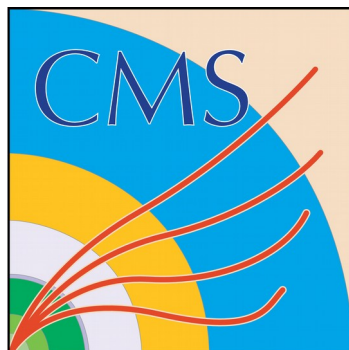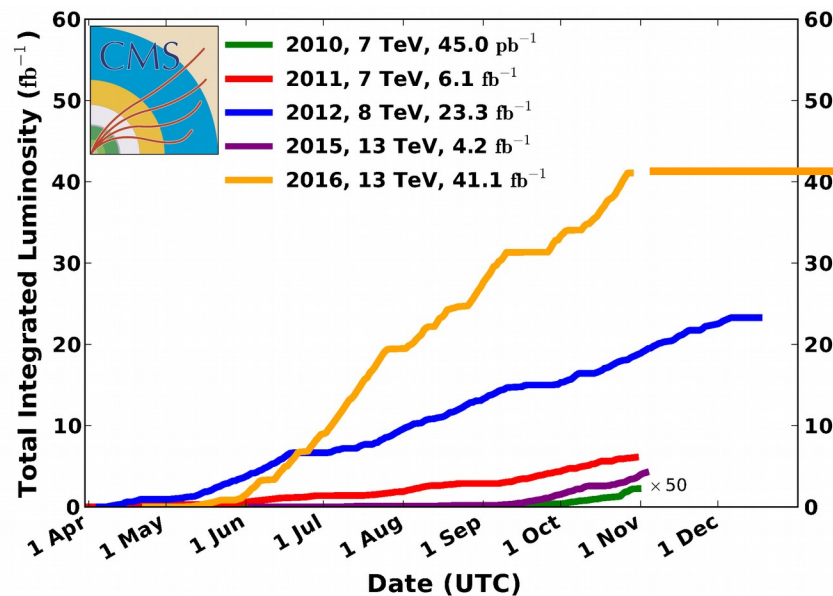# CMS Searches:
Jets, Leptons, Photons

Dominick Olivito
University of California, San Diego

Run 2 represents a sweet spot for (canonical) searches at the LHC

- **2015**: Center of mass energy → 13 TeV
  - Rapid gains in sensitivity for high scale / strong production
- **2016**: large increase in integrated luminosity
  - Thanks to excellent LHC performance
  - Factor ~10 more lumi than 2015, almost ~2 more than Run 1
- Lumi doubling times will be longer from now on
  - Expect additional 1-2x lumi in **2017**
- → **2016** is an interesting and critical year for searches!

35.9 fb^{-1}
After full certification
and offline calibration

Many CMS searches have analyzed the full 2016 dataset of 35.9 fb^{-1}

Strong SUSY

- **0ℓ + jets**
  - H_T/MH_T, **M_{T2}**
  - stop, bb/cc
- 1ℓ + jets: M_J
- 2ℓ + jets: SS, OS stop
- ≥3ℓ + jets
- **γ + jets**
- **H(γγ)+jets**

Electroweak SUSY

- **≥3ℓ**
- **2ℓ (OS soft, SS)**
- **HH(4b)+E_T^{miss}**

Exotic Models

- Dijet resonance
- **$X_{5/3}$ top partner (SS 2ℓ)**
- **Type-III Seesaw (≥3ℓ)**
- W' → tb → bbℓν

+ more covered in Eva's jet substructure talk

Generic Search

- **MUSiC (jets, ℓ, γ, MET)**

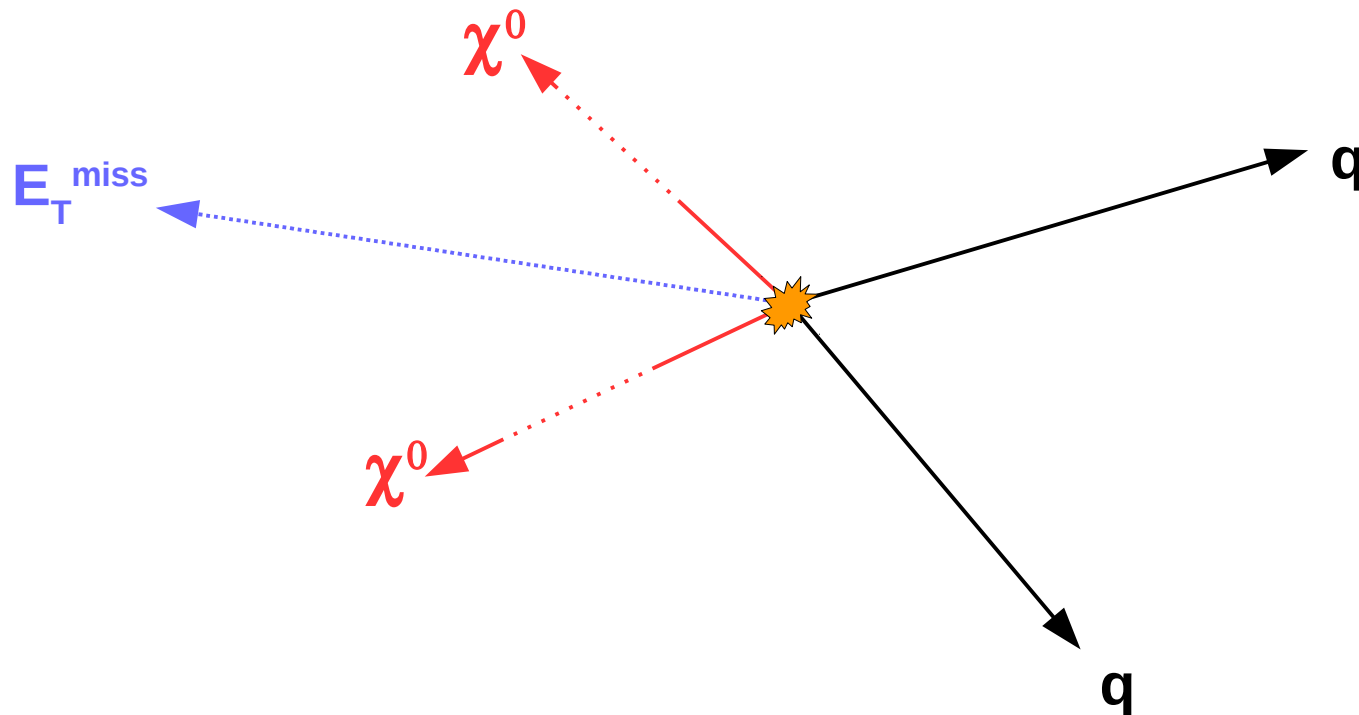**All NEW for this week!**

χ^0

E_T^{miss}

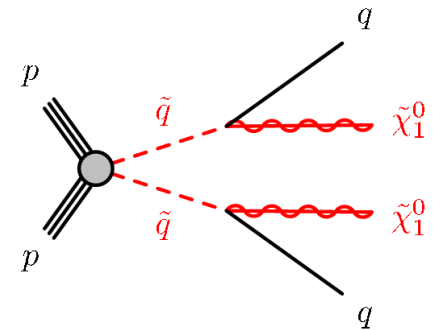**jet**

χ^0

jet
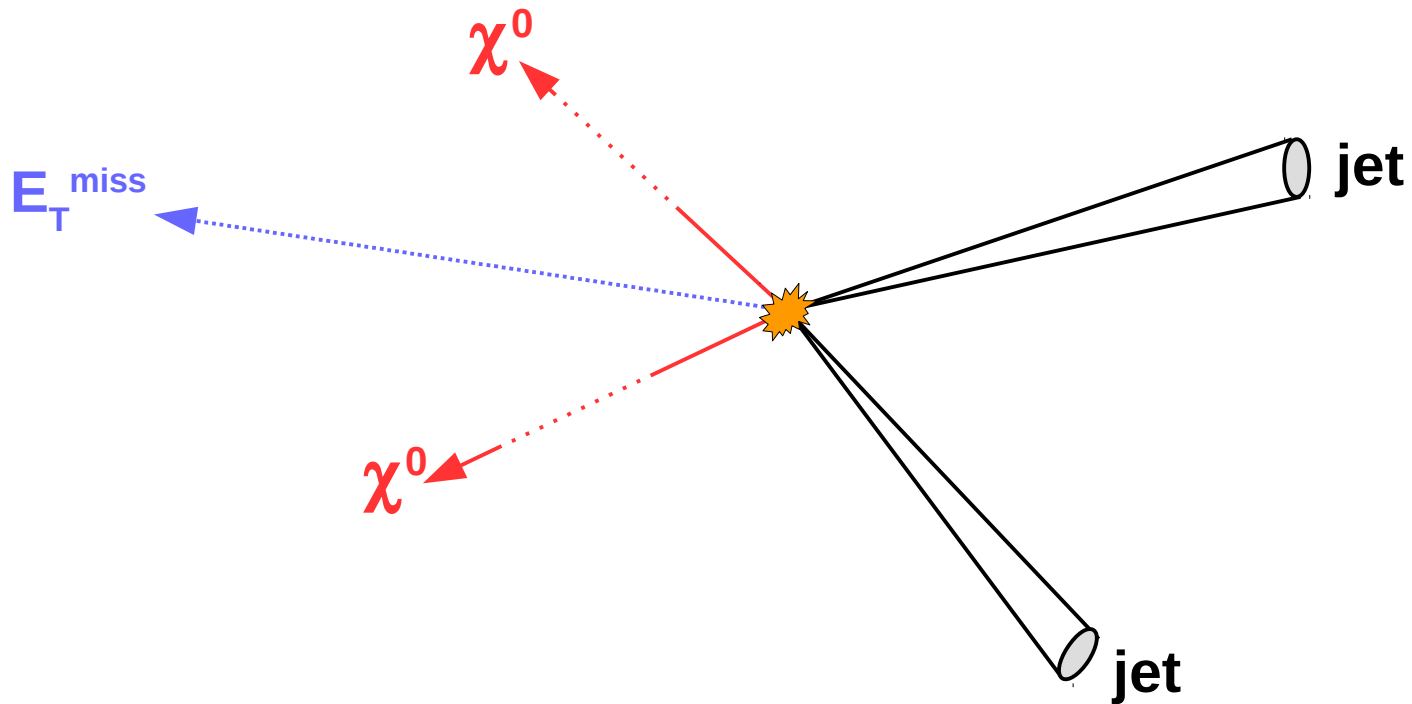
Strong SUSY production

Strong SUSY searches typically look for jets + E_T^{miss} (+ X)
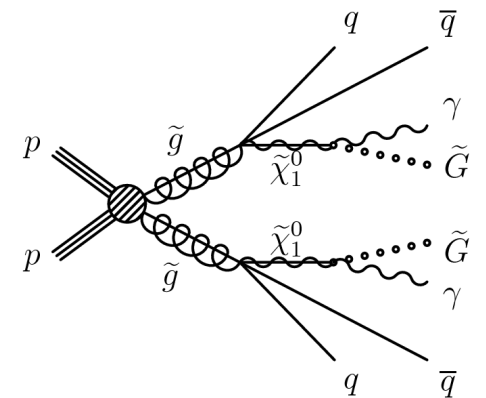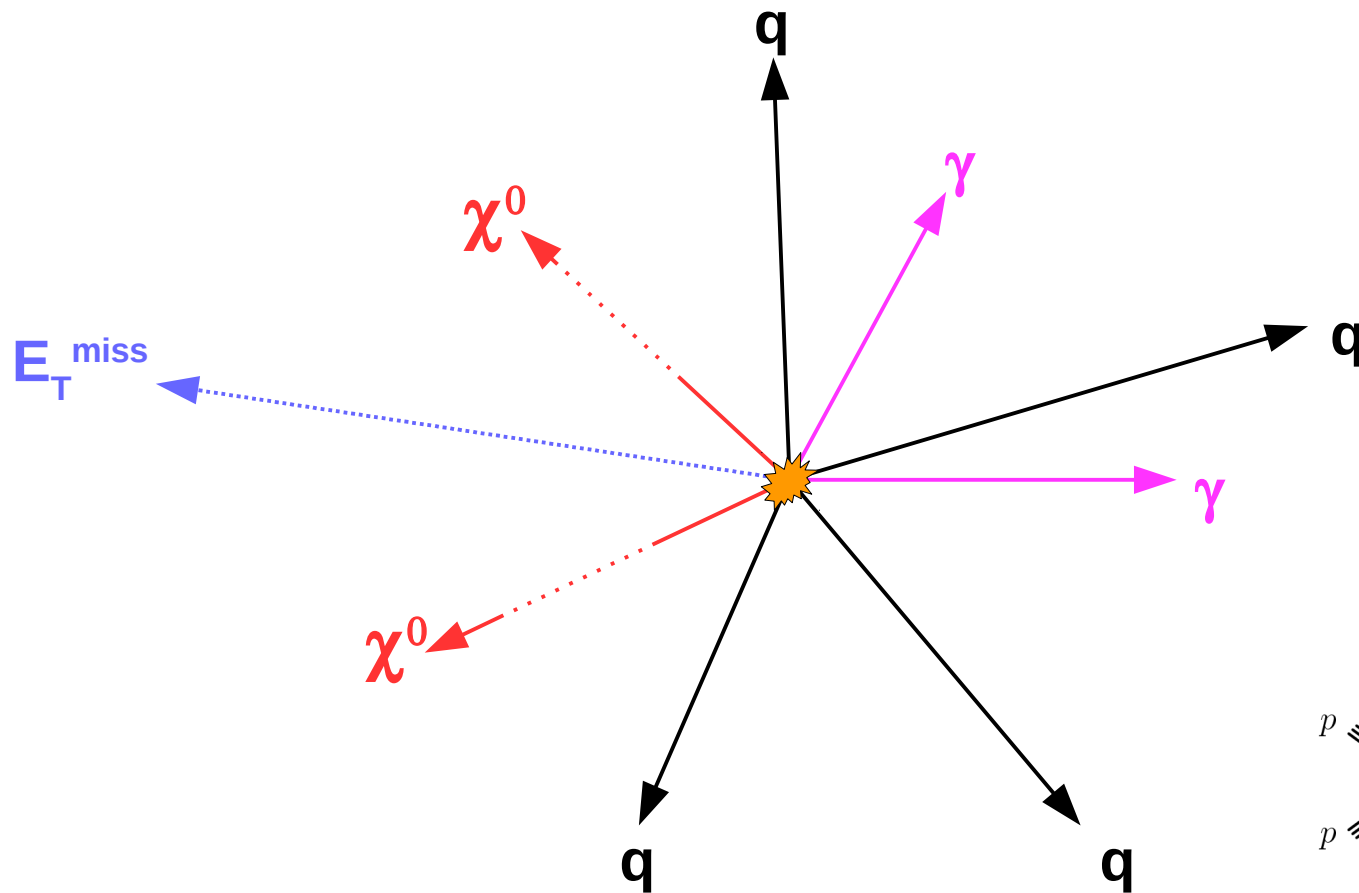
- **LSPs** do not interact and escape the detector (r-parity)
- We infer their presence through an **imbalance in the event**
- Strong production, or initial state radiation → **hadronic jets**

Plane transverse to beam

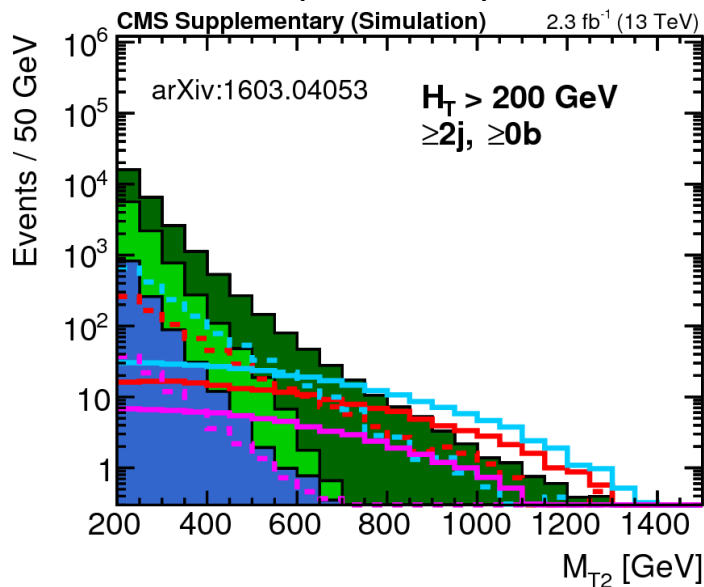# More complicated decay chains lead to busier final states

We categorize events for sensitivity to a broad range of signatures

Example from M_{T2} jets + E_T^{miss} search

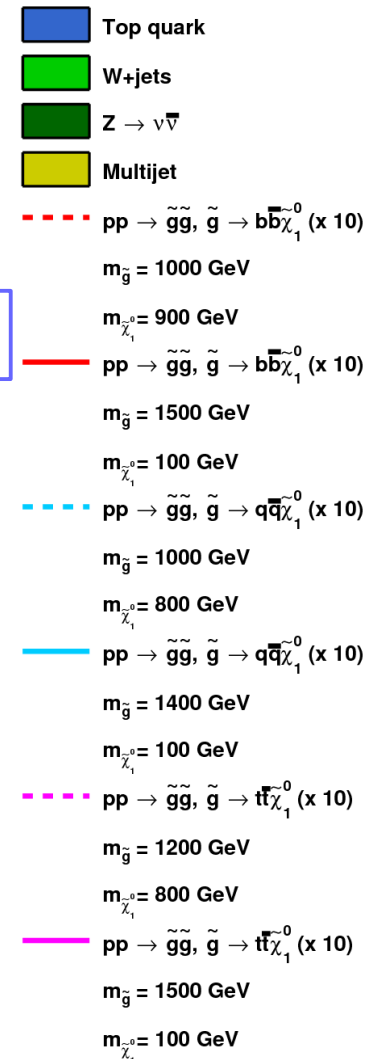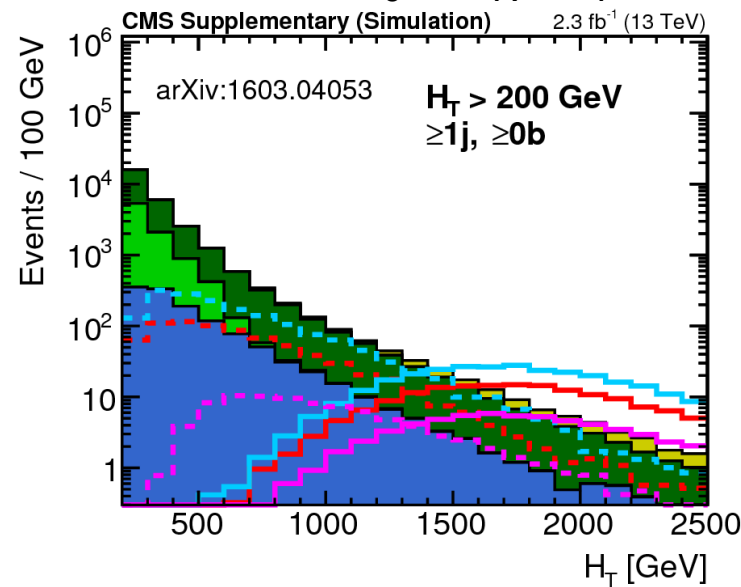Unknown mass scale and mass splittings for new physics

M_{T2}: invisible energy scale
Also: E_T^{miss}, H_T^{miss}, R^2
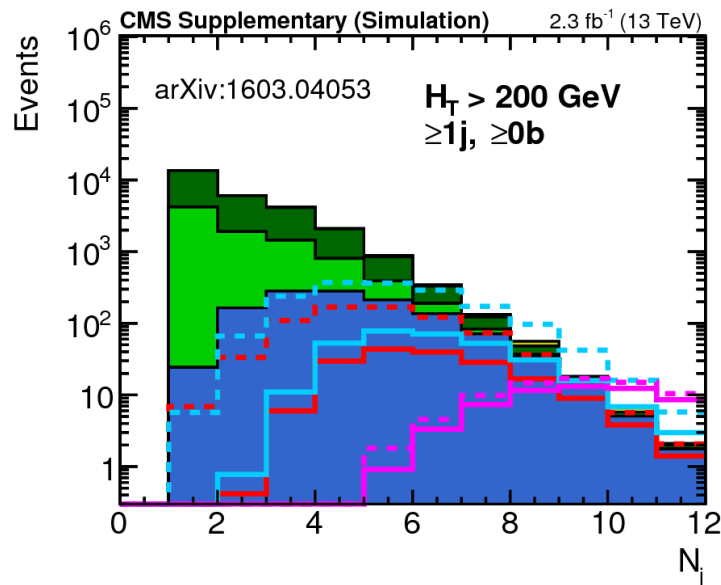
H_T: visible energy scale
Also: M_J, M_R, p_T^{jet}

We categorize events for sensitivity to a broad range of signatures
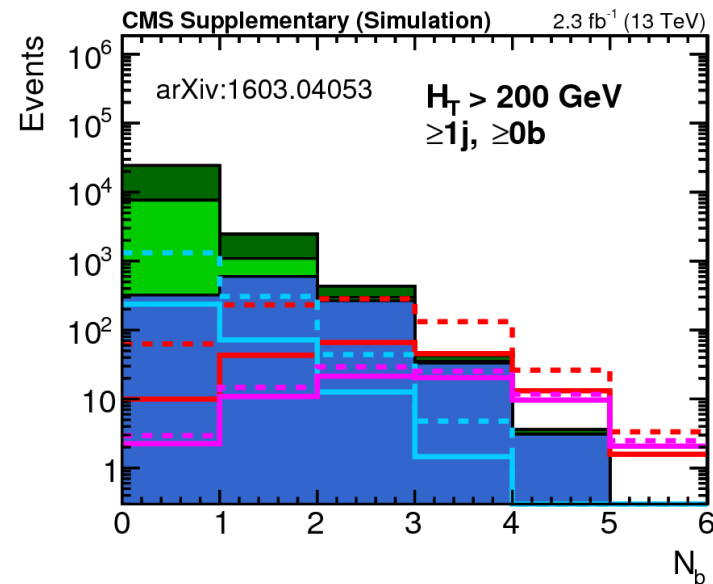
Unknown parton multiplicity

N_J: number of jets

Top quark

W+jets

$Z \rightarrow \nu \bar{\nu}$

Multijet

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1000 GeV

$m_{\tilde{\chi}_1^0}$ = 900 GeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1500 GeV

$m_{\tilde{\chi}_1^0}$ = 100 GeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1000 GeV

$m_{\tilde{\chi}_1^0}$ = 800 GeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1400 GeV

$m_{\tilde{\chi}_1^0}$ = 100 GeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1200 GeV

$m_{\tilde{\chi}_1^0}$ = 800 GeV

$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (x 10)

$m_{\tilde{g}}$ = 1500 GeV

$m_{\tilde{\chi}_1^0}$ = 100 GeV

8

We categorize events for sensitivity to a broad range of signatures
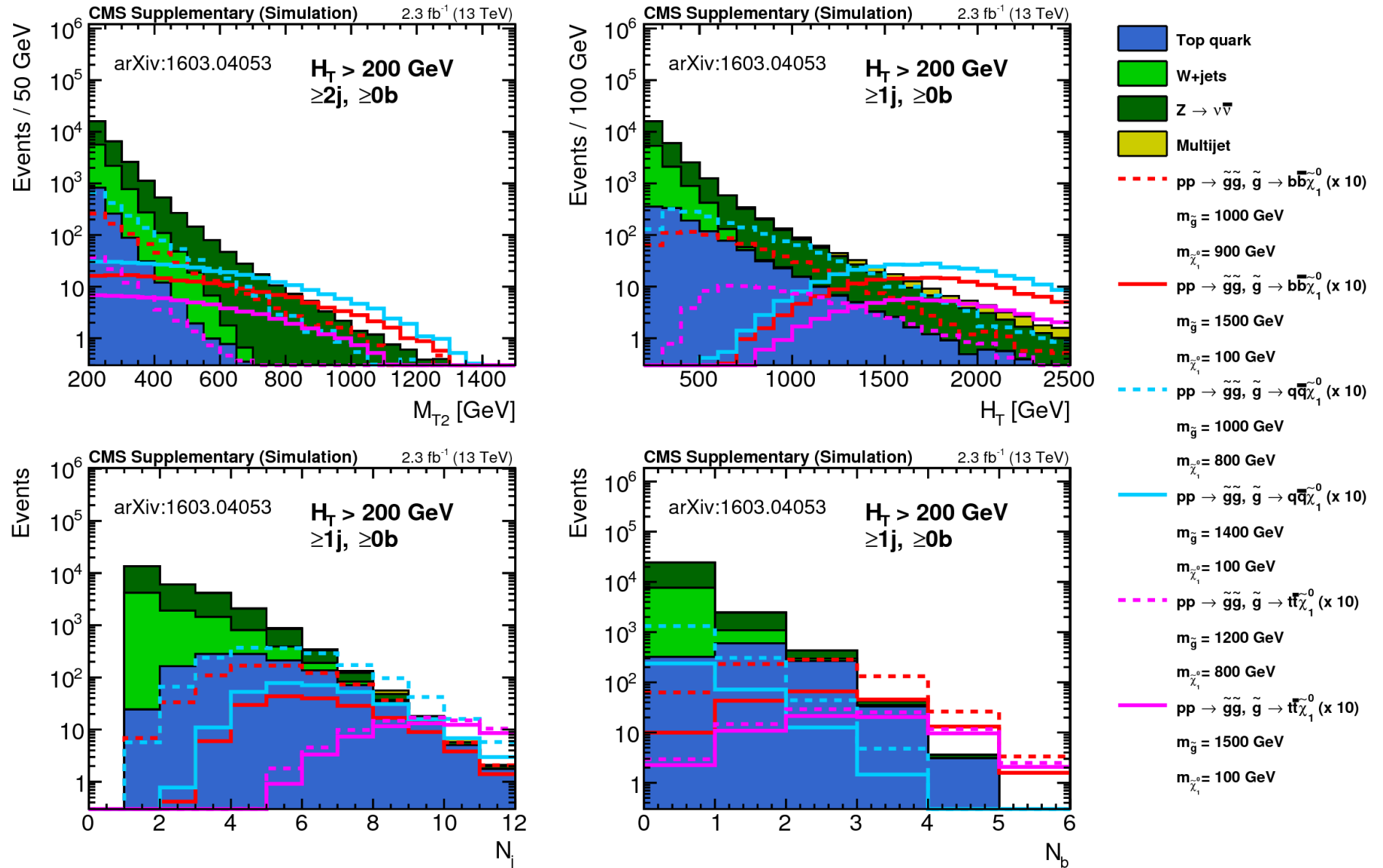
Unknown flavor content

