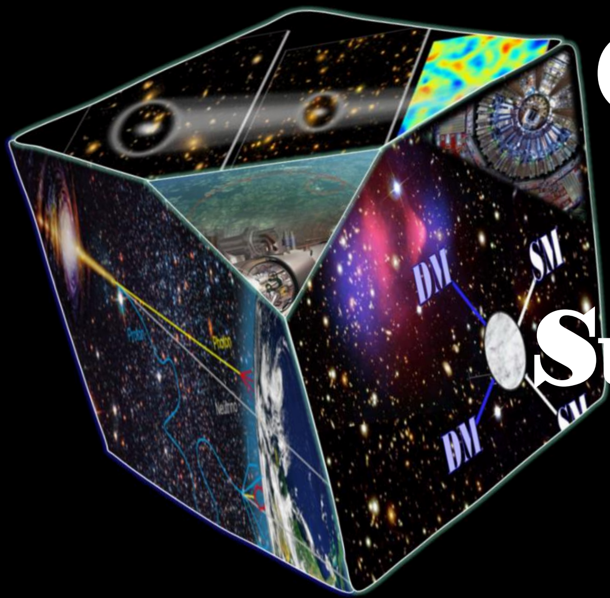


CMS Search for Supersymmetry at the LHC

[Credits]
- Images of Baryon Acoustic Bscillations with Cosmic Microwave Background by E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian (Lawrence Berkeley National Laboratory)
- Image of Neutrino Astrophysics, taken from https://astro.desy.de/
- Image of the LHC by CERN Photo
- Image of Bullet Cluster by NASA/ Chandra X-ray Center

Teruki Kamon
on behalf of the CMS Collaboration
Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University

International Symposium on Higgs Boson and Beyond Standard Model Physics

Shandong University (山东大学威海分校), Weihai, August 15-19, 2016

Prologue

CMS: >10 fb^{-1}, ~80 Papers, 0 Discovery

CERN Press Lease PR05.16

05.08.2016

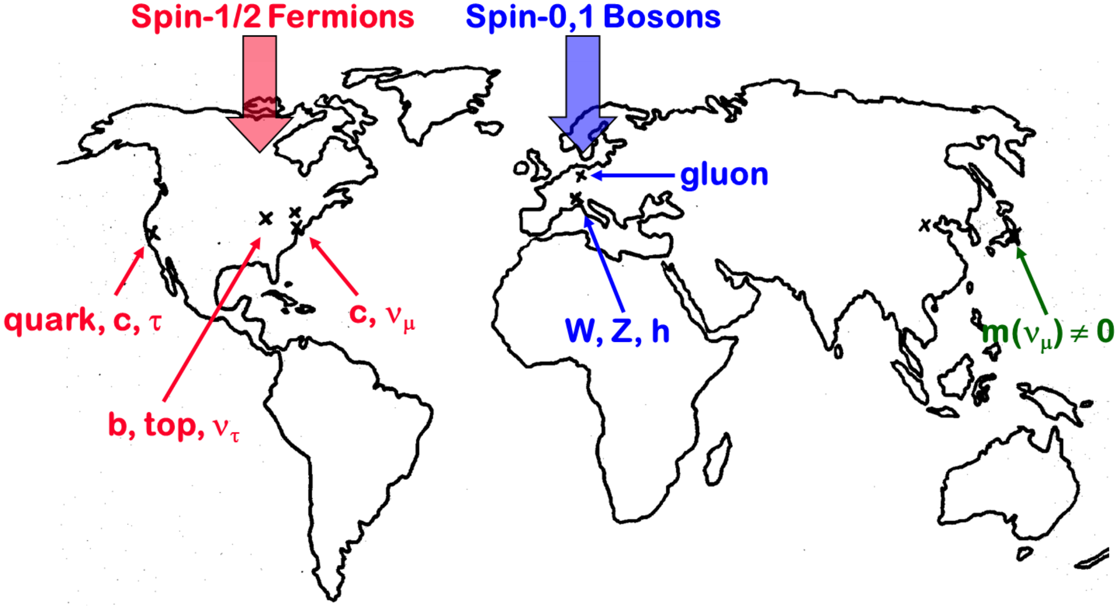
CHICAGO SEES FLOODS OF LHC DATA AND NEW RESULTS AT THE ICHEP 2016 CONFERENCE

"ATLAS and CMS have also looked for any signs of the direct production of new particles predicted by Supersymmetry and other exotic theories of physics beyond the Standard Model, but no compelling evidence of new physics has appeared yet. In particular, the intriguing hint of a possible resonance at 750 GeV decaying into photon pairs, which caused considerable interest from the 2015 data, has not reappeared in the much larger 2016 data set and thus appears to be a statistical fluctuation."

"*We're just at the beginning of the journey*," said CERN Director-General, Fabiola Gianotti. "*The superb performance of the LHC accelerator, experiments and computing bodes extremely well for a detailed and comprehensive exploration of the several TeV energy scale, and significant progress in our understanding of fundamental physics.*"

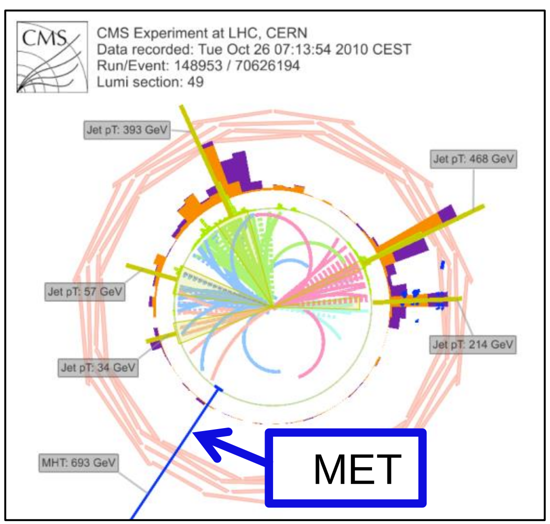
OUTLINE[3]

World “Discovery” Map



Where will next new physics be discovered? How about the dark matter (DM) particles?

Examine pp collision events being consistent with models (or scenarios) that describe DM-SM particle interaction: (e.g..) Supersymmetry (SUSY)



- ❖ DM = Weekly interacting massive particle
- ❖ MET = momentum imbalance or missing transverse energy - Hallmark signature for DM

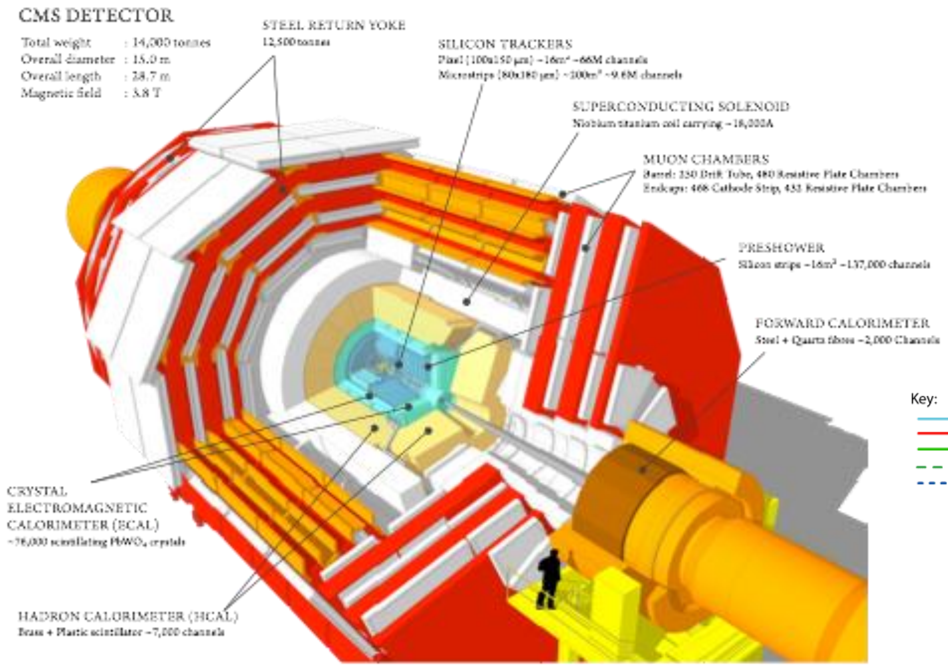
1) **SUSY colored sectors**
2) **SUSY electroweak sectors**
3) **Summary & Remarks**

Compact Muon Solenoid (CMS) Experiment

links

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

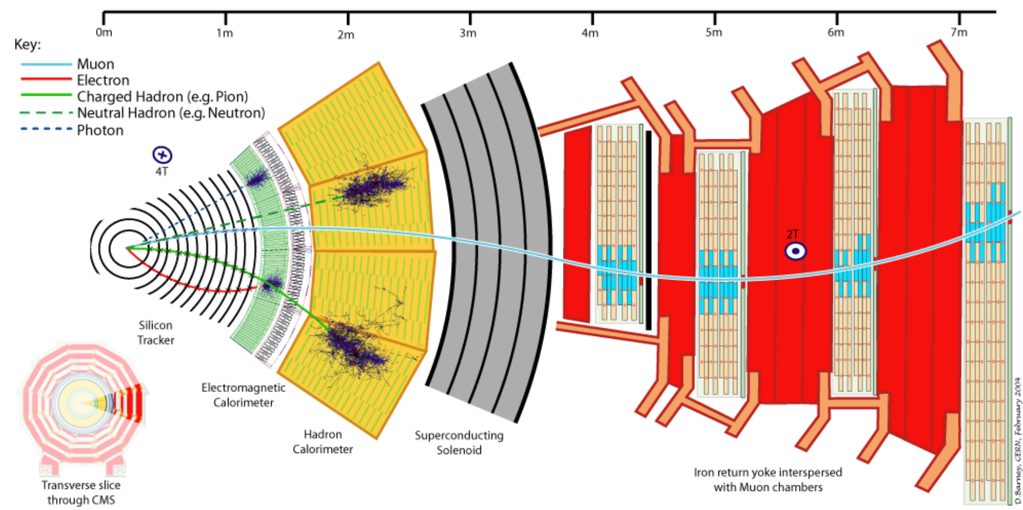
Schematic view of the CMS Detector with its main components.



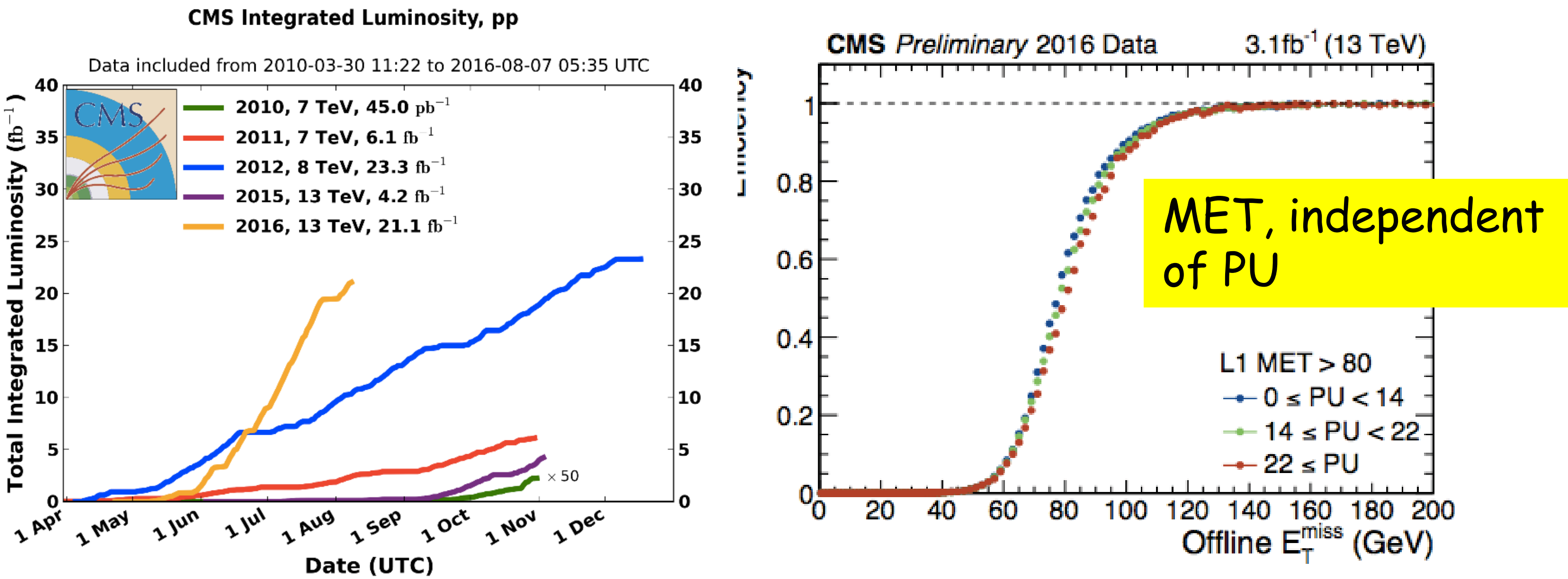
Triggers

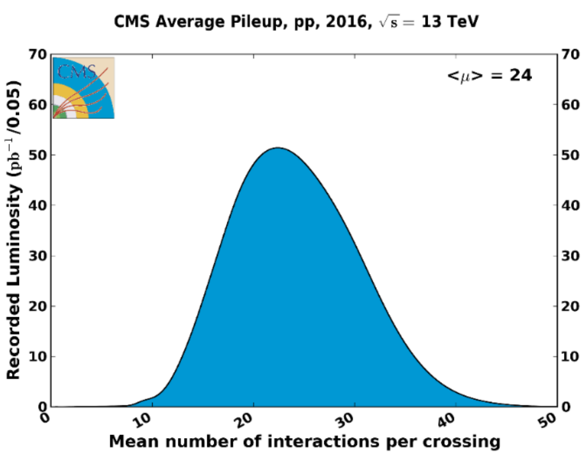
1) Tagging energetic jets (+ MET) from cascade decays
2) Tagging leptons
3) Tagging photons
4) Tagging with timing
5) ISR jet(s)
6) VBF dijet
7) …

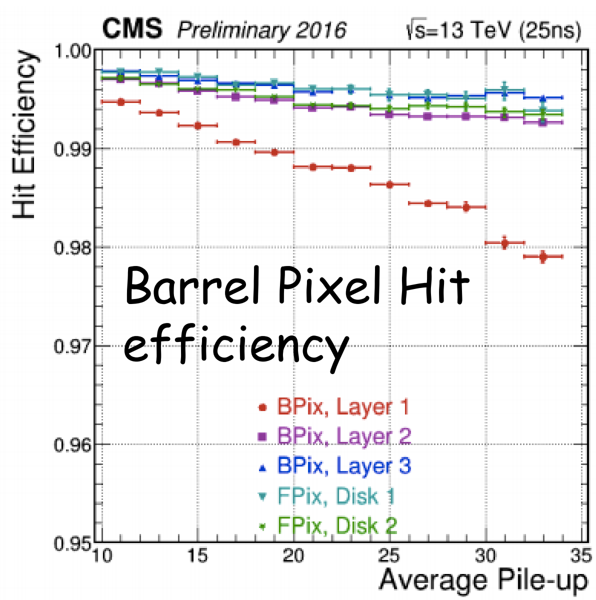
Particle IDs with Particle Flow

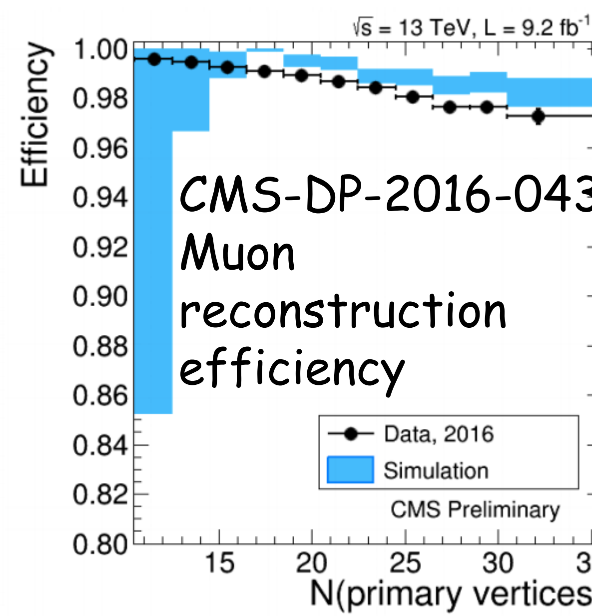


Challenges with High Luminosity (= PU)

