



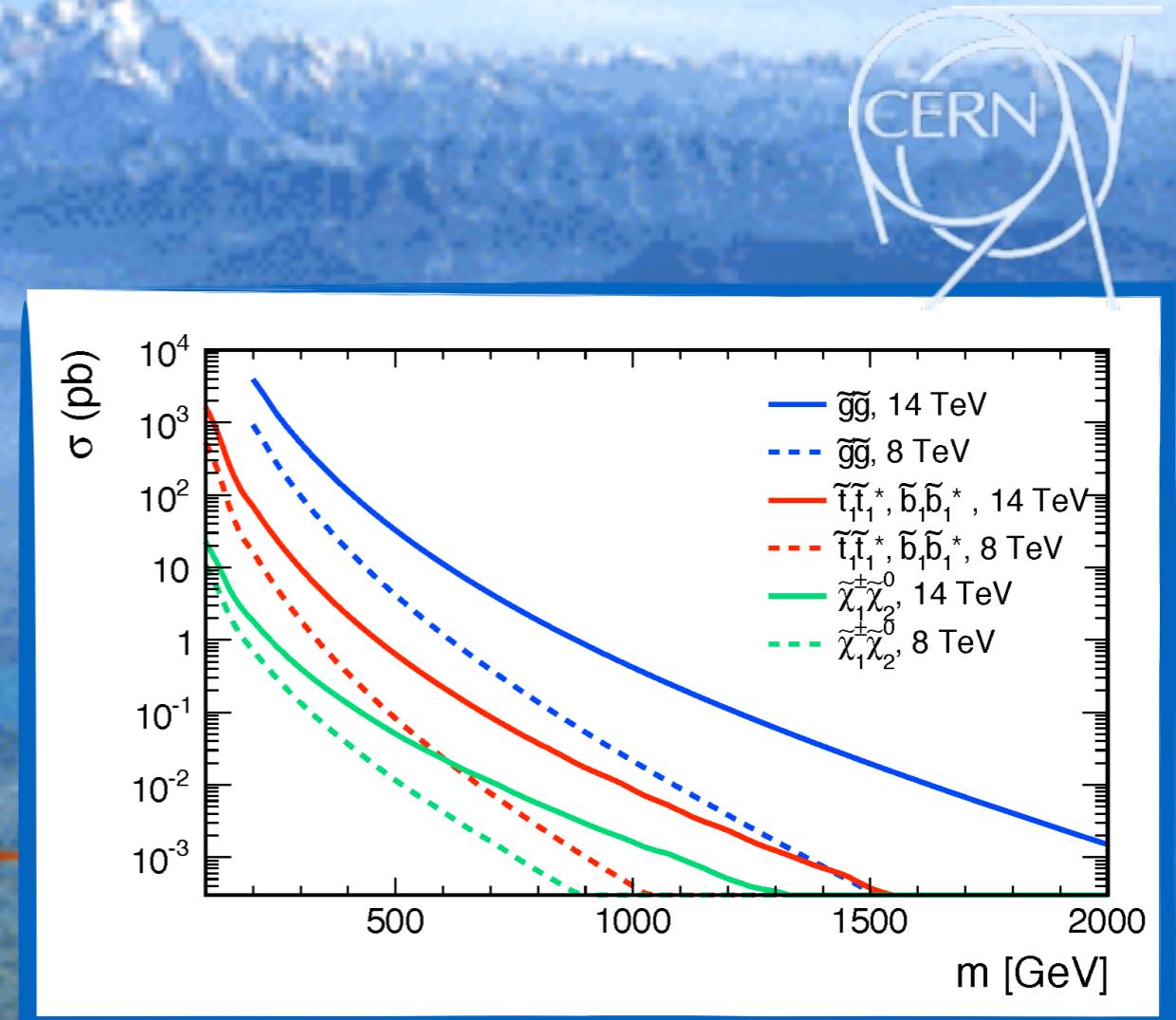
New  
directions  
in  
searches  
at LHC

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for ATLAS and CMS Collaborations  
SUSY15, Lake Tahoe, 23-29 Aug 2015



# In this talk:

- ATLAS and CMS SUSY sensitivity studies and discovery scenarios for 14 TeV LHC at 300 and 3000  $\text{fb}^{-1}$ .
- New directions becoming relevant in SUSY searches at LHC Run2.





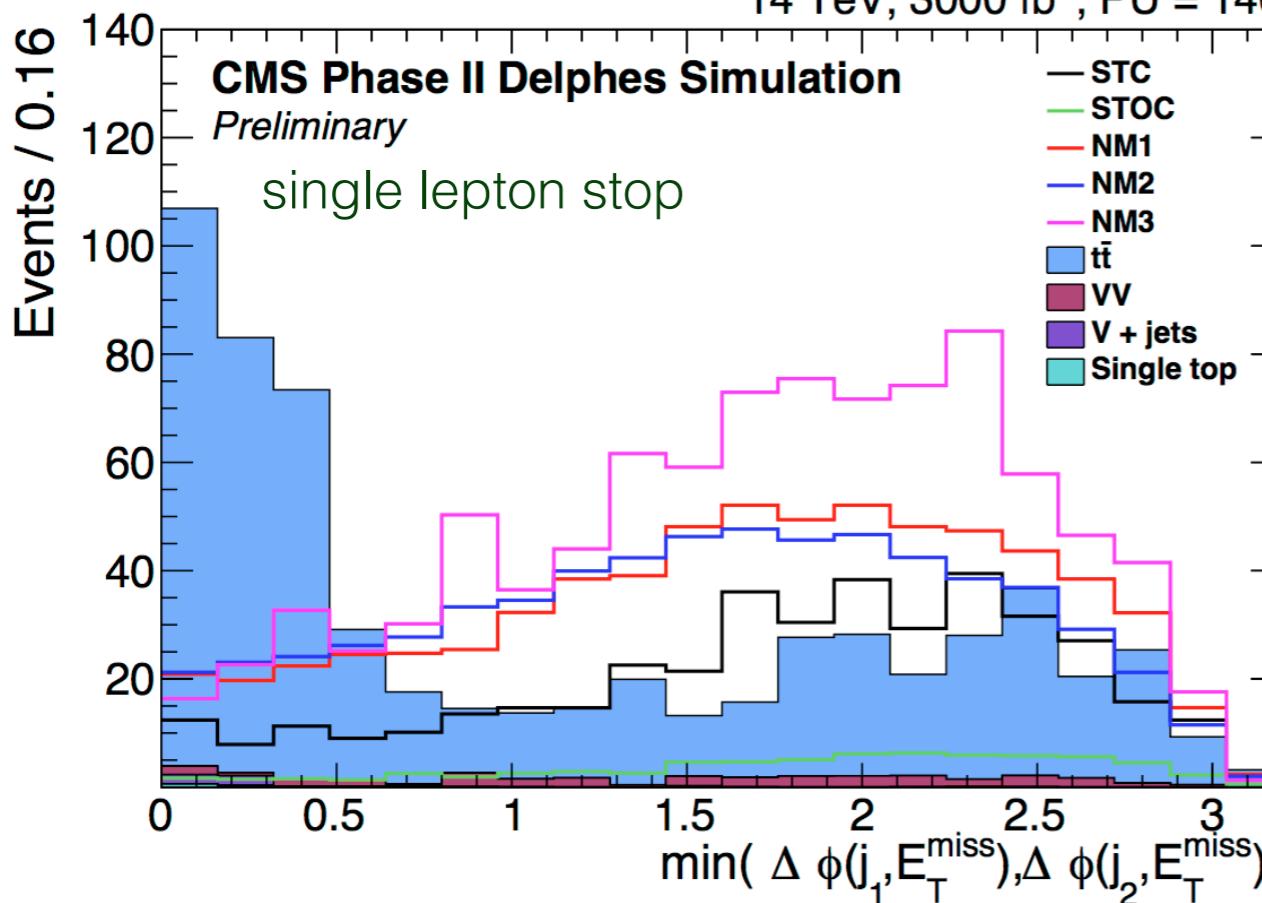
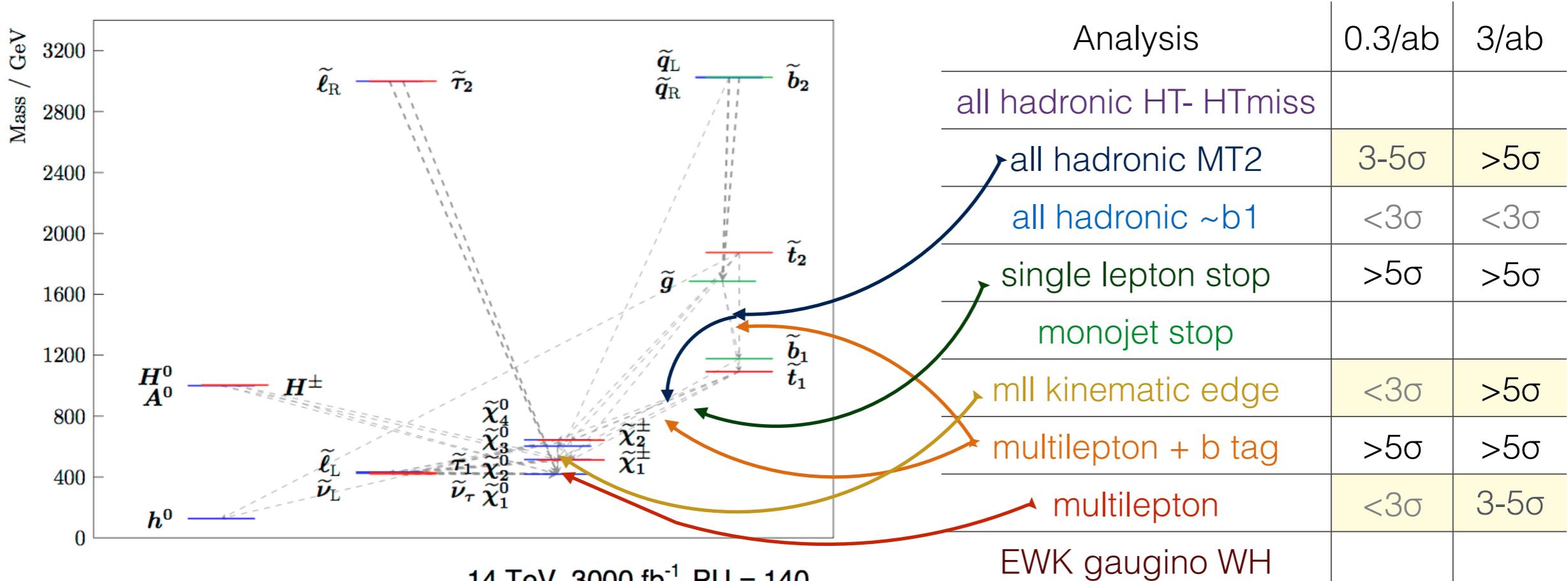
# SUSY discovery potential at HL-LHC

ATLAS and CMS performed detailed SUSY discovery potential studies for LHC at 14 TeV for 300 and 3000  $\text{fb}^{-1}$  using analyses that address a diversity of final states ([ATLAS PHYS-PUB-2013-01](#), [COM-PHYS-2014-555](#), [ATL-PHYS-PUB-2015-032](#), [CMS SUS-14-012](#), [FTR-13-014](#)).

- Event selections were built upon existing 8 TeV analyses, by adjusting selection criteria (mostly tightening cuts). Novel methods and kinematic variables were not necessarily explored.
  - CMS used phenomenological MSSM benchmark points to test the effect of using complementary search channels to increase discovery chances and to demonstrate how actual measurements would be made in case of discovery.
  - ATLAS used simplified models (where decay branching ratios are fixed, mostly to 100%) to assess sensitivity to various sparticles.



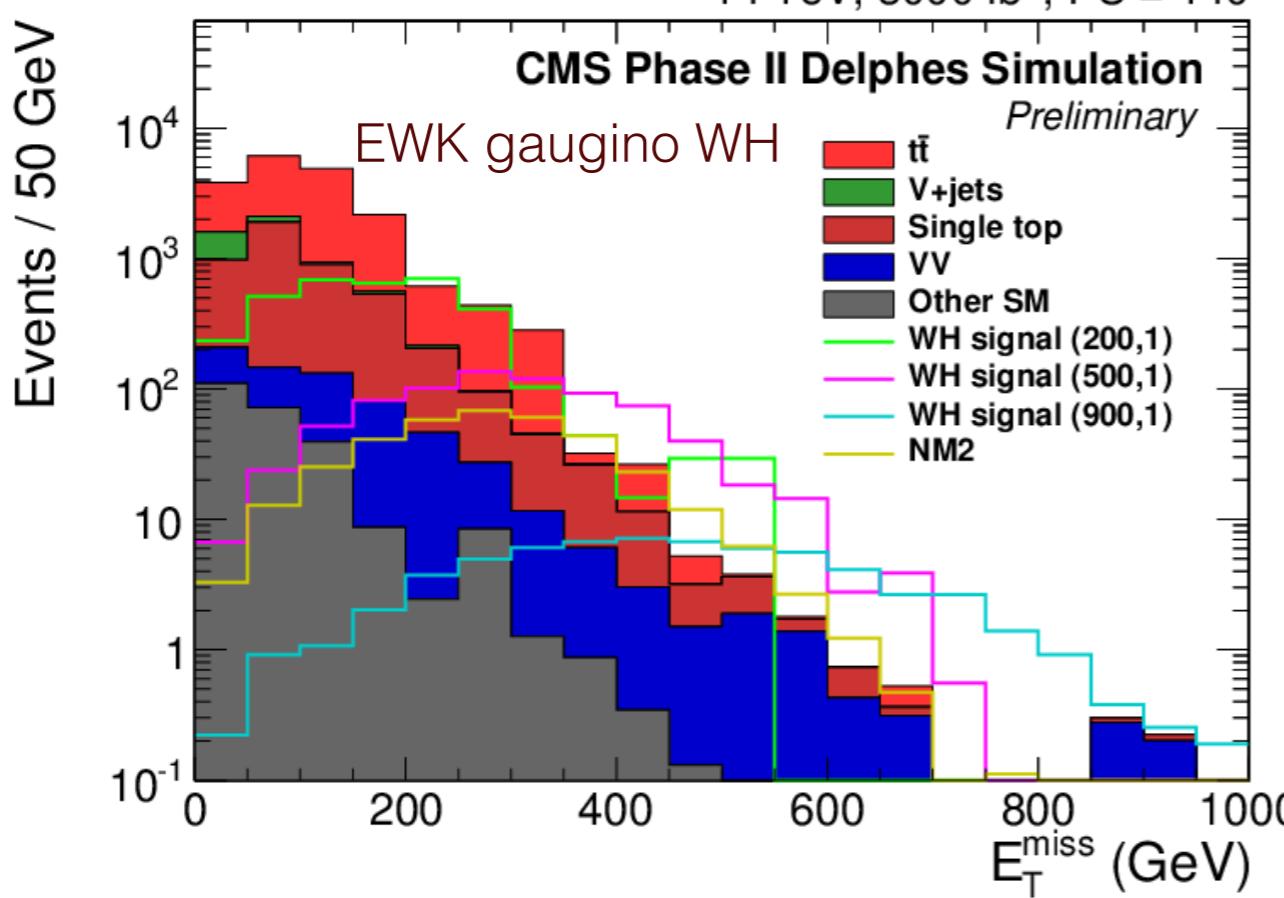
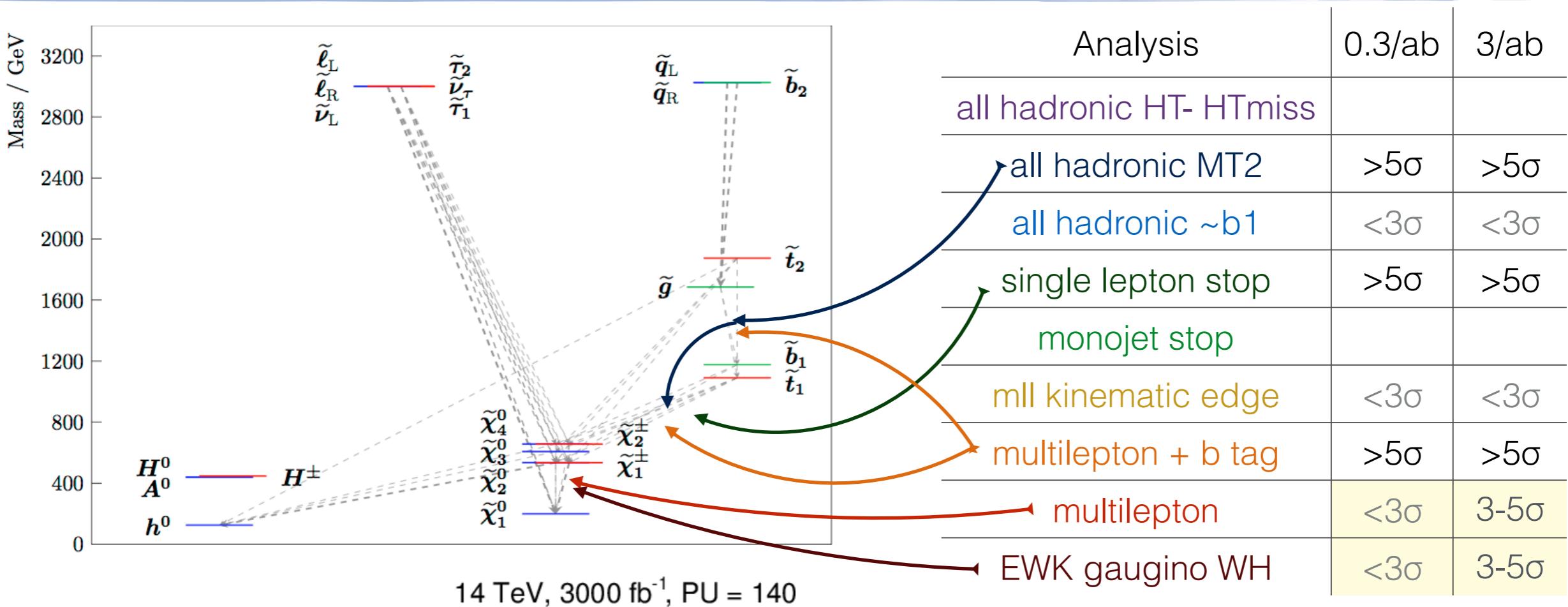
# Natural SUSY point NM1



- Multiple b quarks and leptons from gluino decay are good handles.
- Stop pair production is not easily accessible due to high SUSY backgrounds.
- Can observe edge in dilepton mass spectrum which can inform us about neutralino and slepton masses.



