What happened to SUSY? An experimentalist’s perspective on winos, binos, higgsinos and our place in the Universe

DESY Colloqium, 3 June 2025, Sam Bein, UCLouvain


Der Wanderer über dem Nebelmeer

Caspar David Friedrich 1818

Der Abend

Caspar David Friedrich 1821

Part 1

$$
\begin{aligned}
\{Q_\alpha,\, Q_\beta\} = \{Q^\dagger_{\dot\alpha},\, Q^\dagger_{\dot\beta}\} &= 0 \\
[P_\mu,\, Q_\alpha] = [P_\mu,\, Q^\dagger_{\dot\alpha}] &= 0 \\
\{Q_\alpha,\, Q^\dagger_{\dot\beta}\} &= 2\,(\sigma^\mu)_{\alpha\dot\beta}\, P_\mu
\end{aligned}
$$

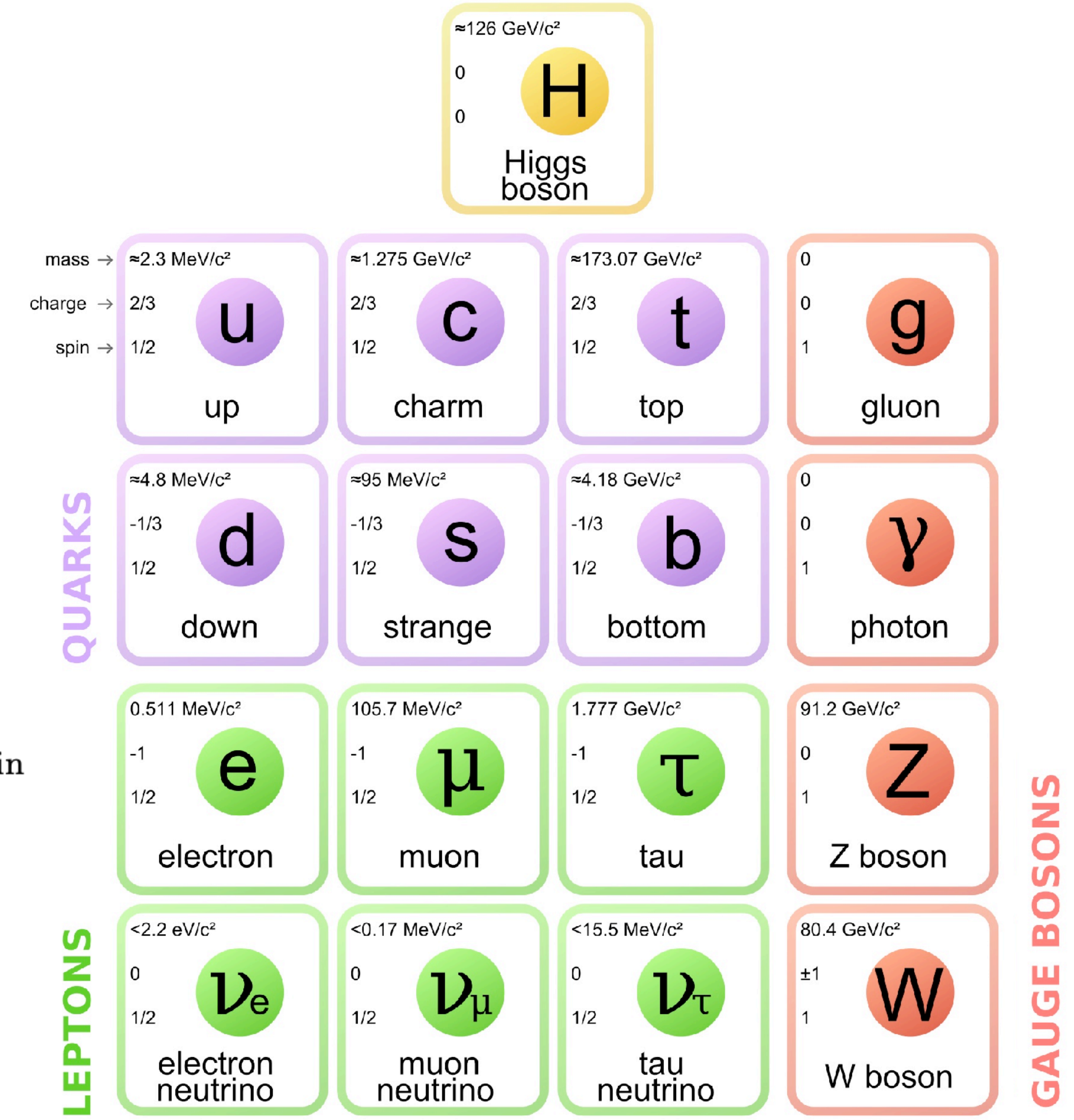
Extension of the Algebra of Poincare Group Generators and Violation of p Invariance, Yu. A. Golfand and E. P. Likhtman, 1071

Supergauge Transformations in Four-Dimensions, J. Wess and B. Zumino, 1974

The Standard Model

$$\mathcal{L}_{\mathrm{SM}} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4}\phi^4 + \frac{1}{4}g_1^2(\mathrm{B}_\mu)^2\phi^2 + \frac{1}{4}\sum_{i=1}^{3} g_2^2(\sigma^i \mathrm{W}_\mu^i)^2\phi^2$$

$$+ \sum_{i,j=1}^{9} \psi_i y_{ij} \psi_j \phi + \sum_{i=1}^{8} \frac{1}{4}\left[\partial_\mu \mathrm{G}_\nu^i - \partial_\nu \mathrm{G}_\mu^i - \sum_{j,k=1}^{8} g_s f_{ijk} \mathrm{G}_\mu^j \mathrm{G}_\nu^k\right]^2 + \mathcal{L}_{\mathrm{gauge,kin}}$$



(19 free parameters)

The Standard Model but prettier

$$\mathcal{L}_{\mathrm{SM}} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4}\phi^4 + \frac{1}{4}g_1^2(\mathrm{B}_\mu)^2\phi^2 + \frac{1}{4}\sum_{i=1}^{3} g_2^2(\sigma^i \mathrm{W}_\mu^i)^2\phi^2$$
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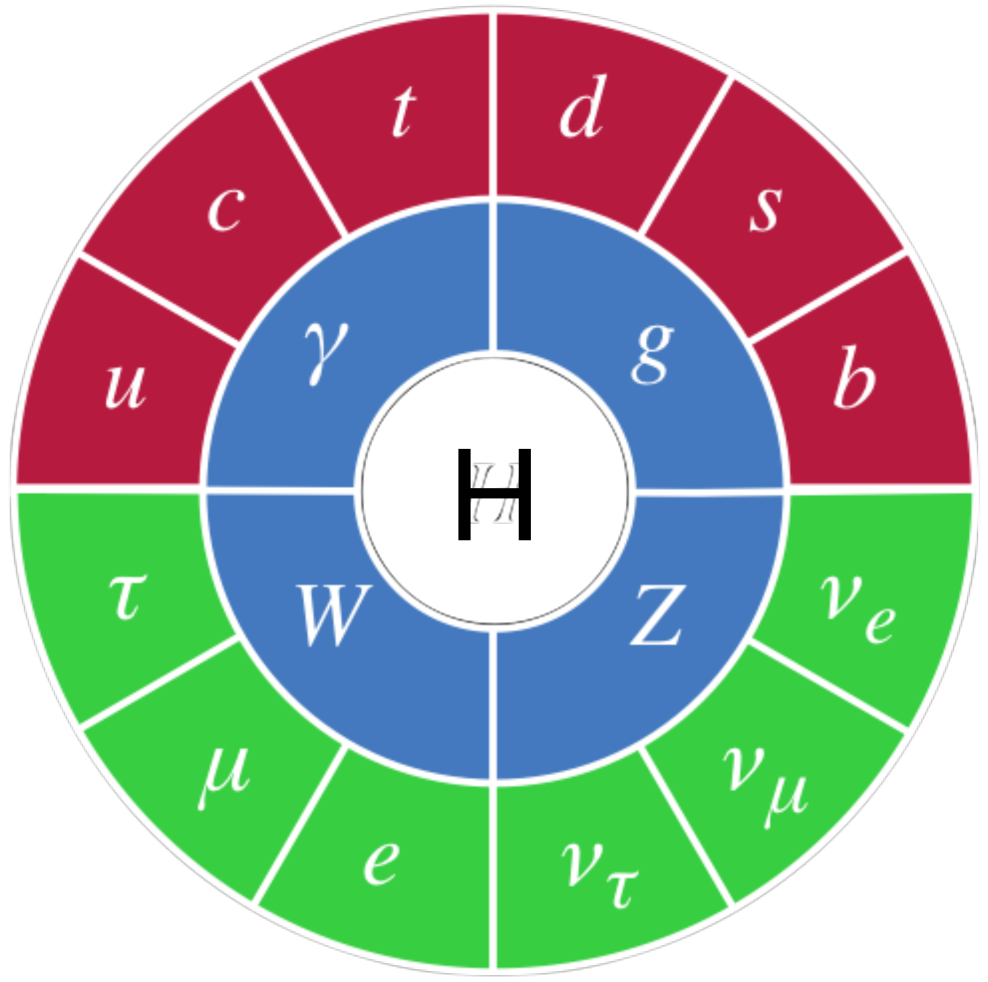
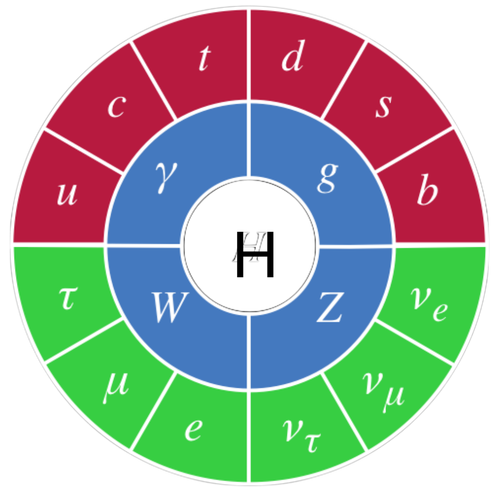
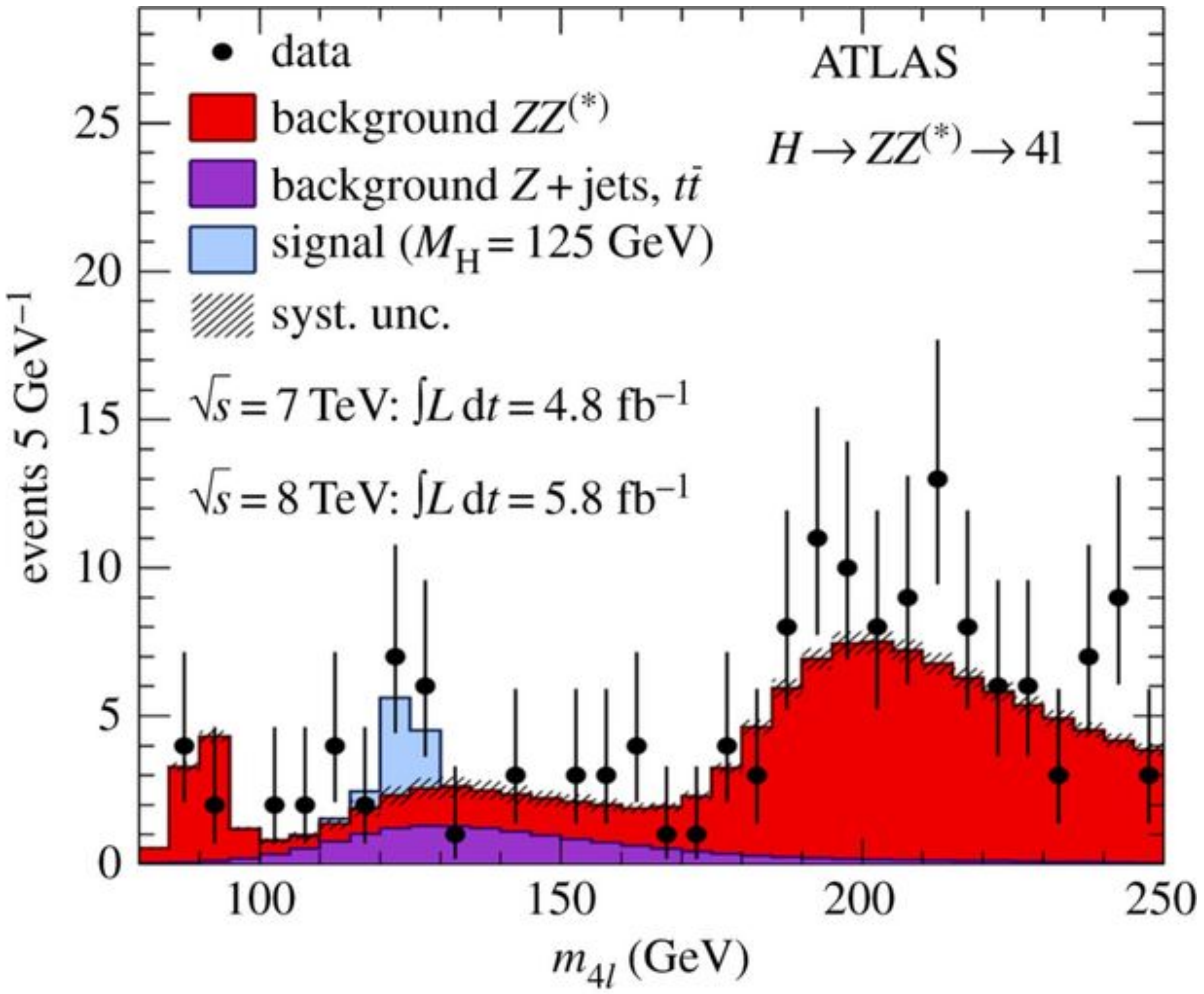
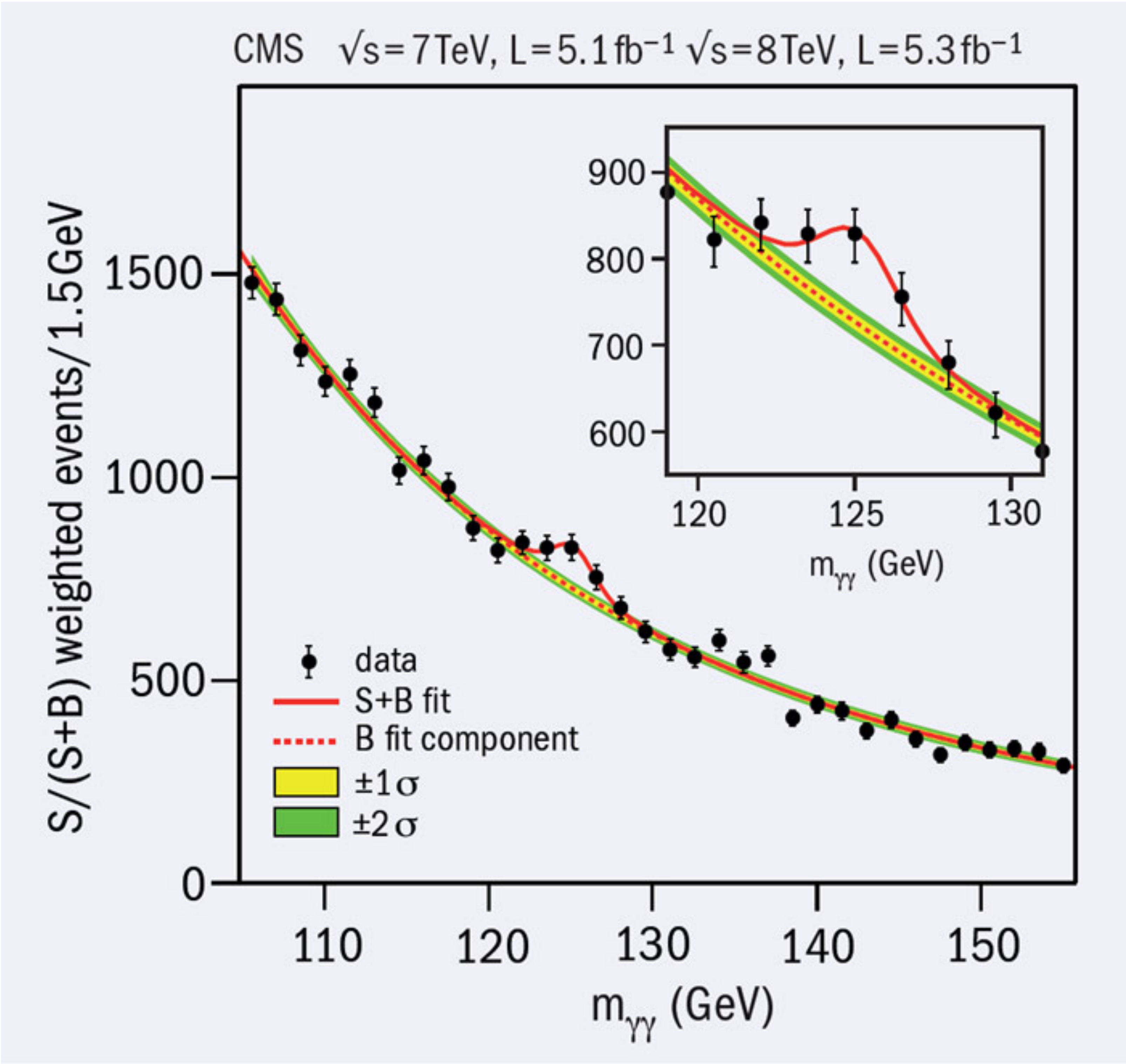


Observation of Higgs boson

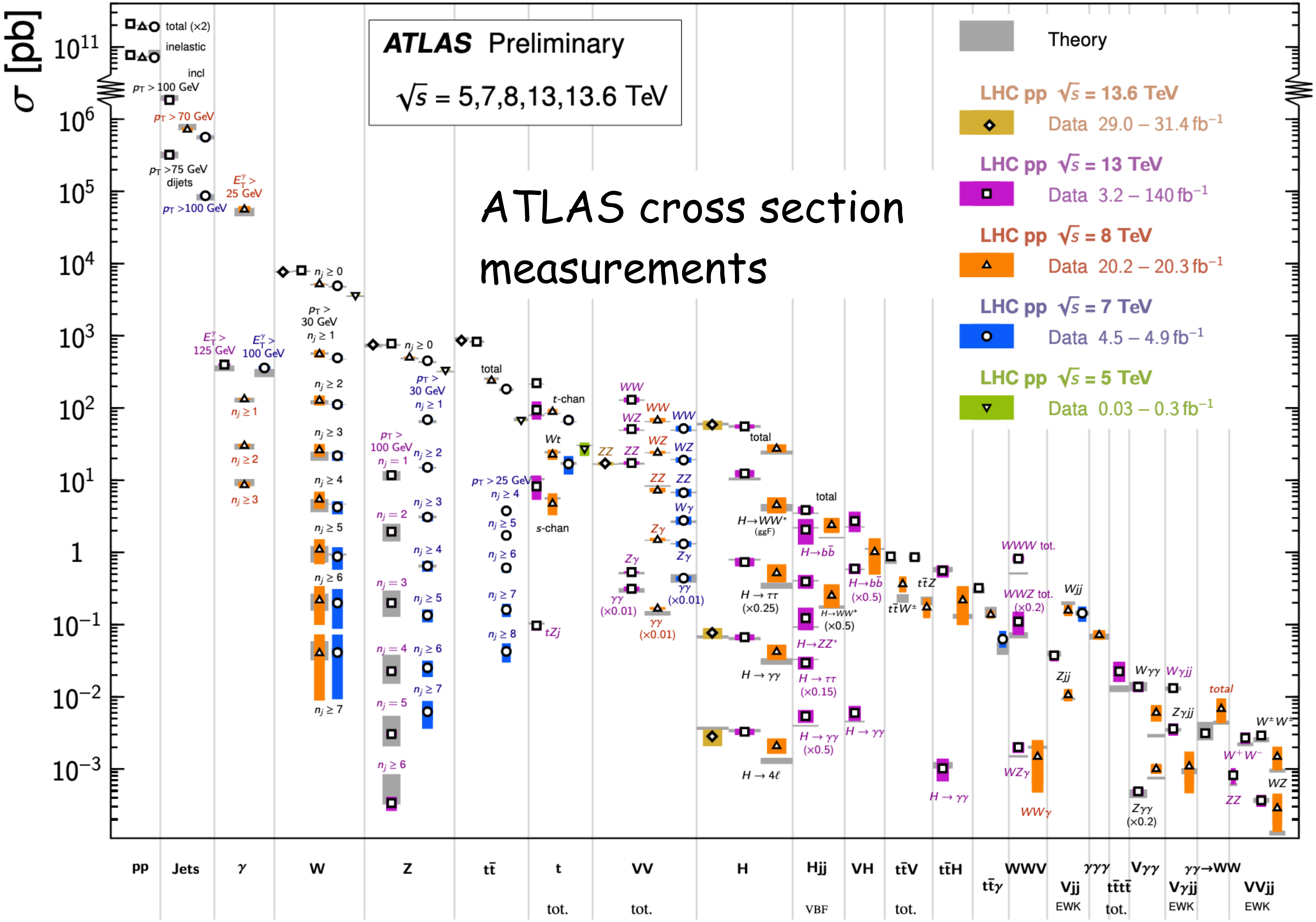


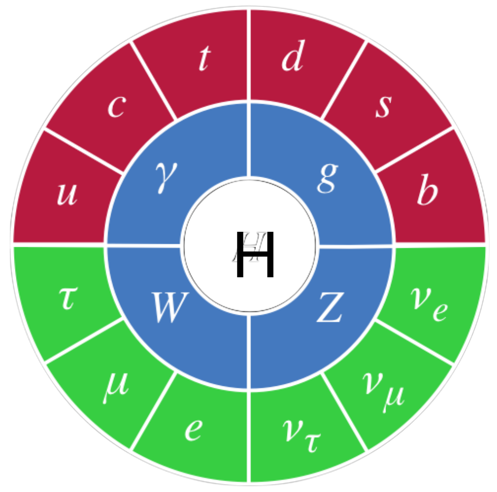




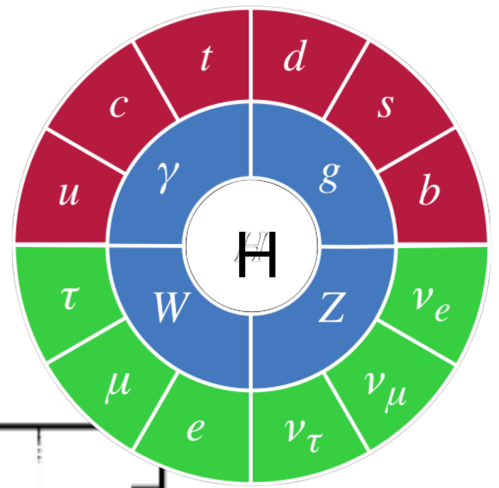
First and only scalar (spin=0) particle discovered, m_H = 125 GeV

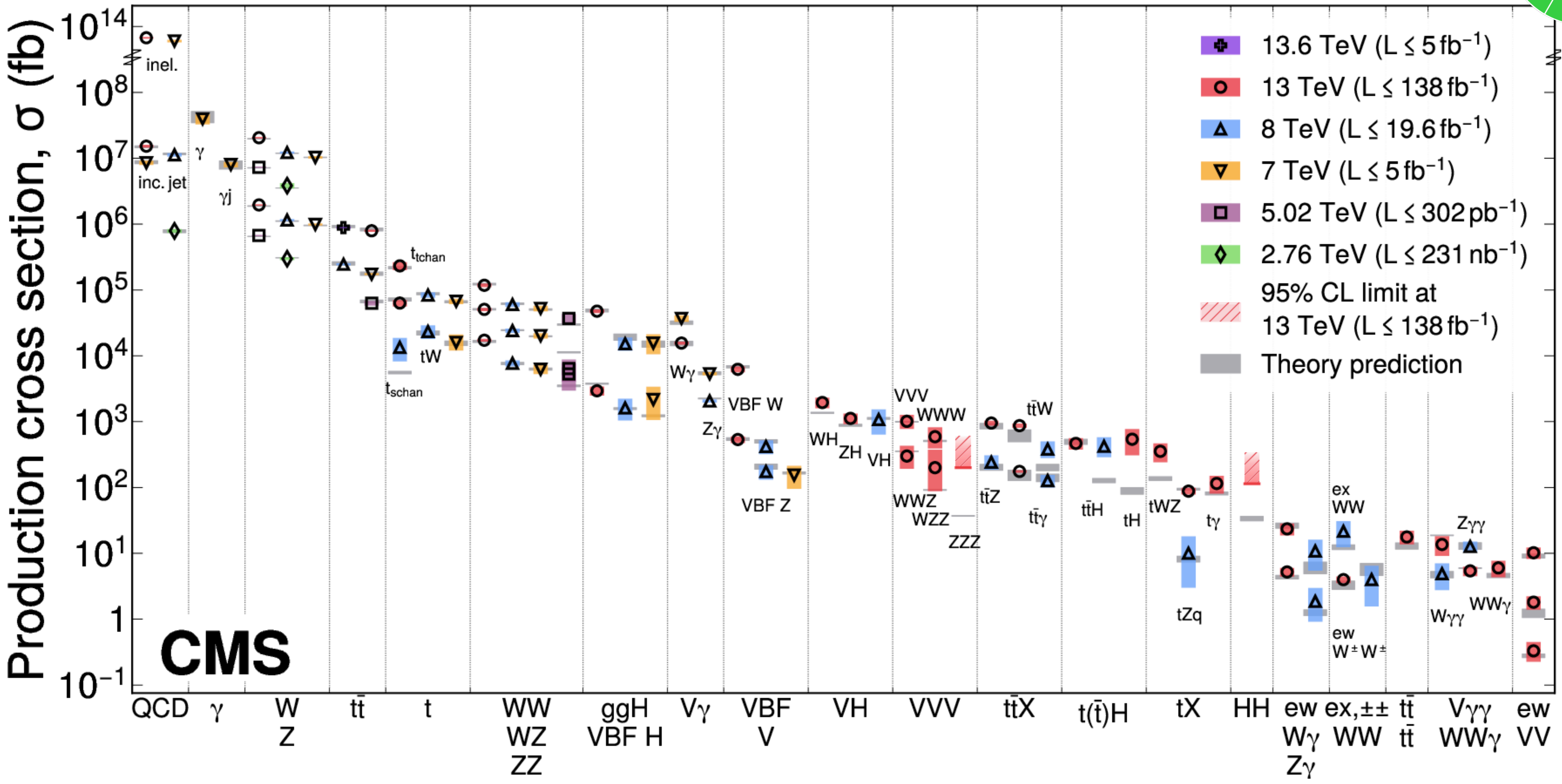
ATLAS cross section measurements

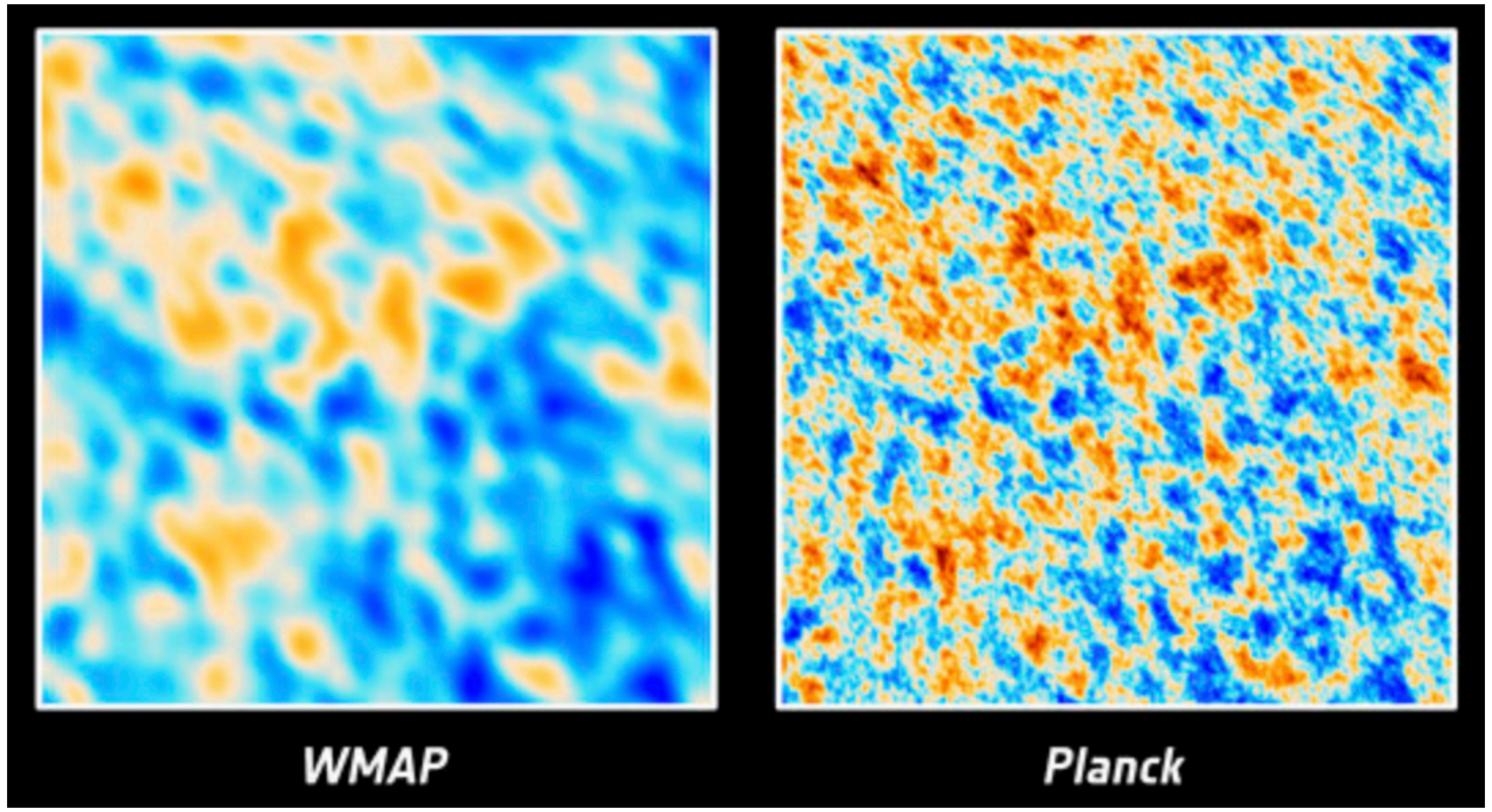




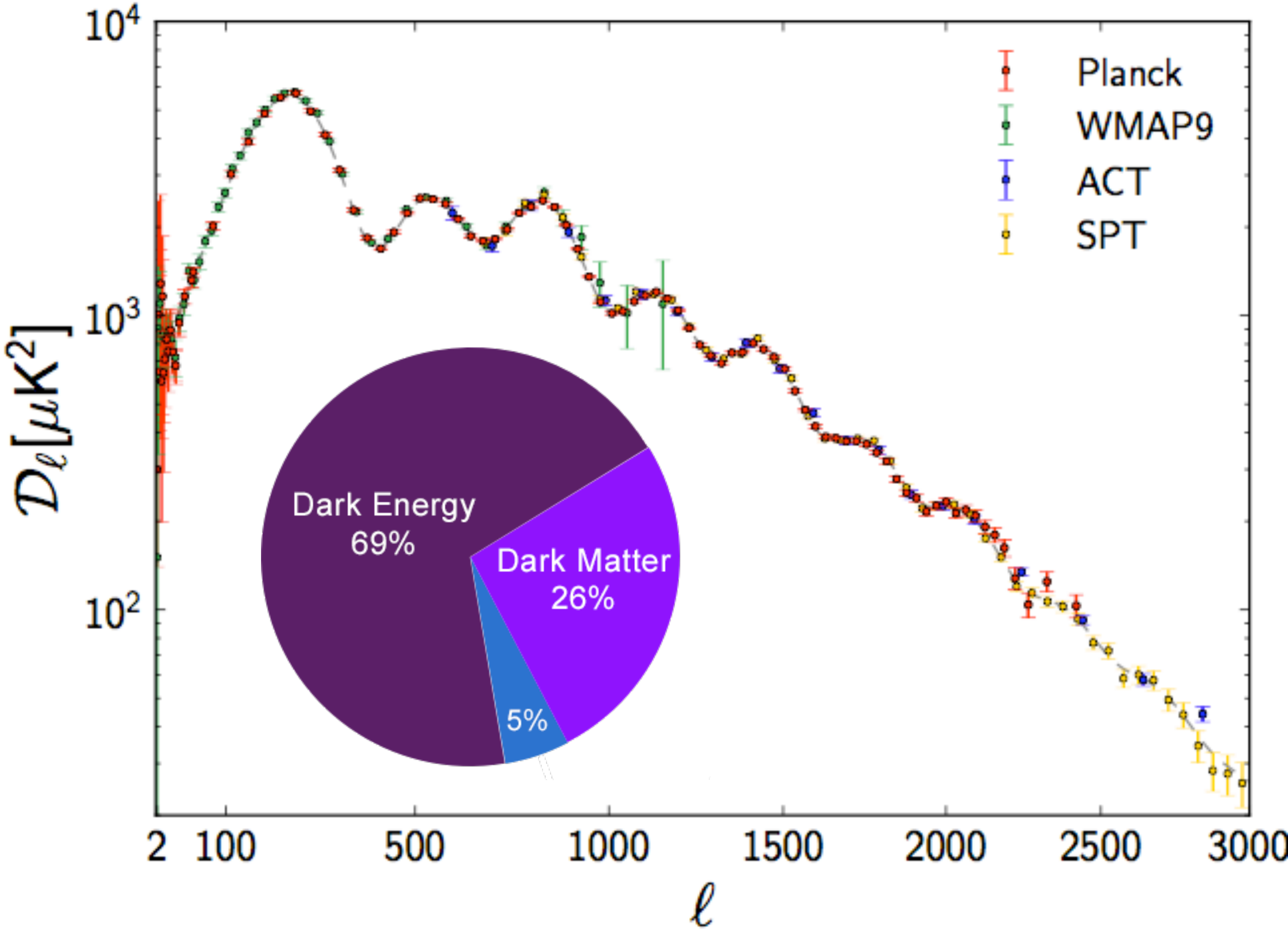
CMS cross section measurements

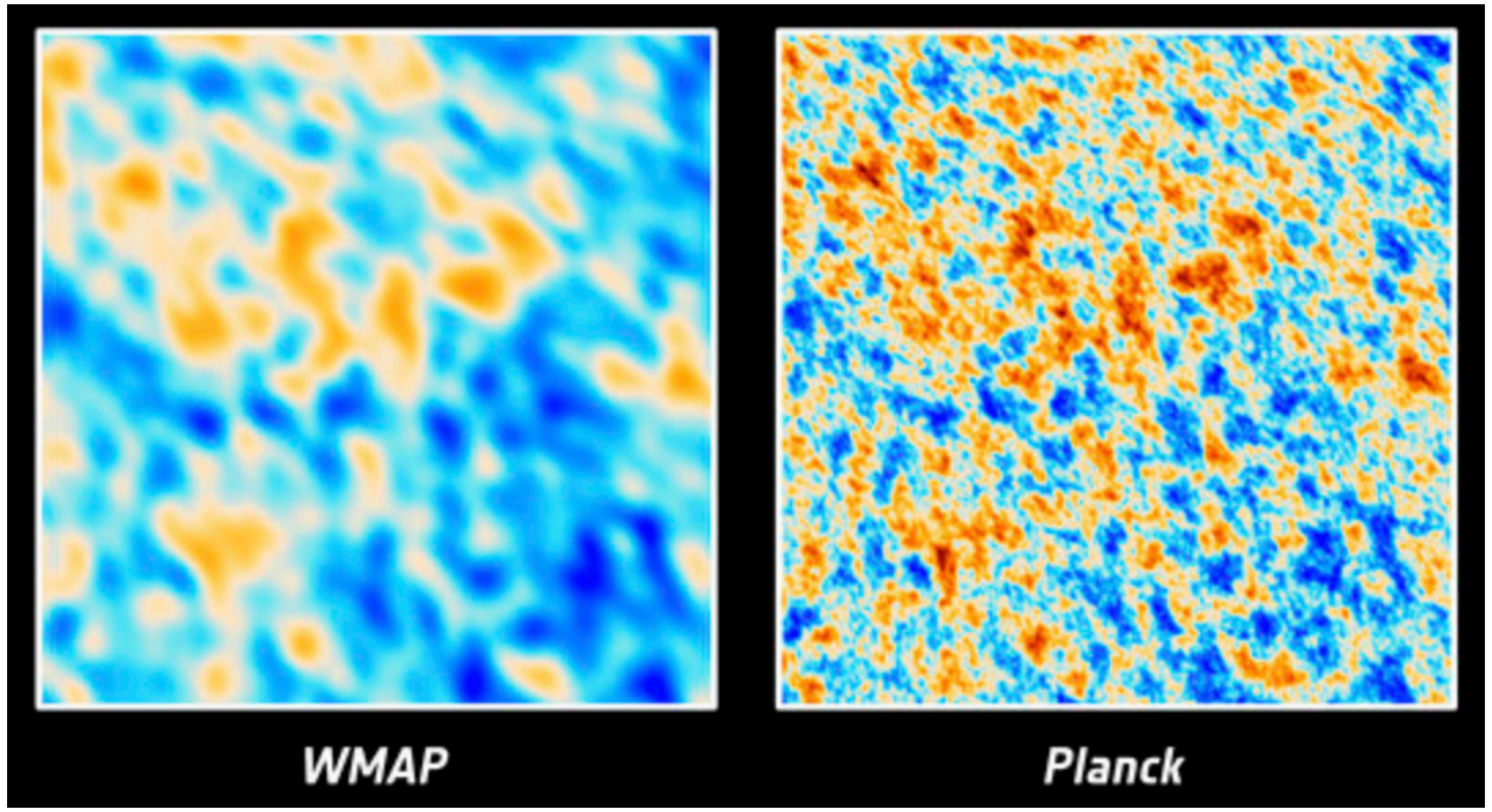






13 billion years ago
(40 billion LY away)





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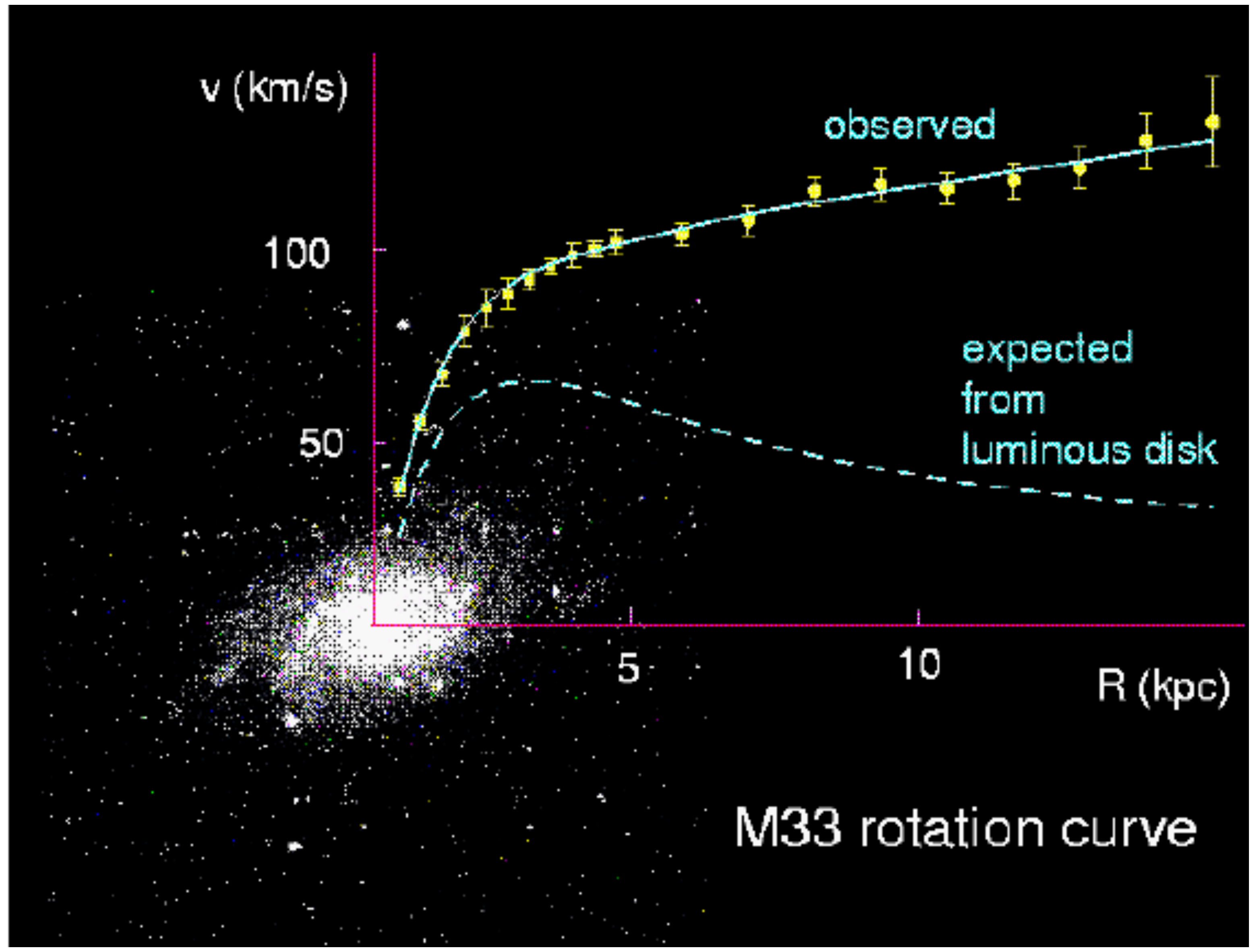
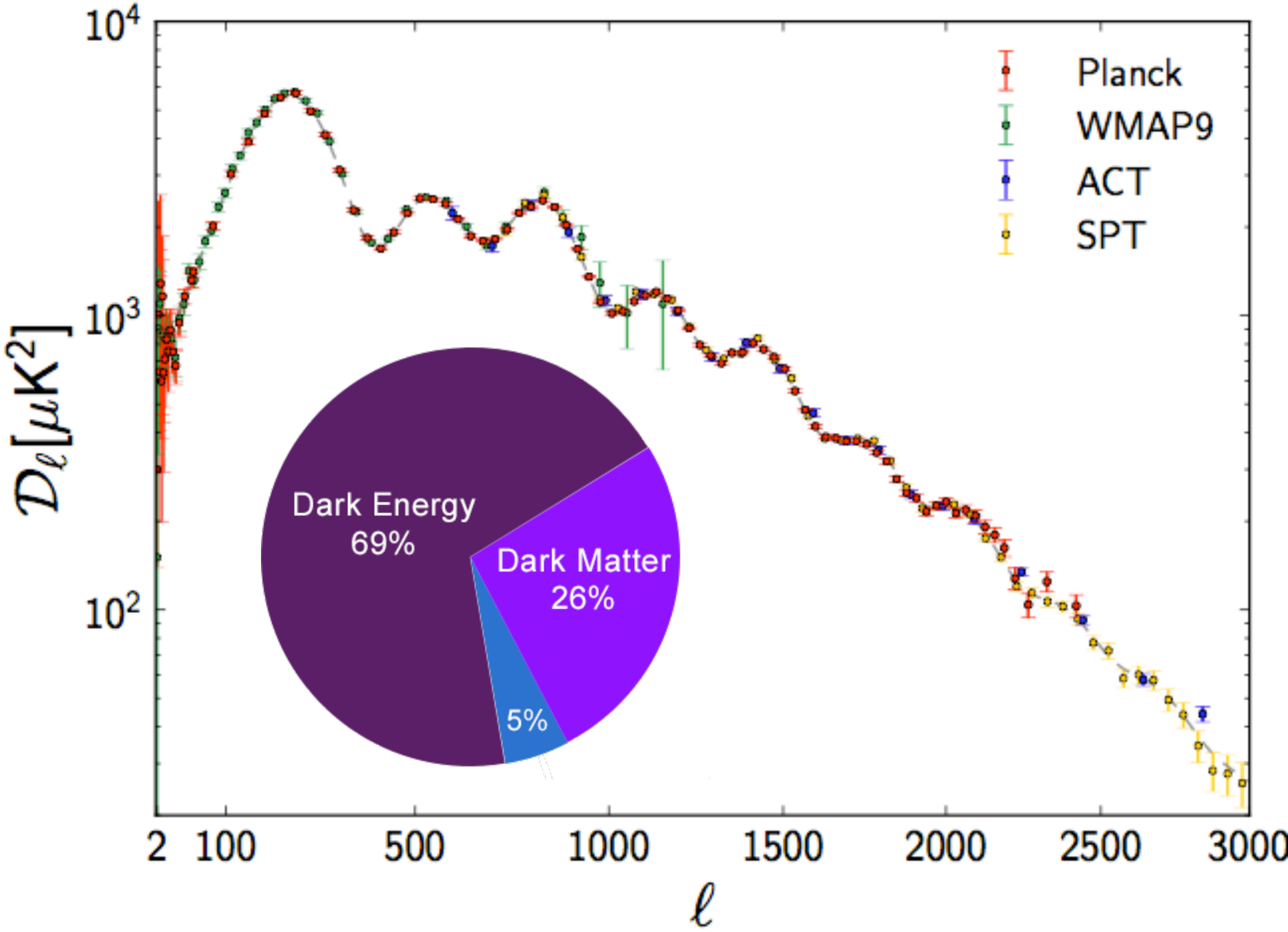
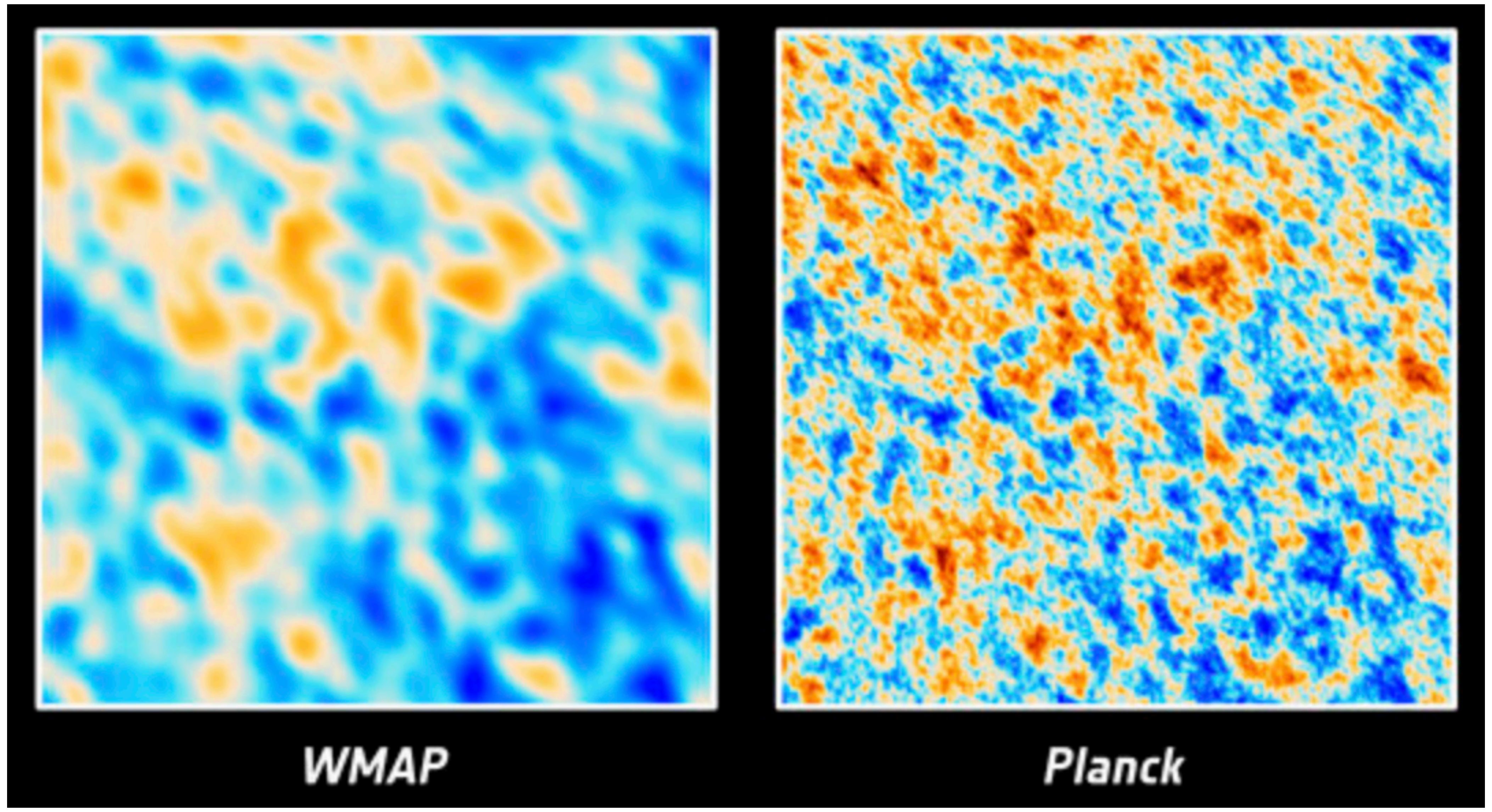


2 million years ago





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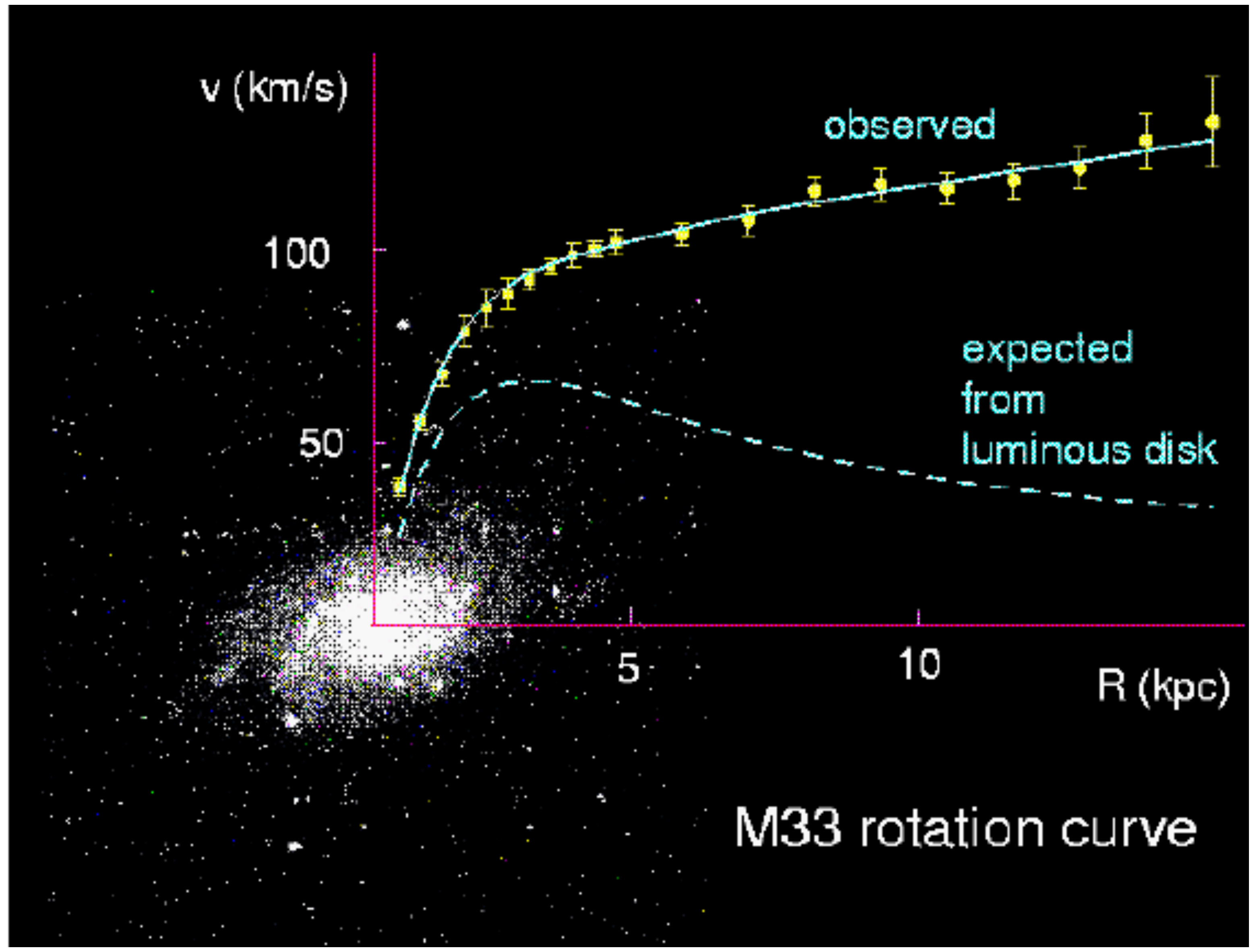

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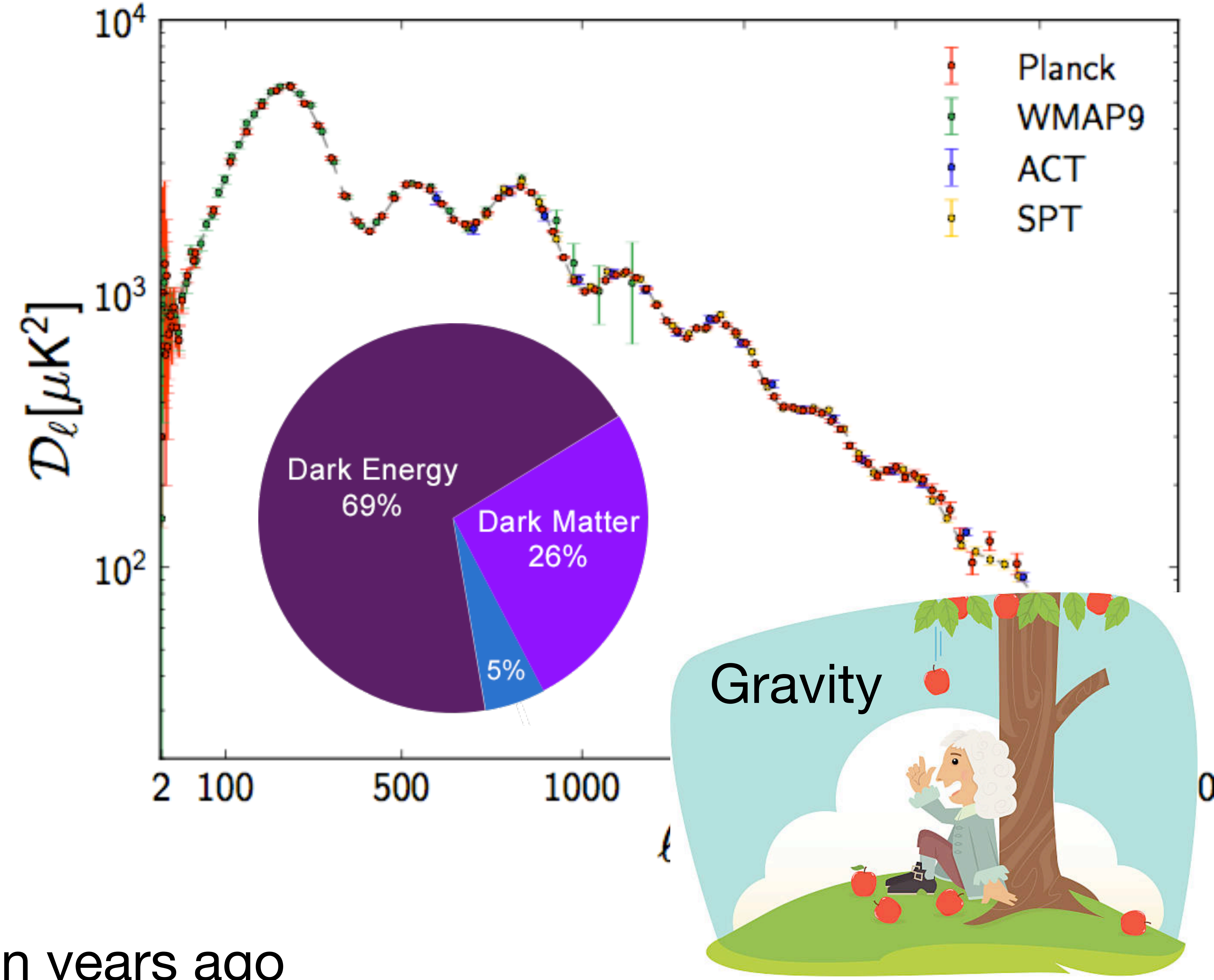
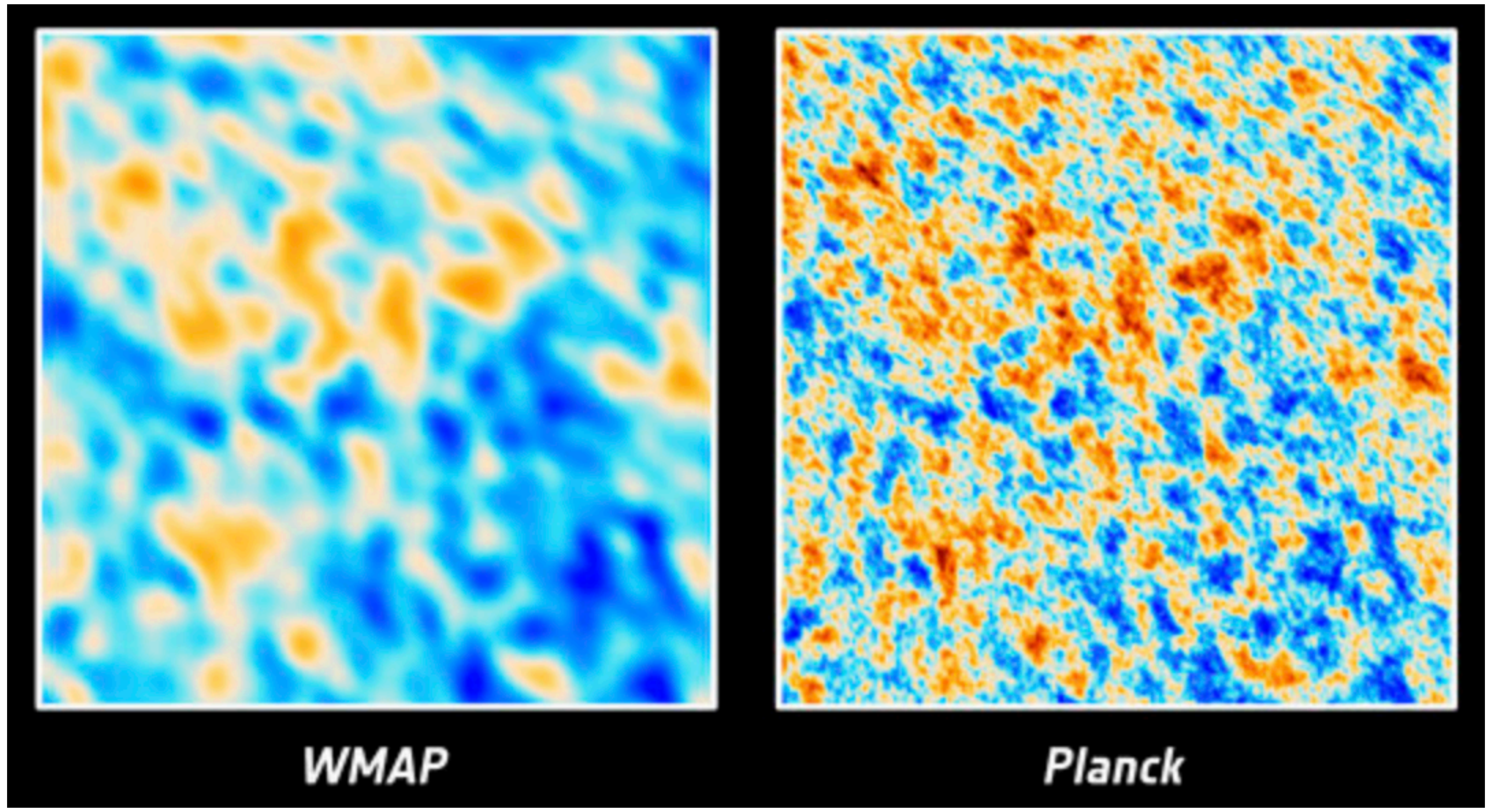


Neutrino mass



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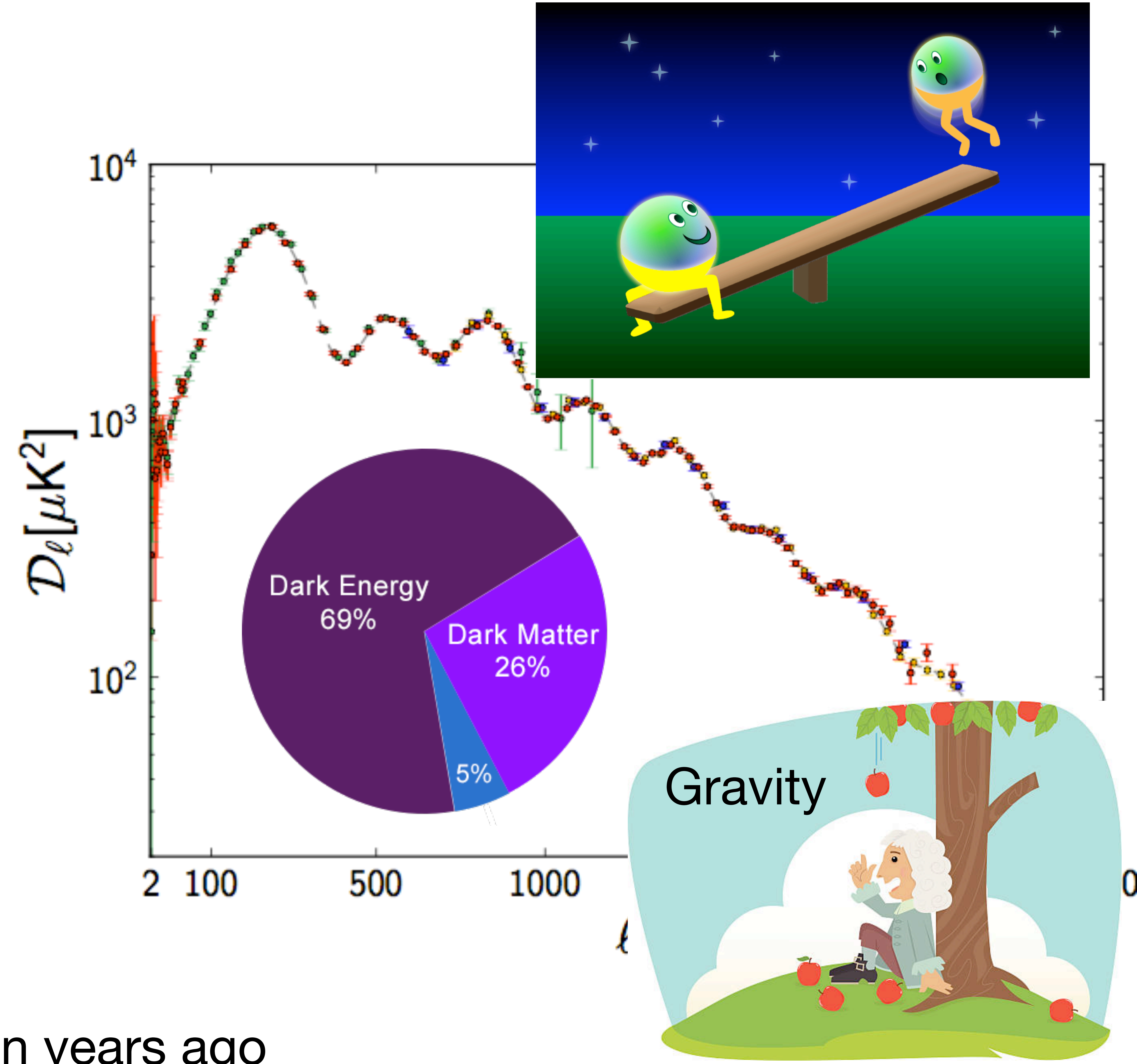