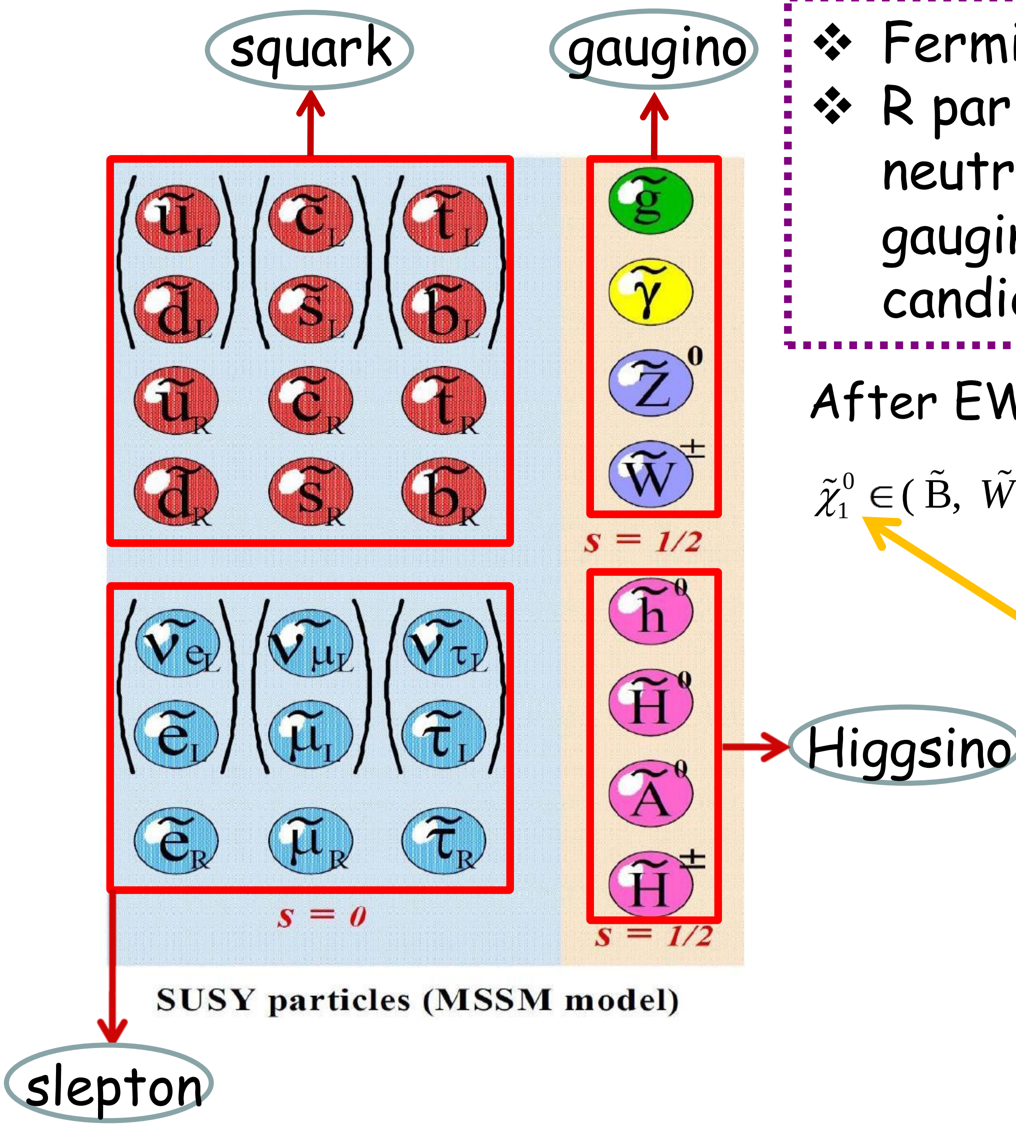








One-page Simplified SUSY Summary

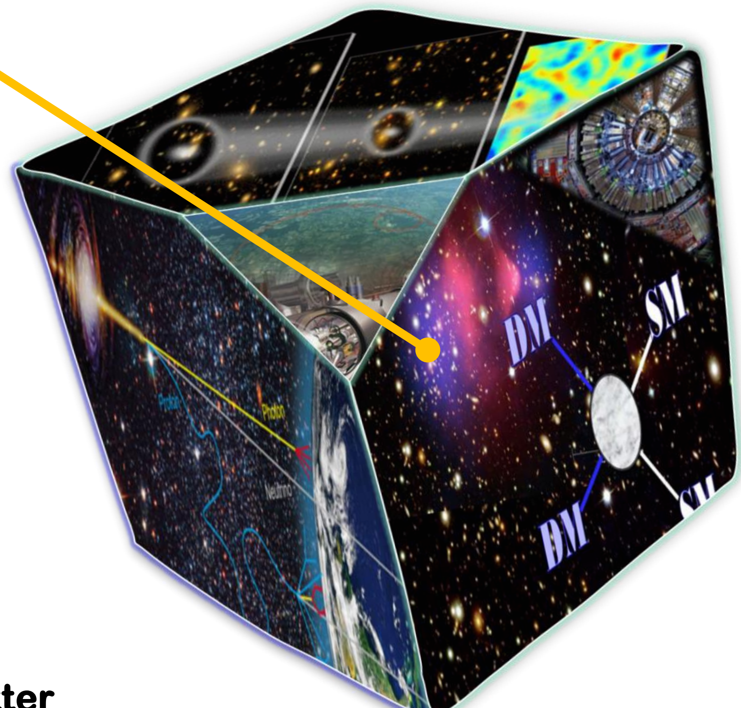


SUSY particles (MSSM model)

- Fermion ↔ Boson
- R parity conserving SUSY: Lightest neutralino (Lightest non-colored gaugino) $\tilde{\chi}_1^0$ → cold dark matter candidate

After EW symmetry breaking,

$$\tilde{\chi}_1^0 \in (\tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u) \quad \tilde{\chi}_1^+ \in (\tilde{W}^+, \tilde{H}_u^+) \quad \tilde{\chi}_1^- \in (\tilde{W}^-, \tilde{H}_d^-)$$

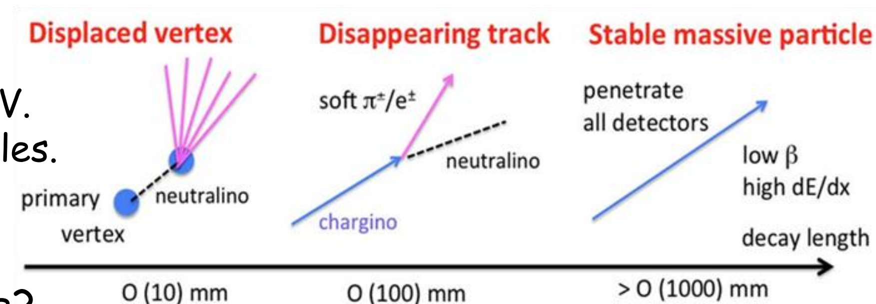


"SUSY + Another Higgs" Menu

- MSSM Higgs (e.g., A $H^{\pm}$ and $H^{+}H^{-}$), Non-MSSM Higgs
- Colored Sectors
  - Gluinos
  - Heavier(?) 1st/2nd generation scalar quarks (squaks)
  - Lighter(?) 3rd generation squarks (**stop**, **sbottom**)
- Charginos (C1, C2), Neutralinos (N1, N2, N3, N4), decaying into:
  - Leptons, Higgs, W, Z
- LSP?
  - Lightest Neutralino (N1): Bino-like, **Wino-like**, **Higgsino-like**, Bino-Higgsino-like ..

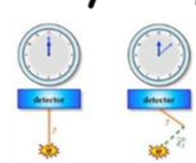
  [Example] Higgsino LSP → chargino and neutralinos below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.
  - Gravitino
- Sleptons
  - Selectrons and smuons - mass degenerate?
  - Special case: Stau is lighter.
- Displaced Tracks
- Long-Lived (LL)
- RPV + ???

Compressed scenarios at hadron collides



"non-pointing" γ

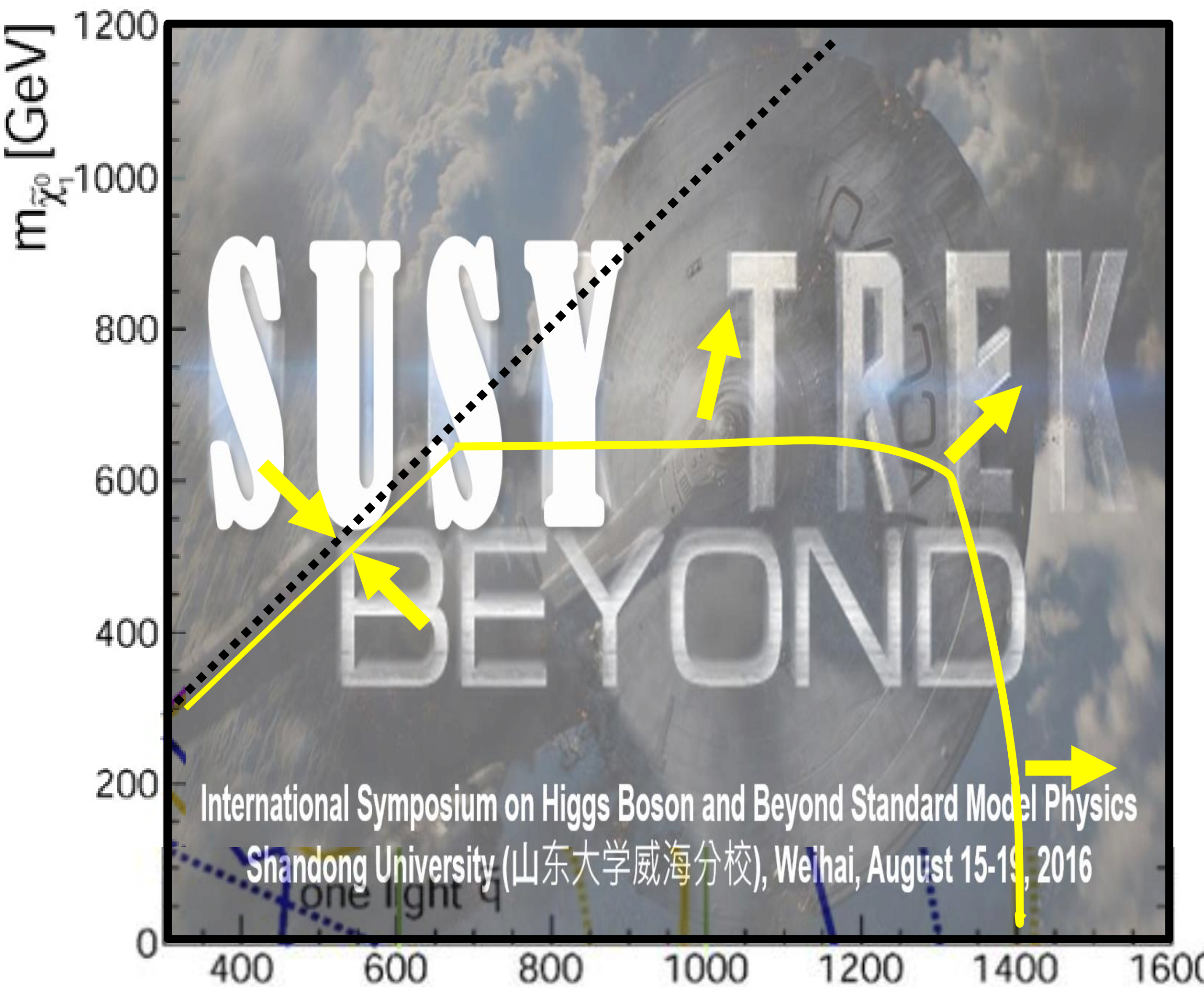
"delayed" γ



16 SUSY PASes for ICHEP 2016

- ✓ SUS-16-012: Search for SUSY in Events with a Higgs Decaying to Two Photons Using the Razor Variables.
- ✓ SUS-16-013: Search for RPV SUSY in 0l and 1l final states.
- ✓ SUS-16-014: Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV.
- ✓ SUS-16-015: Search for new physics in the all-hadronic final state with the MT2 variable.
- ✓ SUS-16-016: Search for new physics in final states with jets and missing transverse momentum in sqrt(s) = 13 TeV pp collisions with the alpha_T variable.
- ✓ SUS-16-019: Search for supersymmetry in events with one lepton.
- ✓ SUS-16-020: Search for SUSY in same-sign dilepton events at 13 TeV.
- ✓ SUS-16-021: Search for SUSY in final states with opposite-sign dileptons at 13 TeV.
- ✓ SUS-16-022: Search for SUSY with multileptons in 13 TeV data.
- ✓ SUS-16-023: Search for SUSY in photon + MET final states at 13 TeV.
- ✓ SUS-16-024: Search for electroweak SUSY production in multi-lepton final state at 13 TeV.
- ✓ SUS-16-025: Search for SUSY in the soft opposite-sign dilepton final state at 13 TeV.
- ✓ SUS-16-026: Search for electroweak SUSY in the WH final state at 13 TeV.
- ✓ SUS-16-028: Search for direct stop pair production in the single lepton final state at 13 TeV.
- ✓ SUS-16-029: Search for direct stop pair production in the fully hadronic final state at 13 TeV.
- ✓ SUS-16-030: Search for SUSY with a customized top tagger at 13 TeV.

LHC SUSY Exploration Map



- ❖ Probing a TeV scale at LHC13 ☺
- ❖ No hints of NP (yet) in very diverse search programs ☹

- ❖ [Simplified Models] MSSM (>100 parameters) - impossible to have more than 100 measurements at the LHC. Consider a way to test a minimal scenario or simplified scenario, first.
- ❖ [R-parity]
  - R-parity conserving SUSY (with a DM candidate)
  - R-parity violating SUSY (with a DM candidate from somewhere else)…

“Squarks & Gluinos” PASes

- ✓ SUS-16-012: Search for SUSY in Events with a Higgs Decaying to Two Photons Using the Razor Variables.
- ✓ SUS-16-013: Search for RPV SUSY in 0l and 1l final states.
- ✓ SUS-16-014: Search for supersymmetry in the multijet and missing transverse momentum channel in pp collisions at 13 TeV.
- ✓ SUS-16-015: Search for new physics in the all-hadronic final state with the MT2 variable.
- ✓ SUS-16-016: Search for new physics in final states with jets and missing transverse momentum in sqrt(s) = 13 TeV pp collisions with the alpha_T variable.
- ✓ SUS-16-019: Search for supersymmetry in events with one lepton.
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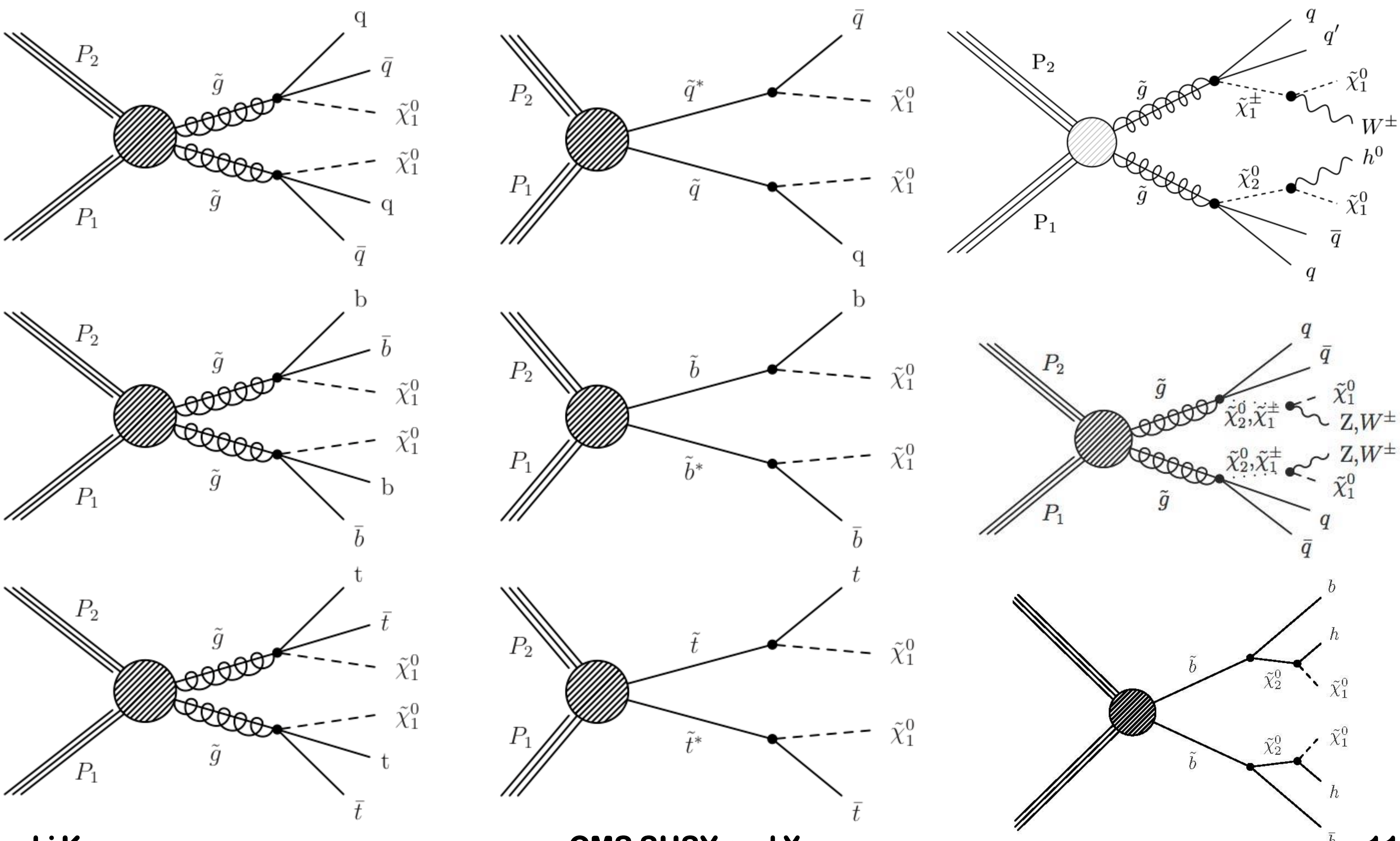
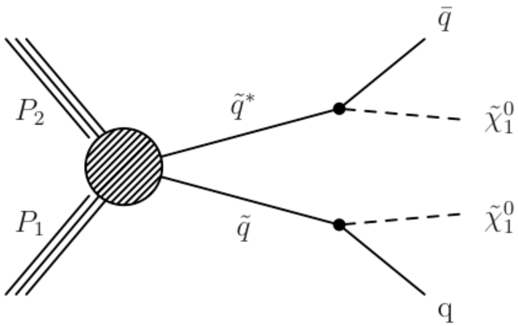
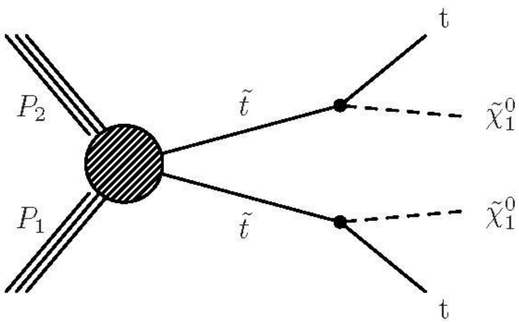
- ✓ SUS-16-029: Search for direct stop pair production in the fully hadronic final state at 13 TeV.
- ✓ SUS-16-030: Search for SUSY with a customized top tagger at 13 TeV.

