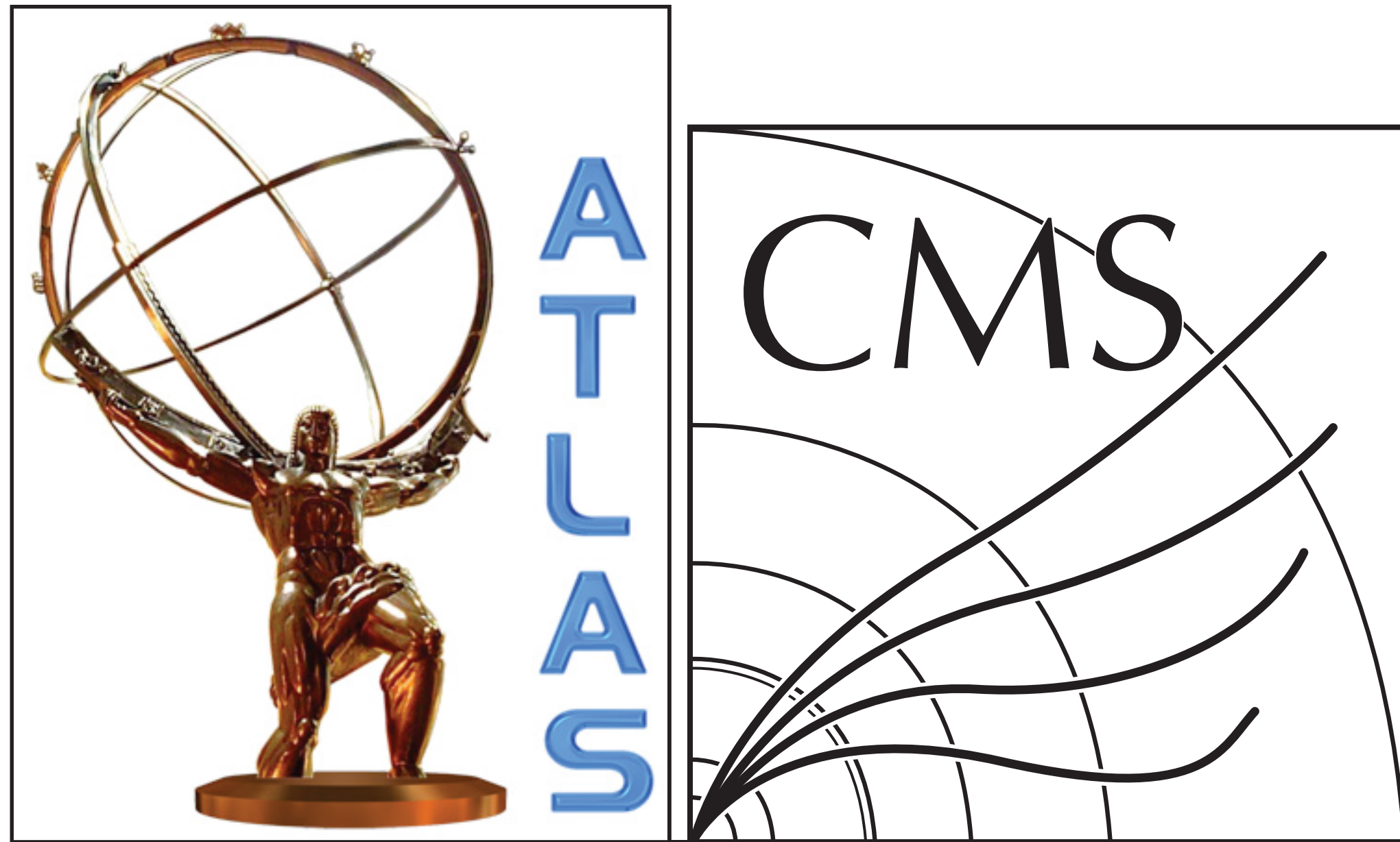


Searches for supersymmetry and extra Higgses at the LHC

Blois 2024: 35th Rencontres de Blois on "Particle Physics and Cosmology"



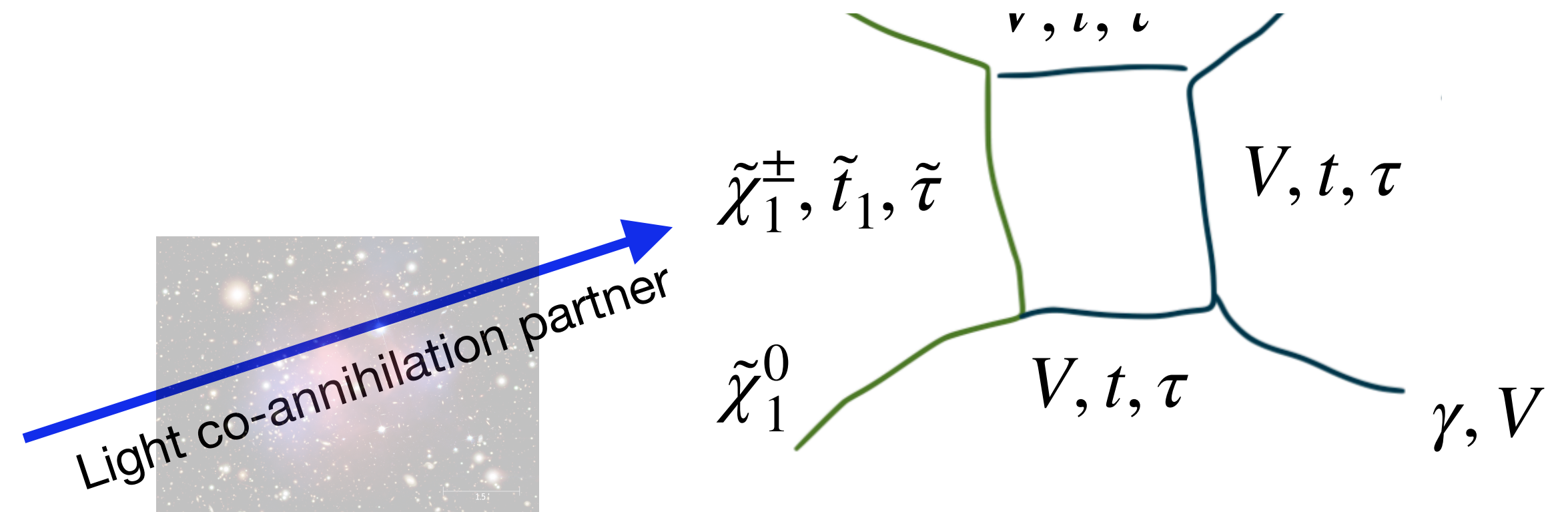
Sam Bein, for the
ATLAS and CMS
Collaborations



Supersymmetry can

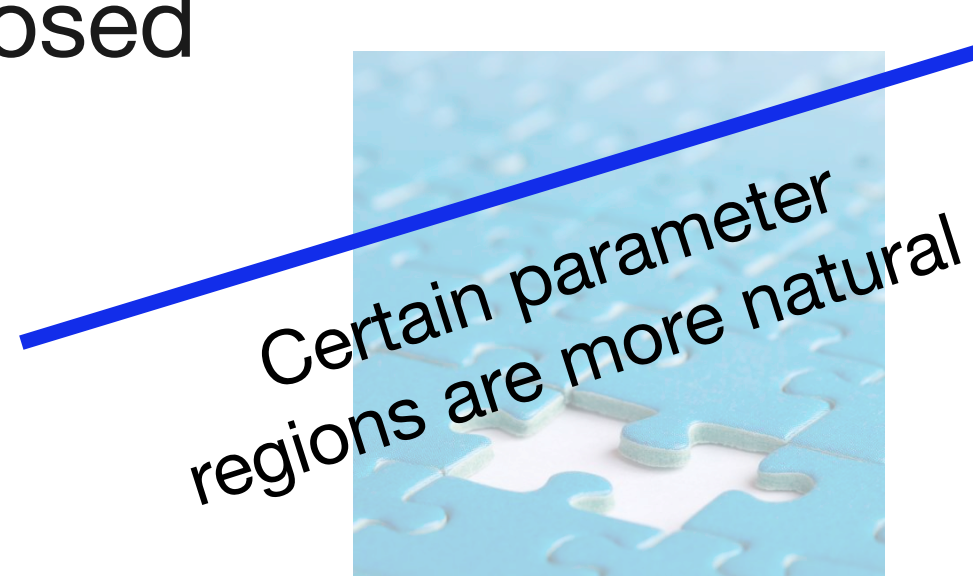
1. account for DM if

- neutralino $\tilde{\chi}_1^0$ is the LSP
- R-parity is conserved (RPC)
- if enough LSPs can annihilate before freeze-out - requires small Δm or funnel



2. solve a fine tuning puzzle if

- SUSY is only softly broken - many proposed breaking mechanisms
- if little hierarchy problem doesn't arise



$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_\mu^\mu) \tan\beta}{\tan^2\beta - 1} - \mu^2$$

Labels and arrows pointing to terms in the equation:

- m_Z^2 : Z mass
- $m_{H_d}^2$: Down-type Higgs mass
- Σ_d^d : sfermion loops
- $\tan^2\beta - 1$: VEV ratio
- Σ_μ^μ : sfermion loops
- μ^2 : Higgsino mass

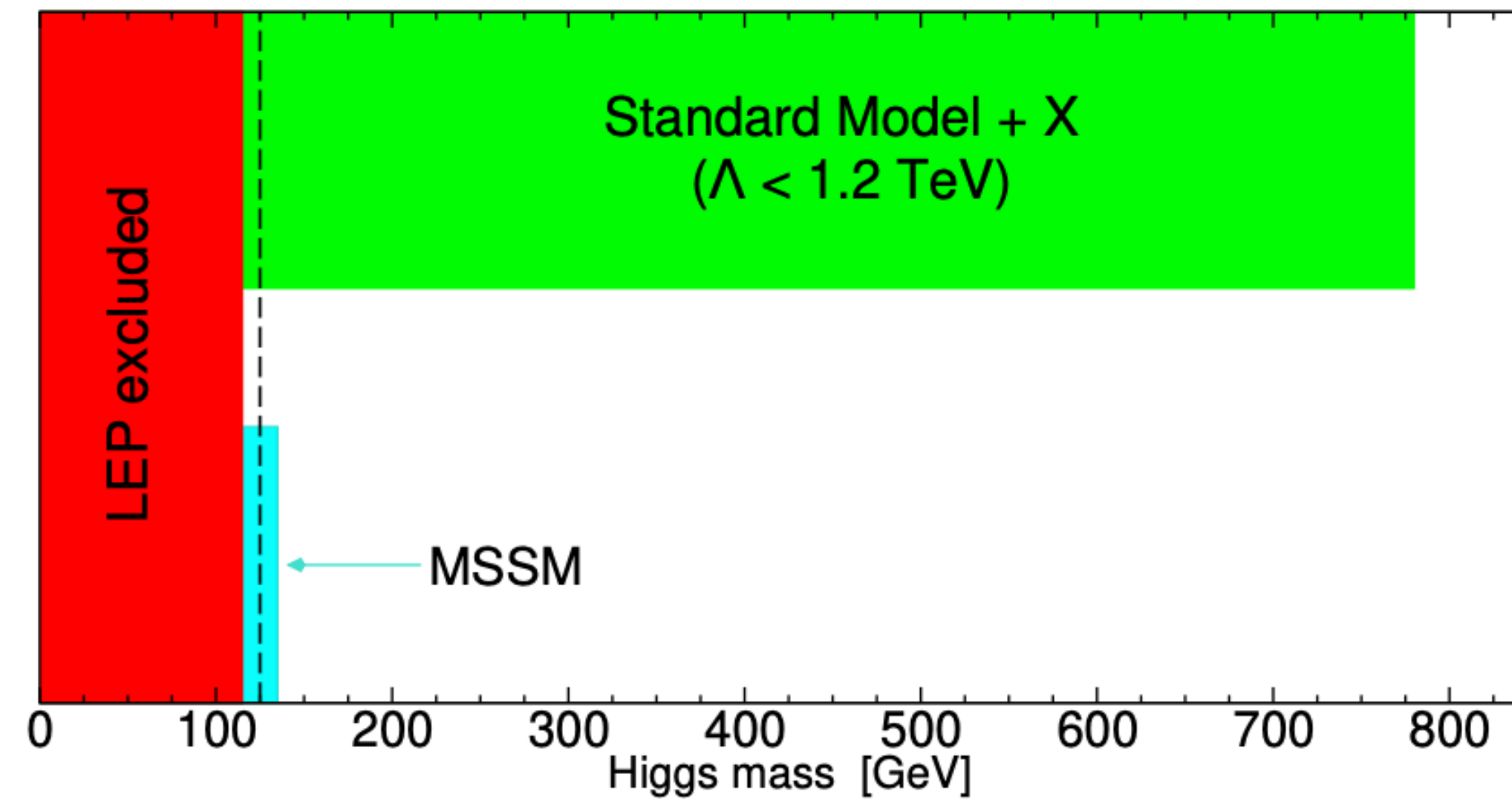
A green bracket is drawn under the terms Σ_d^d and Σ_μ^μ .

→ Simplified models don't allow us to comment on these constraints because the constraints depend on the full particle spectrum and not just 2-3 masses

Independent terms need to cancel to give something in line with $m(Z)$ - so they shouldn't be too big

Supersymmetry can

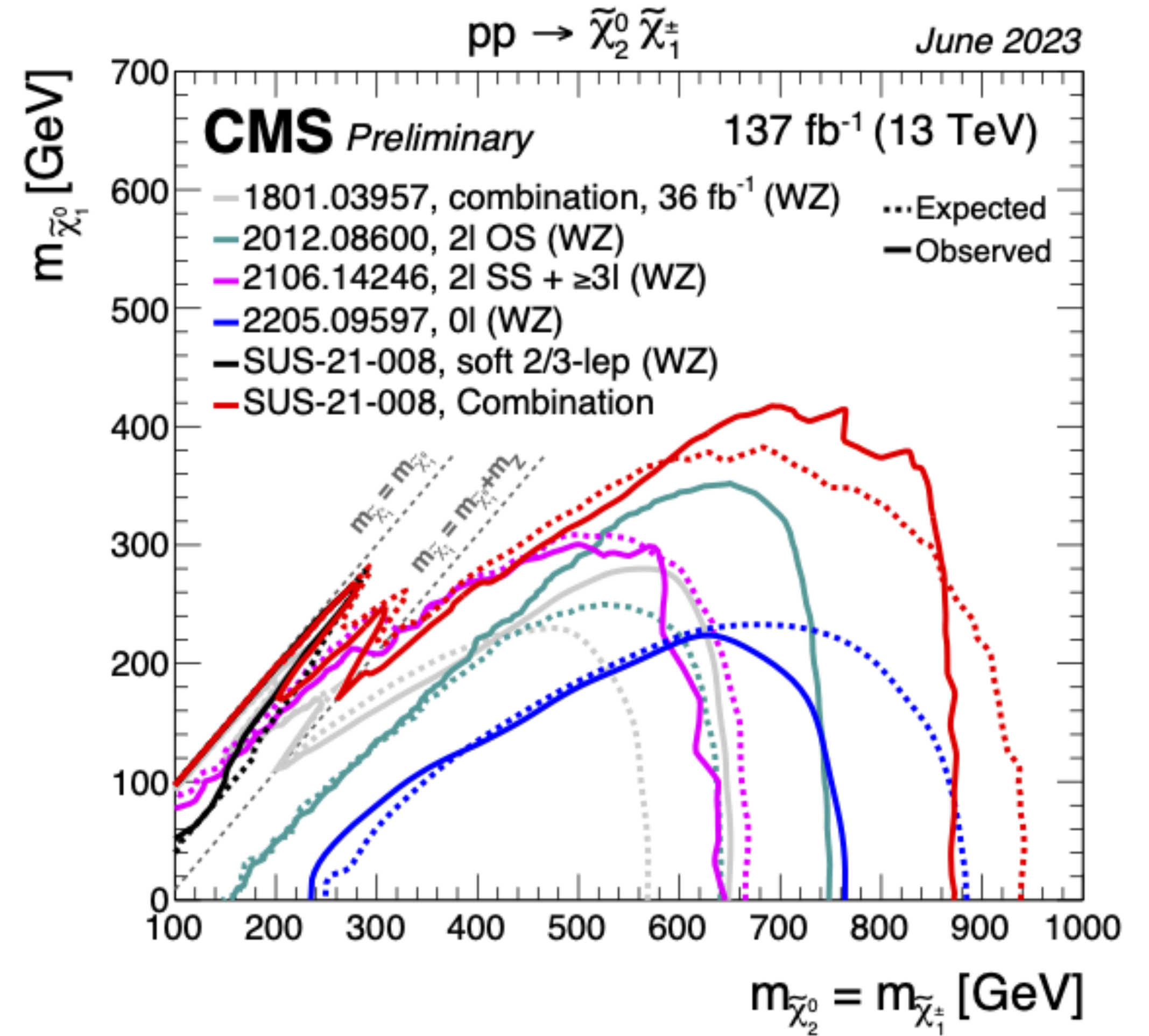
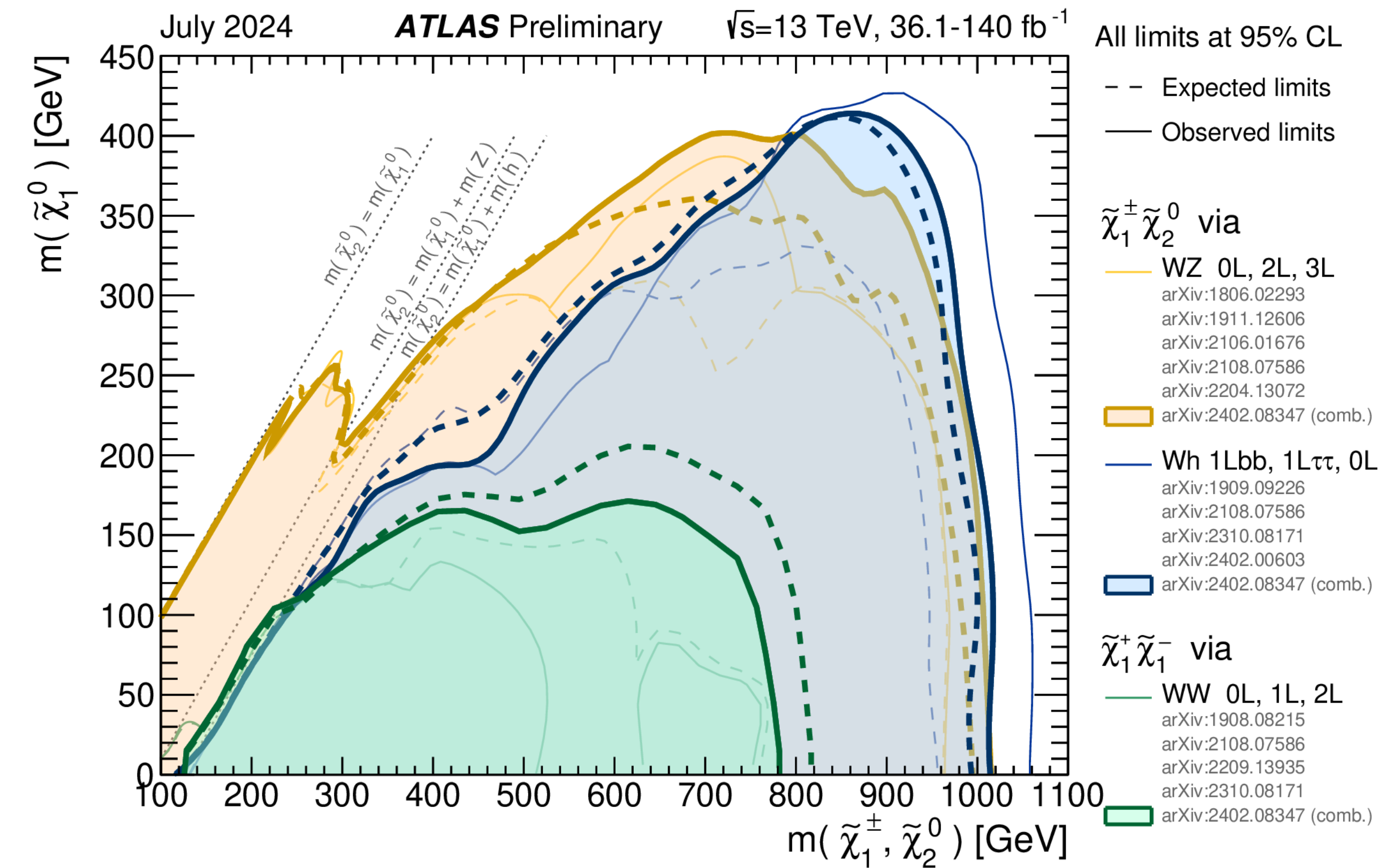
3. Make successful predictions, like the Higgs mass



Future of supersymmetry, Stephen Martin@SUSY2023

4. ...

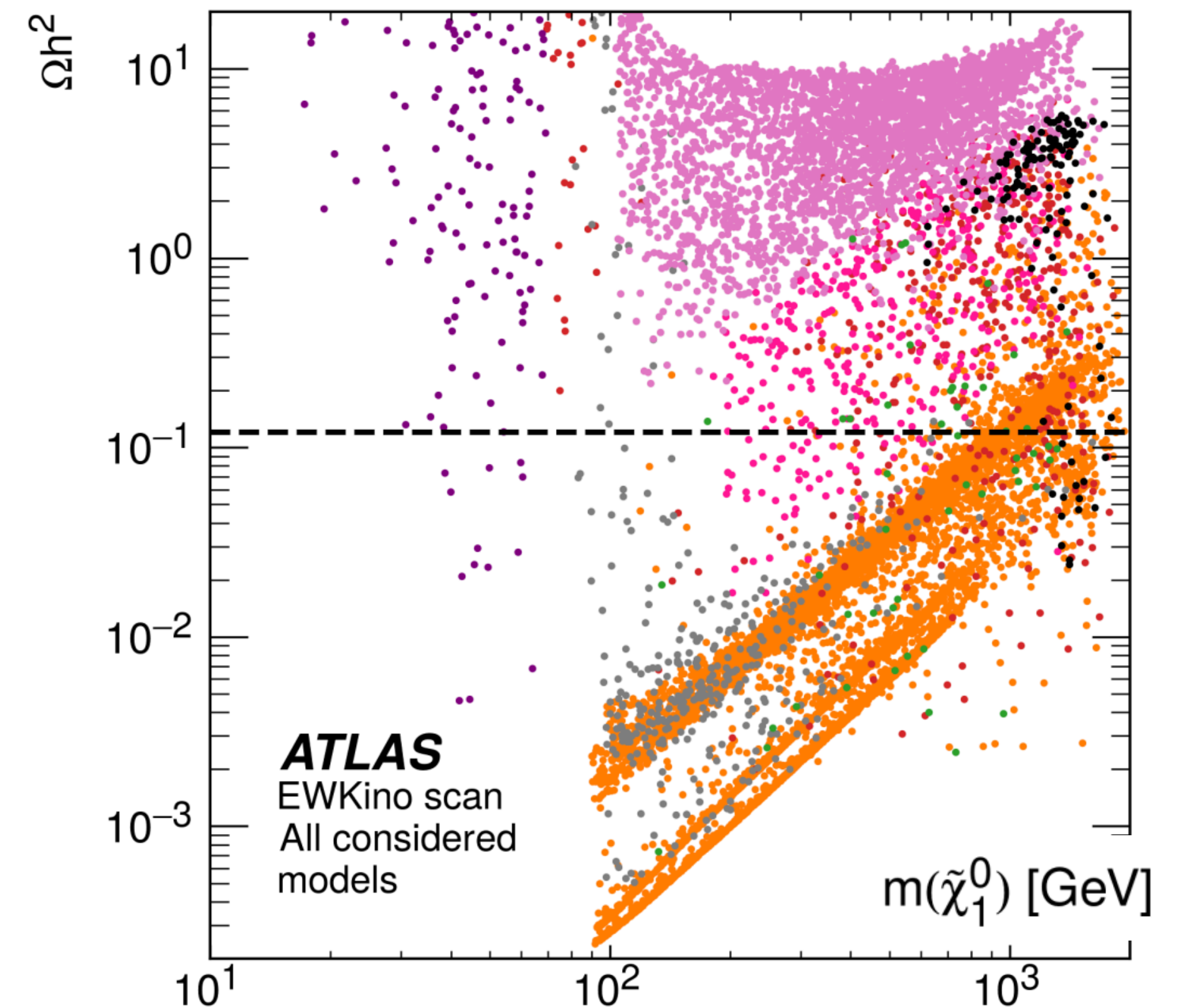
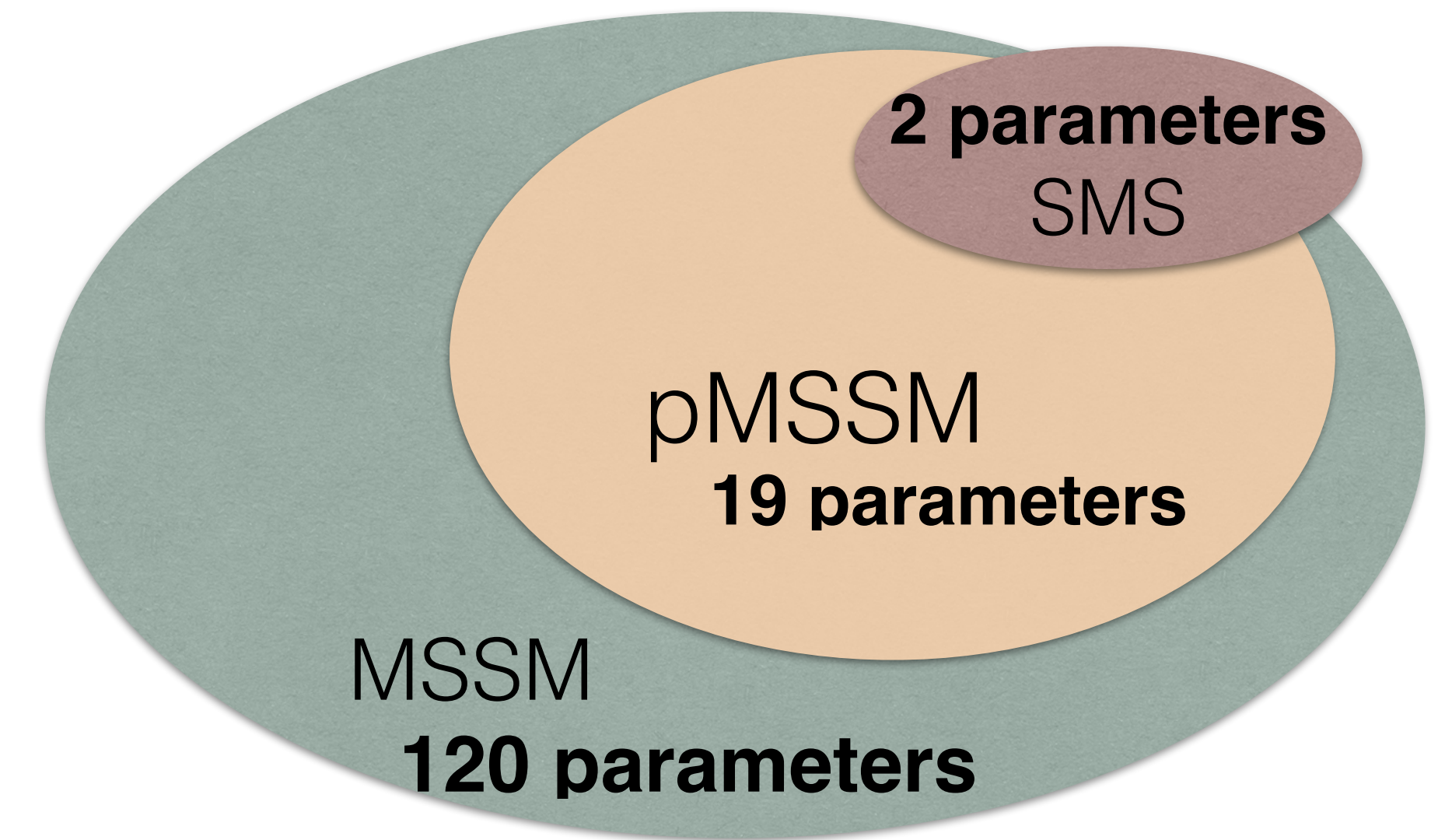
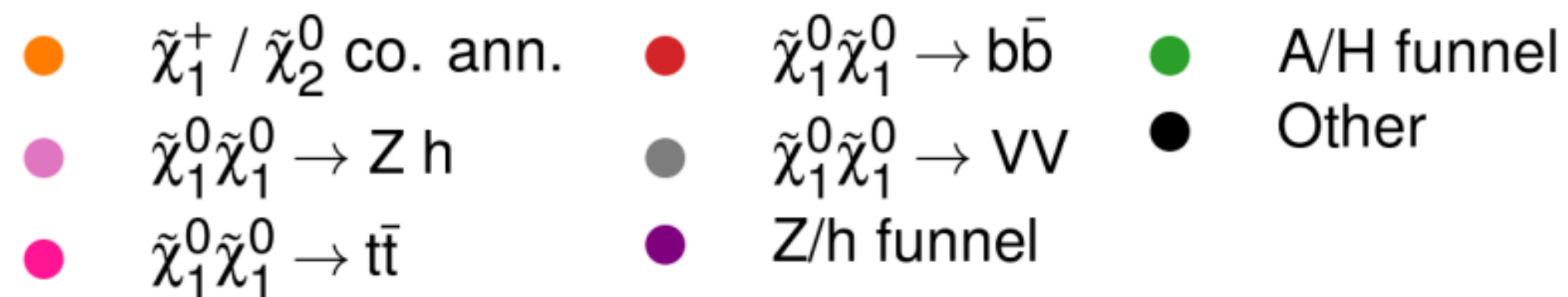
Dozens of searches in Run 2



Mapping RPC SUSY

Supersymmetry without prejudice, Berger, Gainer, Hewett, Rizzo

- “phenomenological minimal supersymmetric Standard Model” (pMSSM)
- 19-parameter sub-model of MSSM
- captures most phenomenology
- LHC, dark matter, naturalness insights



Mapping RPC SUSY

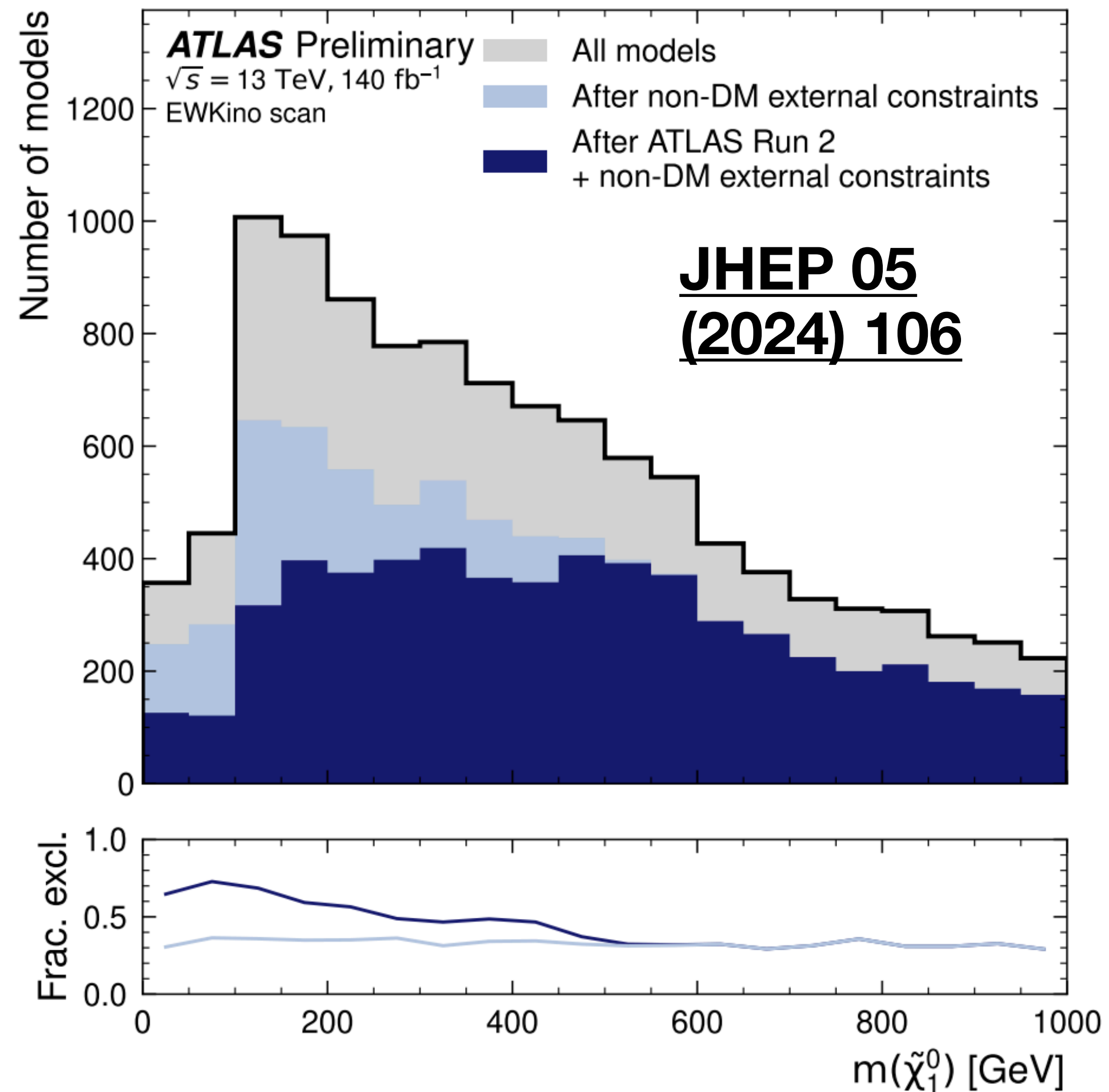
- There are now Run 2 pMSSM studies from ATLAS and CMS
 - ATLAS: **JHEP 05 (2024) 106** - *Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM*
 - *electroweak SUSY* with 2 dedicated scans - general and bino-stocked
 - 8 analyses, ~20k models points randomly scanned
 - CMS: **PAS-24-004** - *Phenomenological MSSM interpretation of CMS searches in pp collisions at 13 TeV*
 - *Electroweak and strong SUSY* production in a single scan
 - 5 analyses, 500k model points scanned with MCMC likelihood

Included final states

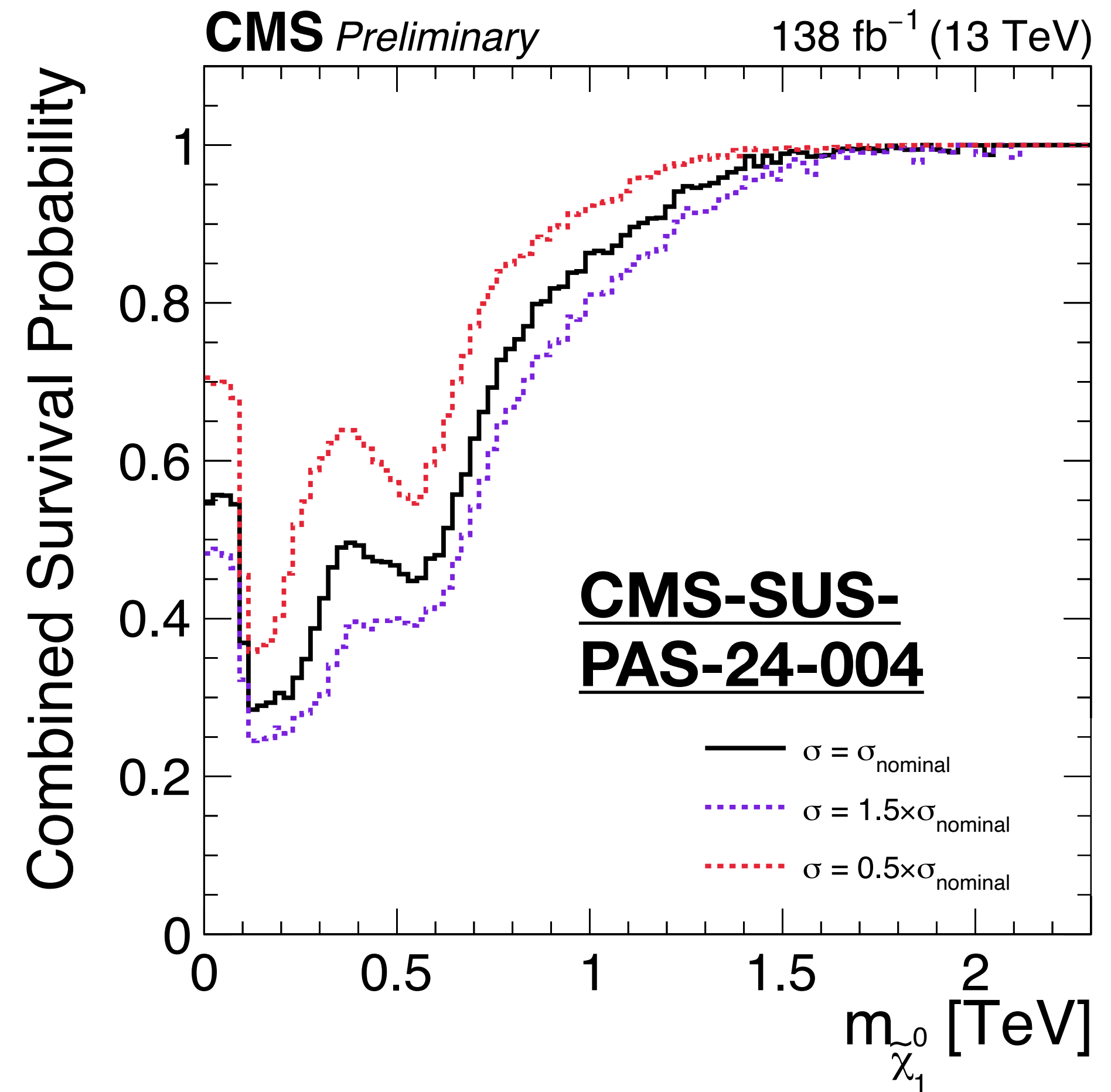
Final State Category	Experiment	Analyses / Final State	Journal Reference
0 lepton (all-hadronic)	ATLAS	Hadronic boosted V	Phys. Rev. D 104 (2021) 112010
	CMS	Jets+MHT, HT, n(b-tags)	JHEP 10 (2019) 244
1 lepton	ATLAS	1Lbb	Eur. Phys. J. C 80 (2020) 691
	CMS	Single-lepton $\Delta\phi$	JHEP 09 (2023) 149
2-lepton	ATLAS	2L0J	Eur. Phys. J. C 80 (2020) 123
	ATLAS	2L2J	Eur. Phys. J. C 83 (2023) 515
	CMS	Same-flavor opposite sign	JHEP 04 (2021) 123
3-lepton	ATLAS	3L	Eur. Phys. J. C 81 (2021) 1118
Compressed/Soft	ATLAS	Compressed	Phys. Rev. D 101 (2020) 052005
	CMS	Soft opposite-sign leptons	JHEP 2204 (2022) 91
Disappearing track	ATLAS	tracklet, pT spectrum	Eur. Phys. J. C 82 (2022) 606
	CMS	short tracks with dE/dx	Phys. Rev. D 109 (2024) 072007

Dark matter candidate mass

Number of models



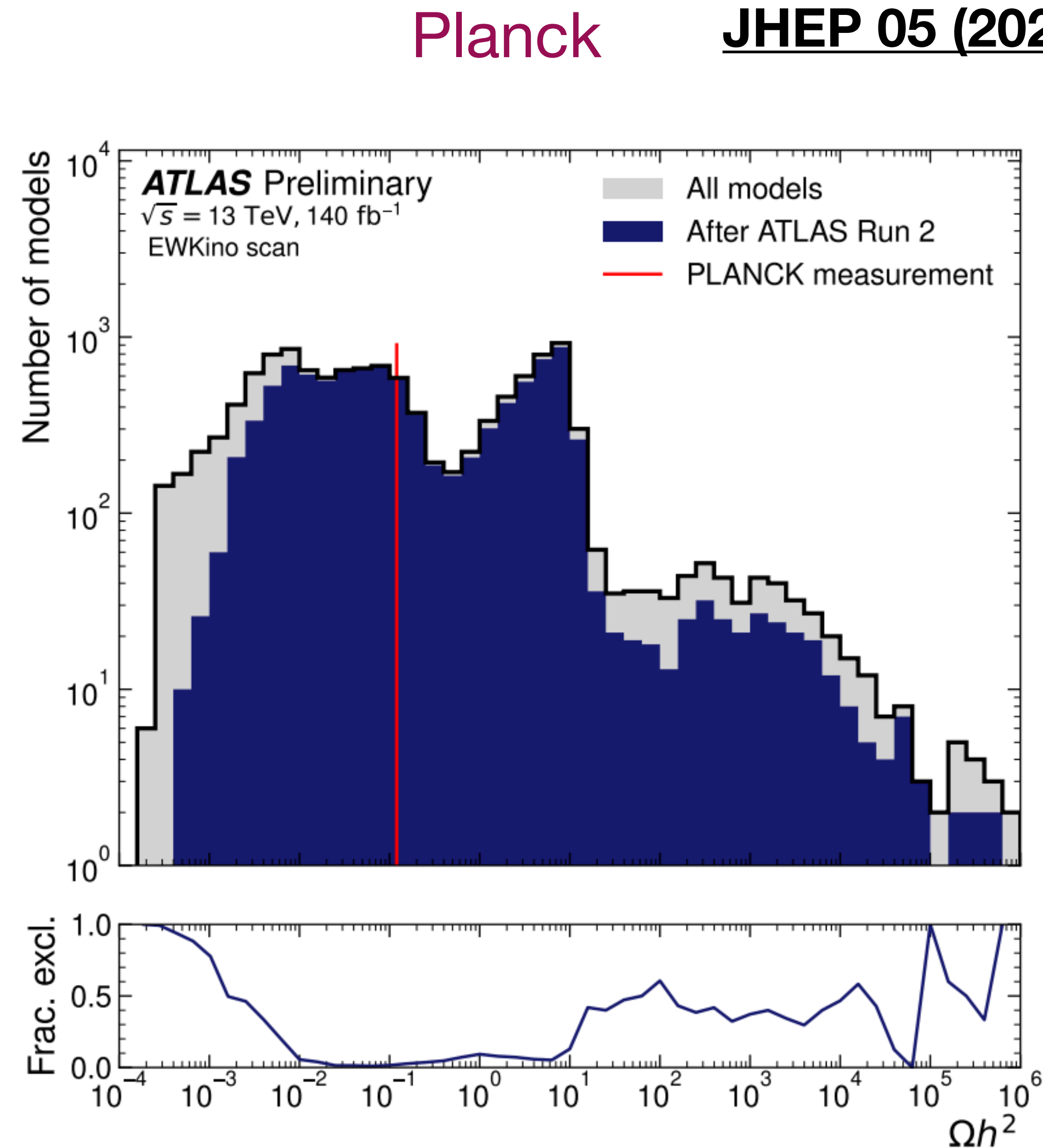
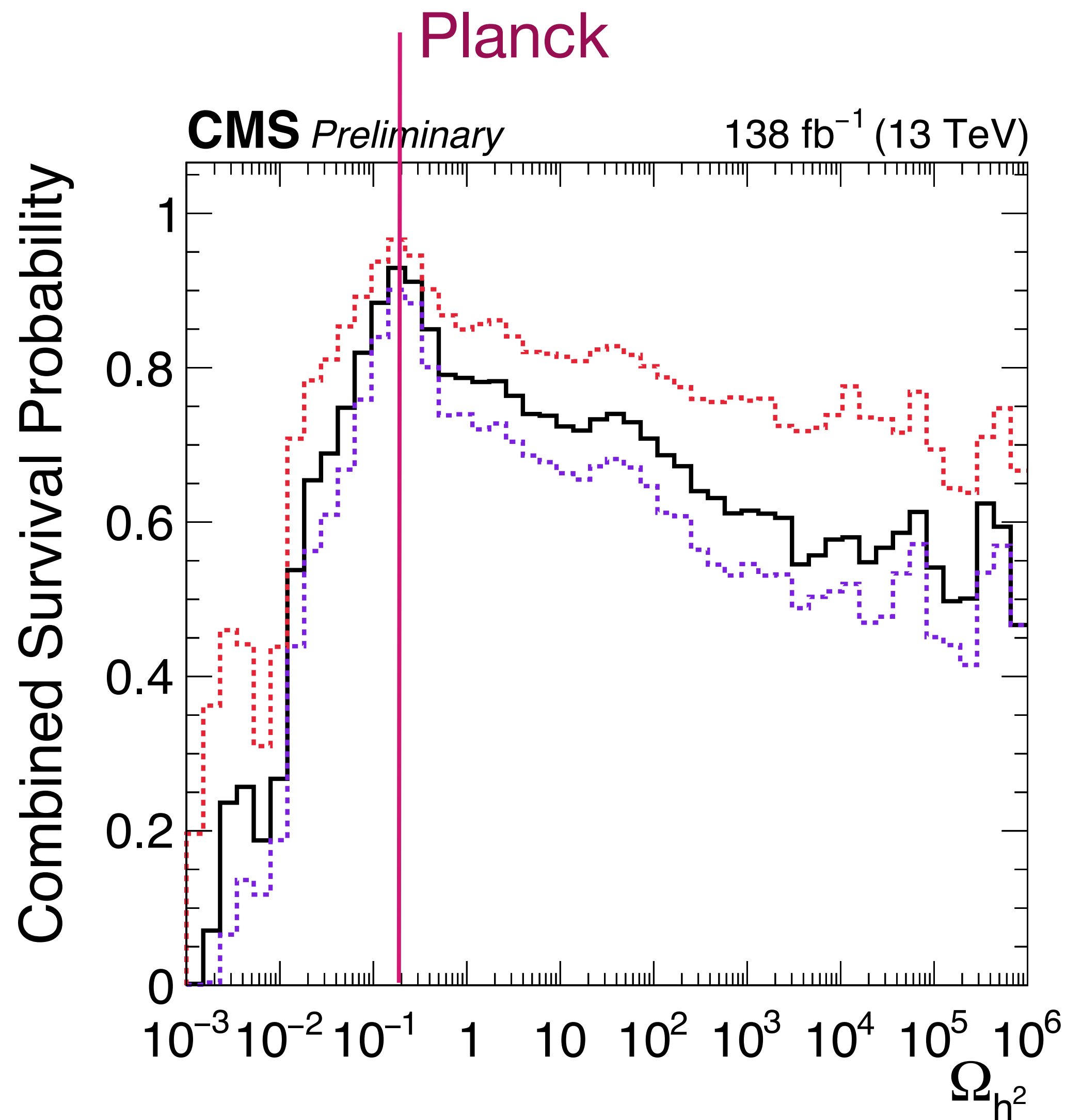
Survival probability



Relic density

CMS-SUS-PAS-24-004

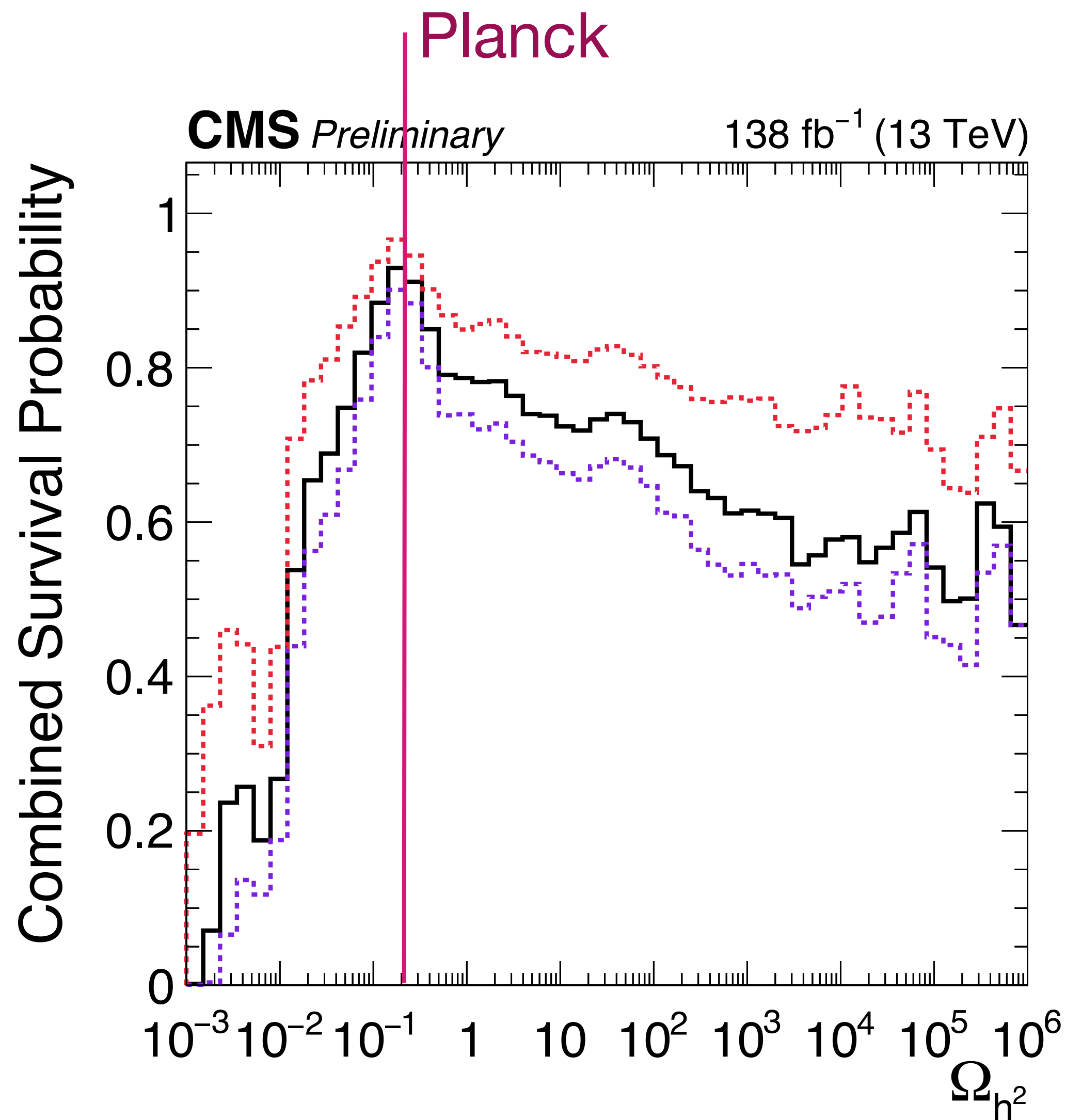
JHEP 05 (2024) 106



>90% of relic density models survive

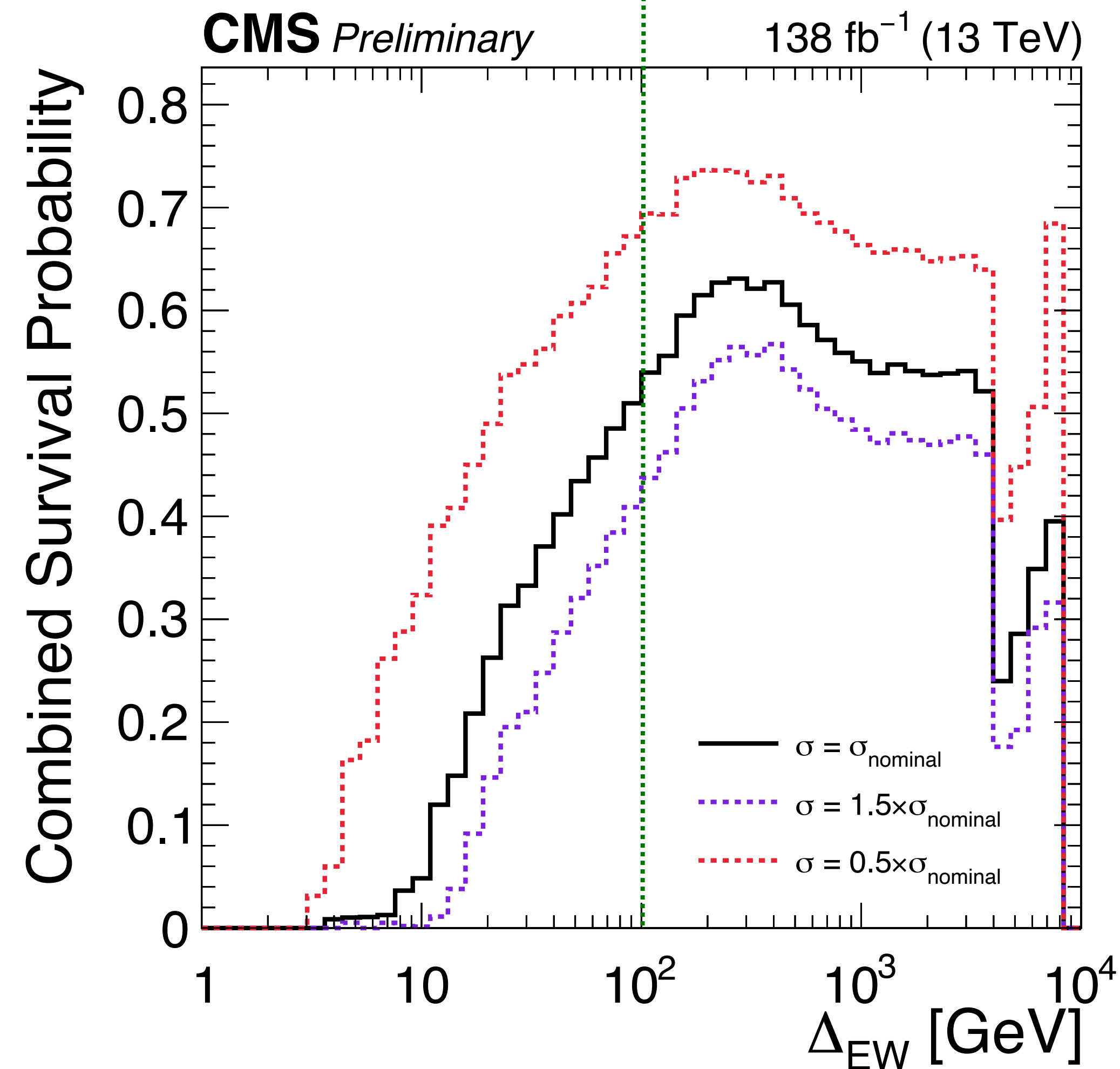
Relic density and fine-tuning

CMS-SUS-PAS-24-004



>90% of relic density models survive

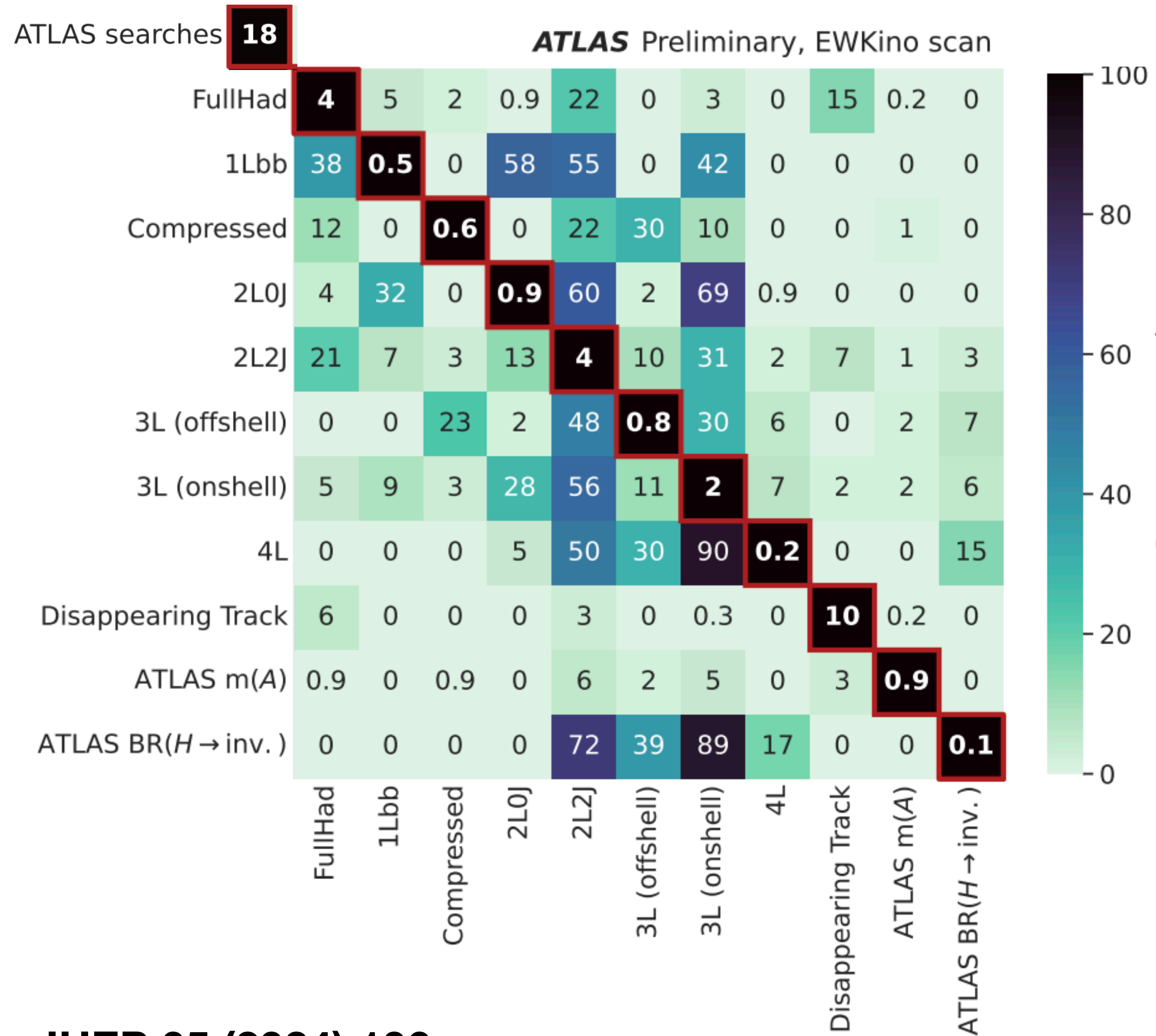
More natural ← → Less natural



<50% of natural models survive

Analysis impact

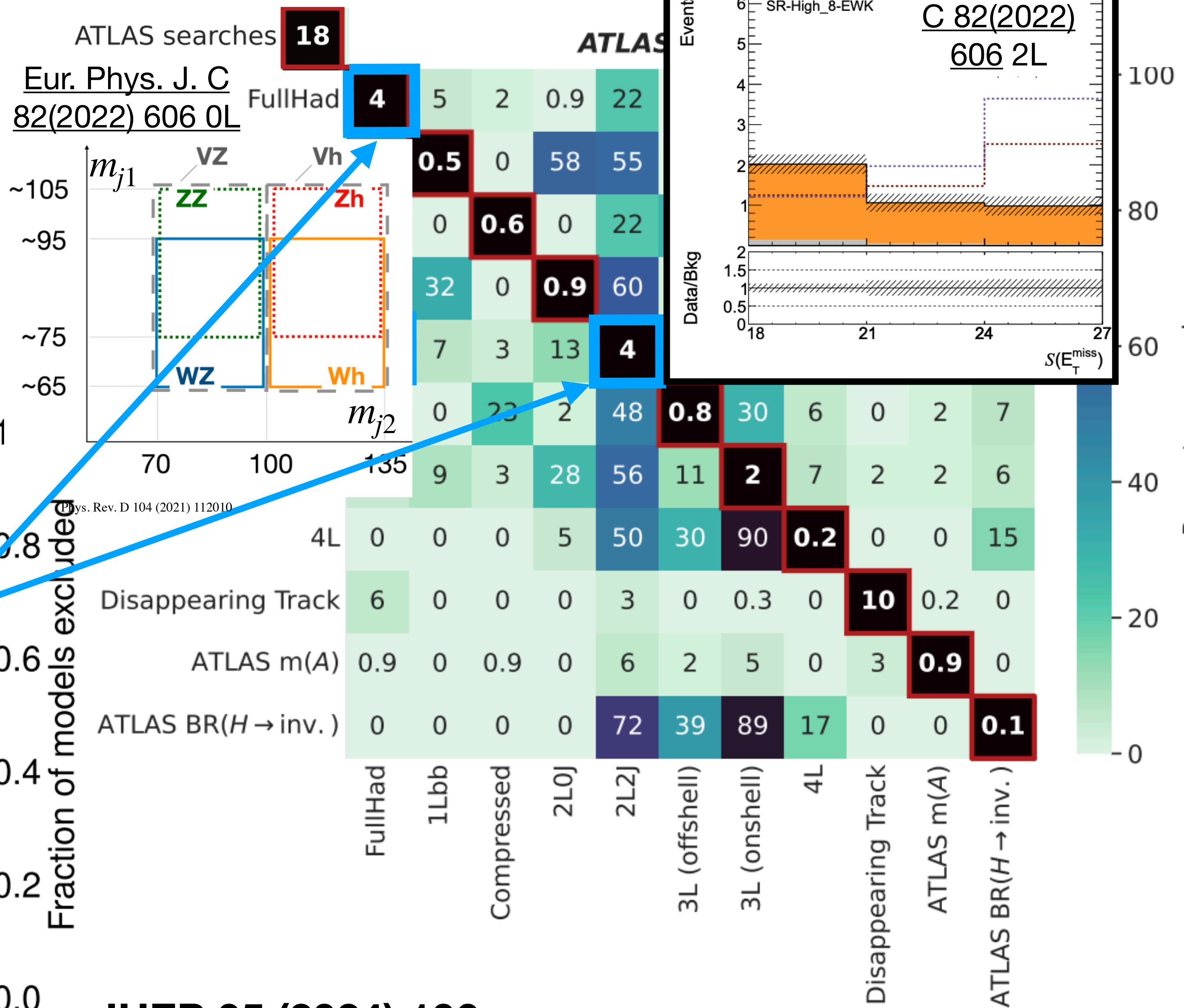
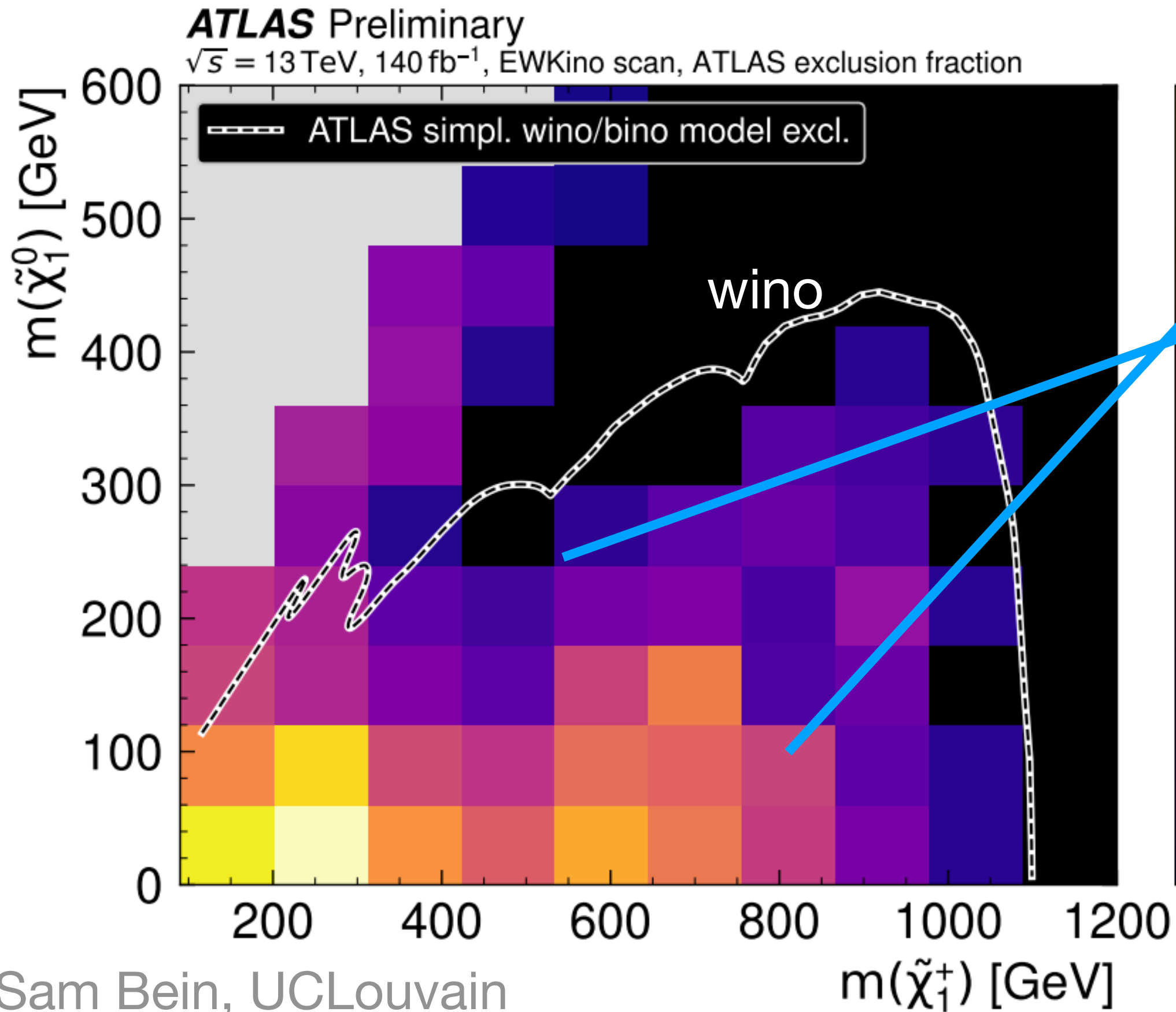
- Diagonal numbers: percentage of models excluded by given analysis
- Off-diagonals: event overlap in signal regions



