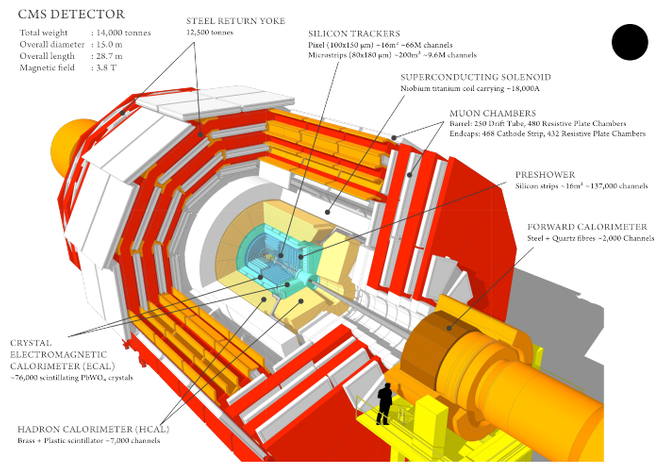
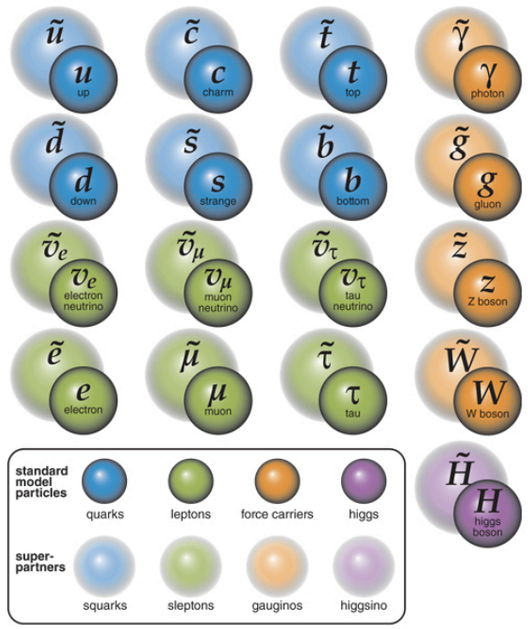
Recent searches for electroweak production of SUSY particles and third generation SUSY particles with CMS

Margaret Lazarovits
on behalf of the CMS Collaboration
ICHEP 2024, 18 July

Overview

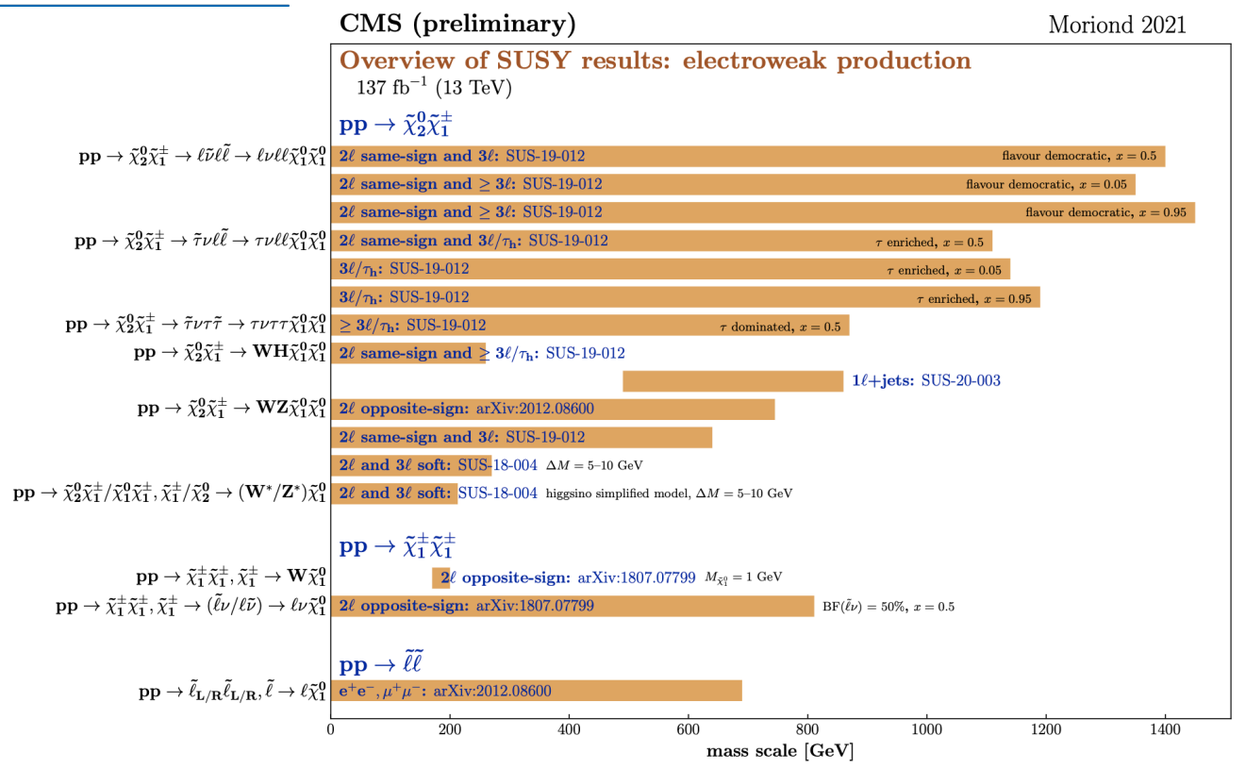


- The Story So Far: SUSY at CMS
- Where to look: the Electroweak Sector
- The Big Squeeze: Compressed SUSY

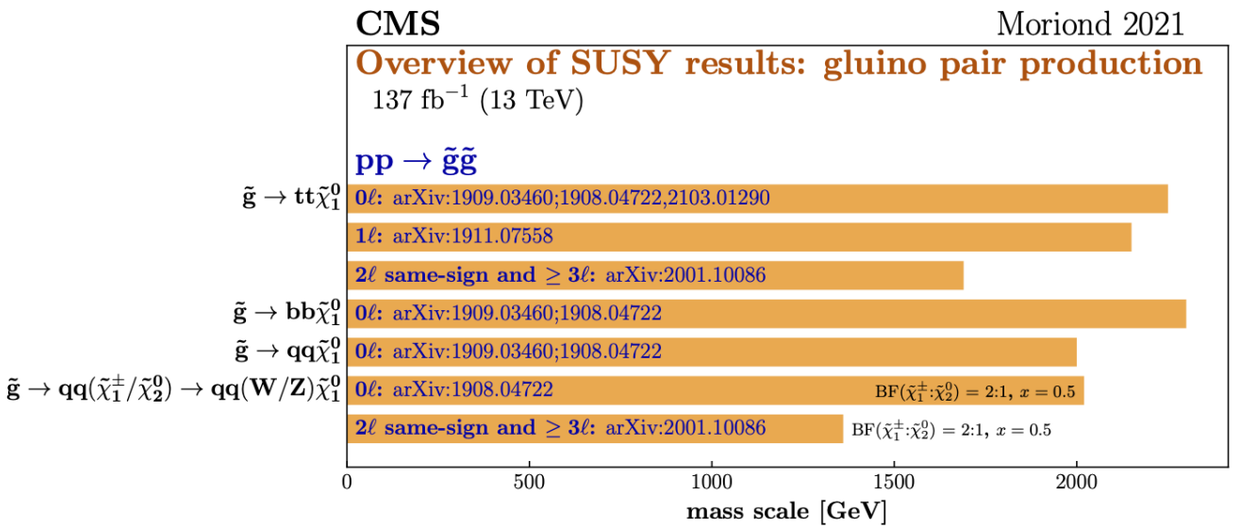


- Achieving Generality and Probing Compression
- EW SUSY Combination Search
  CMS-SUS-21-008, arXiv:2402.01888
- pMSSM Interpretation CMS-SUS-24-004
- Recursive Jigsaw Reconstruction Search CMS-SUS-23-003
- Pushing the Limit: Results
- Summary and Future Directions for Electroweak SUSY searches

The Story So Far: SUSY at CMS



Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.



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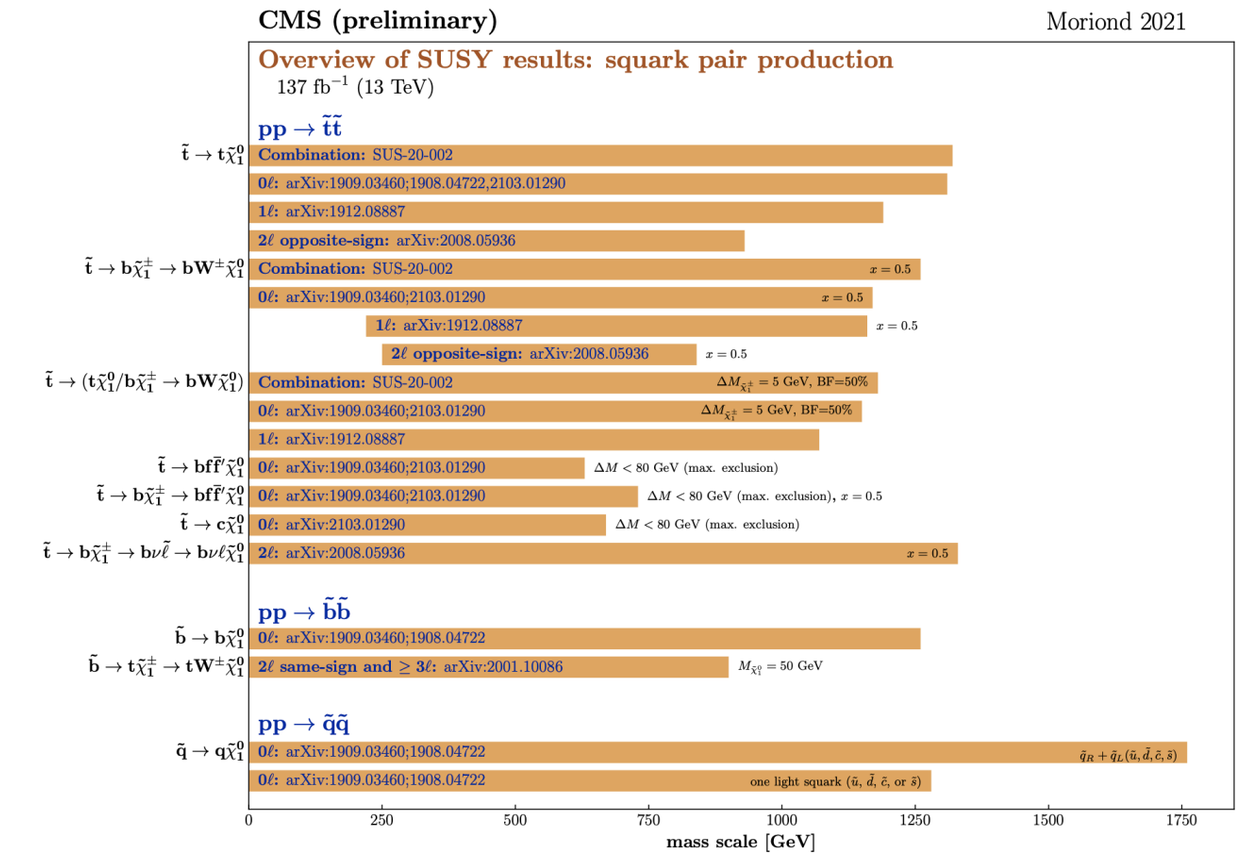

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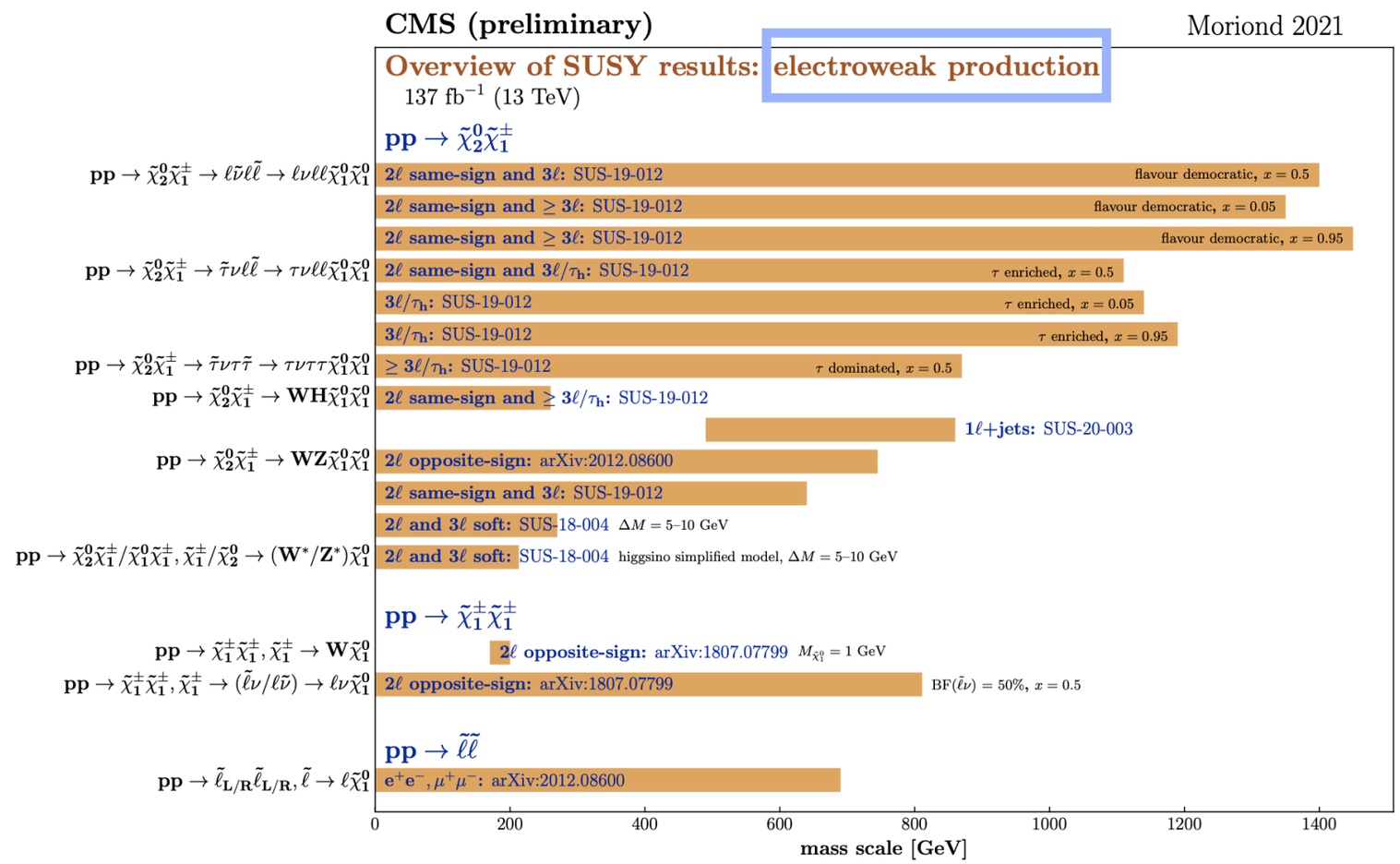
Where to look: The Electroweak sector



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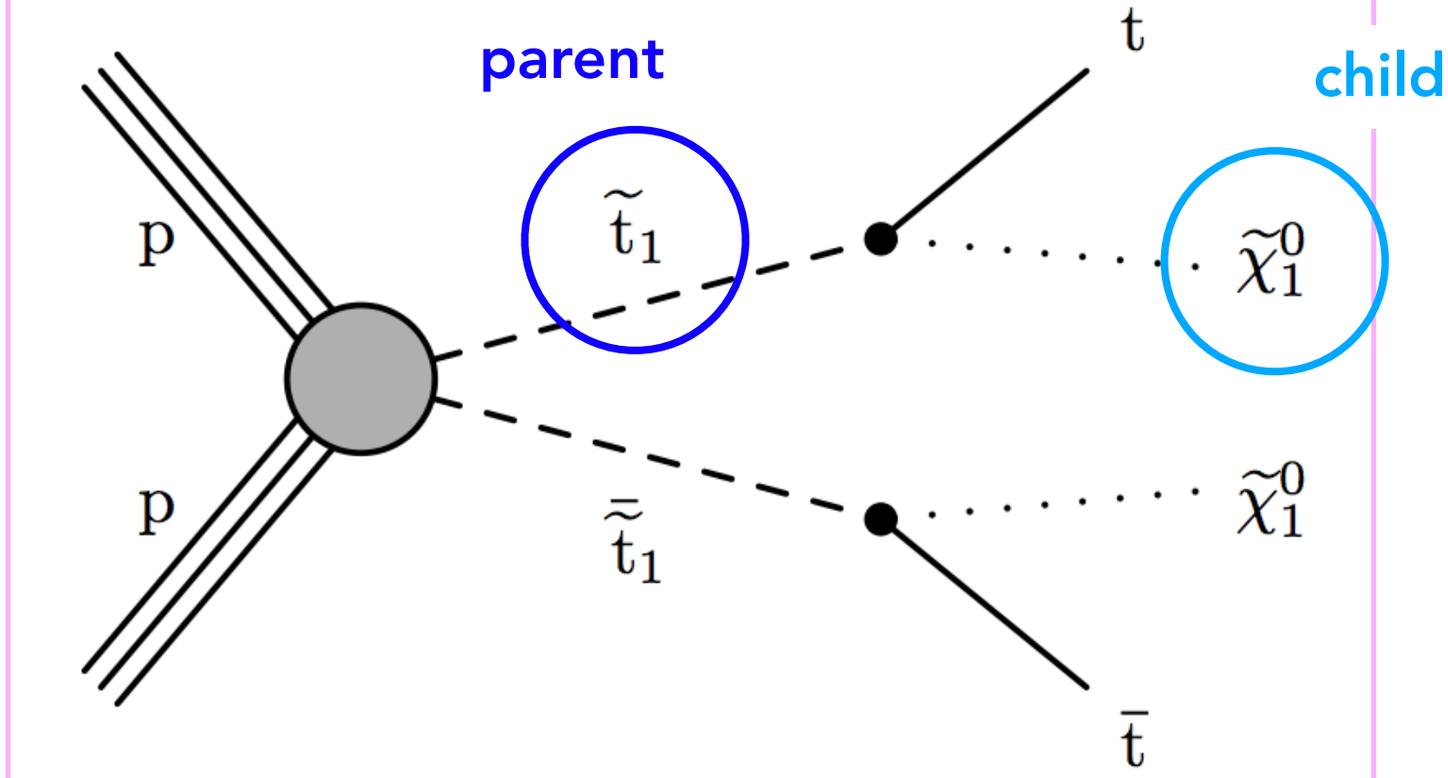
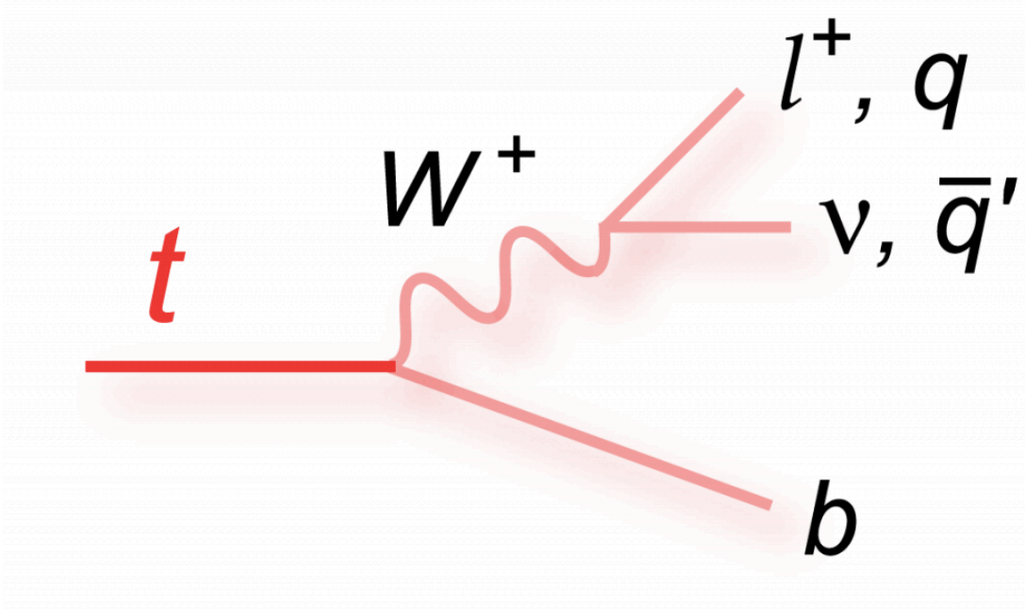
- Promising dark matter candidate
- Energies and luminosities currently achievable at the LHC
- Specific, isolated final states (leptons, b-jets, etc.)
- Compressed or uncompressed scenarios

The Big Squeeze: Compressed SUSY





- Compressed signals: $m_{\text{parent}} - m_{\text{child}} \sim m_{\text{SM}}$
  - Low momentum final states (leptons)
  - Difficult to reconstruct in detectors

Achieving Generality, Probing Compression

CMS-SUS-21-008, arXiv:2402.01888

Combination search

- SRs and CRs of competitive EW SUSY Run II analyses
- Combined in simultaneous ML fit

CMS-SUS-24-004

pMSSM Interpretation

- Bayesian analysis of CMS Run II analyses in pMSSM space
- Chosen to cover wide range of final states

CMS-SUS-23-003

Recursive Jigsaw Reconstruction search

- Recursive Jigsaw Reconstruction
- Extensive SRs constrained by carefully chosen CRs

General searches, target electroweak sector, probe compression

Achieving Generality: Combination Search

CMS-SUS-21-008

- Latest CMS Run II EW analyses
- Combination of CRs and SRs capture different signal models and mass points
  - Wino-bino model
  - Higgsino-bino model
  - GMSB model
  - Slepton pair production
- Cover *wide area of phase space*
- *Extend limits* from previous combination analysis

Many final states from a variety of analyses

Search	Wino-bino WZ	Wino-bino WH	GMSB ZZ	GMSB HZ	GMSB HH	Higgsino-bino WW	Higgsino-bino HH	Higgsino-bino WH	Sleptons $\ell^+\ell^-$
$2/3\ell$ soft [73]	all								2ℓ soft
2ℓ on-Z [71]	EW		EW	EW					
2ℓ nonres. [71]									Slepton
$2SS\ell / \geq 3\ell$ [74]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
$1\ell 2b$ [72]		all						all	
4b [75]					all		3-b, 4-b, 2-bb		
Hadr. WX [76]	all	all				ex H		ex H	

Achieving Generality: Combination Search

CMS-SUS-21-008

- Latest Run II EW analyses
- Combination of CRs and SRs capture different signal models and mass points
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  - Higgsino-bino model
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Many final states from a variety of analyses

Search	Wino-bino WZ	Wino-bino WH	GMSB ZZ	GMSB HZ	GMSB HH	Higgsino-bino WW	Higgsino-bino HH	Higgsino-bino WH	Sleptons $\ell^+\ell^-$
$2/3\ell$ soft [73]	all								2ℓ soft
2ℓ on-Z [71]	EW		EW	EW					
2ℓ nonres. [71]									Slepton
$2SS\ell/\geq 3\ell$ [74]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
$1\ell 2b$ [72]		all						all	
4b [75]					all		3-b, 4-b, 2-bb		
Hadr. WX [76]	all	all				ex H		ex H	

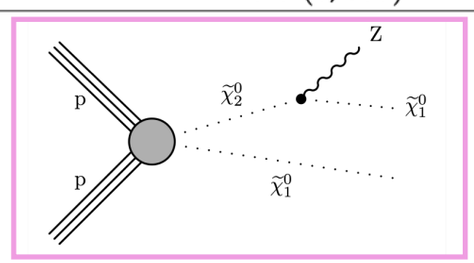
- Cover *wide area of phase space*
- *Extend limits* from previous combination analysis

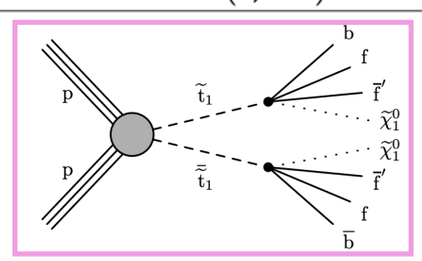
Probing Compression: Combination Search

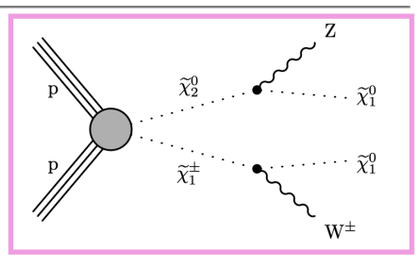
CMS-SUS-21-008

- Sensitivity in compressed wino-bino and slepton models is driven by *2/3L soft OS analysis**
- SRs divided into MET bins
- Tailored for targeted signal
- Orthogonal CRs used to constrain background

Variable	2ℓ-Ewk		2ℓ-Stop		3ℓ-Ewk	
	Low-MET	Higher-MET	Low-MET	Higher-MET	Low-MET	Higher-MET
N_{lep}	2	2	2	2	3	3
$p_T(\ell_1)$ [GeV] for e(μ)	(5,30)	(5(3.5),30)	(5,30)	(5(3.5),30)	(5,30)	(5(3.5),30)
$p_T(\ell_2)$ [GeV] for e(μ)	(5,30)	(5(3.5),30)	(5,30)	(5(3.5),30)	(5,30)	(5(3.5),30)
$p_T(\ell_3)$ [GeV] for e(μ)	—	—	—	—	(5,30)	(5(3.5),30)
1 OS pair	✓	✓	✓	✓	✓	✓
1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i\ell_j)$ $(i,j=1,2,3, i\neq j)$	—	>0.3	—	>0.3	—	>0.3
$M_{SFOS}(\ell\ell)$ ($M^{min}_{SFOS}(\ell\ell)$ in 3ℓ) [GeV]	(4,50)	(1,50)	(4,50)	(1,50)	(4,50)	(1,50)
$M^{max}_{SFAS}(\ell\ell)$ (AS=any sign) [GeV]	—	—	—	—	<60	—
$M_{SFOS}(\ell\ell)$ ($M^{min}_{SFOS}(\ell\ell)$ in 3ℓ) [GeV]	veto (3,3.2) and (9,10.5)					
$p_T(\ell\ell)$ [GeV]	>3		>3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_T(\ell_i, p_T^{miss})$ [GeV] $(i=1,2)$	<70		—		—	
H_T [GeV]			>100			
p_T^{miss}/H_T	(2/3,1.4)		(2/3,1.4)		—	
$N_b(p_T>25\,GeV)$			$=0$			
$M_{\tau\tau}$ [GeV]	veto (0,160)		veto (0,160)		—	







*CMS-SUS-18-004, arxiv:2111.06296

Probing Compression: Combination Search

CMS-SUS-21-008

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$p_T(\ell_3)$ [GeV] for e(μ)	—	—	—	—	(5,30)	(5(3.5),30)
1 OS pair	✓	✓	✓	✓	✓	✓
1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i\ell_j)$ $(i,j=1,2,3, i\neq j)$	—	> 0.3	—	> 0.3	—	> 0.3
$M_{SFOS}(\ell\ell)$ ($M^{min}_{SFOS}(\ell\ell)$ in 3ℓ) [GeV]	(4,50)	(1,50)	(4,50)	(1,50)	(4,50)	(1,50)
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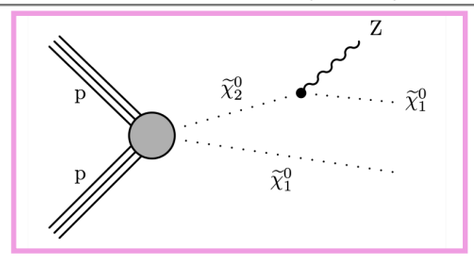
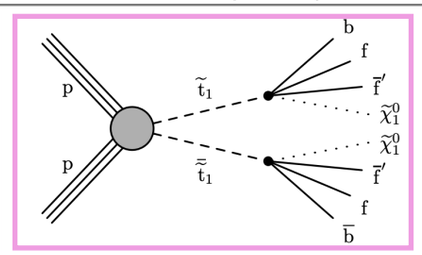
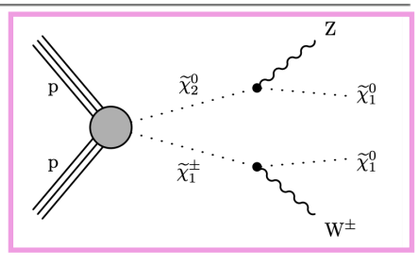
$p_T(\ell\ell)$ [GeV]	> 3		> 3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_T(\ell_i, p_T^{miss})$ [GeV] $(i=1,2)$	< 70		—		—	
H_T [GeV]	> 100					
p_T^{miss}/H_T	(2/3,1.4)		(2/3,1.4)		—	
$N_b(p_T > 25\,GeV)$	= 0					
$M_{\tau\tau}$ [GeV]	veto (0,160)		veto (0,160)		—	