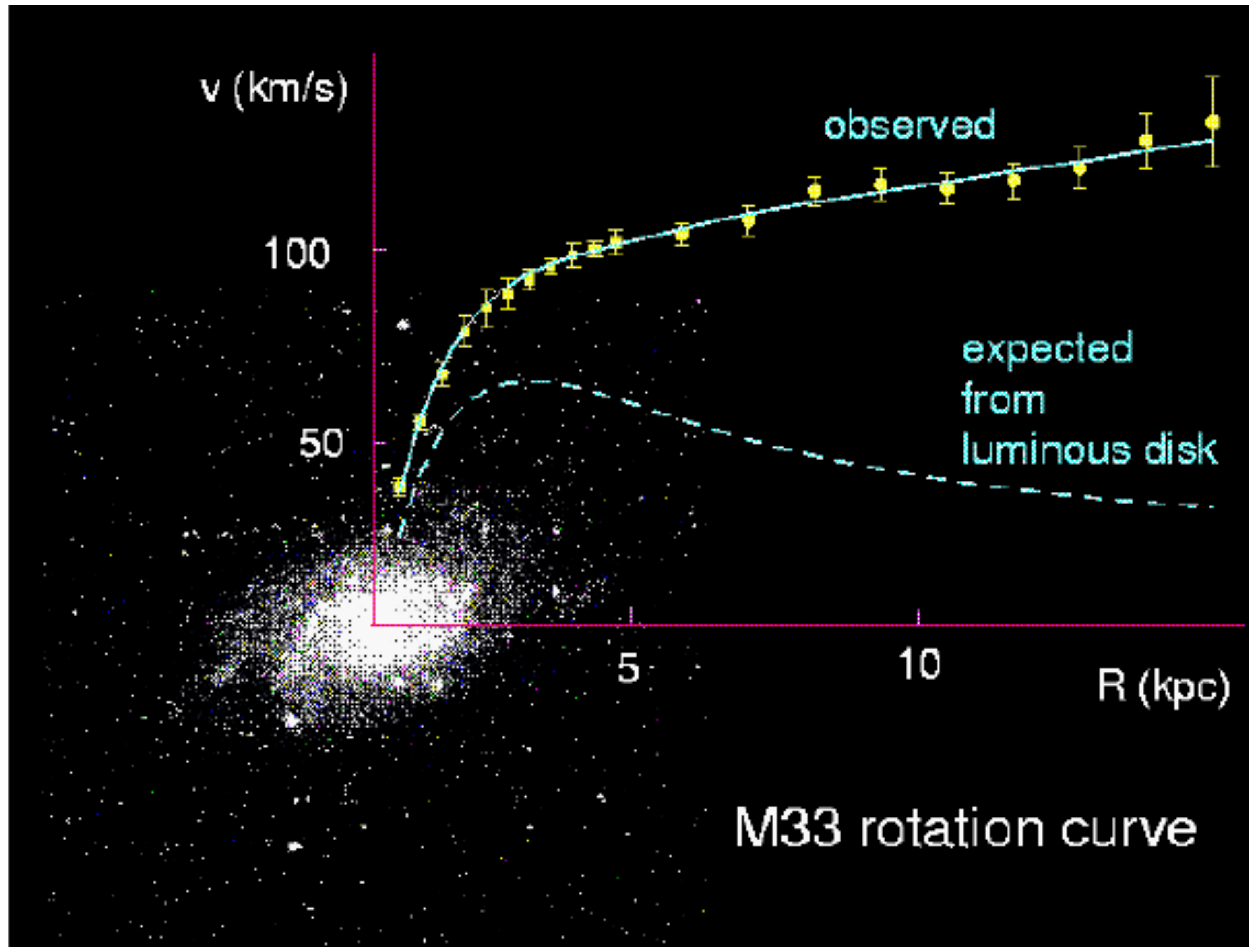

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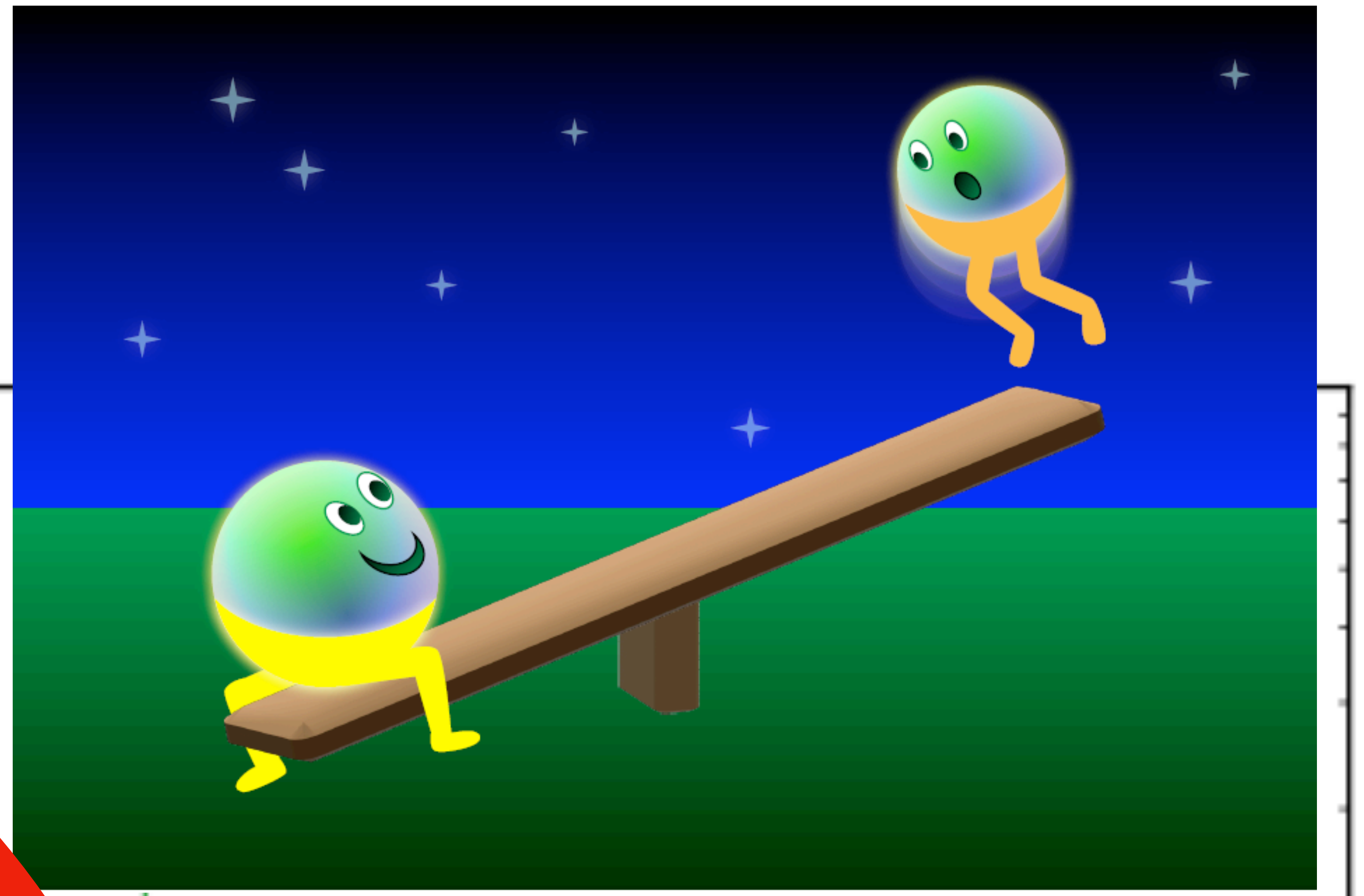

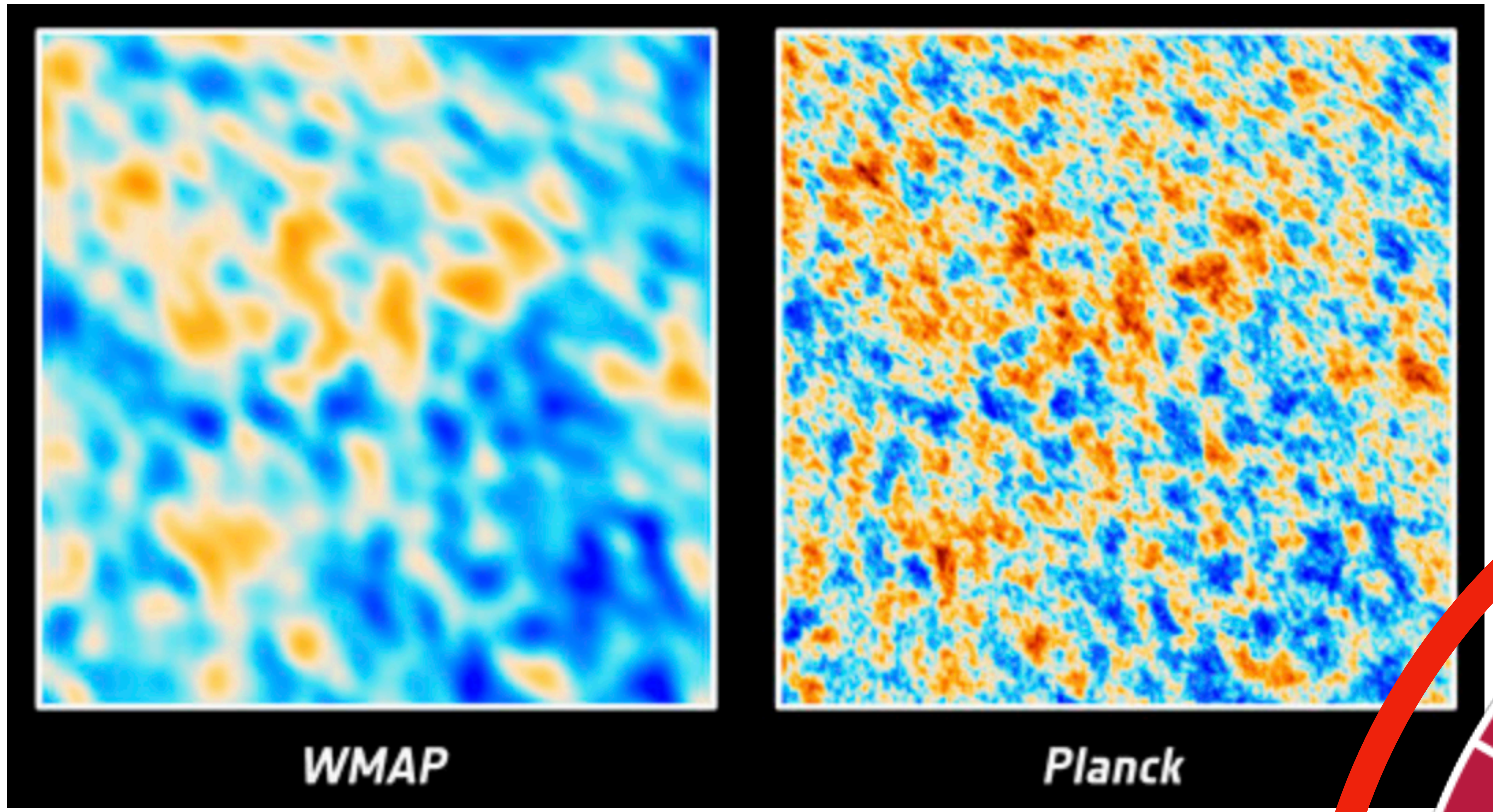

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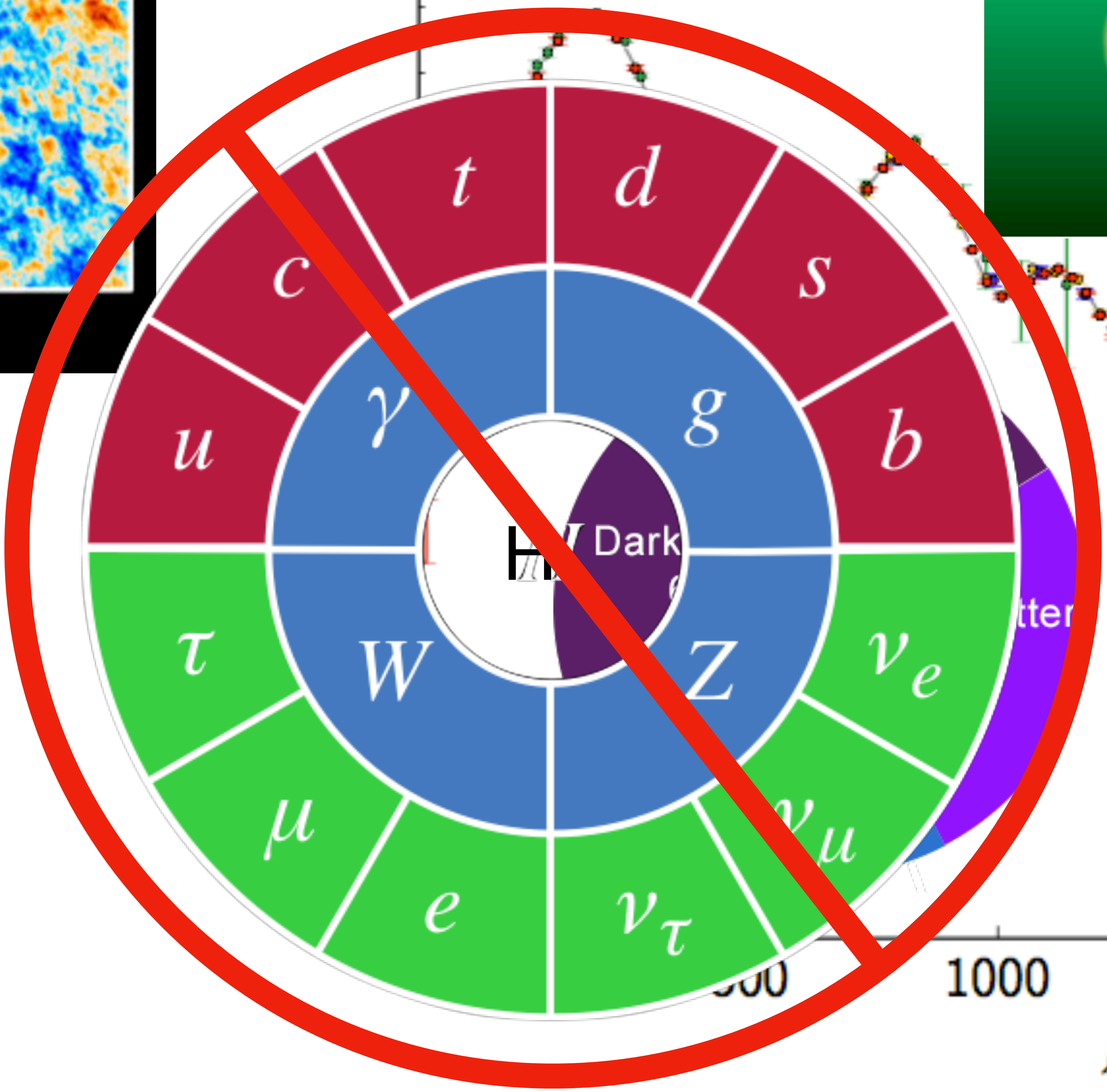

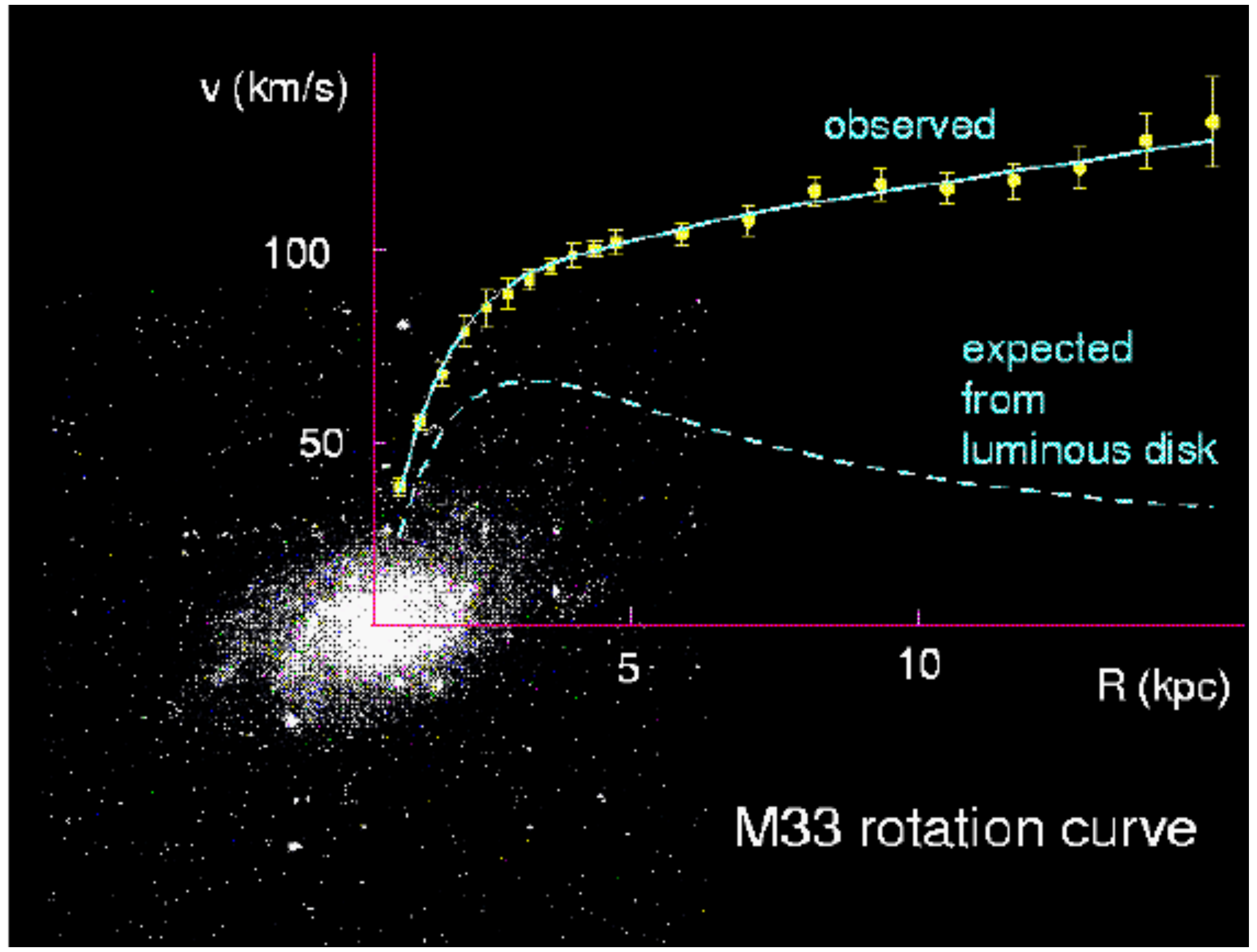

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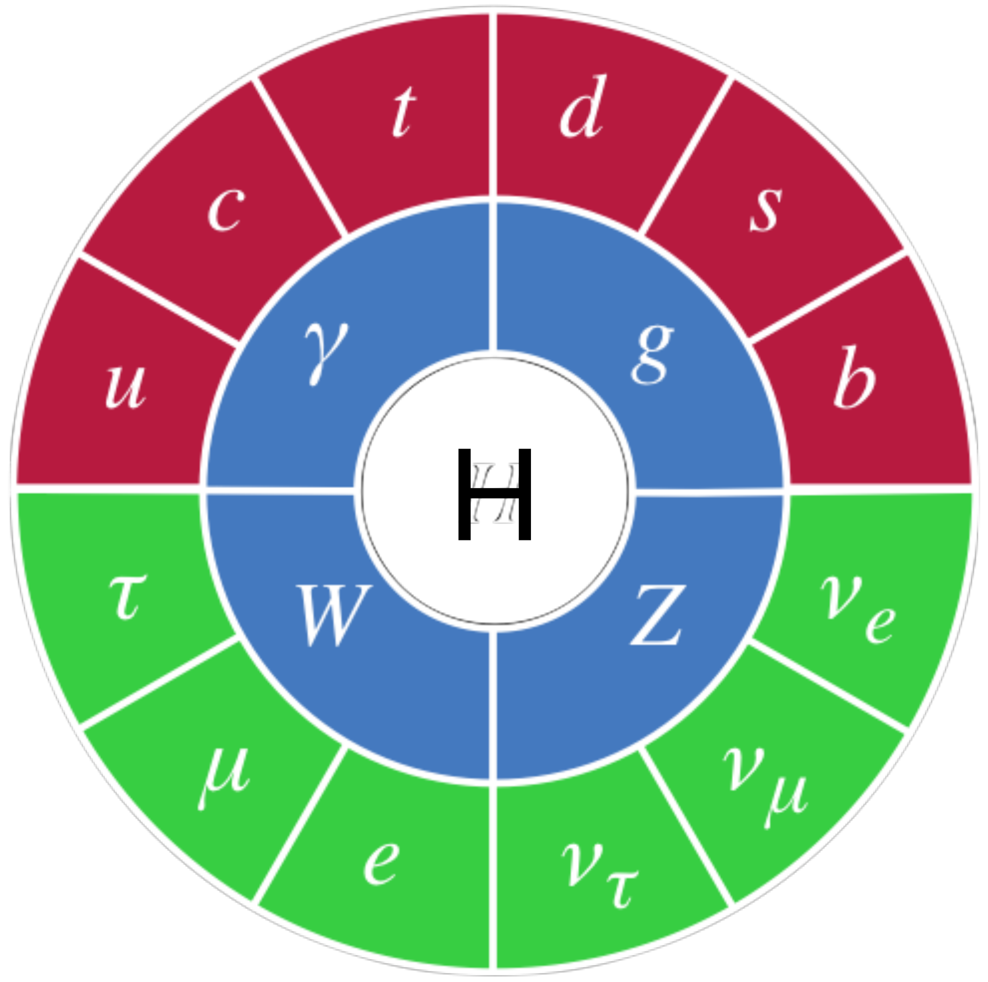
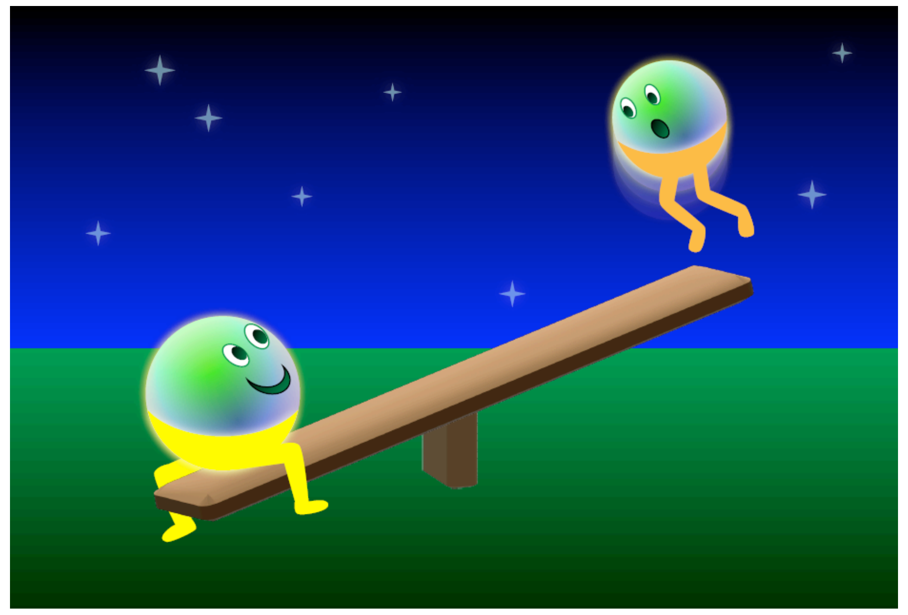


Scale of new physics Λ

- Gravity: $\Lambda \sim O(10^{18}$ GeV)
- Neutrino see-saw scale: $\Lambda \sim O(10^{16}$ GeV)



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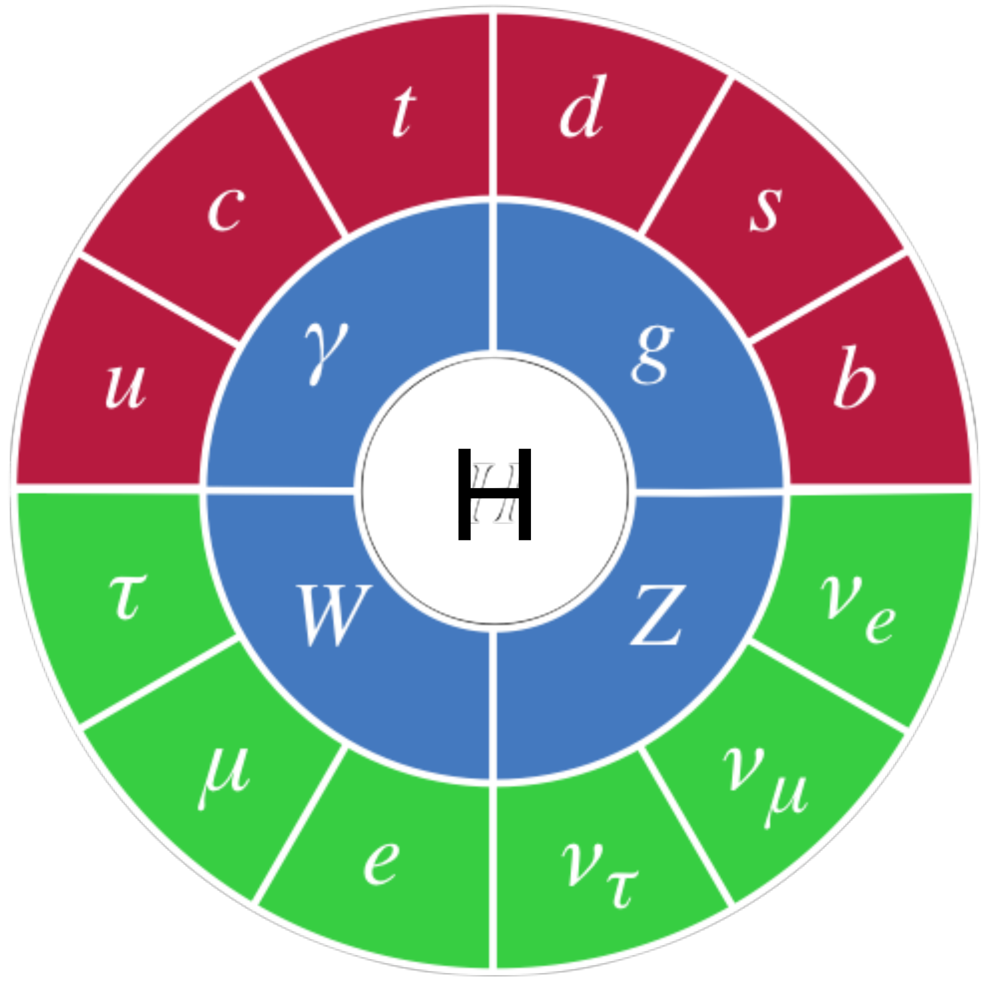

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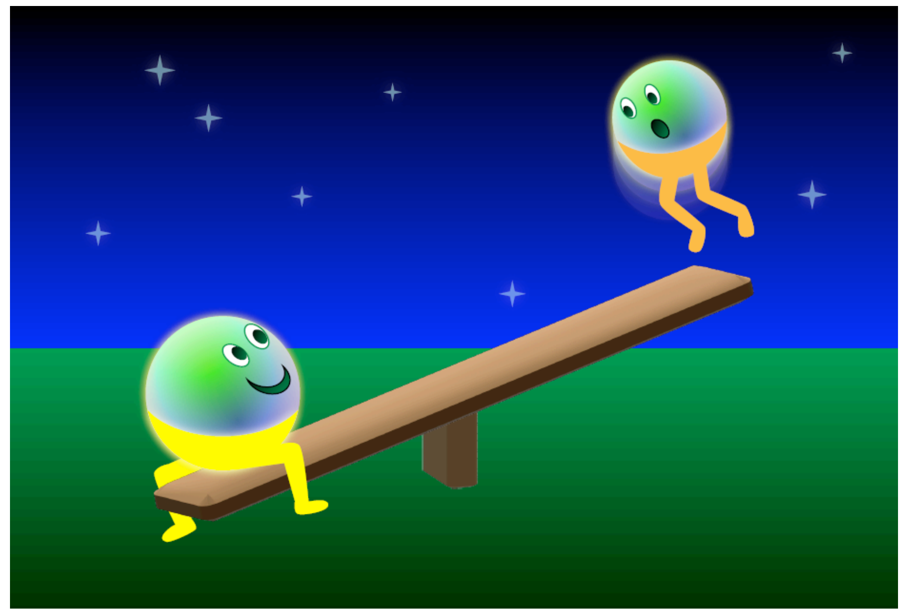
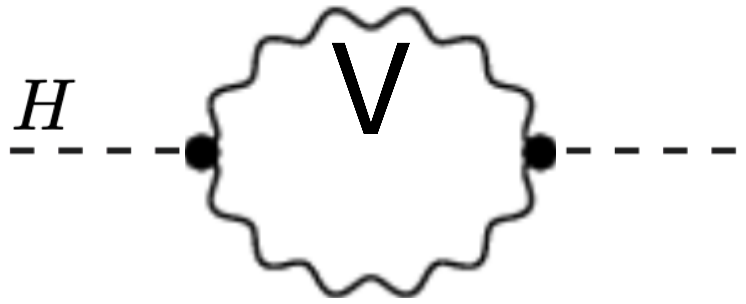


Scalars receive radiative corrections!

$$\Delta m_{H,v}^2 = \boxed{\frac{3\,g_V^2}{16\pi^2}\left[\Lambda^2\right.} - M_V^2 \ln\left(\frac{\Lambda^2}{M_V^2}\right) + \cdots \Big]$$



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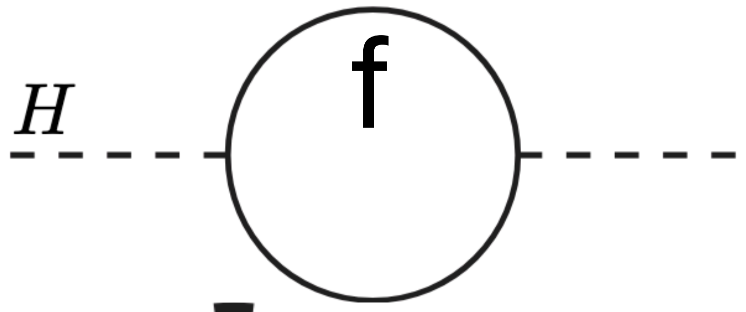

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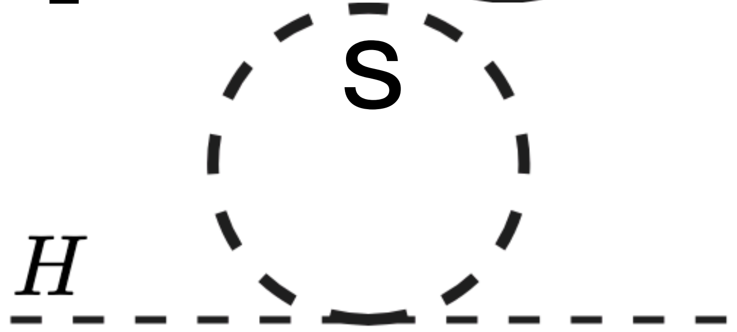

Big hierarchy puzzle:
Enormous unrelated contributions cancel

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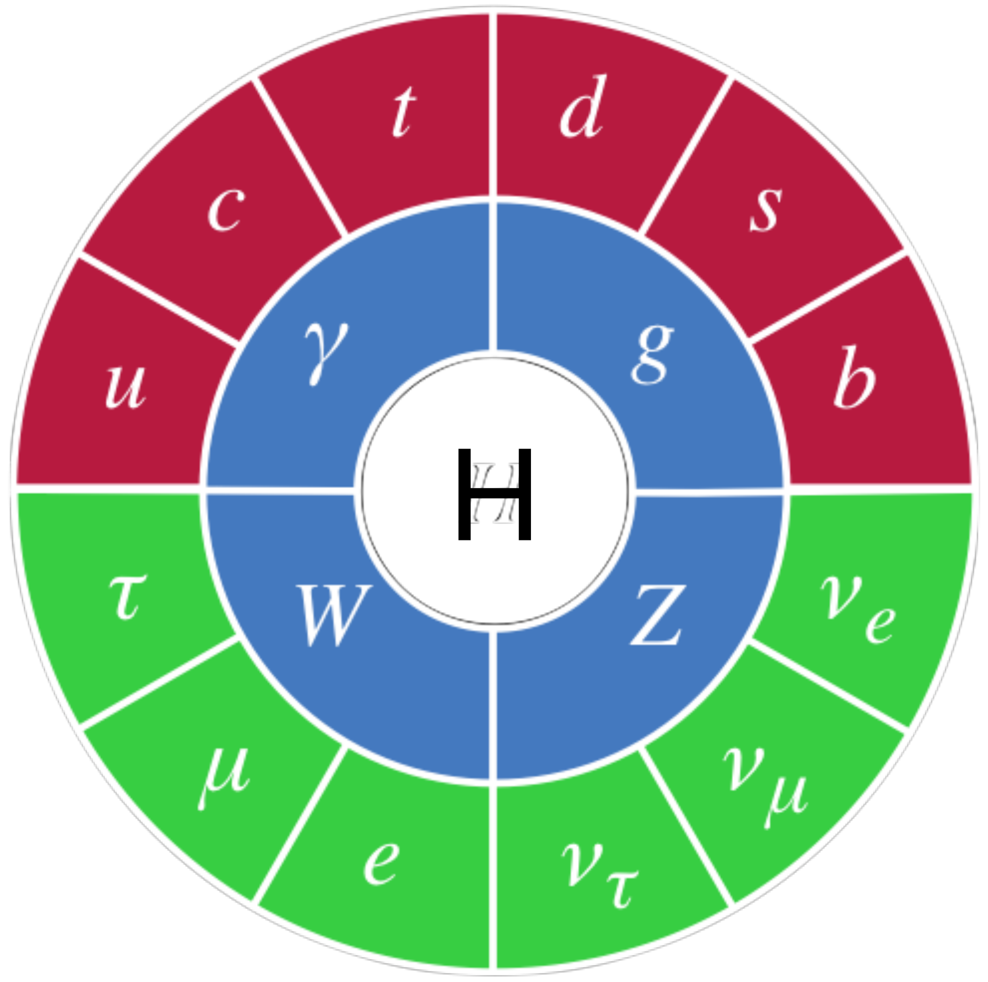

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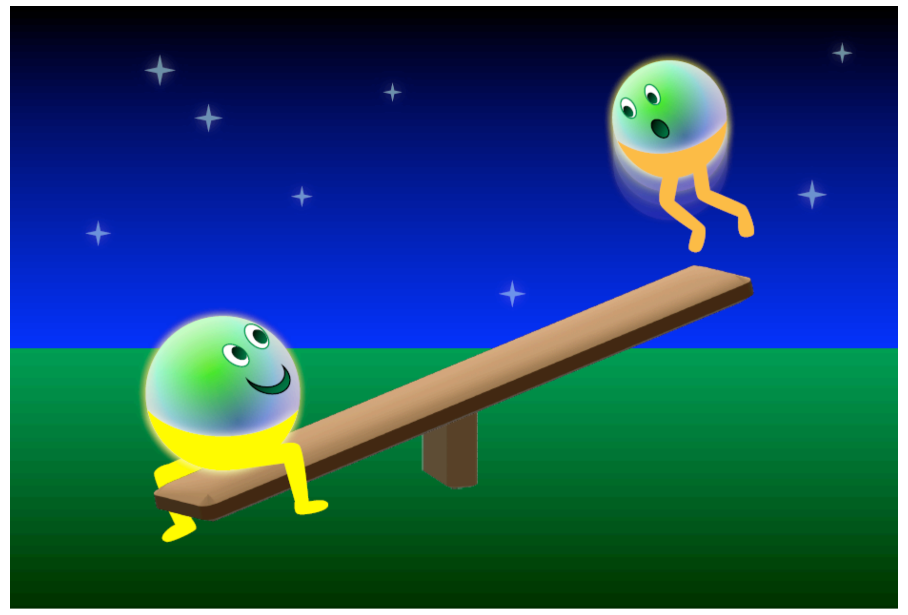

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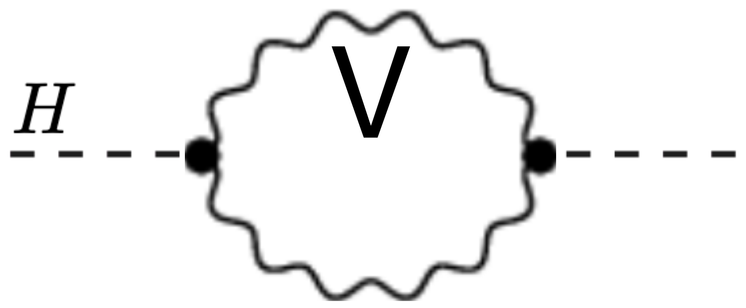

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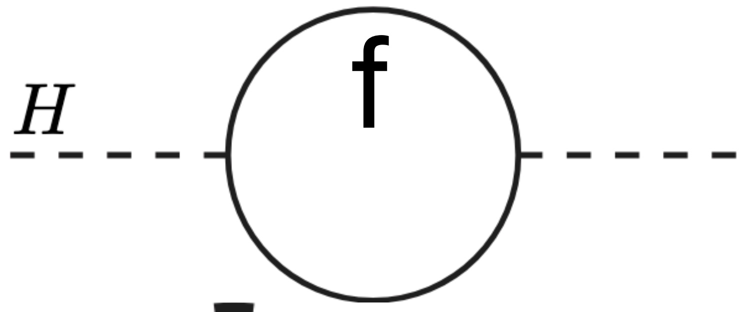

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Fine tuning problem? Can of worms?

Hierarchy puzzle can of worms

- Asked ChatGPT to make a naive simulation to illustrate intuition (and absurdity) behind the fine-tuning problem assuming assume $\Lambda = 10^{18}$ GeV…
  - With great audacity, sample SM parameters
    - What parameter ranges? Take RMS=SM, 2*SM, etc.
    - How to sample? Try different things - flat in m, in m^2, in log(m).

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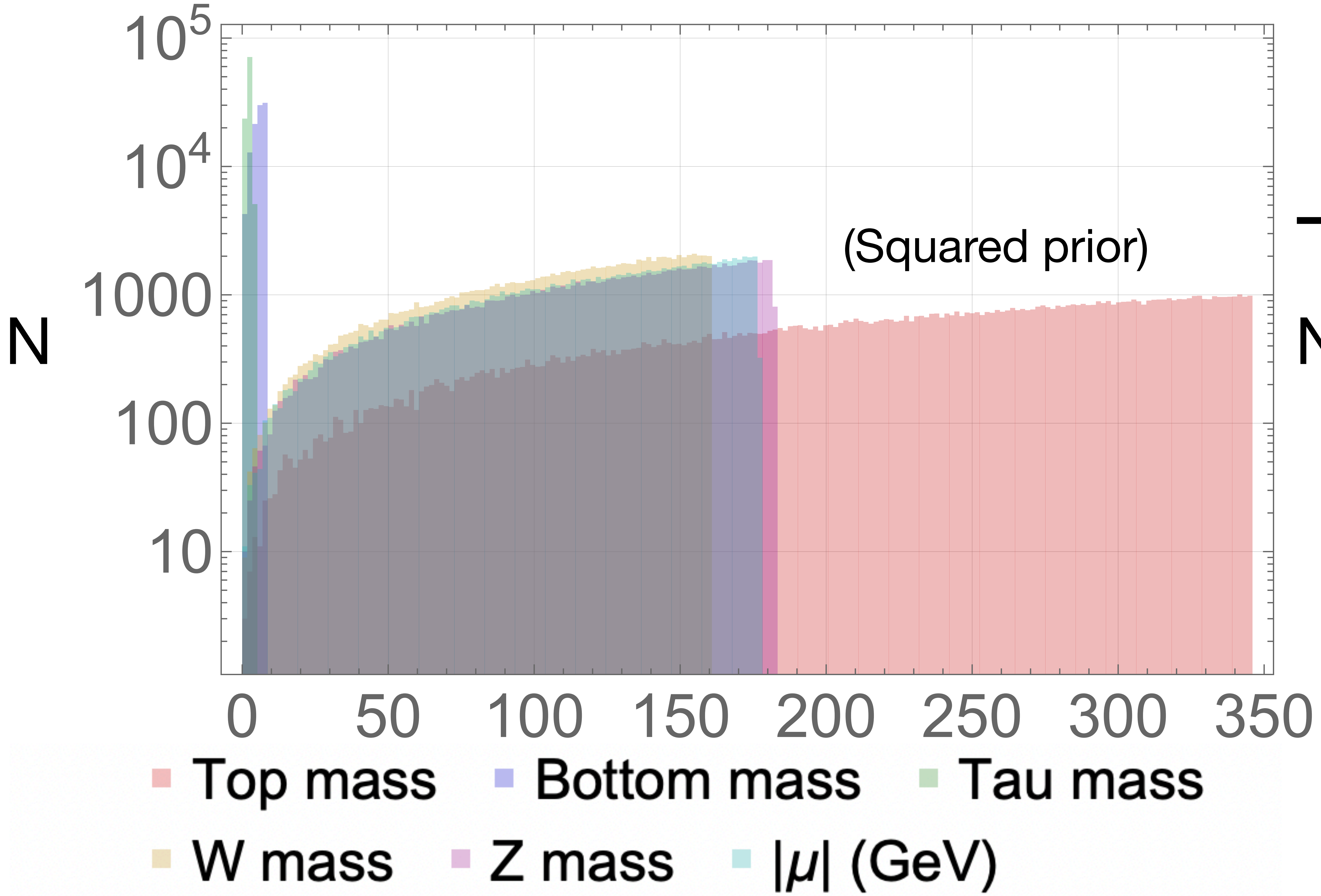

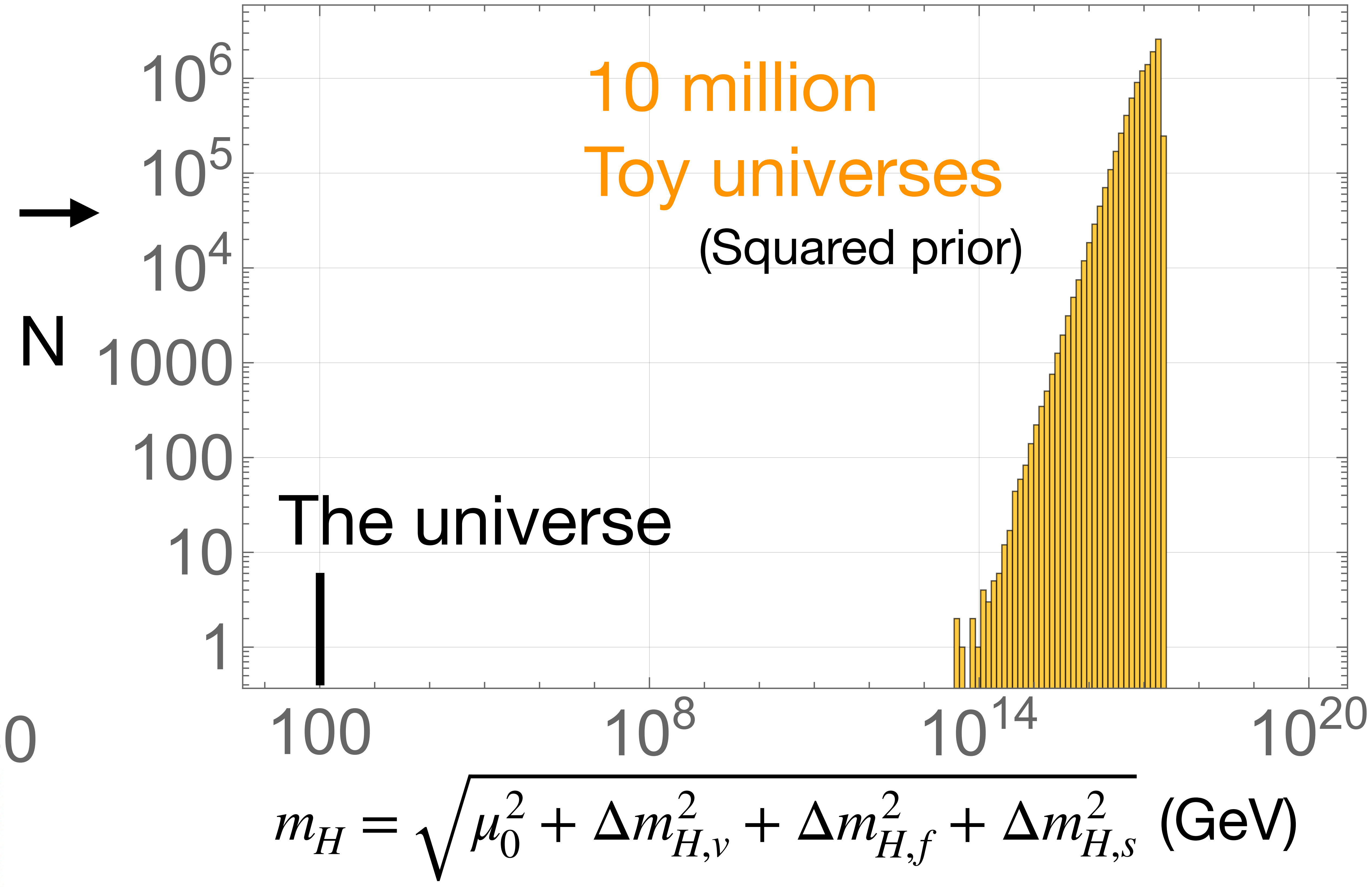

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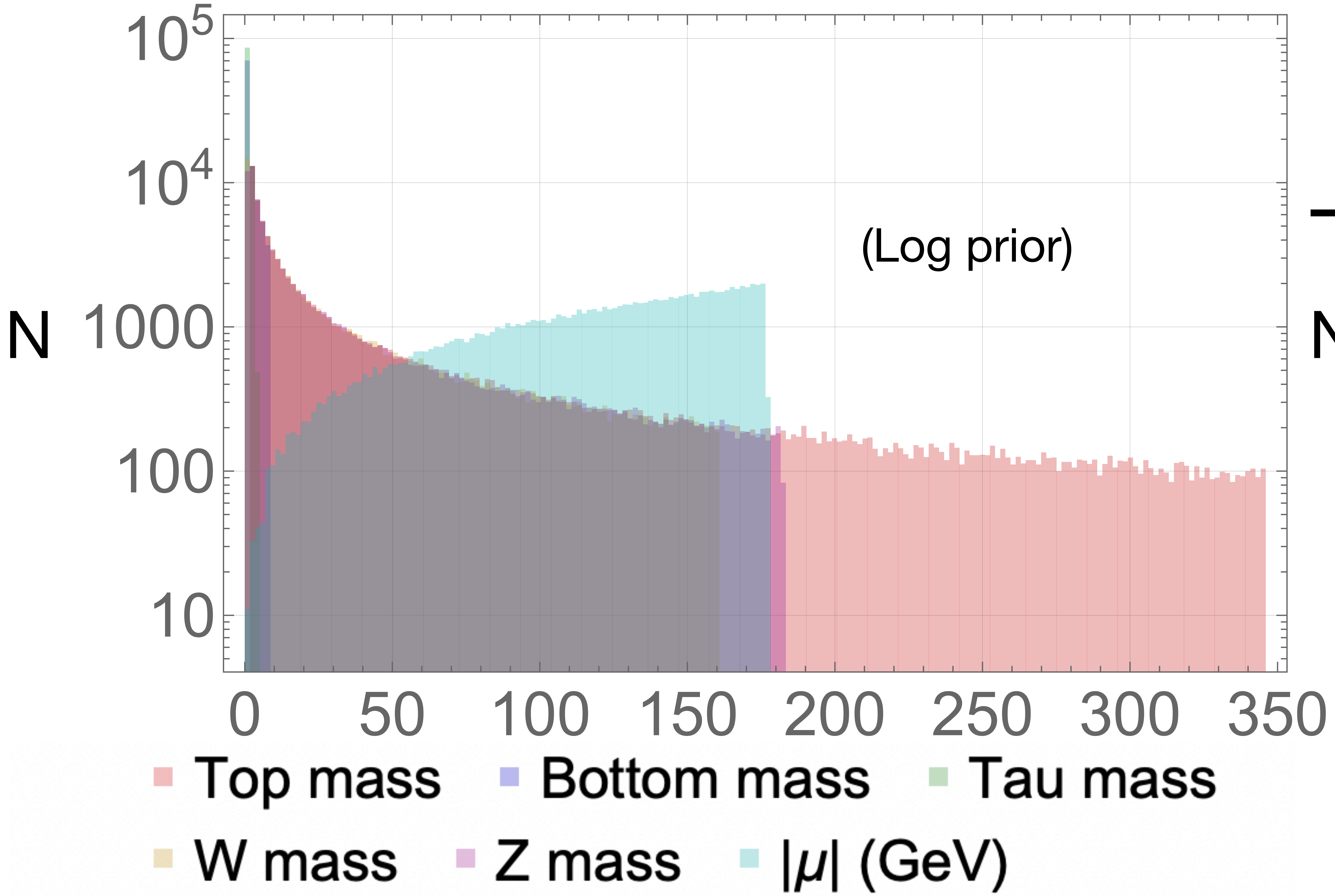

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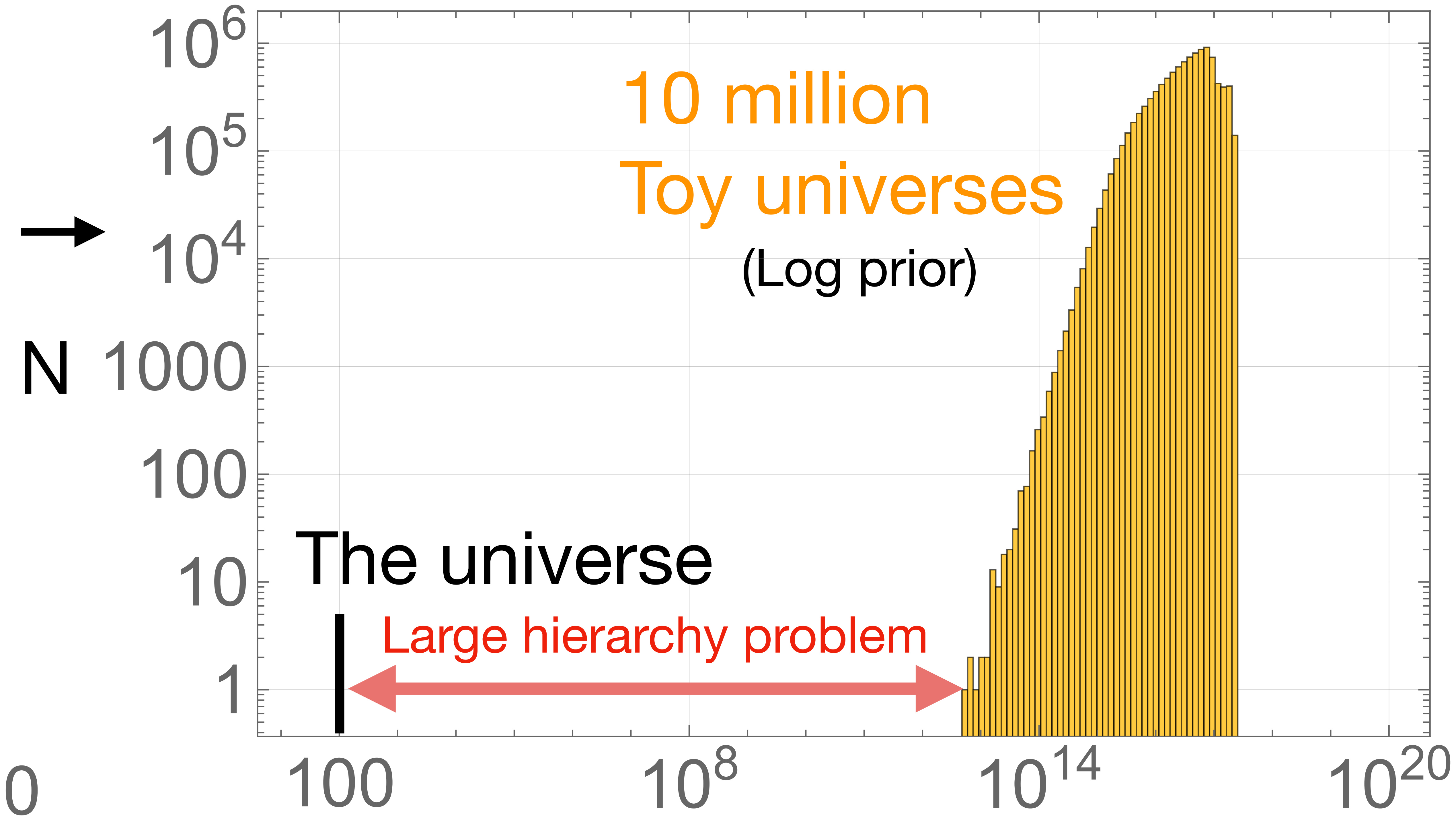

$$m_H = \sqrt{\mu_0^2 + \Delta m_{H,v}^2 + \Delta m_{H,f}^2 + \Delta m_{H,s}^2} \text{ (GeV)}$$

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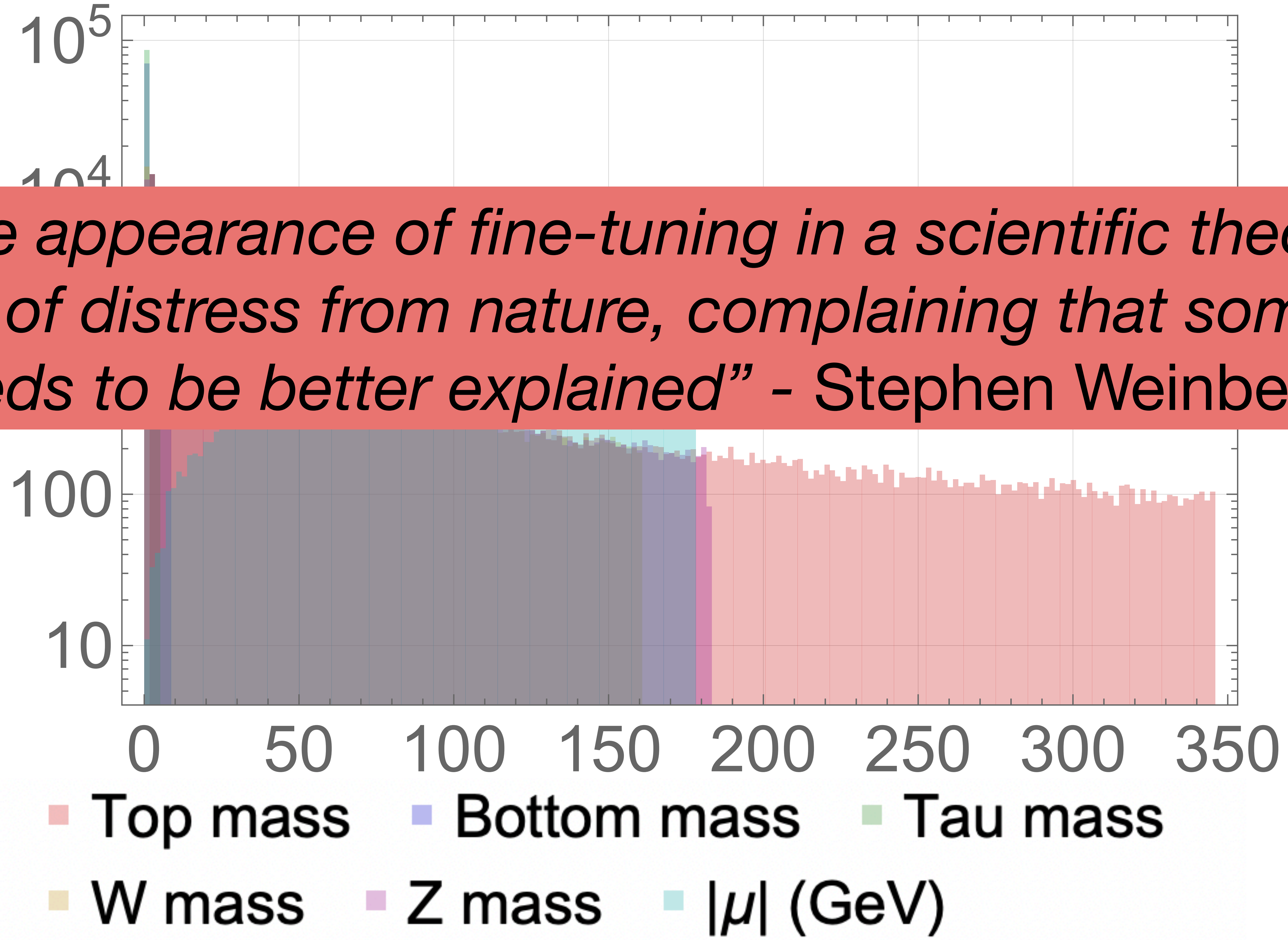
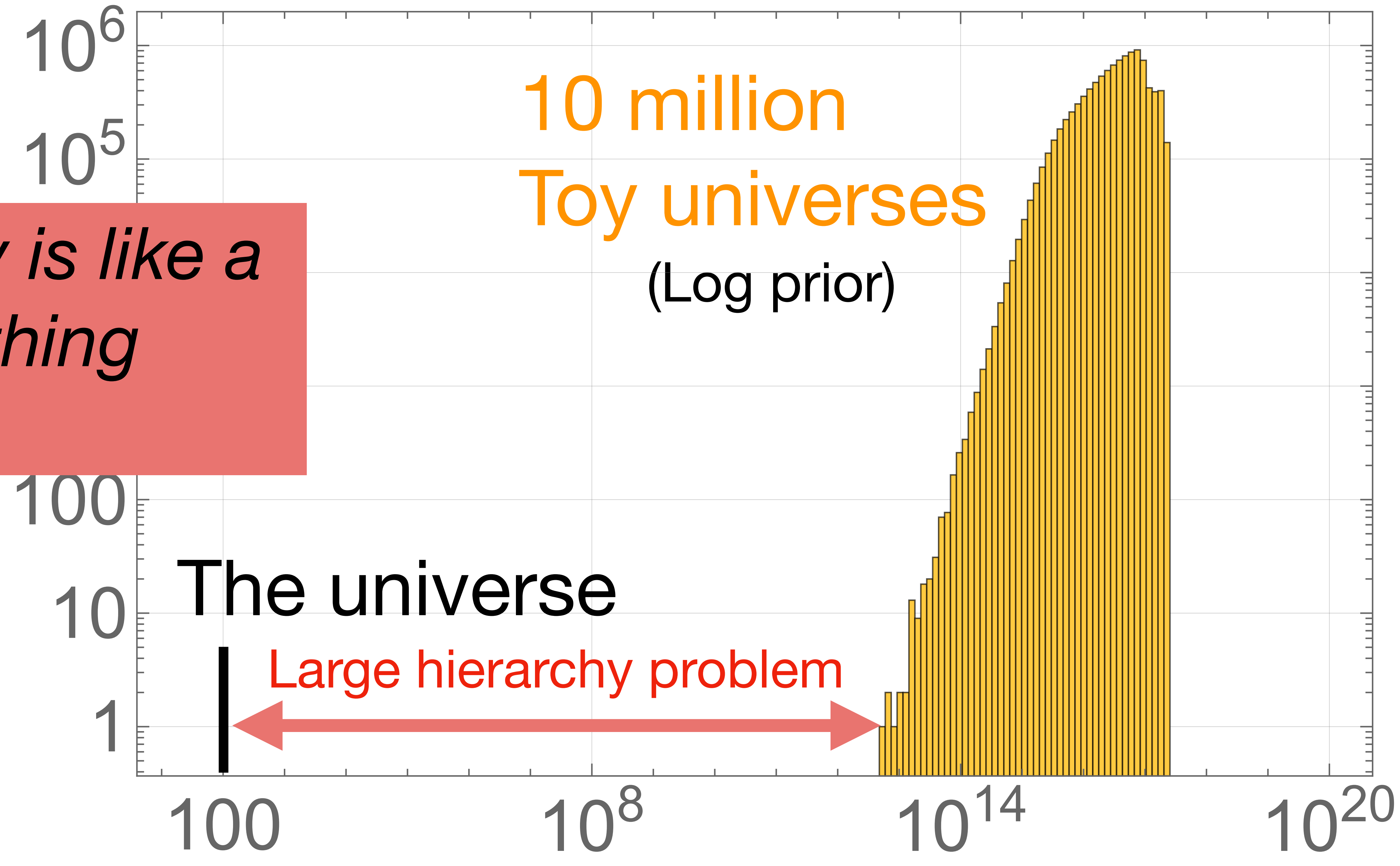


"the appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained" - Stephen Weinberg



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Da ist was Faul?

