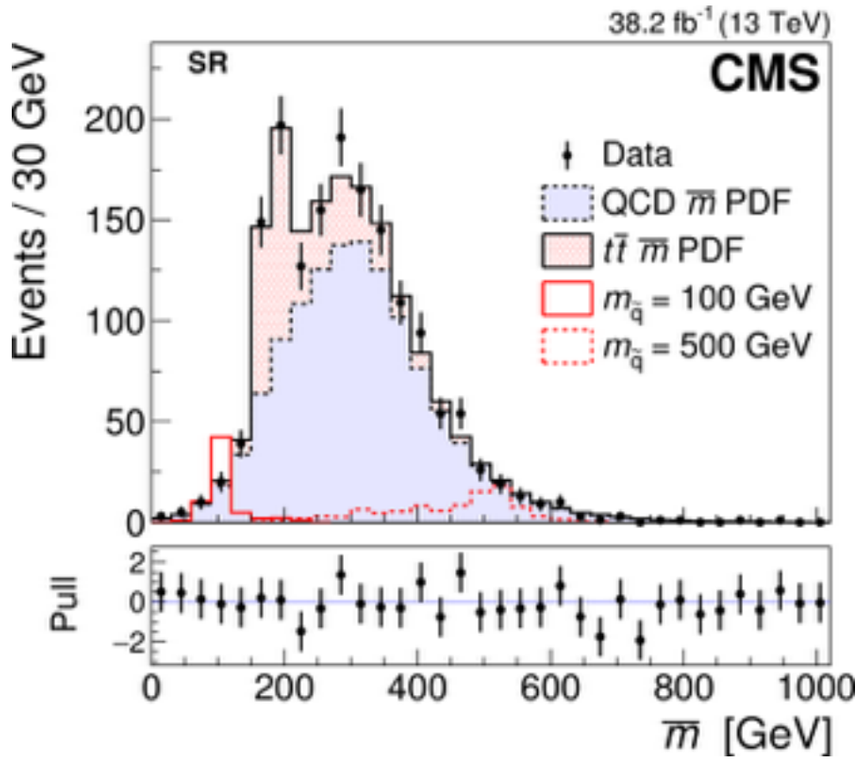
EXO: RPV Boosted Searches

- Trigger on high HT events (HT>900GeV)
- Decays to quad jet resonances really requires “fat-jets” (CA12), sub-jettiness, and pruned mass:
  - Focus on back to back gluino/squark decays (lesser chance of bad combinations in signal)
  - Fat jet tag: pT>200GeV, τ42<0.5, τ43<0.8
  - Fat jet-pairs: mass asymmetry less than 0.1, |Δη|<1.0, avg the mass of the pairs

EXO-17-022



- Can derive a PDF for QCD and top production in b-tagged and not b-tagged control regions
  - **Have sensitivity to very low mass signals down to 100GeV!** Low signal acceptance but huge cross section, AND cleaner signal with lower number of combinations



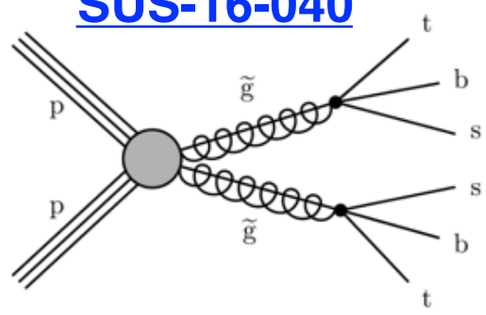
Minimal Flavor Violating RPV SUSY

- Consider more specific RPV scenarios where **RPV couplings are large for heavy flavor quarks**

RPV Violating Terms in Super-potential

$$W = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k + \mu'^{i} L_i H_u.$$

SUS-16-040



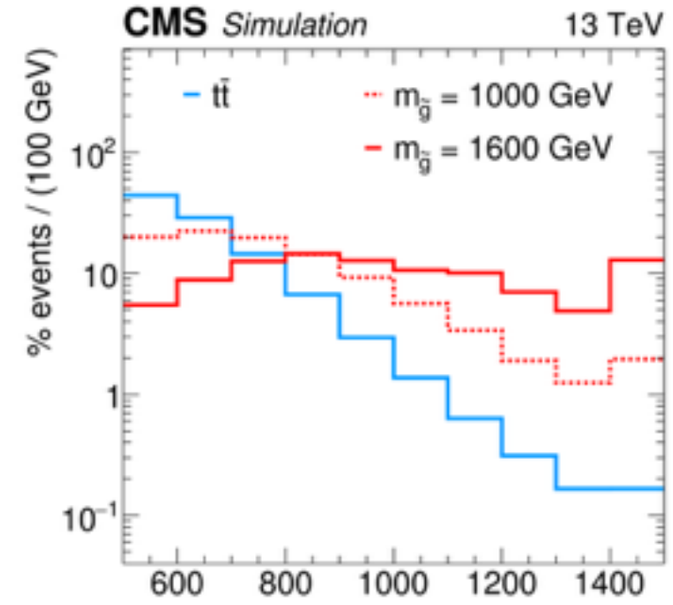
- In this search, look for new physics on top of semi-leptonic Top:
  - Don't resolve the trijet-mass BUT discriminate SUSY **mass scale (MJ)** from top