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$\Delta R(\ell_i\ell_j)$ $(i,j=1,2,3, i\neq j)$	—	> 0.3	—	> 0.3	—	> 0.3
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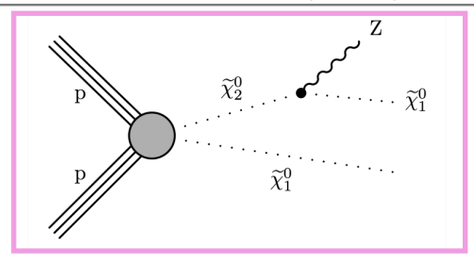
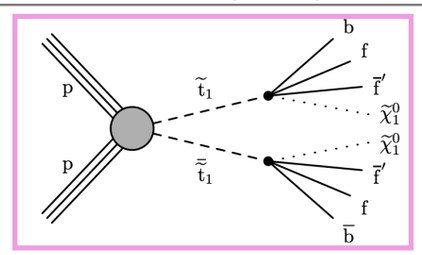
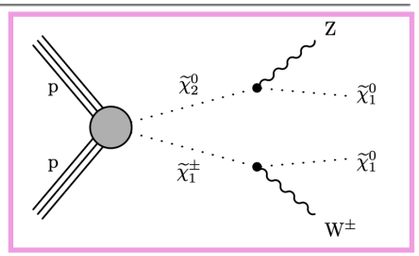
$p_T(\ell\ell)$ [GeV]	> 3		> 3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_T(\ell_i, p_T^{miss})$ [GeV] $(i=1,2)$	< 70		—		—	
H_T [GeV]	> 100					
p_T^{miss}/H_T	(2/3,1.4)		(2/3,1.4)		—	
$N_b(p_T > 25\,GeV)$	= 0					
$M_{\tau\tau}$ [GeV]	veto (0,160)		veto (0,160)		—	







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Probing Compression: Combination Search

CMS-SUS-21-008

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1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i\ell_j)$ $(i,j=1,2,3, i\neq j)$	—	> 0.3	—	> 0.3	—	> 0.3
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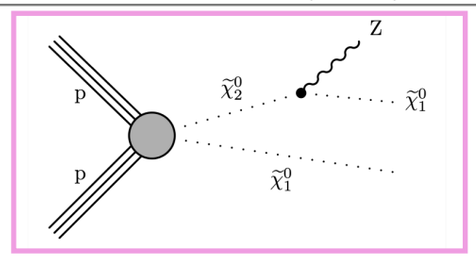
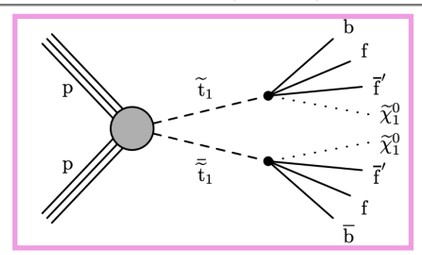
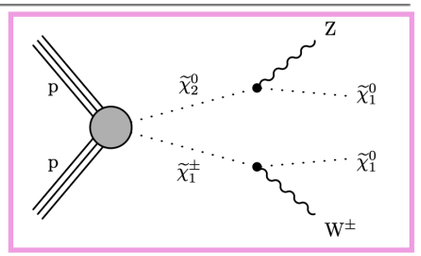
Leading jet "Tight lepton veto"	✓		✓		—	
$m_T(\ell_i, p_T^{miss})$ [GeV] $(i=1,2)$	< 70		—		—	
H_T [GeV]	> 100					
p_T^{miss}/H_T	(2/3,1.4)		(2/3,1.4)		—	
$N_b(p_T > 25\,GeV)$	= 0					
$M_{\tau\tau}$ [GeV]	veto (0,160)		veto (0,160)		—	







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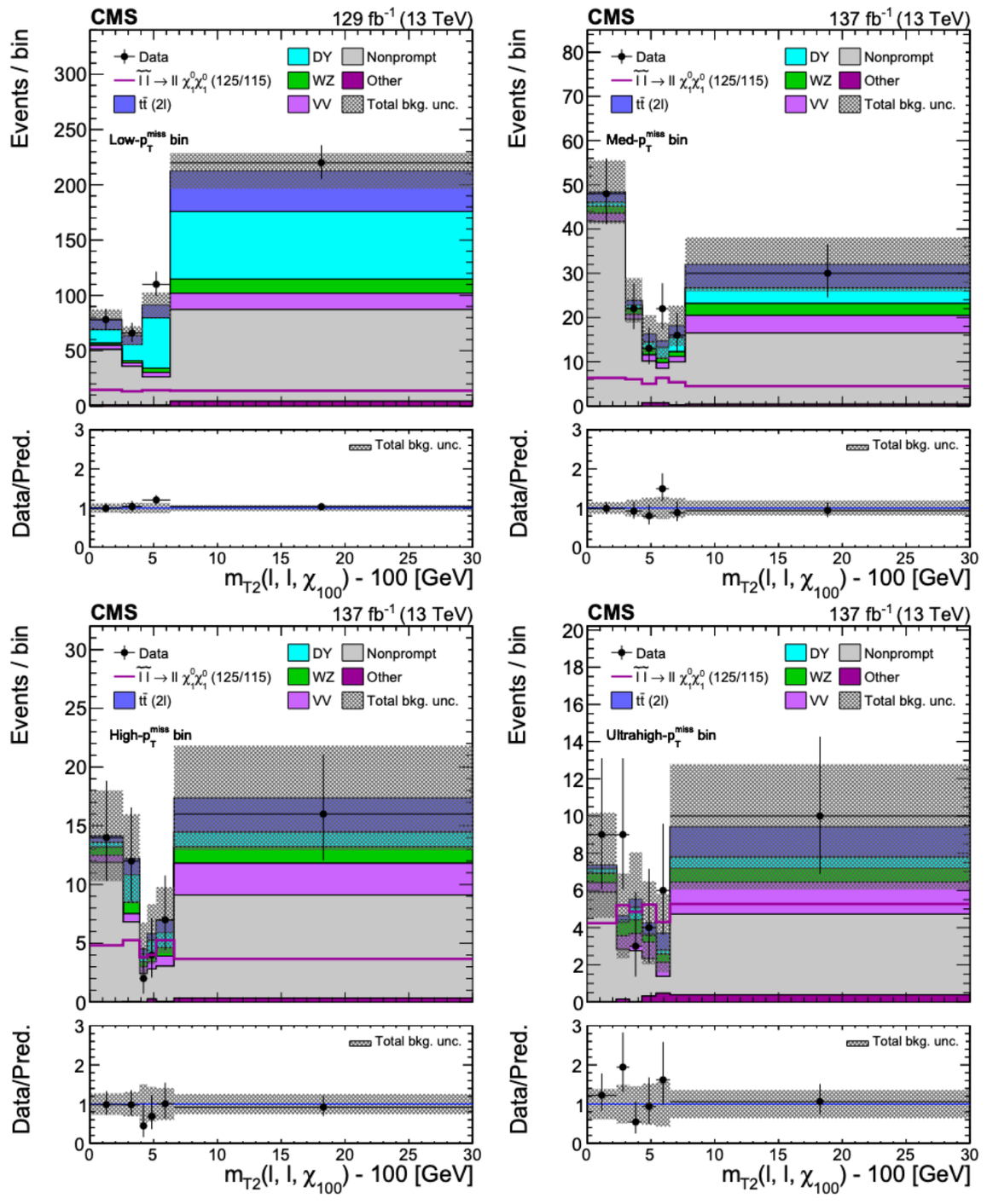
Probing Compression: Combination Search

CMS-SUS-21-008

- Sensitivity in compressed wino-bino and slepton models is driven by *2/3L soft OS analysis**
- *Additions* included in combination
- *Parametric binning* in $m_{\ell\ell}$ optimized for *WZ topology*
- *Replacing* $m_{\ell\ell}$ with $m_{T2}(\mathrm{k},\mathrm{k},\tilde{\chi}_1^0)$ in 2L channel for *new* slepton interpretation



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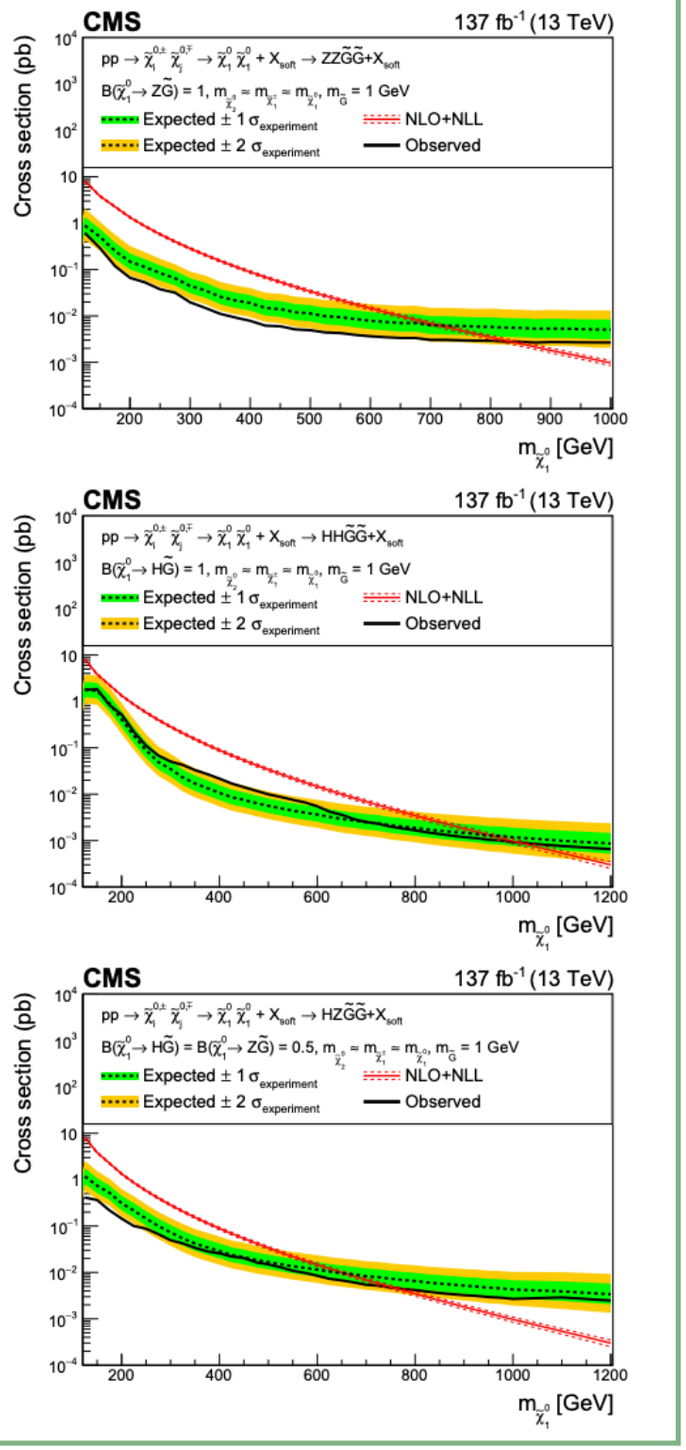
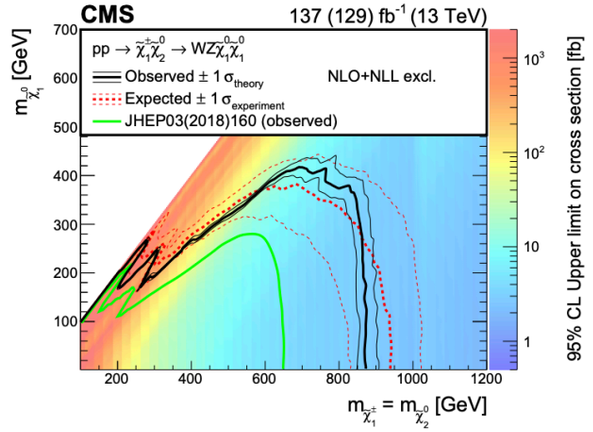
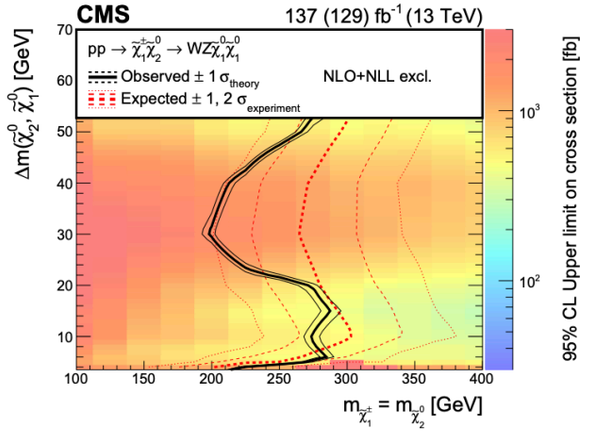
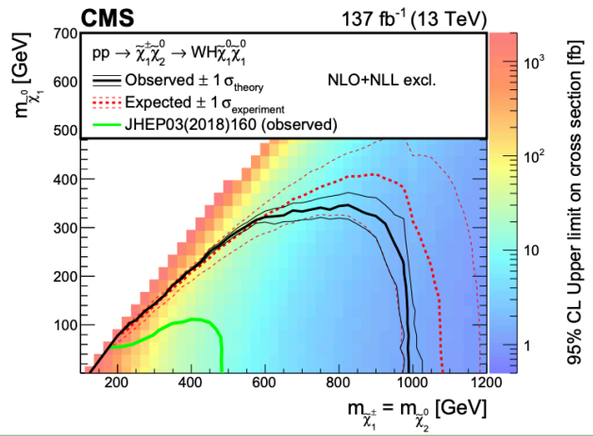
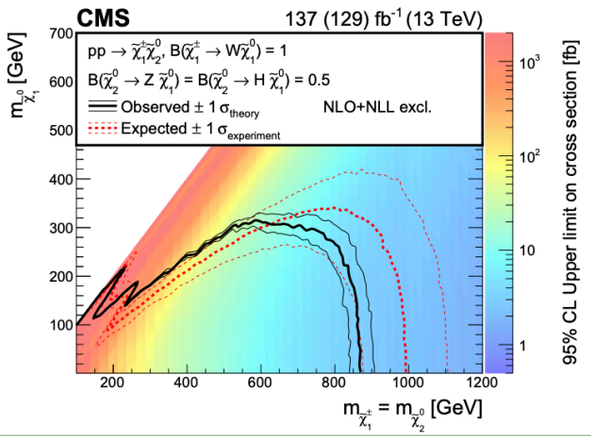
Detecting the Invisible:
Pushing the Limit with Combination

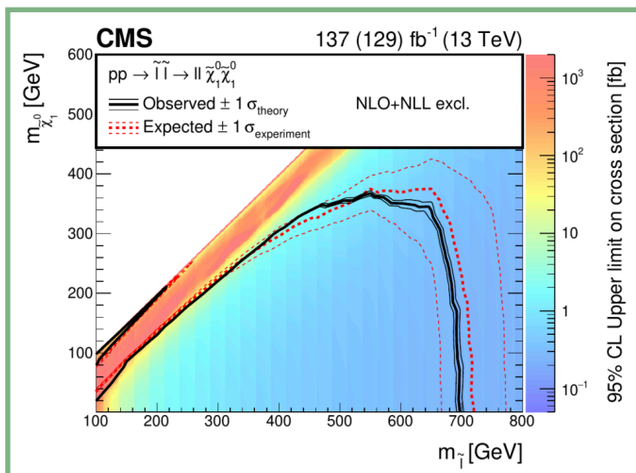


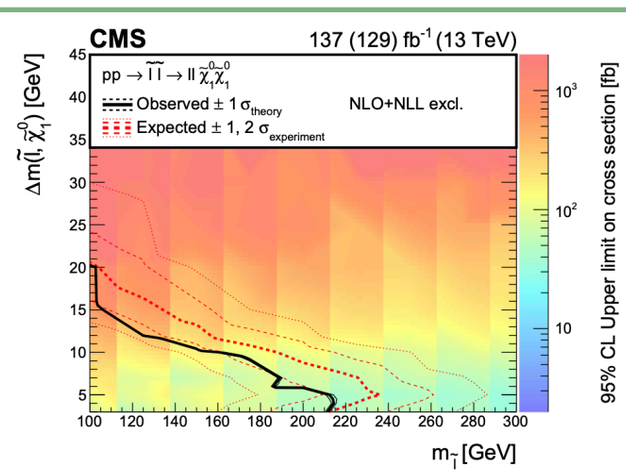












Combining analyses shows overall competitive results in various (compressed) signal models

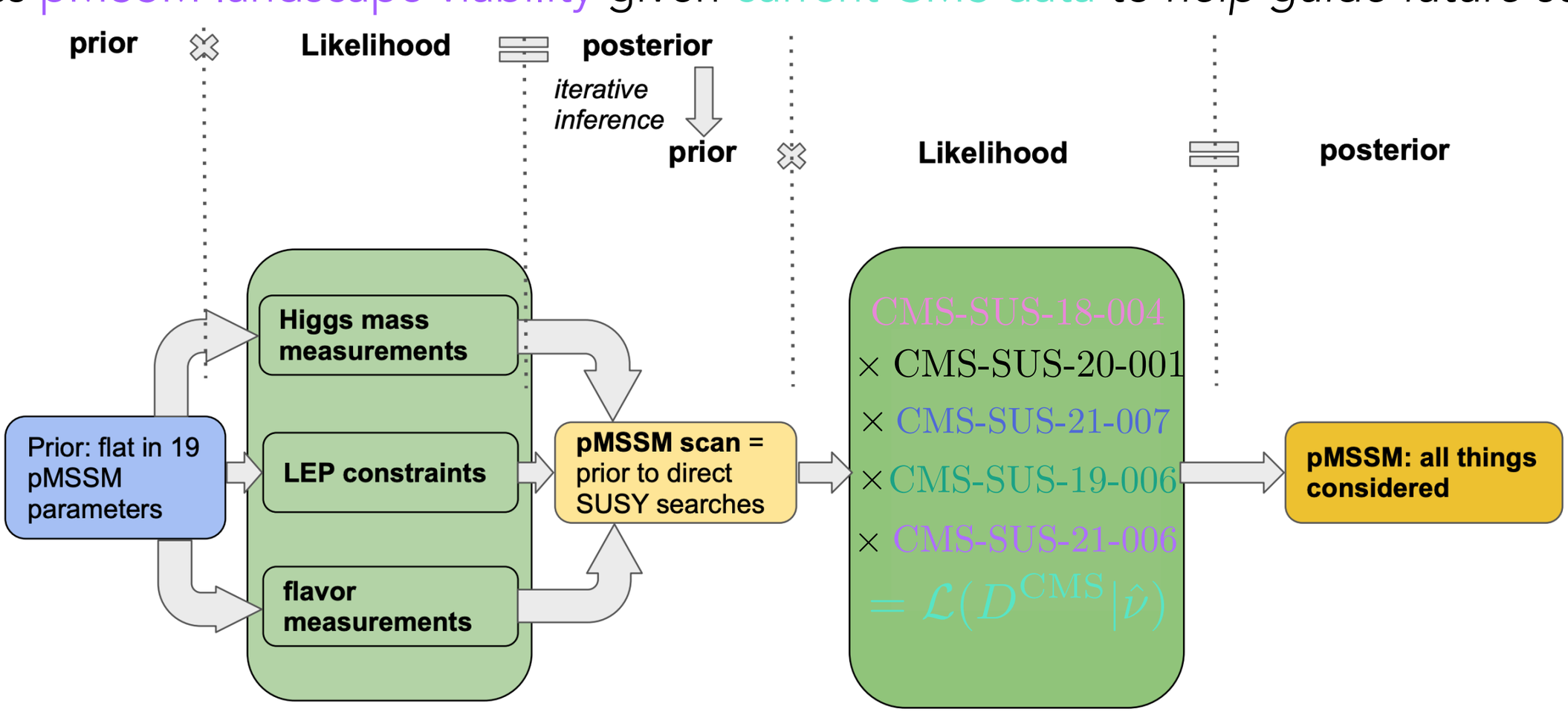
CMS-SUS-21-008

Achieving Generality:

pMSSM Interpretation

CMS-SUS-24-004

- Combination of likelihoods for largely orthogonal analyses, includes EW and 3rd gen interpretations
- *Bayesian approach* includes LHC prior (MCMC pMSSM scan) and historic DM constraints
- Assess pMSSM landscape viability given current CMS data to *help guide future searches*

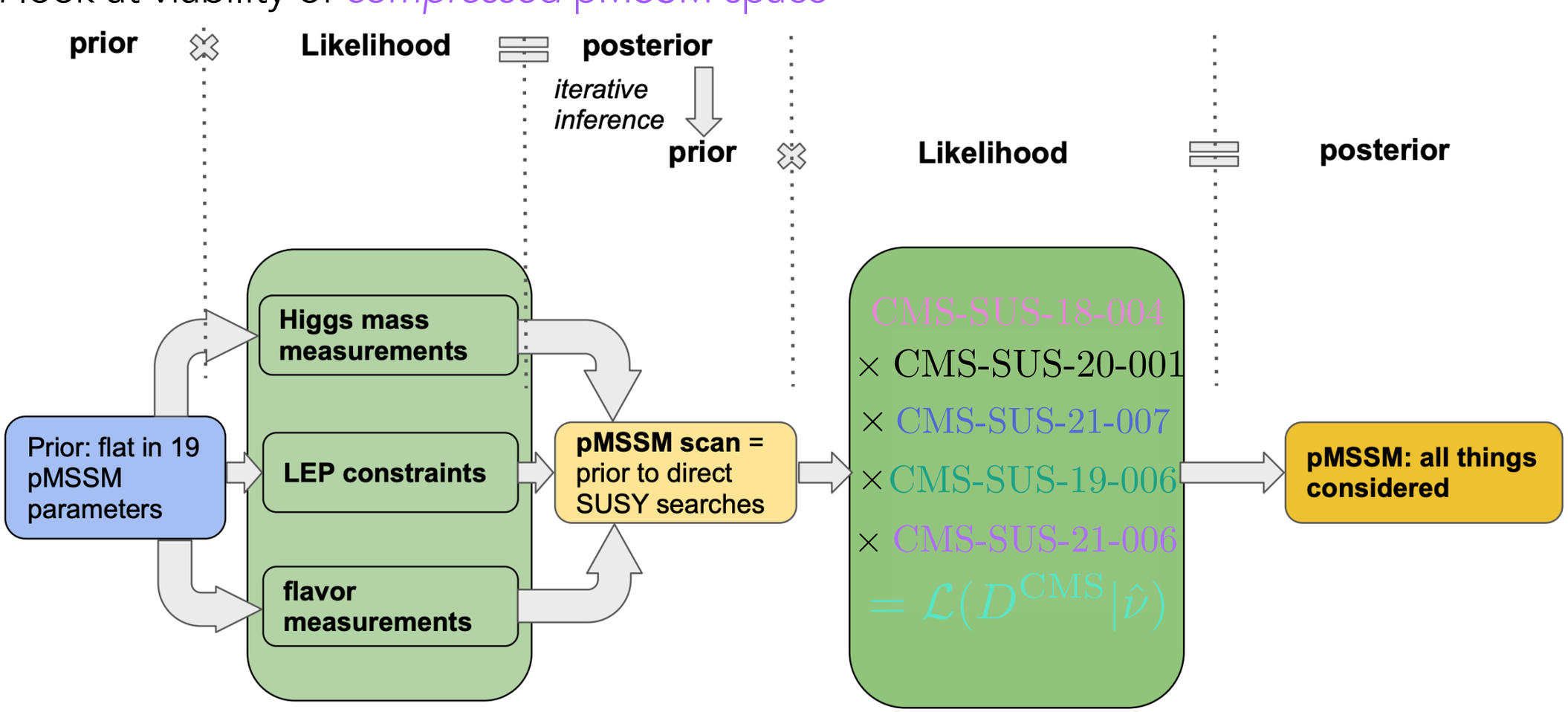


Probing Compression:

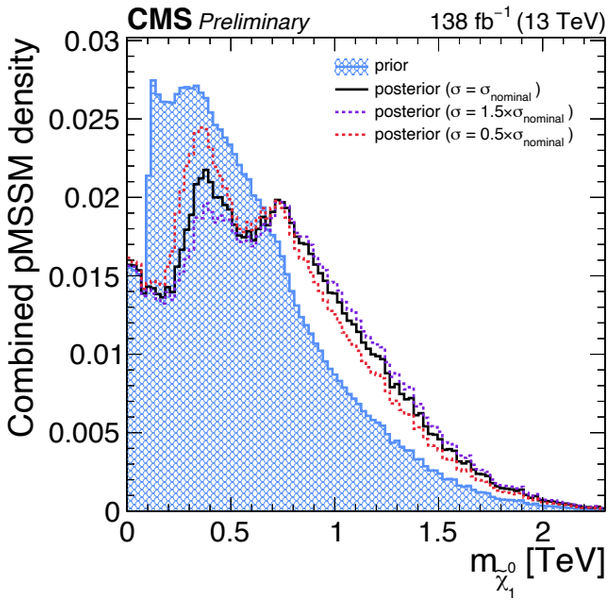
pMSSM Interpretation

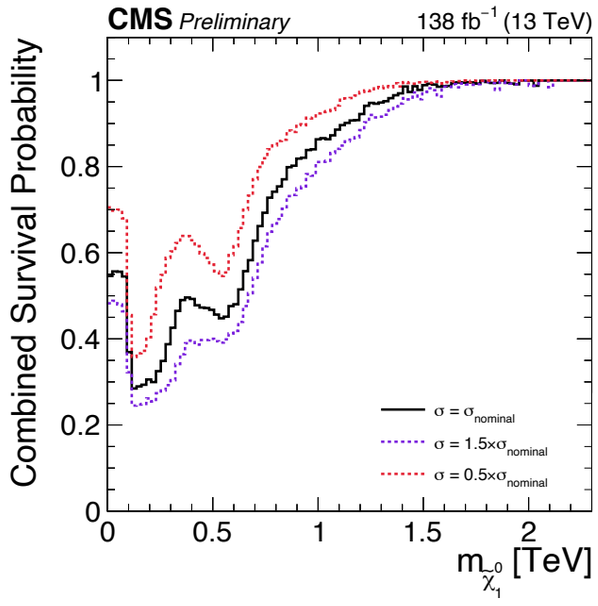
CMS-SUS-24-004

- Sensitivity in compressed areas of pMSSM space is driven by
  - EW: *2/3L soft OS analysis, disappearing tracks analysis*
  - Strong: MET+jets, *single lepton dPhi analysis*
- *Global* look at viability of *compressed* pMSSM space



Detecting the Invisible:
Pushing the Limit with pMSSM Interpretation

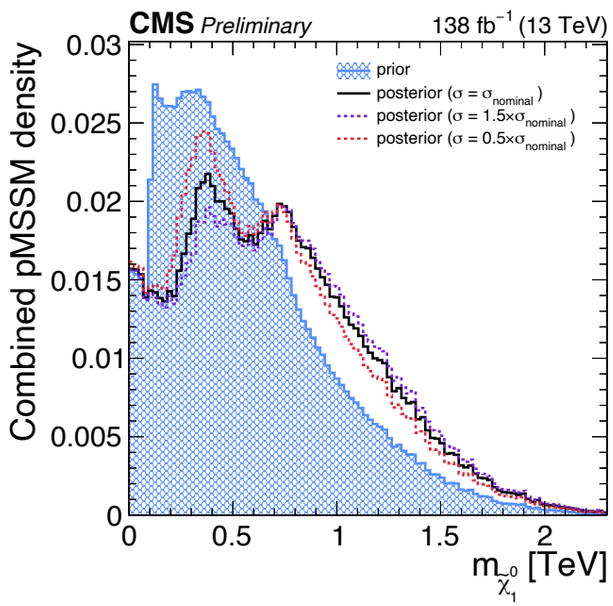


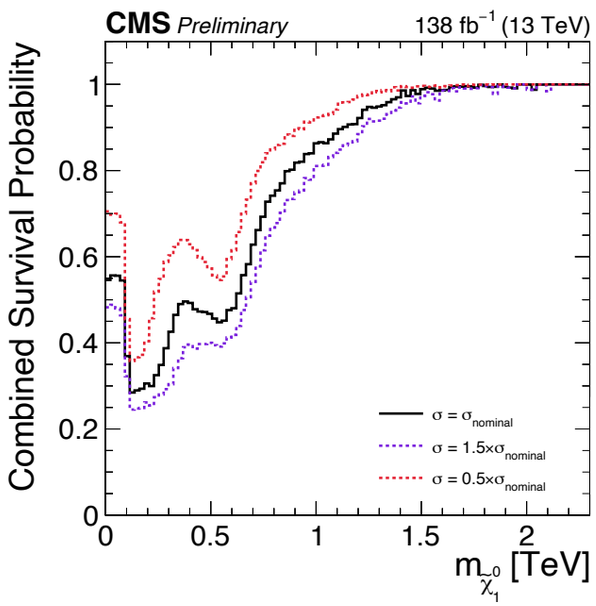


Complementary designs of carefully chosen Run II analyses combined with historical LHC data in a Bayesian framework