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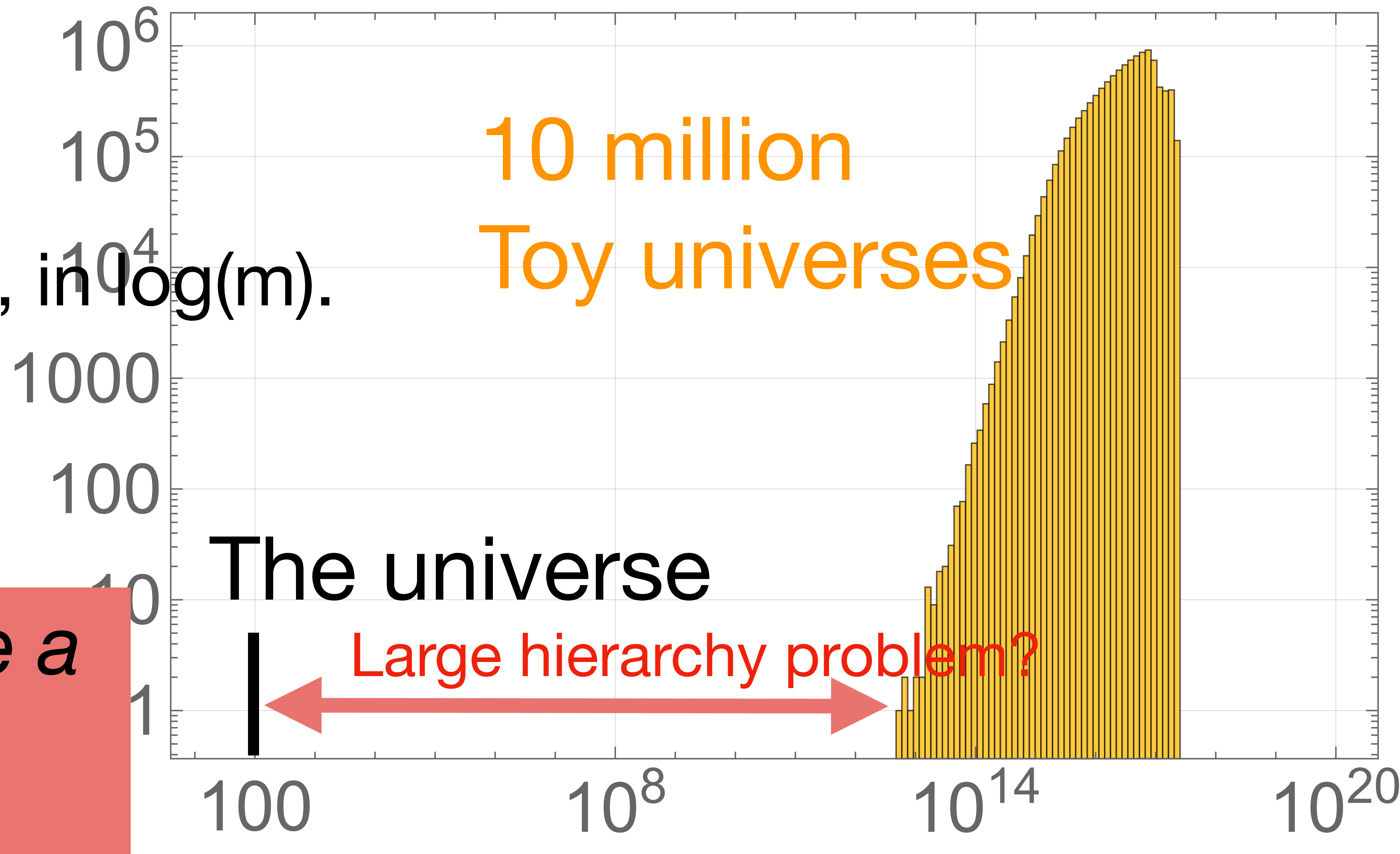
"the appearan… ry is like a cry of distress … ething needs to be b… g

Caspar David Friedrich



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Ist das was faul? (Is there really a problem?)

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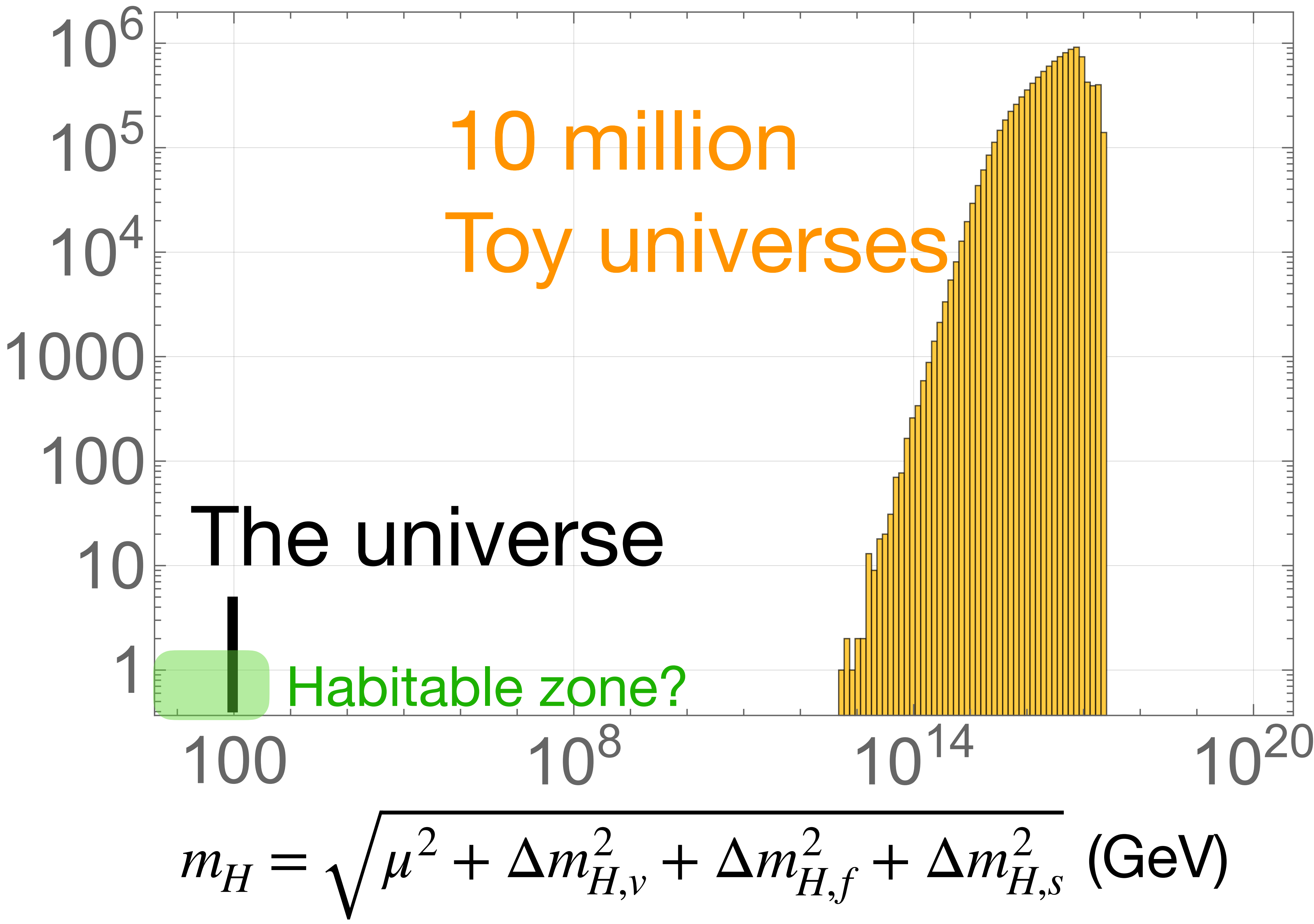

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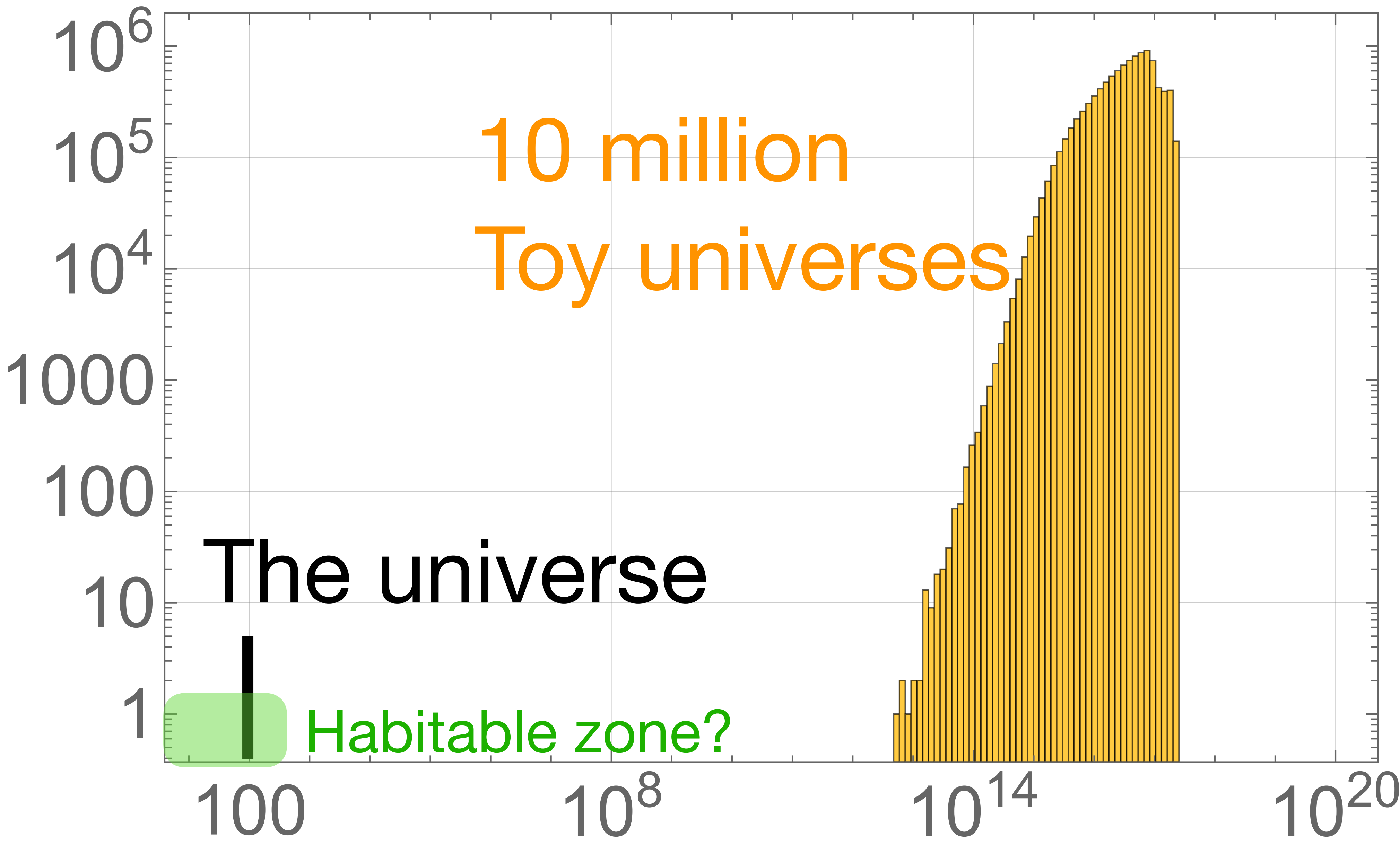

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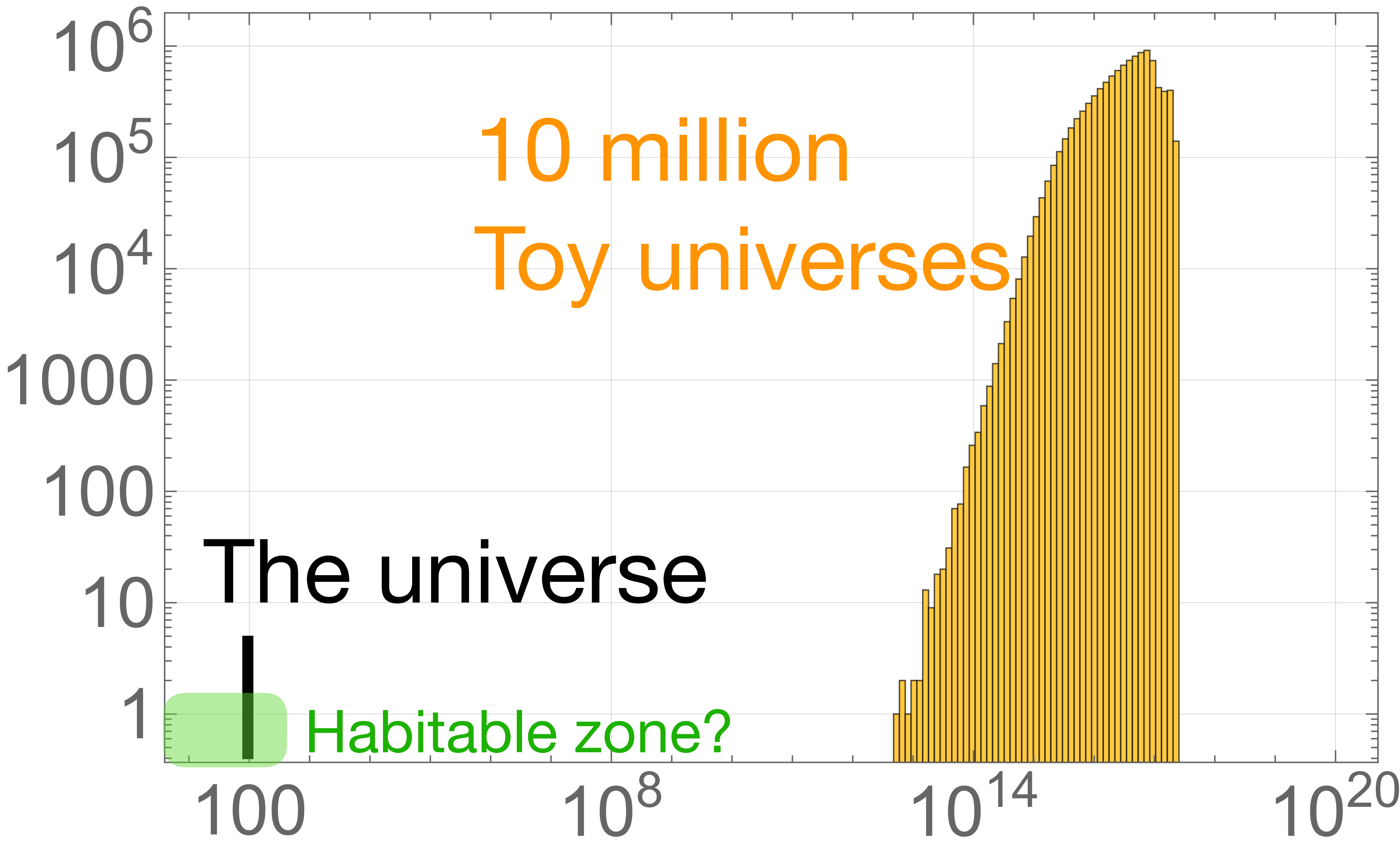
3. Subjectivity: who said I was allowed to choose any prior whatsoever? I could have chosen a prior where the yellow ended up covering the black



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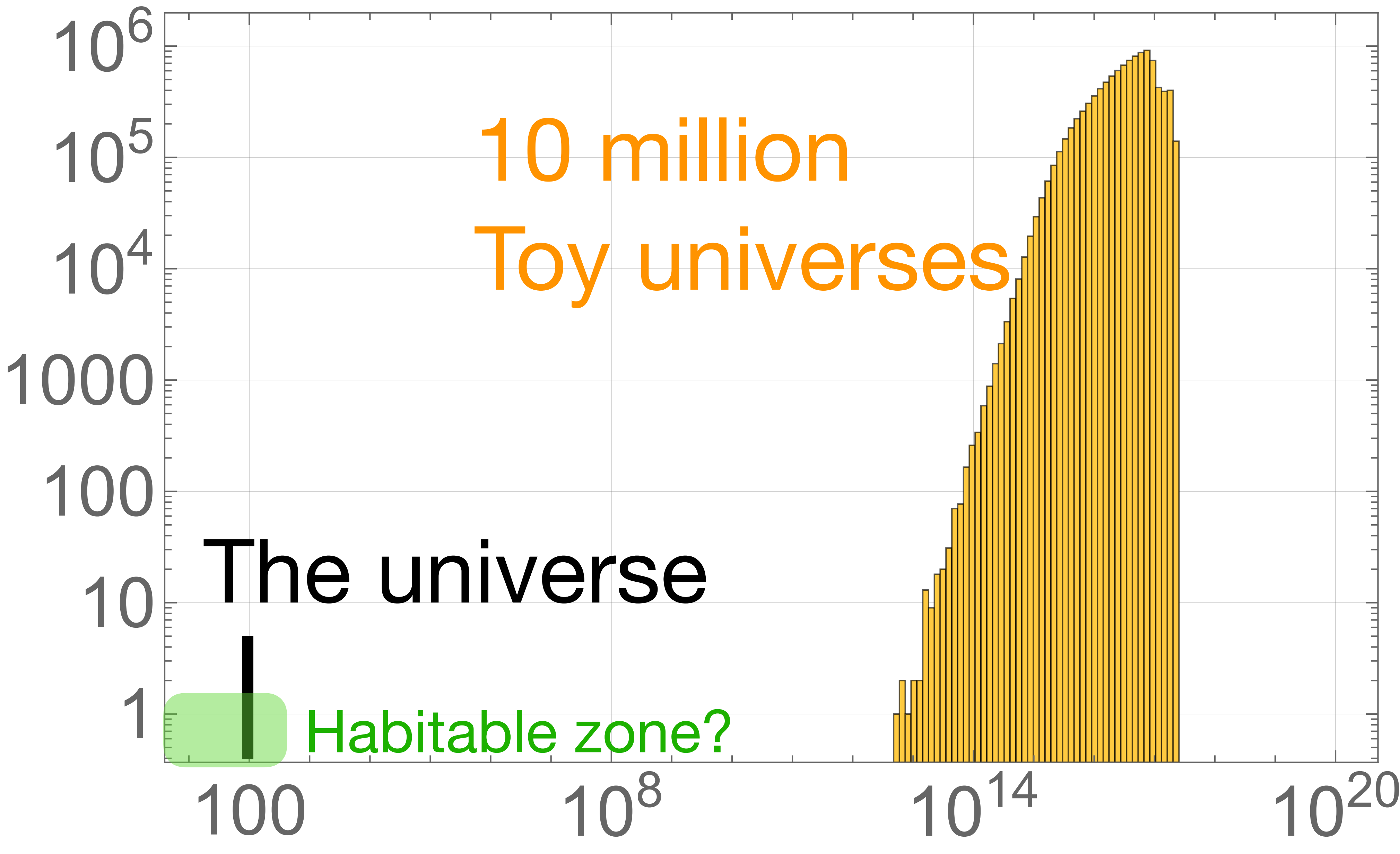
2. "We need a mechanism for making multiverses to allow anthropic pressure arguments - without [it], there is only a tautology" - Alexander Westphal
3. Subjectivity: who said I was allowed to choose any prior whatsoever? I could have chosen a prior where the yellow ended up covering the black



$$m_H = \sqrt{\mu^2 + \Delta m^2_{H,v} + \Delta m^2_{H,f} + \Delta m^2_{H,s}} \text{ (GeV)}$$

My reflections

1. Anthropic pressure can definitely solve the hierarchy problem. But if one has to invoke the existence of at O(10^14) universes, that hardly seems like Occam's razor.

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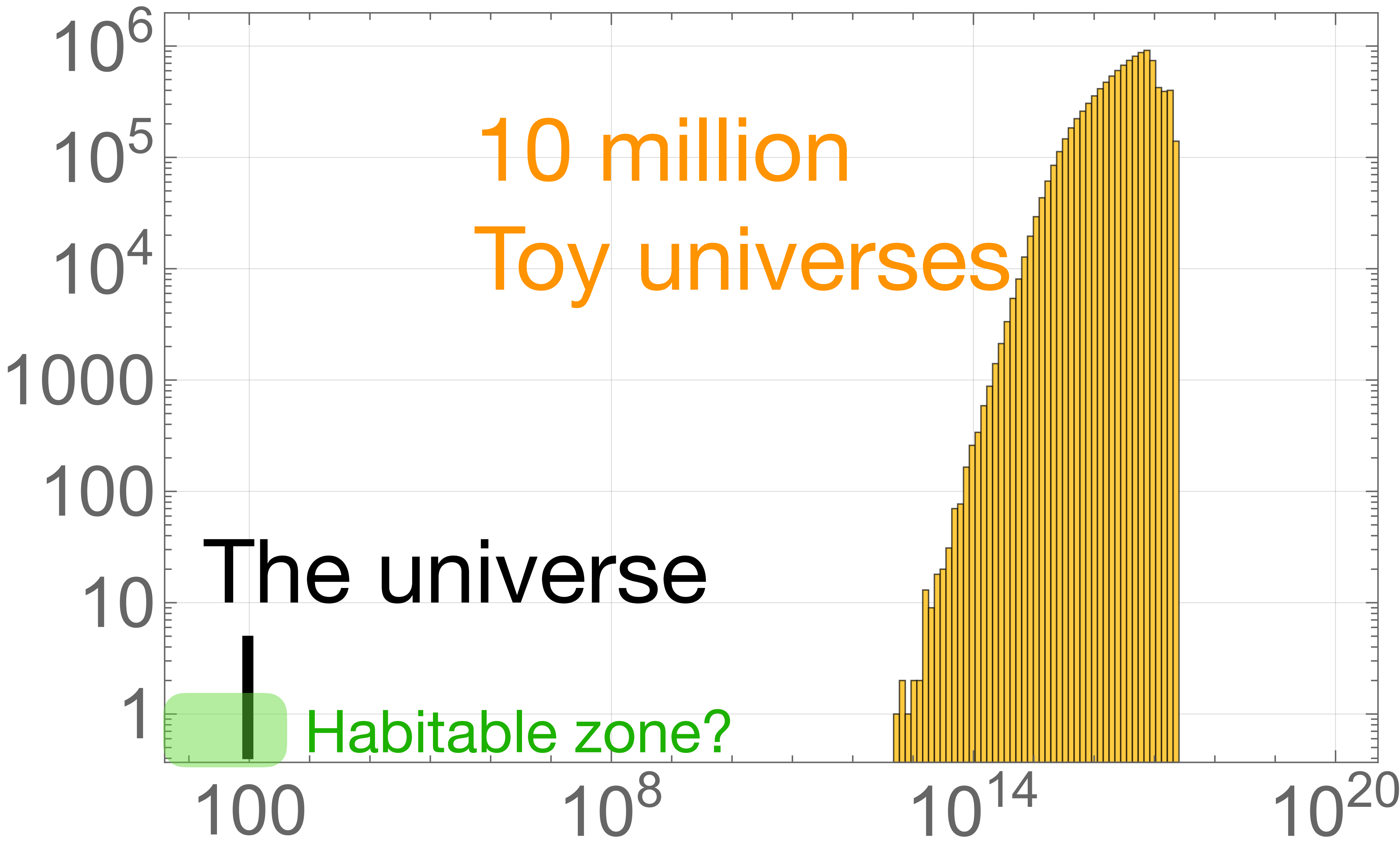

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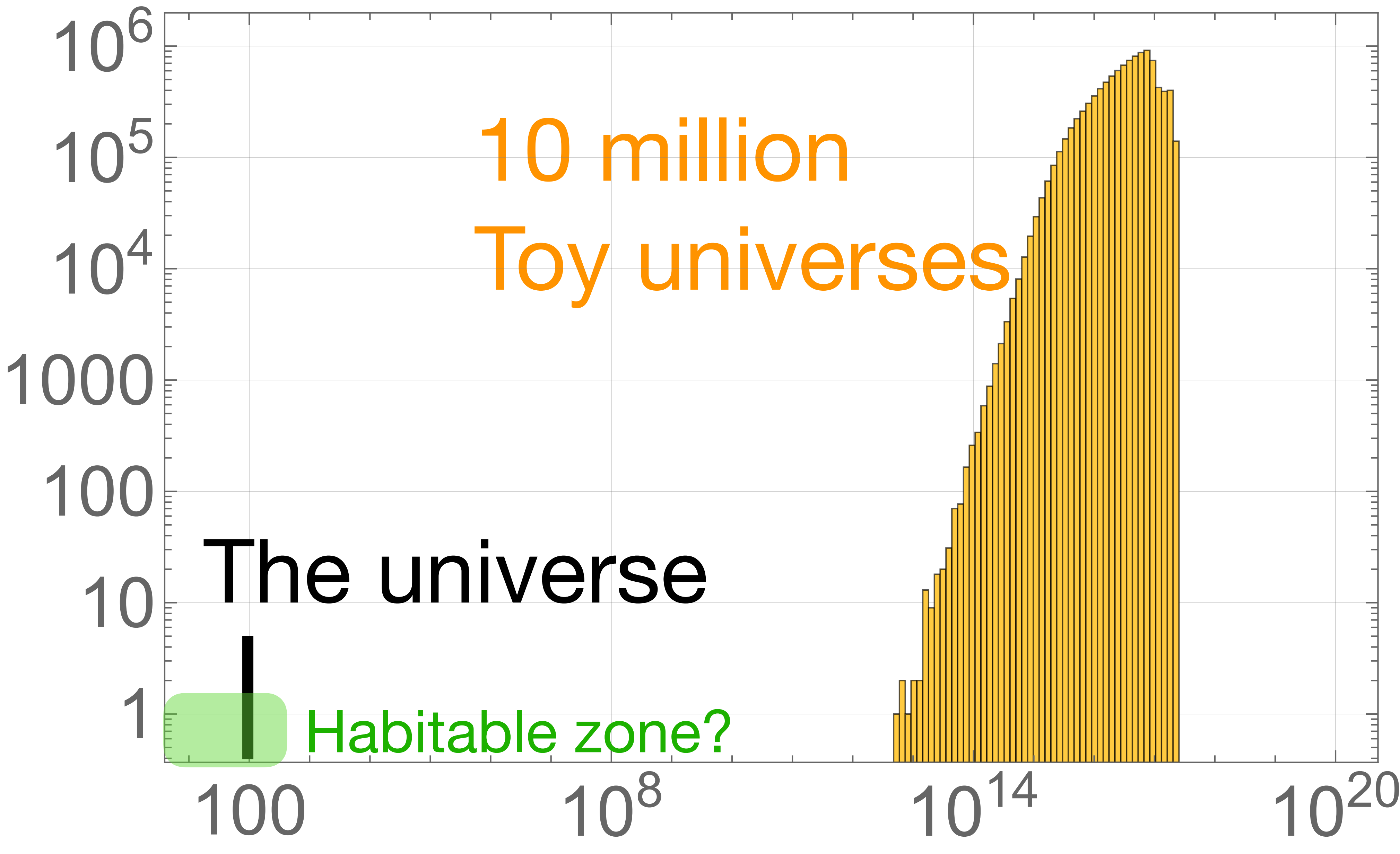

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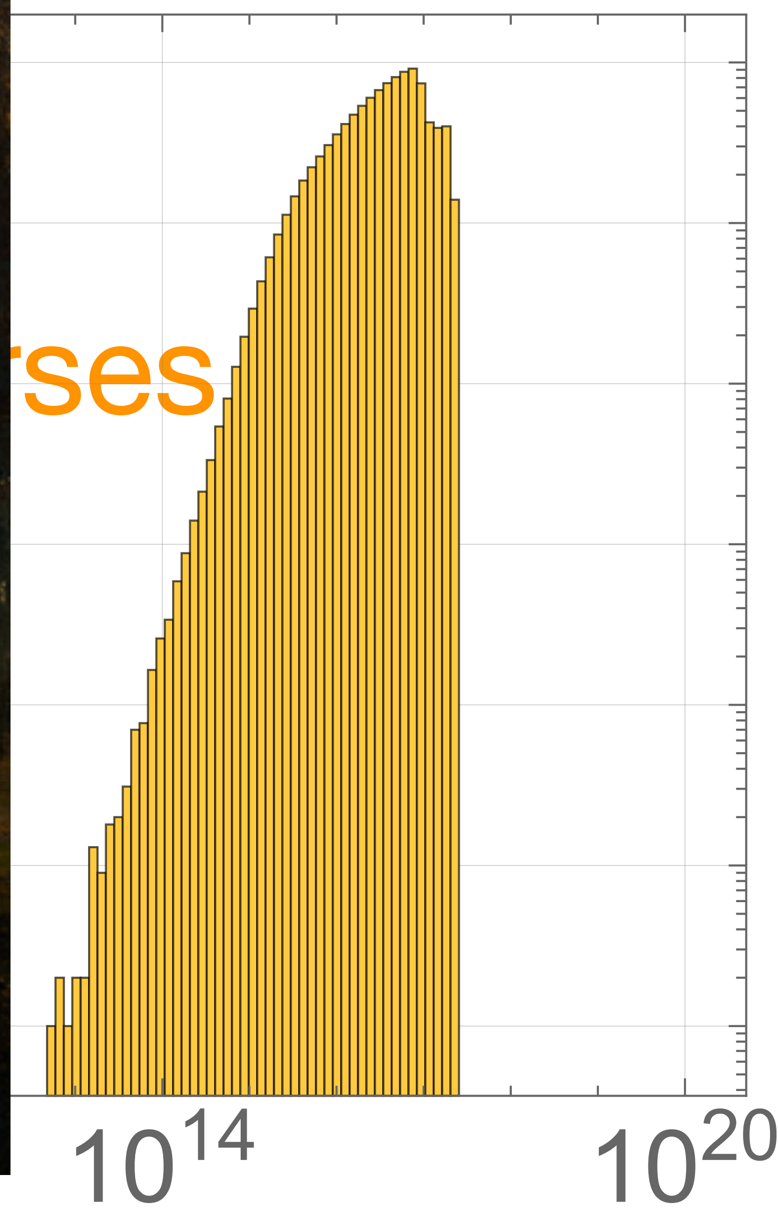

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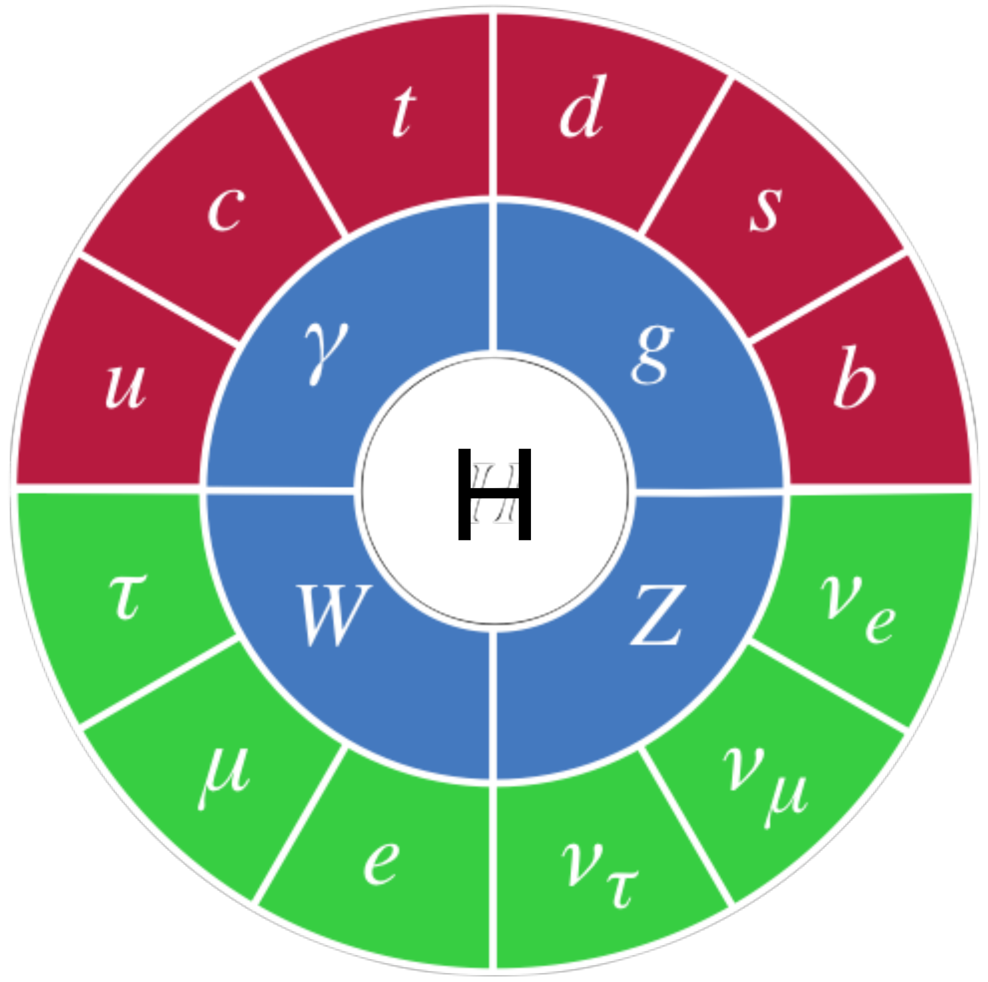
3. Might discover the new fields; if not, make some inference on π(SM) or N(universes)

Standard Model

$$\mathcal{L}_{\mathrm{SM}} = \frac{1}{2}(\partial_\mu \phi)^2 \boxed{- \frac{1}{2}\mu^2\phi^2} \boxed{- \frac{\lambda}{4}\phi^4} \boxed{+ \frac{1}{4}g_1^2(\mathrm{B}_\mu)^2\phi^2 + \frac{1}{4}\sum_{i=1}^{3} g_2^2(\sigma^i \mathrm{W}_\mu^i)^2\phi^2}$$
$$\boxed{+ \sum_{i,j=1}^{9} \psi_i y_{ij} \psi_j \phi} + \sum_{i=1}^{8} \frac{1}{4}\left[\partial_\mu \mathrm{G}_\nu^i - \partial_\nu \mathrm{G}_\mu^i - \sum_{j,k=1}^{8} g_s f_{ijk} \mathrm{G}_\mu^j \mathrm{G}_\nu^k\right]^2 + \mathcal{L}_{\mathrm{gauge,kin}}$$

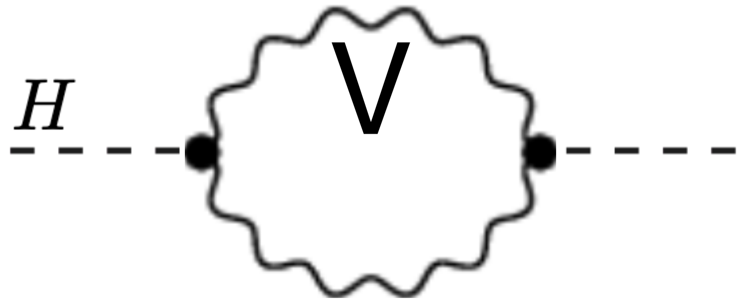


Scale of new physics Λ

$$\Lambda \sim O(10^{16}\ \text{GeV}) - O(10^{18}\ \text{GeV})$$

Scalars receive radiative corrections

$$\Delta m_{H,v}^2 = \boxed{\frac{3\, g_V^2}{16\pi^2}\left[\Lambda^2\right.} - M_V^2 \ln\left(\frac{\Lambda^2}{M_V^2}\right) + \cdots \Big]$$



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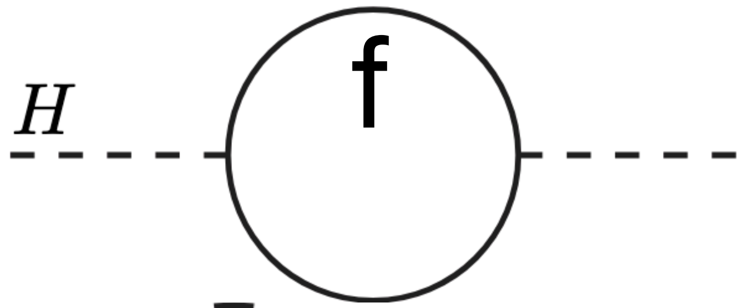

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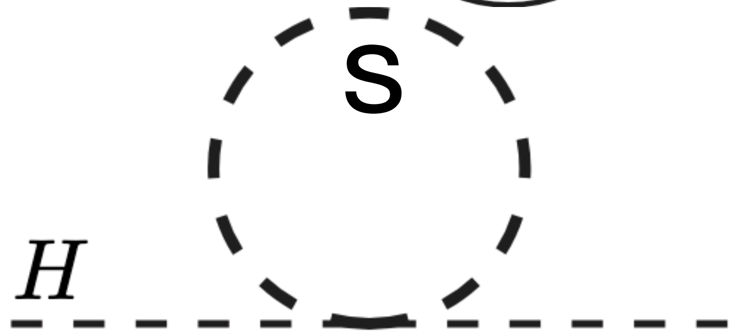

Big hierarchy puzzle:
Enormous unrelated contributions cancel

$$m_H^2 = \boxed{\mu_0^2} \boxed{+ \Delta m_{H,v}^2} \boxed{+ \Delta m_{H,f}^2} \boxed{+ \Delta m_{H,s}^2}$$

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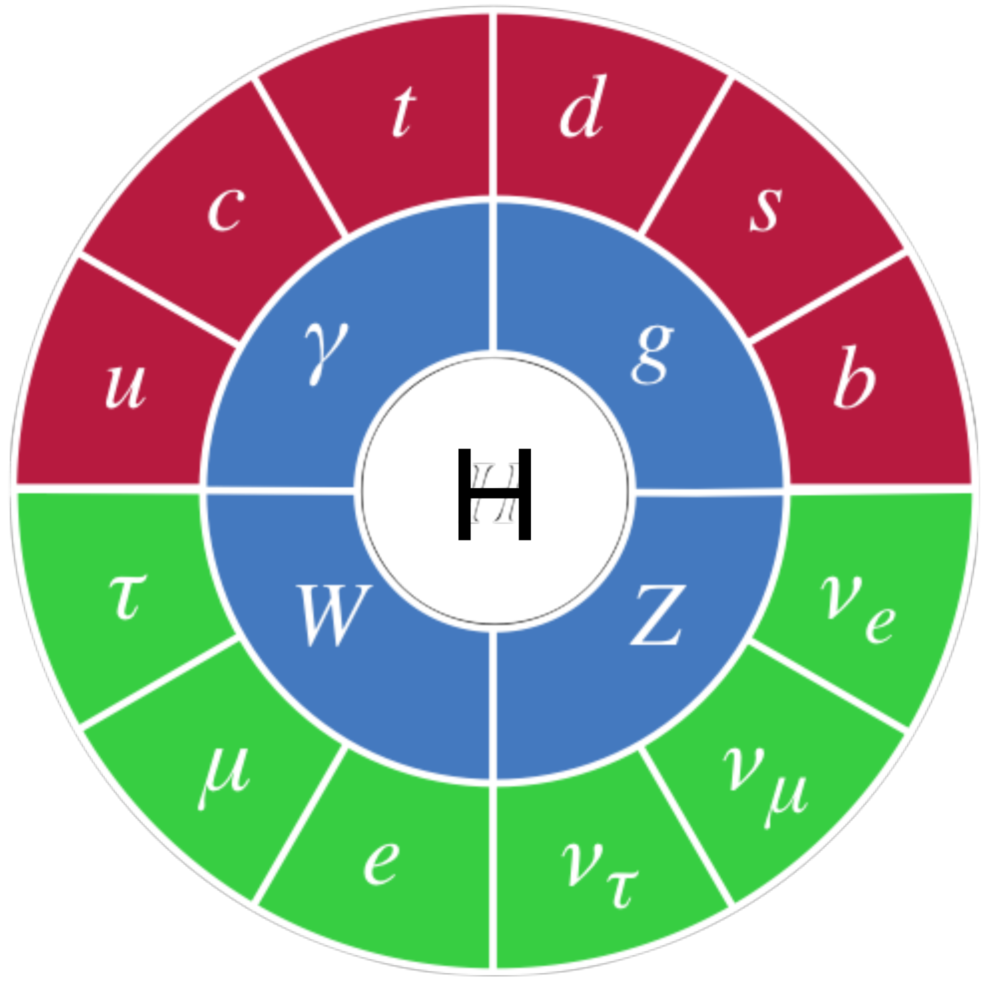

+

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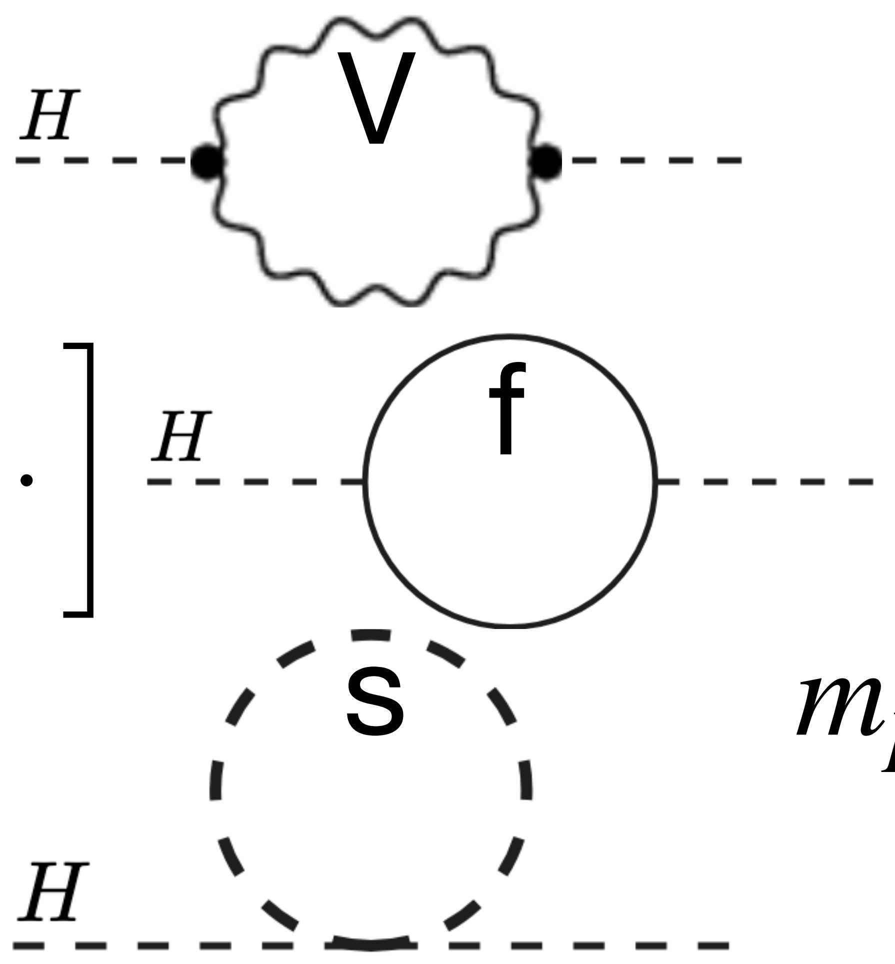

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Minimal Supersymmetric Standard Model

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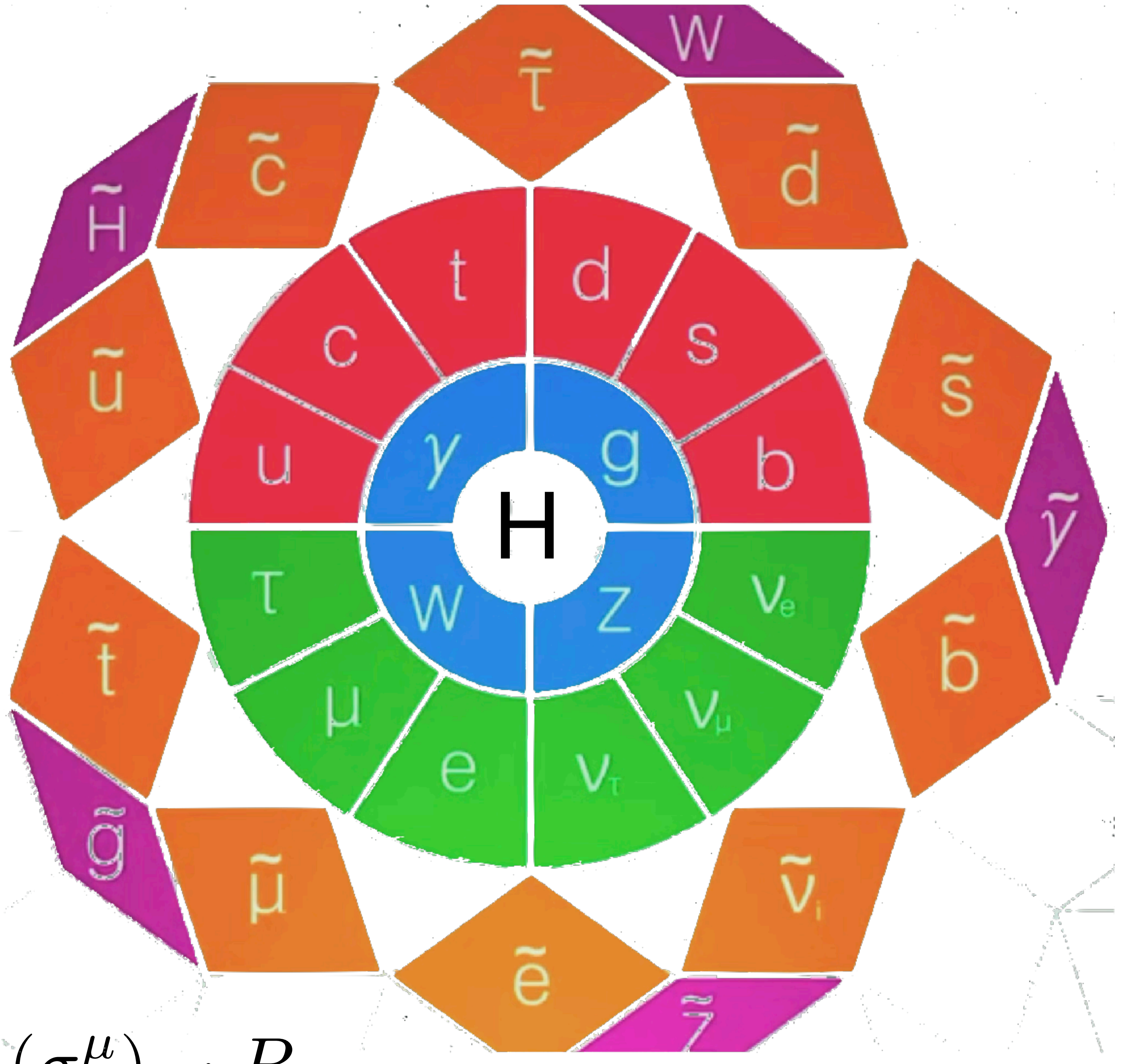

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Radiative corrections

$$\longrightarrow\ W_{MSSM} = \bar{u}\mathbf{y}_d Q H_u - \bar{d}\mathbf{y}_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d$$

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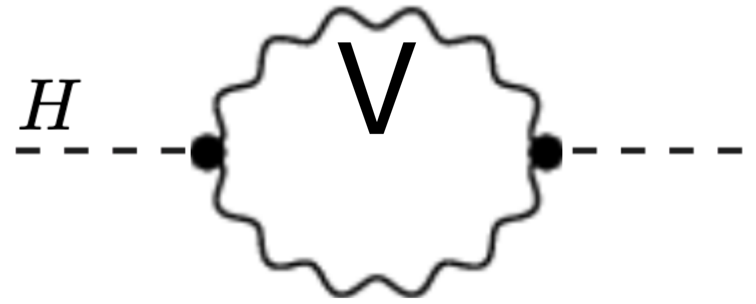

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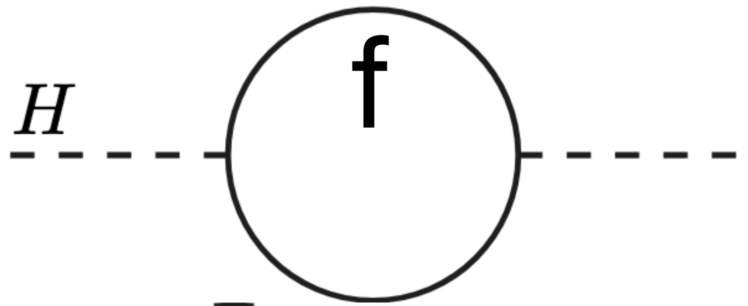

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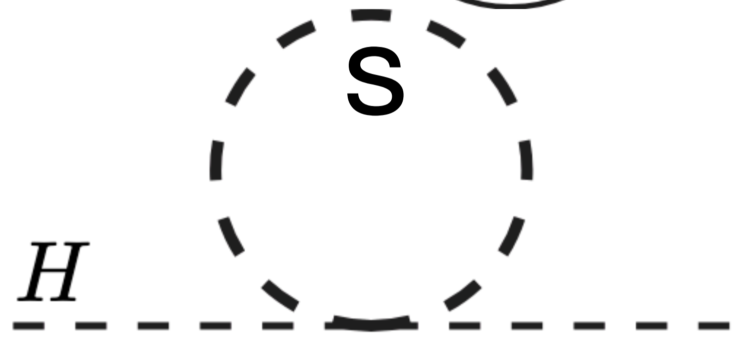
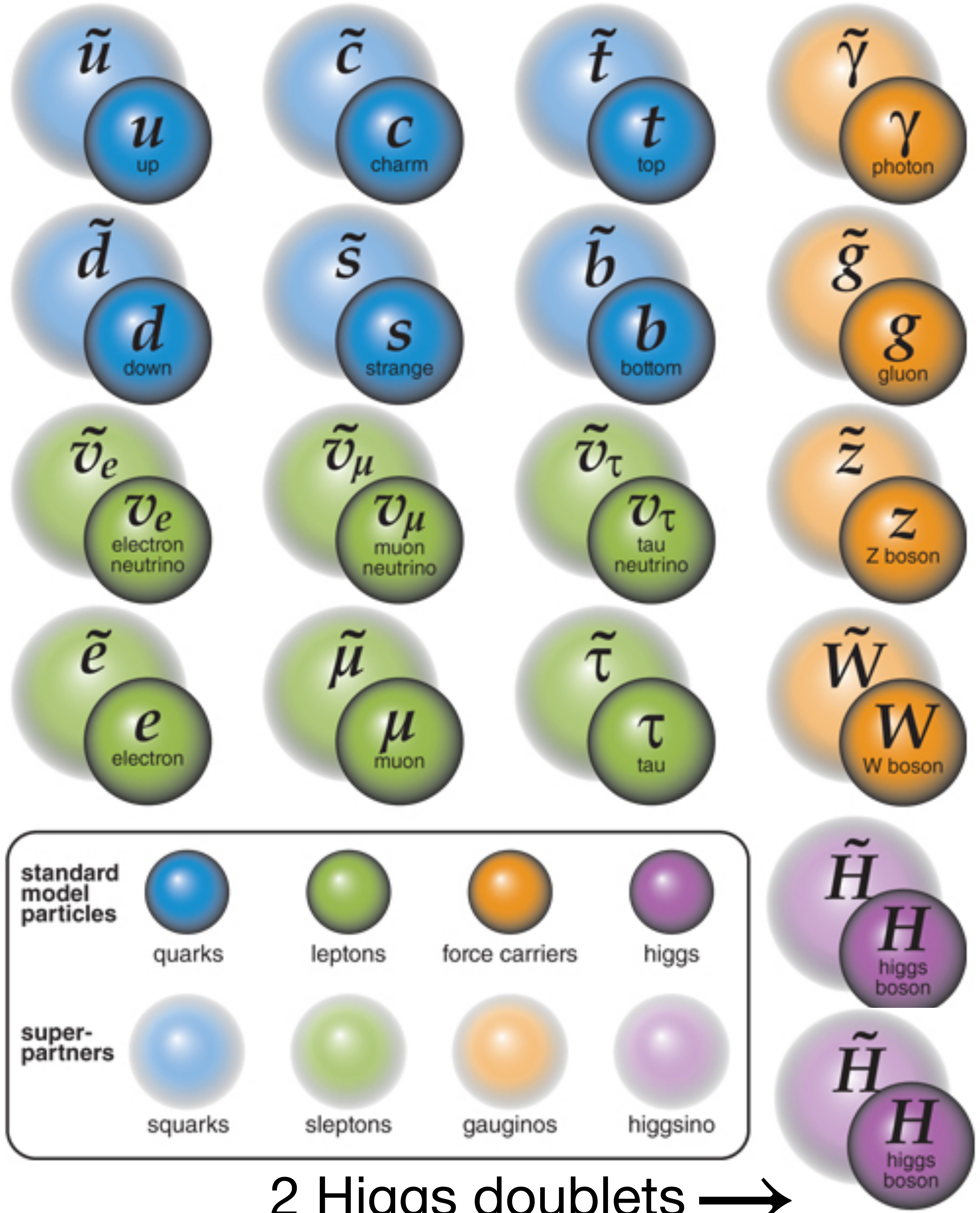


Minimal Supersymmetric Standard Model (MSSM) 1981



2 Higgs doublets ⟶

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Particle/field		**Superpartner**
fermion (spin 1/2)	⟷	sfermion (spin-0)
gauge boson (spin 1)	⟷	gaugino (spin 1/2)
Higgs boson (spin 0)	⟷	Higgsino (spin-1/2)

Unbroken fermions (Bino, wino, Higgsino) $\xrightarrow{\text{EWK SSB}}$ (Photino, Zino, Higgsino)

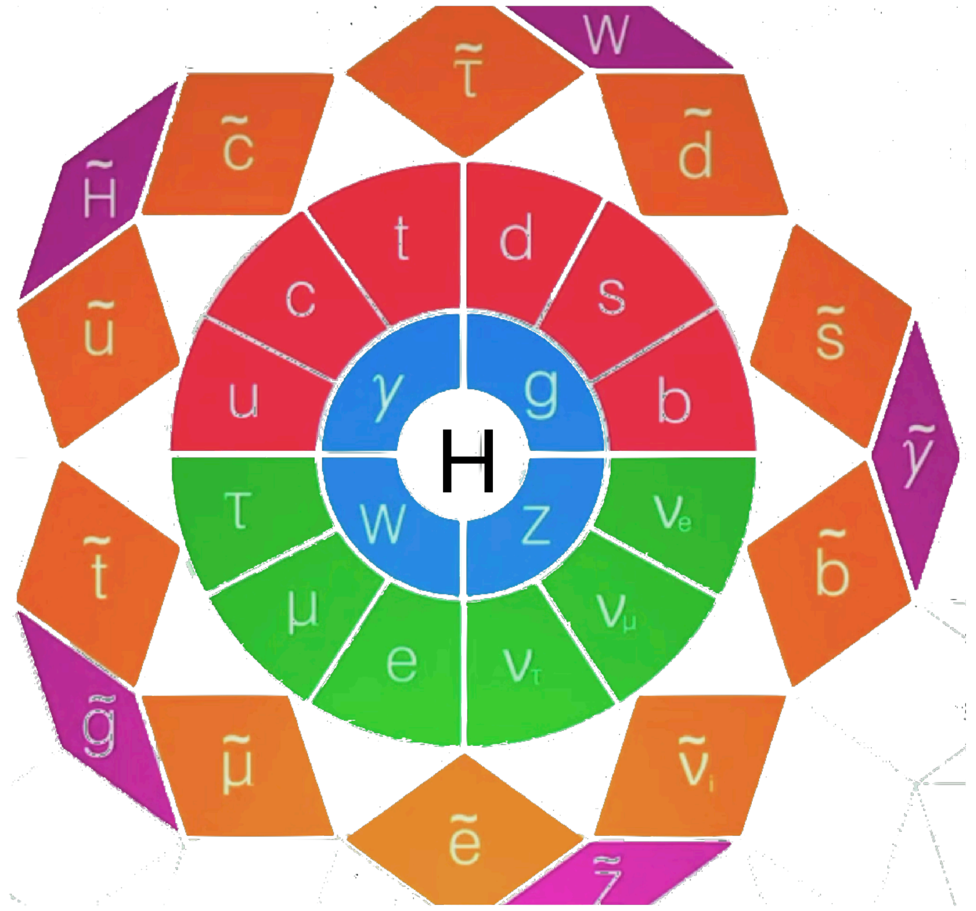
? ⟶ ?