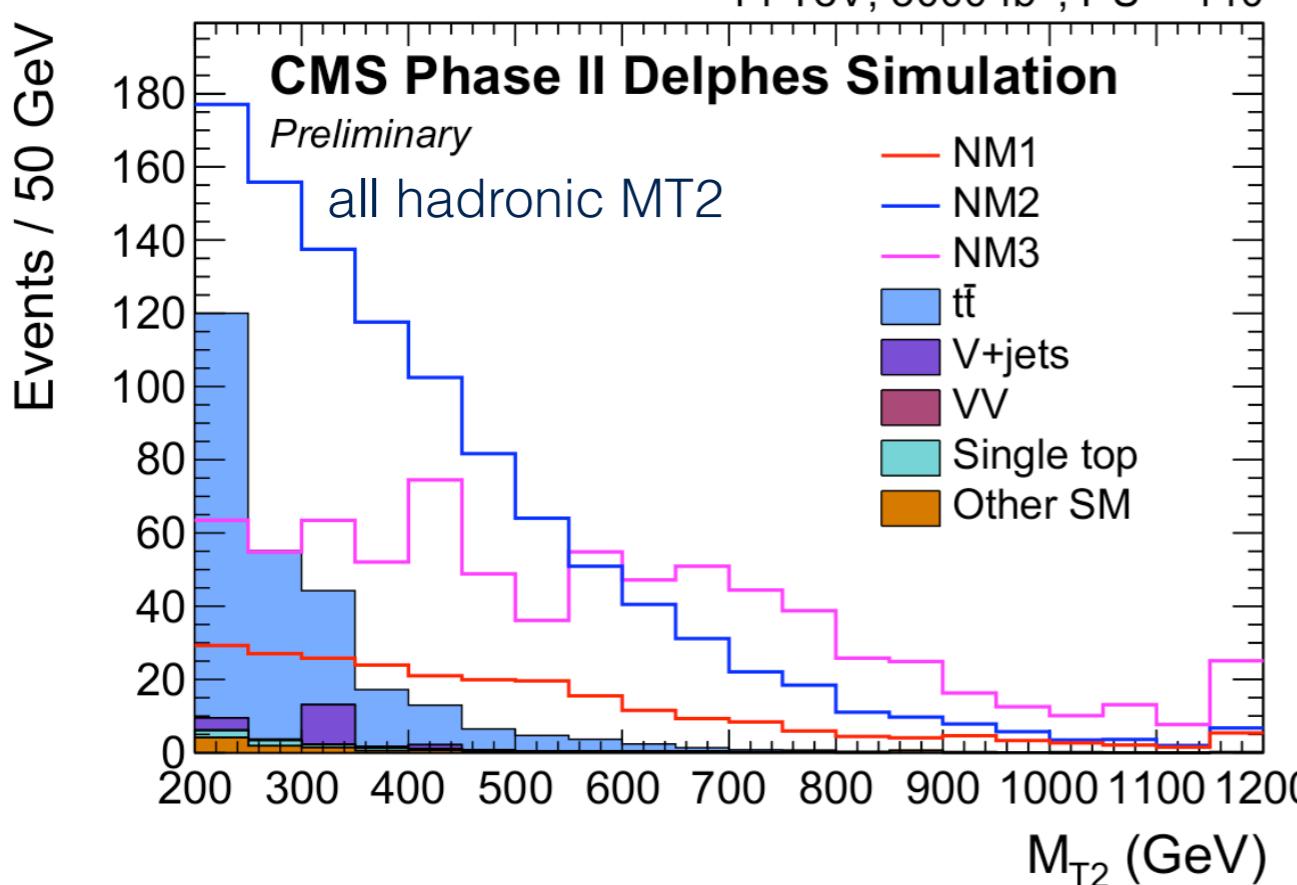
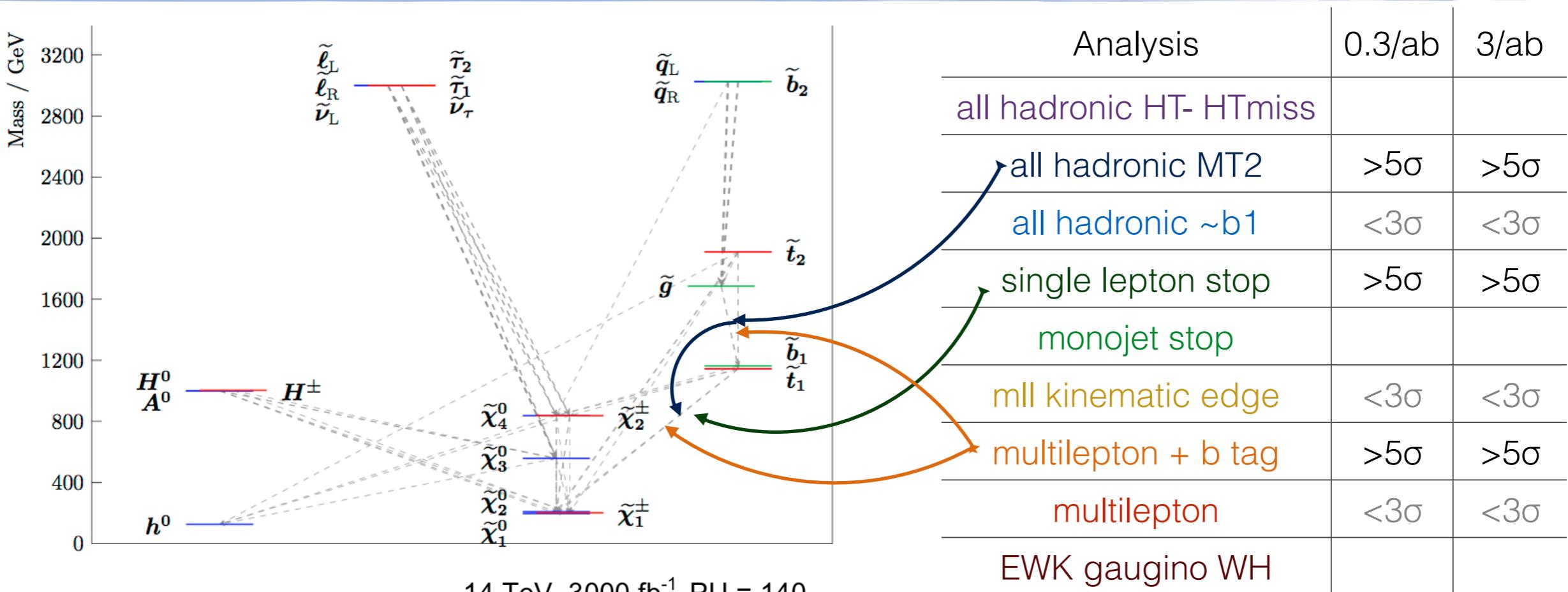
# Natural SUSY point NM2



- Multiple b quarks and leptons from gluino decay are good handles.
- Stop pair production is not easily accessible due to high SUSY backgrounds.
- Can observe signal at WH + E<sub>T</sub><sup>miss</sup> channel (H → bb, W → ll) or at WZ + E<sub>T</sub><sup>miss</sup> channel.



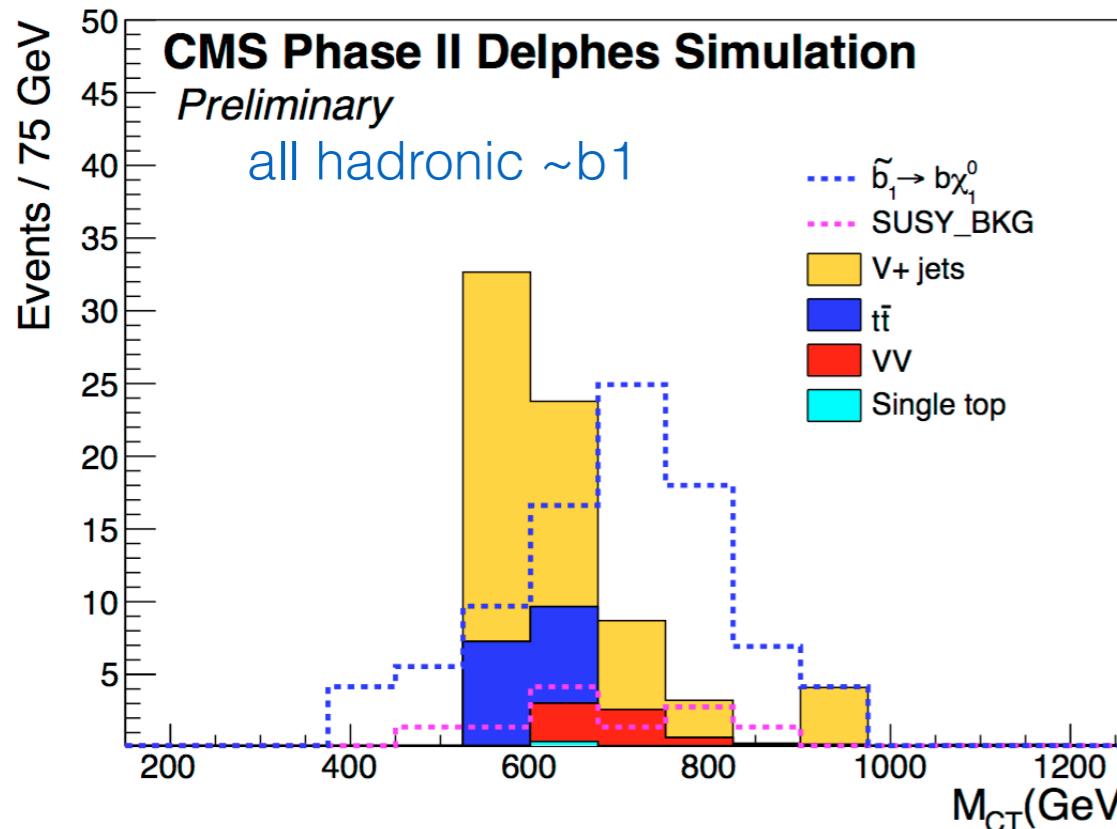
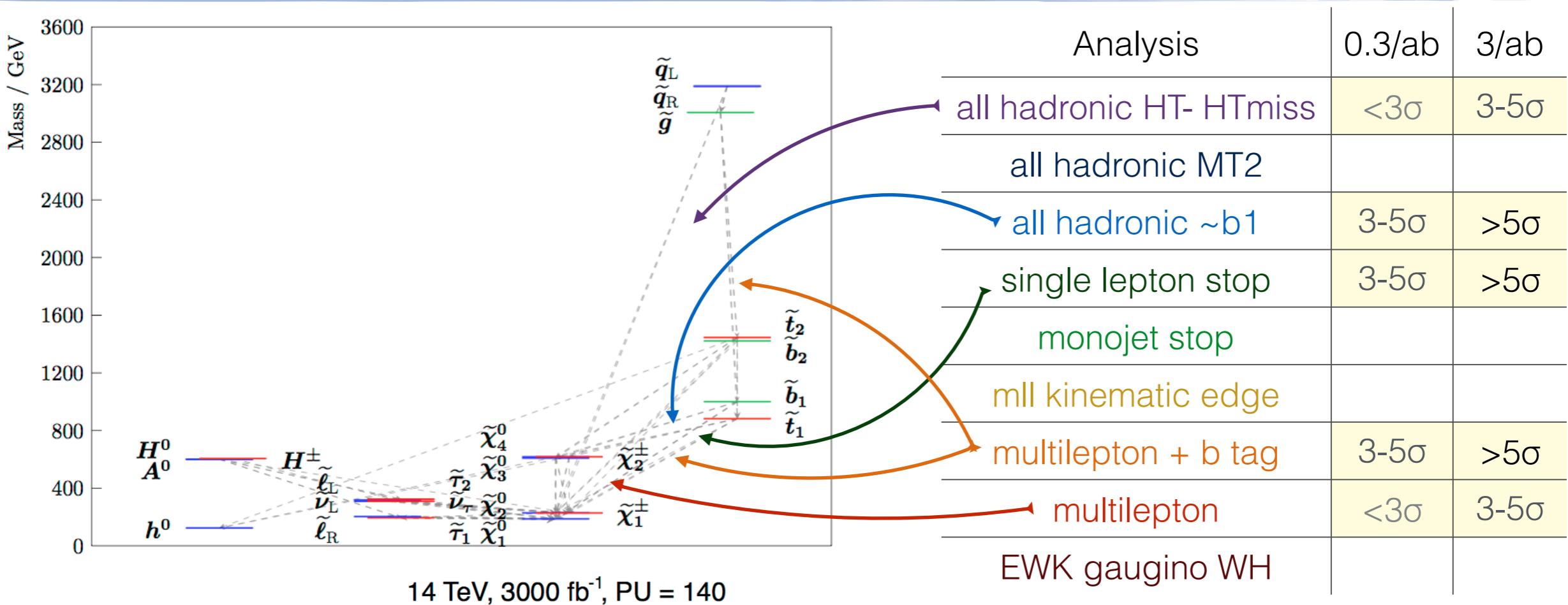
# Natural SUSY point NM3



- Multiple b quarks and leptons from gluino decay are good handles.
- Stop pair production is not easily accessible due to high SUSY backgrounds.
- Gives excess at very large  $M_{T2}$  due to larger mass gap between  $\tilde{t}_1/\tilde{b}_1$  and  $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$ .



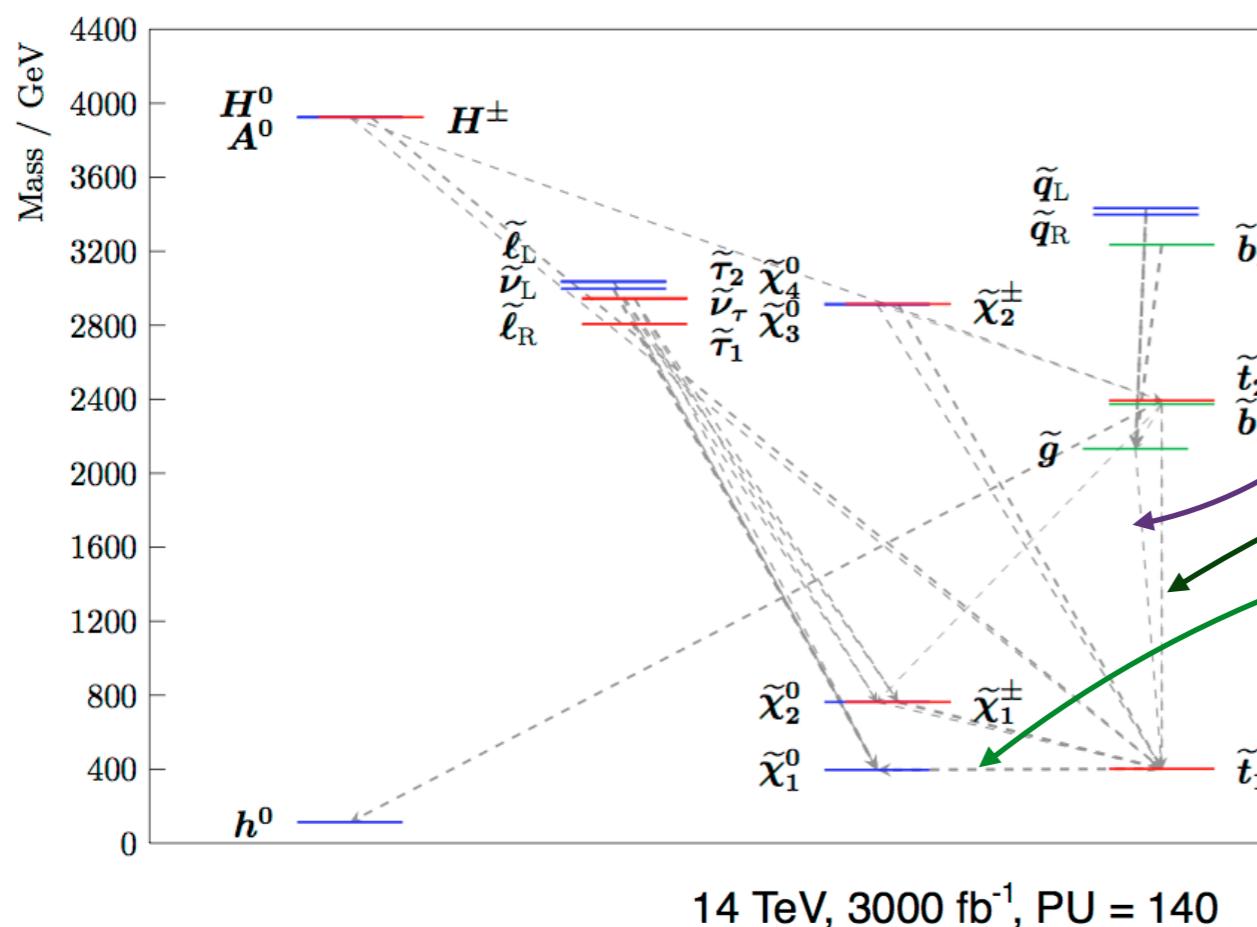
# stau coannihilation point STC



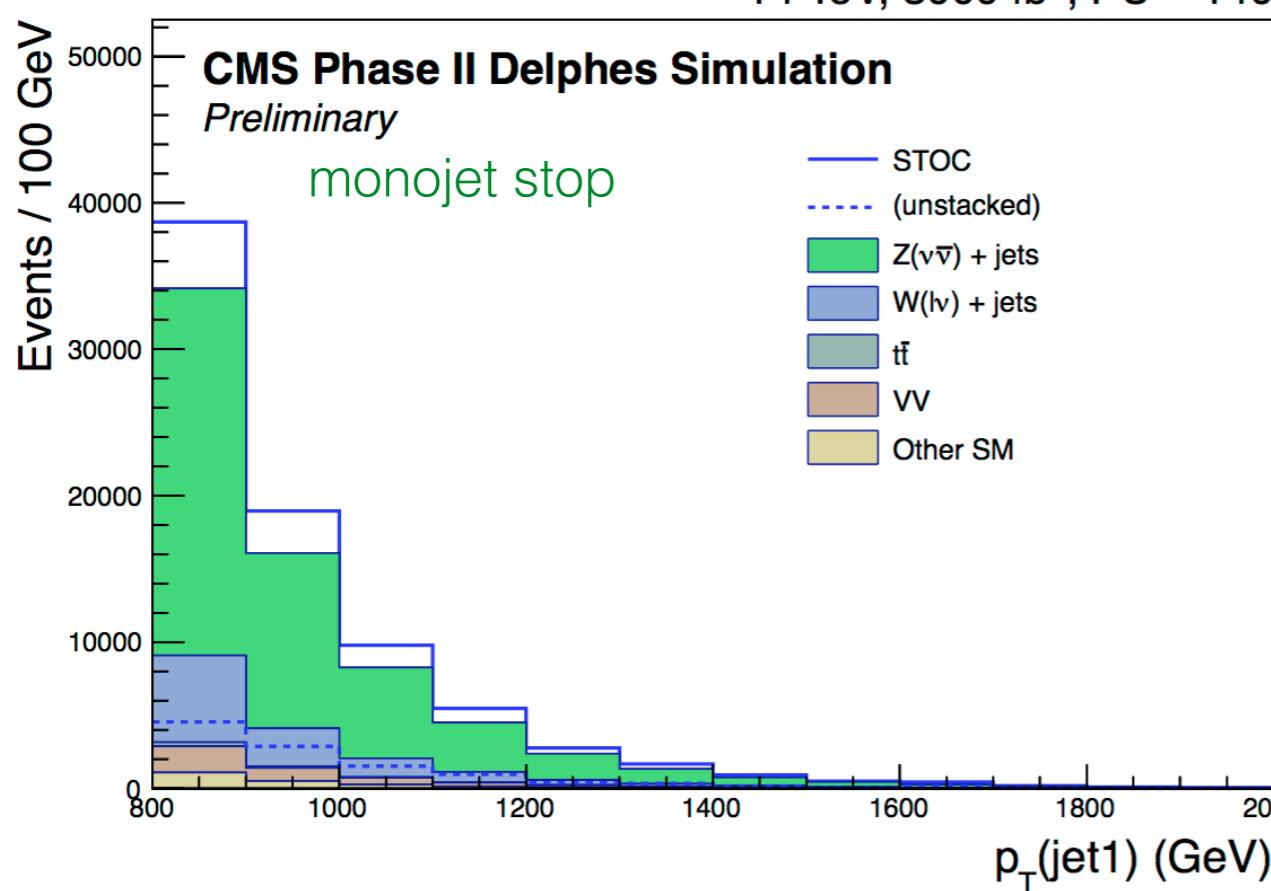
- bb + E<sub>T</sub><sup>miss</sup> channel sees sbottom pair production. This channel is not sensitive to other SUSY processes.
- In case of discovery, boost corrected contransverse mass M<sub>CT</sub> can be used for measuring the sbottom mass.