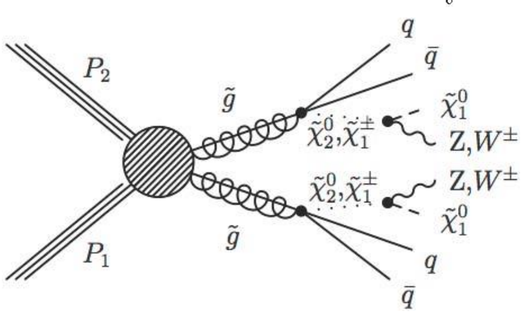
Squarks/Gluinos – SMS Diagrams

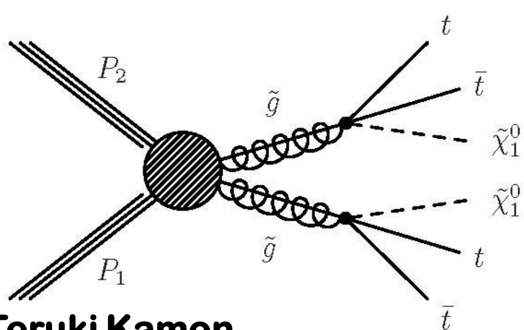


Squarks/Gluinos Searches

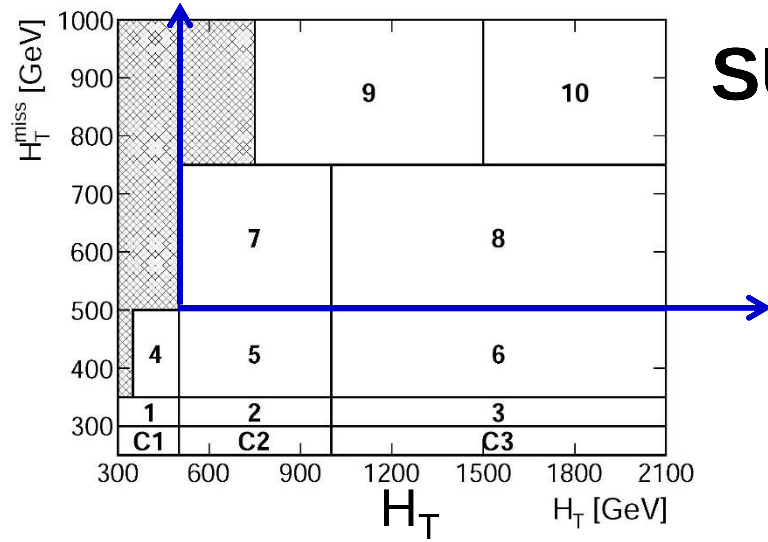








H_T^{miss}

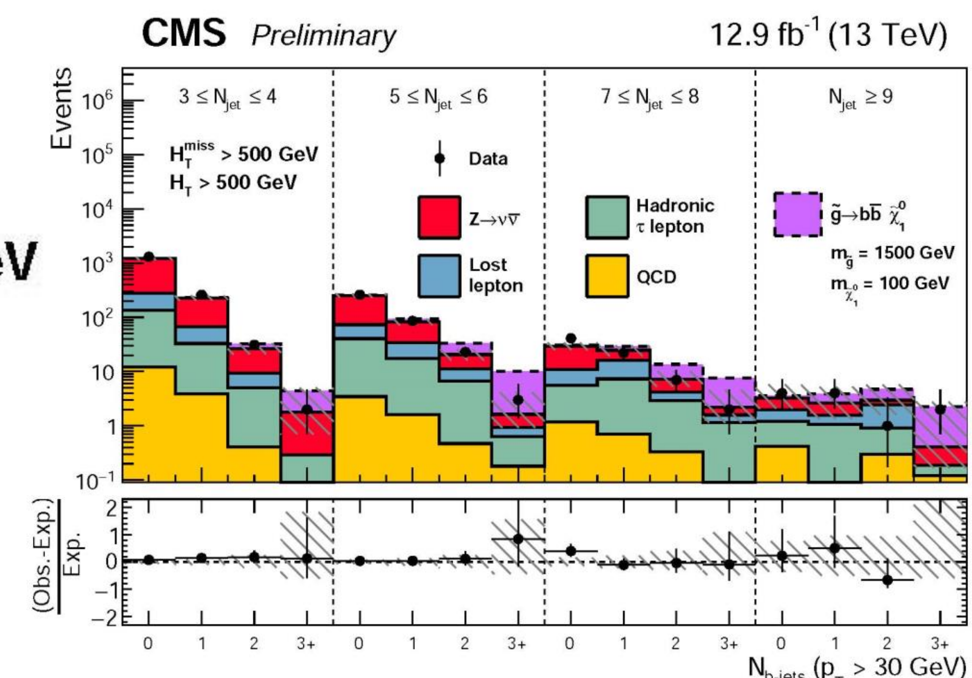


SUS-16-014

$3 \leq N_{jet} \leq 4$

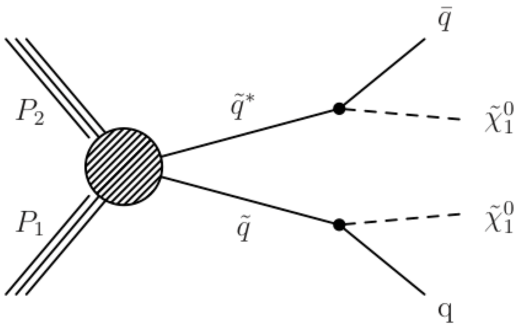
H_T^{miss} > 500 GeV

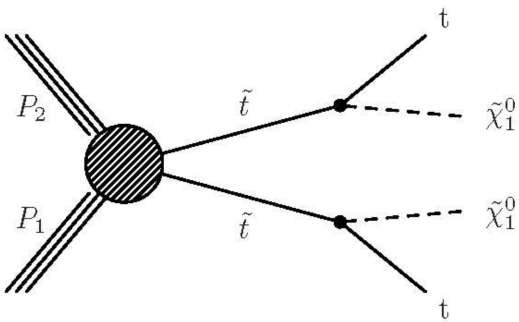
H_T > 500 GeV

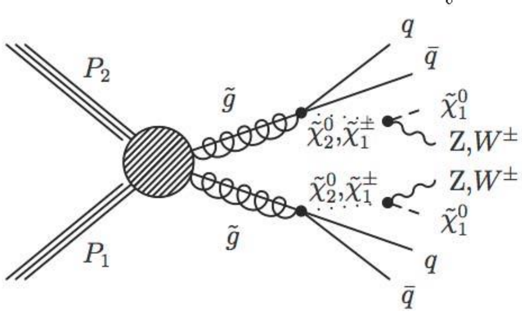


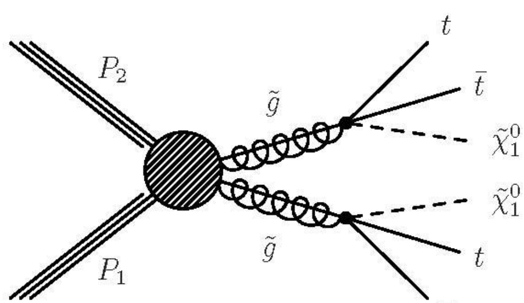
N_b

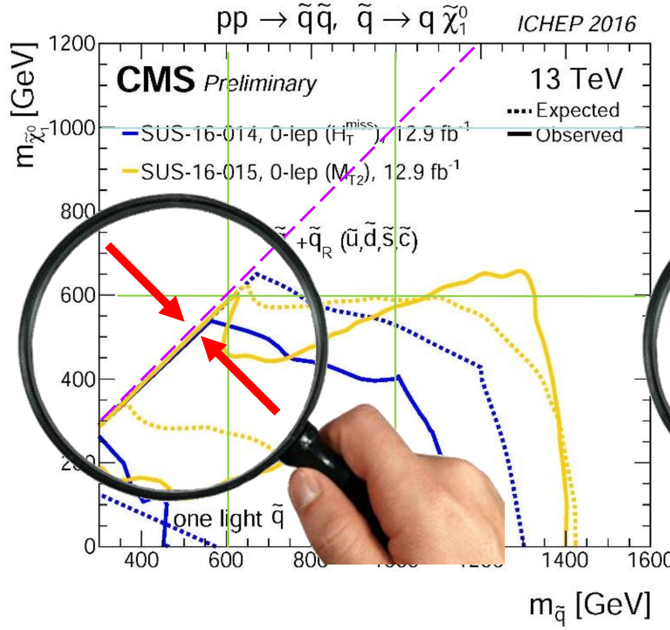
Squarks/Gluinos Results

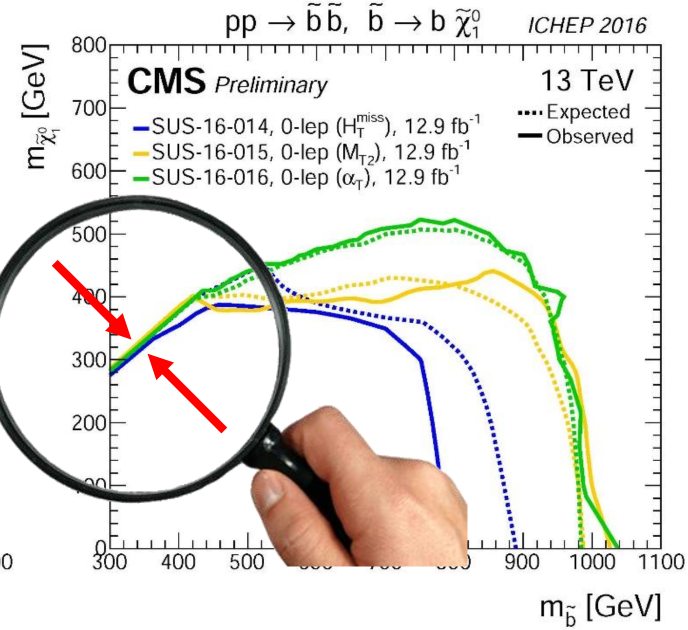


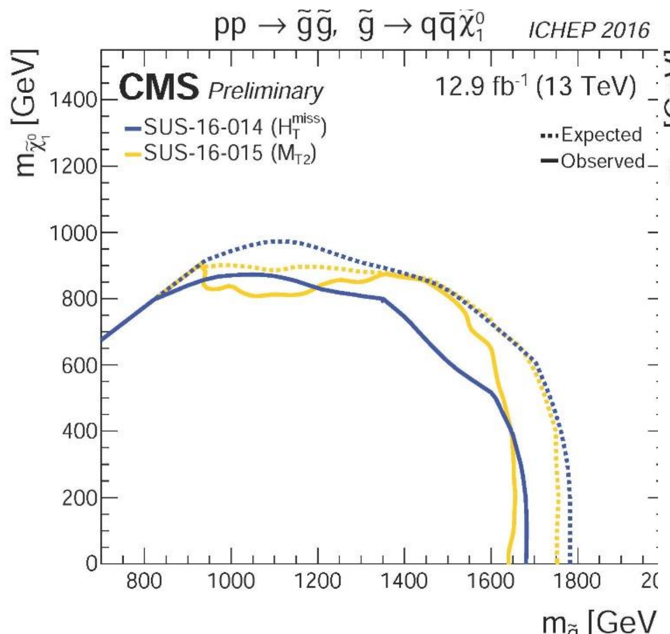


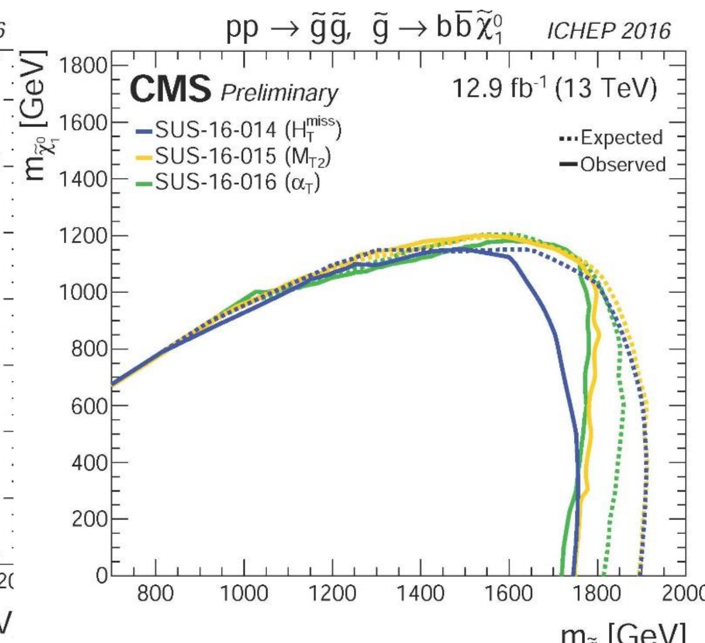




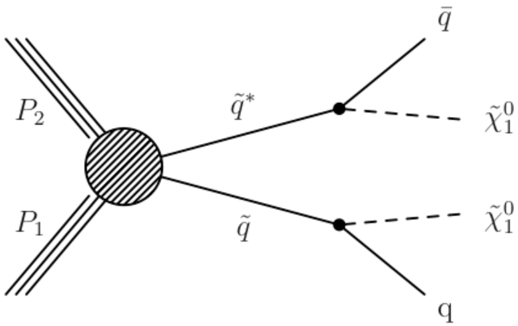


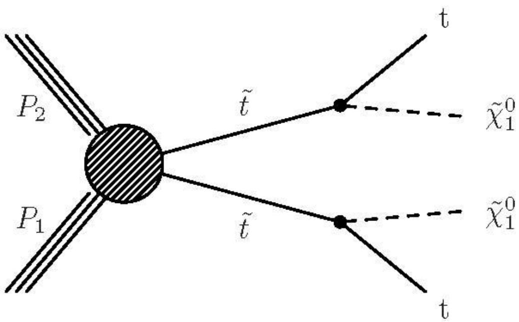


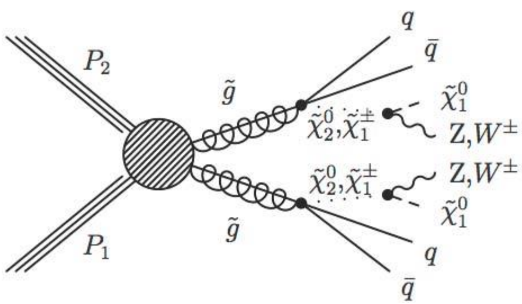


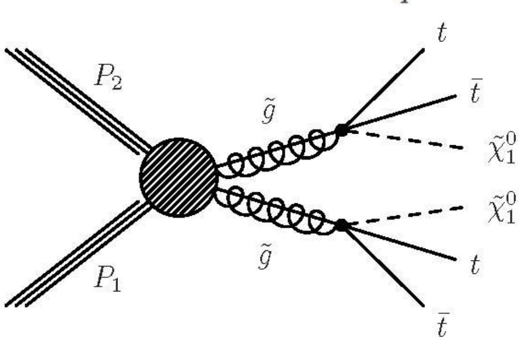


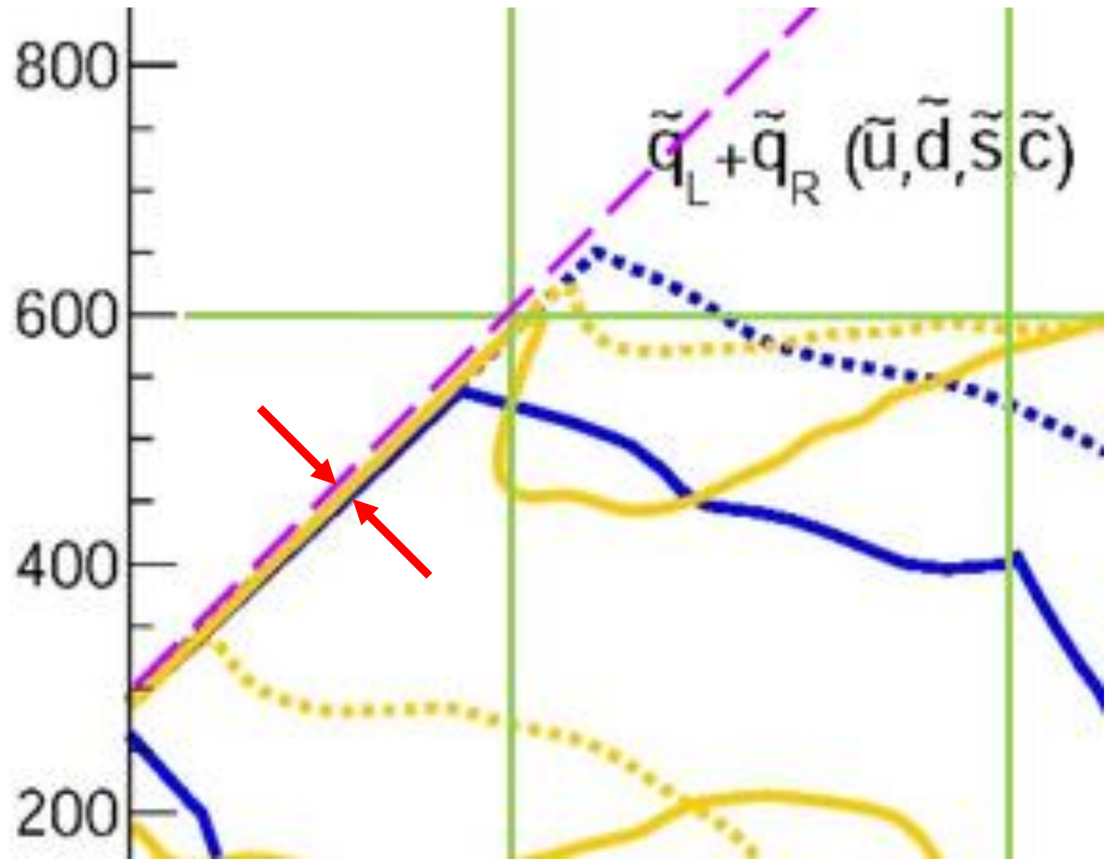