N_B: number of b-tagged jets
Also: top tags, charm tags, secondary vertices

CMS Supplementary (Simulation)   2.3 fb^{-1} (13 TeV)

arXiv:1603.04053 H_T > 200 GeV
                          ≥1j, ≥0b

Top quark
W+jets
$Z \rightarrow \nu\bar{\nu}$
Multijet
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1000 GeV
$m_{\tilde{\chi}_1^0}$ = 900 GeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1500 GeV
$m_{\tilde{\chi}_1^0}$ = 100 GeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1000 GeV
$m_{\tilde{\chi}_1^0}$ = 800 GeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1400 GeV
$m_{\tilde{\chi}_1^0}$ = 100 GeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1200 GeV
$m_{\tilde{\chi}_1^0}$ = 800 GeV
$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ (x 10)
$m_{\tilde{g}}$ = 1500 GeV
$m_{\tilde{\chi}_1^0}$ = 100 GeV

9

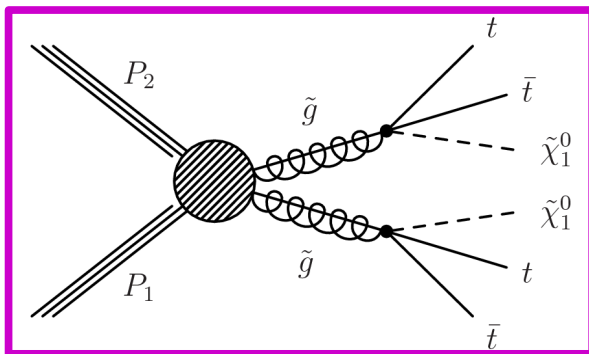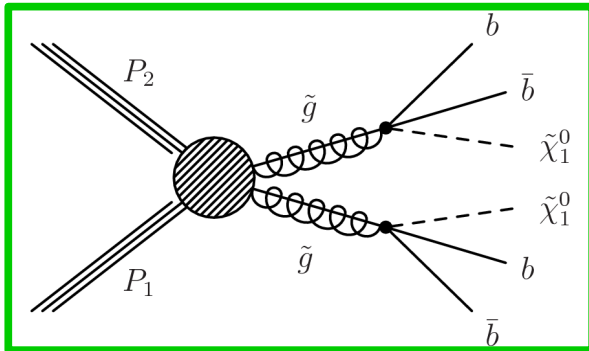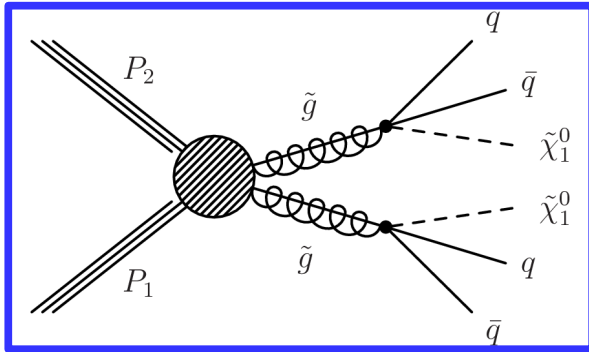# We categorize events for sensitivity to a broad range of signatures

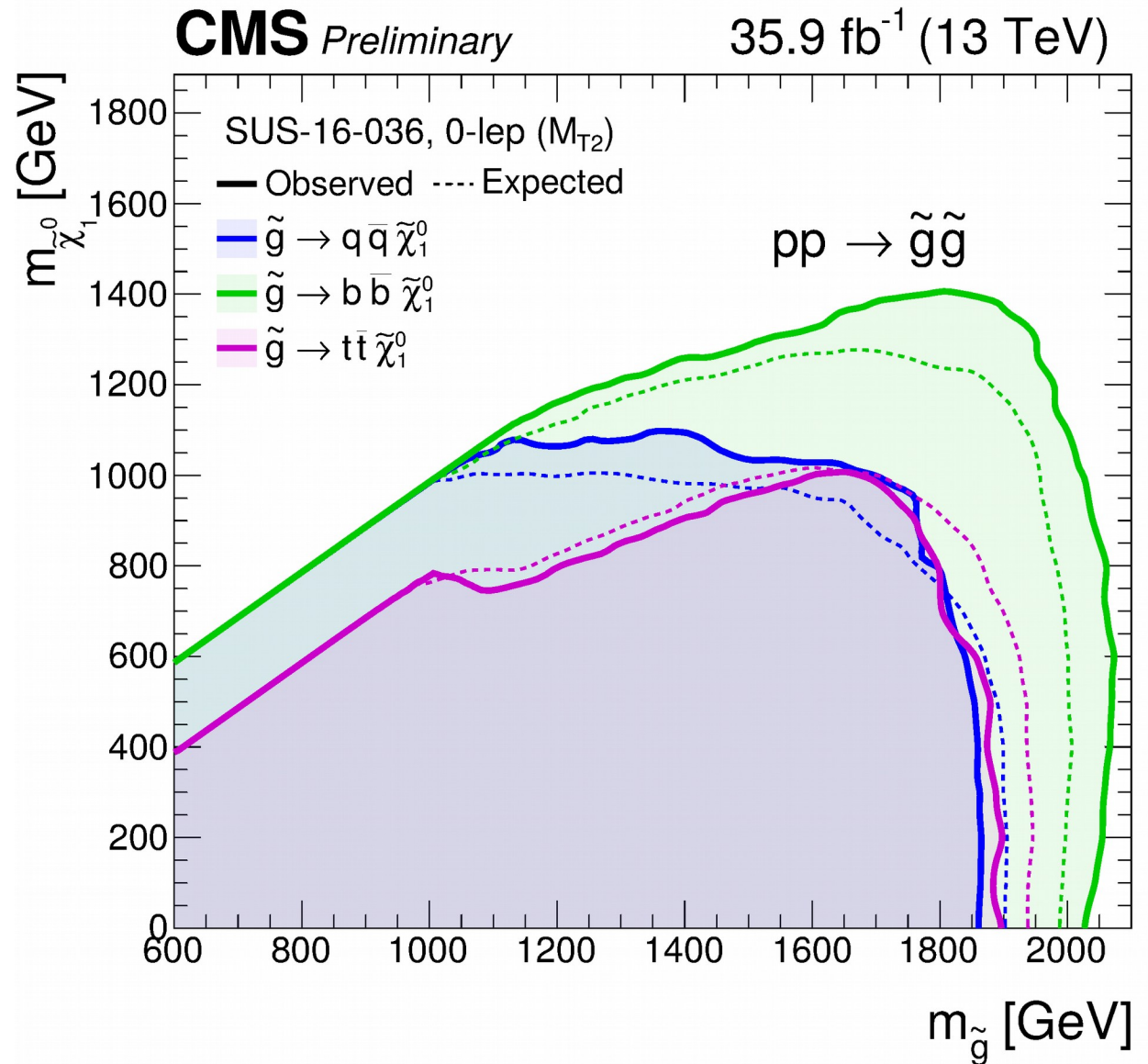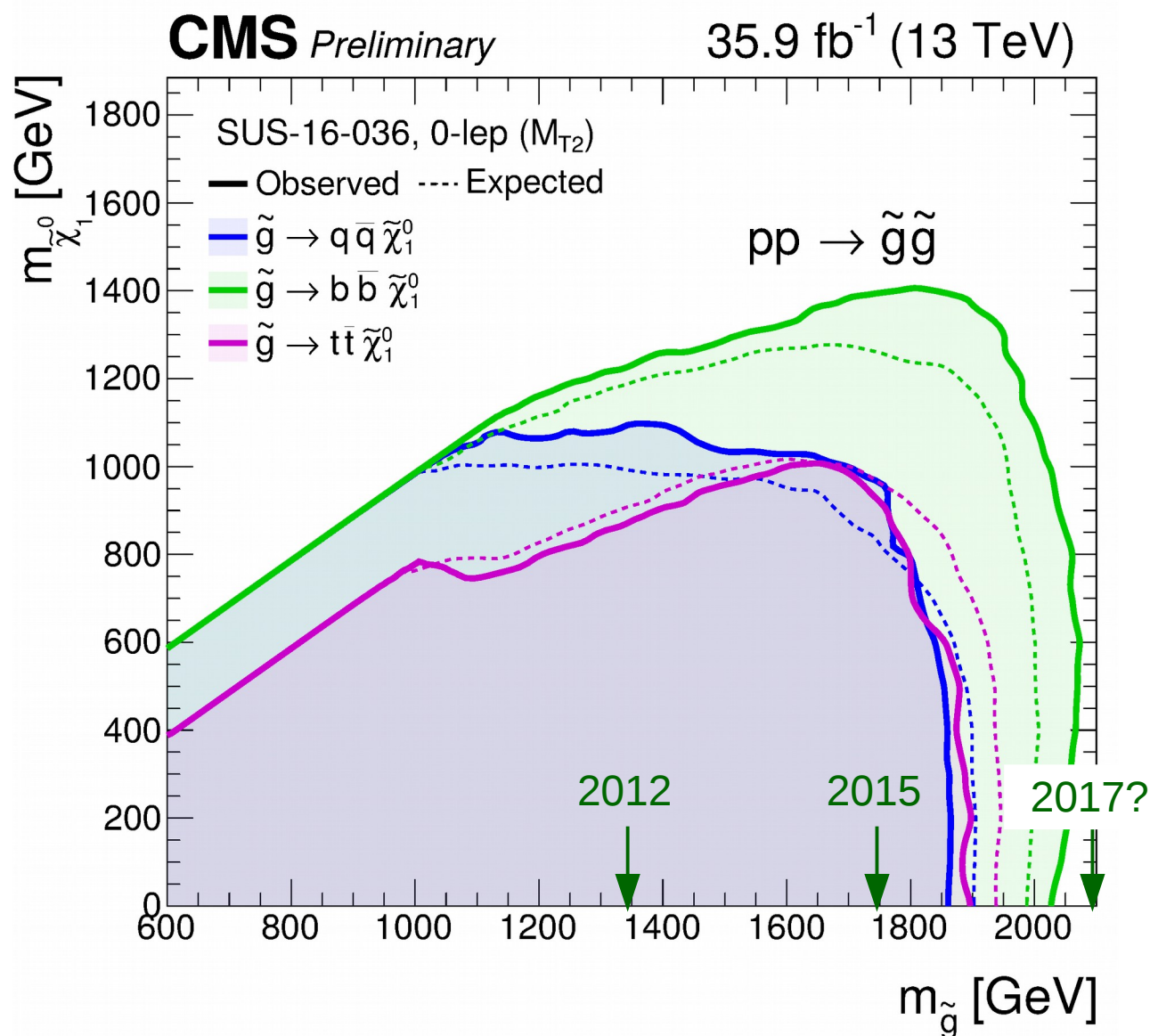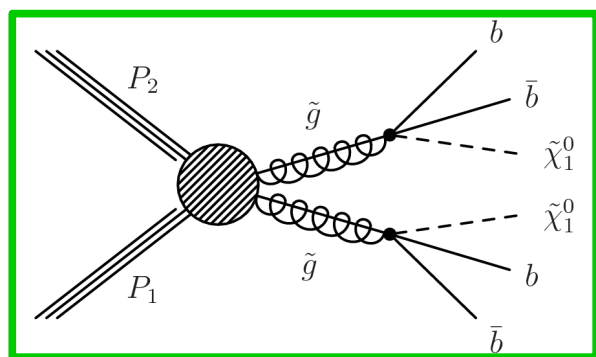# M$_{T2}$ search results: collapsing the M$_{T2}$ dimension

SUS-16-036

11
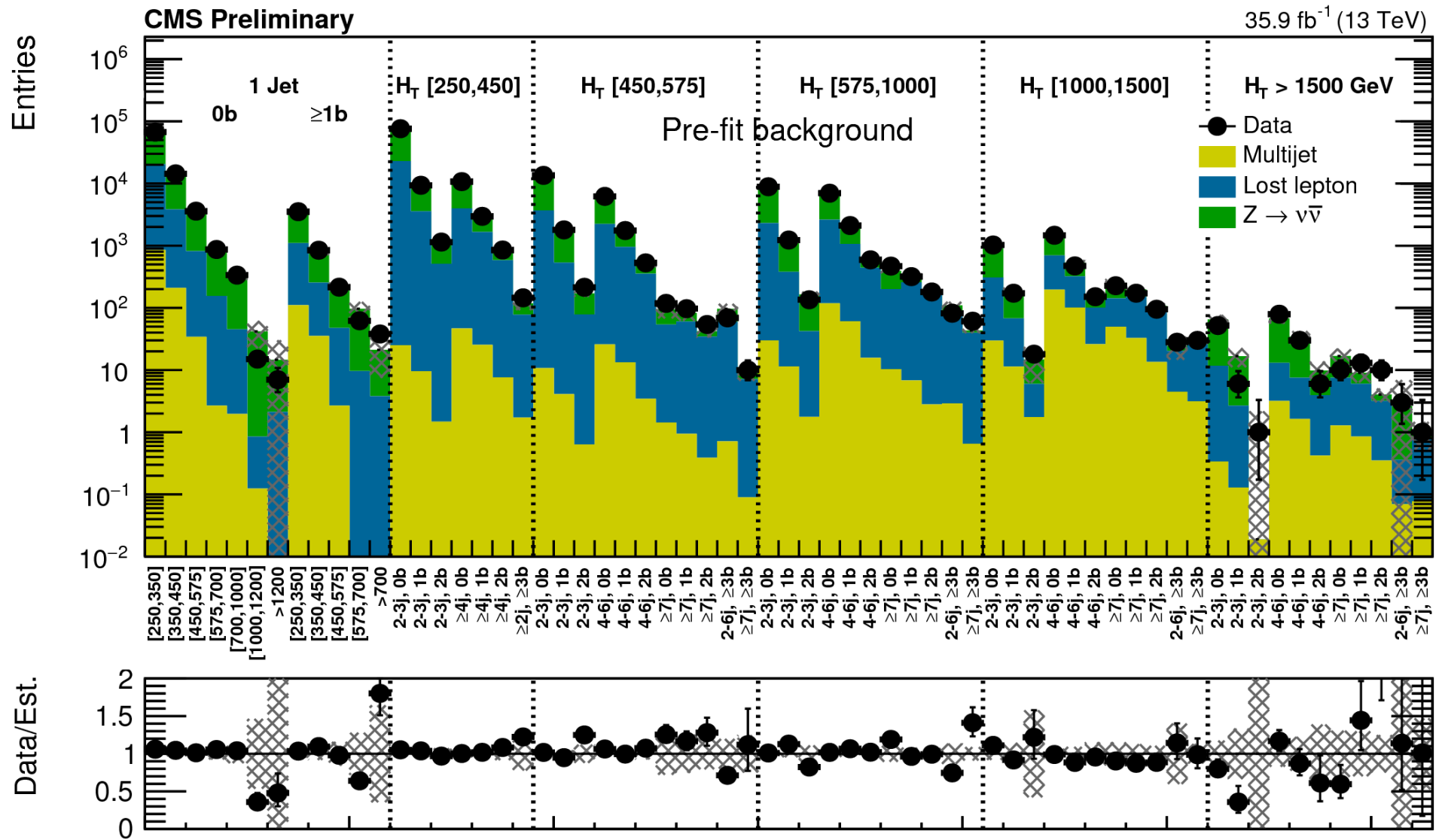
# We exclude gluino masses up to 2 TeV, depending on their decays

# Sensitivity has increased rapidly, now expect ~100 GeV for 3x more lumi

# γ+H$_T$ search is broadly sensitive to strong production with photon decays

- Require high p$_T$(γ), H$_T$, E$_T^{miss}$
- Instrumental E$_T^{miss}$ backgrounds predicted from multijet events
- Electroweak backgrounds from MC (Wγ, Zγ, etc)
- No significant deviations in E$_T^{miss}$ tails
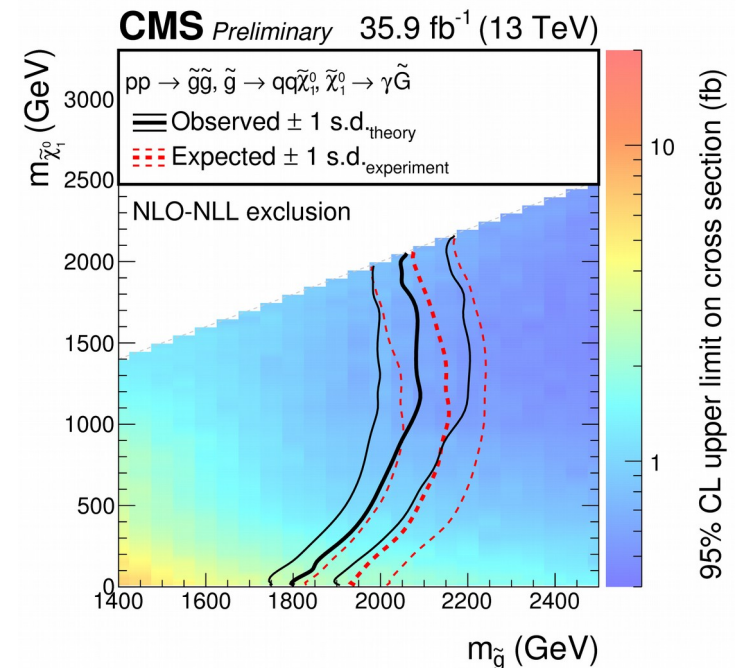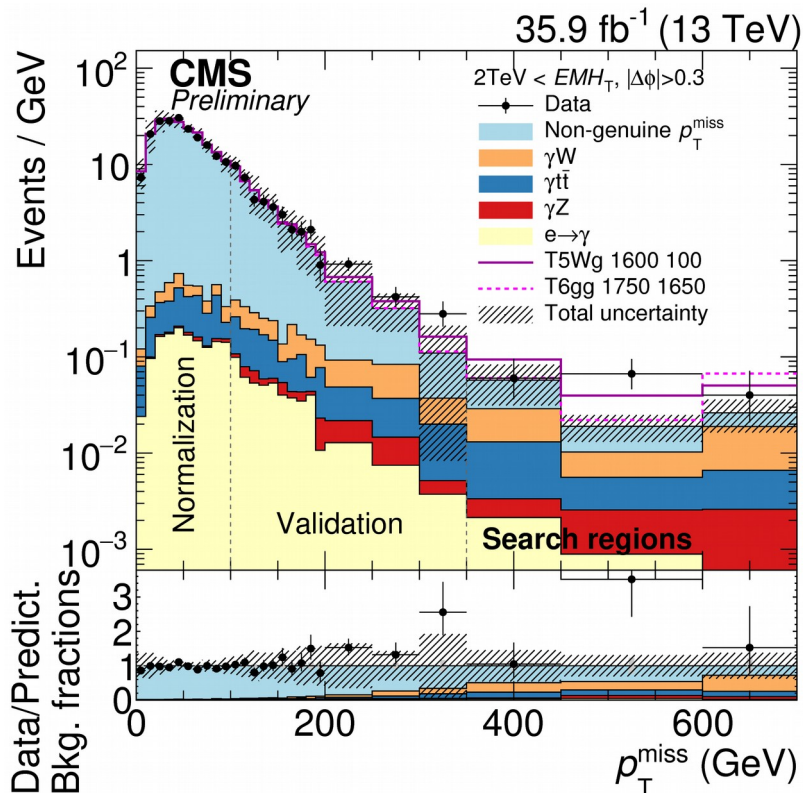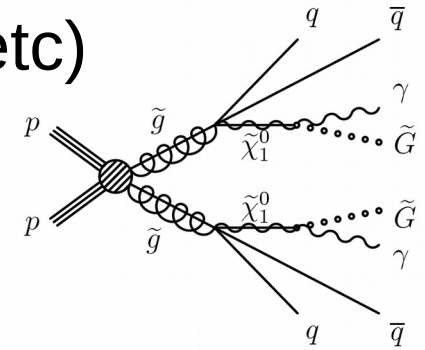
Razor H($\gamma\gamma$)+jets search targets both strong and ewk production

- Categories based on diphoton p_T and resolution, presence of bb pair, then kinematically split using razor vars M_R and R^2
- Non-resonant backgrounds from fitting $M_{\gamma\gamma}$
- Resonant H($\gamma\gamma$) backgrounds from MC
- No significant deviations seen

SUS-16-045
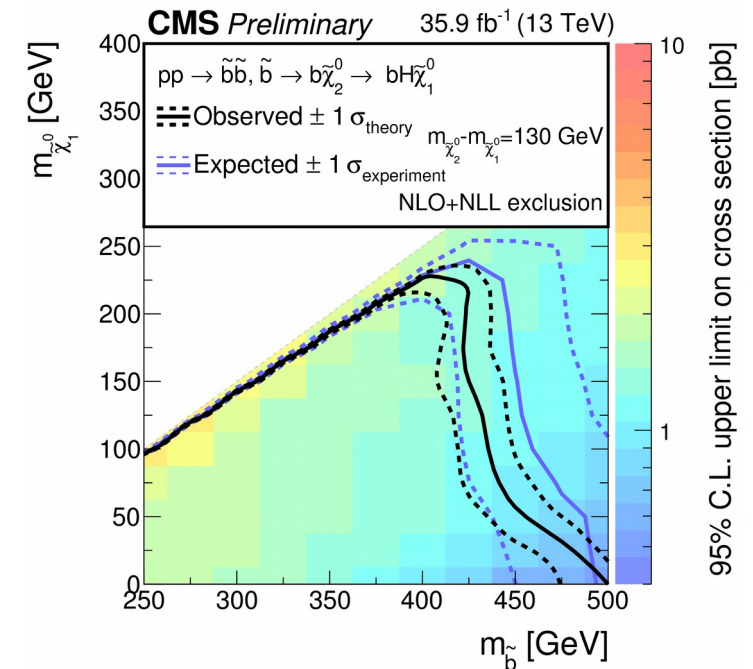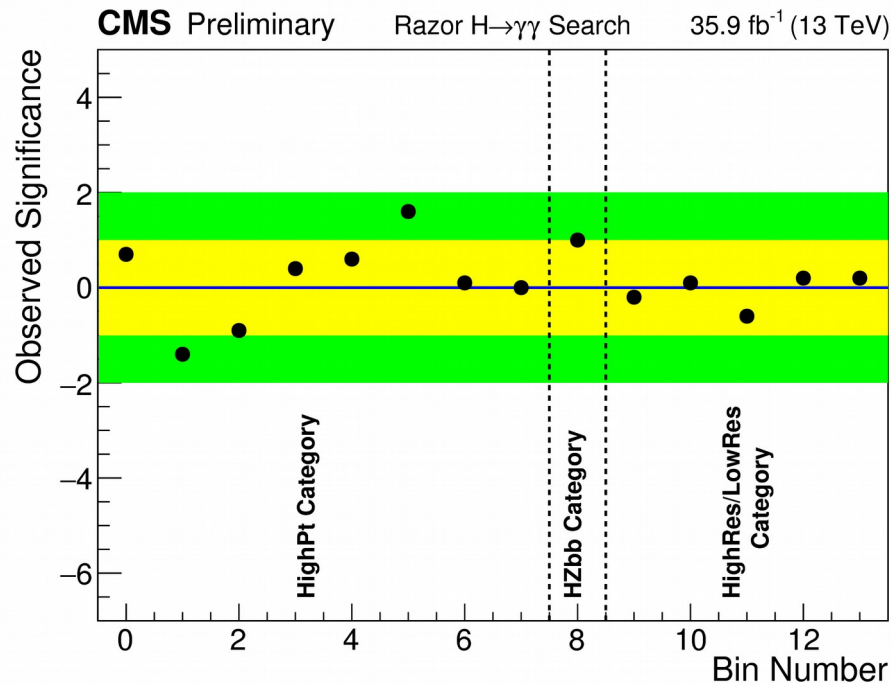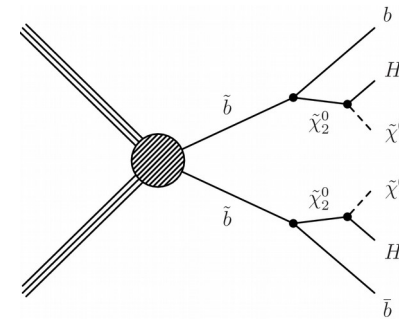
Several more strong searches, no compelling deviations from SM