# stop coannihilation point STOC



| Analysis                | 0.3/ab       | 3/ab         |
|-------------------------|--------------|--------------|
| all hadronic HT- HTmiss | 3-5 $\sigma$ | >5 $\sigma$  |
| all hadronic MT2        |              |              |
| all hadronic $\sim b1$  | <3 $\sigma$  | <3 $\sigma$  |
| single lepton stop      | <3 $\sigma$  | >5 $\sigma$  |
| monojet stop            | 3-5 $\sigma$ | 3-5 $\sigma$ |
| mll kinematic edge      |              |              |
| multilepton + b tag     |              |              |
| multilepton             |              |              |
| EWK gaugino WH          |              |              |

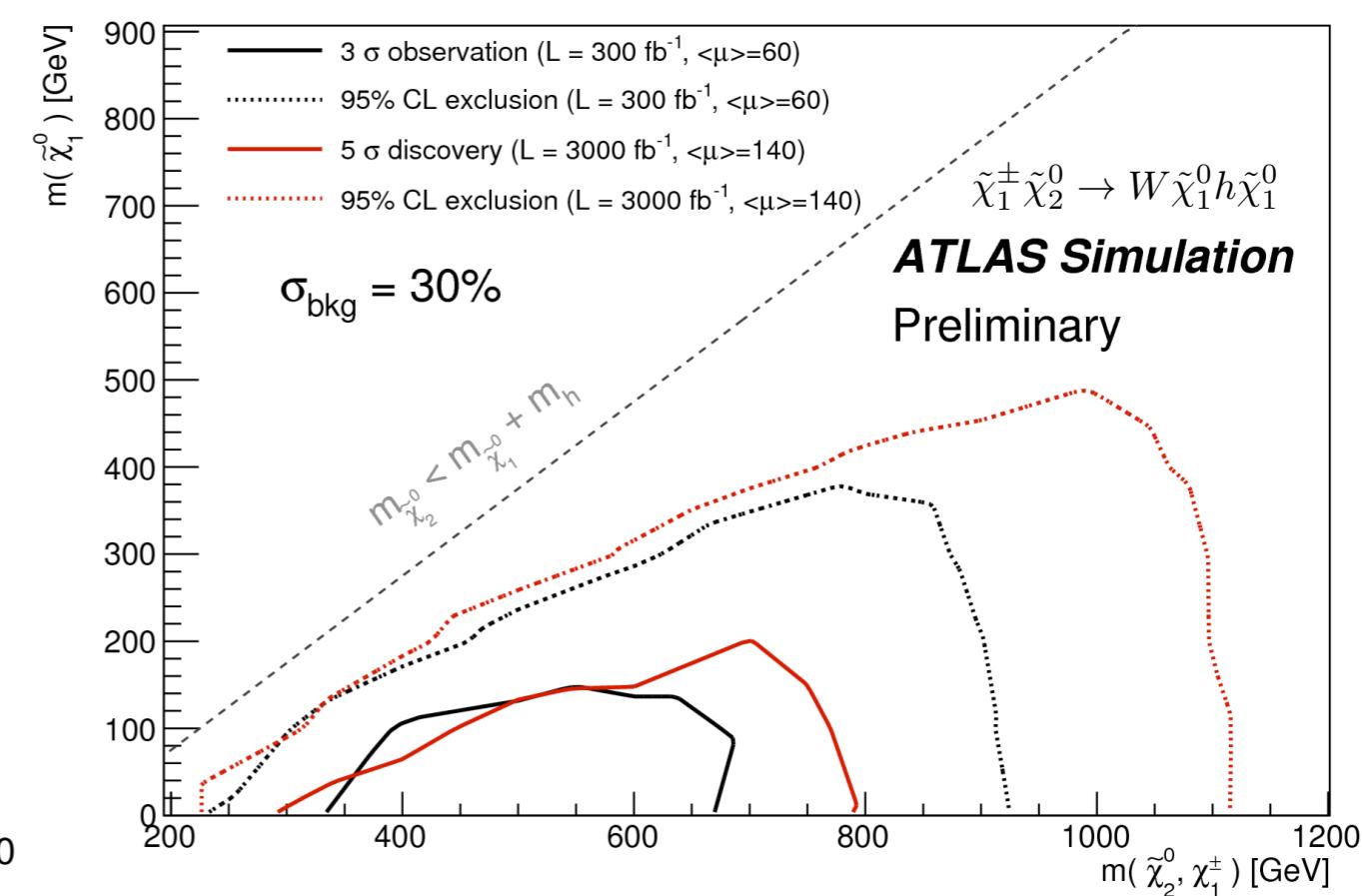
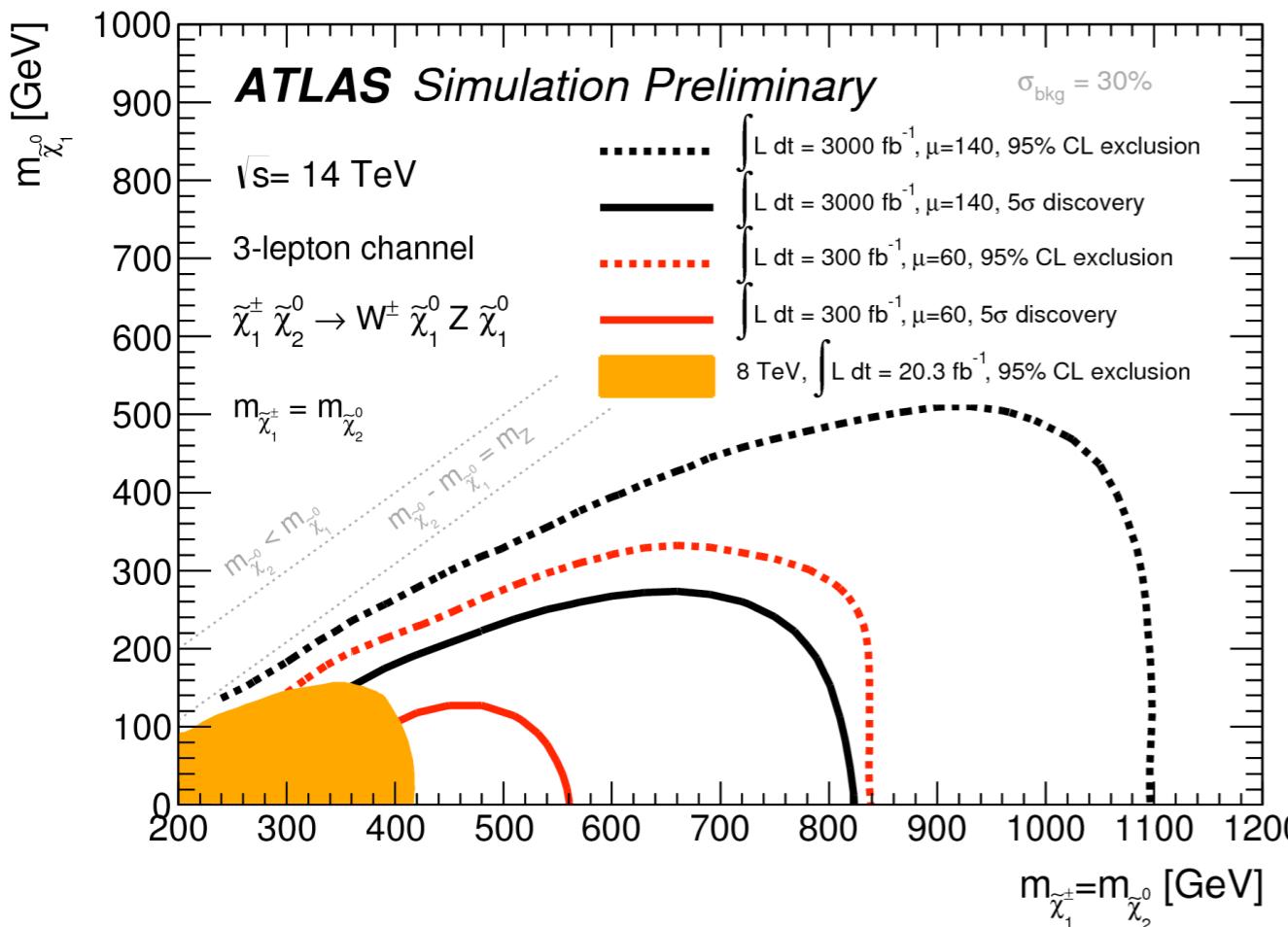


- Since stop is almost degenerate with  $\tilde{\chi}_1^0$ , it decays to very soft products, and direct stop production leads to almost invisible final states. They can be probed through hard ISR jets via monojet +  $E_T^{\text{miss}}$  searches.



# Reach for EW gauginos

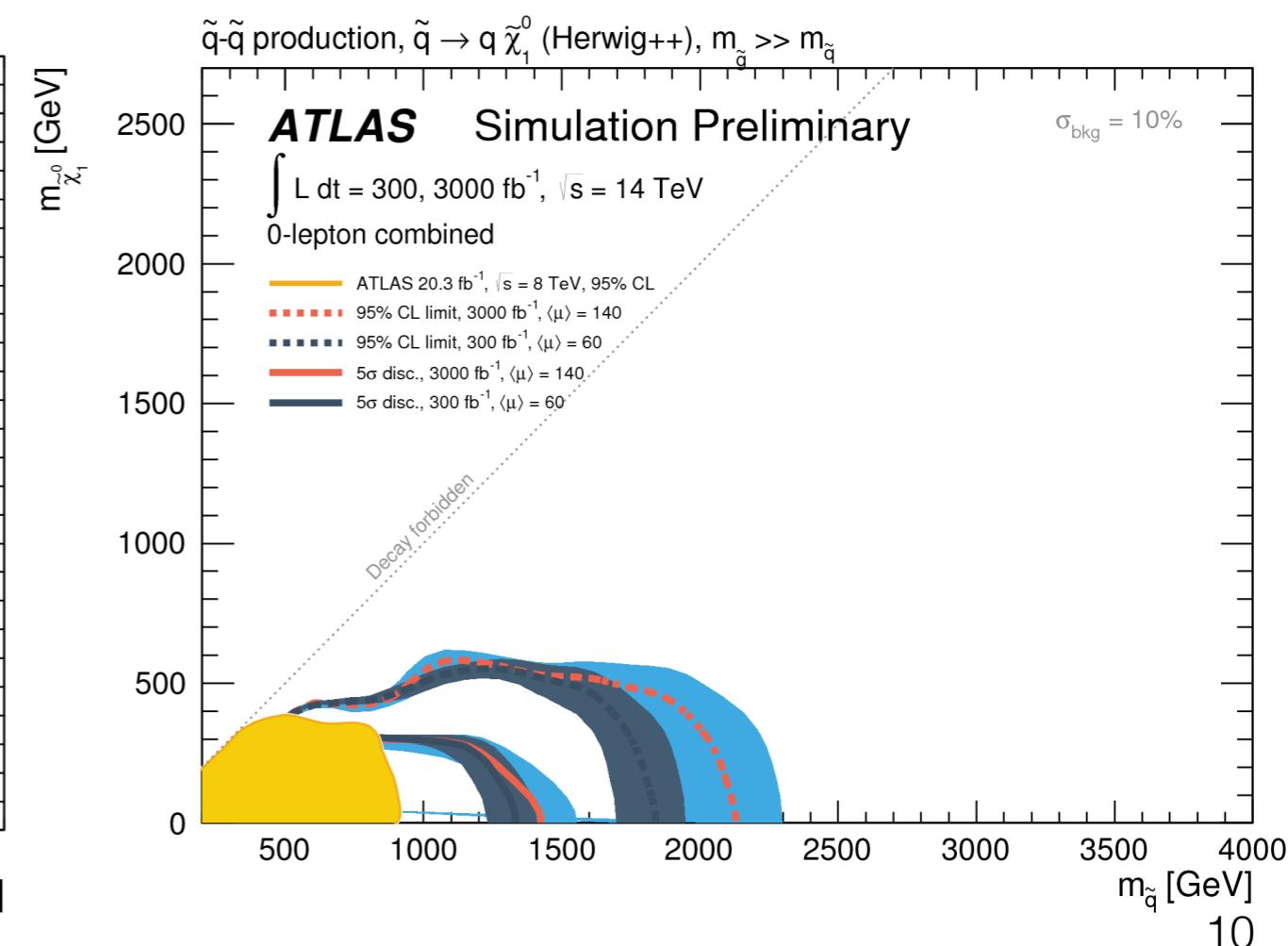
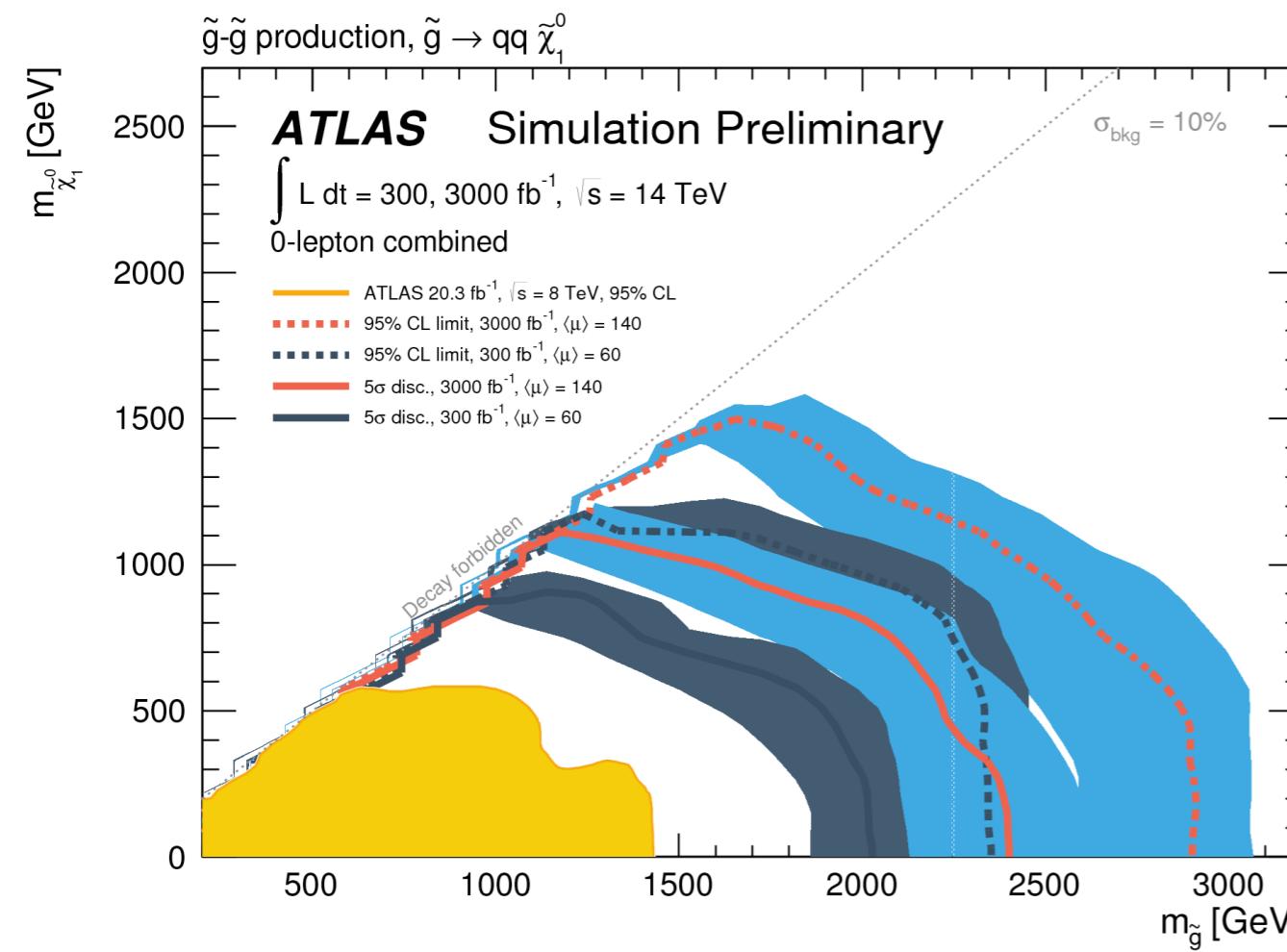
- Based on **naturalness** arguments, **neutralinos and charginos** should be in the **O(100 GeV)** range, and be accessible by the LHC.
- Direct chargino-neutralino pair production becomes **important when squarks and gluinos are very heavy** and outside the LHC reach.
- Searches performed
  - 1) WZ +  $E_T^{\text{miss}}$  channel: multiple leptons final state
  - 2) Wh +  $E_T^{\text{miss}}$  channel: lepton + (h $\rightarrow$ ) bb final state





