LHCP Bologna
June 7th, 2018

# COMPRESSED SUSY SEARCHES IN CMS

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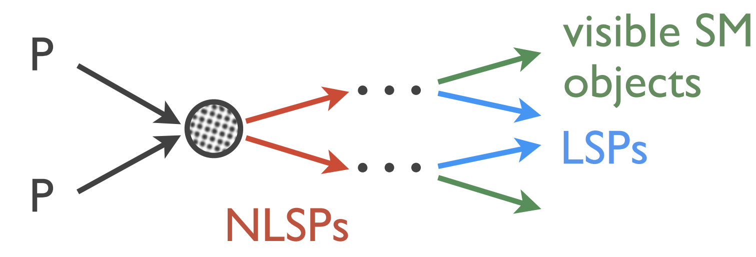
on behalf of the CMS Collaboration

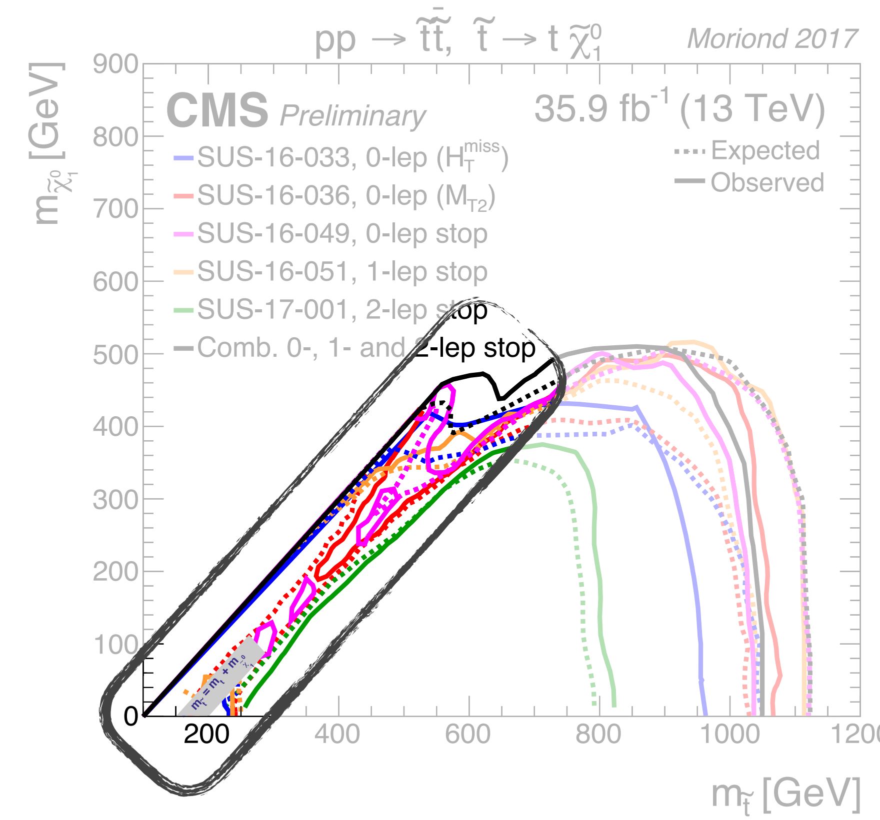
# Why “Compressed SUSY” ?




+ MASS(SUSY PARTICLE PRODUCED IN THE HARD COLLISION)
- MASS(LIGHTEST SUSY PARTICLE)

= **MASS SPLITTING** =: $\Delta m$

- theoretically interesting
  - relic density of compressed models expected to be consistent with cosmological observations [*]
  - natural SUSY expects light and compressed (MeV—GeV) higgsinos [**]
- experimentally motivated
  - level of compression determines possible final states
  - thus: same SUSY scenario leads to different final states
  - especially particles with low transverse momentum („soft“) can be produced in decay
  - hard to resolve compressed signatures at the LHC!
- and of course:
  - we haven’t found SUSY yet in noncompressed spectra, maybe it pops up in the compressed?




[*] C. Balázs et al., “Dark matter, light top squarks, and electroweak baryogenesis”, Phys. Rev. D 70 (2004), 015007, doi:10.1103/PhysRevD.70.015007
[**] H. Baer, A. Mustafayev, and X. Tata, Monojet plus soft dilepton signal from light higgsino pair production at LHC14, Phys. Rev. D 90 (2014) 115007, doi:10.1103/PhysRevD.90.115007.

# Compressed SUSY Searches in CMS

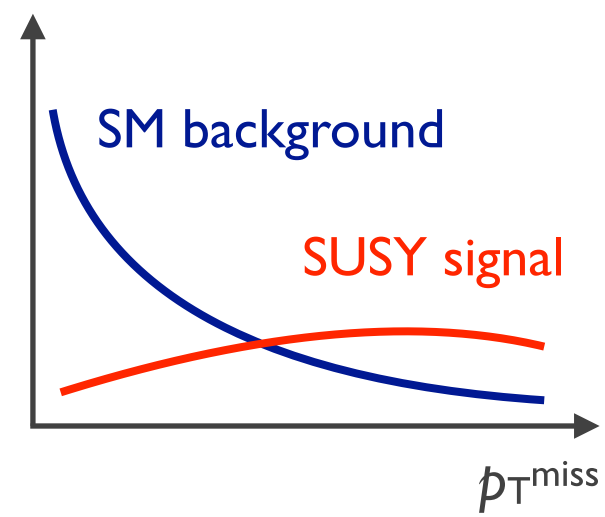
… at 13 TeV with the 2016 data set (35.9/fb):

| Colored SUSY | | |
|---|---|---|
| SUS-16-032 | third-generation squark production and FCNC in the cc or bb + $p_T^{miss}$ final states | PLB 778(2018)263 |
| SUS-16-036 | exploring the jets + $p_T^{miss}$ final state with the $M_{T2}$ variable | EPJC 77(2017)710 |
| SUS-16-049 | dedicated top squark search in all-hadronic signatures | JHEP 10(2017)005 |
| SUS-16-052 | soft single lepton search for compressed top squark spectra | CDS:2273394 |
| SUS-17-005 | soft single lepton search for compressed top squark spectra (MVA update) | CDS:2308382 |
| SUS-17-010 | two opposite-sign lepton search for top squark models | CDS:2309556 |
| **Electroweak SUSY** | | |
| SUS-16-039 | probing a multitude of final states with two or more leptons | JHEP 03(2018)166 |
| SUS-16-045 | exploring the WH + $p_T^{miss}$ signature with $H \rightarrow \gamma\gamma$ decays using the Razor variables | PLB 779(2018)166 |
| SUS-16-048 | search for light and compressed higgsinos in events with two soft opposite-sign leptons | Submitted to PLB |
| SUS-17-004 | search for SUSY in WZ + $p_T^{miss}$ events in the trilepton final state | JHEP 03(2018)160 |

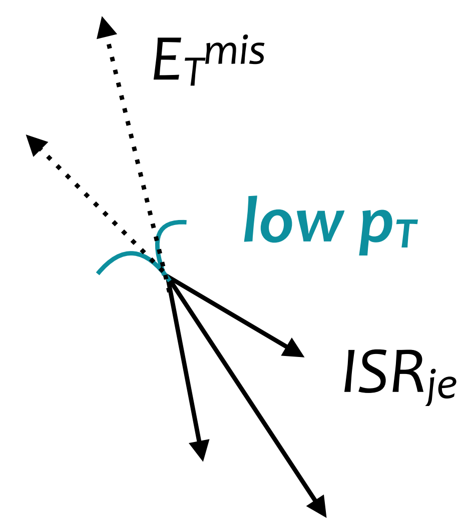
- going to discuss the most recent and most challenging searches highlighted in blue

# Search Strategy in the Compressed

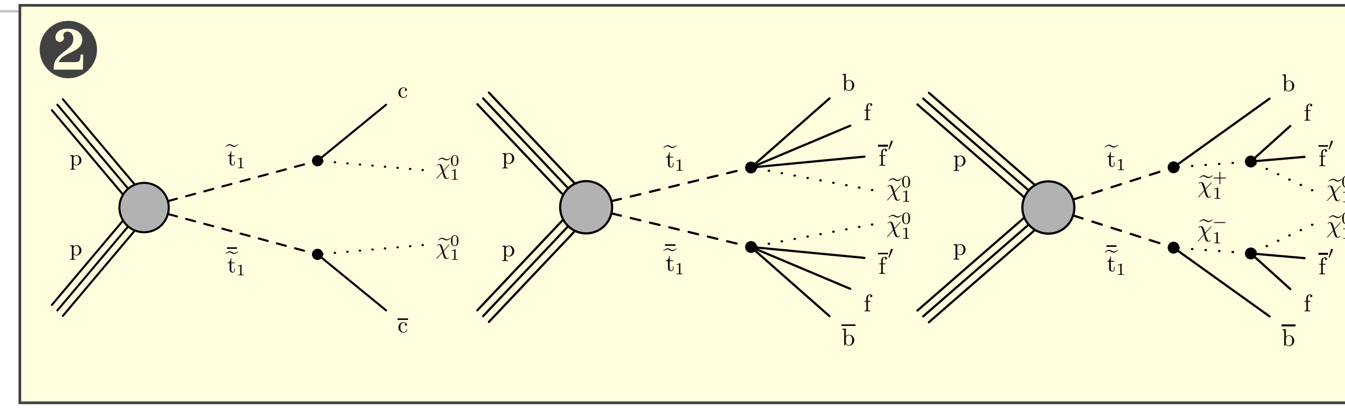
- conventional searches designed for large mass splittings
  - thus, large amounts of free energy in the particle decay
  - yields hard final state objects, but also gives Lorentz boost to the LSPs
  - also leads to large values of $p_T^{miss}$ in signal — shape difference between background and signal
  - can trigger on hard visible objects (electrons, muons, jets) and/or $p_T^{miss}$