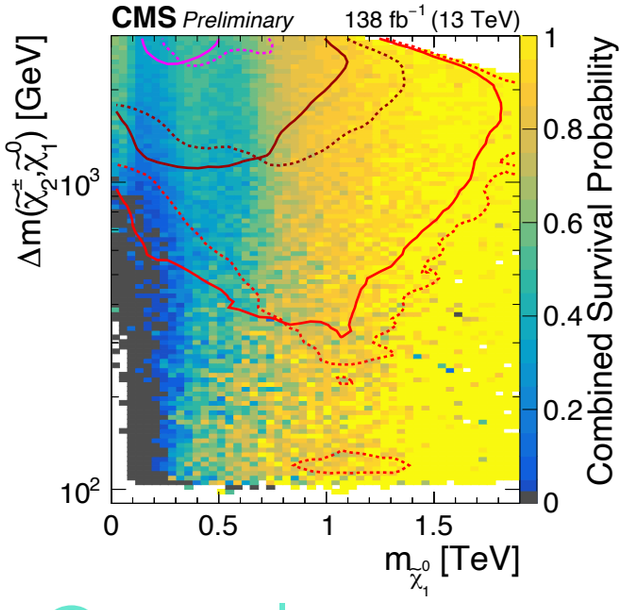
CMS-SUS-24-004 demonstrates promising areas of pMSSM

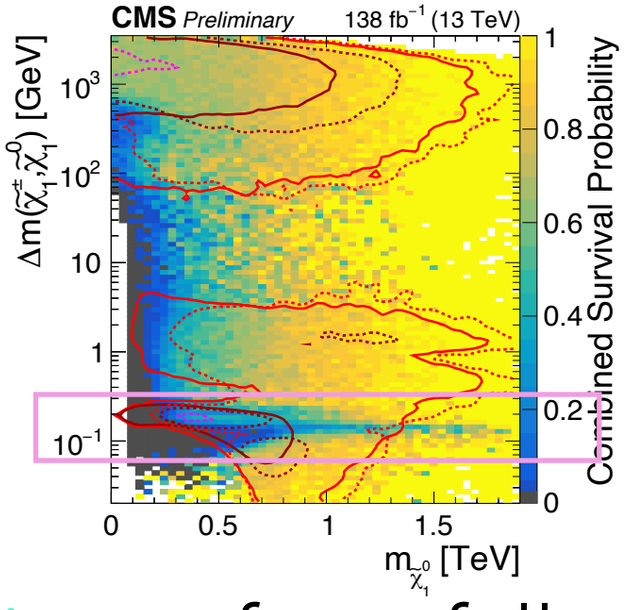
Detecting the Invisible:
Pushing the Limit with pMSSM Interpretation

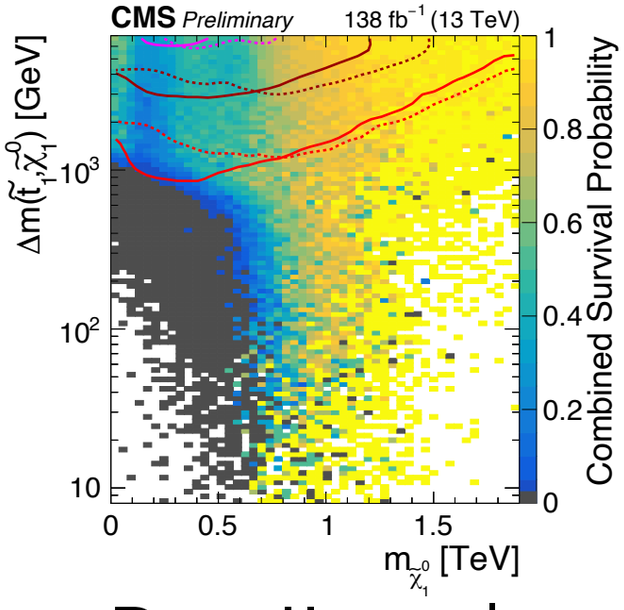




CMS-SUS-24-004

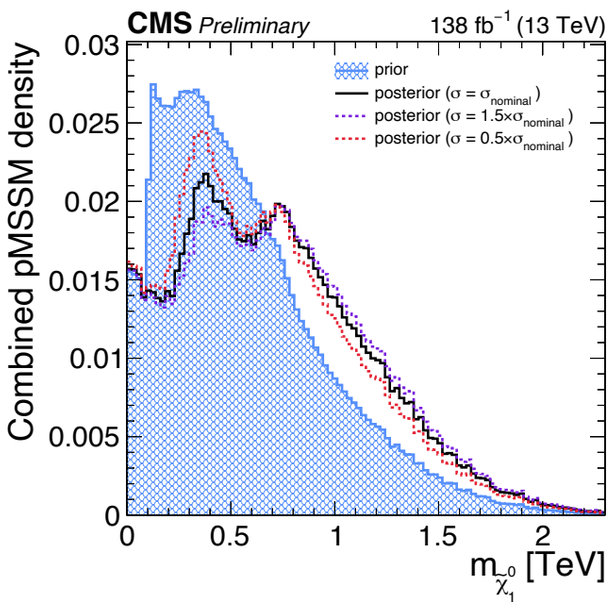


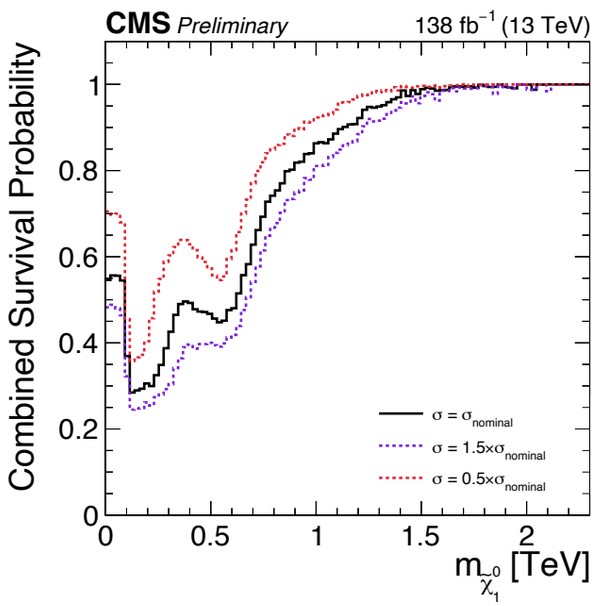




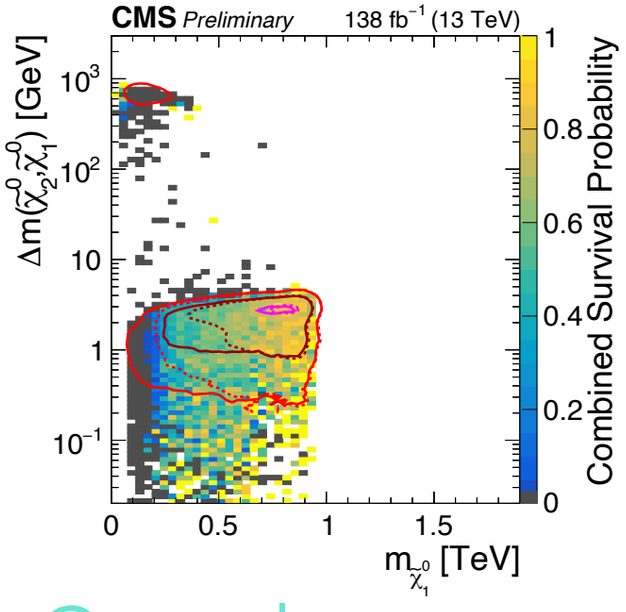
Complementary designs of carefully chosen Run II analyses combined with historical LHC data in a Bayesian framework demonstrates promising areas of pMSSM

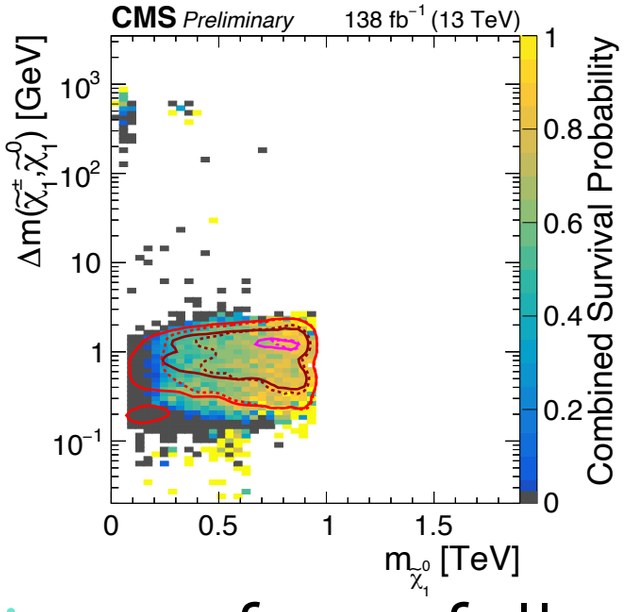
Detecting the Invisible:
Pushing the Limit with pMSSM Interpretation

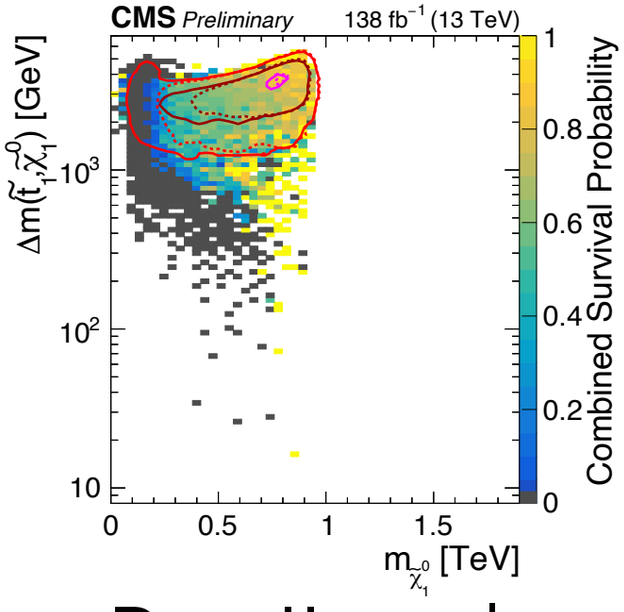




CMS-SUS-24-004

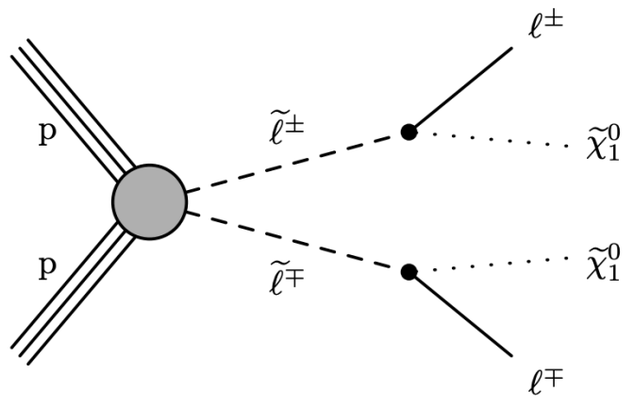


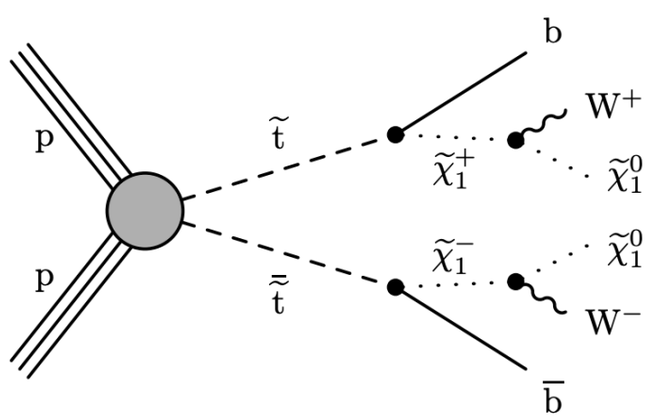


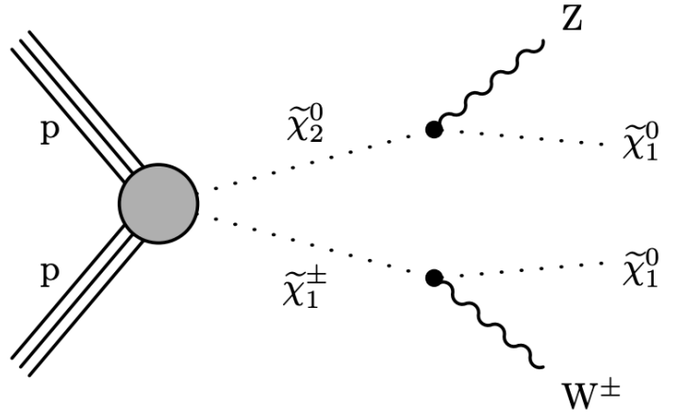


Complementary designs of carefully chosen Run II analyses combined with historical LHC data and *DM constraints* in a Bayesian framework demonstrates promising areas of pMSSM

Achieving Generality: RJR Search







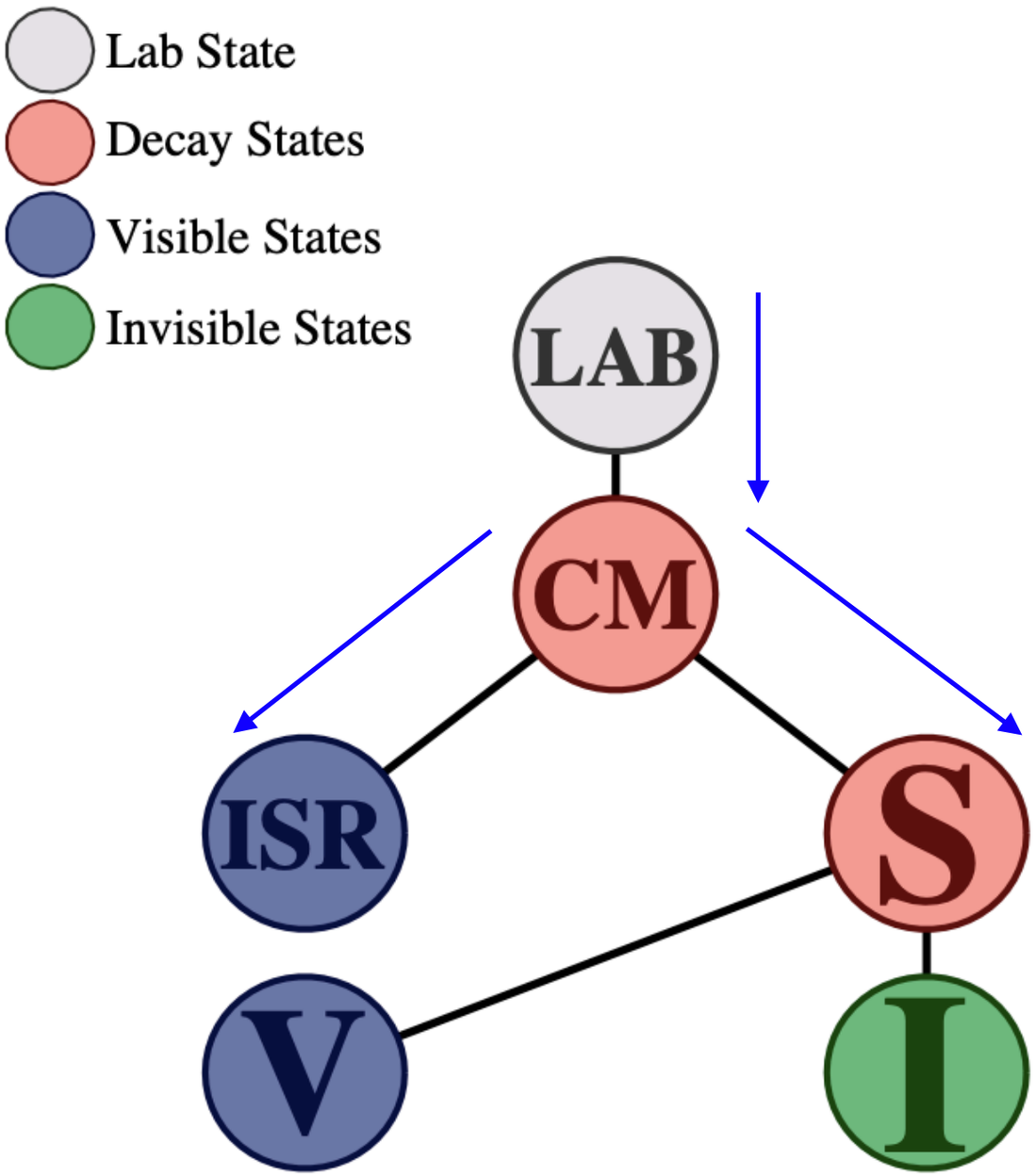
- Intrinsically generic kinematics and search regions
- Multiple signal models
- Variety of soft final states: 0-3 leptons + jets + SVs + MET
  - Soft SVs tagged with dedicated DNN

CMS-SUS-23-003

$N_{\text{jet}}^{\text{S}}$	lep qual	lep cat	$N_{\text{b tag}}^{\text{S}}$	$N_{\text{b tag}}^{\text{ISR}}$	N_{SV}^{S}	kin	$p_{\text{T}}^{\text{ISR}}$ [GeV]
0J	gold or silver or bronze				≥ 1	svc or svf	$[250, \infty)$
	gold	e^+e^- or $\mu^+\mu^-$ or $e^{\pm}\mu^{\mp}$ SS		0 or ≥ 1	0	p- or p+	$[250, 350]$ or $[350, \infty)$
	silver or bronze	ee or $\mu\mu$ or $e\mu$					$[250, \infty)$
1J	gold	Z* or noZ (OS)	0 or 1	0 or ≥ 1		p- or p+	$[250, 350]$ or $[350, \infty)$
	silver or bronze	SS ee or $\mu\mu$ or $e\mu$					$[350, \infty)$
2J	gold	Z* or noZ (OS)	0 or ≥ 1	0 or ≥ 1		p- or p+	$[250, 350]$ or $[350, \infty)$
	silver or bronze	SS ee or $\mu\mu$ or $e\mu$					$[350, \infty)$

2 lepton region category definitions

Achieving Generality: RJR Search



- Analyzing events: recursive jigsaw reconstruction (RJR)
  - Recursively iterate through approximations of rest frames
  - Apply interchangeable rules at each step (like jigsaw pieces)
  - Get *basis of ~uncorrelated observables* instead of just one

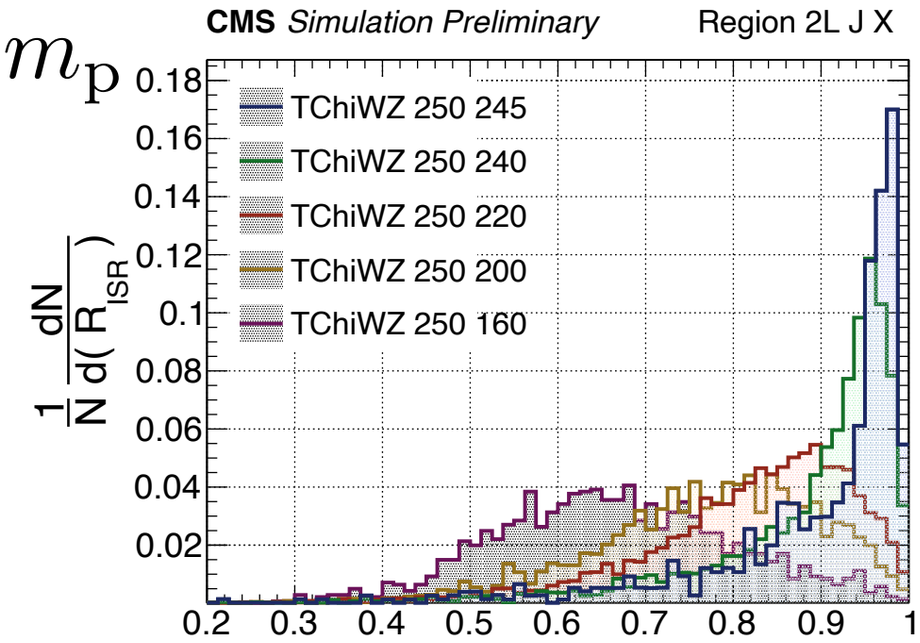
Phys. Rev. D 95, 035031
arXiv:1607.08307

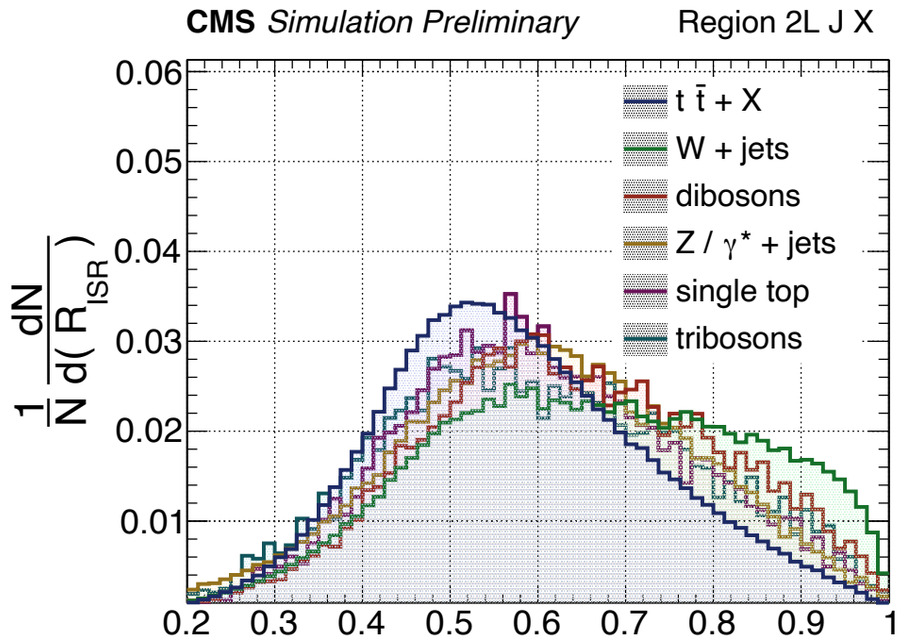
Probing Compression:

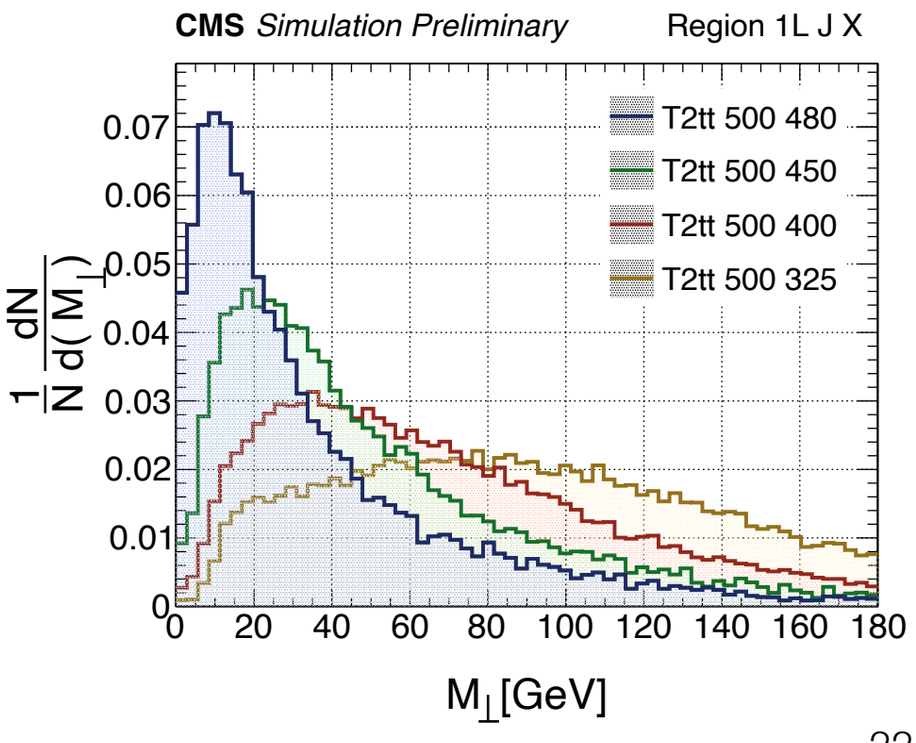
CMS-SUS-23-003 **RJR Search**

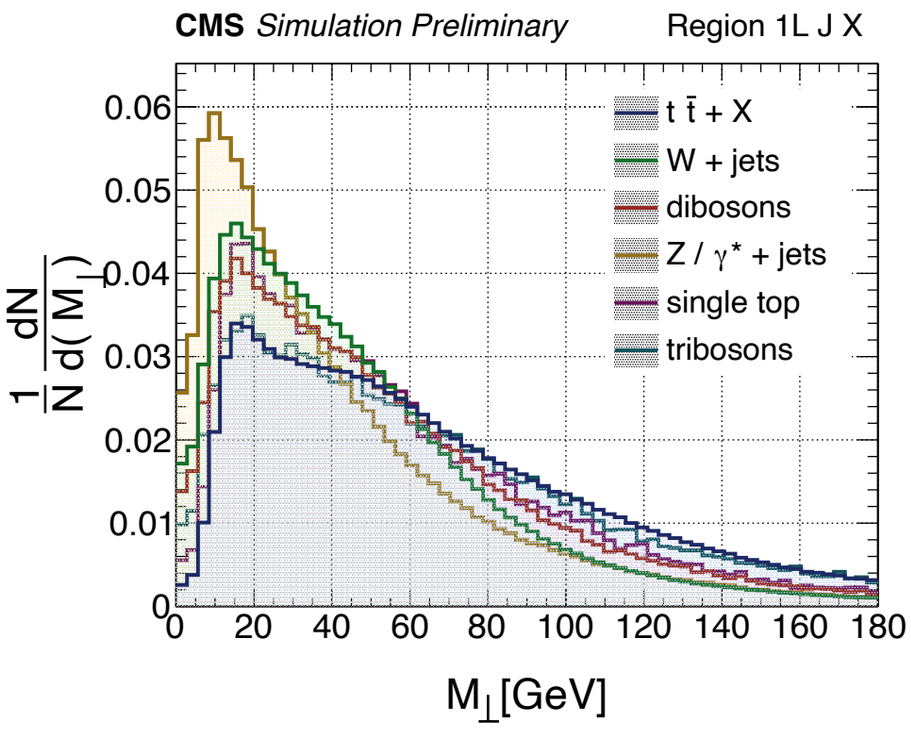
$$R_{ISR} \sim \frac{m_c}{m_p}$$

$$M_\perp \sim m_p - m_c$$



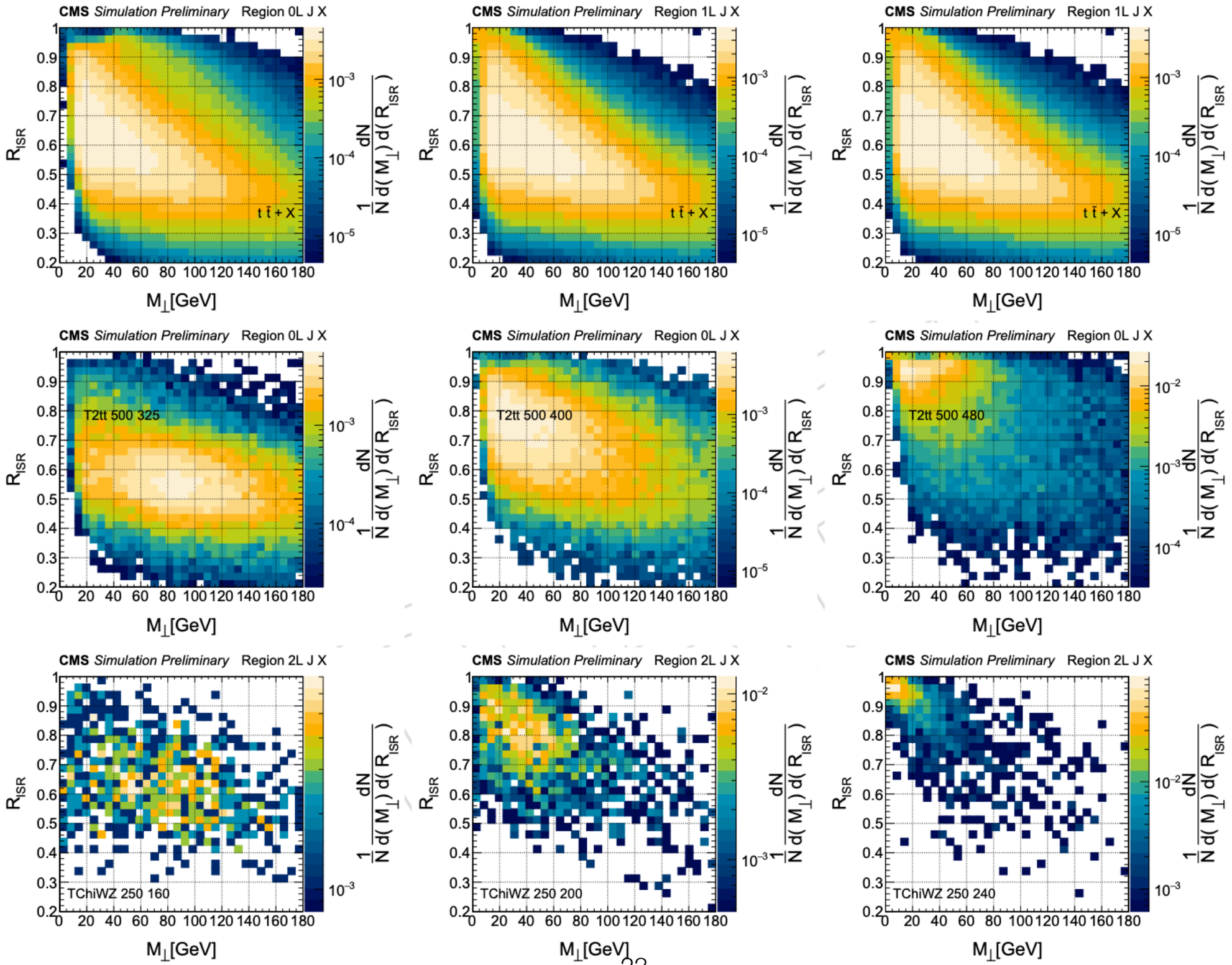




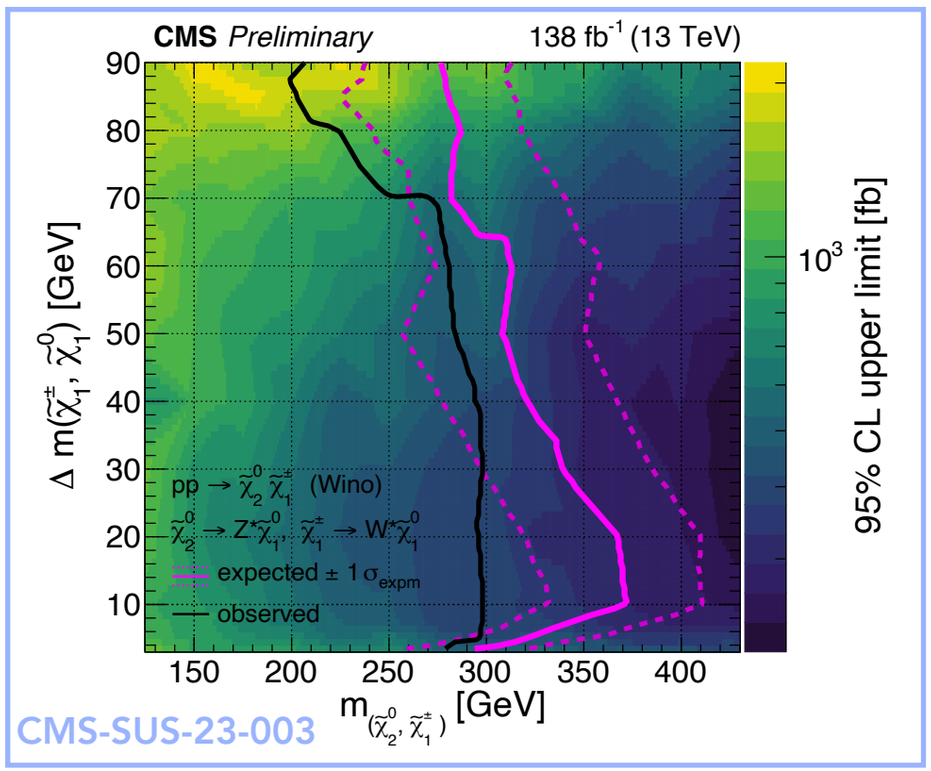


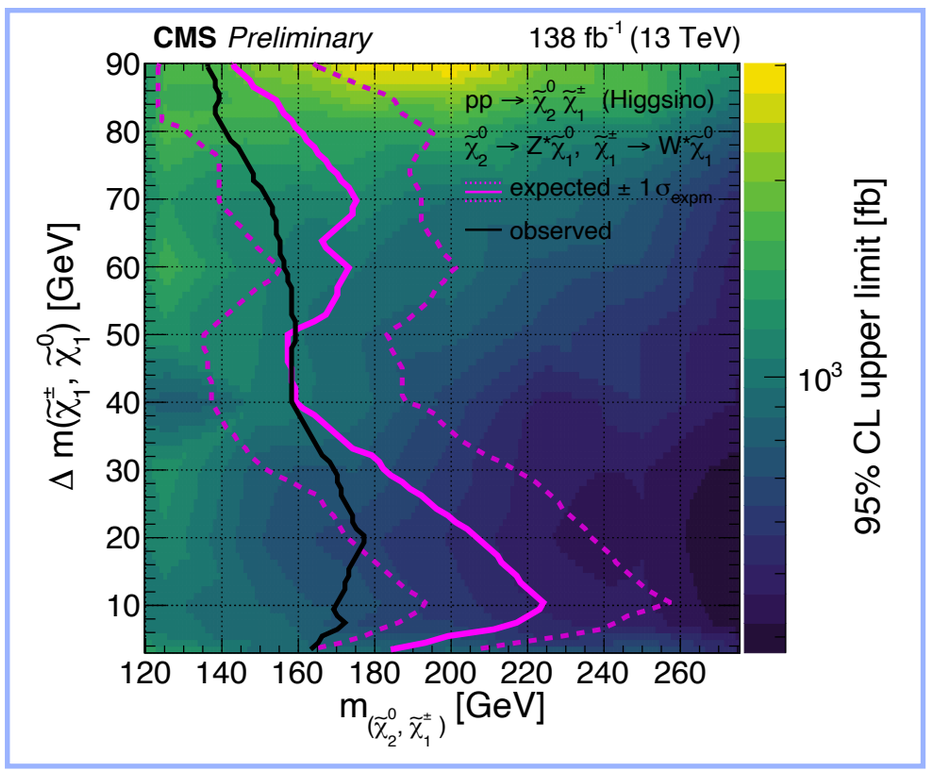
Probing Compression:

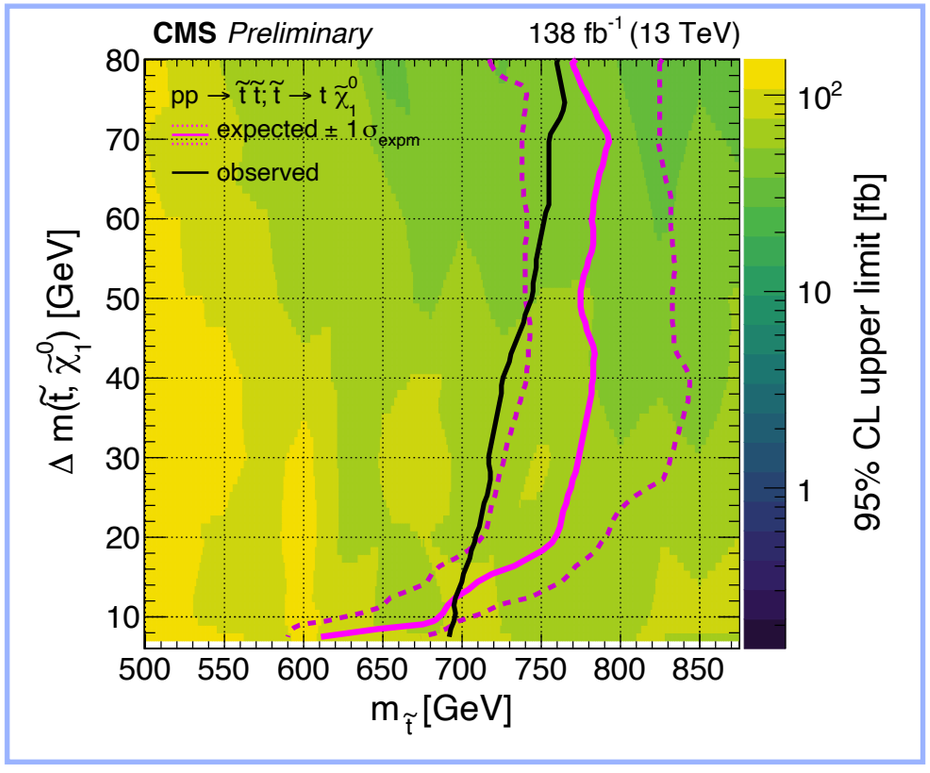
CMS-SUS-23-003 RJR Search



Detecting the Invisible: Pushing the Limit with RJR

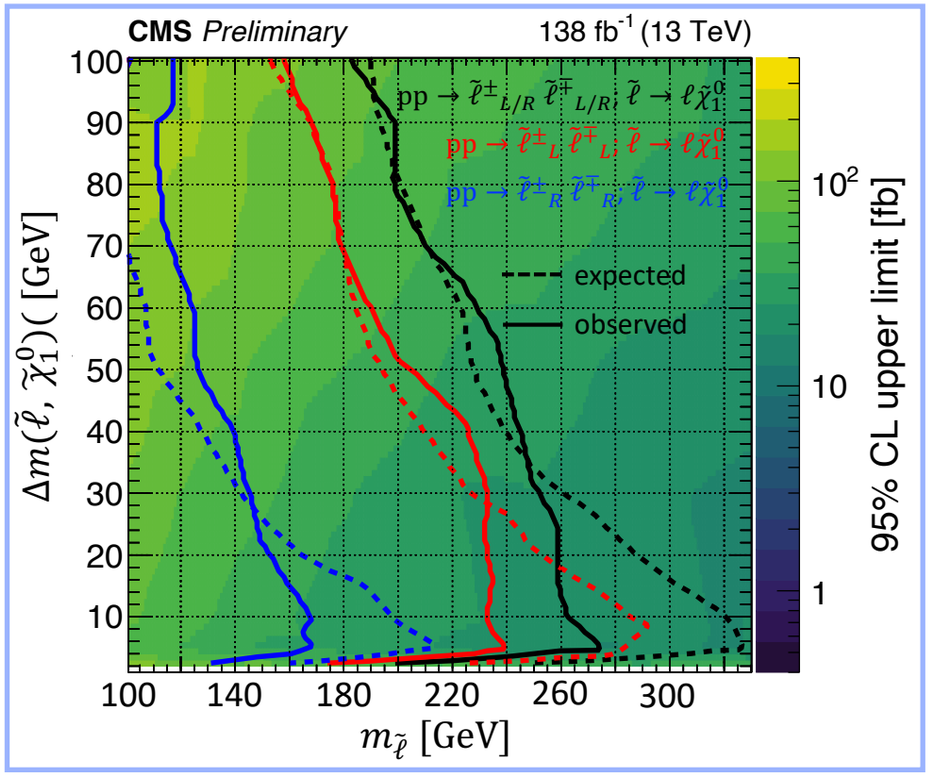




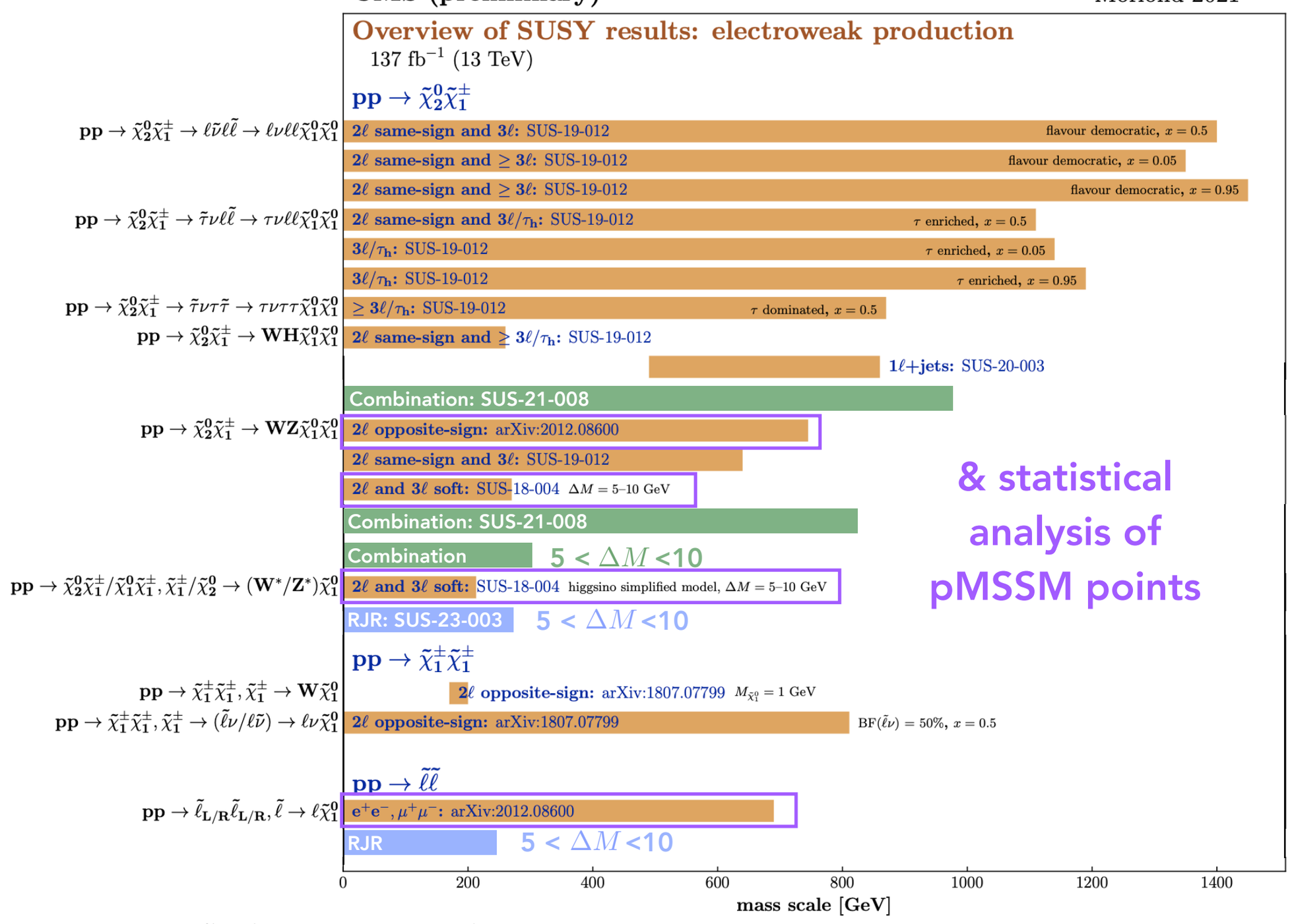


Generic sensitivity, especially in the compressed regime

Stringent limits in difficult to probe ares of phase space



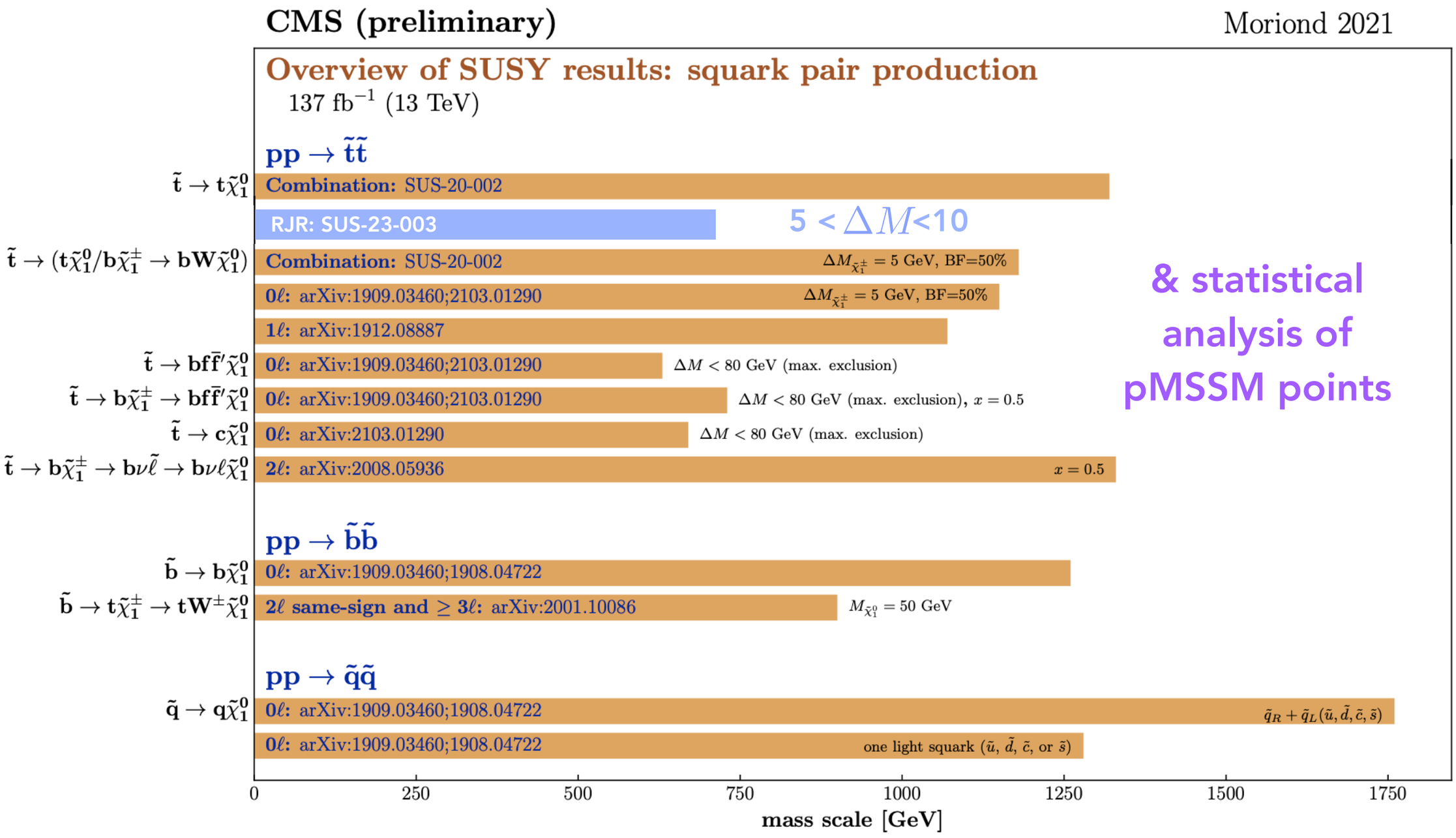
Electroweak SUSY now



& statistical analysis of pMSSM points

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Third Generation SUSY now



& statistical analysis of pMSSM points

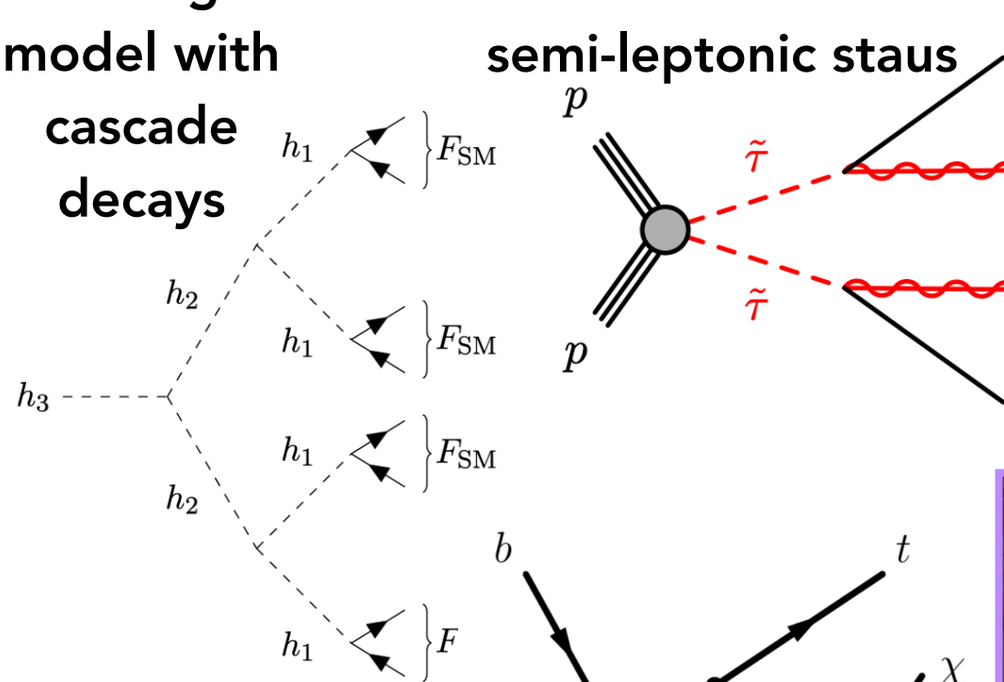
Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

Future Directions

CMS is effectively probing electroweak SUSY to set competitive limits on promising areas of SUSY phase space

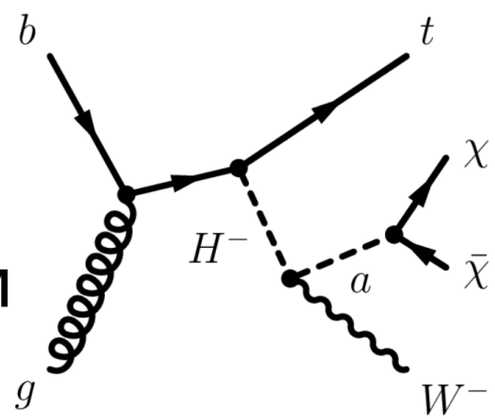
New signatures

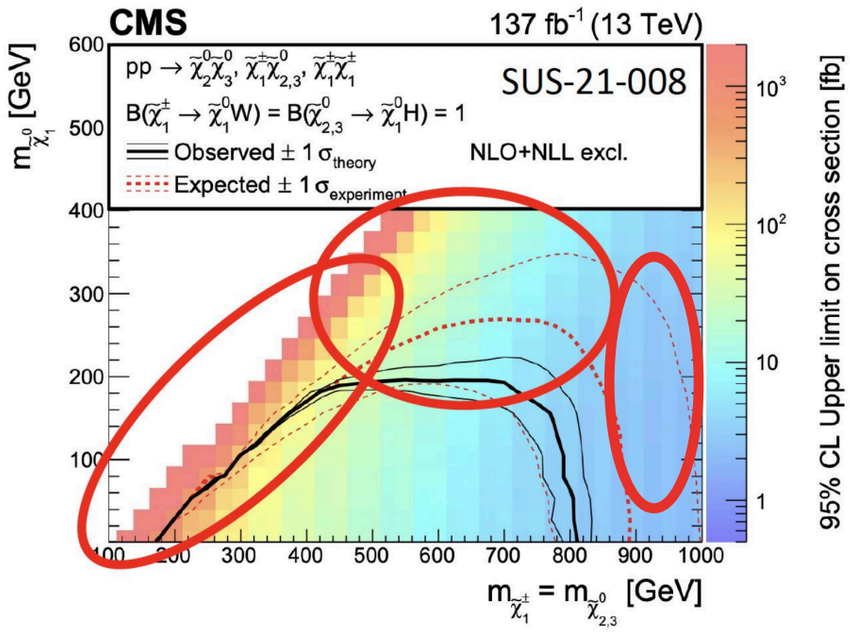
Real singlet model with cascade decays



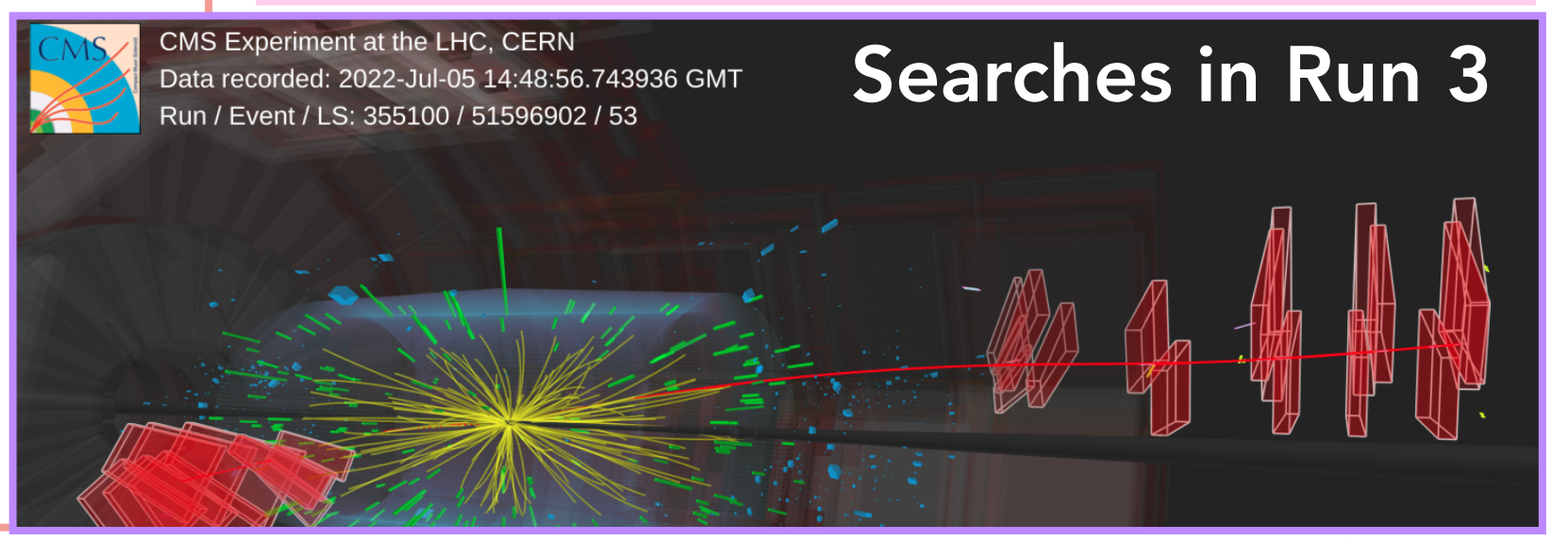
semi-leptonic staus

2HDMa tW+DM production





Unexplored phase space & combinations



Searches in Run 3

Illustration: Sandbox Studio, Chicago with Steve Shanabruch

HAVE YOU SEEN ME?

SUSY

A.K.A. SUPERSYMMETRY

HIGGS BOSON!

HIGGS BOSON!