# Reach for squarks and gluinos

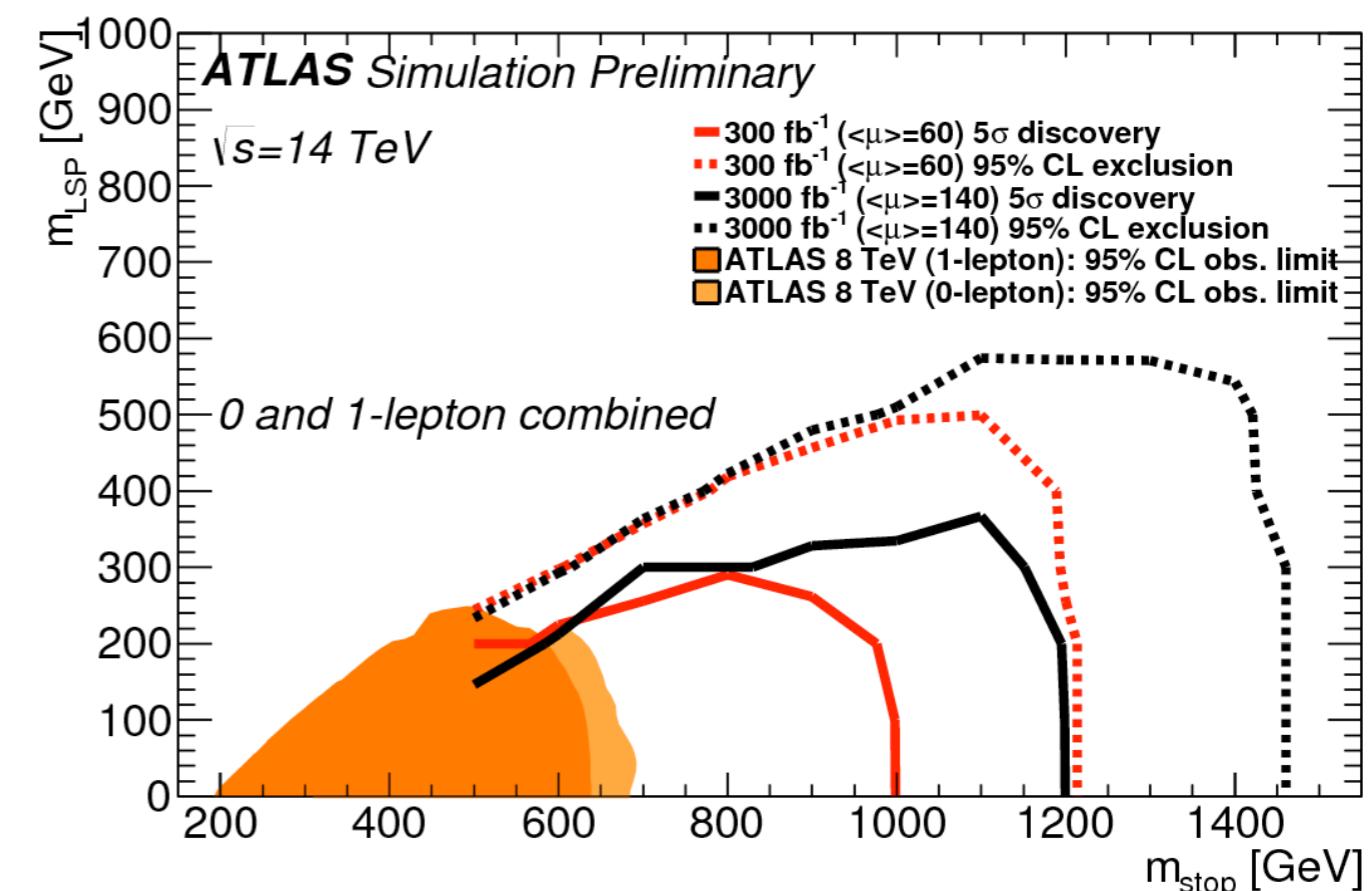
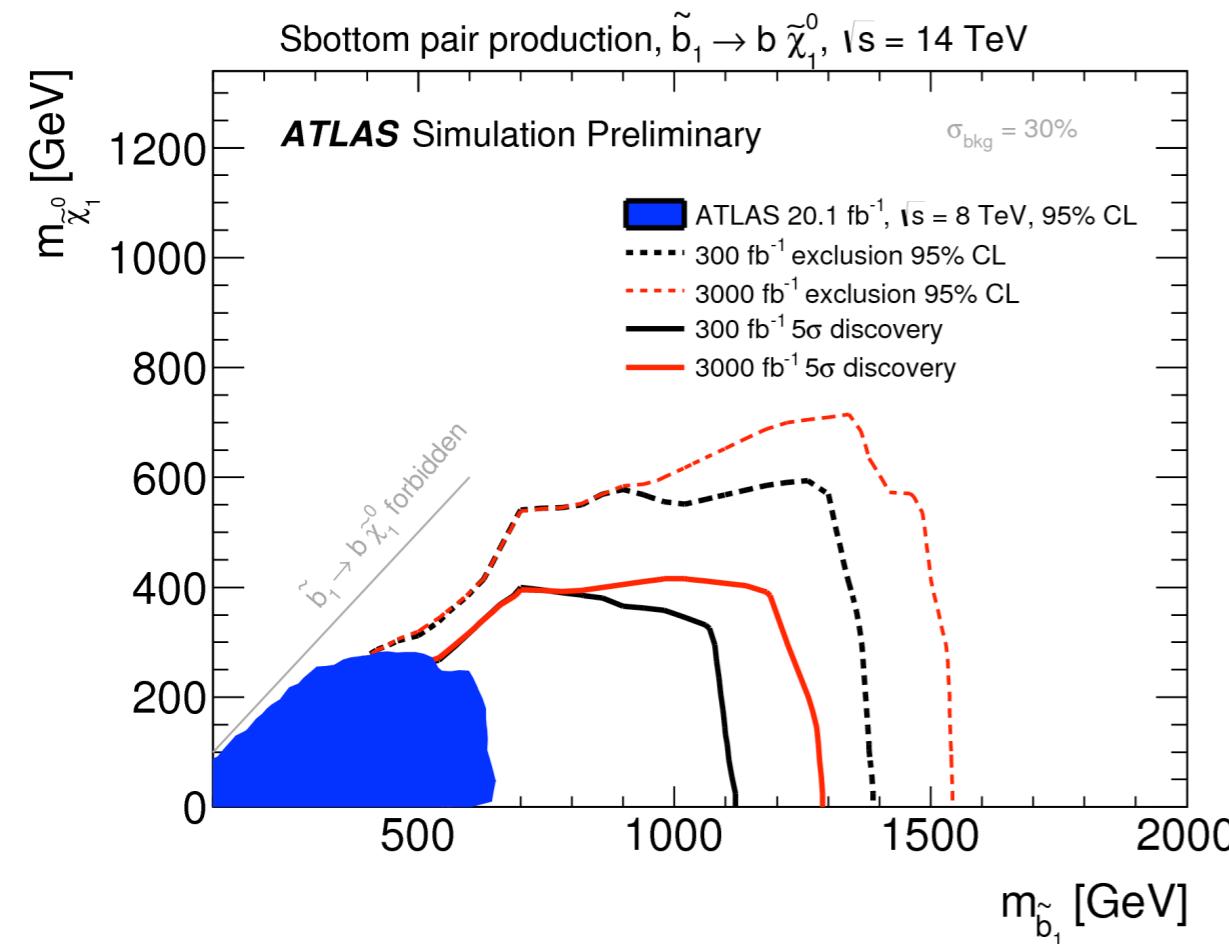
- Gluinos and squarks have the highest cross sections at the LHC.
- A generic search was performed at the **multiplets +  $E_T^{\text{miss}}$  channel** using combinations of  $E_T^{\text{miss}}$ ,  $H_T$ , and  $m_{\text{eff}} = E_T^{\text{miss}} + \sum |p_T^{\text{jet}}|$  variables for signal discrimination.
- Multiple search regions based on different jet multiplicities and variable selections were used to target different sparticle production mechanisms.





# Reach for sbottoms and stops

- Naturalness favors light stops and sbottoms at < 1-2 TeV which will be pursued further in Run2 on to seek a final word on naturalness.
- Sbottom pair production search:  $bb + E_T^{\text{miss}}$  channel, using the boost corrected contransverse mass  $M_{\text{CT}}$  which supresses backgrounds drastically.
- Stop pair production search: 1) 1 lepton channel: using  $E_T^{\text{miss}}$ ,  $m_T$ ,  $H_T$   
2) 0 lepton channel: using  $E_T^{\text{miss}}$ ,  $m_T$





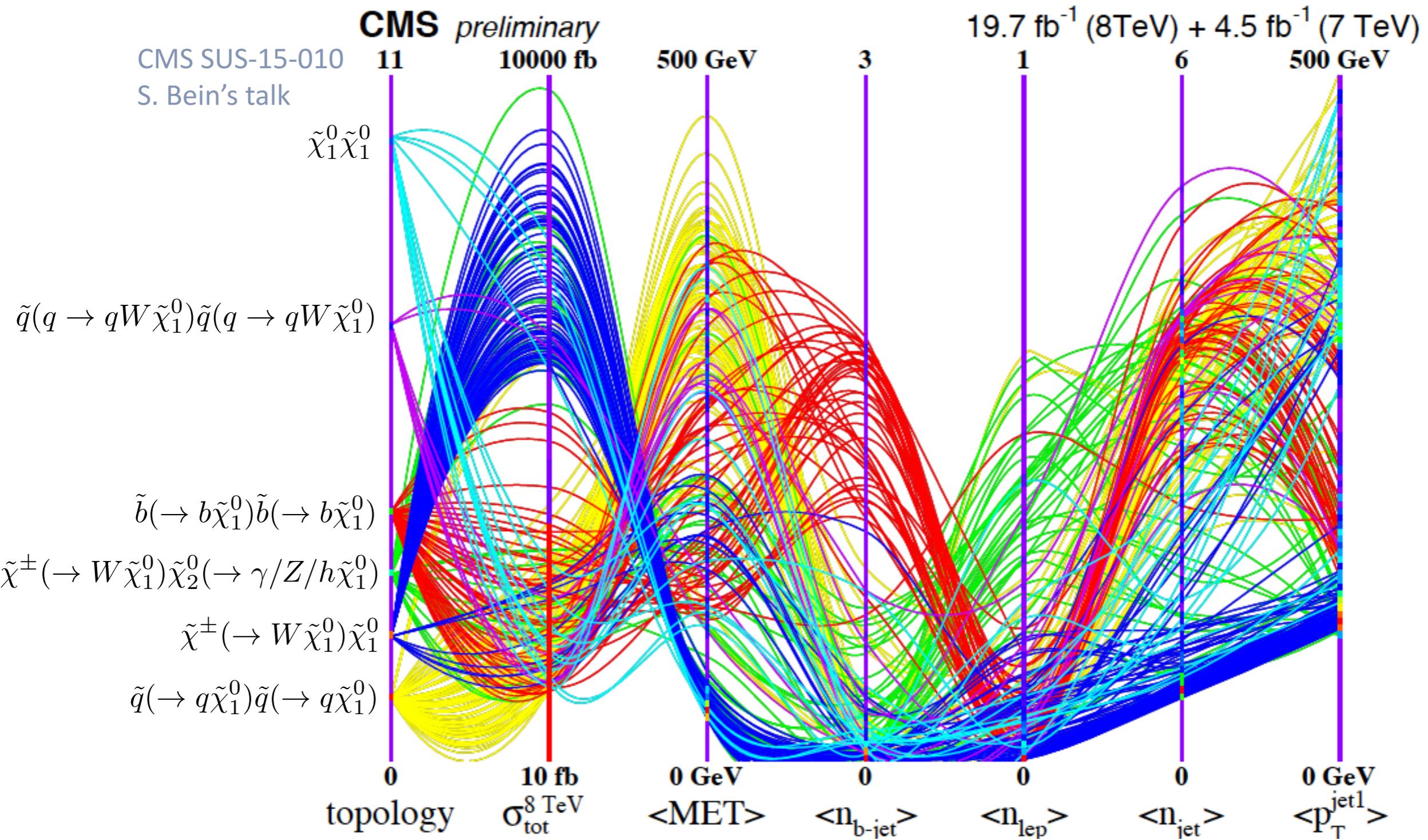
# How to find new directions

Conventional SUSY searches (inclusive multijet, 1 lepton + X, 2 lepton+X, ...) will always continue at LHC - but we need to adapt our searches and design new ones based on the opportunities Run2 offers. How?

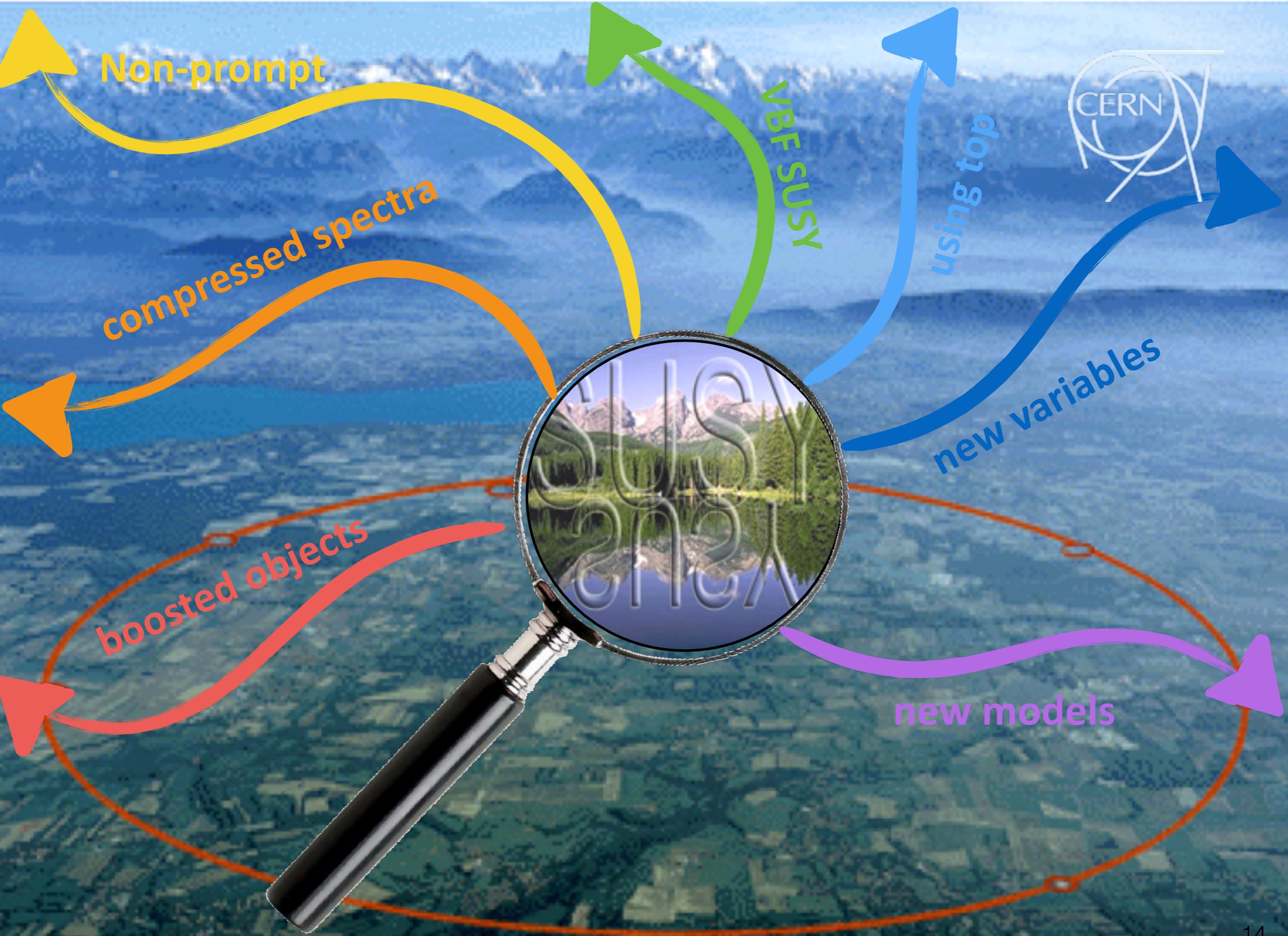
- **Unexplored regions:** Find topologies unexplored in Run1, but can be probed in Run2 due to increasing energy and luminosity, and design analyses targeting them.
  - CMS SUS-15-010 used phenomenological MSSM to find and characterize full model signatures unexplored by a variety of Run1 searches.
- **New signatures and methods:** What will become applicable at Run2?
  - New models/signatures, analysis methods, kinematic variables, background suppression ideas, statistical methods ... for finding SUSY?
  - Already existing signatures and ideas that become truly relevant at Run2 energy and luminosity?



# Characterizing unexplored regions in pMSSM



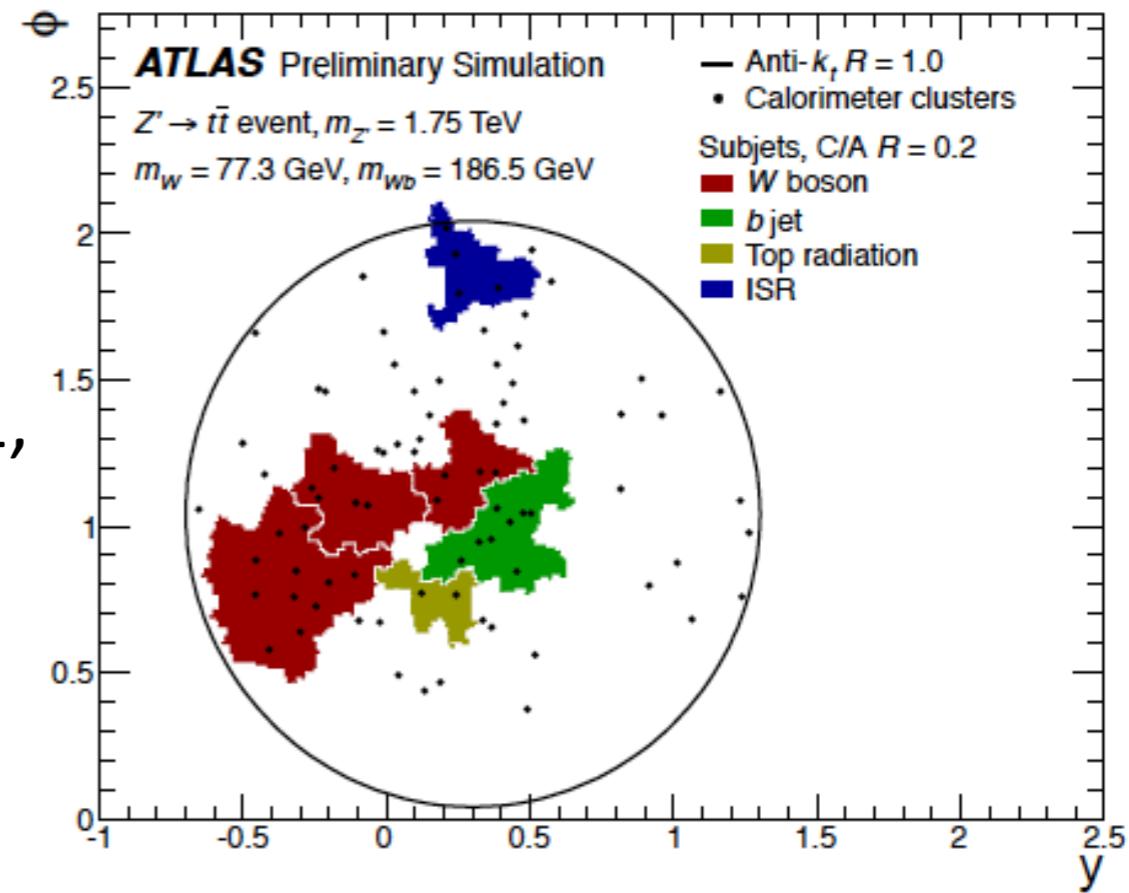
Dominant signatures for dominant unexplored topologies can be found, and dedicated analyses can be designed to target these signatures..





# Boosted SUSY: boosted objects

- Heavy particles potentially lead to larger mass differences → decay products with higher momenta → merged decay products → boosted objects.
- Boosted objects used extensively in Run1, but mostly for heavy resonances. Now relevant / compulsory for SUSY ( $\sigma_{13\text{TeV}} / \sigma_{8\text{TeV}}$  increases for heavier sparticles). Use boosted W, top, higgs and sparticles.



Boosted object tagging:

- Jet mass: peaks at mother particle mass. Grooming methods used to eliminate pile-up effects.
- Jet substructure: Find multiple cores using jet constituents (mass drop, soft drop, N-subjettiness, HEP TopTagger, template methods, ...)