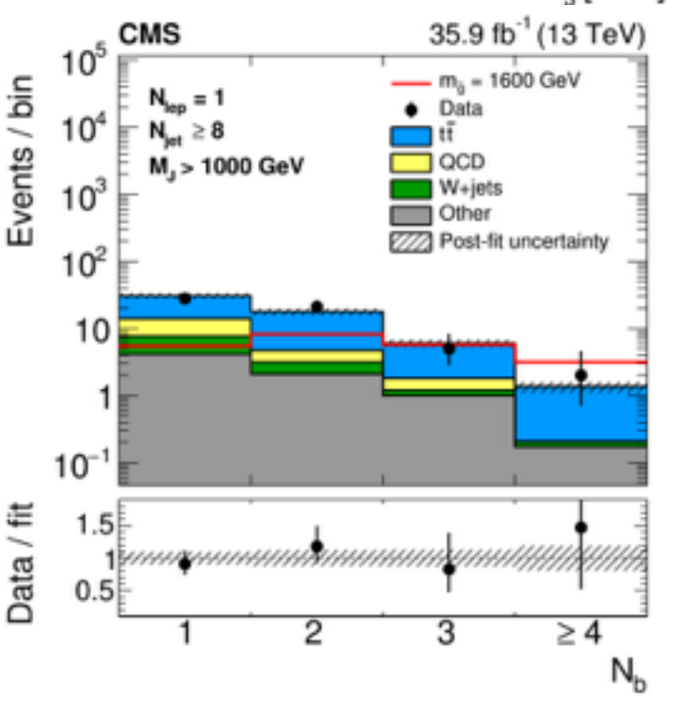
$$M_J = \sum_{J_i \in \text{large-}R\text{ jets}} m(J_i).$$

Cluster AK4 jets into a single jet R=1.2 (can then **use AK4 b-tags**) and bin in number of Ak4 jets

M_J [GeV]	N_{jet}		
	4–5	6–7	≥8
500–800	CR	CR	SR
800–1000	CR	SR	SR
>1000		SR	SR

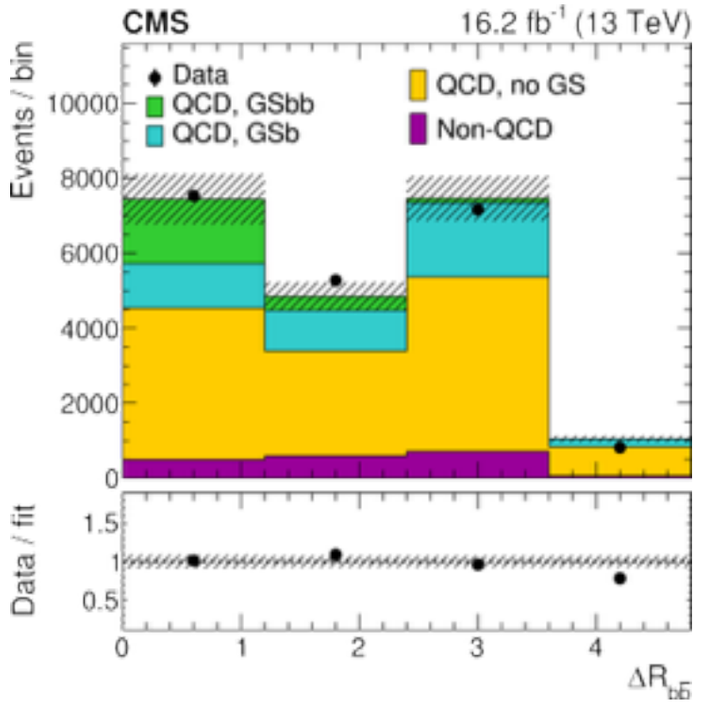
- Construct a likelihood fit to b-tags across the search bins:
  - Top is the main background BUT still need to understand **QCD g—>bb systematic on the b-shape**
  - Background can be further suppressed by double-b tags





Top tails in mJ are driven mainly by ISR with contributions overlapping with the b-jets

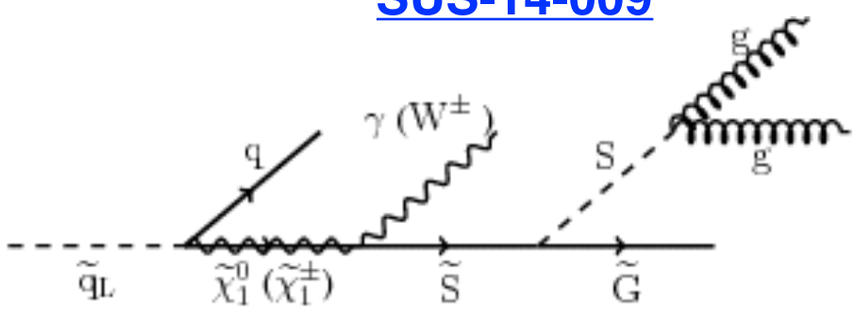
while the **signal is driven by jets merge due to the boost** from the gluino