JHEP 05 (2024) 106

Analysis impact

All-hadronic MET + 2 fat V-jets
2-lepton+2 jets



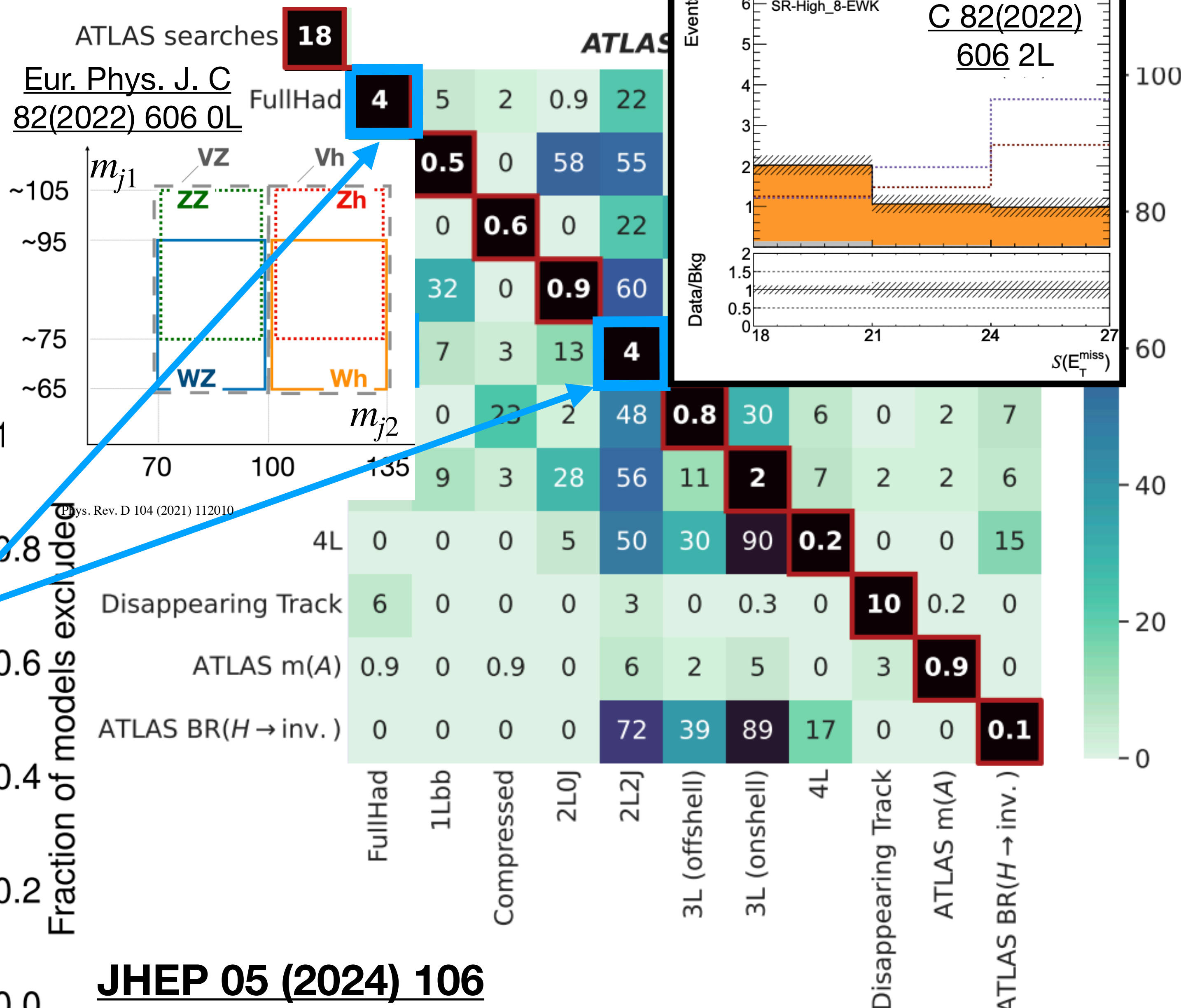
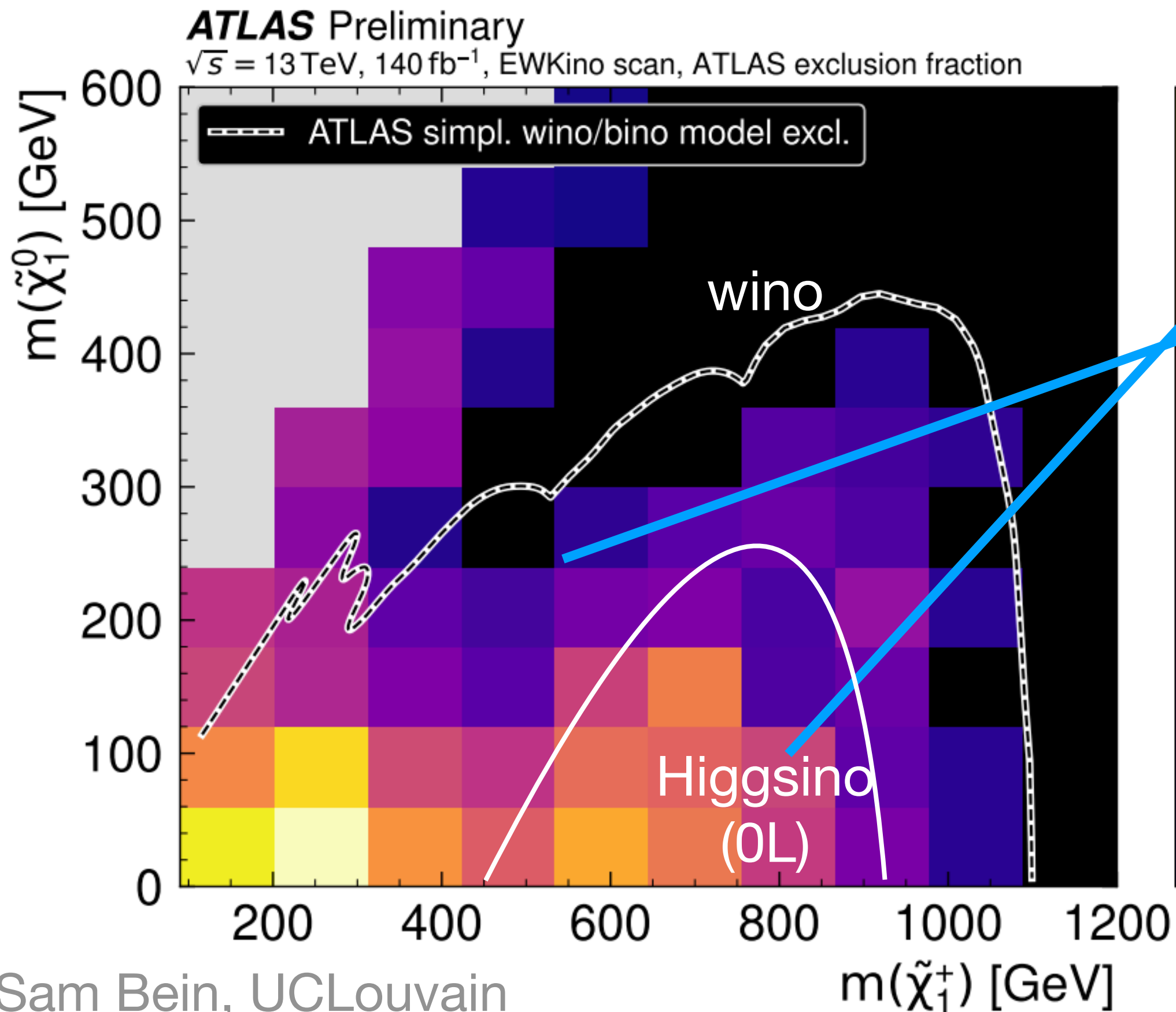
JHEP 05 (2024) 106

Analysis impact

All-hadronic MET + 2 fat V-jets

2-lepton+2 jets

- No exhaustive exclusion!

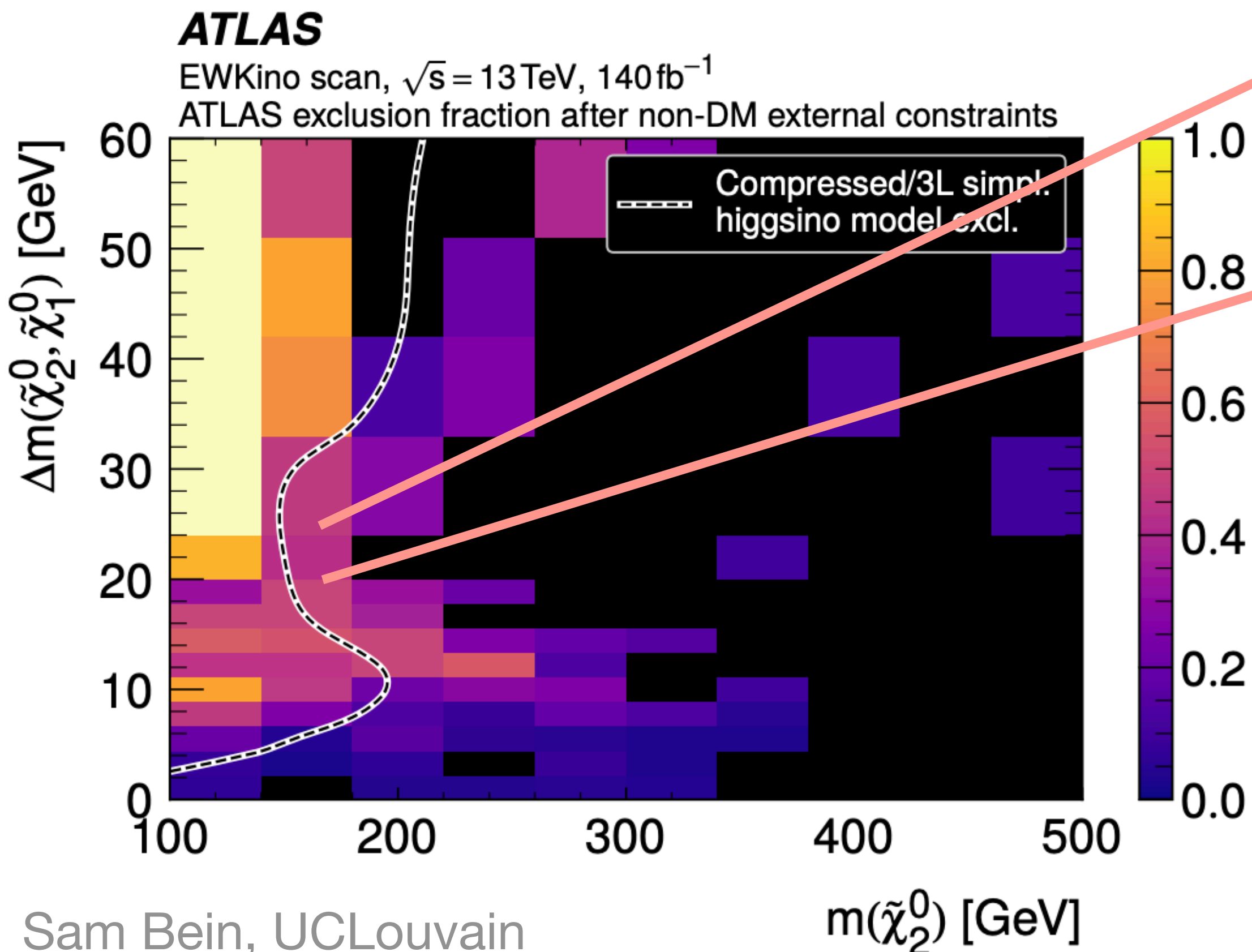


JHEP 05 (2024) 106

Talk Wednesday BSM session: "Electroweak SUSY with ATLAS" - Ben Hodkinson

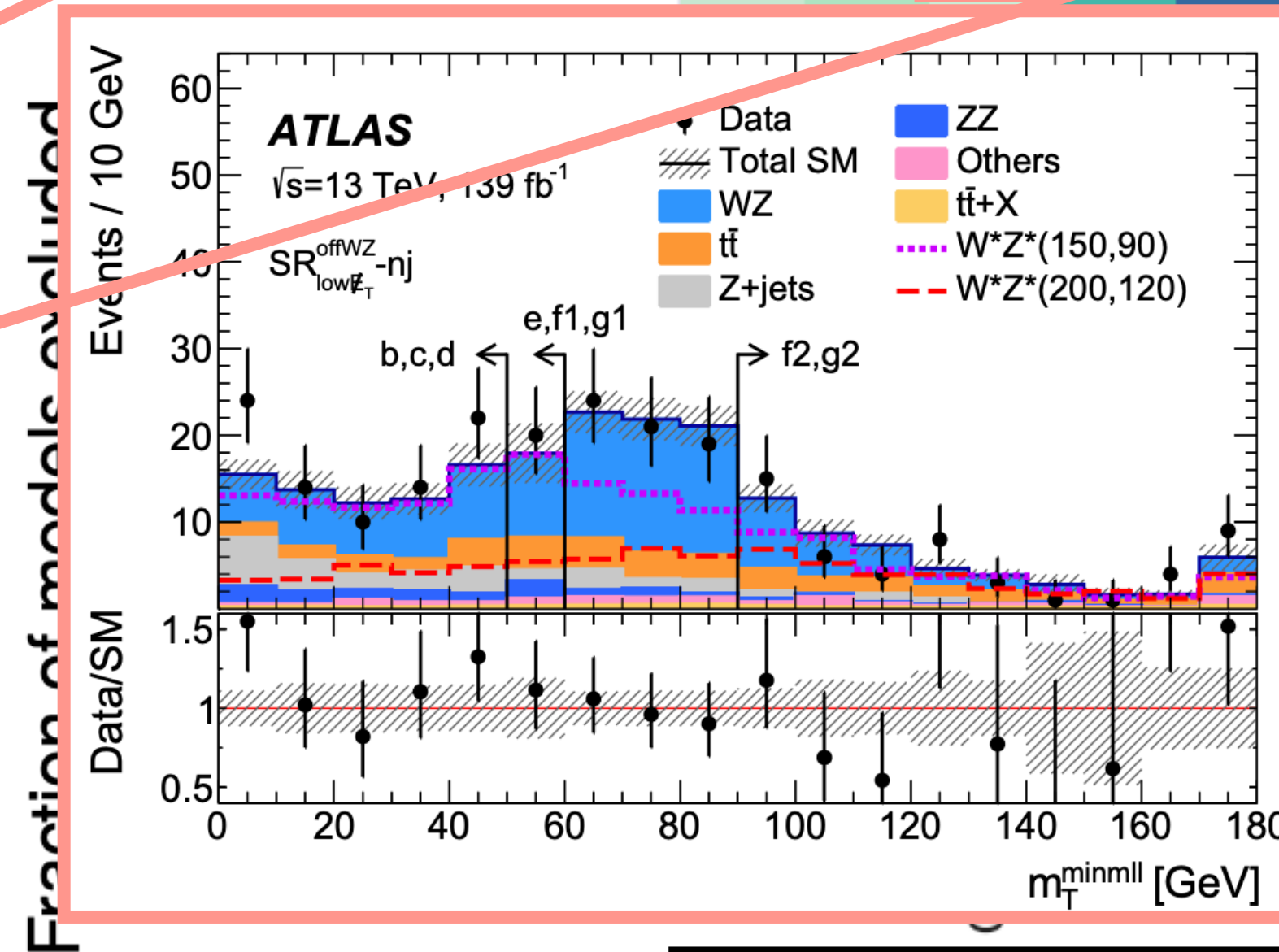
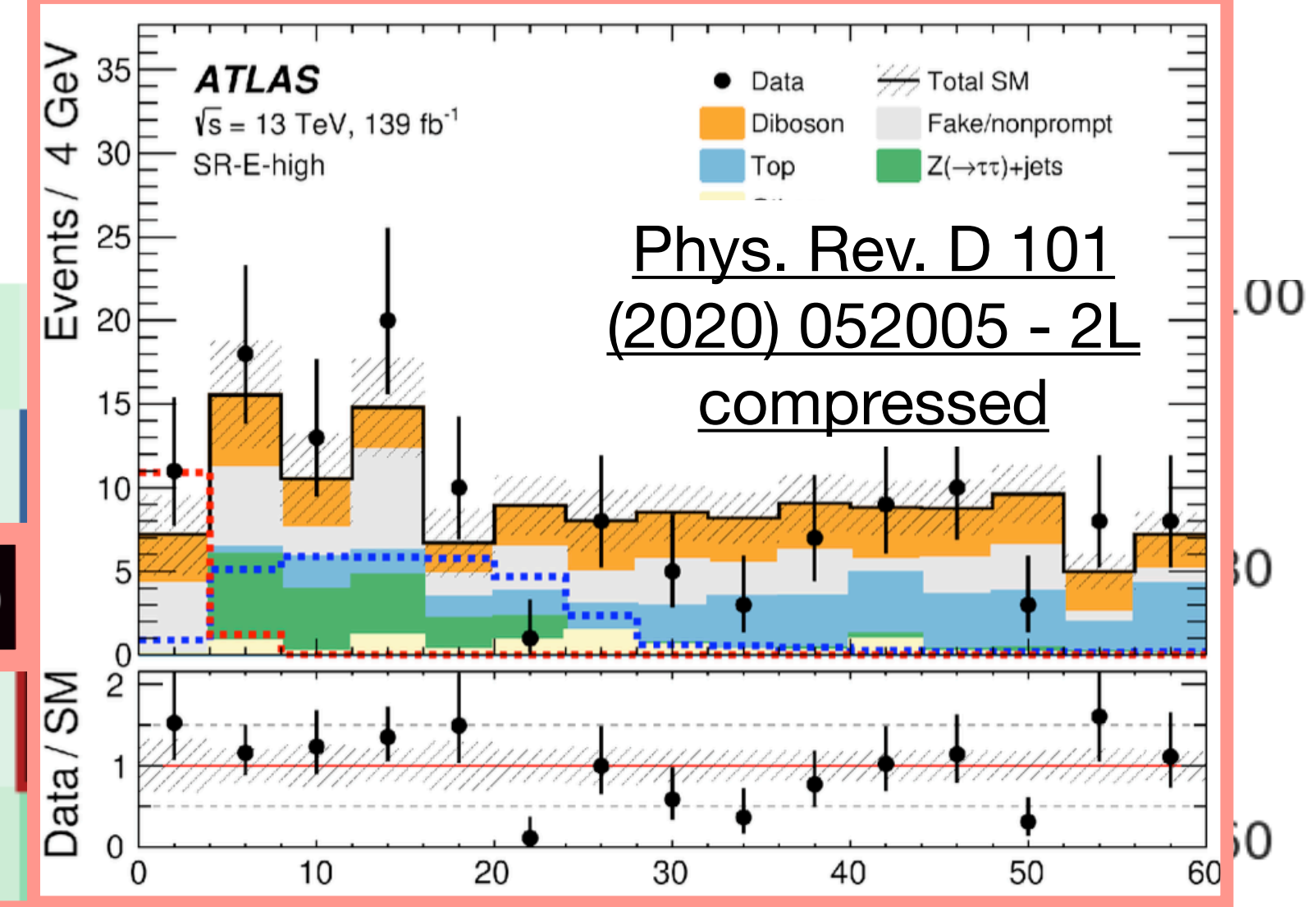
Analysis impact

- Overlapping excess in CMS and ATLAS soft lepton, multi-lepton analyses
- weakened limits around $\Delta m=25$ GeV contour back up in pMSSM



ATLAS searches **18**

FullHad	4	5	2
1Lbb	38	0.5	0
Compressed	12	0	0.6
2L0J	4	32	0
2L2J	21	7	3
3L (offshell)	0	0	23



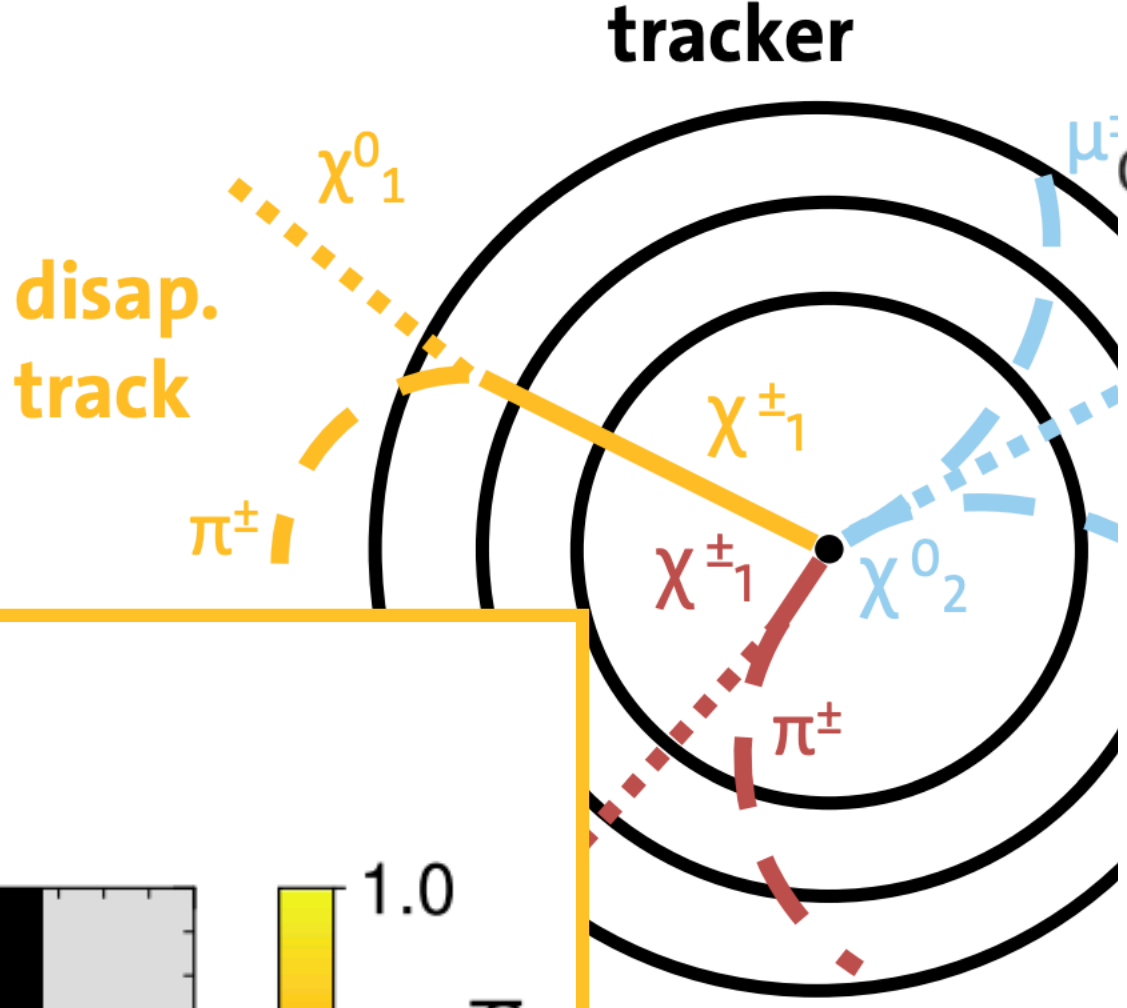
Eur. Phys. J. C 81 (2021) 1118 - 3L

3L (offshell)	11	2	7	2	2	6
3L (onshell)	30	90	0.2	0	0	15
4L	0	0.3	0	10	0.2	0
Disappearing Track	2	5	0	3	0.9	0
ATLAS m(A)	39	89	17	0	0	0.1
ATLAS BR($H \rightarrow \text{inv.}$)						

Percentage overlap

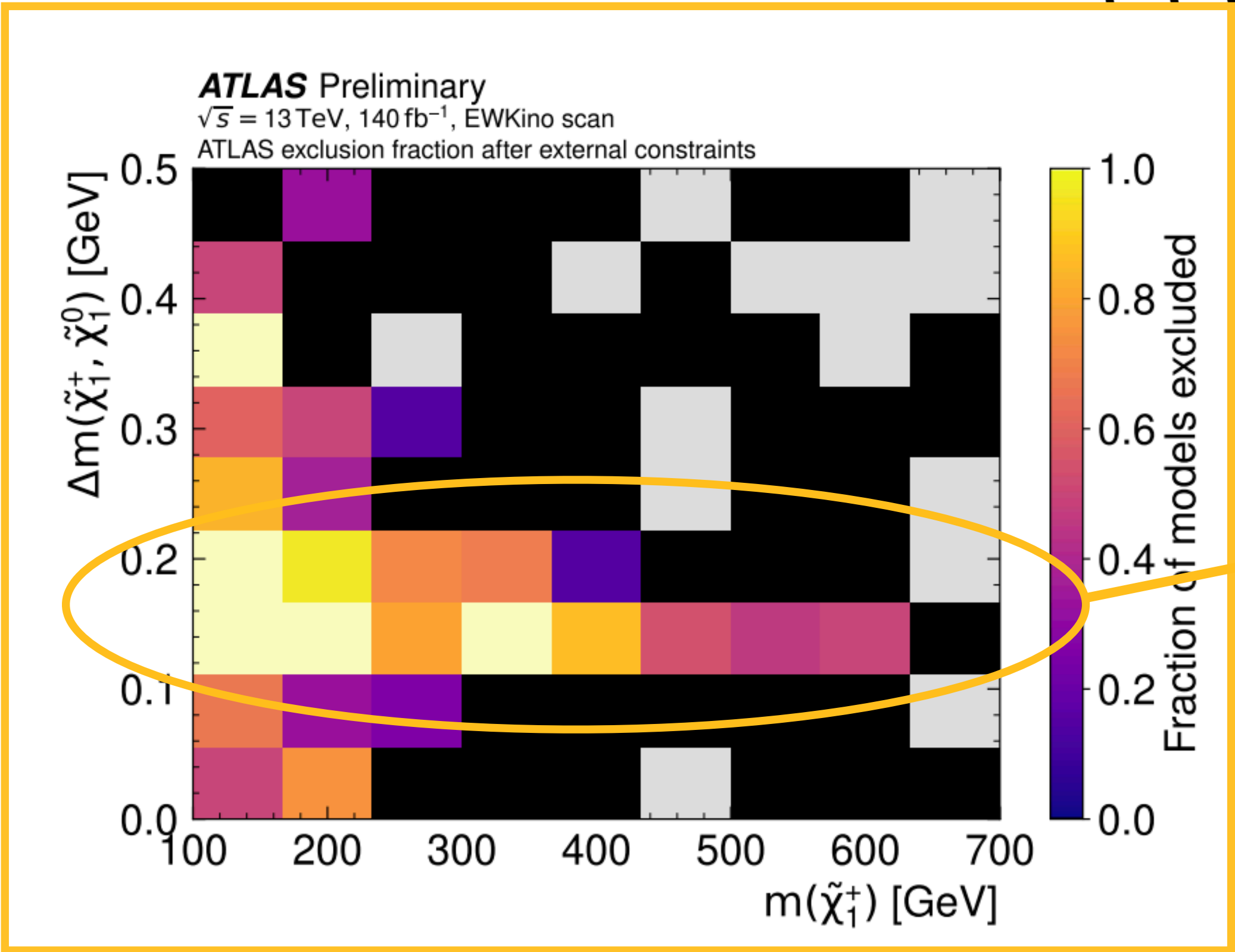
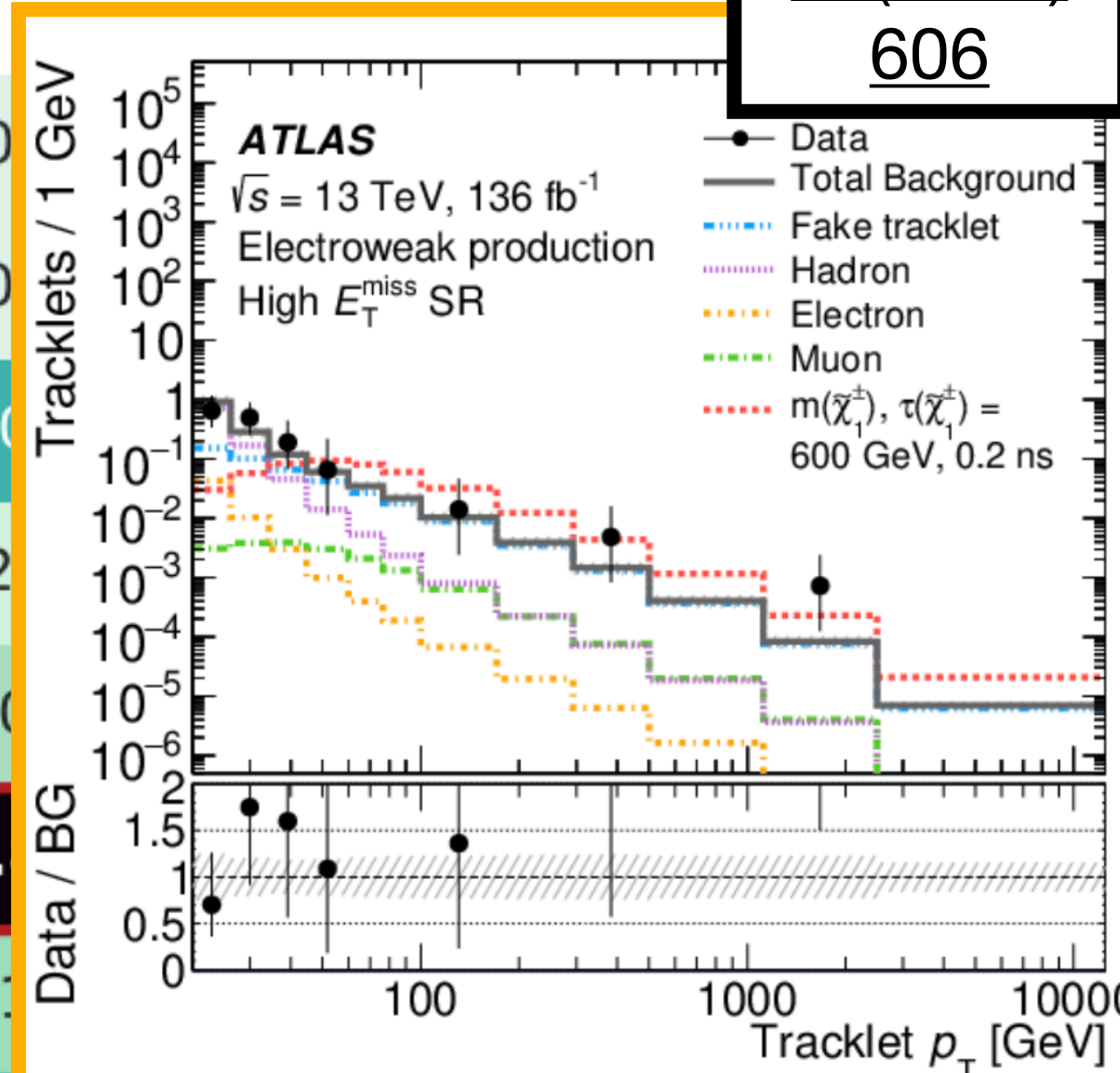
Analysis impact

- Disappearing track analysis brings vast exclusion
- Half of wino-like LSP models excluded



ATLAS searches **18**

FullHad	4	5	2	0.9	22	0					
1Lbb	38	0.5	0	58	55	0					
Compressed	12	0	0.6	0	22	30					
2L0J	4	32	0	0.9	60	2					
2L2J	21	7	3	13	4	10					
3L (offshell)	0	0	23	2	48	0.1					
3L (onshell)	5	9	3	28	56	15					
4L	0	0	0	5	50	30	90	0.2	0	0	15
Disappearing Track	6	0	0	0	3	0	0.3	0	10	0.2	0
ATLAS m(A)	0.9	0	0.9	0	6	2	5	0	3	0.9	0
ATLAS BR(H → inv.)	0	0	0	0	72	39	89	17	0	0	0.1
FullHad		1Lbb	Compressed	2L0J	2L2J	3L (offshell)	3L (onshell)	4L	Disappearing Track	ATLAS m(A)	ATLAS BR(H → inv.)

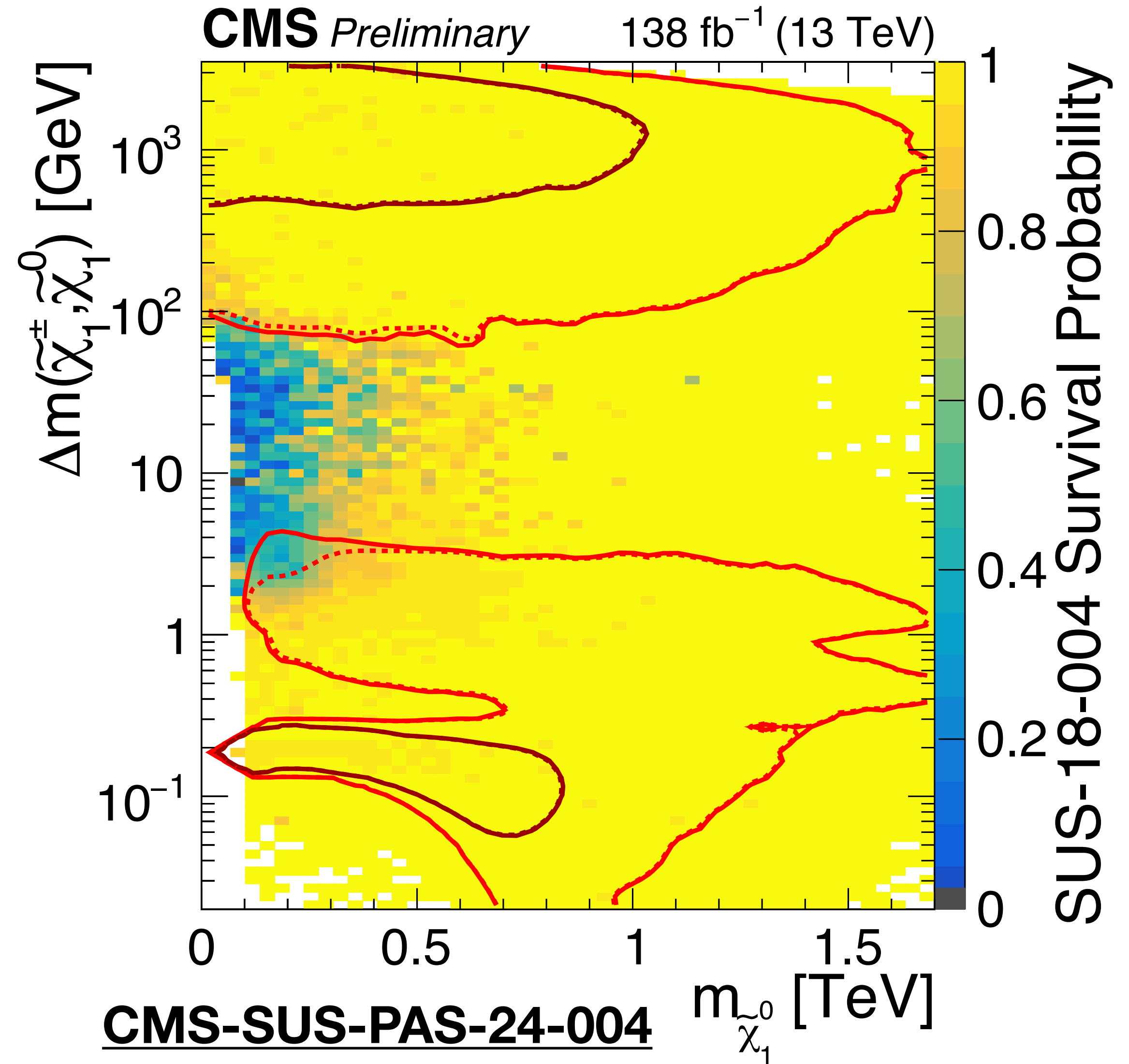
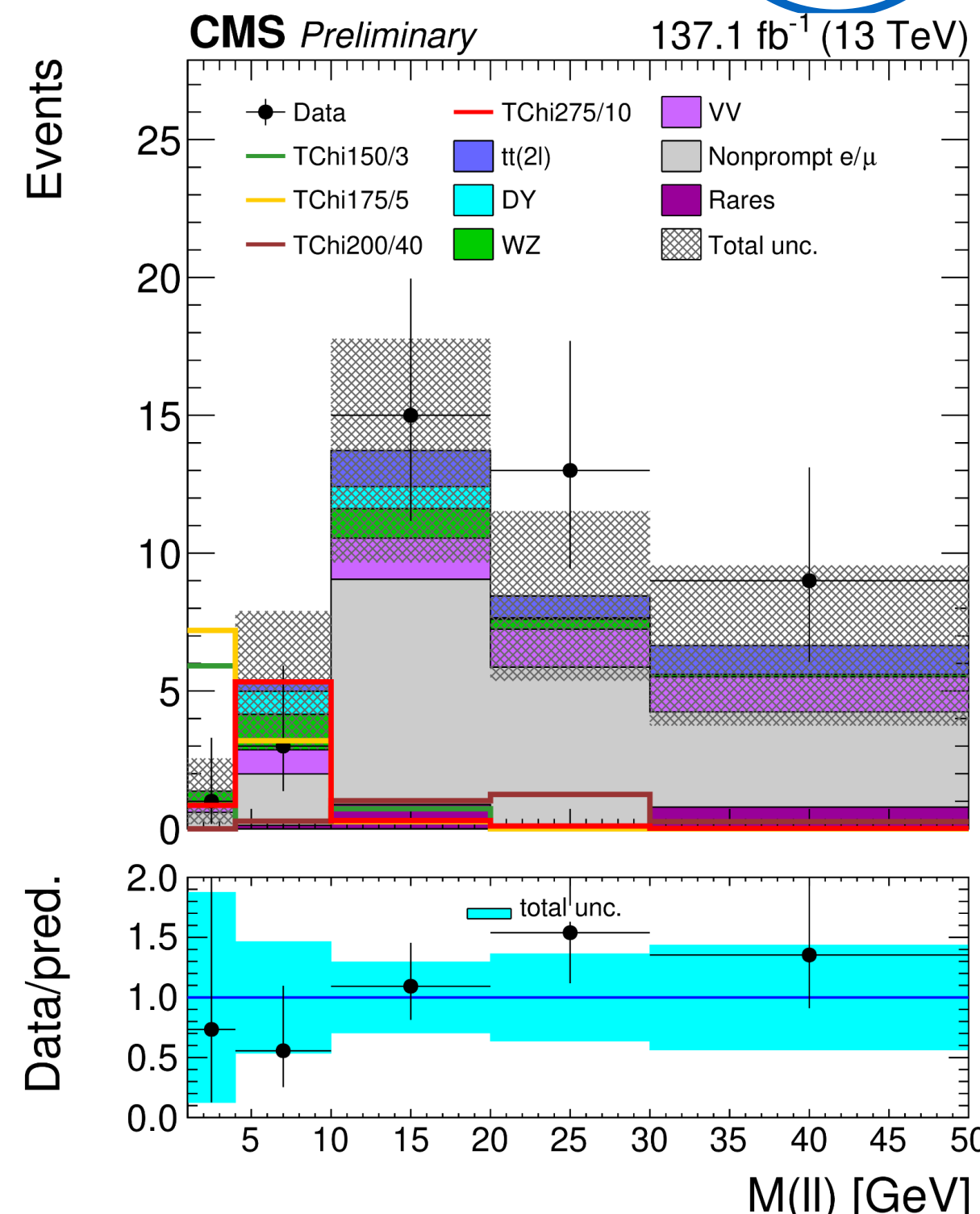
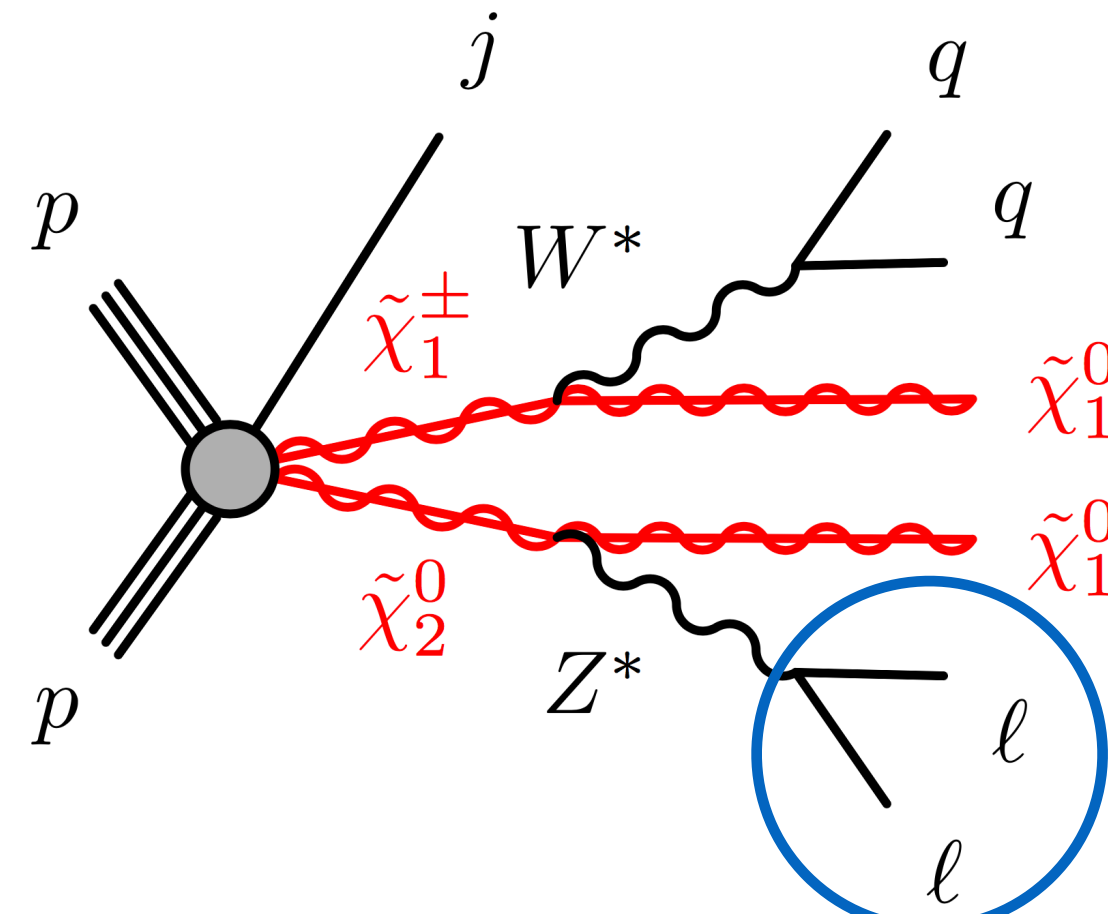


JHEP 05 (2024) 106

pMSSM impact, analysis sequence

Soft opposite-sign lepton
[JHEP 2204 \(2022\) pp.091](#)

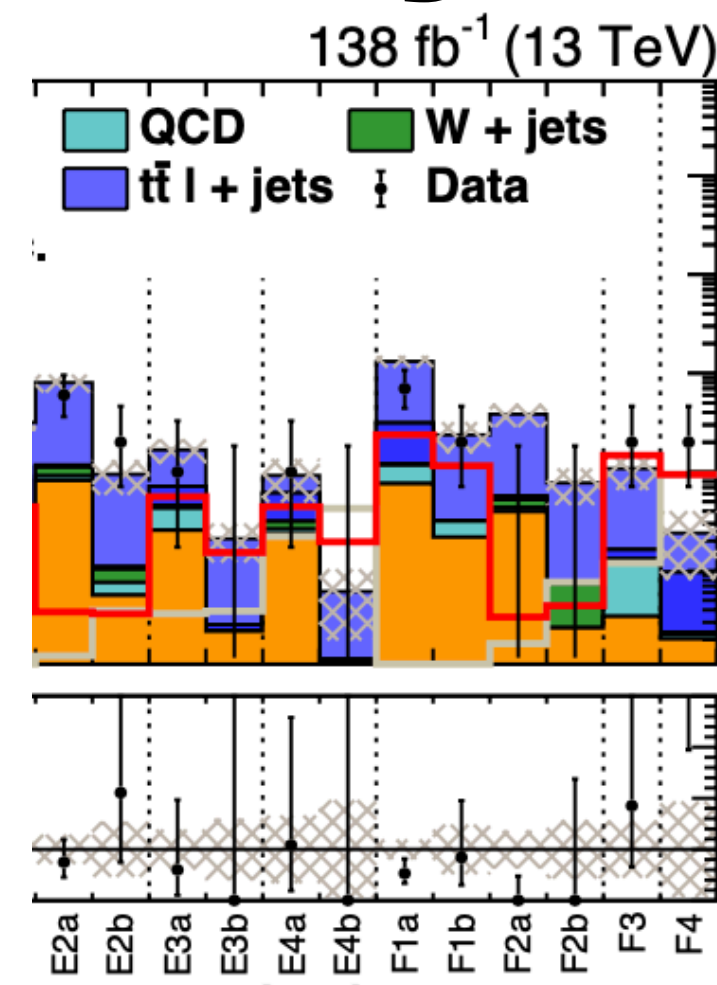
- 2- or 3 soft leptons
- OSSF pair
- $\geq 2\ell$ with $p_T > 3$ GeV
- ISR jet
- Binning in invariant mass $M(\ell\ell)$



pMSSM impact, analysis sequence

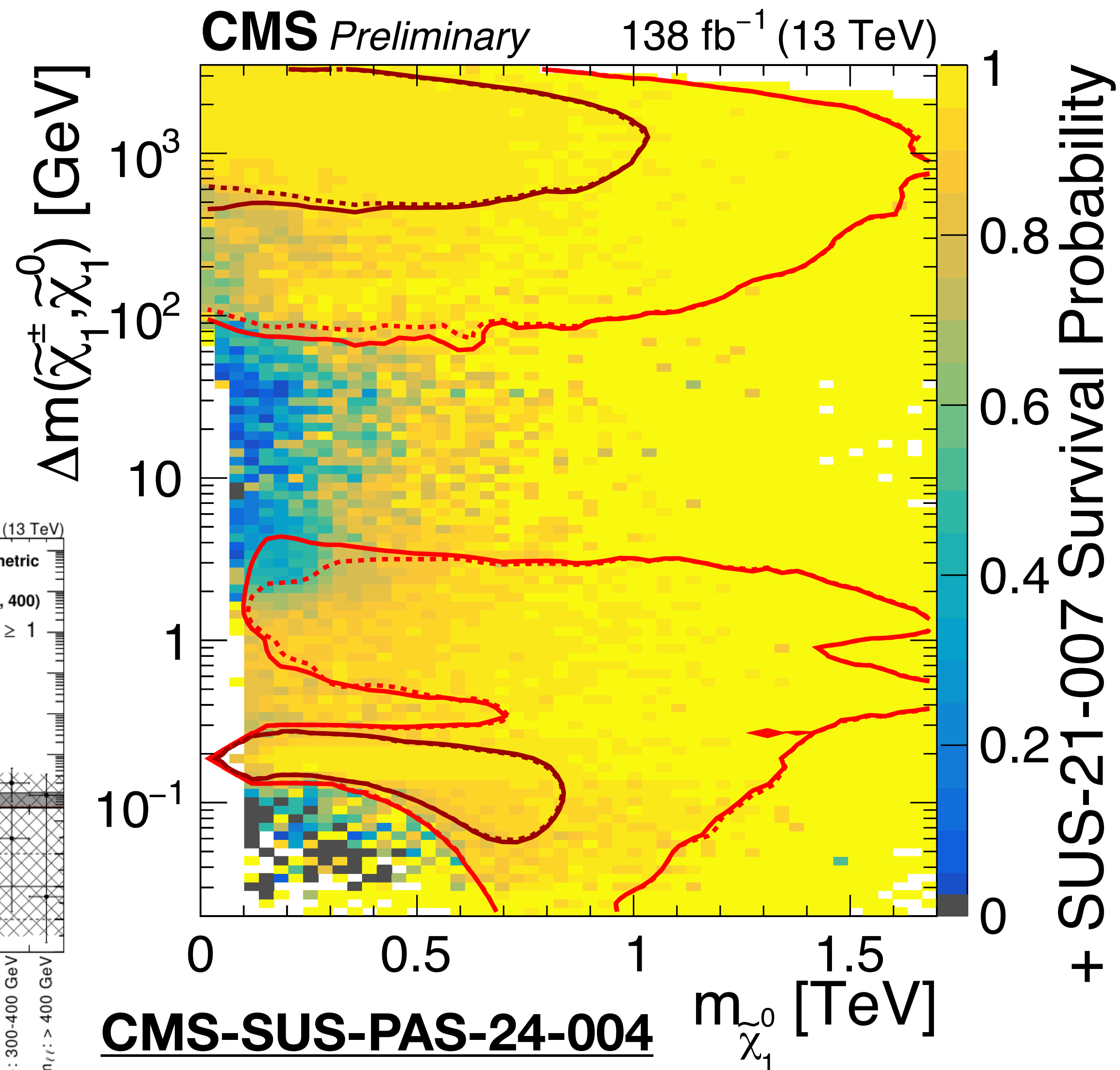
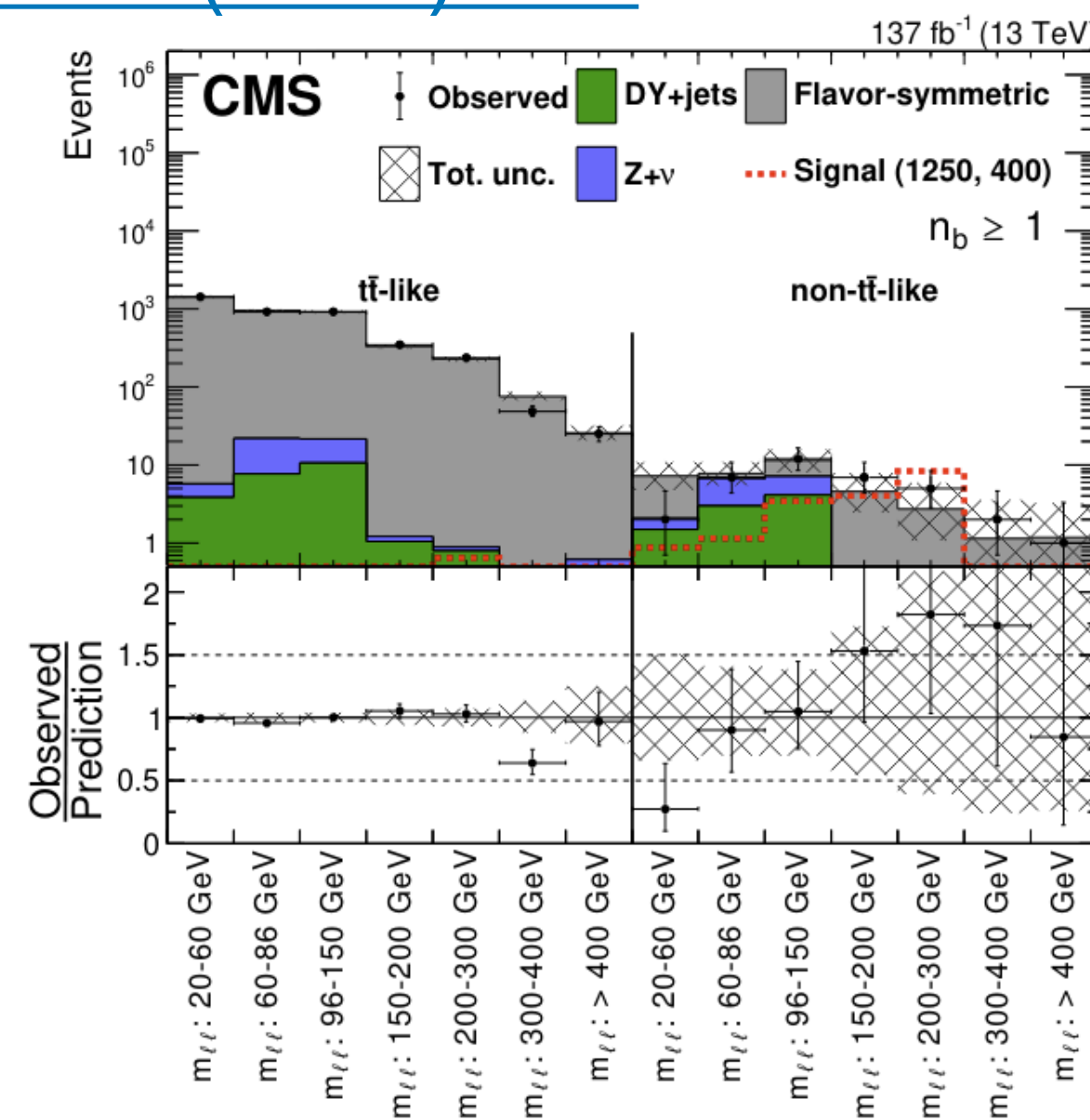
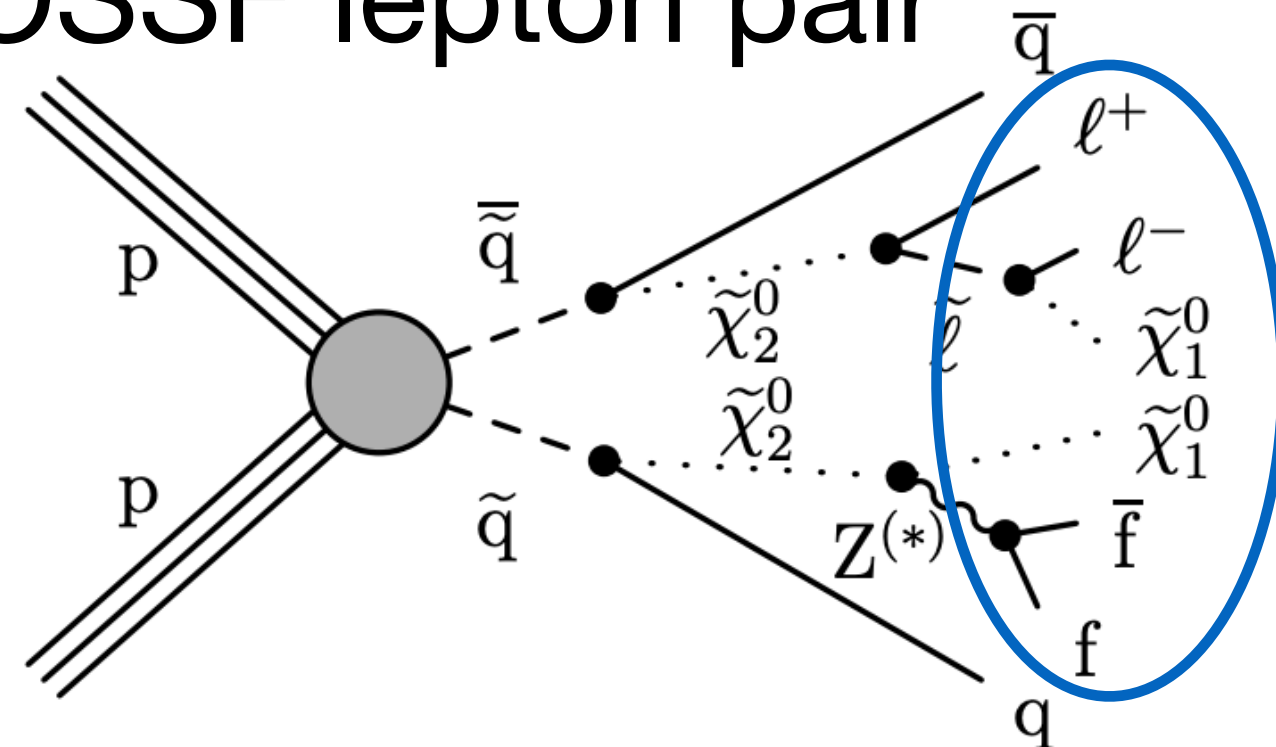
+Single-lepton, Delta-phi
[JHEP 09 \(2023\) 149](#)