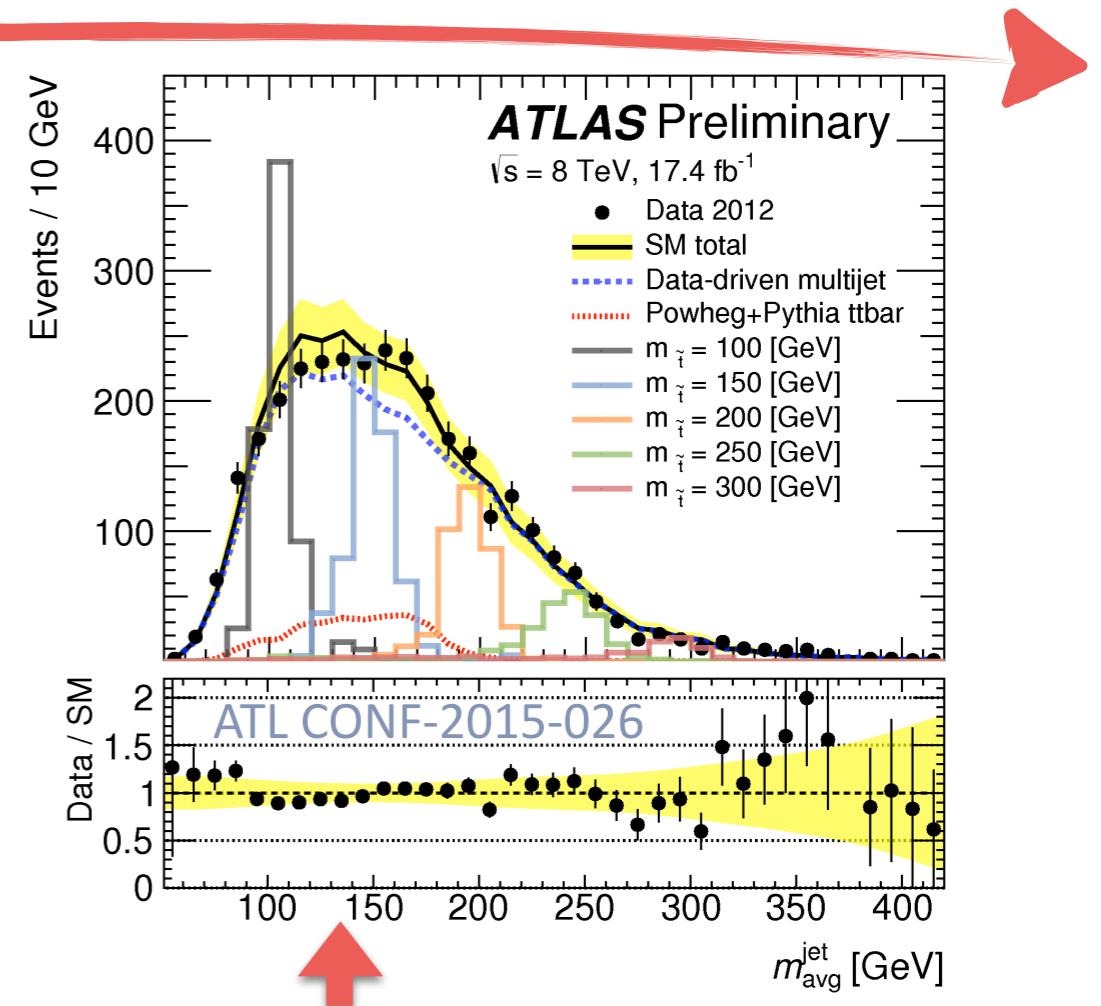
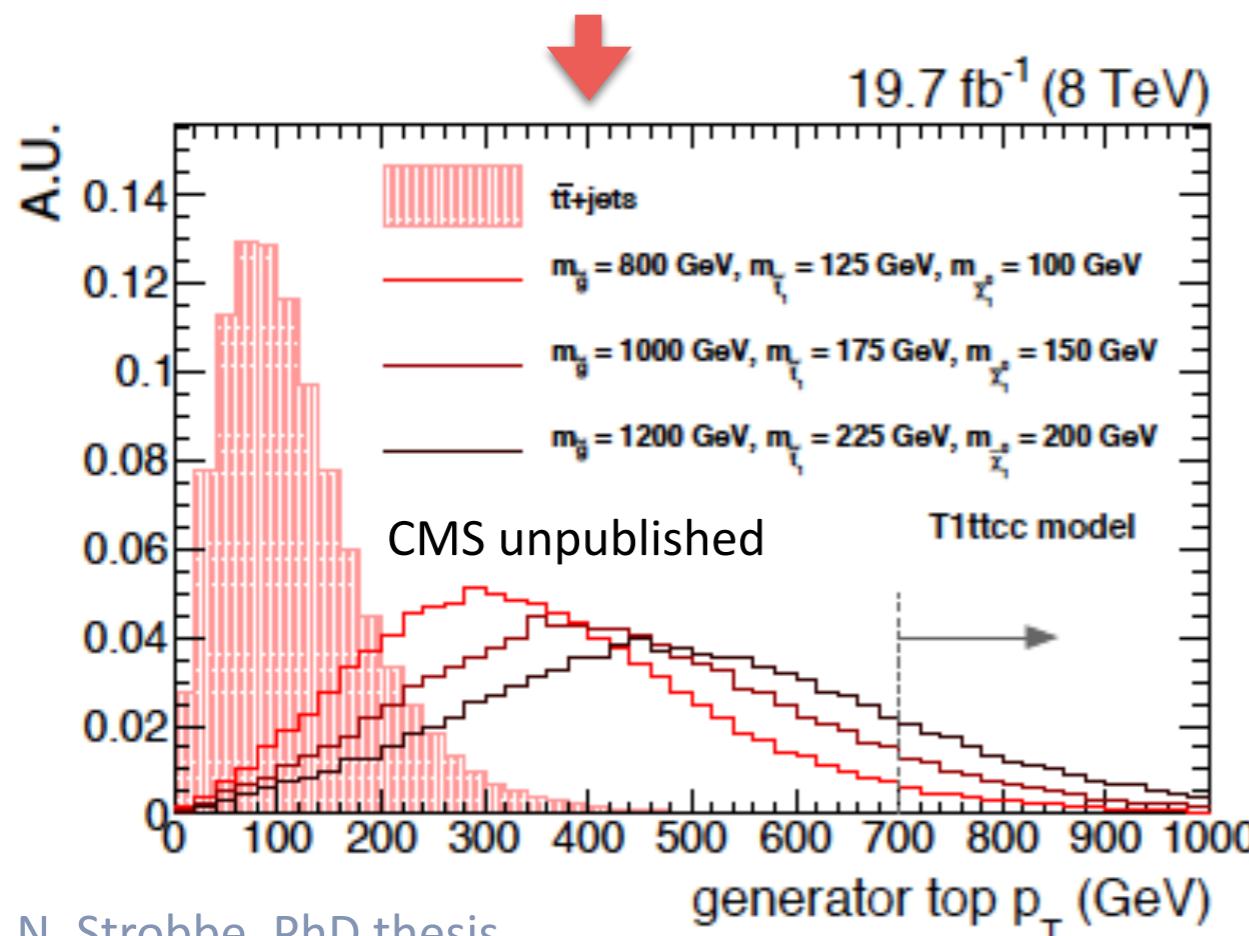
Specific to Run2:

- PU elimination: becomes very important, work ongoing.
- Triggers designed using boosted object tagging: will allow more efficient data collection for boosted analyses.



# Boosted SUSY: analyses

- Boosted Ws from top decays used in CMS in a search with razor variables to probe  $\tilde{g} \rightarrow \tilde{t}_1 t$  where  $m_{\tilde{g}} - m_{\tilde{t}_1}$  is large, and direct stop production for heavy stops ([CMS SUS-14-007](#)).
- Becomes important for completing Naturalness searches. Already pursued for Run2 in with flavors of boosted tops.

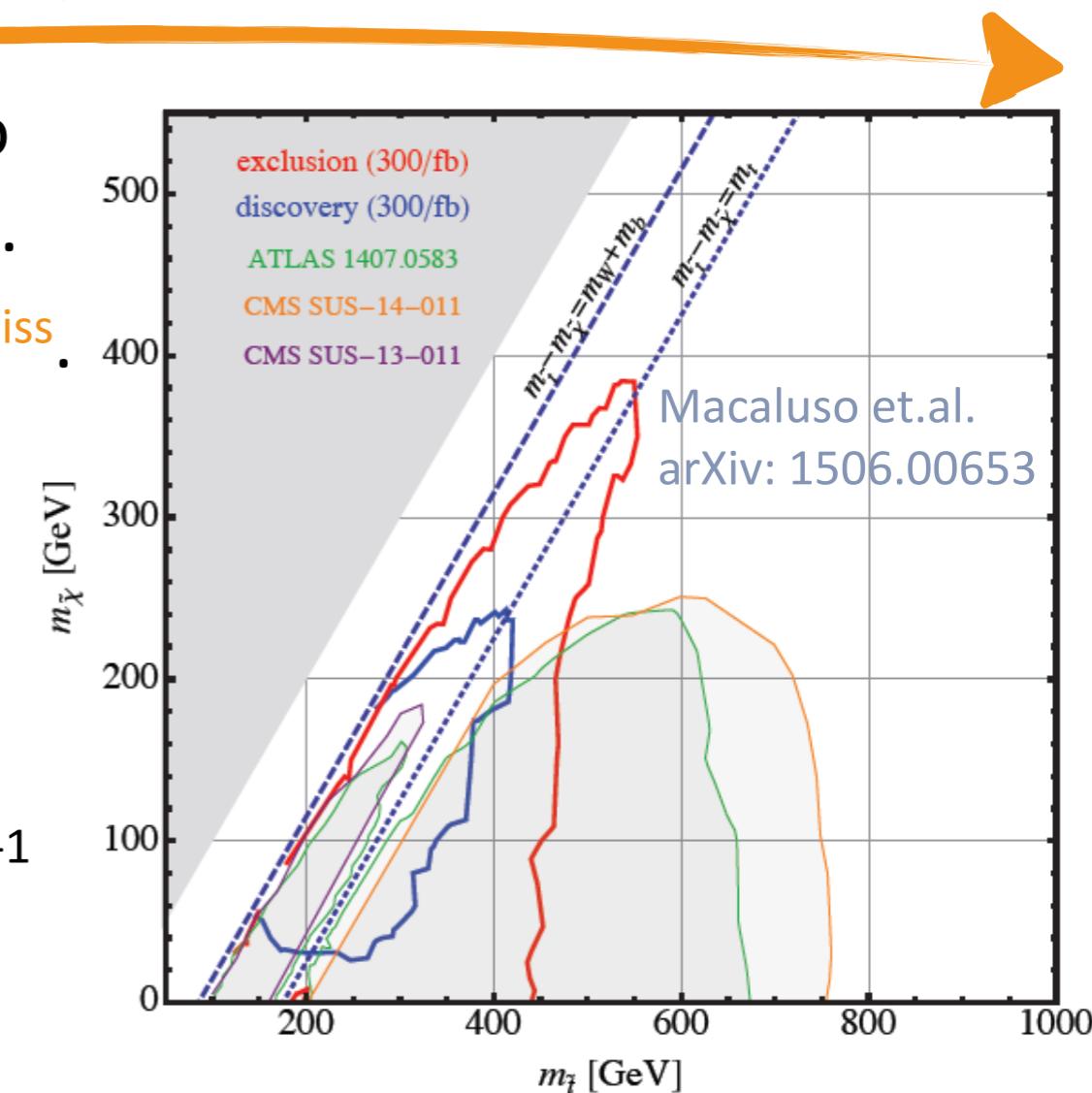
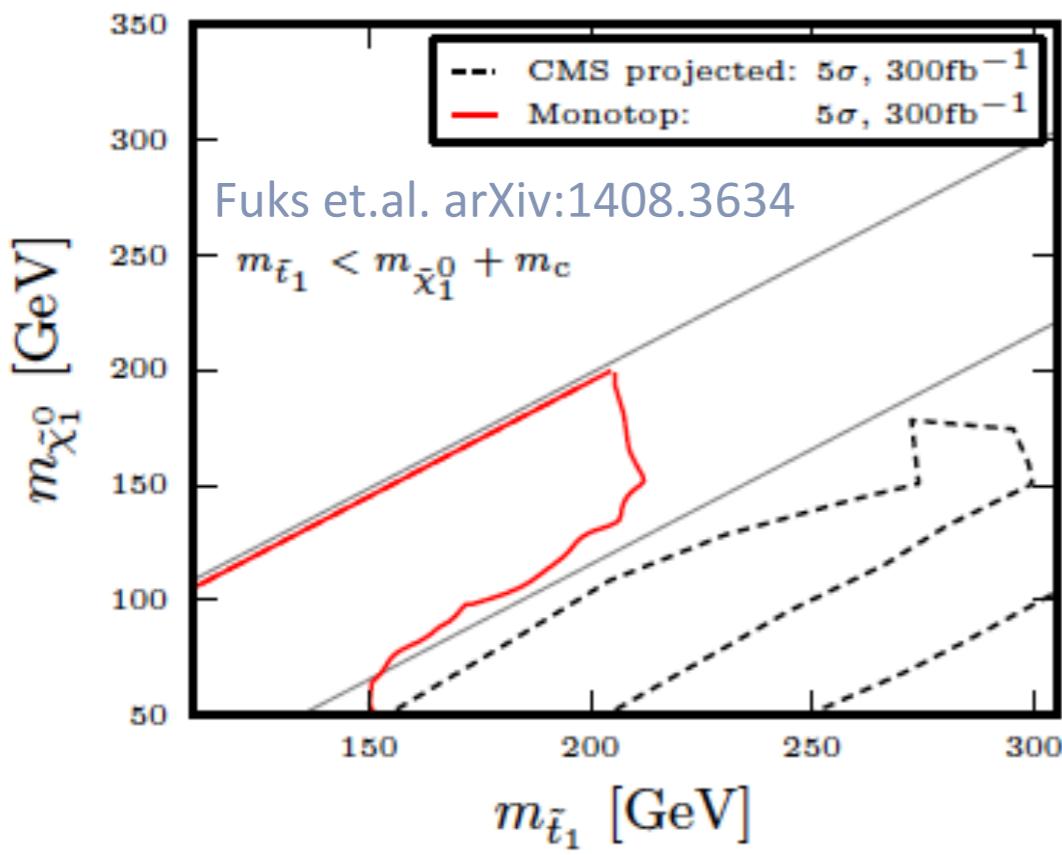


- RPV SUSY leads to no  $E_T^{\text{miss}}$  signatures: build sparticles from visible decay products.
- ATLAS studied  $\tilde{g} \rightarrow qqq$  ([SUSY-2013-07](#)) and  $\tilde{t} \rightarrow bs$  ([CONF-2015-026](#)).
- Used  $M_{\text{jet}}^{\Sigma}$  for  $\tilde{g}$ ; jet mass and substructure for  $\tilde{t}$ . Substructure for RPV can be further optimized.



# Compressed spectra: stops

- When  $\tilde{t}_1 - \tilde{\chi}_1^0$  degenerate, stop decays to very soft products  $\rightarrow E_T^{\text{miss}} + \text{soft particles}$ .
- Probe with a hard jet recoiling against  $E_T^{\text{miss}}$ . Distinctive anti-correlation between  $E_T^{\text{miss}}$  and recoil jet.
- Run1 monojet stop studies in ATLAS (SUSY 2013-21) and CMS (SUS-13-009).
- 14 TeV  $5\sigma$  reach up to  $m_{\tilde{t}_1} \sim 600$  for  $3\text{ab}^{-1}$  (An et.al. arXiv:1506.00653)

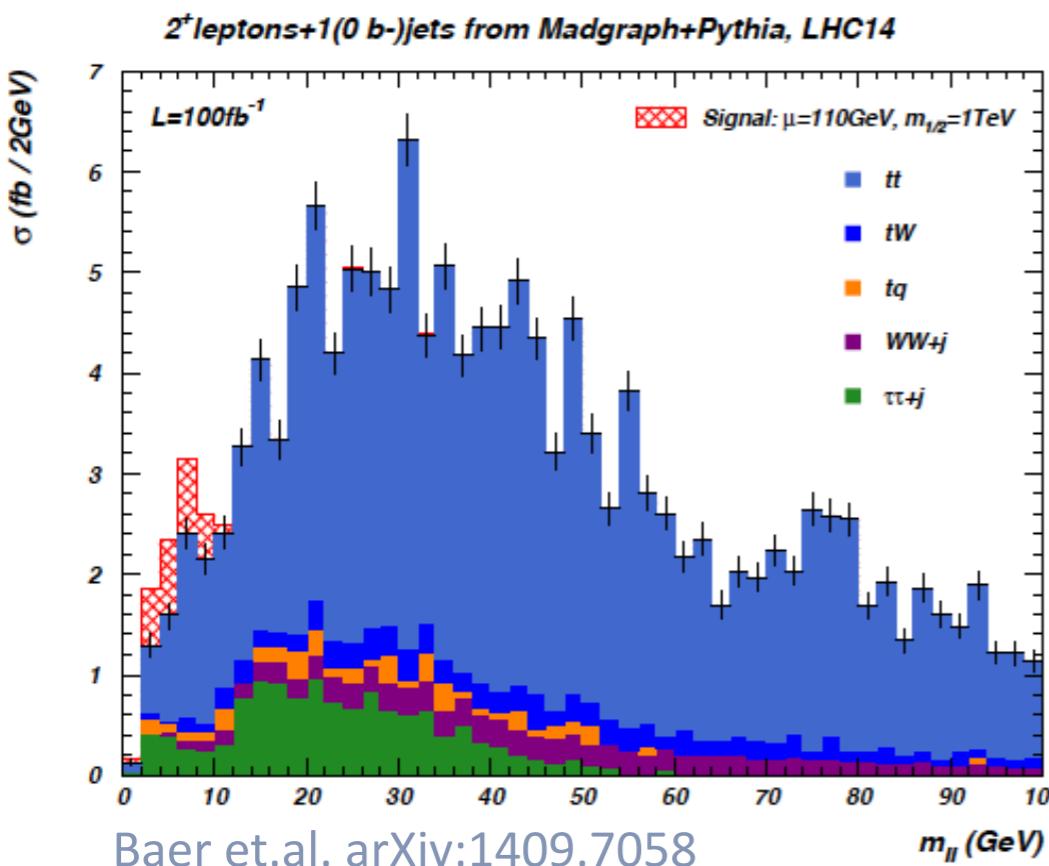
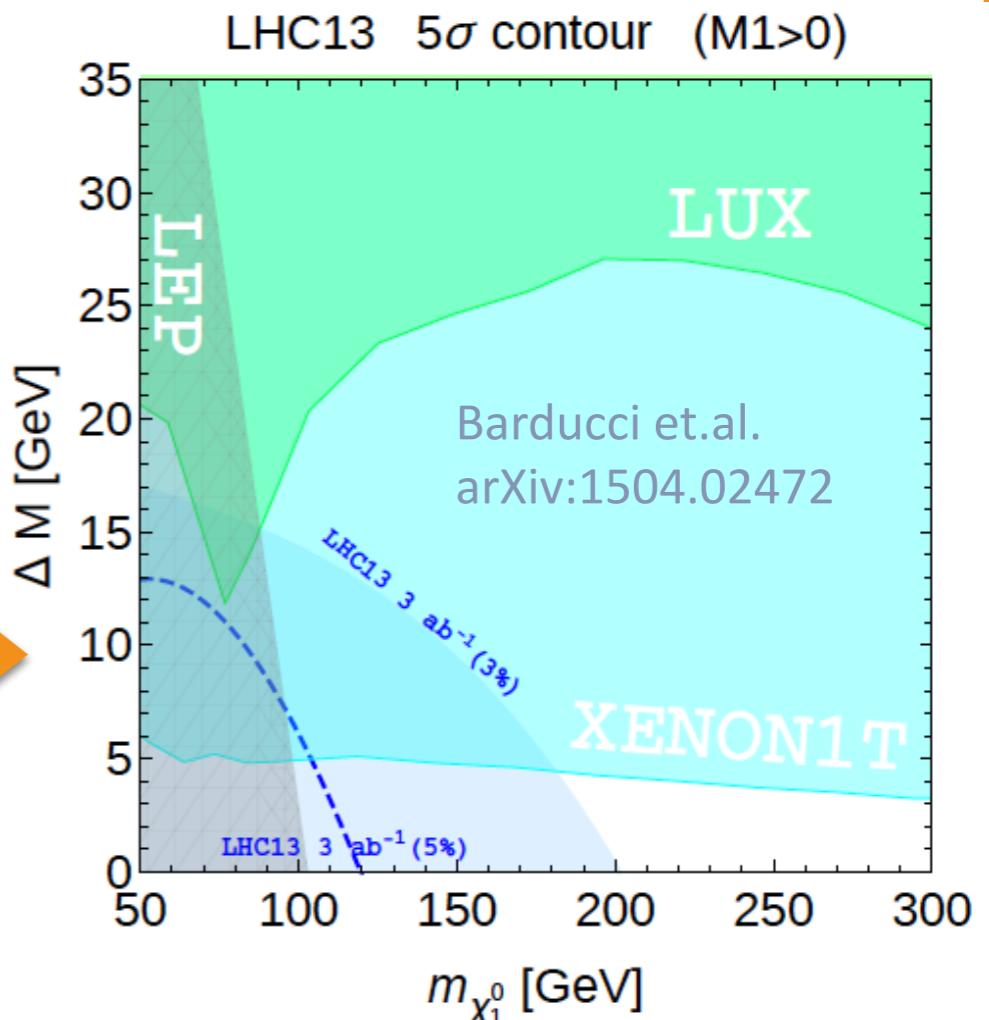


- Monotops feasible: not competitive for  $t\tilde{t}_1\tilde{g}$  but uniquely sensitive for  $t\tilde{t}_1\tilde{\chi}_1^0$ .
- Stop pair associated production with Higgs can be studied, but  $\tilde{t}_1\tilde{t}_1 h$  cross section is low (Djoudi et. al. hep-ph/9903218, Belanger et.al. arXiv:1506.00665).