SUSY Breaking

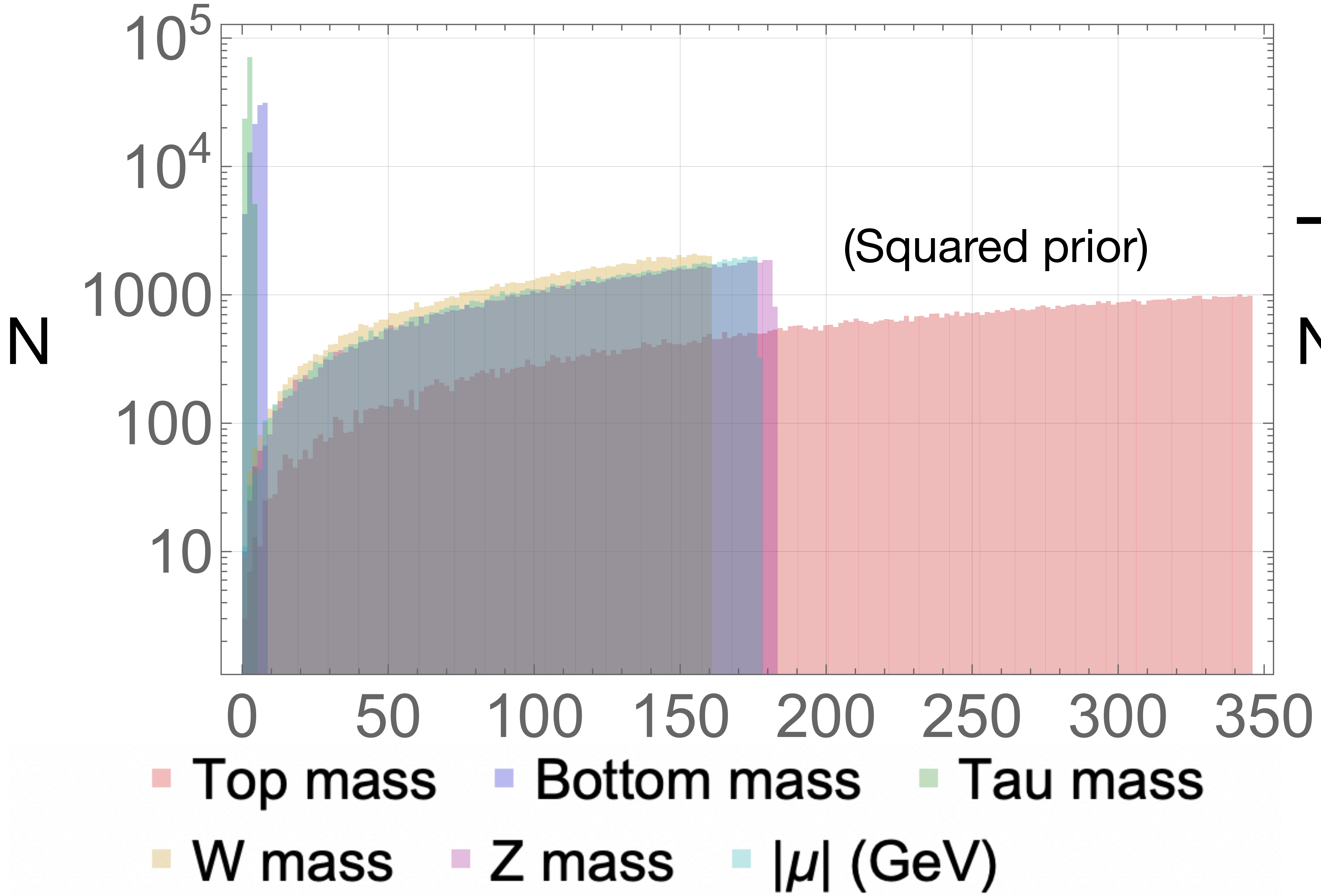
110 parameters

(Charginos, neutralinos) $(\tilde{\chi}^{\pm}_{1,2}, \tilde{\chi}^{0}_{1,2})$ $\xrightarrow{\text{Conserve R-parity}}$ $\tilde{\chi}^0_1$ Stable dark matter candidate

Hierarchy with MSSM



- Ask ChatGPT to make a silly simulation to illustrate intuition (and absurdity) behind the fine-tuning problem assuming assume $\Lambda = 10^{18}$ GeV…
  - With great audacity, sample SM parameters
    - What parameter ranges? Take RMS=SM, 2*SM, etc.
    - **Now cancel off the Lambda^2 terms…**



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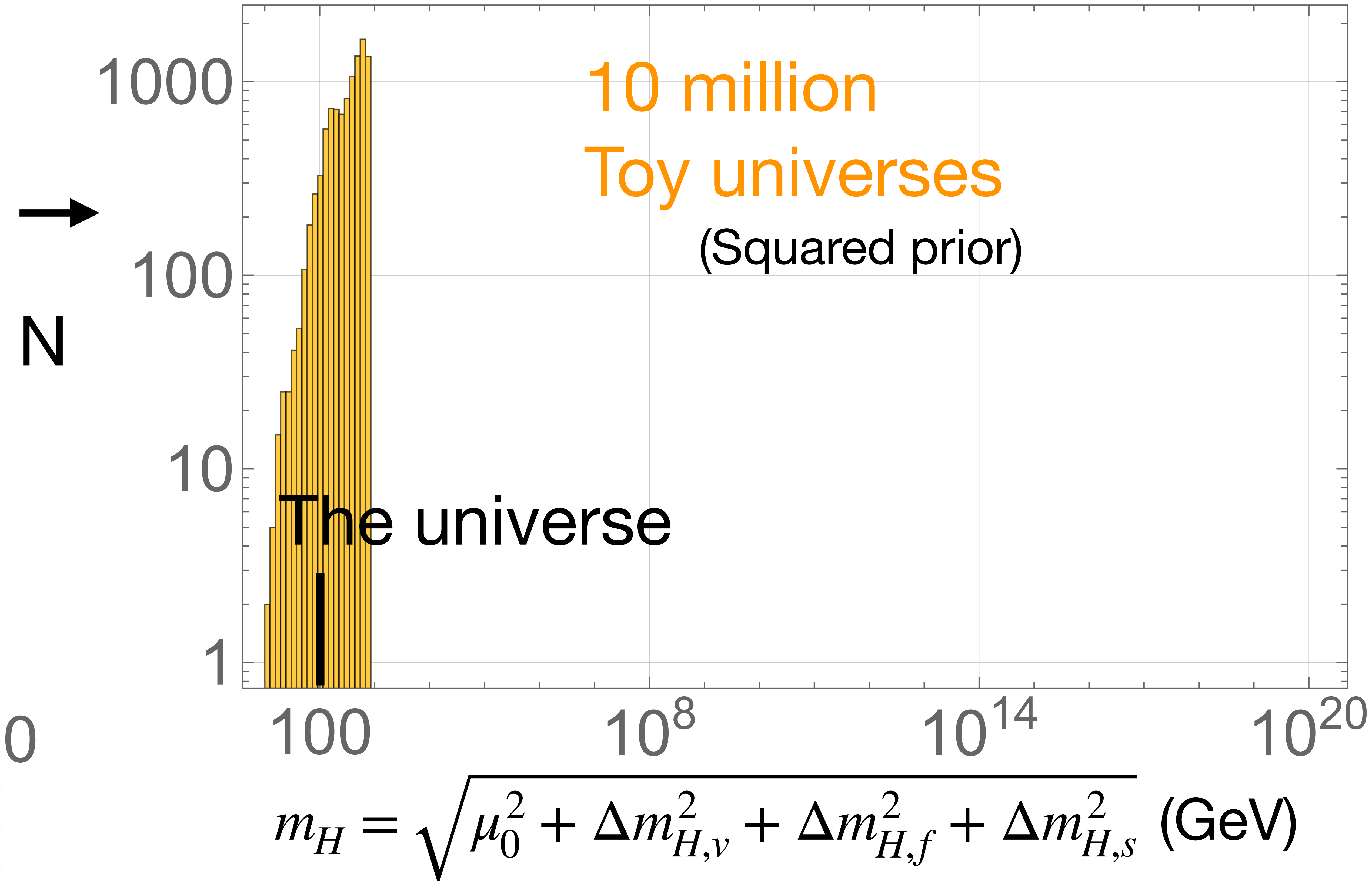

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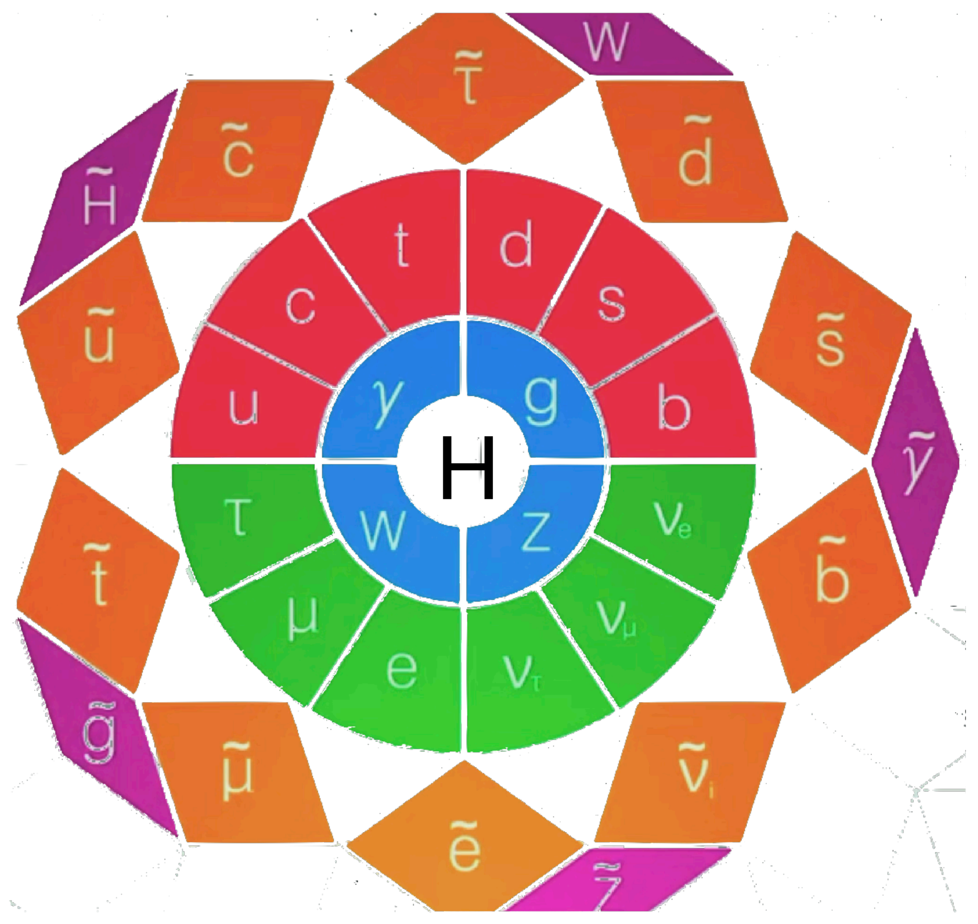

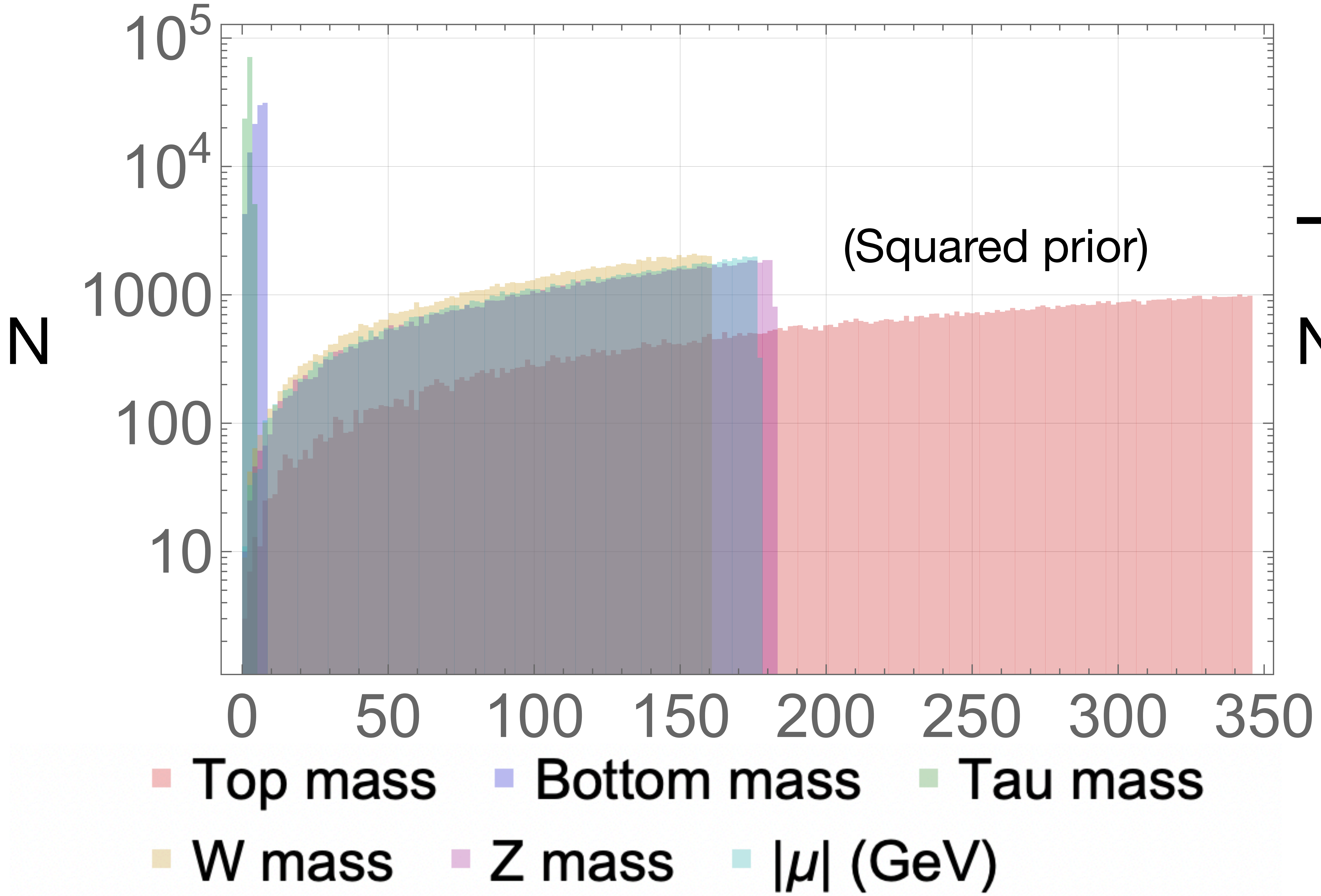

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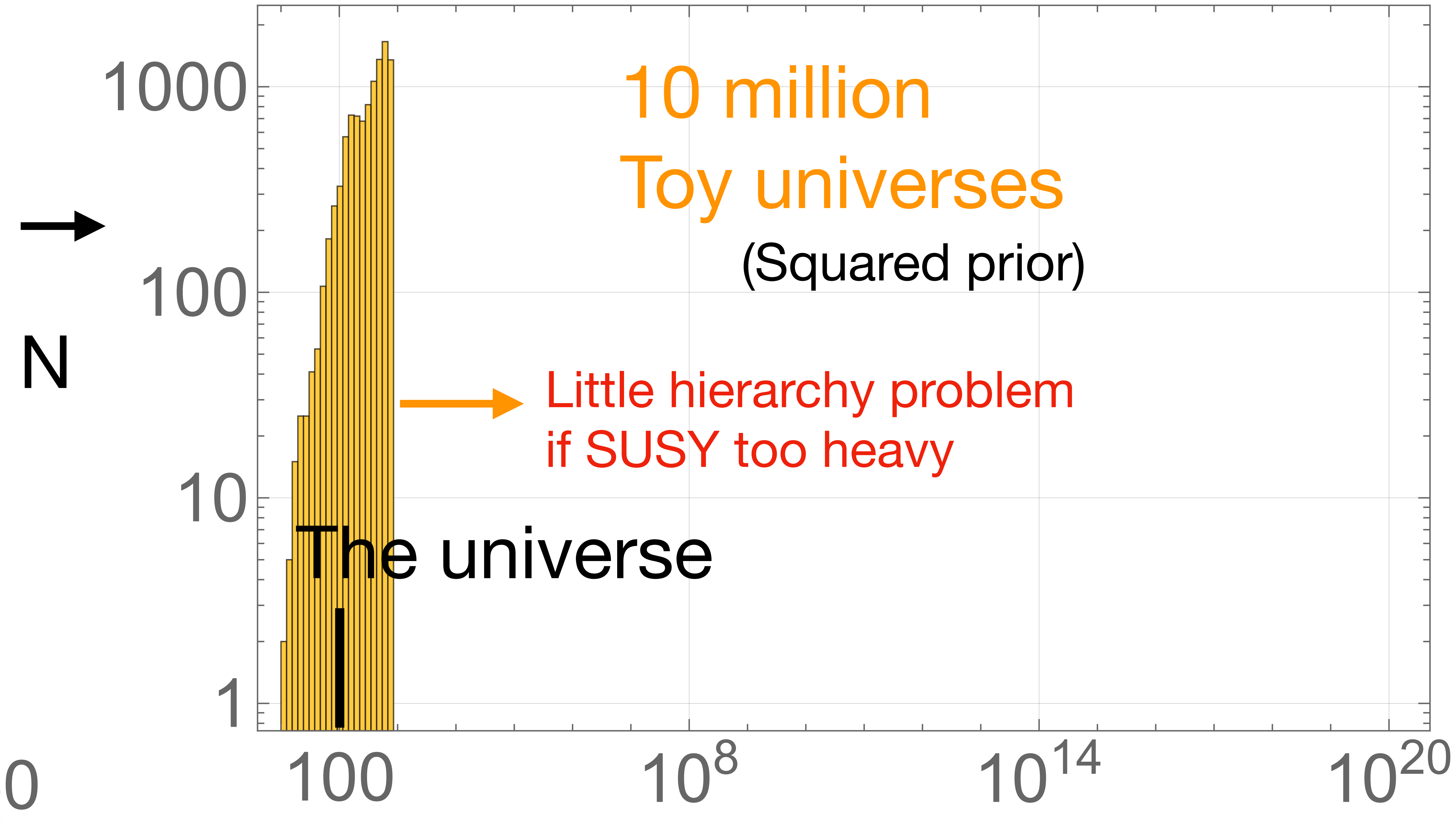

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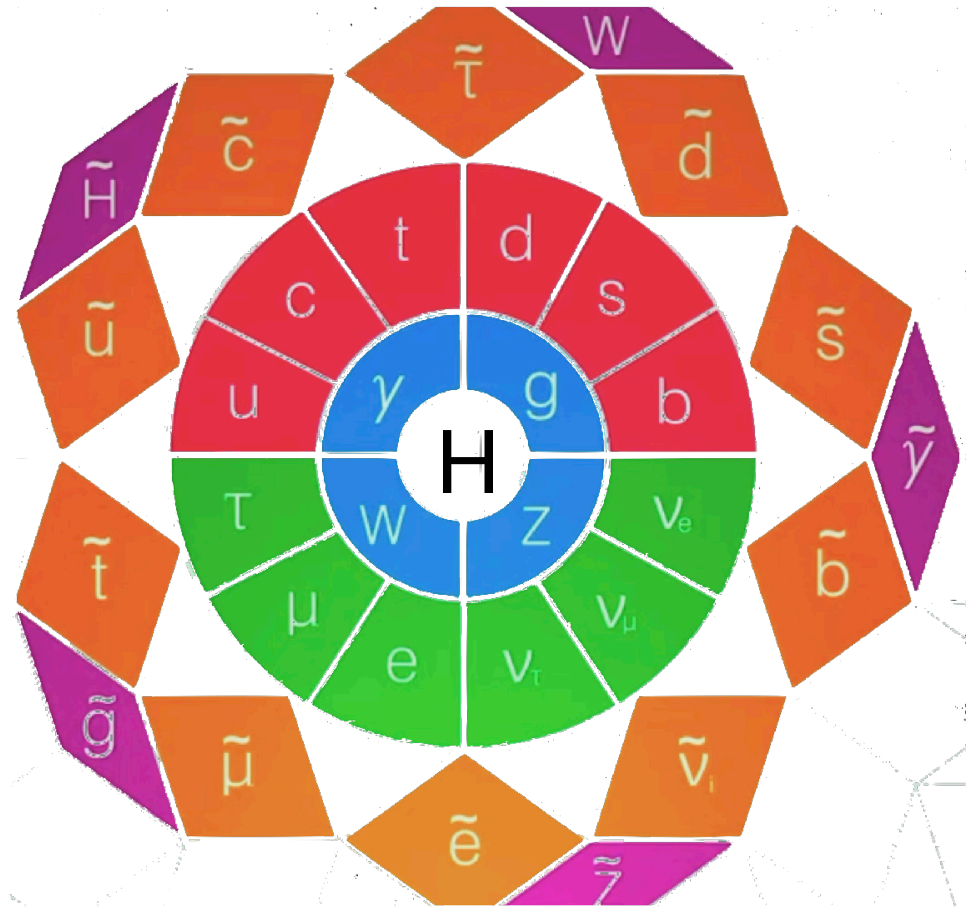
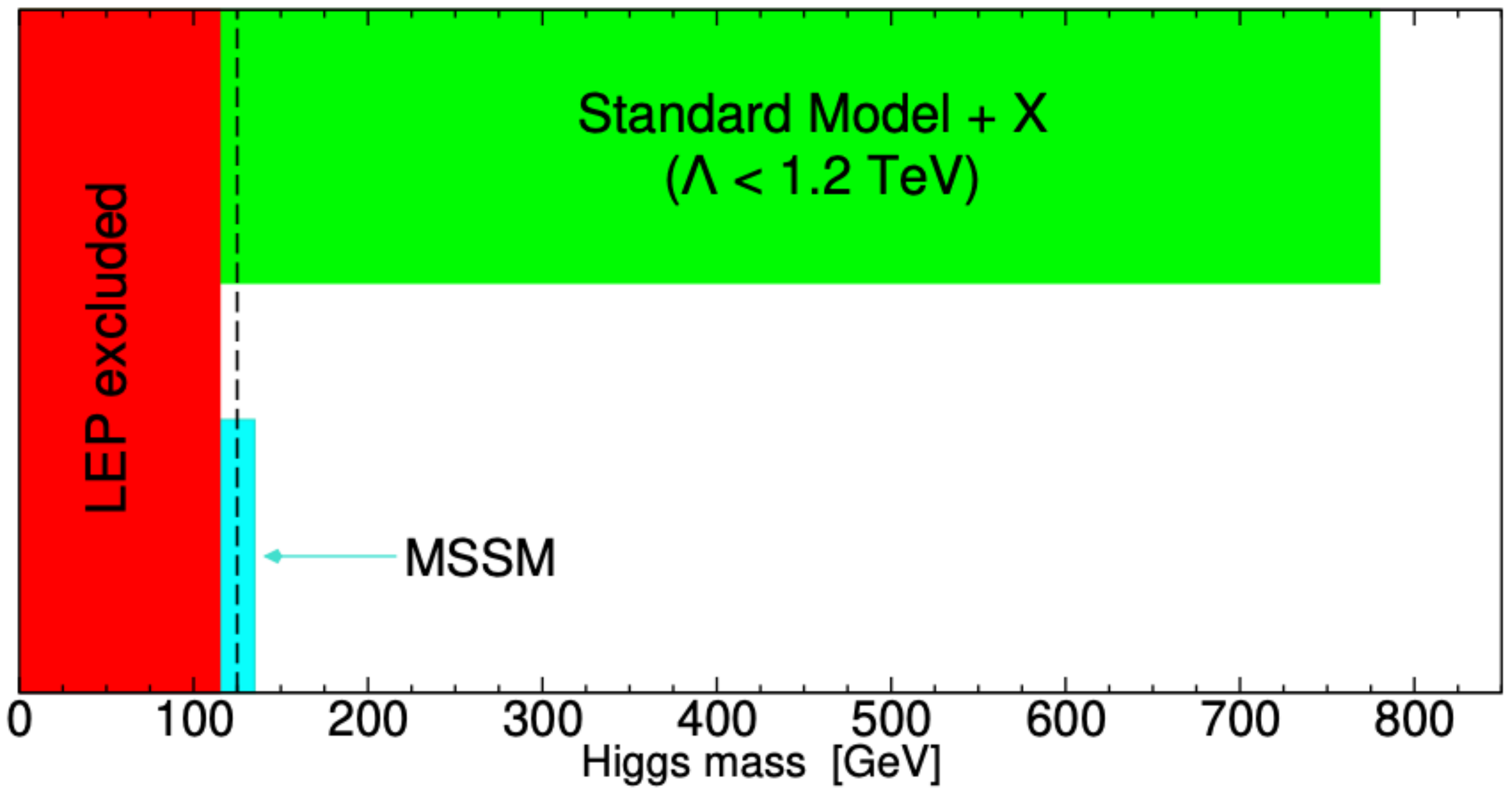
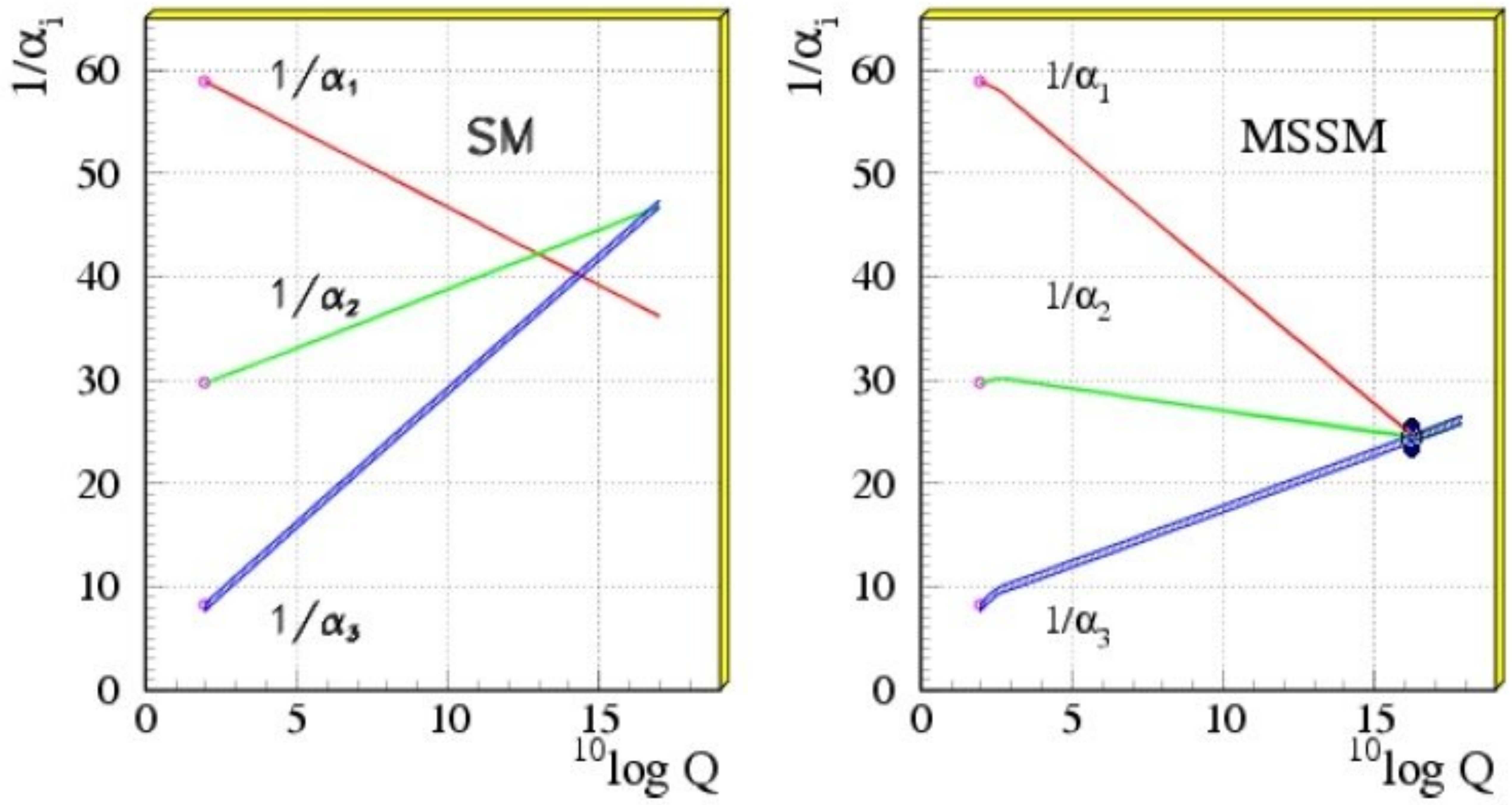
Other predictions/postdictions, puzzle pieces



"The LHC had one chance to exclude supersymmetry…"

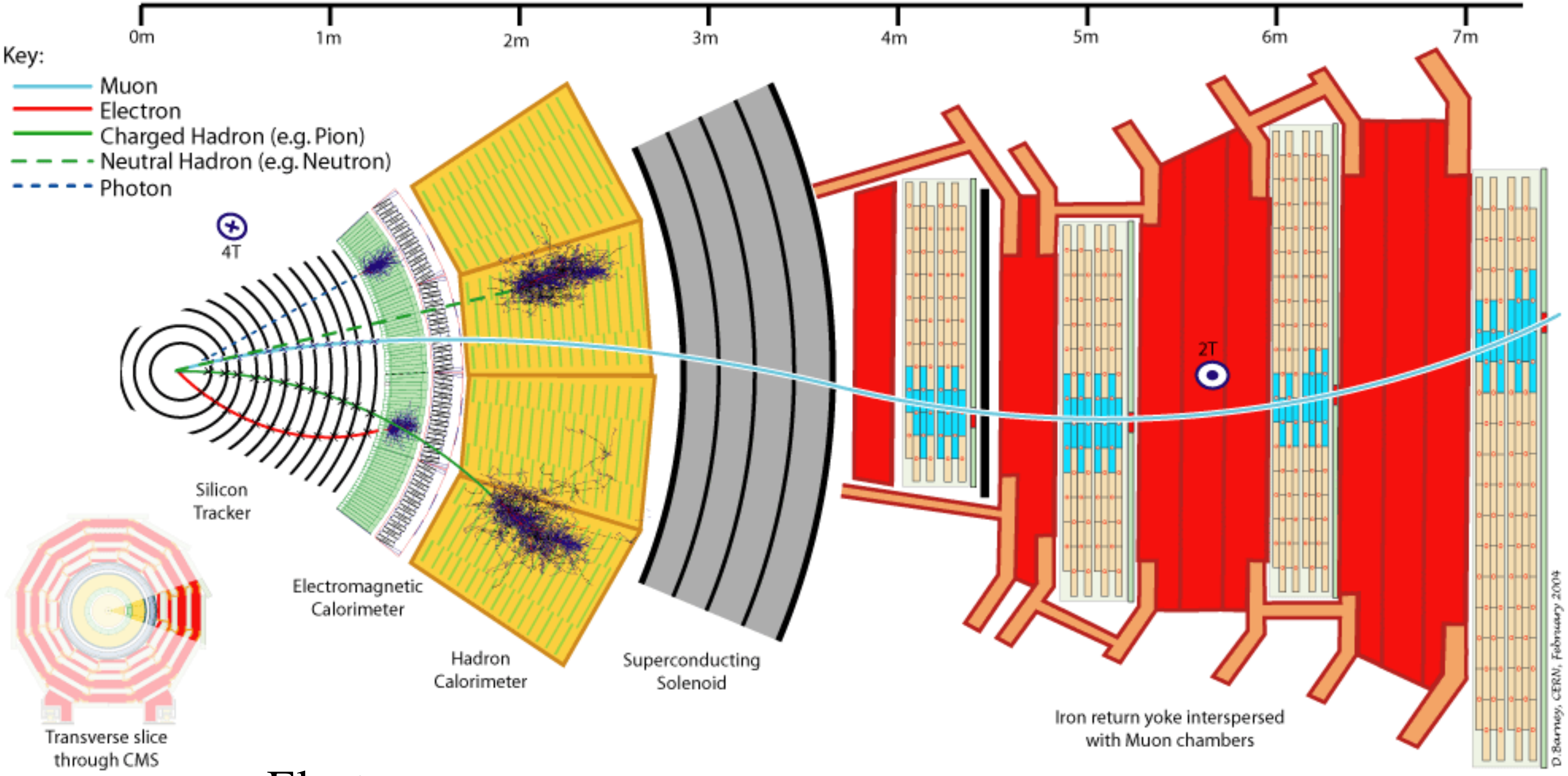
- Stephen Martin





No other new fields needed to realize gauge unification consistent with GUT models

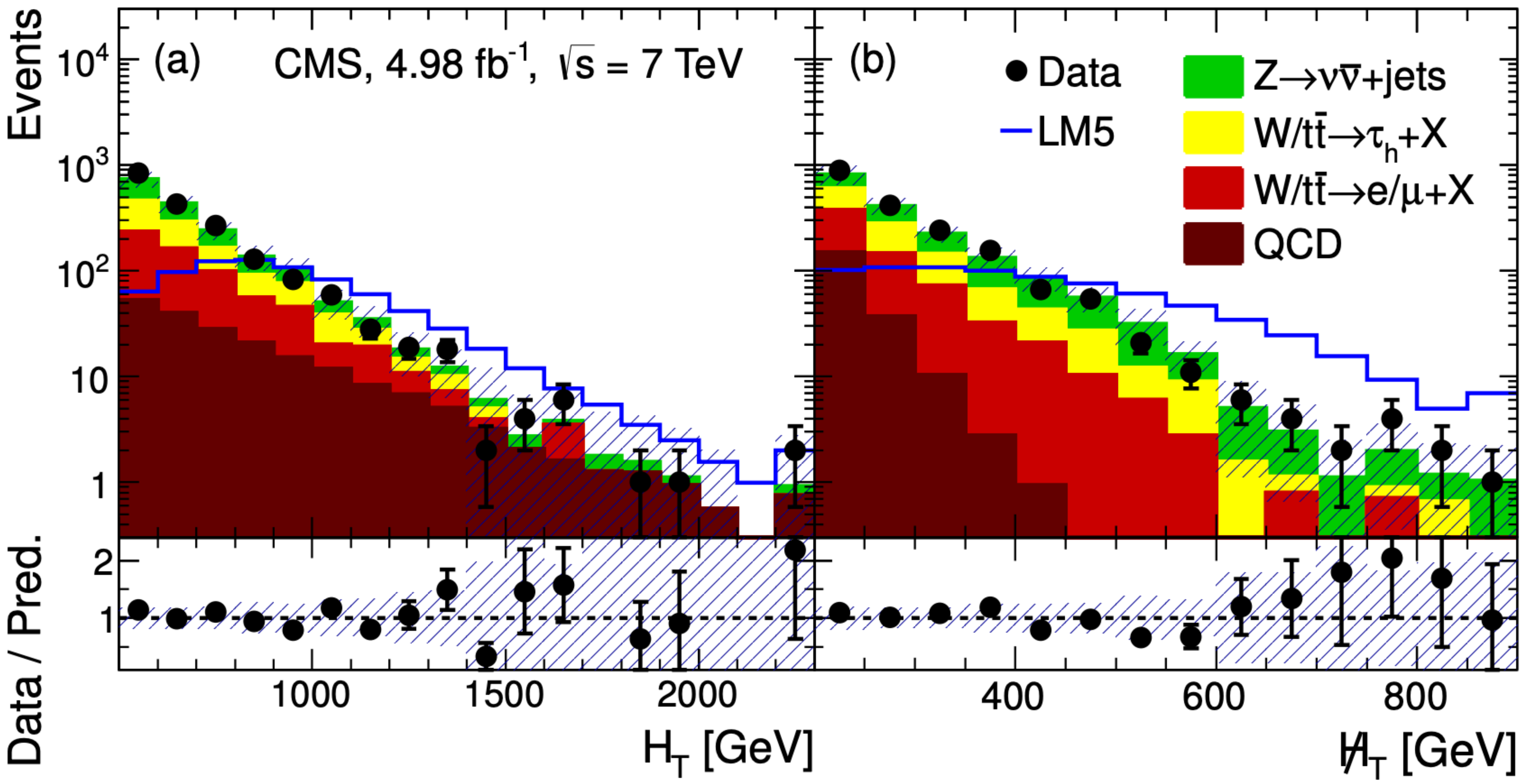
Compact Muon Solenoid



Tracks Electrons Photons Jets Muons Missing pT

SUSY Searches at the LHC

CMS Collaboration, “Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 7$ TeV”



We looked at 7 TeV

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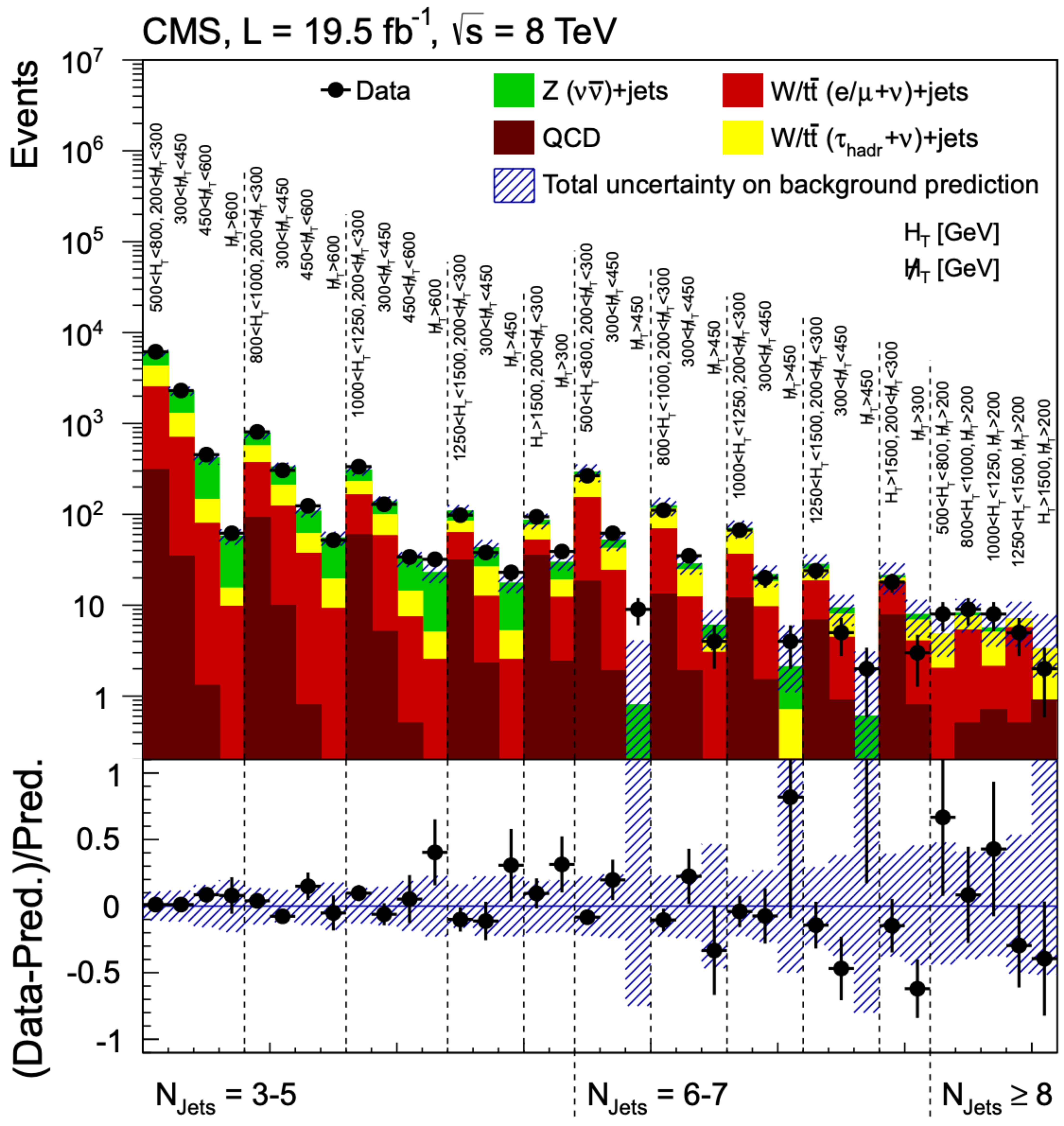
CMS Collaboration, "Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8$ TeV"



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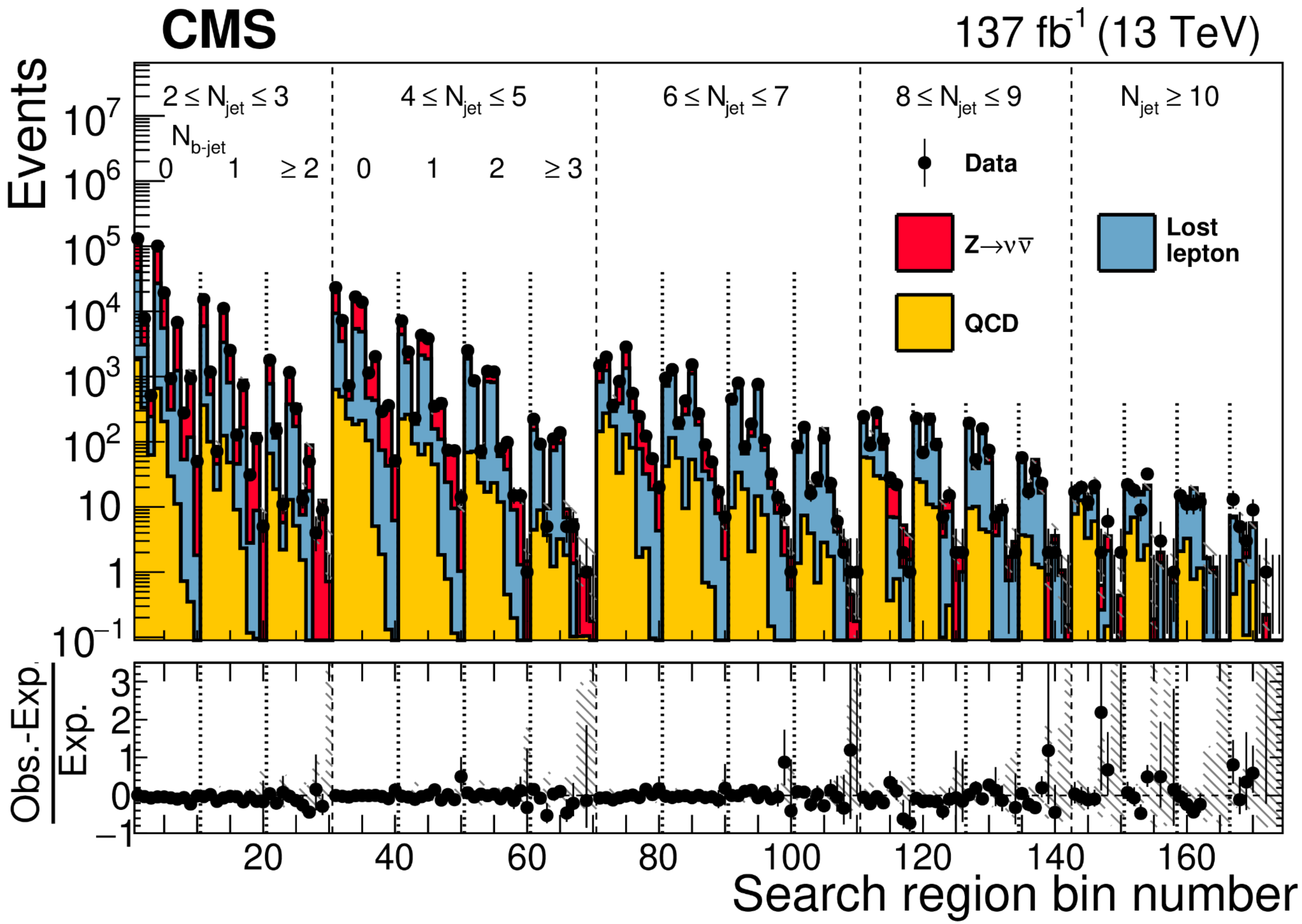

We looked at 7 TeV… at 8 TeV… at 13 TeV

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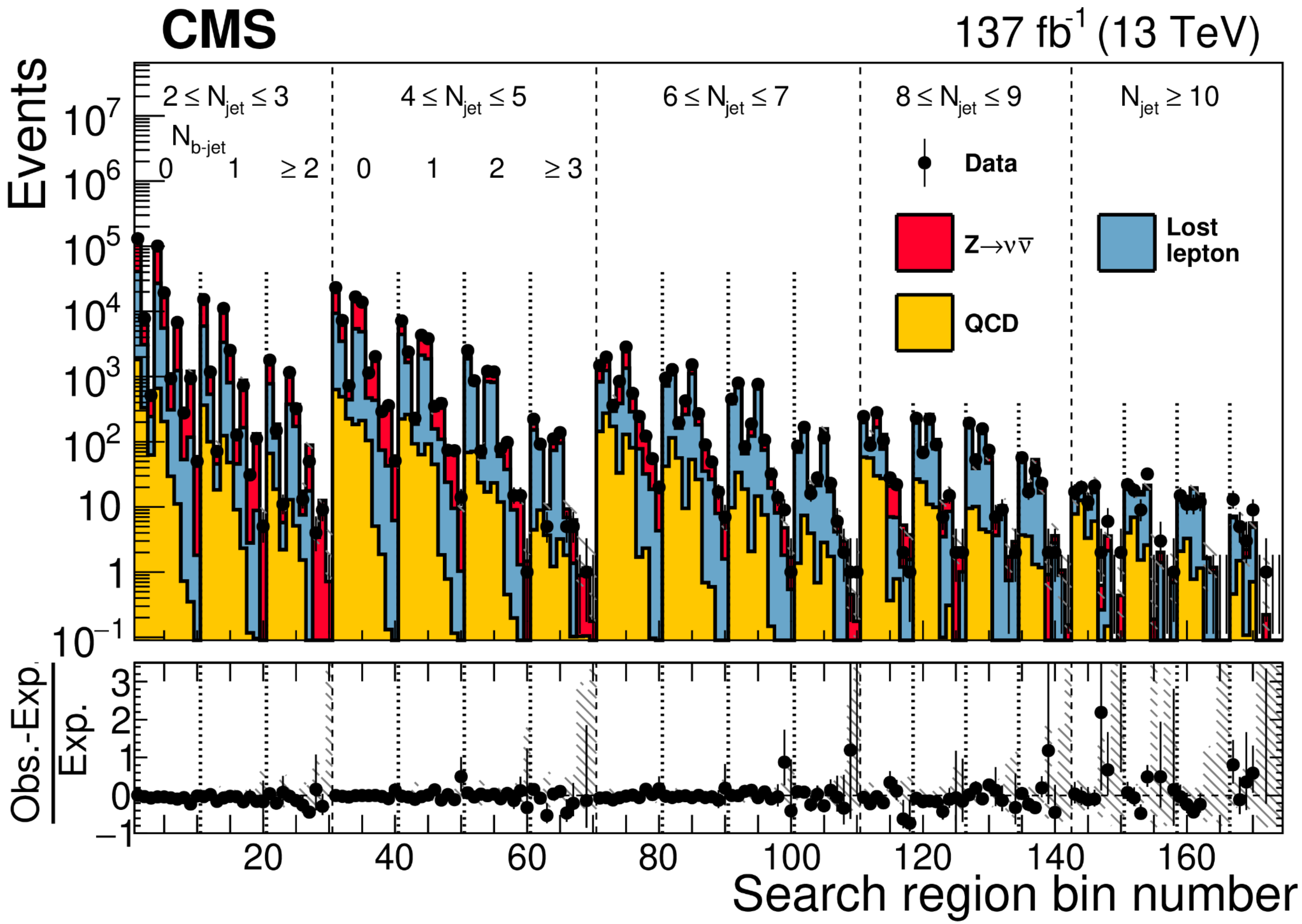
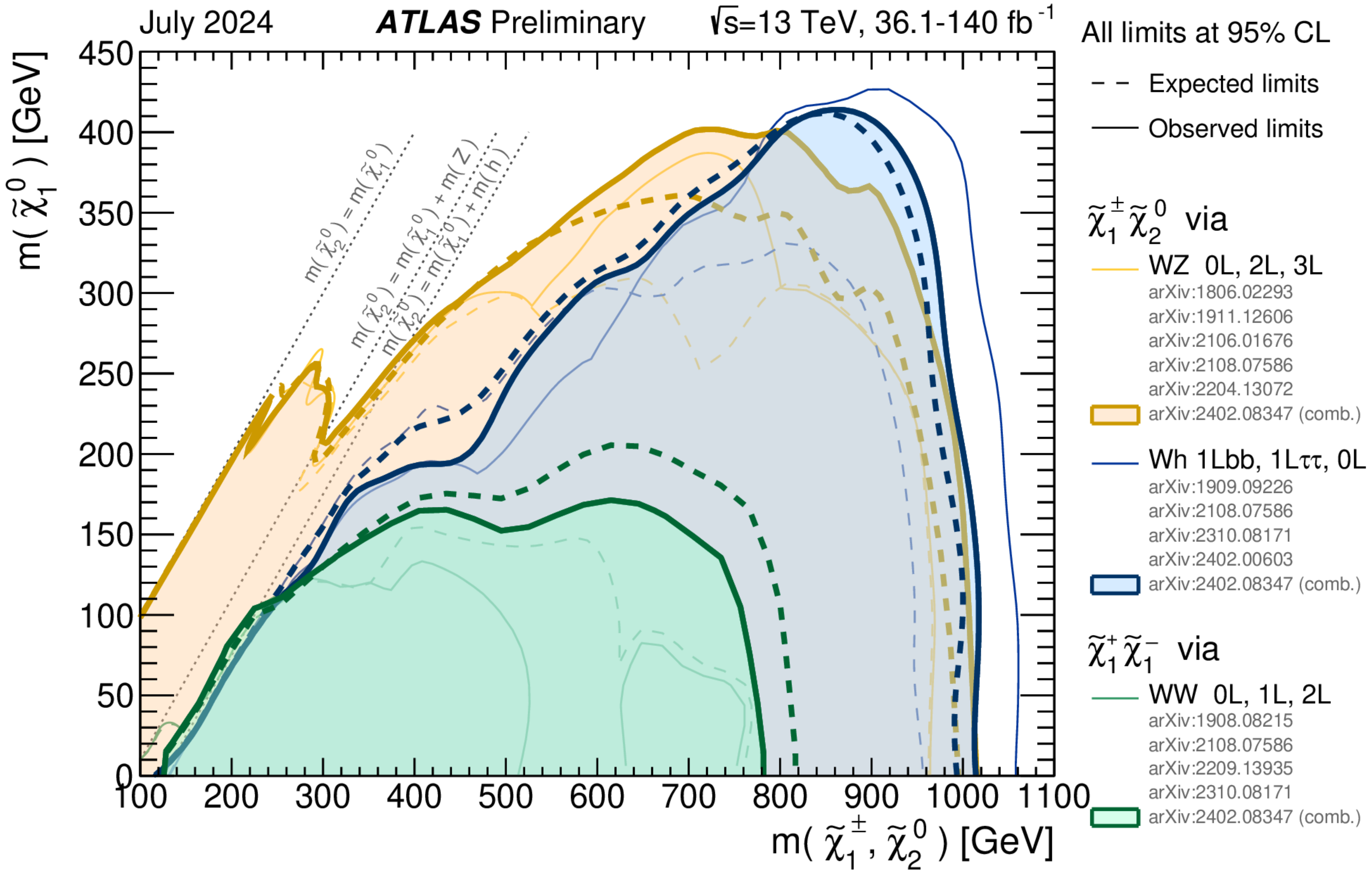
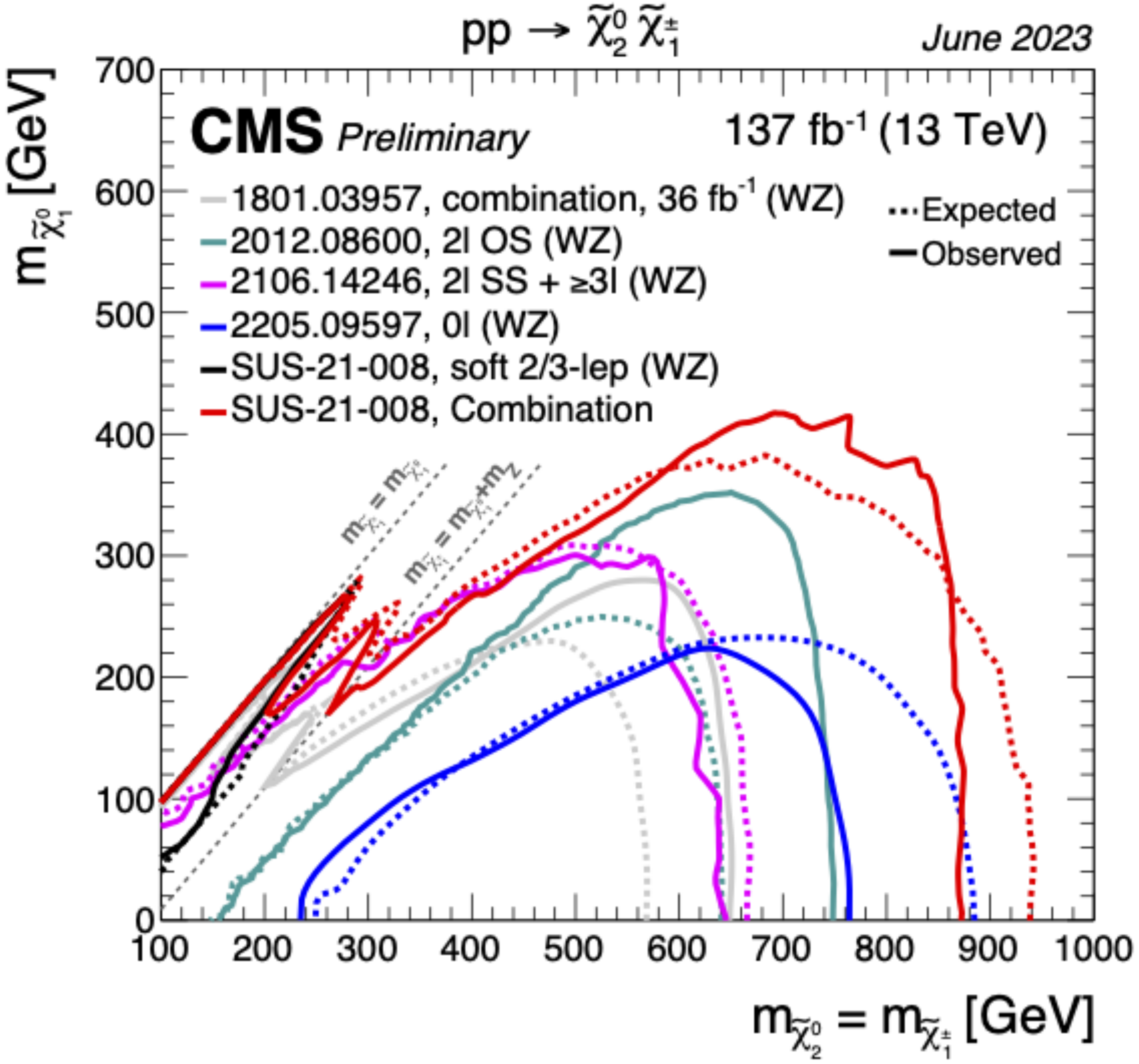


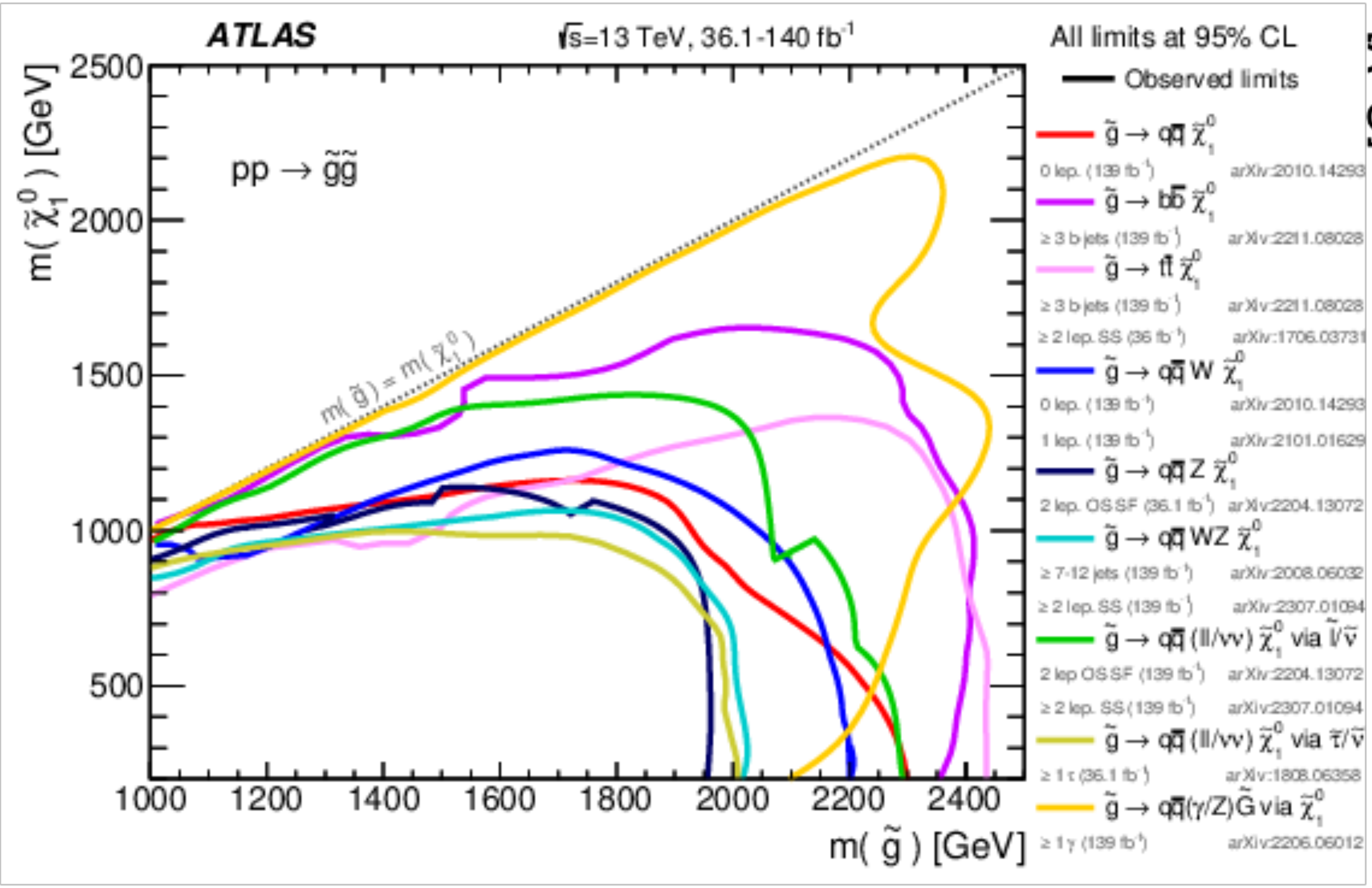
We looked at 7 TeV… at 8 TeV… at 13 TeV… many times in many places

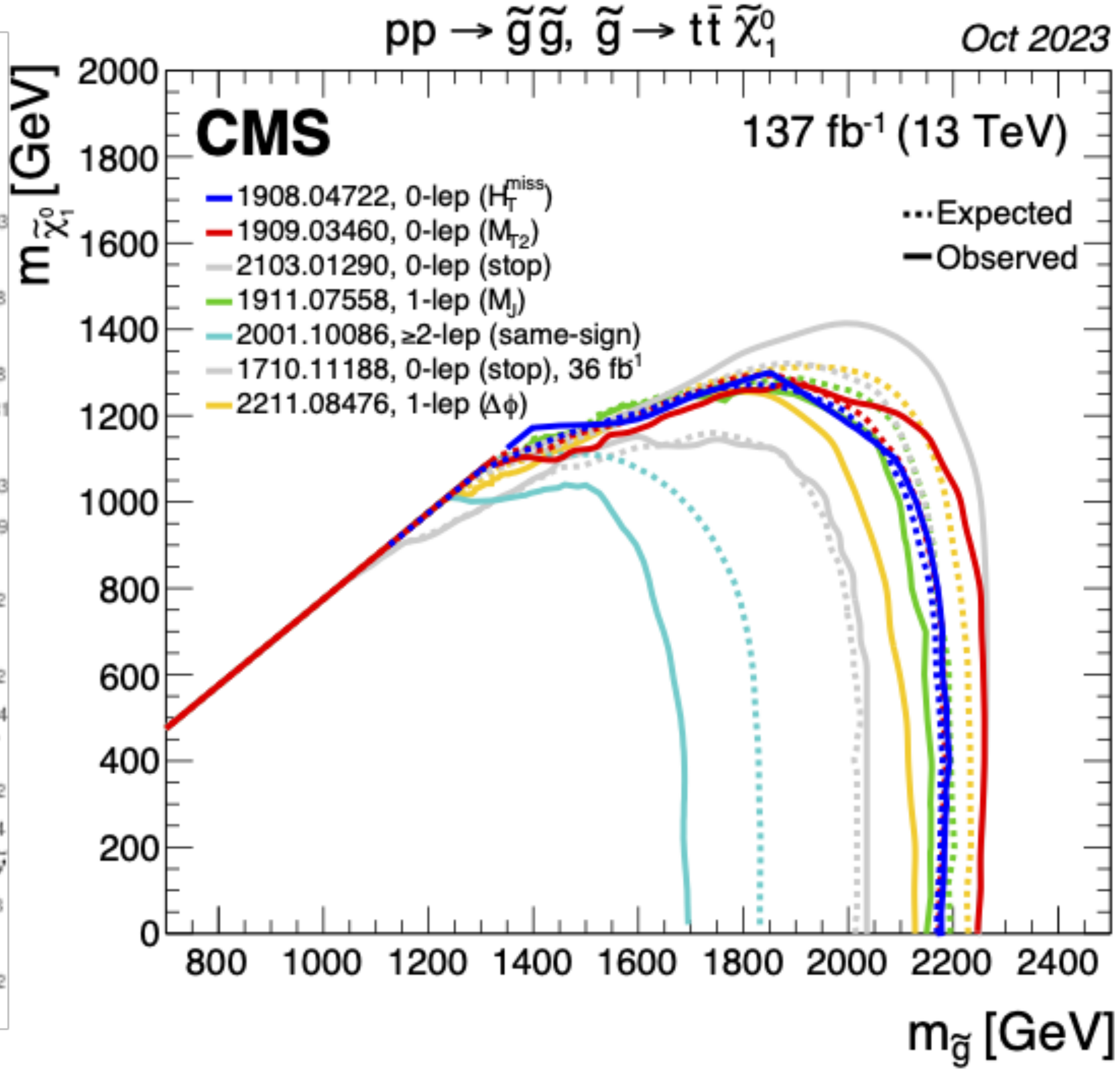
Electroweak SUSY limits at the LHC





Strong SUSY limits at the LHC





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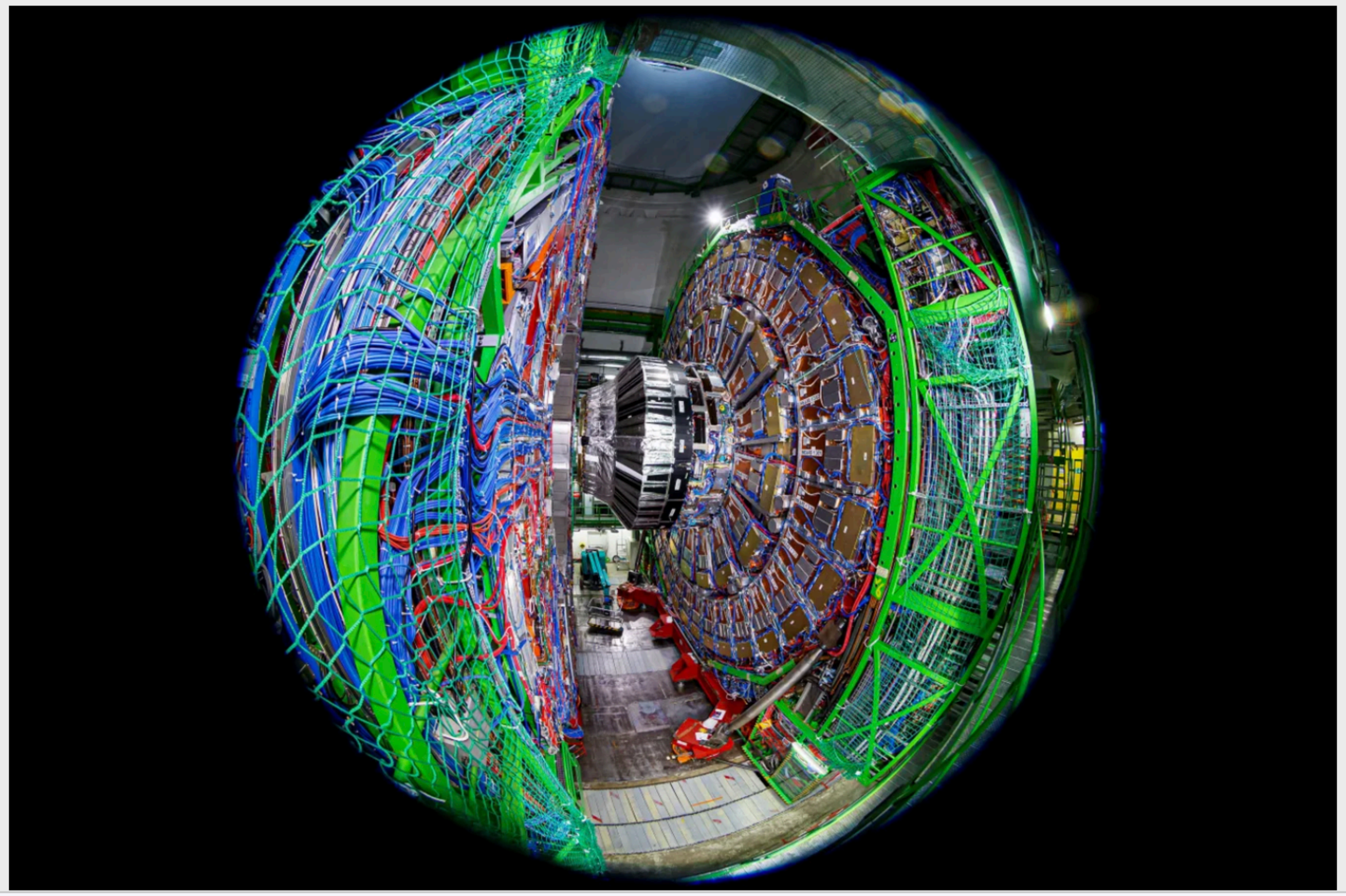
Supersymmetry Washes Out at the Large Hadron Collider

Supersymmetry, long considered the golden child of theoretical physics, has officially lost its luster at the world's reigning particle accelerator

BY ELENI PETRAKOU EDITED BY LEE BILLINGS



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Supersymmetry's Long Fall from Grace