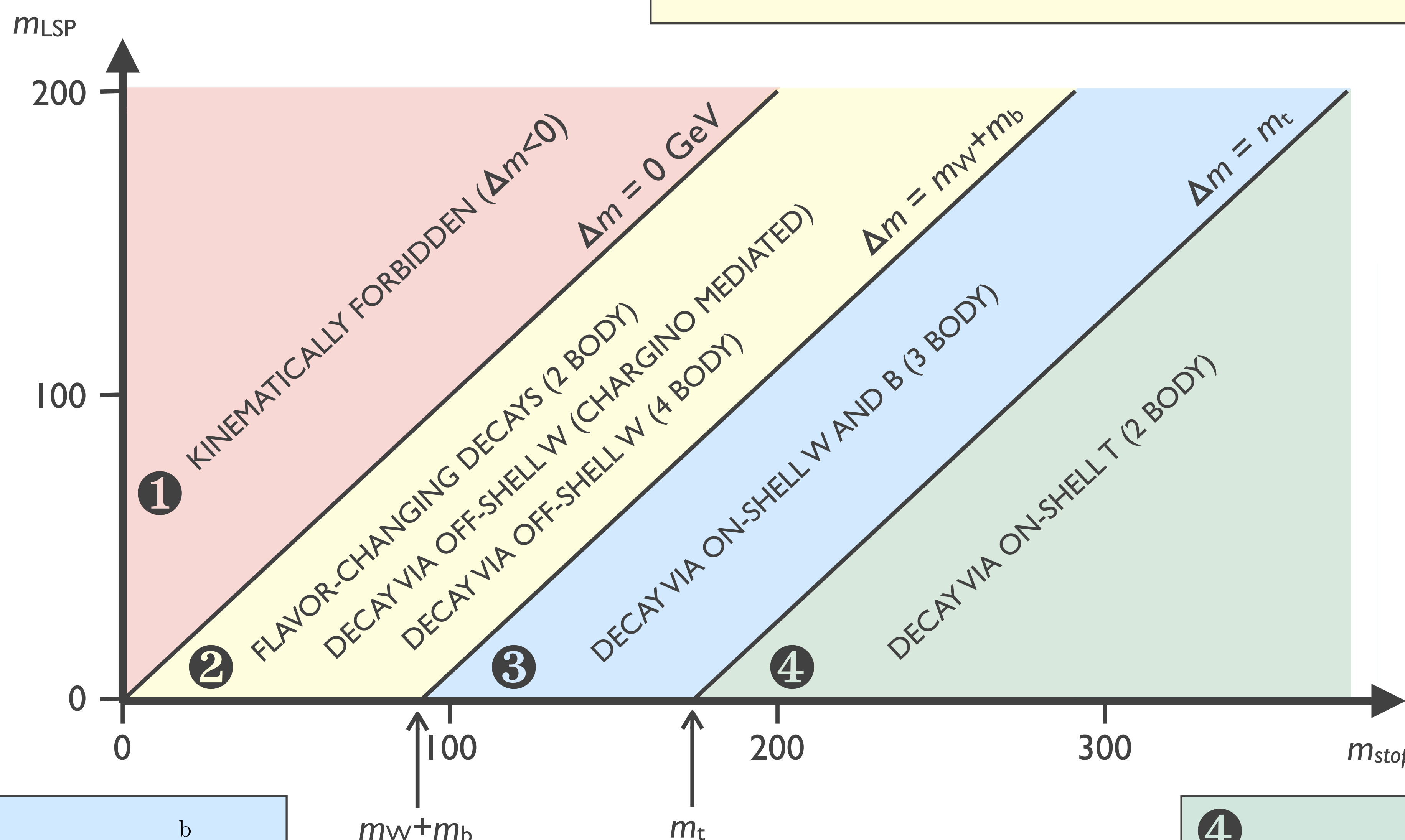


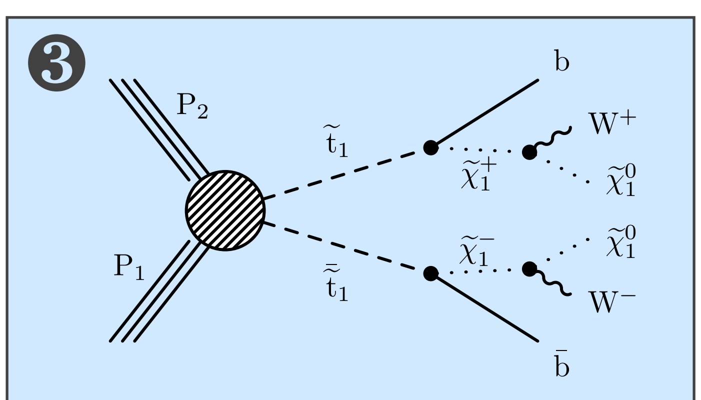

- not so easy in the compressed region
  - LSPs not boosted due to low $\Delta m$ — low values of $p_T^{miss}$ — no shape difference to SM bkg
  - but: shape difference restored in initial state radiation (ISR) boosts the SUSY particle system
  - cannot trigger on soft visible objects, but on $p_T^{miss}$
  - look for shape difference in other variables for events with high $p_T^{miss}$