Backup

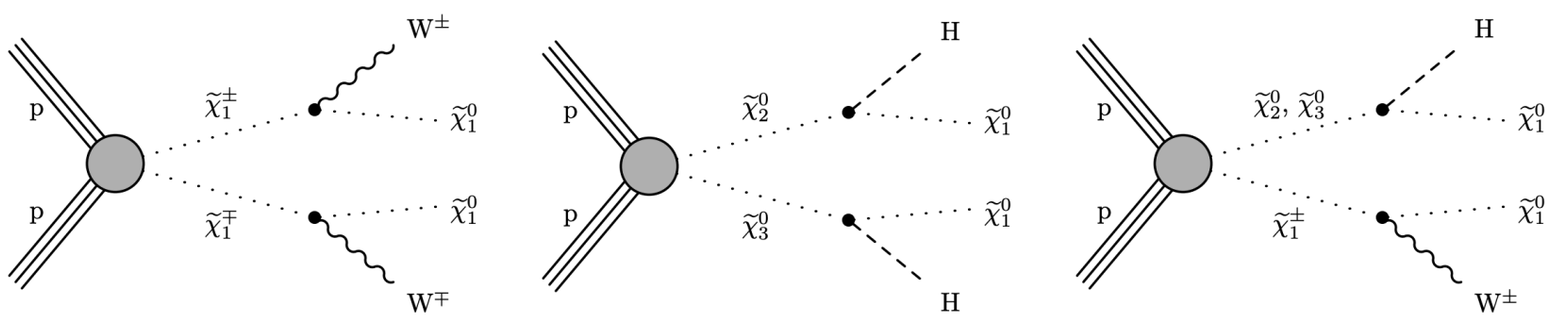
Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV

Signal Interpretations

- **Electroweakino pair production**
  - Compressed scenarios
- **Slepton pair production**
- **GMSB models**

Final states

- 1L + 2b
- 2 - 3+ leptons
  - 2L OSSF, 2L SS, 2 - 3L OS
  - 4b
  - Hadronic WX
  - Missing transverse momentum



arXiv:2402.01888

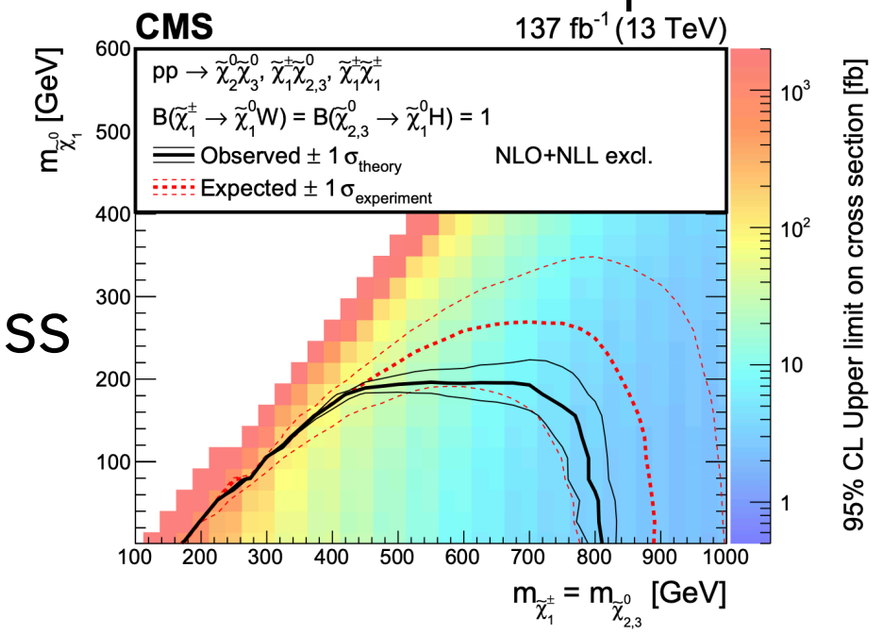
Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV

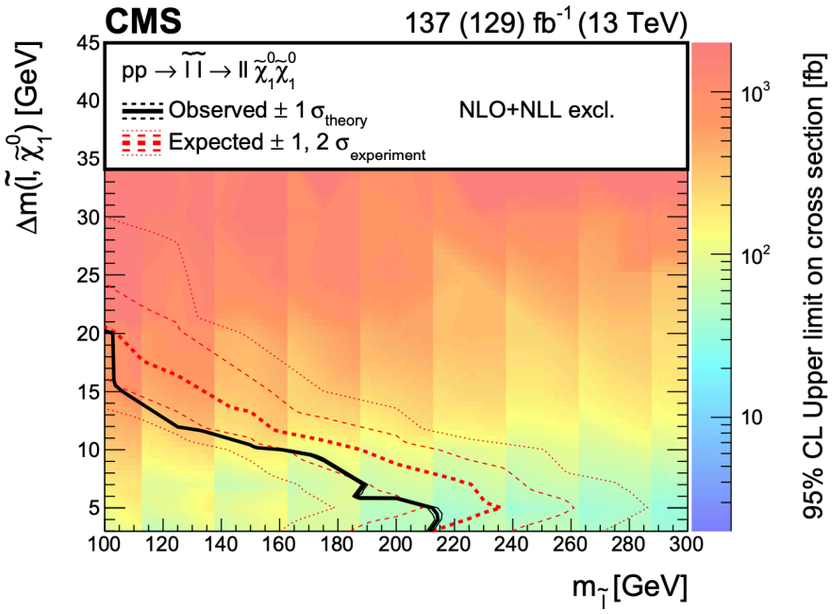
Methods

- Combination of 6 separate analyses in simultaneous ML fit
- Most analyses binned in p_T^{miss}
  - Transverse mass

Results

- Extends limits on various interpretations by O(100) GeV
- Compressed slepton production is explored for the first time in CMS



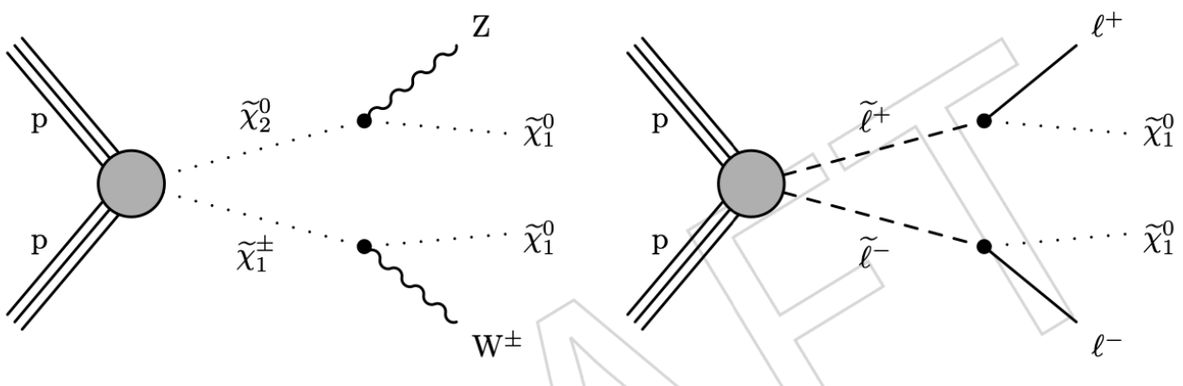


arXiv:2402.01888

General search for supersymmetric particles in scenarios with compressed mass spectra using proton-proton collisions at $\sqrt{s}$ = 13 TeV

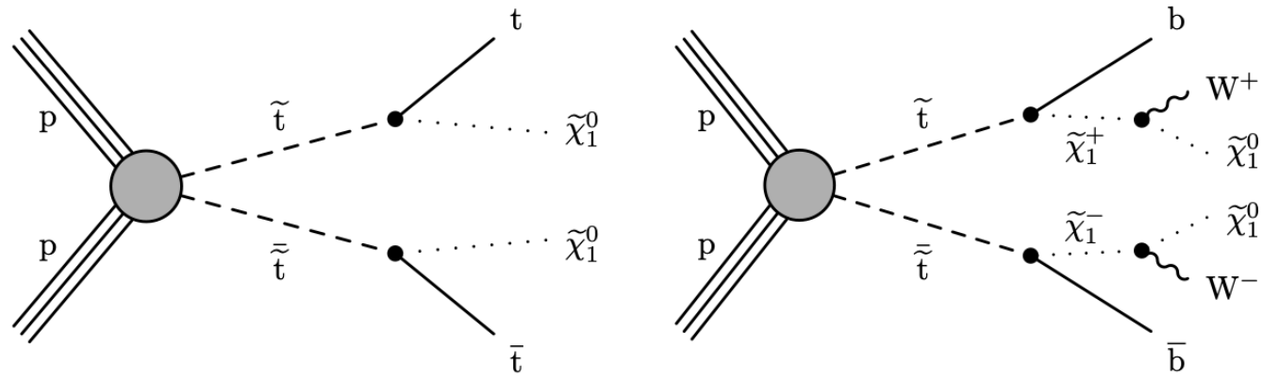
Signal Interpretations

- **Top squark pair production**
- **Electroweakino pair production**
- **Slepton pair production**



Final states

- 0-3 leptons, 0-5 jets
- B-jets, soft SVs
- Missing transverse momentum



General search for supersymmetric particles in scenarios with compressed mass spectra using proton-proton collisions at √s = 13 TeV

Methods

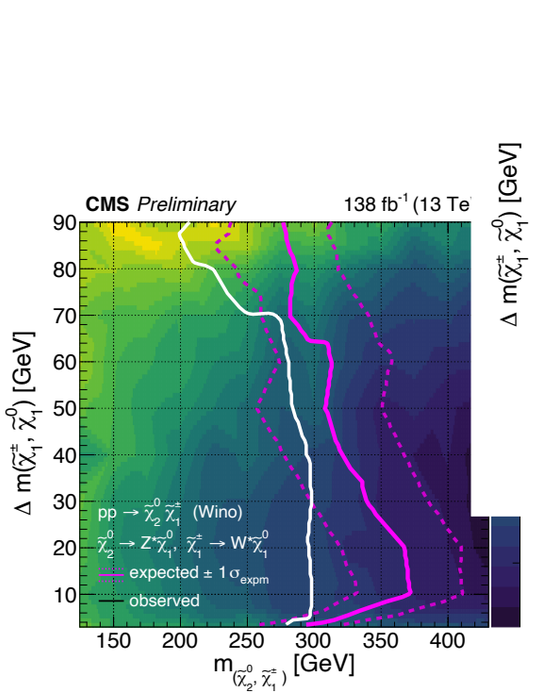
$$R_{\mathrm{ISR}} = \frac{|\vec{p}_{\mathrm{I}}^{\,\mathrm{CM}} \cdot \hat{p}_{\mathrm{ISR}}^{\,\mathrm{CM}}|}{|\vec{p}_{\mathrm{ISR}}^{\,\mathrm{CM}}|} \sim \frac{m_{\mathrm{I}}}{m_{\mathrm{P}}}$$

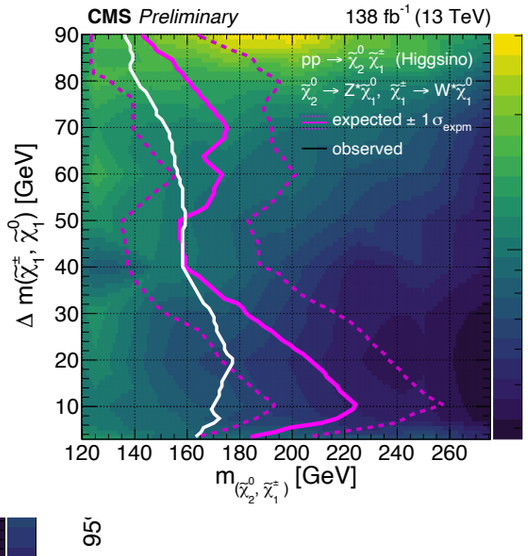
$$M_{\perp} = \sqrt{\frac{M_{\mathrm{P}_a,\perp}^2 + M_{\mathrm{P}_b,\perp}^2}{2}}$$

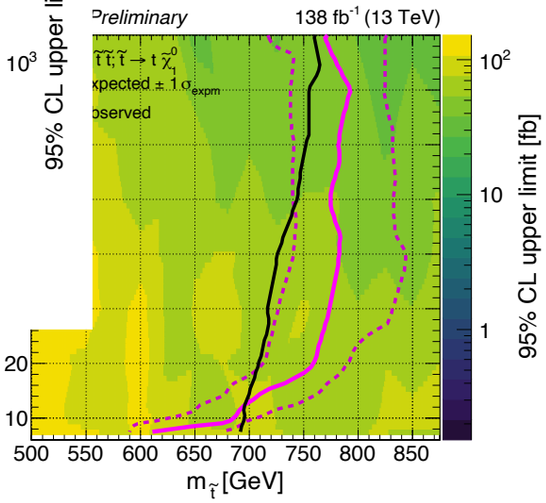
- Recursive Jigsaw Reconstruction
- Binned in ~orthogonal basis of kinematic observables
- Interpretable event topology
- Further divided by analysis-specific lepton quality selection, object number

Results

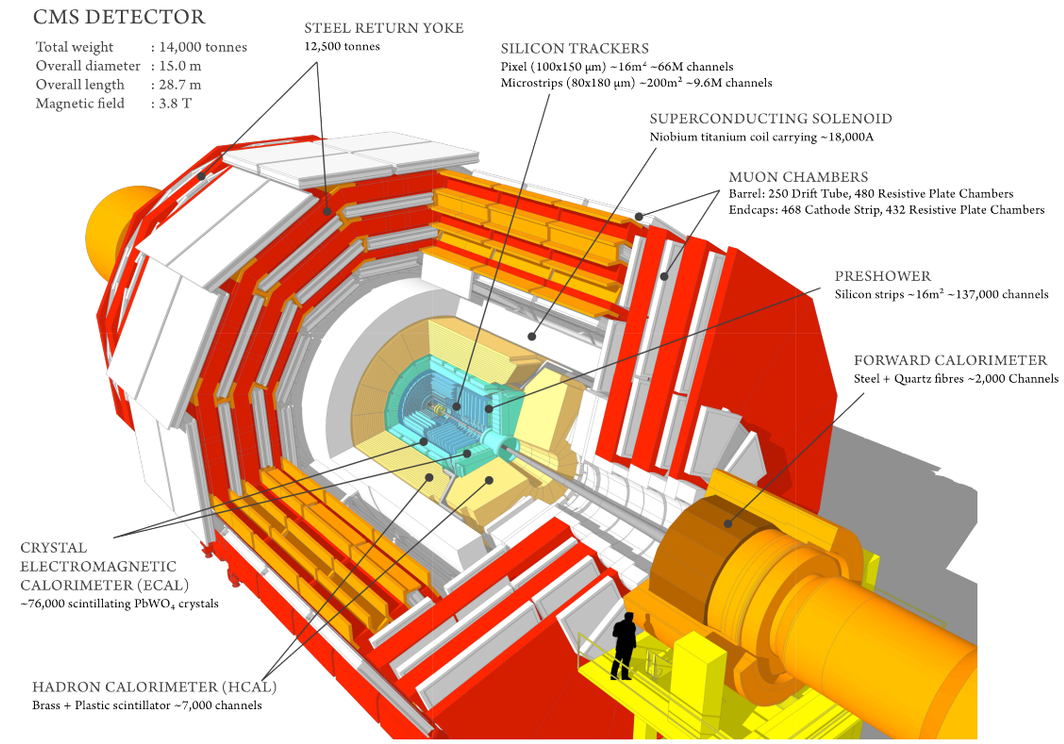
- Most stringent limits to date across a variety of signal interpretations
- Compressed regions





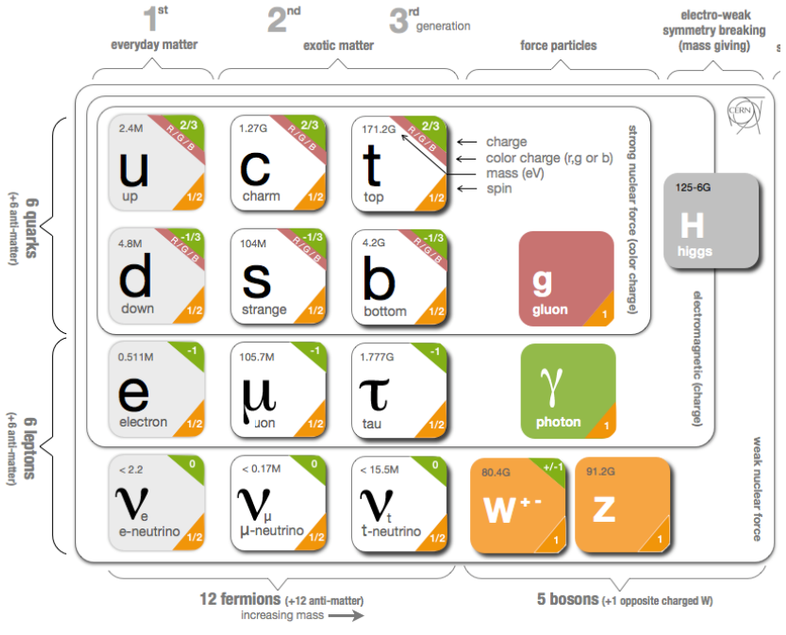


Understanding the Universe with CMS

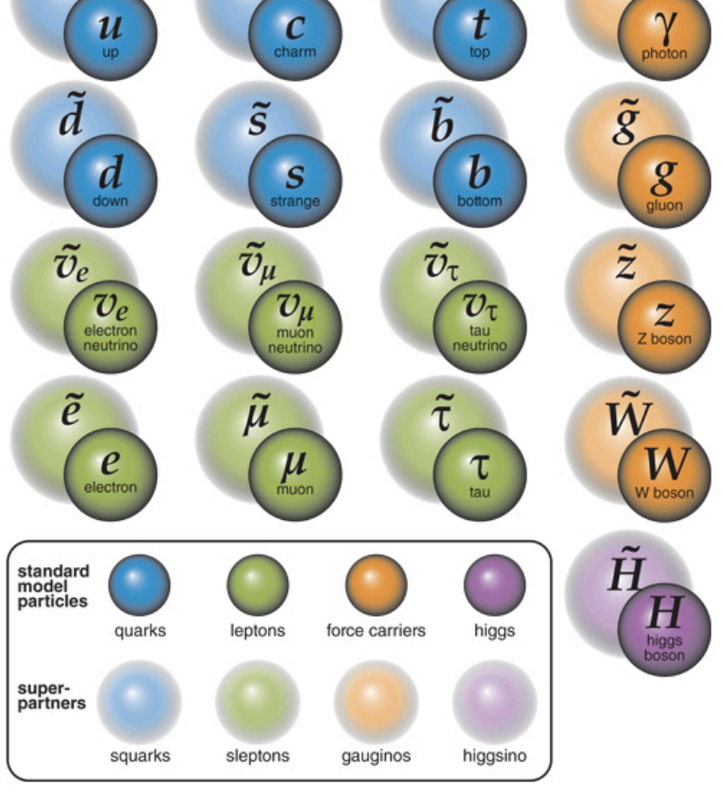


Compact Muon Solenoid

Standard Model

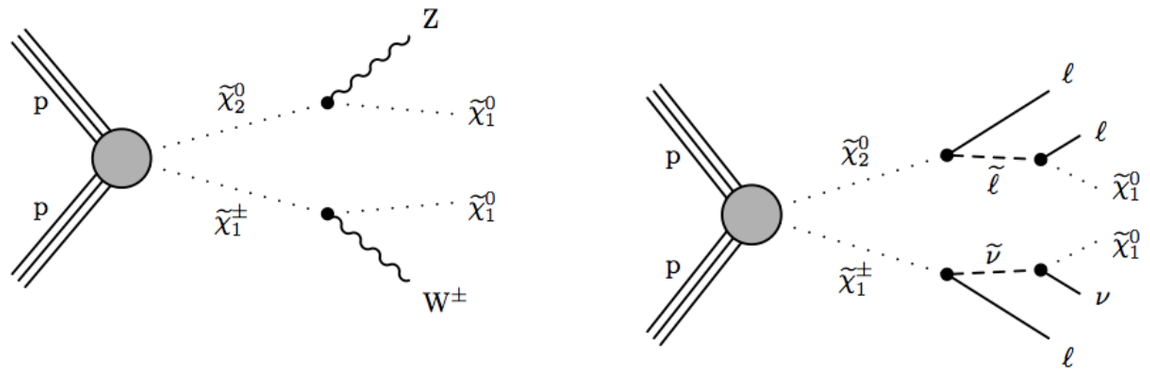


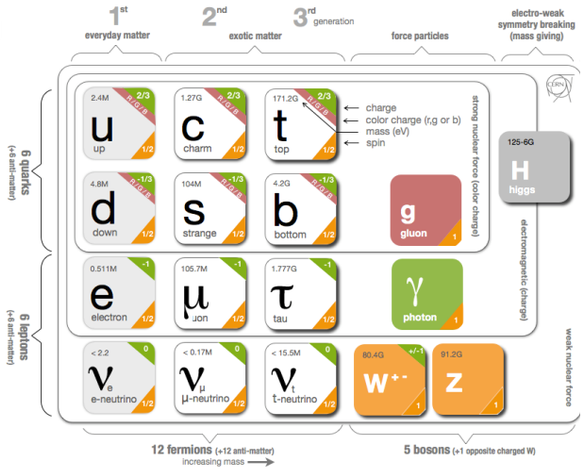
Supersymmetry

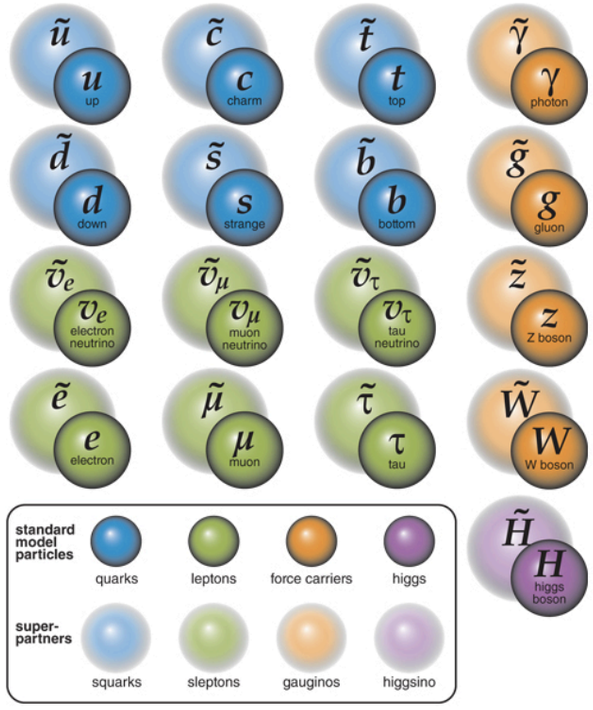


SUSY motivation

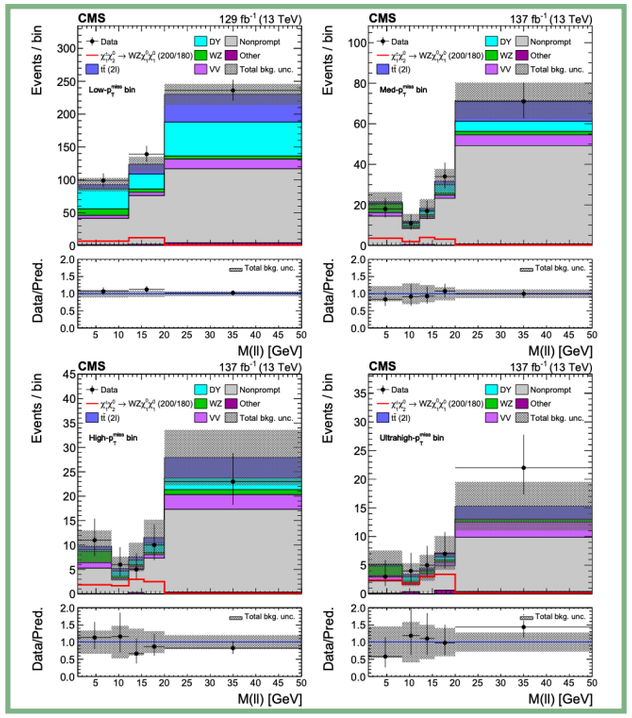
- Addresses SM discrepancies in an intuitive way
  - Additional parameters cancel SM quadratically divergent terms (hierarchy problem)
- Provides DM candidate (LSP
- Force unification
- SUSY @ electroweak scale







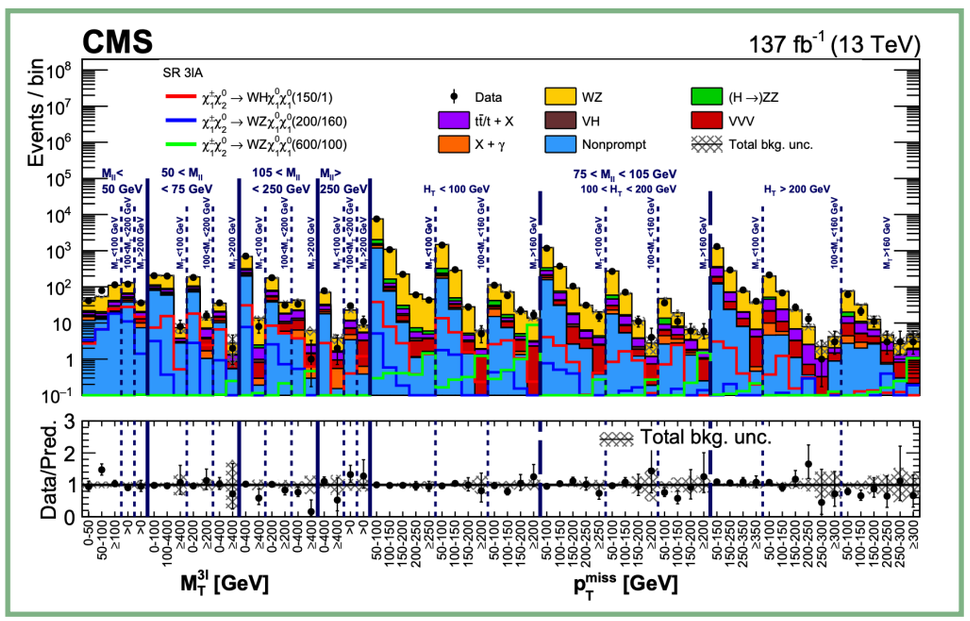
Detecting the Invisible: Strategy & Kinematics