- Requires exactly 1 lepton
- Ele or Mu with $p_T > 25$ GeV



+Opposite-charge lepton [JHEP 04 \(2021\) 123](#)

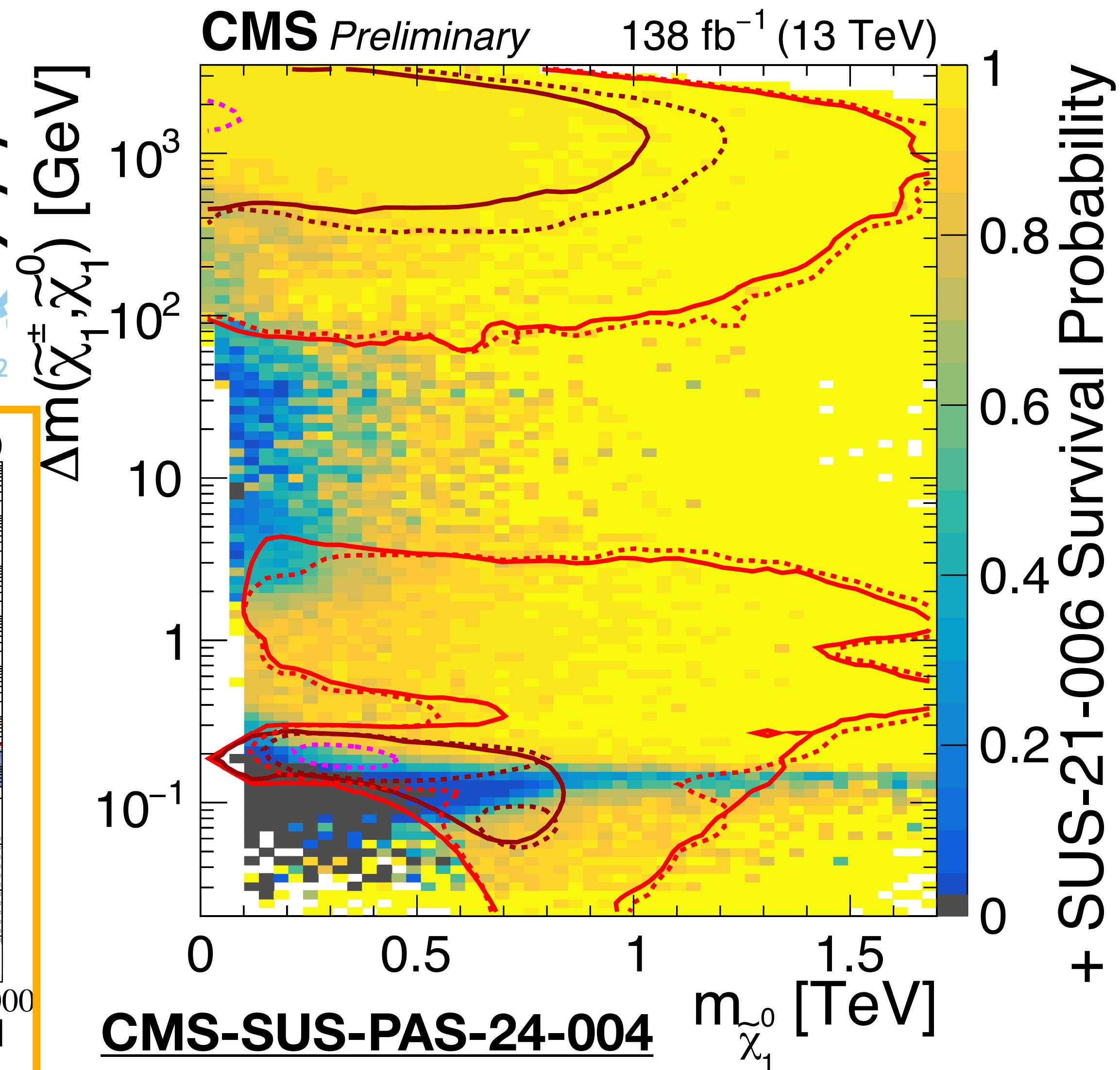
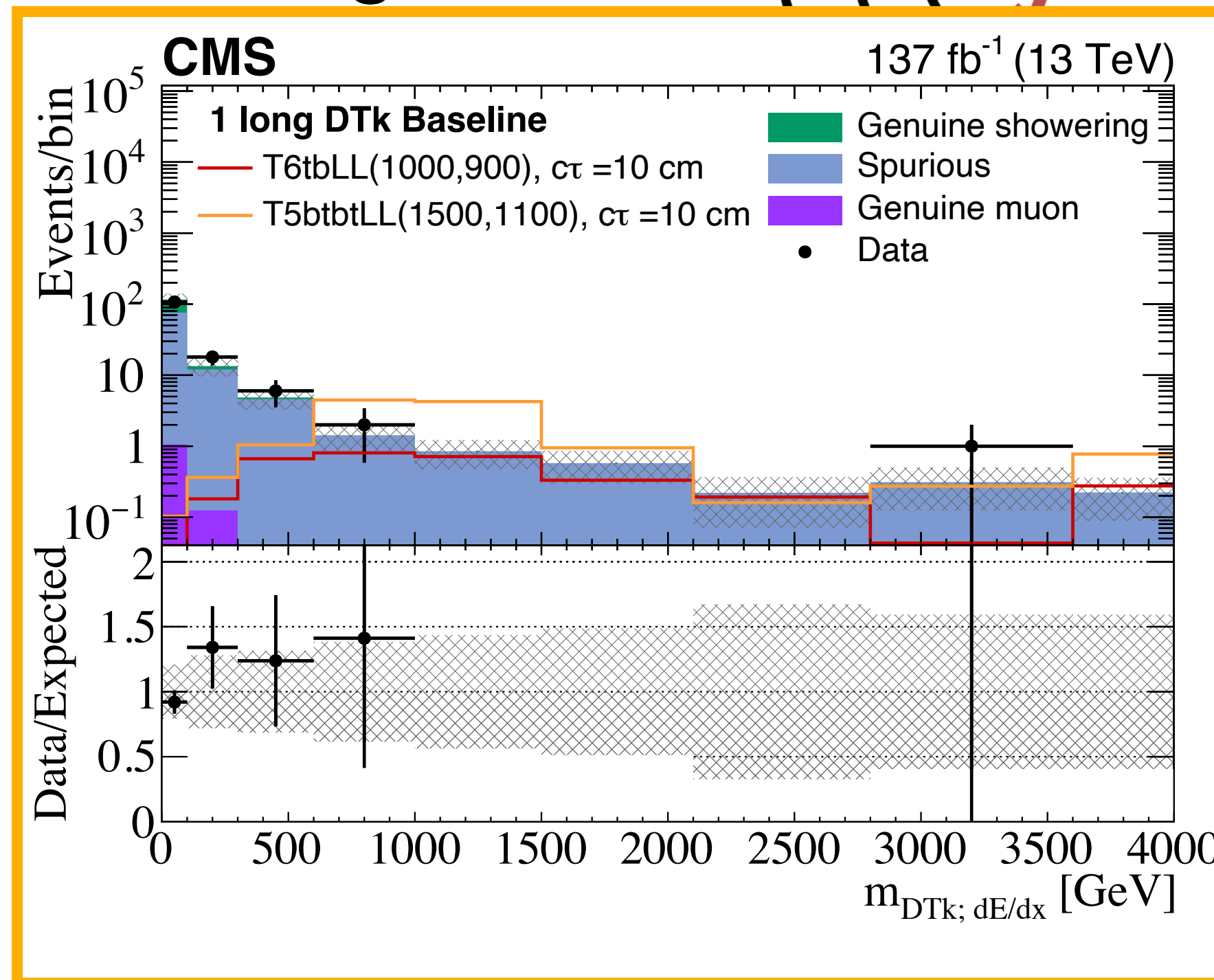
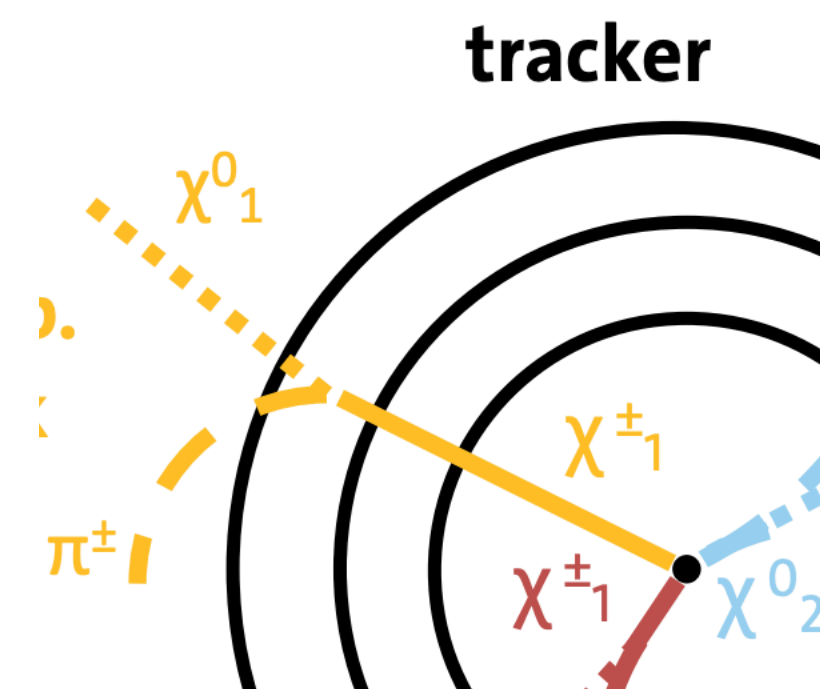
- 2 high- p_T leptons
- OSSF lepton pair



pMSSM impact, analysis sequence

+SUSY disappearing track
[Phys. Rev. D 109 \(2024\) 072007](#)

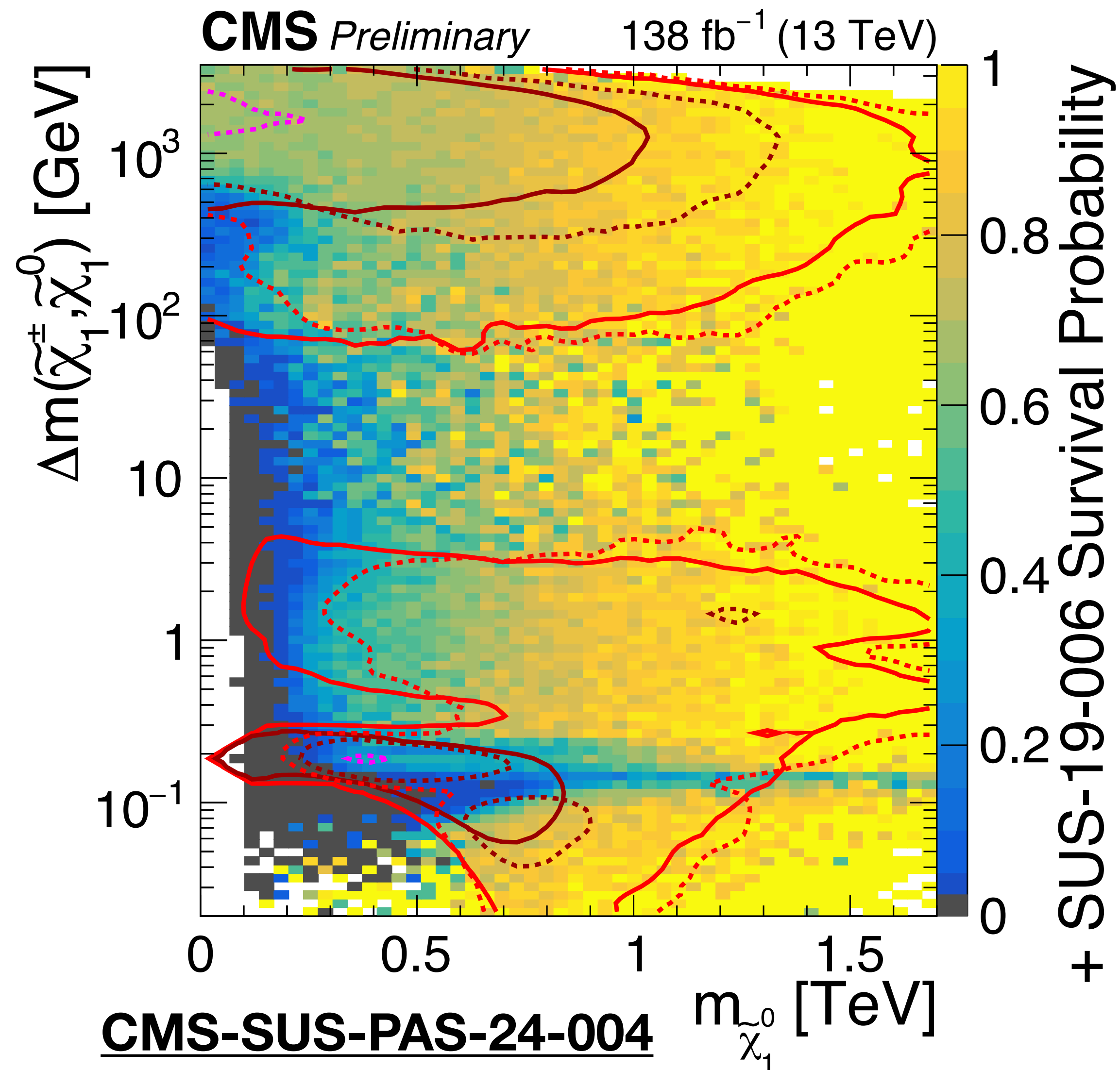
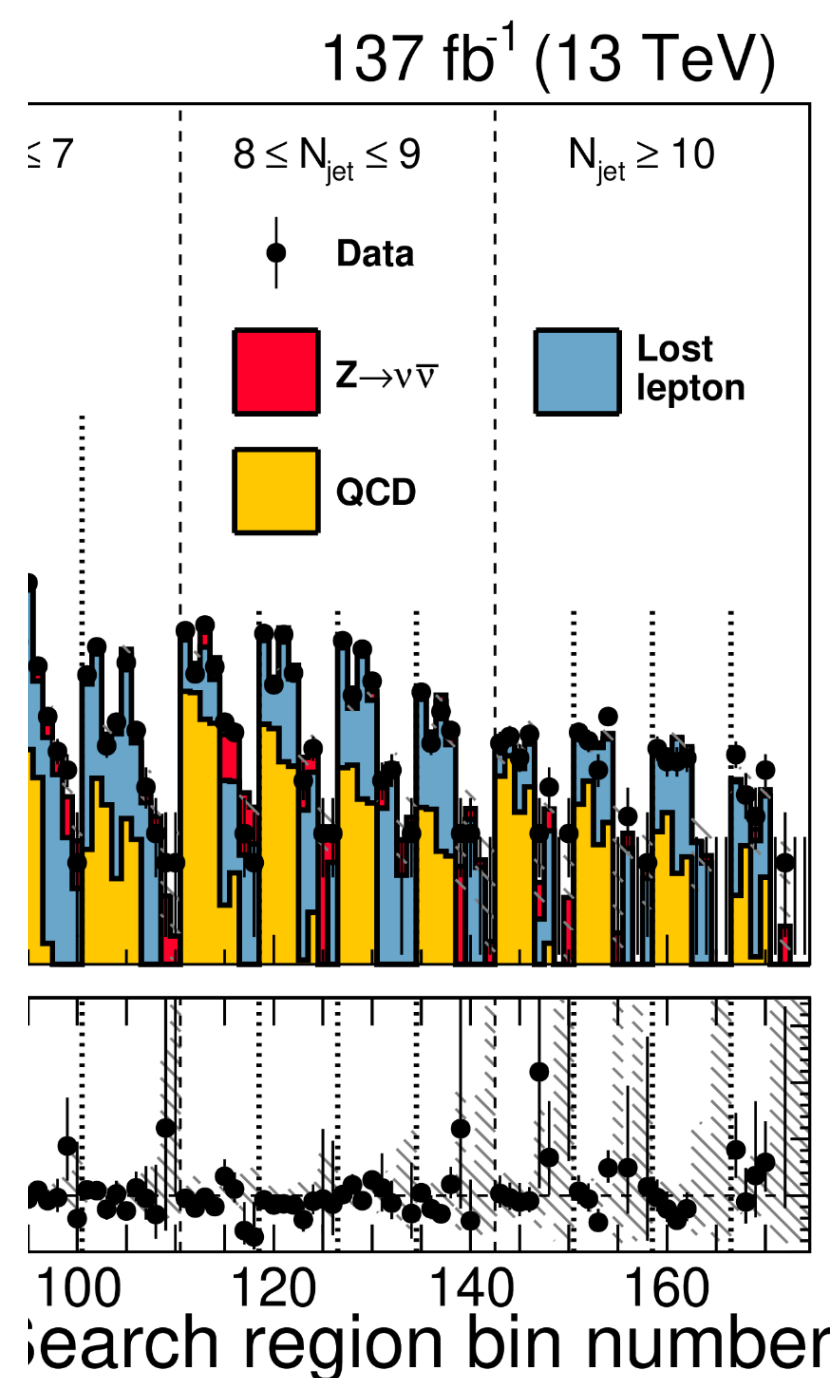
- ≥ 1 disappearing tracks
- 0, 1 leptons; 0, >0 b-tags
- long/short
- dE/dx binning



pMSSM impact, analysis sequence

+Zero-lepton, jets, MHT
[JHEP 10 \(2019\) 244](#)

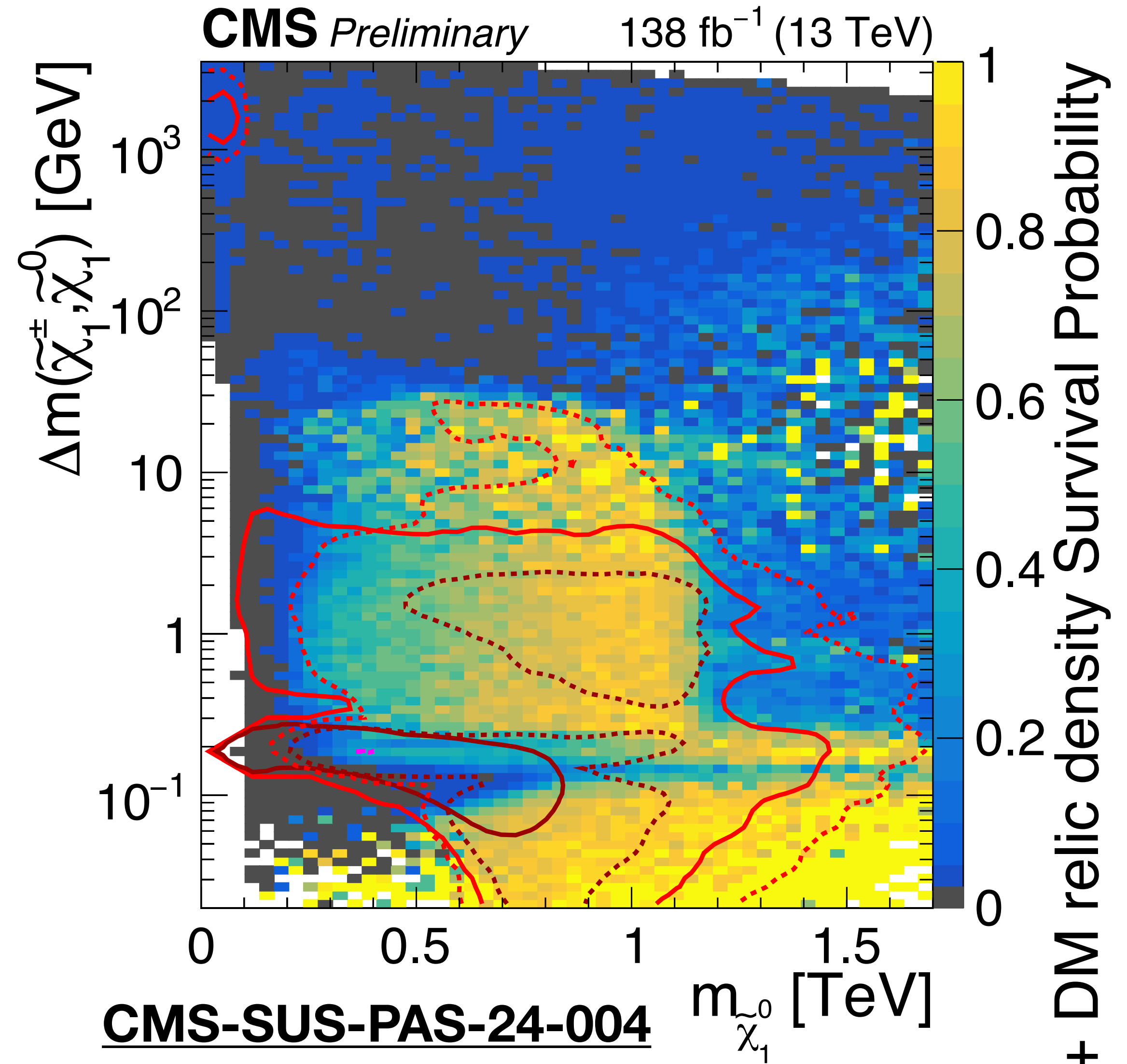
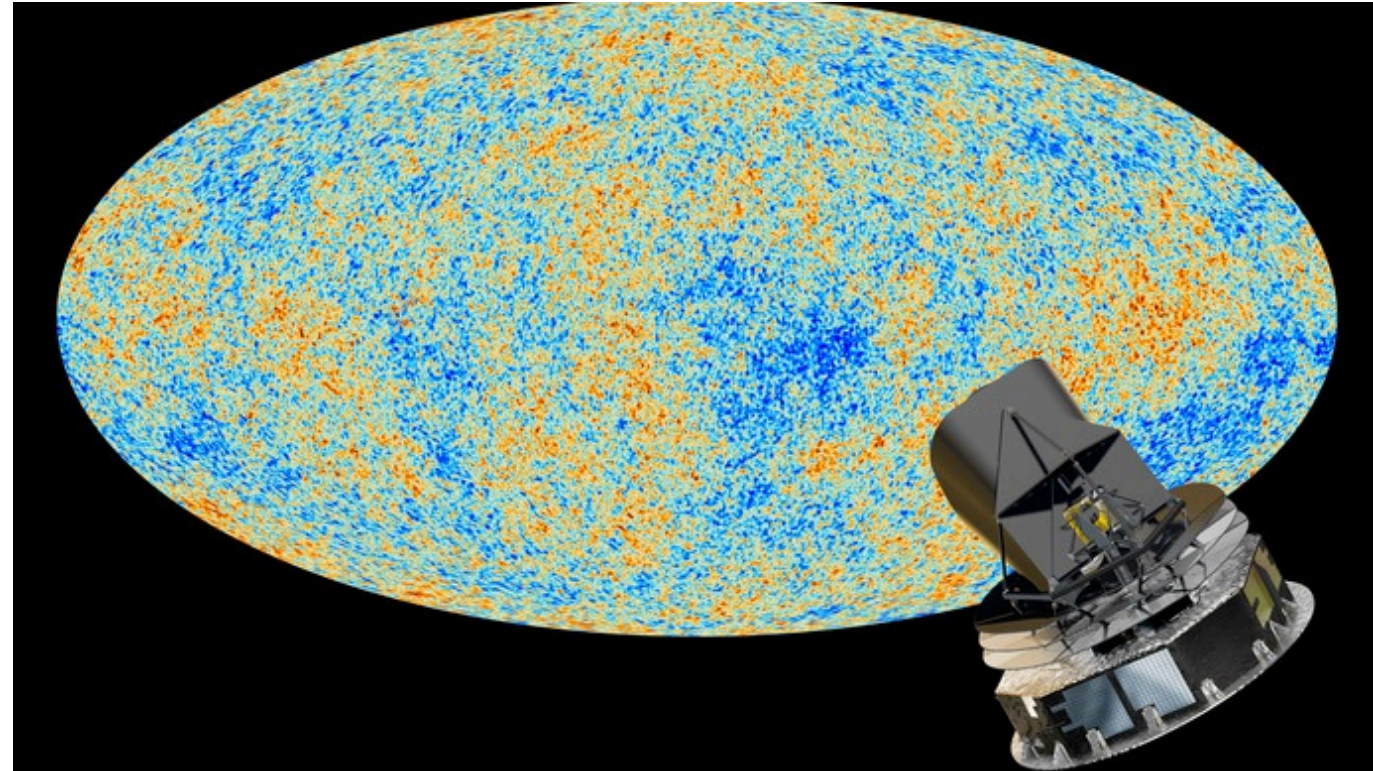
- Inclusive 0-lepton
 - Veto electron, muon candidates with $p_T > 5$ GeV
- > 1 ak4 jets
- 0, > 0 b-tagged jets
- Binning in MHT, HT, $n(\text{jets})$, nb



SUSY dark matter

+Relic density (Planck)

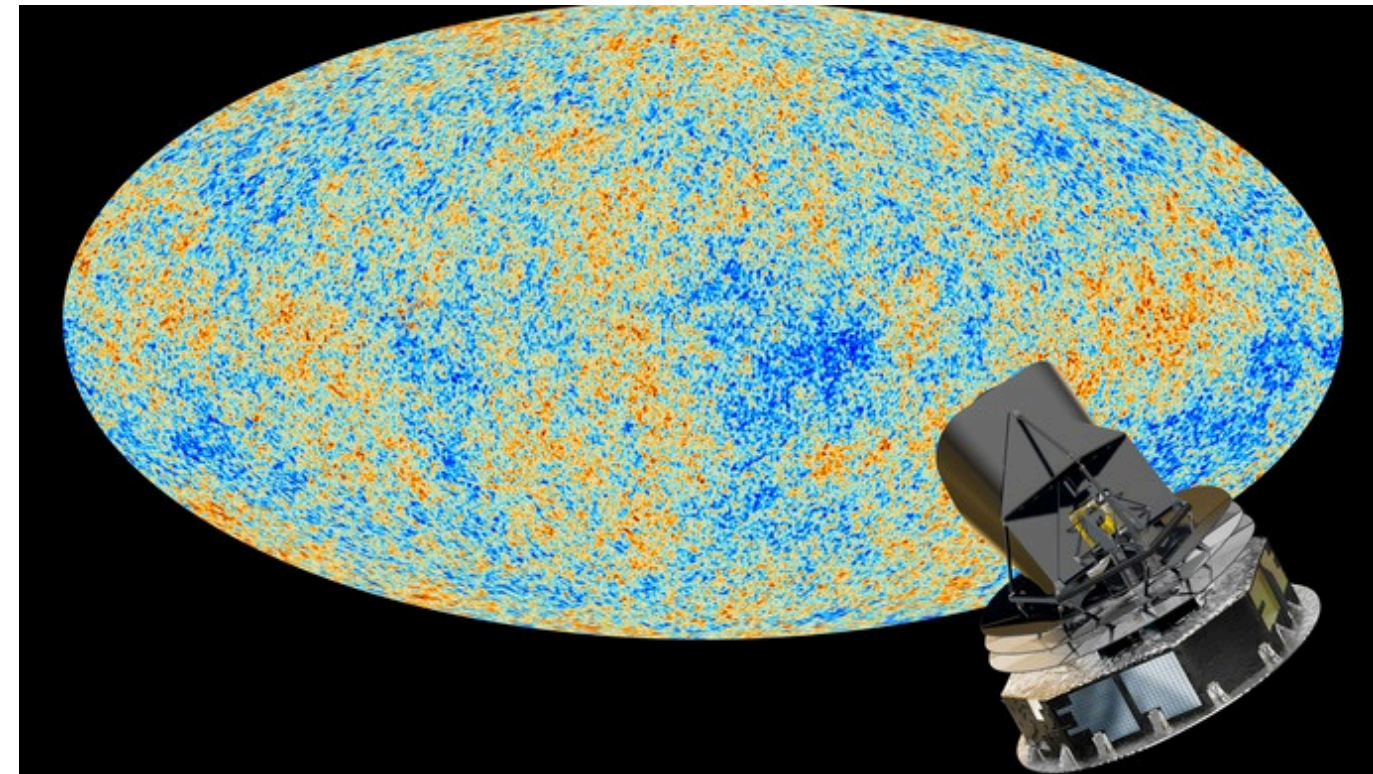
$$\Omega_h^2 < 0.12 * 1.1$$



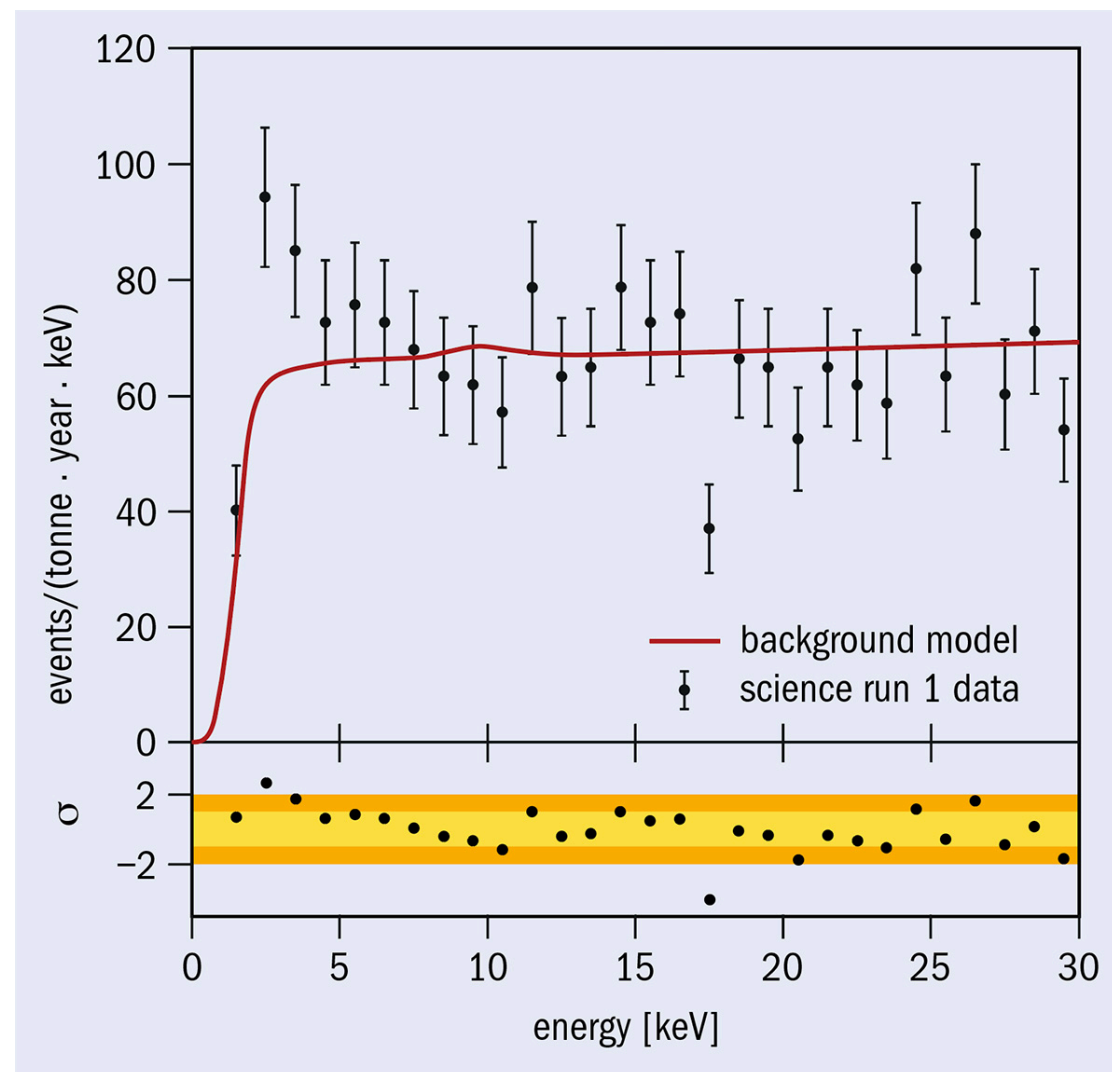
SUSY dark matter

+Relic density (Planck)

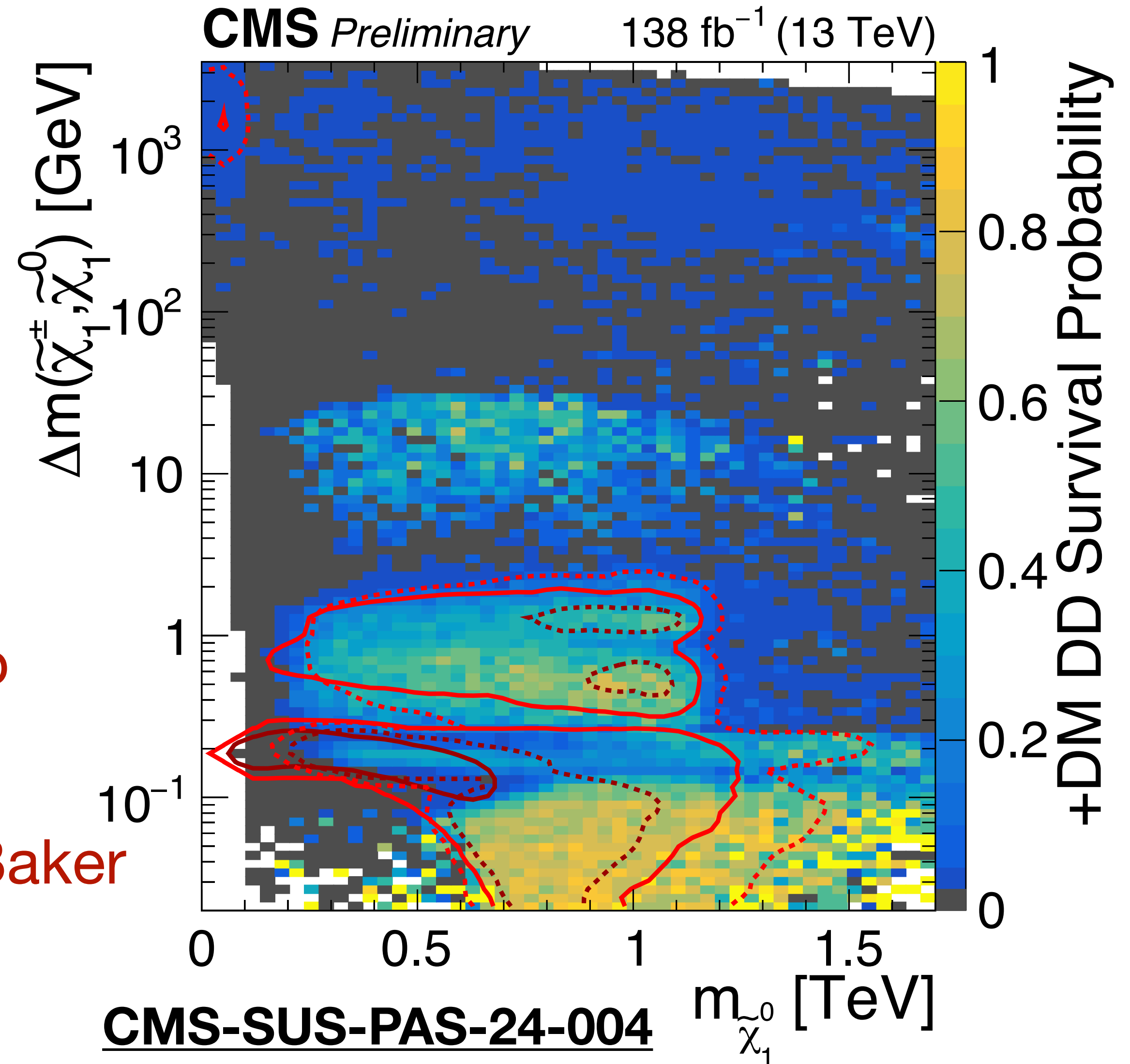
$$\Omega_h^2 < 0.12 * 1.1$$



+Direct-detection LZ(22)



Update with LZ24 to this! "Recent results from (LZ)" - talk on Wednesday Albert Baker

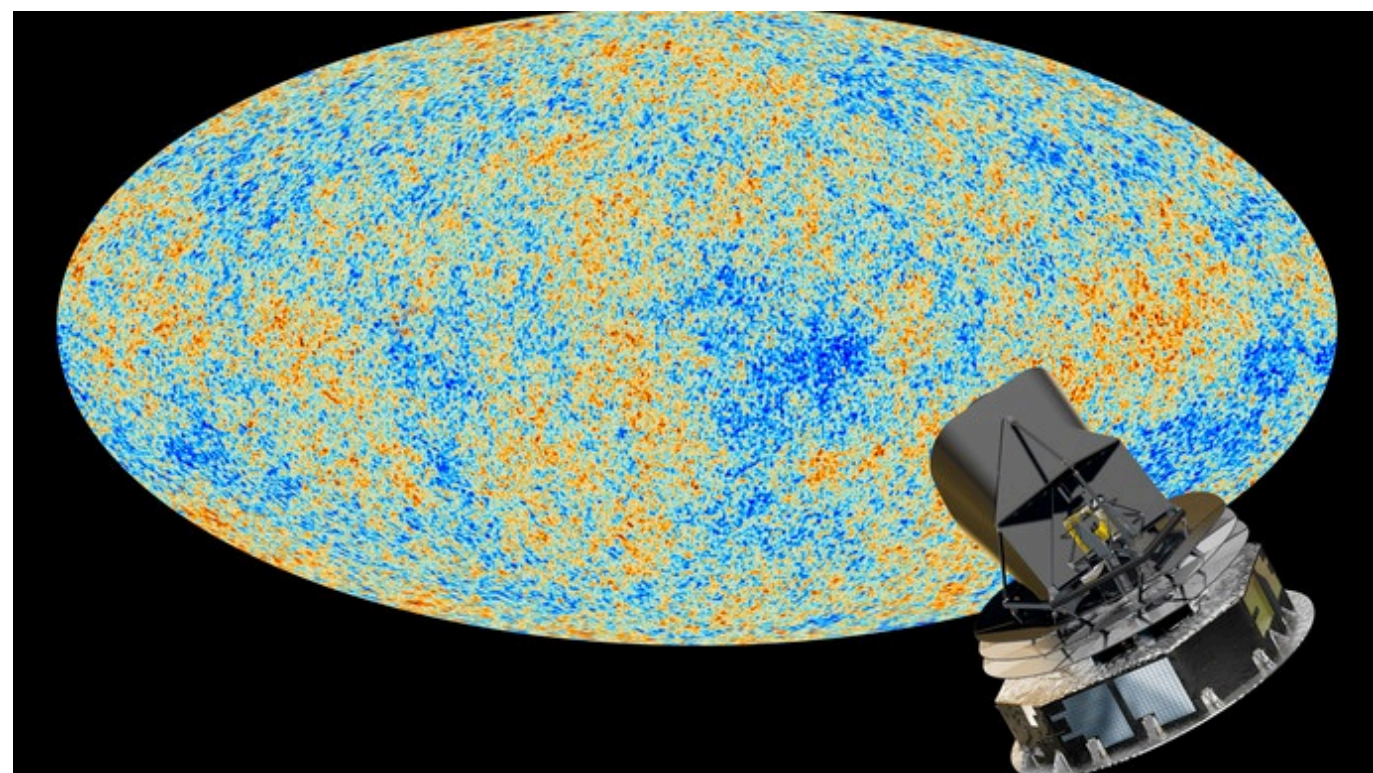


Natural SUSY dark matter

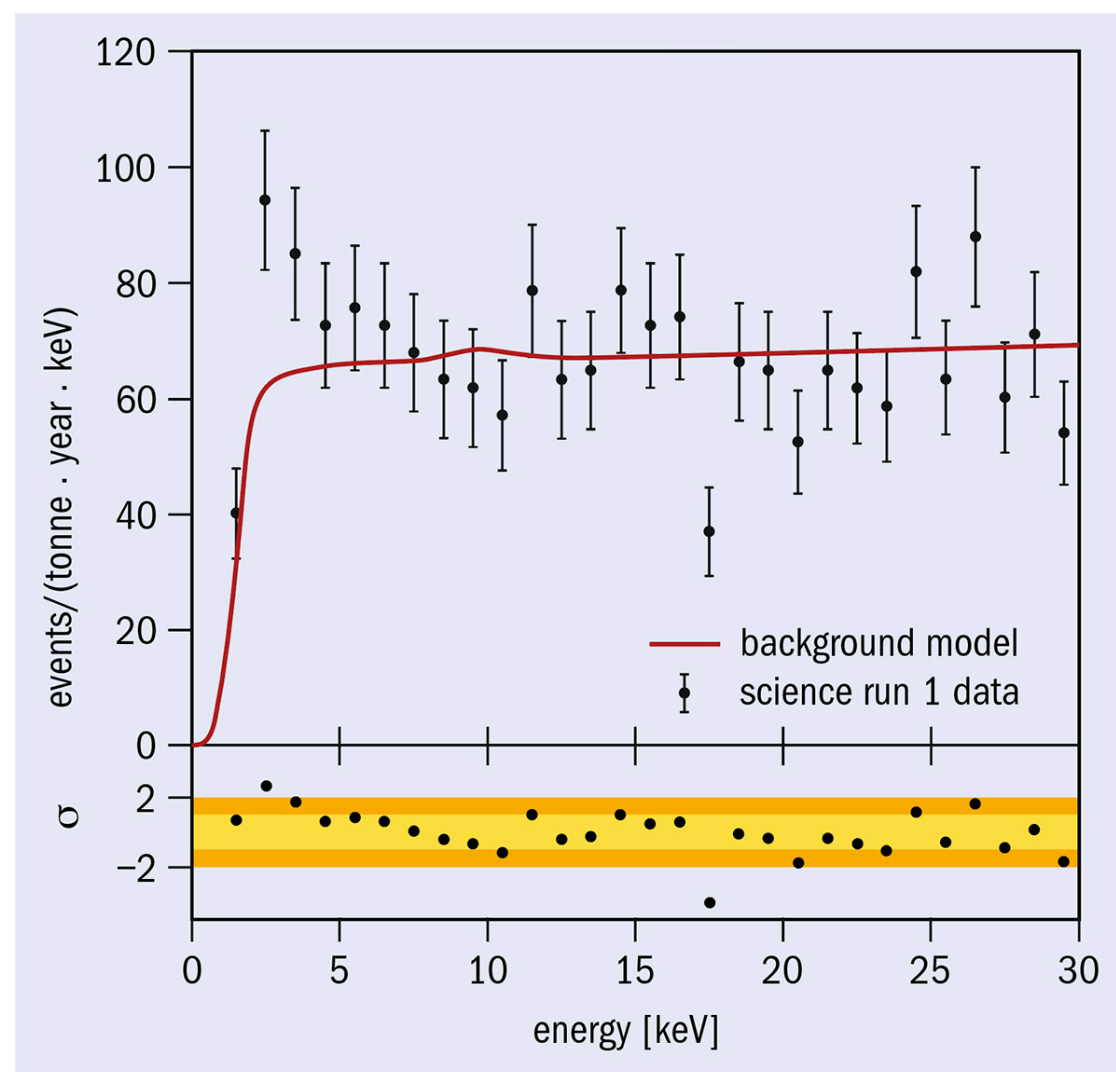
CMS-SUS-PAS-24-004

+Relic density (Planck)

$$\Omega_h^2 < 0.12 * 1.1$$



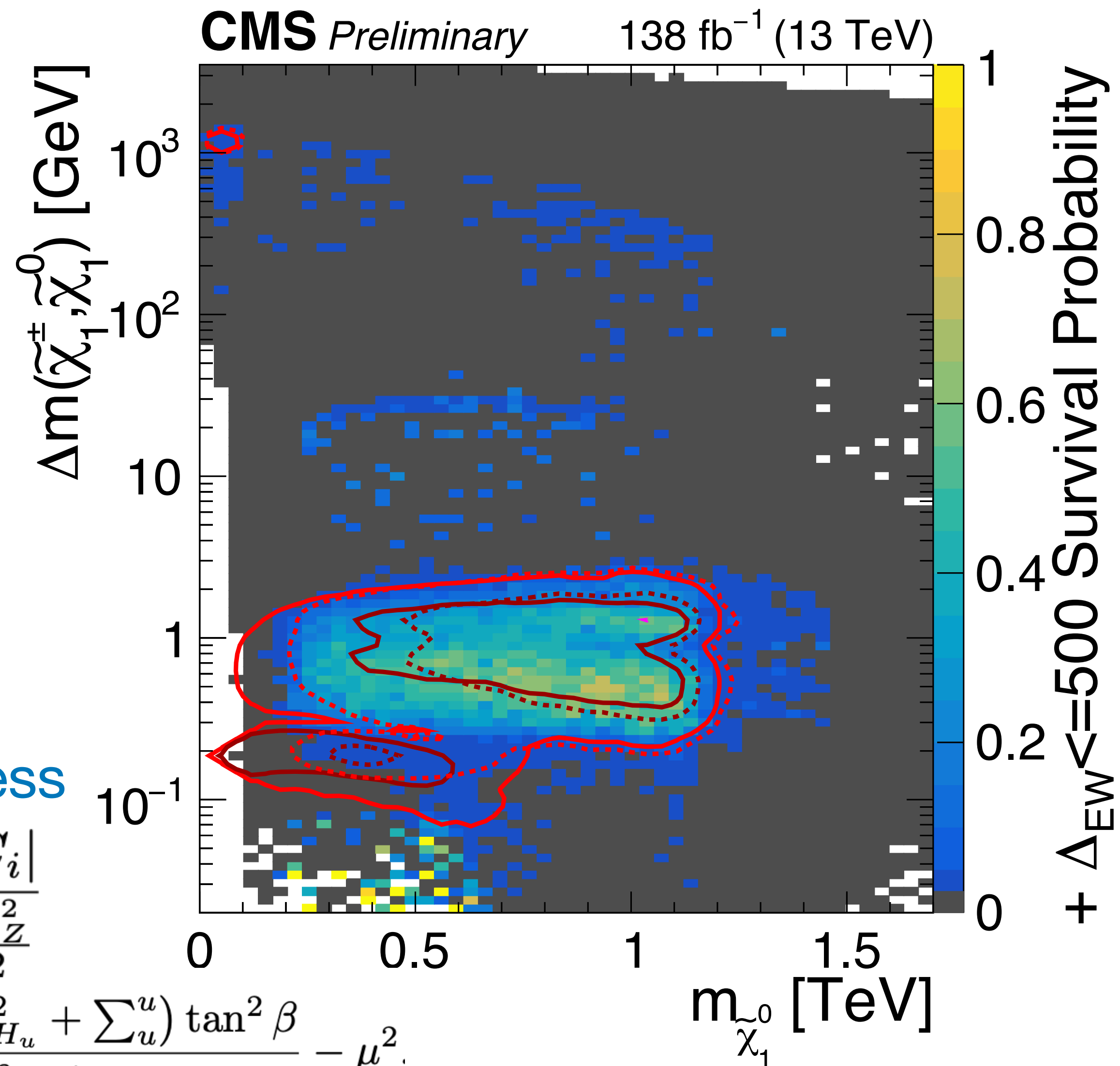
+Direct-detection LZ(22)



+Fine-tuning/naturalness

$$\Delta_{EW} = \max_i \frac{|C_i|}{\frac{m_Z^2}{2}}$$

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \sum_d^d - (m_{H_u}^2 + \sum_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2$$

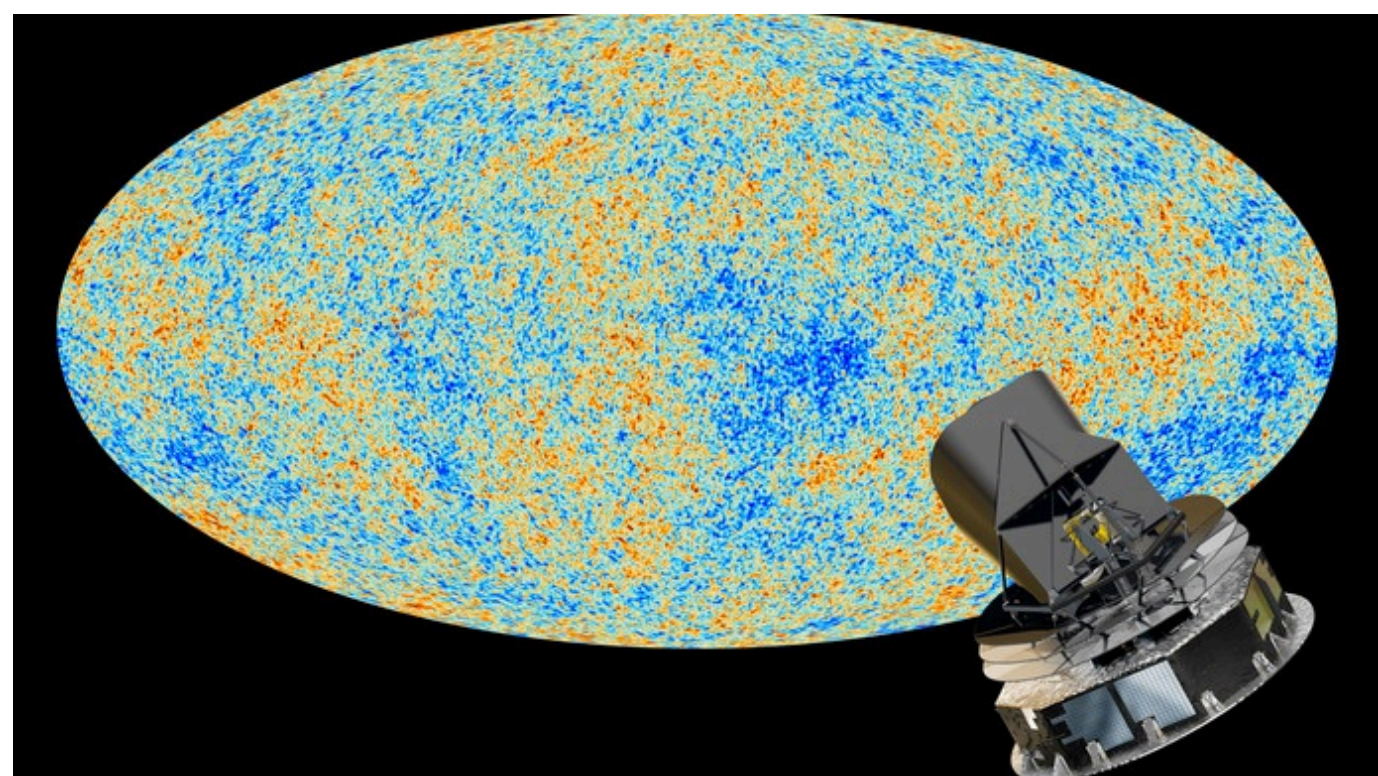


Natural SUSY dark matter

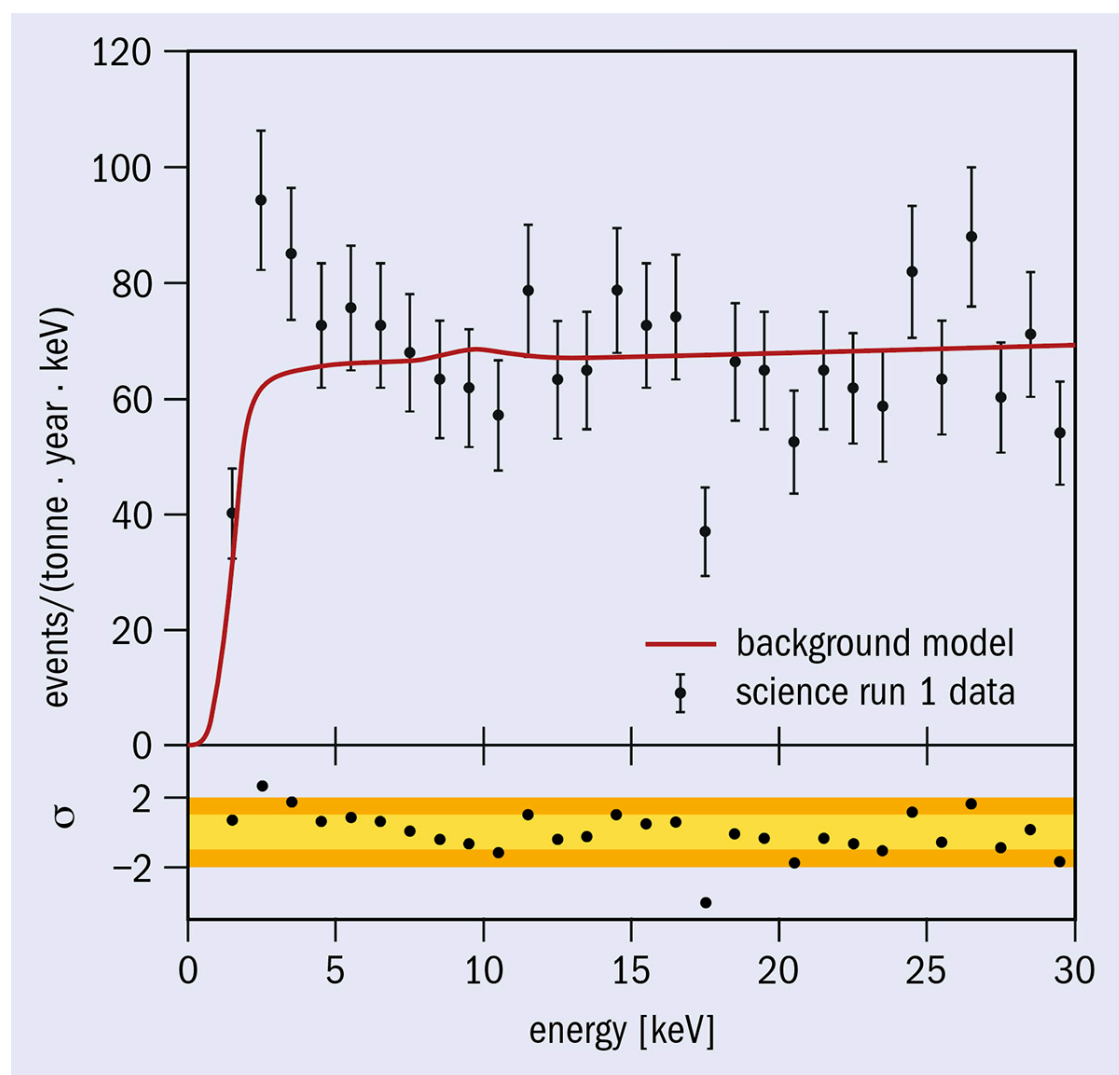
CMS-SUS-PAS-24-004

+Relic density (Planck)

$$\Omega_h^2 < 0.12 * 1.1$$



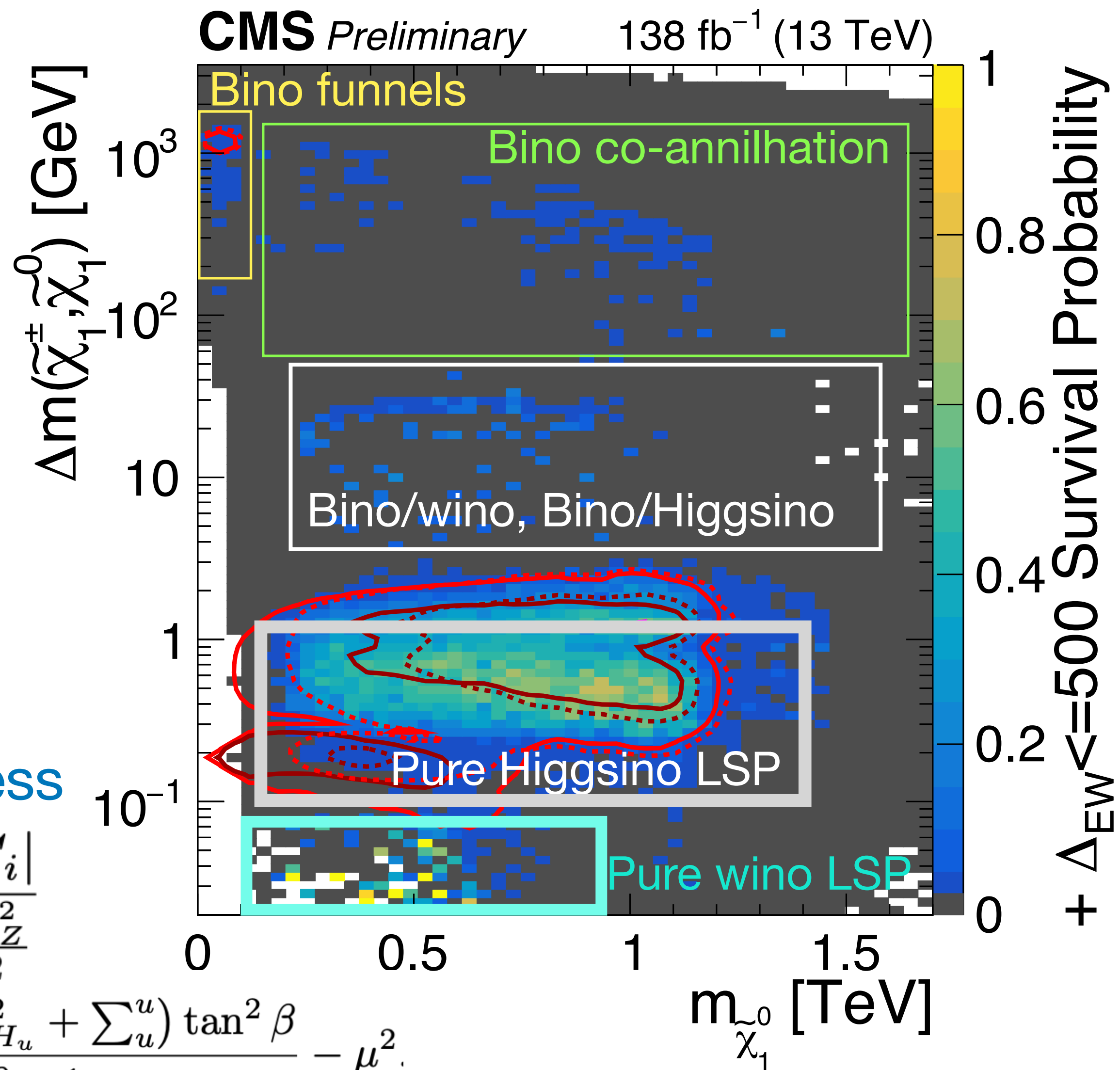
+Direct-detection LZ(22)