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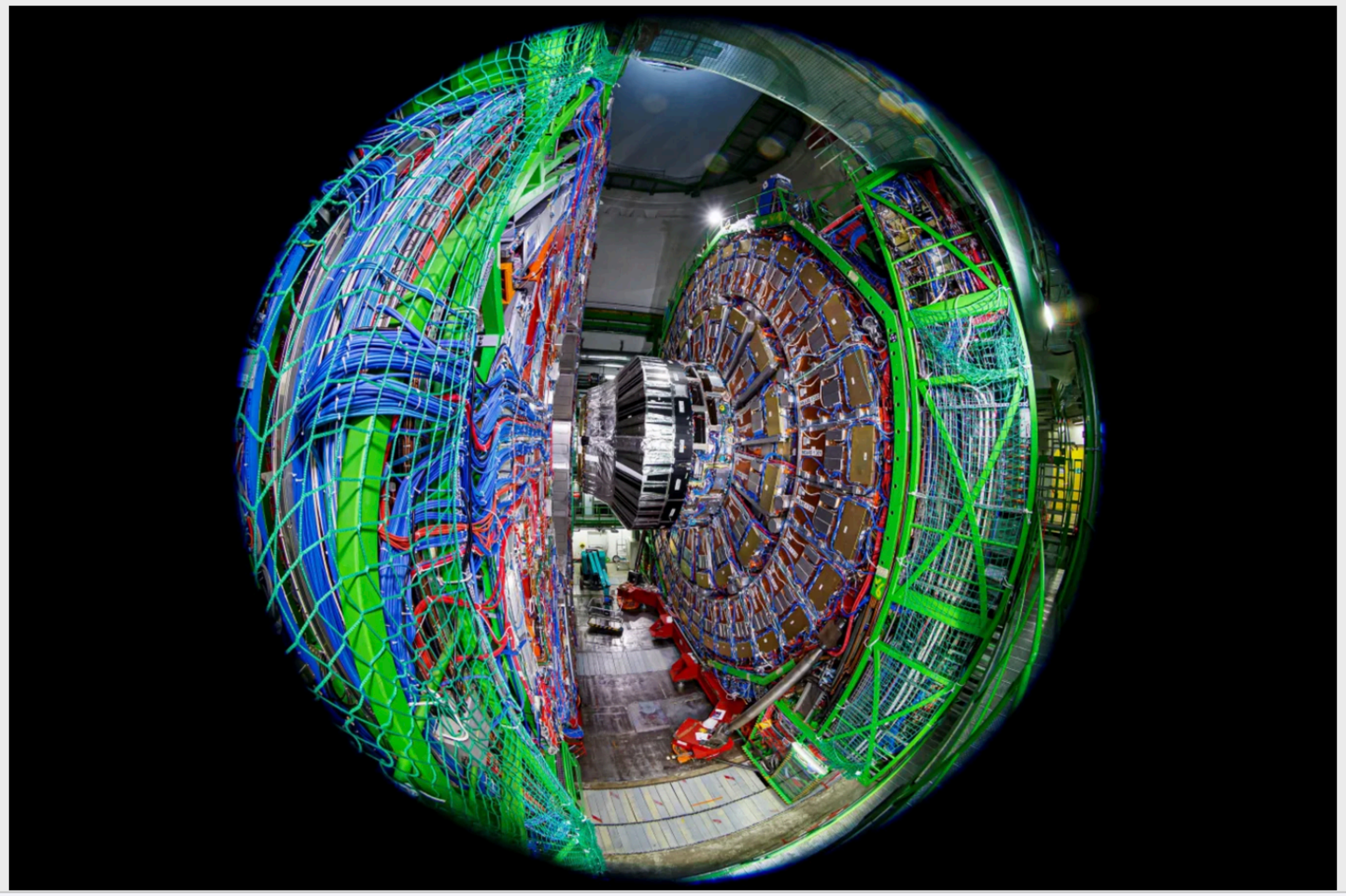

"The lack of a discovery of super partners after the LHC upgrade…was a turning point for most in the community" - Adam Falkowski

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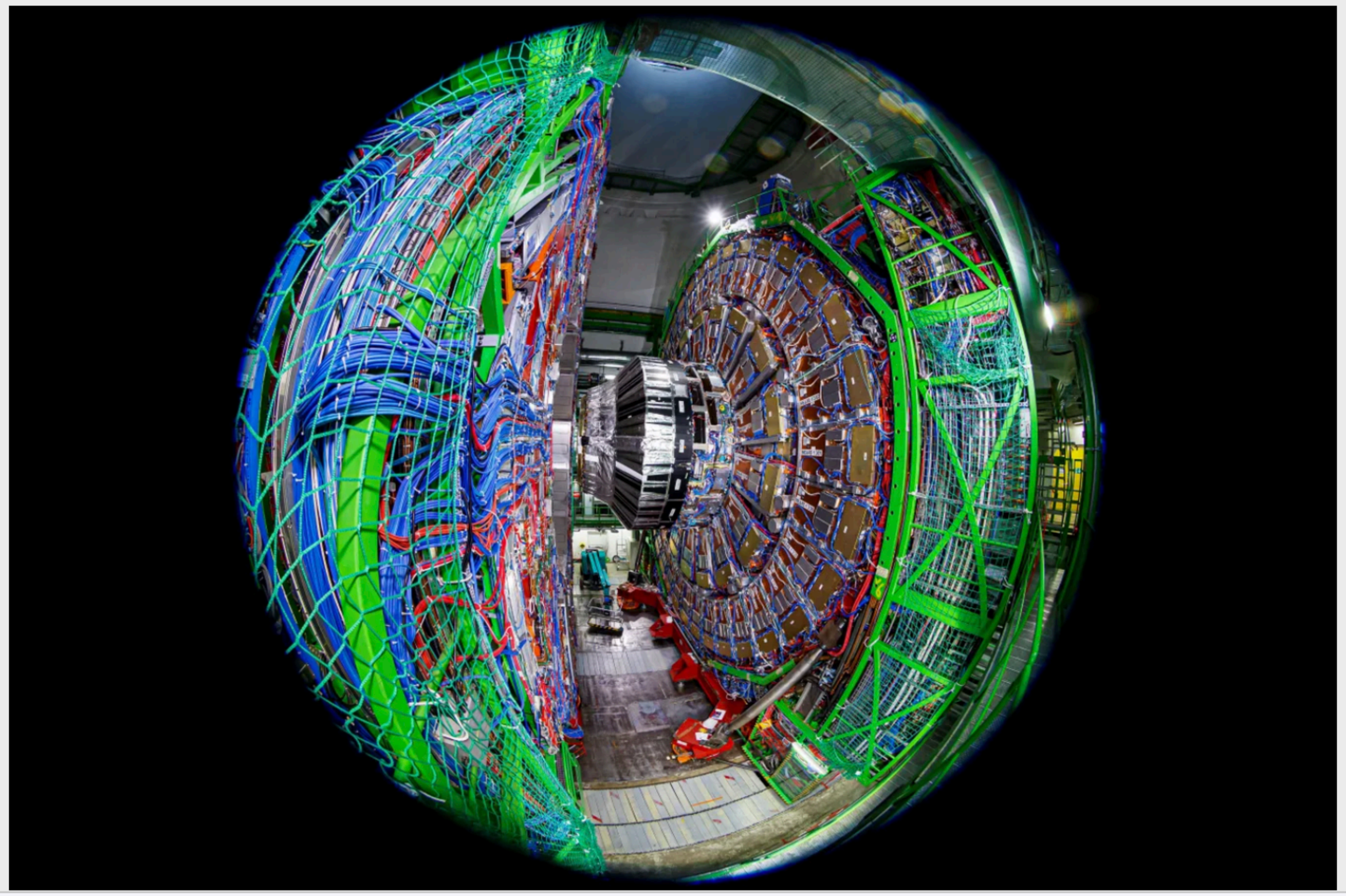

"supersymmetric models grew notoriously unfalsifiable [because of their] arbitrary features"

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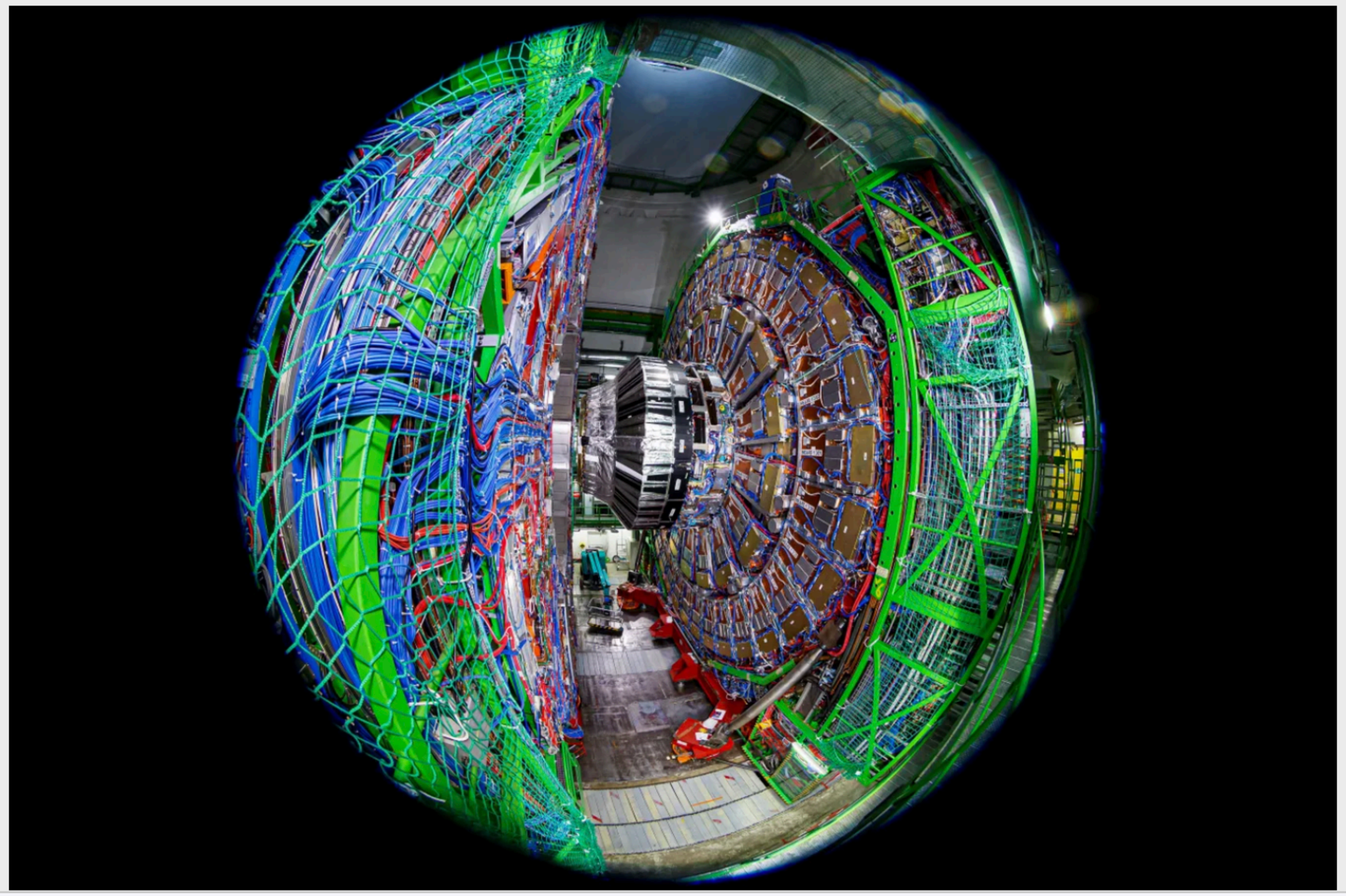

"ATLAS and CMS teams no longer have working groups dedicated to supersymmetry"

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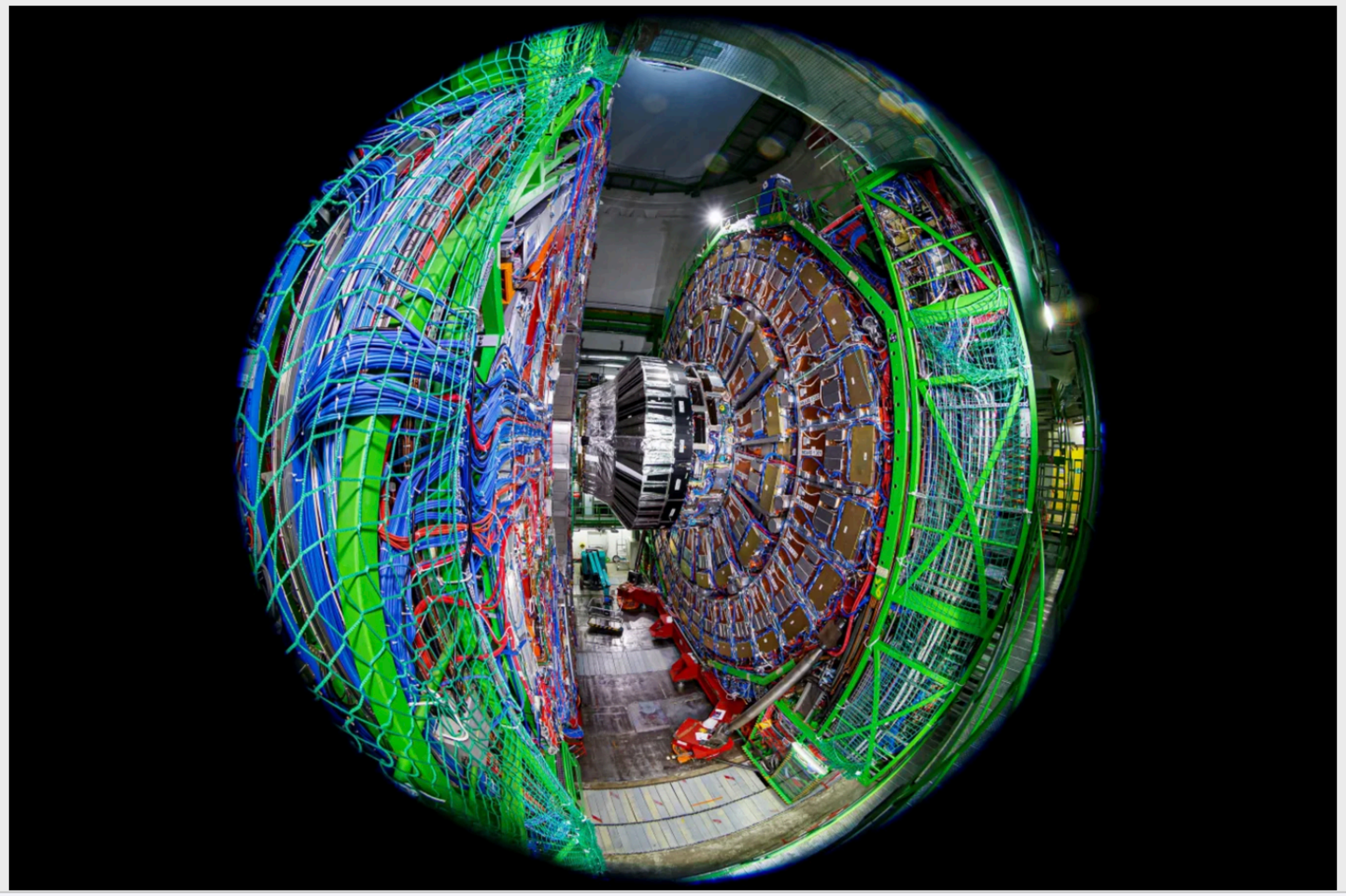
Supersymmetry, long considered the golden child of theoretical physics, has officially lost its luster at the world's reigning particle accelerator

BY ELENI PETRAKOU EDITED BY LEE BILLINGS



"no longer makes sense to consider it a privileged theory"

End of Part 1

Part 2

Malte Mrowietz

Malte Mrowietz

$$
\begin{aligned}
\mathcal{L}_{\text{SOFT, MSSM}} = & -1/2(M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g}) \\
& -\tilde{\bar{u}}\hat{\mathbf{a}}_u\tilde{Q}H_u - \tilde{\bar{d}}\hat{\mathbf{a}}_d\tilde{Q}H_d - \tilde{\bar{e}}\hat{\mathbf{a}}_e\tilde{Q}H_d \\
& -\tilde{Q}^\dagger\hat{\mathbf{m}}^2_Q\tilde{Q} - \tilde{L}^\dagger\hat{\mathbf{m}}^2_L\tilde{L} - \tilde{\bar{u}}\hat{\mathbf{m}}^2_u\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\hat{\mathbf{m}}^2_d\tilde{\bar{d}}^\dagger \\
& -\tilde{\bar{e}}\hat{\mathbf{m}}^2_e\tilde{\bar{e}}^\dagger - bH_uH_d \\
& -m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d,
\end{aligned}
$$

Malte Mrowietz

$$
\begin{aligned}
\mathcal{L}_{\text{SOFT, MSSM}} = & -1/2\left(M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}\tilde{g}\right) \\
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& -\tilde{Q}^\dagger\hat{\mathbf{m}}_Q^2\tilde{Q} - \tilde{L}^\dagger\hat{\mathbf{m}}_L^2\tilde{L} - \tilde{\bar{u}}\hat{\mathbf{m}}_u^2\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\hat{\mathbf{m}}_d^2\tilde{\bar{d}}^\dagger \\
& -\tilde{\bar{e}}\hat{\mathbf{m}}_e^2\tilde{\bar{e}}^\dagger - bH_uH_d \\
& -m_{H_u}^2H_u^*H_u - m_{H_d}^2H_d^*H_d,
\end{aligned}
$$

Real conversation:

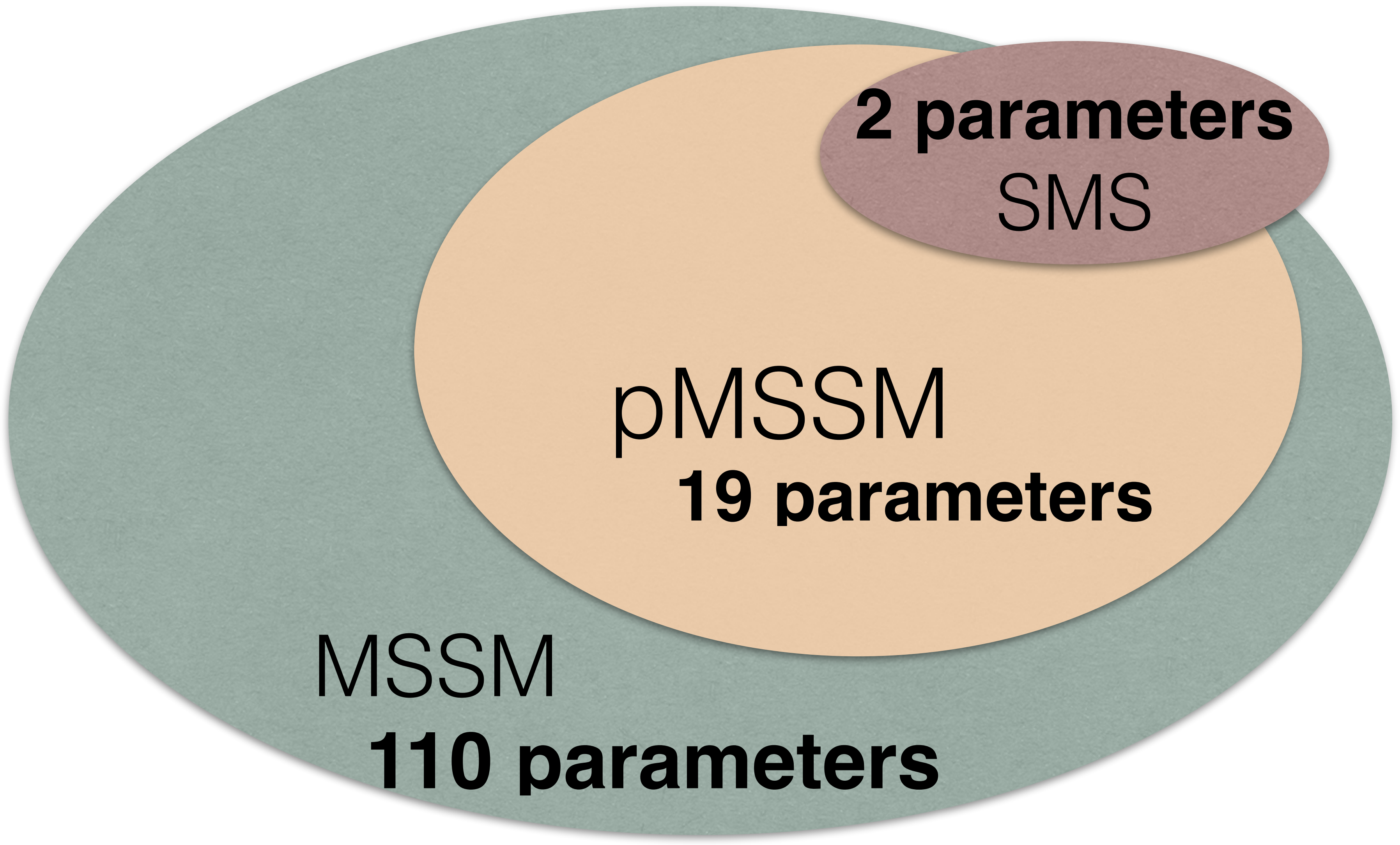
Sam: “The MSSM has 110 free parameters”

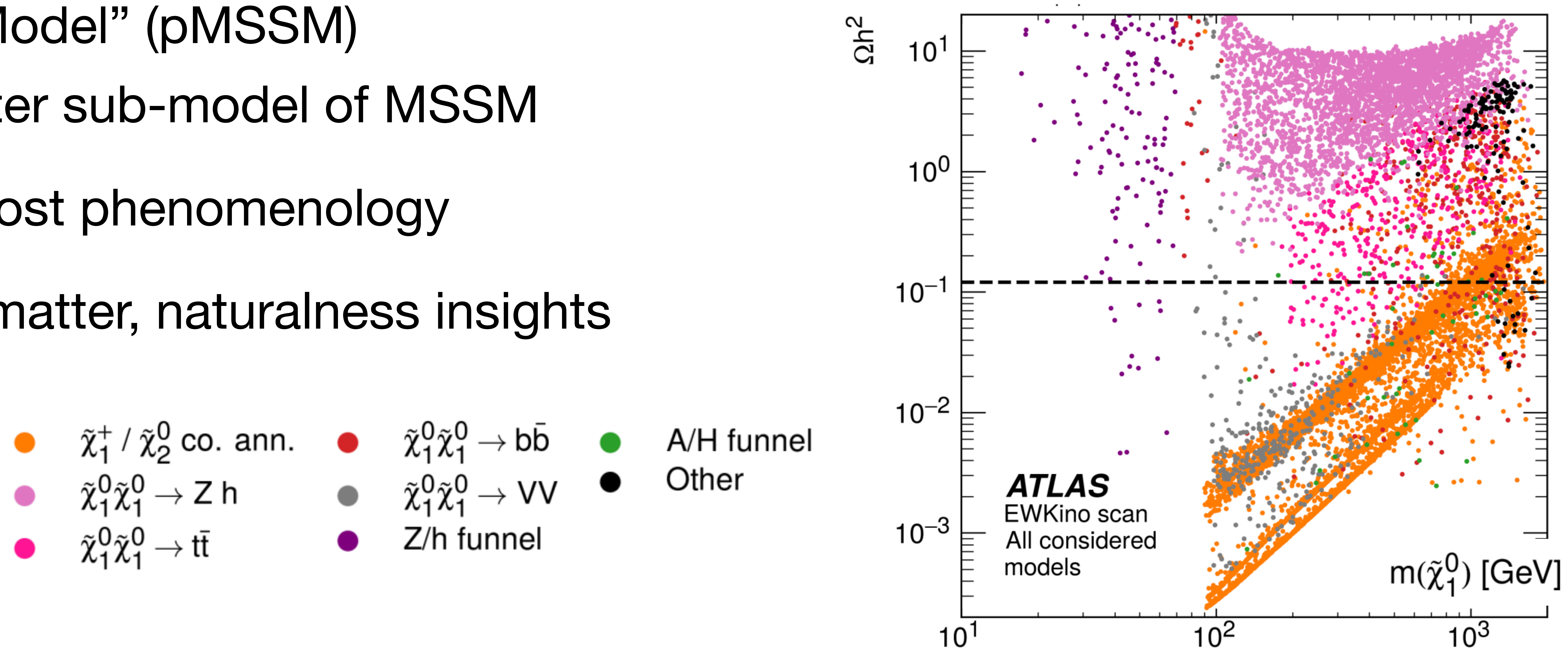
Malte: “Hold my beer”

Mapping SUSY

Supersymmetry without prejudice, Berger, Gainer, Hewett, Rizzo; 2008

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

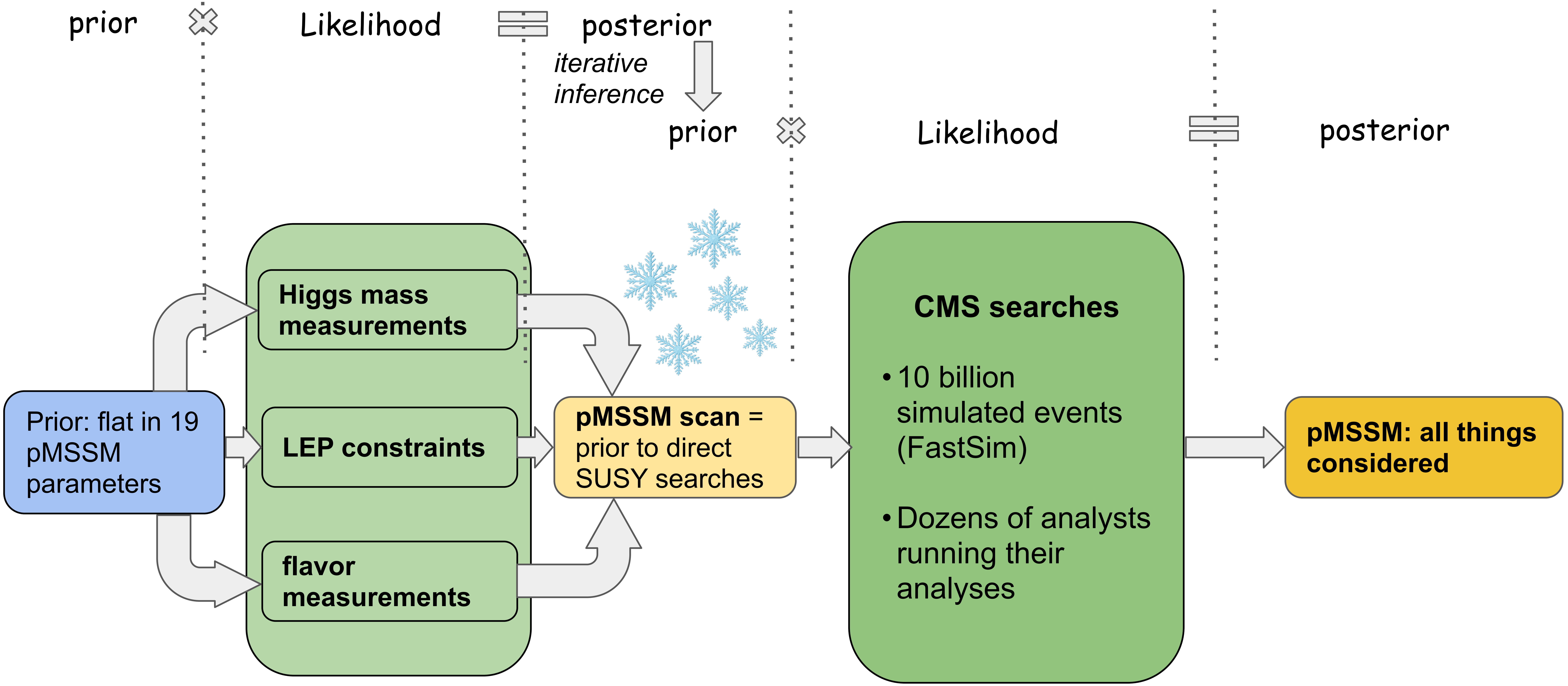




Mapping SUSY

- Two Run 2 pMSSM studies by the LHC experiments
  - 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
  - **Goals:** assess viability of SUSY, create roadmap for systematic study

Bayesian pMSSM analysis



Prior

Flat prior in pMSSM-19

squarks up to 10 TeV

gluino up to 10 TeV

sleptons up to 4 TeV

heavy Higgs up to 4 TeV

electroweakinos up to 4 TeV

trilinear couplings up to 7 TeV

tan β from 2 to 60

Likelihood

Markov chain Monte Carlo (McMC)

Higgs mass: m(h^0)***

LEP constraints

flavor measurements:

BR($b \to s\,\gamma$)*

BR($b \to s\,\mu\mu$)*

BR($b \to s\,ee$)*

BR($B_s \to \mu\mu$)*

BR($B_d \to \mu\mu$)*

BR($B_u \to \tau\nu$)*

BR($D_s \to \tau\nu$)**

BR($D_s \to \mu\nu$)**

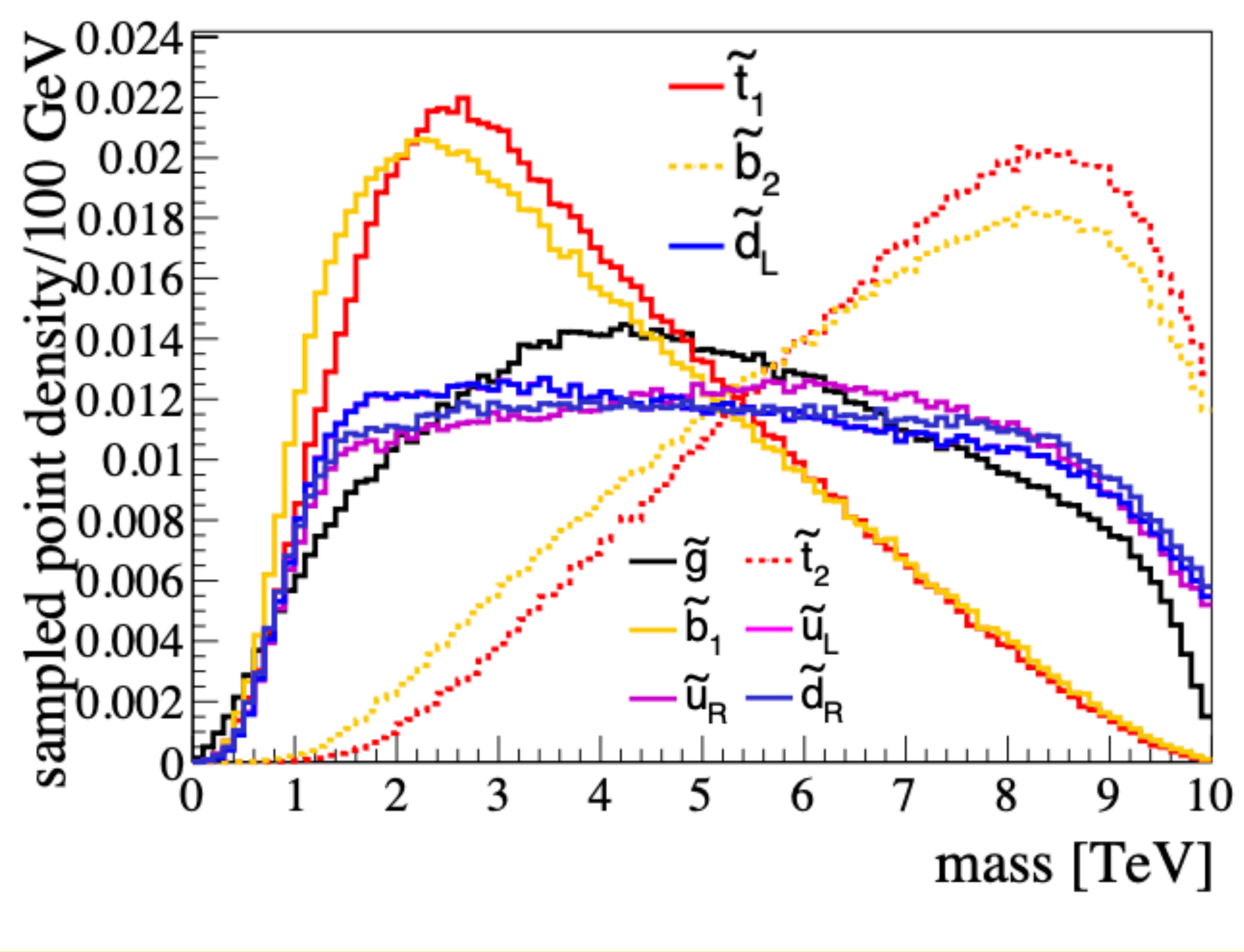
BR($B^0 \to K^{*0}\,\gamma$)*

Δ_0 ($B \to K^*\,\gamma$) **

Δρ

Posterior

- 1 grand scan, 500k points



- Bounds->~50% EWK, 50% strong production

LSP Flavors

Any mass allowed

- Bino (lonely),
    - Totally inert - no production of its own - needs annihilation mechanism

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- Wino (Near mass degenerate triplet)
  - Large production cross section
  - LEP/DM allow m = [100 GeV, 2 TeV]

} 0.2-10 GeV

LSP Flavors

Any mass allowed

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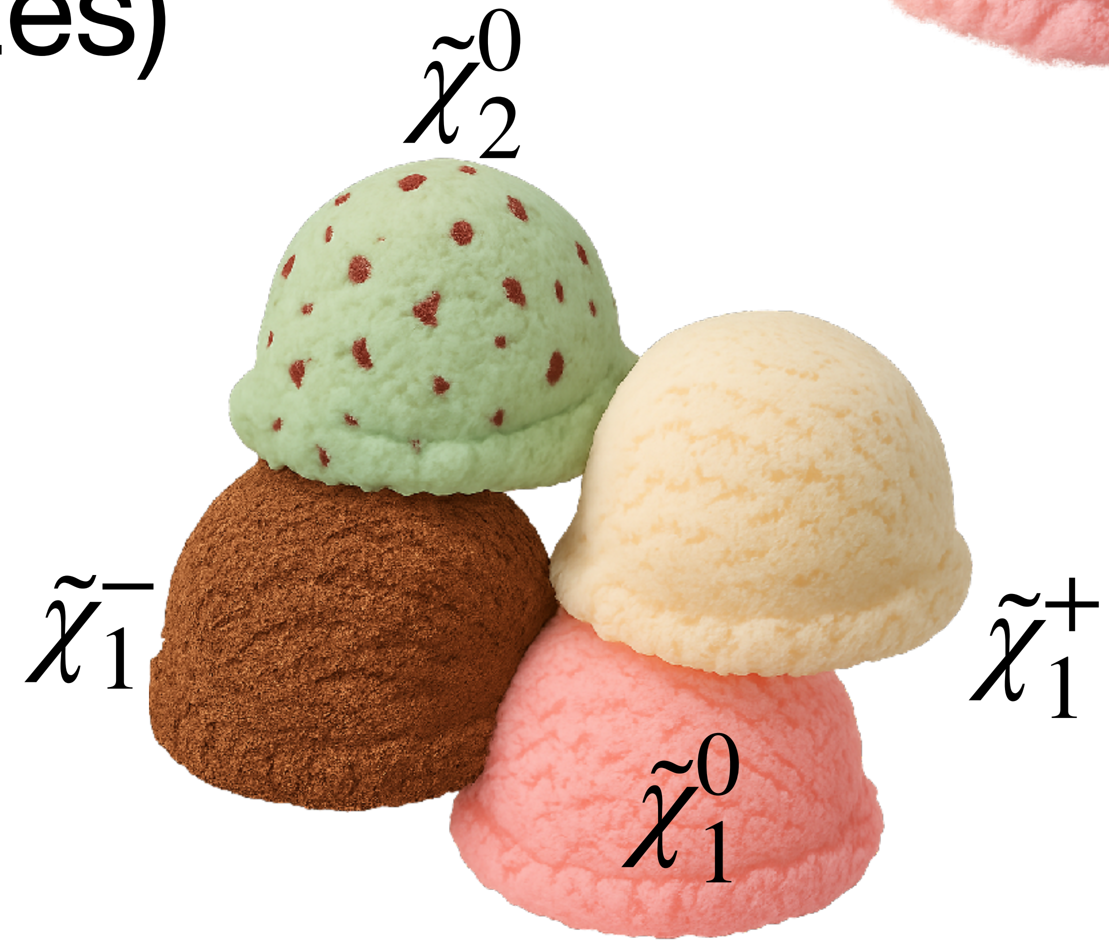
  - Totally inert - no production of its own - needs annihilation mechanism
- Wino (Near mass degenerate triplet)
  - Large production cross section
  - LEP/DM allow m = [100 GeV, 2 TeV]

} 0.2-10 GeV

- Higgsino (4 near-degenerate states)
  - Medium production cross section
  - LEP/DM allow m = [100 GeV, 1 TeV]



} 0.3-50 GeV

7 CMS Data Analyses

Analysis	Final state	Reference	PAS
Multi-jet, missing pT	0 lepton	JHEP 10 (2019) 244	SUS-19-006
Single-lepton, $\Delta\phi$	1-lepton	JHEP 09 (2023) 149	SUS-21-007
Dilepton edge, on-Z	2 opposite charge lepton	JHEP 04 (2021) 123	SUS-20-001
Disappearing track	short tracks + X	Phys. Rev. D 109 (2024) 072007	SUS-21-006
Soft opposite sign (SOS)	2, 3 low-pT leptons	JHEP 2204 (2022) 91	SUS-18-004
*Direct stau	1, 2 hadronic tau	Phys. Rev. D 108 (2023) 012011	SUS-21-001
*Soft lepton+track	Pairs of muons, tracks	CMS-PAS-SUS-24-003	SUS-24-003

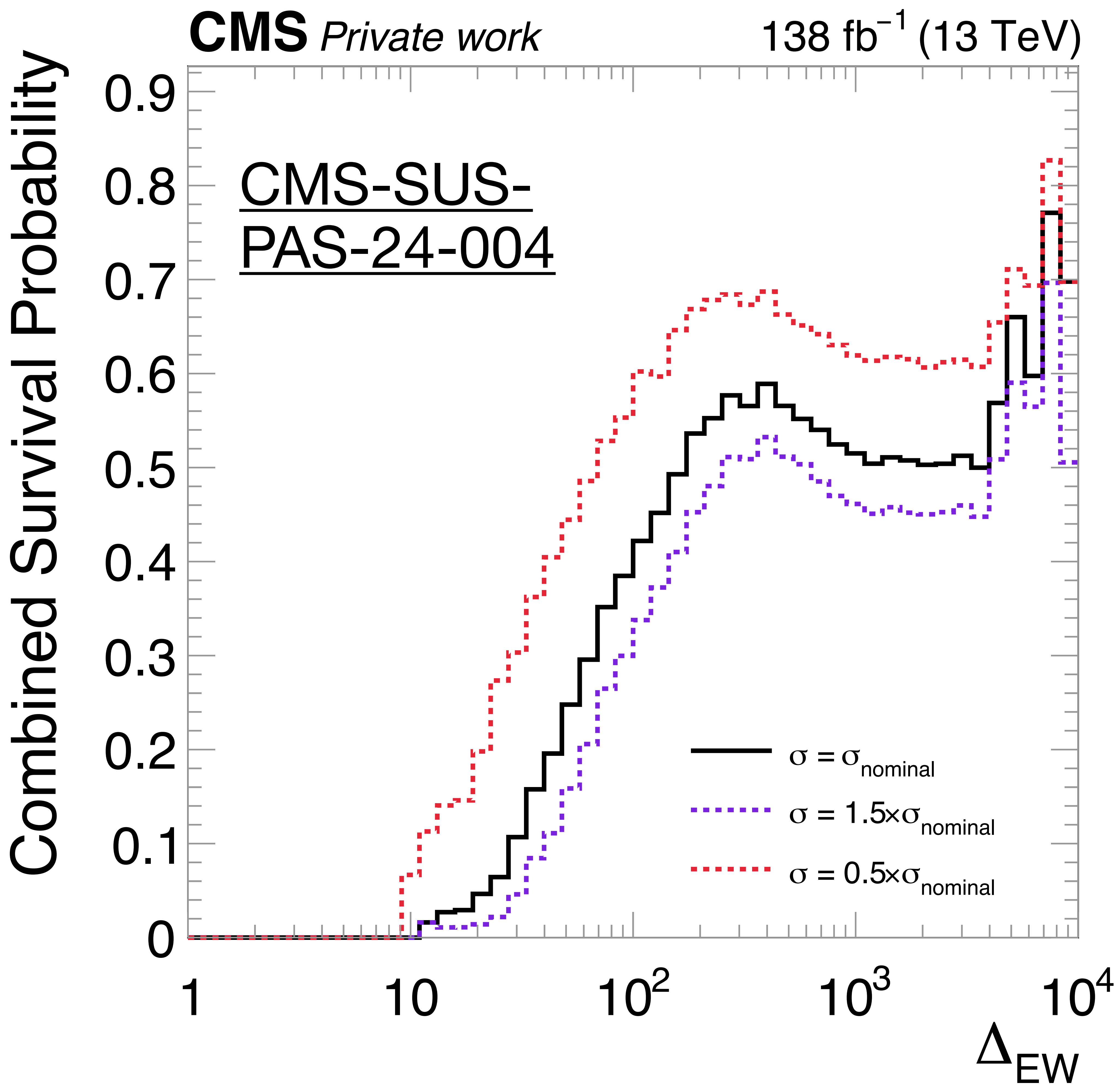
- CMS-PAS-SUS-24-004 released August, 2024 - planned paper with more analyses

New today

- *Two new analyses added above
- Updates, new plots, projections from SUS-24-004 cleared to show today with “Private work” label

Fine-tuning/naturalness:

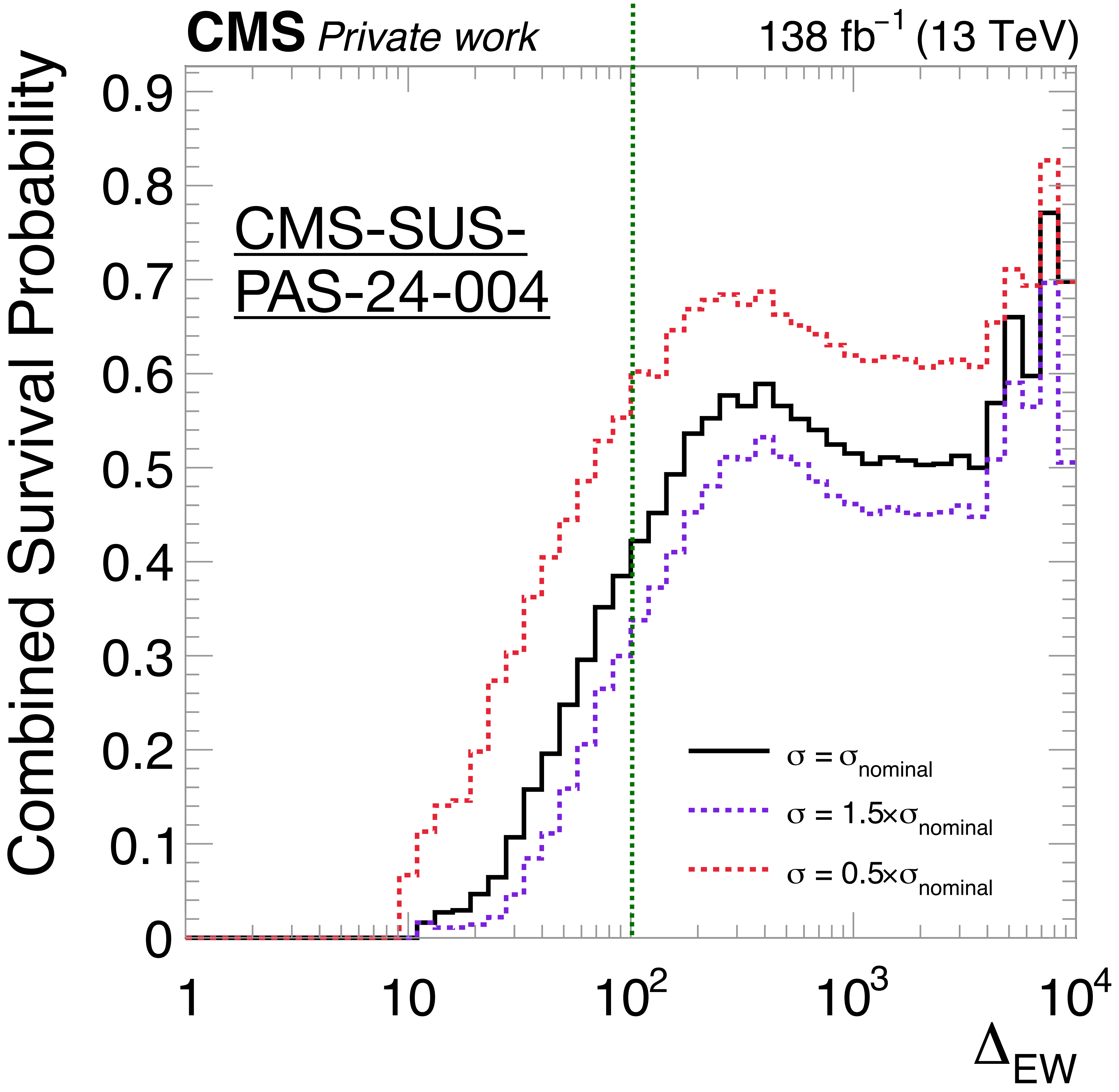
Δ_{EW} as lower bound on fine-tuning (arXiv:1712.01399)

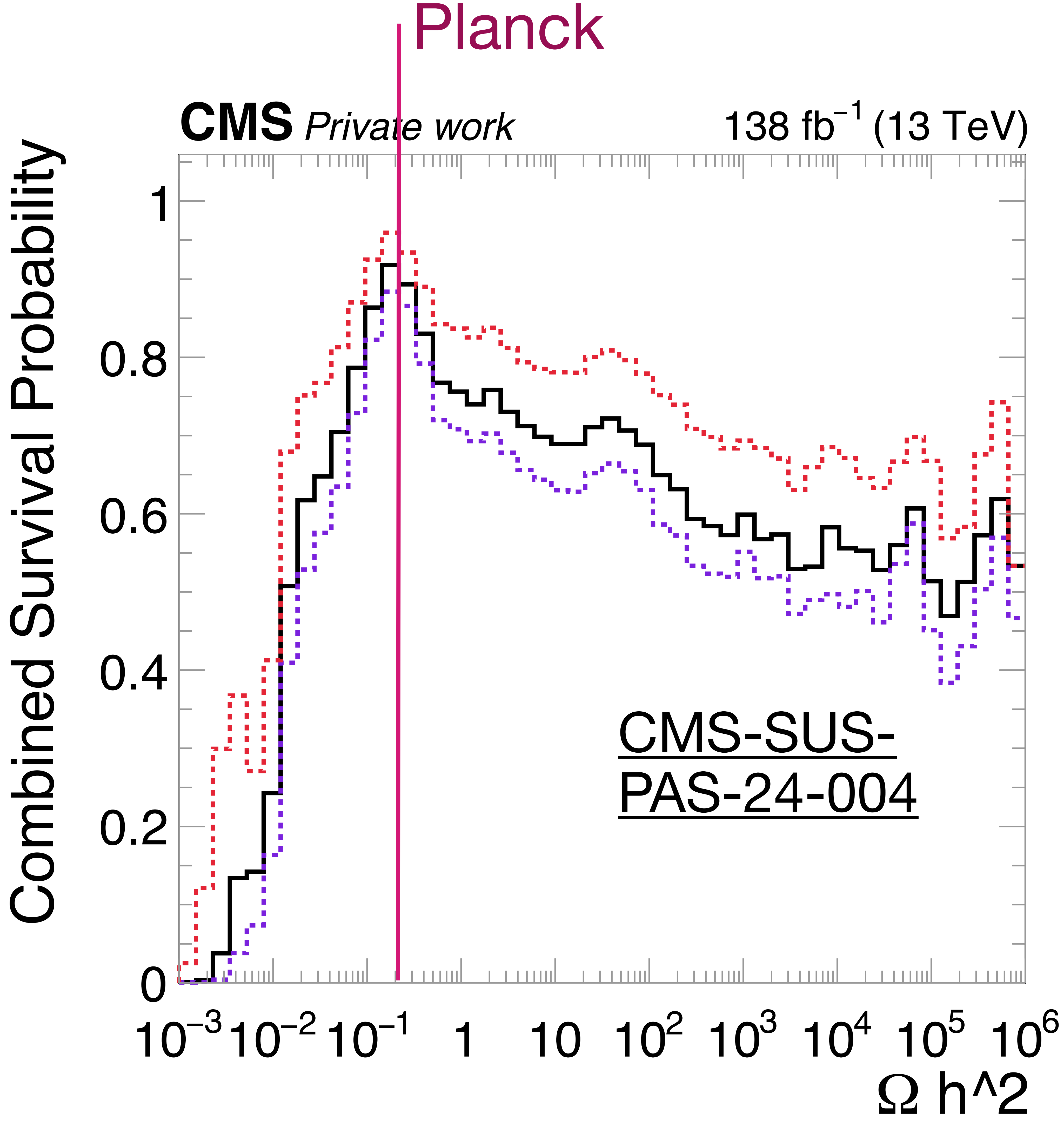


"Natural" one universe ⟷ Multiverse, anthropic pressure

Large hierarchy problem if SUSY too heavy

More natural ⟷ Less natural





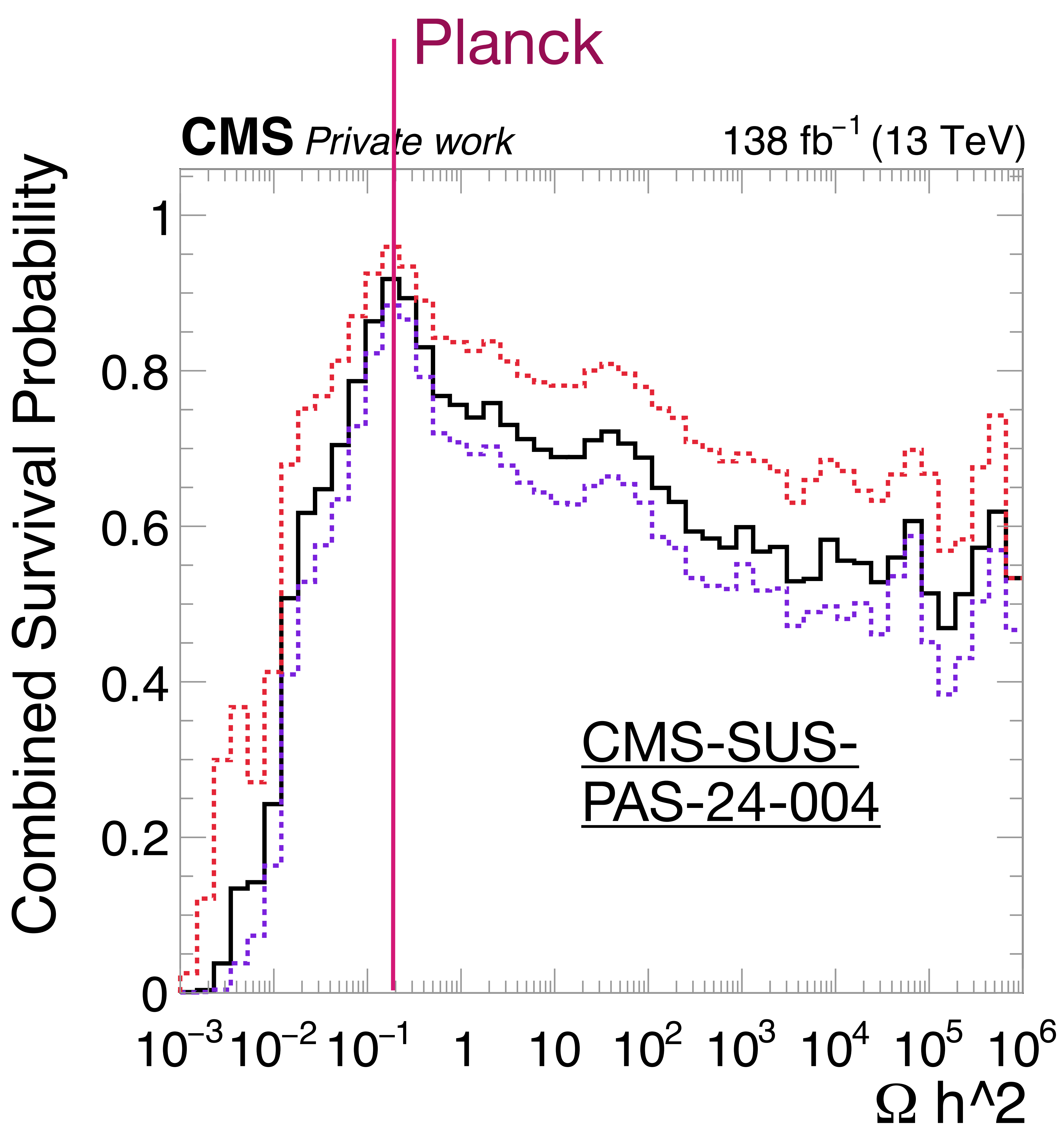
<50% of natural models survive

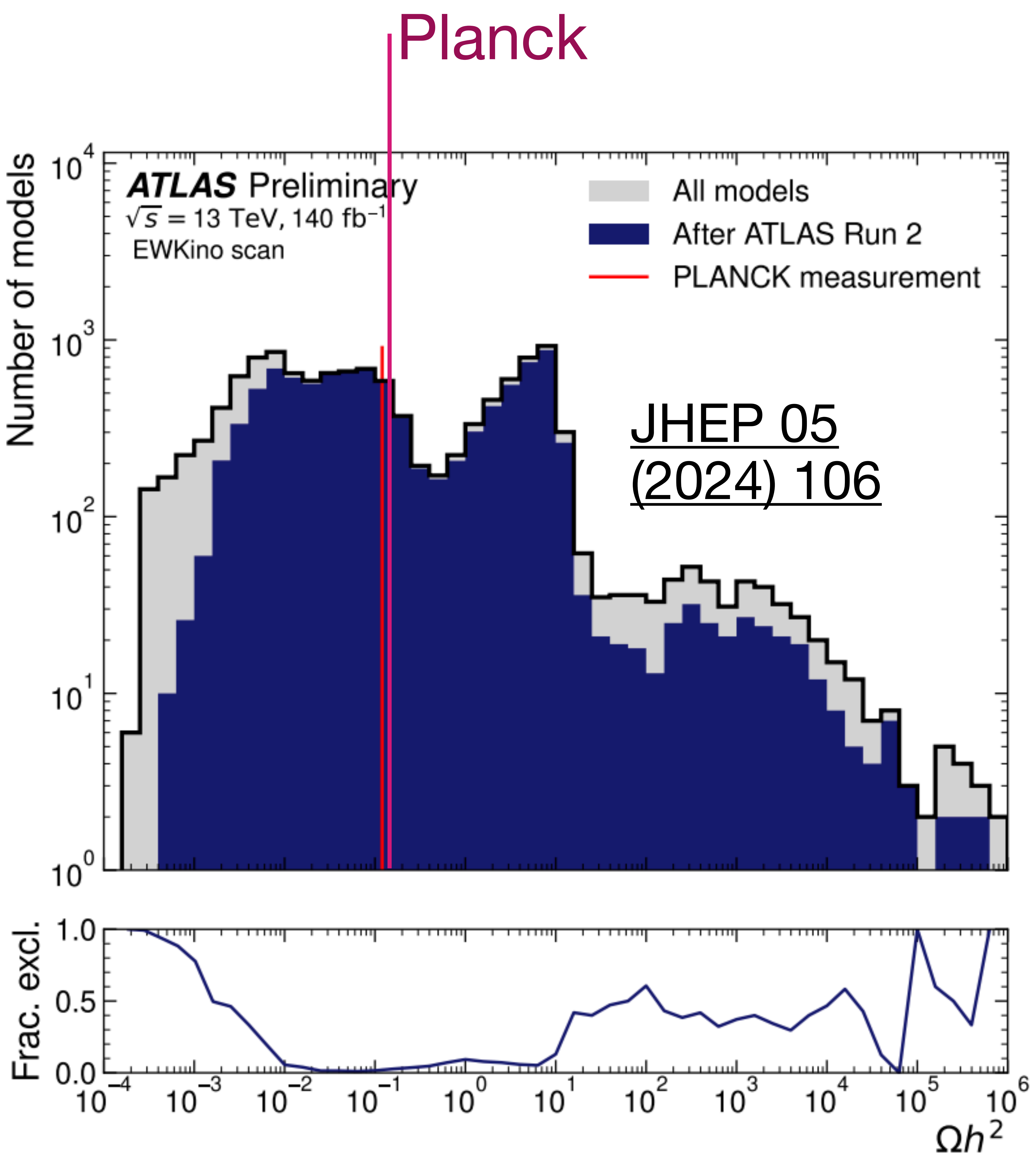
>90% of relic density models survive

Δ_{EW} as lower bound on fine-tuning (arXiv:1712.01399)

CMS great at probing (and excluding) natural SUSY, pretty bad at dark matter relics