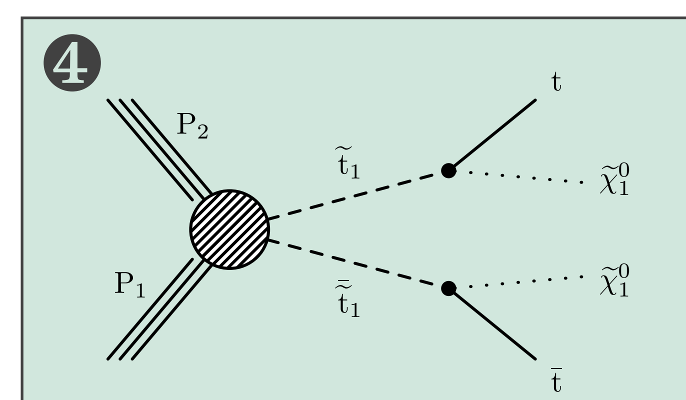


# Top Squark Pairs

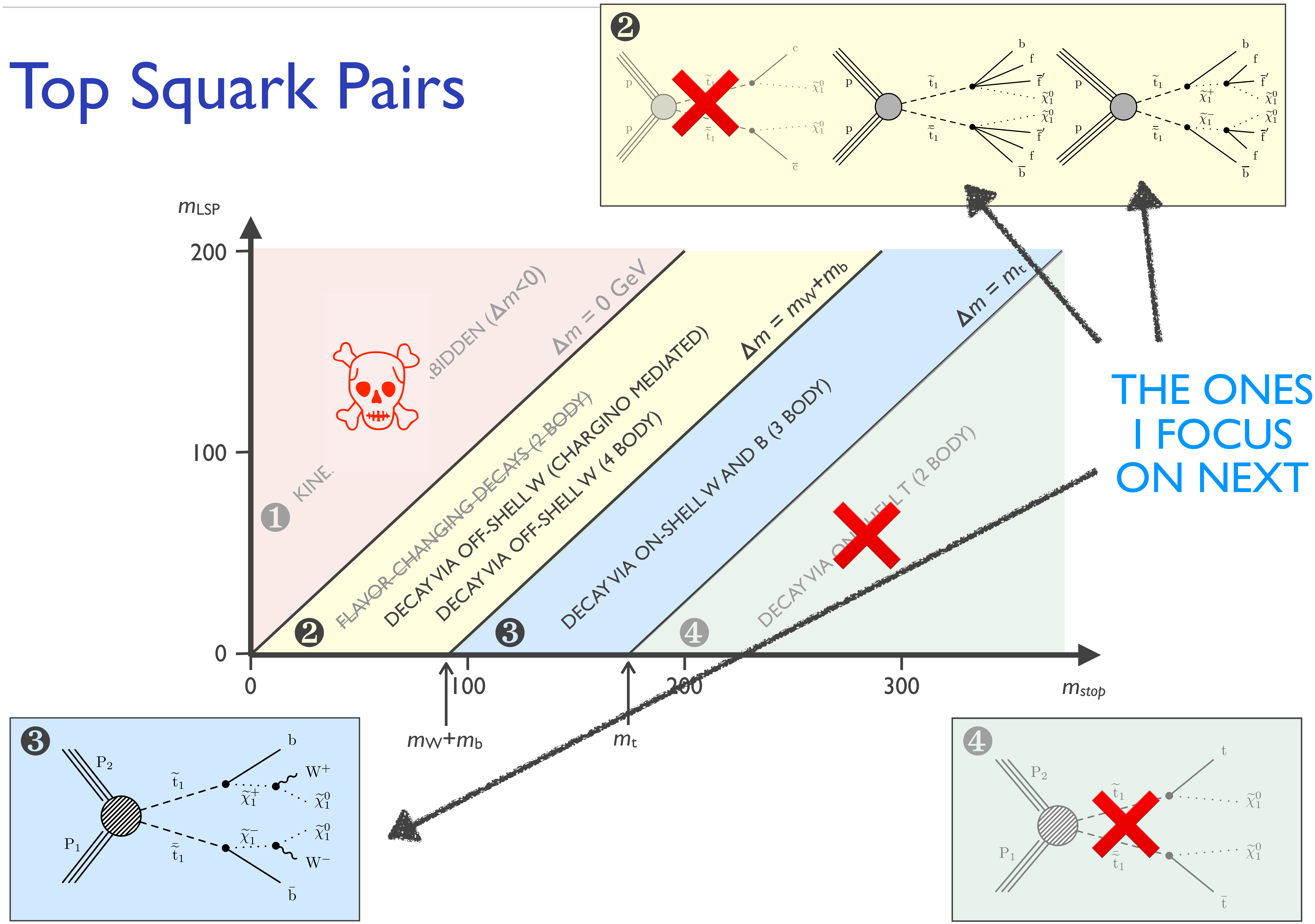


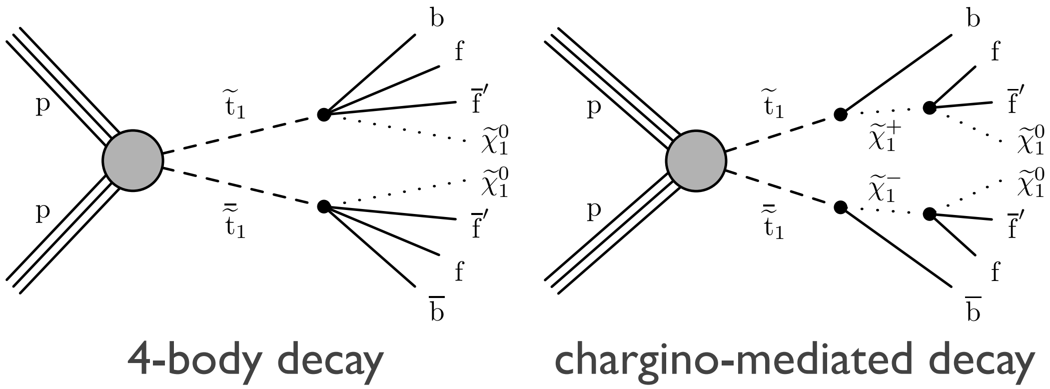



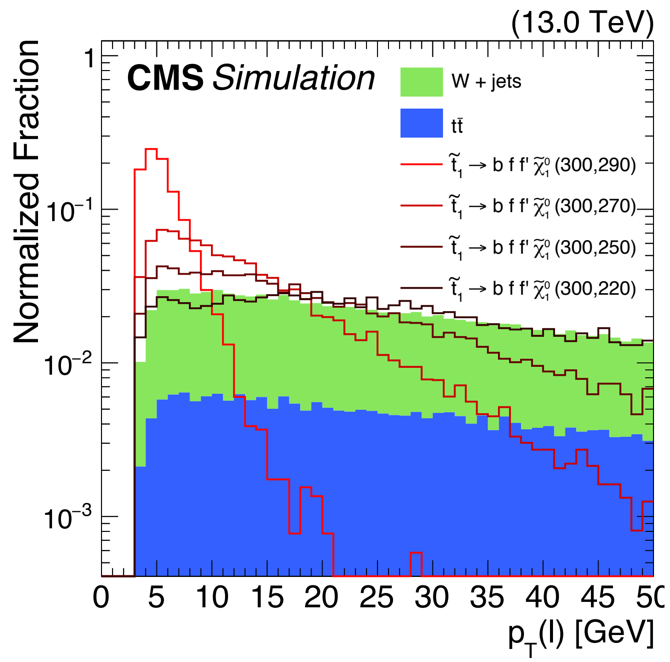
# Top Squark Pairs

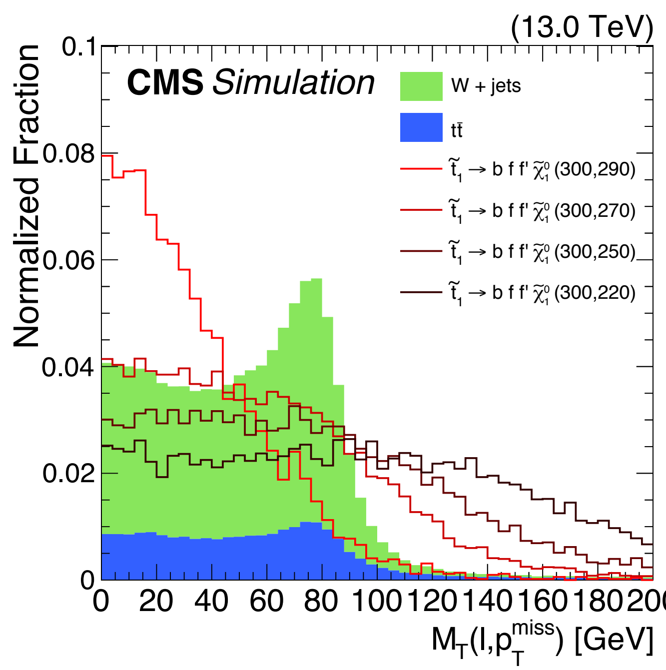


# Single Soft Lepton Search




- dedicated search for top squark decay via W and b
  - exactly one electron ($p_T$ > 5 GeV) or muon ($p_T$ > 3.5 GeV)
  - soft lepton ($p_T$ < 30 GeV) and one ISR jet with $p_T$ > 100 GeV
- expect $p_T^{miss}$ > 200 GeV and $H_T$ > 300 GeV
- $\Delta\phi$(jet1, jet2) < 2.5 rad — suppresses dijet and multijet background
  - remaining background is dominated by W+Jets and ttbar
  - estimate from simulation, extract normalization from control regions (lepton-$p_T$ > 30 GeV)
- two set of regions: for very low $\Delta m$ and higher $\Delta m$
  - lepton-$p_T$ spectrum depends on $\Delta m$ — use optimized lepton-$p_T$ bins (3.5-5-12-20-30)
  - expect shape difference between signal and background in $M_T(\ell, p_T^{miss})$ and $p_T^{miss}$ (in the bulk of the distributions!)



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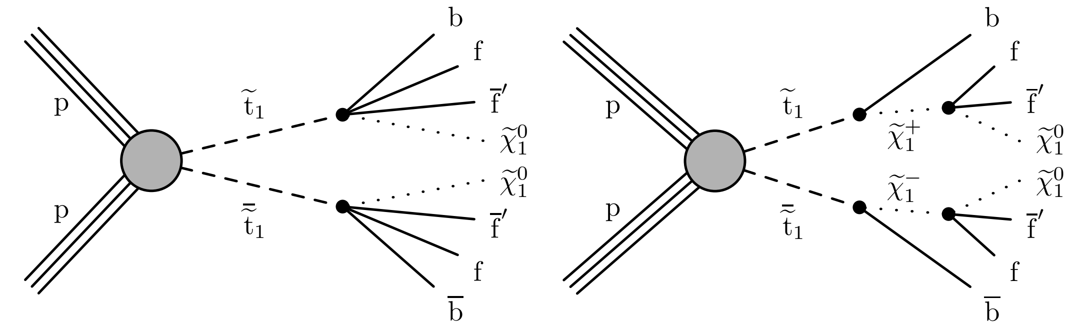
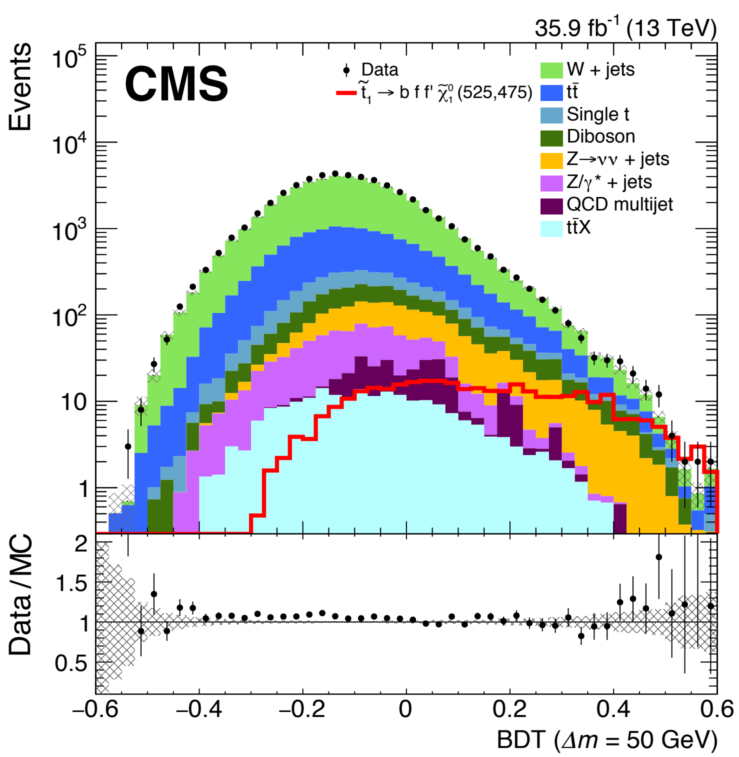
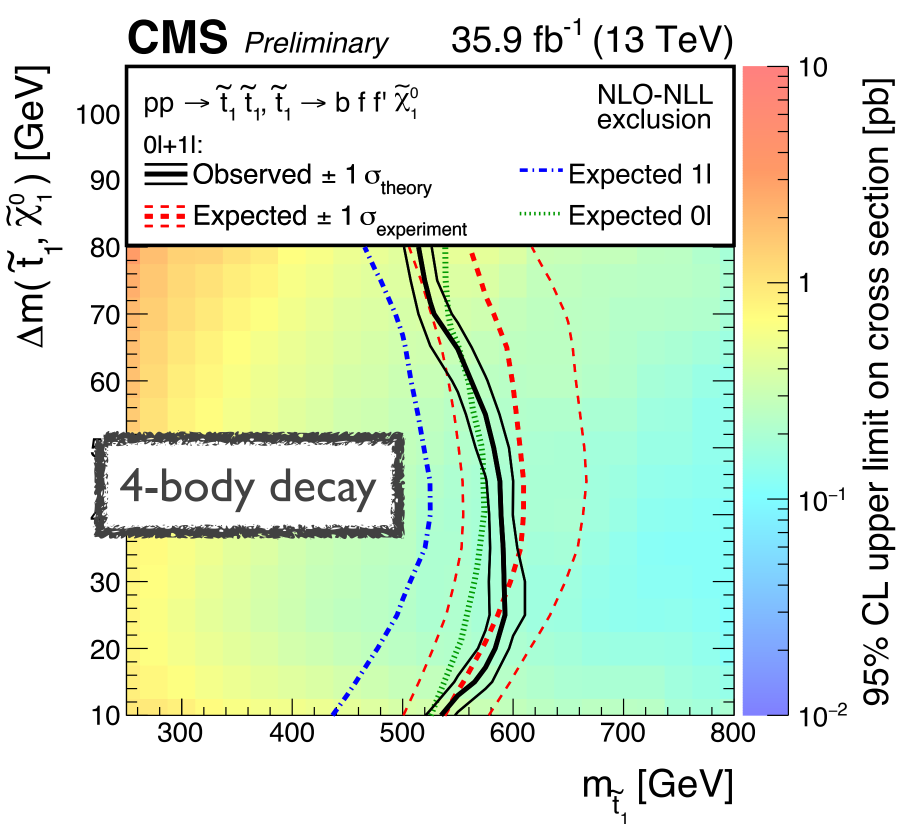
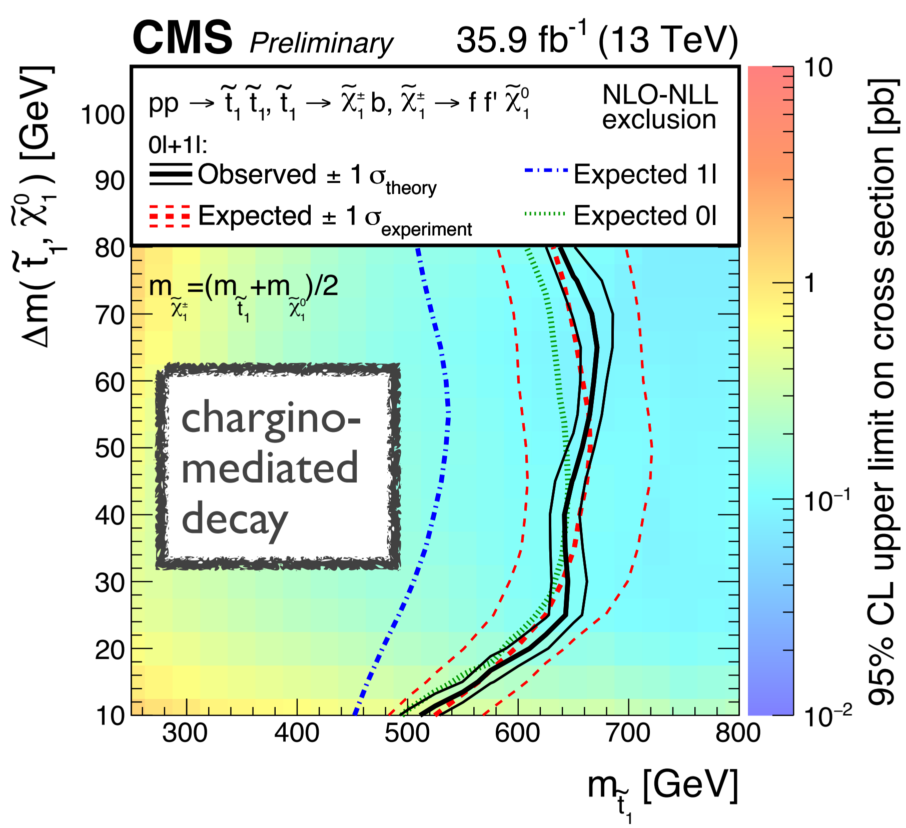