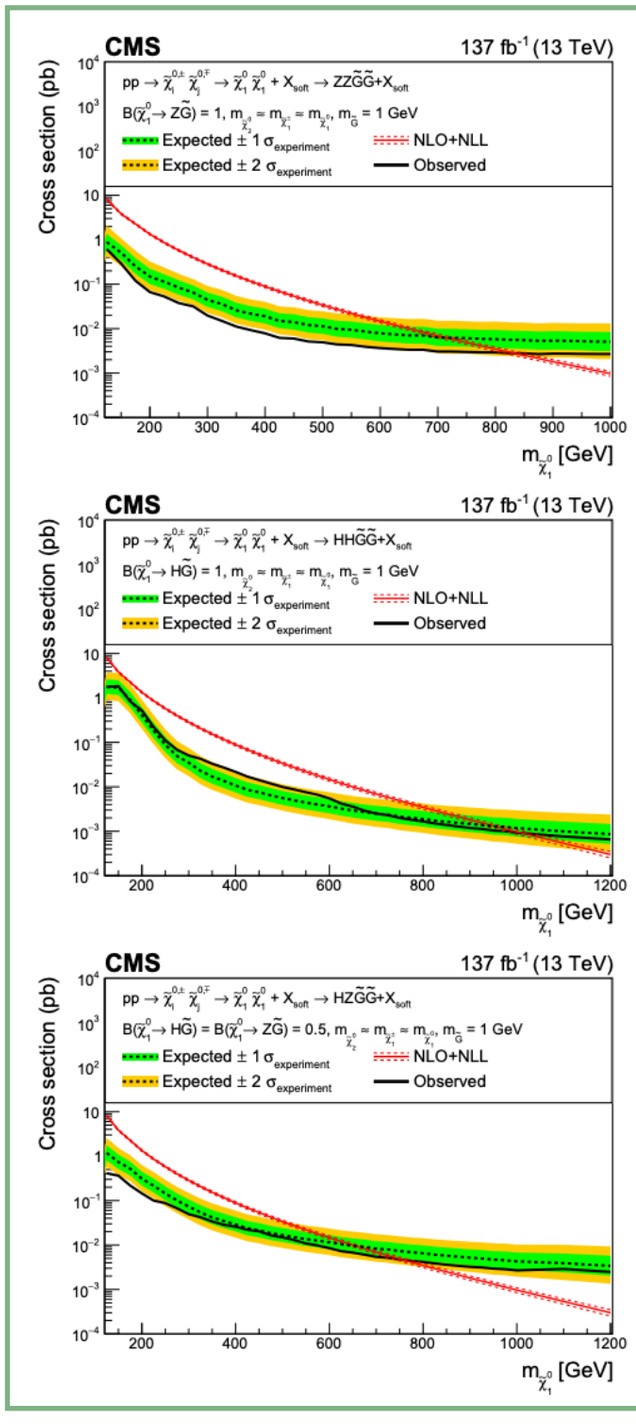
Combination search

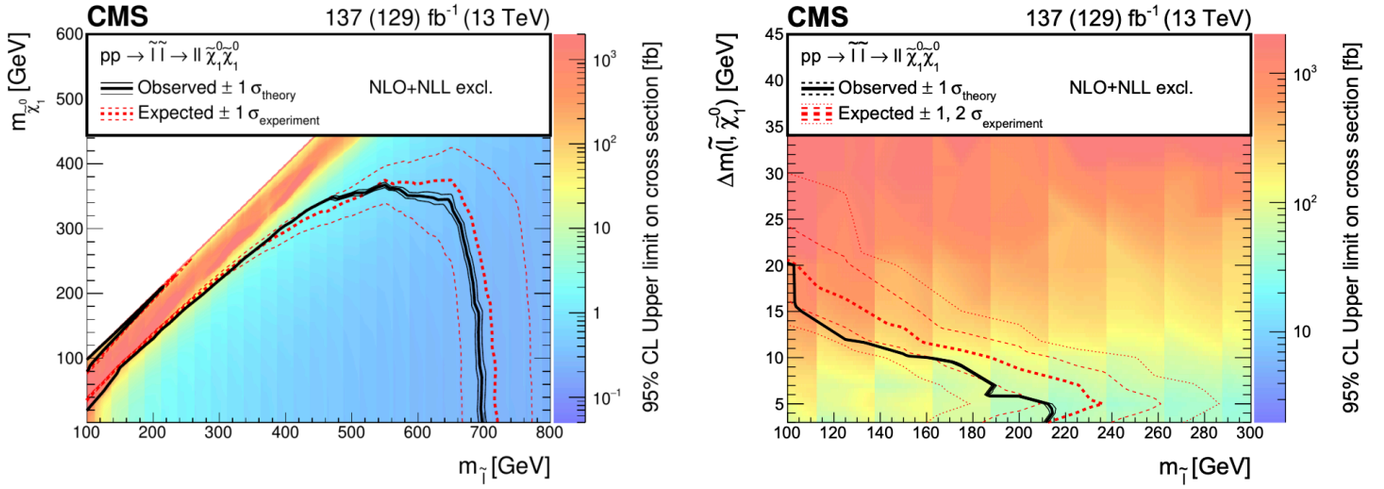
CMS-SUS-21-008

Combination of missing pT, mT2, and other kinematics



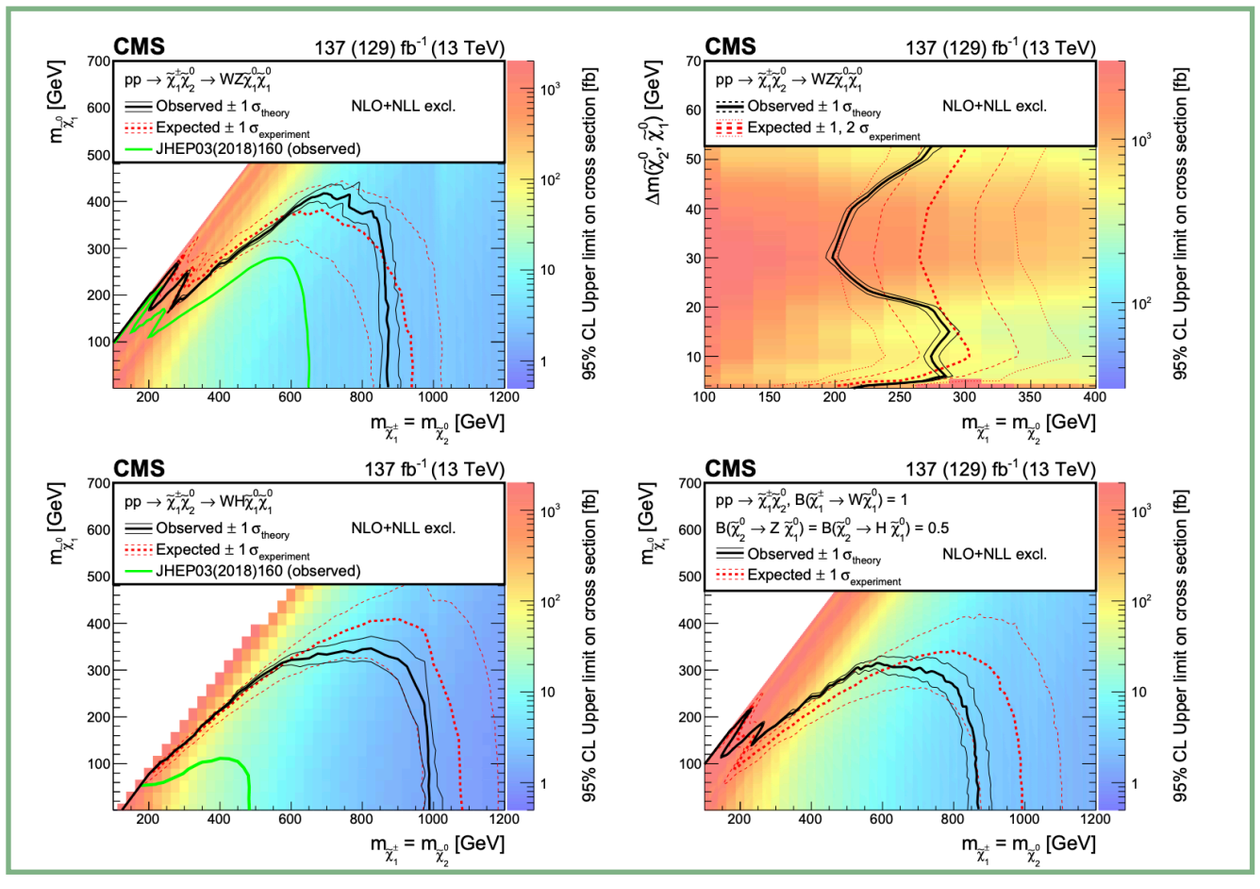
Outcomes of Run II Compressed SUSY Searches