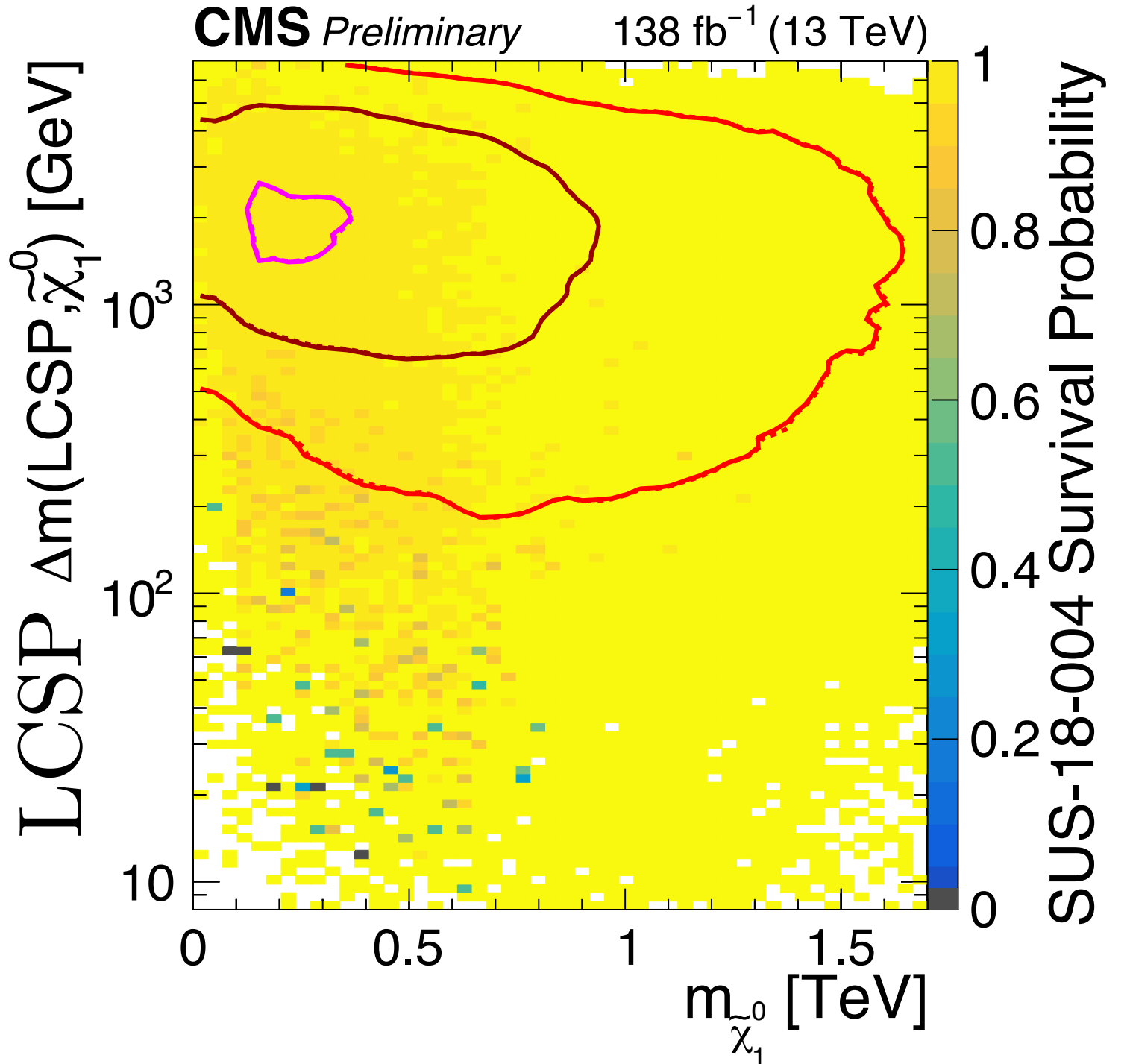
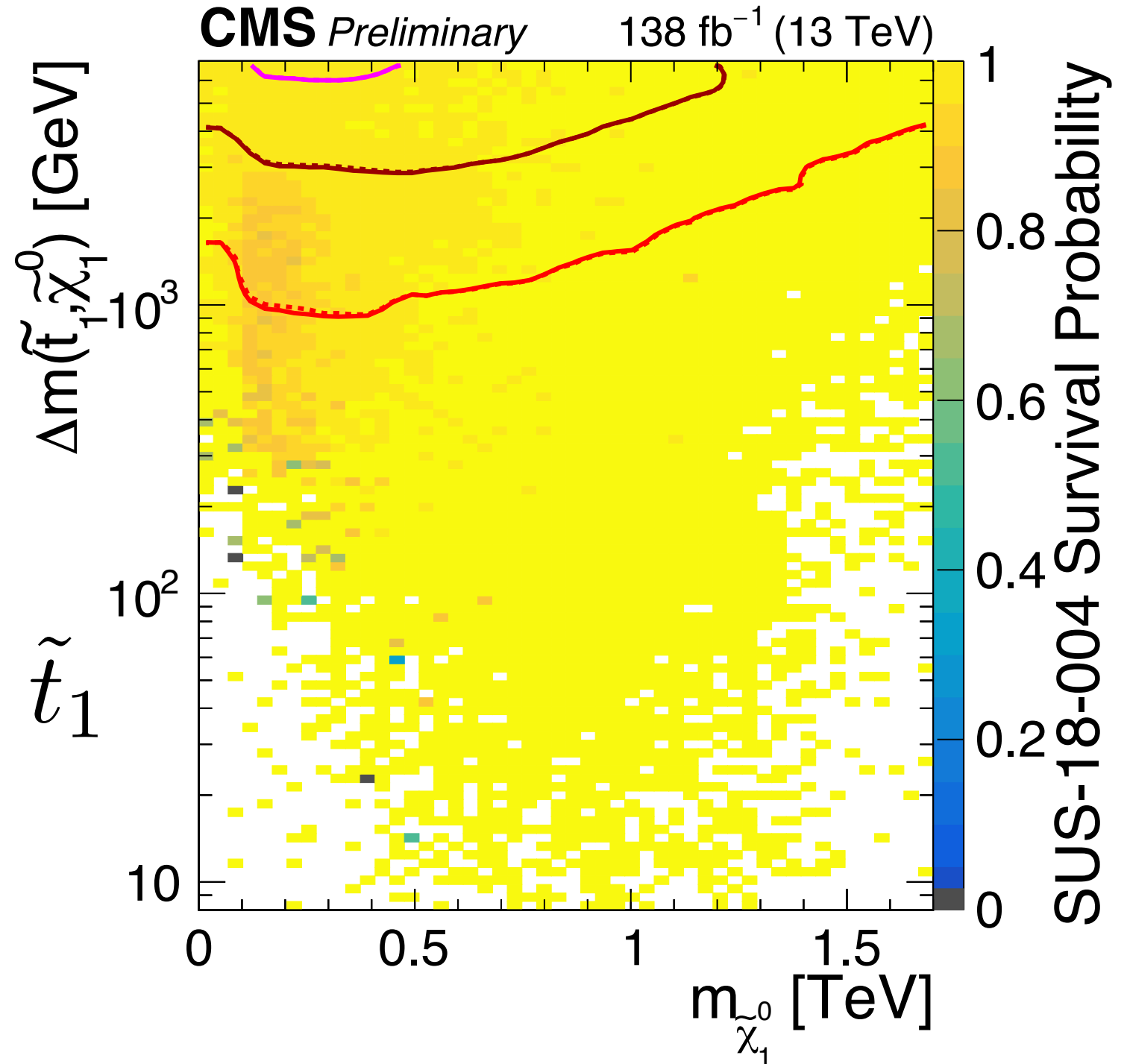
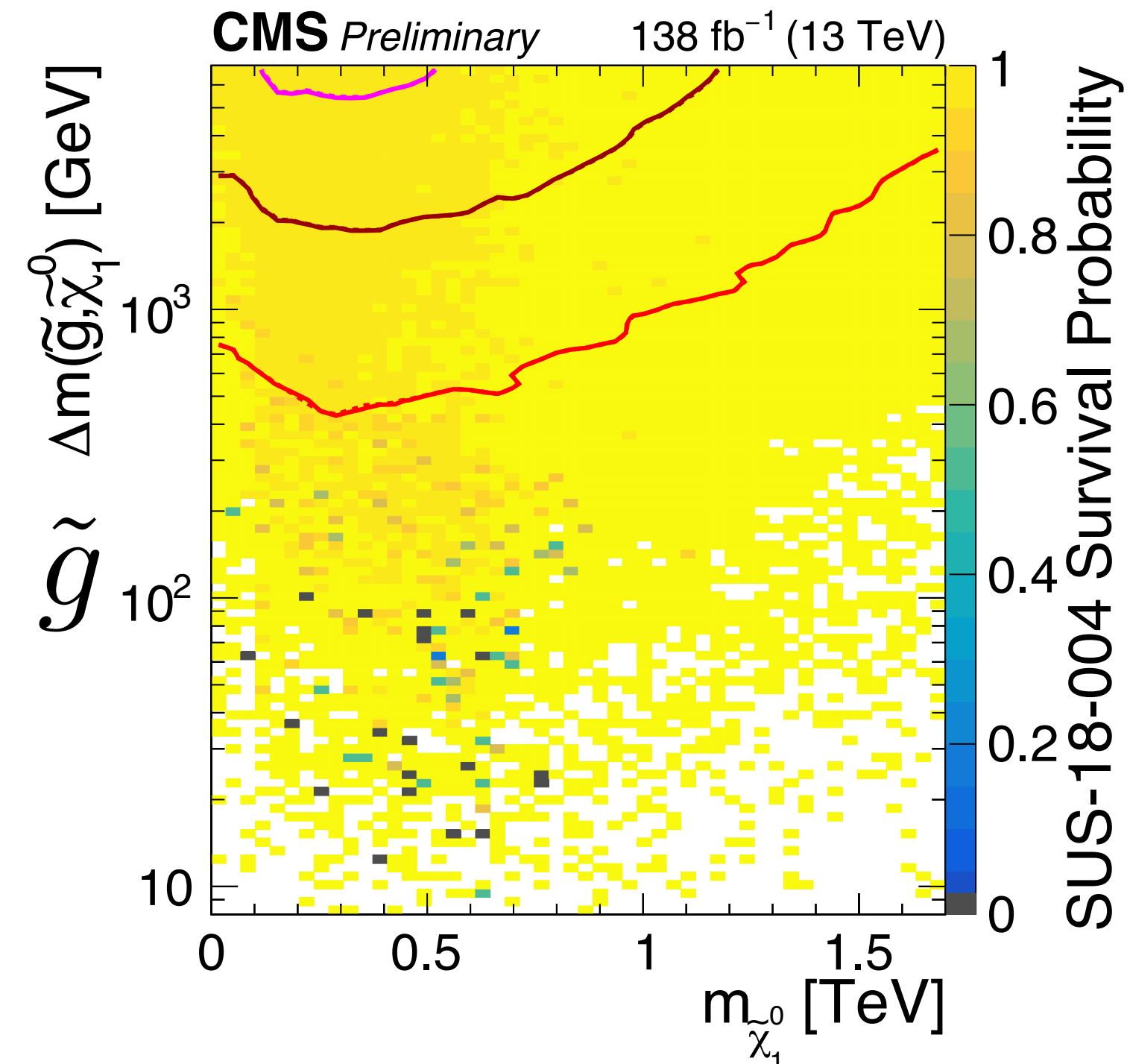
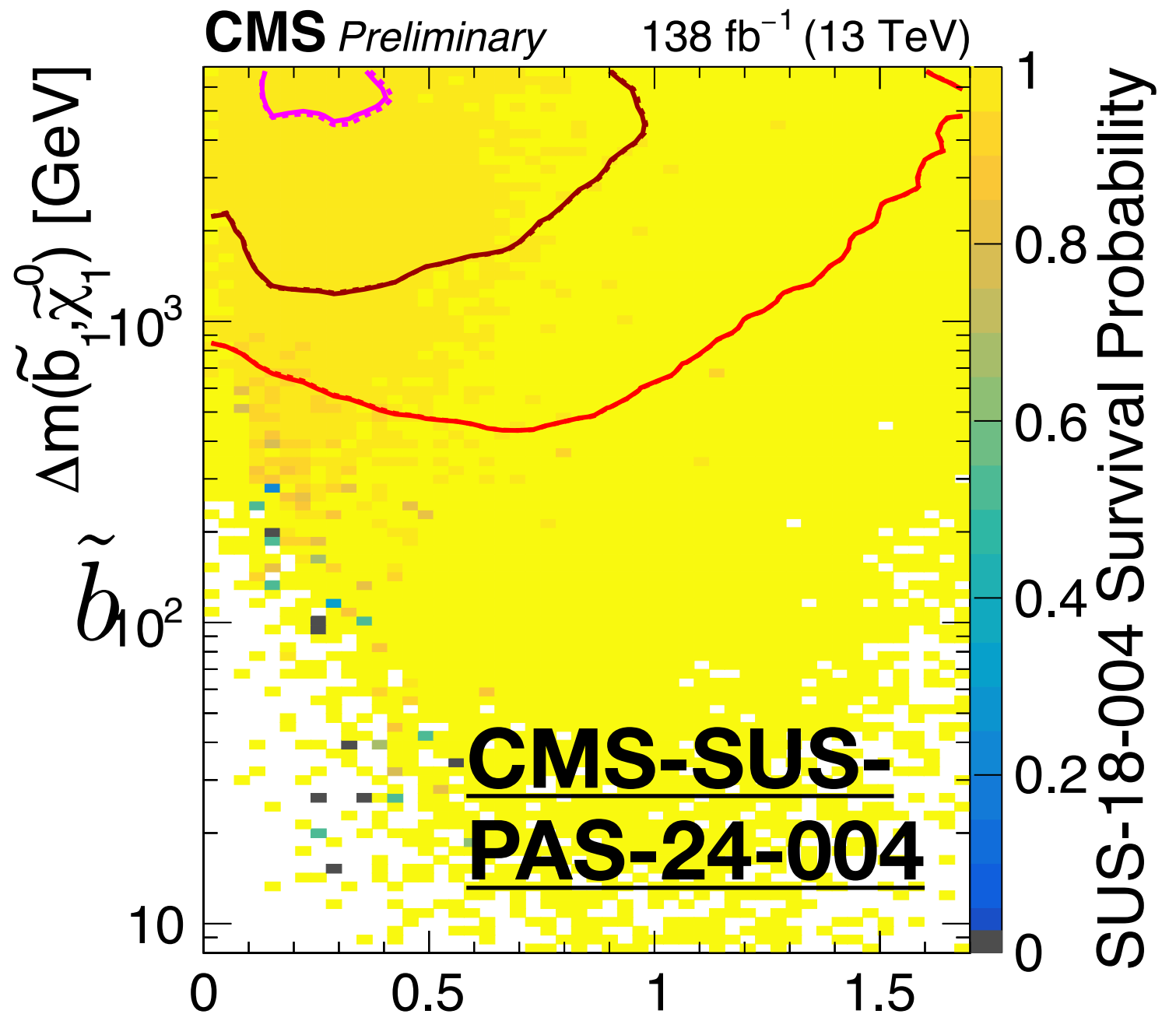
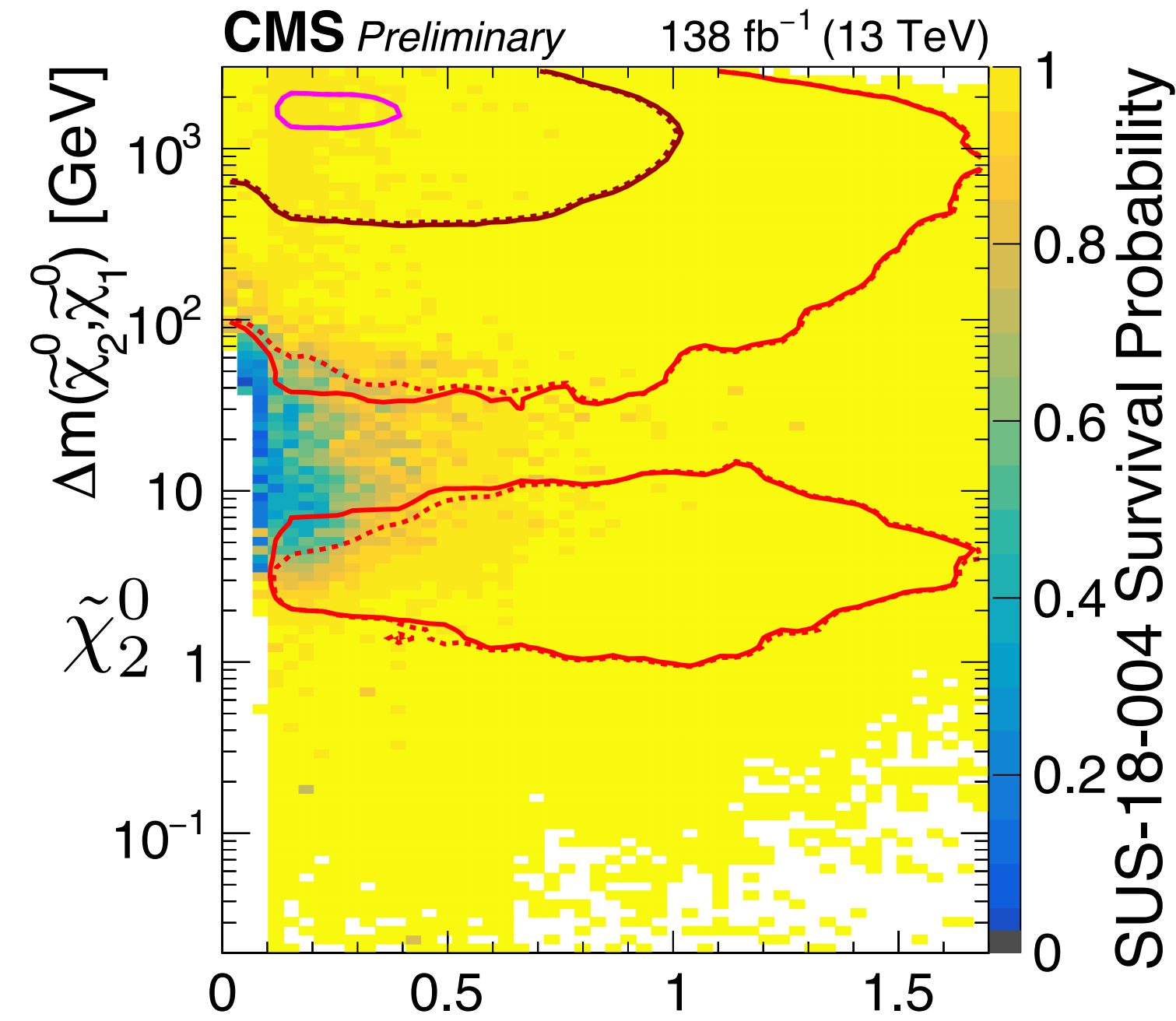
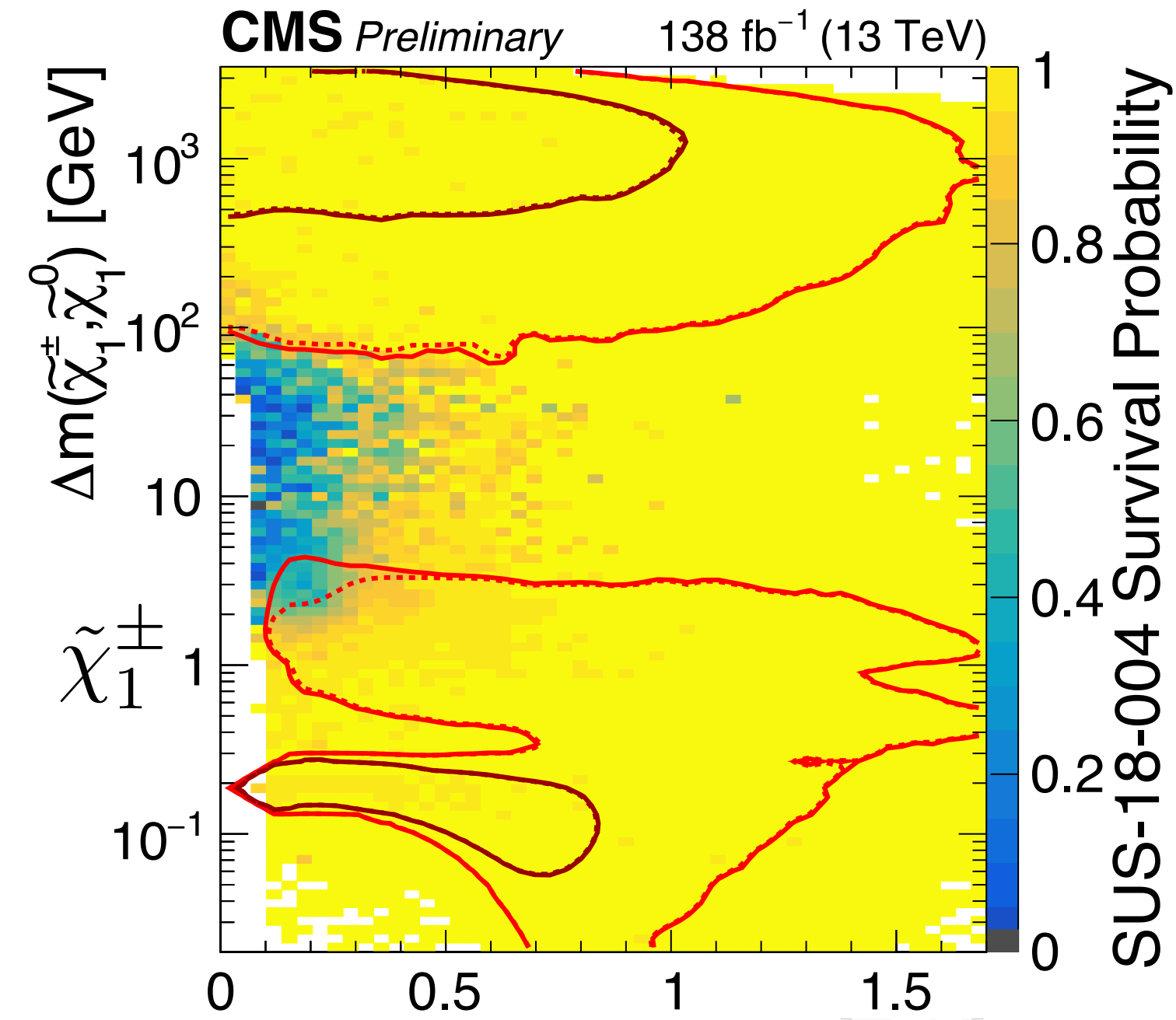
+Fine-tuning/naturalness

$$\Delta_{EW} = \max_i \frac{|C_i|}{\frac{m_Z^2}{2}}$$

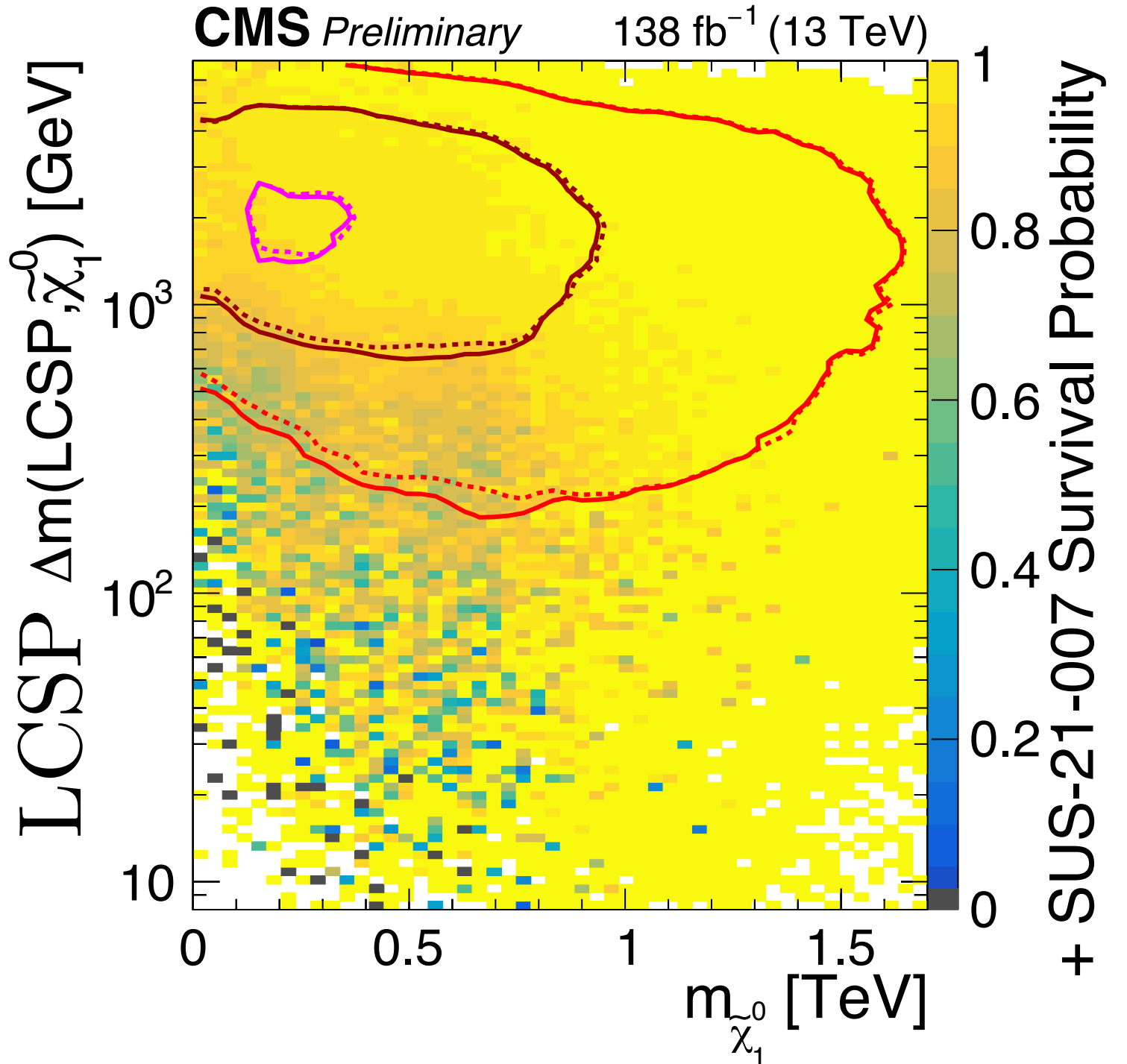
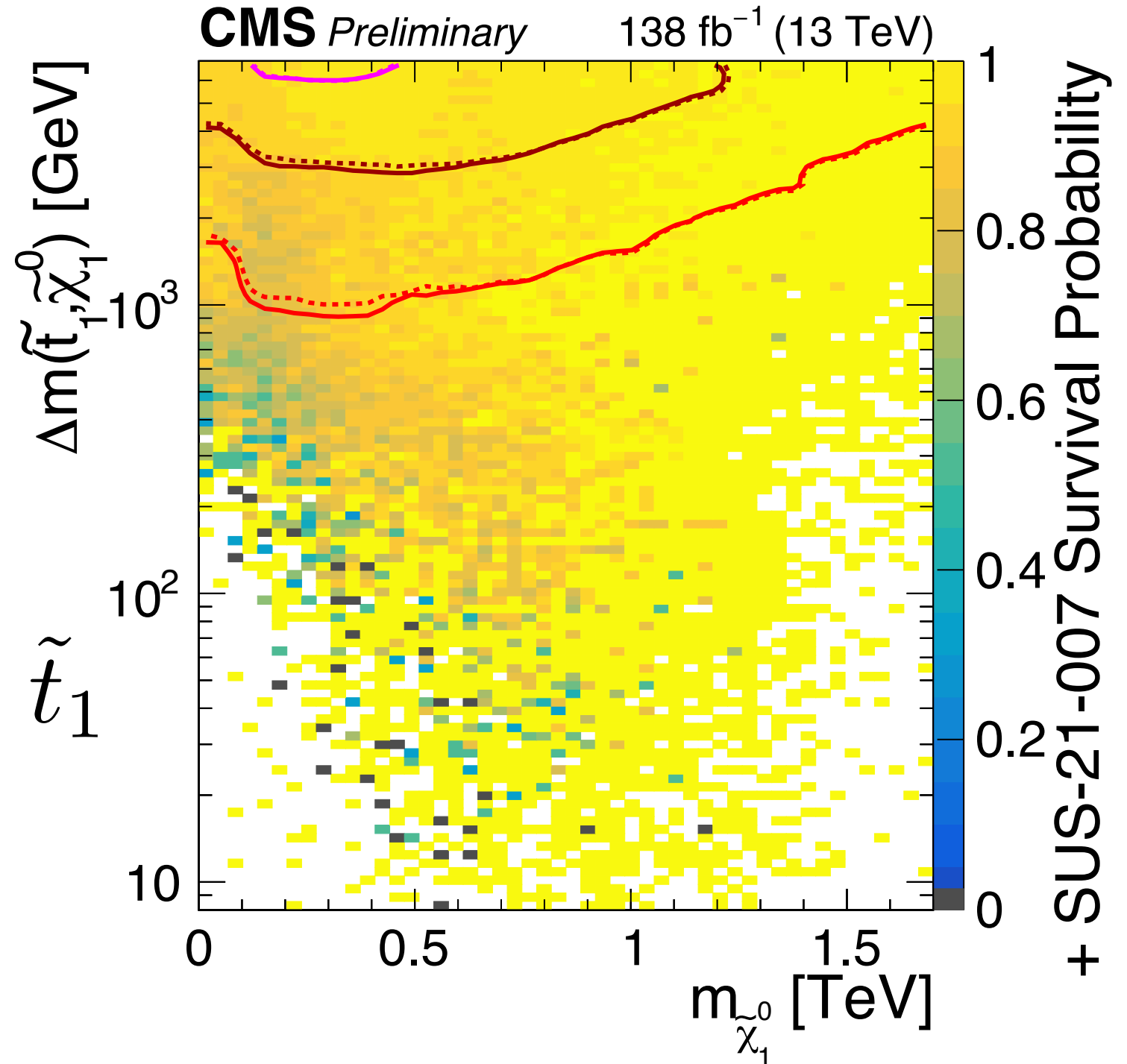
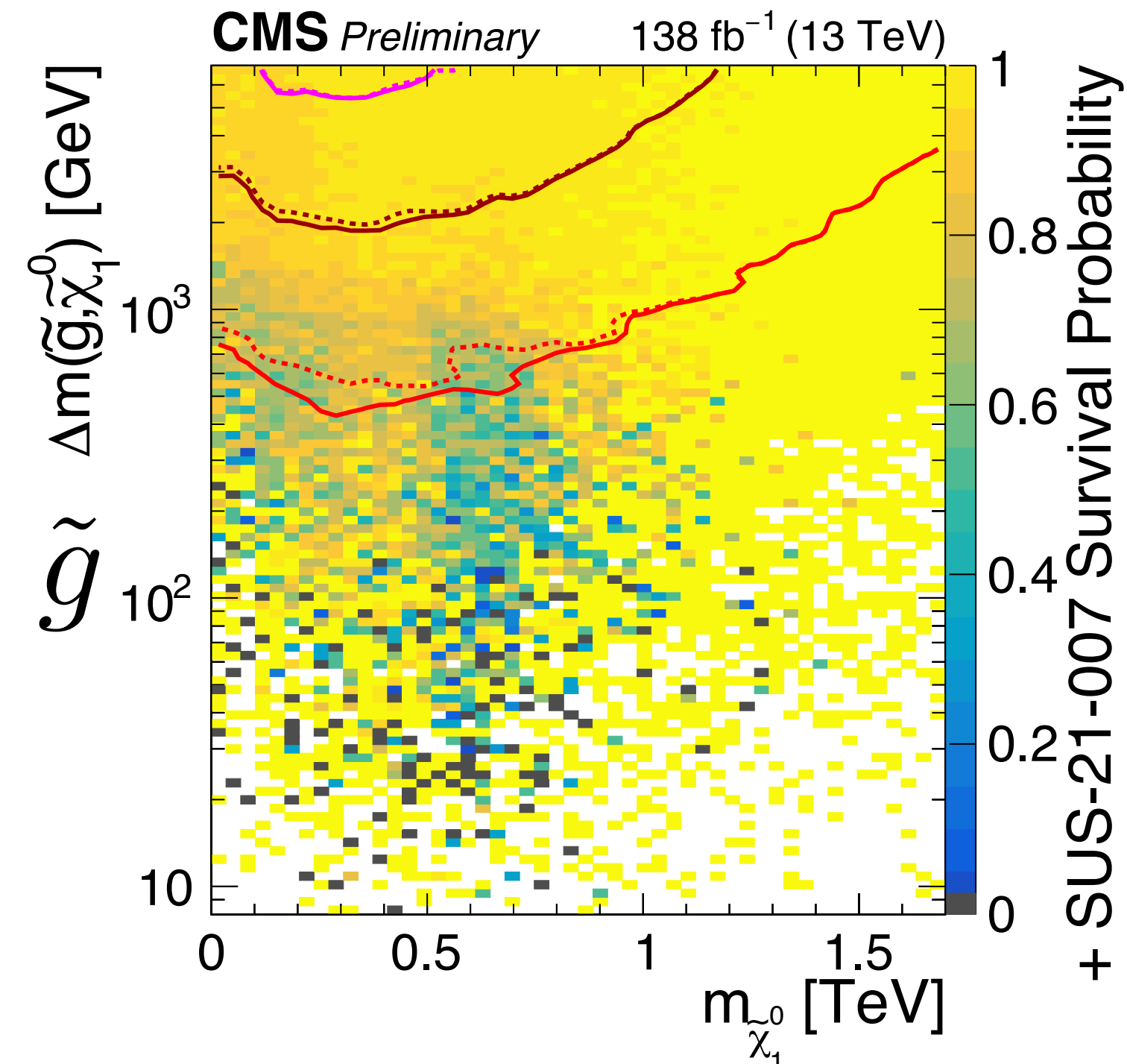
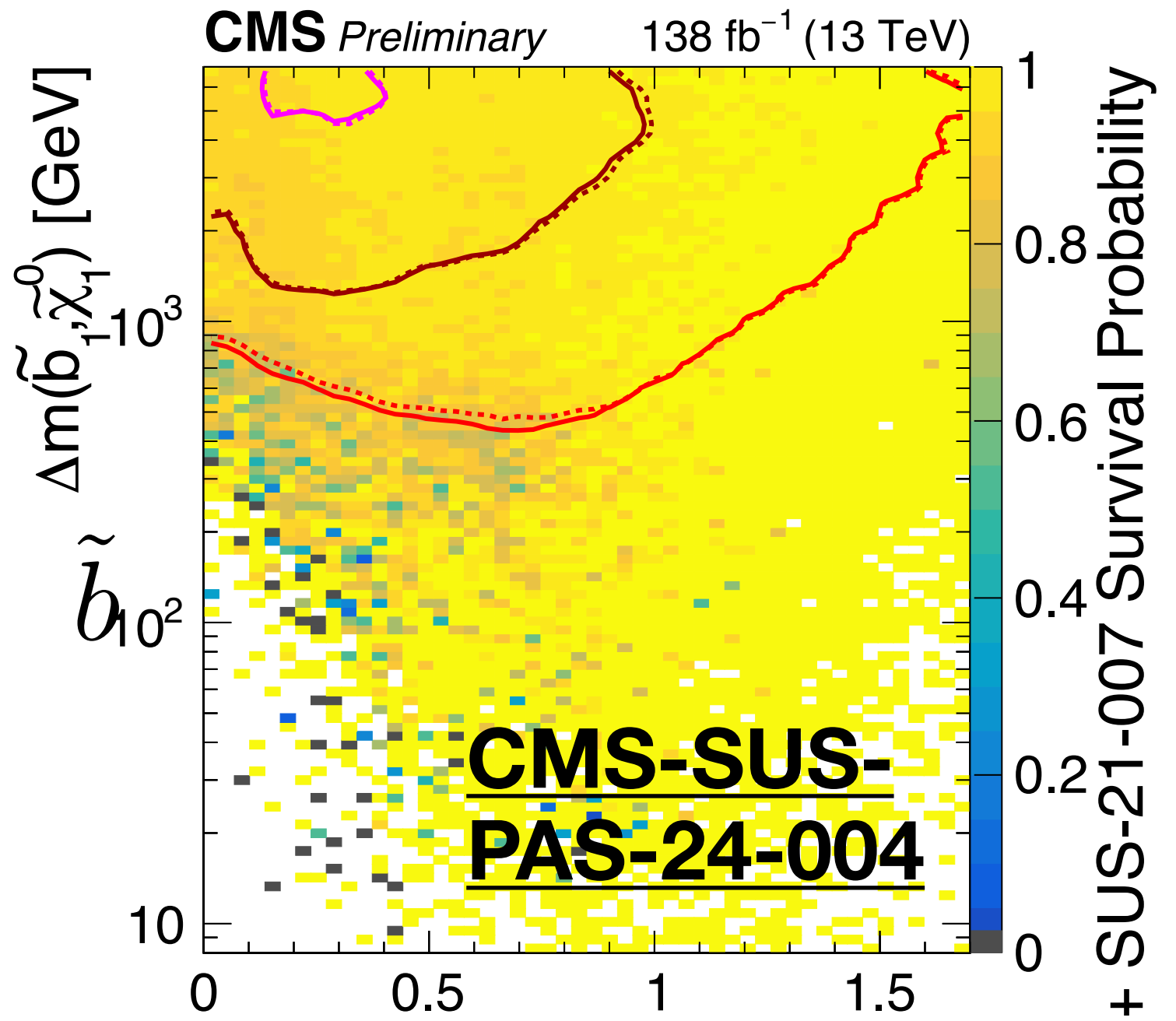
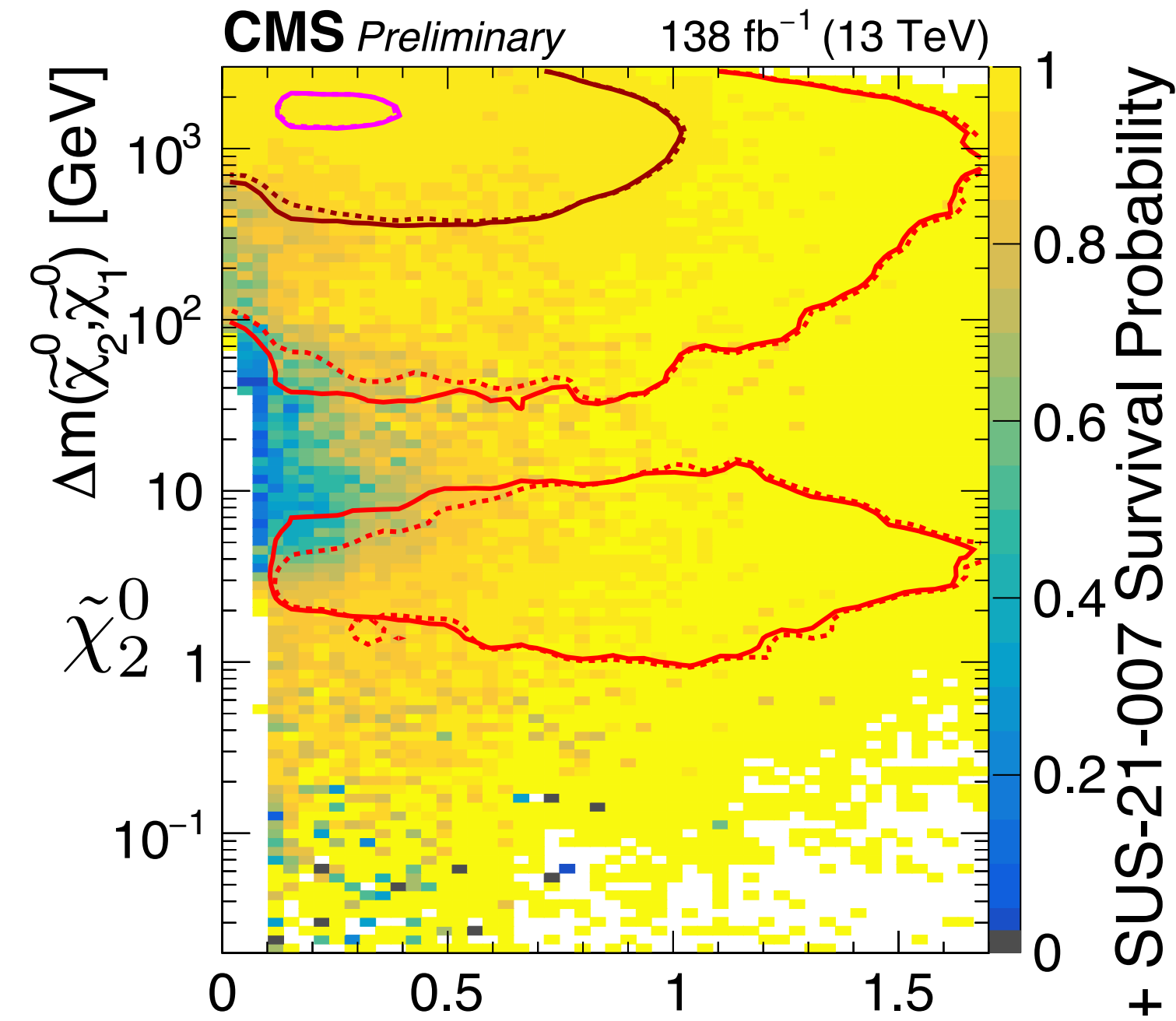
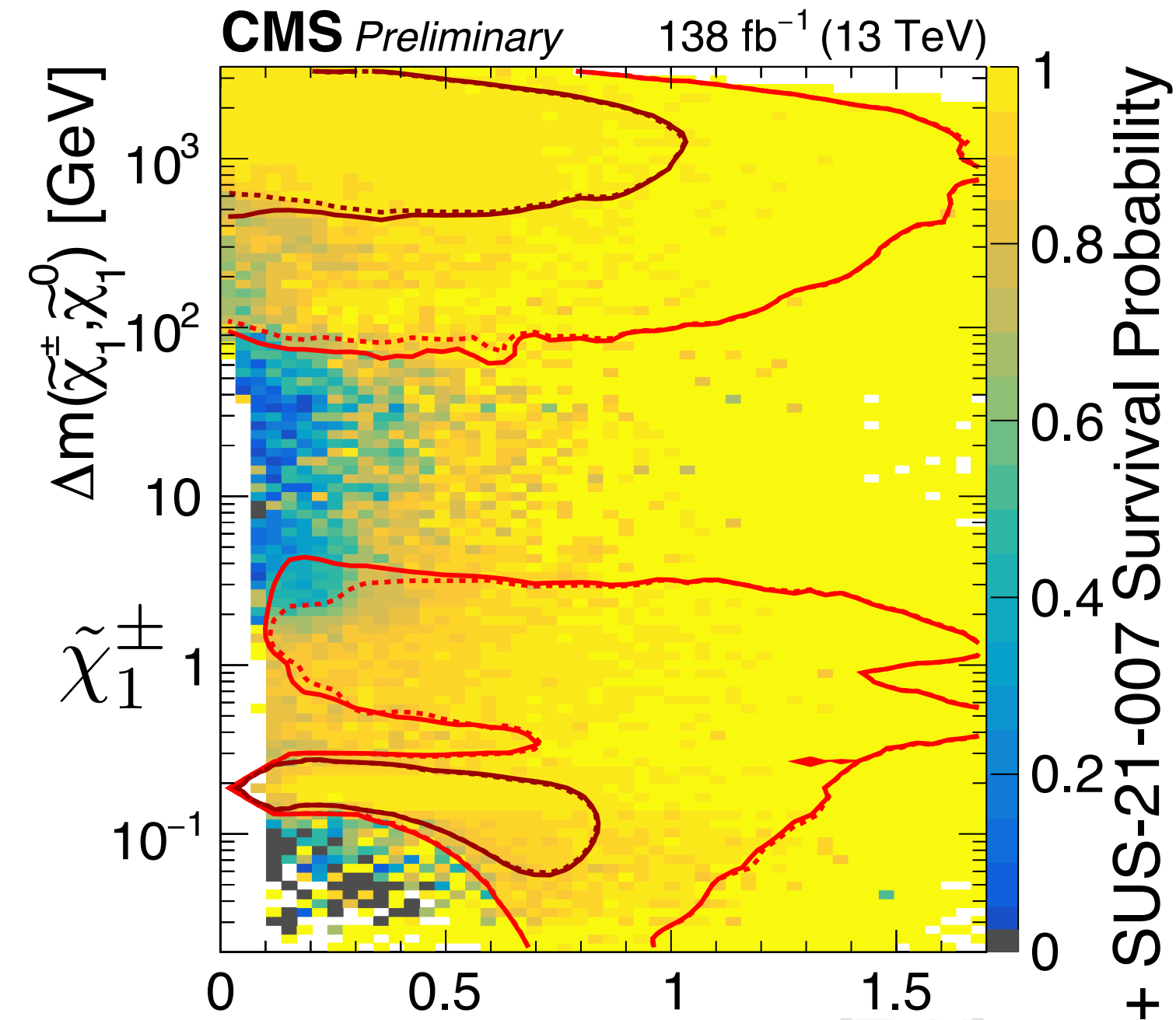
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \sum_d^d - (m_{H_u}^2 + \sum_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2$$



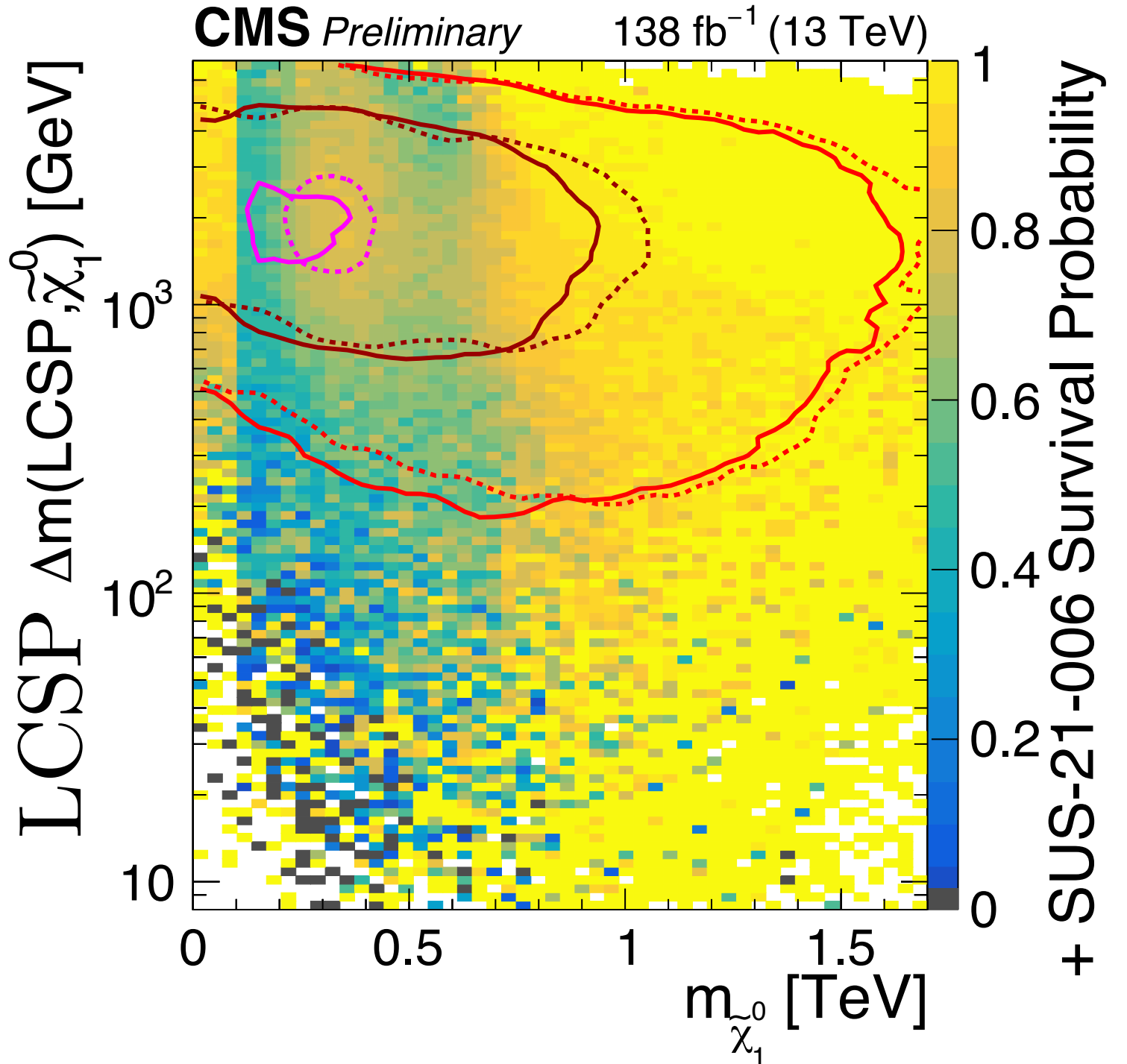
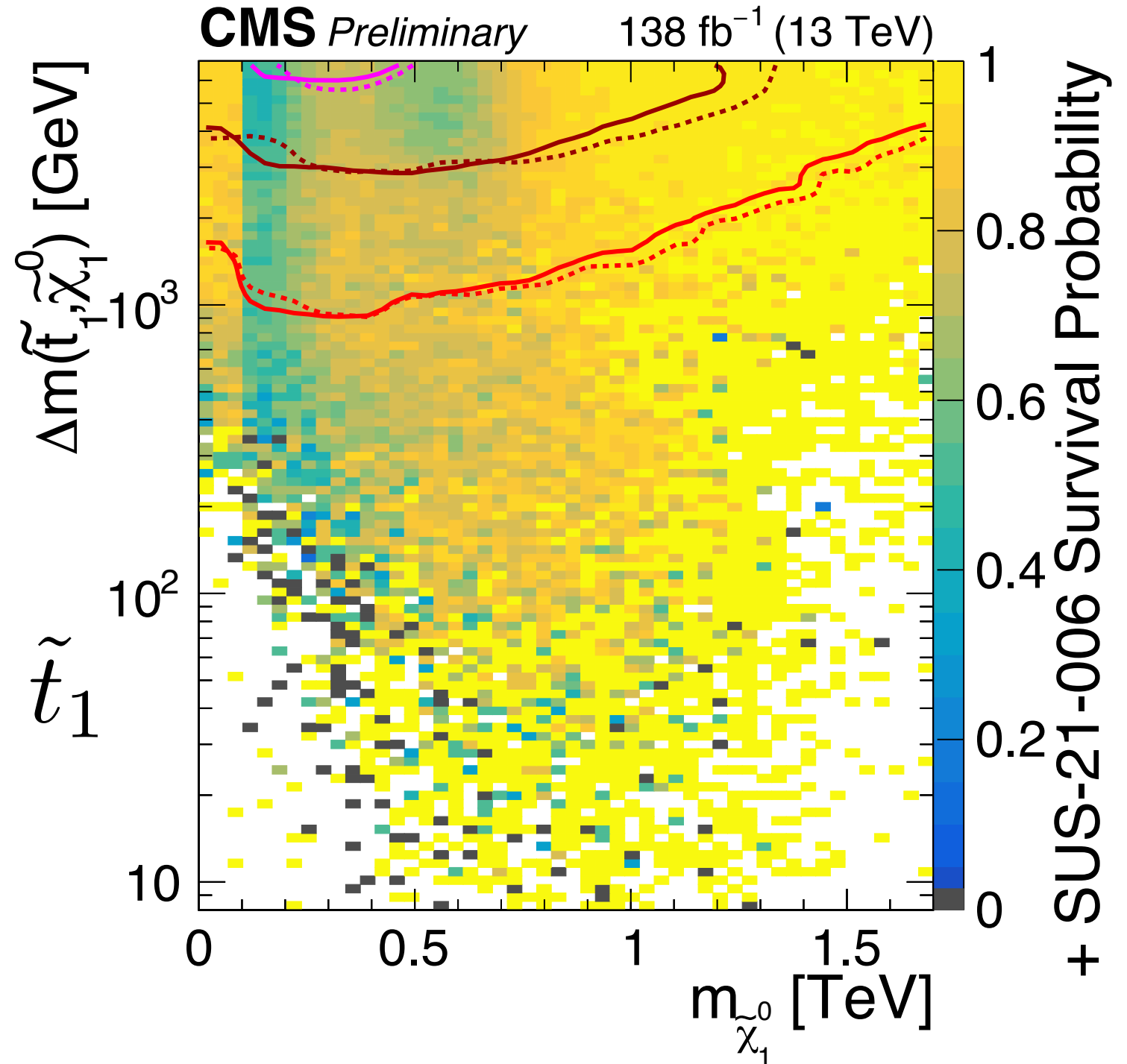
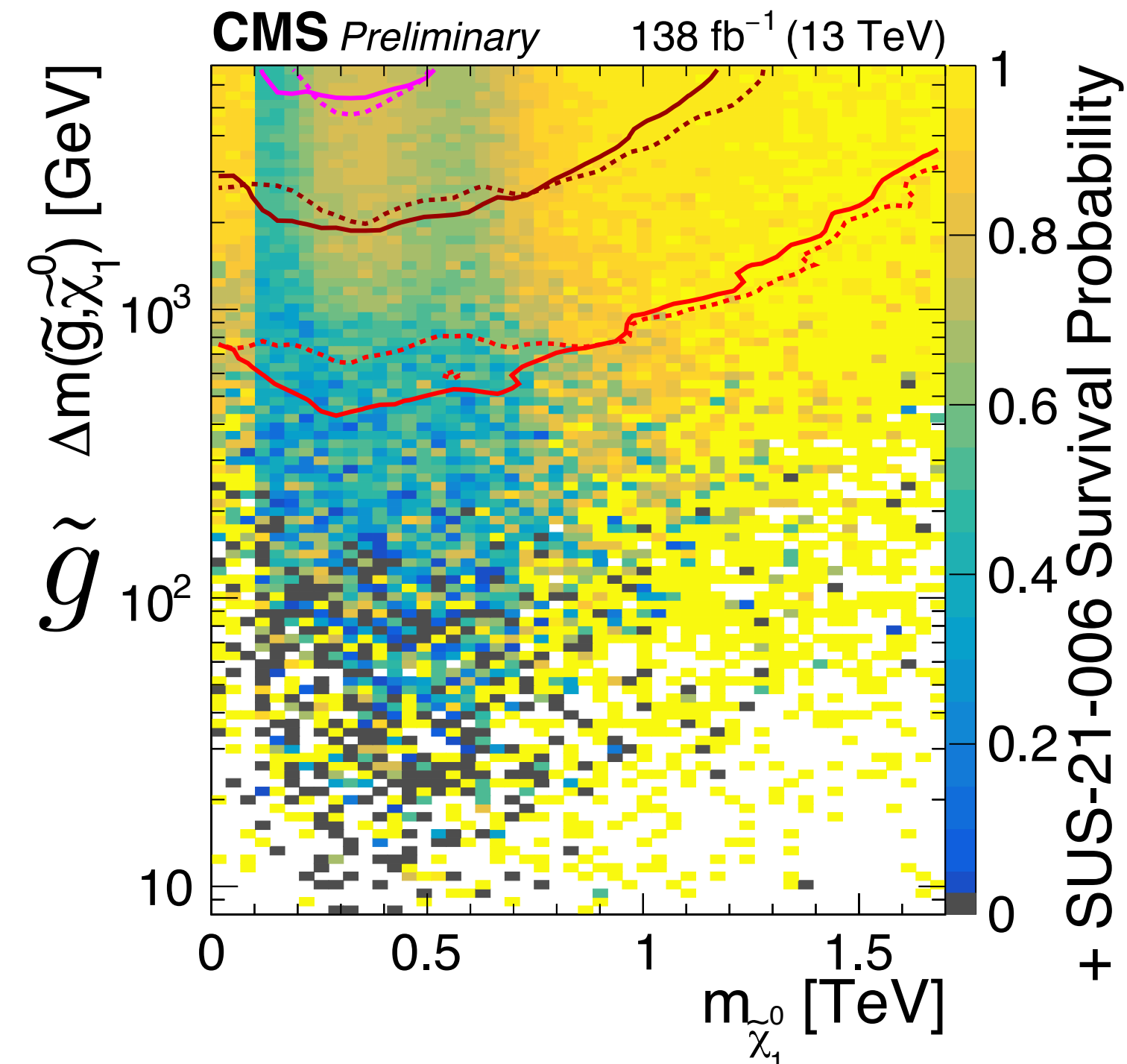
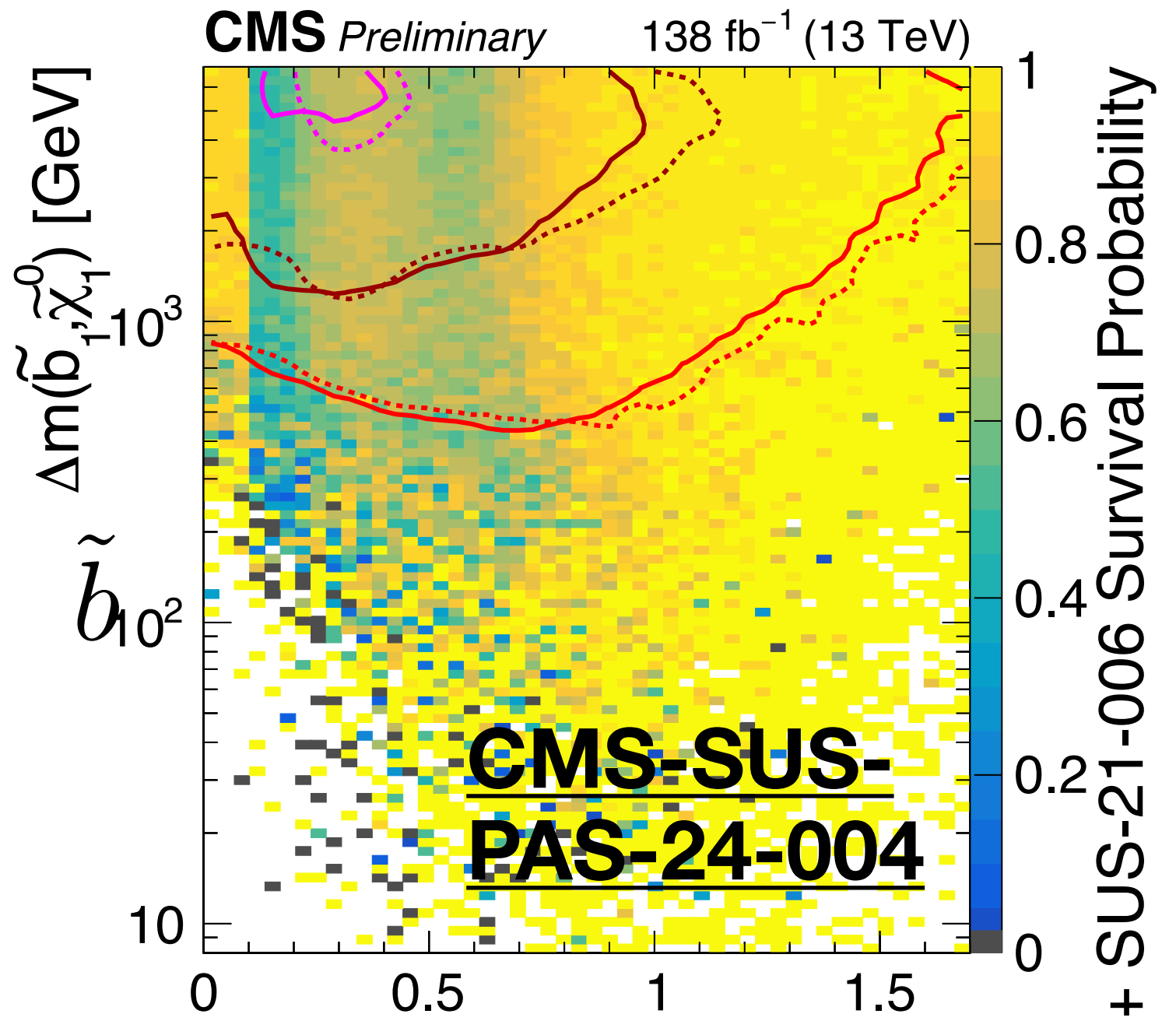
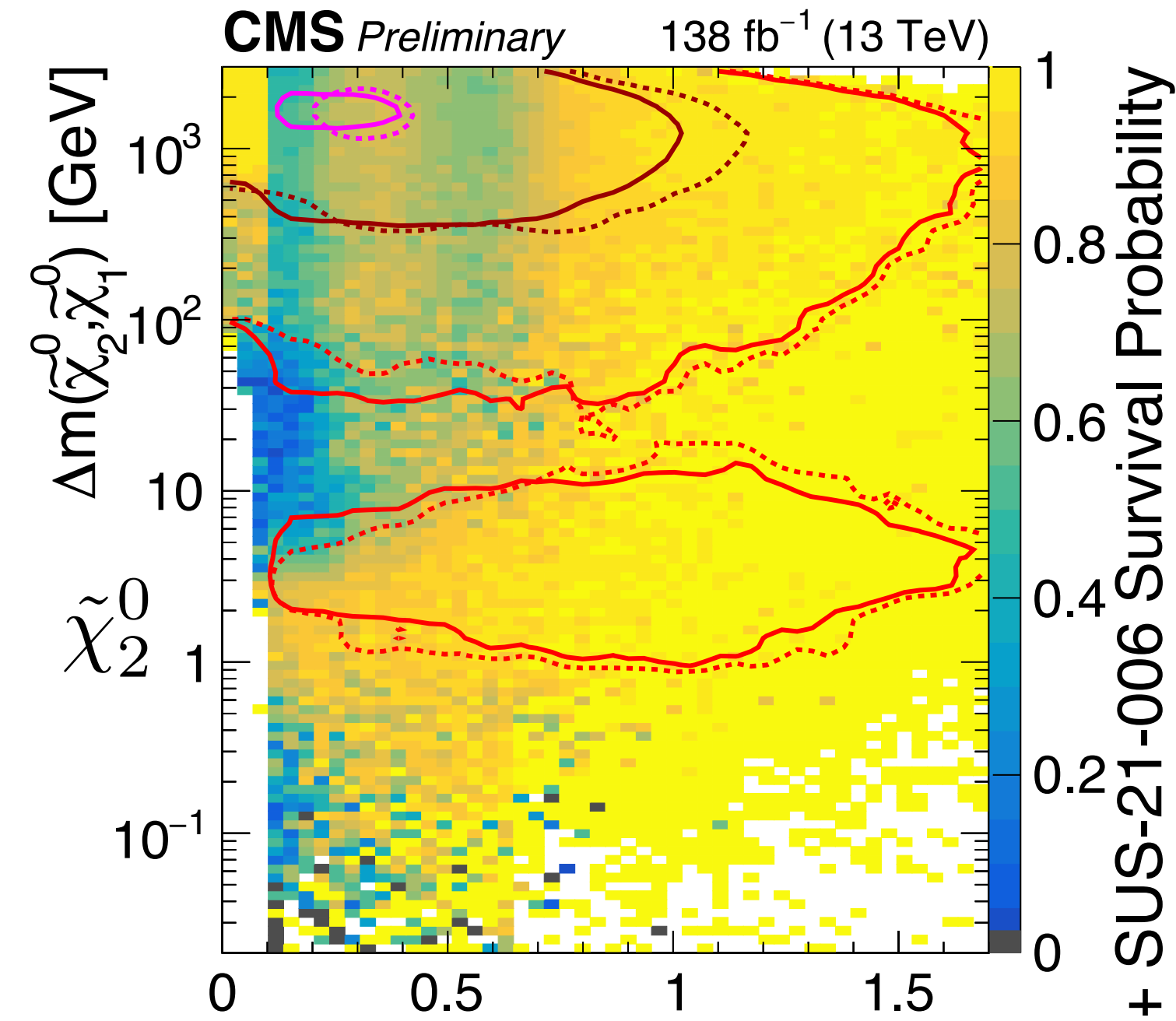
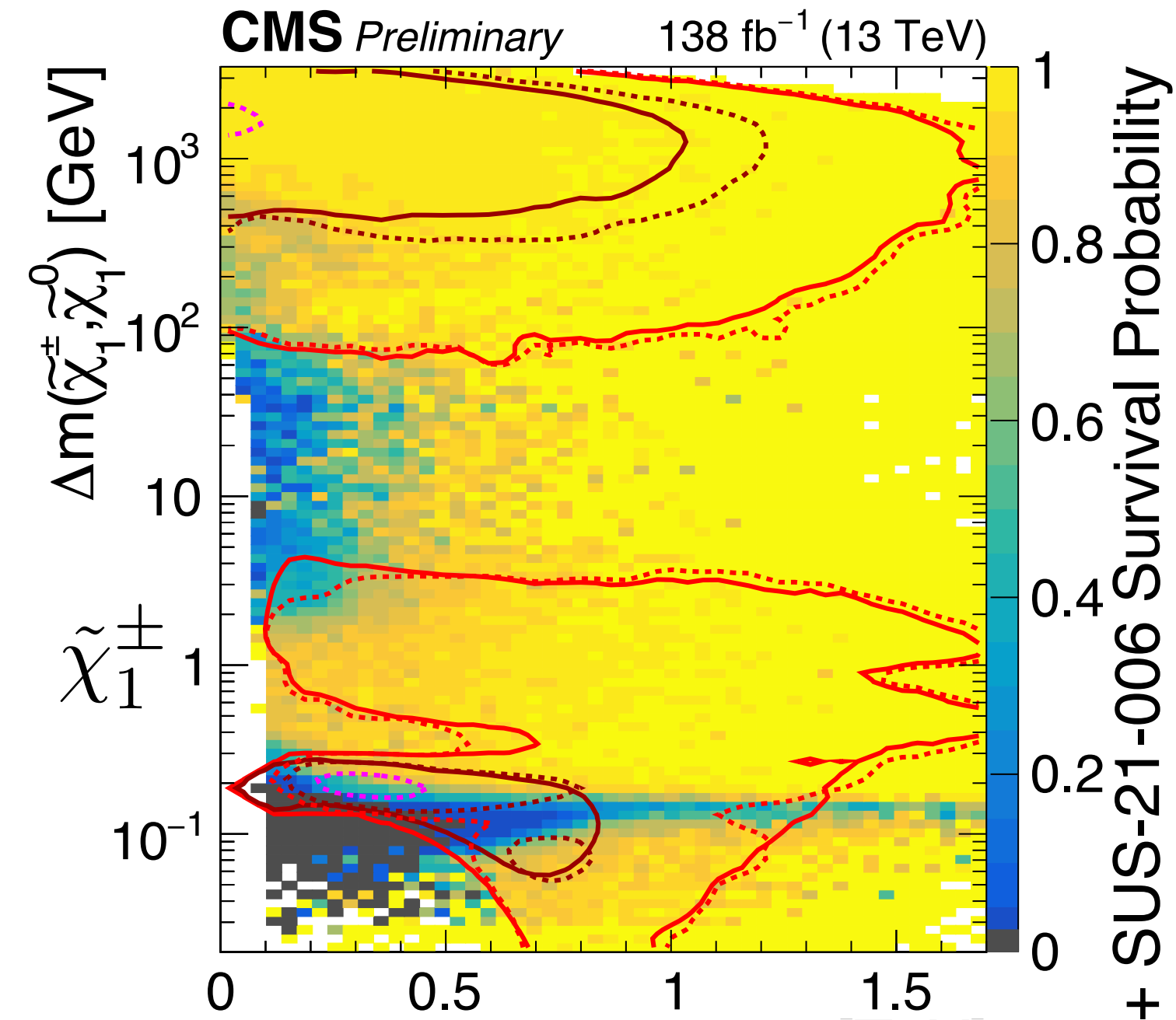
pMSSM impact analysis sequence