- alternative search region extraction
  - boosted decision tree (BDT) built on kinematic variables of the lepton and the jets in the event
  - separate training for different SUSY scenarios (= $\Delta m$); build 8 SR requiring a minimum BDT score
  - largest improvement for mass splittings 40–80 GeV
- combination with all-hadronic analysis (SUS-16-049)

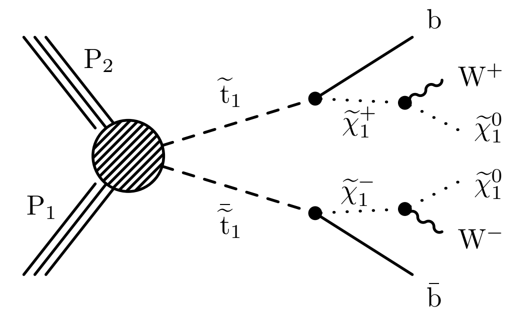



BDT score for $\Delta m$ = 50 GeV



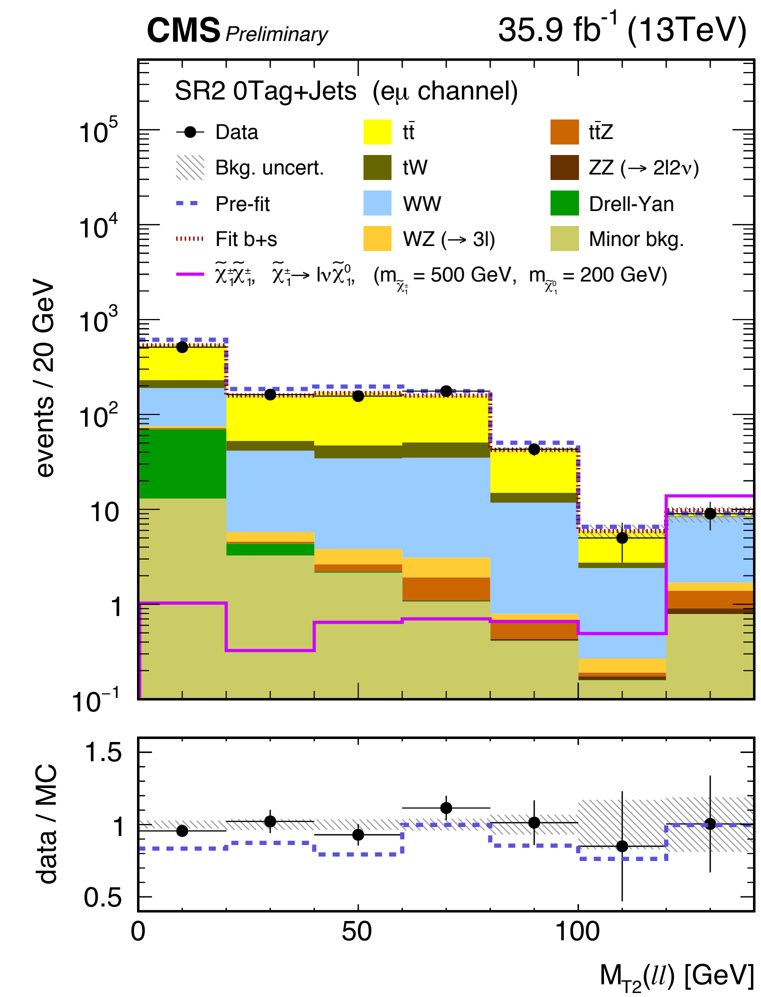
# Two OS Leptons

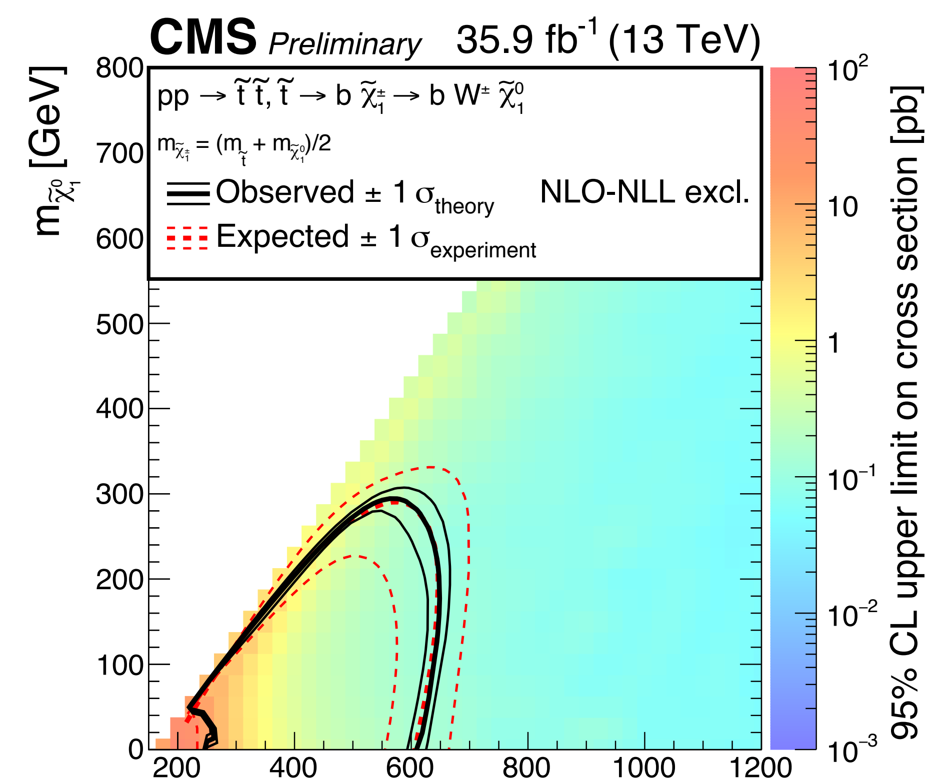



- require leptonic decays from the on-shell W bosons
  - can give two opposite-sign (OS) leptons
- optimized for moderate mass splittings $m_W < \Delta m < m_t$
  - leading (trailing) lepton has $p_T > 25$ (20) GeV
  - $m_{\ell\ell} > 20$ GeV to remove low-mass resonances
  - remove Z resonances by requiring same-flavor pairs $| m_{\ell\ell} - m_Z | > 15$ GeV
  - require $p_T^{miss} > 140$ GeV
- remaining backgrounds have W resonances but no LSPs
  - use $M_{T2}$ to discriminate between SM and SUSY

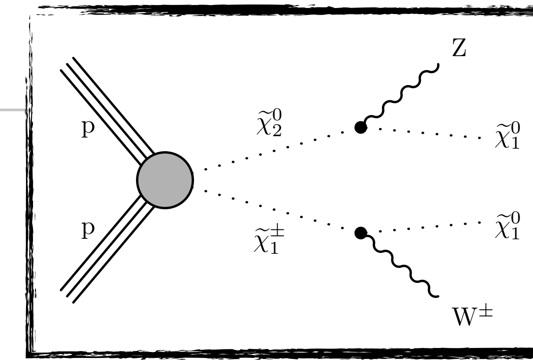
$$M_{T2}(\ell\ell) = \min_{\vec{p}_T^{\,miss1}+\vec{p}_T^{\,miss2}=\vec{p}_T^{\,miss}} \left( \max \left[ M_T(\vec{p}_T^{\,lep1}, \vec{p}_T^{\,miss1}), M_T(\vec{p}_T^{\,lep2}, \vec{p}_T^{\,miss2}) \right] \right)$$