16
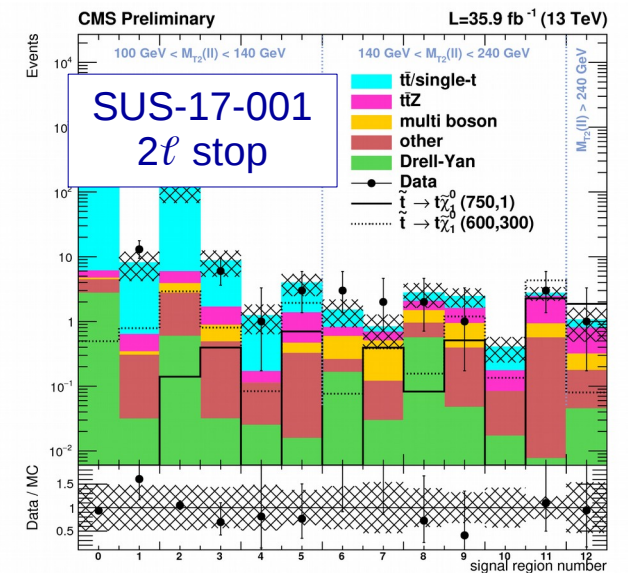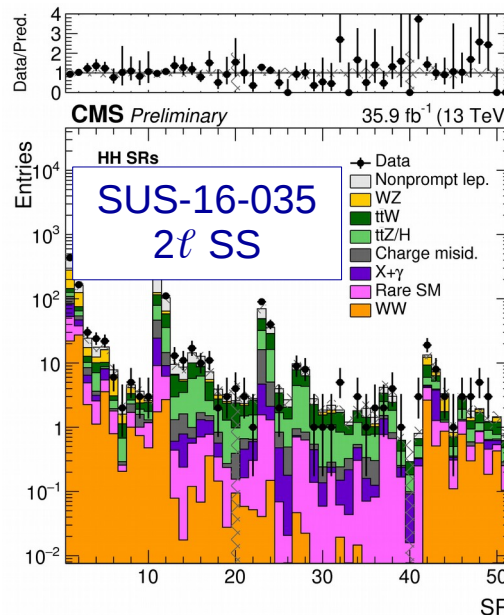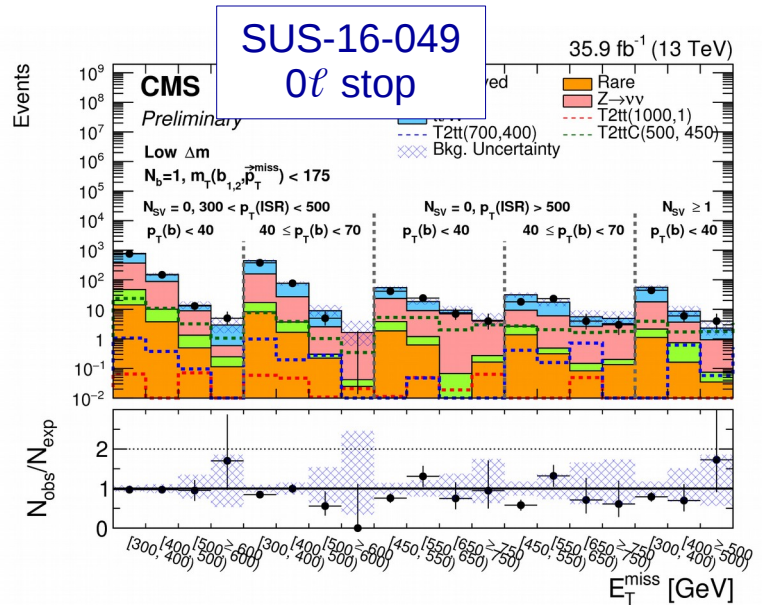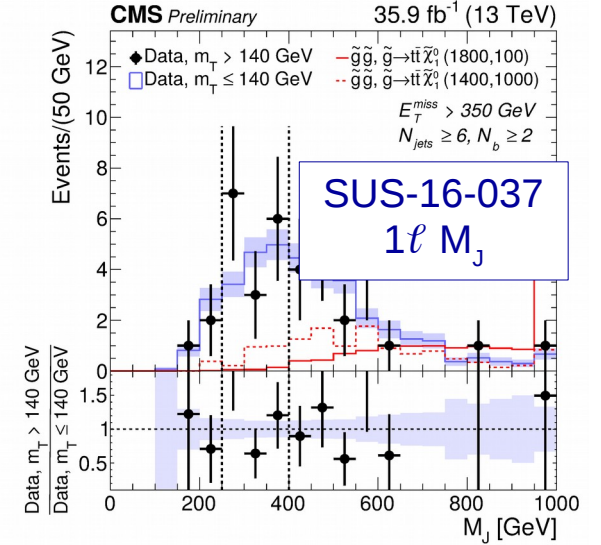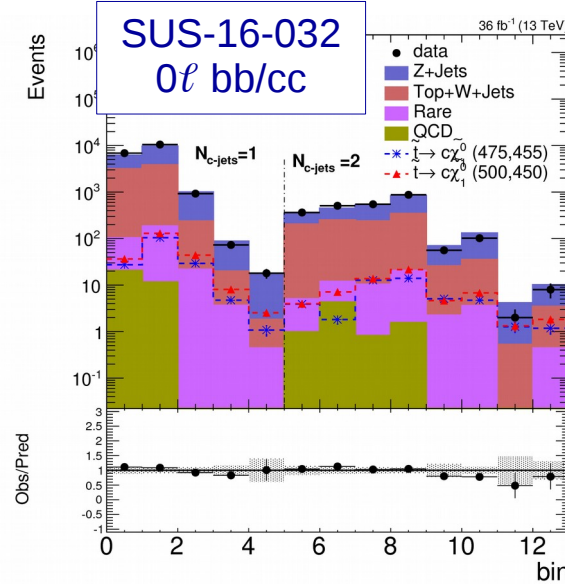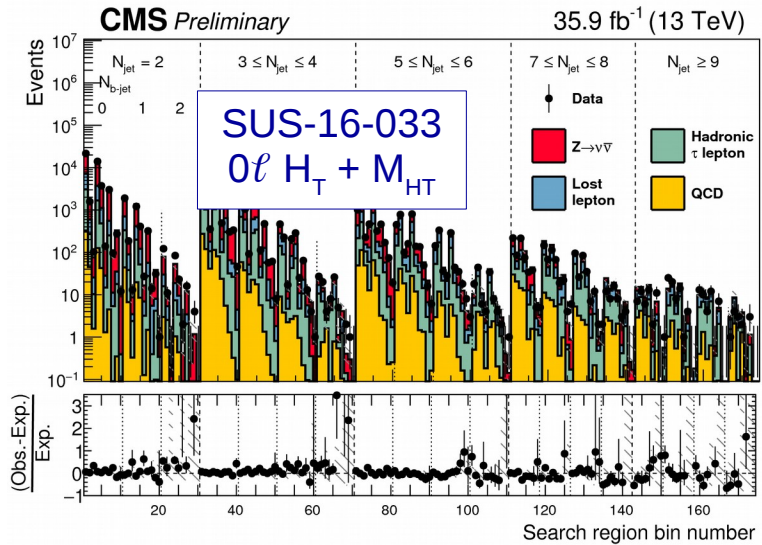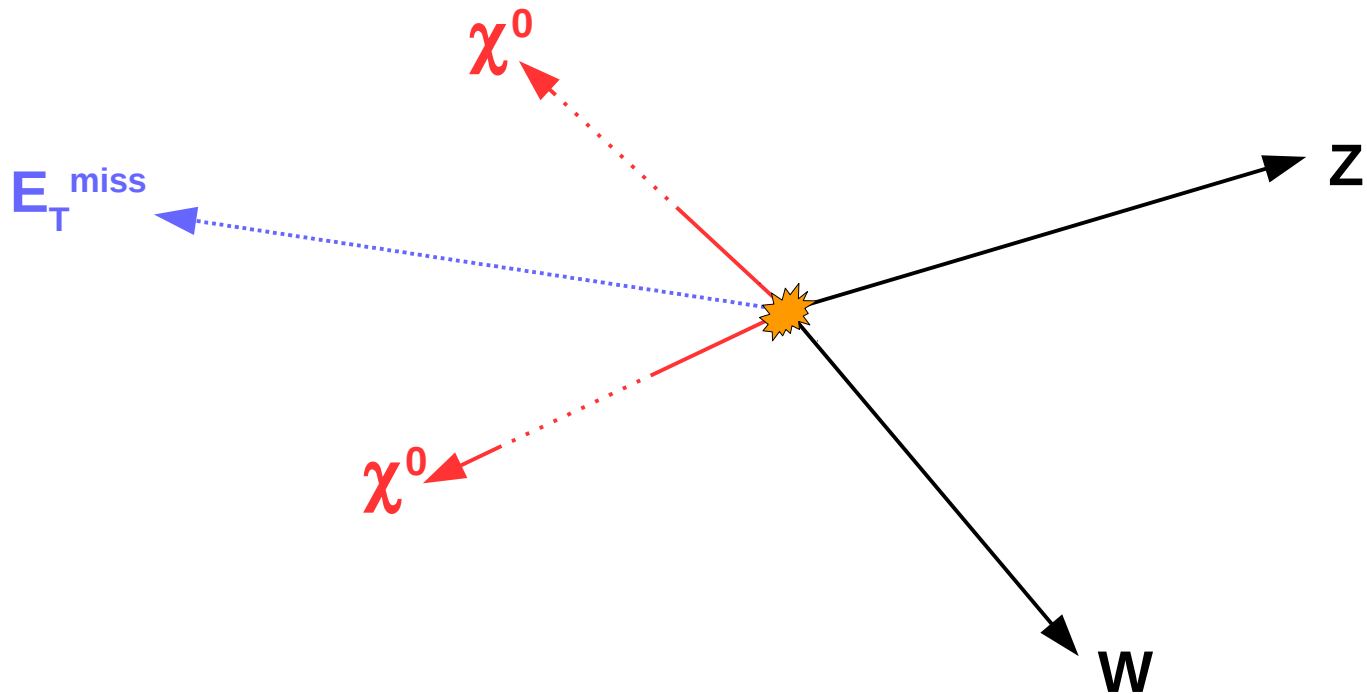
Electroweak SUSY production

Typical signatures: many leptons, and/or multiple bosons (W, Z, H, γ)

Low mass sleptons:
- High branching fraction to leptons (e, μ, τ) and neutrinos
- Strongest constraints, from multilepton analysis
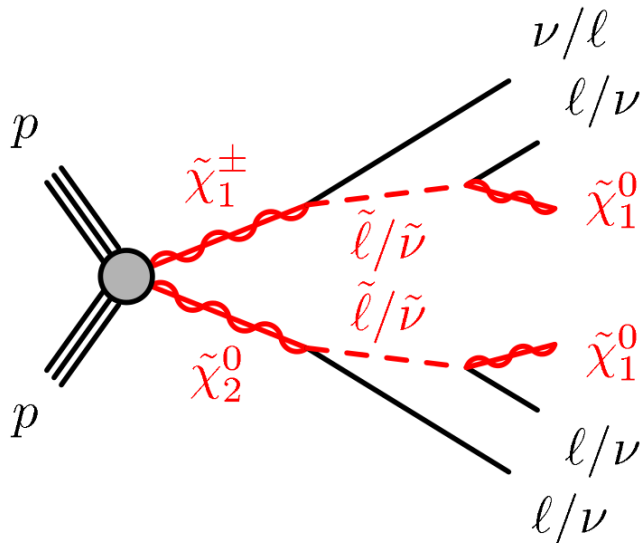
Sleptons decoupled:
- Decays go through bosons
- Many different final states from boson decays, often with leptons
- Broad program of searches
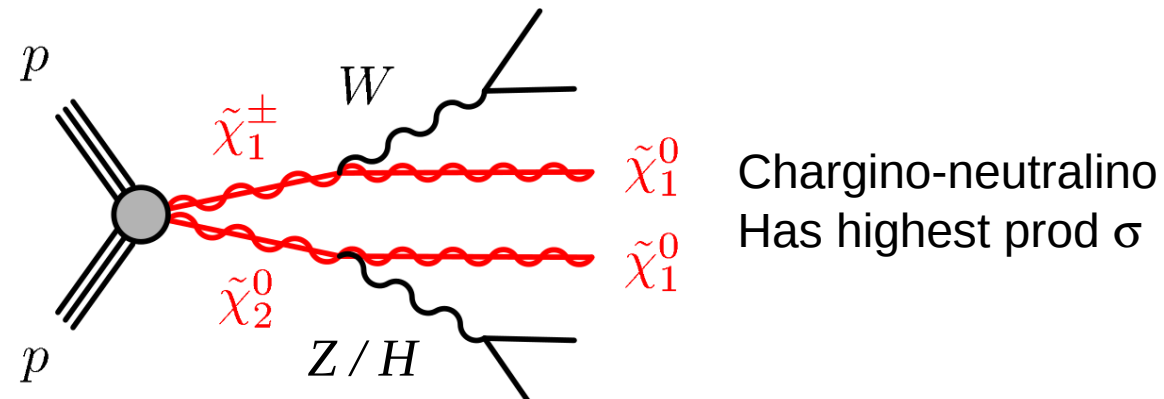
Chargino-neutralino
Has highest prod σ

GMSB / GGM Model
massless Gravitino
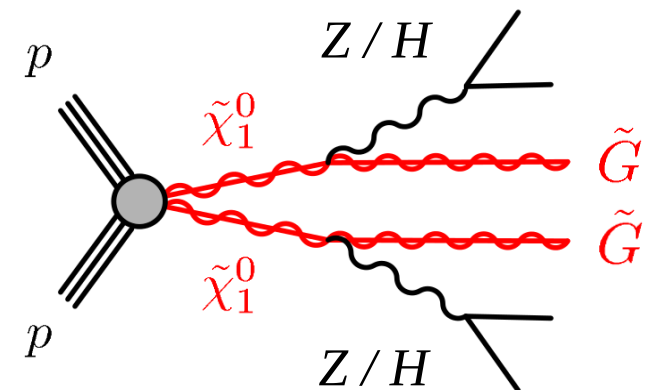
SUSY multilepton analysis uses many categories targeting varied signatures
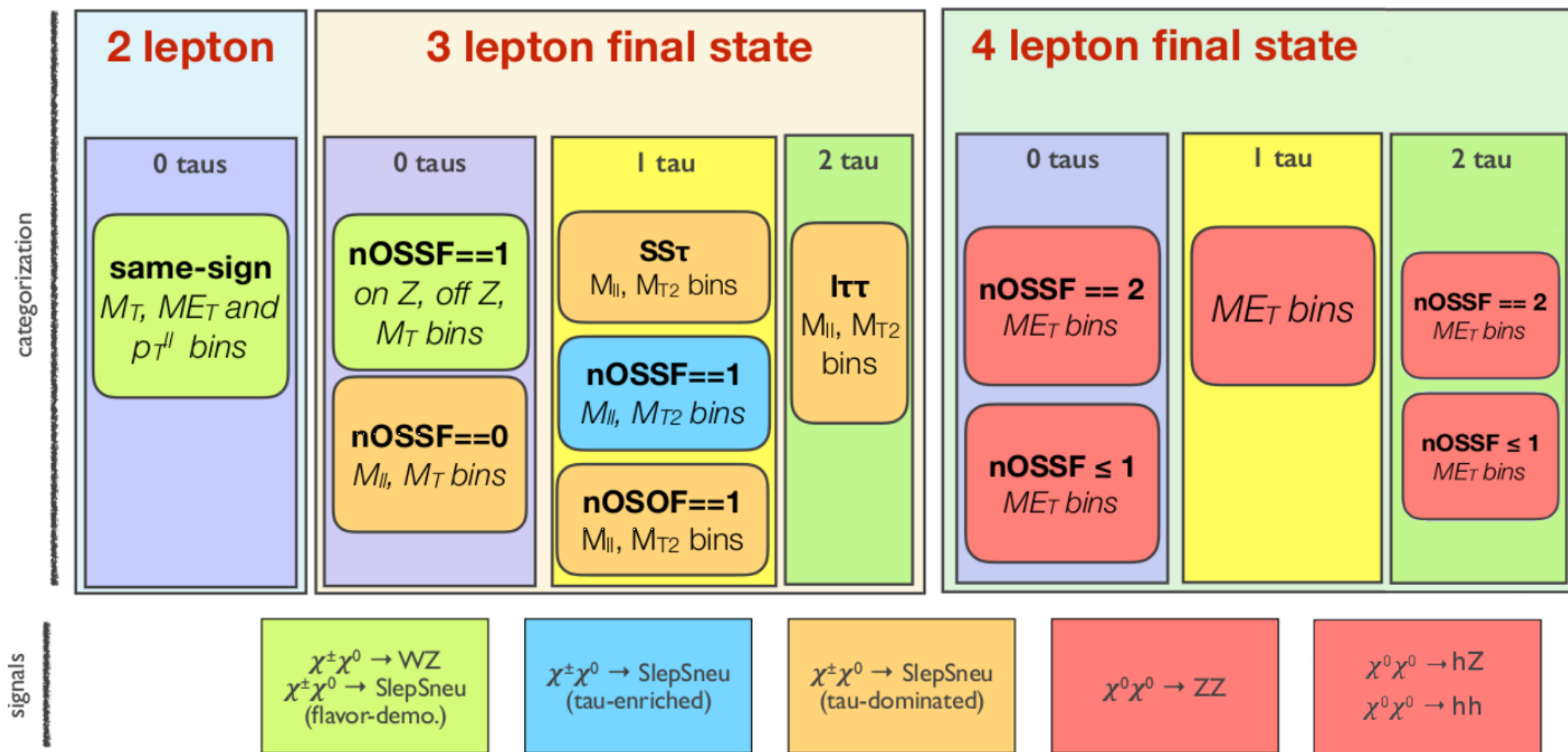
Total of 158 exclusive bins

SUS-16-039

SUSY multilepton analysis uses many categories targeting varied signatures
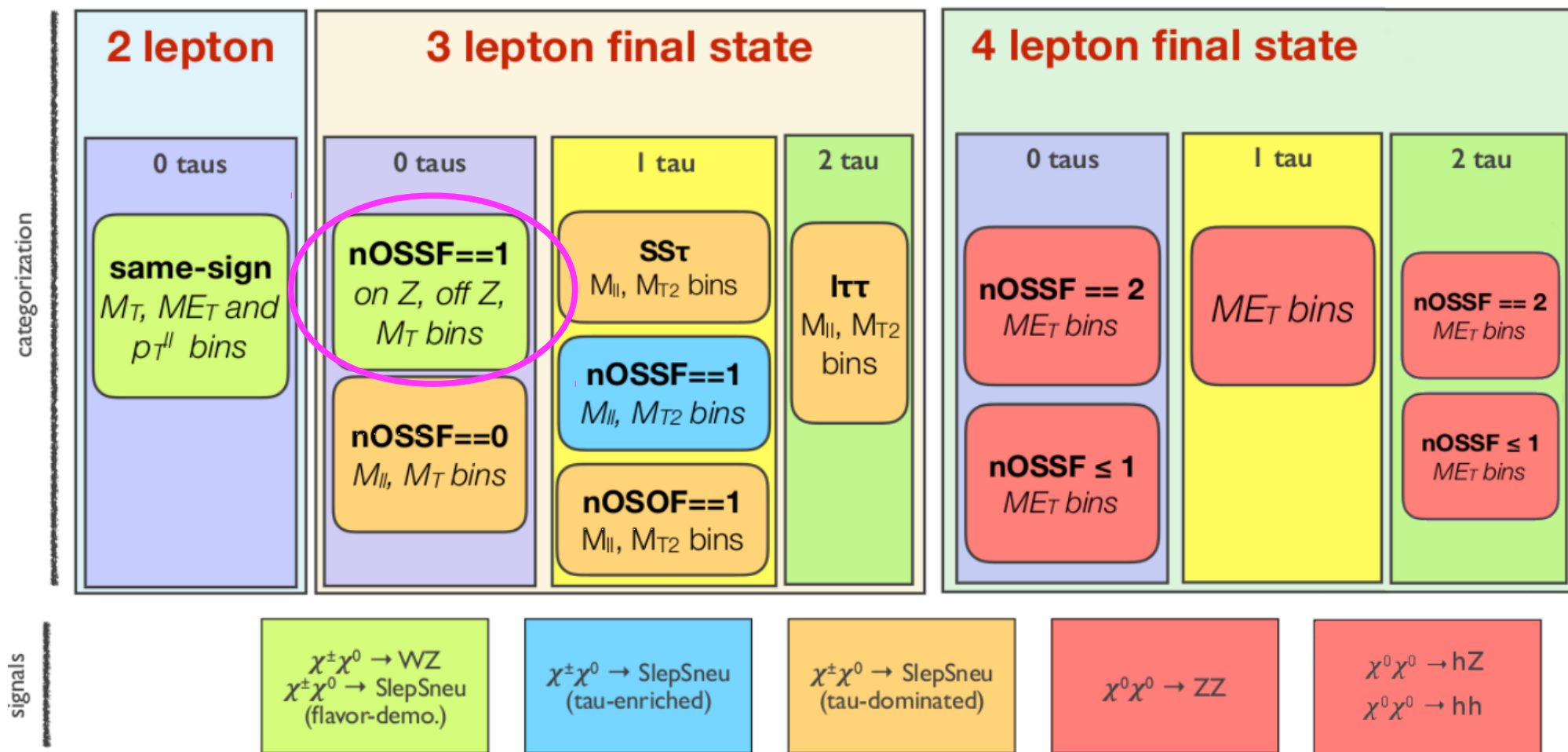
Total of 158 exclusive bins