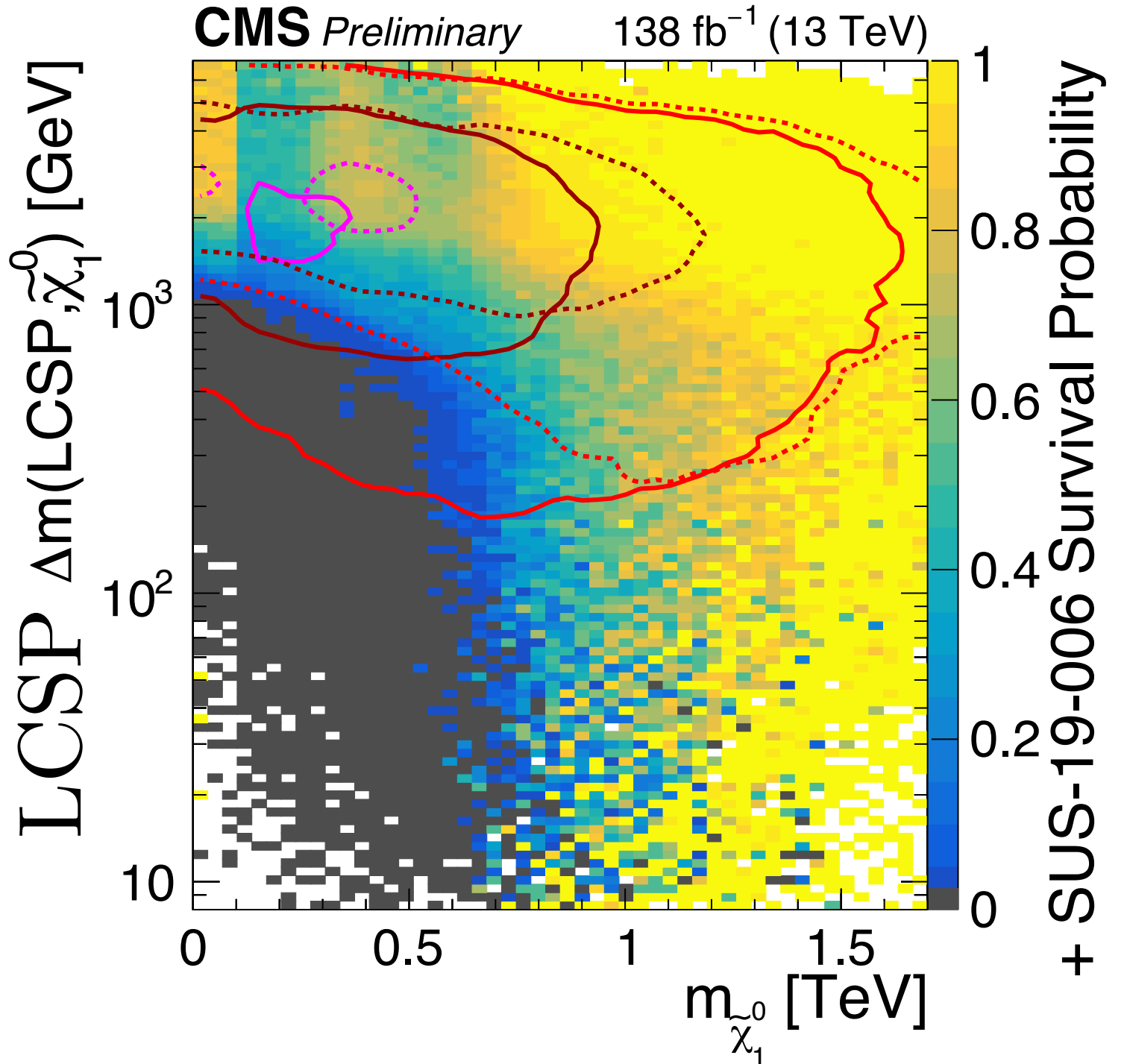
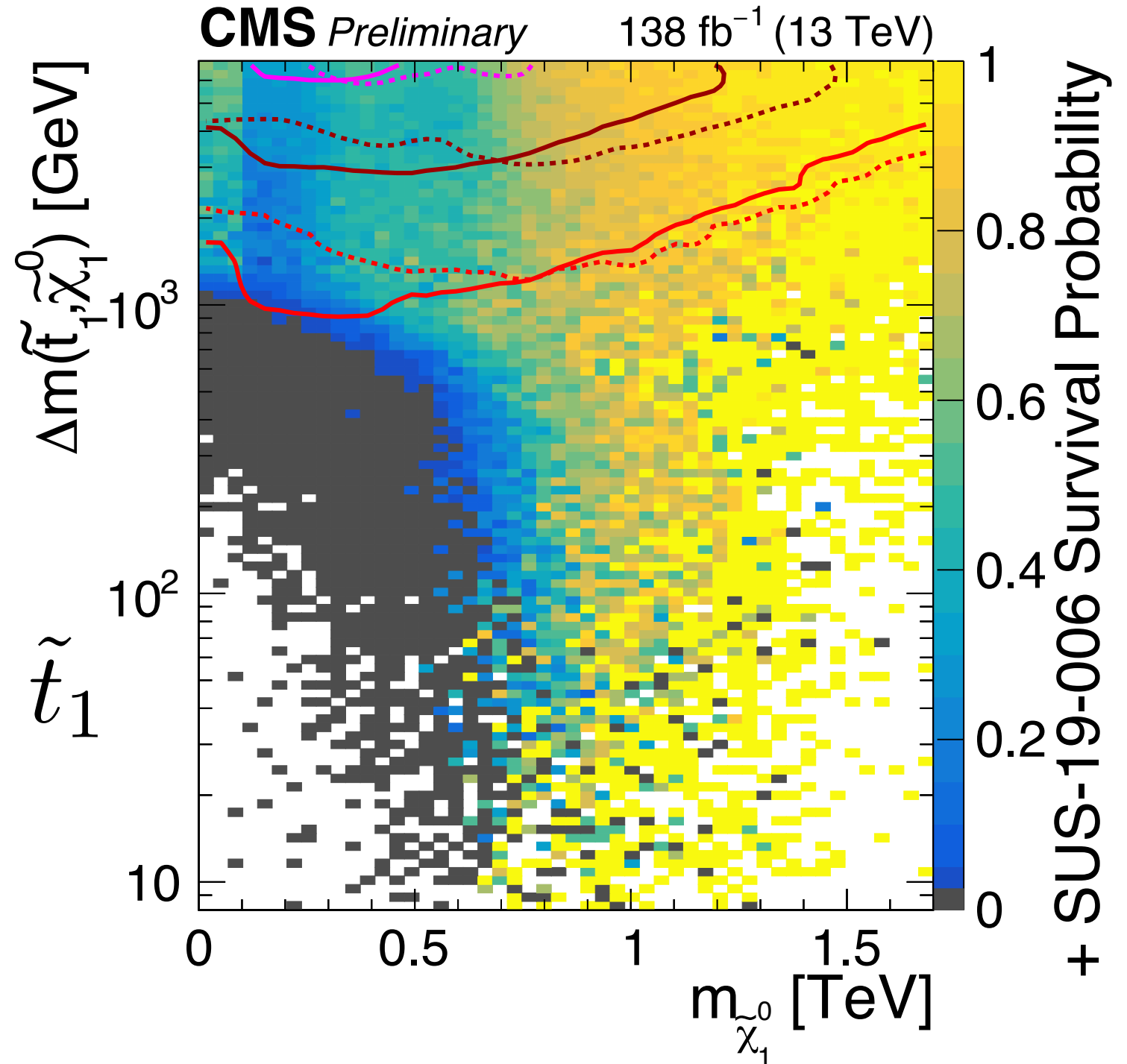
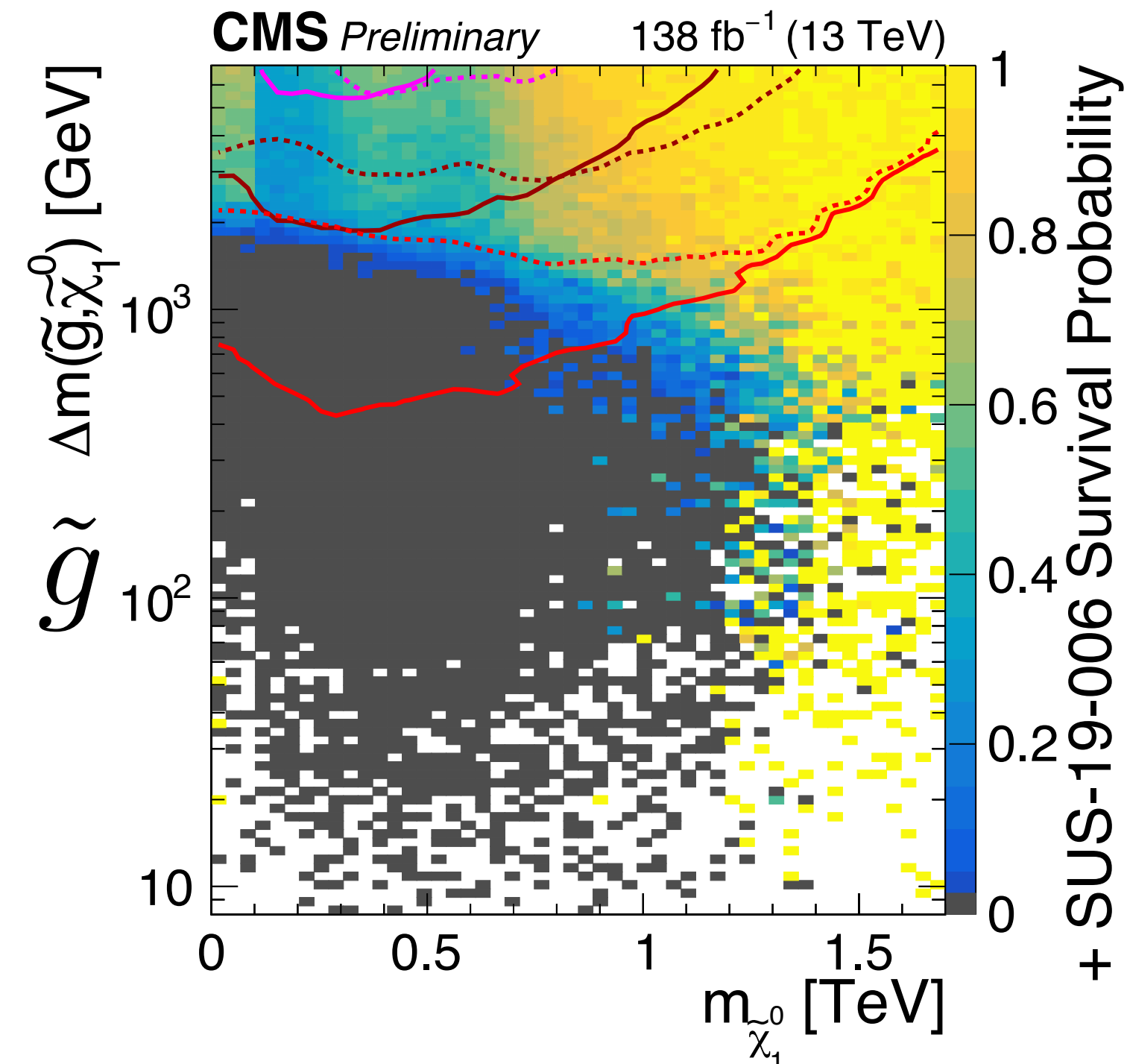
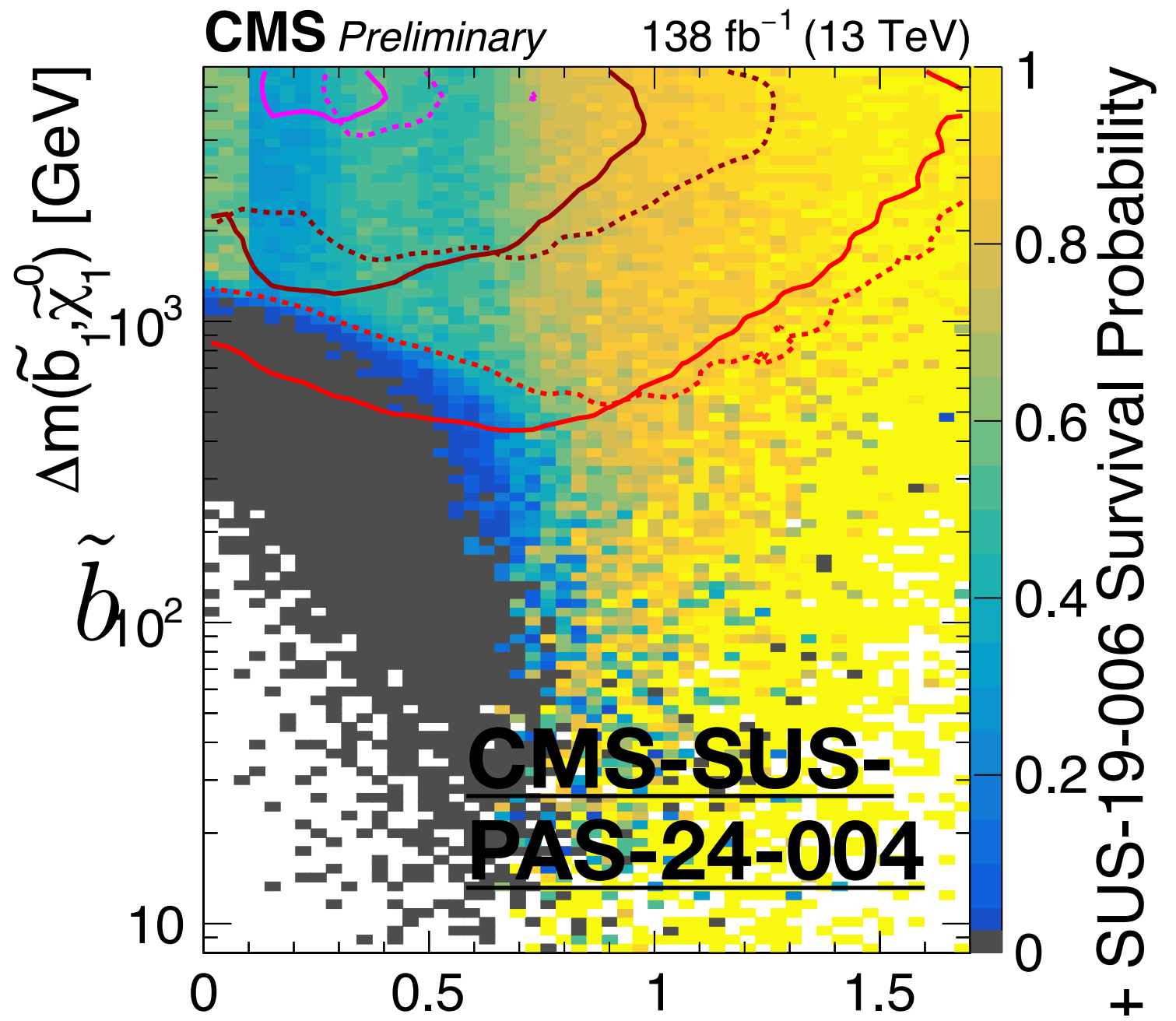
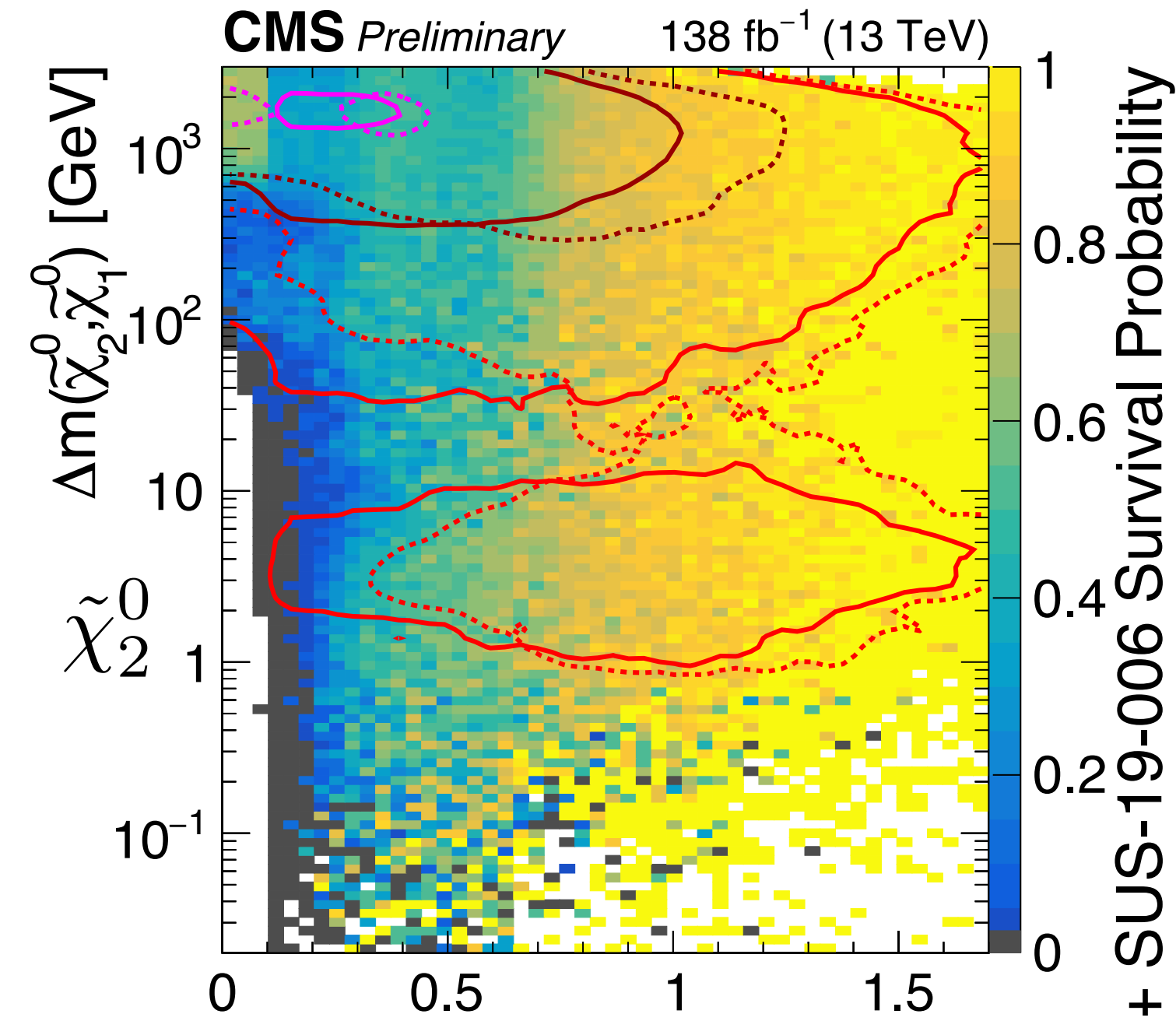
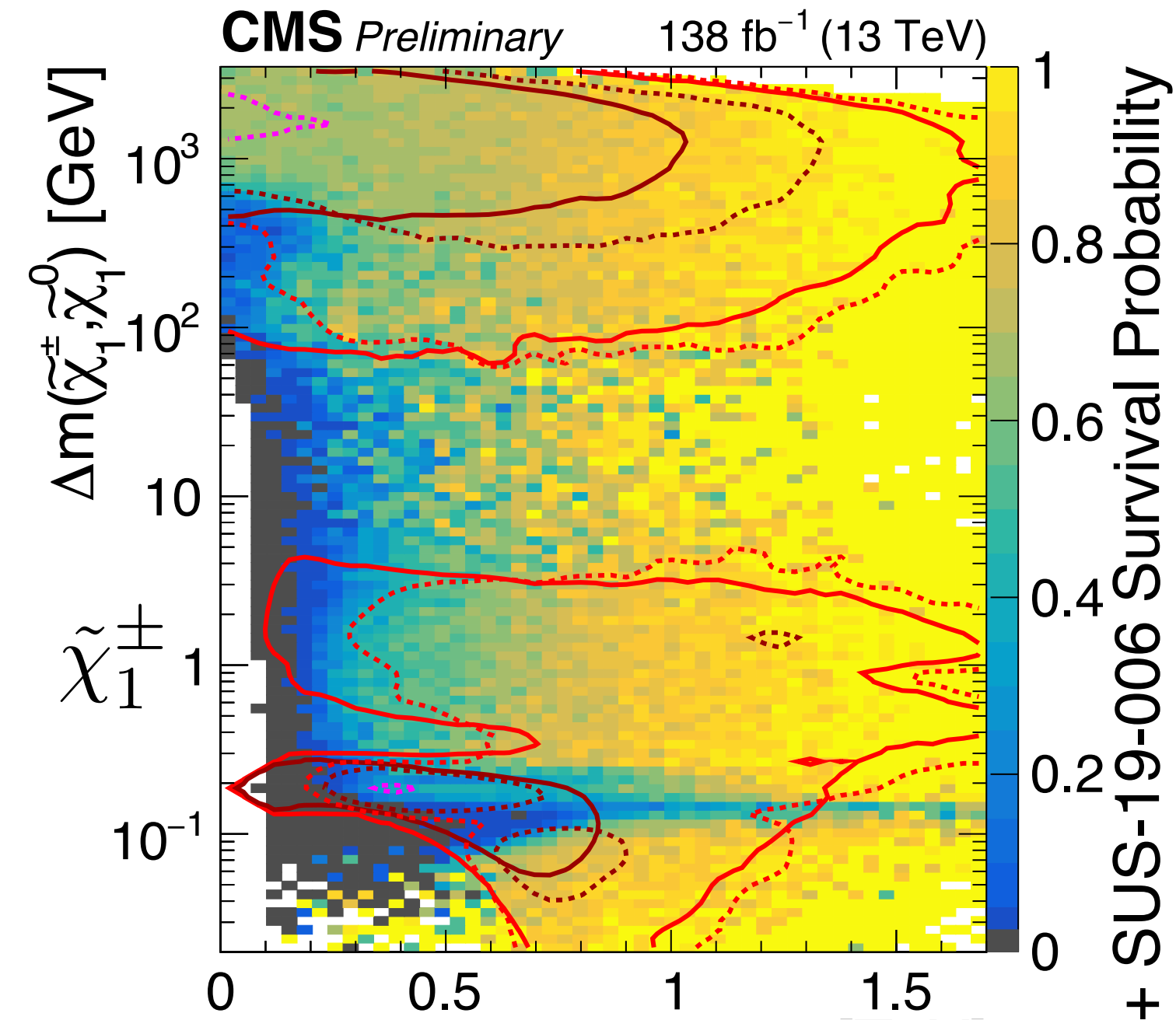
pMSSM impact analysis sequence



pMSSM impact analysis sequence

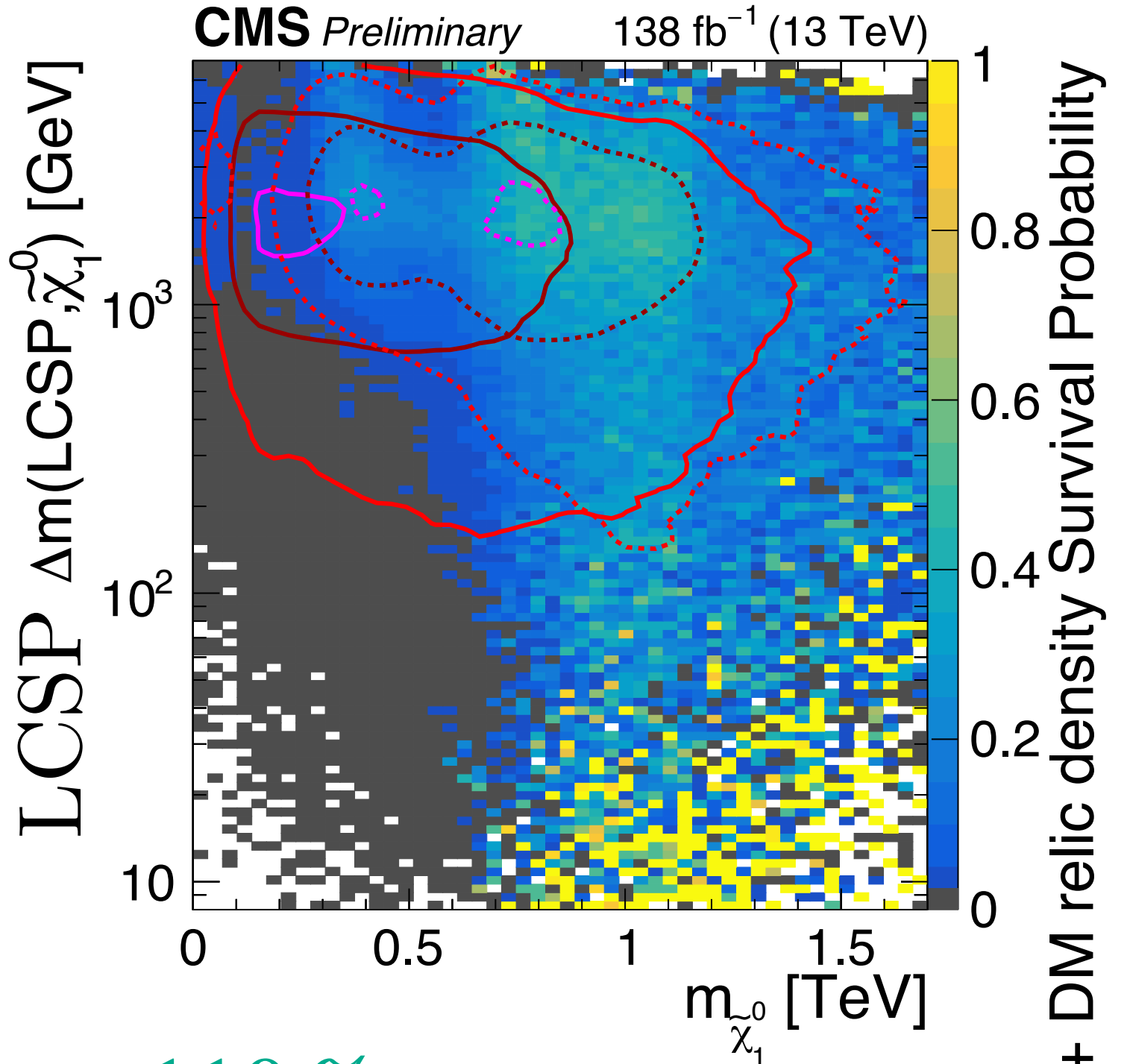
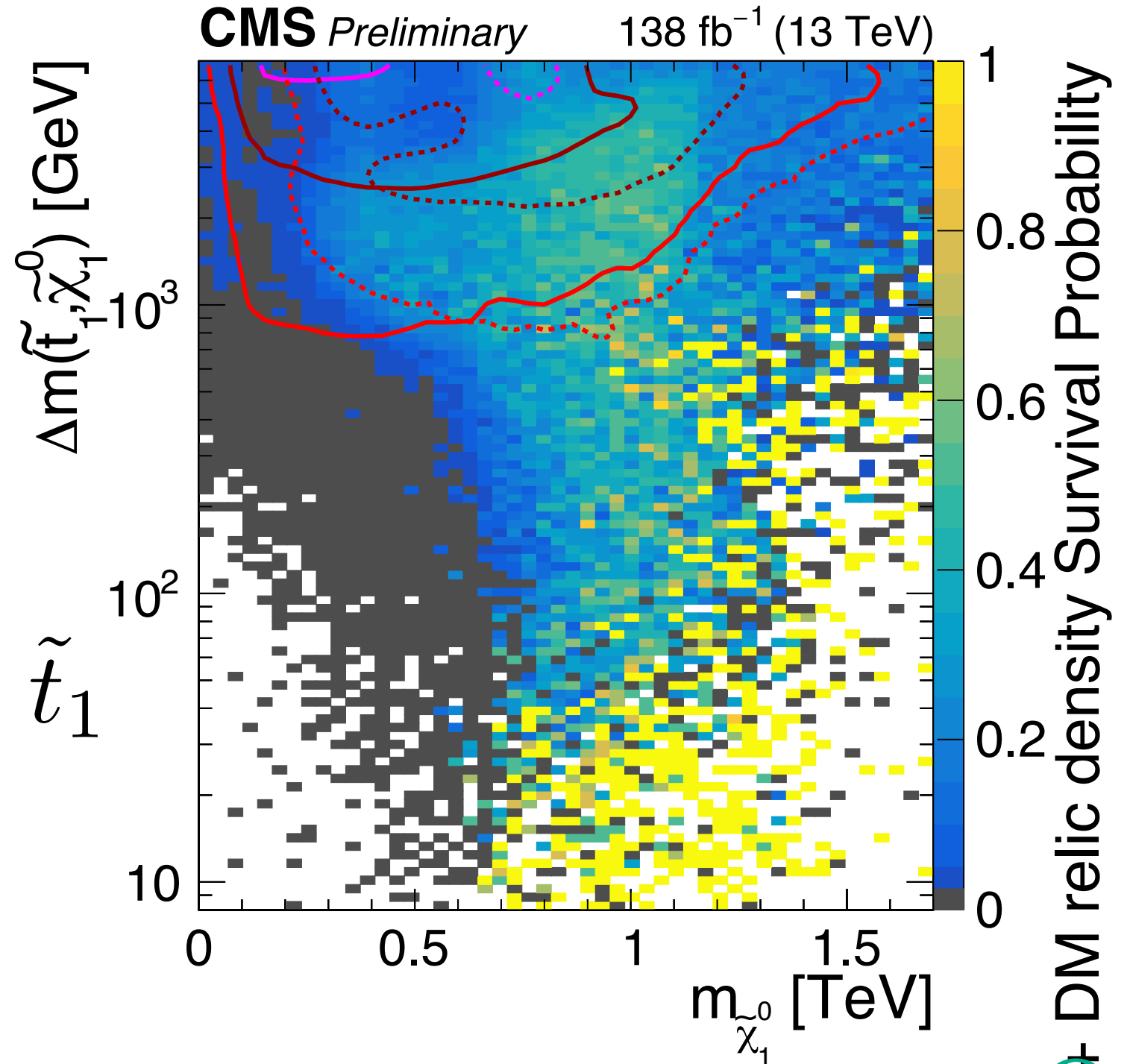
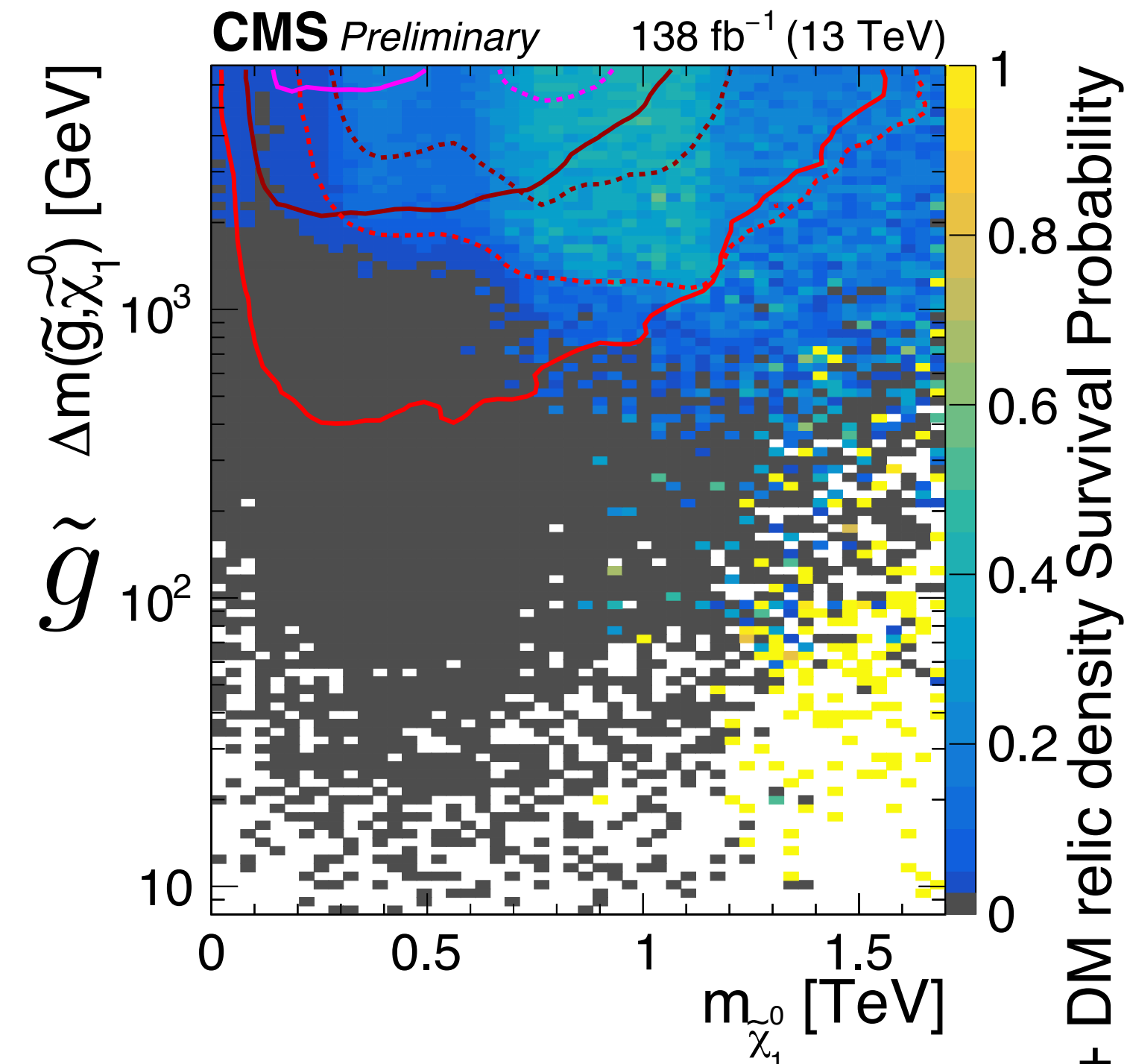
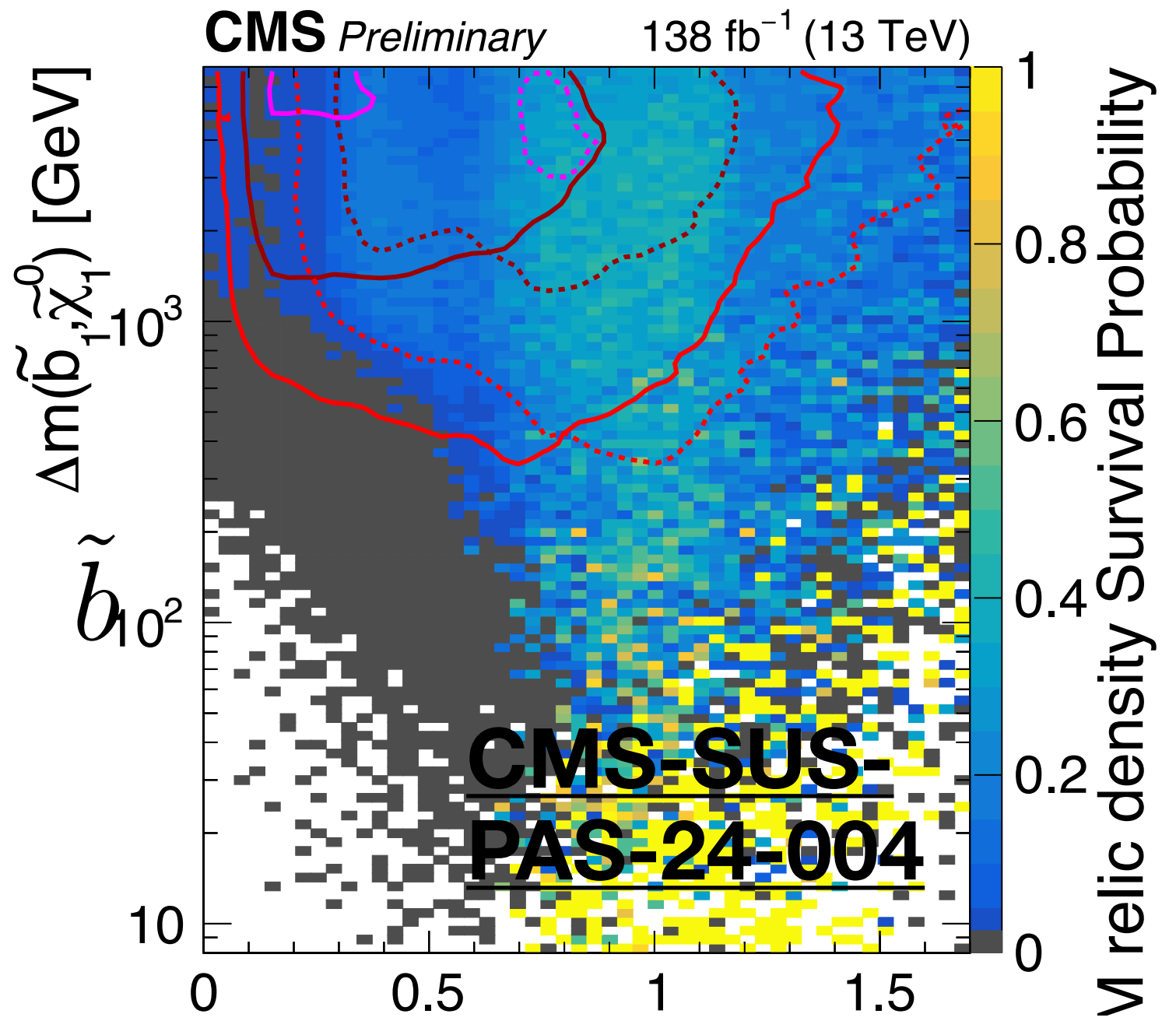
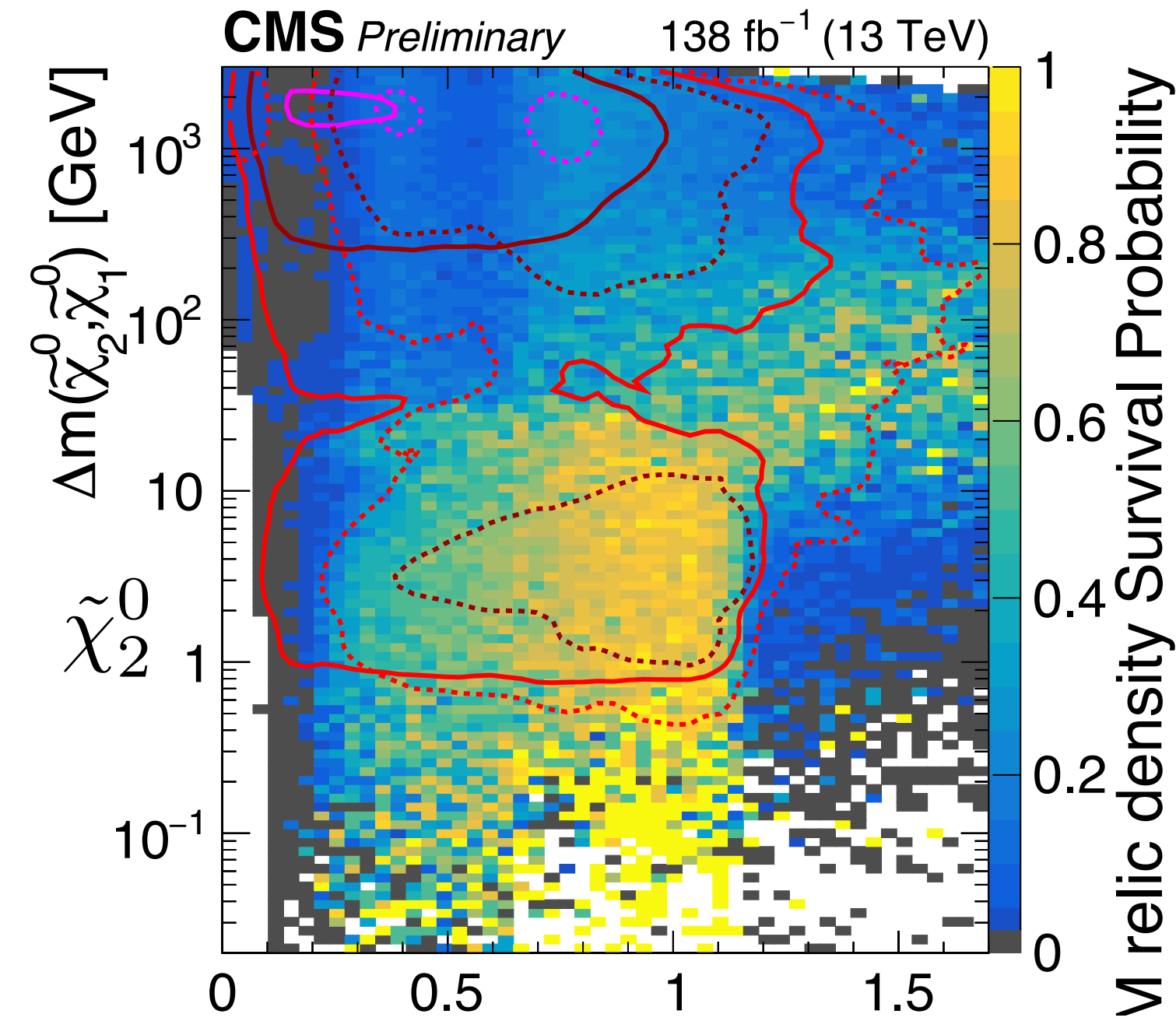
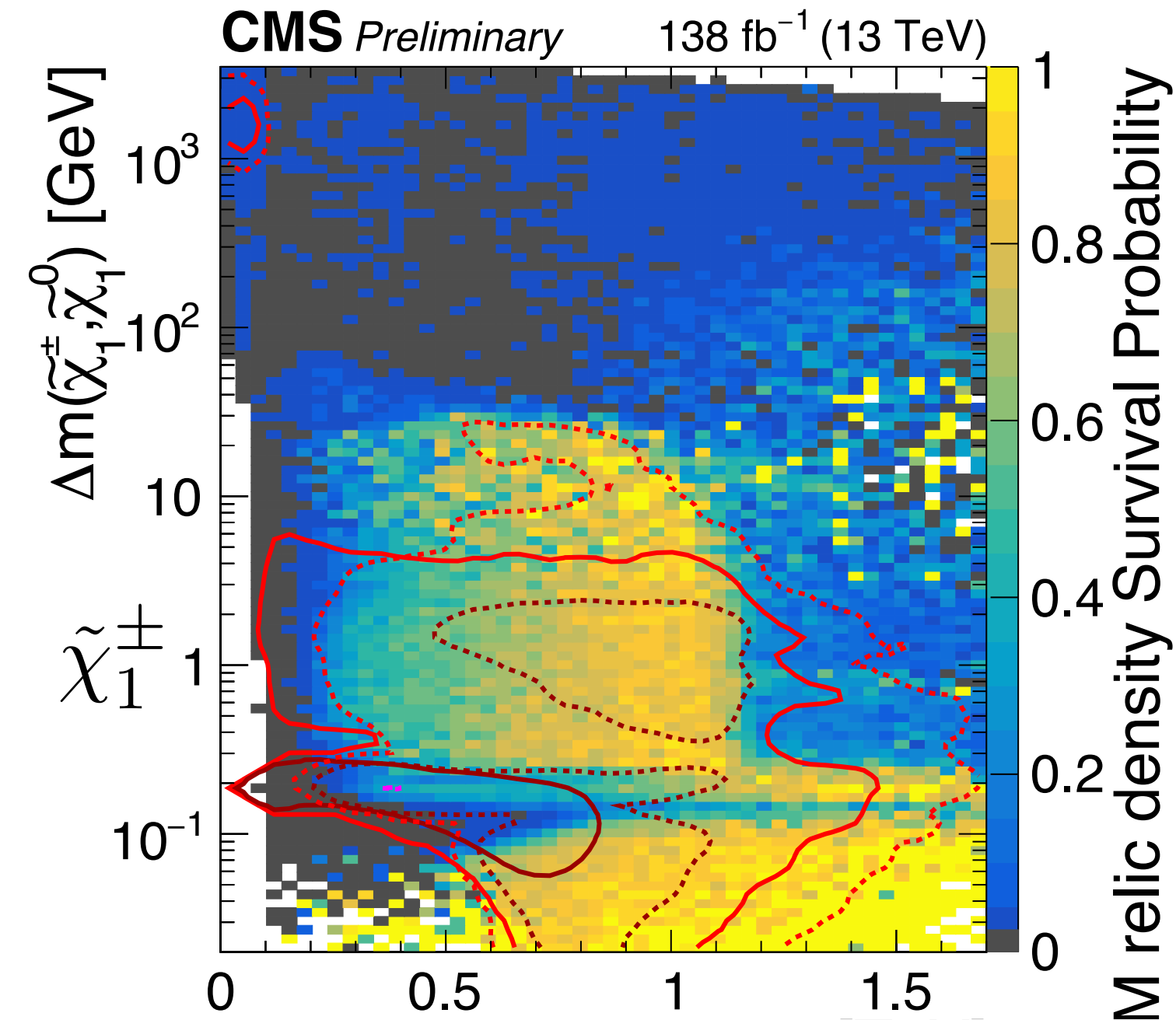