Squarks Results





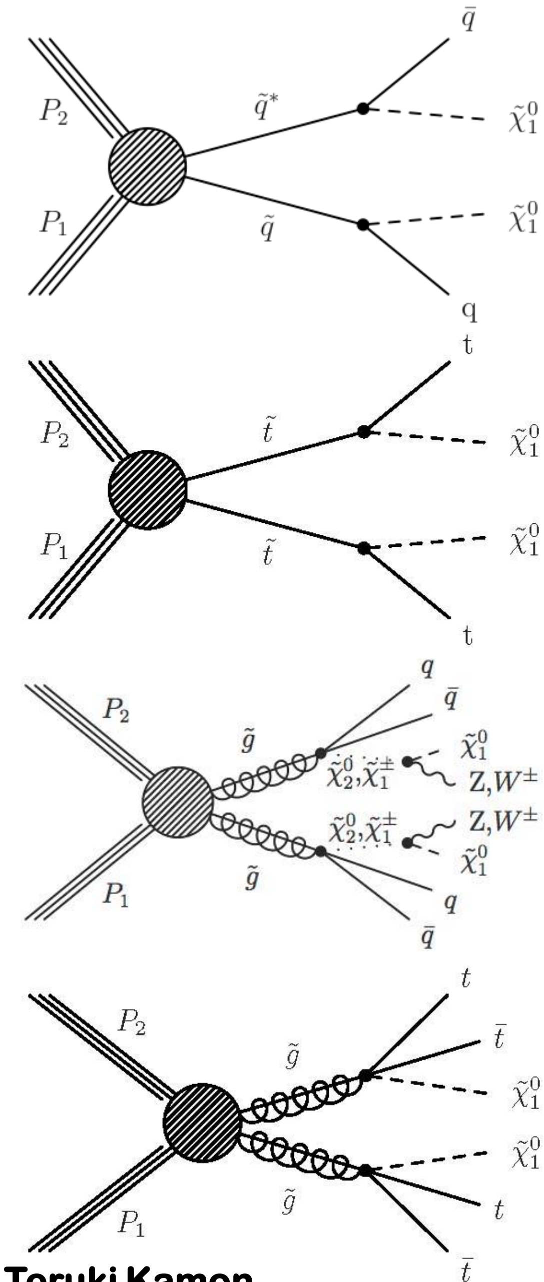


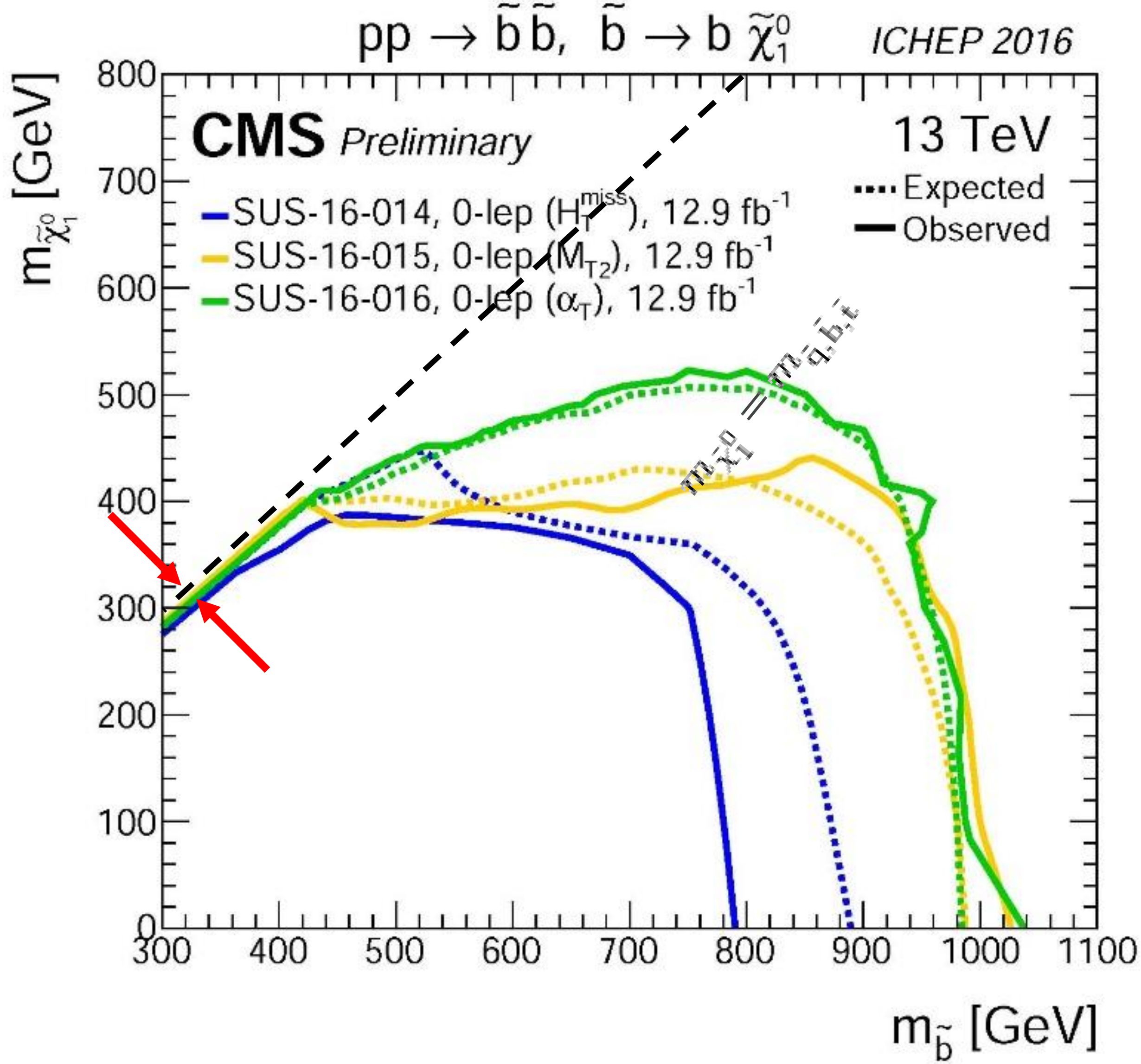




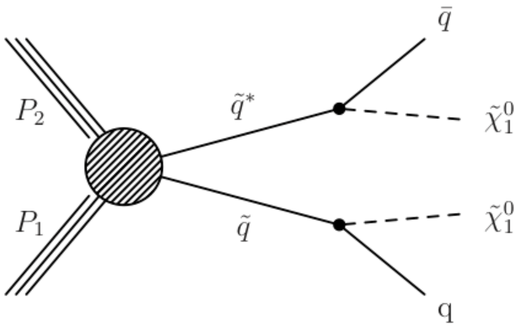
[Q] Do we still care of the extremly compressed mass scenario?

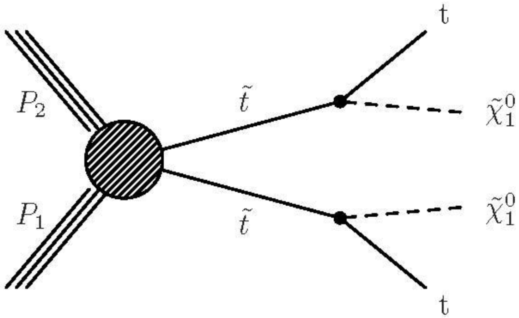
Bottom Squarks Results

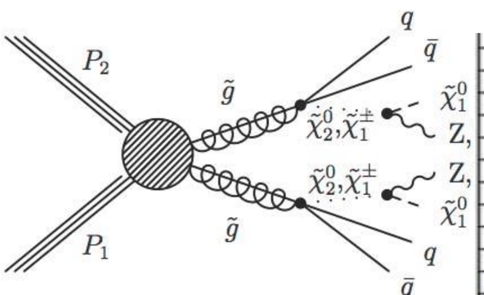


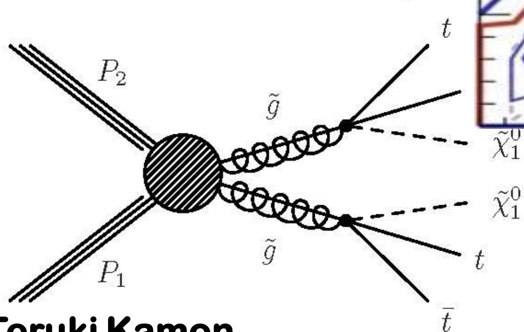


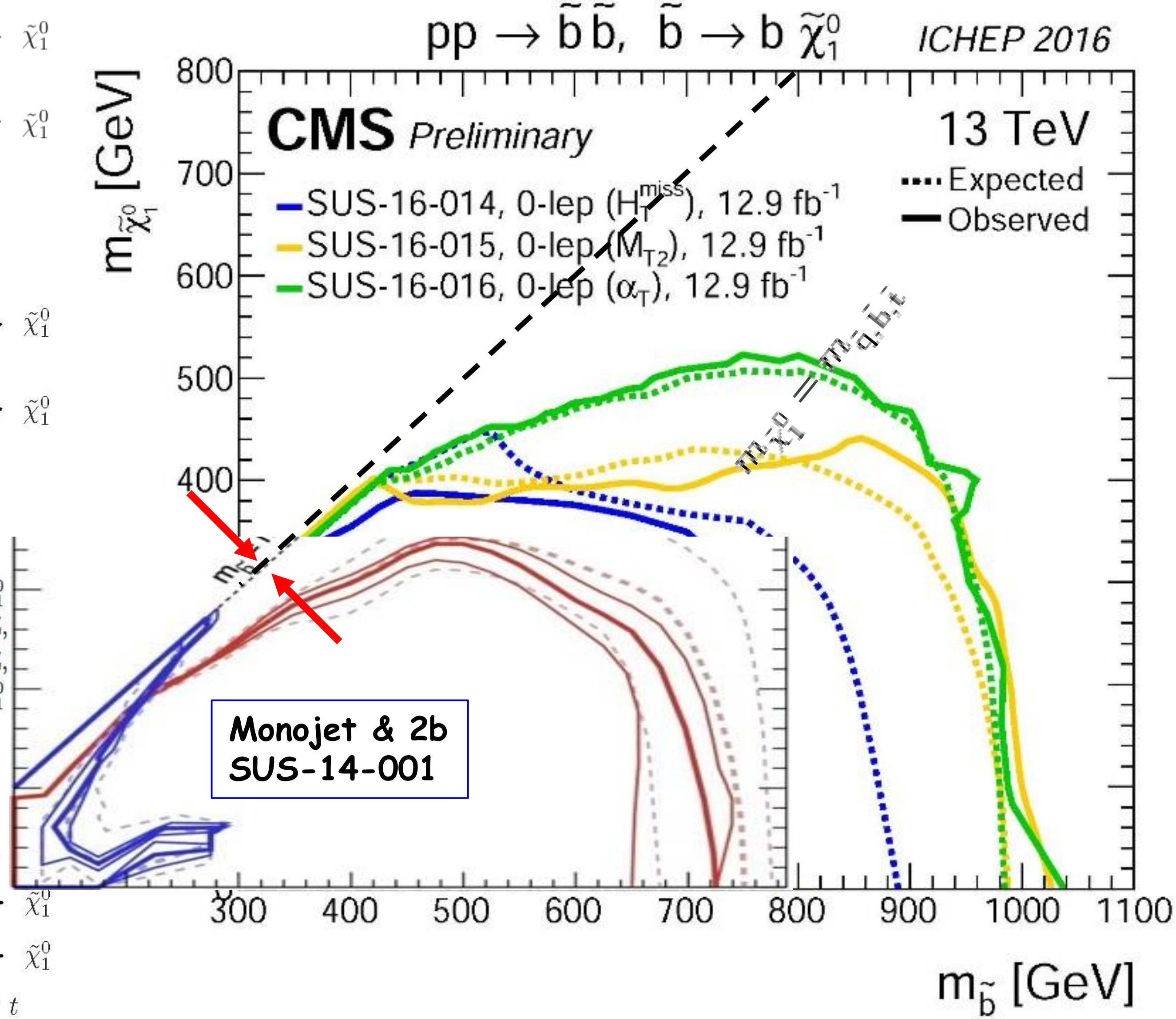
Bottom Squarks Results



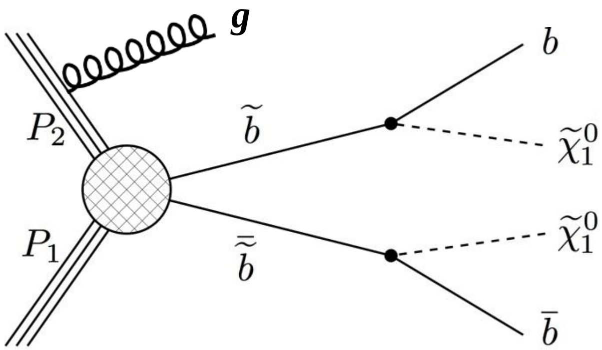


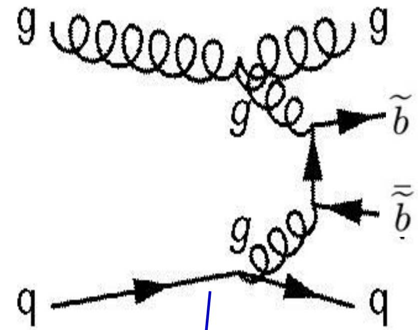






Compressed Bottom Squark: ISR vs. VBF

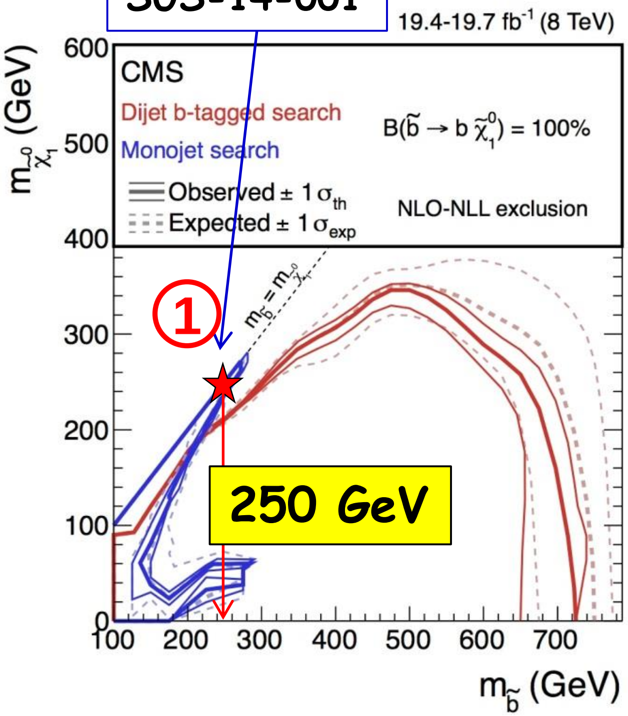


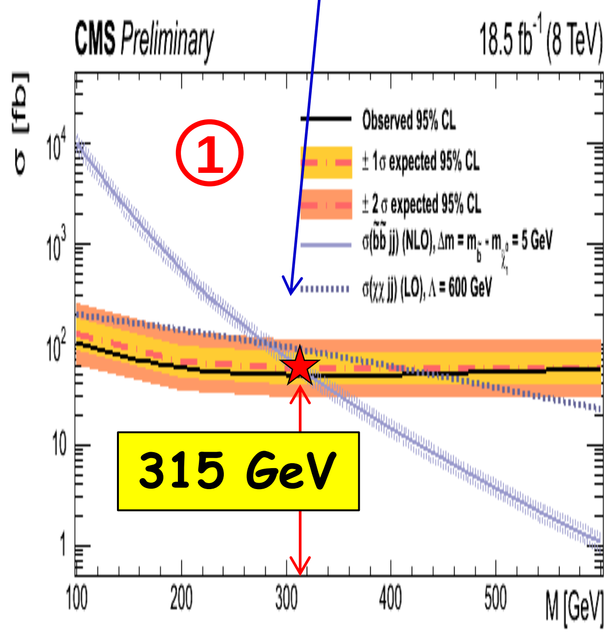


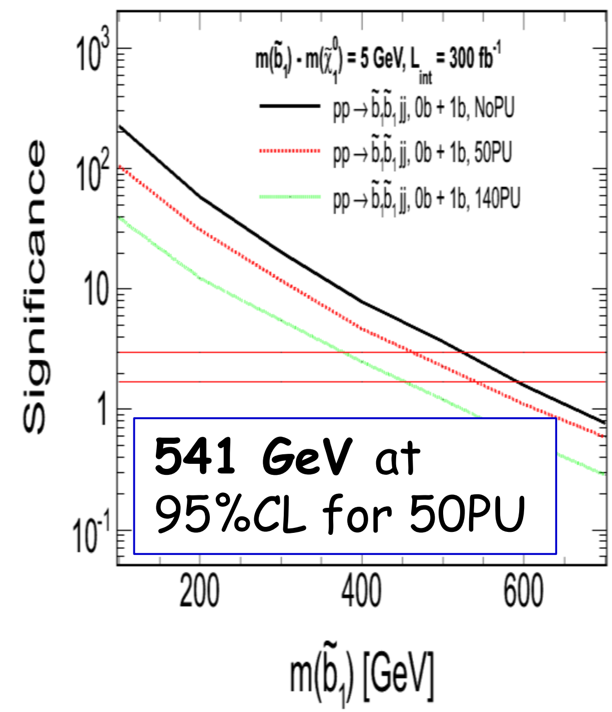
Monojet
SUS-14-001

VBF
SUS-14-019

VBF
[1507.01001]

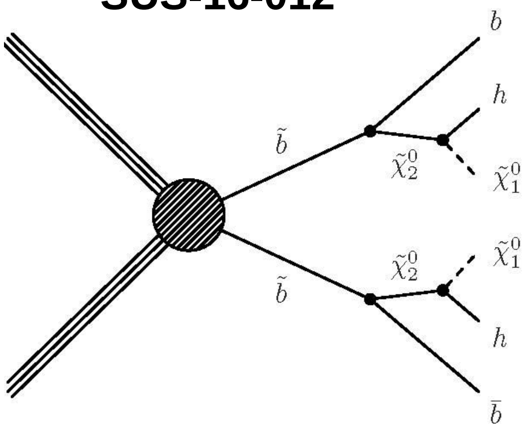


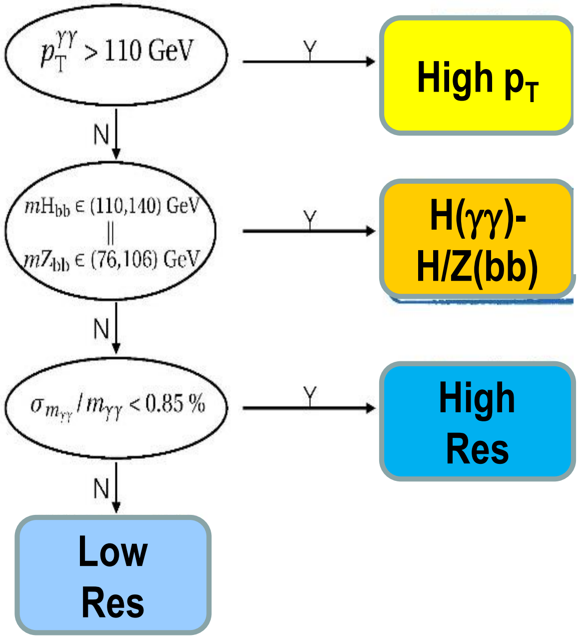




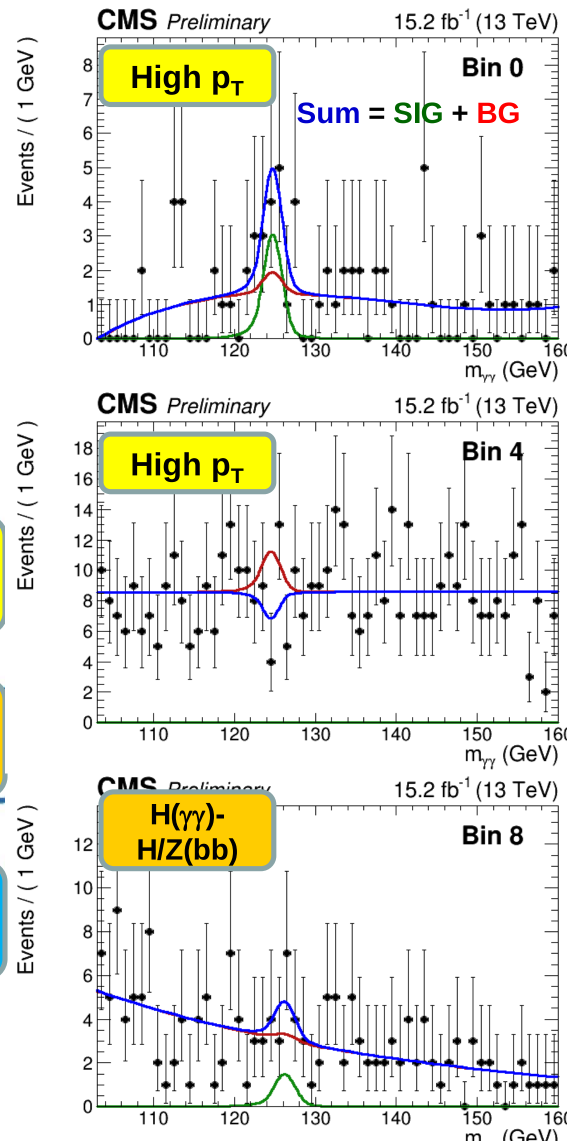
Bottom Squark with H(γγ)