  - discrimination power enhanced by ISR boost of LSPs

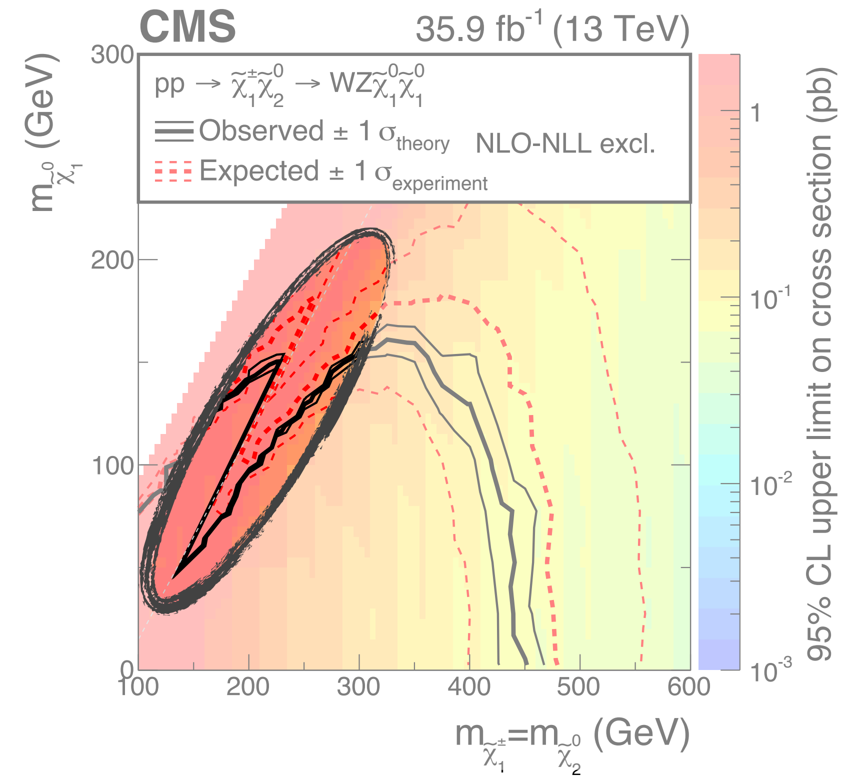


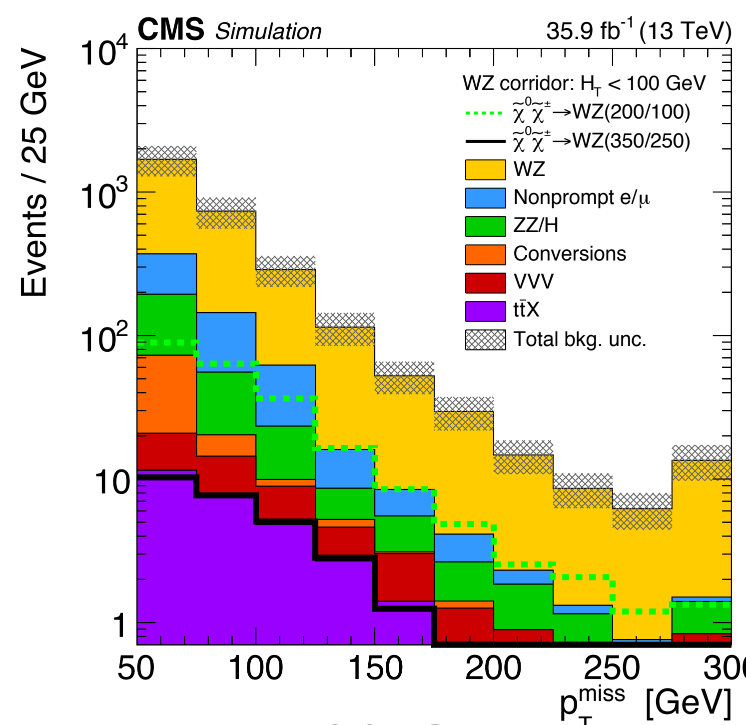



# Electroweak SUSY:WZ + $p_T^{miss}$

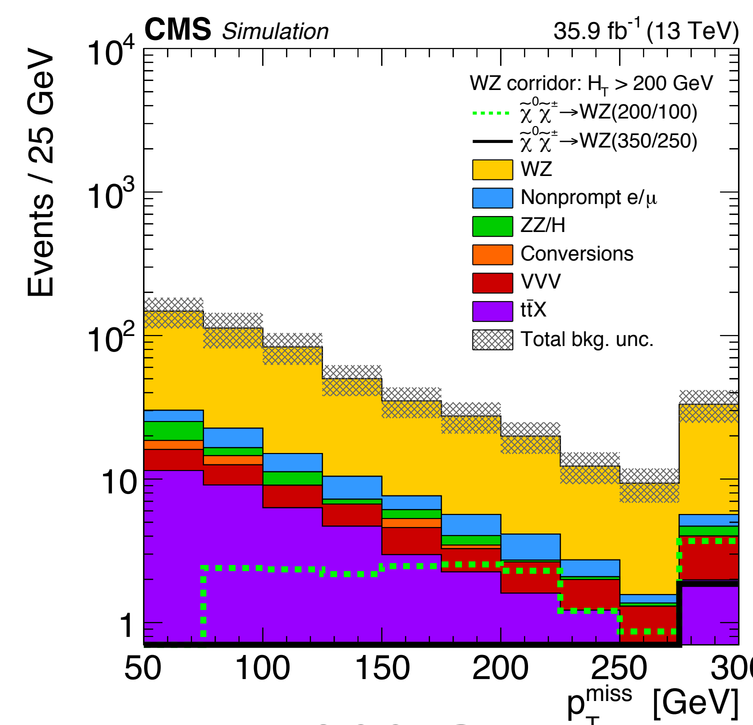



- inclusive multilepton search probes chargino-neutralino production with moderate mass splittings
  - covering broad region of parameter space (small to large $\Delta m$)
- significant loss in sensitivity at $\Delta m \sim m_Z$ („WZ corridor")
  - signal has $m_Z$ available to produce W or Z boson
  - hence, signal is very similar to SM WZ process
- but signal is a bit different
  - due to mass constraint from chargino / neutralino signal rarely has $m_{\ell\ell}$ > 105 GeV
  - in case of an ISR boost, $p_T^{miss}$ and $M_T(\ell_3, p_T^{miss})$ larger for signal than for bkg due to LSPs



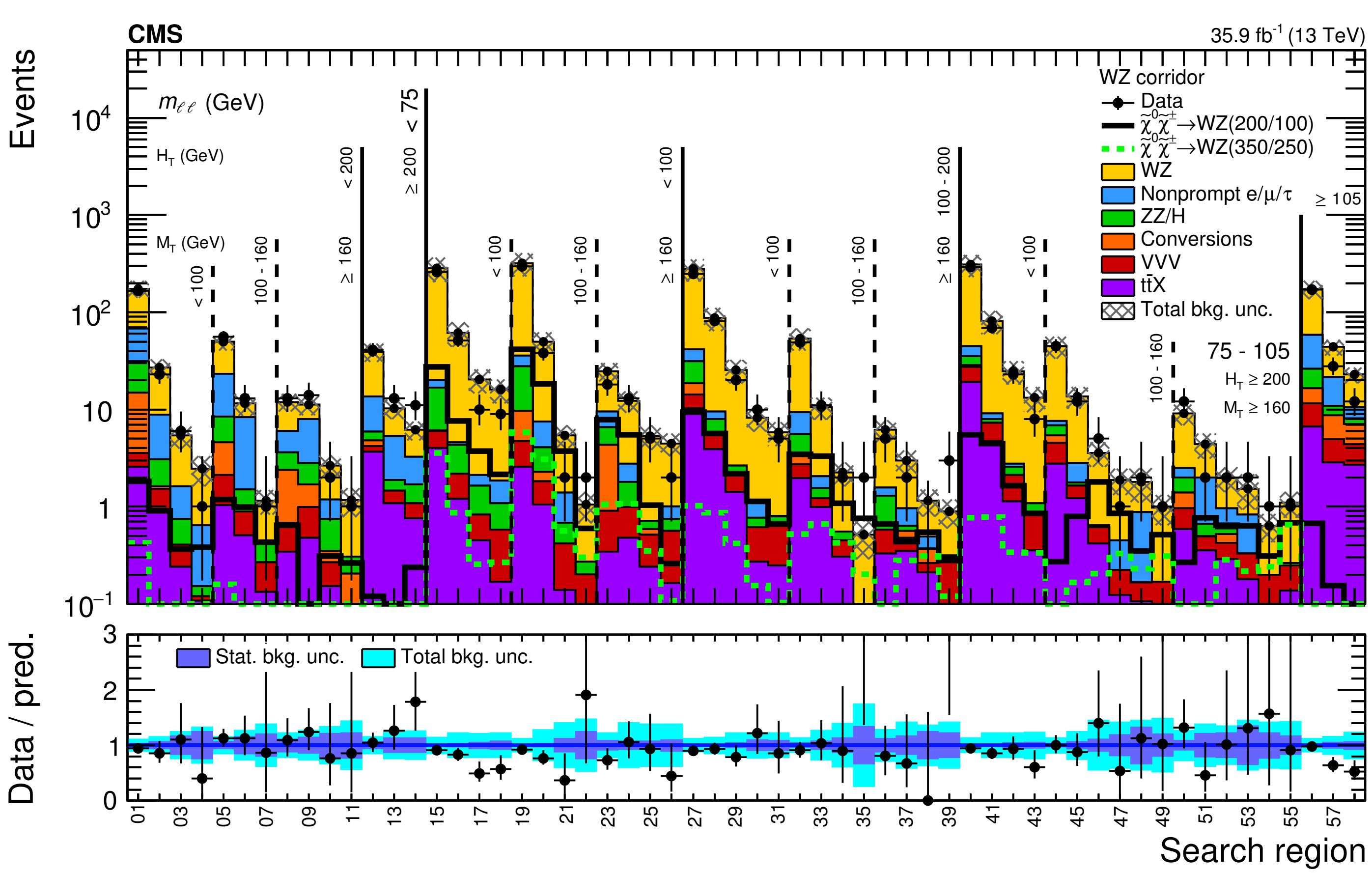

$H_T$ < 100 GeV

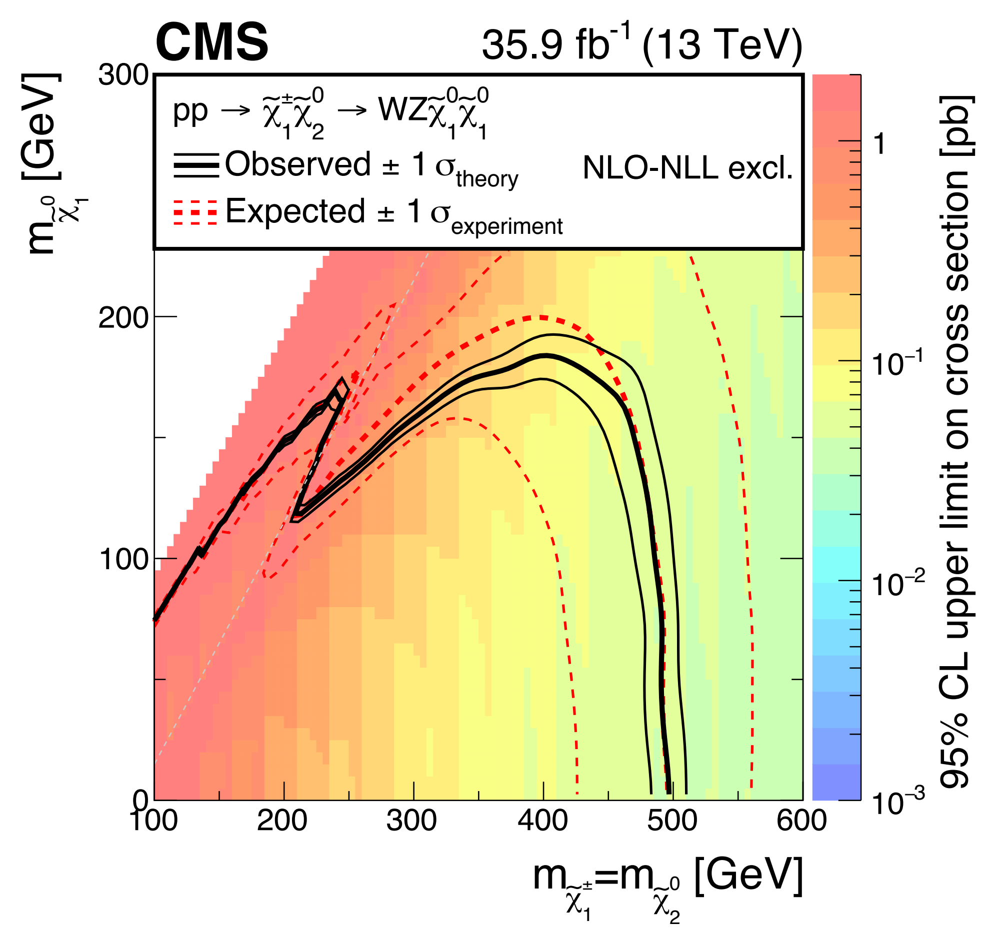



$H_T$ > 200 GeV

# Electroweak SUSY: WZ + $p_T^{miss}$

- finer granularity binning in 75 < $m_{\ell\ell}$ < 105 GeV region via additional $H_T$ bins
  - significant limit improvement of about 60 GeV (or 30%) along the WZ corridor
- quite impressive (combined) CMS exclusion in compressed scenarios for EWK model
  - for more details see Mia's talk (plenary) and Carlos' talk (parallel)