No significant deviations are seen in the multilepton analysis

Events with no taus and an OSSF pair
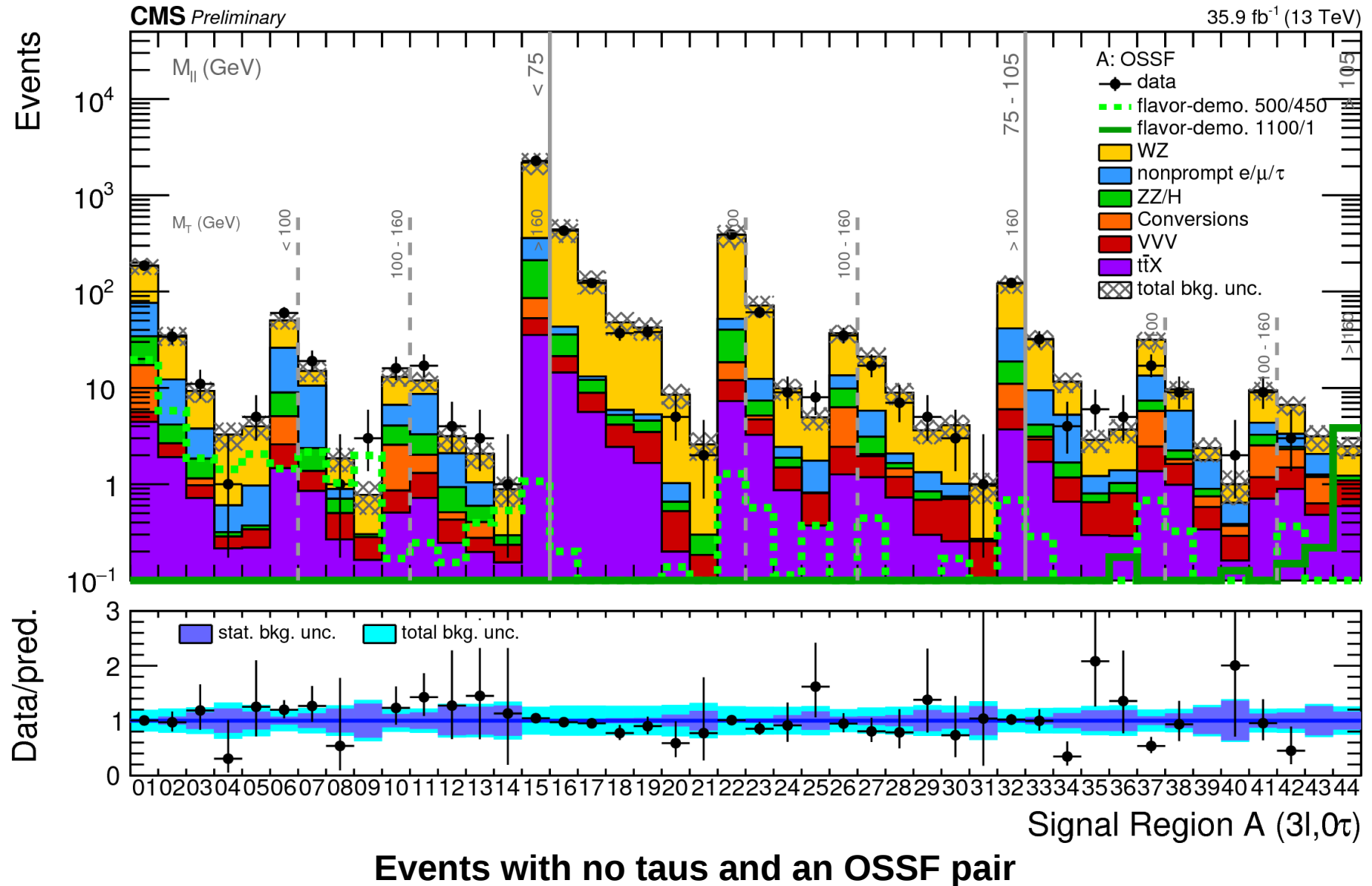
For small mass splittings, rely on boost from an ISR jet to see soft $\ell^+\ell^-$
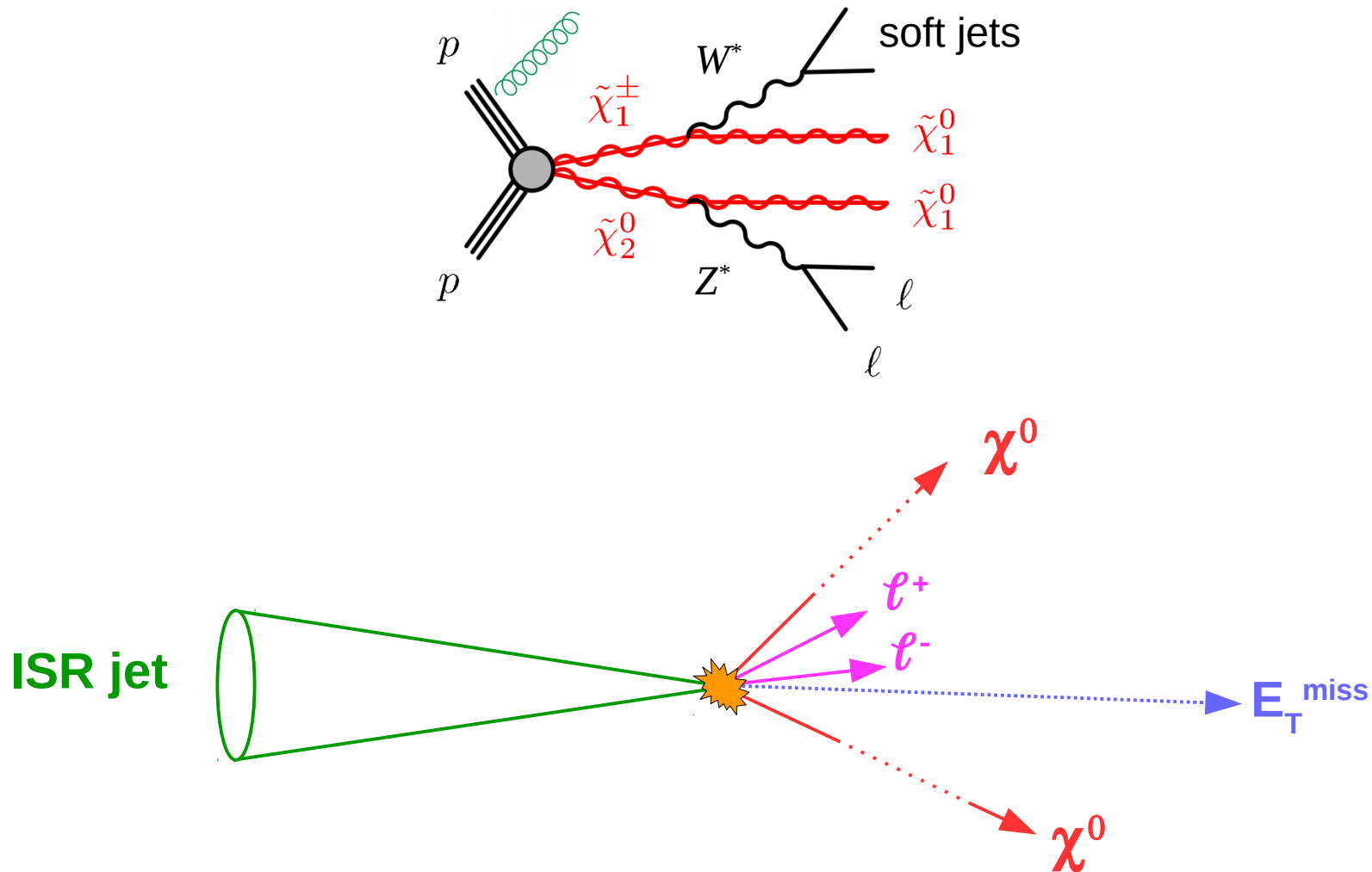
Soft $\ell^+\ell^-$ search uses dedicated trigger to access to low E_T^{miss}

- Non-prompt background from fake-rate method
- ttbar and DY backgrounds constrained by control regions
- No significant deviations observed

MET (GeV)

E_T^{miss} trigger

$\mu\mu + E_T^{miss}$ trigger
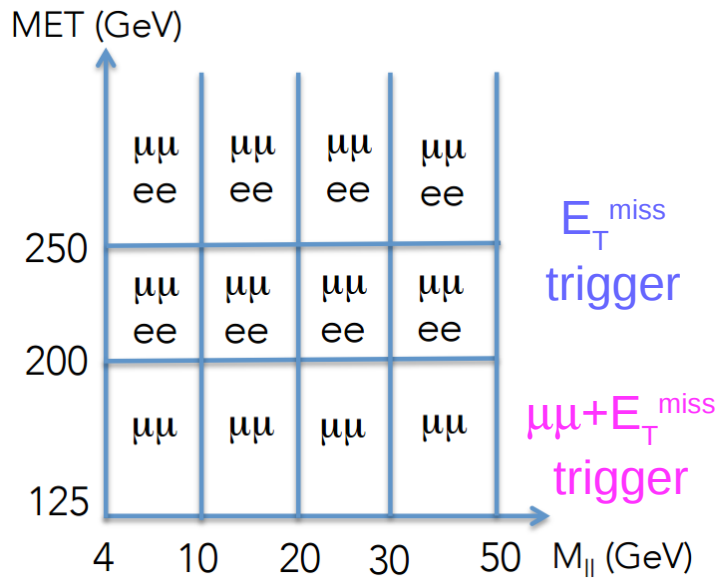
$m_{\ell\ell} \leq \Delta m$:
Target different mass splittings

$125 < E_T^{miss} < 200$ GeV

$\mu\mu$ only

$E_T^{miss} > 250$ GeV

ee+$\mu\mu$

SUS-16-048

23
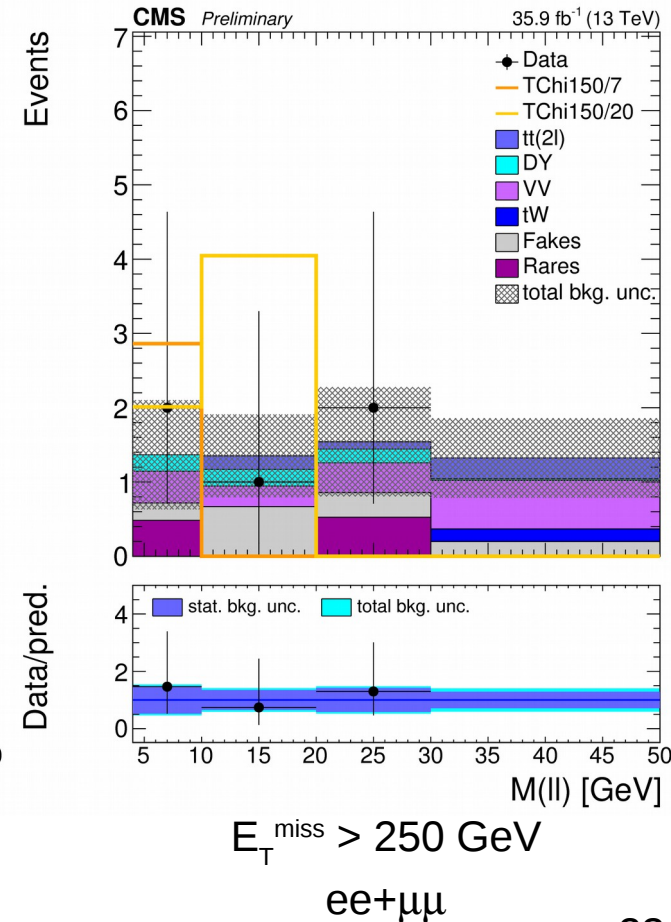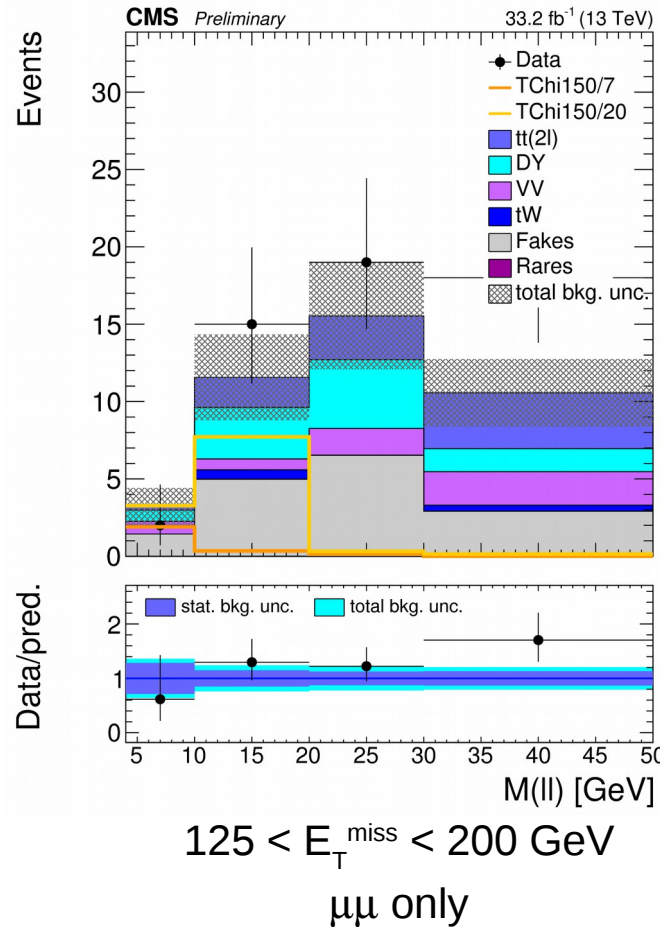
Probing unique phase space for $\chi^\pm\chi^0$ production in Run 2
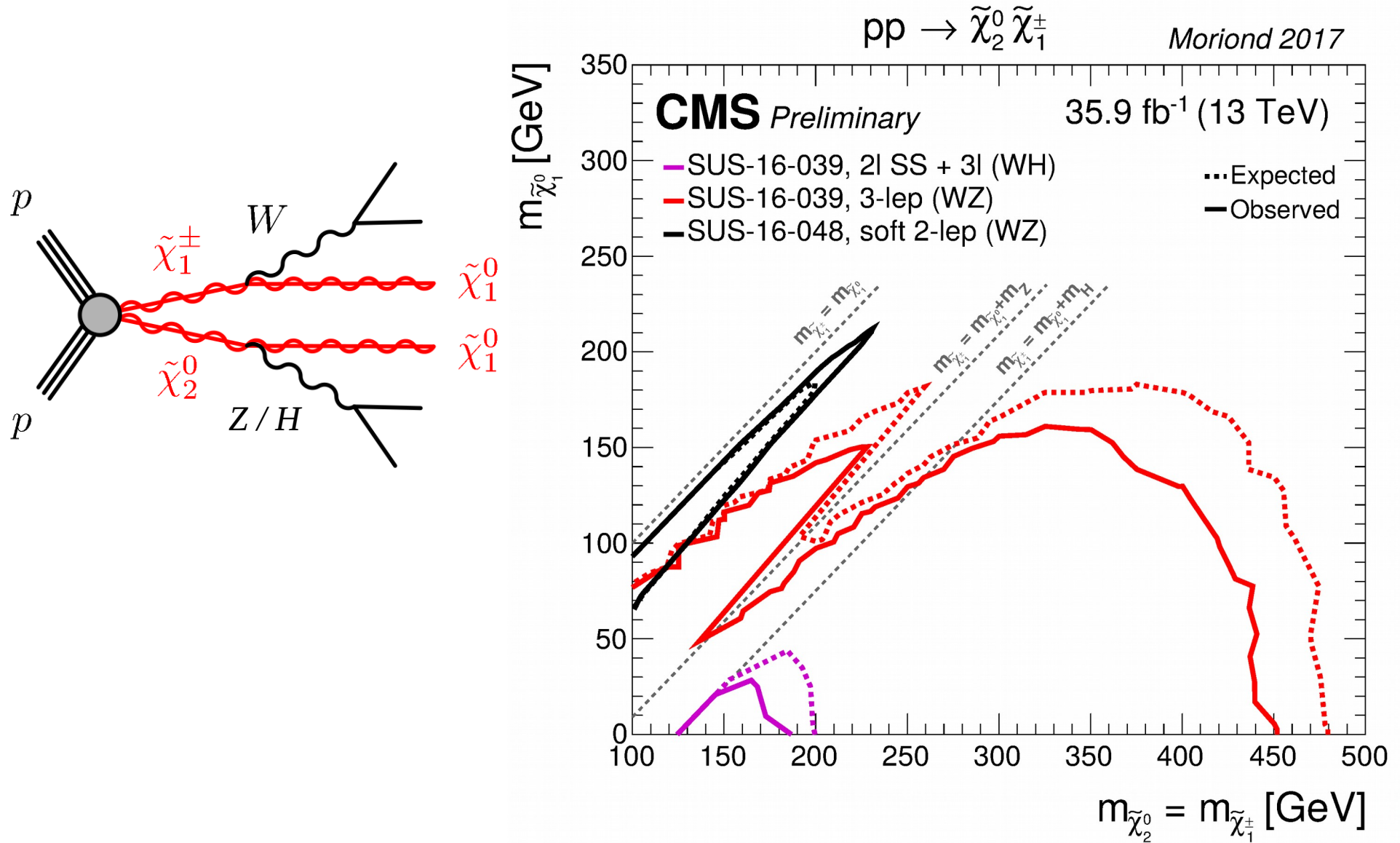
Probing unique phase space for $\chi^{\pm}\chi^0$ production in Run 2
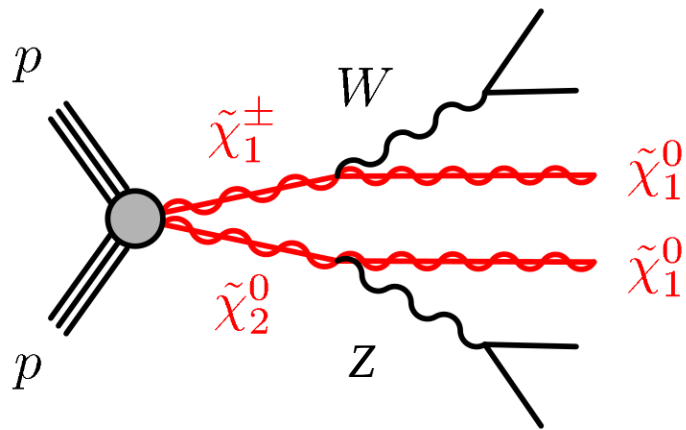
WZ+E_T^{miss} exclusion extended everywhere beyond 8 TeV & ICHEP limits

Upward fluctuation at 8 TeV, not seen at 13 TeV

Probing unique phase space for $\chi^{\pm}\chi^0$ production in Run 2

Exclusions at small Δm
from soft $\ell^+\ell^-$
Assuming here Wino-like cross section
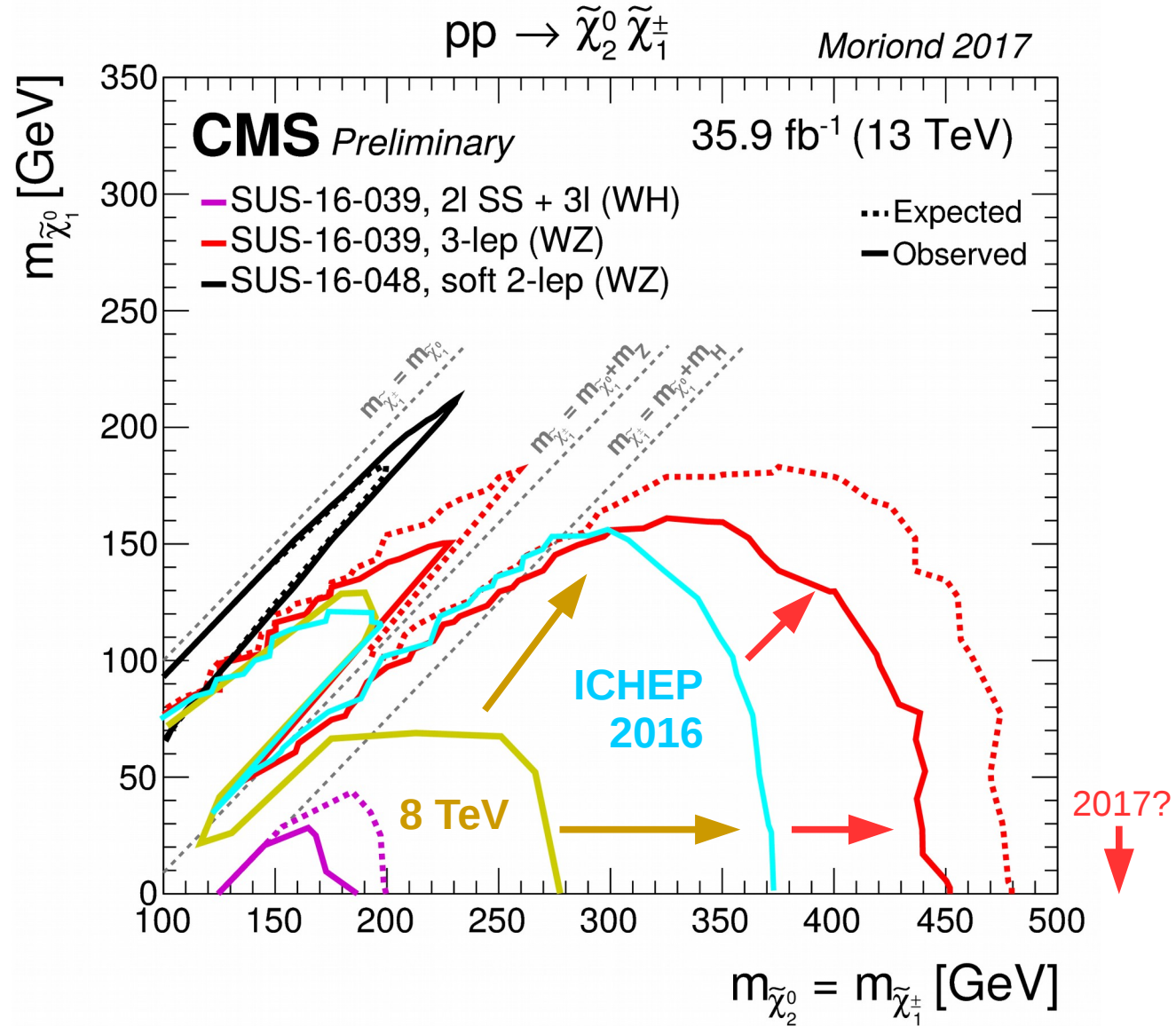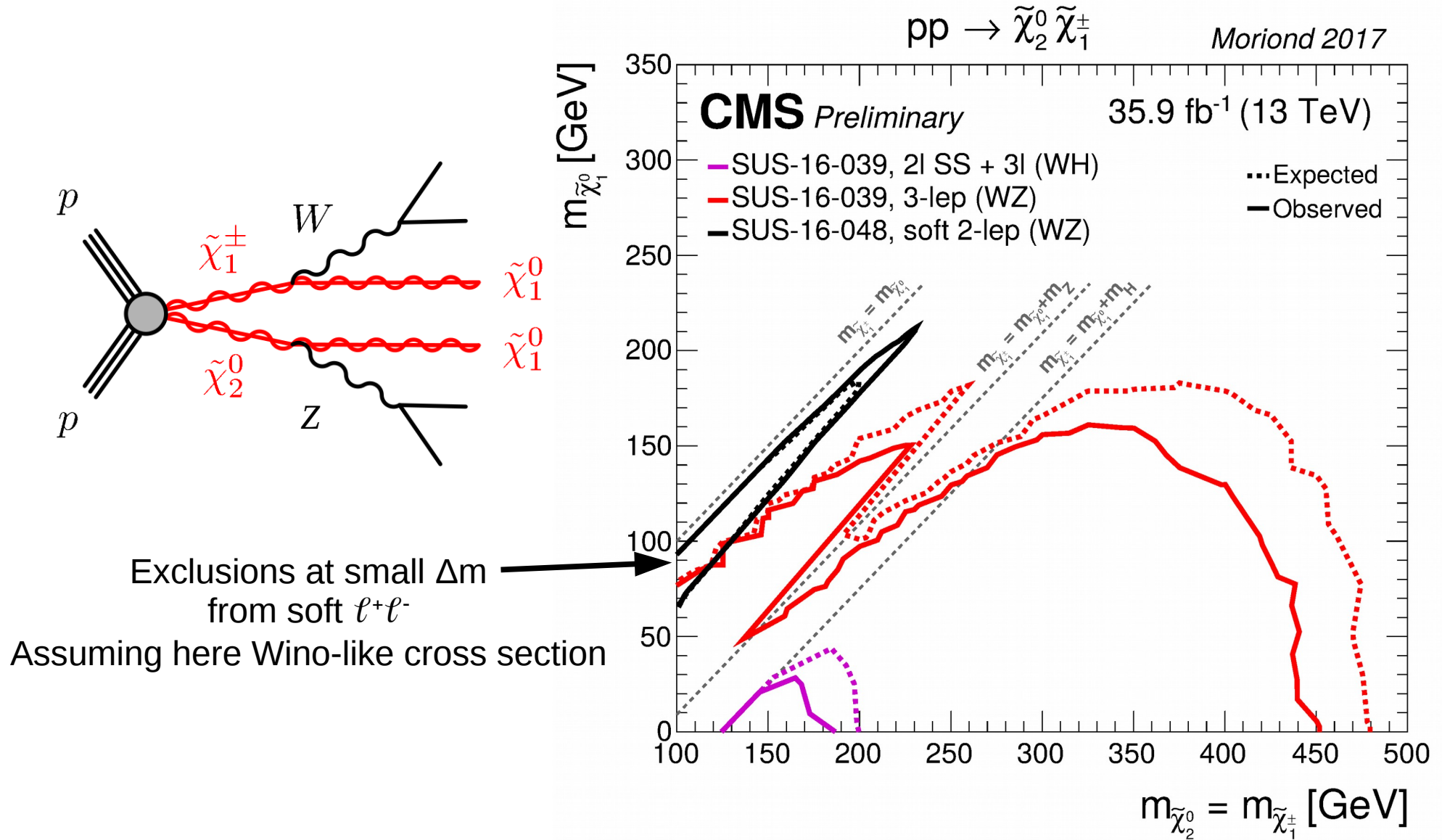
4b+E_T^{miss} search targets ewk production of HH+LSPs

- Select 4-5 jets, bin in N(b-tags)
  - p_T(jet) > 50/50/20 GeV
- **Deep learning b-tagger!**
- **Pair jets into Higgs candidates**
  - Select pairing which minimizes difference in invariant masses
- Mean invariant mass of pairs **peaks at M(H) for signal**

- <u>Background</u>: ttbar, QCD multijets
  - Suppress with cuts on pair mass, topological cuts
  - Also E_T^{miss} / sqrt(H_T)
  - Estimate from sidebands in mass, N(b-tags)

SUS-16-044
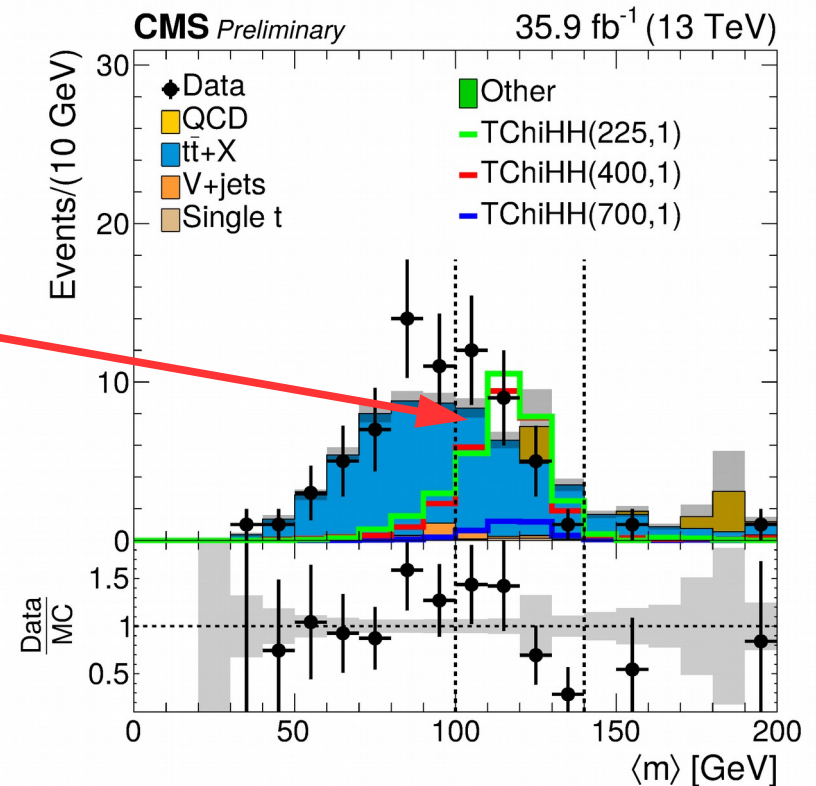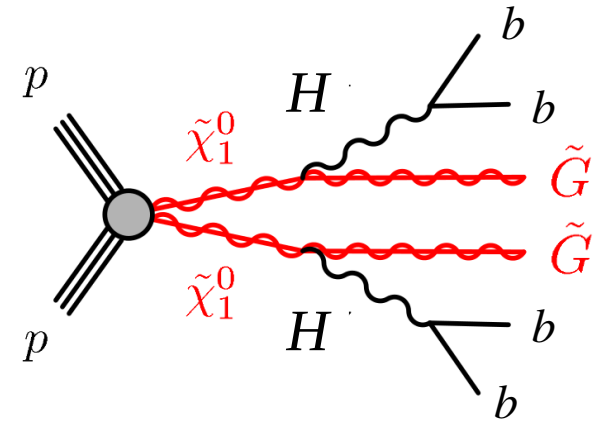
4b+E_T^{miss} sensitivity greatly exceeds 8 TeV version of search