DM relic density

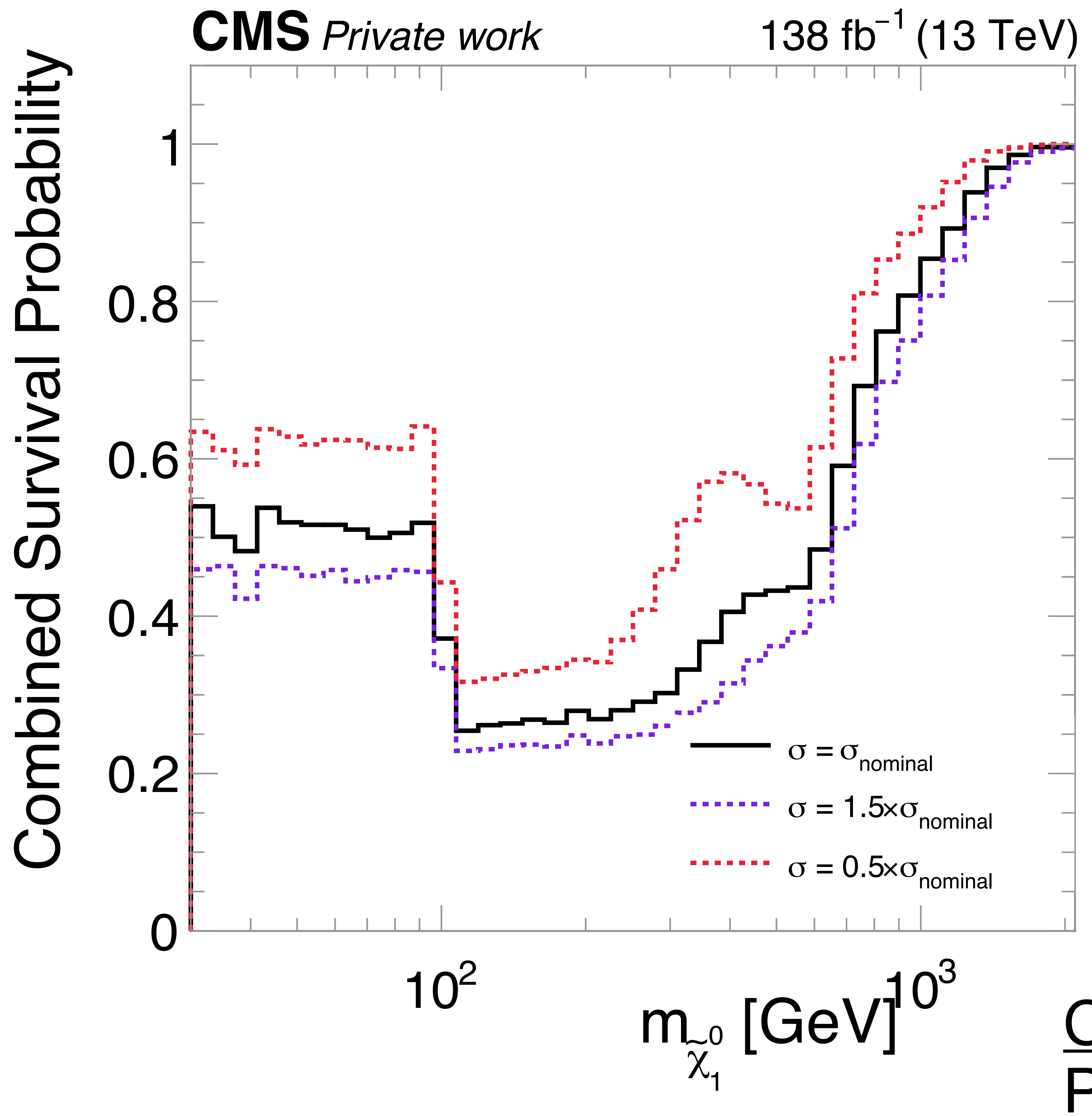




>90% of relic density models survive

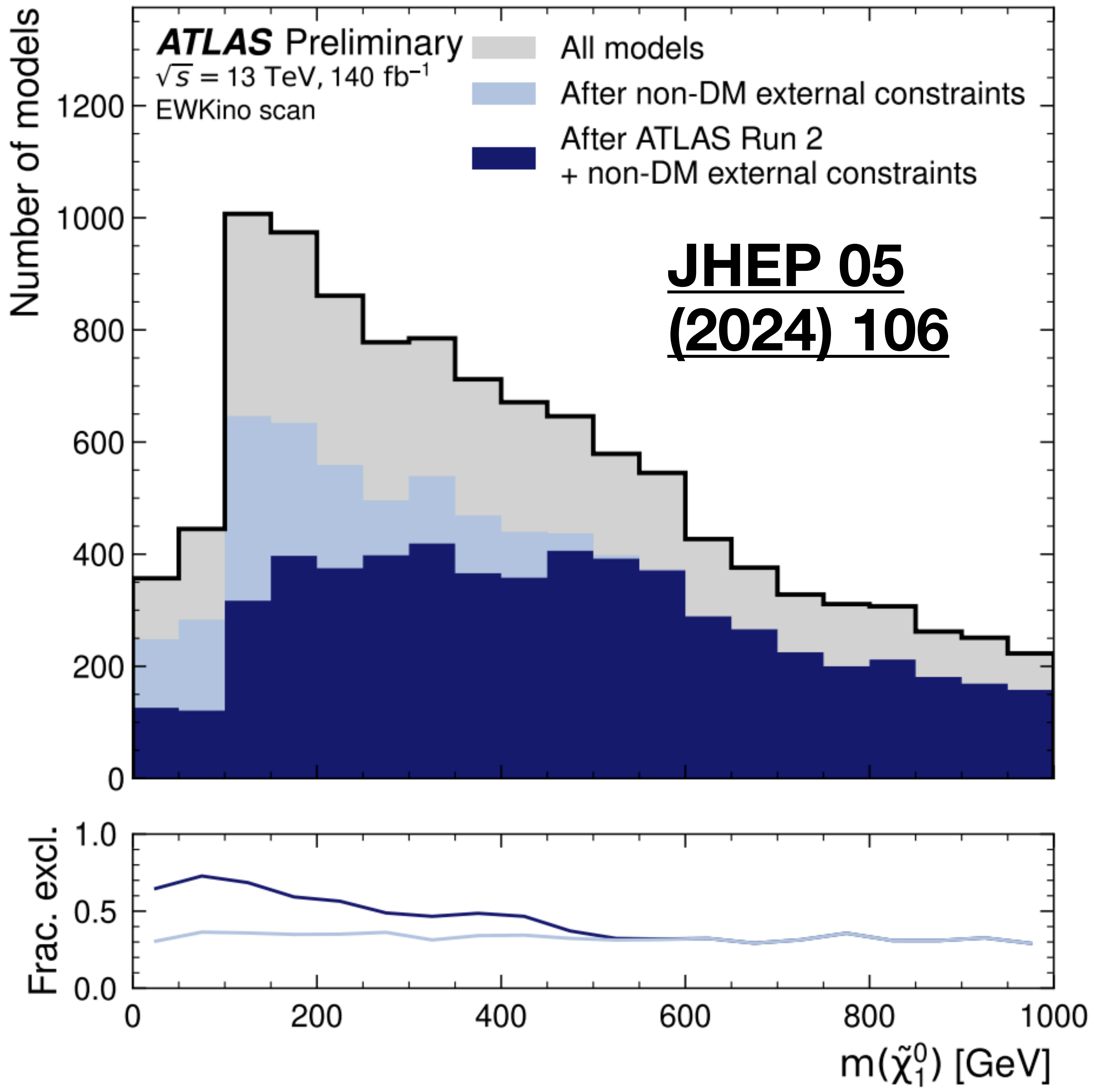
DM candidate mass

Fraction of models surviving



CMS-SUS-PAS-24-004

Number of models

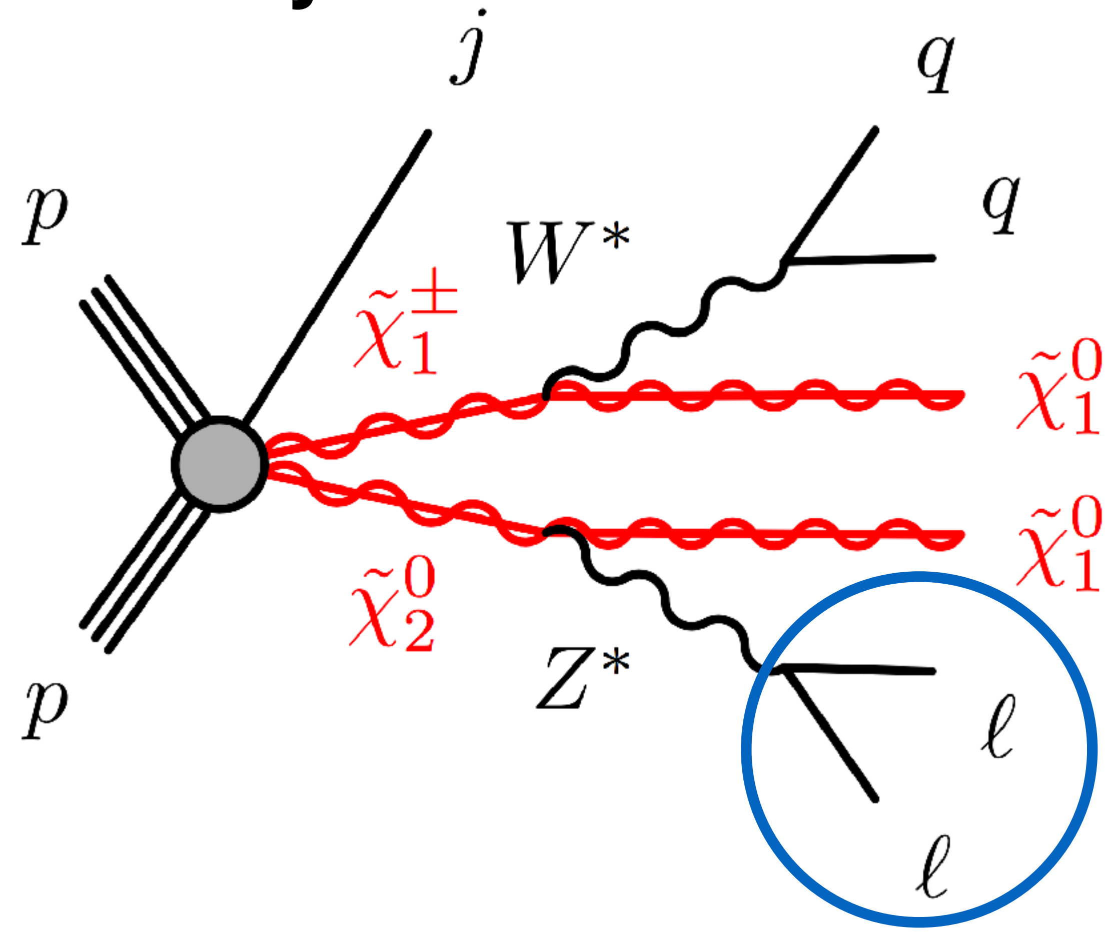


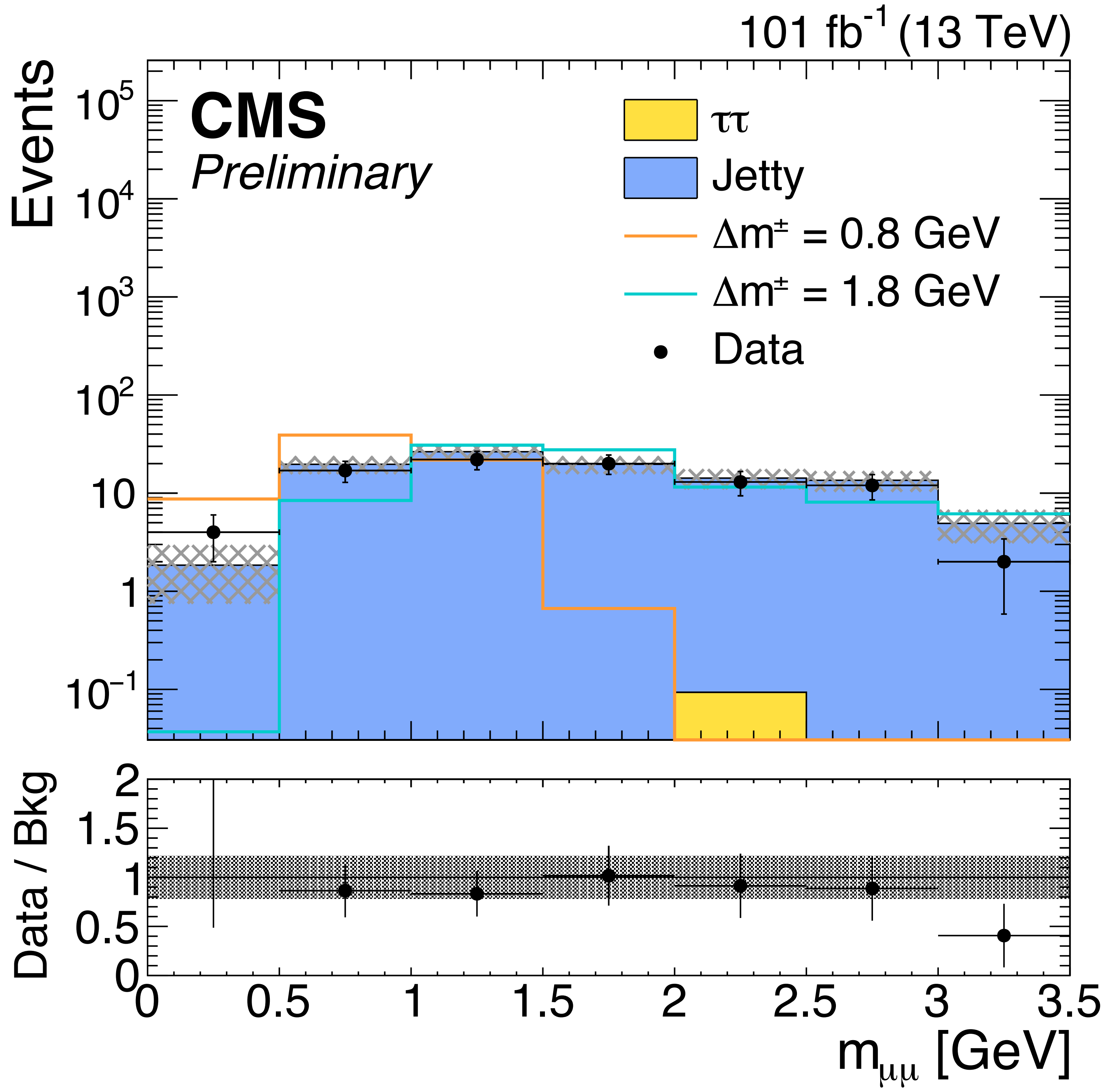
JHEP 05 (2024) 106

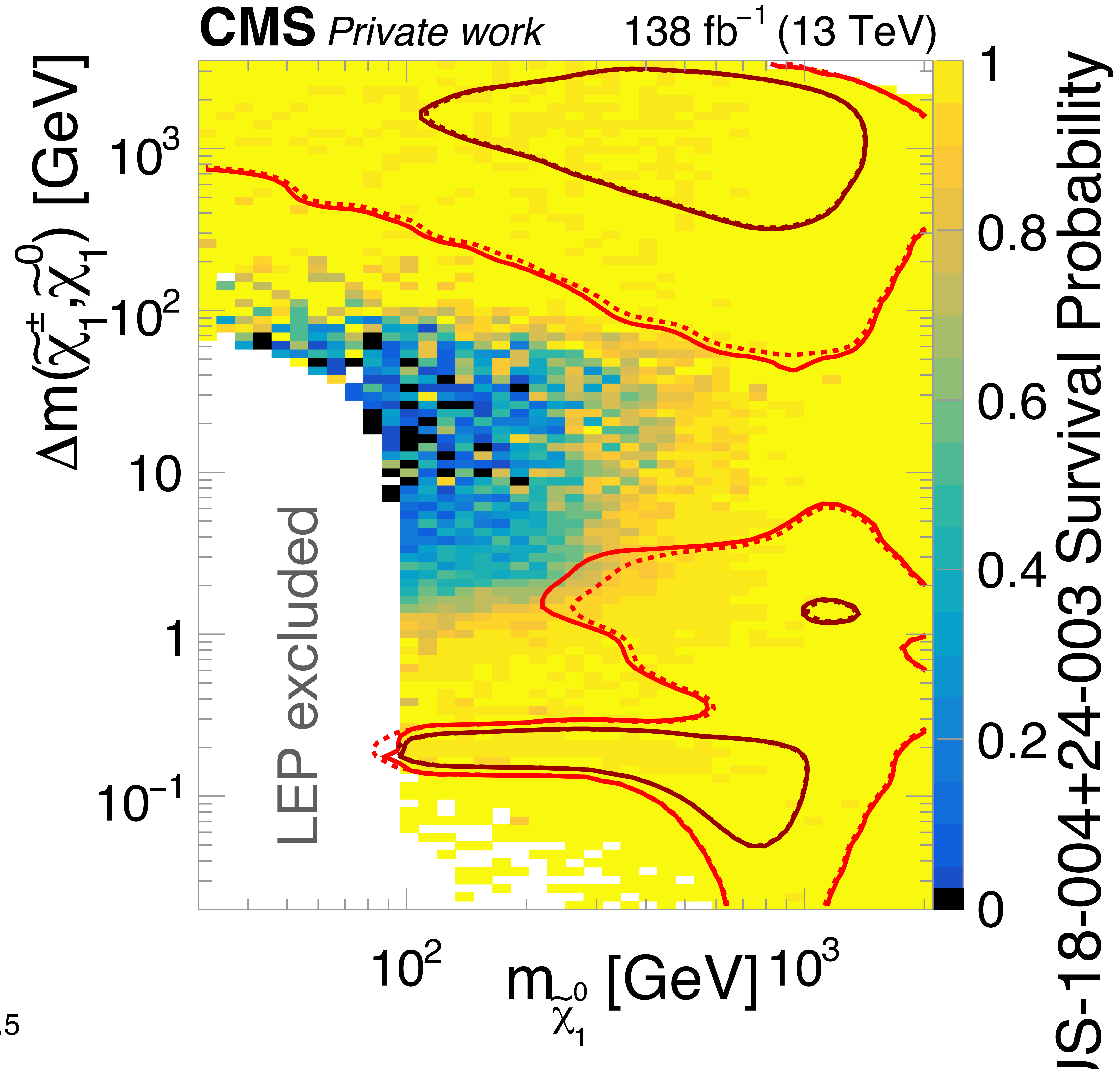
Survival probability and posterior density

Analysis	Final state	PAS
Soft opposite sign (SOS)	2, 3 low-pT leptons	SUS-18-004
*Soft lepton+track	Pairs of muons, tracks	SUS-24-003

- 2- or 3 soft leptons
  - >1 OSSF pair
  - >2 soft
- ISR jet

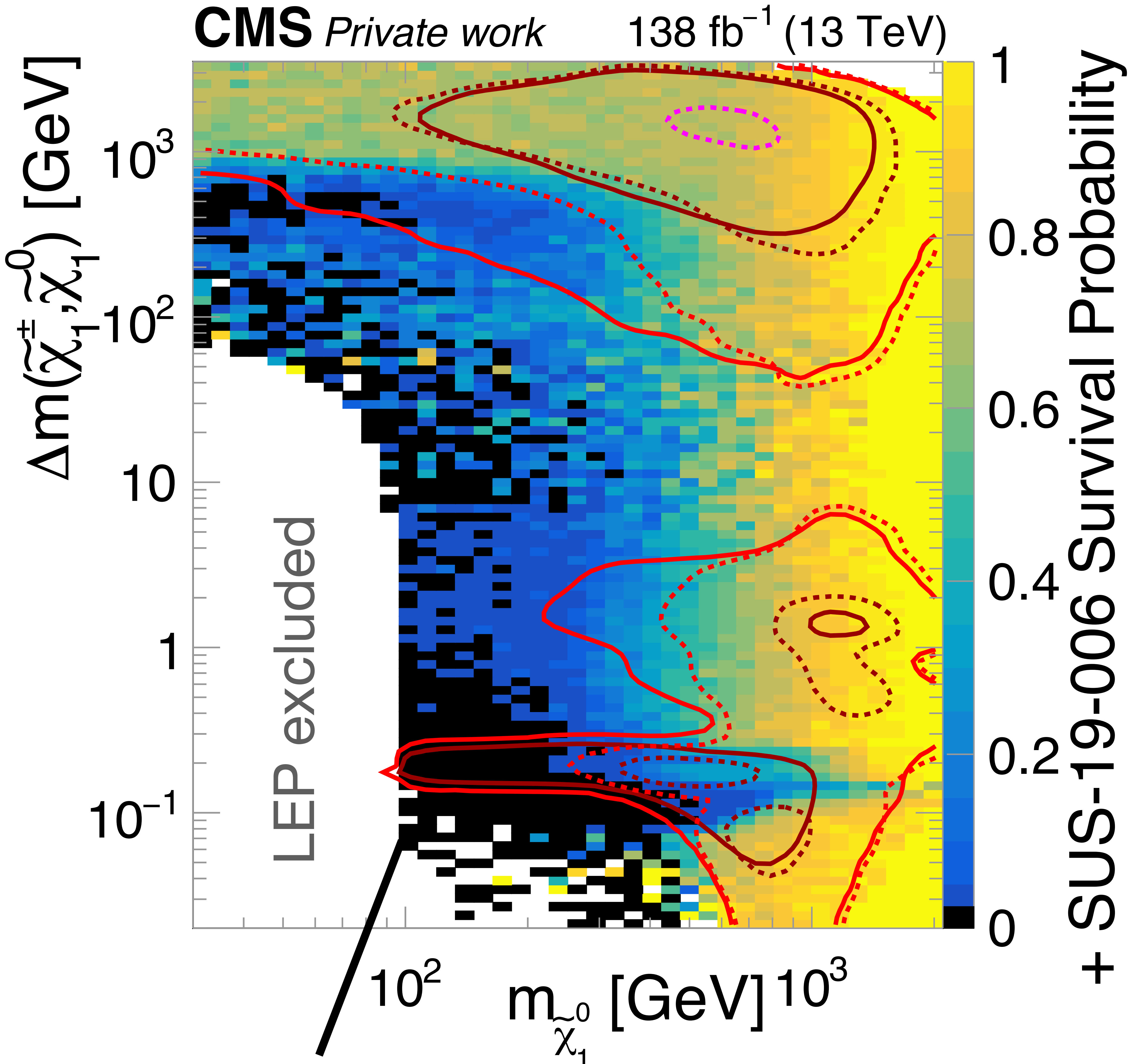






Survival probability and posterior density

Analysis	Final state	PAS
Multi-jet, missing pT	0 lepton	SUS-19-006
Single-lepton, Δϕ	1-lepton	SUS-21-007
Dilepton edge, on-Z	2 opposite charge lepton	SUS-20-001
Disappearing track	short tracks + X	SUS-21-006
Soft opposite sign (SOS)	2, 3 low-pT leptons	SUS-18-004
*Direct stau	1, 2 hadronic tau	SUS-21-001
*Soft lepton+track	Pairs of muons, tracks	SUS-24-003



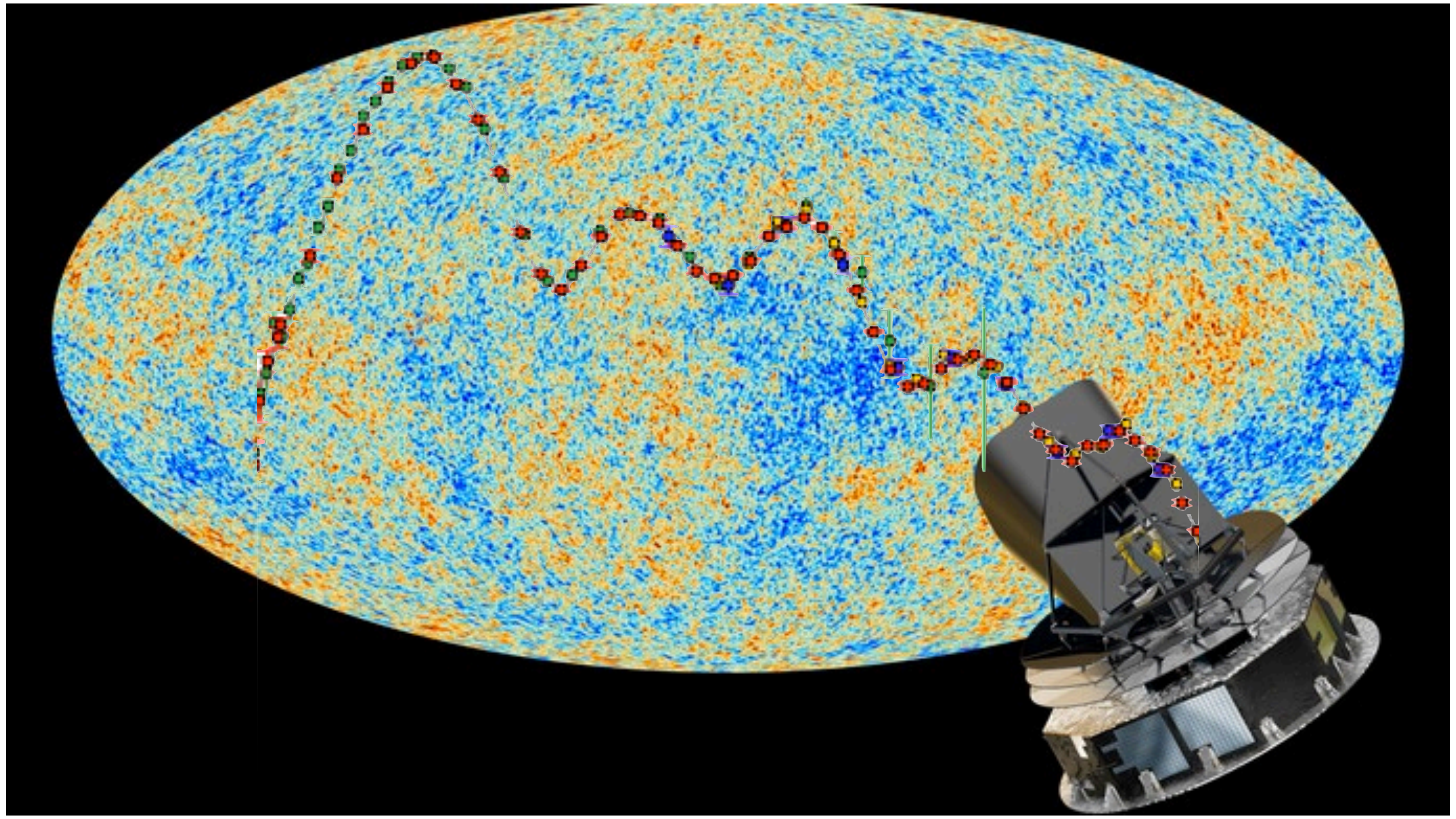
Black → CMS excluded all points in bin

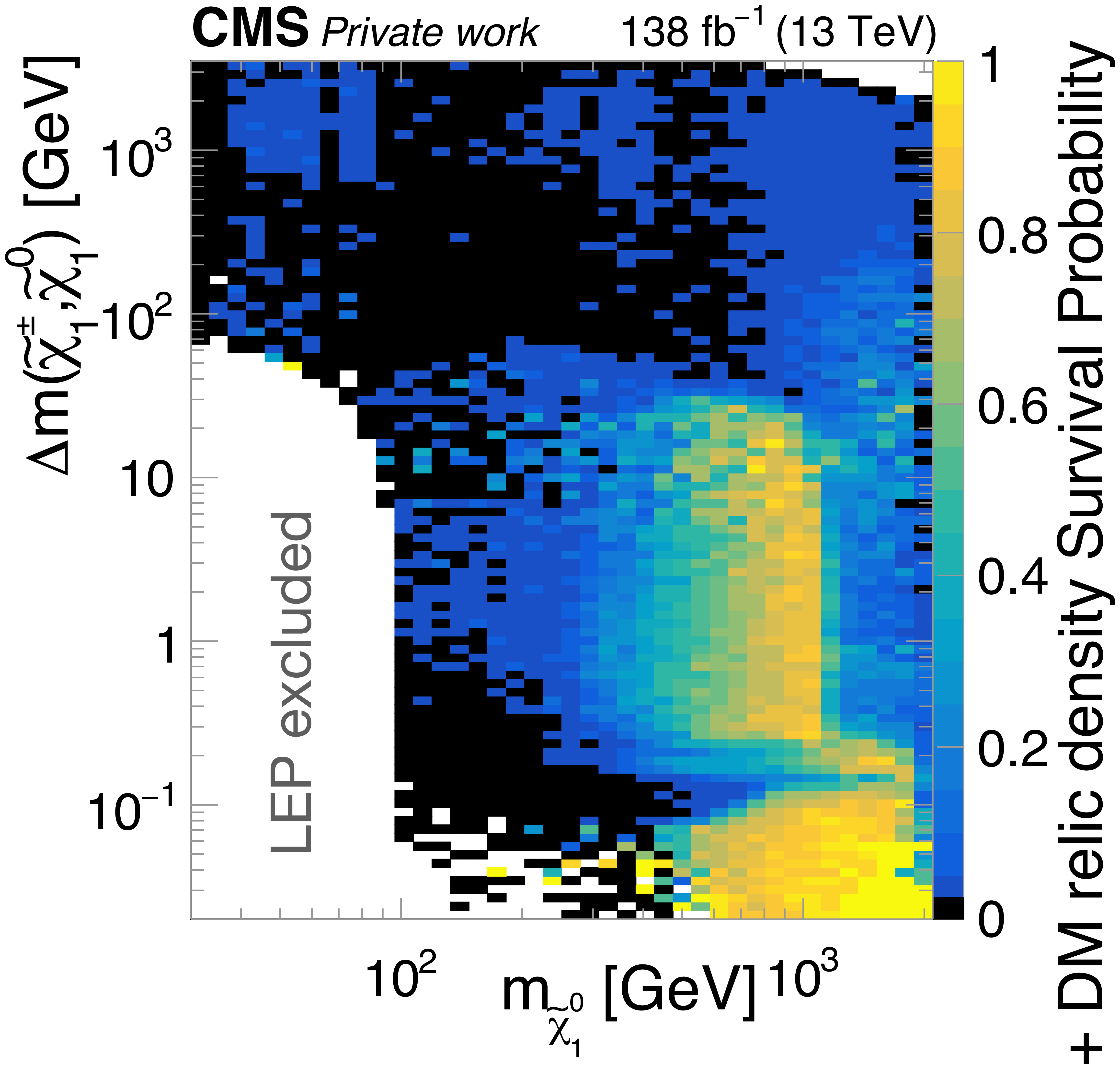
SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006

Survival probability and posterior density

+Relic density (Planck)

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

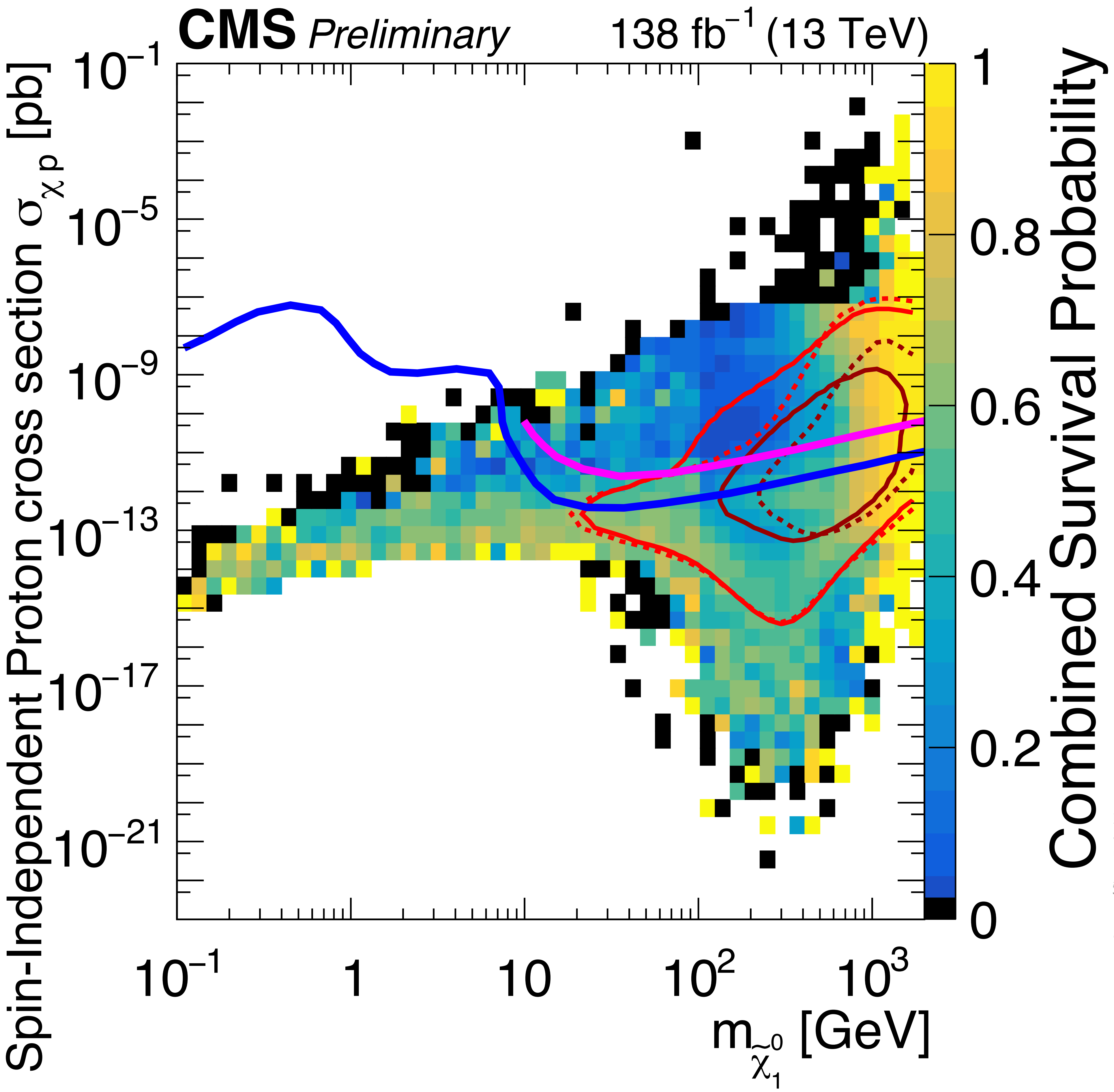


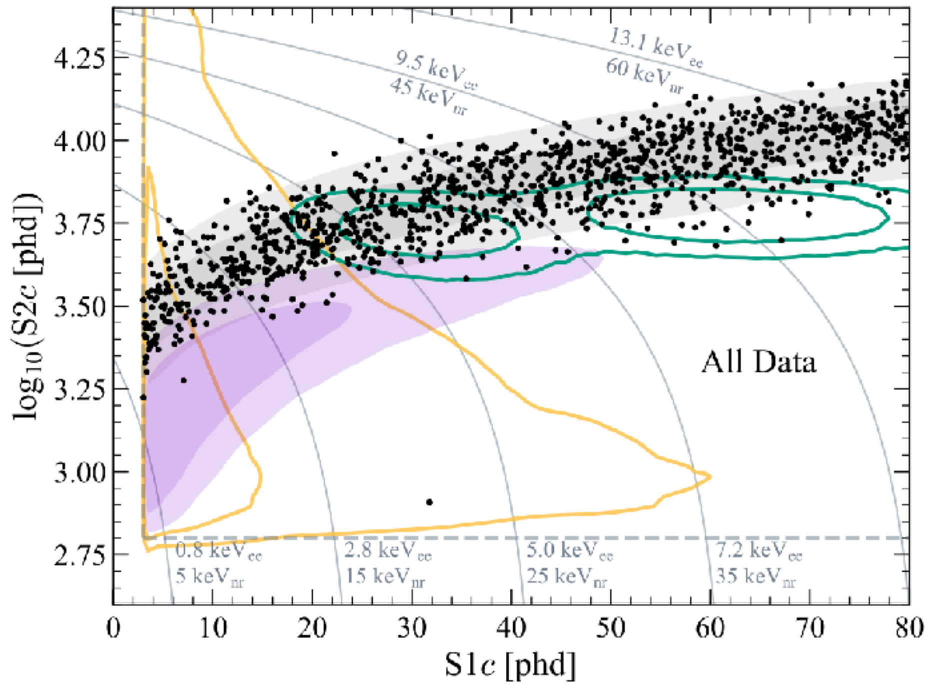


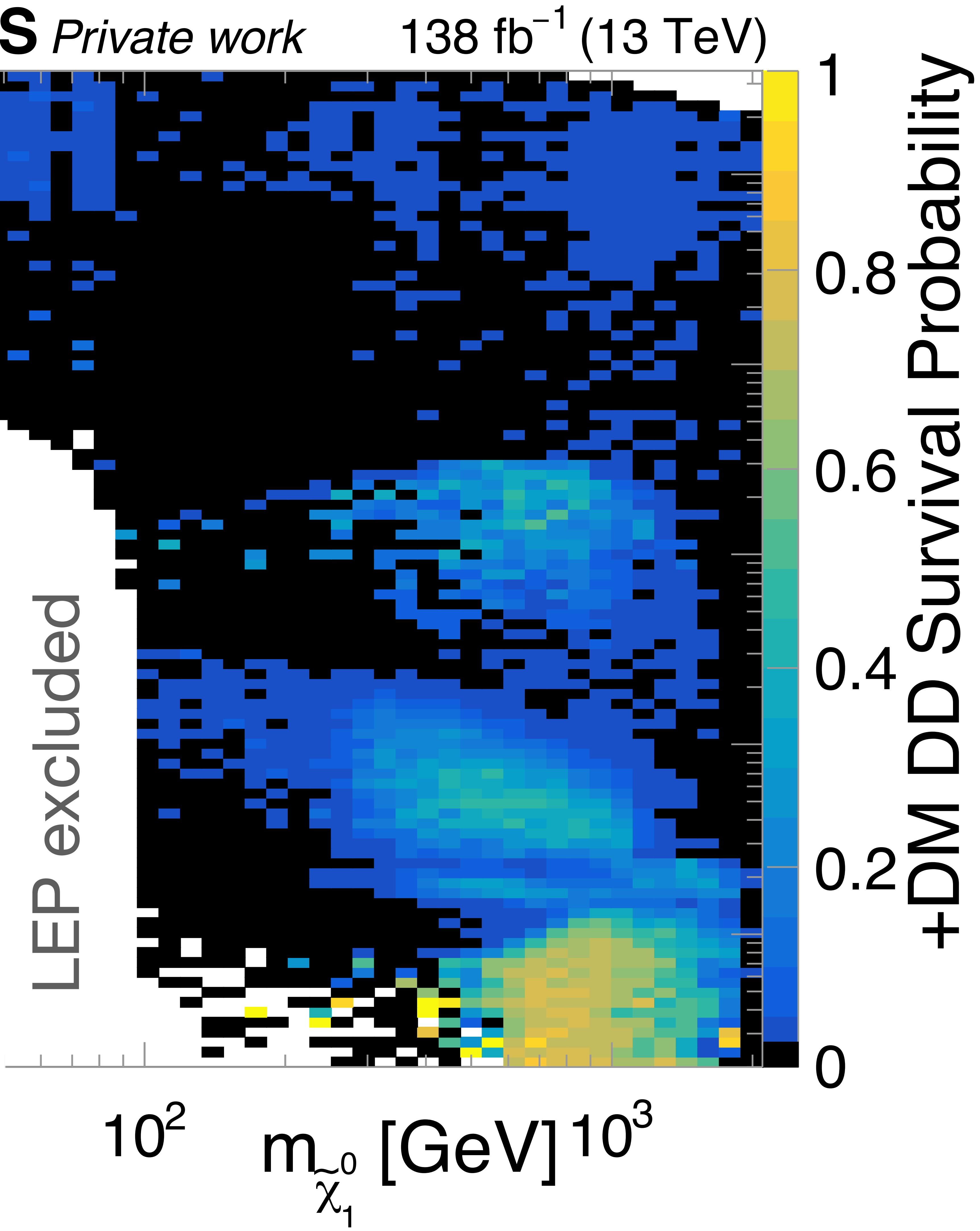
Survival probability and posterior density

arxiv:2410.17036

+LZ (2024) **4.2 Tonne-Years of Exposure**

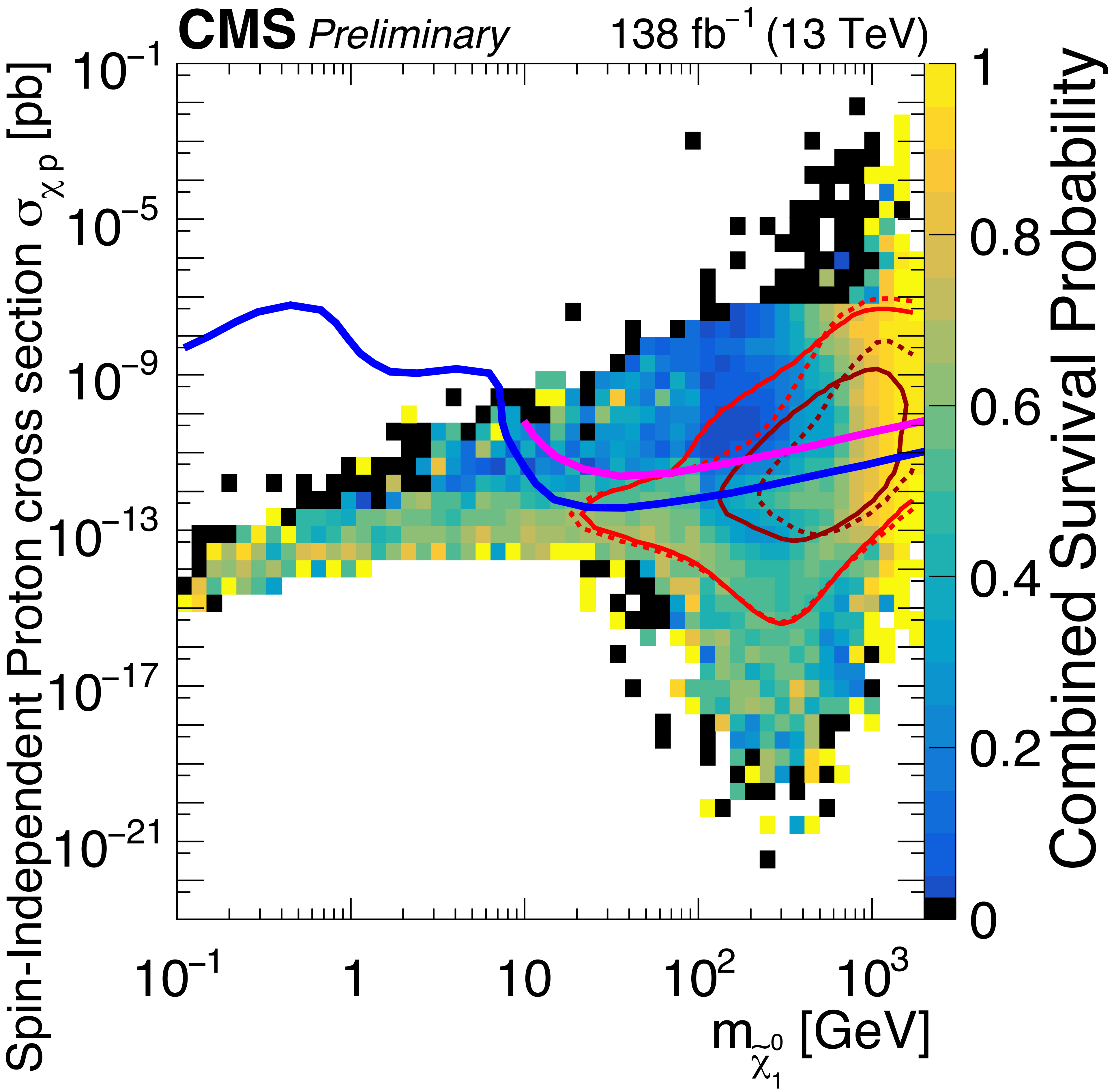


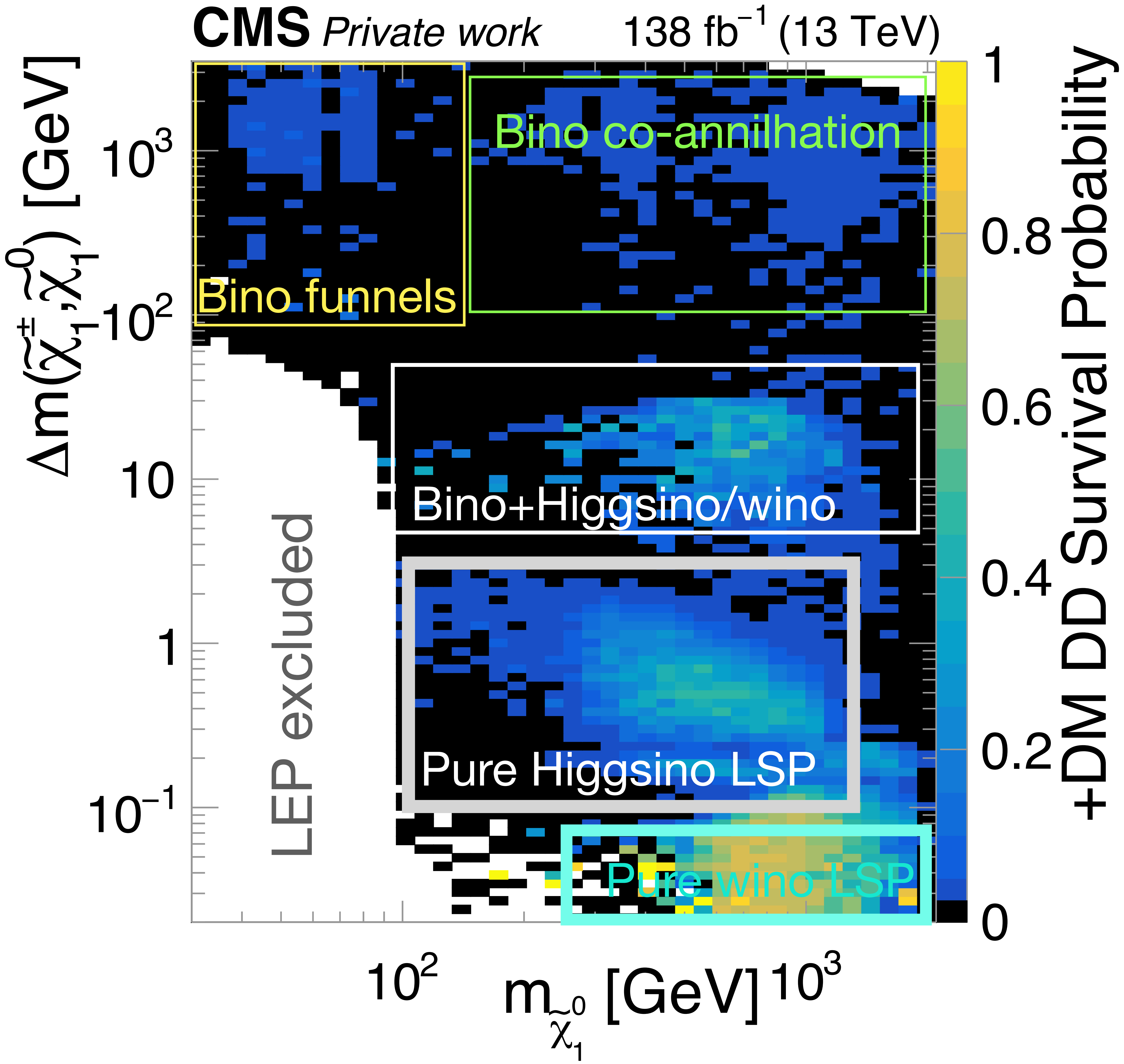




SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006 + DM constraints

Survival probability and posterior density





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Survival probability and posterior density

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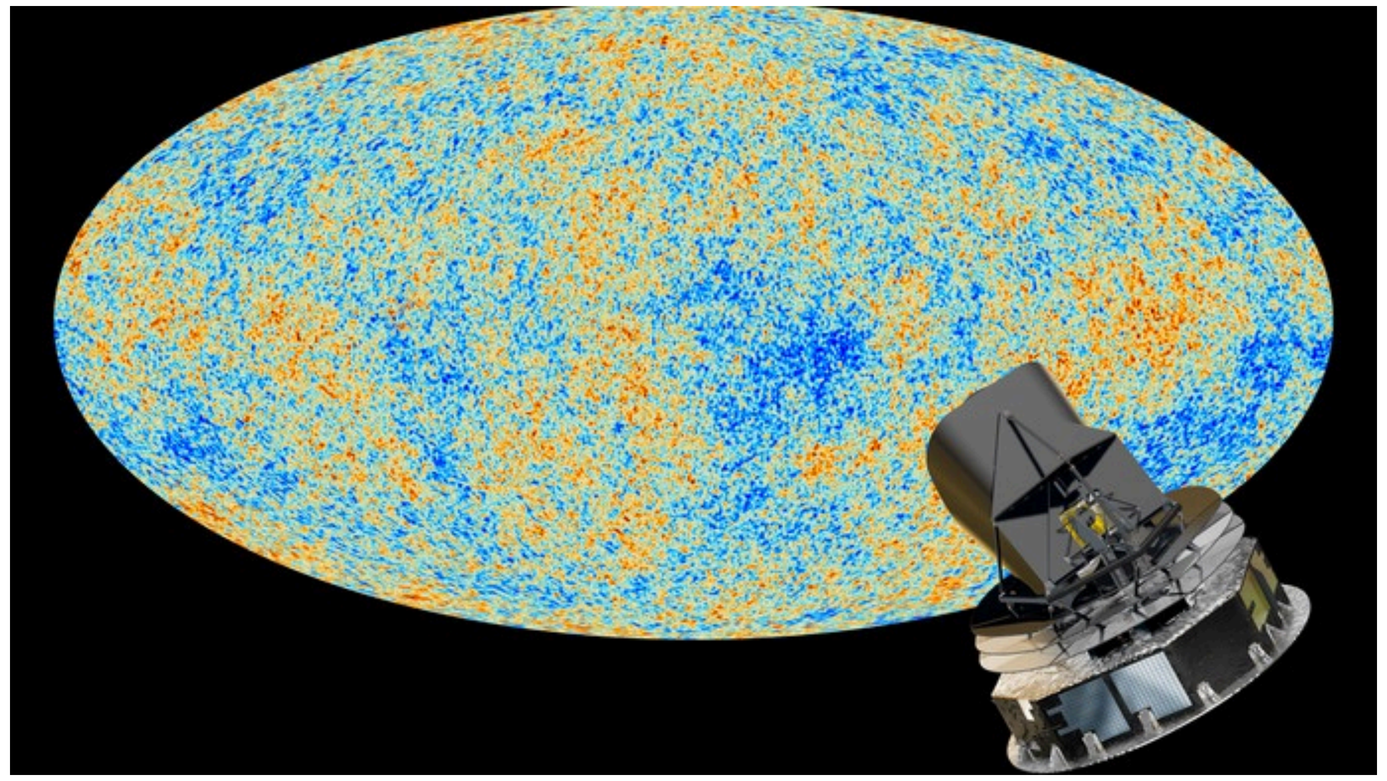
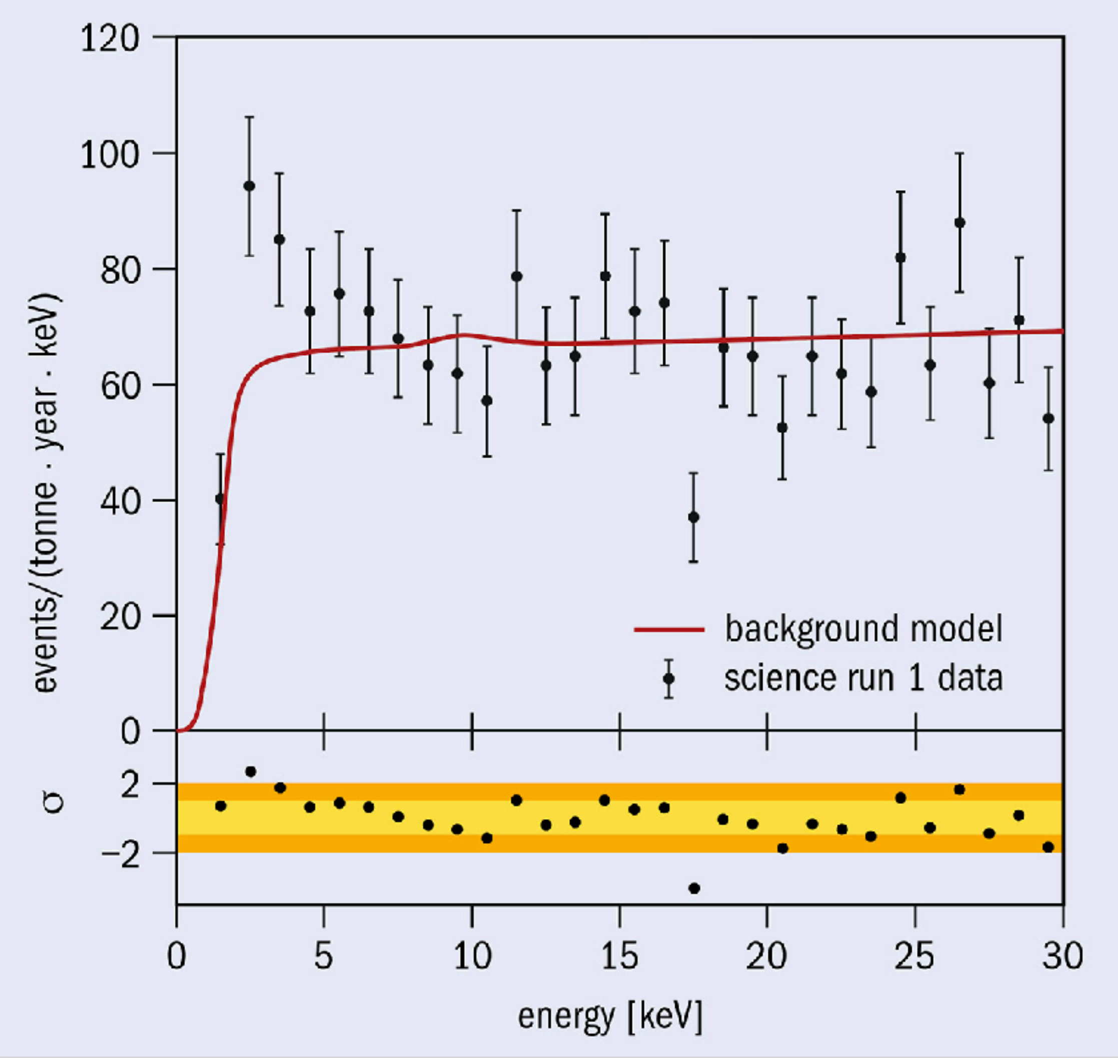
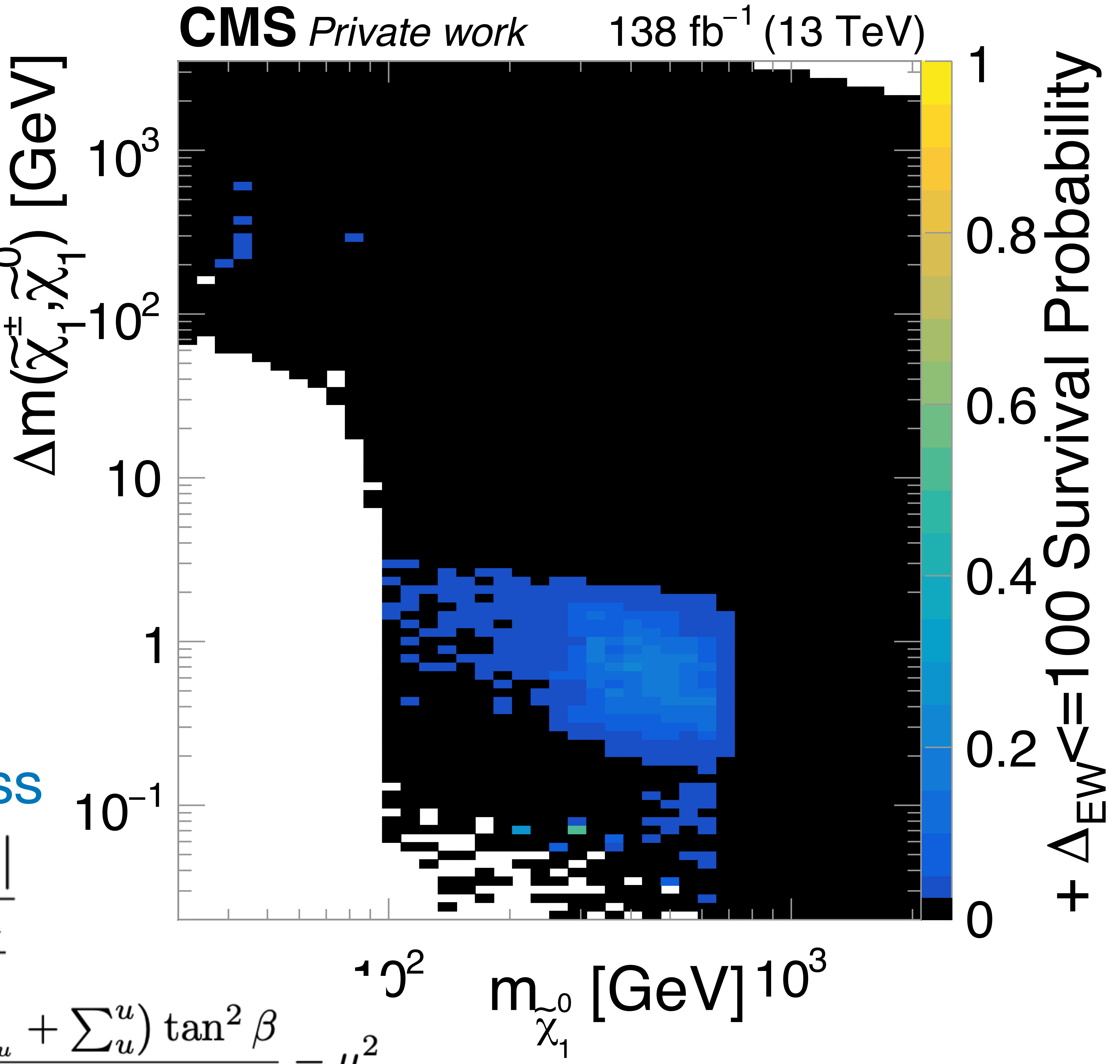


+Direct-detection XENON-1t





+Fine-tuning/naturalness

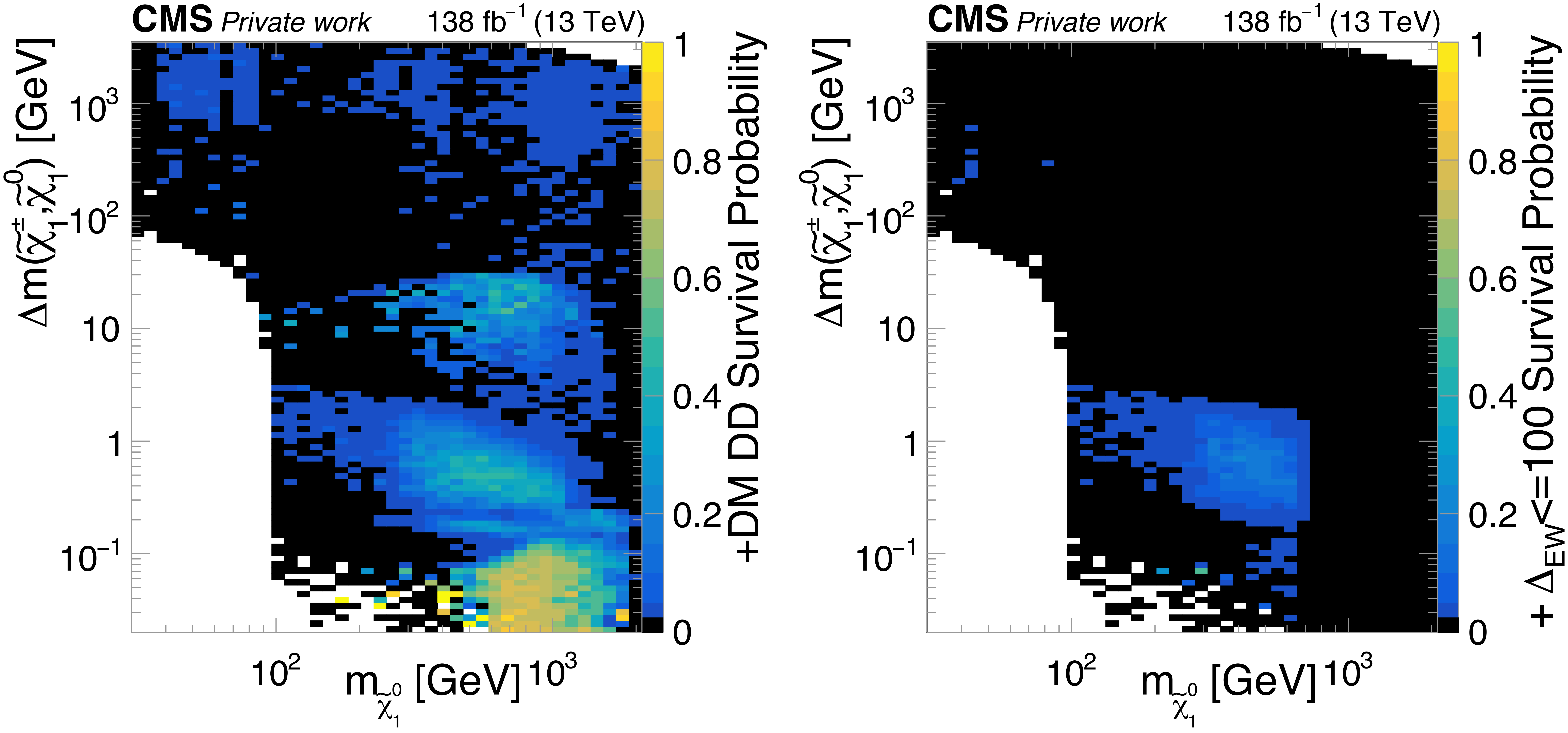
$$\Delta EW = max_i \frac{|C_i|}{\frac{m_Z^2}{2}}$$

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

SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006 + DM constraints + deltaEW<100

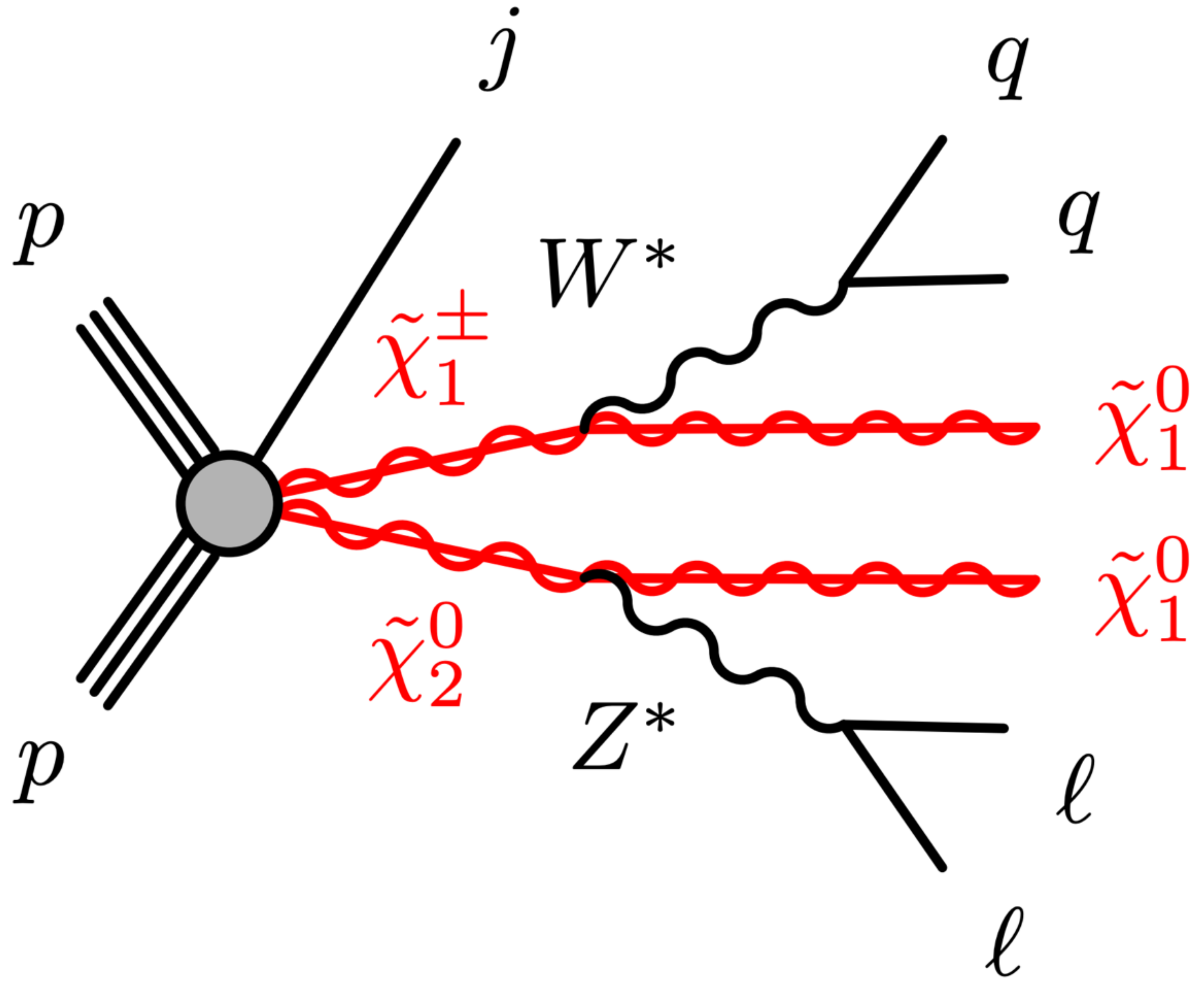
SUSY dark matter

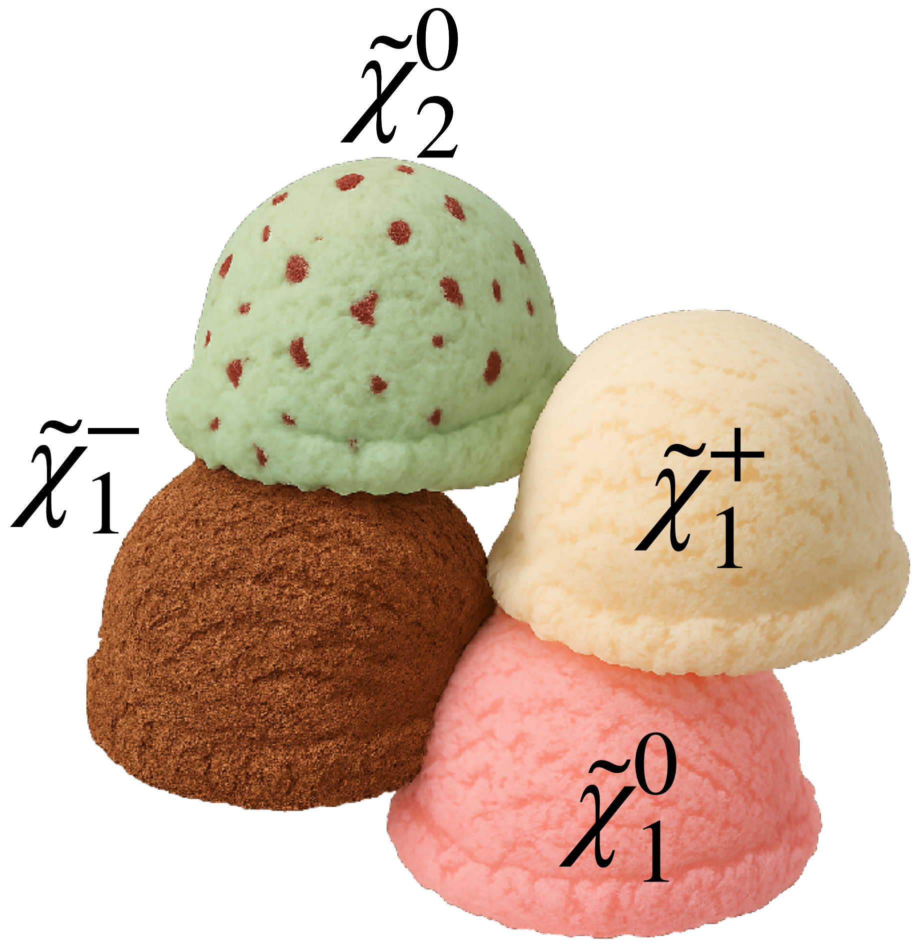
Natural SUSY dark matter

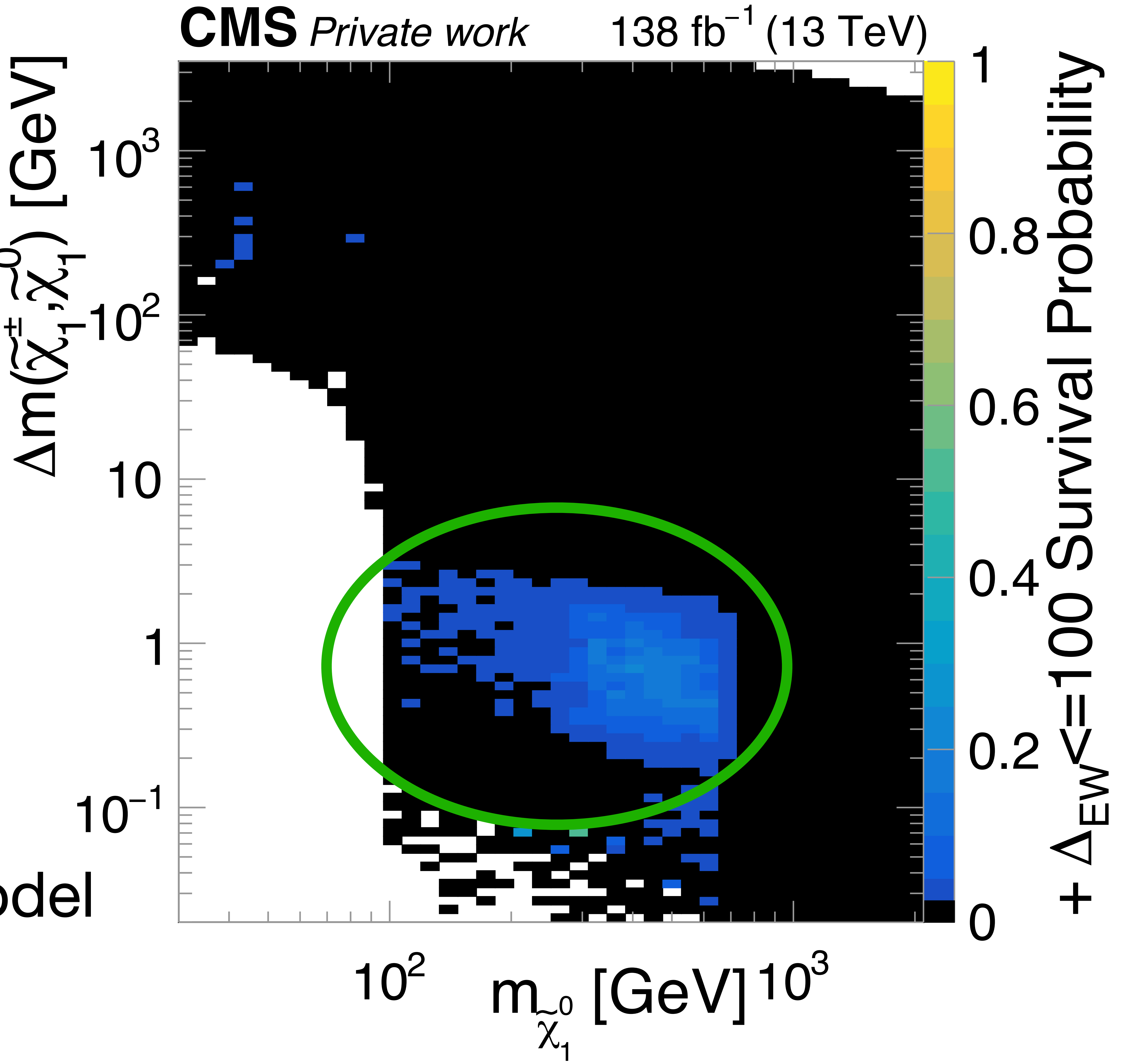


Targeting the remaining space

- Compressed Higgsinos
- $pp \to \tilde{\chi}\tilde{\chi}$ events copious



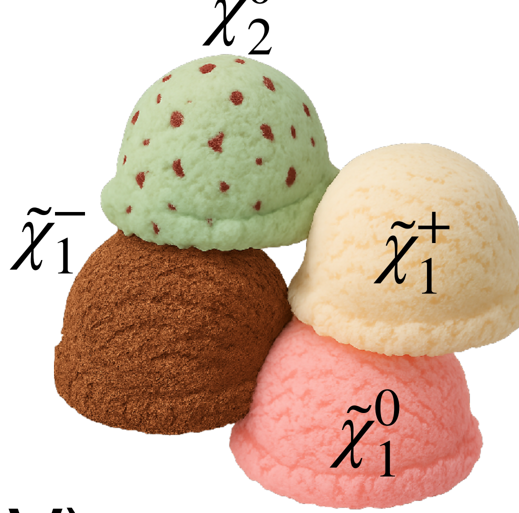




- but challenging - Adopt new simplified model
  - high-tan(beta) “sandwich model”