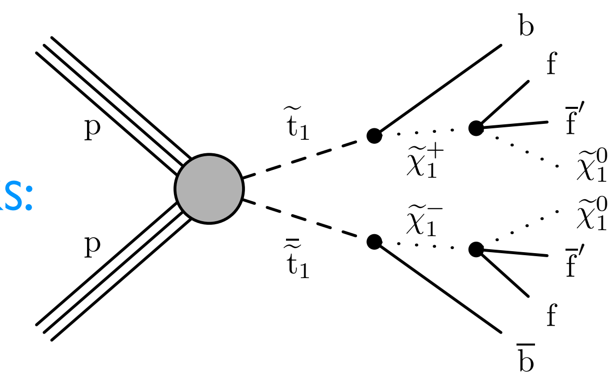




SUS-17-004

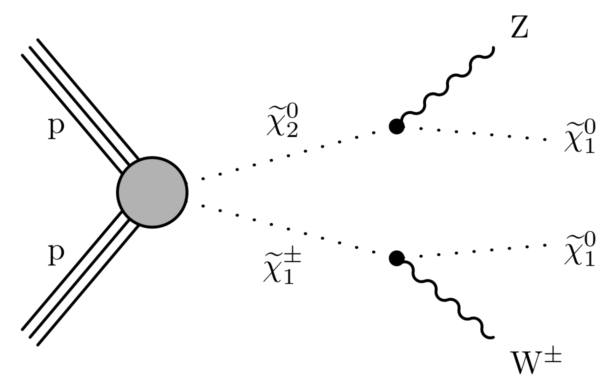
# Soft OS Leptons Pairs

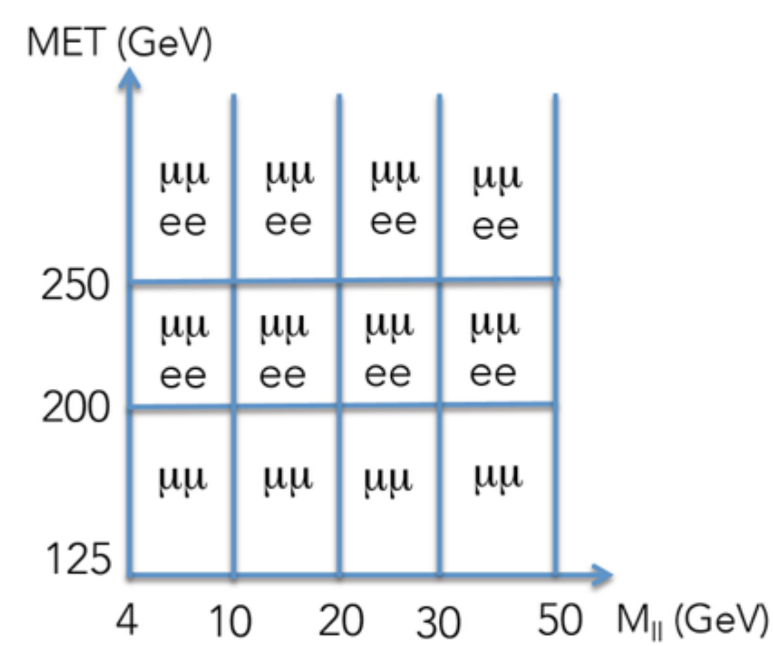
- two soft leptons from off-shell bosons
  - EWK: opposite-sign same-flavor pair from Z (+ hadronic W)
  - Top squarks: opposite-sign any-flavor pair from two W's
- μ (e) $p_T$ between 3.5 (5) and 30 GeV
  - dedicated ID and trigger strategy
  - $p_T^{miss} \geq$ 125 GeV possible in μμ final state thanks to specially developed soft μμ + $p_T^{miss}$ trigger
- strong suppression against important backgrounds
  - boosted Drell-Yan→ττ — reconstruct $m_{\tau\tau}$ to remove the bkg
  - dilepton ttbar — reject events with b jets
  - diboson production — suppress events with $M_T(\ell, p_T^{miss})$ > 70 GeV
- challenge: reject misidentified leptons (e.g. from jets)

TOP SQUARKS:



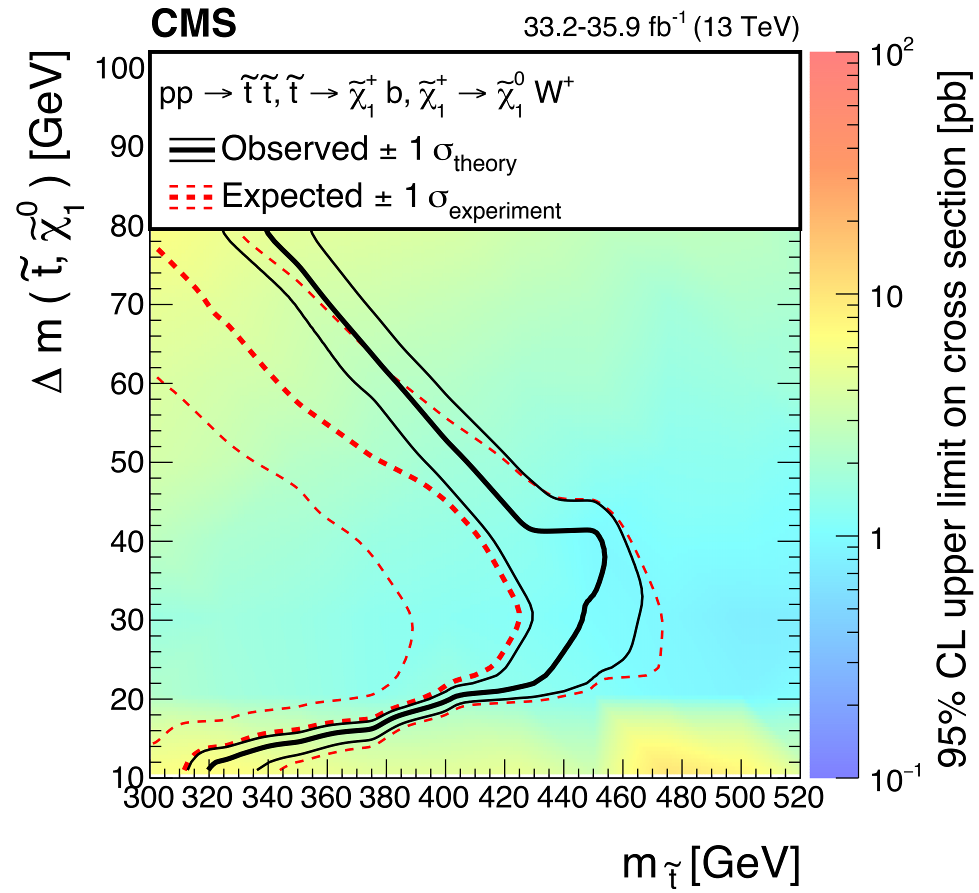

EWK:

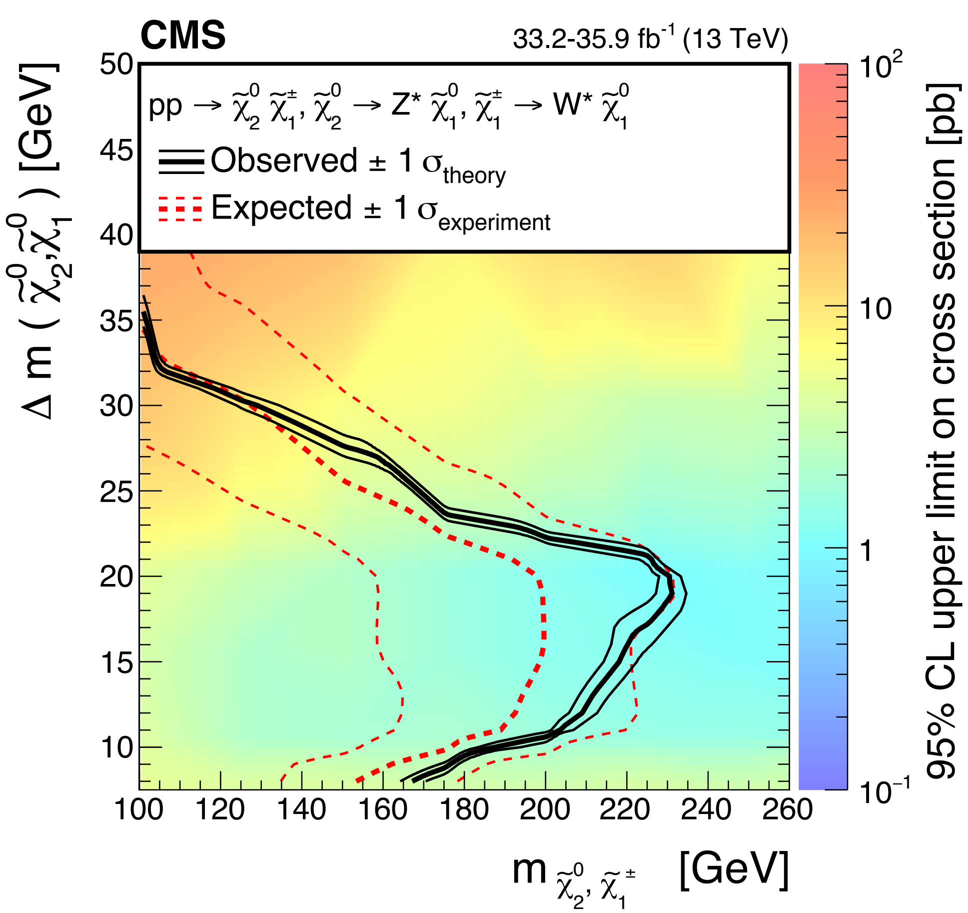


# Soft OS Leptons Pairs

- top squarks case
  - categorize events in $p_T^{miss}$ and leading lepton $p_T$
- exclude top squarks up to 450 GeV at Δm ~ 30 GeV