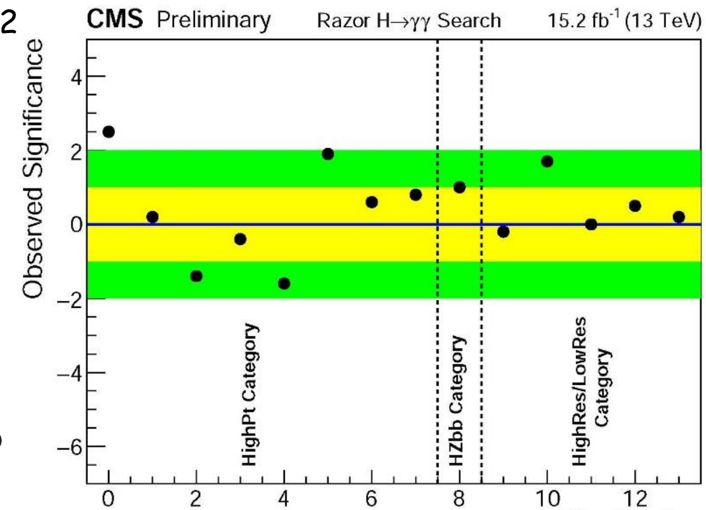
SUS-16-012

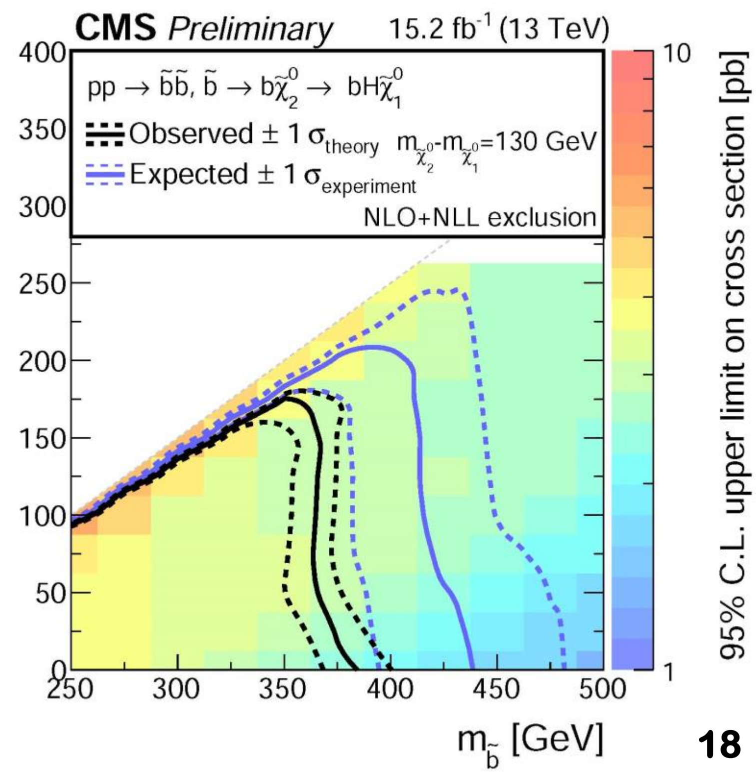




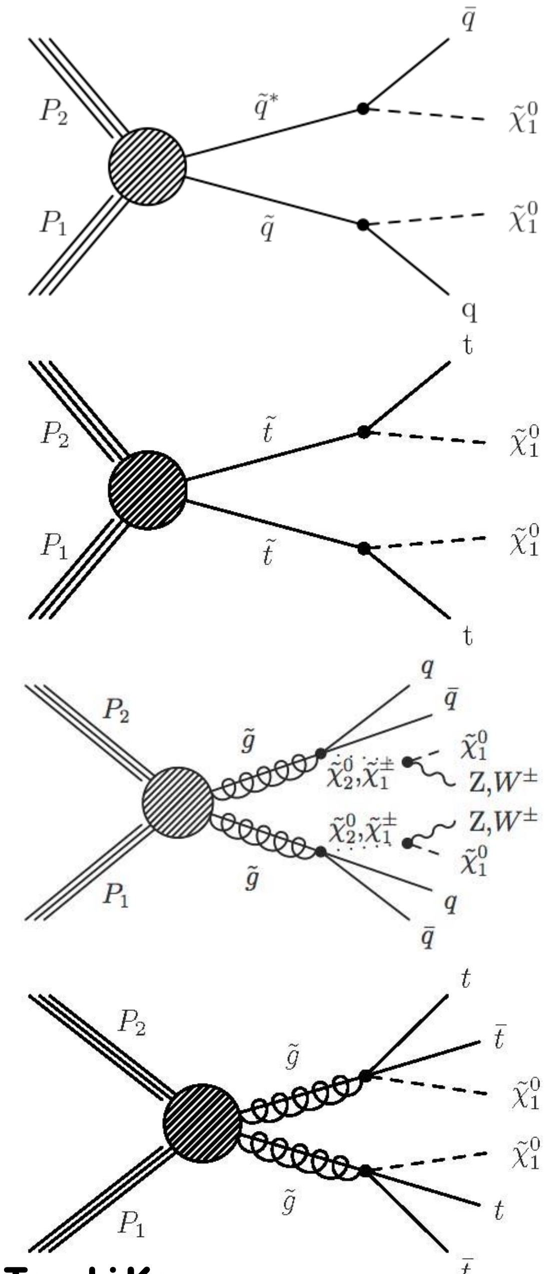
Search bins by M_R and R^2

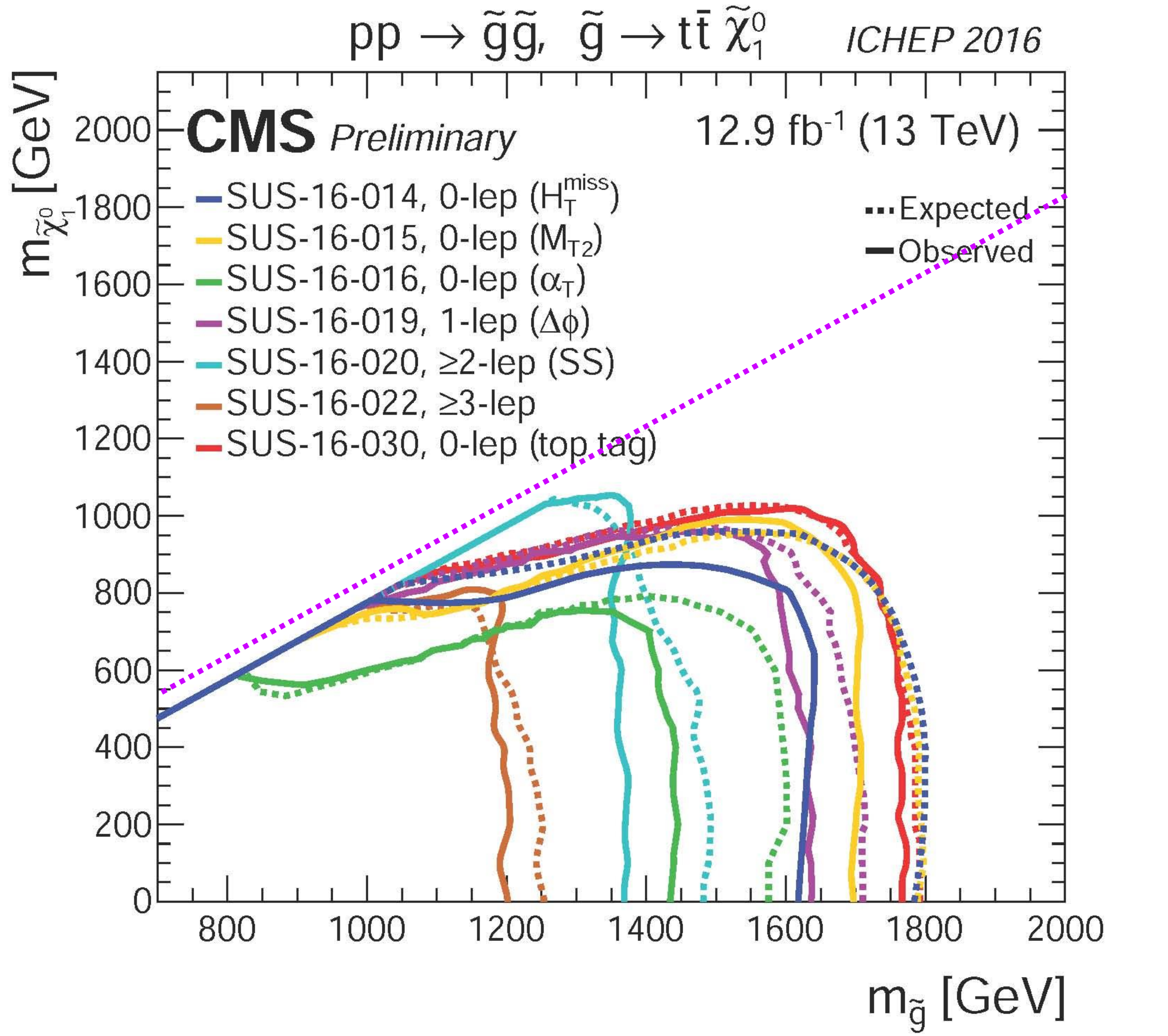






Gluios with Top Quarks

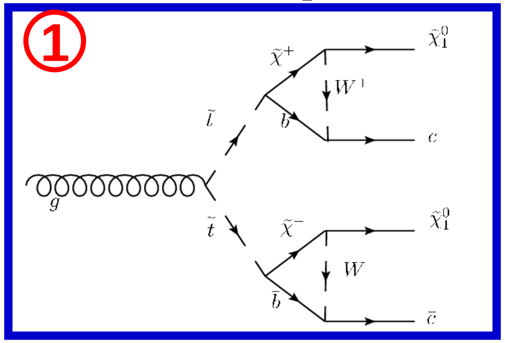


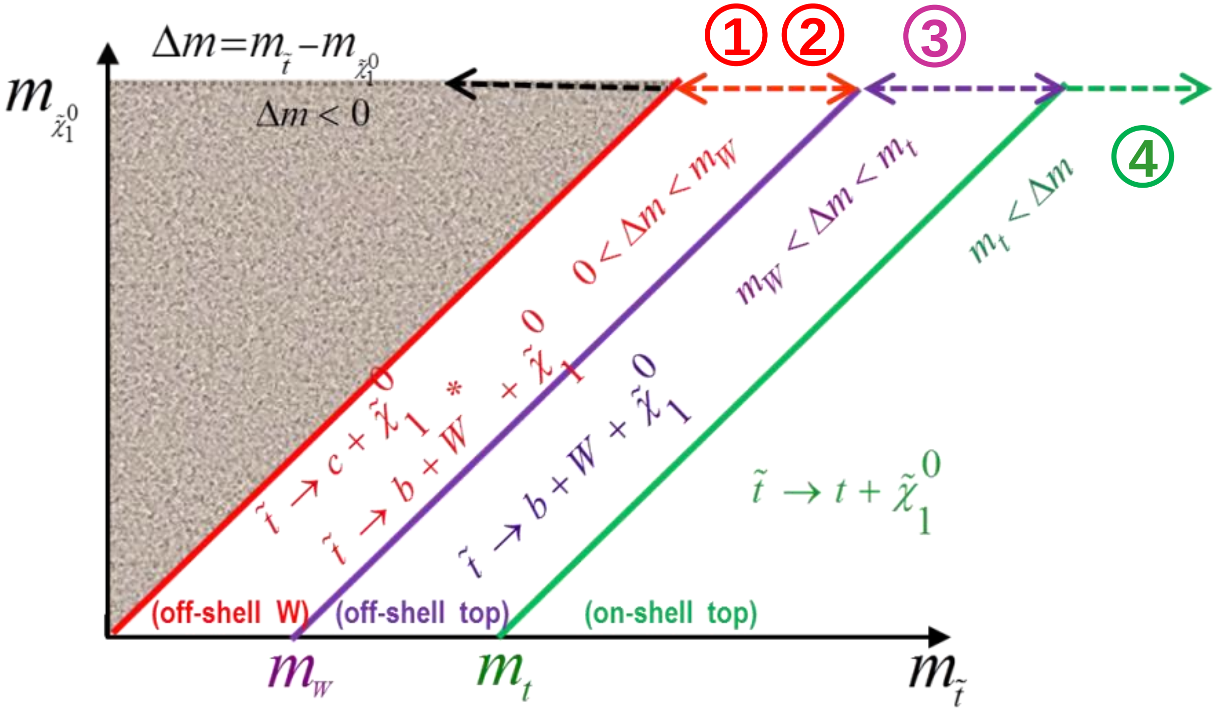


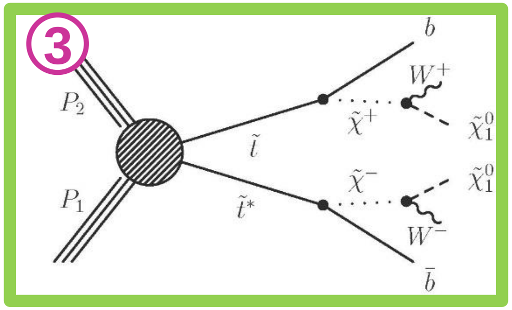
Top Squarks

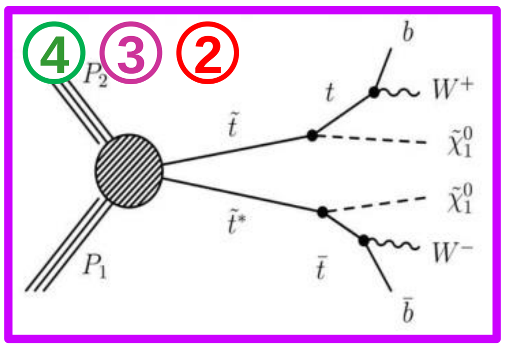
Stop decay ← Stop mixing & neutralino/chargino composition & $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

LSP	Allowed stop decays	Why
$\tilde{\chi}_1^0 = \tilde{B}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_R \tilde{\chi}_1^0$	U(1) couples L to L and R to R
$\tilde{\chi}_1^0 = \tilde{W}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0$	SU(2) only acts on L
$\tilde{\chi}_1^0 = \tilde{H}_d^0$	none	Only couples to down-type
$\tilde{\chi}_1^0 = \tilde{H}_u^0$	$\tilde{t}_L \to t_R \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_L \tilde{\chi}_1^0$	Higgs couple L to R (mass term)