# Compressed spectra: EWK gauginos

- Natural SUSY low  $\mu$  parameter → higgsino-like  $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow$  degenerate with  $\tilde{\chi}_1^0$ . Higgsino pair production →  $E_T^{\text{miss}} +$  soft products.
- Degenerate EWK gaugino pair production probed with monojets, monophotons or mono-Ws.



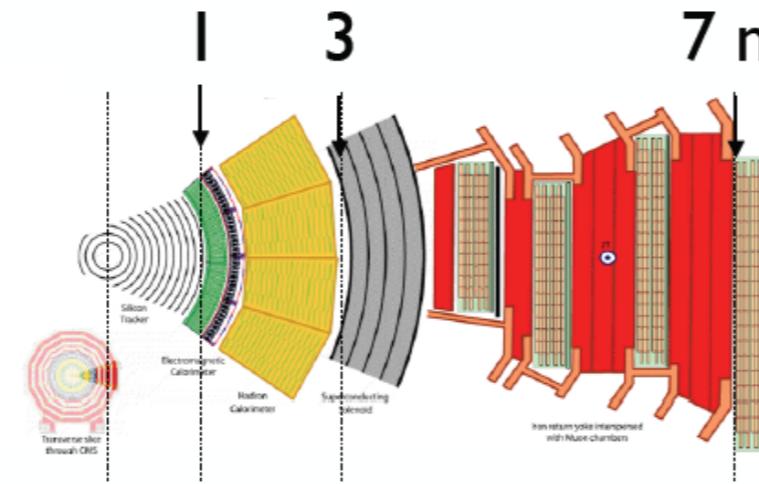
- To improve performance of monojet searches, get help from soft daughter leptons from higgsino decays in monojet events.



# Non-prompt searches

- In many cases, sparticles may decay **non-promptly**, outside the beamspot.
- A wide diversity of **dedicated searches** for non-prompt particles nicely complement the prompt searches. Improve and explore further in Run2.
- Not much **SM background** outside the beamspot. Mostly detector noise, cosmic rays, reconstruction failure, etc. estimated from data.

Non-prompt  
signatures and  
target SUSY  
models:

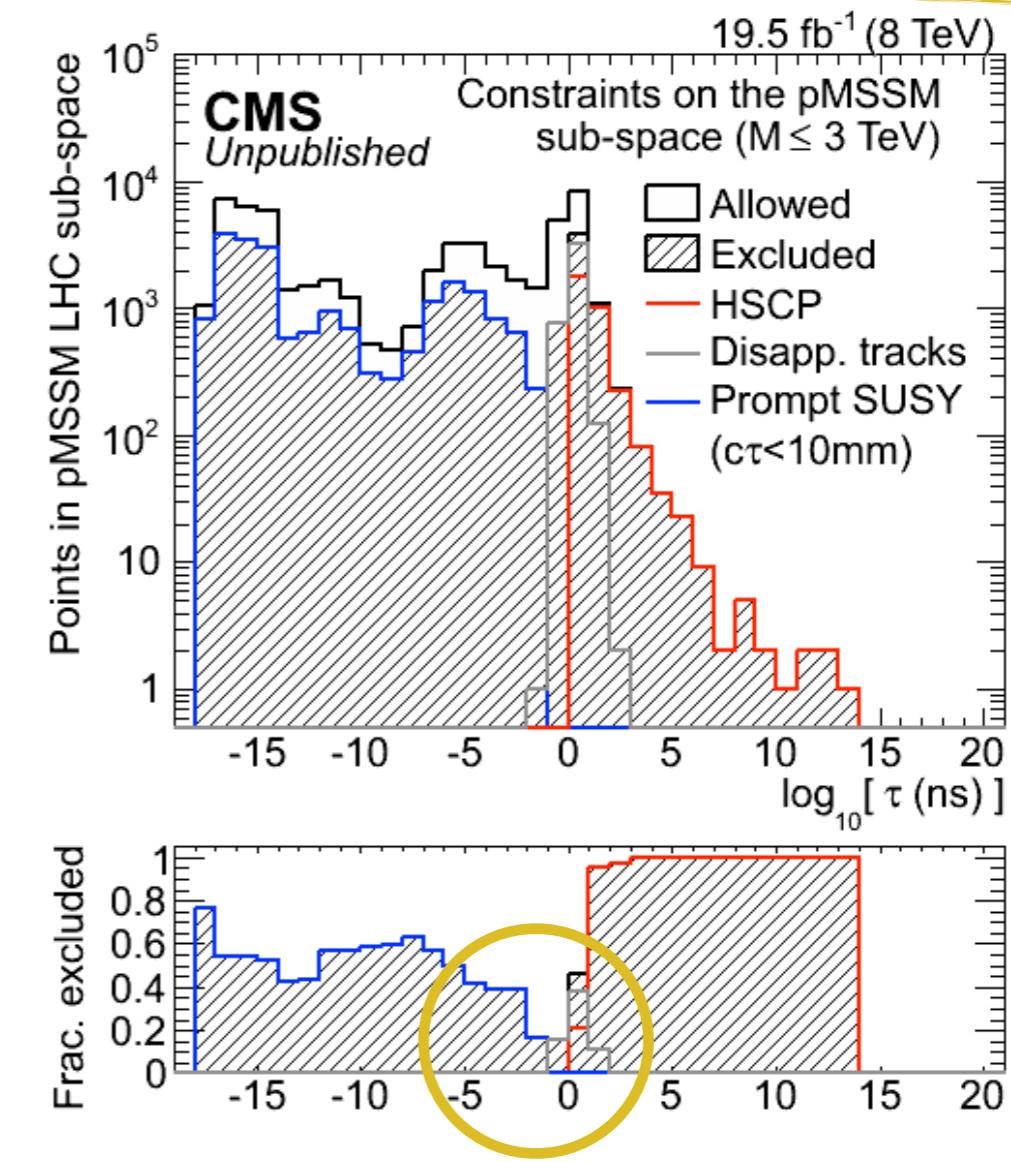
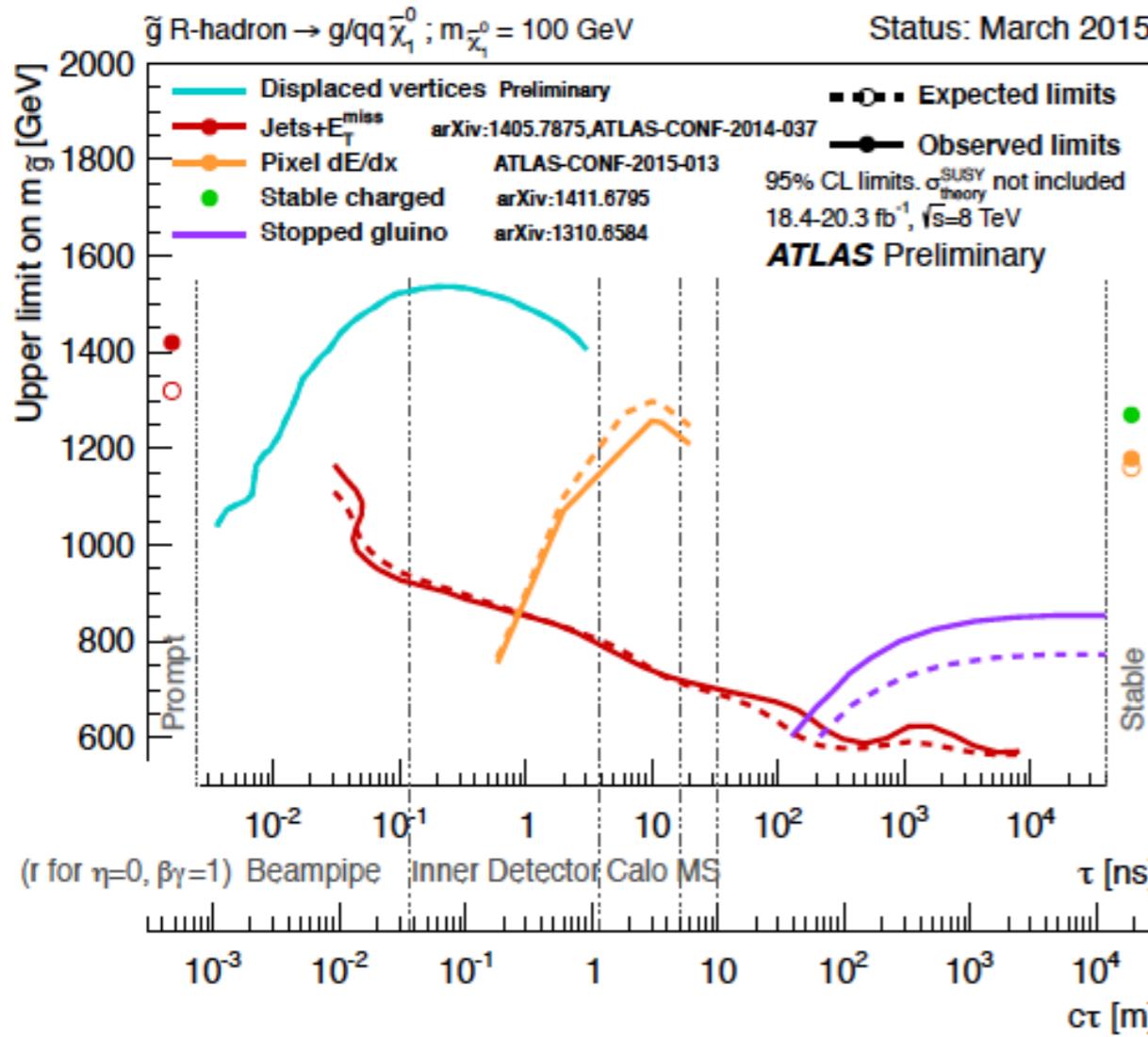


from W. Wulsen

| Region of BSM particle decay   |                                                               |
|--------------------------------|---------------------------------------------------------------|
| displaced jets                 | → RPV SUSY ( $\chi^0 \rightarrow q\bar{q}\mu$ ), stealth SUSY |
| lepton jets                    |                                                               |
| displaced leptons              | → RPV SUSY ( $\chi^0 \rightarrow l\bar{l}v$ ), displaced SUSY |
| displaced vertices             | → Split SUSY, RPV, GMSB                                       |
| displaced / delayed photons    | → GMSB                                                        |
| stopped particles              | → split SUSY gluino, stop, ...                                |
| heavy stable charged particles | → gluino, stop, GMSB slepton, chargino ...                    |
| disappearing tracks            | → degenerate chargino                                         |



# Non-prompt searches



Unexplored regions still exist in pMSSM.

- Disappearing track searches may be too stringent. Can relax the cuts and combine the selection with usual SUSY search variables ( $E_T^{\text{miss}}$ , multijets, etc.) to increase sensitivity. ATL SUSY-2013-01 uses  $E_T^{\text{miss}}$ .
- Can use tracker-only trigger, or shorter tracks to probe smaller lifetimes.



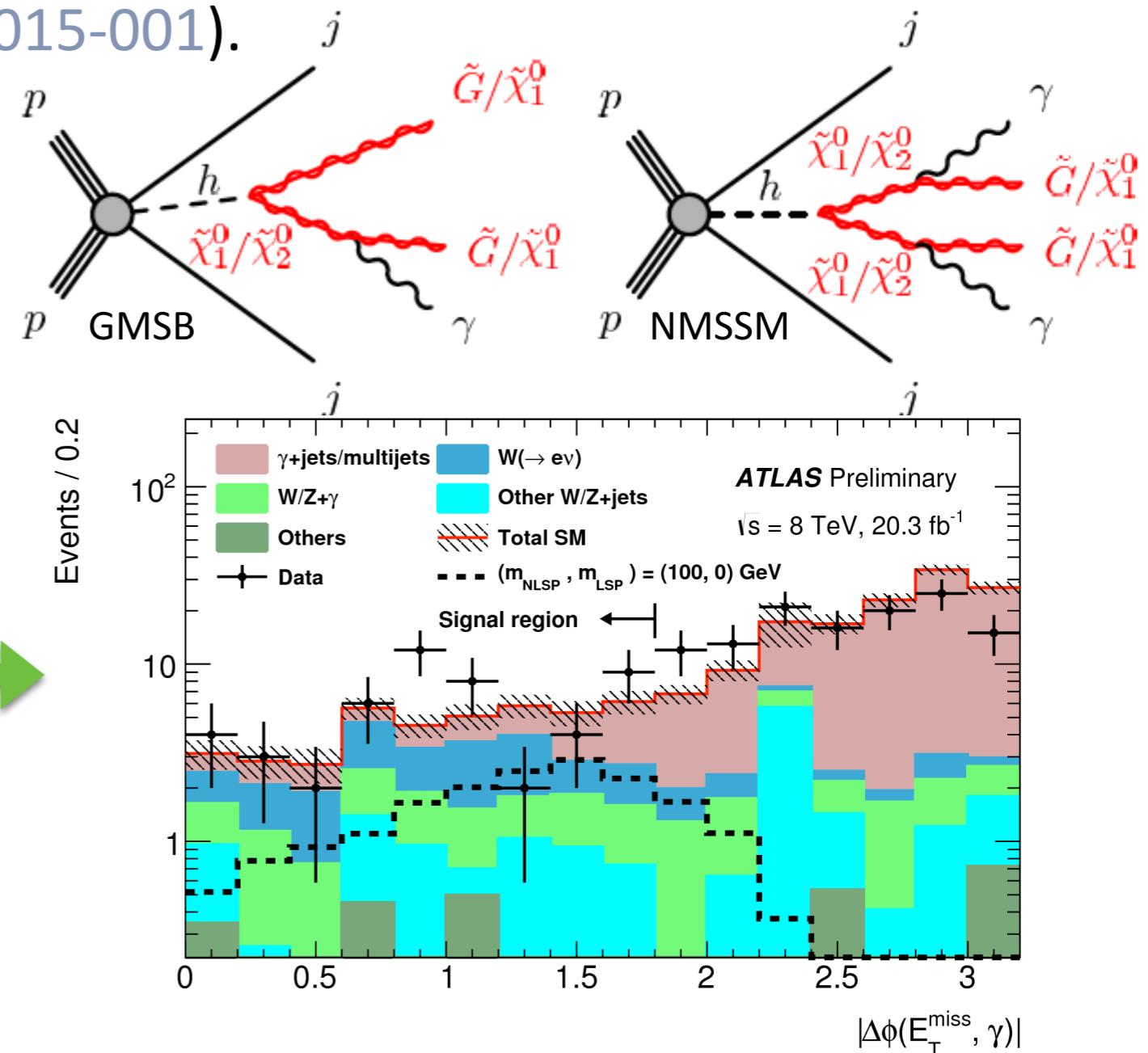
# VBF in SUSY

Vector boson fusion processes proved crucial in purifying signal in Higgs discovery and measurements. Can also be used in SUSY.

- ATLAS study with SUSY Higgs with  $\geq 1$  photon +  $E_T^{\text{miss}}$  + 2 VBF (forward) jets final states (ATLAS-CONF-2015-001).