- No significant deviations seen
- No exclusion observed at 8 TeV
- Now exclude 225 – 775 GeV
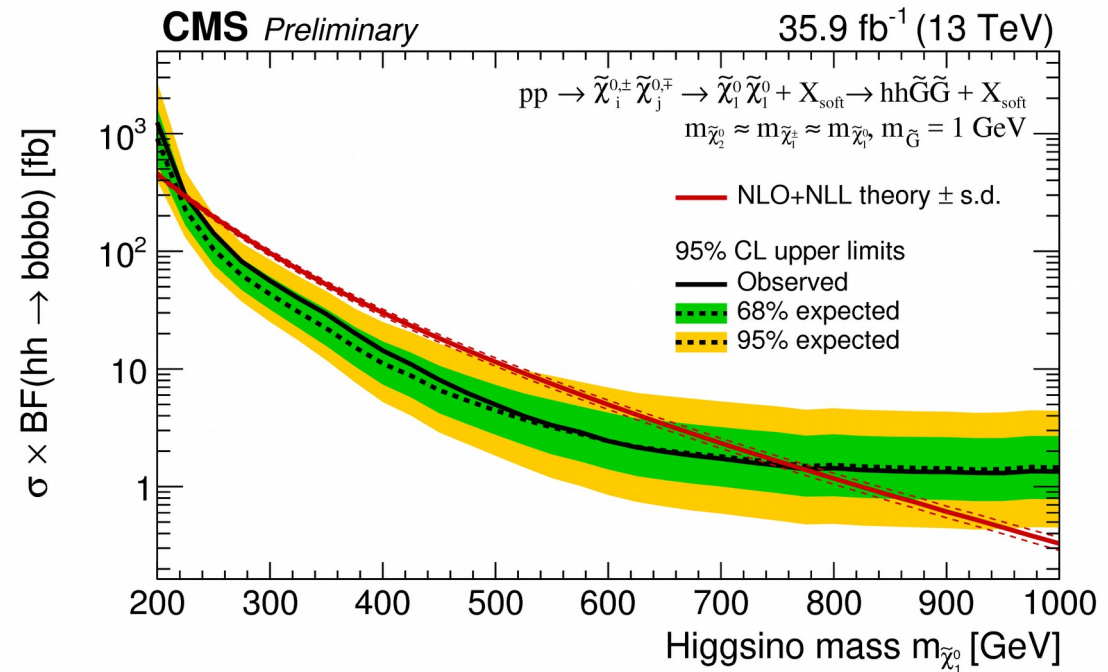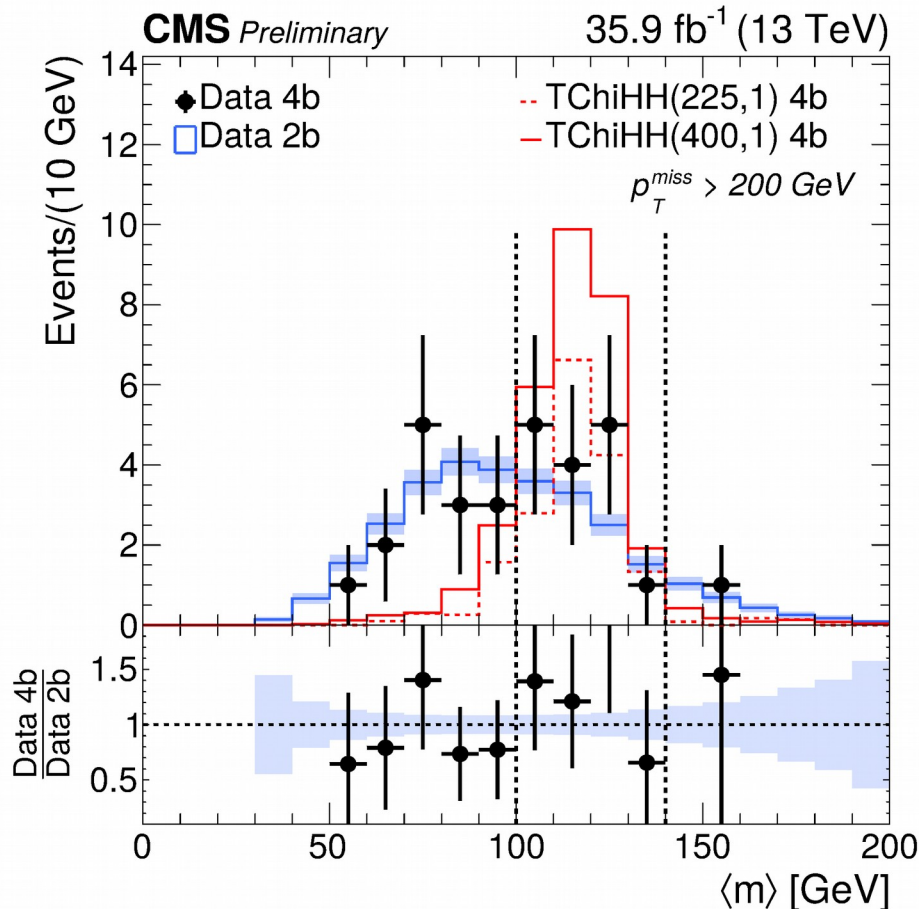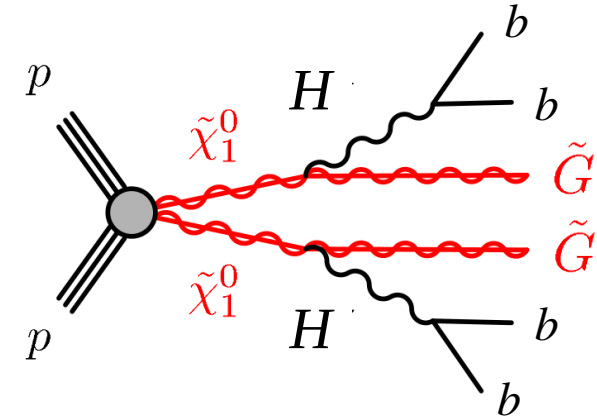
Exotic Models / Generic Search

An analysis using ≥3ℓ constrains heavy majorana neutrinos

- Categorize in N(ℓ), L_T+E_T^{miss}, M_T, nOSSF for 48 bins
- No significant deviations observed
- 27 prod and decay modes considered
- Limits improved by ~400 GeV from 2015

EXO-17-006
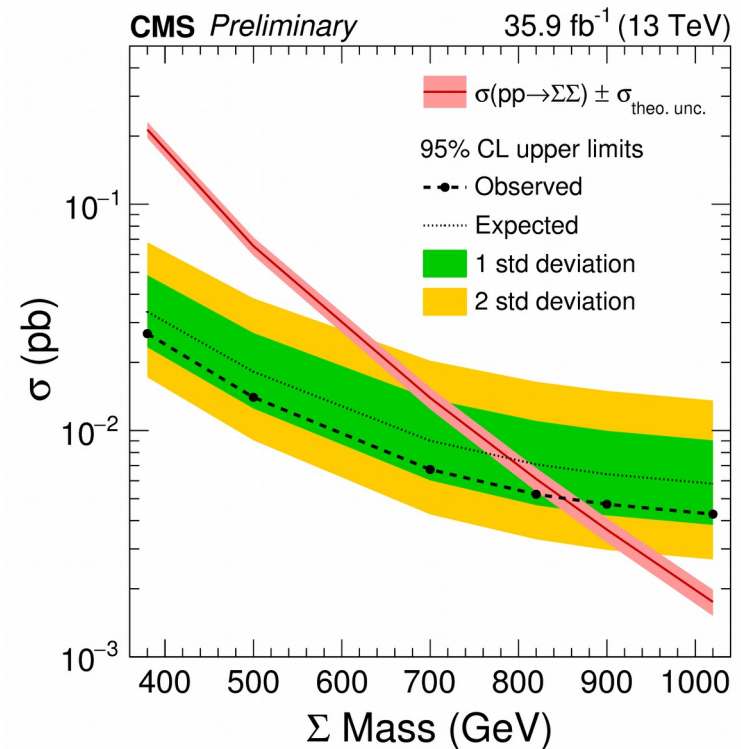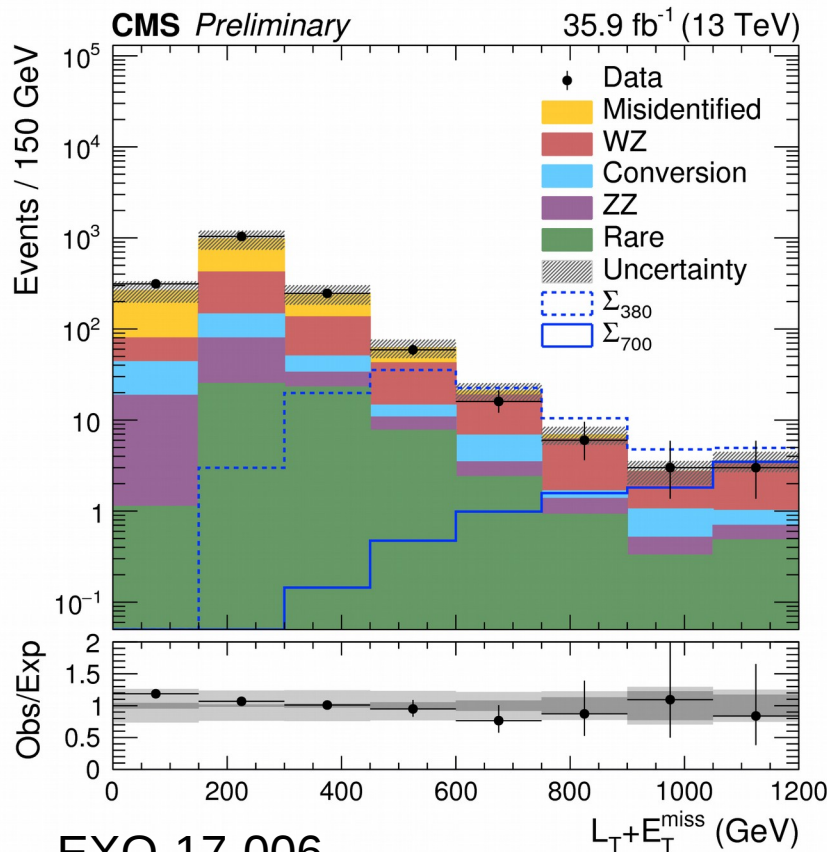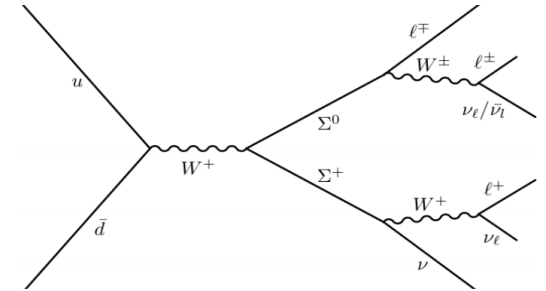
SS 2ℓ events are used to constrain the top partner X$_{5/3}$

- Main variable: $H_T^{lep} = H_T + \Sigma p_T(\ell)$
- Backgrounds: non-prompt, charge flips, rares
- No significant deviations
- Limit improved by ~200 GeV from 2015

B2G-16-019
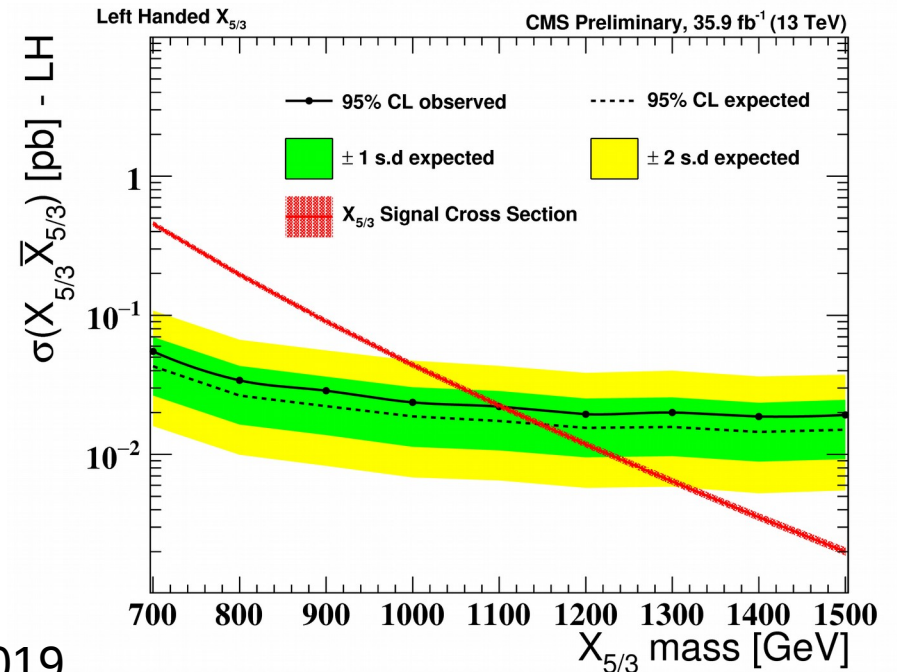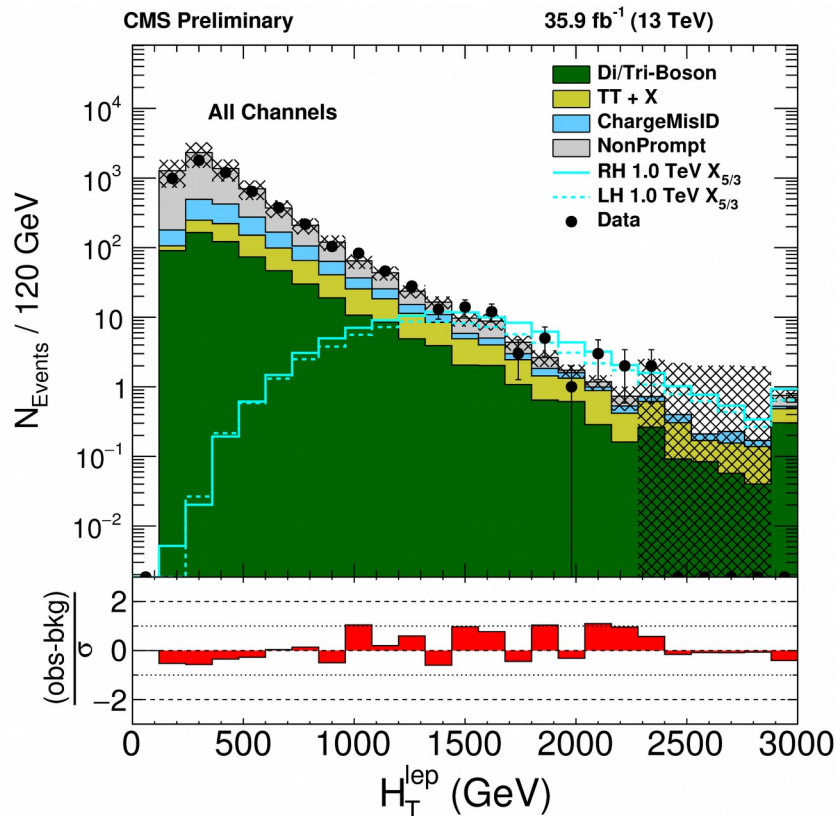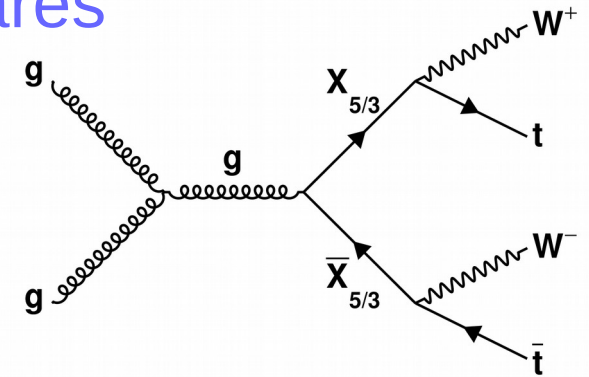
MUSiC:
Model Unspecified Search in CMS

- Place events in "classes" based on object content
- Look at kinematic distributions for each class
- Scan for most discrepant classes, regions within distributions
- Backgrounds taken from MC
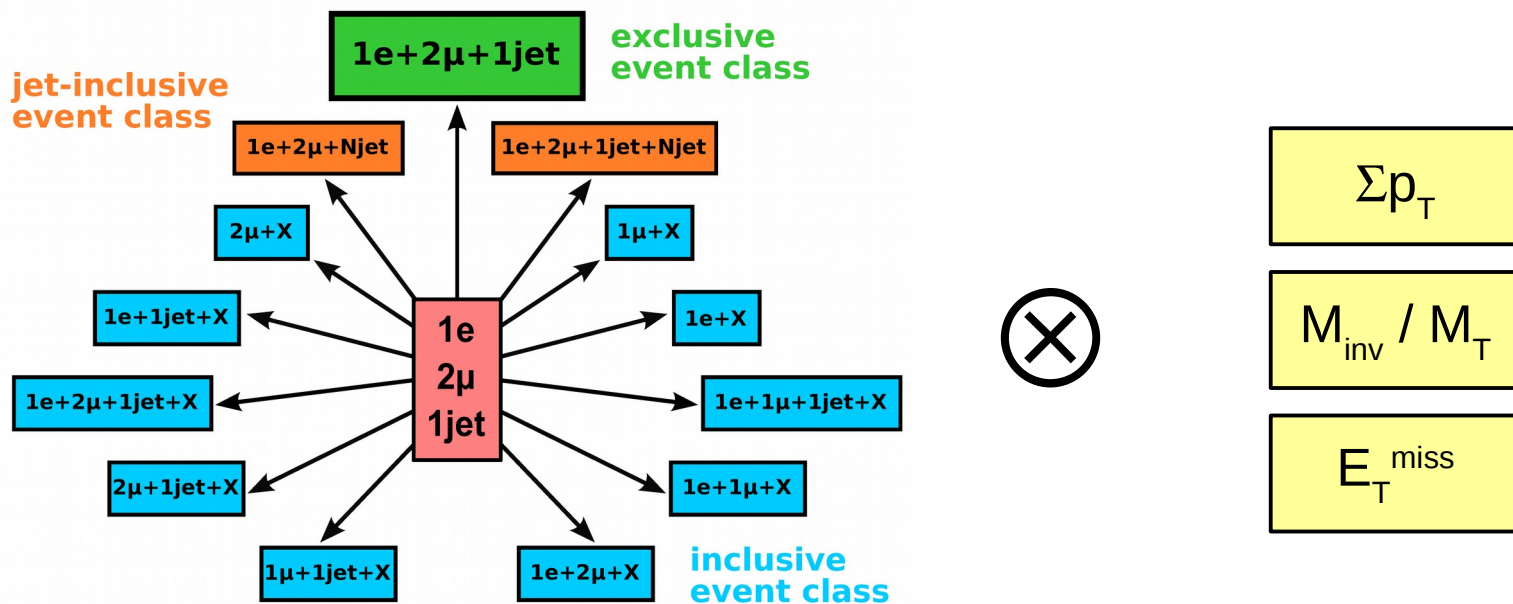
Event classes, based on objects:
e, μ, γ, jets, E_T^{miss} (> 50 GeV)
classes: 337, 341, 321

Kinematic distributions,
Binned following resolution

EXO-14-016

Identify discrepant classes and regions of distributions using p-value

- Most discrepant exclusive classes
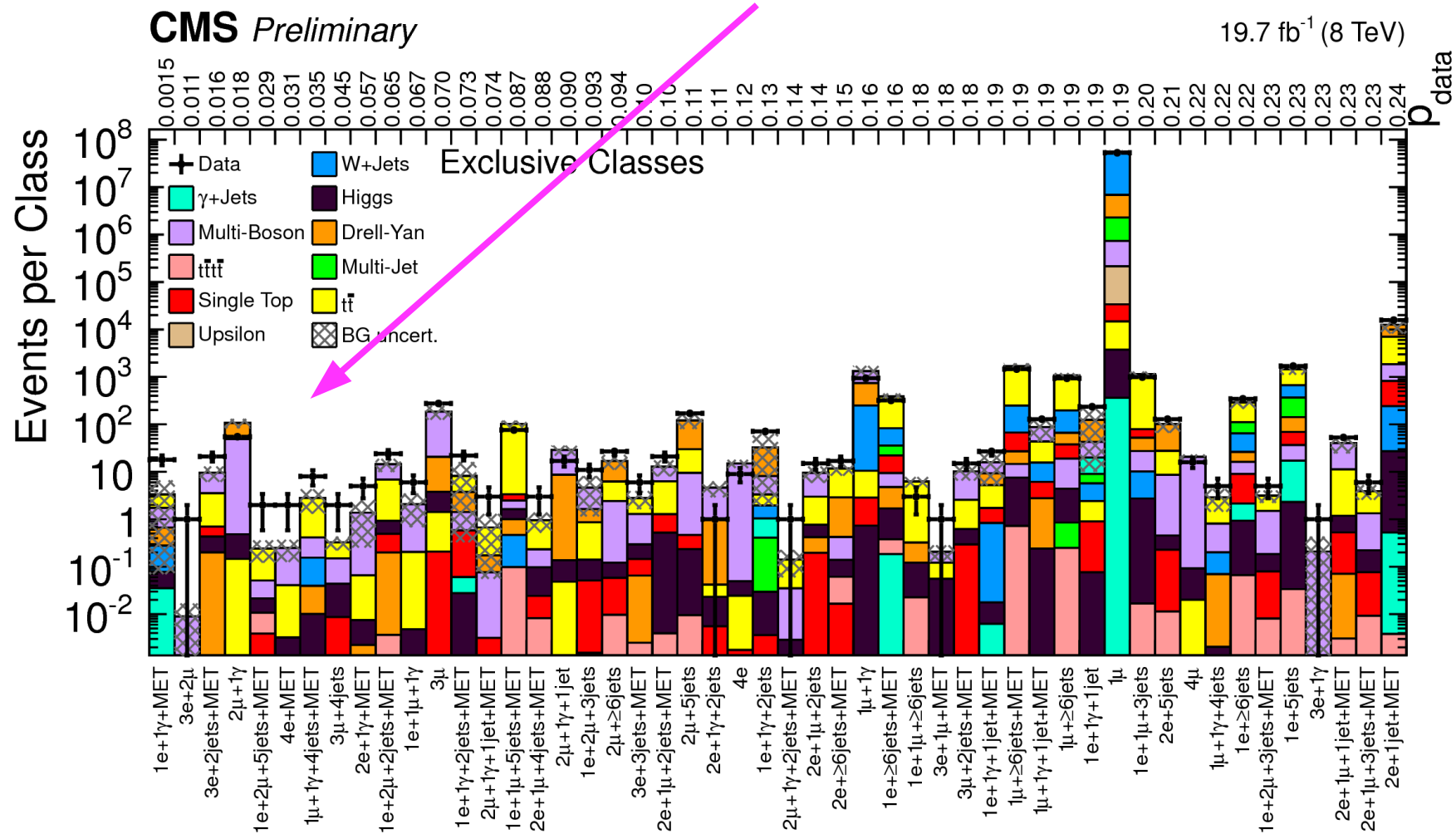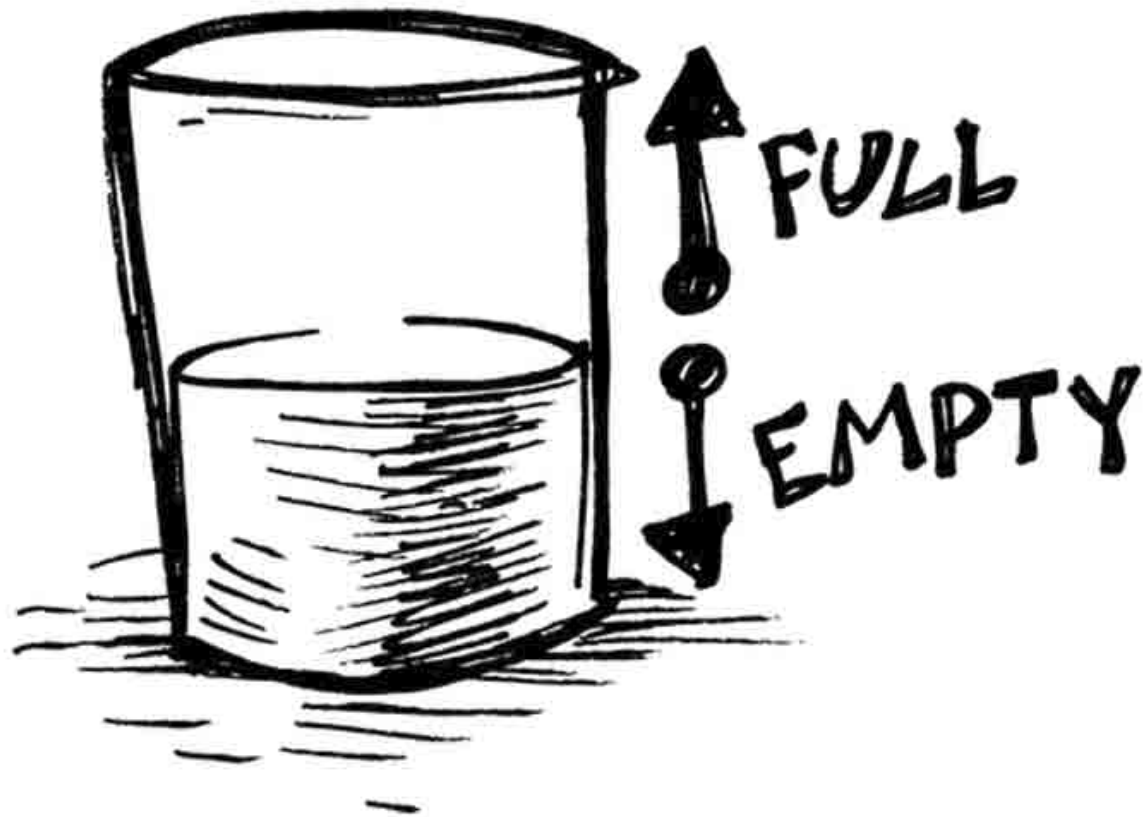
Reinterpretations