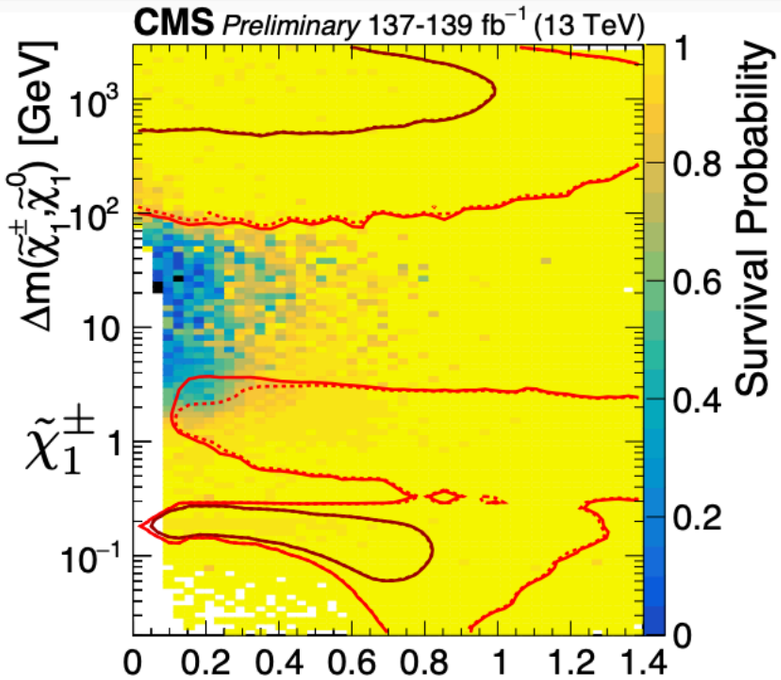


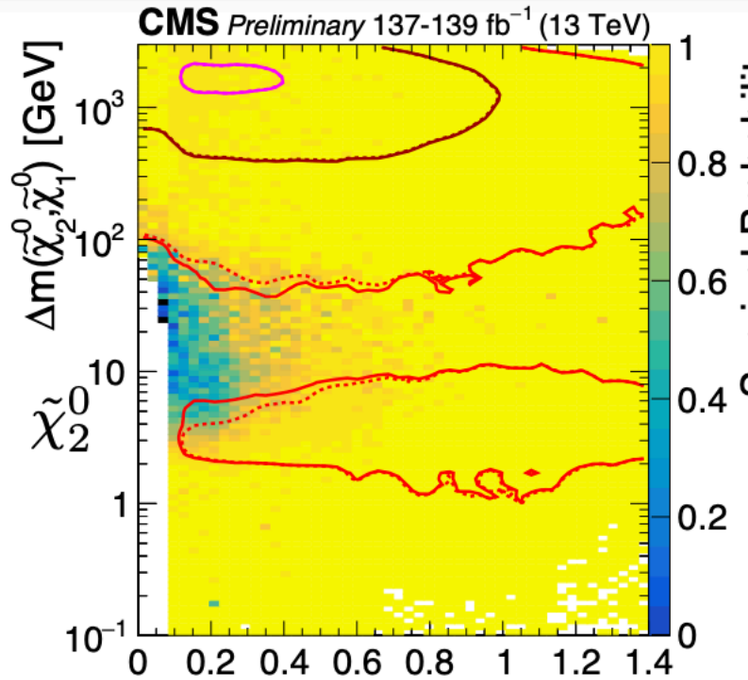
Combination search

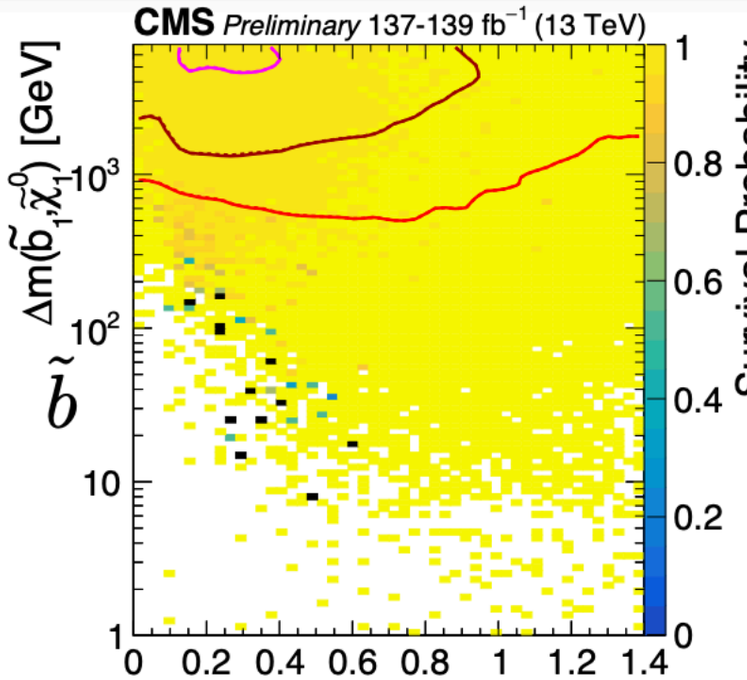
CMS-SUS-21-008

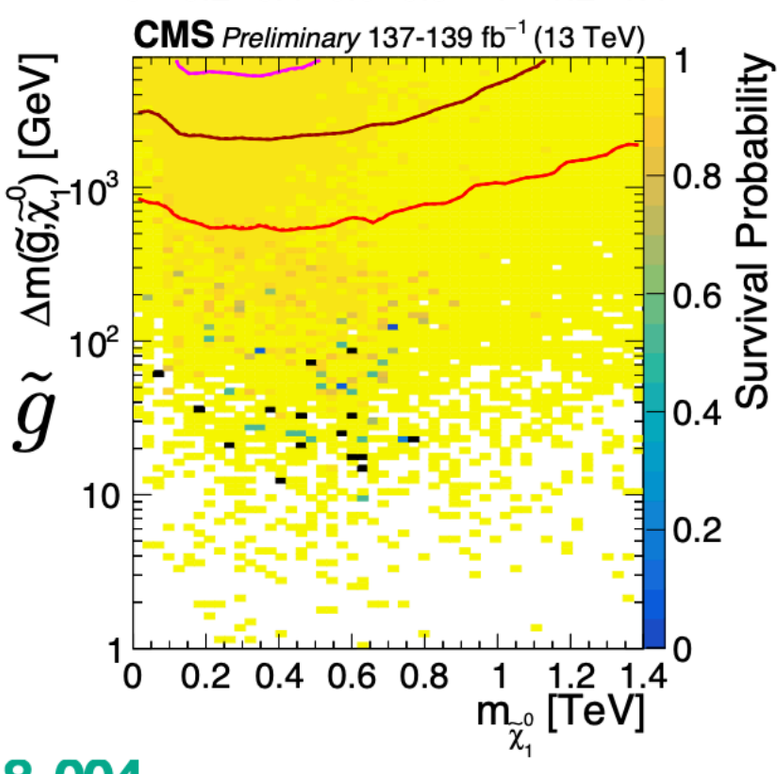


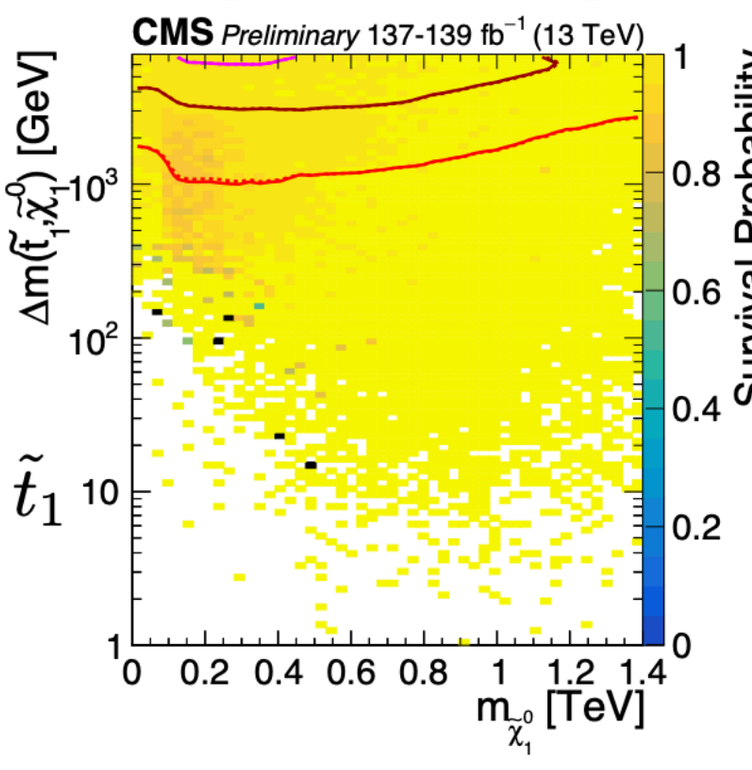
pMSSM flipbook plots

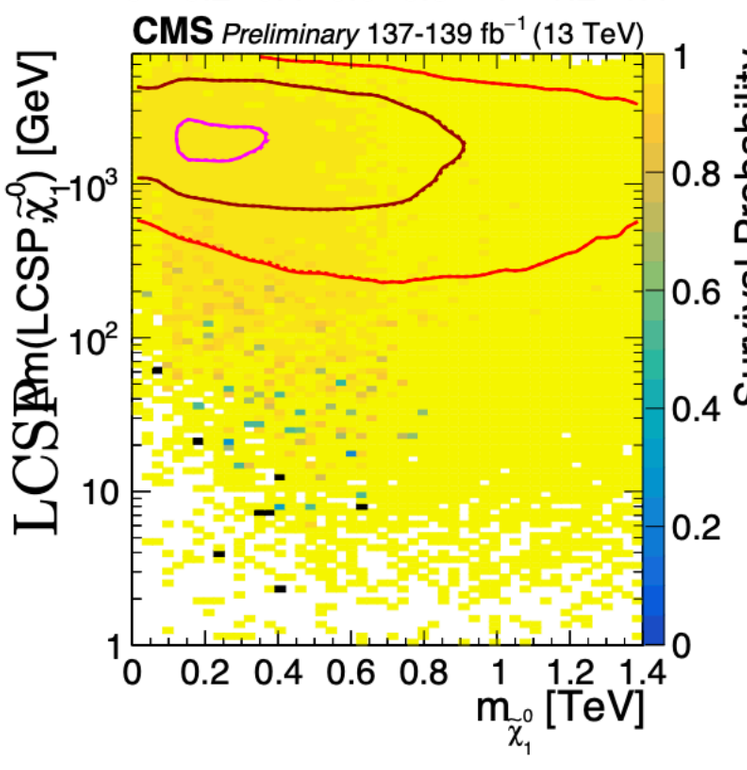






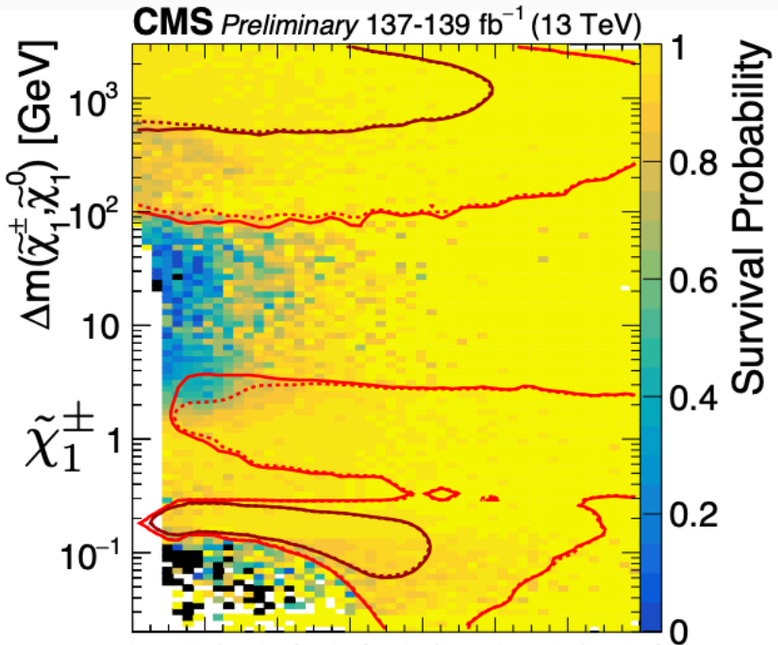


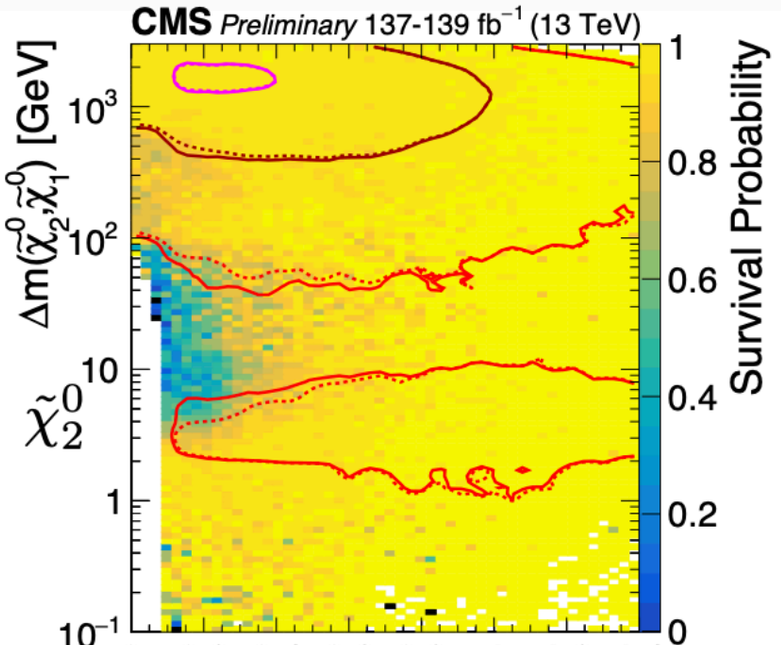


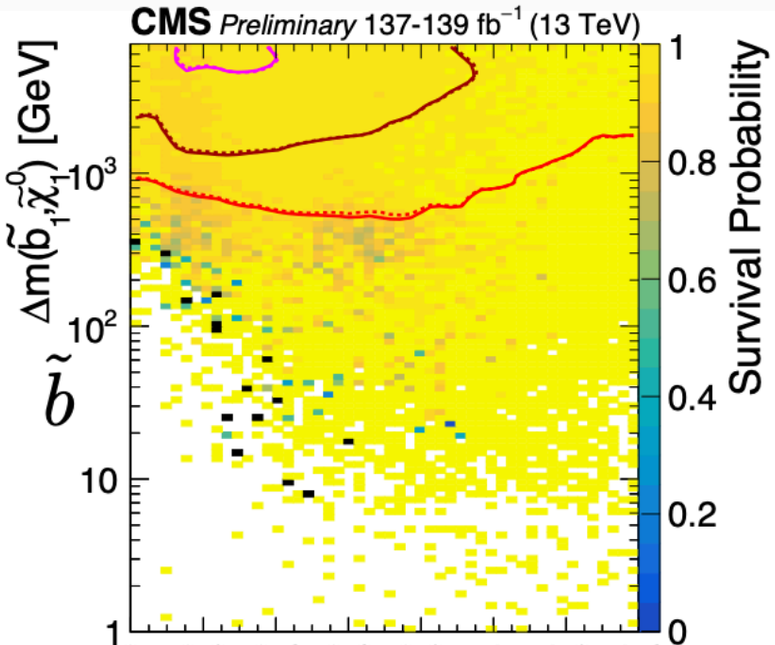


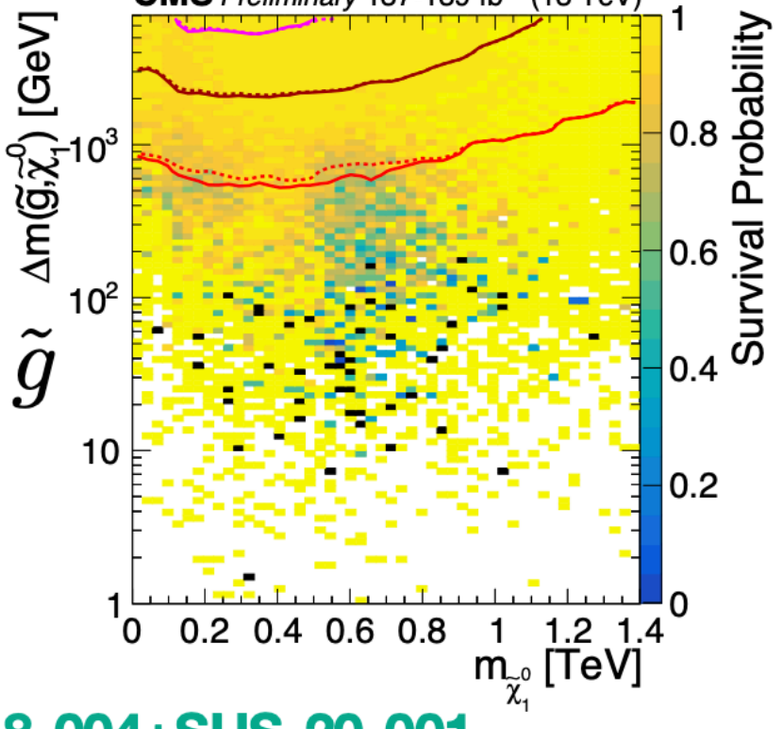
SUS-18-004

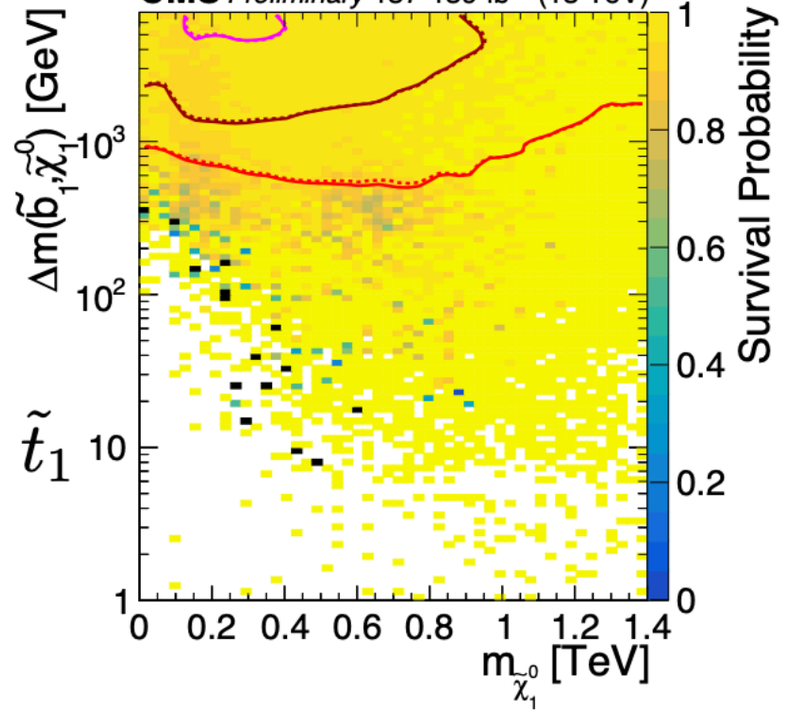
pMSSM flipbook plots

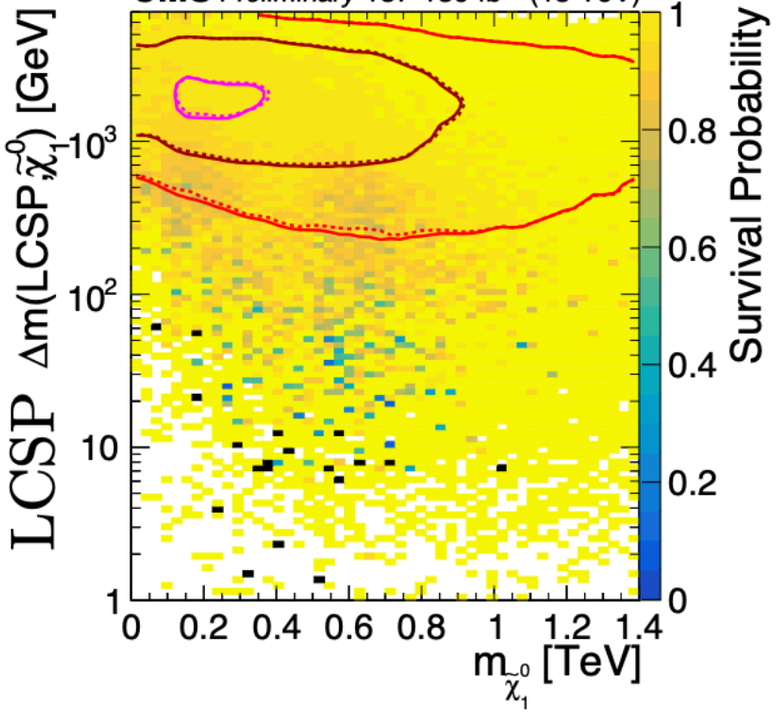






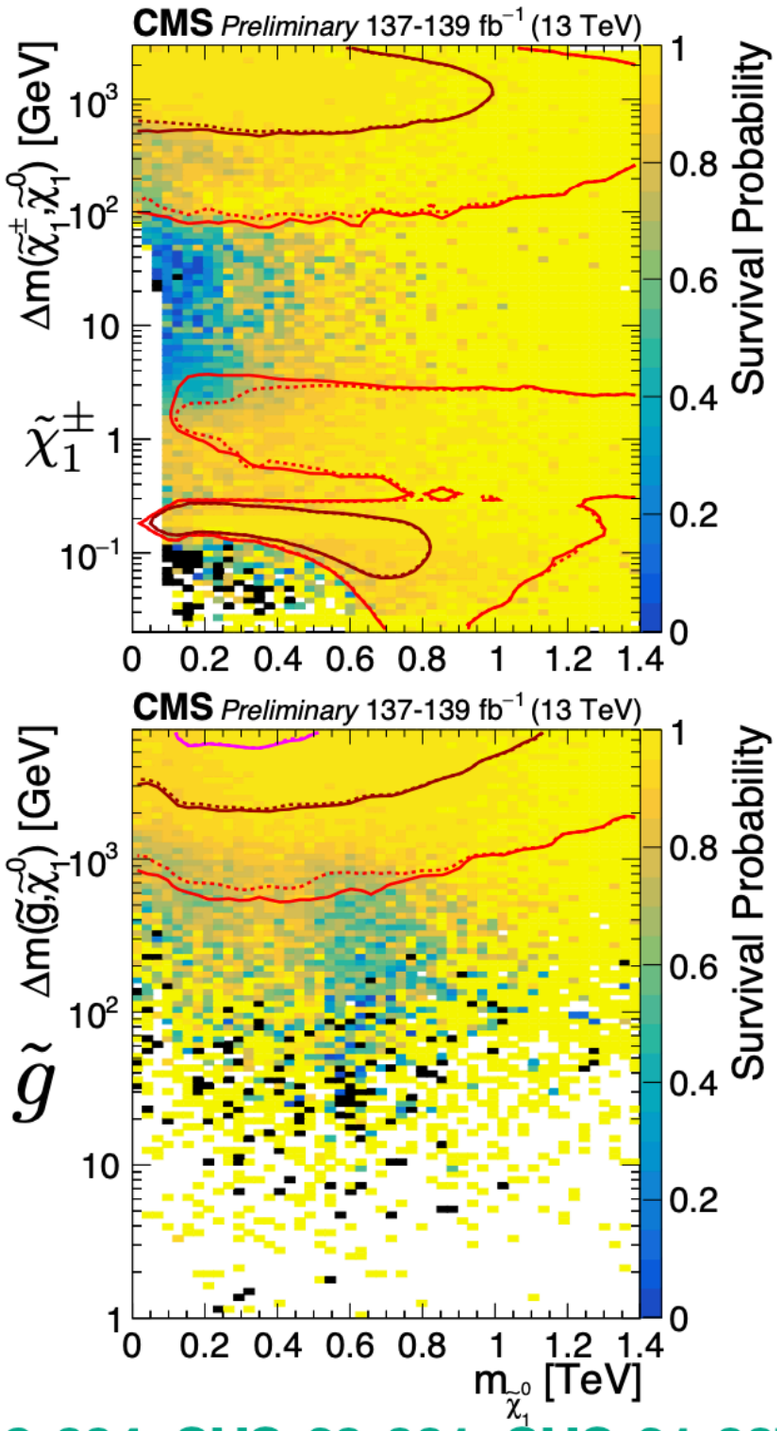


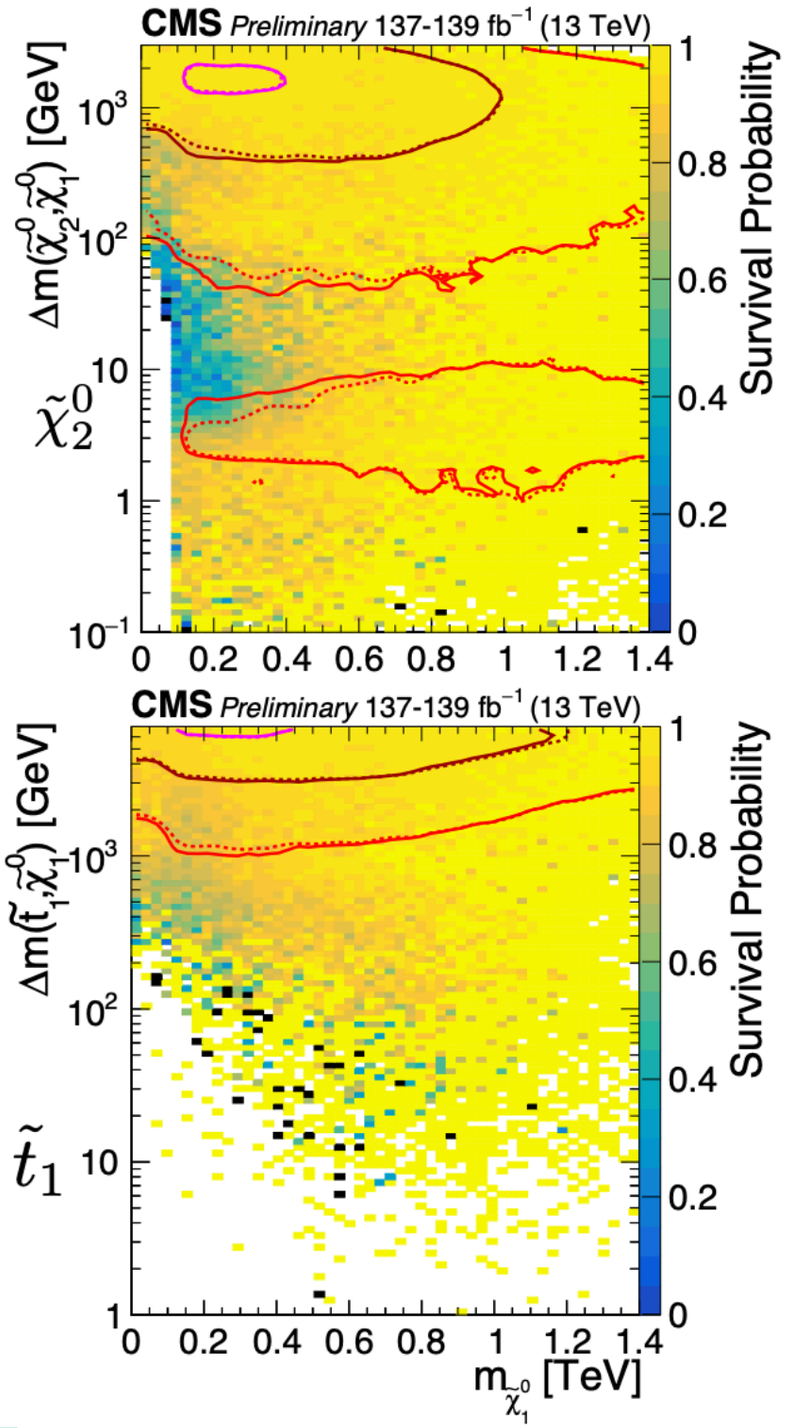


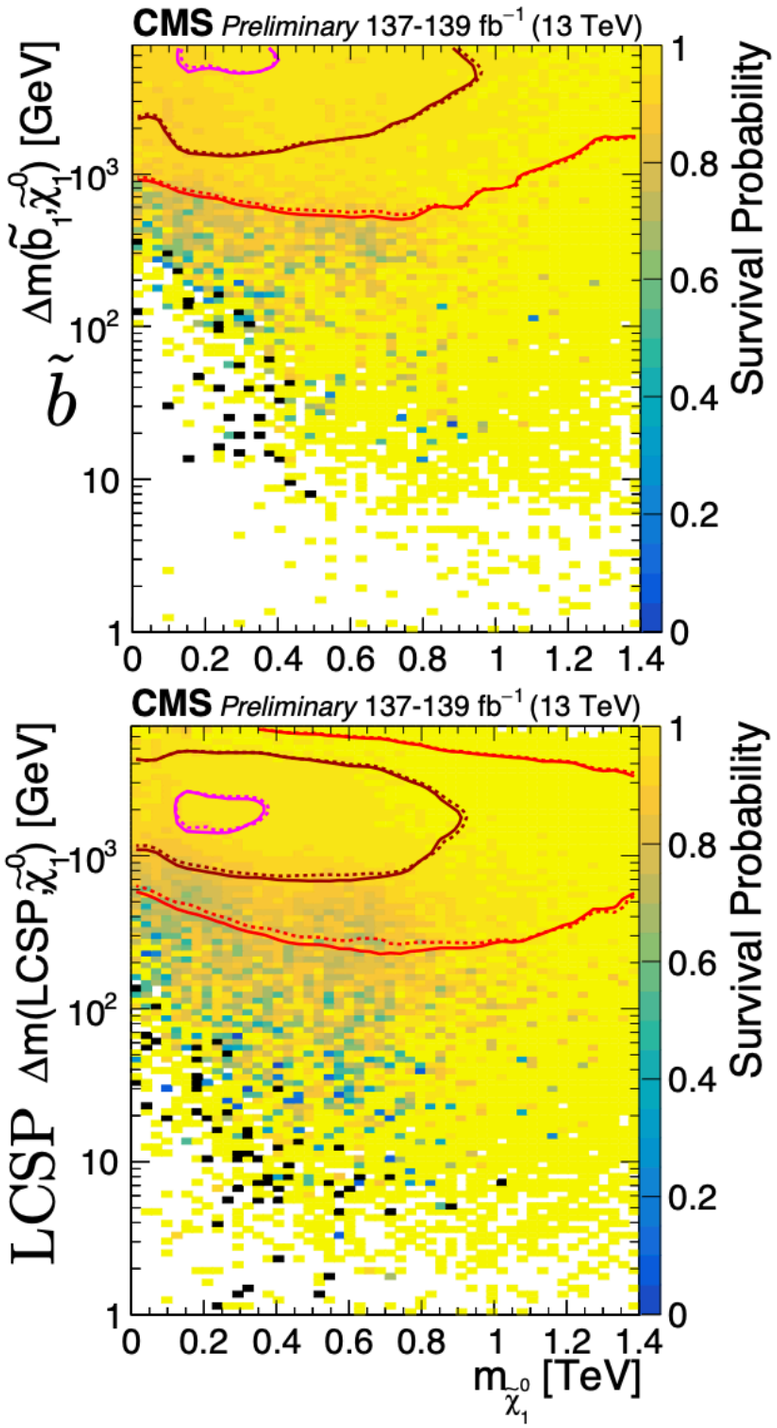


SUS-18-004+SUS-20-001

pMSSM flipbook plots

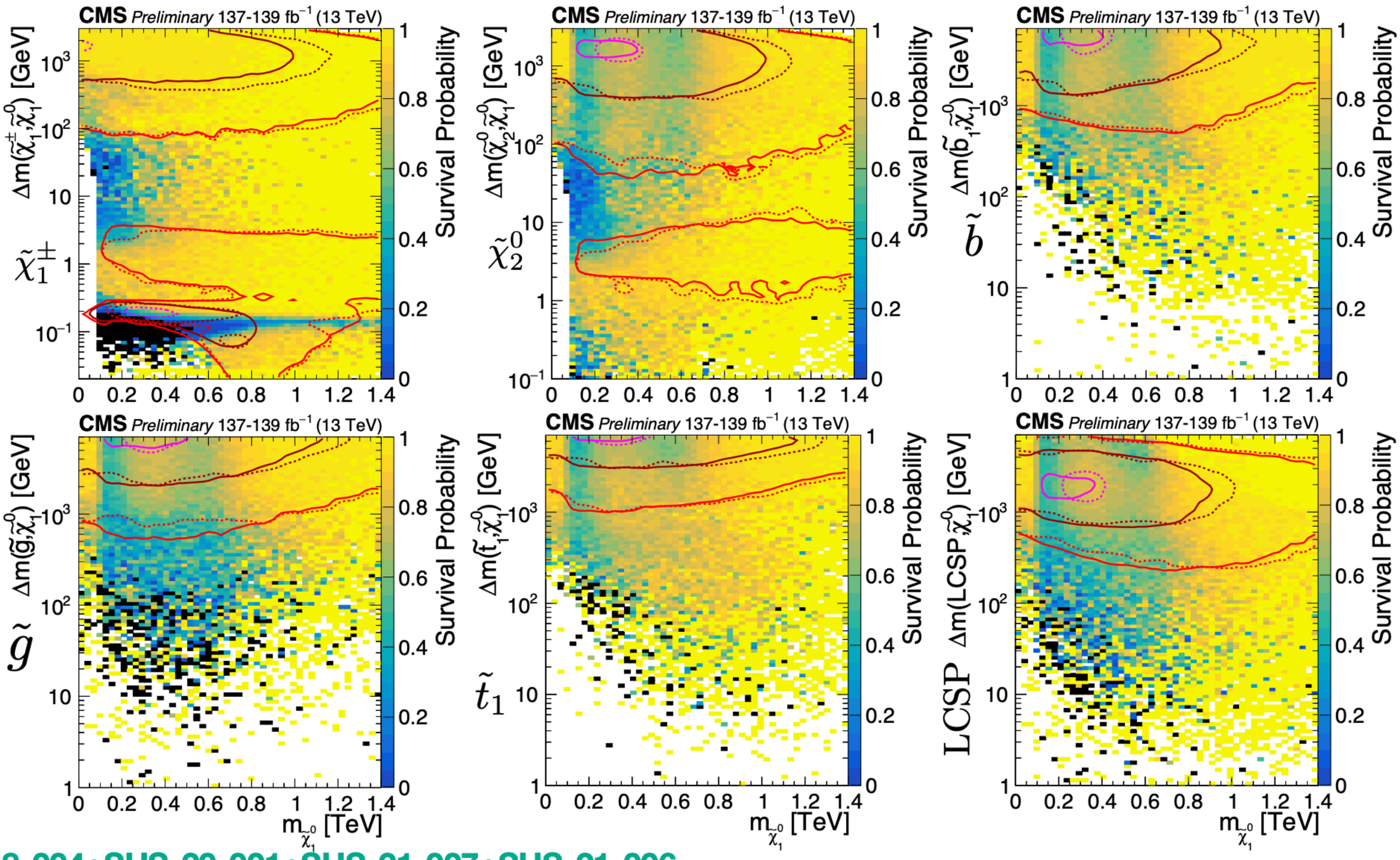






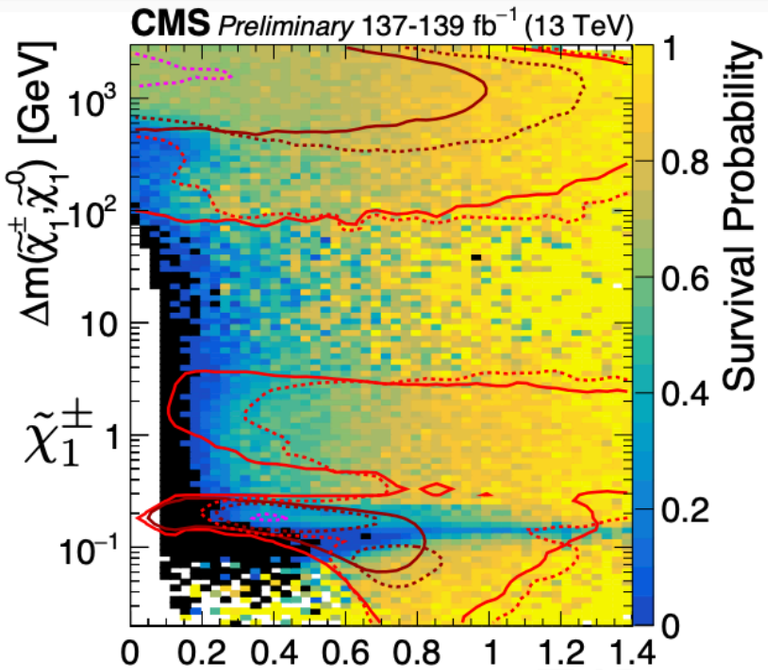
SUS-18-004+SUS-20-001+SUS-21-007

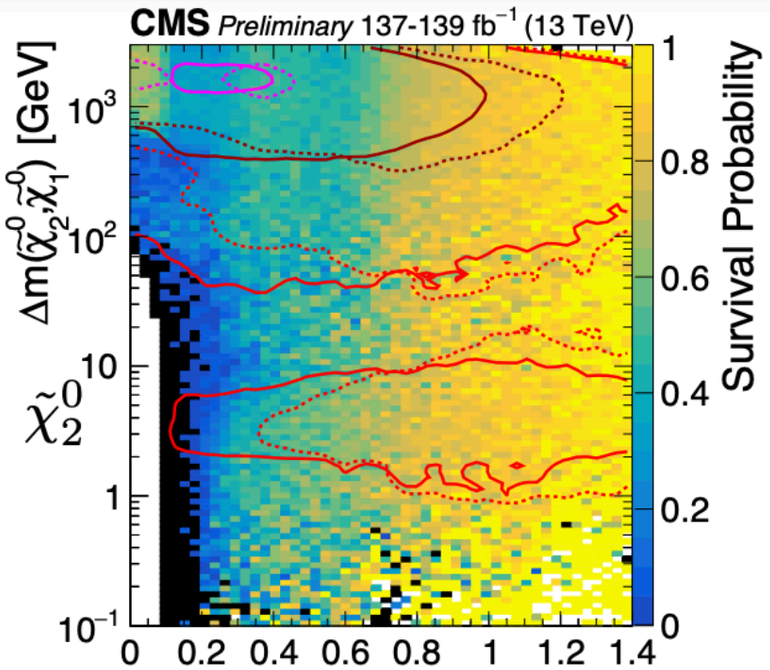
pMSSM flipbook plots

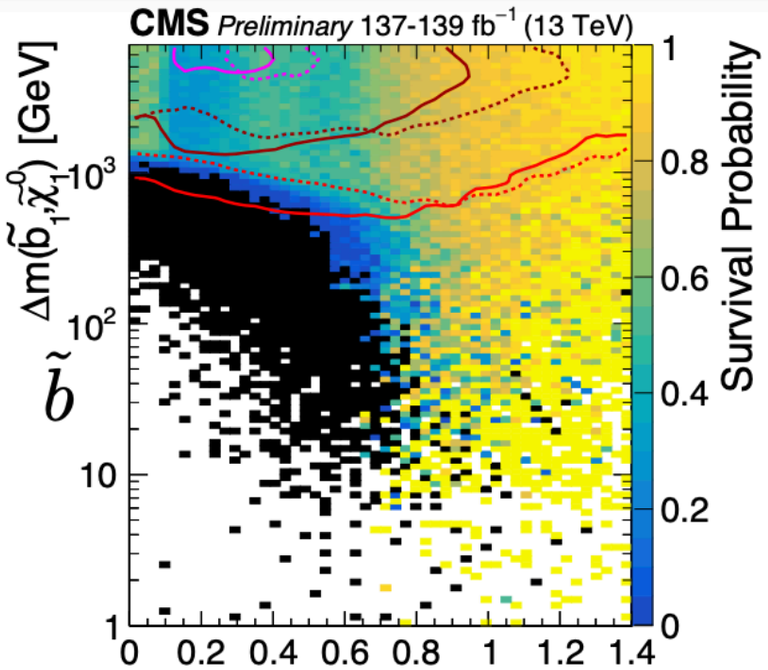


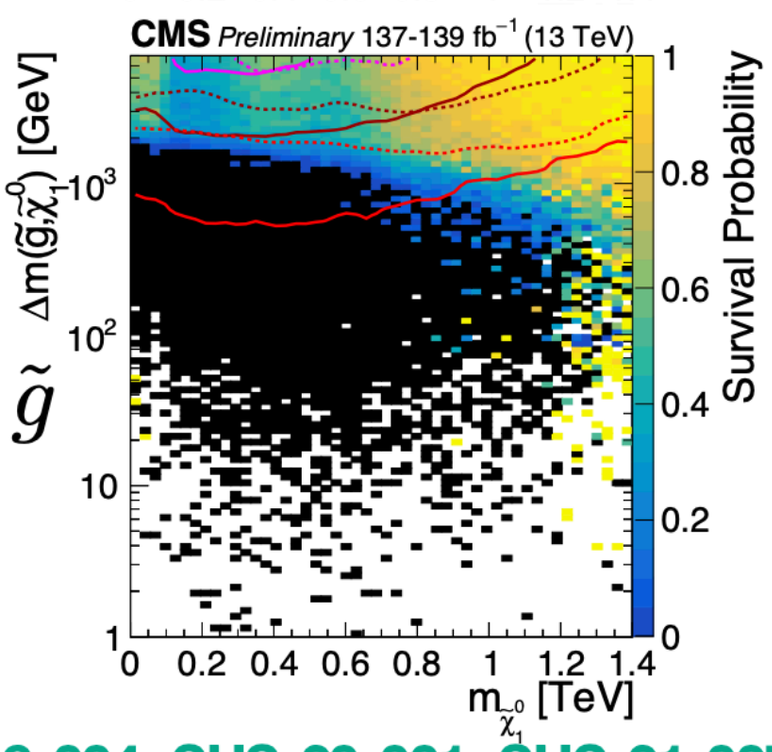
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006

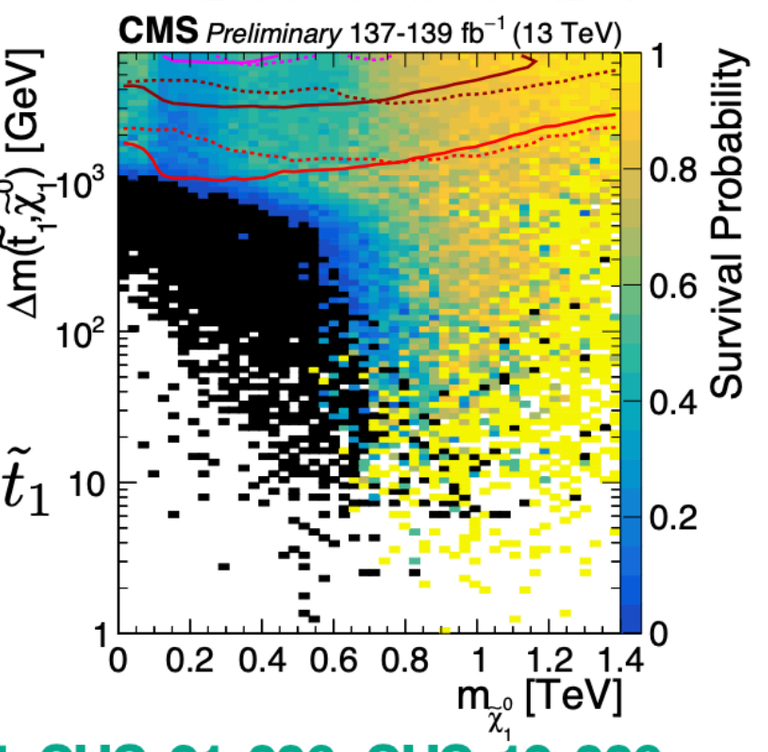
pMSSM flipbook plots

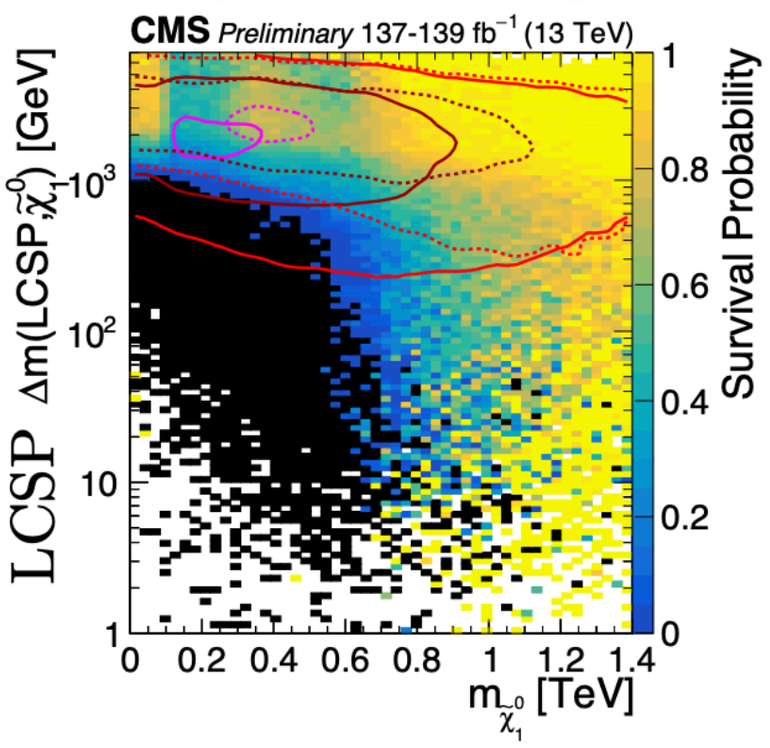






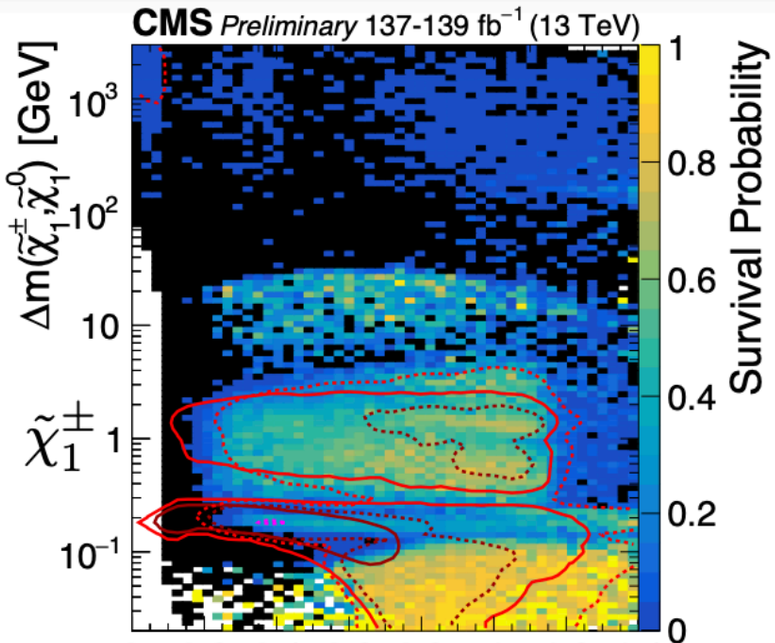


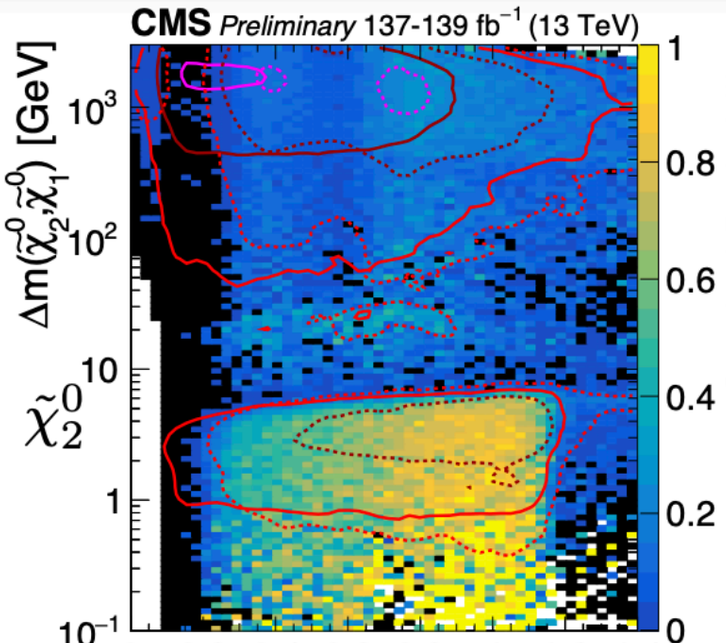


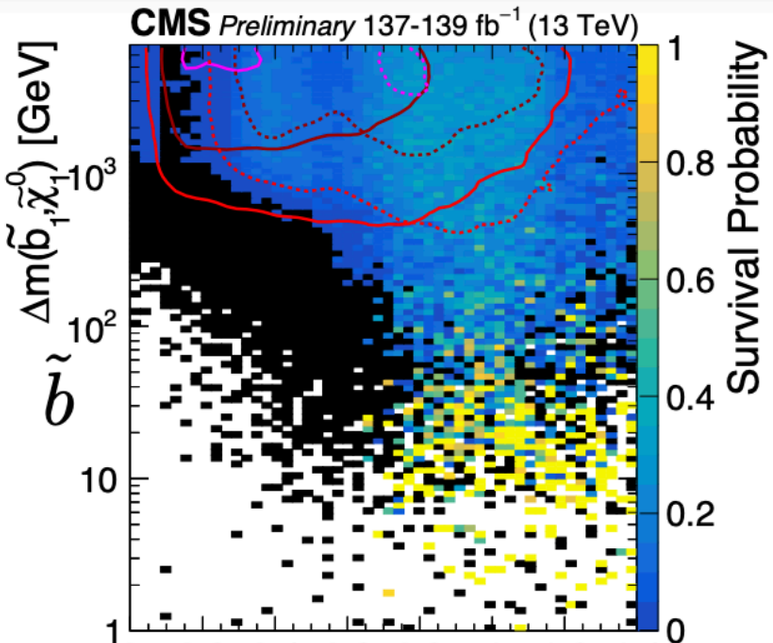


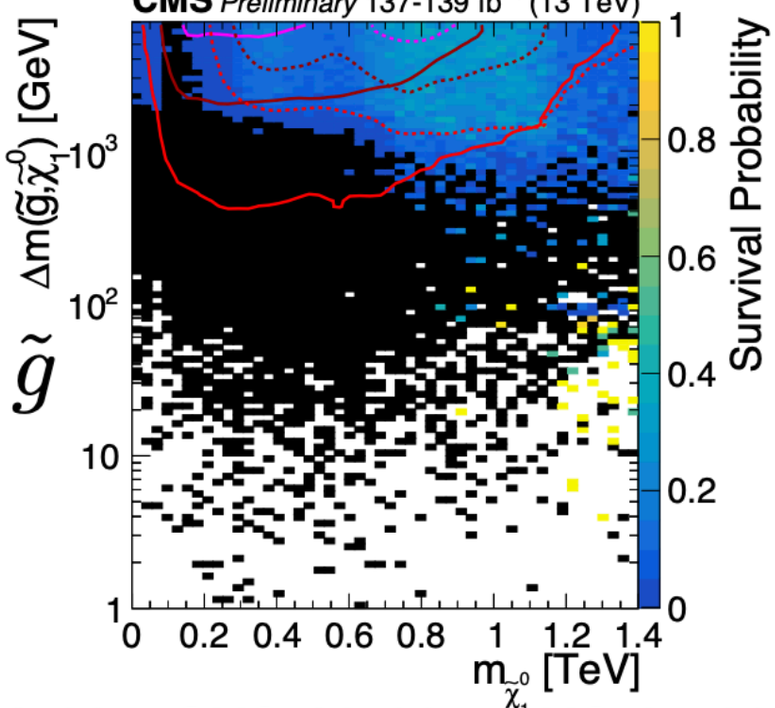
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006