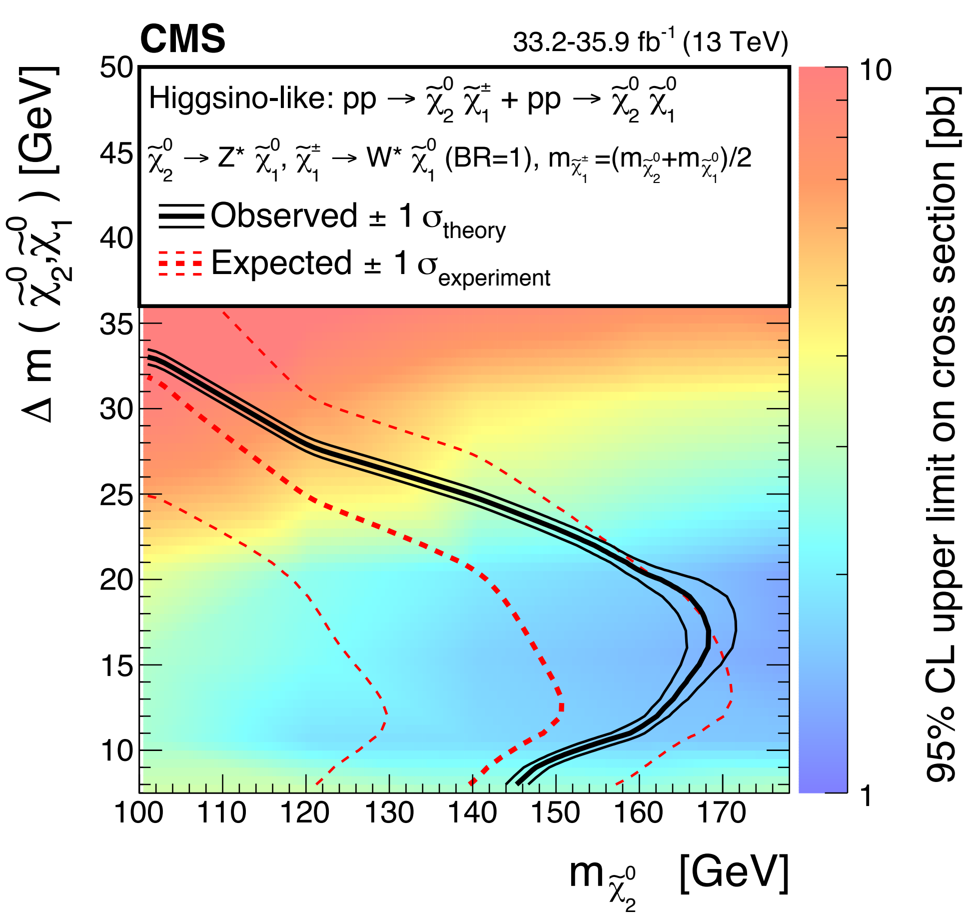


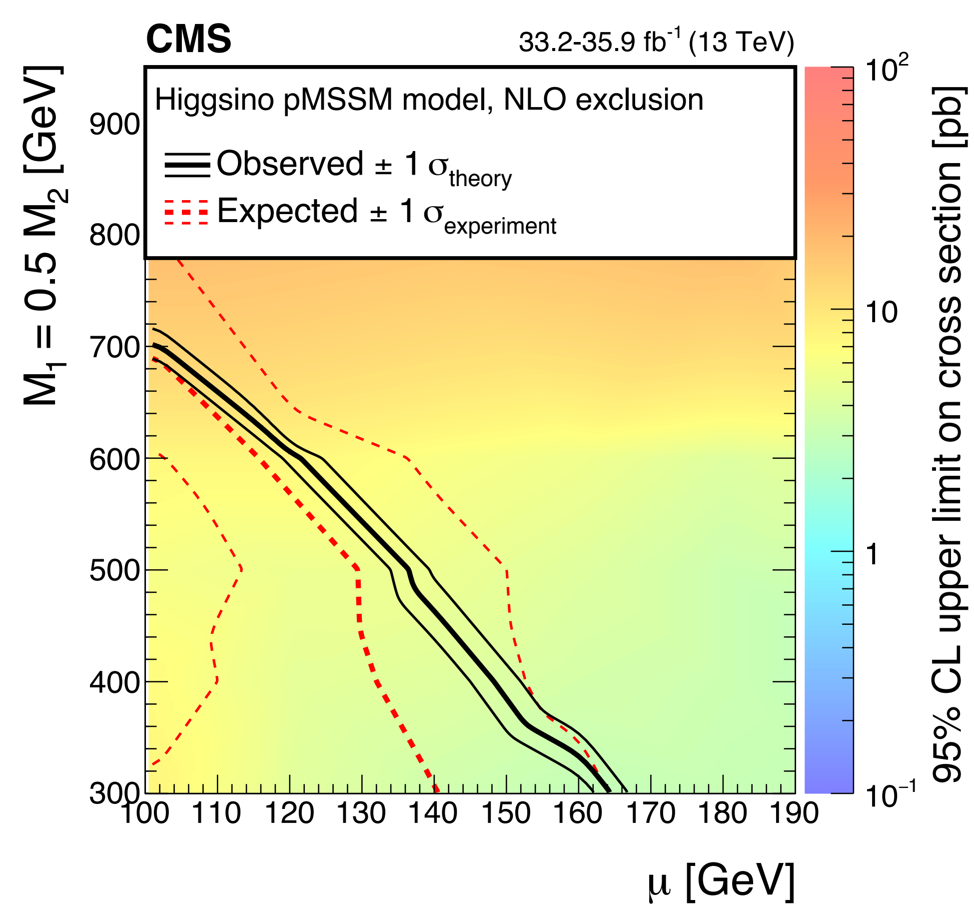




- electroweak case (WZ-like model)
  - categorize events in $p_T^{miss}$ and invariant mass $m_{\ell\ell}$
- exclude wino-like charginos / neutralinos up to 230 GeV at Δm ~ 20 GeV

# Soft OS Leptons Pairs

- when it comes to natural SUSY, particular interest lies upon higgsinos!
  - i.e. charginos and neutralinos with dominant higgsino component
- re-interpretation of the WZ-like model with dominant higgsino component (left)
  - improvement of the LEP limit (~ 100 GeV) for the first time!
- also interpretation in pMSSM framework as function of $M_1$=(1/2)$M_2$ and μ (right)

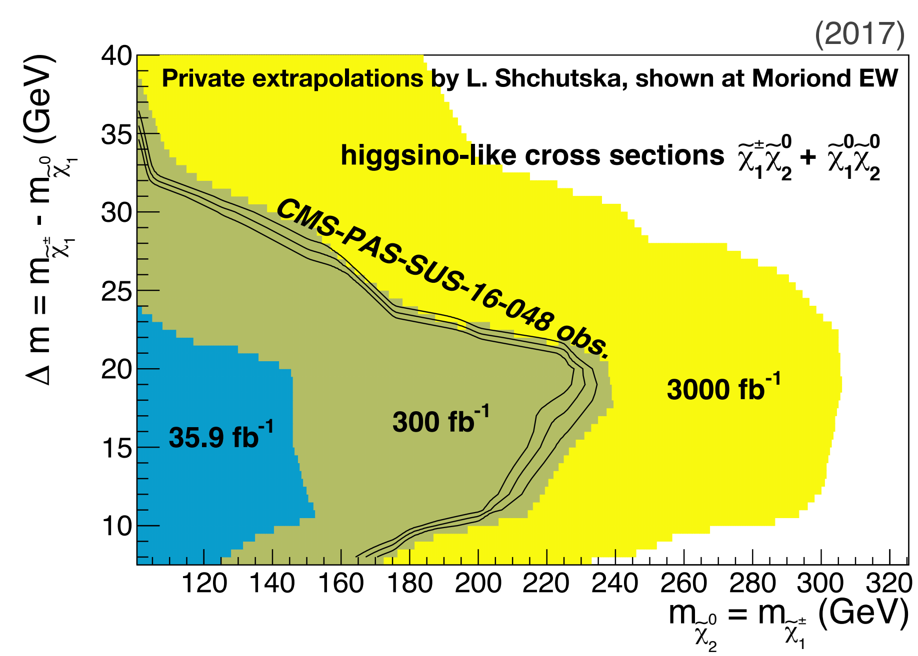



**MASS PARAMETERS:**
μ = higgsinos
$M_1$ = bino
$M_2$ = wino
$M_3$ = gluino (decoupled)

# Conclusion

- excellent performance of LHC in 2016 provided CMS with enough data to search for new physics in yet unprobed regions of phase space
- extensive search program performed at CMS covering a huge variety of topologies, both for colored SUSY and EWK SUSY
- development and optimization of key analysis tools allows probing of very compressed regions
  - tackle shape different between SUSY and SM in regimes with ISR
  - novel techniques improve sensitivity to difficult regions of phase space
  - first time sensitivity to higgsino at the LHC, improving the LEP limit!
- larger data sets and improved techniques will allow to probe more unconventional scenarios
  - long-lived higgsinos?
  - disappearing tracks?
- if you want to search for higgsinos (and thus natural SUSY), this is the time!



# The End

# References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[SUS-16-036] CMS Collaboration, *Search for new phenomena with the* $M_{T2}$ variable in the all-hadronic final state produced in proton–proton collisions at $\sqrt{s}$ = *13 TeV,* EPJC 77 (2017) 710, doi:10.1140/epjc/s10052-017-5267-x.

[SUS-16-039] CMS Collaboration, *Search for electroweak production of charginos and neutralinos in multilepton final states in proton-proton collisions at* $\sqrt{s}$ = *13 TeV,* JHEP 03 (2018) 166, doi:10.1007/JHEP03(2018)166.

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[SUS-16-048] CMS Collaboration, *Search for new physics in events with two soft oppositely charged leptons and missing transverse momentum in proton-proton collisions at* $\sqrt{s}$ = *13 TeV*, submitted to Phys. Lett. B, arXiv:1801.01846.

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[SUS-16-049] CMS Collaboration, *Search for direct production of supersymmetric partners of the top quark in the all-jets final state in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, JHEP 10 (2017) 005, doi:10.1007/JHEP10(2017)005.

[SUS-16-052] CMS Collaboration, *Search for supersymmetry in events with at least one soft lepton, low jet multiplicity, and missing transverse momentum in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, CMS-PAS-SUS-16-052, CDS:2273394

[SUS-17-004] CMS Collaboration, *Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, JHEP 03 (2018) 160, doi:10.1007/JHEP03(2018)160.

[SUS-17-005] CMS Collaboration, *Search for top squarks decaying via four-body or chargino-mediated modes in the single-lepton final state at* $\sqrt{s}$ *= 13 TeV*, CMS-PAS-SUS-17-005, CDS:2308382.

[SUS-17-010] CMS Collaboration, *Search for chargino pair production and top squark pair production in final states with two leptons in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*, CMS-PAS-SUS-17-010, CDS:2309556.