We're working to improve ability to reinterpret CMS searches

- SUSY searches in particular use many exclusive bins to cover large phase space and maximize sensitivity
  - More difficult to implement than single selections
  - Full background correlations weren't made public

Two approaches to improve this:
- "Super signal regions": inclusive selections that can be used as a single bin analysis
  - Easiest to use, somewhat worse sensitivity
- Full covariance matrix for background model
  - Public documentation for usage, CMS-NOT-2017-001
  - Public codes to compute analysis-specific variables and assign events to signal regions

Example: M_{T2} jets + E_T^{miss} analysis

Super Signal Regions

Region	N_j	N_b	H_T [GeV]	M_{T2} [GeV]	Prediction	Data	N_{95}^{obs}
2j loose	≥ 2	–	> 1000	> 1200	38.9 ± 11.2	42	26.6
2j tight	≥ 2	–	> 1500	> 1400	2.9 ± 1.3	4	6.5
4j loose	≥ 4	–	> 1000	> 1000	19.4 ± 5.8	21	15.8
4j tight	≥ 4	–	> 1500	> 1400	2.1 ± 0.9	2	4.4
7j loose	≥ 7	–	> 1000	> 600	$23.5^{+5.9}_{-5.6}$	27	18.0
7j tight	≥ 7	–	> 1500	> 800	$3.1^{+1.7}_{-1.4}$	5	7.6
2b loose	≥ 2	≥ 2	> 1000	> 600	$12.9^{+2.9}_{-2.6}$	16	12.5
2b tight	≥ 2	≥ 2	> 1500	> 600	$5.1^{+2.7}_{-2.1}$	4	5.8
3b loose	≥ 2	≥ 3	> 1000	> 400	8.4 ± 1.8	10	9.3
3b tight	≥ 2	≥ 3	> 1500	> 400	2.0 ± 0.6	4	6.6
7j3b loose	≥ 7	≥ 3	> 1000	> 400	5.1 ± 1.5	5	6.4
7j3b tight	≥ 7	≥ 3	> 1500	> 400	0.9 ± 0.5	1	3.6

Limits worse than full analysis by factor of
1.5-3x for model points near exclusion lines

Covariance Matrix
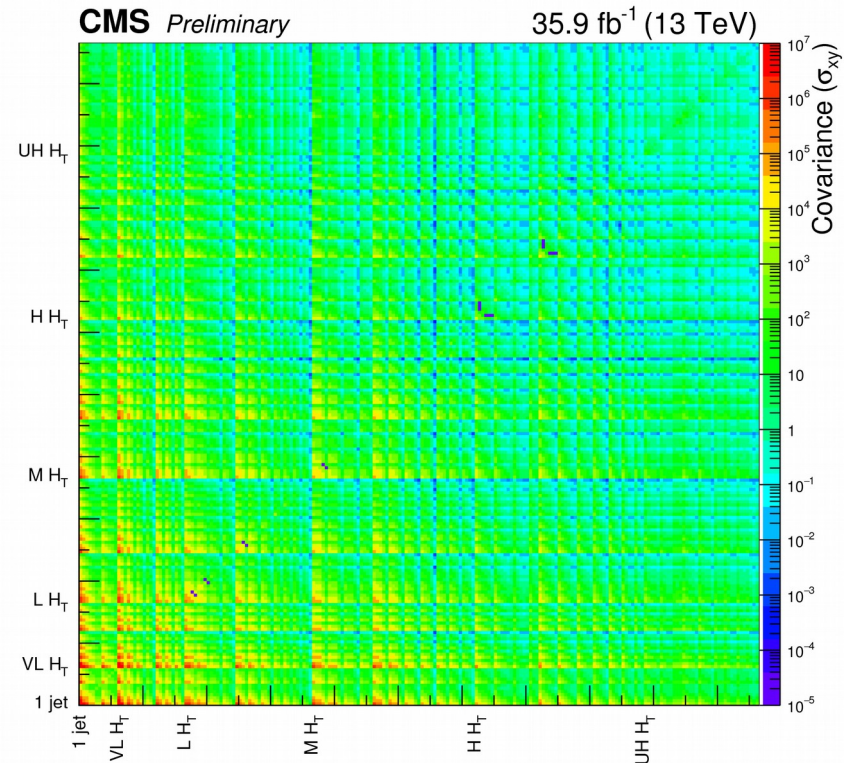
full 213 bins

BSM searches are taking full advantage of the LHC Run 2 dataset

- Unfortunately, no significant deviations yet

- Many searches released for strong SUSY production
  - Limits as high as 2 TeV for gluinos and 1.5 TeV for squarks

- Searches for electroweak production and compressed spectra are breaking new ground
  - Thanks to large dataset and new ideas
  - Look for more results soon!

- Handful of exotica results → many more to come!

- Putting more emphasis on reinterpretation to improve longevity of search results

Bonus Slides

New CMS Searches: Moriond/Aspen

SUSY

Description	CADI Line
Jets+MET with MHT	SUS-16-033
Jets+MET with MT2	SUS-16-036
Jets+MET bb/cc	SUS-16-032
Jets+MET stop	SUS-16-049
1L MJ	SUS-16-037
SS 2L	SUS-16-035
Stop 2L	SUS-17-001
Strong multilep	SUS-16-041
photon+HT	SUS-16-047
H(gg)+jets	SUS-16-045
Ewk multilep	SUS-16-039
Ewk soft 2L OS	SUS-16-048
Ewk HH->4b	SUS-16-044

Exotica / B2G

Description	CADI Line
Dijet resonance	EXO-16-056
Type III seesaw	EXO-17-006
MUSiC generic	EXO-14-016
X5/3 SS 2L	B2G-16-019
W' → tb → 1L	B2G-17-010
VLQs to Z → ll	B2G-17-007
VH had resonance	B2G-17-002
VV had resonance	B2G-17-001

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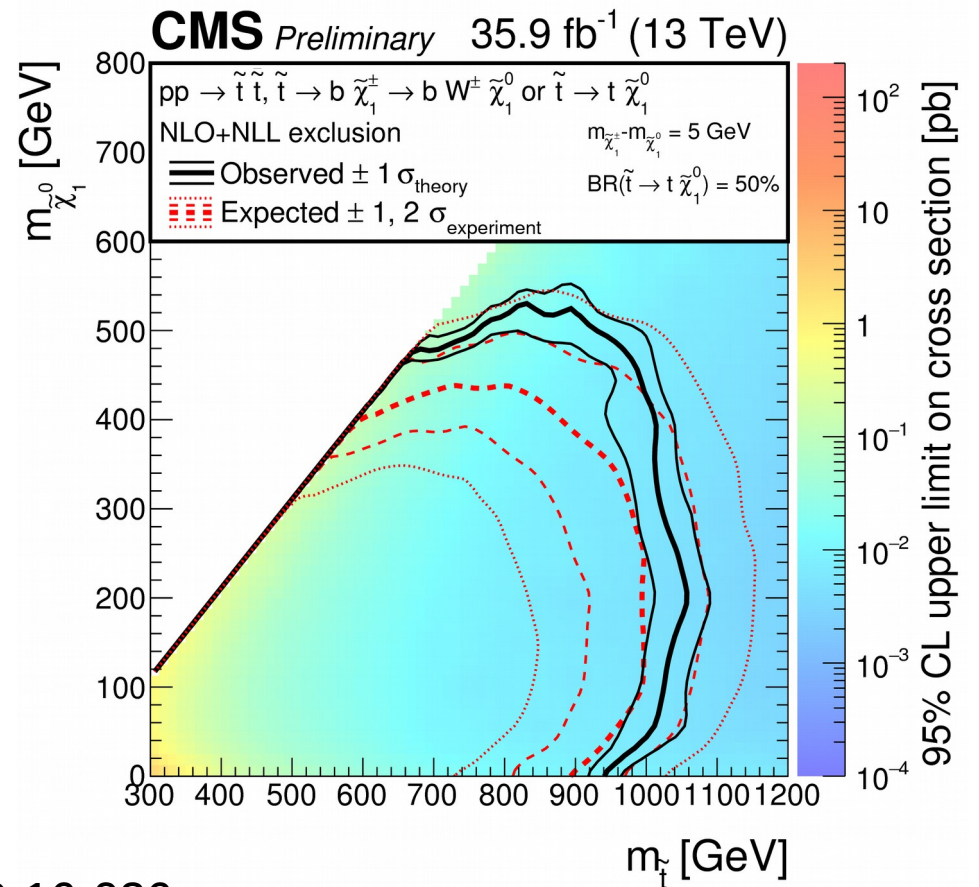https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Stop squark exclusions
up to around 1050 GeV
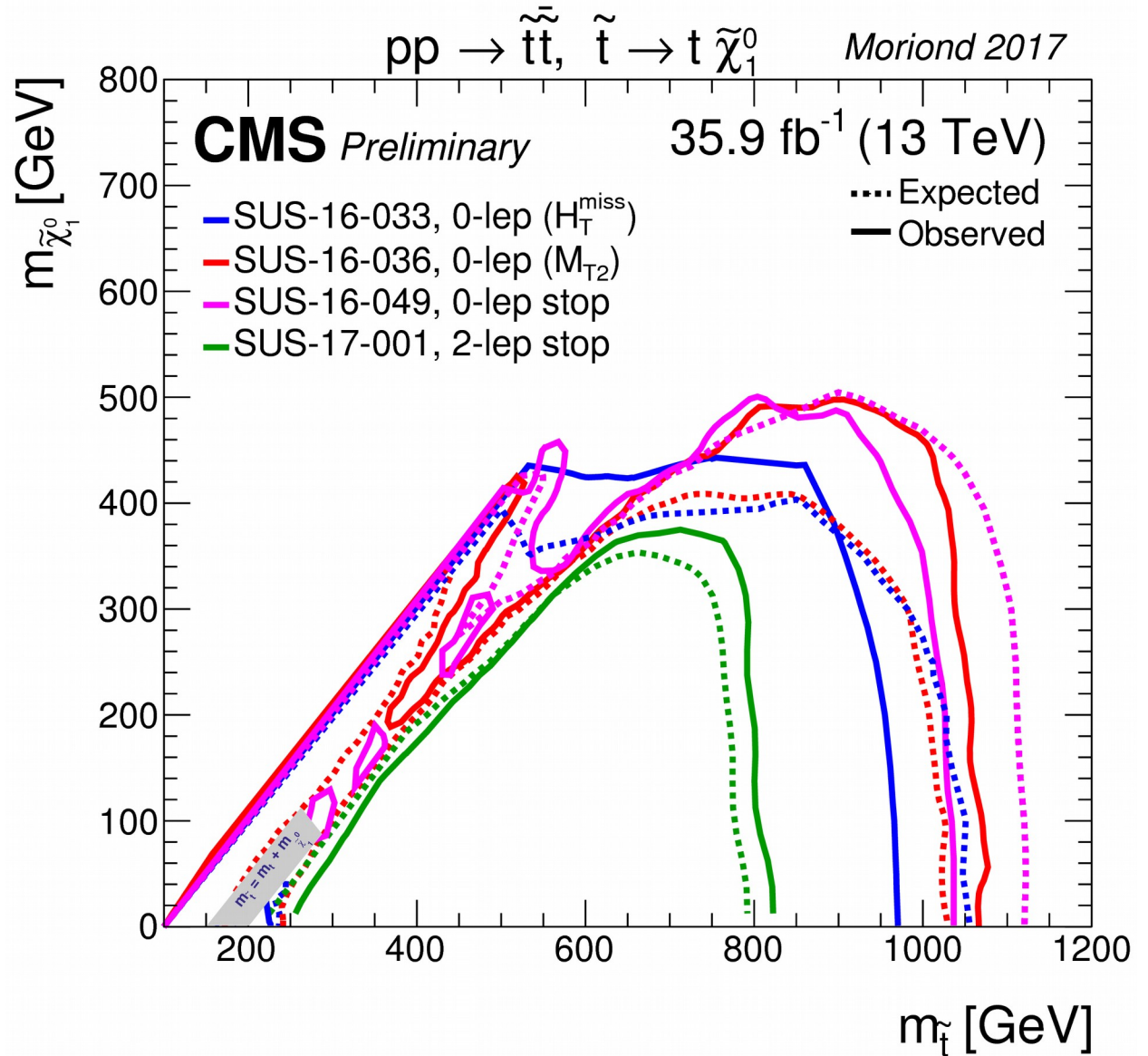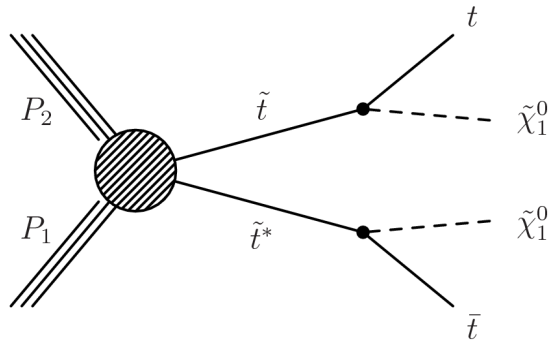
Other stop squark decays
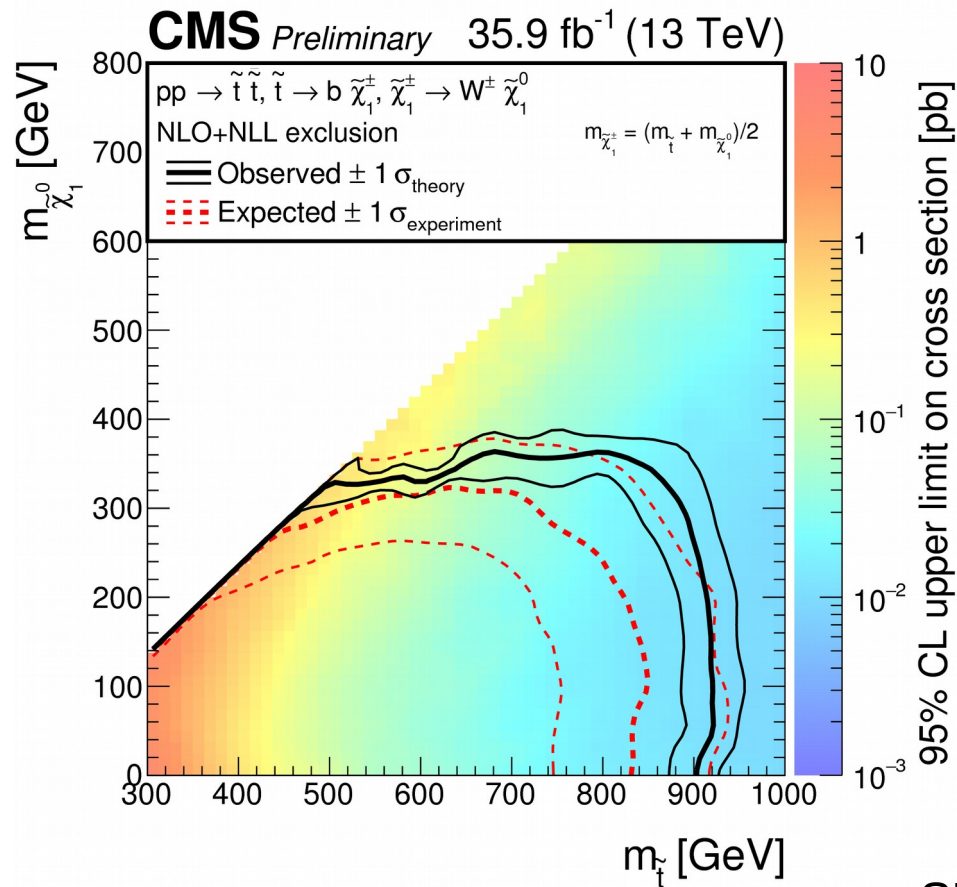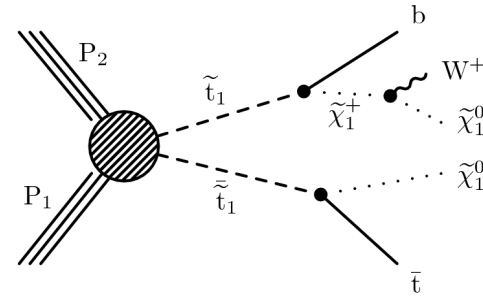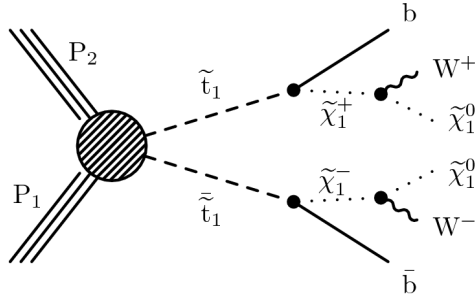
Other stop squark decays, compressed
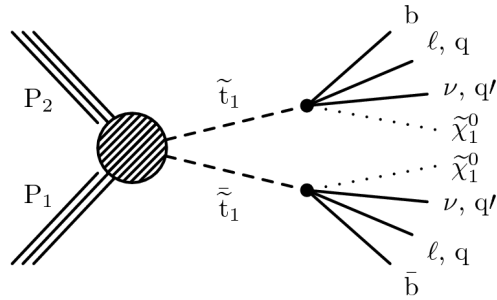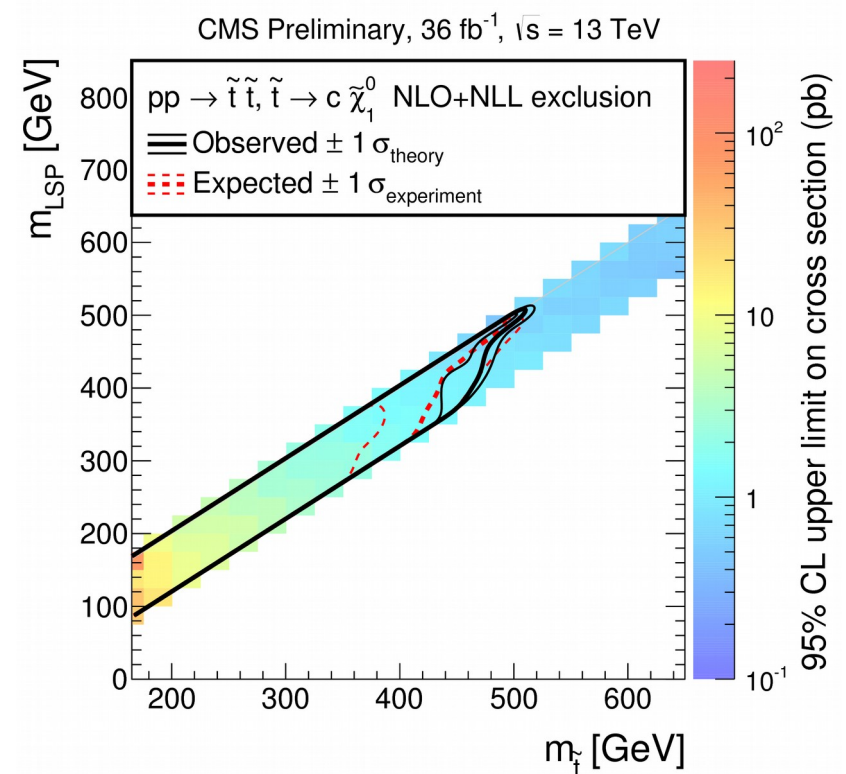
LHC Run 2: through 2016, ~40 fb^{-1} integrated @ 13 TeV

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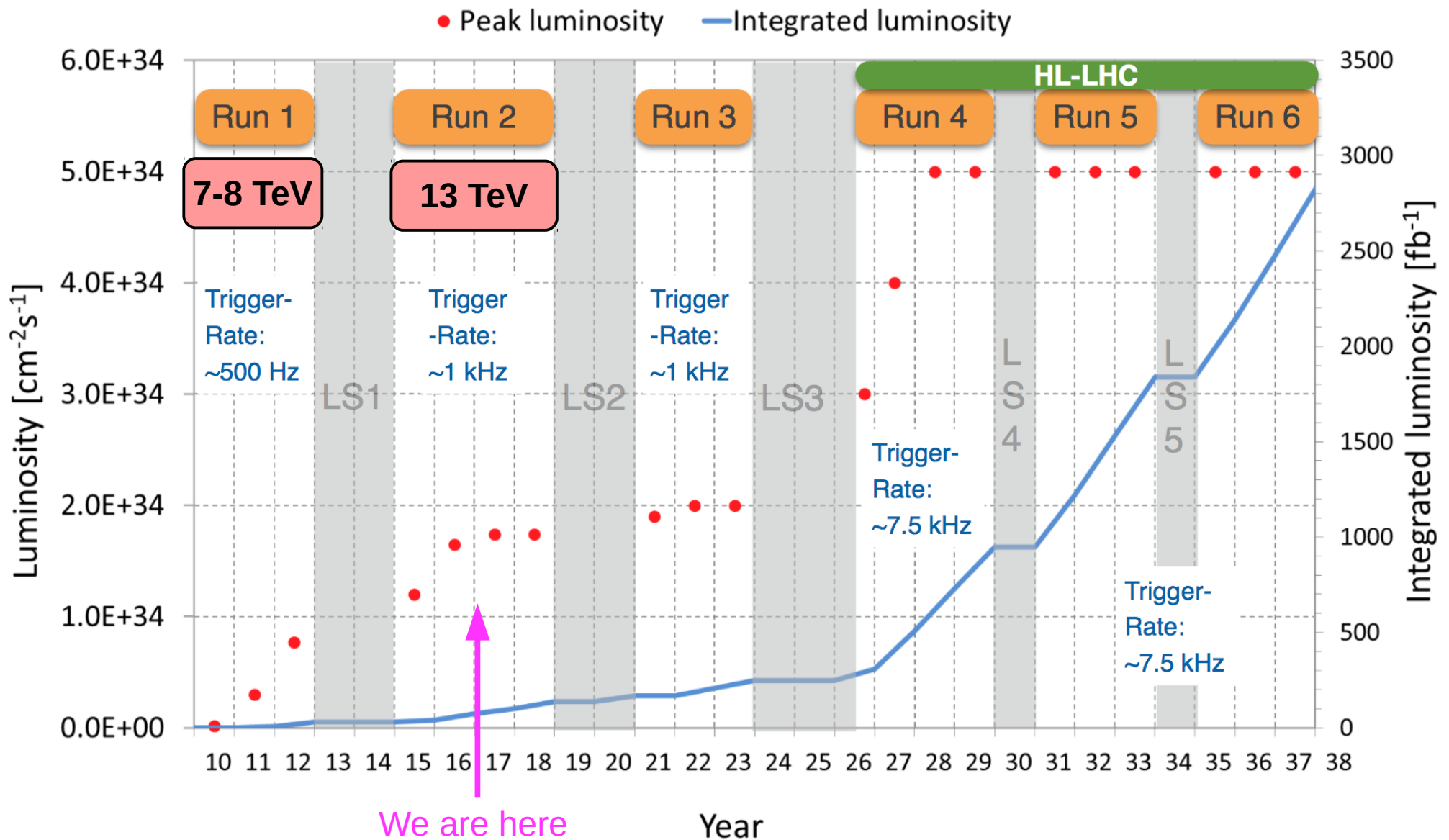
Simplified Models are used to interpret null results
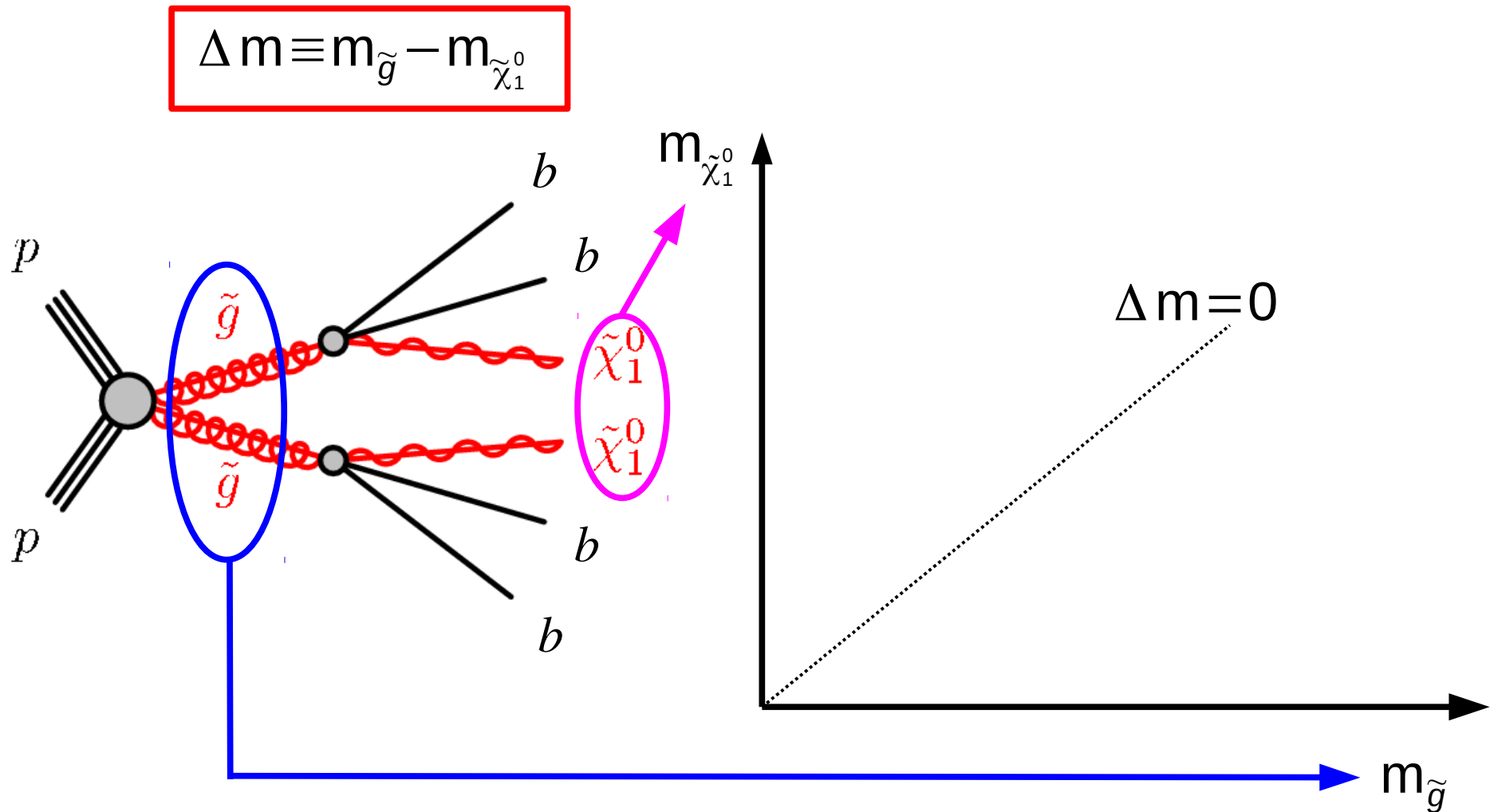
$$\Delta m \equiv m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$$