pMSSM impact analysis sequence



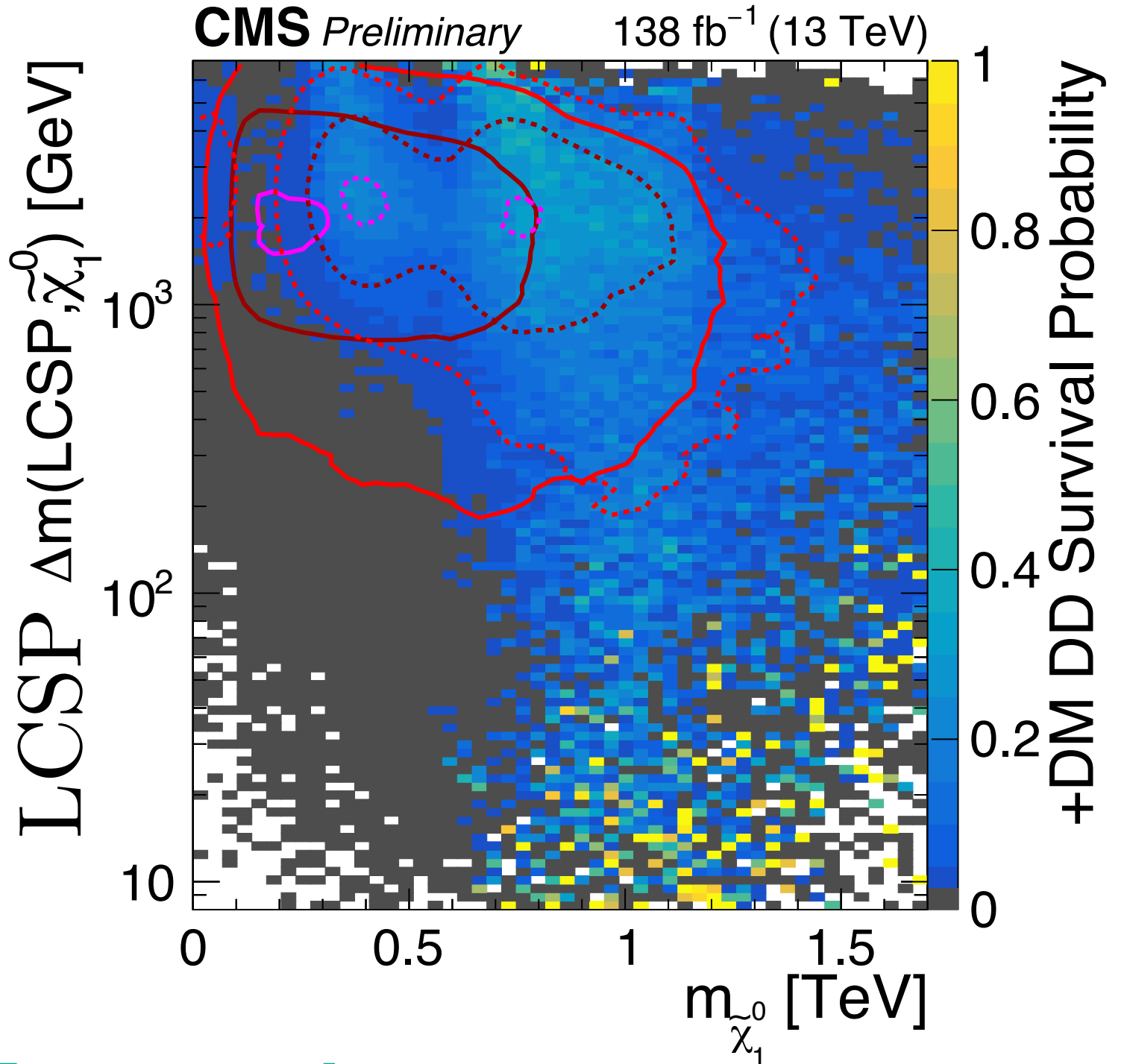
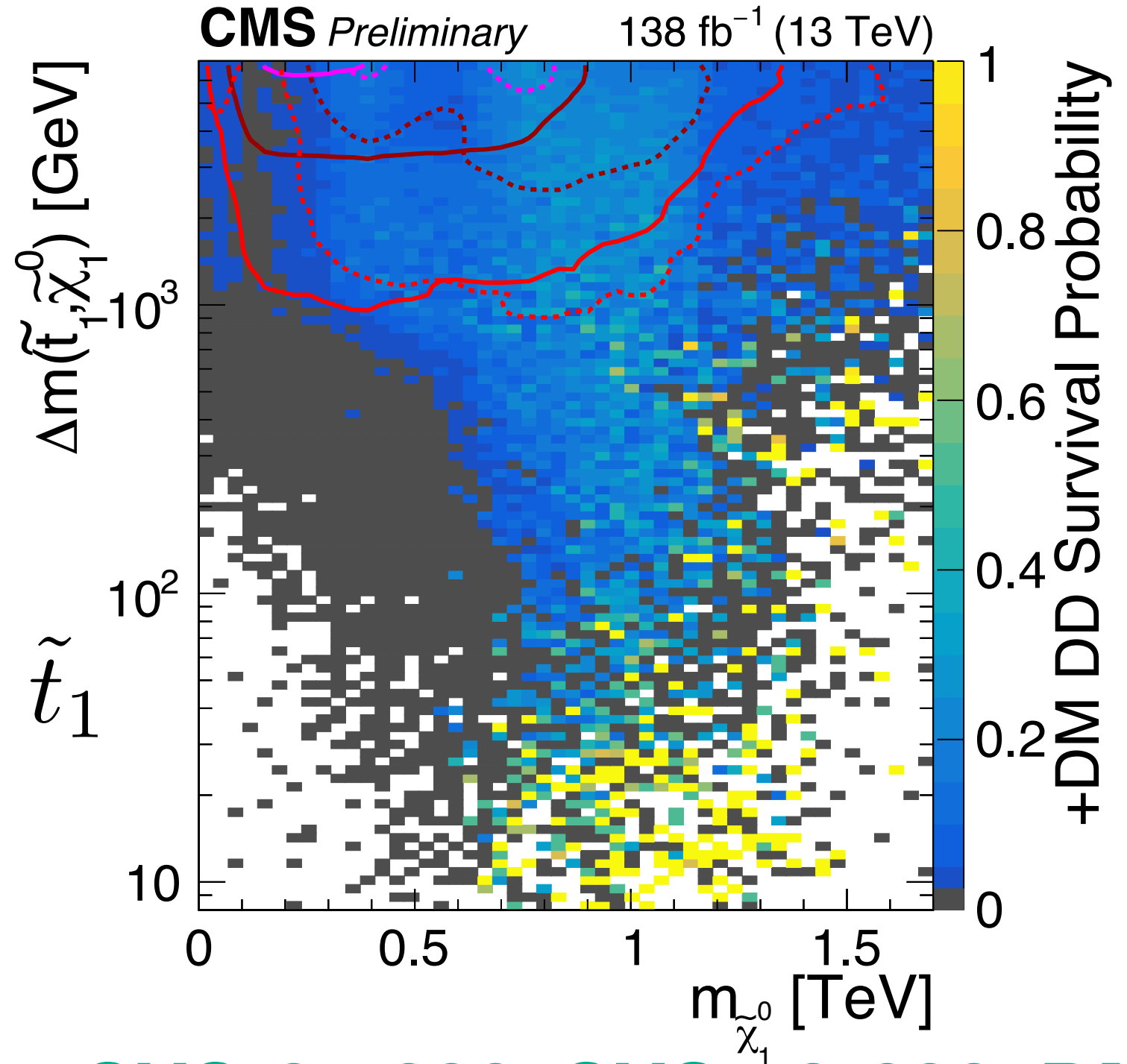
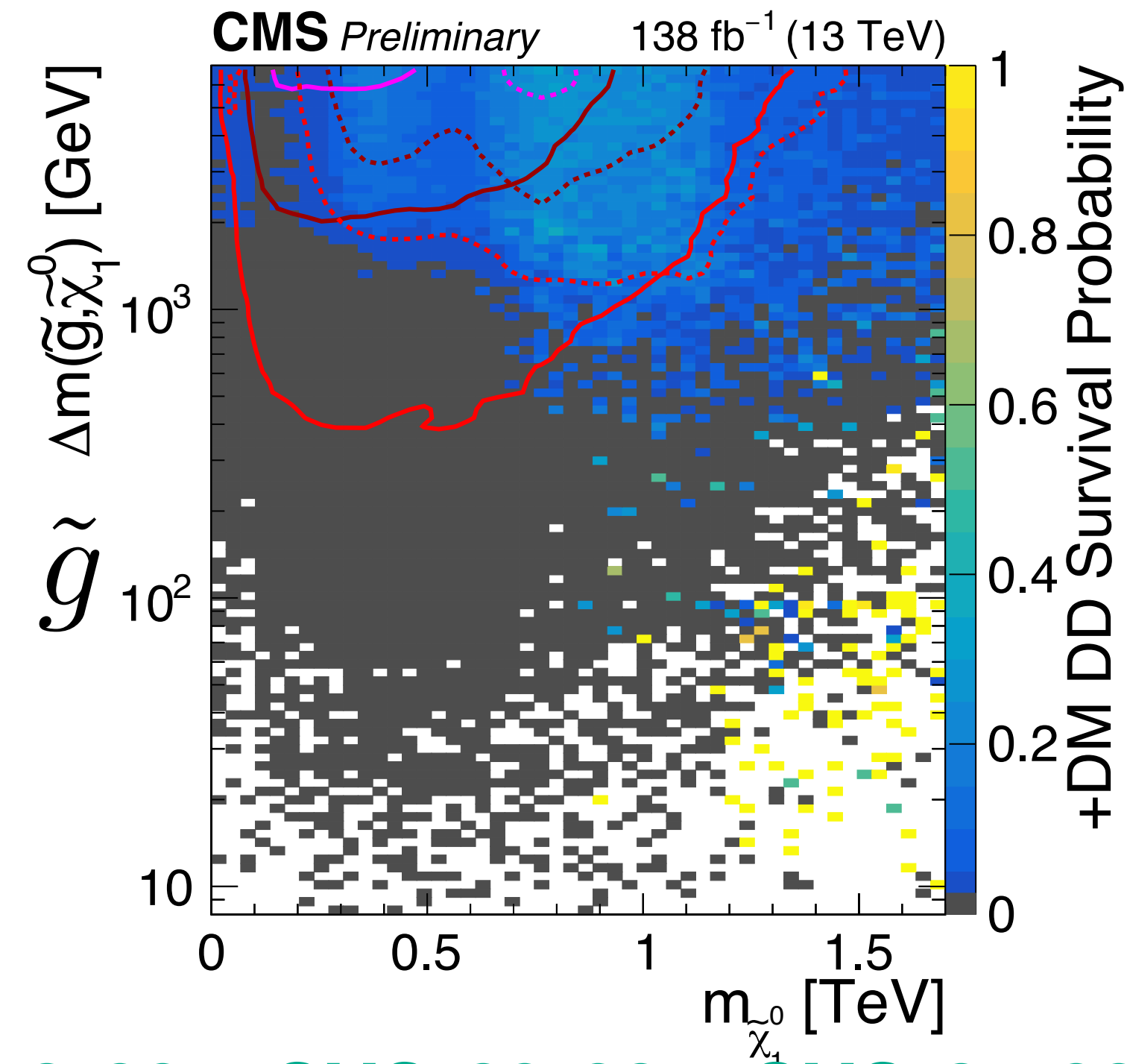
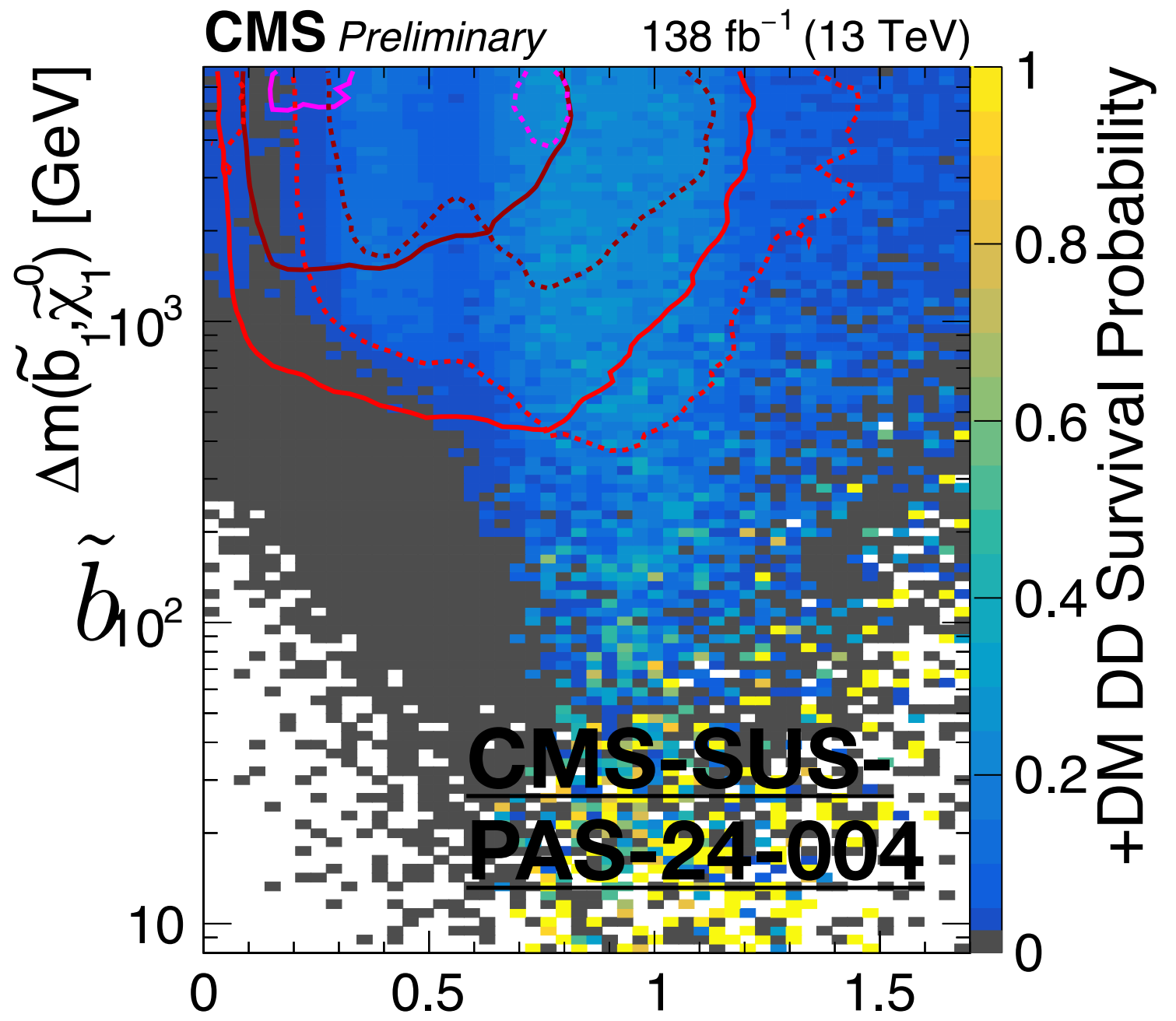
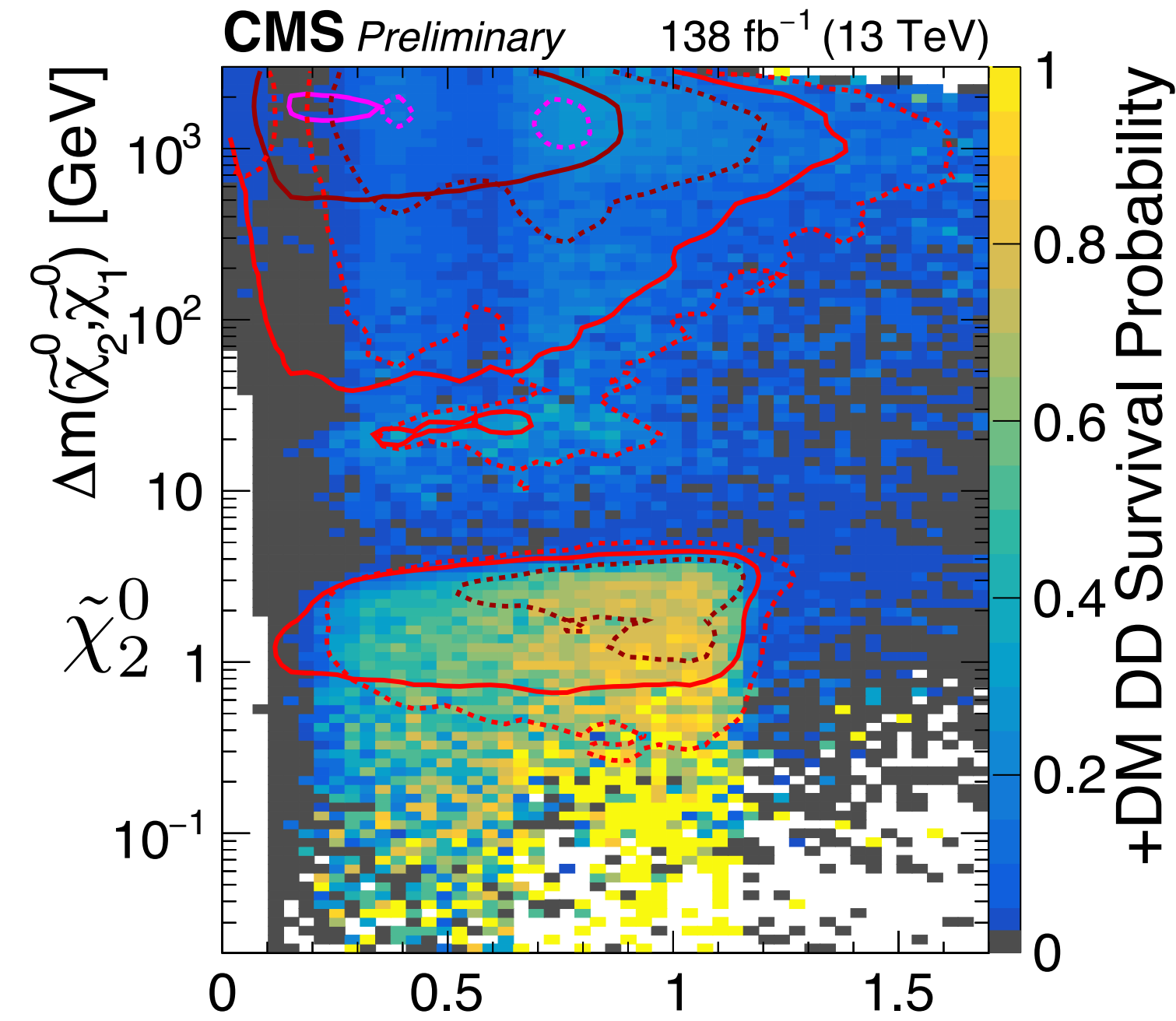
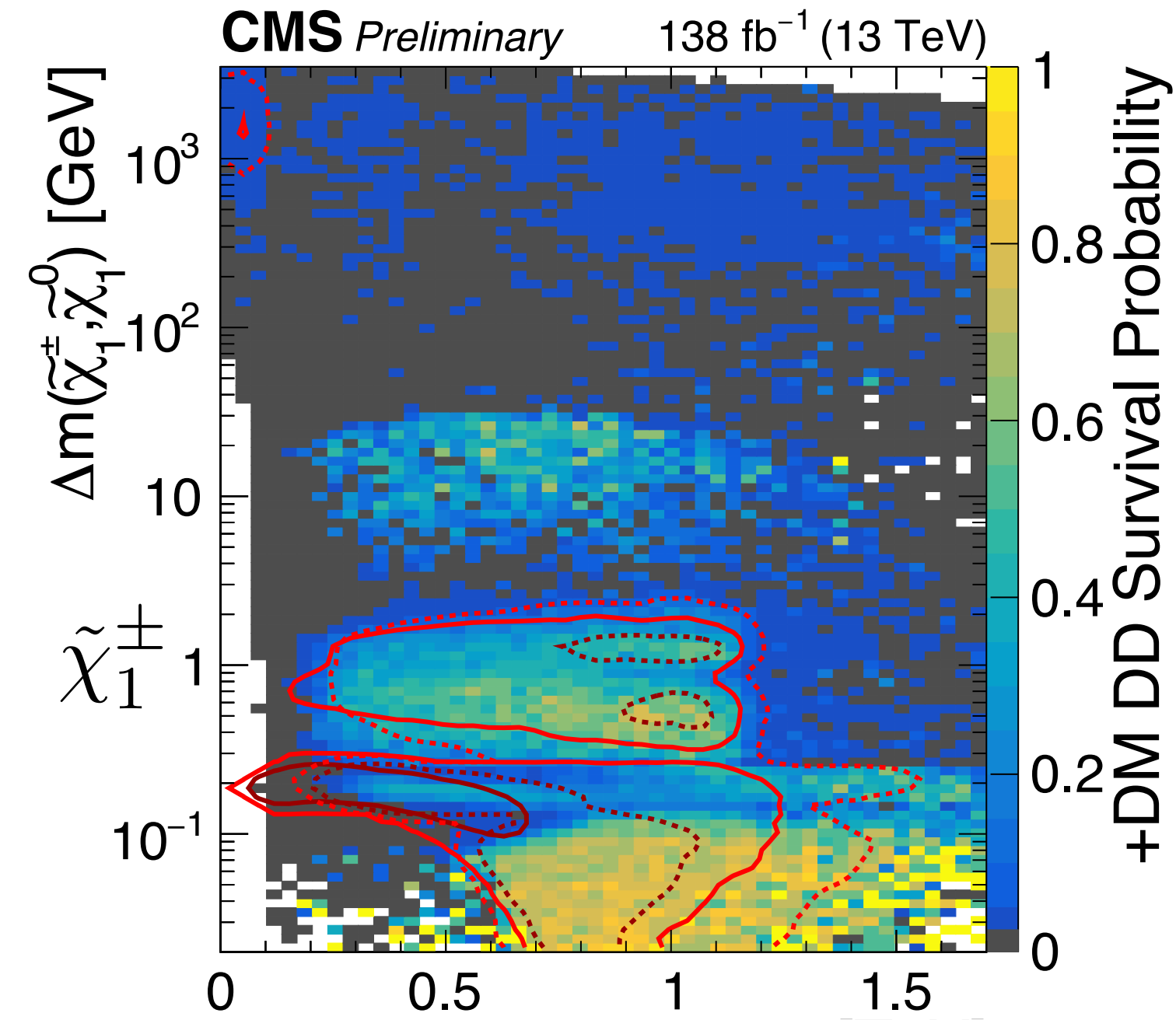
SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006

pMSSM impact analysis sequence

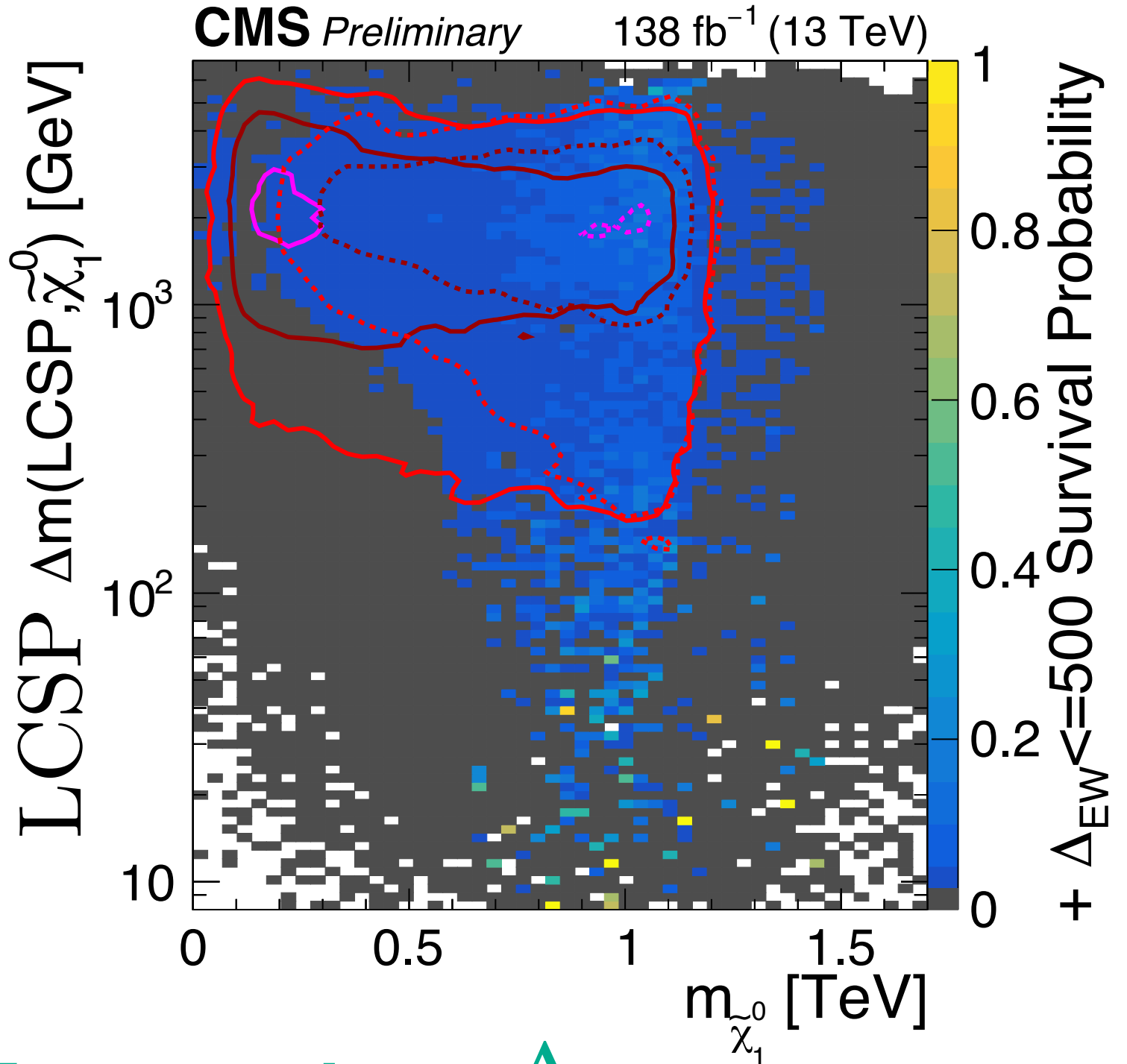
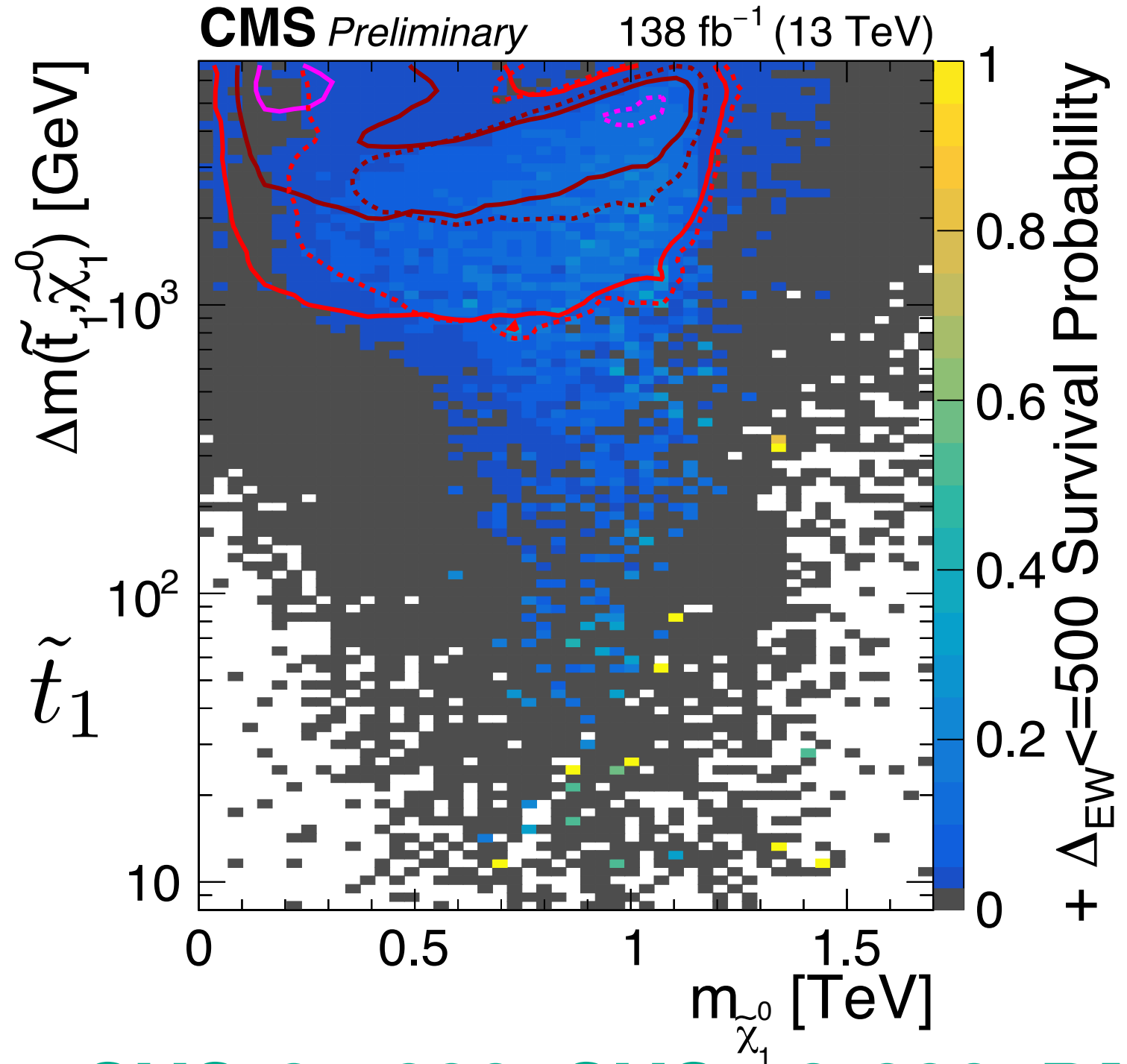
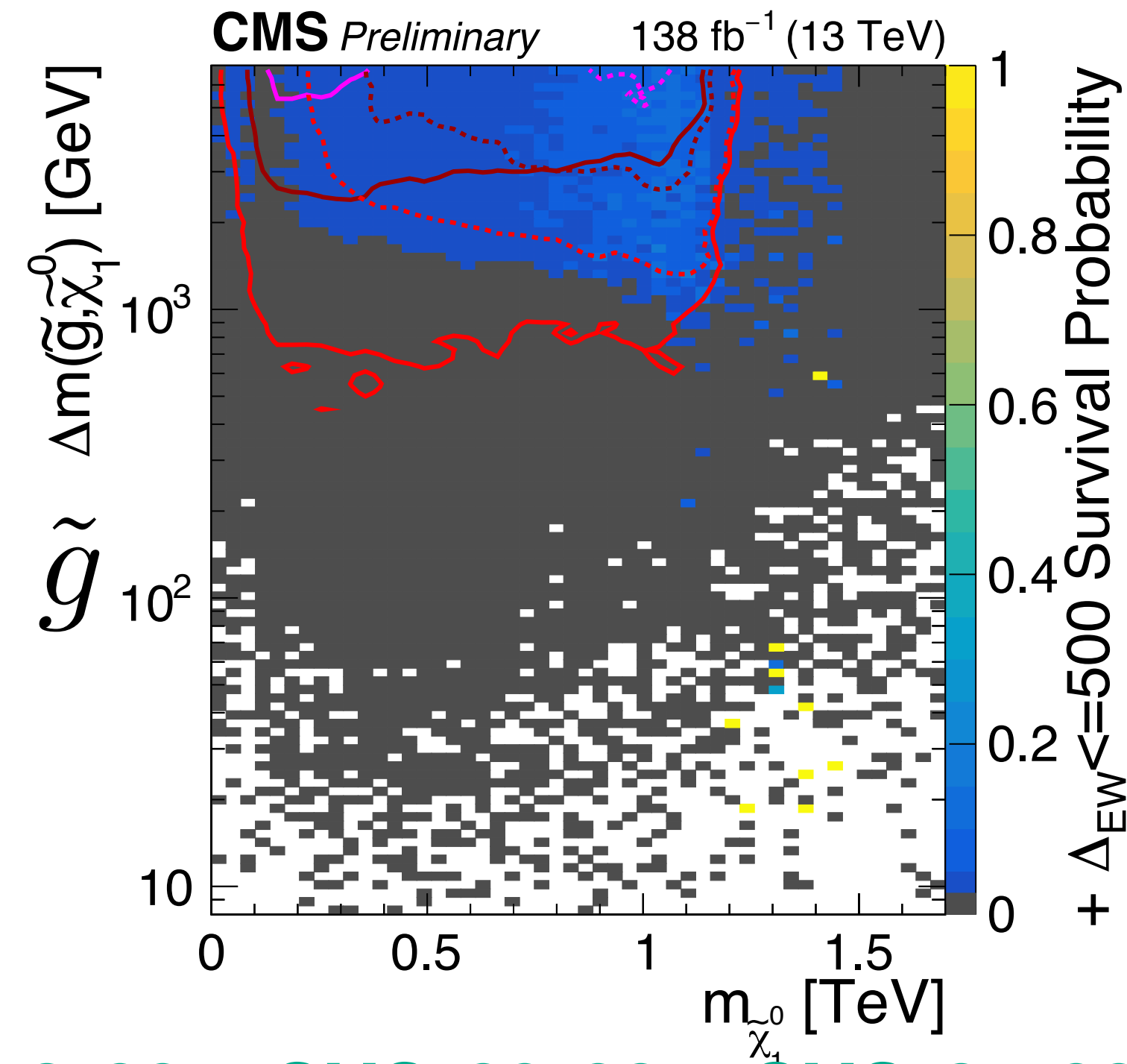
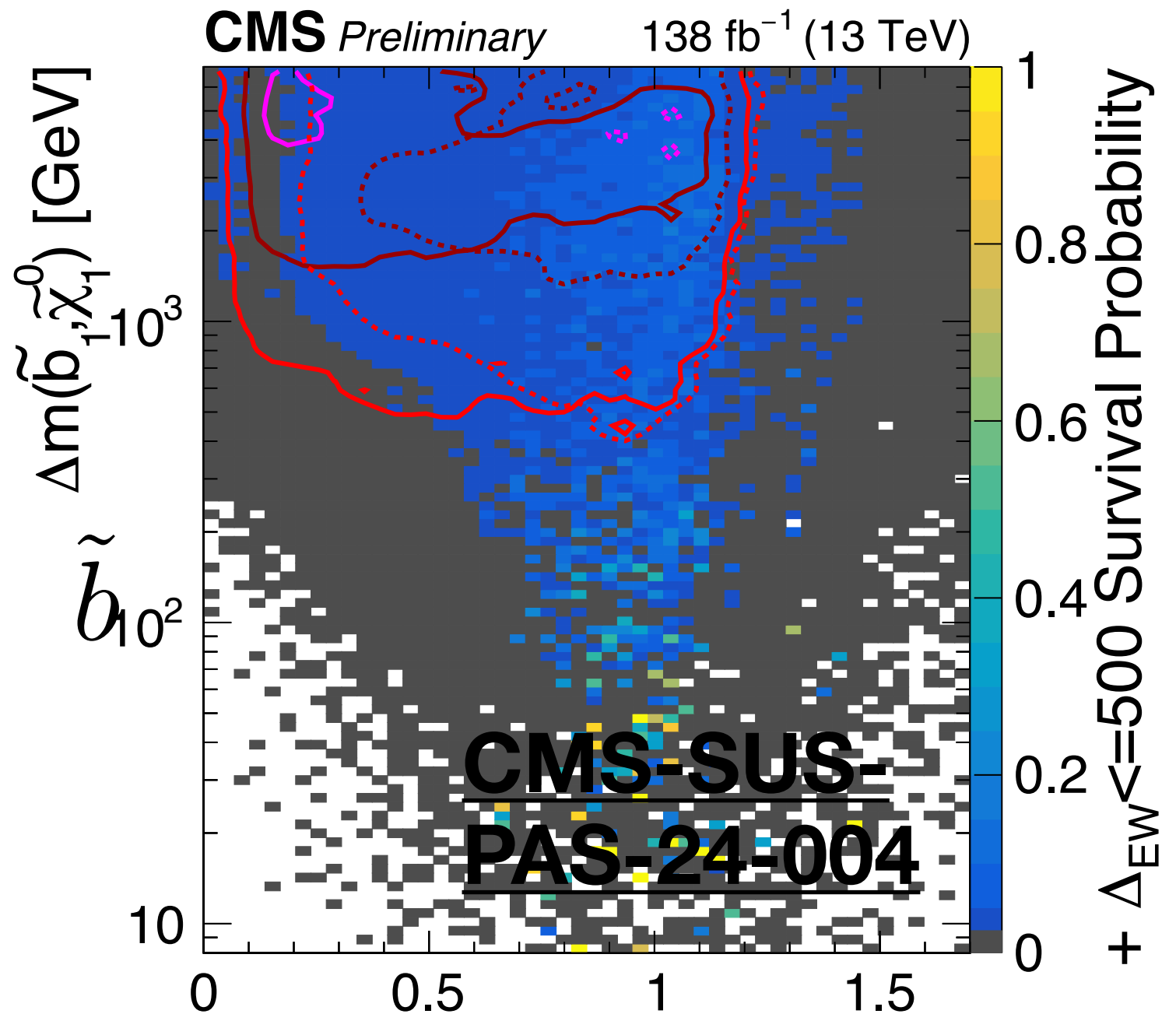
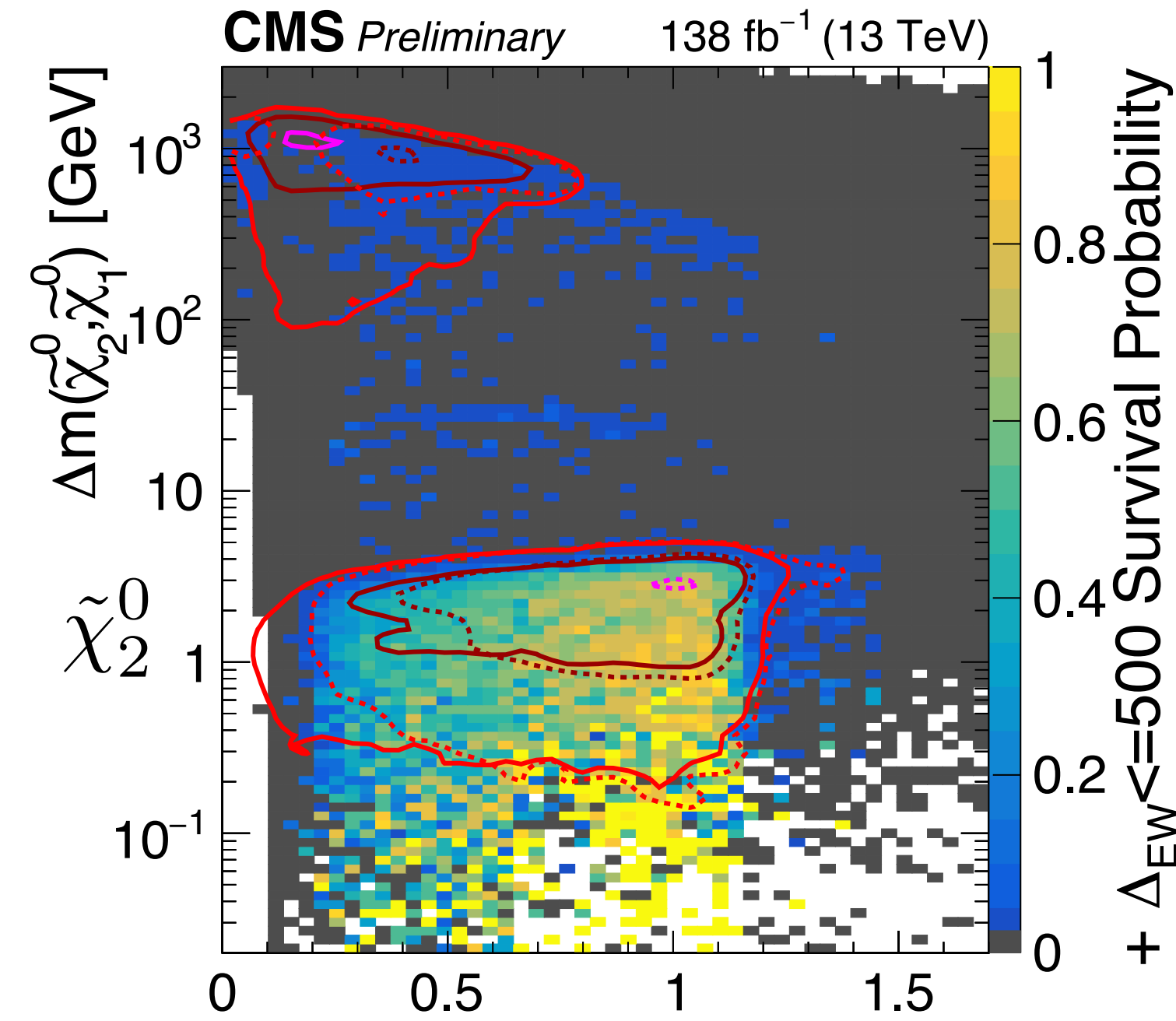
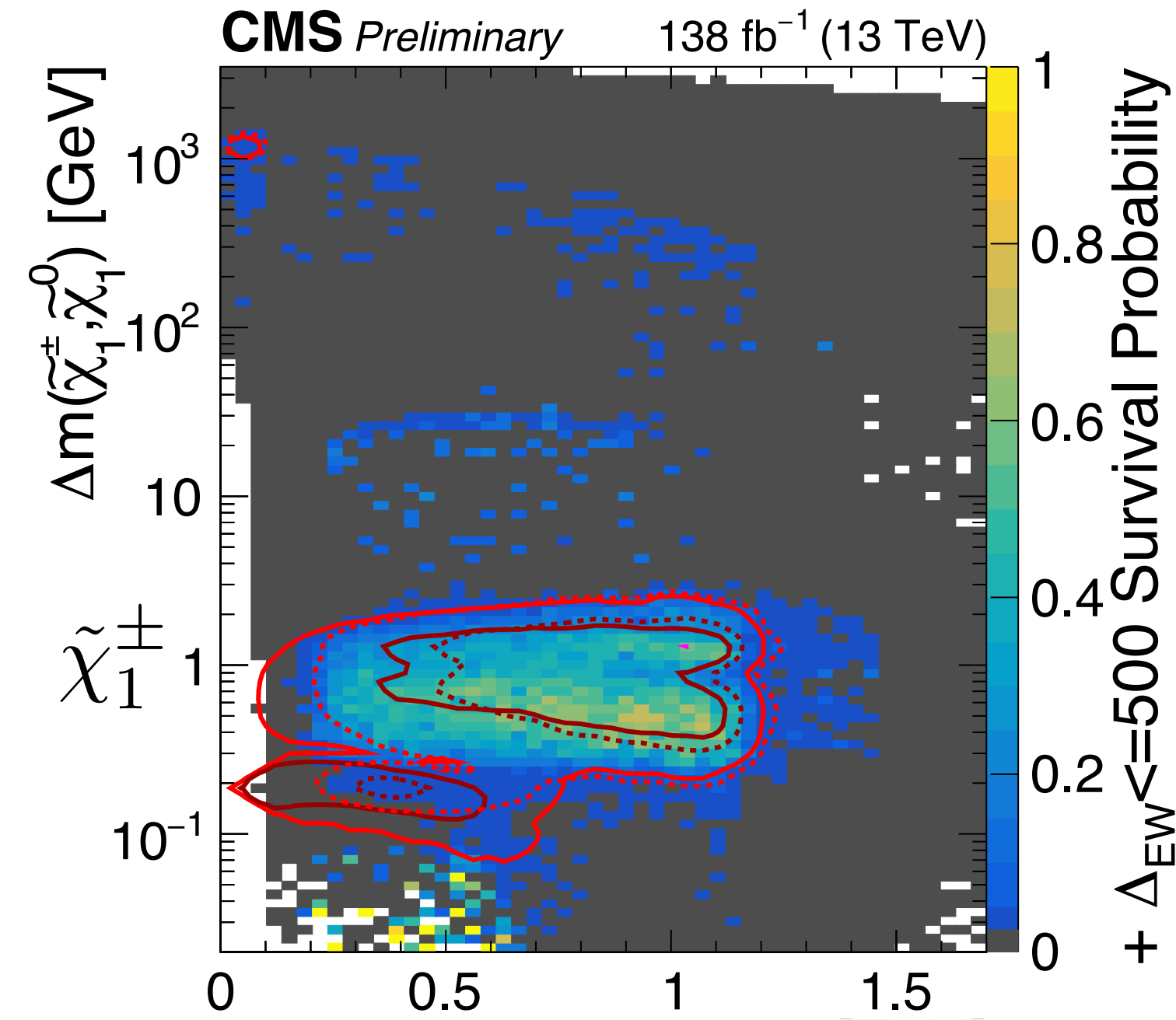


SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+ $\Omega_{h^2} < 110\%$

pMSSM impact analysis sequence



pMSSM impact analysis sequence

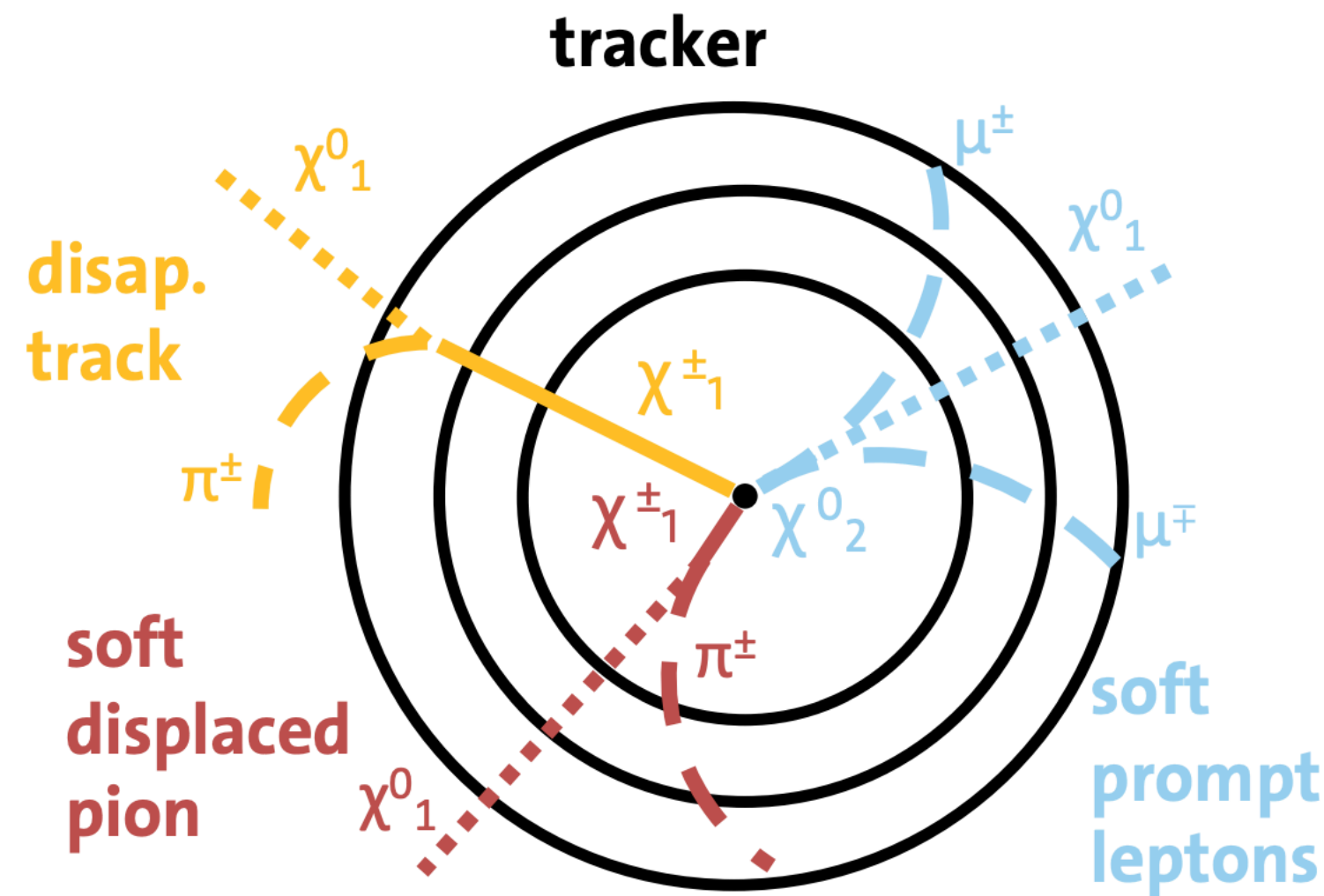


SUS-18-004+SUS-20-001+SUS-21-007+SUS-21-006+SUS-19-006+DM constraints+ $\Delta_{EW} < 200$

Soft pion track

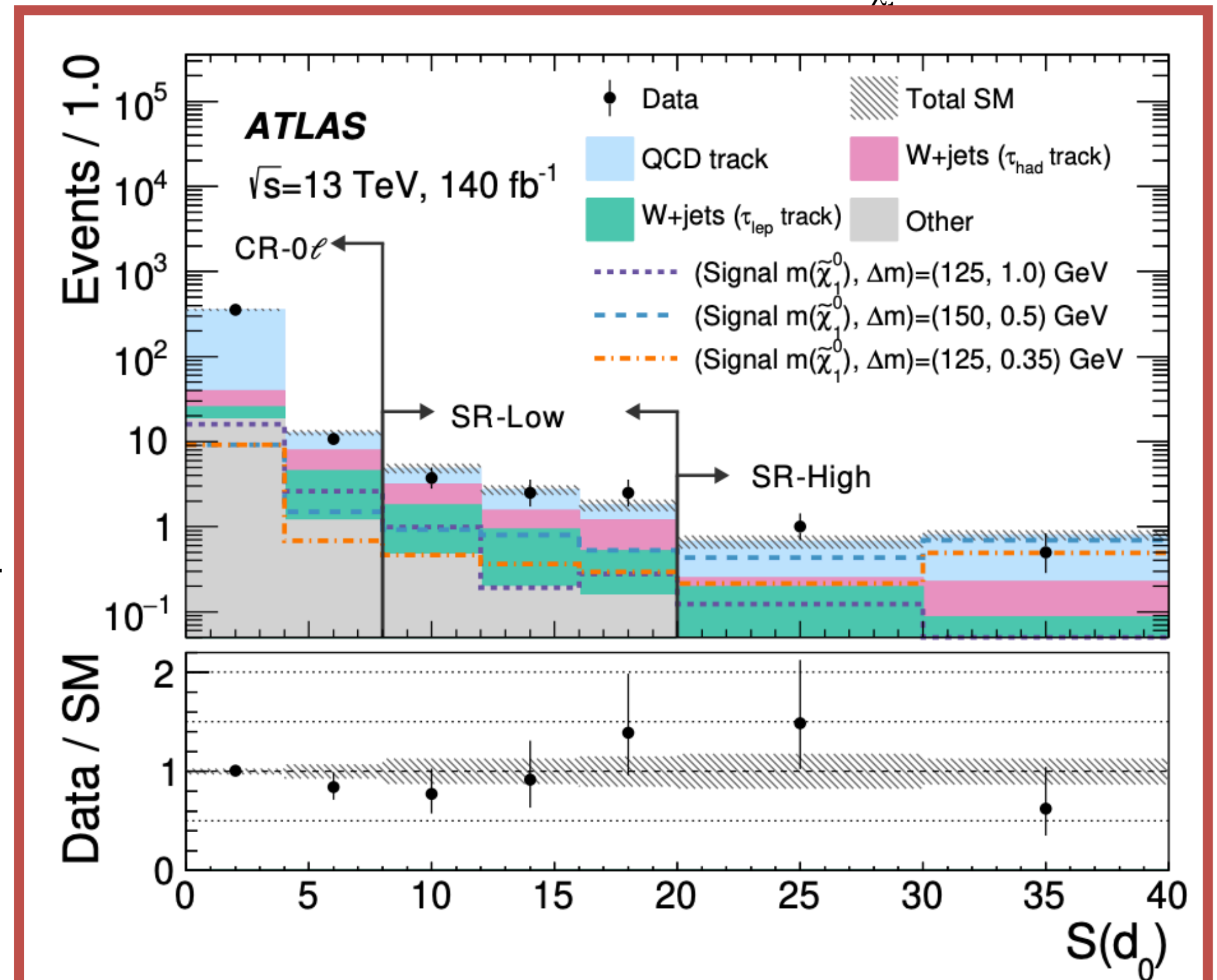
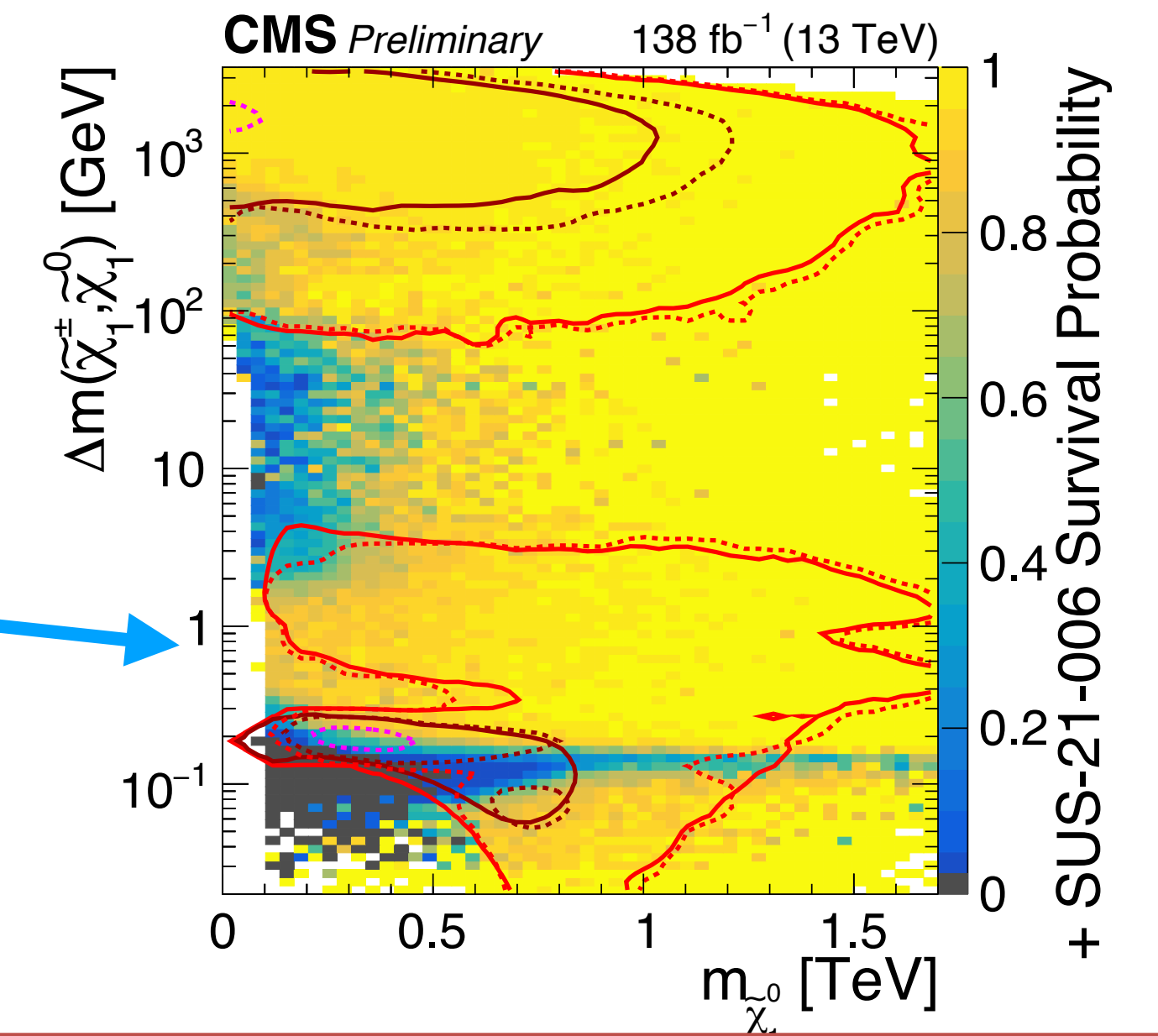
JHEP 1501 (2015) 029

- *Higgsino DM in High-Scale SUSY* - Shirai, Nagata
- Sensitivity gap around $dm = 0.3-1.0$ GeV
- Chargino decays within beam pipe into pion+LSP



Phys. Rev. Lett.
132 (2024) 221801

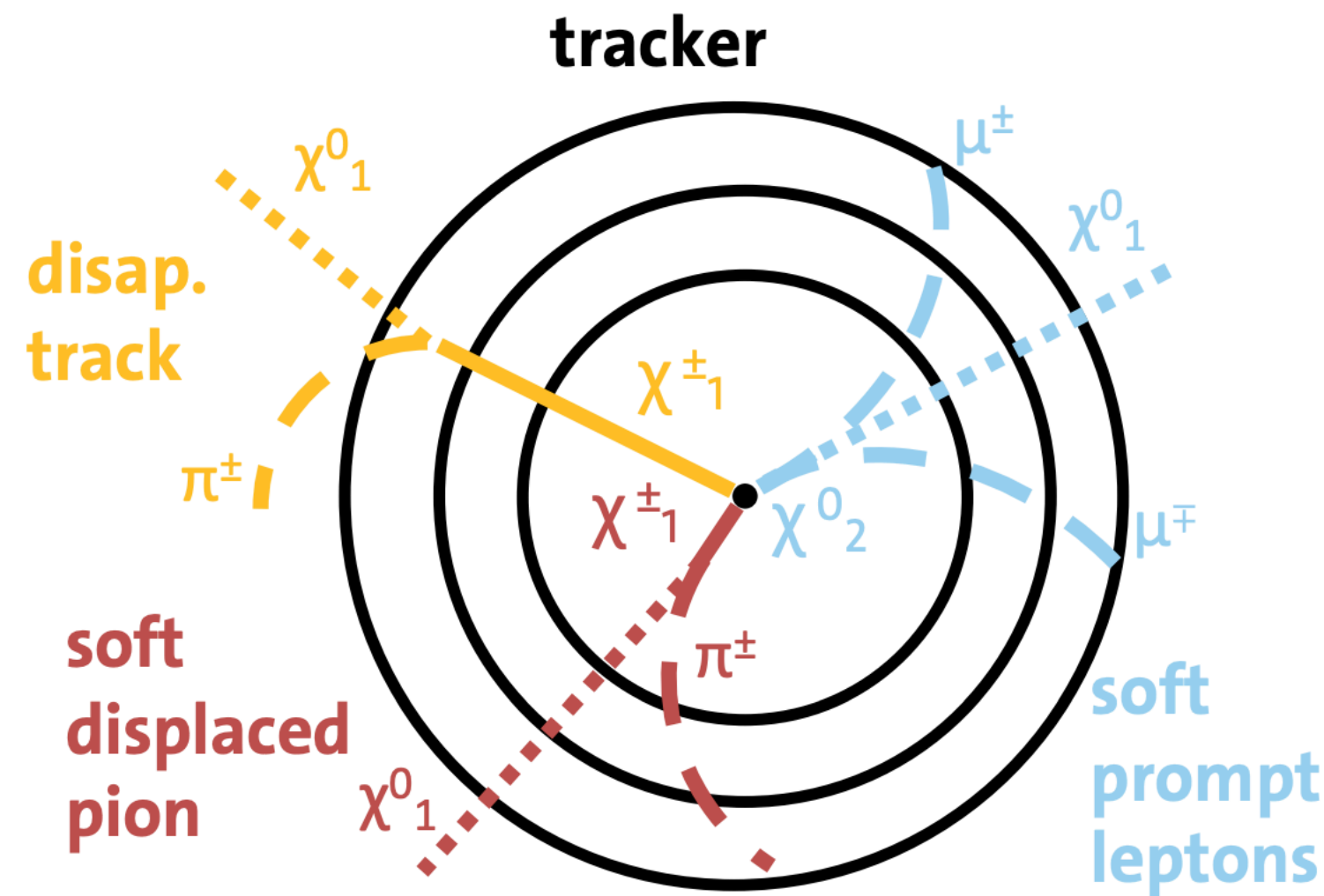
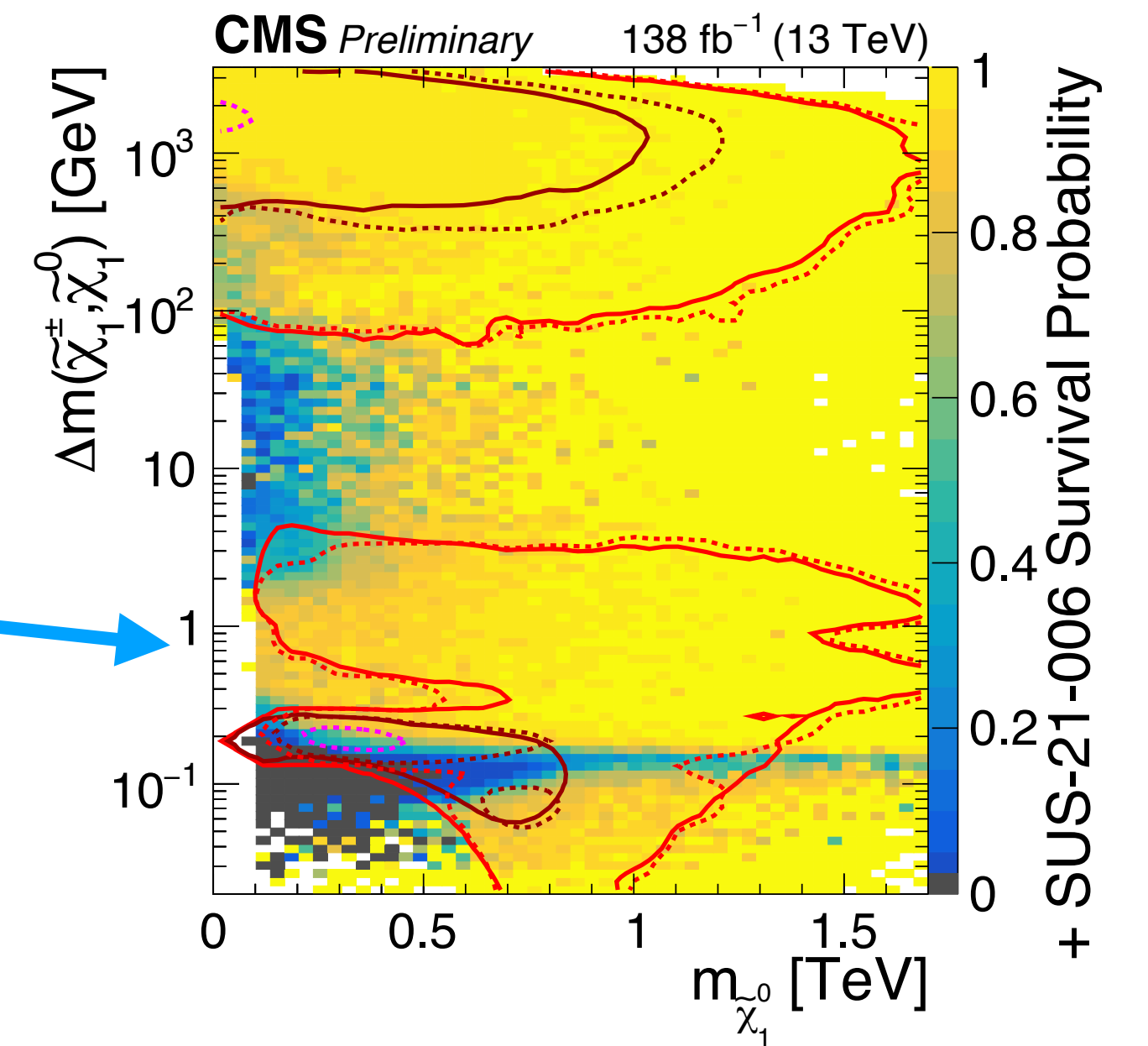
- *Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks*
 - Talk Wednesday BSM session: "Electroweak SUSY with ATLAS" - Ben Hodkinson