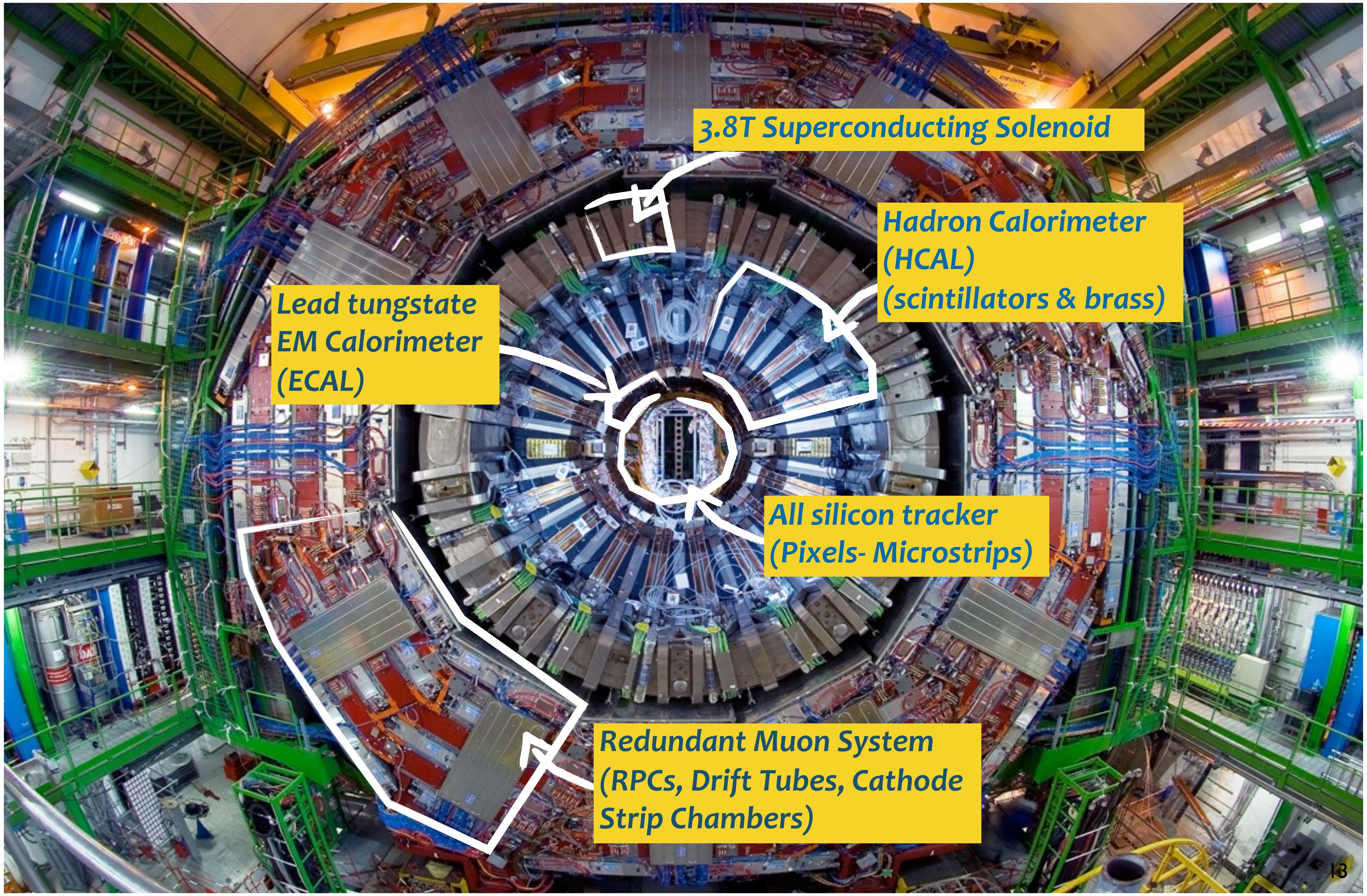
# References

C. Balázs et al., *Dark matter, light top squarks, and electroweak baryogenesis,* Phys. Rev. D 70 (2004) 015007, doi:10.1103/PhysRevD.70.015007.

H. Baer, A. Mustafayev, and X. Tata, *Monojet plus soft dilepton signal from light higgsino pair production at LHC14*, Phys. Rev. D 90 (2014) 115007, doi:10.1103/PhysRevD.90.115007.

# Appendix

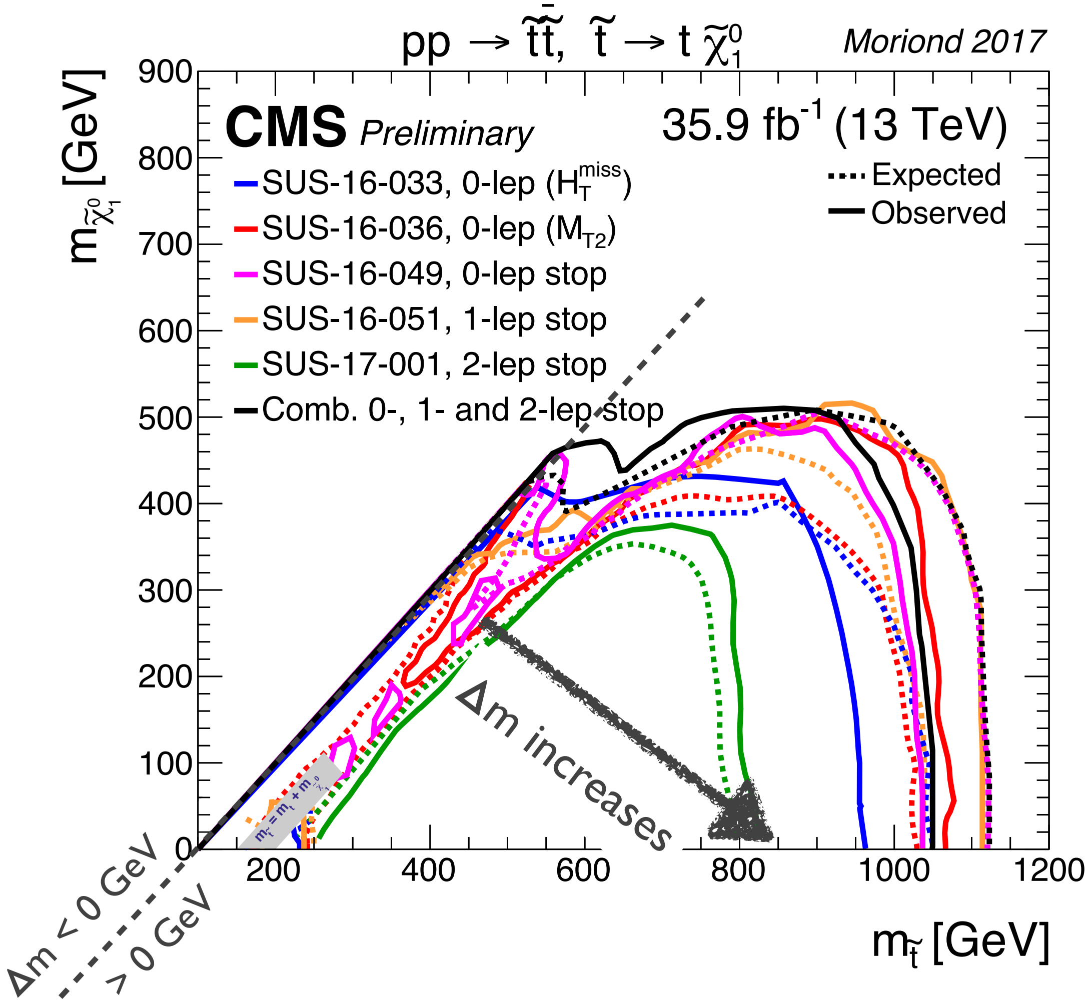
# The CMS Detector



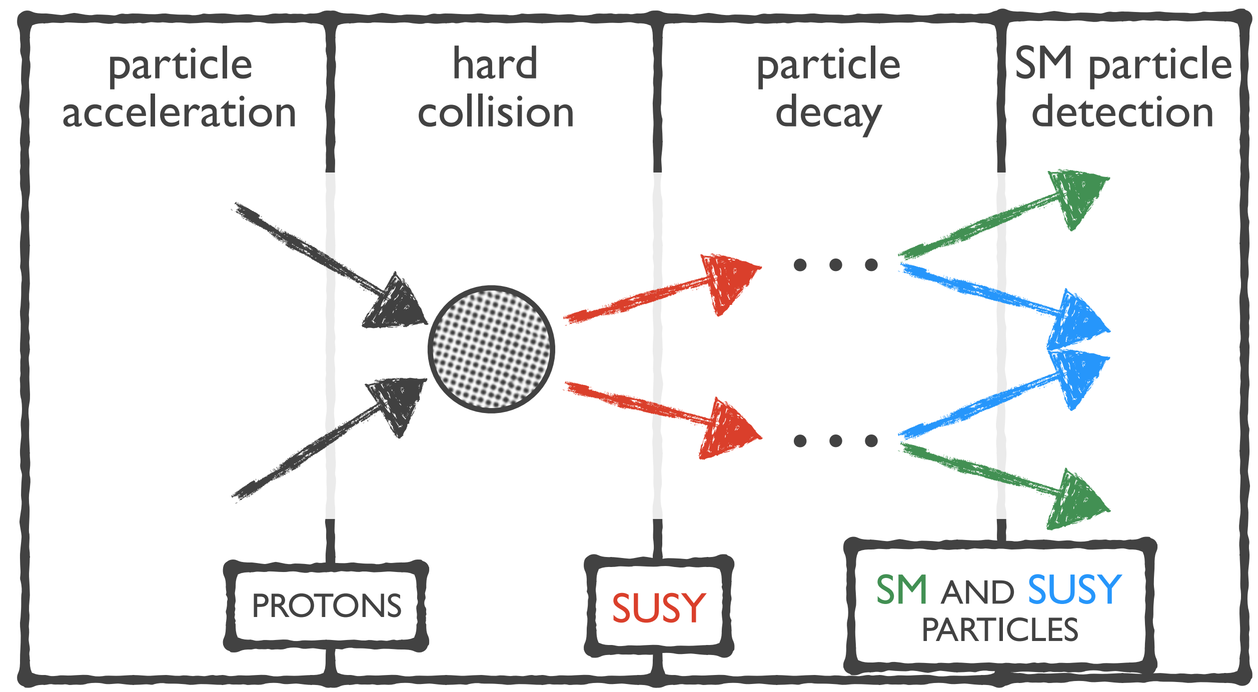

- excellent muon system, tracking and EM energy resolution give good particle identification
  - ideally suited for search for new physics in final states with little hadronic activity (as for EWK SUSY)

# What is "Compressed SUSY" ?

- R-parity:
  - avoids L- or B-number violation
  - common for „mainstream" SUSY searches
- consequence: compressed spectra




**TYPICAL LHC PROCESS:**




- mass splitting:

  + MASS(„INCOMING" SUSY PARTICLE)
  - MASS(„OUTGING" SUSY PARTICLE)

  = **MASS SPLITTING** =: $\Delta m$

  - small $\Delta m$ ↔ „compressed" parameter space
- translates to the „being close to the diagonal" in typical exclusion limit plots