Signal kinematics vary with the splitting between sparticle masses

$$\Delta m \equiv m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$$
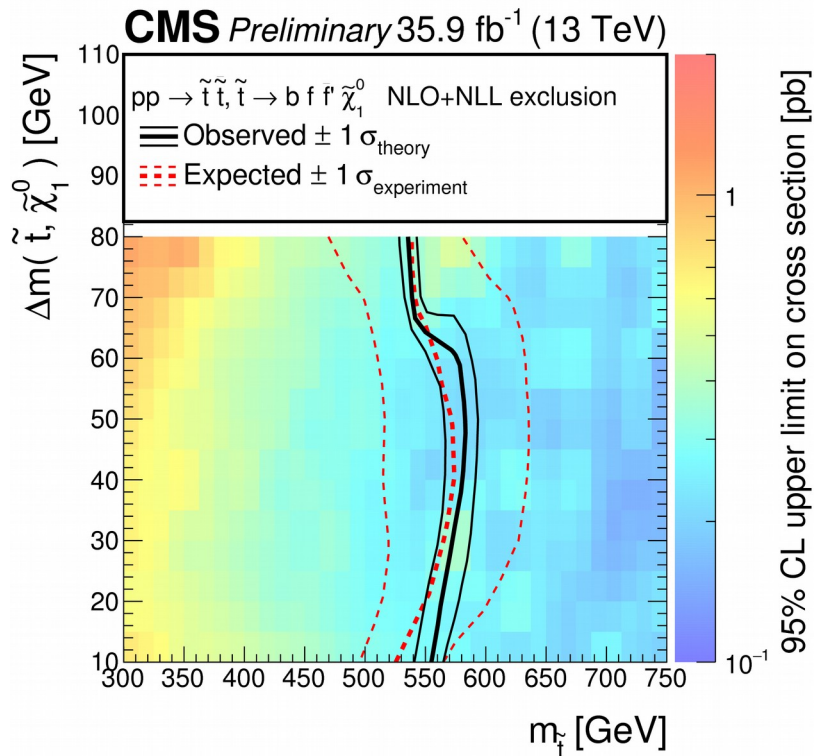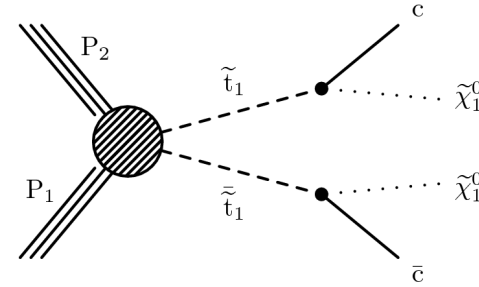
Small Δm region: low p_T or off-shell decay products, rely more on ISR boost

$\Delta m = 0$

$m_{\tilde{\chi}_1^0}$

$m_{\tilde{g}}$

p p $\tilde{g}$ $\tilde{g}$ b b b b $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$
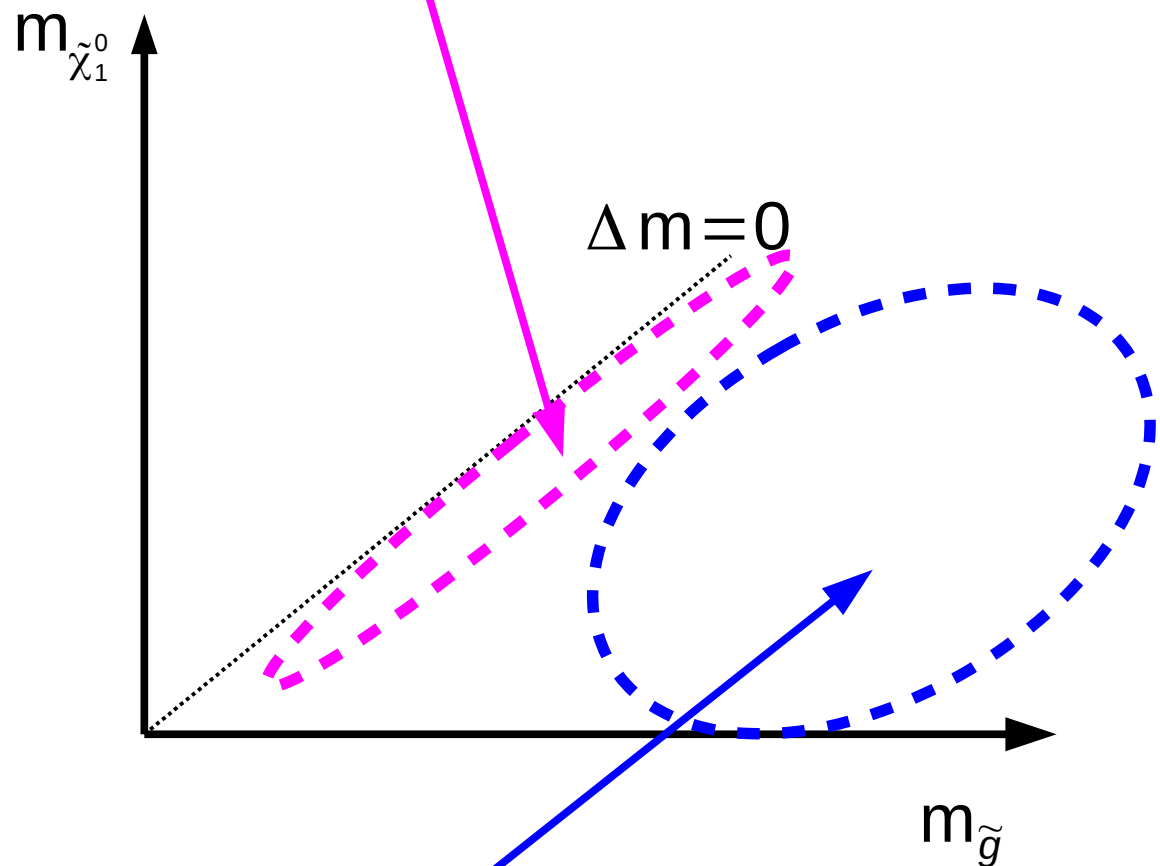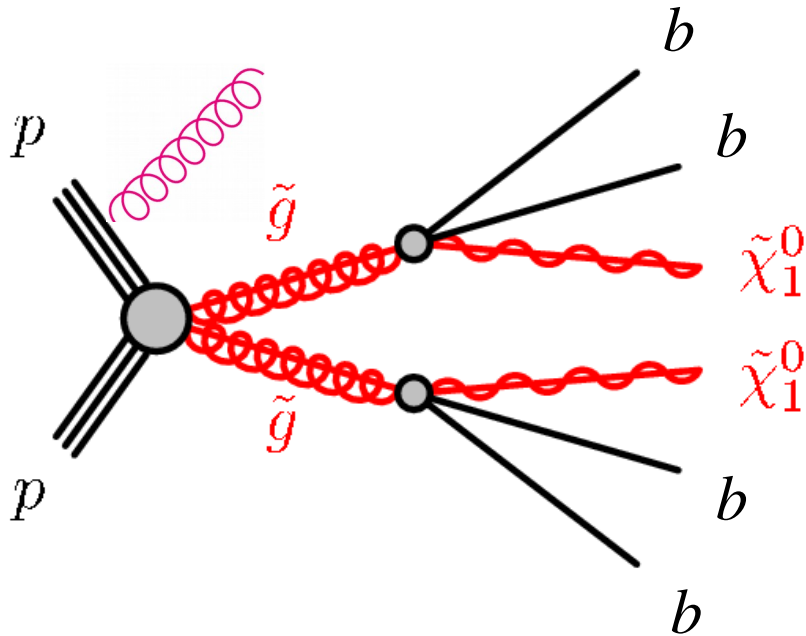
Large Δm region: bulk of phase space, high p_T decay products

What would a signal look like?
M_{T2} jets+E_T^{miss} analysis
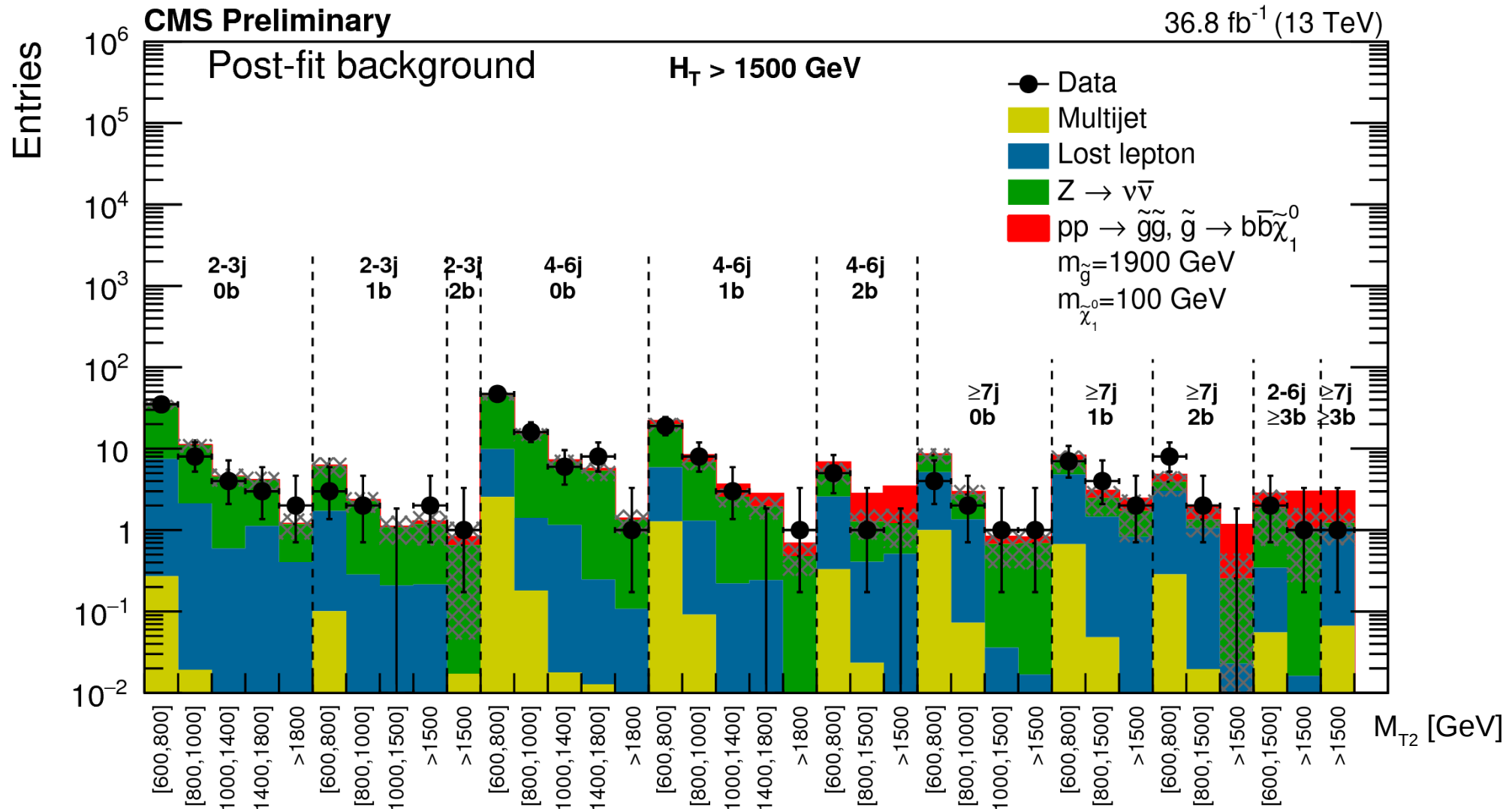
Expect a pattern of excesses – not observed

The M_{T2} analysis constrains squarks up to 1550 GeV
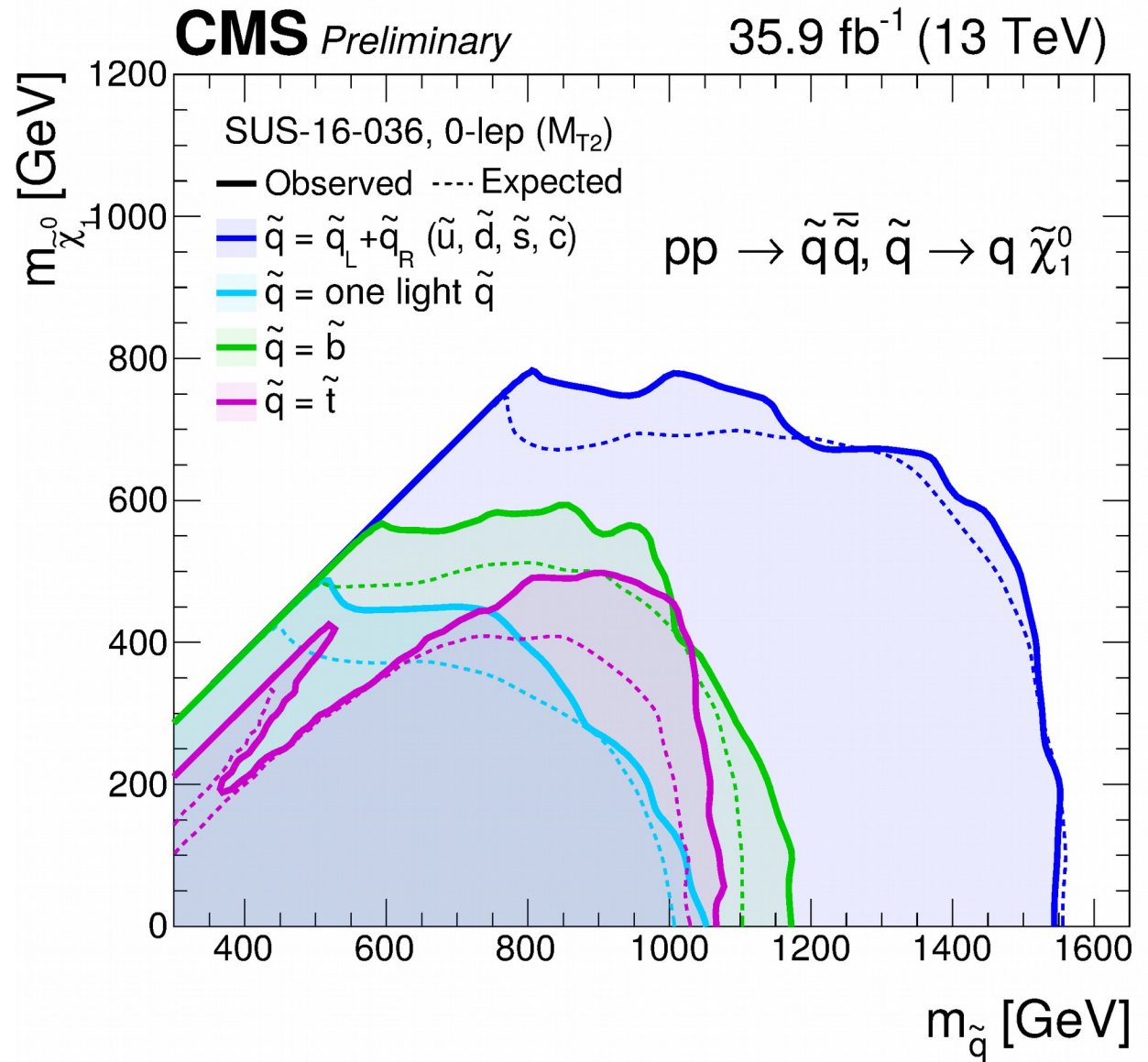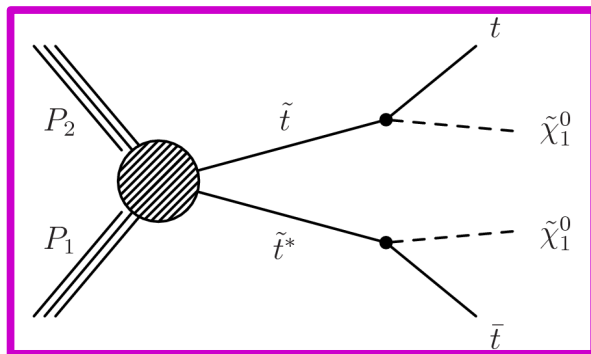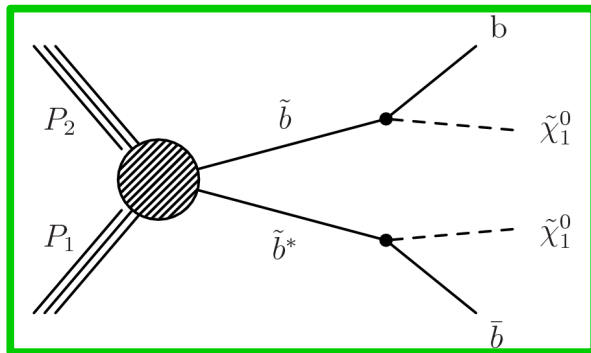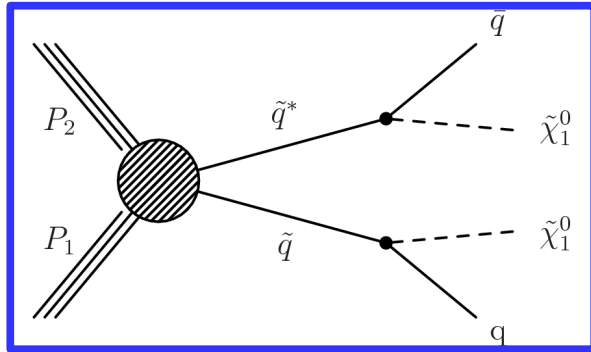
Electroweakino states
(hierarchy can have any order)

$$\widetilde{\chi}_3^0, \widetilde{\chi}_2^\pm, \widetilde{\chi}_4^0 \quad \equiv \quad \widetilde{H} \text{ (higgsino)}$$

Δm ~ few – tens of GeV

$$\widetilde{\chi}_1^\pm, \widetilde{\chi}_2^0 \quad = \quad \widetilde{W} \text{ (wino)}$$

Δm ~ 160 MeV*

$$\widetilde{\chi}_1^0 \quad — \quad \widetilde{B} \text{ (bino)}$$

(gravitino)

$$— \quad \widetilde{G}$$

mass
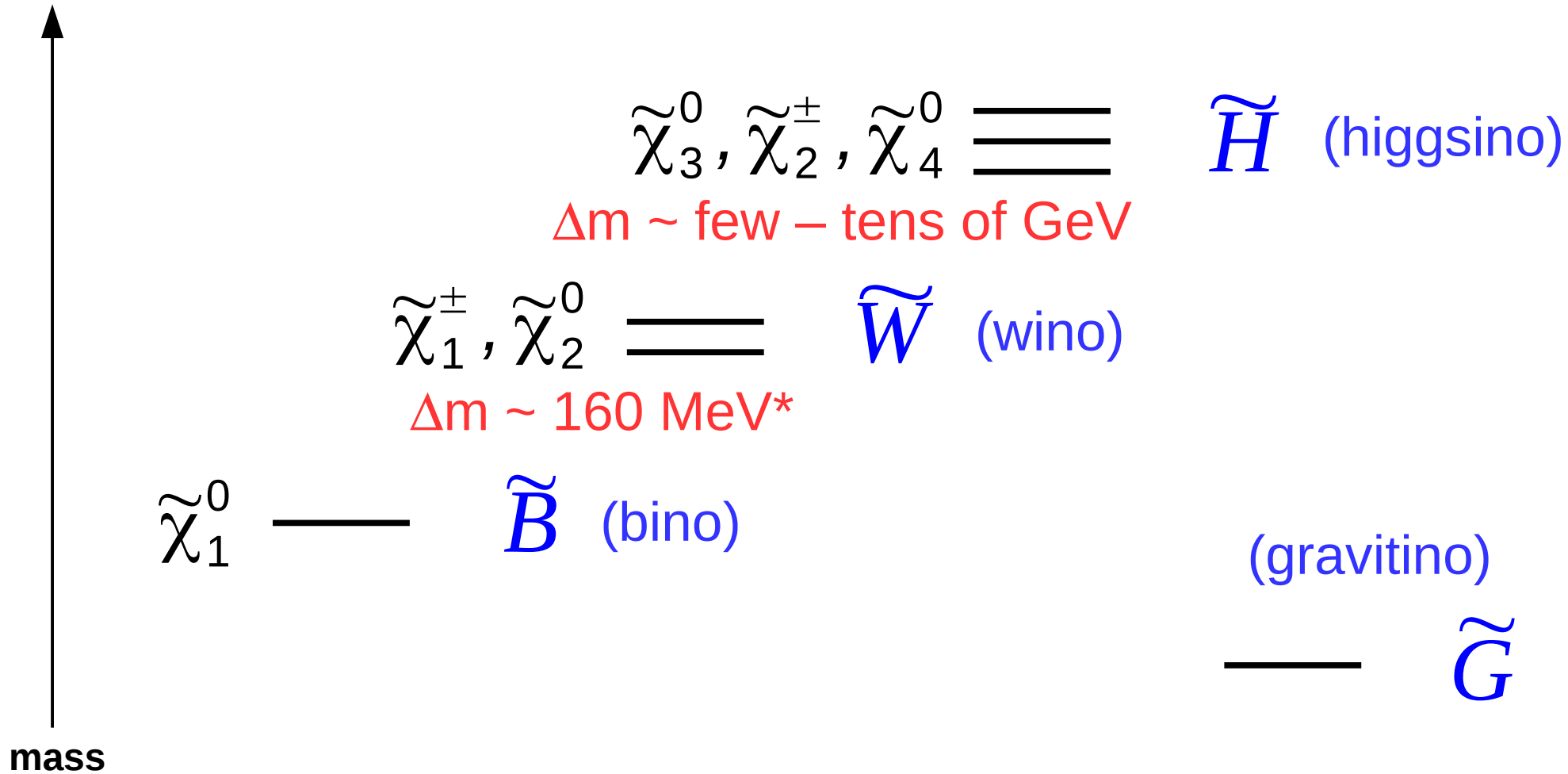
* assuming heavy sfermions and higgsinos

Ewkino decays, without sleptons

GMSB / GGM

$\widetilde{\chi}_1^\pm$ $\qquad$ $\widetilde{\chi}_2^0$ $\left(\widetilde{W}\right)$ $\qquad$ $\widetilde{\chi}_1^0$