Soft pion track

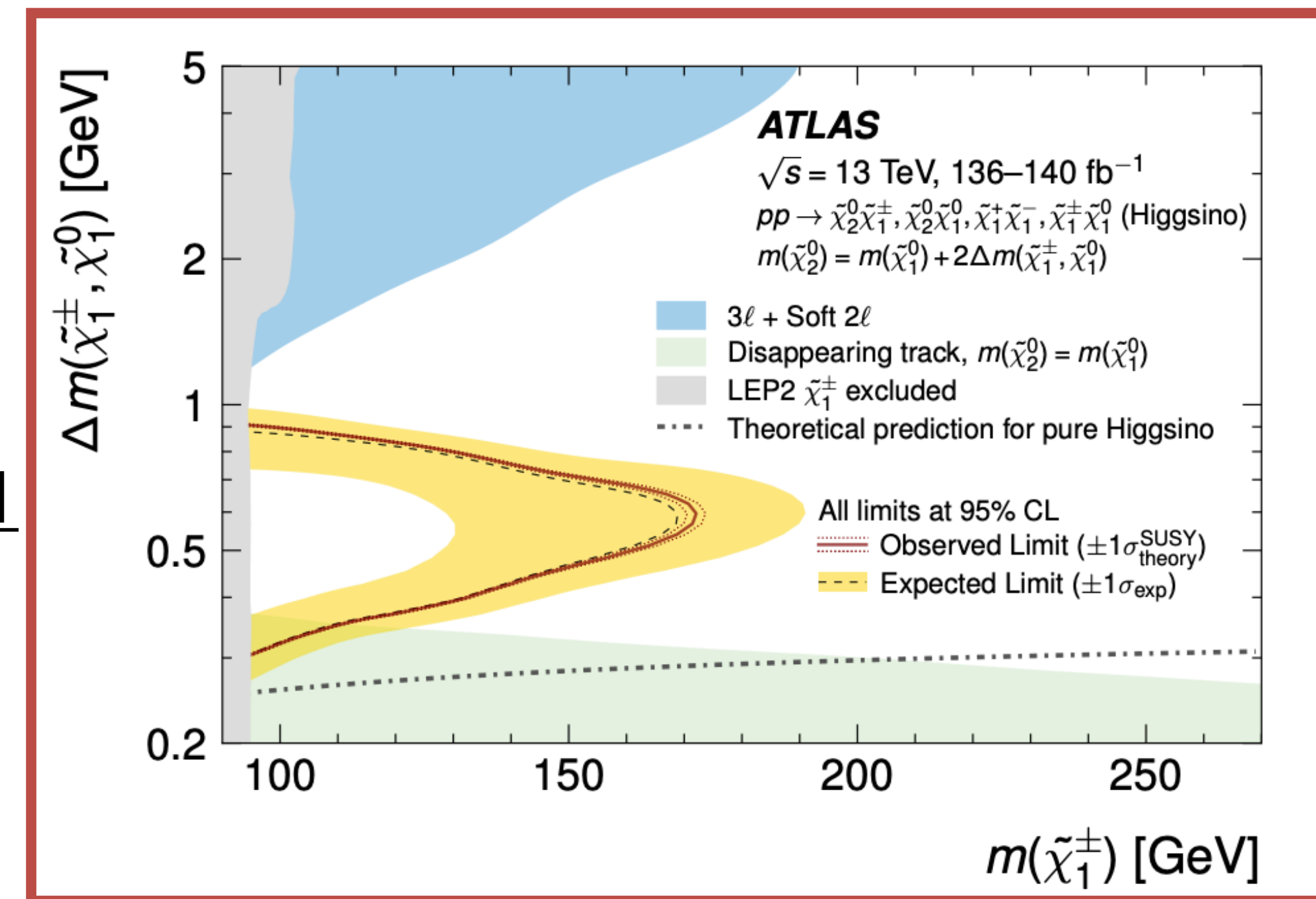
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Phys. Rev. Lett.
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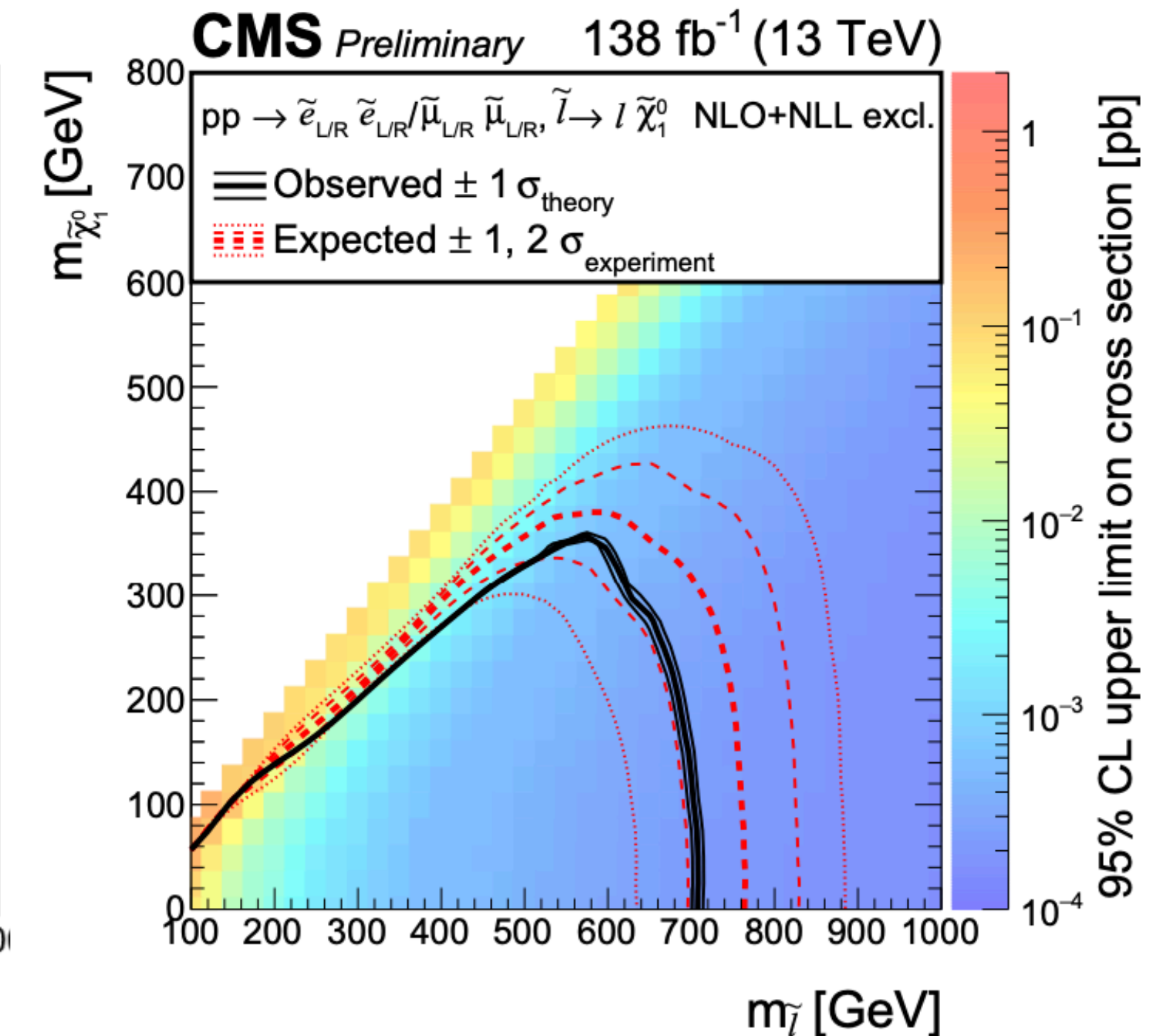
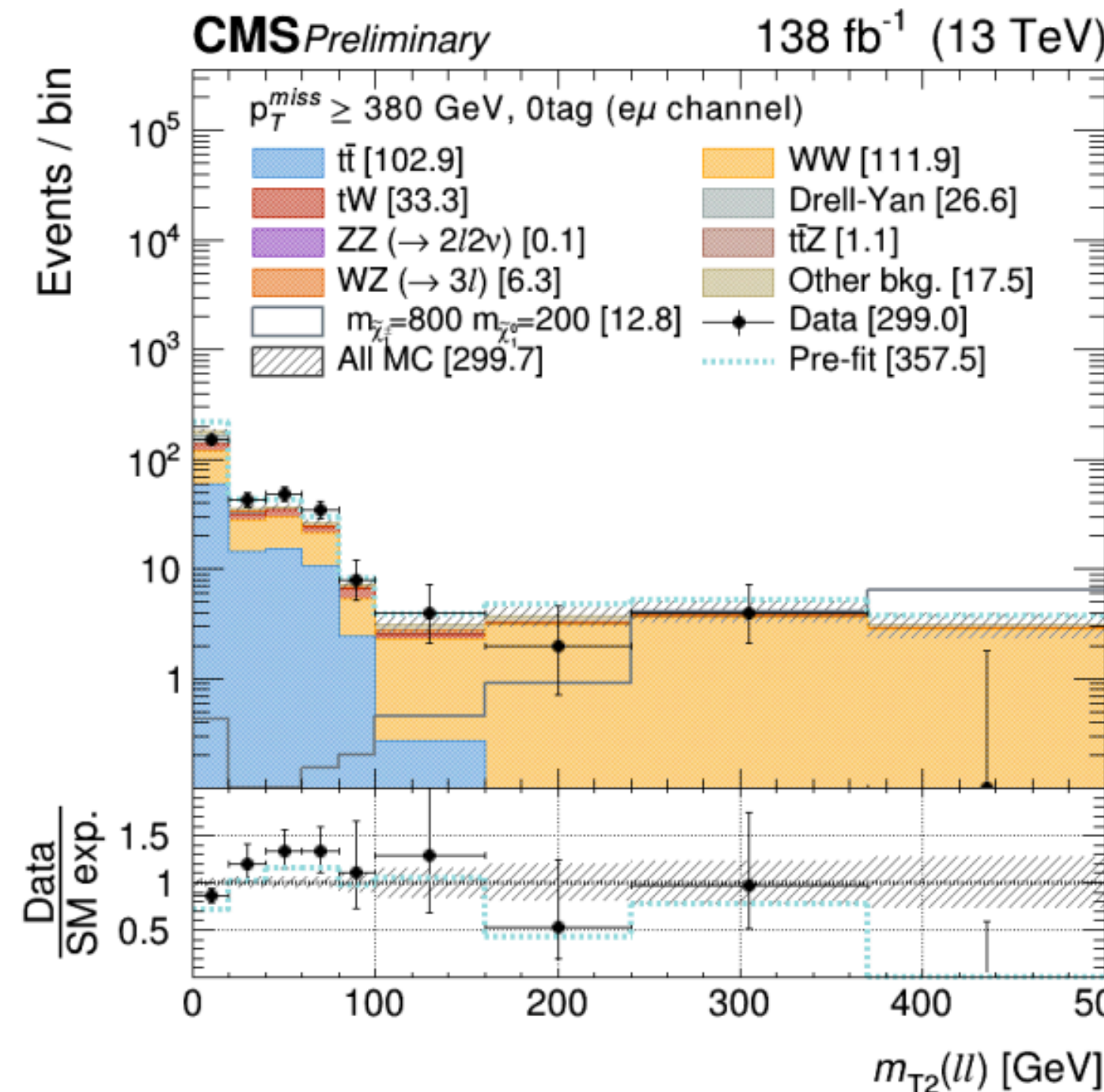
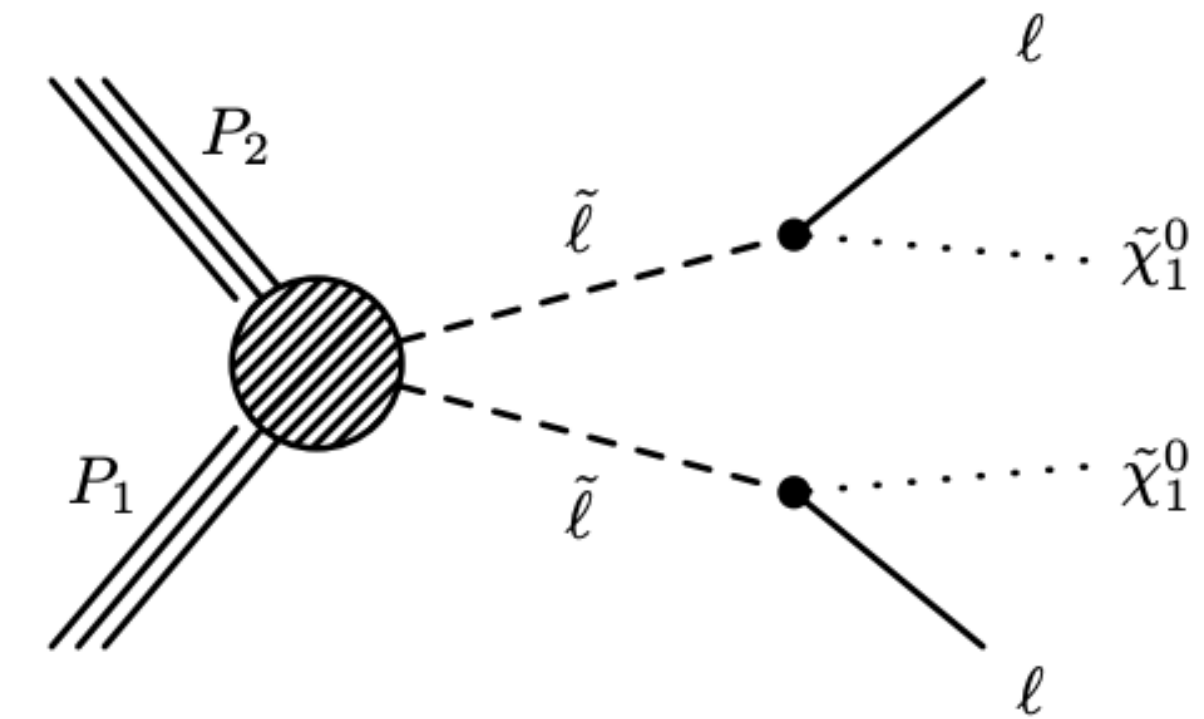
- *Search for Nearly Mass-Degenerate Higgsinos Using Low-Momentum Mildly Displaced Tracks*
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Slepton signatures with 2 leptons

CMS-SUS-PAS-23-002

- Search for SUSY particle[s] in final states with two oppositely charged leptons and large MET at 13 TeV
- Considers *different flavor* (DF) di-lepton final states
- Targets slepton in addition to electroweakino, and top squark production
- SRs binned in p_T^{miss} , m_{T2}
- with and without b-tagged jets



- *Many more SUSY results!*

- *ATLAS recently: RPV stops VBF compressed, etc*

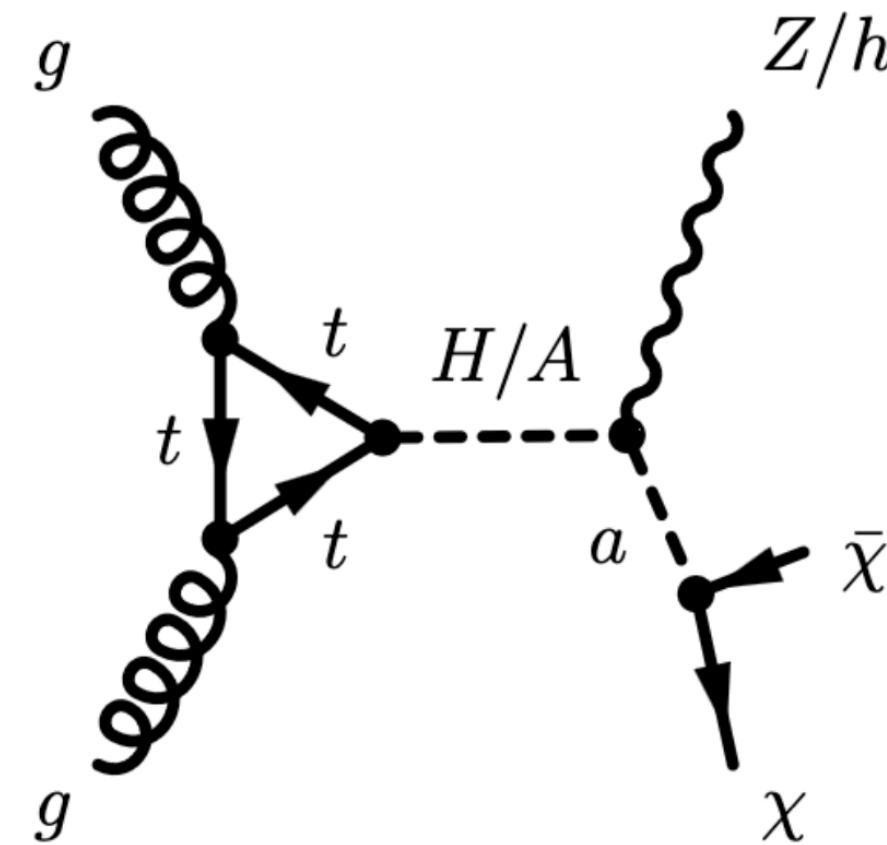
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

- *CMS recently: RPV stops, Recursive Jigsaw Compressed, etc*

<https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html>

Extra Higgses

- In the MSSM variants: (H^0, h, A, H^\pm)
- Extended Higgs sectors
 - 2-Higgs doublet models (2HDM)
 - 2HDM+s, 2HDM+a featuring (pseudo) scalar
 - *LHC DM WG White Paper*
- Dark sectors feebly coupled to the SM



2HDM+a

- 5 Higgs boson
- Light Pseudo scalar mediator
- Rich collider physics and DD complementarity

CMS and ATLAS diphoton resonance searches

- Search for a standard model-like Higgs bosons in mass range 70-110 GeV

- CMS [arXiv:2405.18149](https://arxiv.org/abs/2405.18149)

- ATLAS [arXiv:2407.07546](https://arxiv.org/abs/2407.07546)

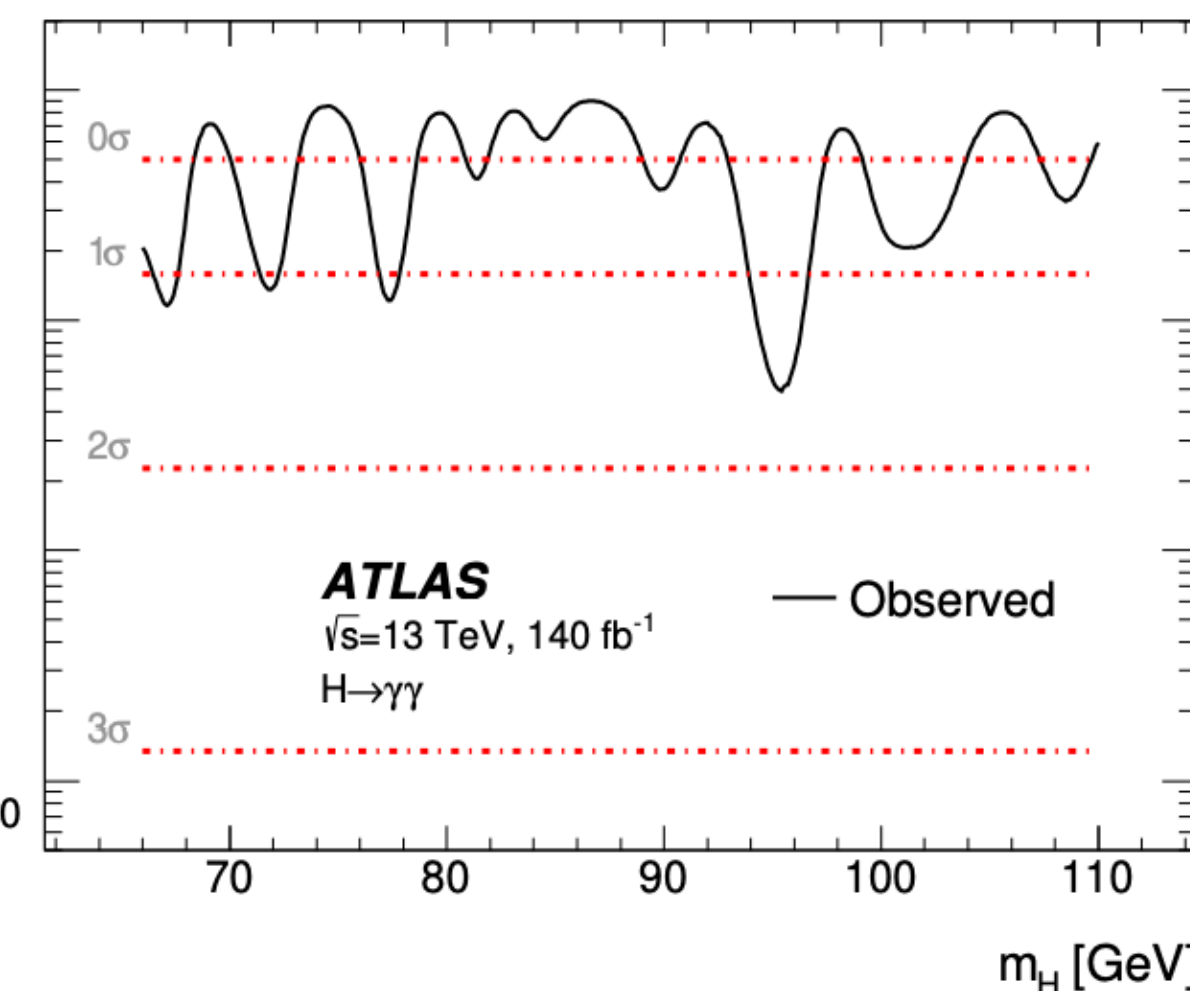
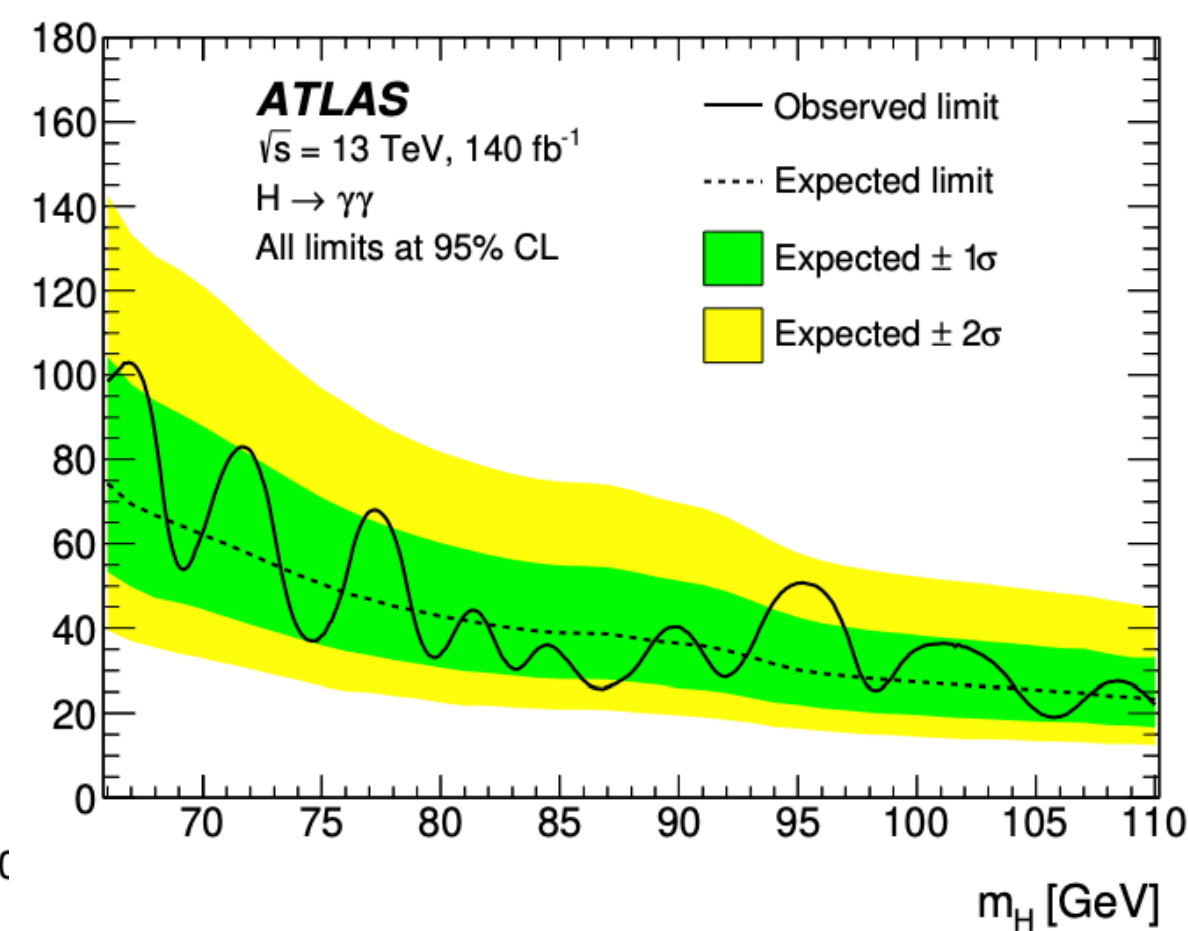
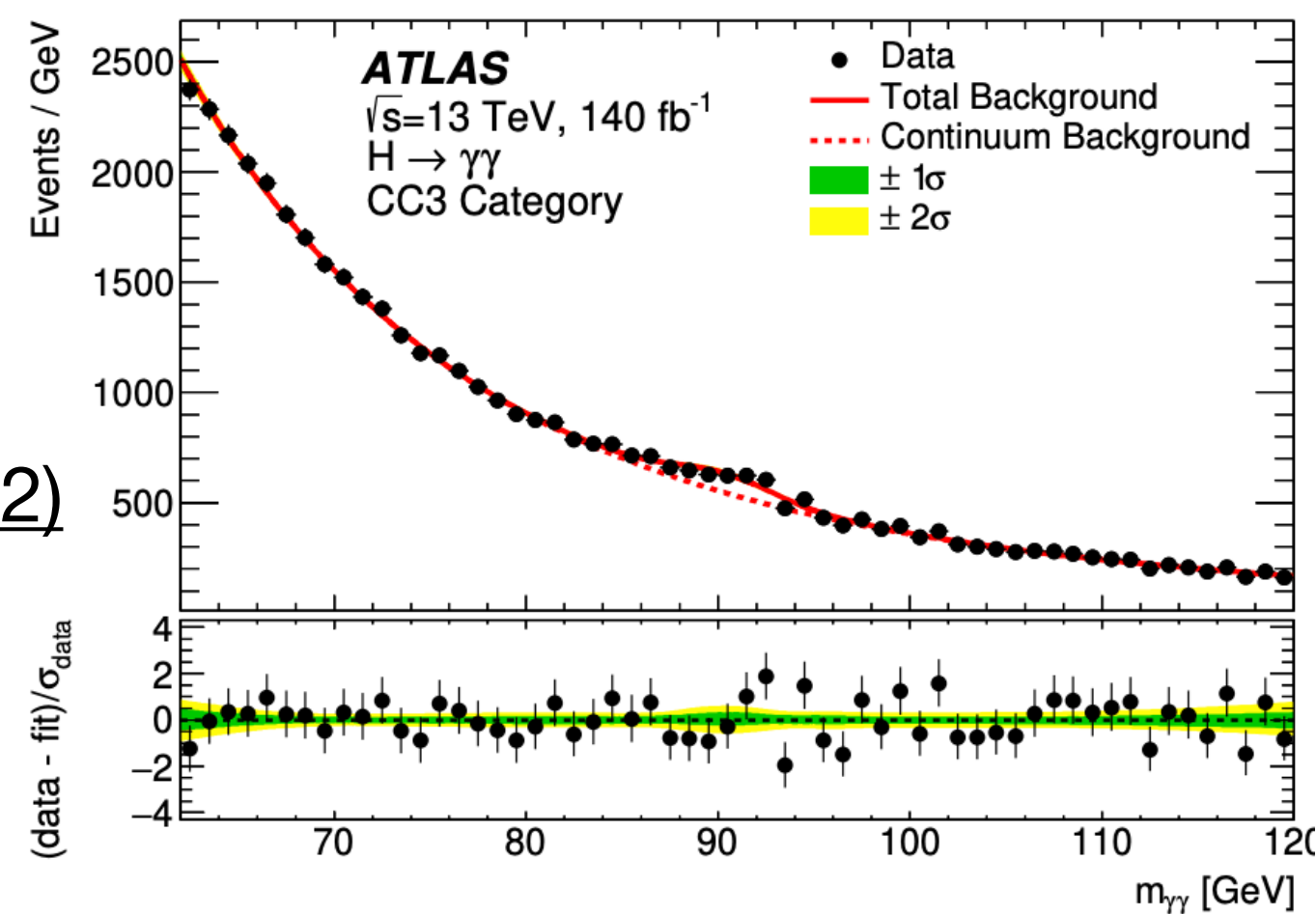
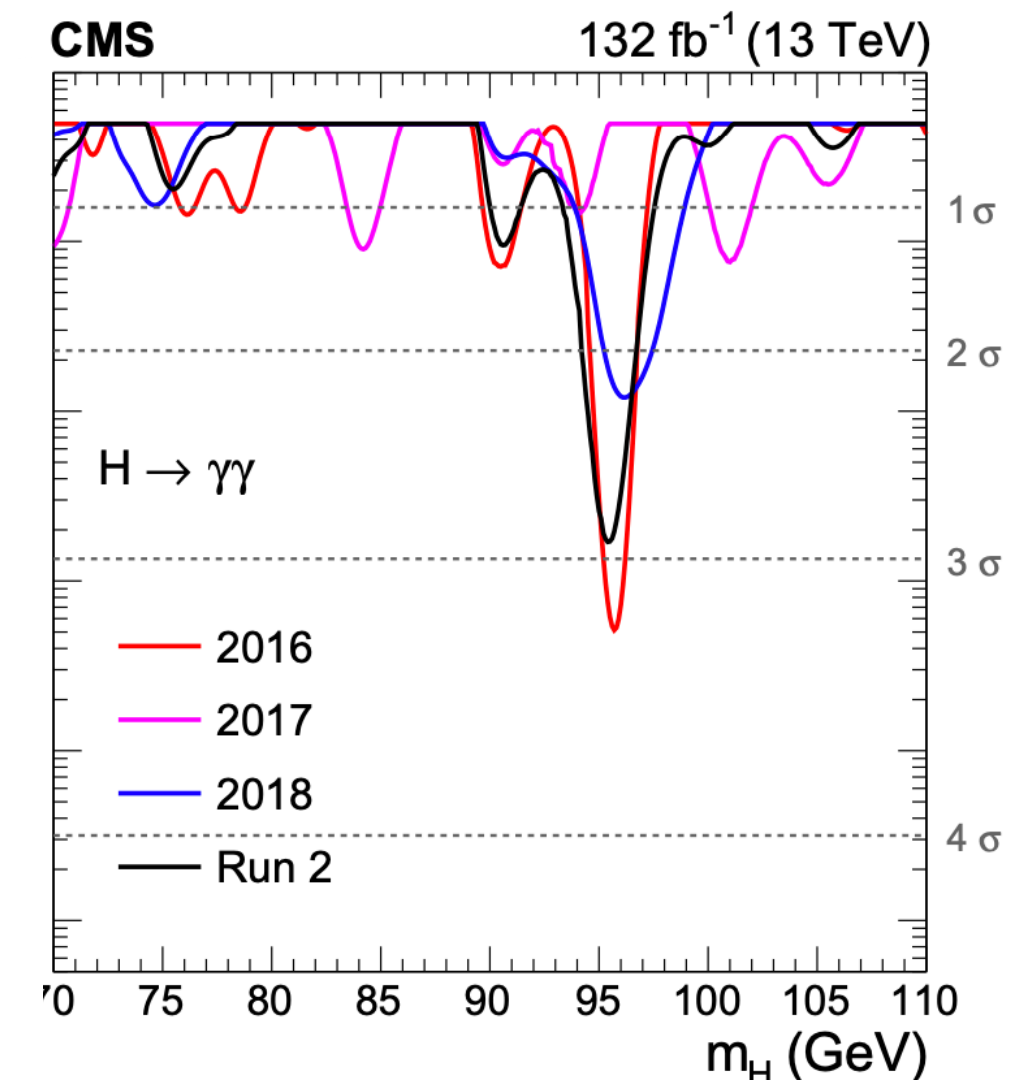
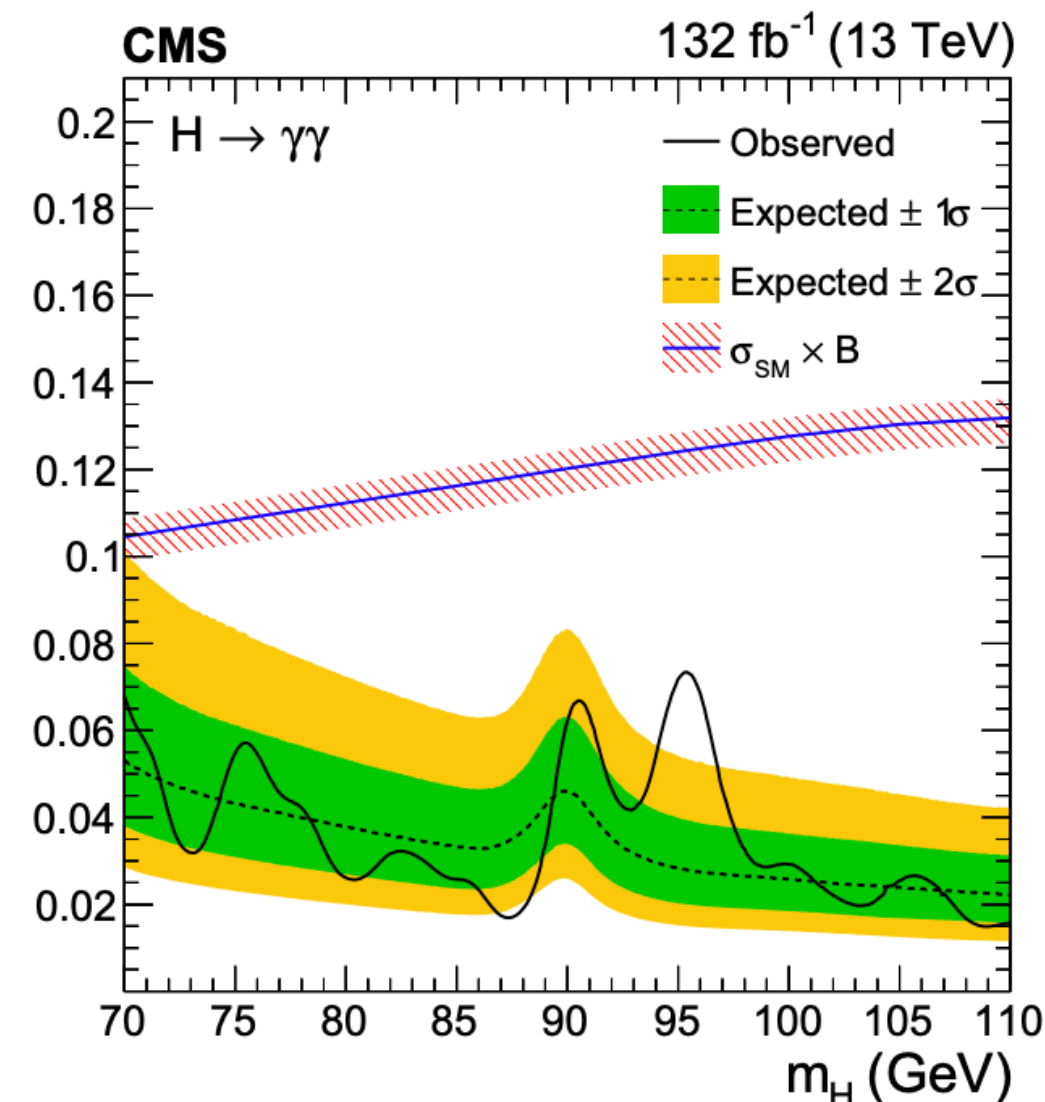
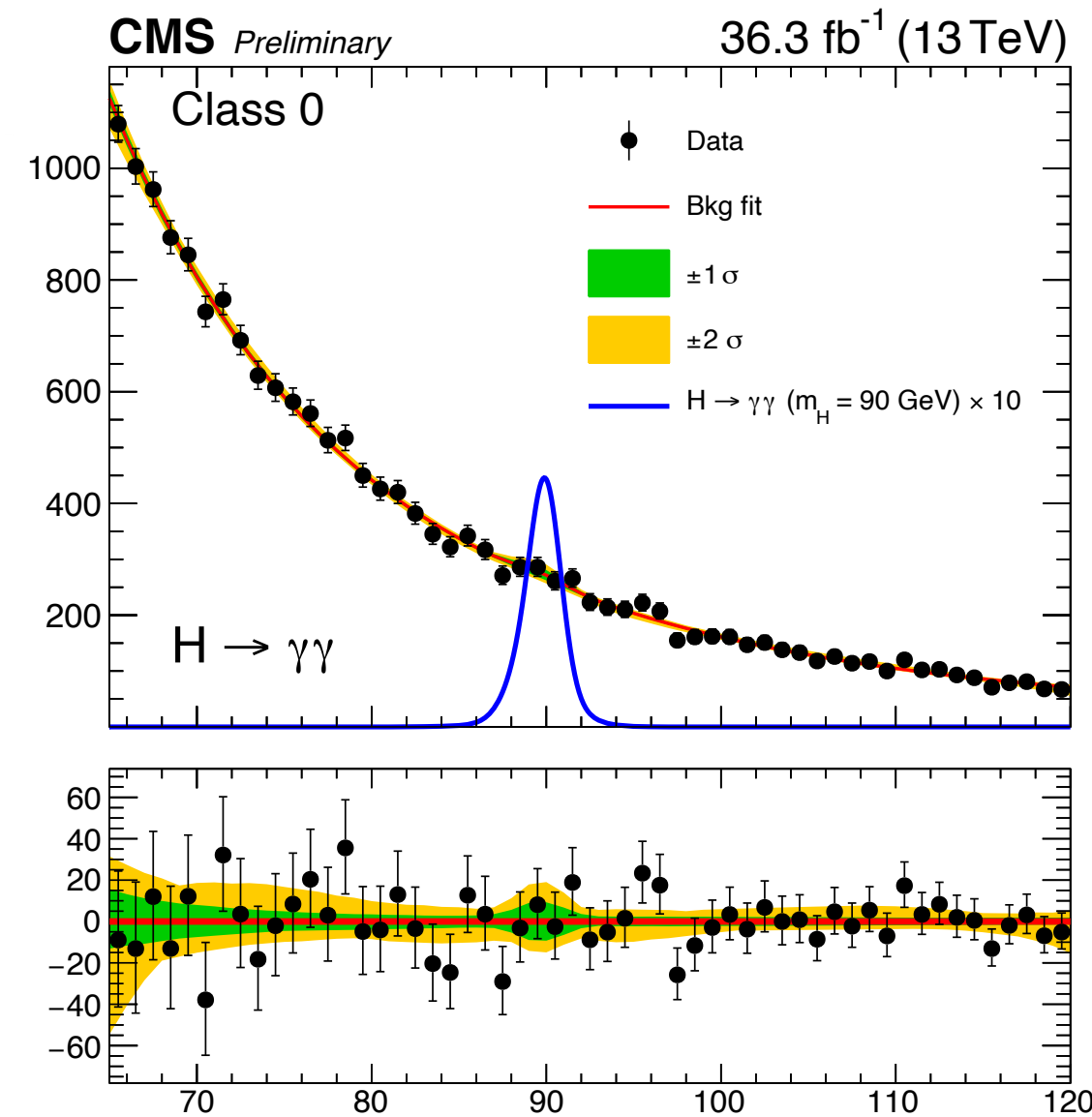
- Model-specific BDT

- Model-independent

- Unofficial combination

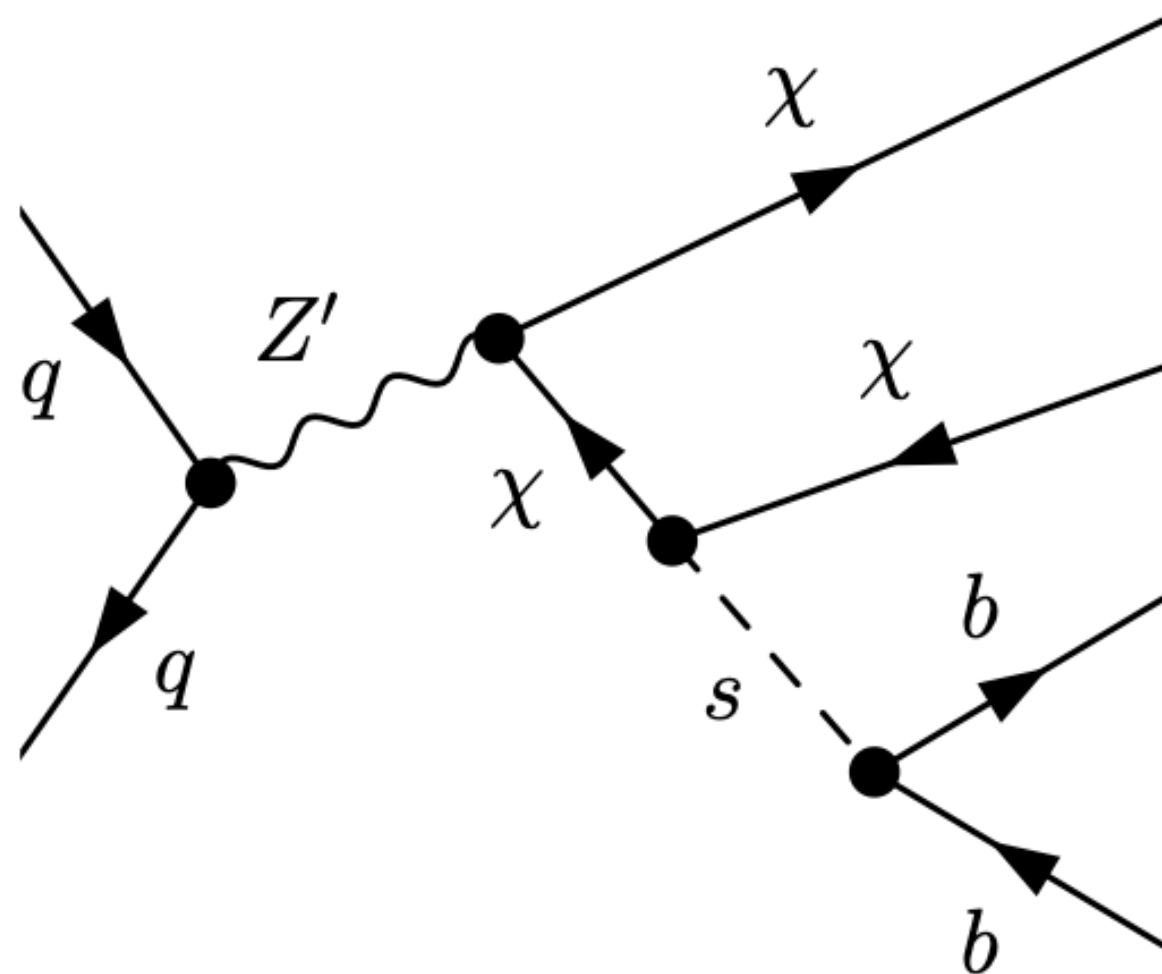
- *The 95.4 GeV diphoton excess*,
Biekötter, Heinemeyer,
Weiglein [JHEP 2022, 201 \(2022\)](https://arxiv.org/abs/2202.0201)

- Significance 3.1σ



Hunting the dark Higgs

- Dark sector models feature new Higgs bosons
 - *Hunting the dark Higgs* R Duerr, et. al 2017
 - New particle content
 - Heavy vector boson, dark matter candidate χ , and lightest dark sector Higgs
- Achieve low enough relic density through $\chi \rightarrow ss, m(\chi) > m(s)!$



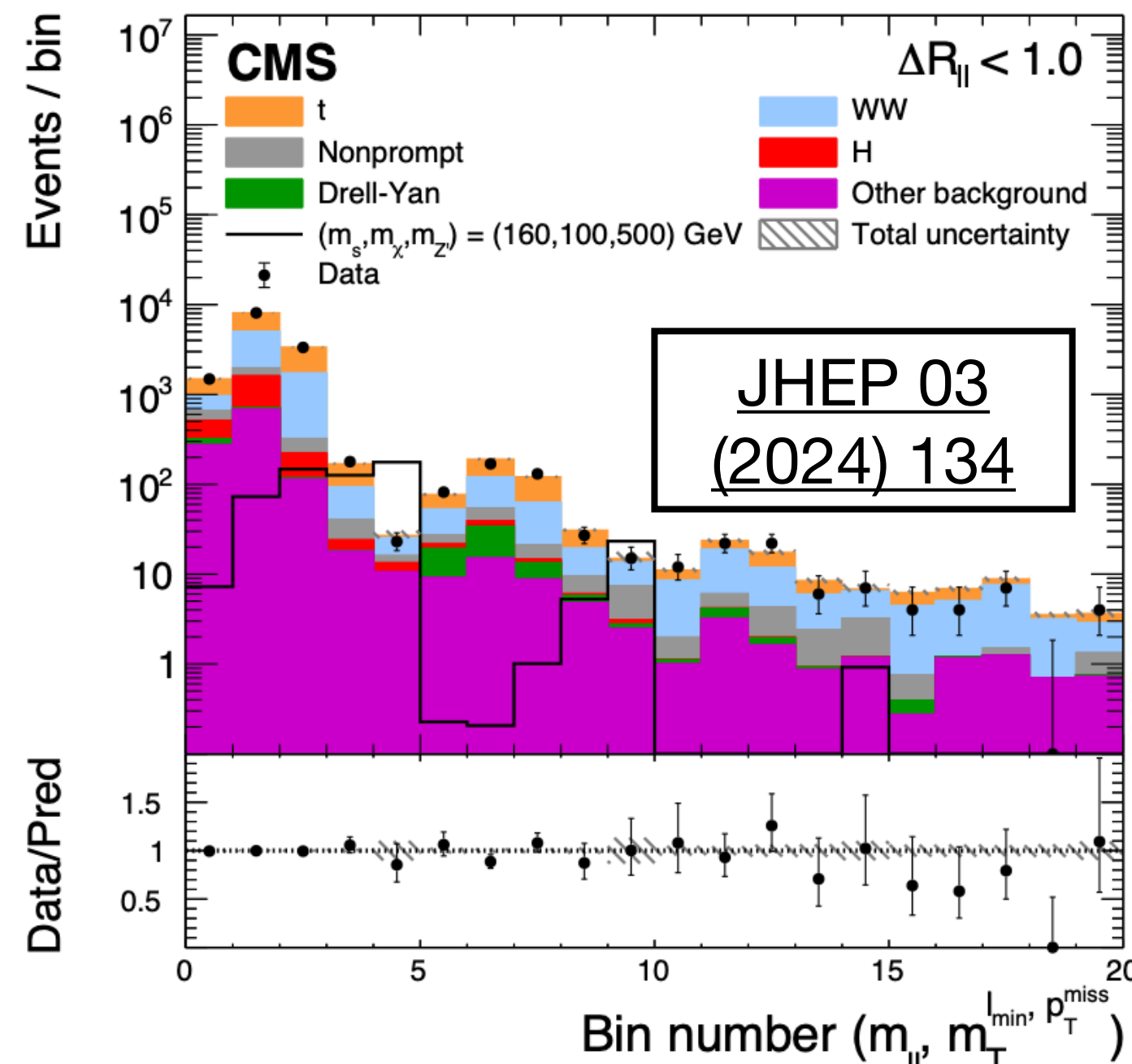
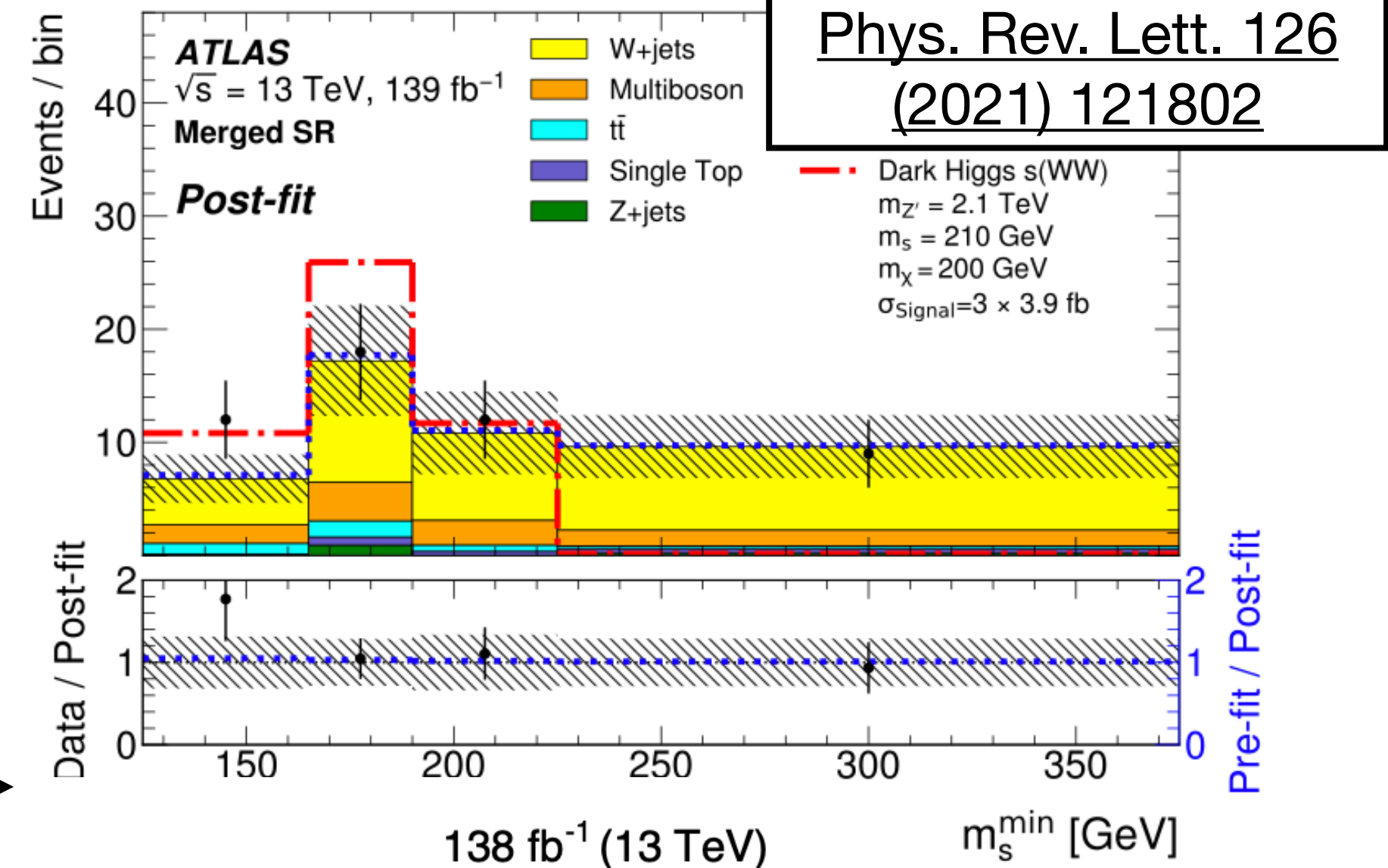
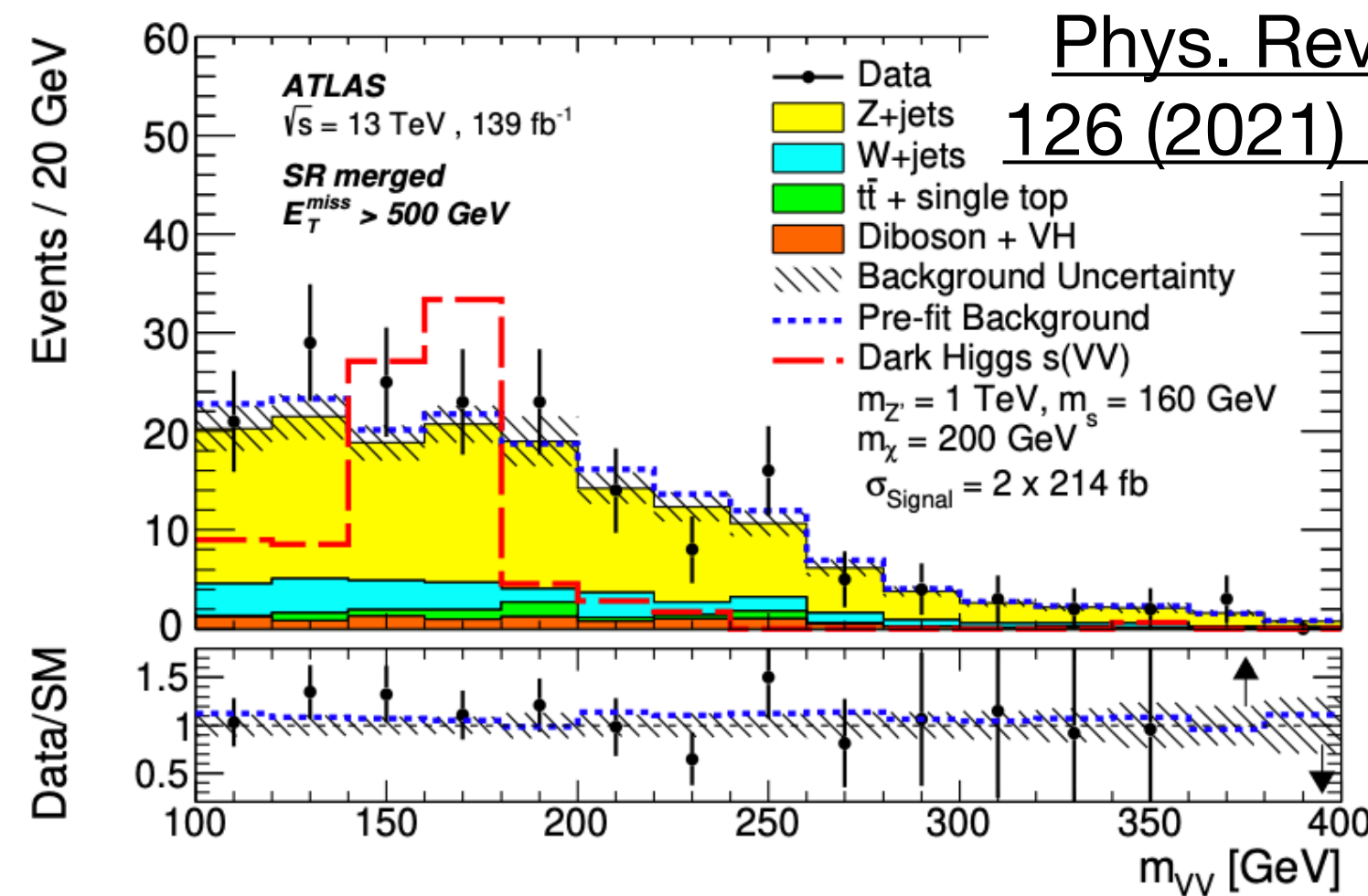
Dark Higgs model

- Can generate relic density
- Light Pseudo scalar mediator
- Rich collider pheno Z' , resonances, MET

Hunting the dark Higgs @ ATLAS & CMS

- $S \rightarrow WW, ZZ$
- Final states
 - All-hadronic \rightarrow
 - single-lepton \rightarrow
 - 2-lepton \rightarrow
- Bin in $m_{\ell, \ell}, m_T(\ell_{\min}, \vec{p}_T^{\text{miss}})$

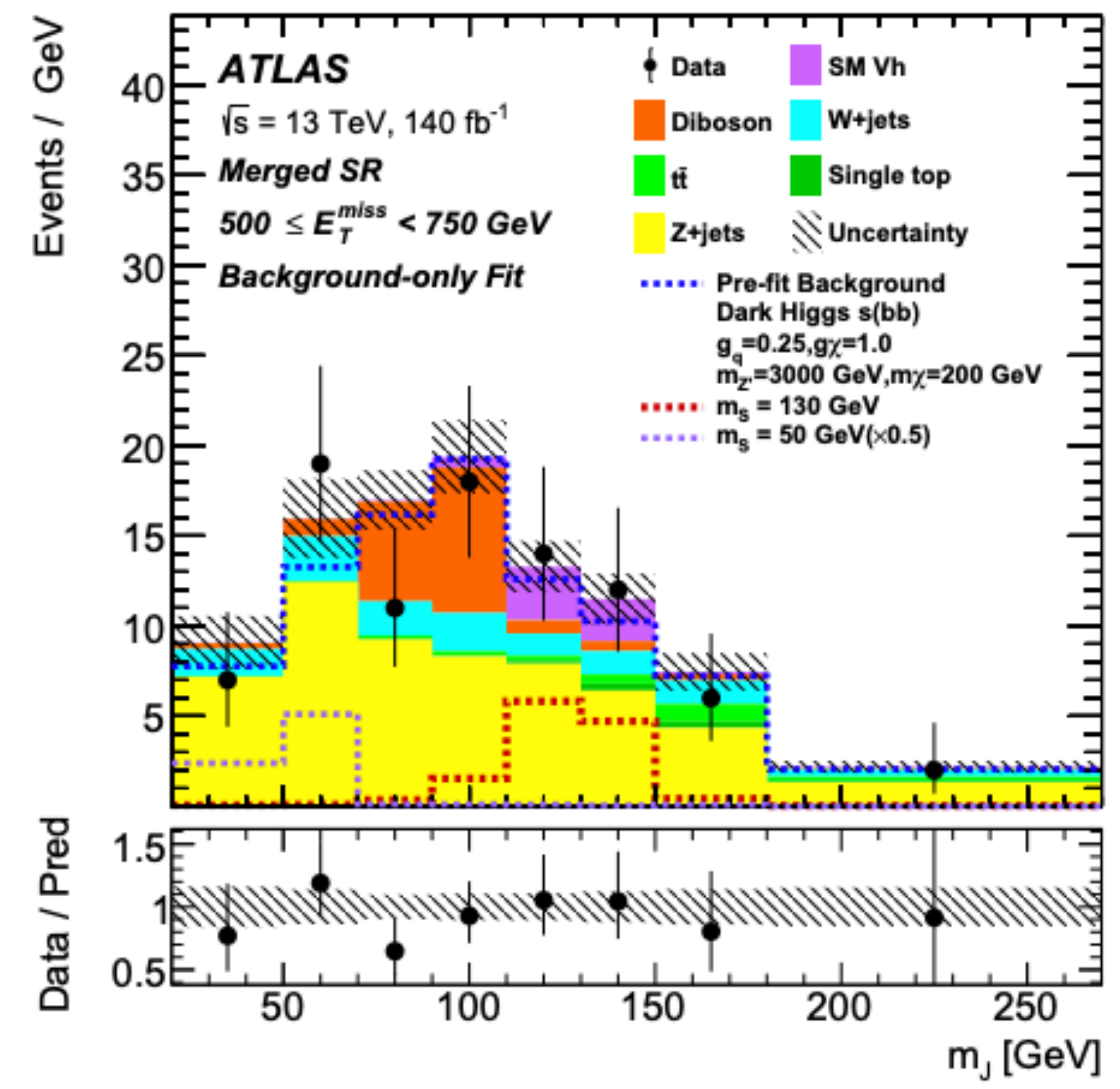
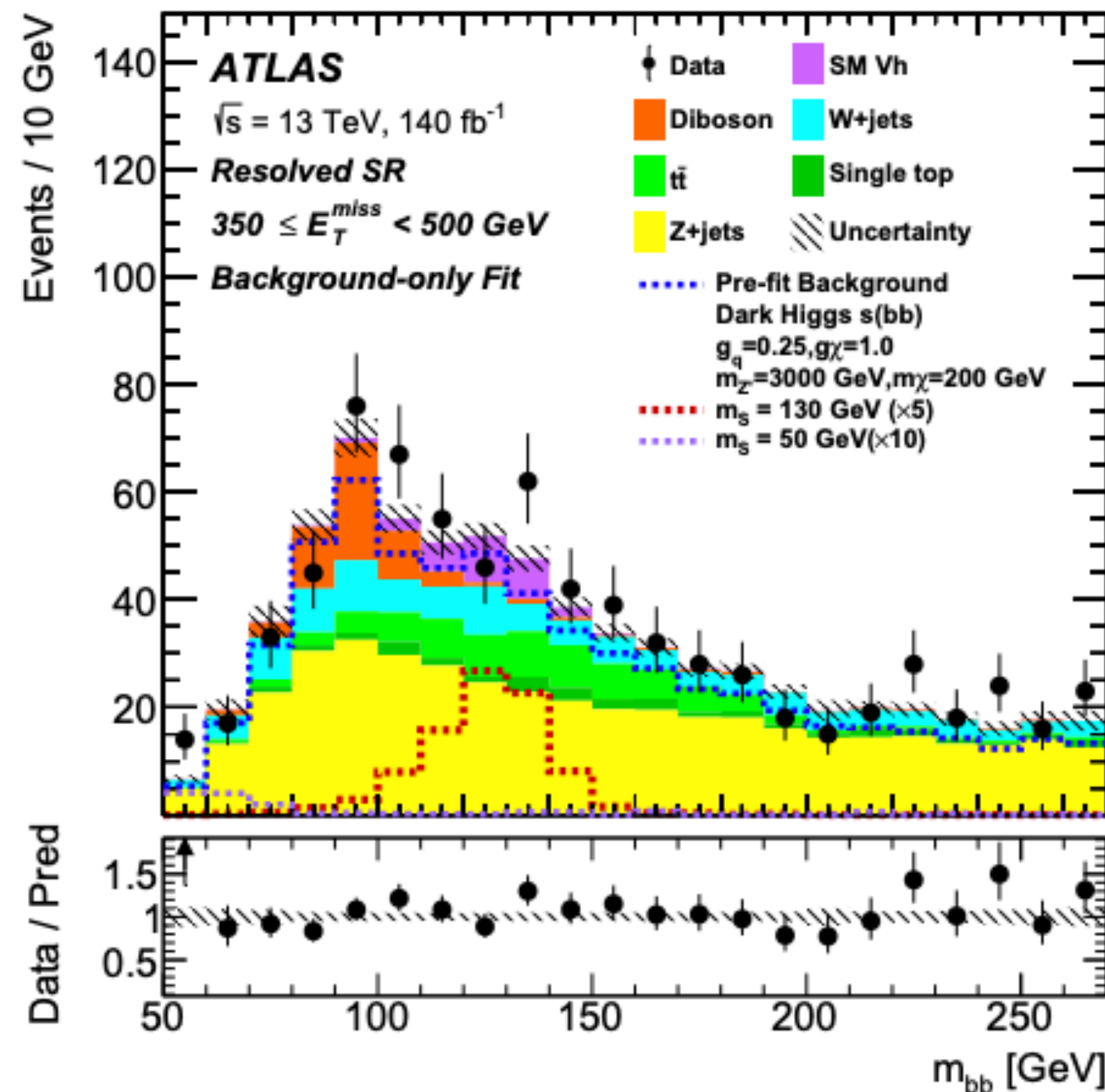
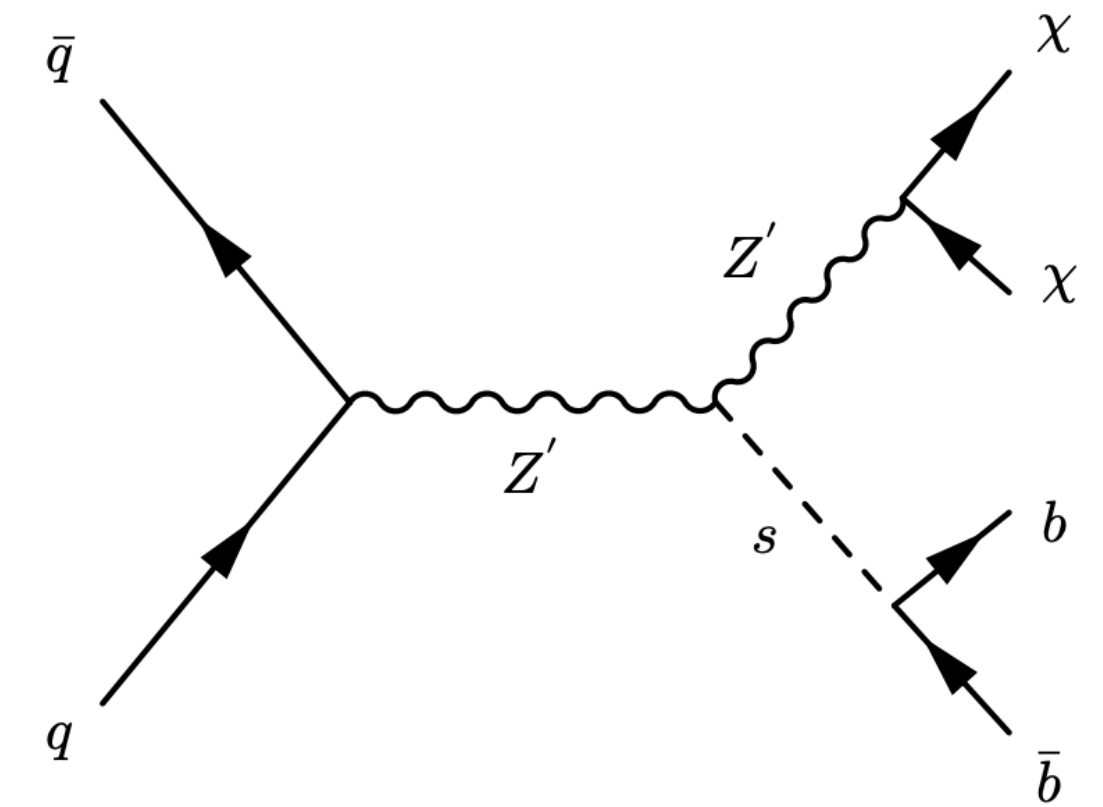
Broad coverage but 95 GeV Higgs not considered