VBF topology:

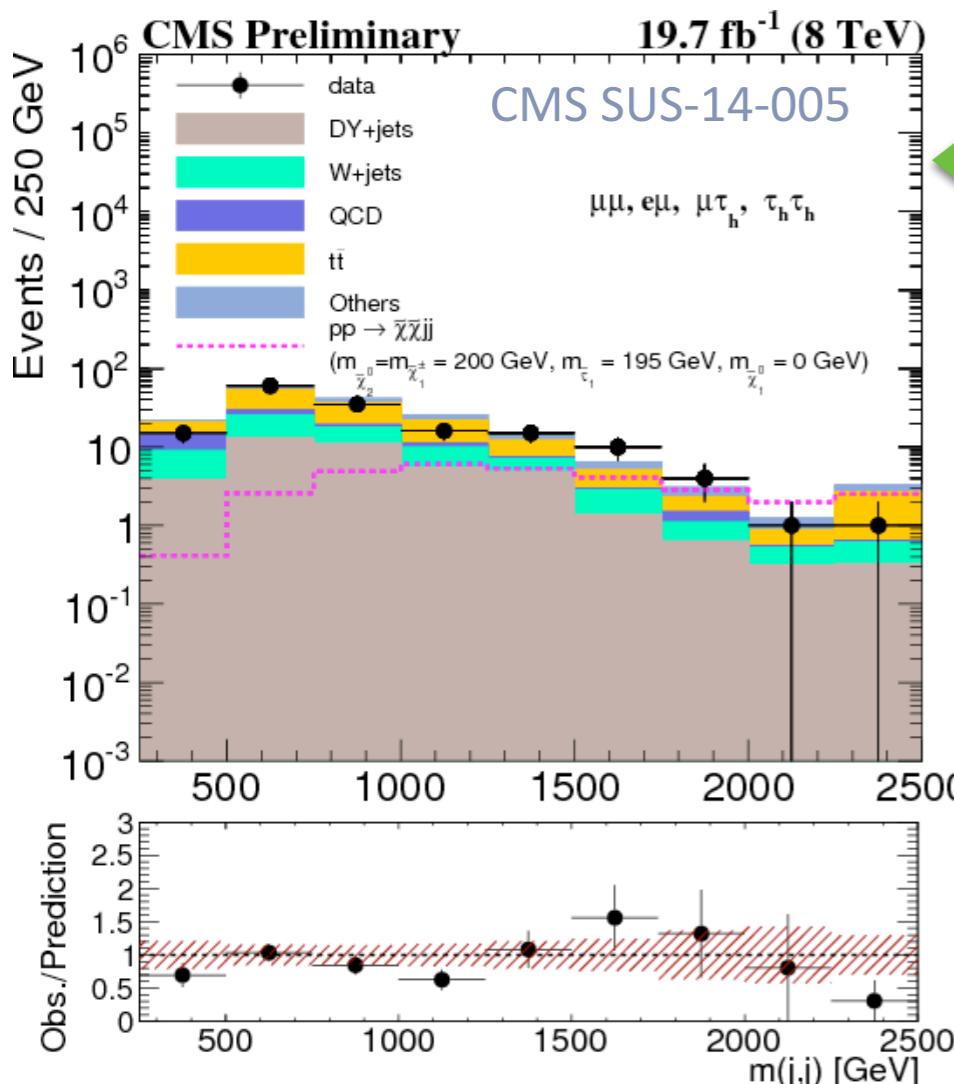
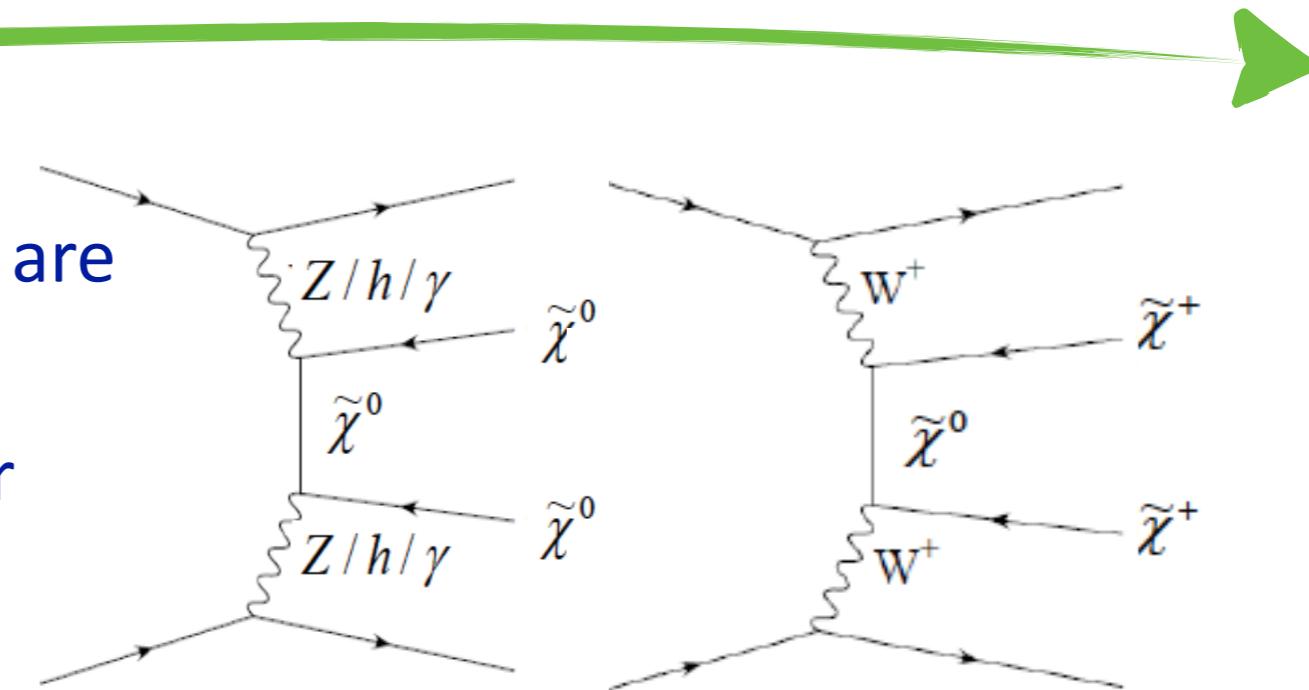
- VBF jets are **highly separated in pseudorapidity** and have a **high dijet invariant mass  $m_{jj}$** .
- Higgs boson boosted in the transverse plane  $\rightarrow$   **$h$  decay products close to each other**  $\rightarrow$  photon and  $E_T^{\text{miss}}$  are not back-to-back.





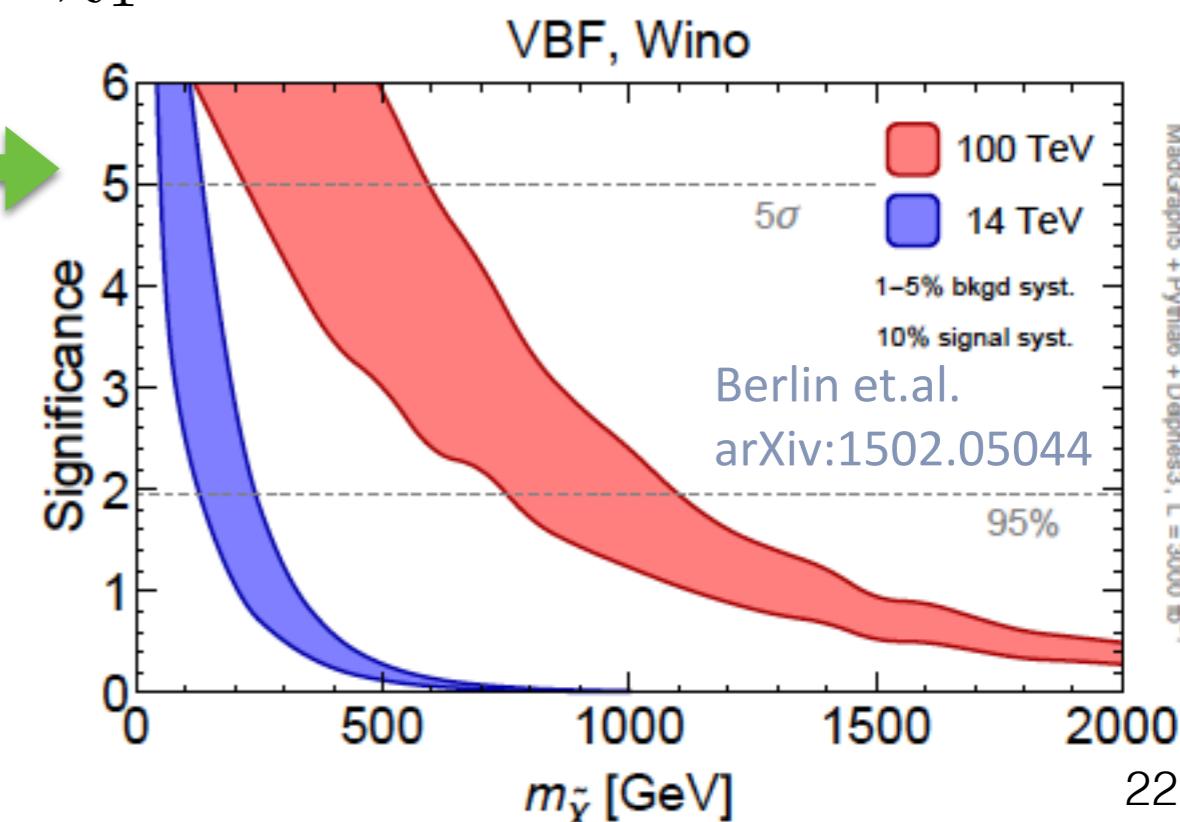
# VBF in SUSY

- VBF also used for probing EW production when colored sparticles are heavy.
- Relevant for compressed spectra, or final states with large colored backgrounds.



CMS study for  $\chi\chi$  at  $lljj$  channel with jets in different hemispheres. Effective in probing large mass gaps, i.e.  $\tilde{\chi}_1^0 \sim 0$

Dark matter study for 14 and 100 TeV using VBF.





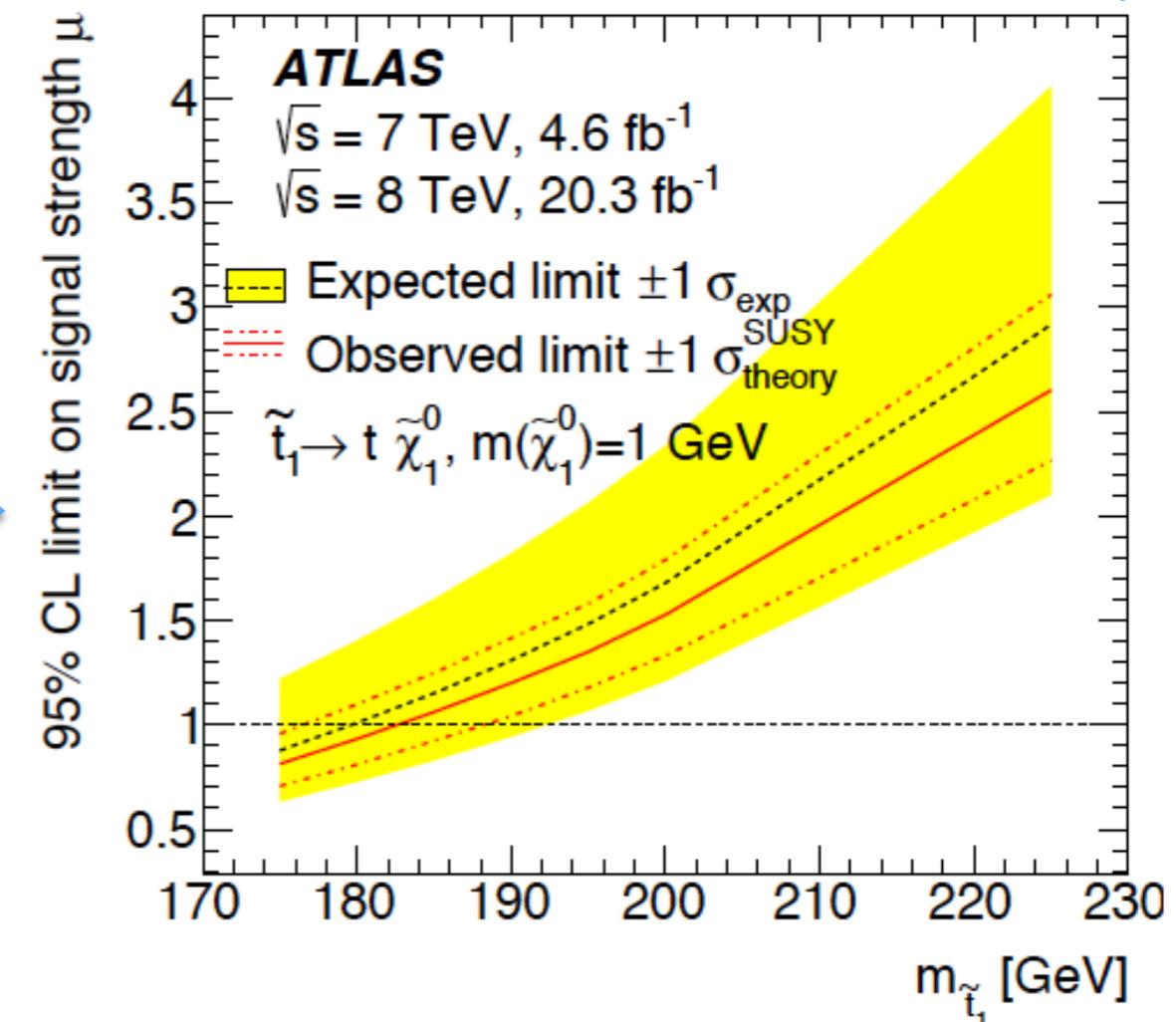
# Using top properties

When stop mass is close to top mass (**stealth stop**) signature is SM-like.

- Stop cross section is 10% of top cross section → stops can be observed as an excess in the top cross section. →
- ATLAS (TOPG-2013-04), CMS (TOP-13-004).

Main issue: theoretical uncertainties on cross section.

- NLO calculation of stop production cross section will become available in **MadGraph**. First studies with stops are NLO are being pursued with **FEYNRULES/aMC@NLO**. First tests agree well with **PROSPINO**. (**Ambrogi et.al. in preparation, Degrande et.al. arXiv:1412.5589**).

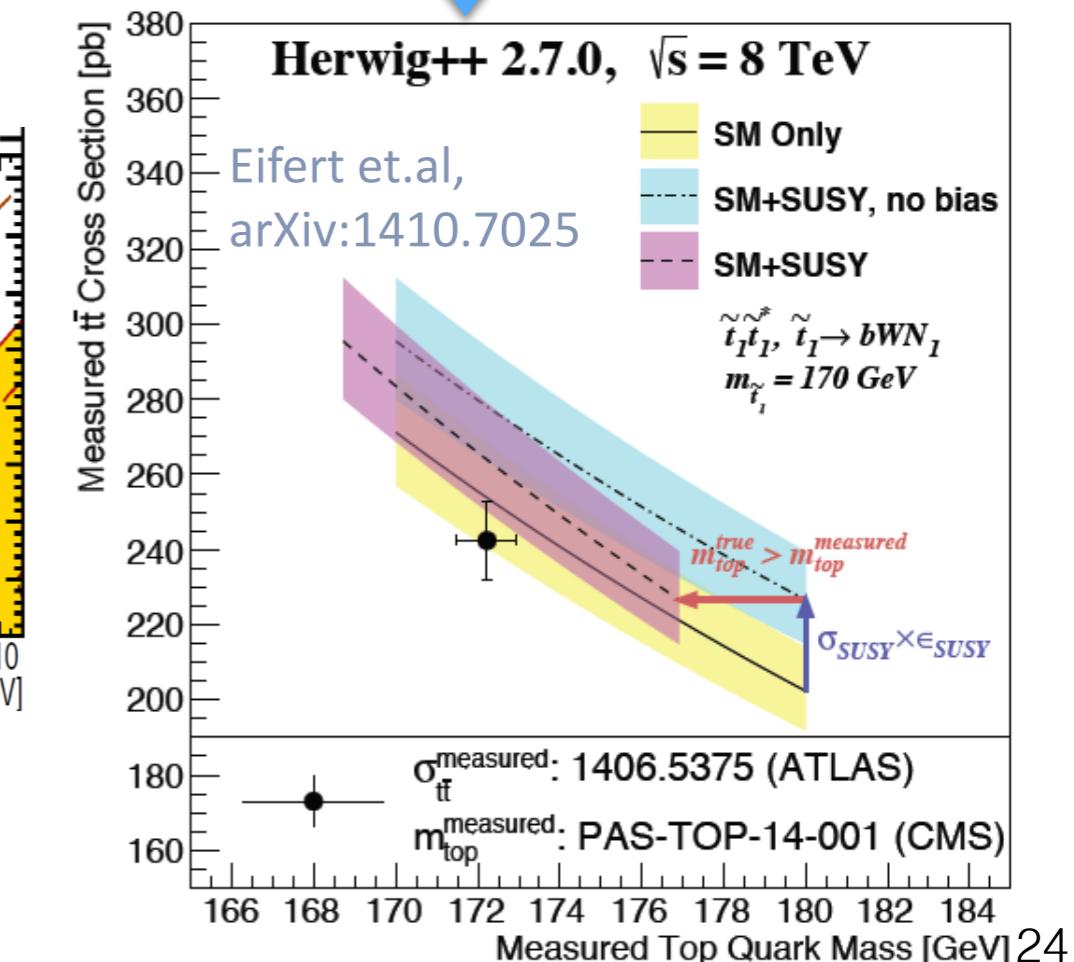
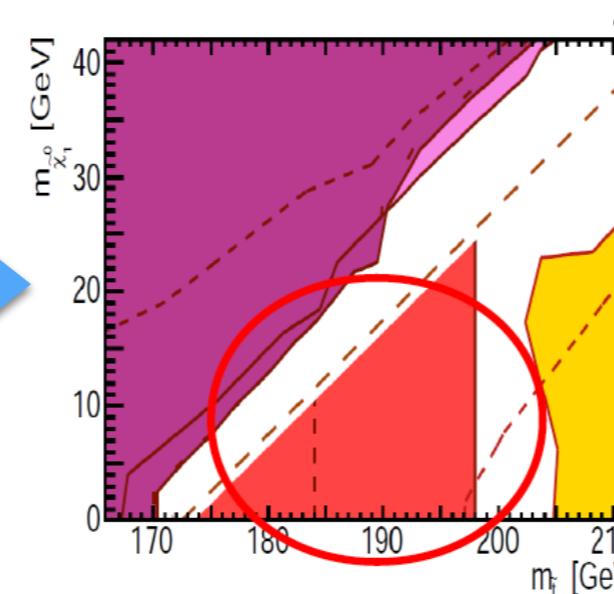
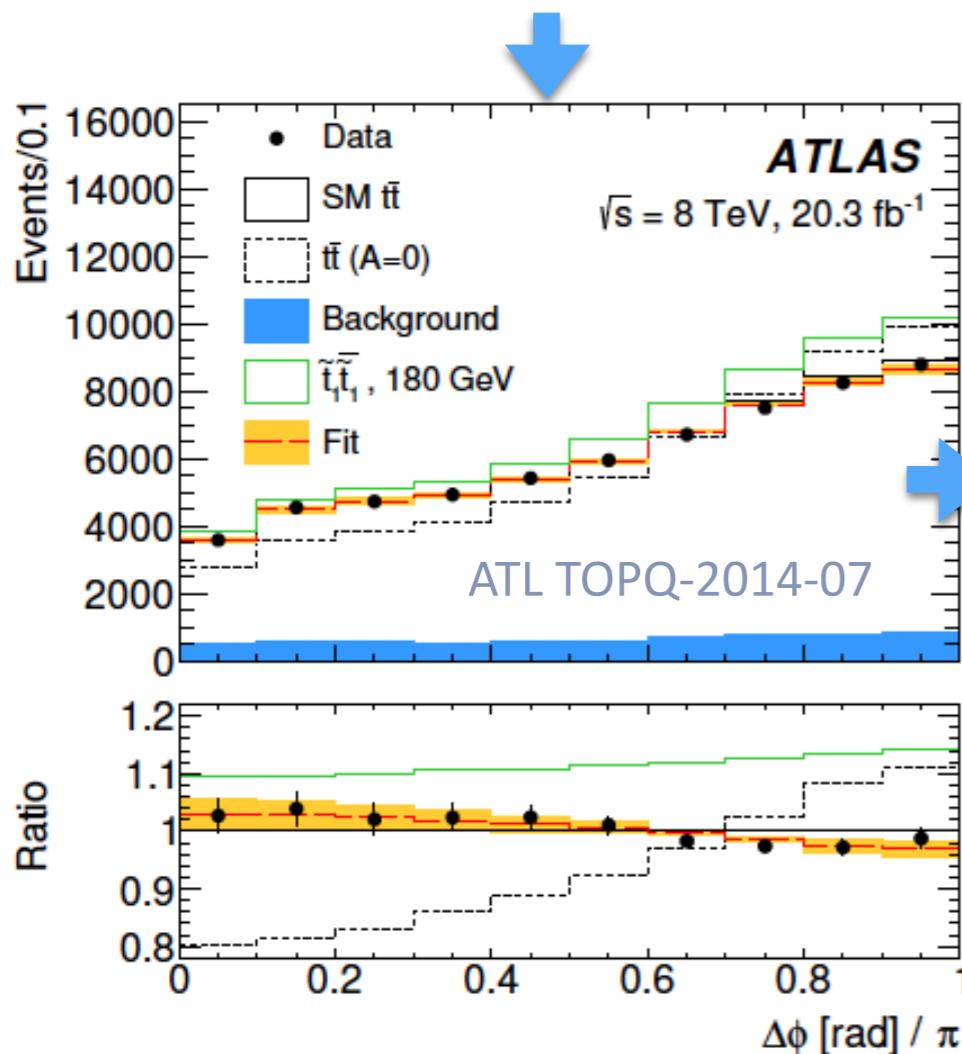




# Using top properties

In SM  $t\bar{t}$  production, top spins are correlated, and this reflects to top decay products. No corr. in SUSY.