“Top Squark” PASes

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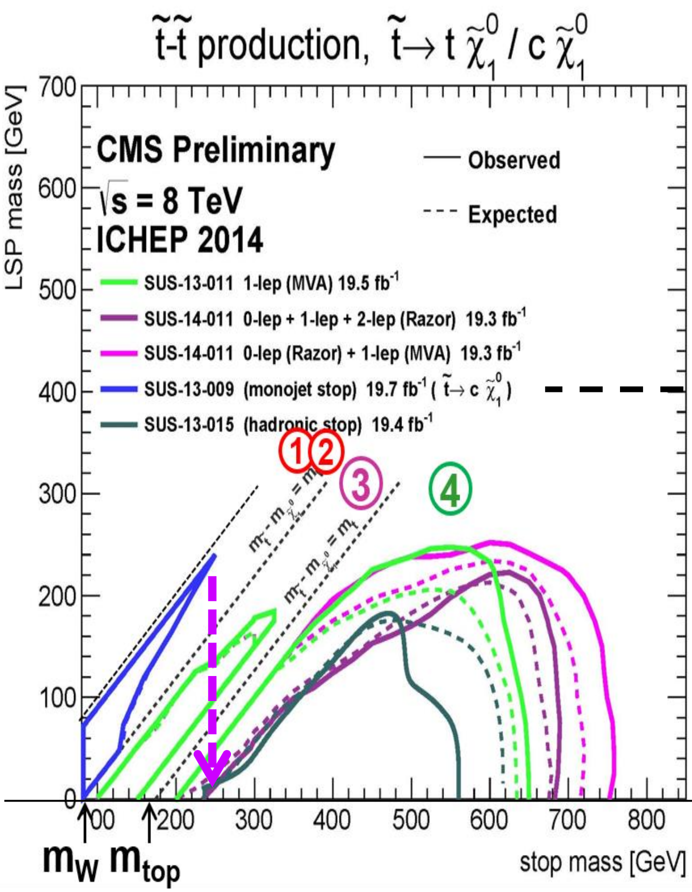
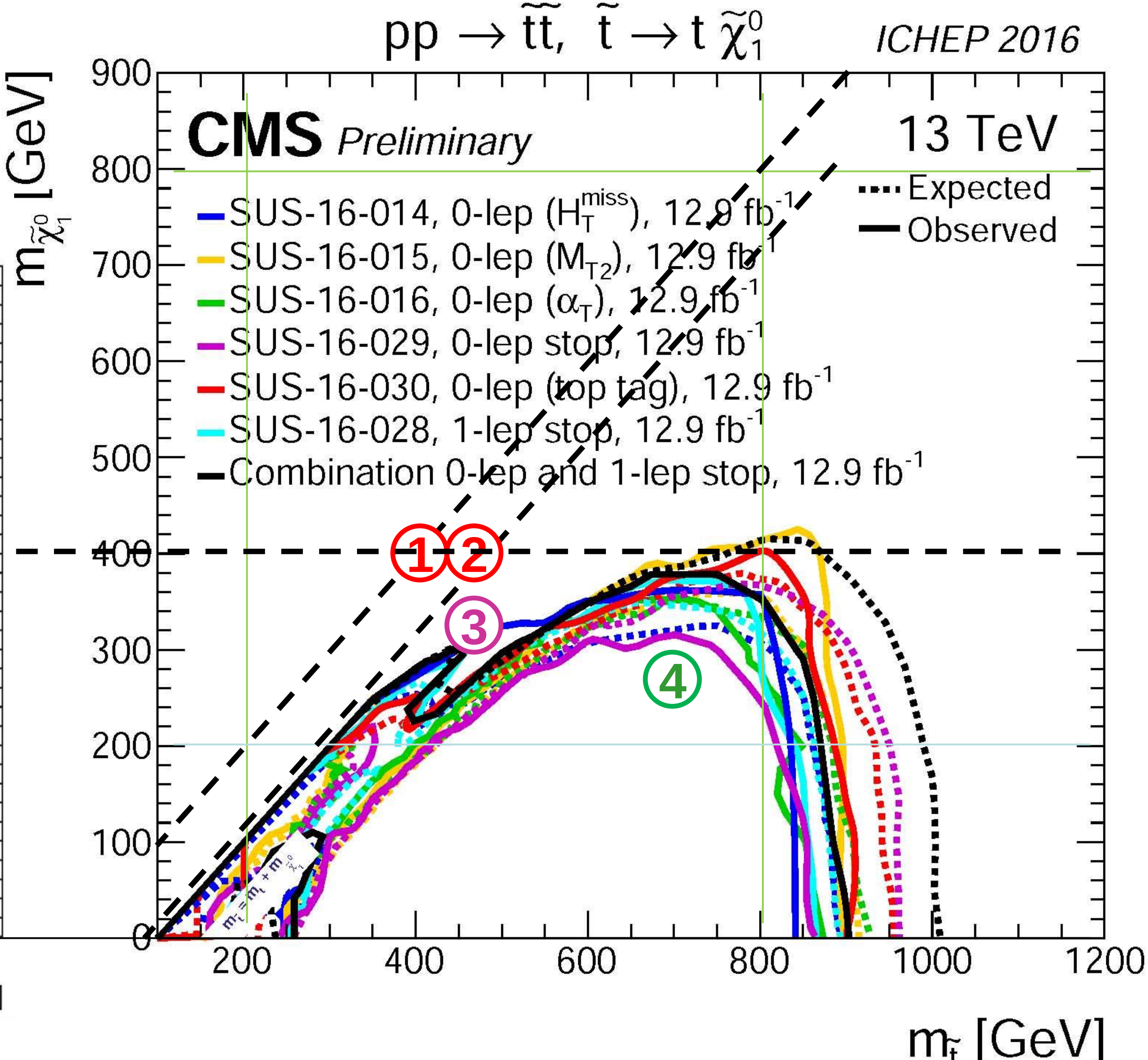
- ✓ SUS-16-025: Search for SUSY in the soft opposite-sign dilepton final state at 13 TeV.
- ✓ SUS-16-026: Search for electroweak SUSY in the WH final state at 13 TeV.
- ✓ SUS-16-028: Search for direct stop pair production in the single lepton final state at 13 TeV.
- ✓ SUS-16-029: Search for direct stop pair production in the fully hadronic final state at 13 TeV.
- ✓ SUS-16-030: Search for SUSY with a customized top tagger at 13 TeV.

Top Squark Results

Searches with 0l + 1l

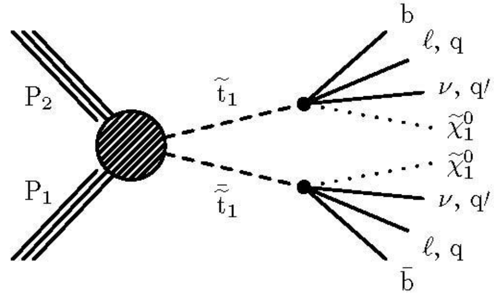




Top Squark Results

② Searches with 2l

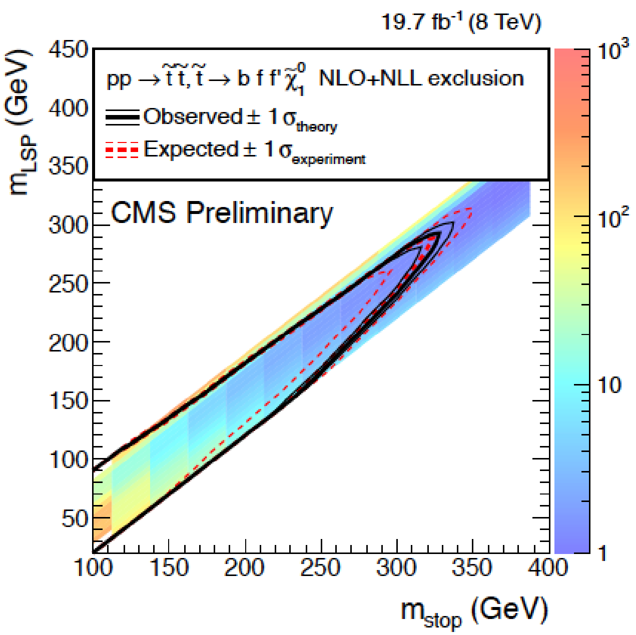
SUS-16-025



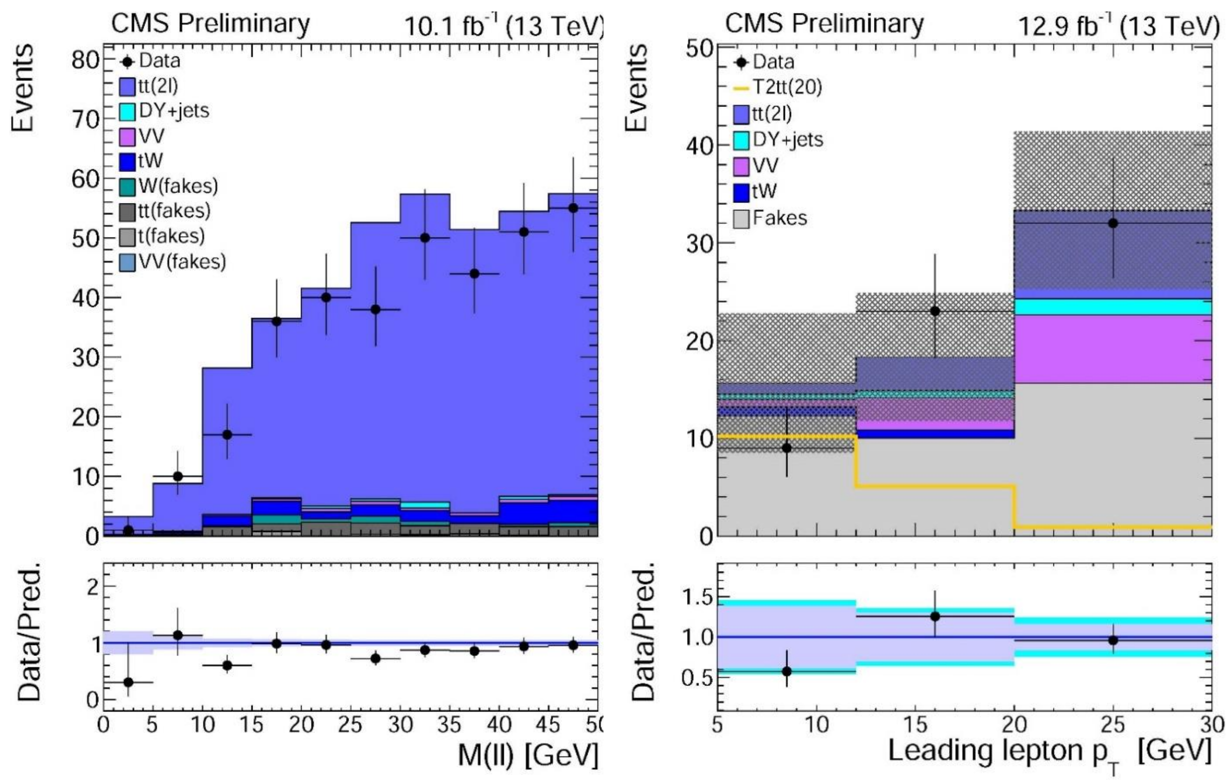
Soft OS dileptons + Low N(jet)

ΔM < 20 GeV

No sensitivity for ΔM < 50 GeV (8 TeV)



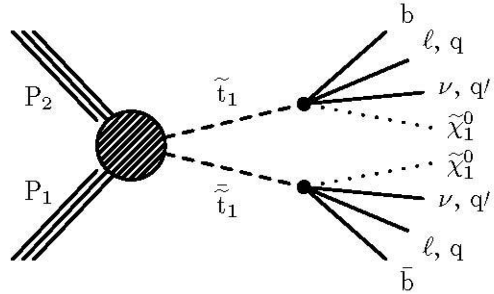
SUS-14-021



Top Squark Results

② Searches with 2l

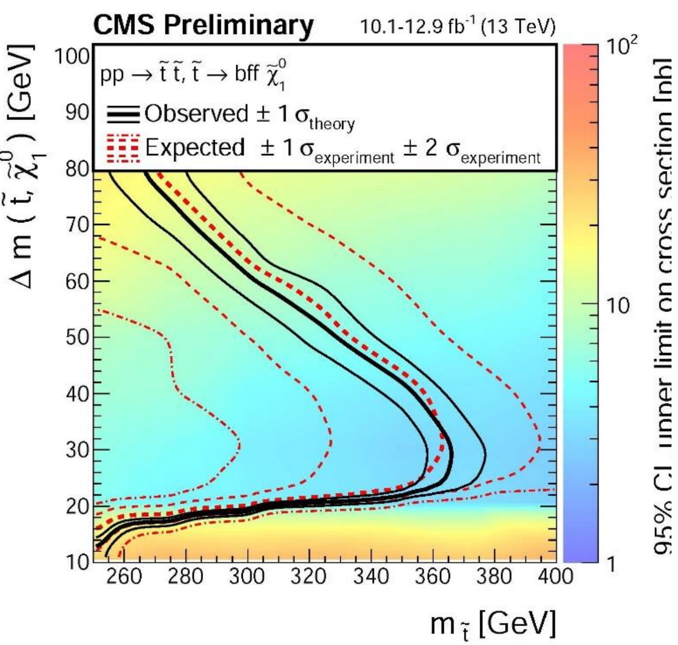
SUS-16-025



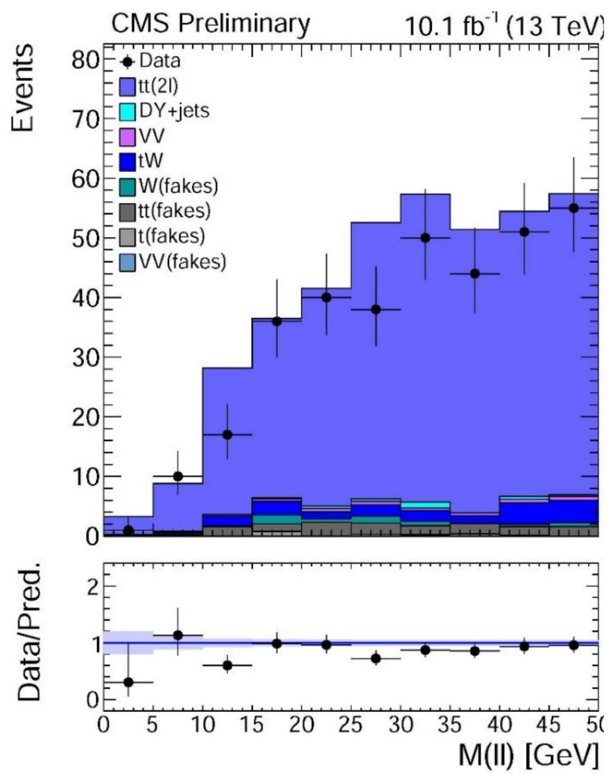
Soft OS dileptons + Low N(jet)

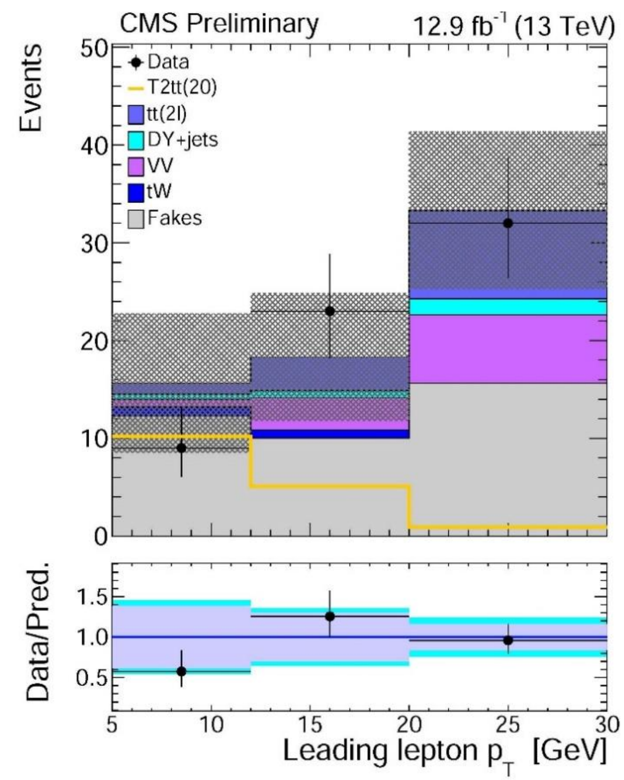
$\Delta M < 20$ GeV

Sensitivity for $\Delta M <$ 20 GeV (13 TeV)



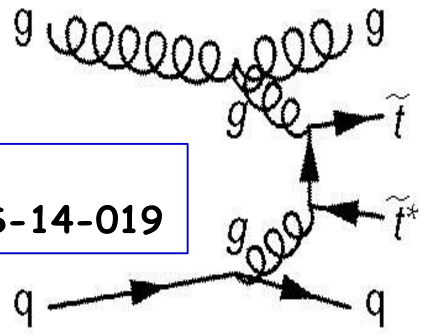
SUS-16-025



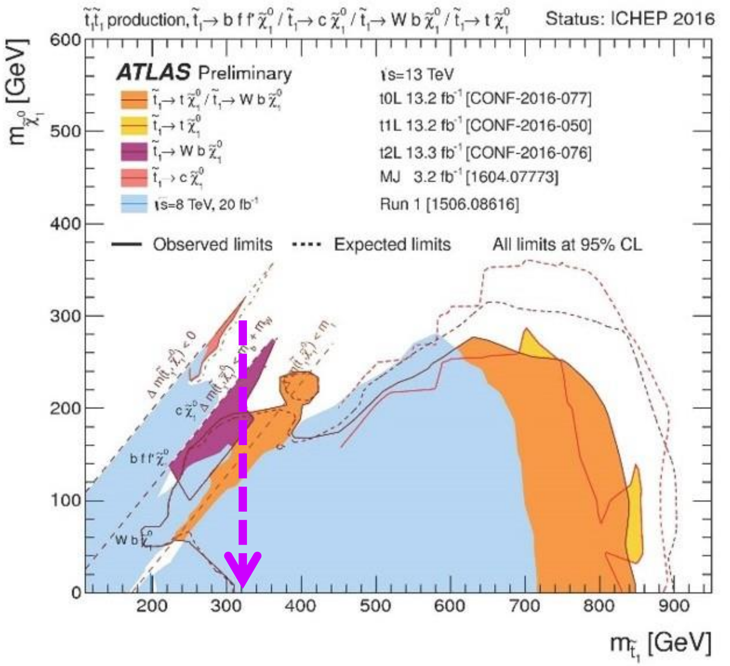


Compressed Top Squark

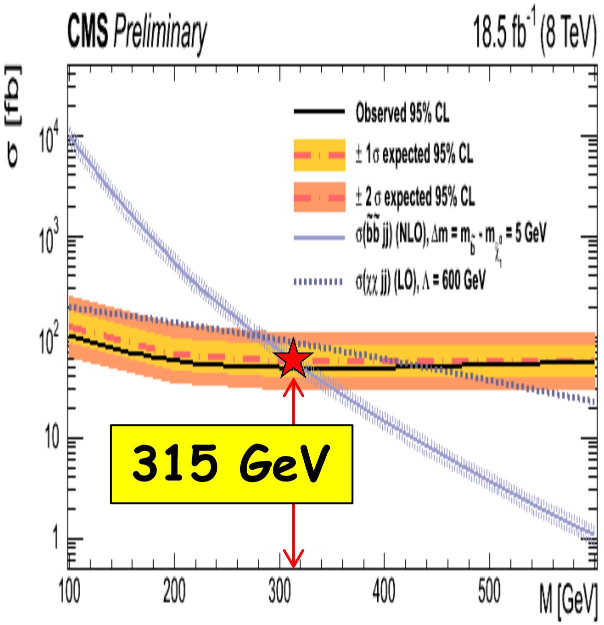
①



VBF
SUS-14-019



Vs.