W $\qquad$ Z/h $\qquad$ Z/h/γ

$\widetilde{\chi}_1^0$ $\qquad$ $\left(\widetilde{B}\right)$ $\qquad$ $\widetilde{G}$
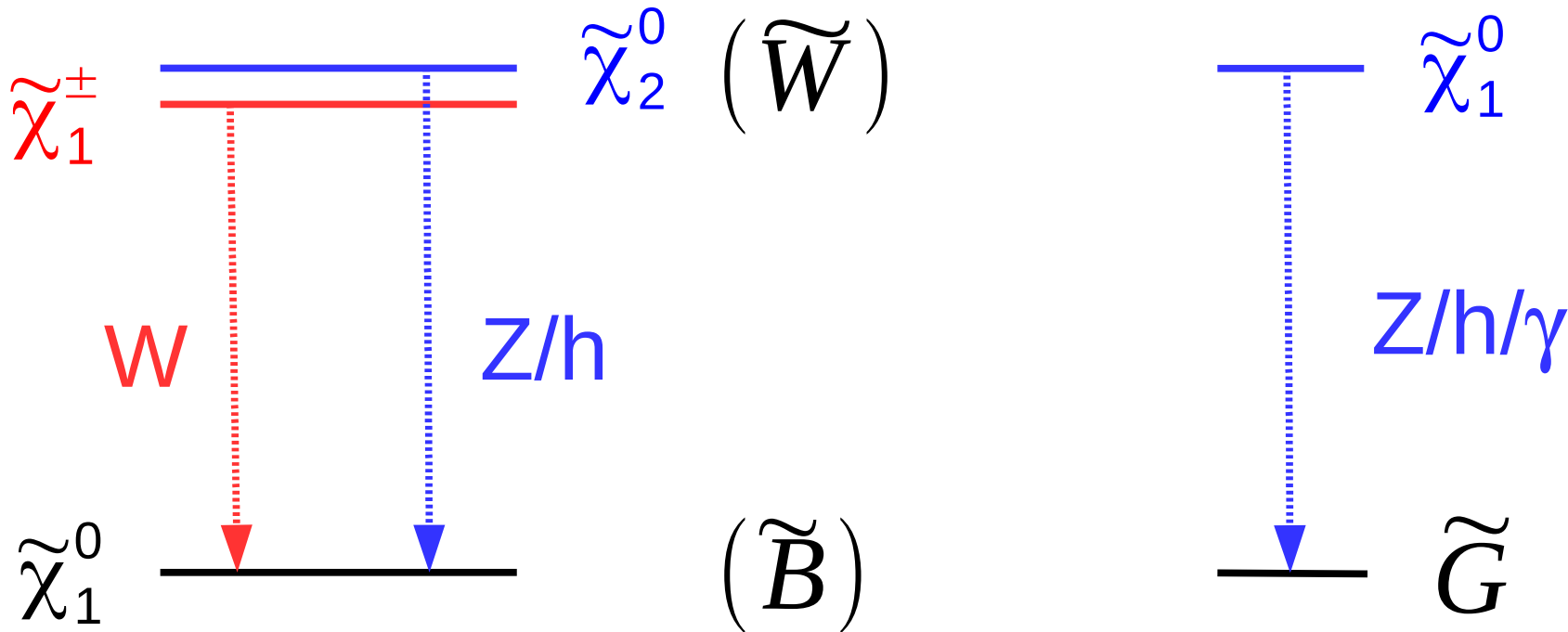
Pair production signature: **Diboson + MET**
W(*), Z(*), Higgs, Photons
→ leptons, jets only from boson decays or ISR, photons
Need to combine analyses to cover all boson decays

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Ewkino decays, with sleptons

Signature: **Leptons + MET**
Large branching fraction to leptons:
Sensitivity dominated by 2, 3, 4 lepton searches

Soft OS: Limit vs deltaM

Ewkino: Limits with Sleptons

$pp \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^\pm$

Moriond 2017

CMS *Preliminary*   35.9 fb^{-1} (13 TeV)

- SUS-16-039, 3-lep (BF(ll)=0.5, x_l=0.5)
- SUS-16-039, 2l SS + 3l (BF(ll)=0.5, x_l=0.05)
- SUS-16-039, 2l SS + 3l (BF(ll)=0.5, x_l=0.95)
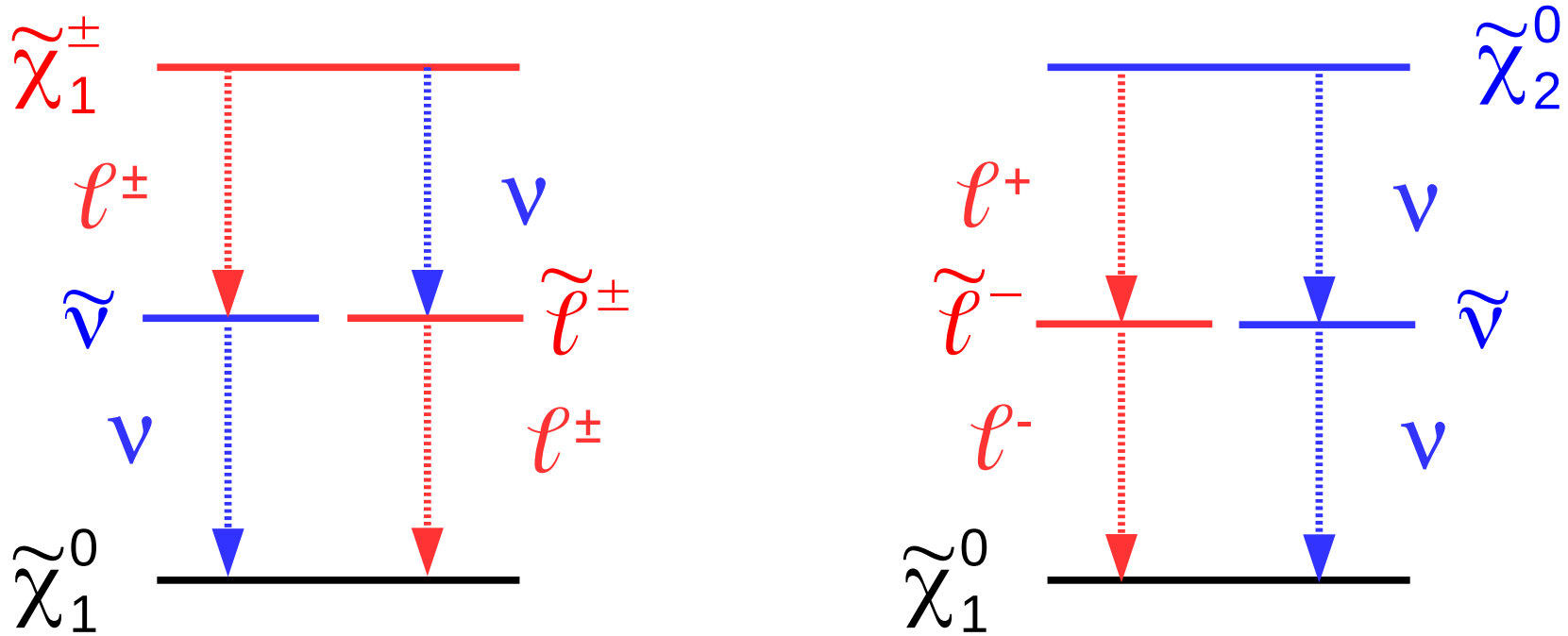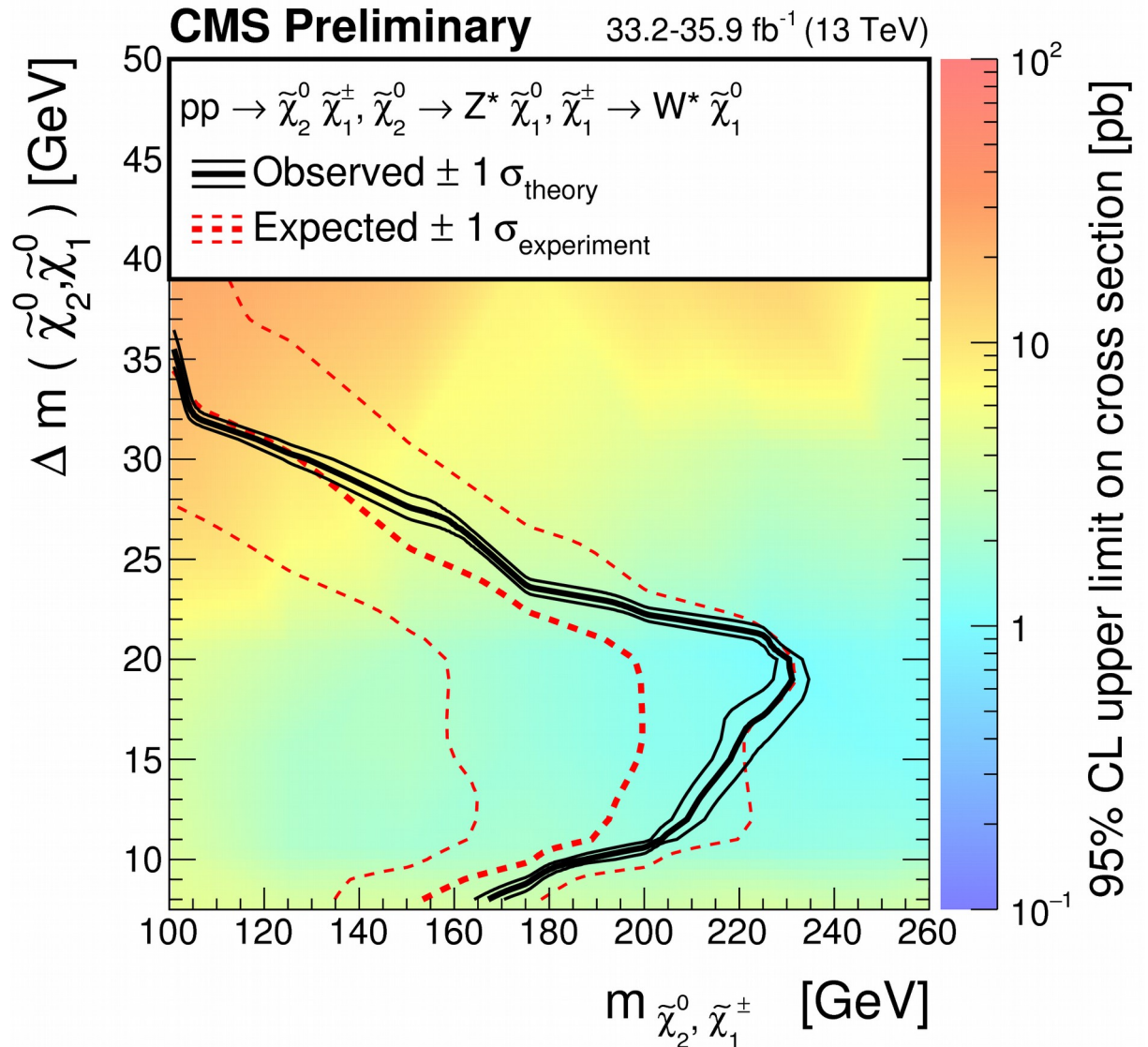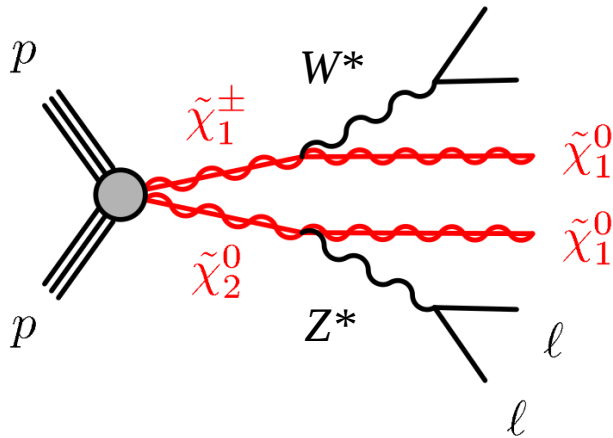- SUS-16-039, 3-lep (BF(ll)=1, x_l=0.5)
- SUS-16-039, 3-lep (BF(ll)=1, x_l=0.05)
- SUS-16-039, 3-lep (BF(ll)=1, x_l=0.95)
- SUS-16-039, 3-lep (BF($\tau\tau$)=1, x_l=0.5)
- SUS-16-039, 2l SS + 3l (WH)
- SUS-16-039, 3-lep (WZ)
- SUS-16-048, soft 2-lep (WZ)

Expected
Observed

$m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_1^0} + m_H$

$m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_1^0}$

$m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_1^0} + m_Z$

$m_{\widetilde{\chi}_1^0}$ [GeV]

$m_{\widetilde{\chi}_2^0} = m_{\widetilde{\chi}_1^\pm}$ [GeV]
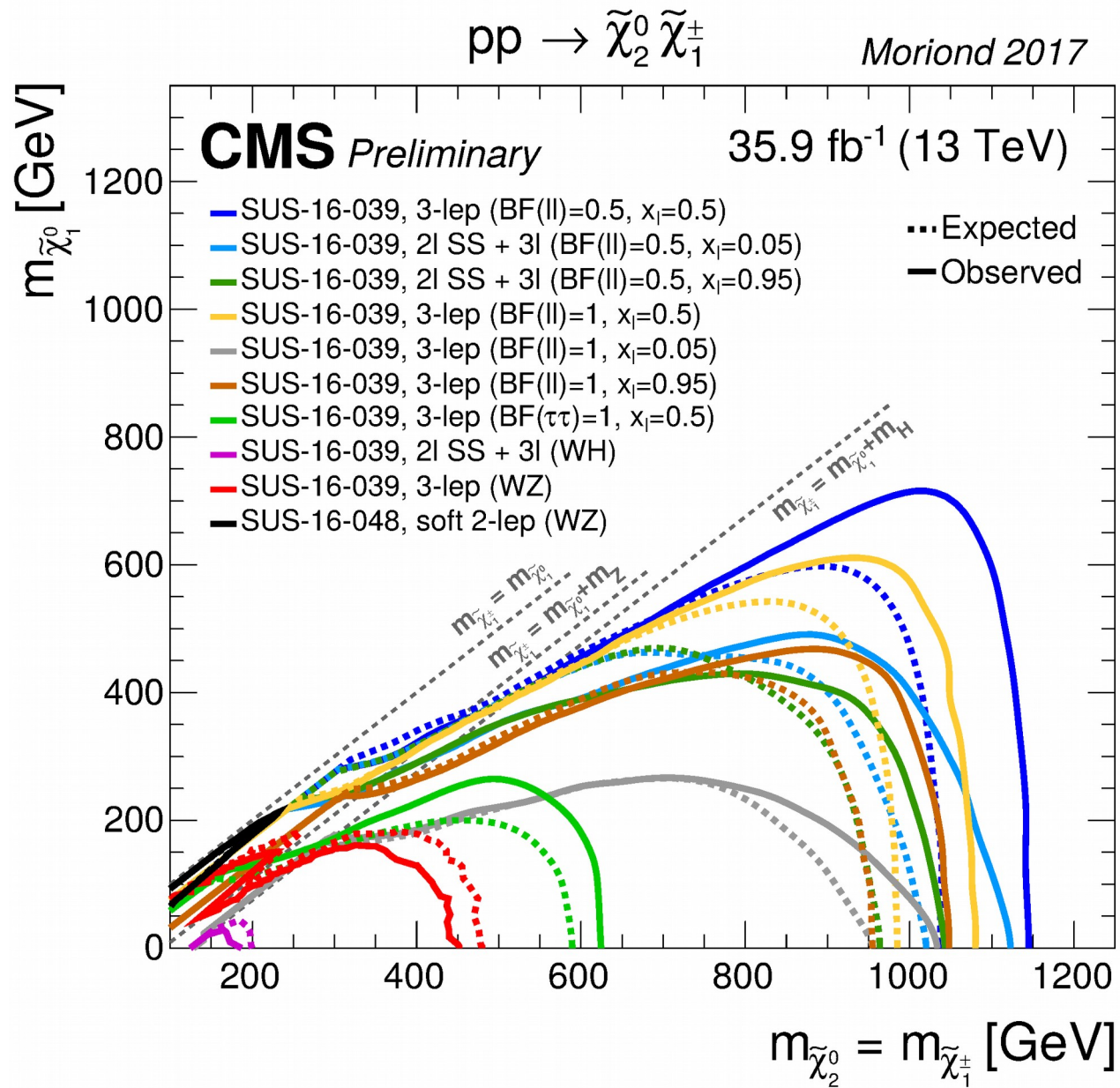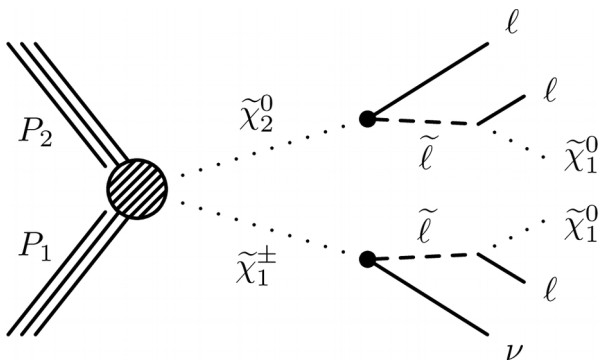
Dijet Resonance Search
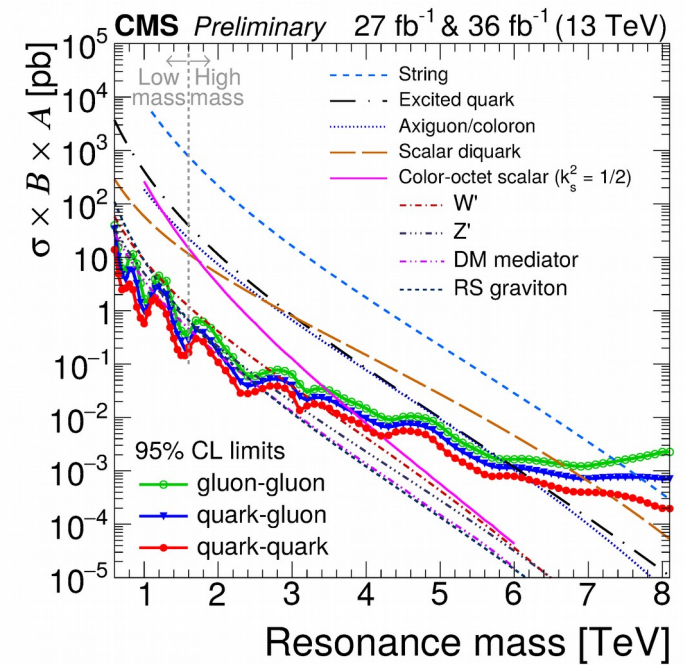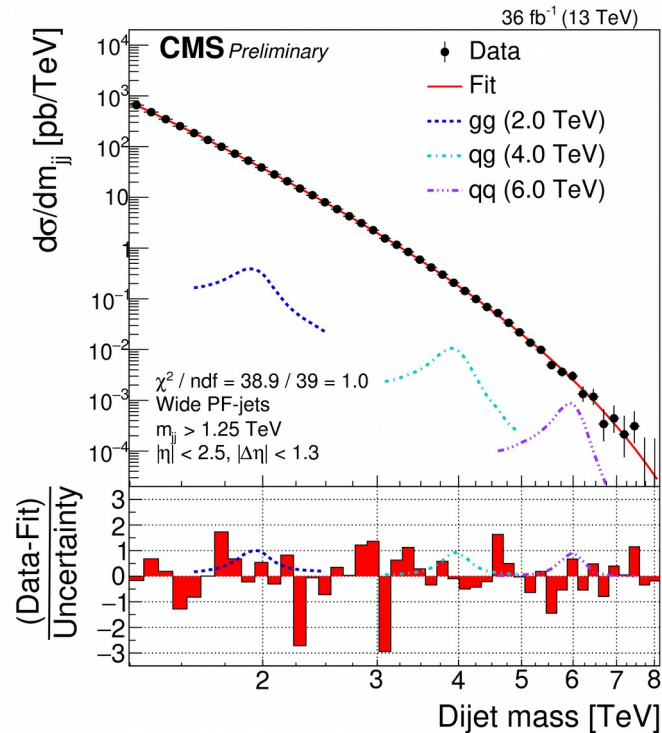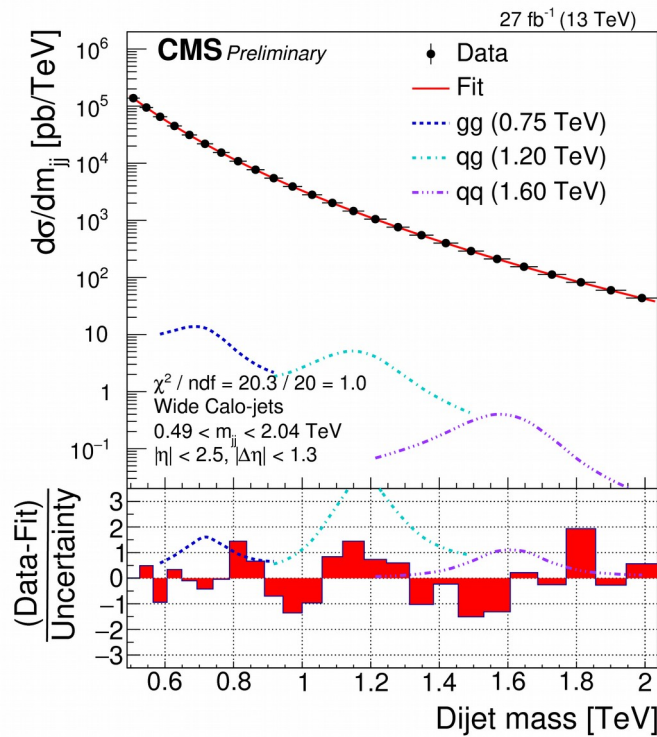
MUSiC: Distributions with the most discrepant kinematic regions

| Scan type		Most significant		Second most significant	
		Event class	$\tilde{p}\ (p)$	Event class	$\tilde{p}\ (p)$
Total Event Yield	excl.	1e+1γ+MET	(0.0015)	3e+2μ	(0.011)
	incl.	3e+2jets+MET+X	(0.014)	3e+2μ+X	(0.019)
	jet-incl.	3e+2jets+MET+Njet	(0.012)	2μ+1γ+Njet	(0.015)
$\sum |\vec{p}_\mathrm{T}|$	excl.	1e+1γ+MET	0.00097	3e+2jets+MET	0.0027
	incl.	2e+1γ+4jets+X	0.00069	3e+2μ+X	0.0041
	jet-incl.	2e+1γ+4jets+Njet	0.00015	3e+2μ+Njet	0.0040
$M_{(T)}$	excl.	1e+1γ+MET	0.0020	1μ+1γ	0.0021
	incl.	2e+1γ+4jets+X	0.00071	2μ+1jet+X	0.0016
	jet-incl.	2e+1γ+4jets+Njet	0.00017	2μ+1jet+Njet	0.0014
MET	excl.	1e+1γ+MET	0.0038	2μ+1γ+1jet+MET	0.0039
	incl.	2μ+1γ+1jet+MET+X	0.0013	3e+2jets+MET+X	0.013
	jet-incl.	2μ+1γ+1jet+MET+Njet	0.0013	3e+2jets+MET+Njet	0.0095

MUSiC tests: Signal W' injection, removal of SM ZZ production
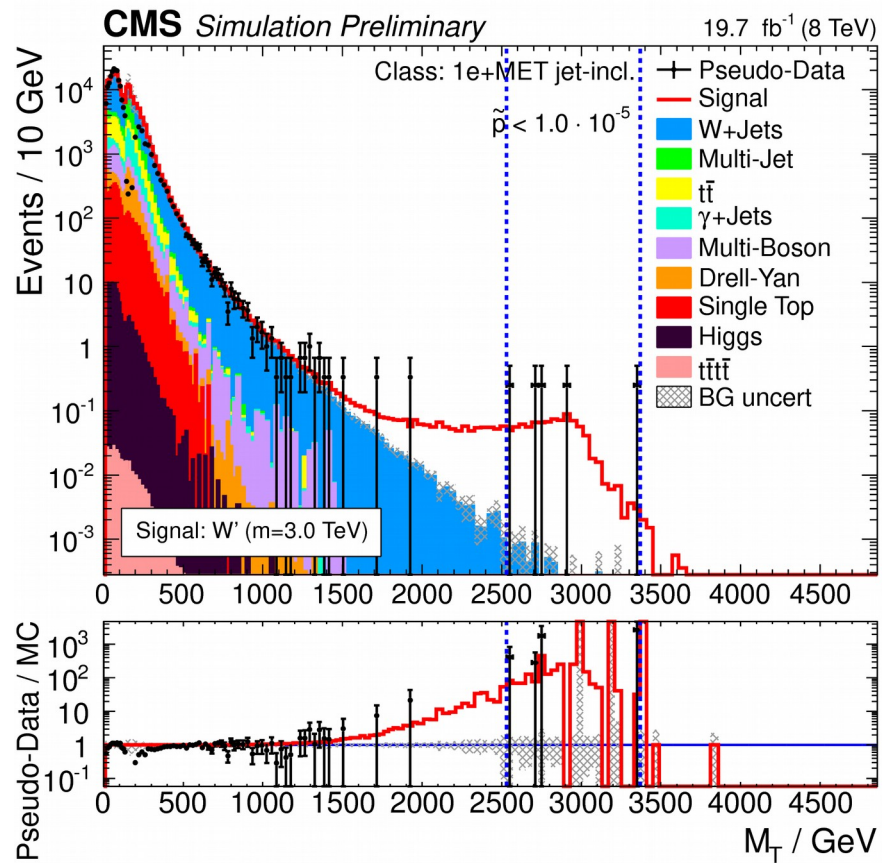
W' 3 TeV injected

SM ZZ removed from bkg