- ATLAS used azimuthal angle between  $|+\rangle - |-\rangle$  to extract  $t\bar{t}$  spin correlations and found consistency with SM. Studies will continue



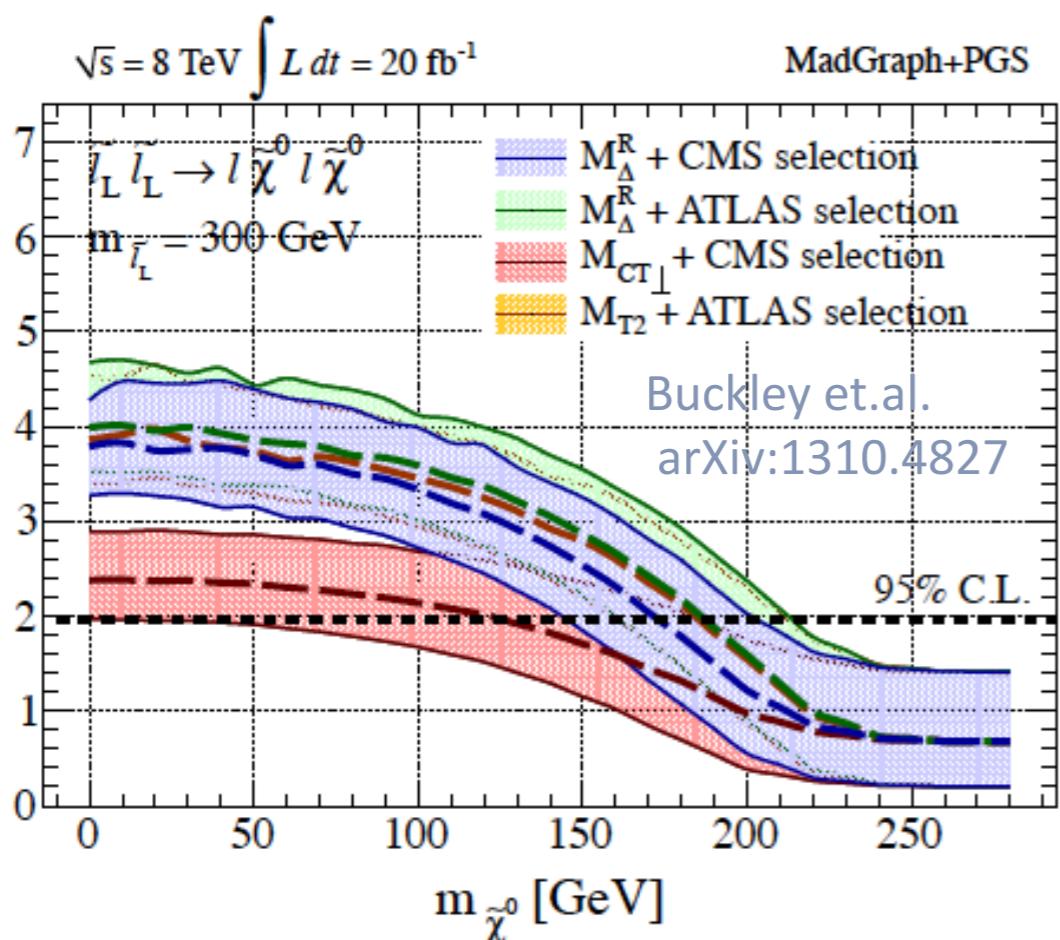
- Presence of stops distorts/softens top mass distribution.
- Falsely lighter top implies higher predicted  $t\bar{t}$  cross section. Stops can make up for the cross section → since SM-like relation is restored, stops can evade detection.

# New variables and methods: Kinematics

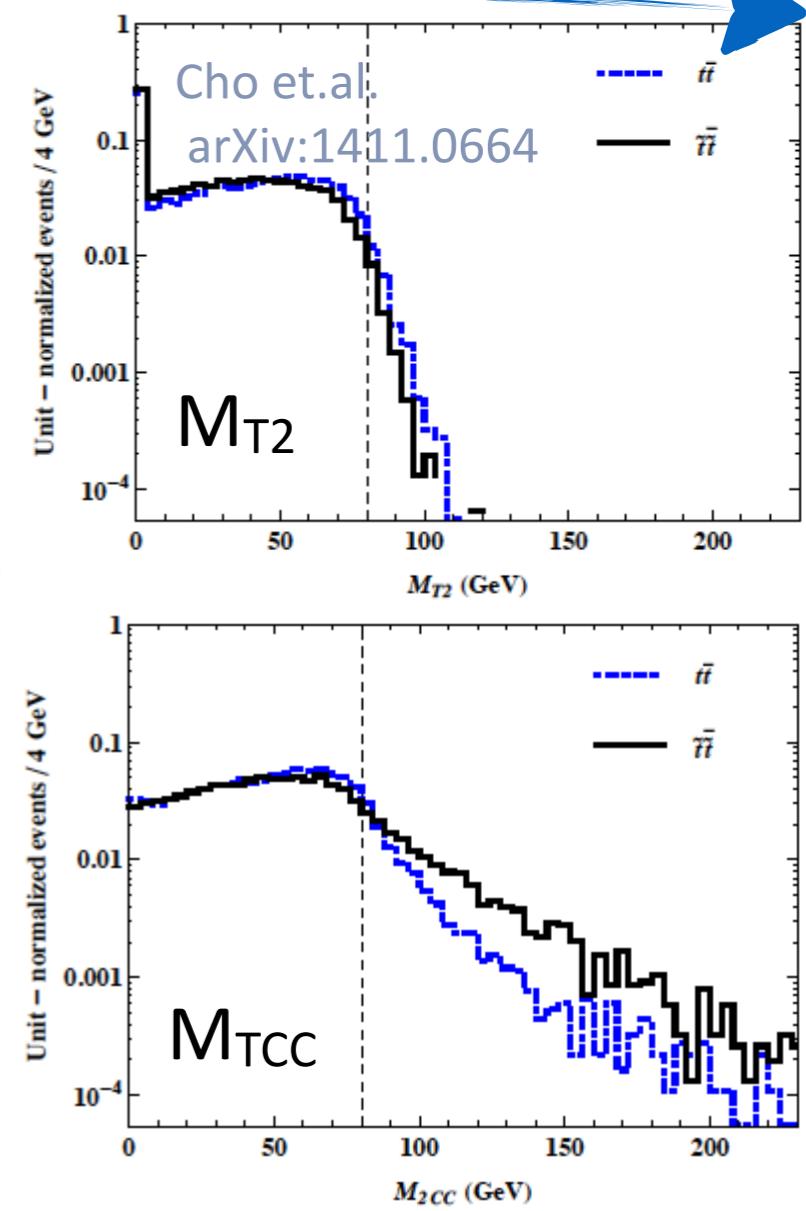


As signal and background become similar, make most of the **subtle kinematic differences**.

- $M_2$ , the on-shell constrained invariant mass variables minimize some parent mass wrt  $p$  of invisible daughters. 3+1 generalizations of  $M_{T2}$ , and improve signal-background discrimination.
- Recent study with stops promising, there is a lot to explore.



Also see **OPTIMASS**, package to minimize kinematic mass functions with constraints  
(arXiv:1508.00589)



Talks by L. Lee, P. Jackson,

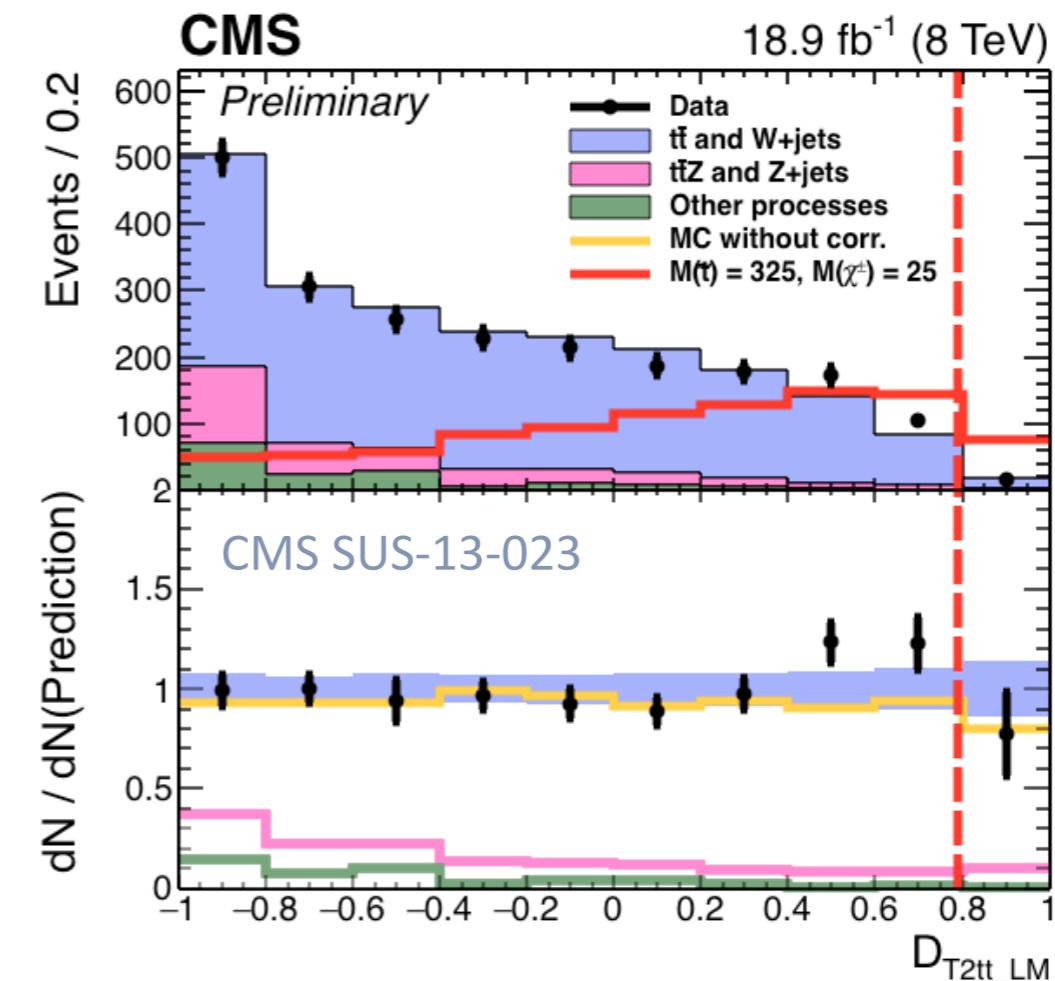
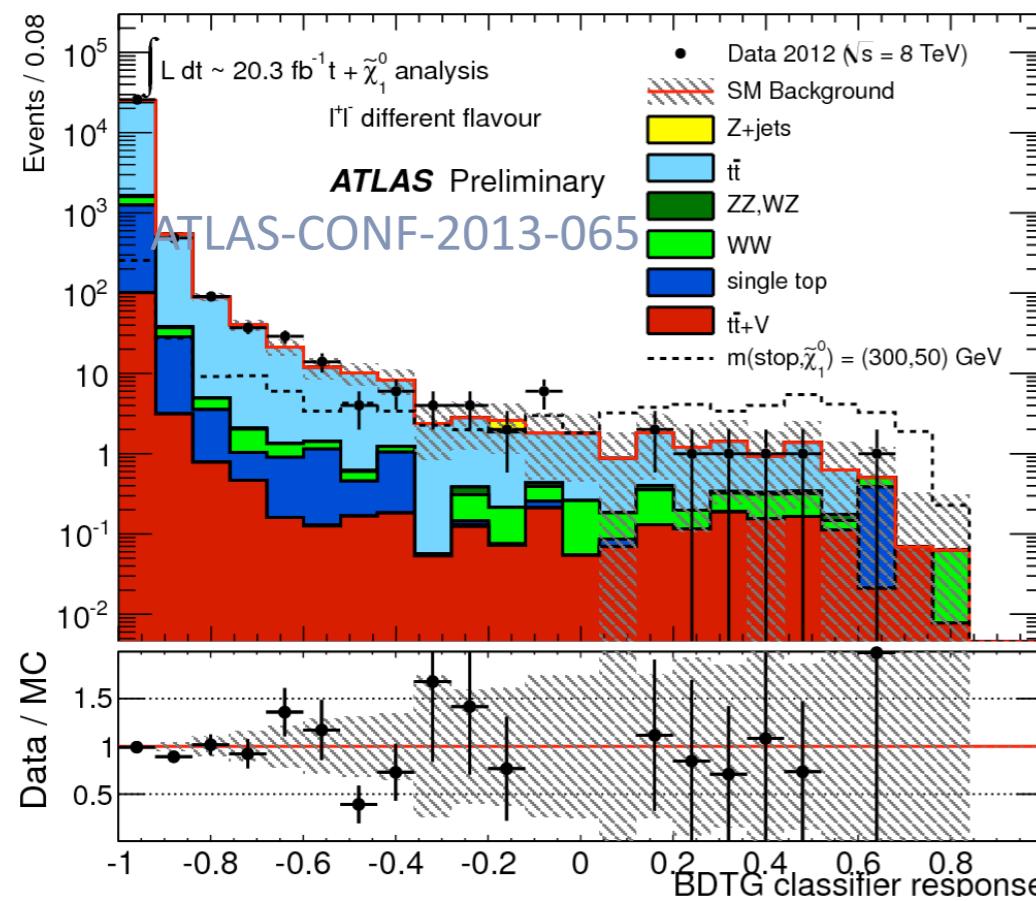
- Recent **super-razor** variables improve sensitivity to EWK gaugino pair production.
- **Recursive jigsaw reconstruction** extends super-razor: recipe to assign 4-vectors to the invisible particles to constrain system at each step of decay.

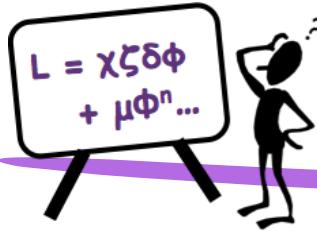
# New variables and methods: MVAs



Multivariate methods like boosted decision trees and neural networks already used in stop searches. Employ to extract utmost sensitivity.

- **Event selection:** MVAs more effective for complex final states and selections.
  - can they be trained to maximize a generic separation from the SM?
- **Object selection with MVAs:** Allows analysis-specific object definition. Used in CMS (e.g., picky jets with variable size parameter)



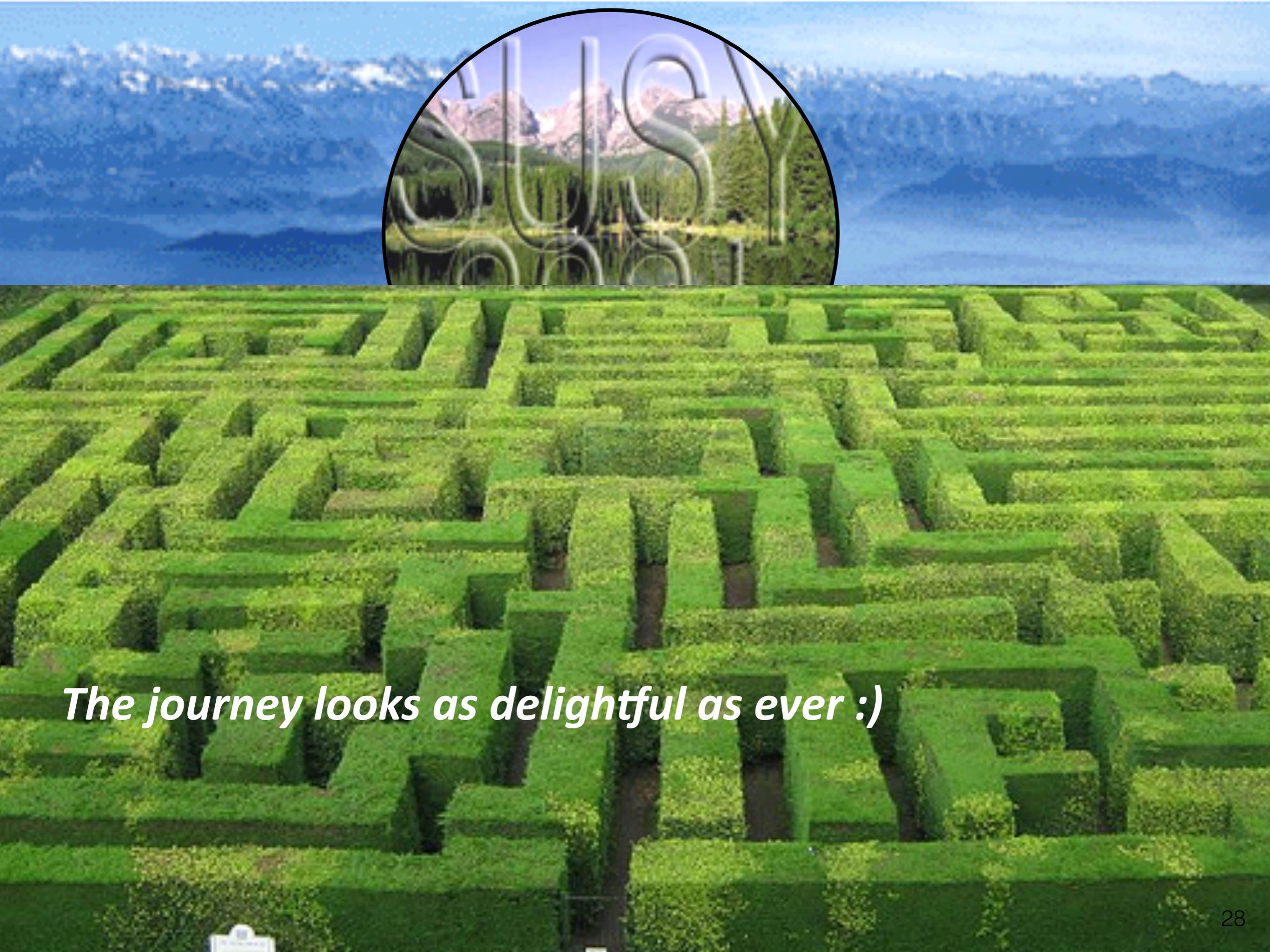


# New models

In Run1, ATLAS and CMS used simplified models to model signatures. In Run2, full models will be more focused on. What models could be interesting / motivated / relevant?

- pMSSM was extensively used, and will continue to be used.
- Flavor violating models?
- Extensions of the MSSM:
  - NMSSM and studies in its rich Higgs sector; models with sneutrino/ axino/... LSP, extended gauge groups (U(1), left-right, E6, ...); ...
  - Run2 will probably say the final word on Naturalness with light stop. Complete Naturalness scans?
    - Different ways of achieving Naturalness? neutral naturalness?
    - Relations with dark matter? Effective field theories?

*We need guidance from theorists!*



*The journey looks as delightful as ever :)*



# Summary



- With  $300\text{fb}^{-1}$ , 14TeV LHC can discover gluinos up to 2TeV, squarks to 1.5TeV, stops/sbottoms to 1.1TeV, EW gauginos to 0.7TeV. Will focus on complementarity in searches to increase discovery potential for a signal.
- In Run2, boosted objects, VBF studies and searches using top properties become more relevant. Mono-X searches for compressed spectra and non-prompt searches will be further developed.
- New kinematic variables and analysis methods are being designed and studied.
- We need guidance from theorists on what models and signatures to pursue!