Satoshi Nagata, et al, “Higgsino Dark Matter in High-Scale Supersymmetry” 2015

Targeting the remaining space



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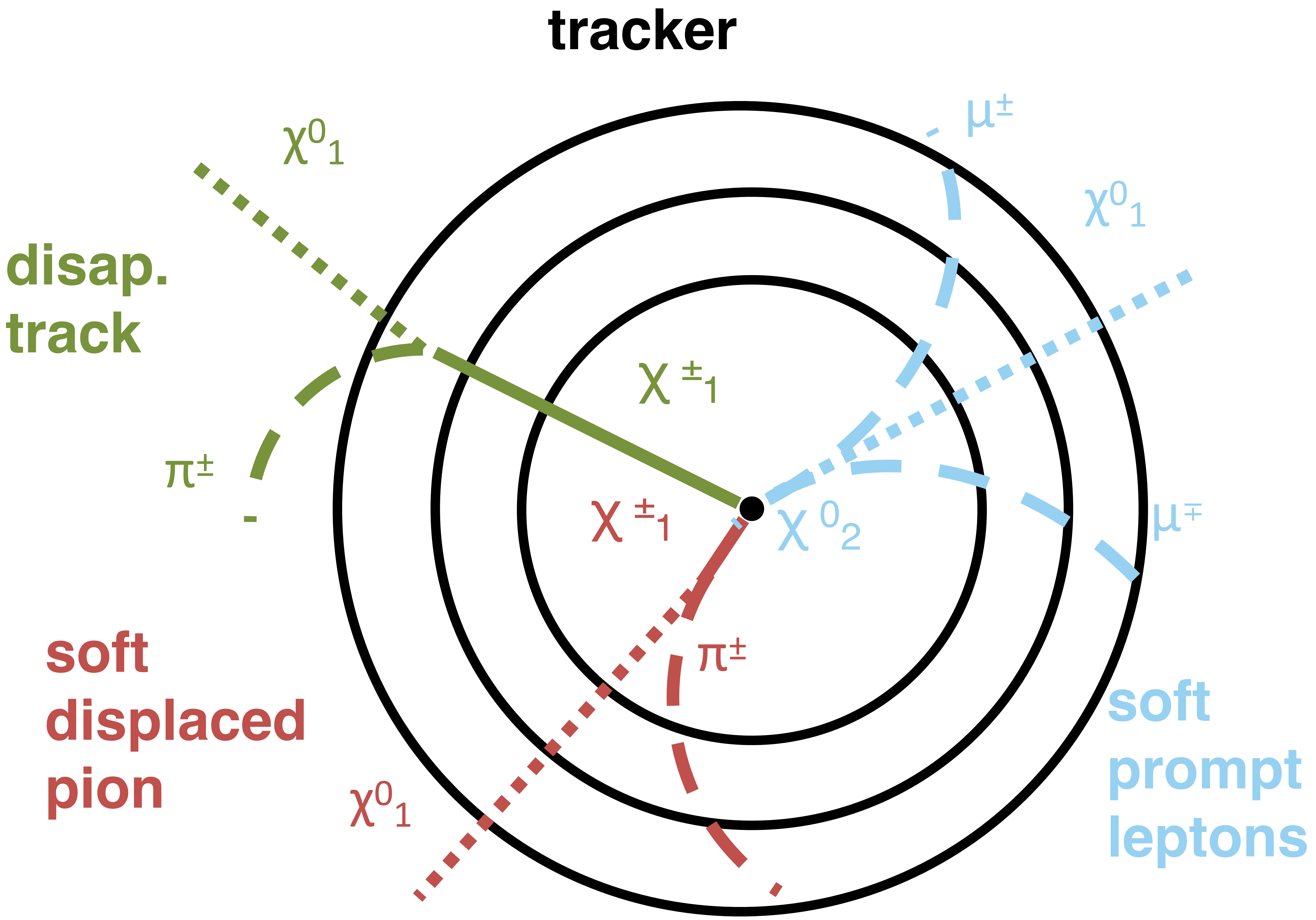
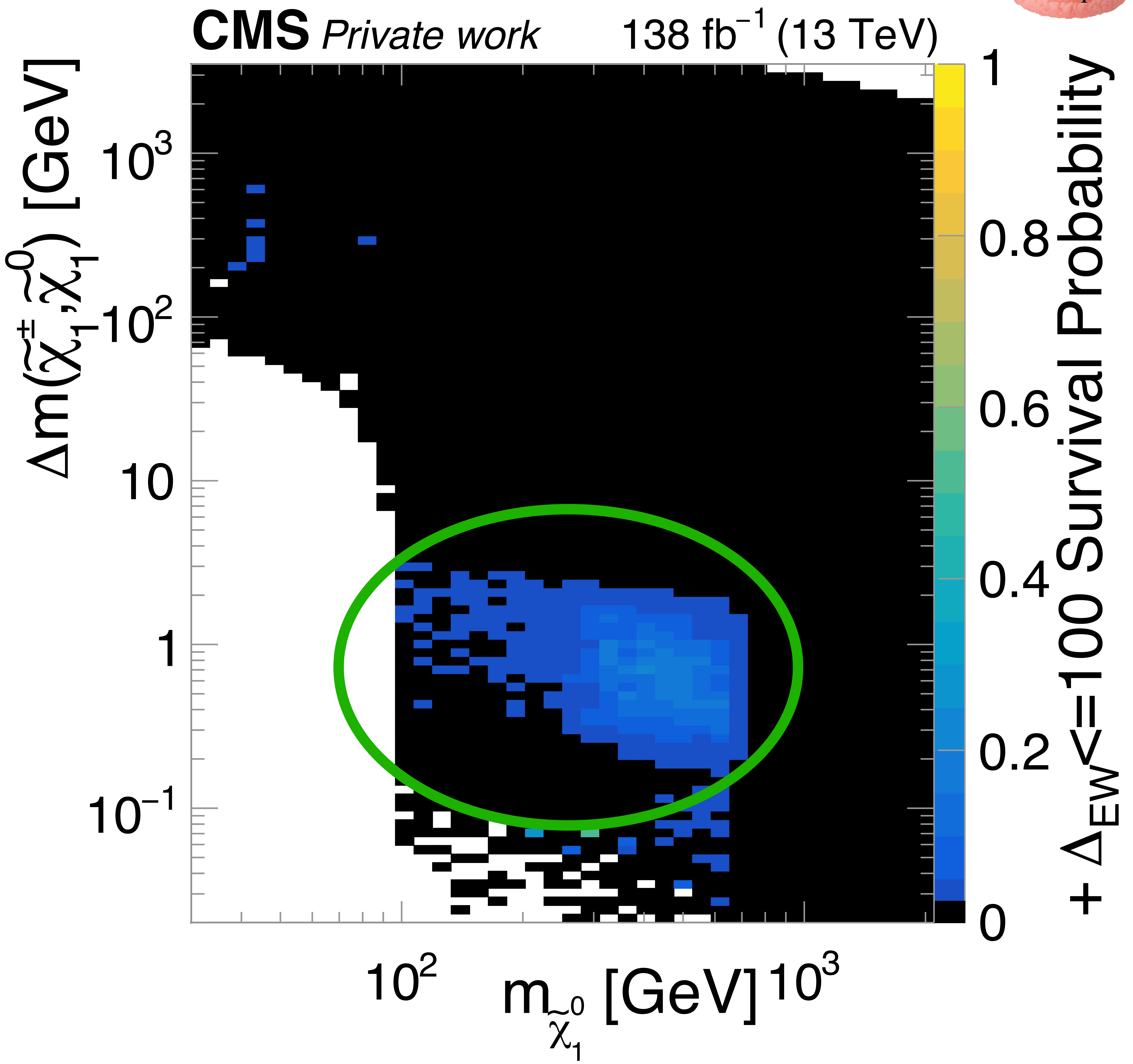
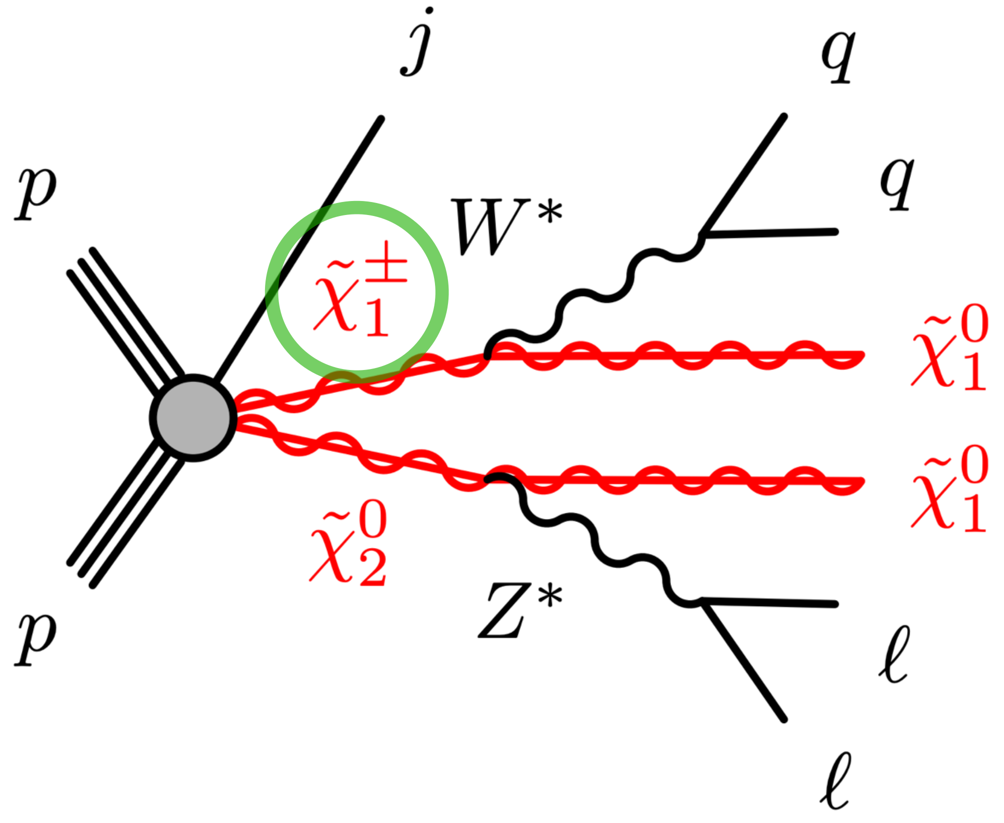


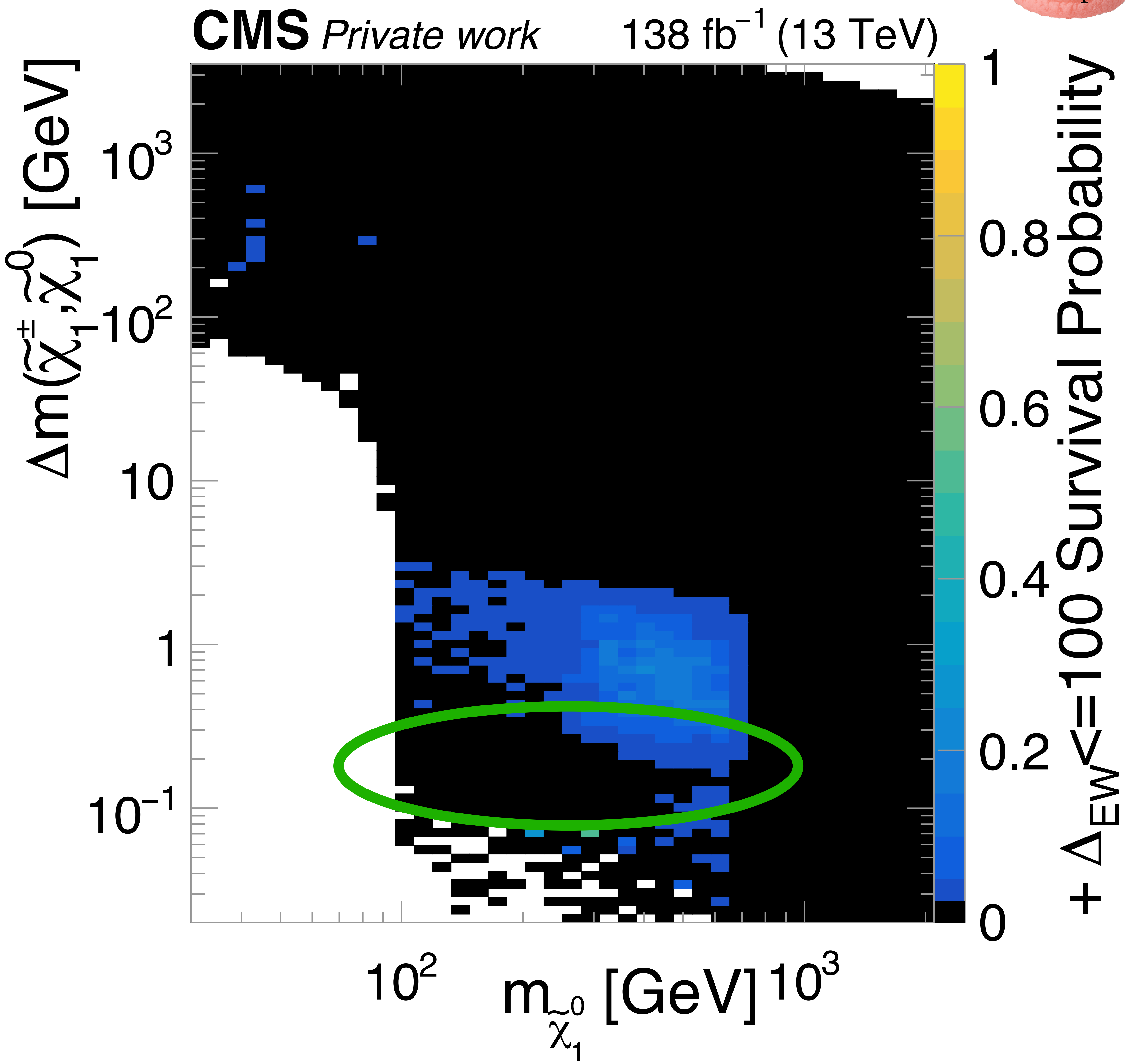


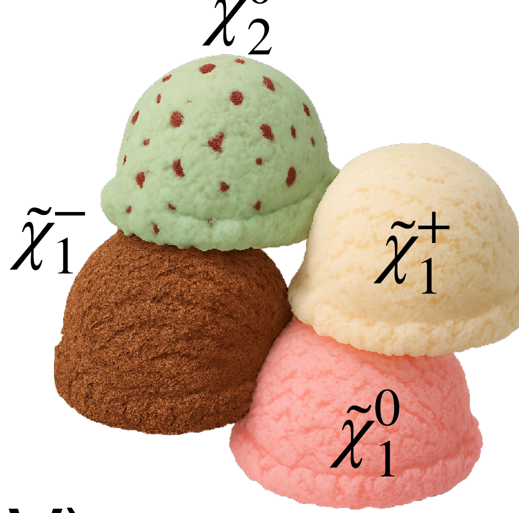
Disappearing tracks

"Search for supersymmetry in final states with disappearing tracks in proton-proton collisions at 13 TeV," CMS Collaboration; arXiv:2309.16823

Viktor Kutzner







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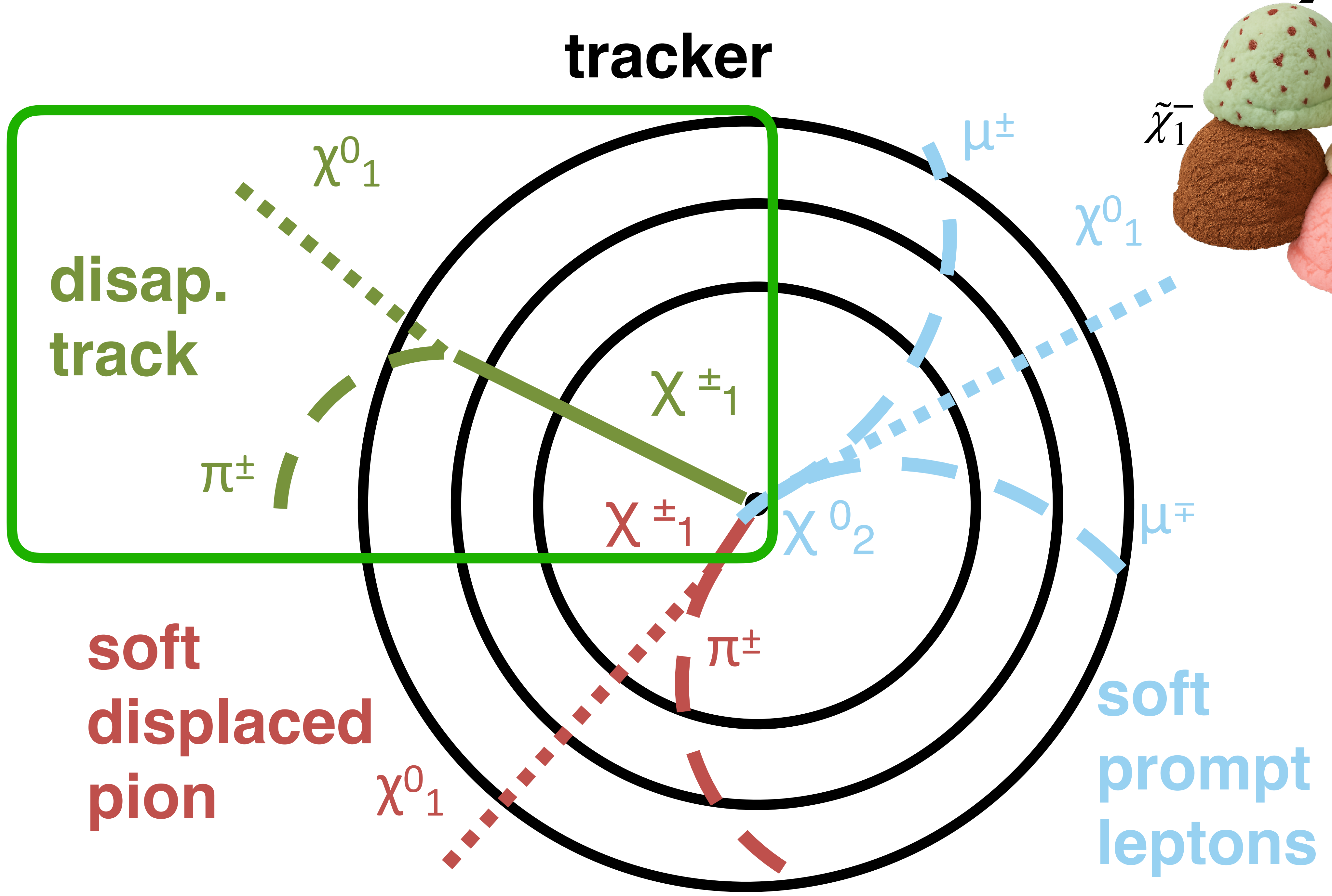
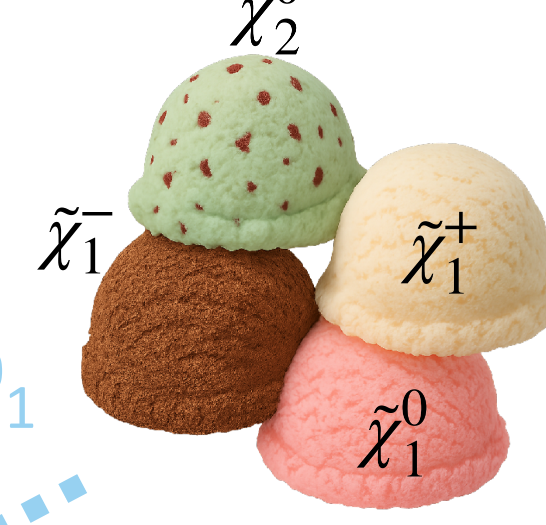
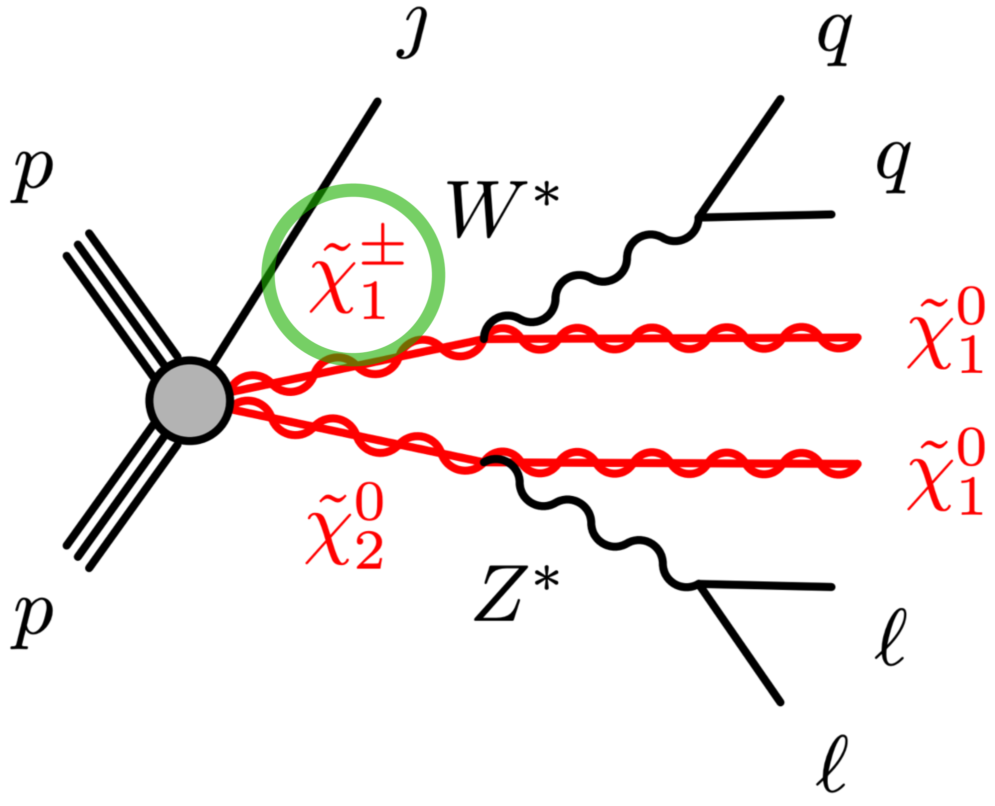
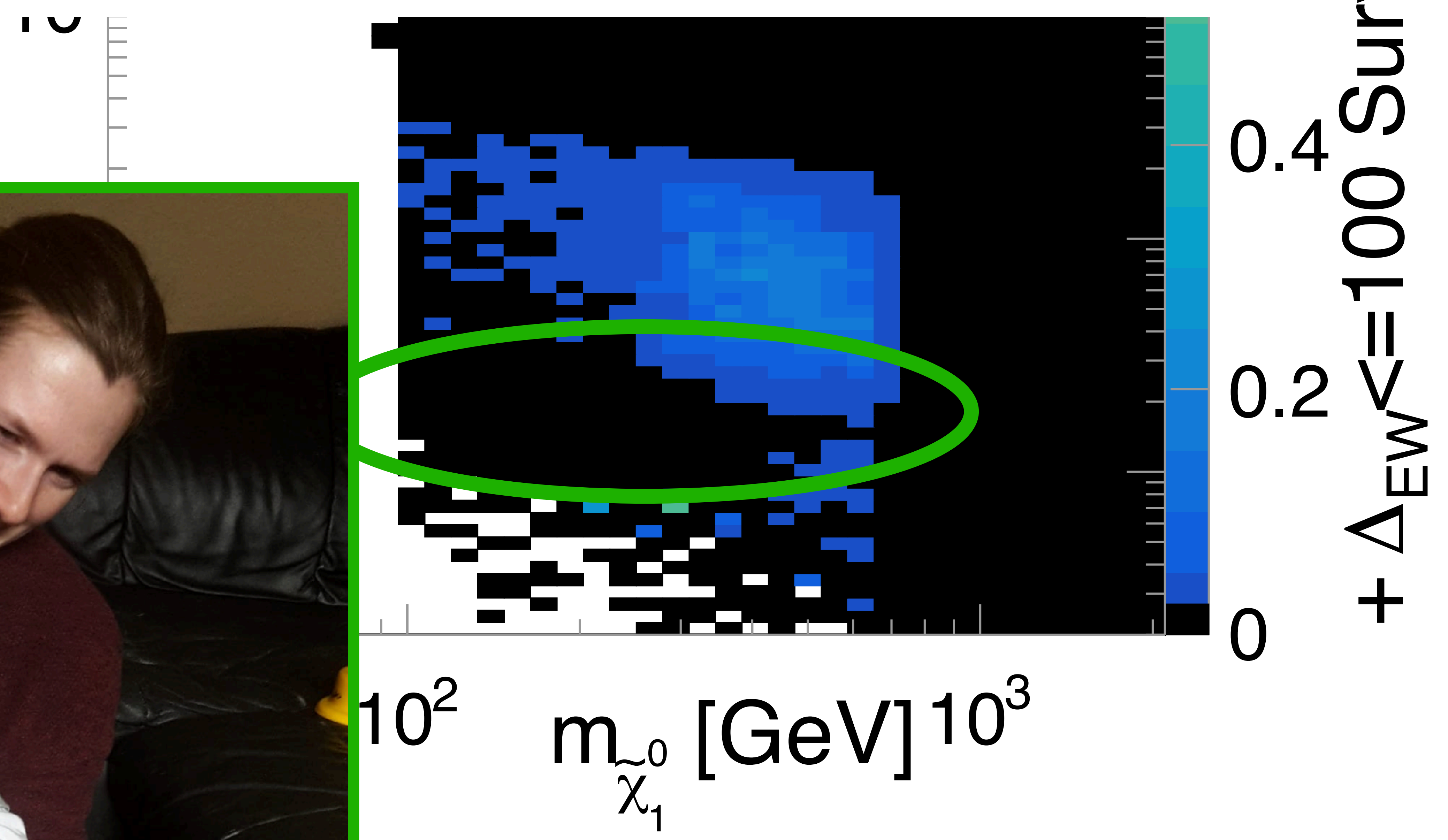






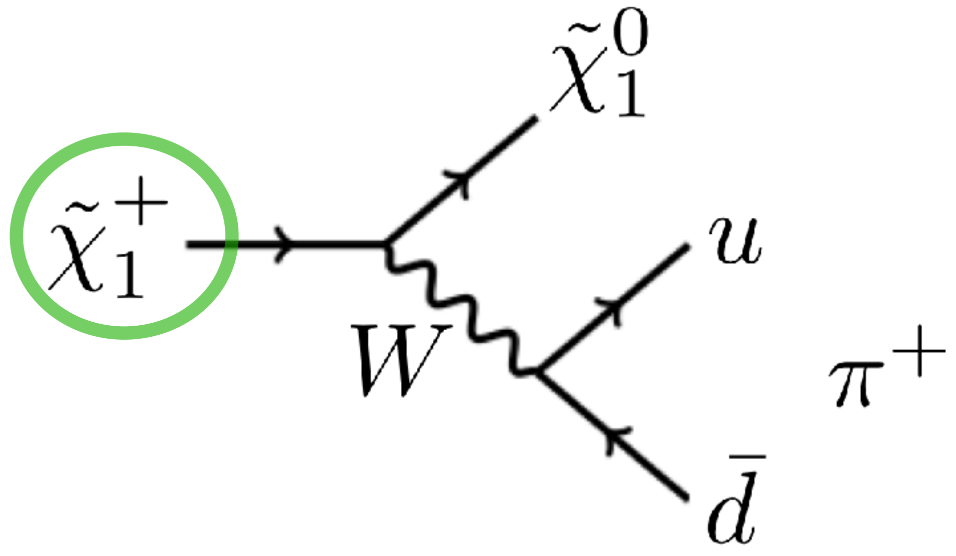


Viktor Kutzner

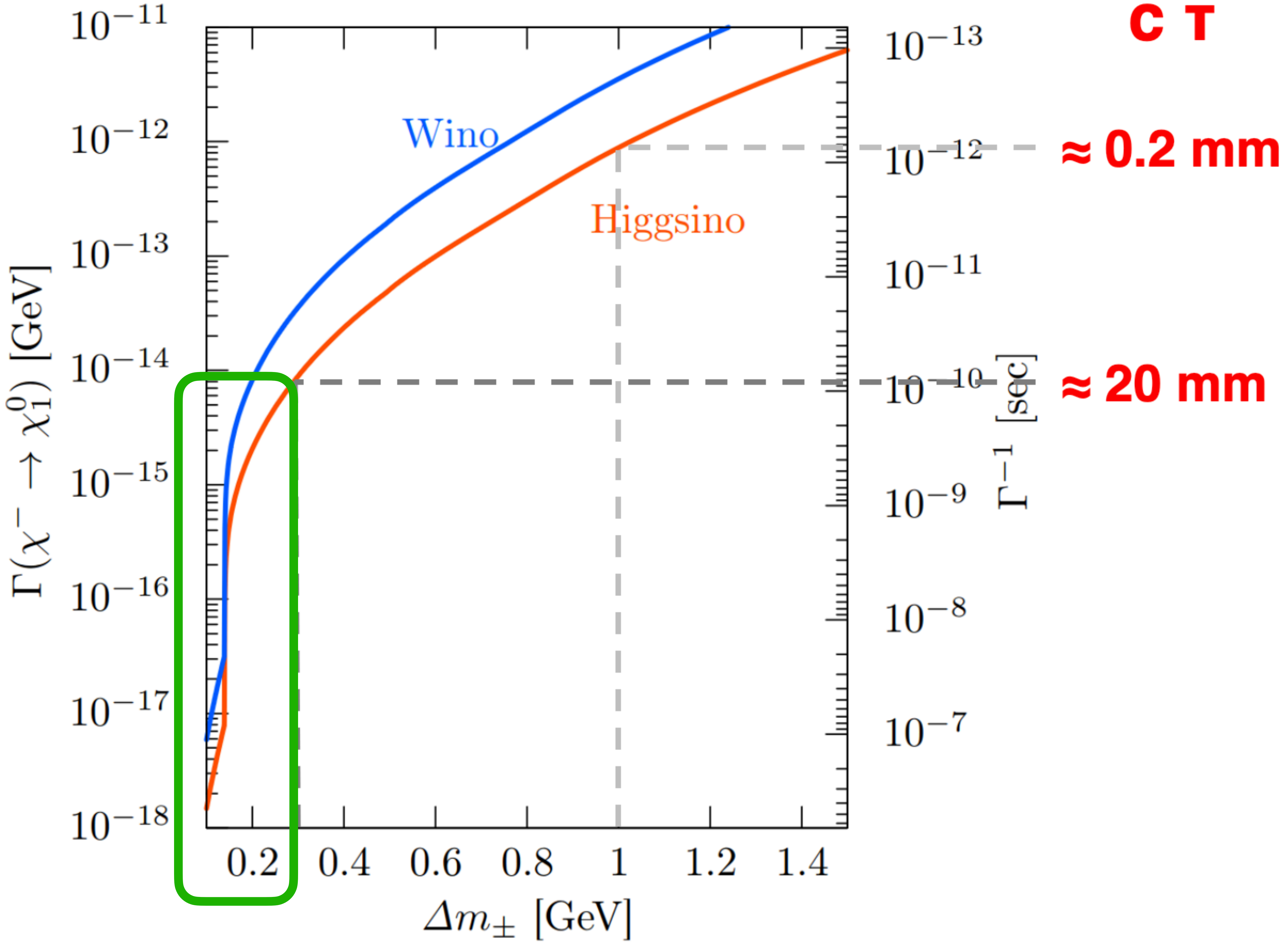
Akshansh Singh

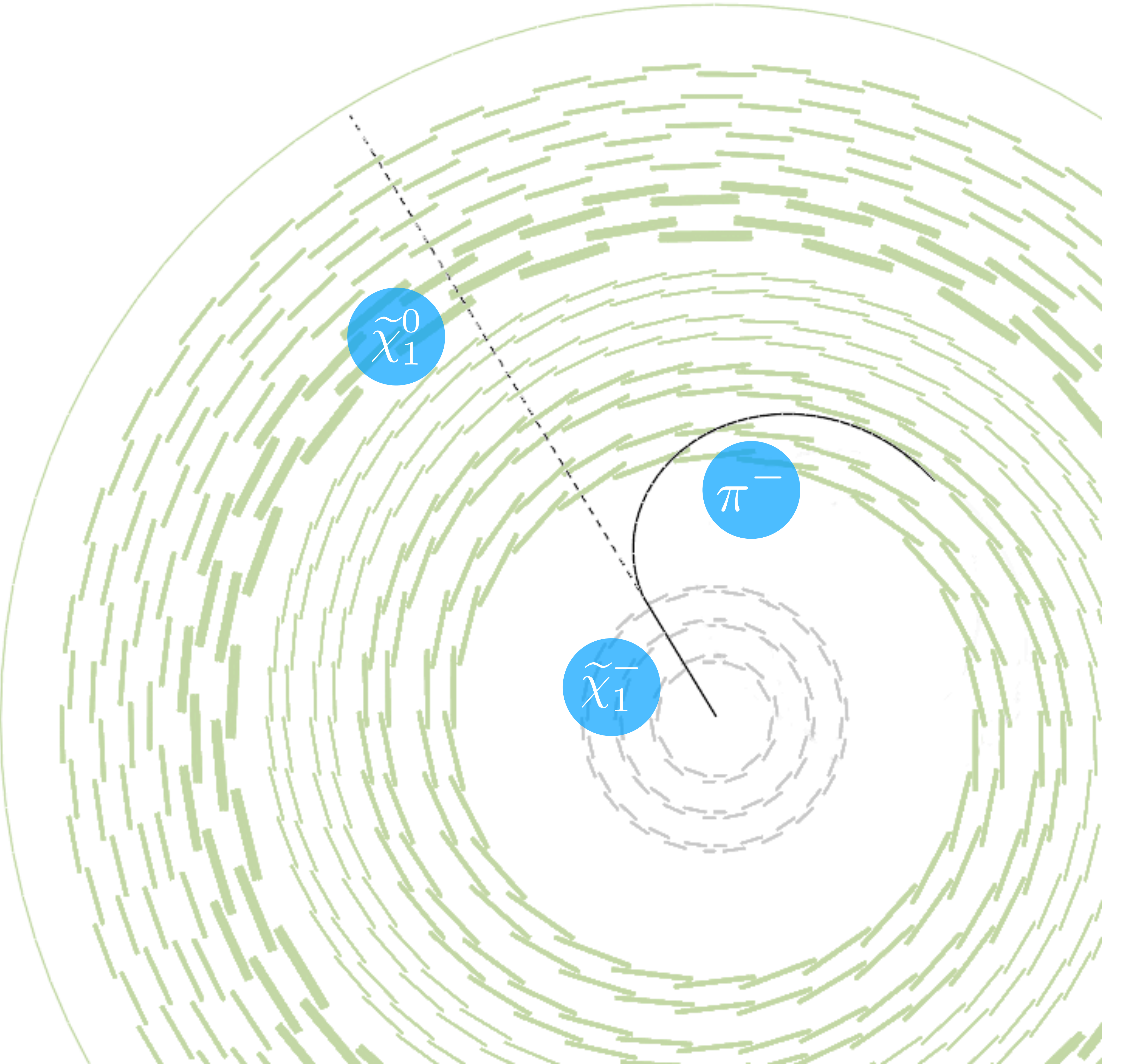
Alexandra Tews

Disappearing tracks

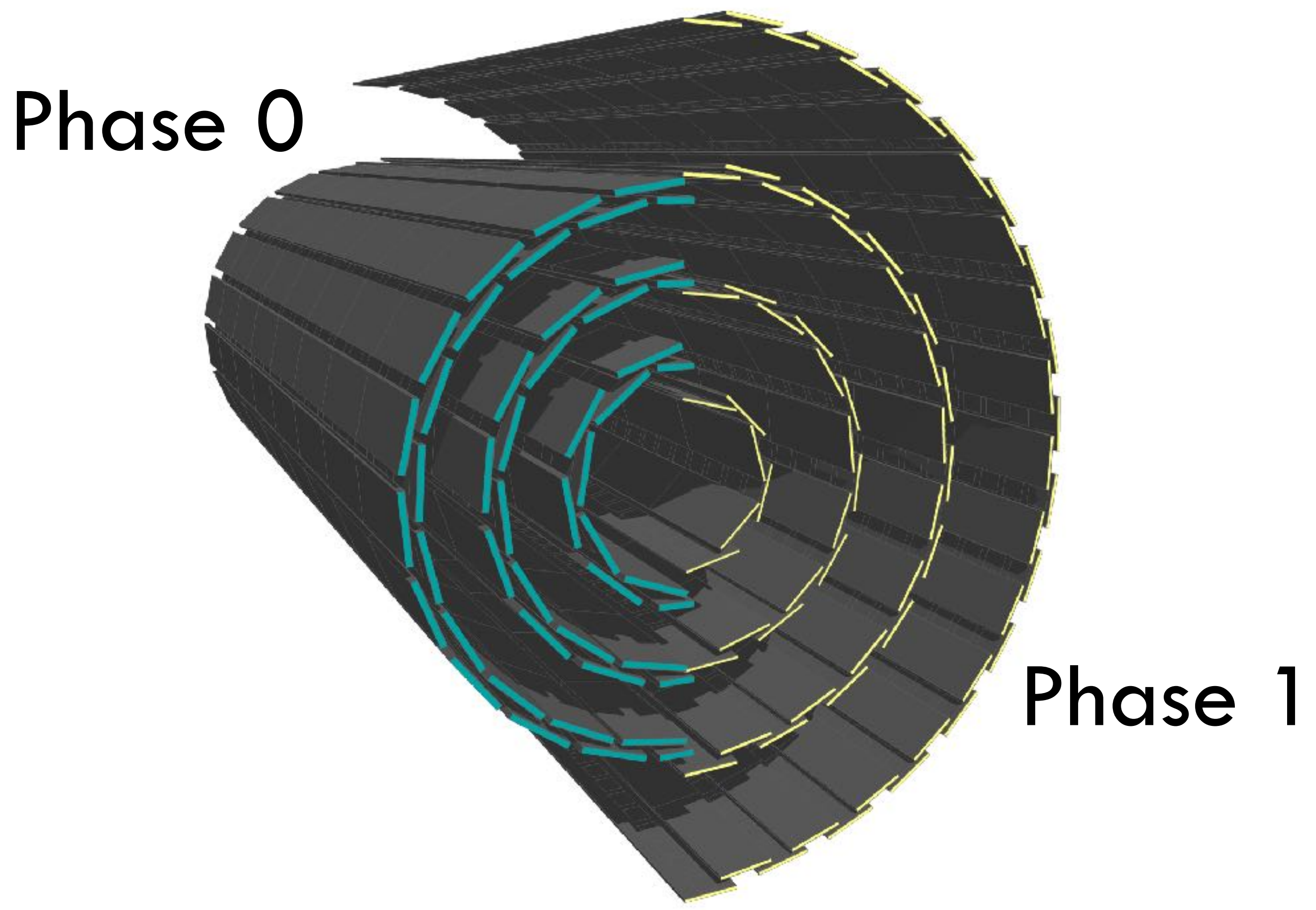


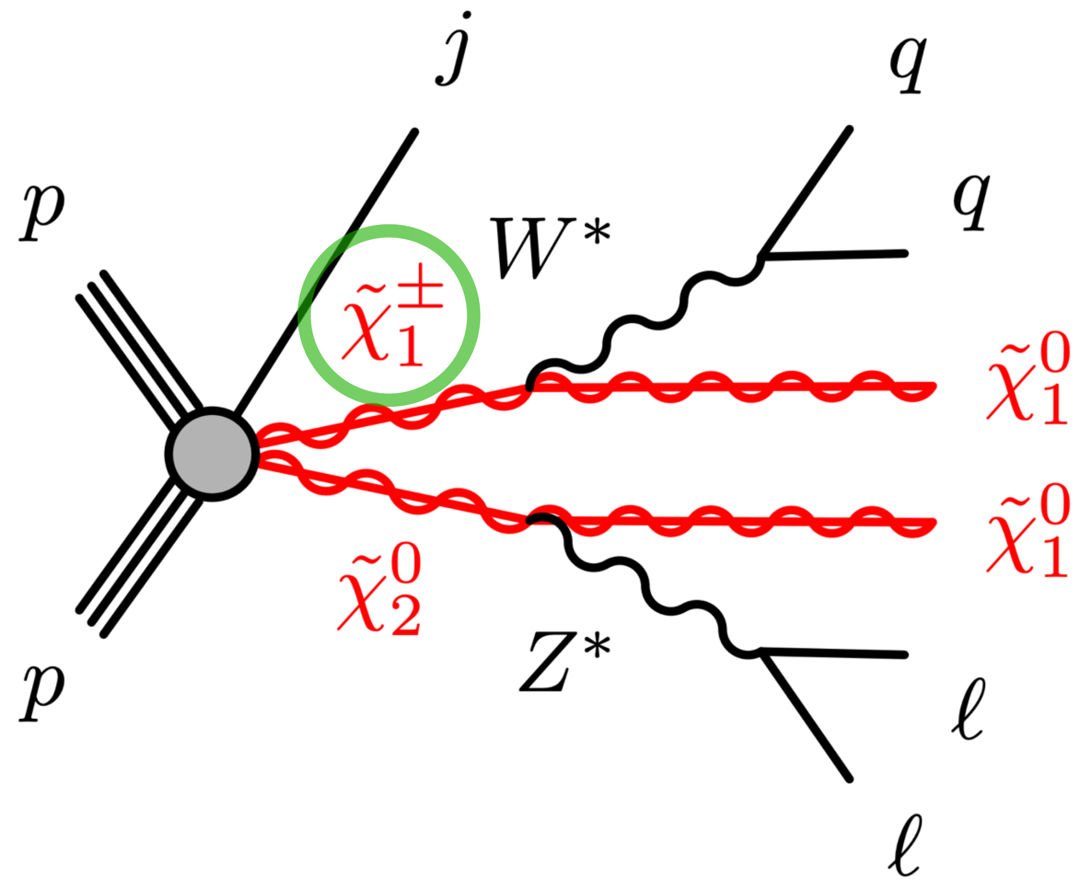
- Chargino produced at the pp vertex
  - $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ < 300 MeV
  - $c\tau(\tilde{\chi}_1^\pm)$ < 7 cm
- Soft pion caries away charge





Reconstruct chargino

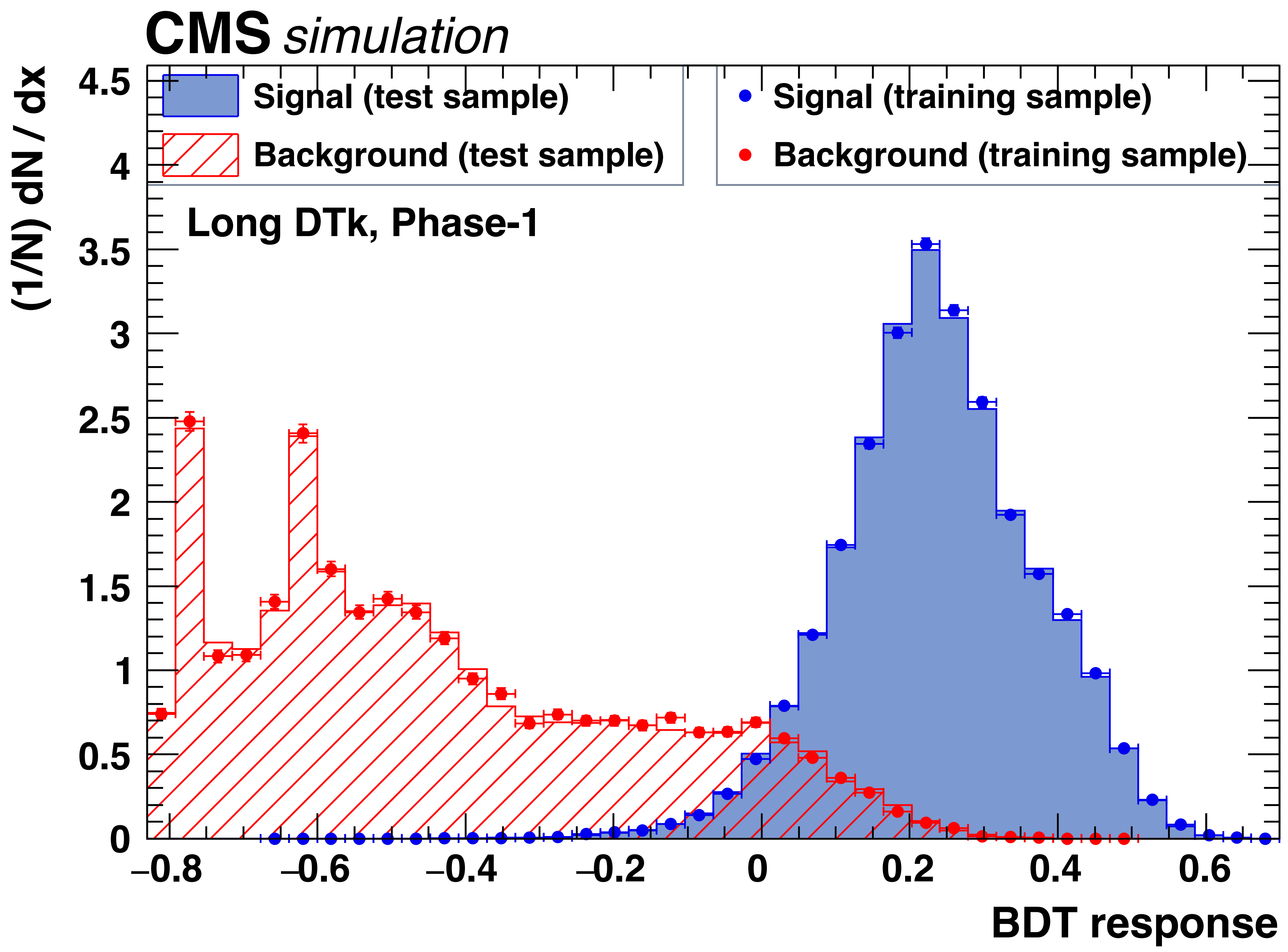




Directly reconstruct $\tilde{\chi}_1^\pm$ as track with

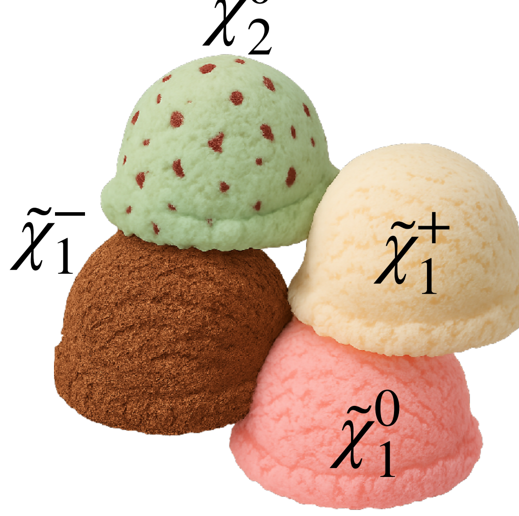
- track p_T > 25 GeV, isolation
- small impact parameter <0.1cm
- **missing outer hits -** disappearing!
- **E_{dep} < 15 GeV**

$\tilde{\chi}_1^\pm$ decay length $c\tau$	short tracks	long tracks	μ-matched tracks	
$\tilde{\chi}_1^\pm$ mass	high dE/dx	low dE/dx		
$\tilde{\chi}_1^\pm$ production mechanism	N_{jet}	$N_{b\text{-}tag}$	hard p_T^{miss}	N_{lep}



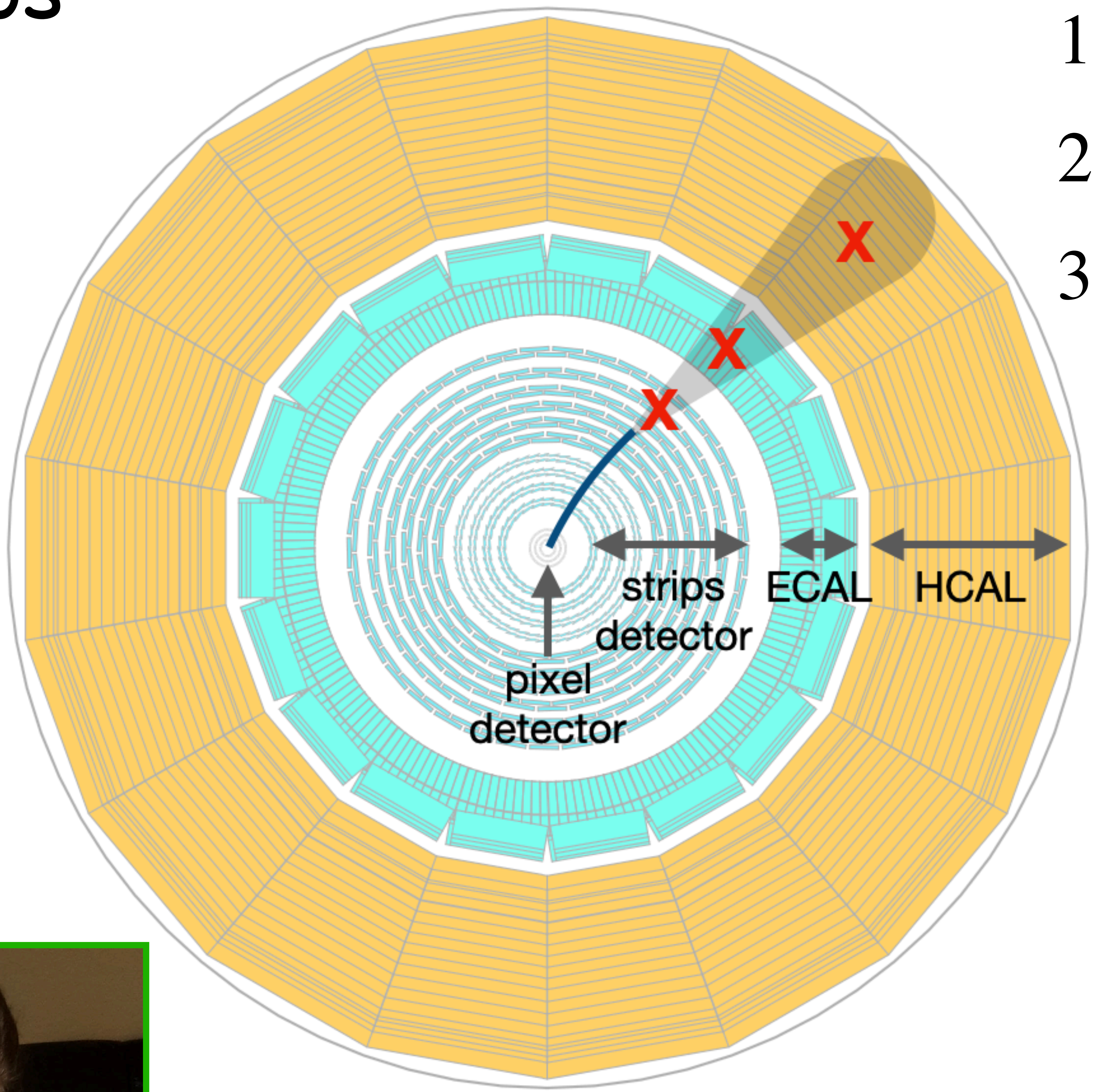
- Track selecting BDT

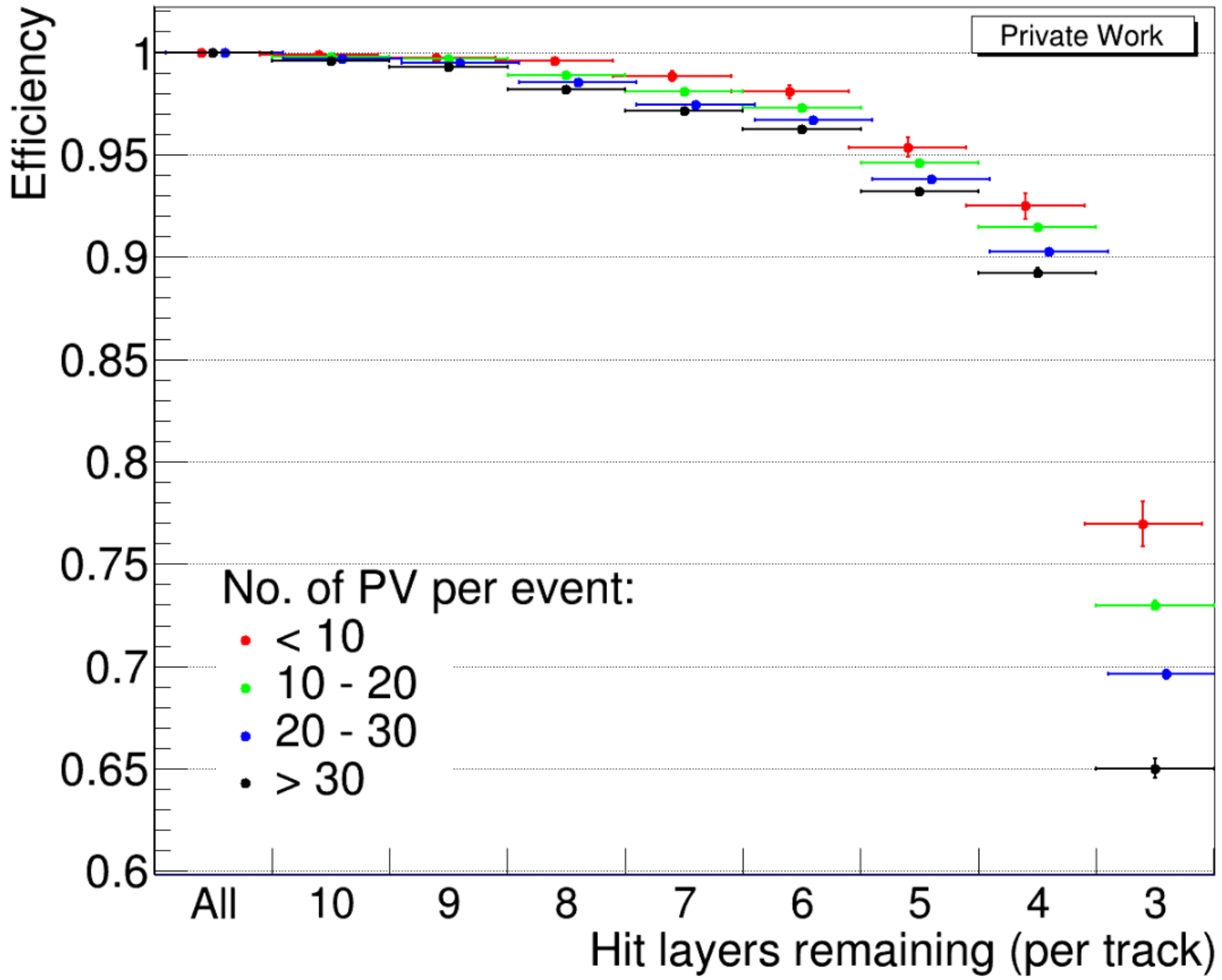
Data proxy for long-lived charginos



"Creating" a chargino in data

1. Identify well-reconstructed muon
2. Remove outer hits from raw data
3. Run full reconstruction

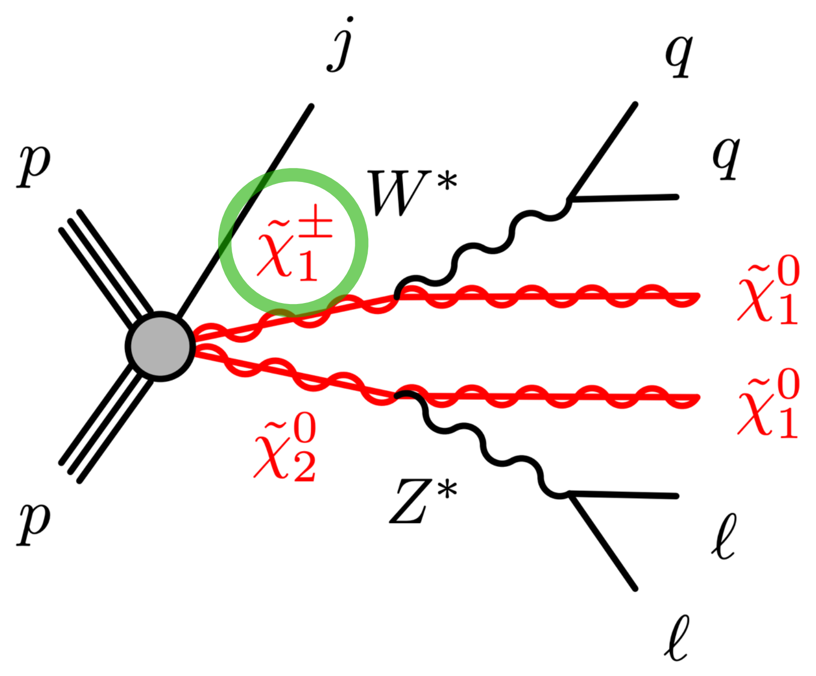


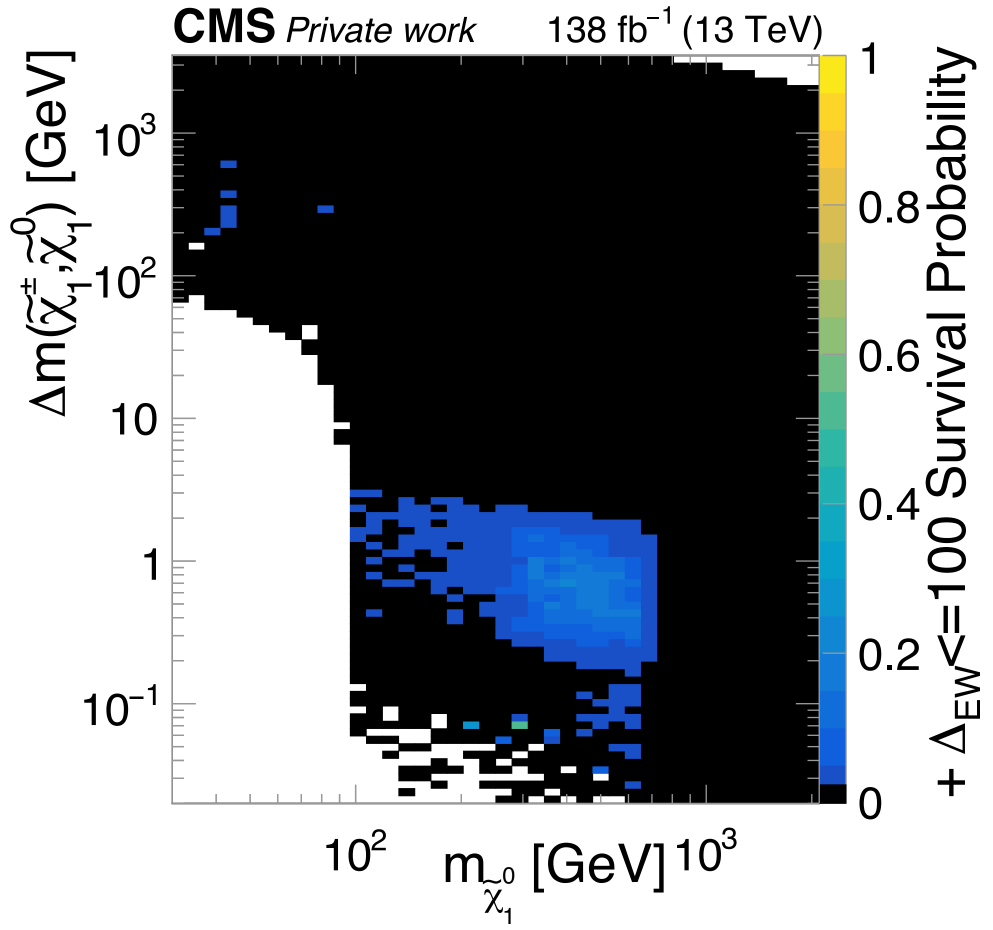


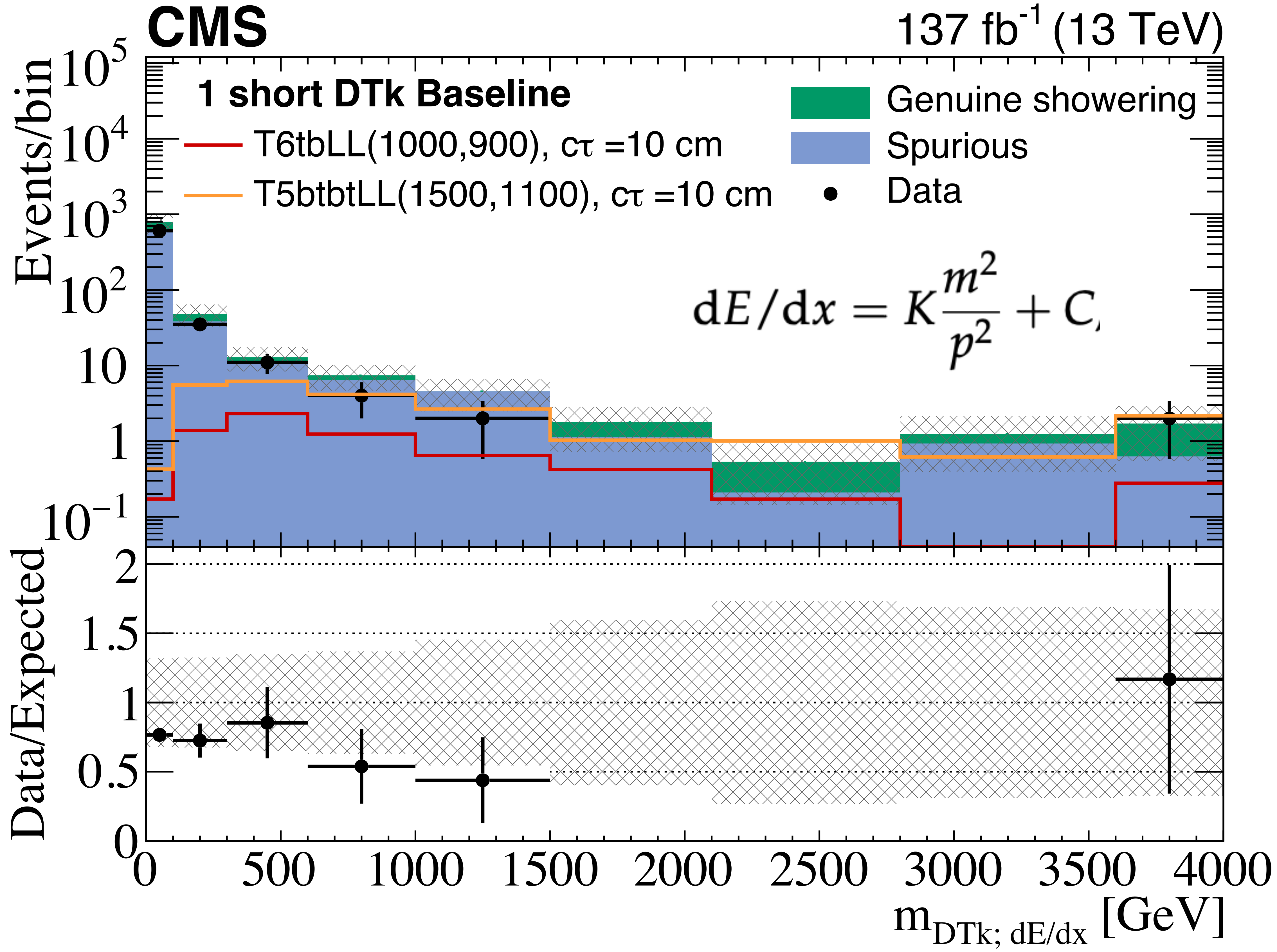
Compare data and simulation for systematics