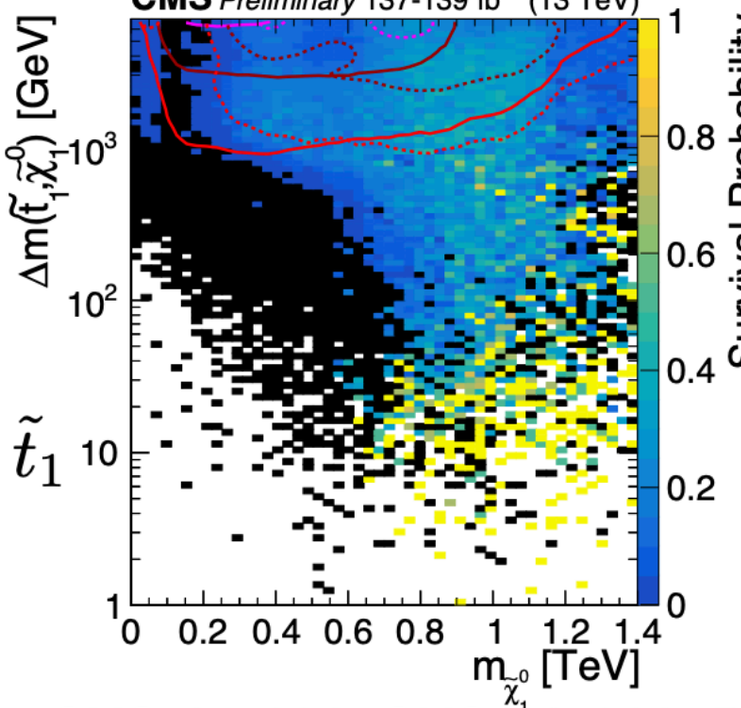
pMSSM flipbook plots

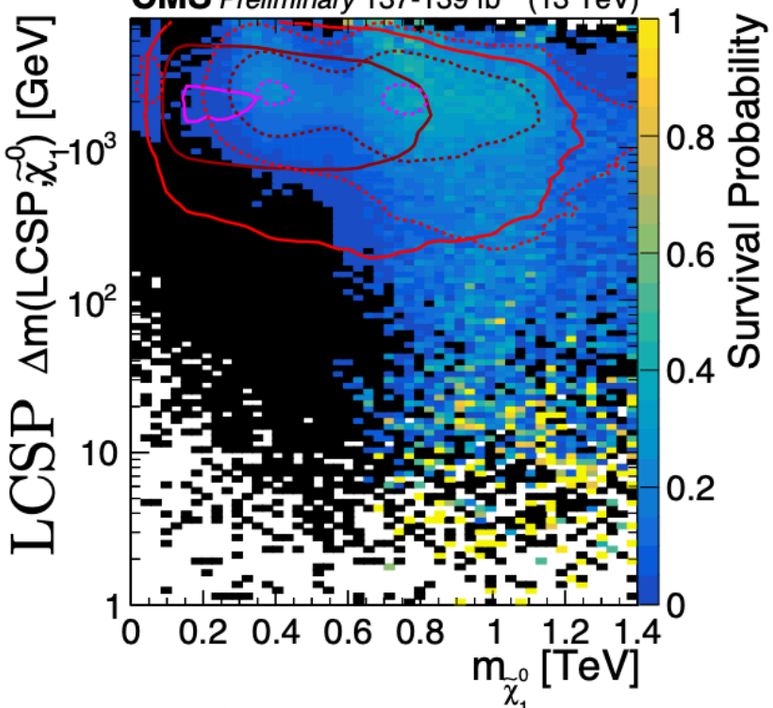






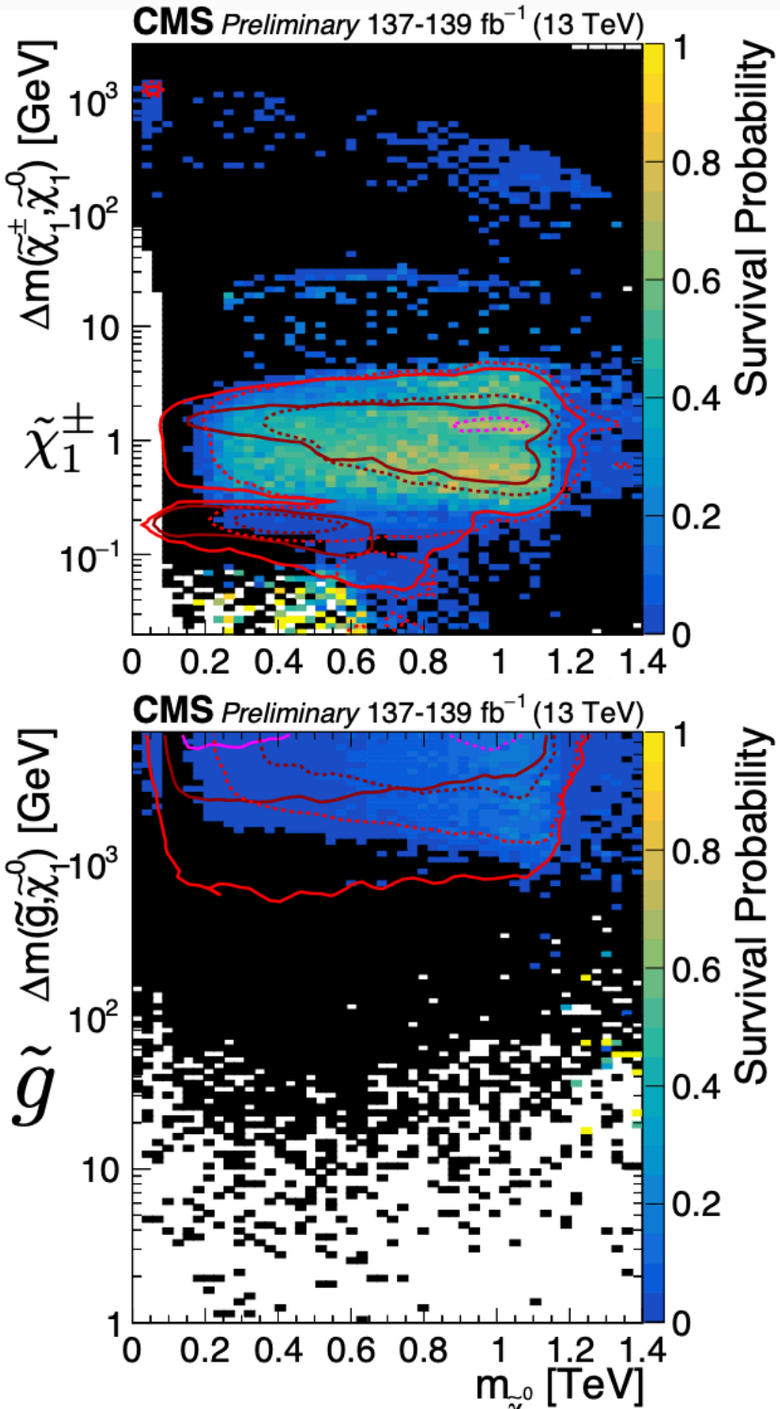


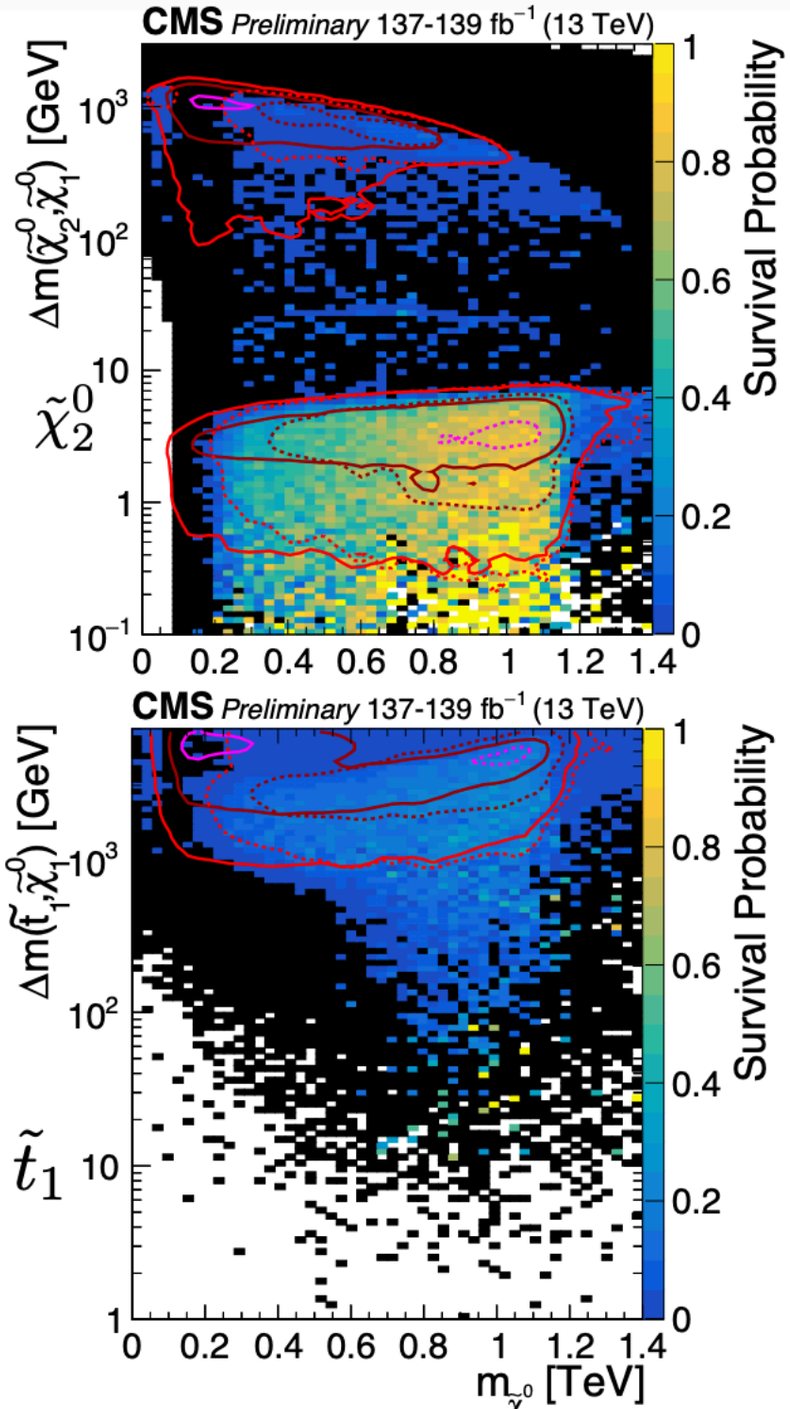


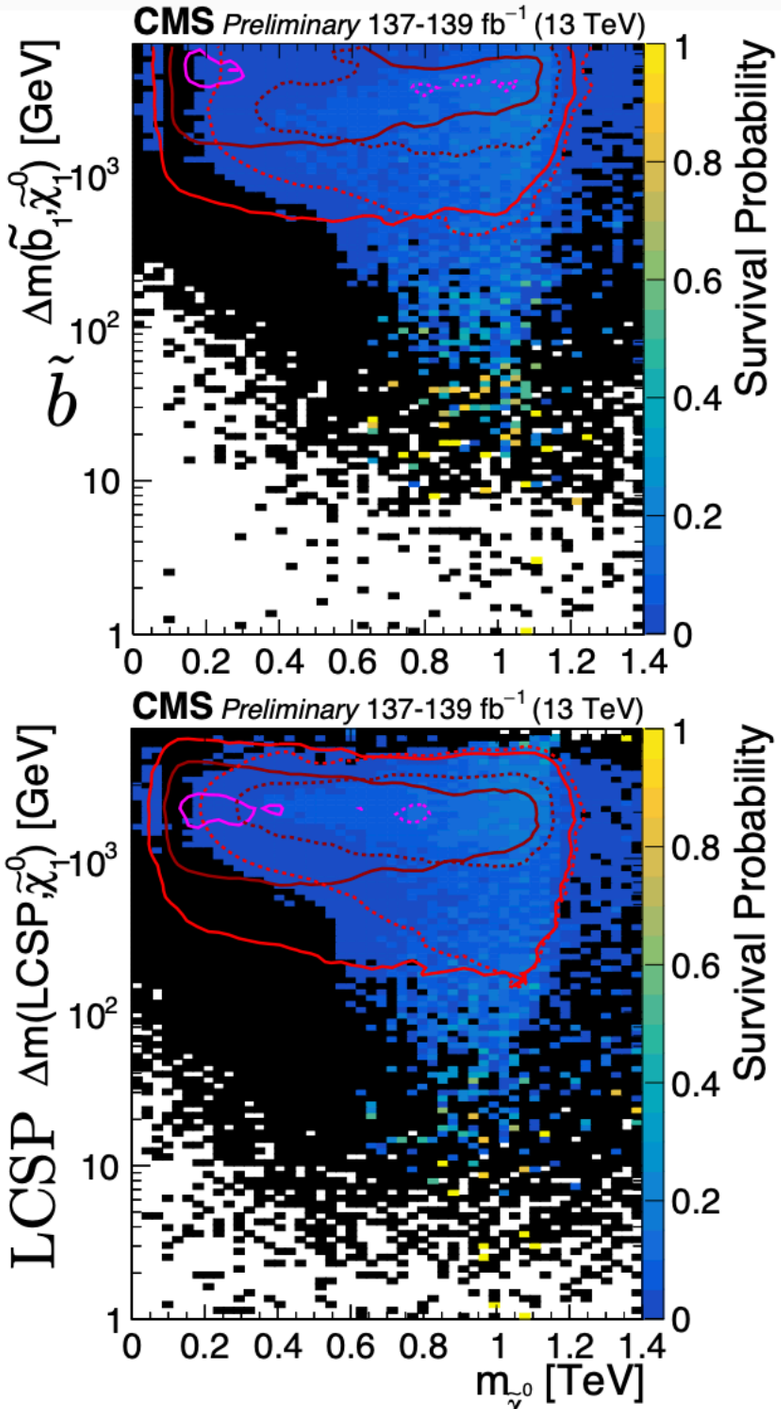


SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints

pMSSM flipbook plots

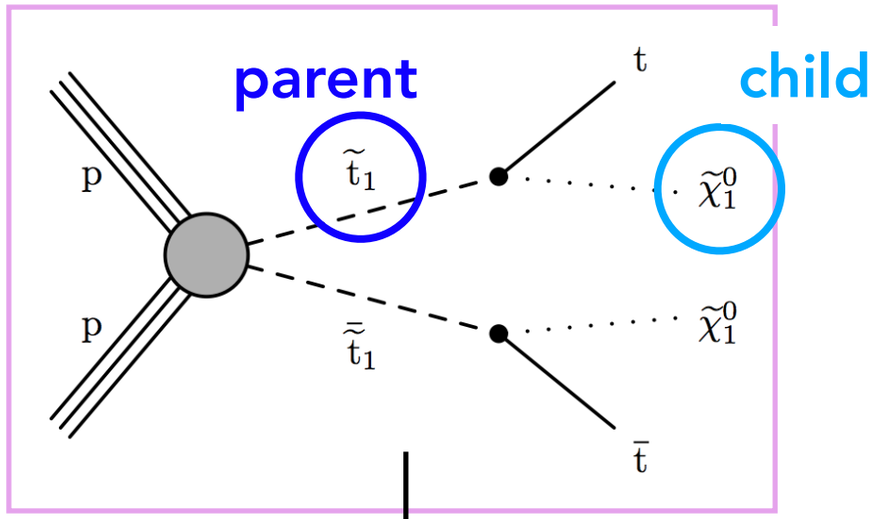


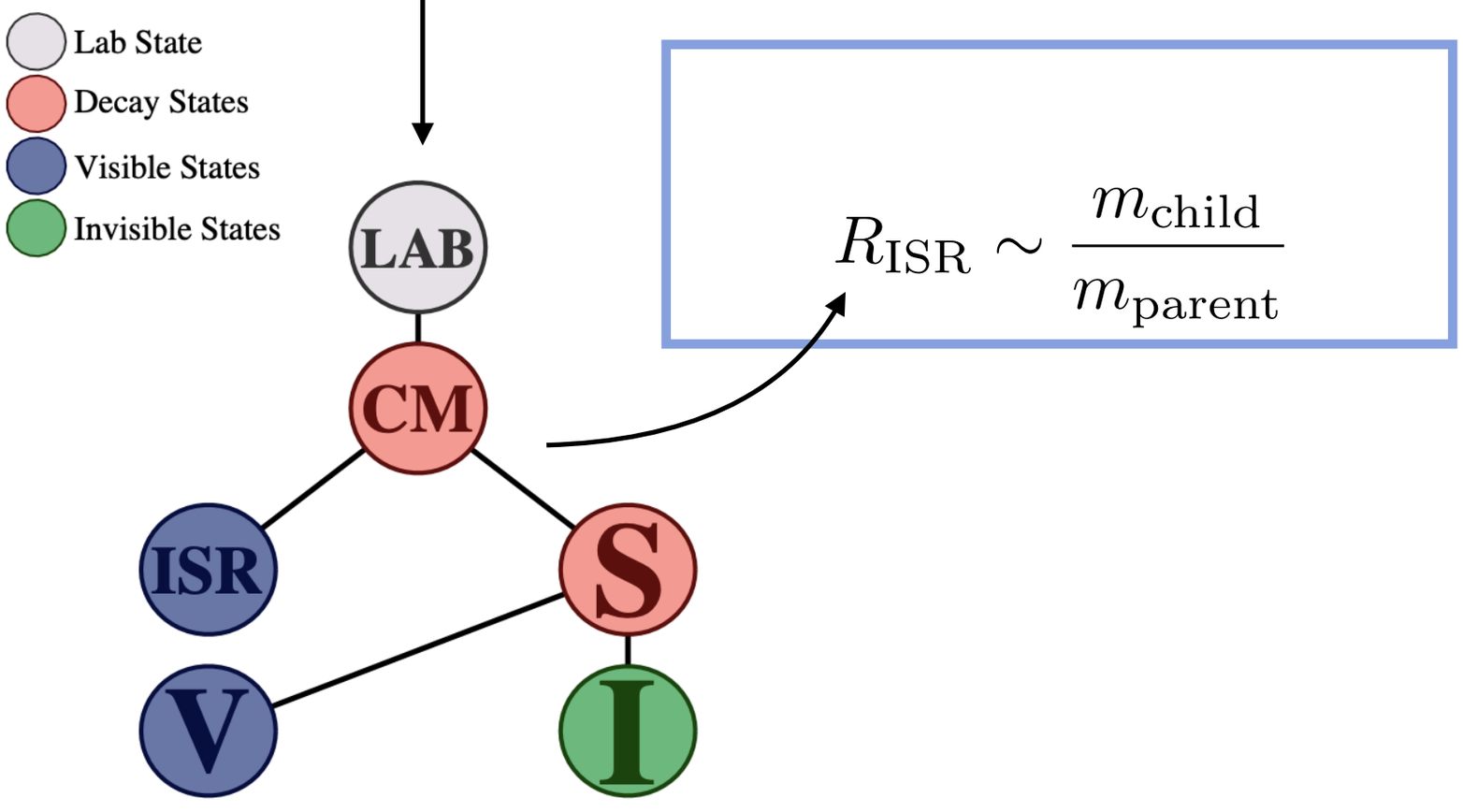




SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints+ Δ_{EW}<200

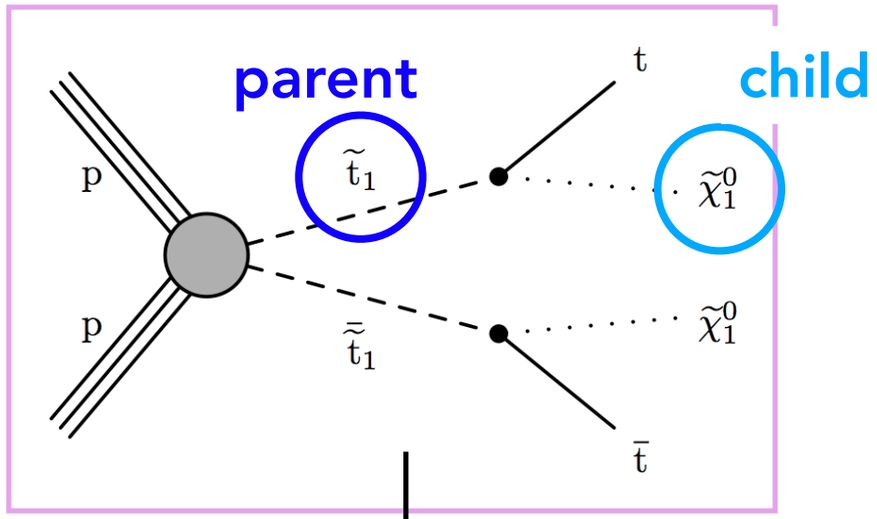
RJR Analysis Strategy





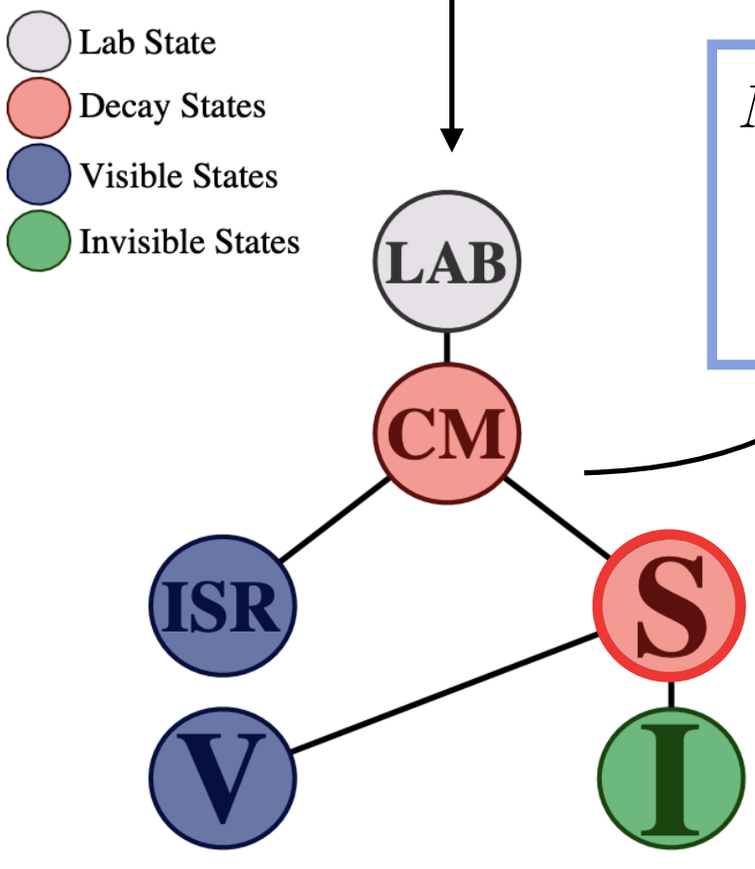
$$R_{\mathrm{ISR}} \sim \frac{m_{\mathrm{child}}}{m_{\mathrm{parent}}}$$

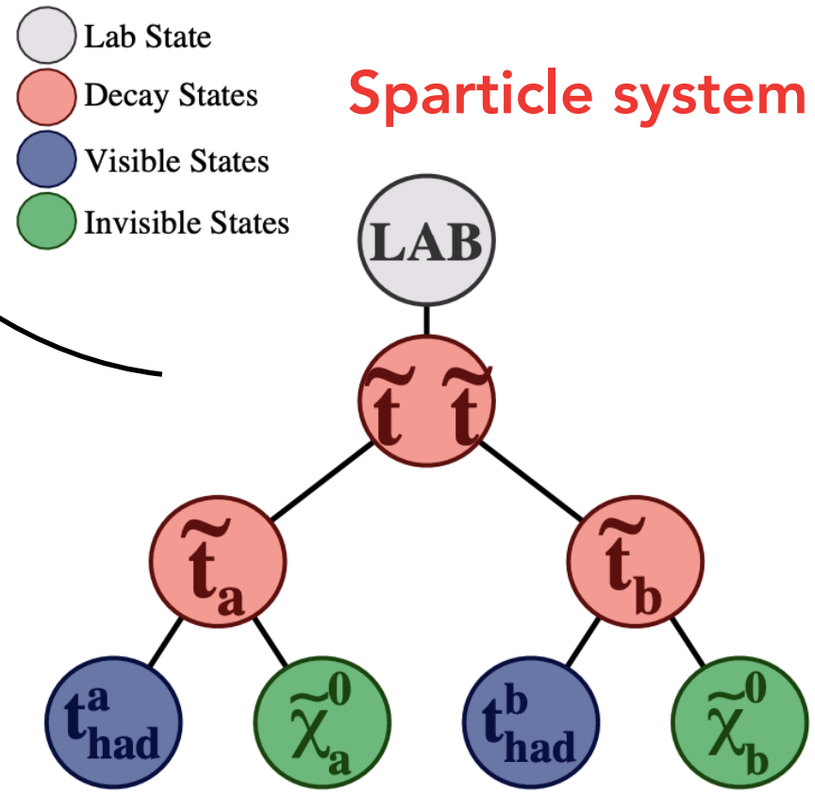
RJR Analysis Strategy



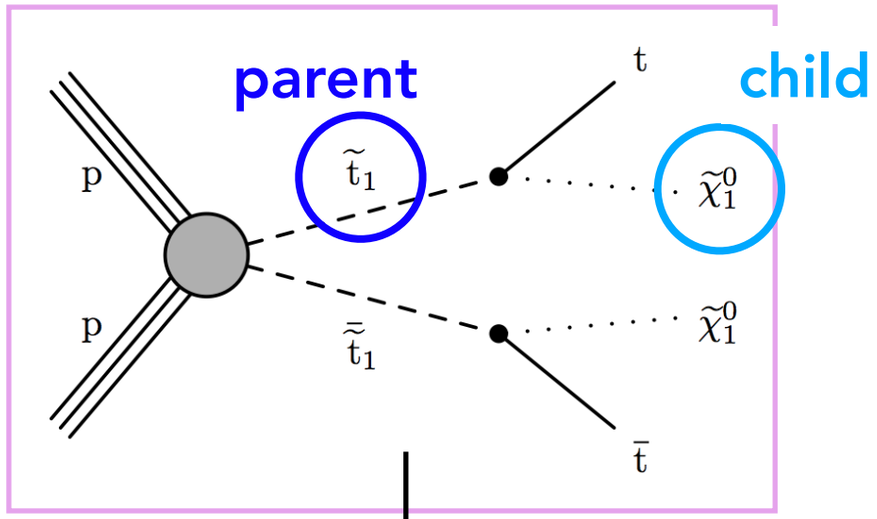
$$M_\perp \sim m_{\text{parent}} - m_{\text{child}} \equiv \Delta m$$

$$R_{\text{ISR}} \sim \frac{m_{\text{child}}}{m_{\text{parent}}}$$





RJR Analysis Strategy



Separate data into regions by sensitive variables

$$M_\perp \sim m_{\text{parent}} - m_{\text{child}} \equiv \Delta m$$

$$R_{\text{ISR}} \sim \frac{m_{\text{child}}}{m_{\text{parent}}}$$