315 GeV

“Electroweakino” PASes

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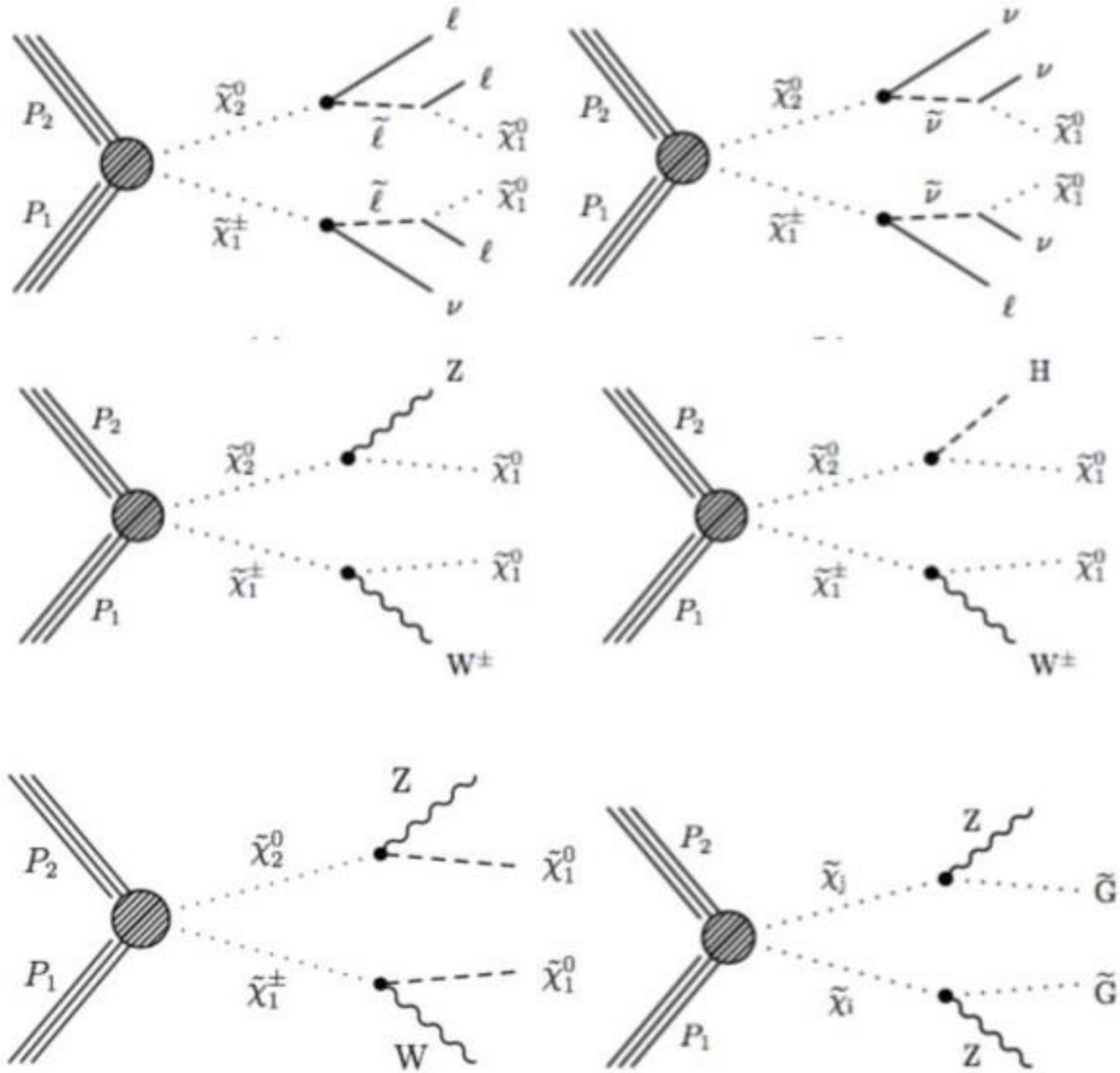
Electroweakinos – SMS Diagrams

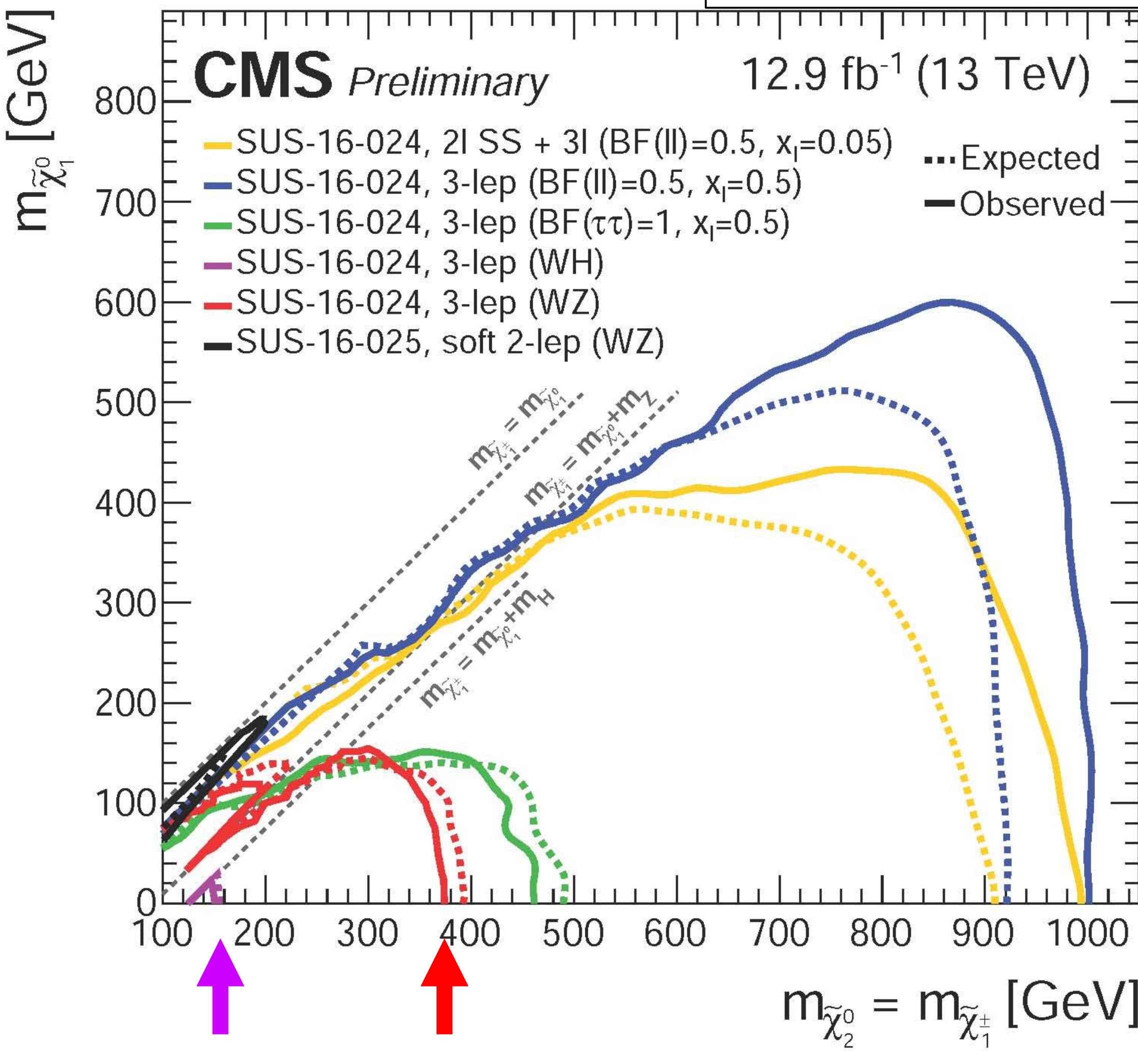


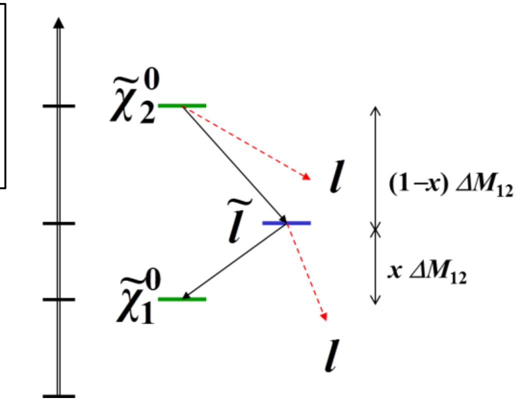
Electroweak Sector

$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$

$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (H\ \tilde{\chi}_1^0)(W\ \tilde{\chi}_1^0)$

$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (Z\ \tilde{\chi}_1^0)(W\ \tilde{\chi}_1^0)$





x = 0.5 (maximum sensitivity)

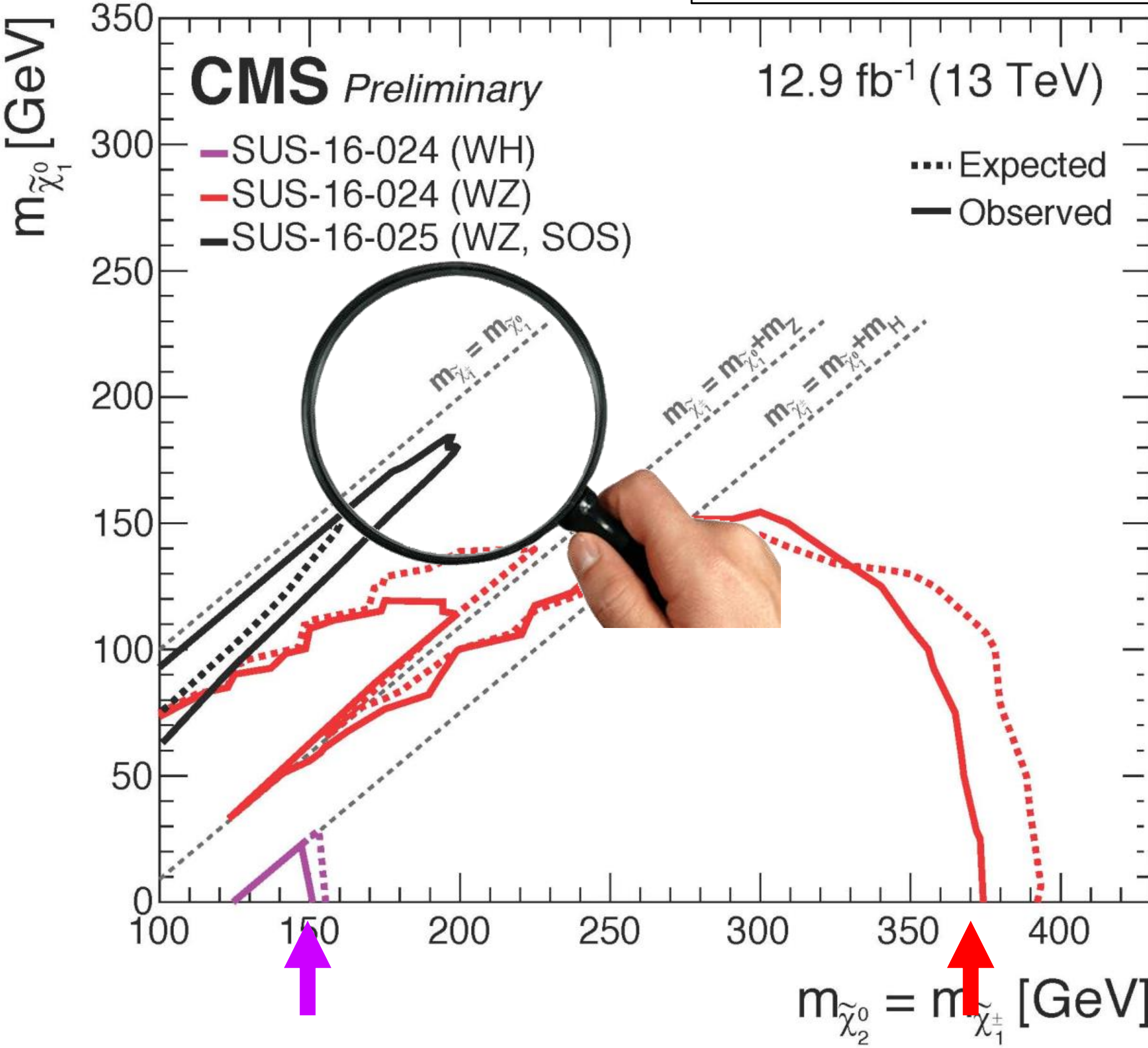
- ❖ **Wino-Chargino and Bino-LSP**
  - ✓ Up to ~1000 and ~600 GeV for light slepton case
  - ✓ Up to 400 and 120 GeV for W and Z cases
- ❖ **Weaker limits for**
  - ✓ heavy slepton
  - ✓ being Higgsinos
  - ✓ small mass difference (compressed mass spectra)

Electroweak Sector

$$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$$

$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (H\ \tilde{\chi}_1^0)(W\ \tilde{\chi}_1^0)$

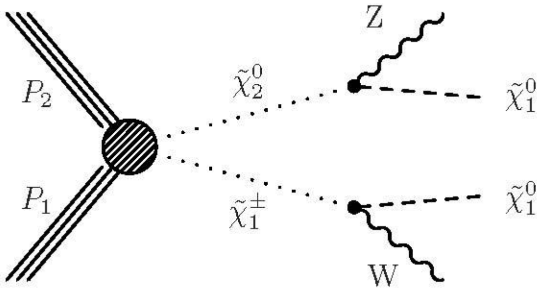
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (Z\ \tilde{\chi}_1^0)(W\ \tilde{\chi}_1^0)$



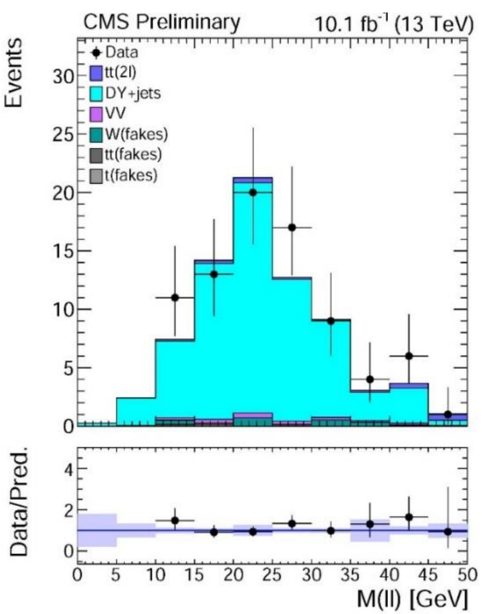
Dimuon (3 GeV) + MET (50 GeV) trigger (offline: p_T > 5 GeV and MET > 125 GeV) → Soft OS dilepton in compressed mass spectra (DM < 20 GeV).

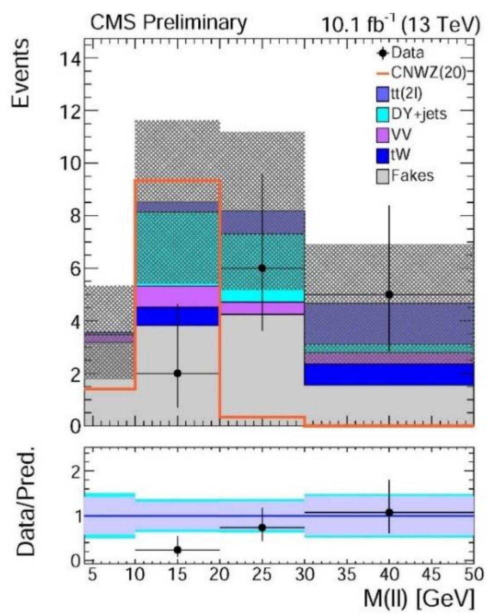
- **Wino-Chargino and Bino-LSP**
  - ✓ Up to ~1000 and ~600 GeV for light slepton case
  - ✓ Up to 400 and 120 GeV for W and Z cases
- **Weaker limits for**
  - ✓ heavy slepton
  - ✓ being Higgsinos
  - ✓ small mass difference (compressed mass spectra)

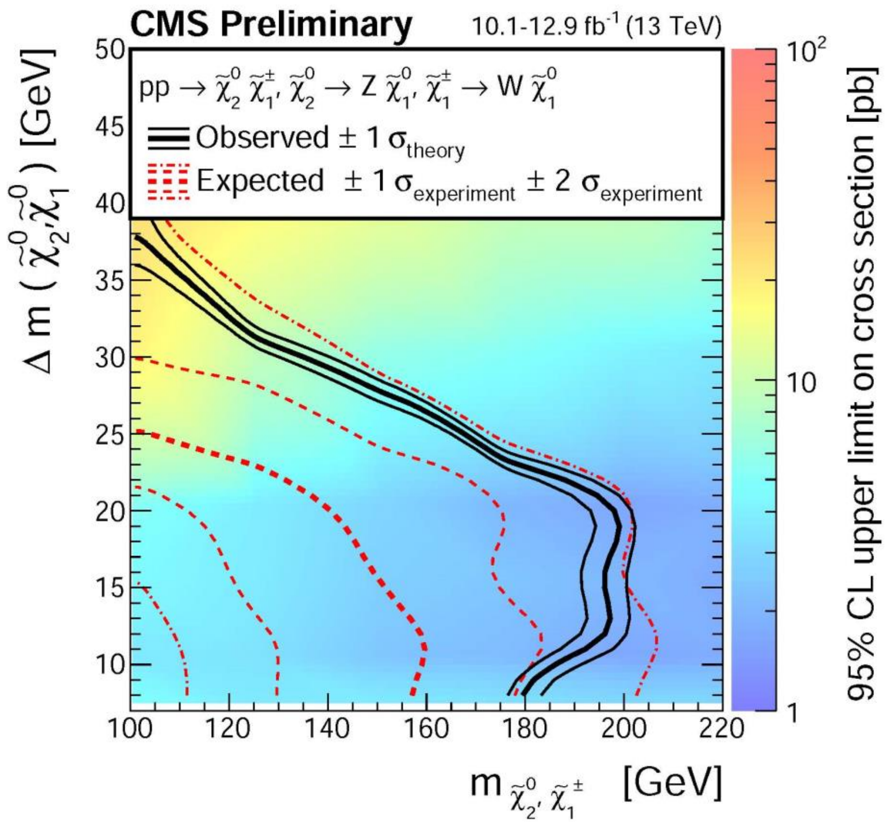
Electroweak Sector



SUS-16-025







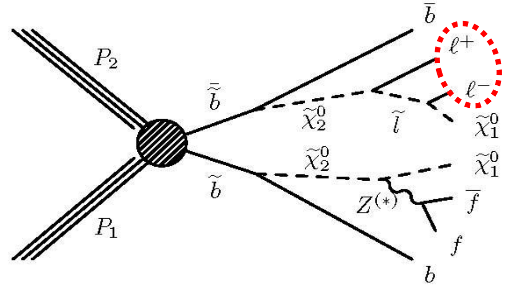
Generic M(ll) Searches

[SUS-16-021] These categories are based on several observables related to the lepton pair and the hadronic system in order to optimize signal efficiency and background rejection. A fit is employed to search for a possible kinematic edge position in the strong, non-resonant search. In addition, signal regions are included for which excesses were reported by the ATLAS and CMS collaborations using 8 TeV and 13 TeV data. The observations in all signal regions are consistent with the expectations from the standard model, and the results are interpreted in the context of simplified models of supersymmetry.