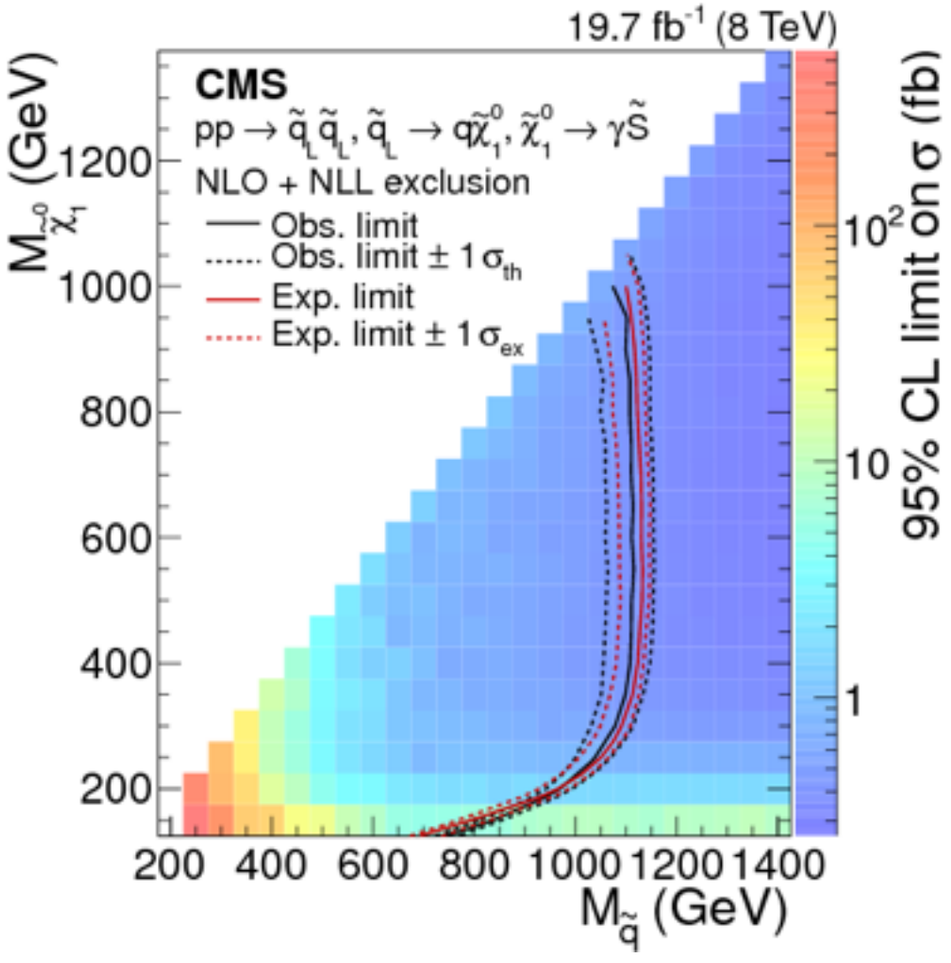


SUSY Stealth with Photons

- Stealth is another SUSY model that conserves R-parity but still has no intrinsic MET
  - Planned search consists of diphoton events binned in ST (scalar sum of all Obj pT)
- At high squark mass but low neutralino mass results in a collimated decay of photons and gluons
  - This plummets the sensitivity due to the isolation requirement on photons
  - B2G search recover these photons by de-clustering the fat jets and identifying the photon constituent (specific ID for photons found inside of jets)

SUS-14-009





Summary

- Though boosted jets have been mainly used for searches for strong production with tops, but they are being extended to **Ewkino production** and RPV scenarios also
  - These techniques could add high purity bins with boosted jets can be combined with searches with narrow cone jets or with 1-lepton
  - Provide complementary results to leptonic searches currently used to constrain neutralino and chargino masses
- The backgrounds in boosted topologies also become interesting to try to hone in on interesting events with jets recoiling against invisible or low mass particles. This could **potentially lower the minimum HT thresholds in the trigger with sub-structure**
- **RPV in heavy flavor scenarios** can benefit from double-b or top tagging with sub-structure in wide cone jets
- **RPV in EXO** multi-jet scenarios is a game of choosing jet combinations. Wide cone jets with anti-kT or even variable cone jets can lasso tri-jet or quad-jet combinations from squark or gluino decays
- In the **stealth scenario in B2G**, objects can be merged with the jet cone at high boost. For photons/electrons you can find sub-jets with high EM content and ID the photon to extend sensitivity in this region