Hunting the dark Higgs @ ATLAS

Search for dark matter produced in association with a dark Higgs boson in the bb final state [arXiv:2407.10549](https://arxiv.org/abs/2407.10549)

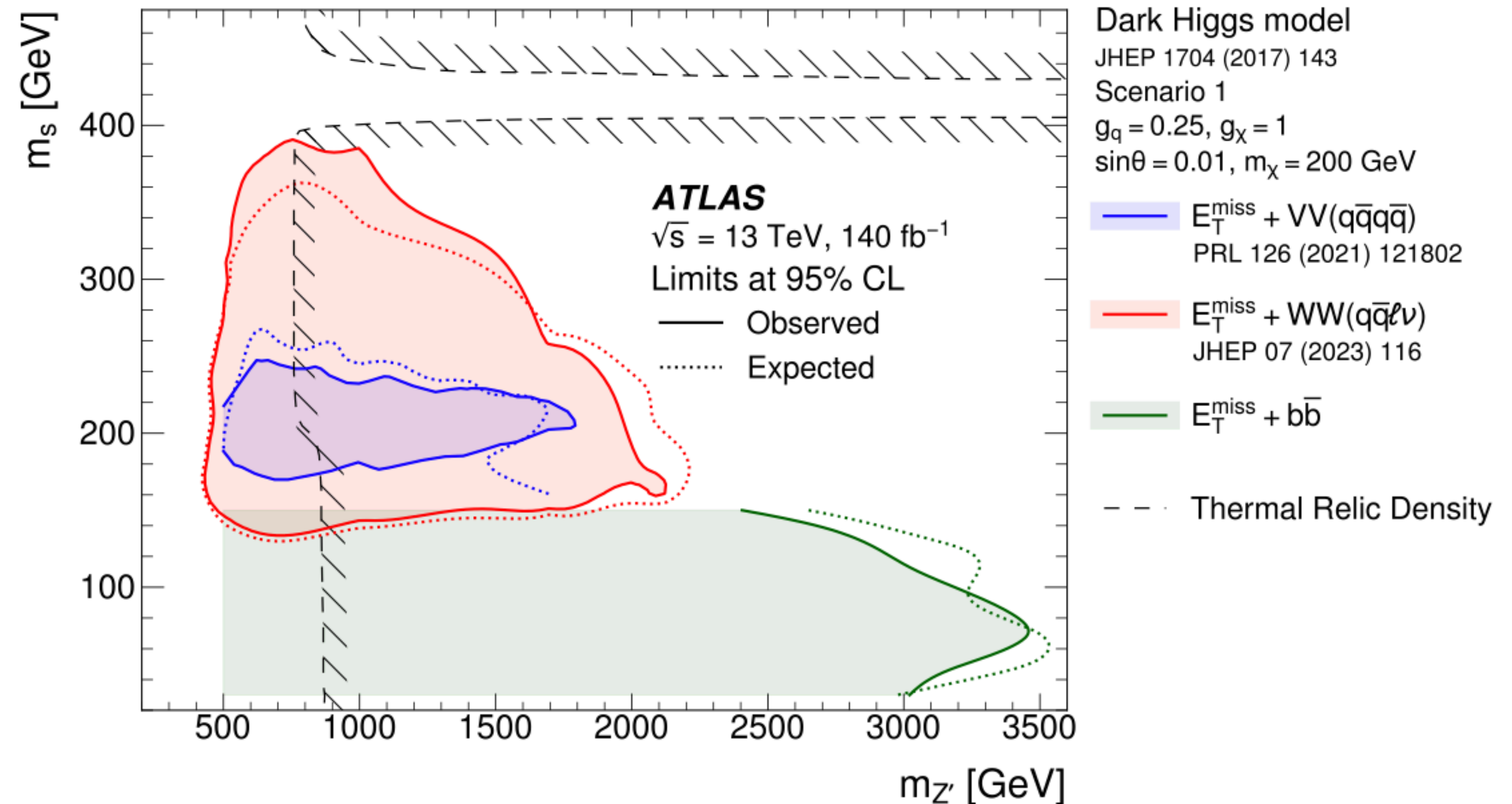
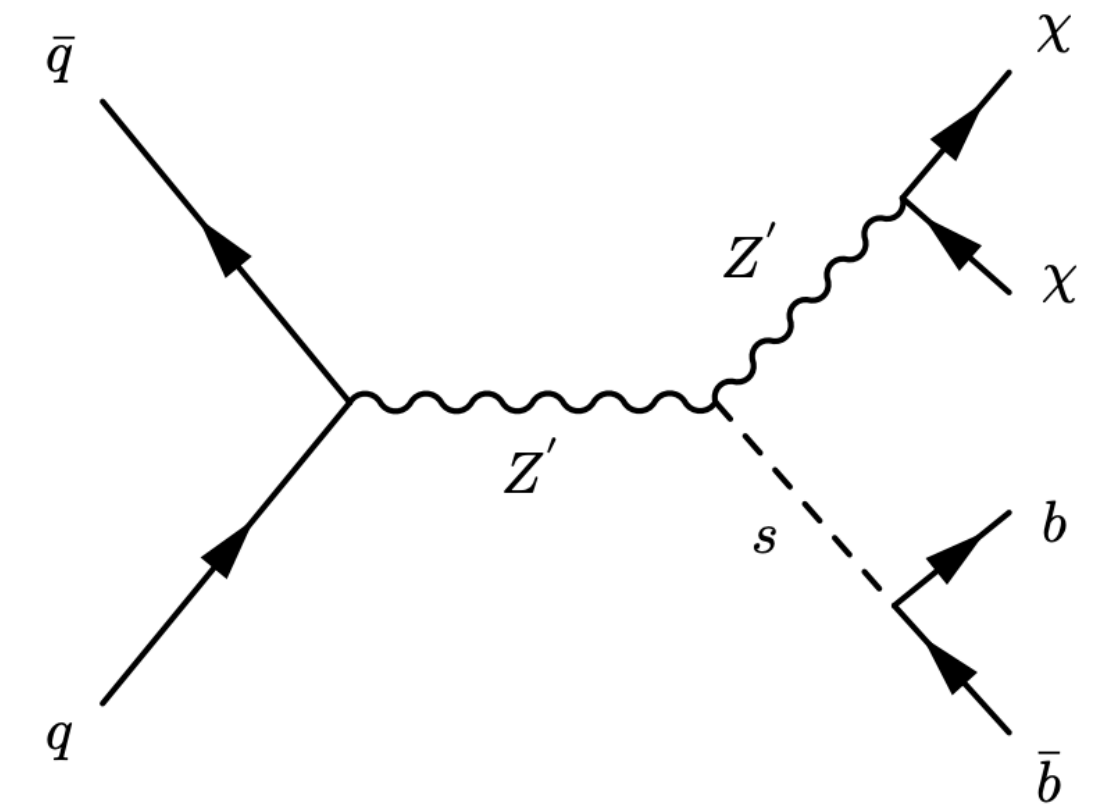
- Resolved
 - 2 small-radius b-jets
- Merged
 - 1 large radius double b-jet (DXbb algorithm)
- Binning in E_T^{miss}
- Targets, probes $m(h)$ 30-150 GeV



Hunting the dark Higgs @ ATLAS

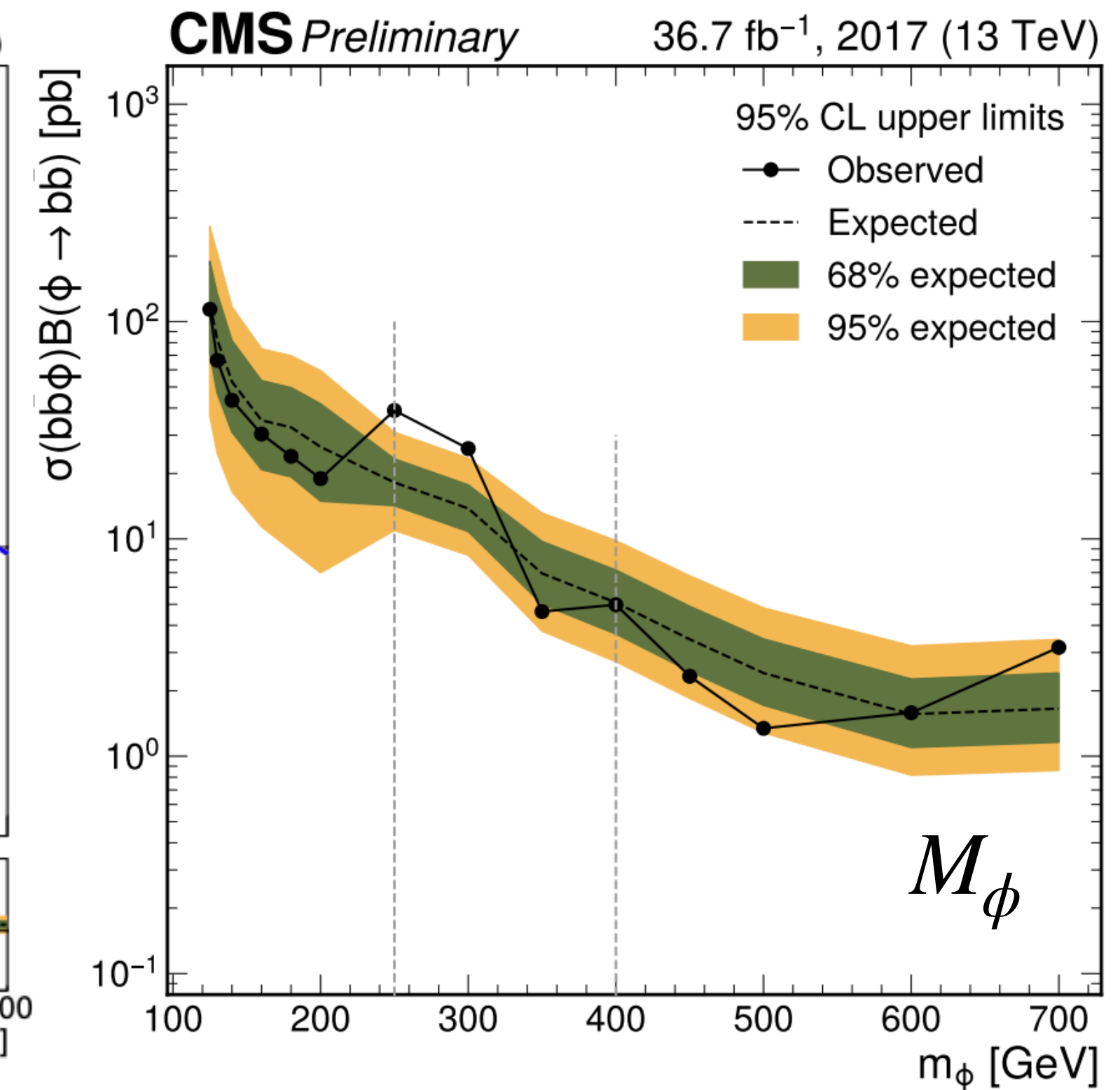
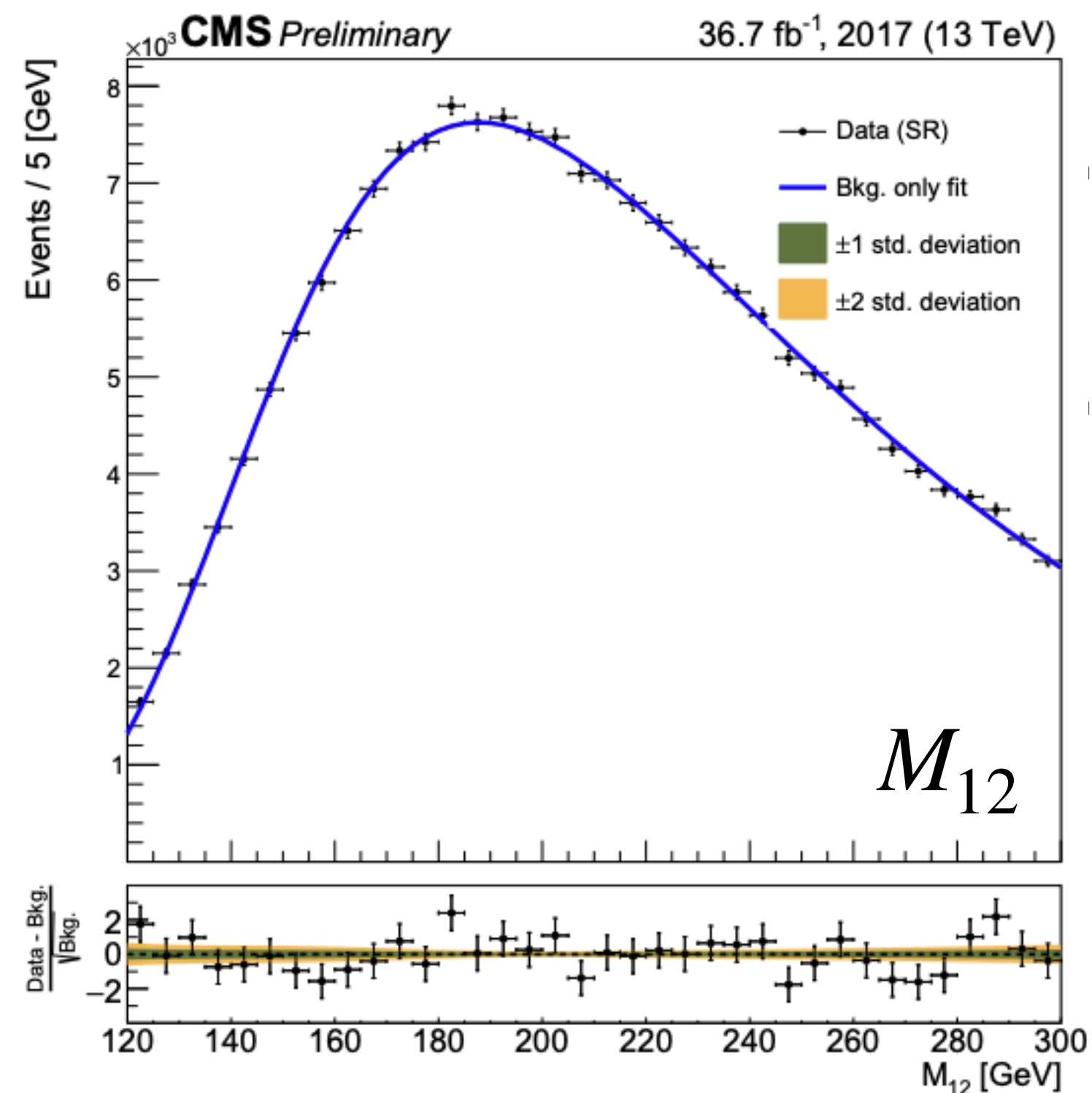
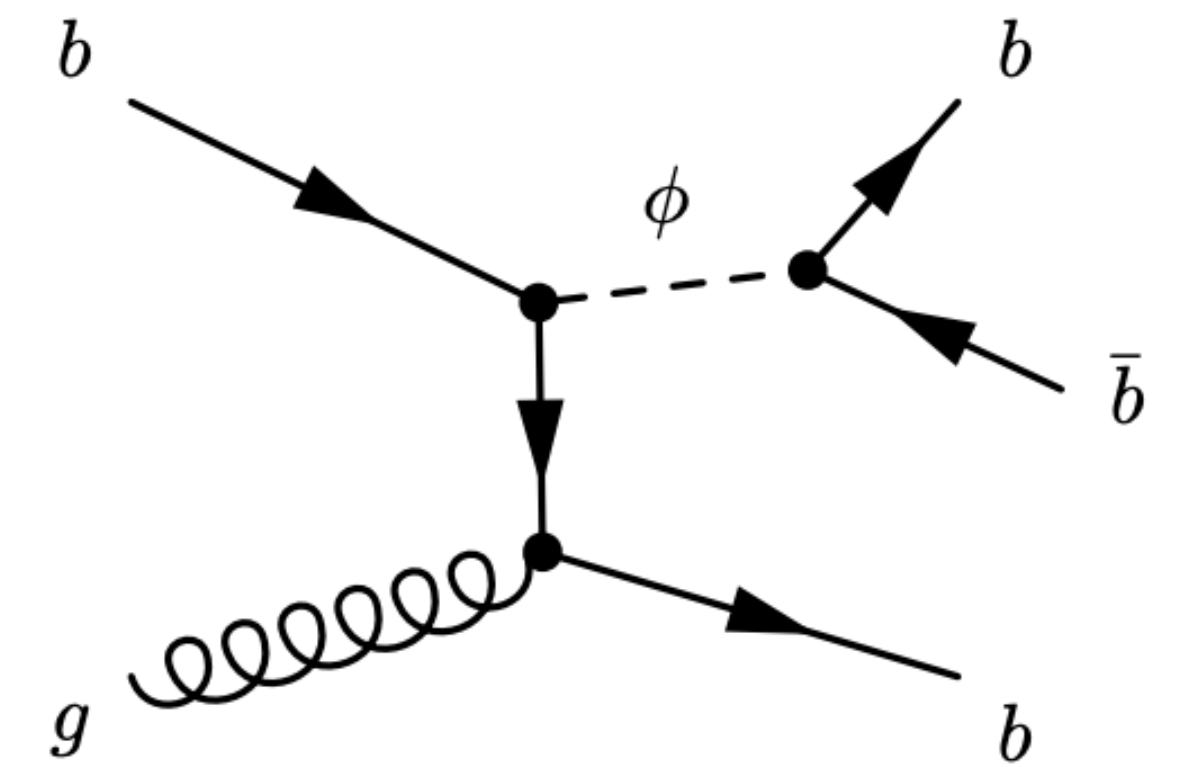
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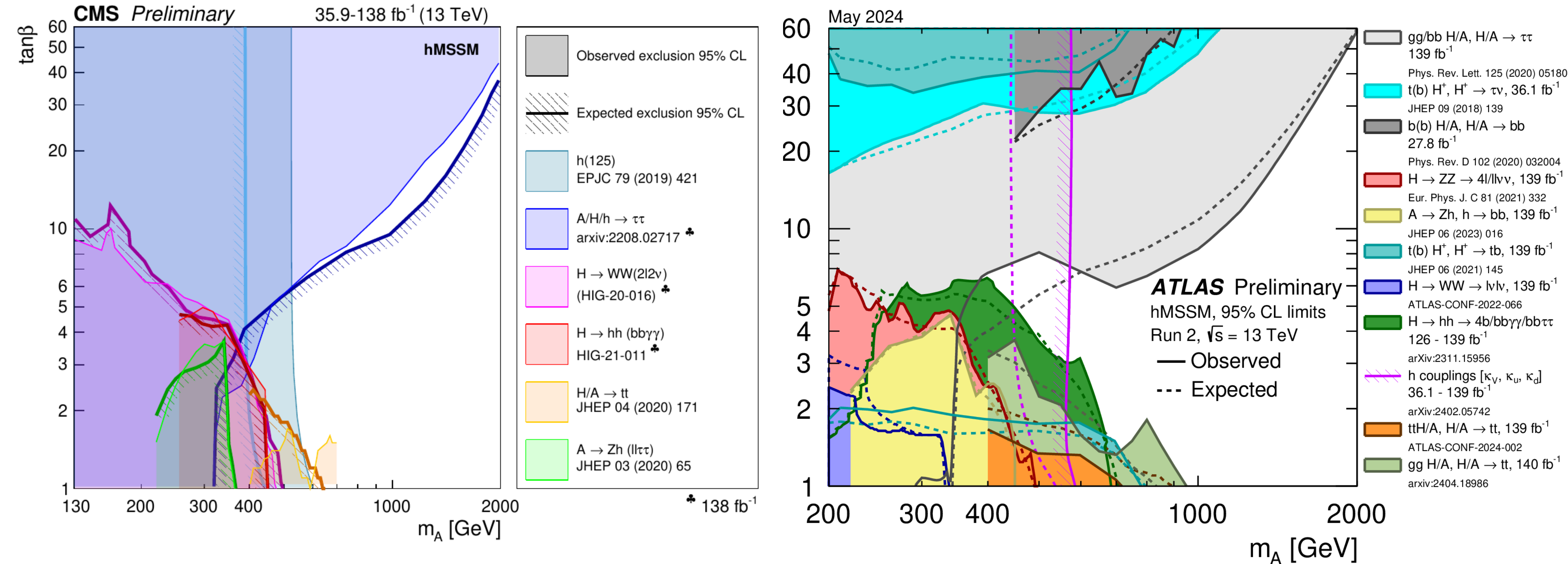


MSSM scenario with $h \rightarrow b\bar{b}$

- Search for bosons of an extended Higgs sector in b quark final states CMS-SUS-PAS-24-001
- Fully hadronic:
 - ≥ 2 high- p_T jets
 - ≥ 3 b -tagged jets
- Single-lepton channel +
 - $p_T > 12$ GeV
 - Probes Lower mass ϕ
- Select highest p_T b -jets M_{12}



Coimpreshensive MSSM coverage



- *Many more extra Higgs results!*

- *ATLAS recently: H- \rightarrow 2-photon+charm, etc*

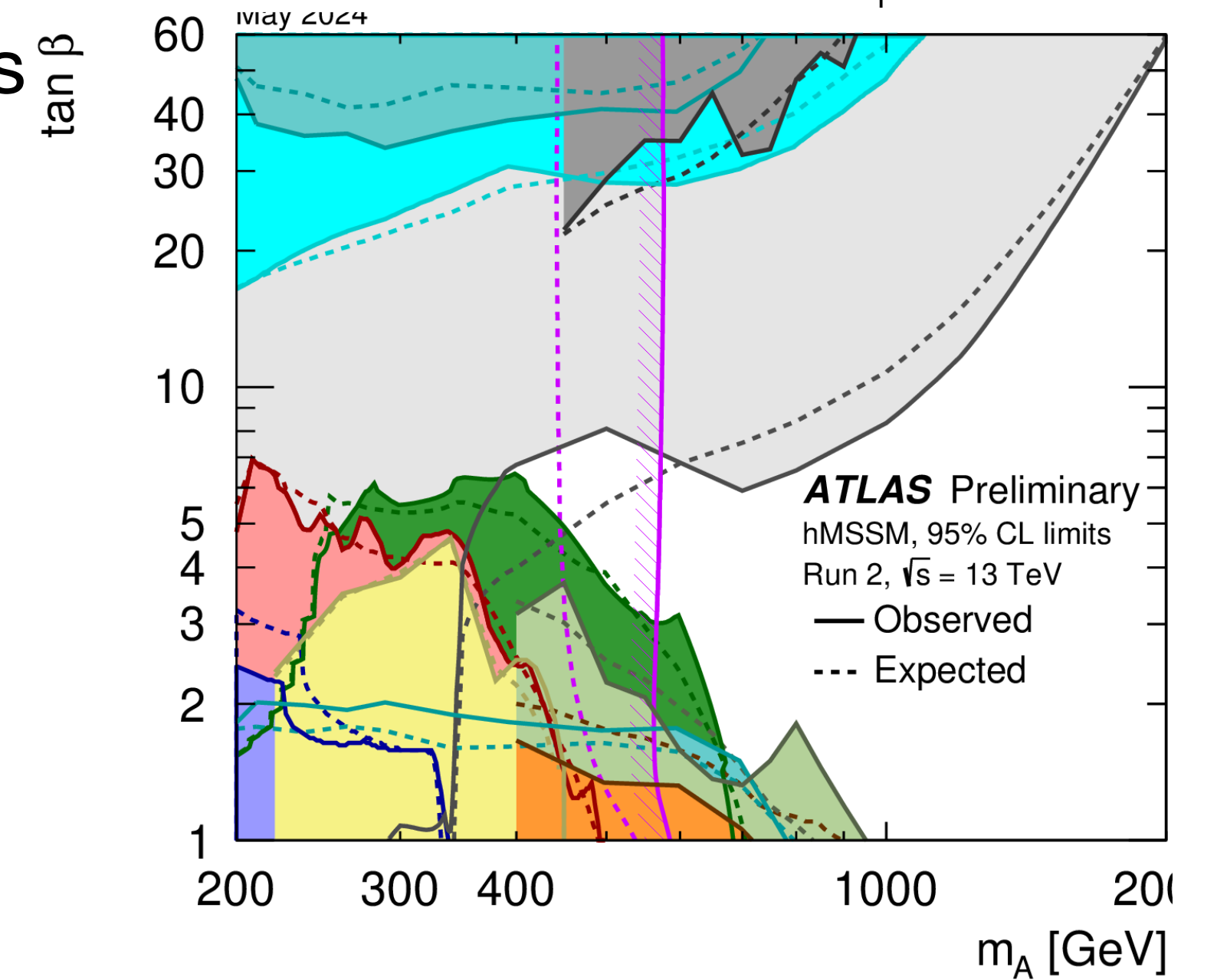
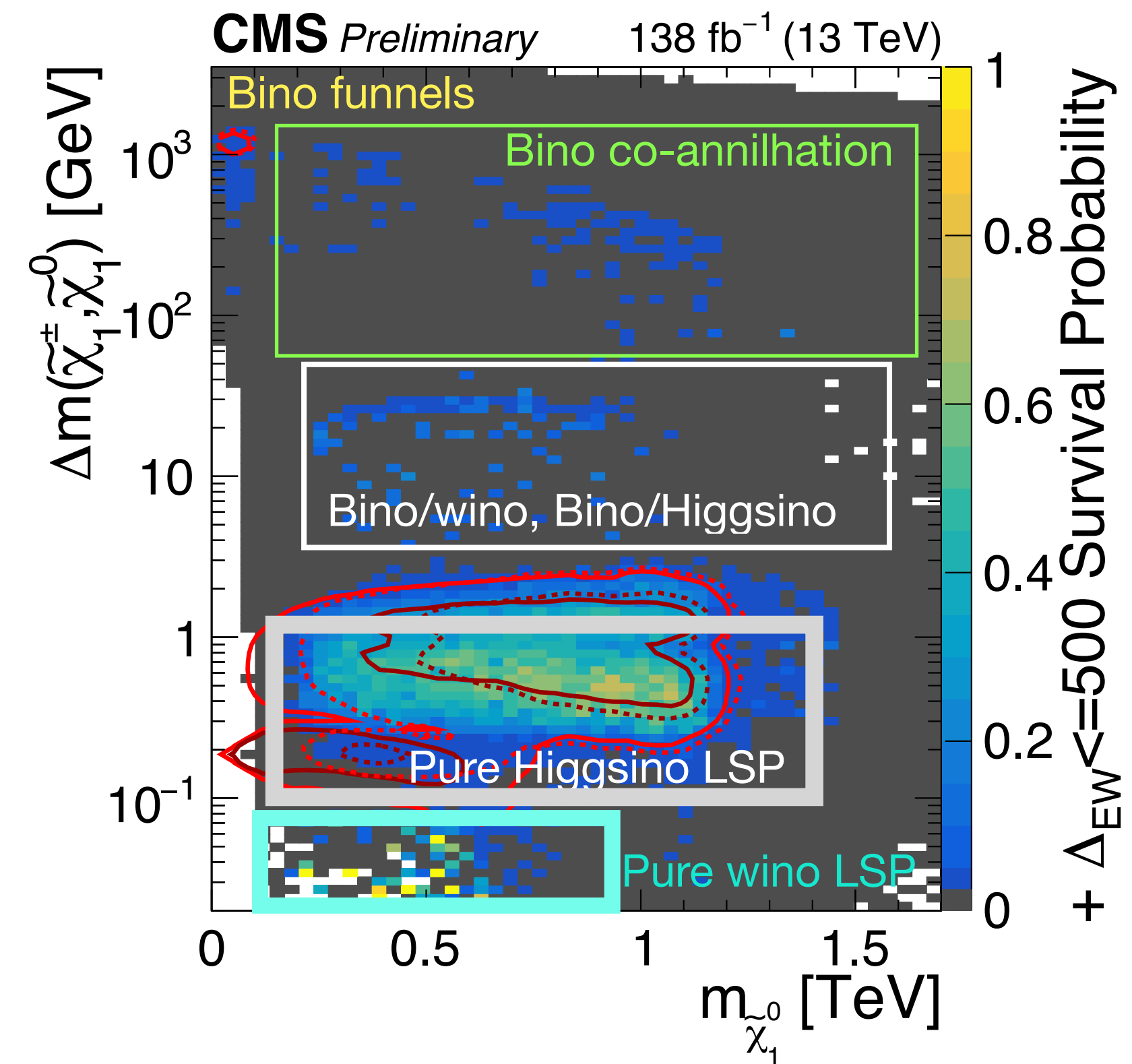
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults>

- *CMS recently: light pseudoscalars in Higgs125 decays, etc*

<https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html>

Closing remarks

- ATLAS and CMS evaluate viability of R-parity conserving SUSY
 - Natural SUSY under pressure, SUSY DM largely unconstrained
 - With DM and naturalness constraints, MSSM bounded from all sides
 - Specific signatures needed, e.g., displaced pion already by ATLAS!
- BSM Higgs extensively searched for in MSSM to 2HDM to dark sectors
 - Moderate excesses in $\gamma\gamma$ mass await answer from future data
 - $s \rightarrow b\bar{b}$ a natural place to look next, need extra handle, e.g., E_T^{miss}
 - Range of masses explored, now including 95 GeV, by ATLAS!



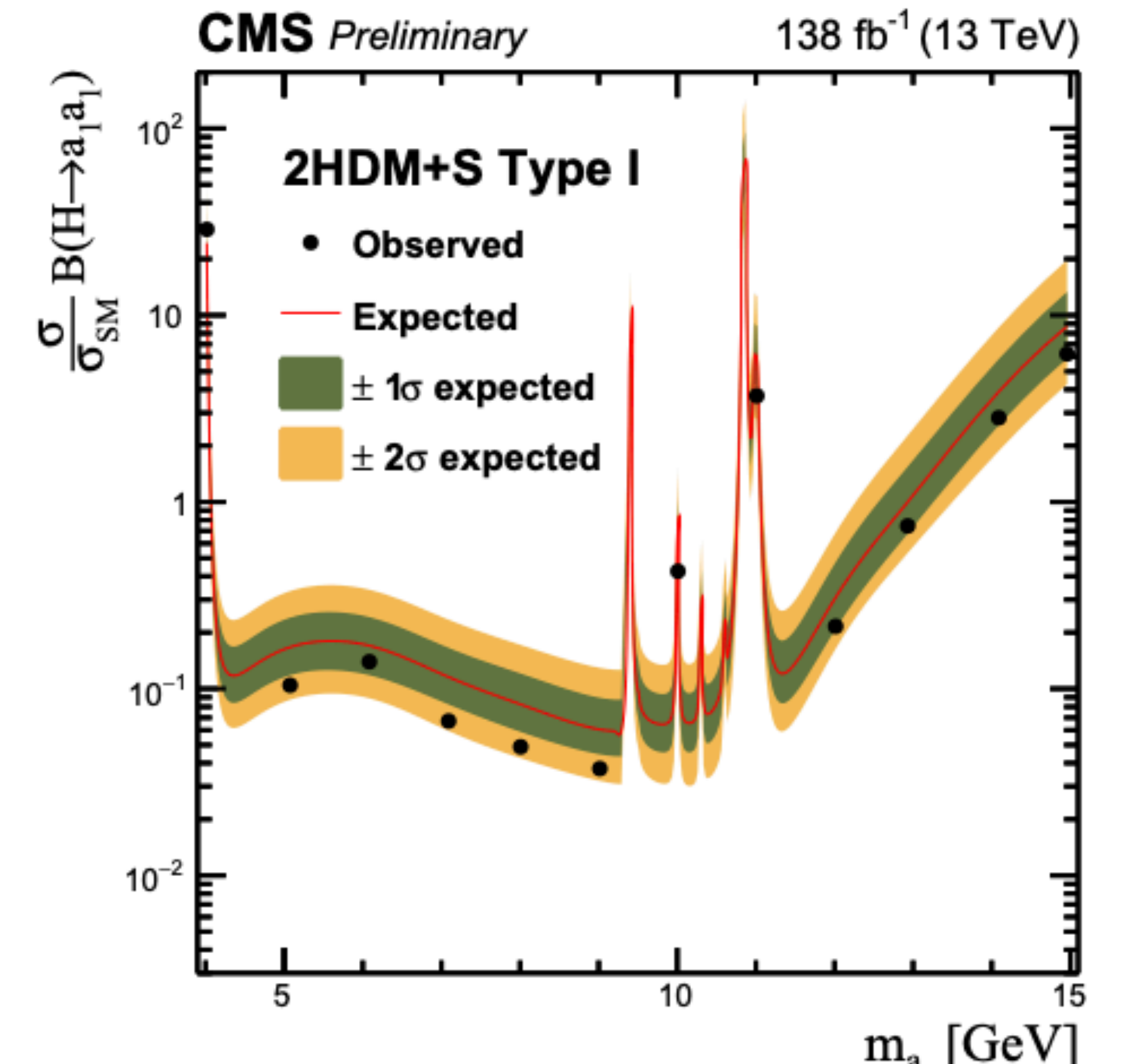
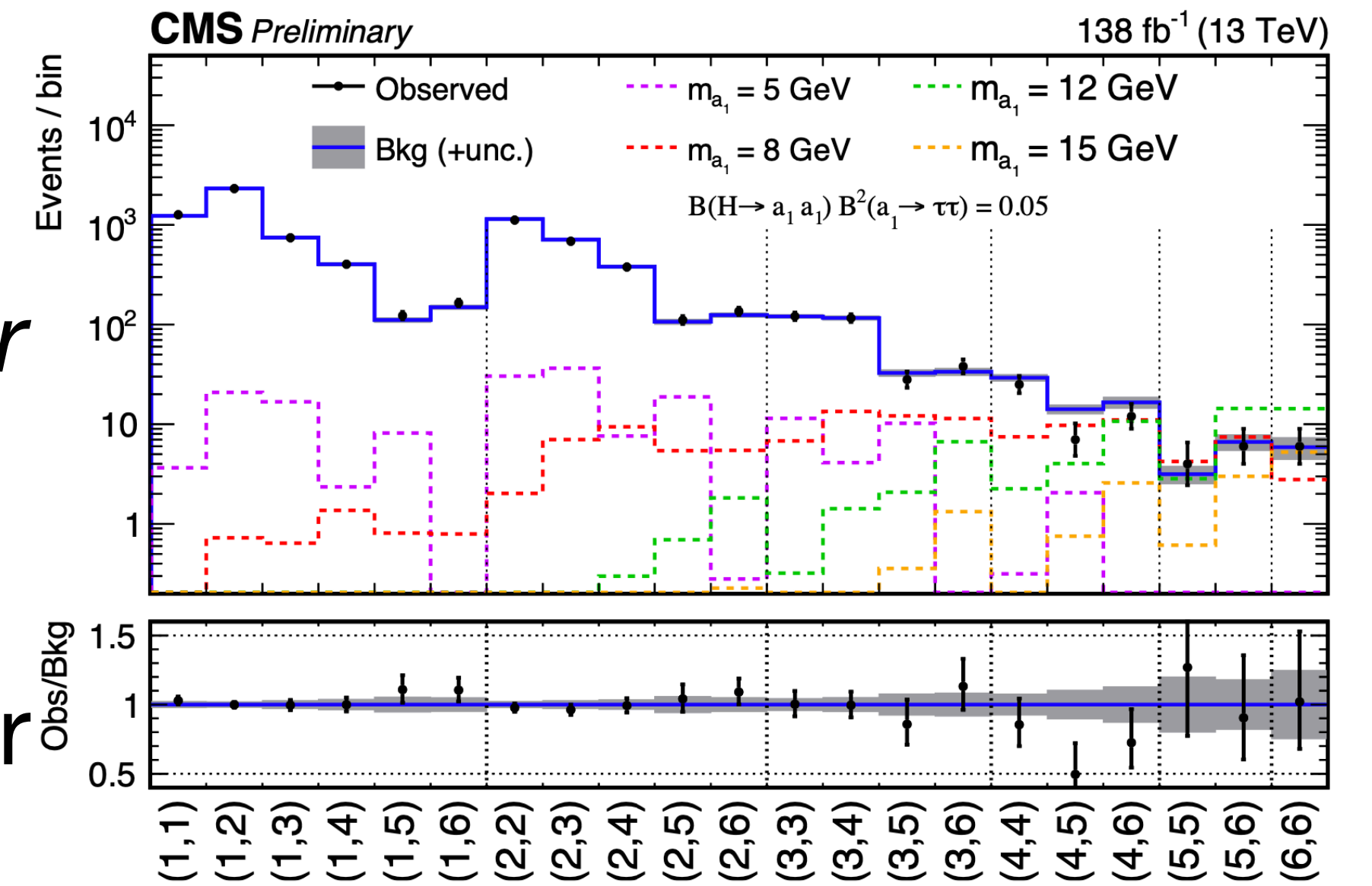
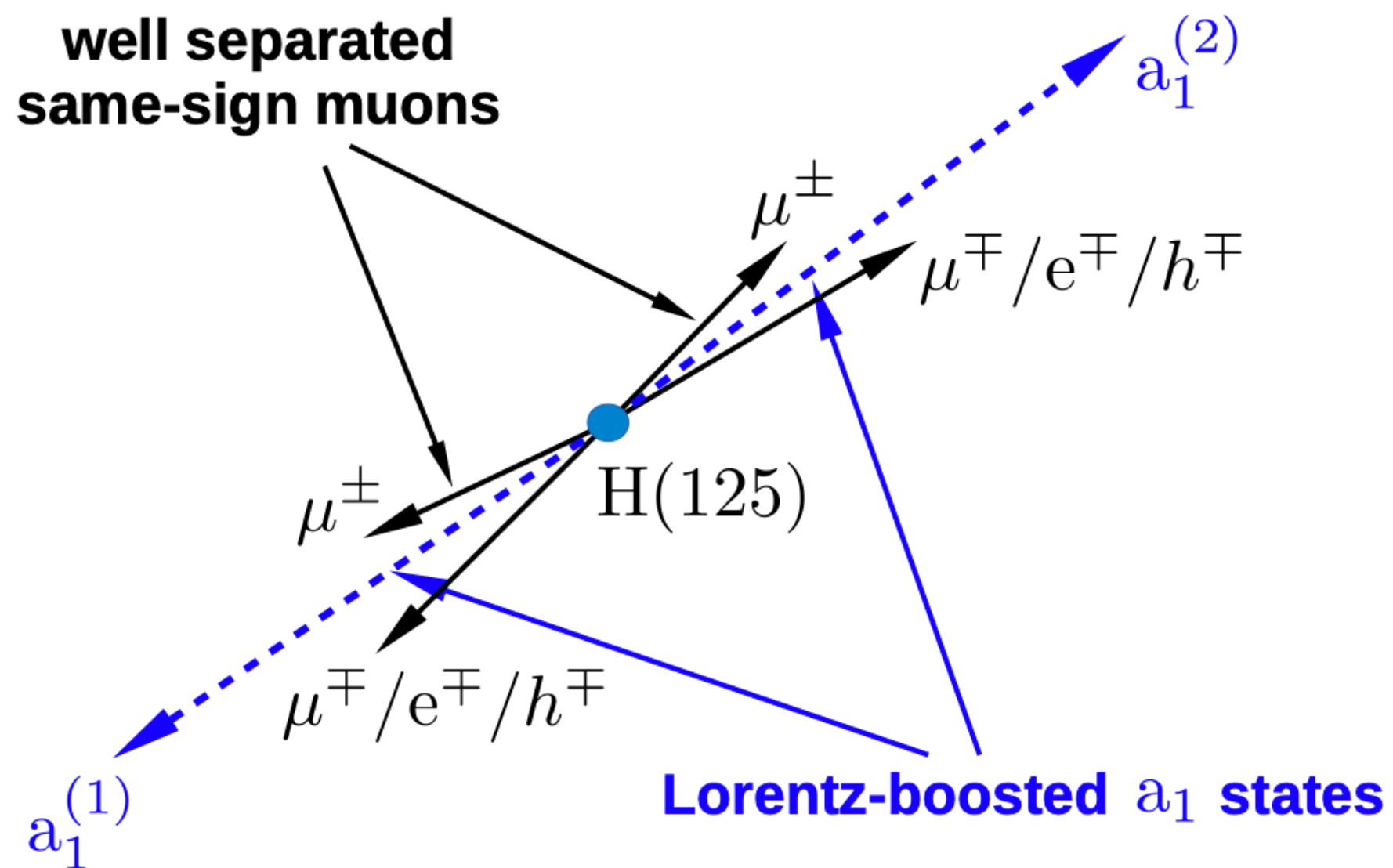
Thanks for your attention!

Backup

Light pseudoscalars

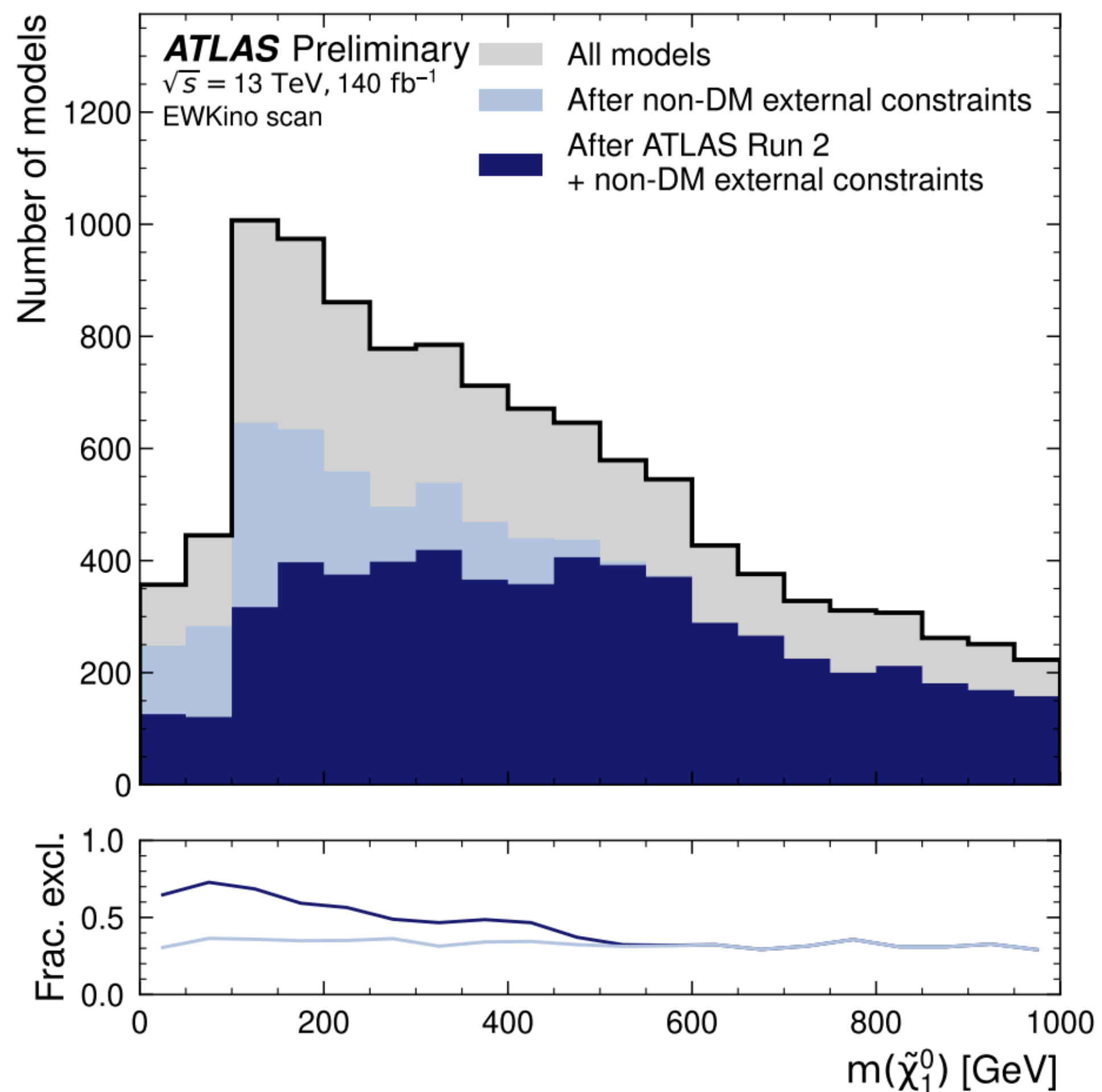
CMS-PAS-SUS-24-002: Search for light pseudoscalar bosons produced in Higgs boson decays in 4τ , $2\tau 2\mu$ final states

- 2HDM+S (NMSSM subspace, a_1 light pseudoscalar
- Select 2 same-charge muons
 - Each with nearby opposite-charged particle
- Search in plane of two invariant masses

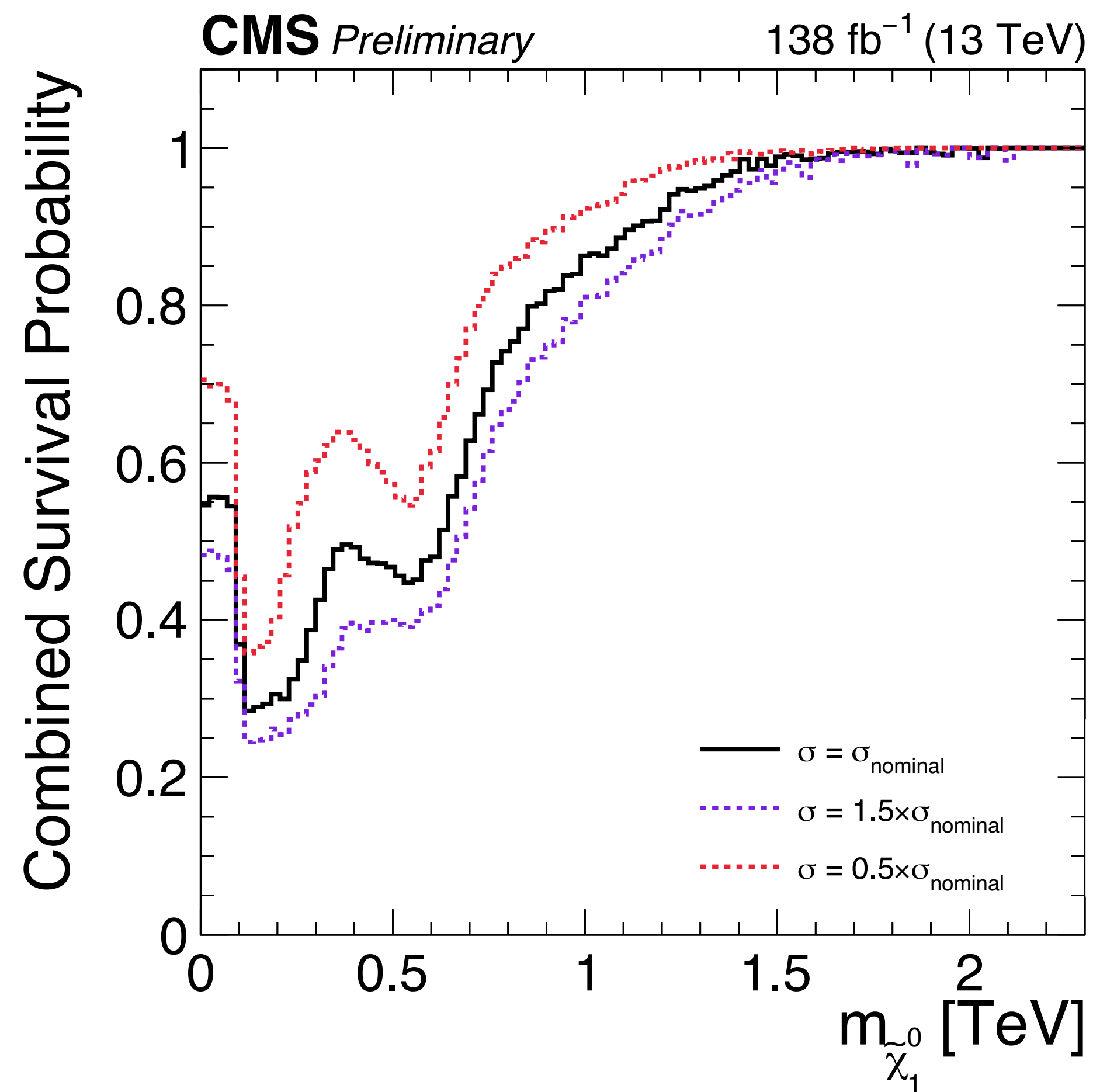


Backup: survival probability

Number of models



Survival probability (Fraction of MCMC surviving)



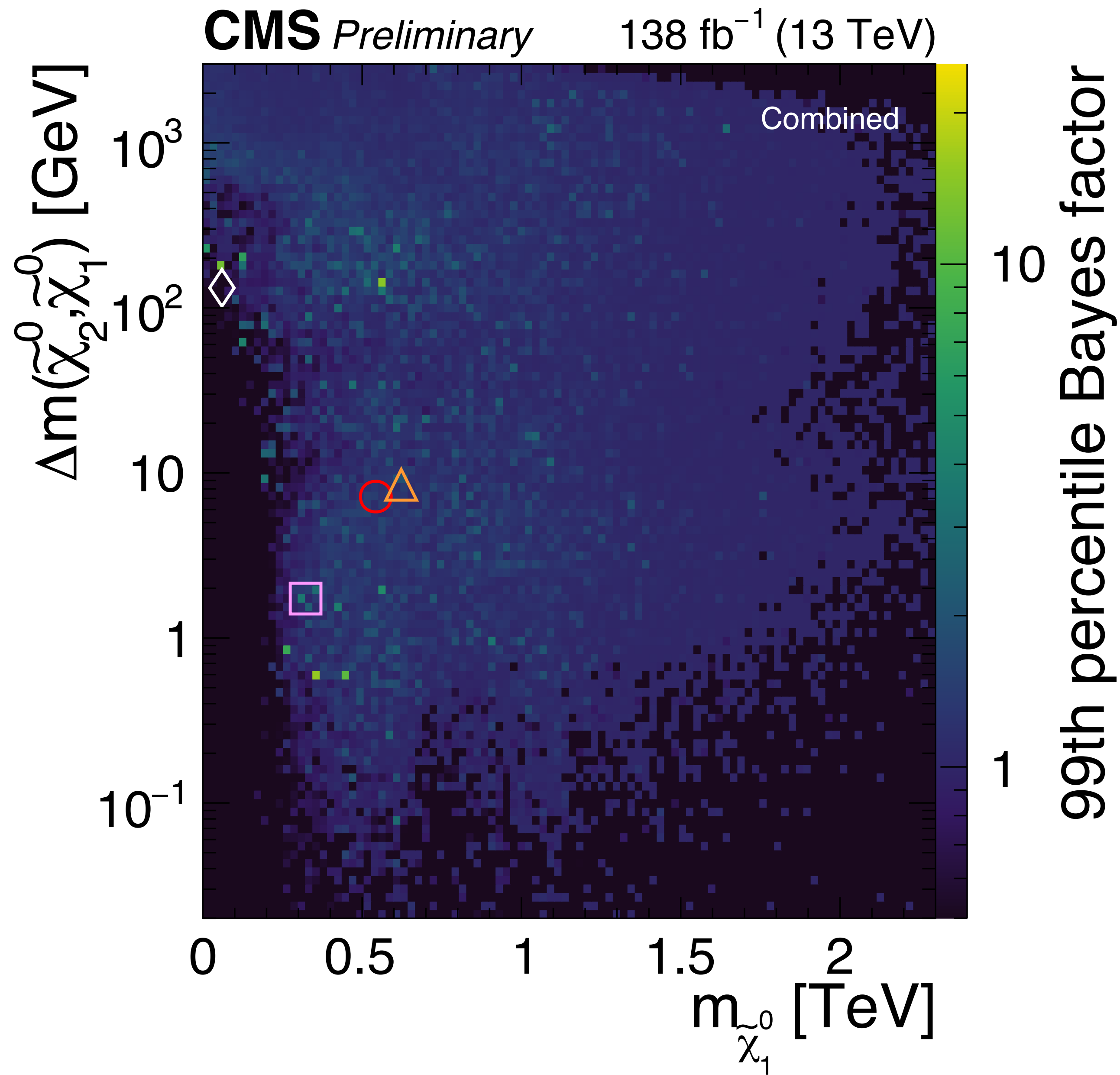
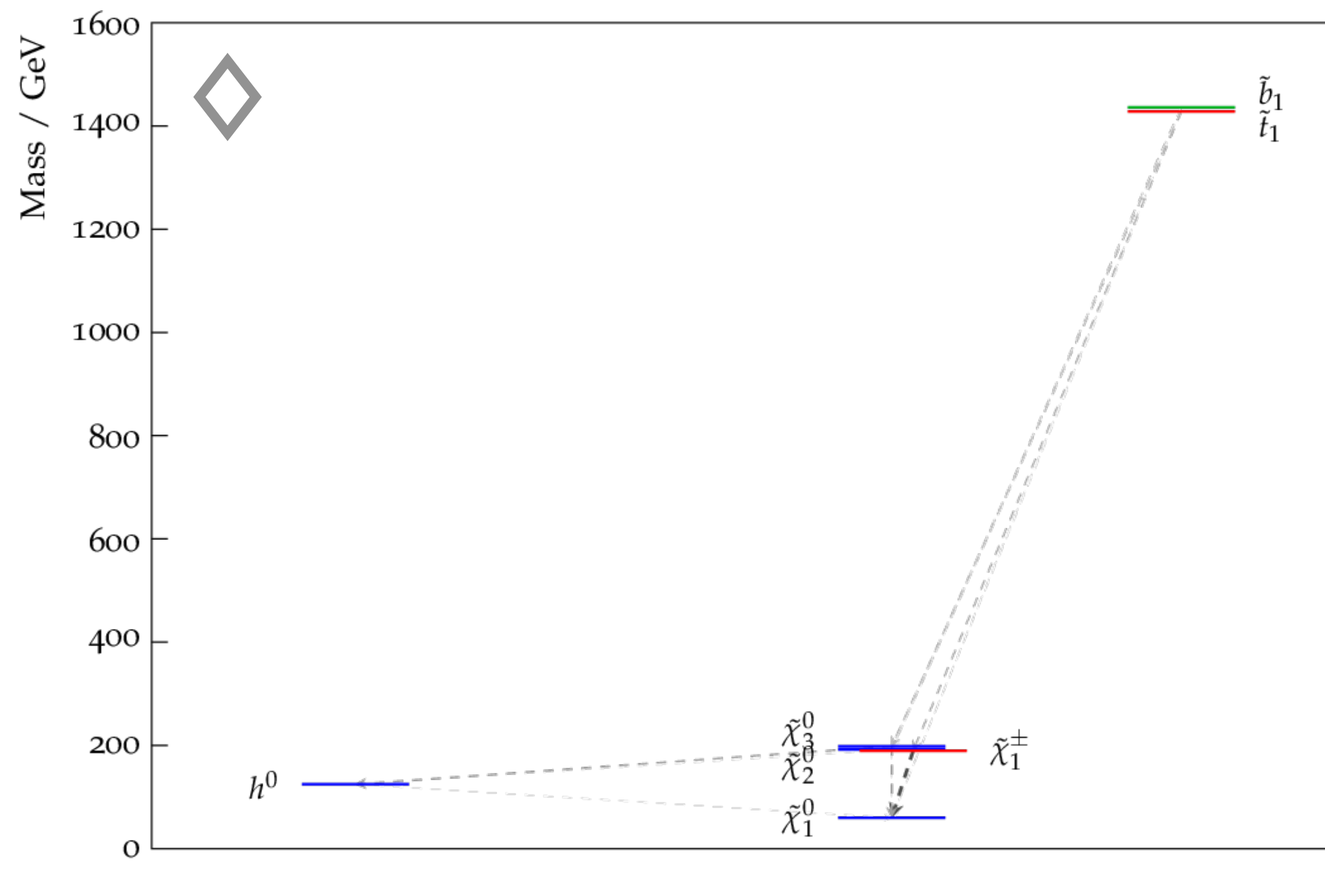
pMSSM Bayes factor quantiles

CMS-SUS-PAS-24-004

5-analysis combination

- plotting upper quantiles of the Bayes Factor:

$$\text{BF}(\theta) = \mathcal{L}(\theta, \mu = 1) / \mathcal{L}(\theta, \mu = 0)$$



ATLAS pMSSM models surviving all constraints