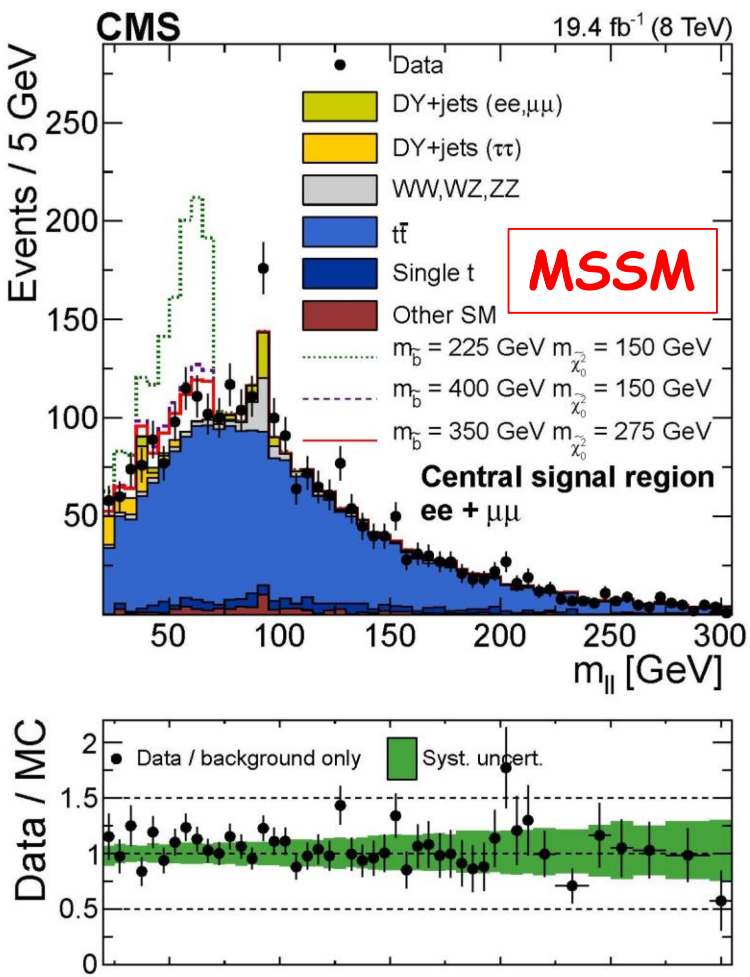
[SUS-16-021 – Table 6] ATLAS-like Z+jets+MET

Total background	$6.1^{+4.0}_{-2.2}$
Observed	8.0

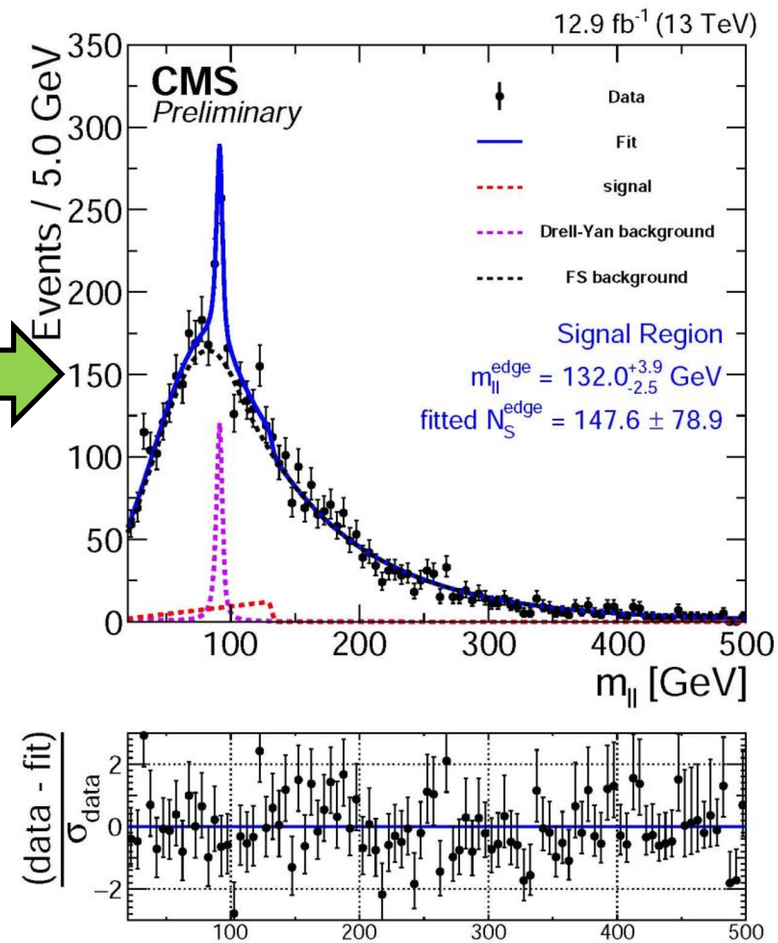
M(ll) Endpoint via Bottom Squark Decays?



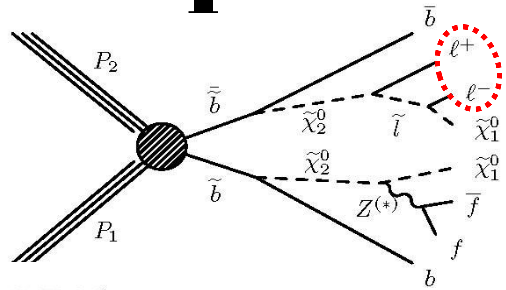
SUS-14-014



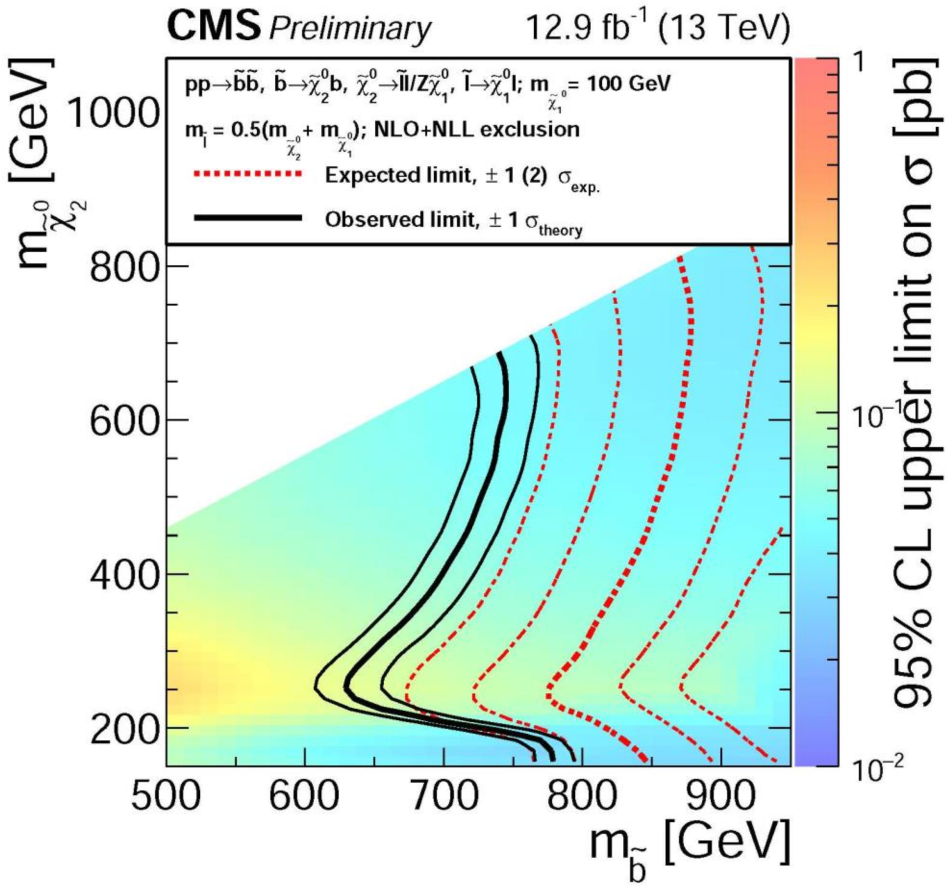
SUS-16-021

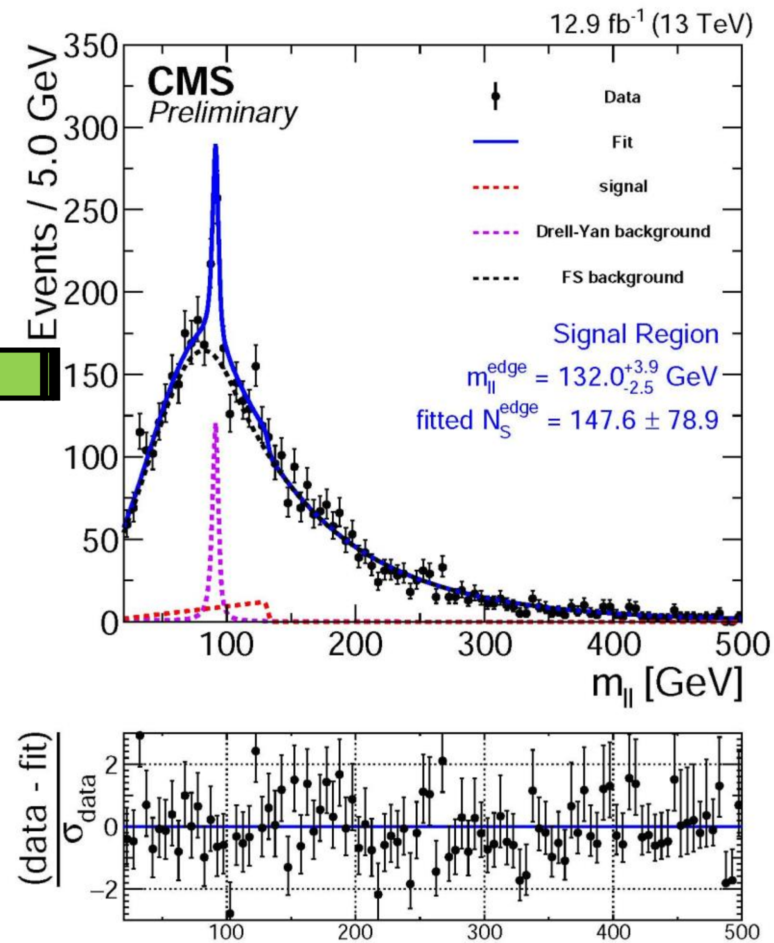


Bottom Squark Decays



SUS-16-021





“Photons + MET” PASes

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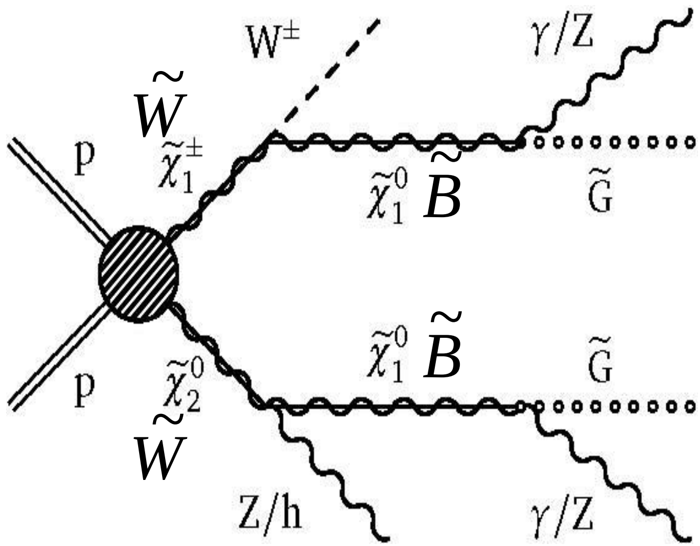
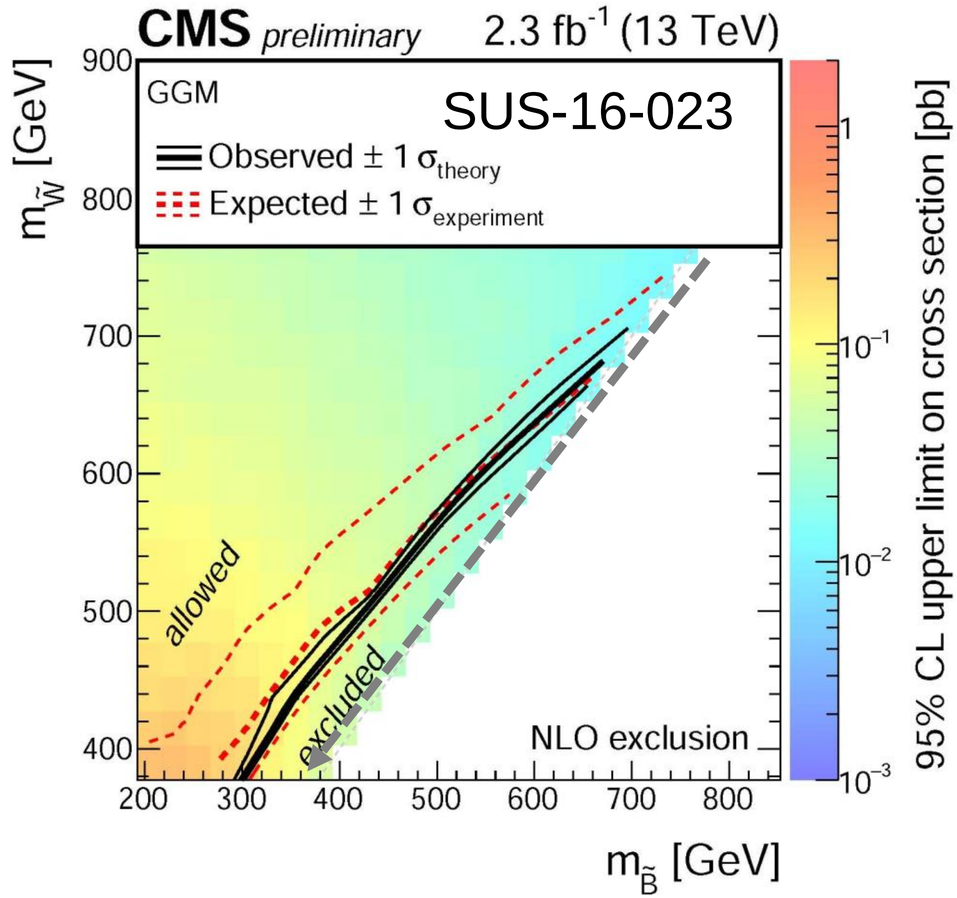
"Photon(s) + MET" Results



- $p_T(\gamma 1) > 180$
- $S_T(\gamma s, MET) > 80$
- $m_T(\gamma 1, MET) > 300$



Summary of Run 2 in 2016

- For MANY more results, see the public result pages: http://cms-results.web.cern.ch/cms-results/public-results/publications/
- We still search for physics beyond the SM (SUSY, DM χ, more) at TeV scale … one of the main motivations for the LHC experiments.

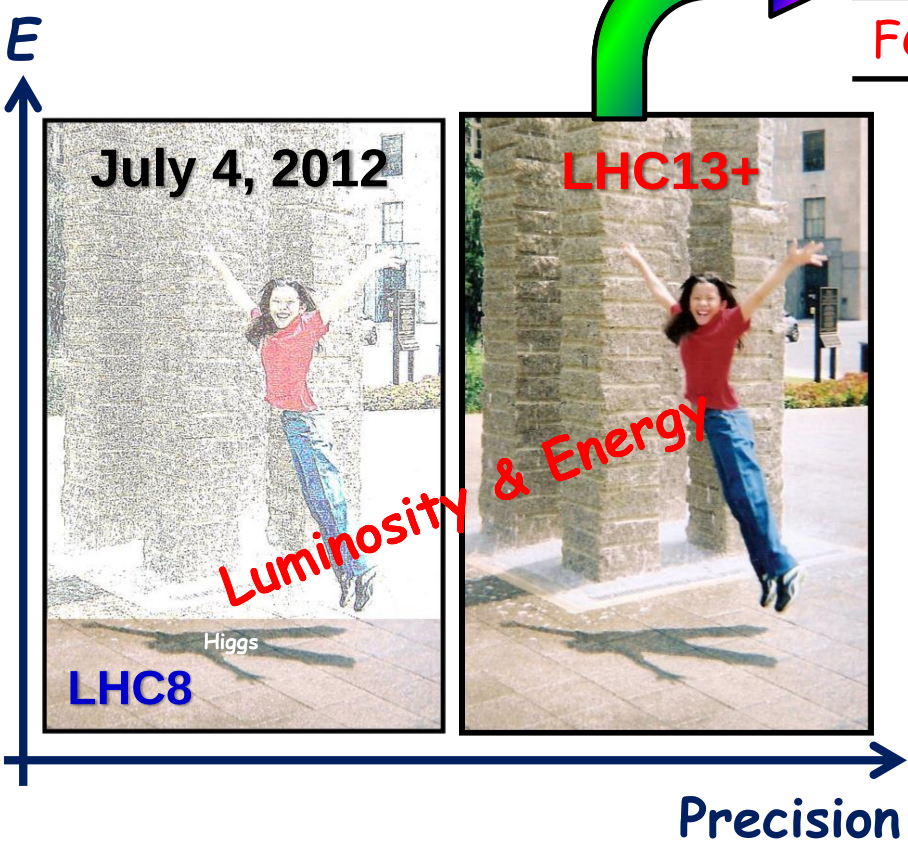
- [13 TeV] CMS covers a large variety of possible final states even with Large pile-up <PU> ~25-50, closing in on challenging scenarios such as compressed SUSY, setting stringent limits on many SUSY scenarios (with a few anomalies?)

Remarks on Run2 and Beyond

Hadron Collider (√s)	Gluino/Squark Mass Reach (M)	M/√s
Tevatron (2 TeV)	~400 GeV	0.20
LHC (8 TeV)	~1.7 TeV	0.21
LHC (14 TeV)	~2.8 TeV*	0.20*
FCC (100 TeV)	~20 TeV*	0.20*

(*) just use a naïve scaling

LHC and beyond will be powerful in producing heavy objects.



Run2 at 13 TeV – the LHC14 is probing a TeV physics: null results on BSM.

Run2 at 13 TeV - Exciting! Understanding the limitations of the LHC13 will be an important step toward the next energy frontier