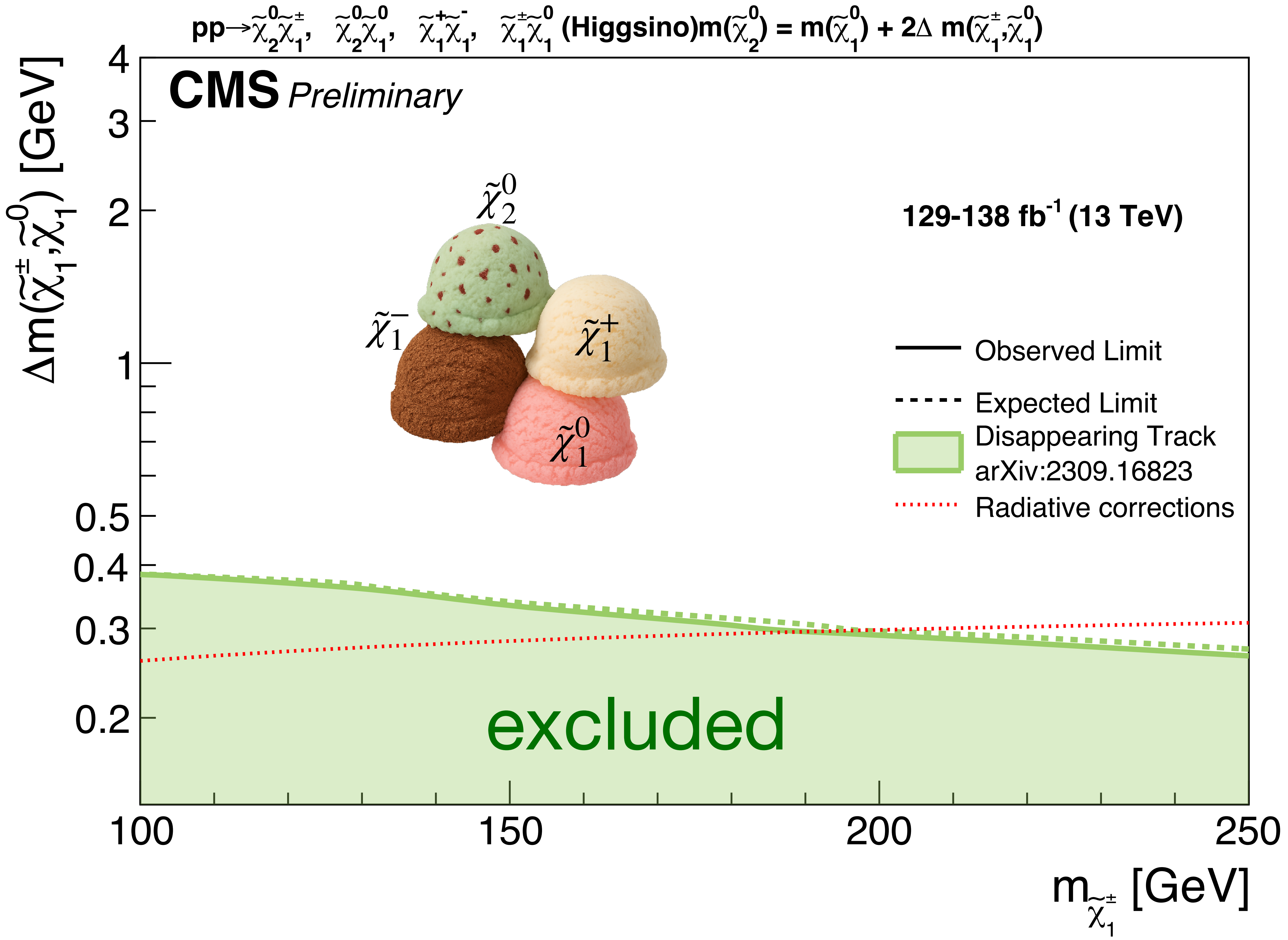
Disappearing results and limits

- Mass from track p and dE/dx
  - Calibrated with $\Lambda^0 -> \text{(soft) } p^{\pm}\pi^{\mp}$







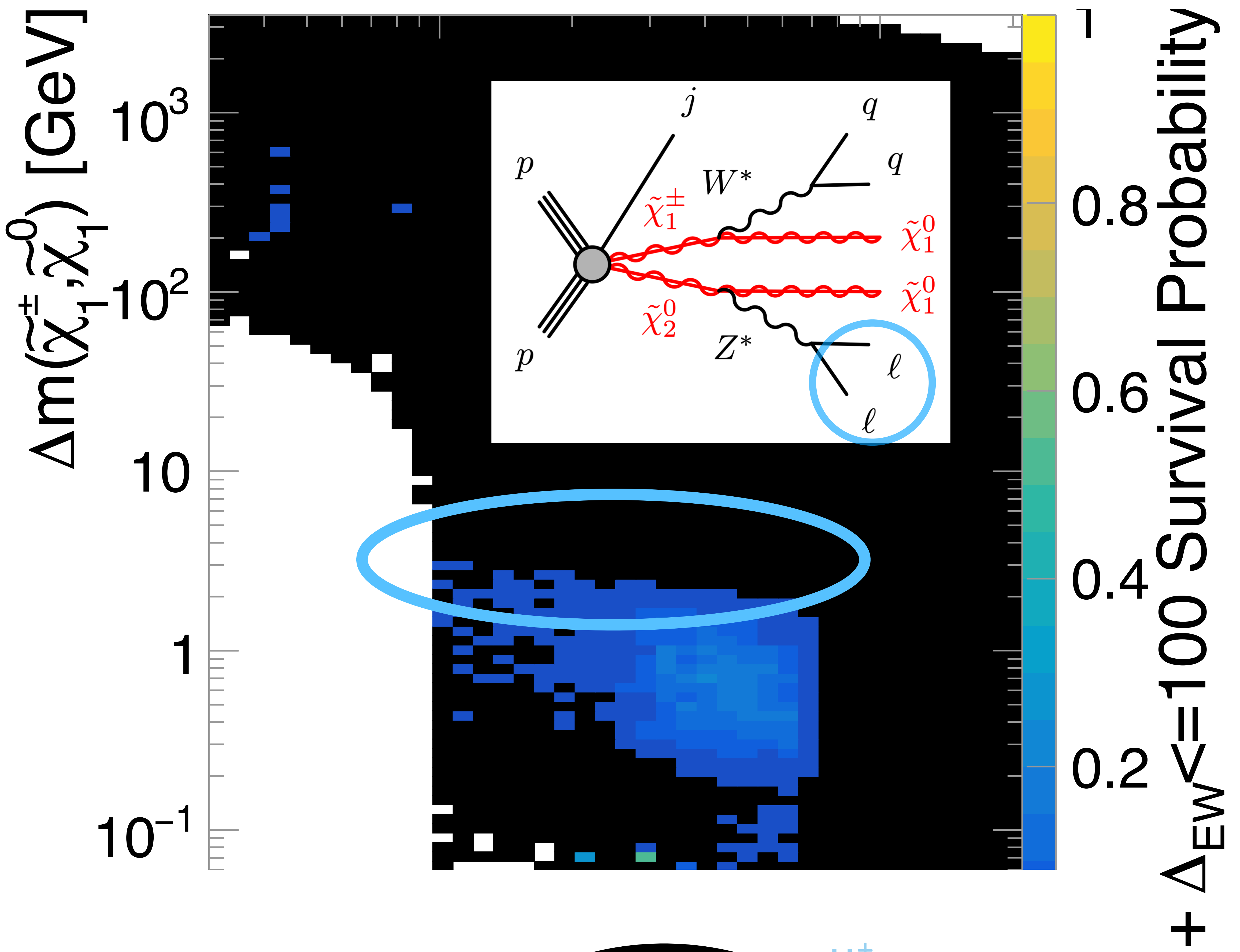


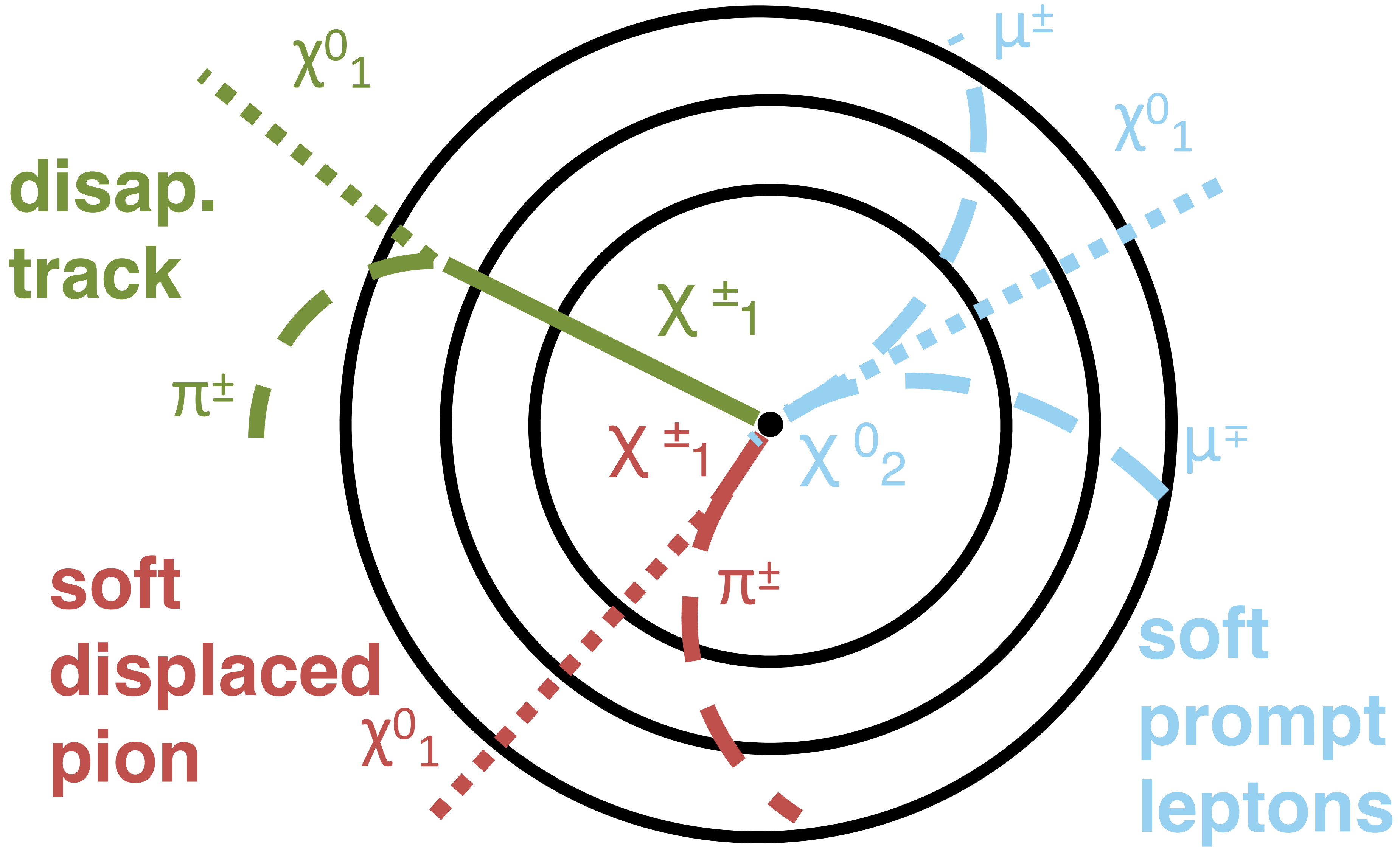
"Search for supersymmetry in final states with disappearing tracks in proton-proton collisions at 13 TeV," CMS Collaboration; arXiv:2309.16823

Targeting $\tilde{\chi}_2^0 \to \ell\ell\tilde{\chi}_1^0$

"Search for Higgsinos in final states with low-momentum lepton-track pairs with CMS at 13 TeV," CMS collaboration; CMS-SUS-24-003.Published: 14 May, 2025.

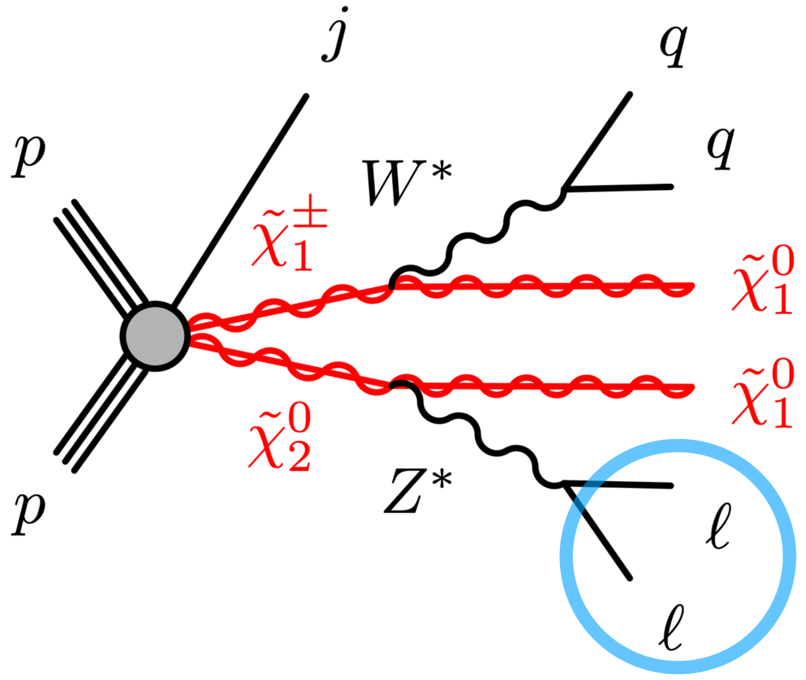
Yuval Nissan

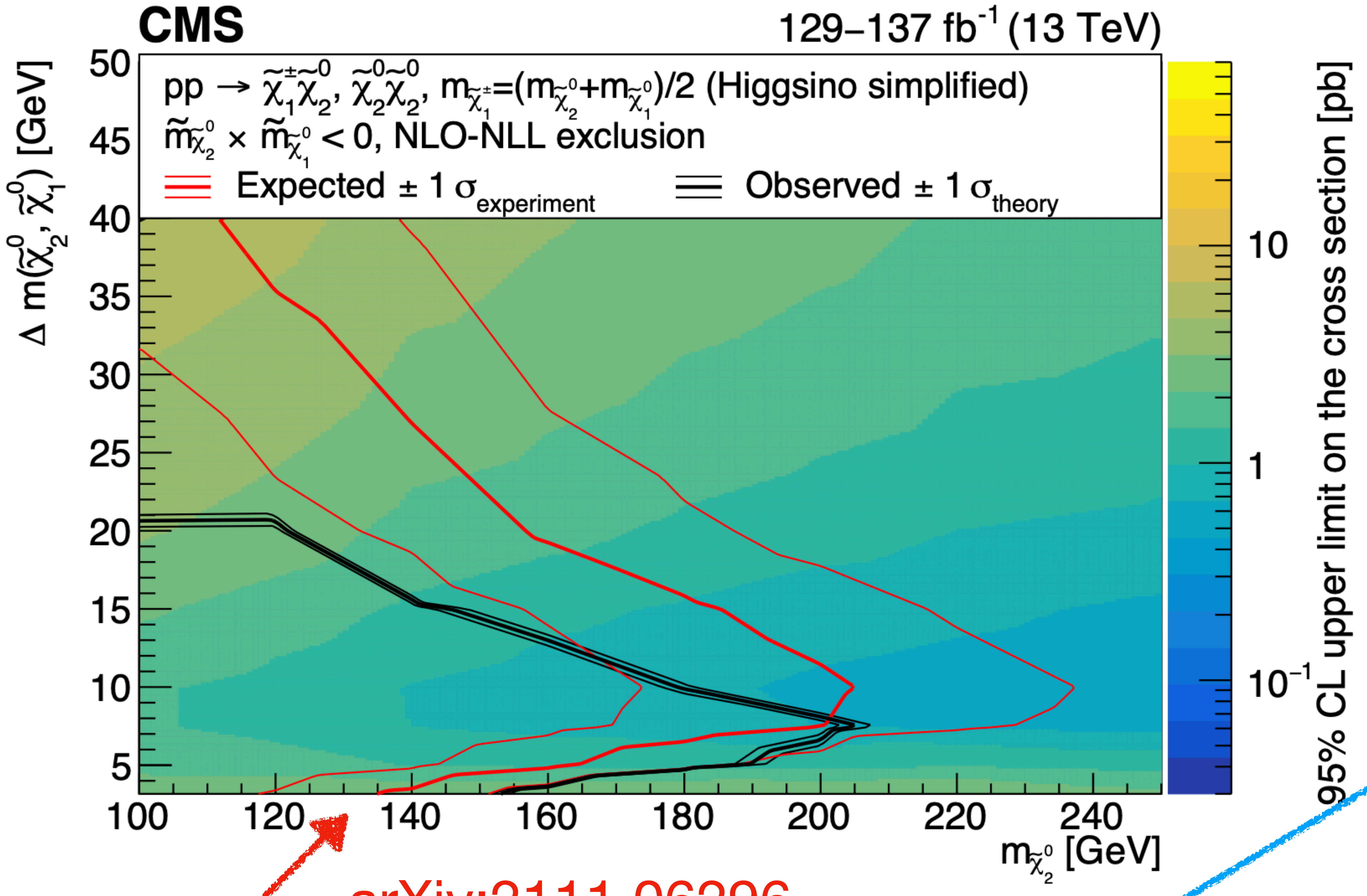




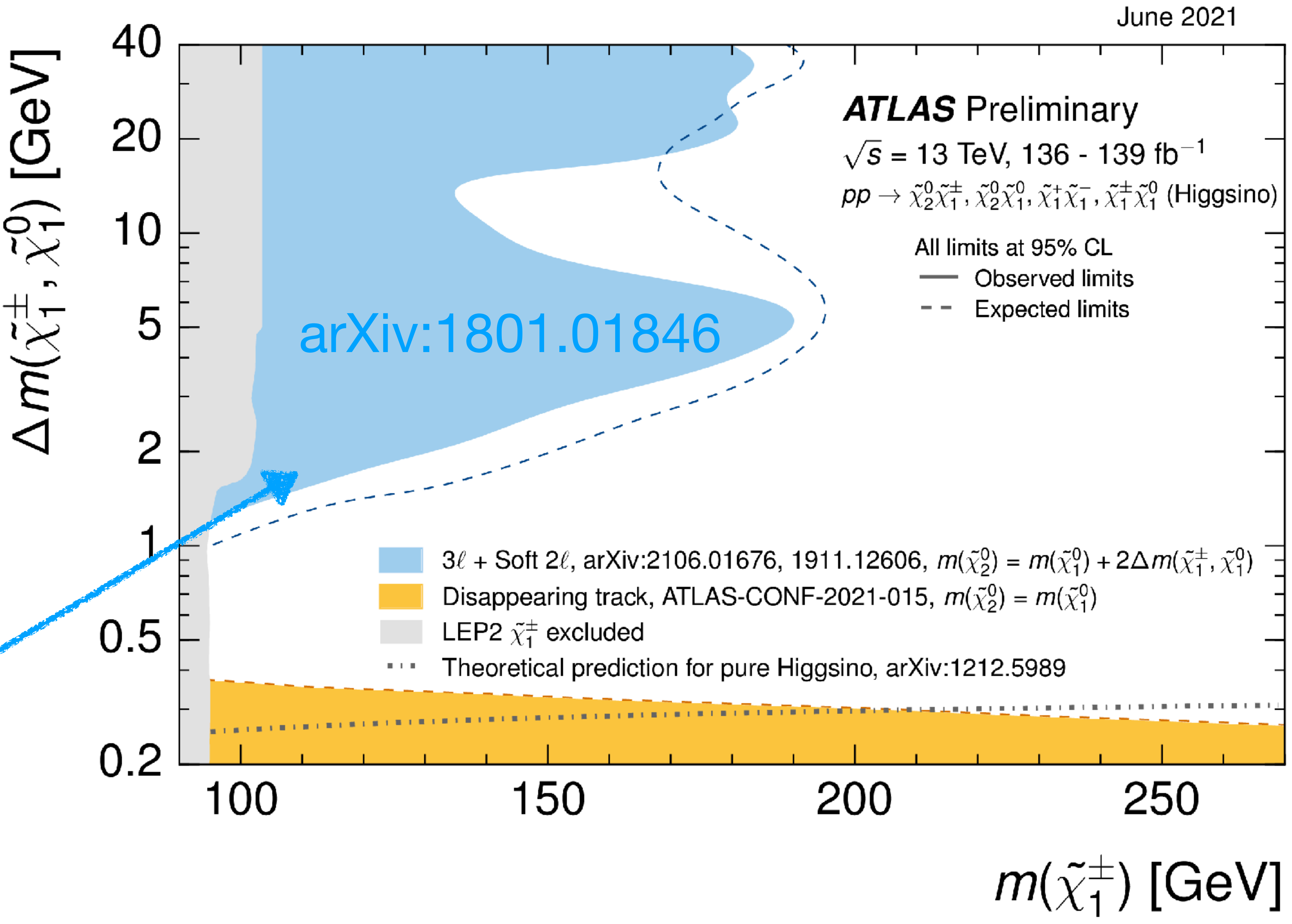
Past dilepton analysis

- SUS-18-004 analysis requires 2 leptons with have $p_T^\ell > 3.5\,GeV$ and $\Delta R > 0.3$
- SUS-24-003 ensures independence: muon $p_T^\ell \leq 3.5\,GeV$ OR $\Delta R \leq 0.3$



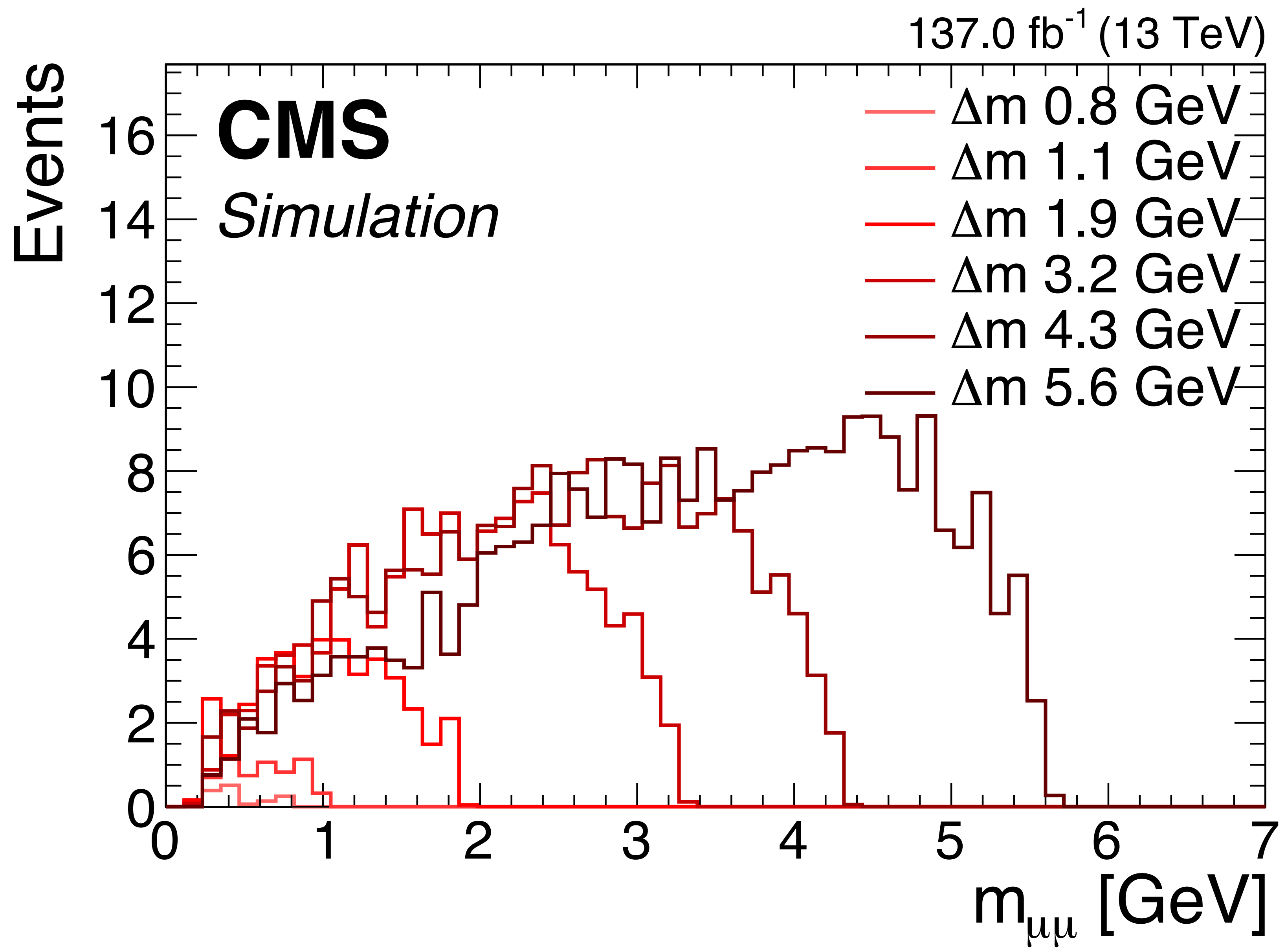


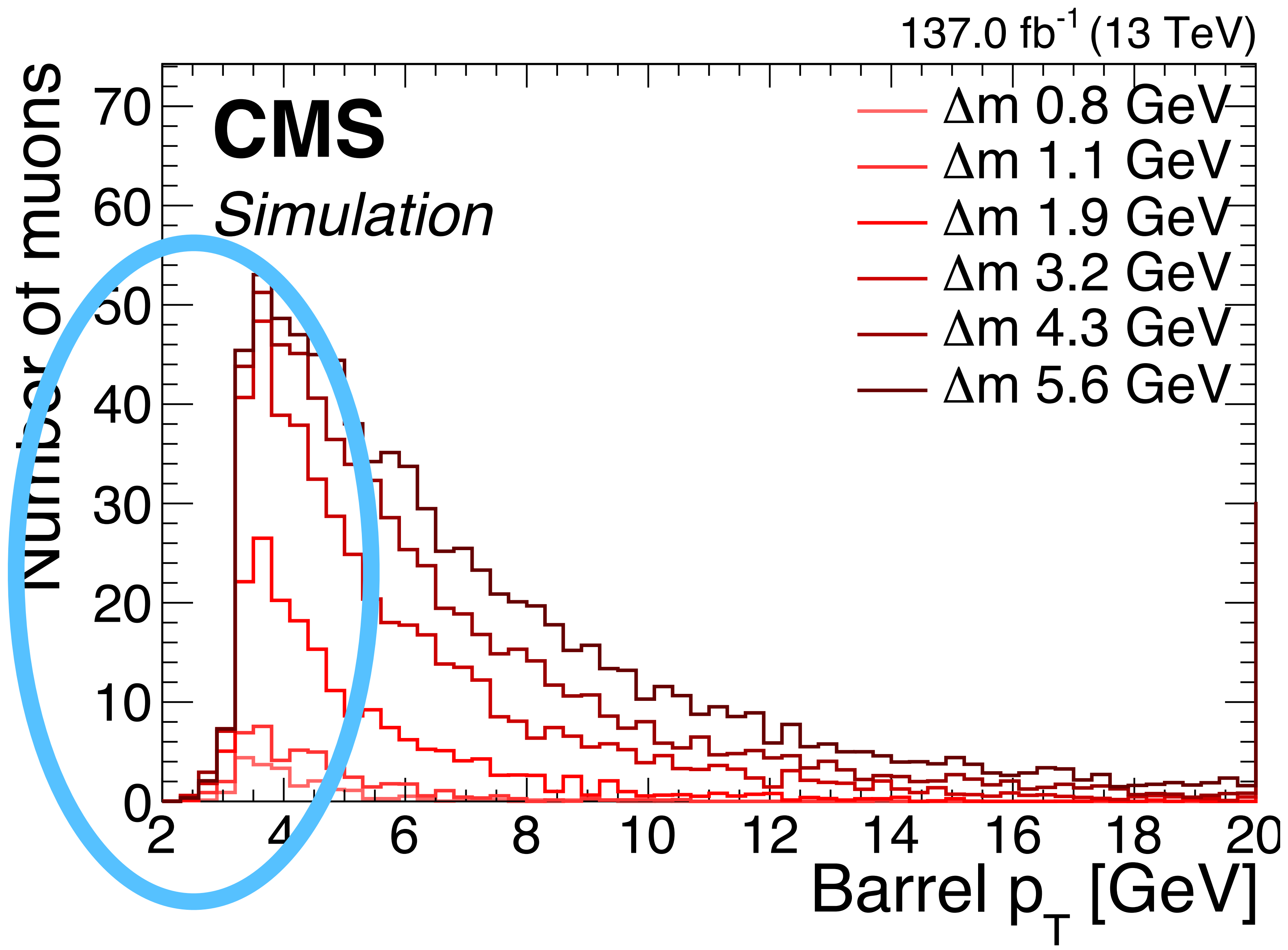
arXiv:2111.06296
(SUS-18-004)

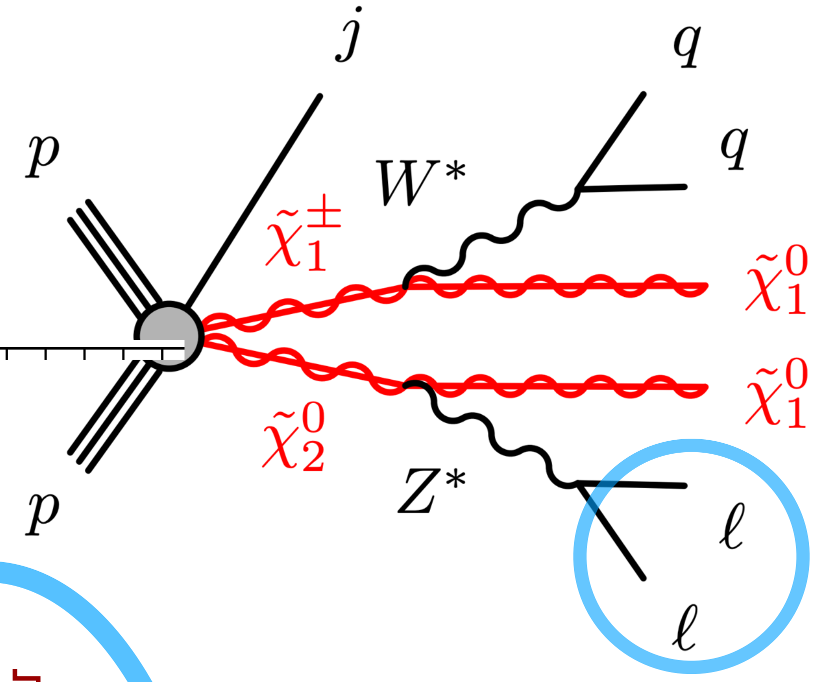


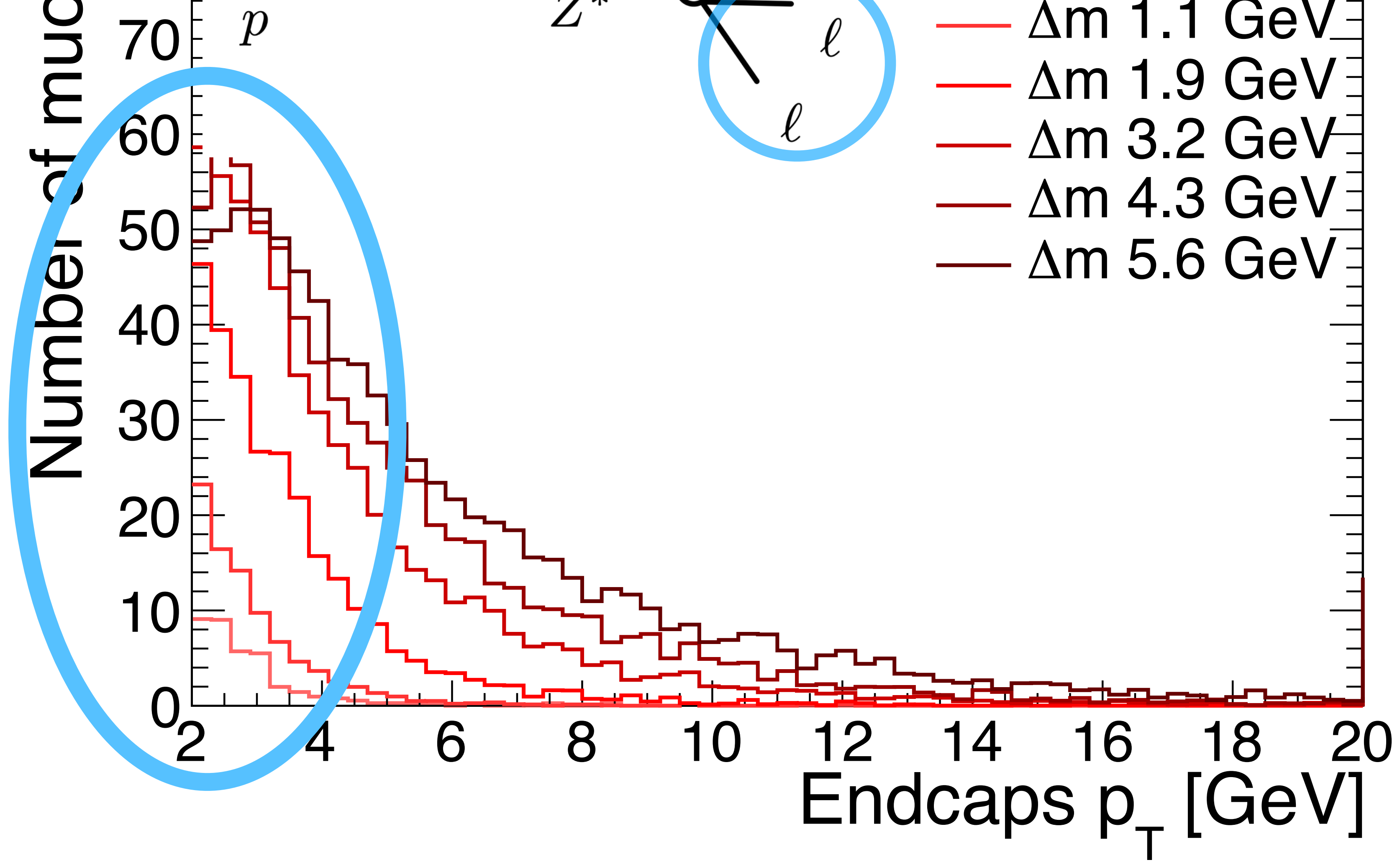
target $\Delta m^0 \in [1,5]\,GeV$

Signal kinematics

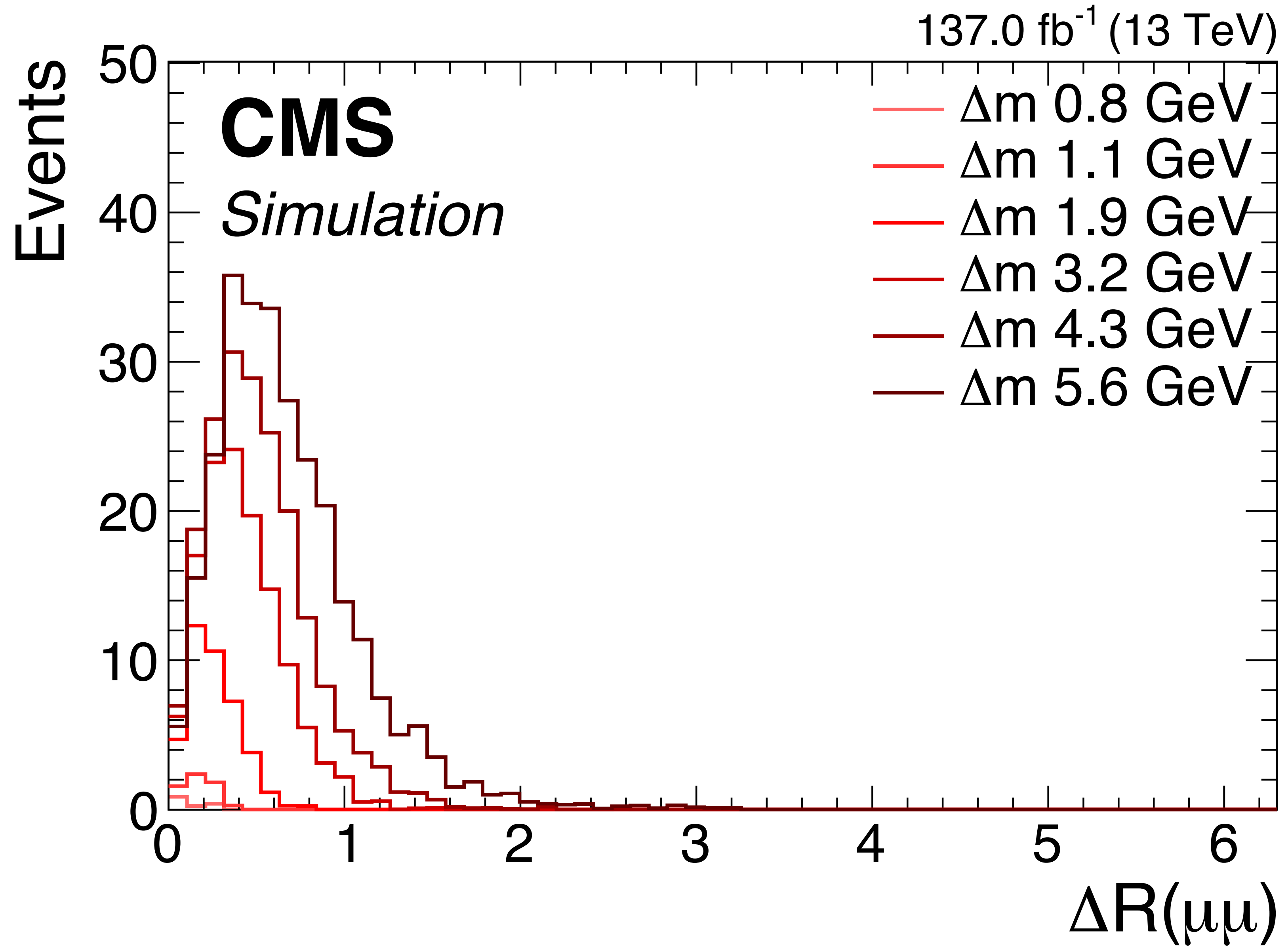








- lower p_T with smaller Δm
- endcaps retain muons below 3 GeV while barrel does not
- ΔR peaks at lower values
- add track + μ category when one μ not reconstructed

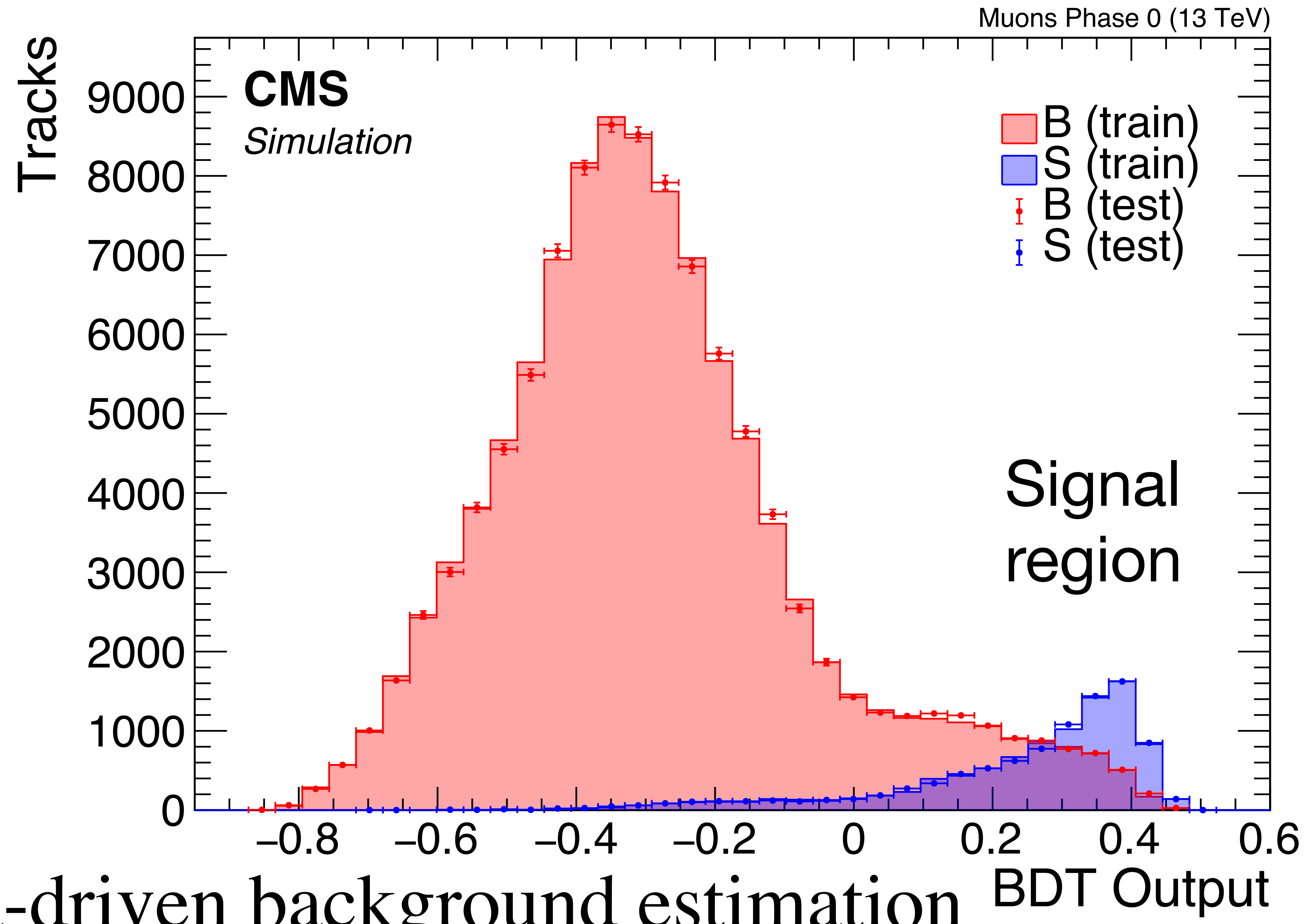


Soft lepton+track strategy

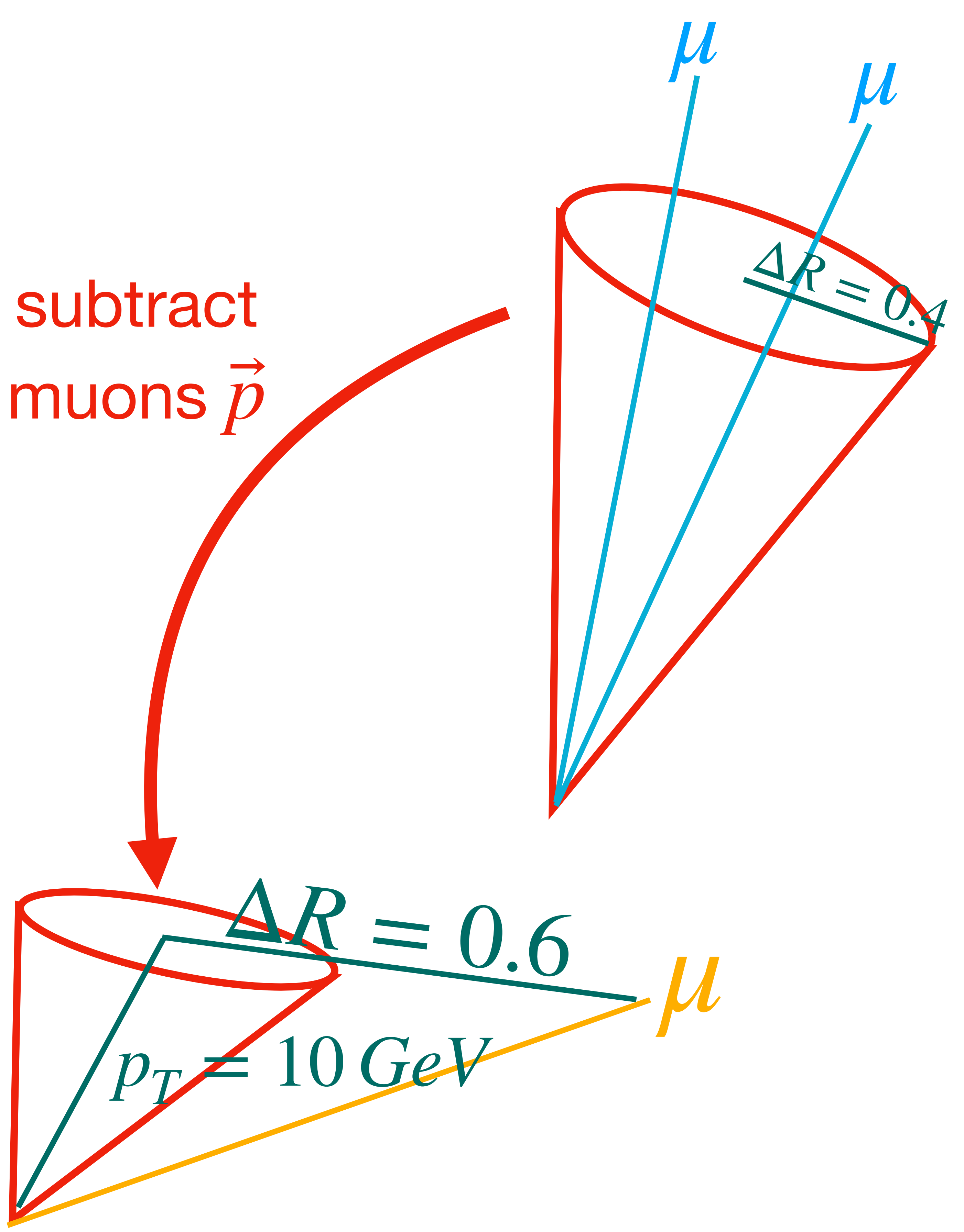
- custom lepton isolation with respect to jets
- Multivariate classifiers for track picking and event selection

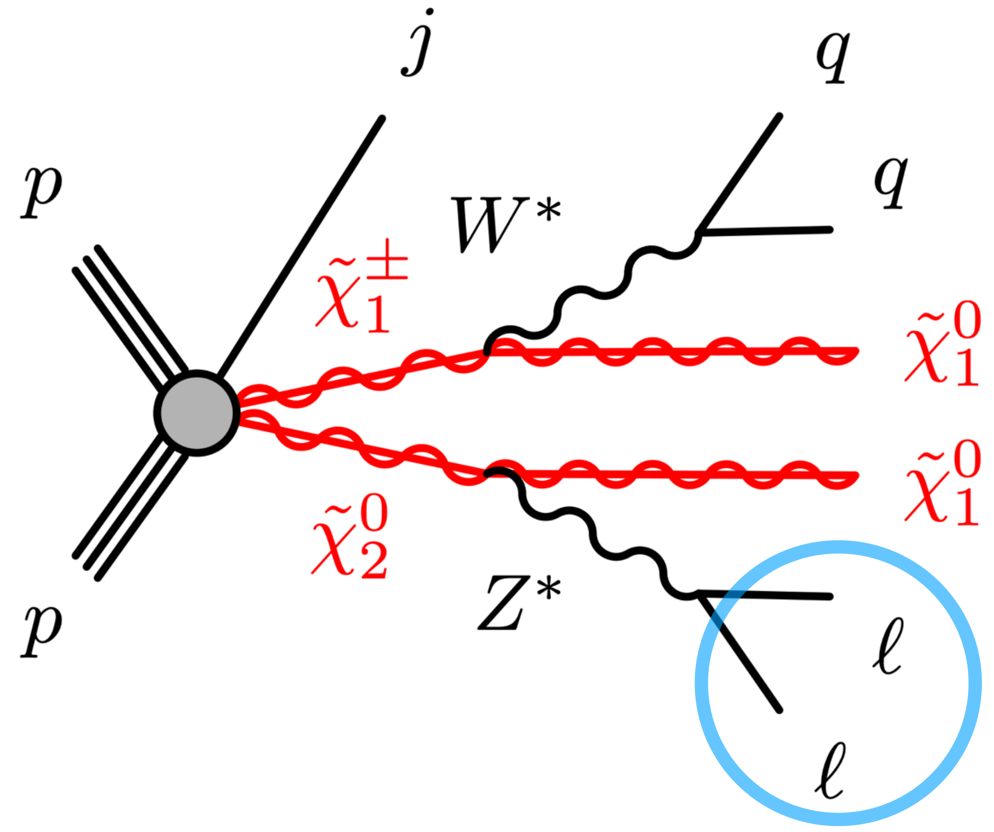
  ➡ $p_{T_t}, \phi_t, \eta_t, \Delta\eta(j_1, t), \Delta R(t, \ell), m_{T_t}$

  $p_{T_\ell}, \phi_\ell, \eta_\ell, \Delta\phi(H_T^{\text{miss}}, t), m_{\ell t}$



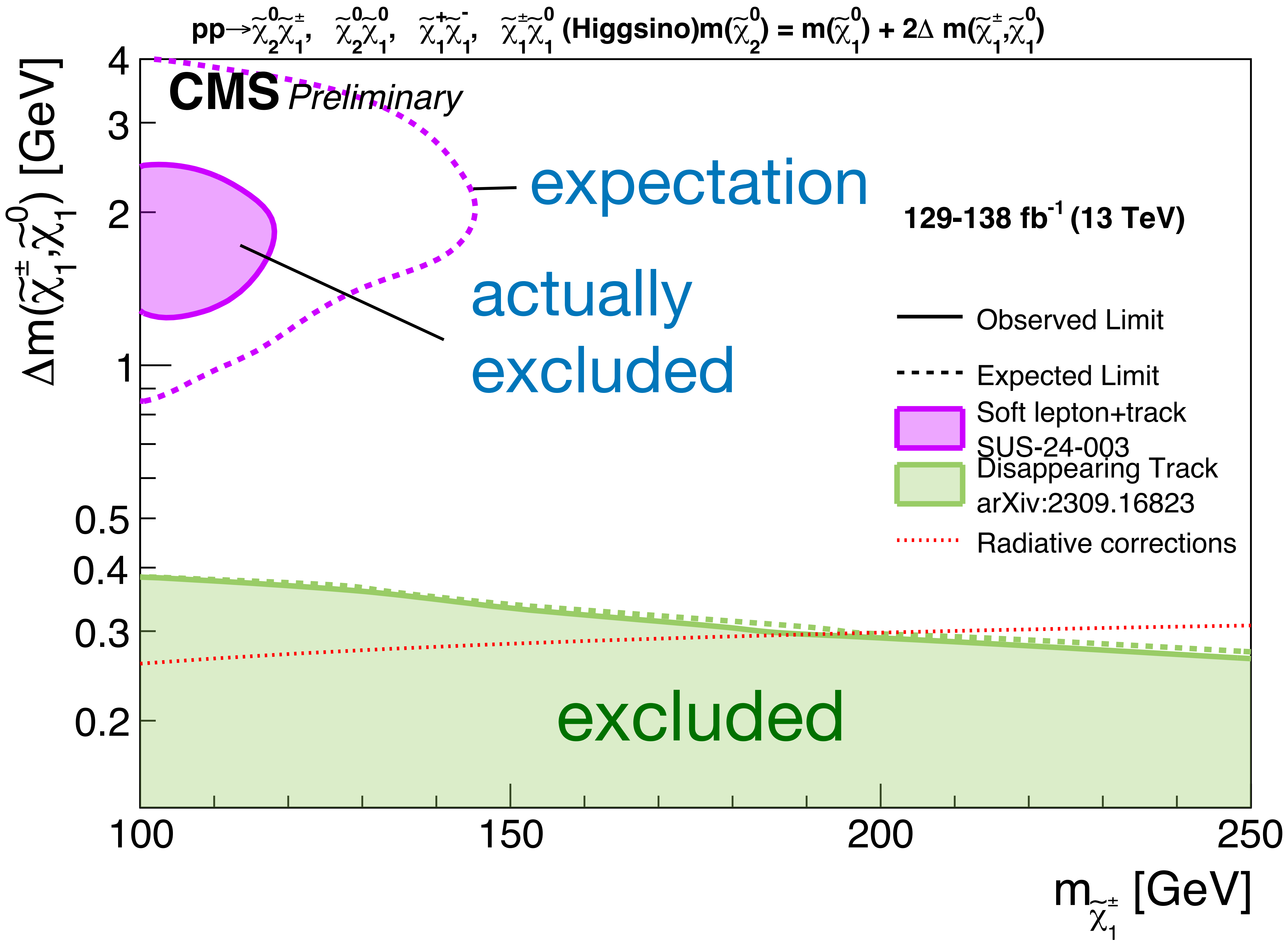
- Data-driven background estimation

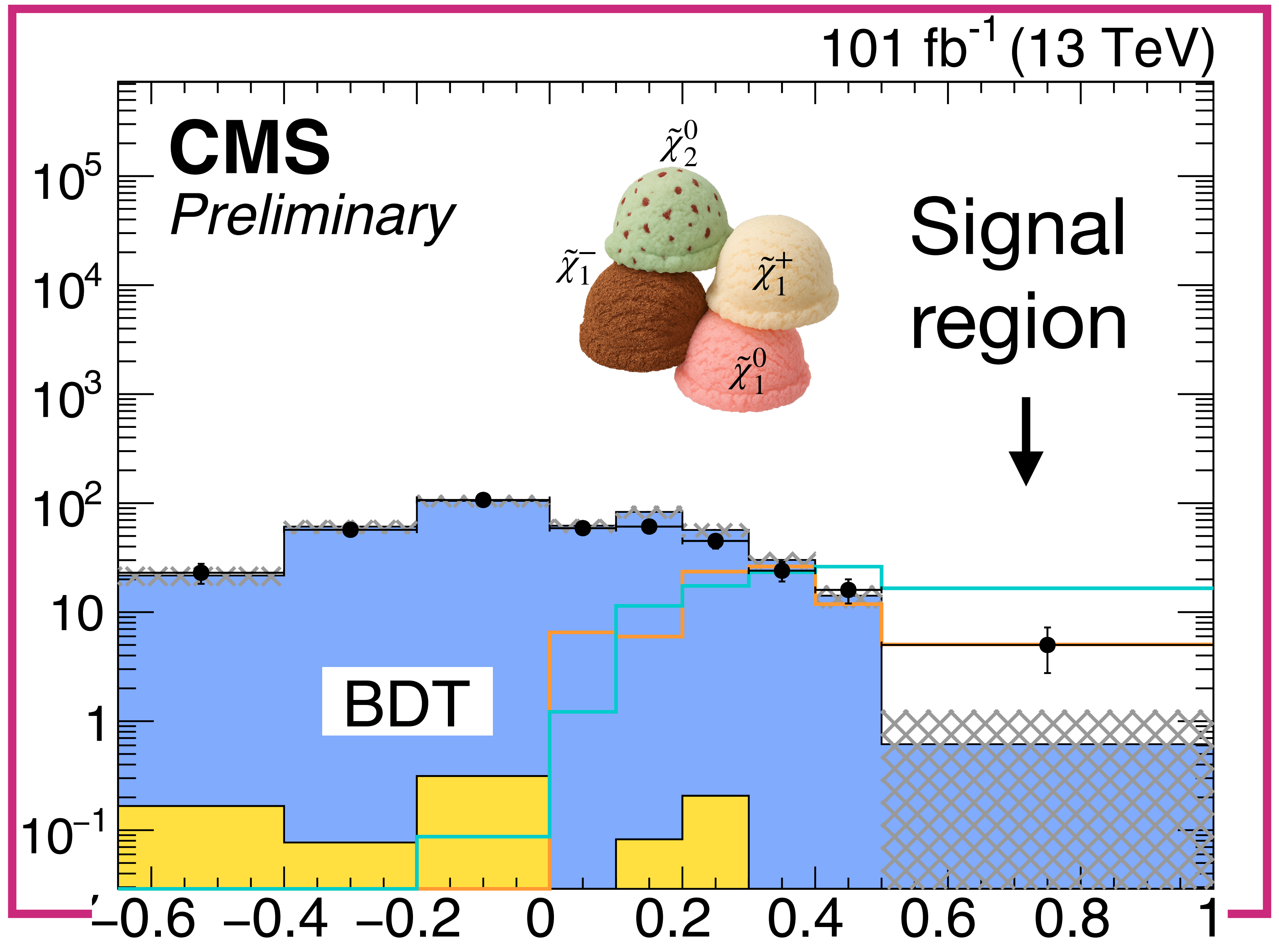


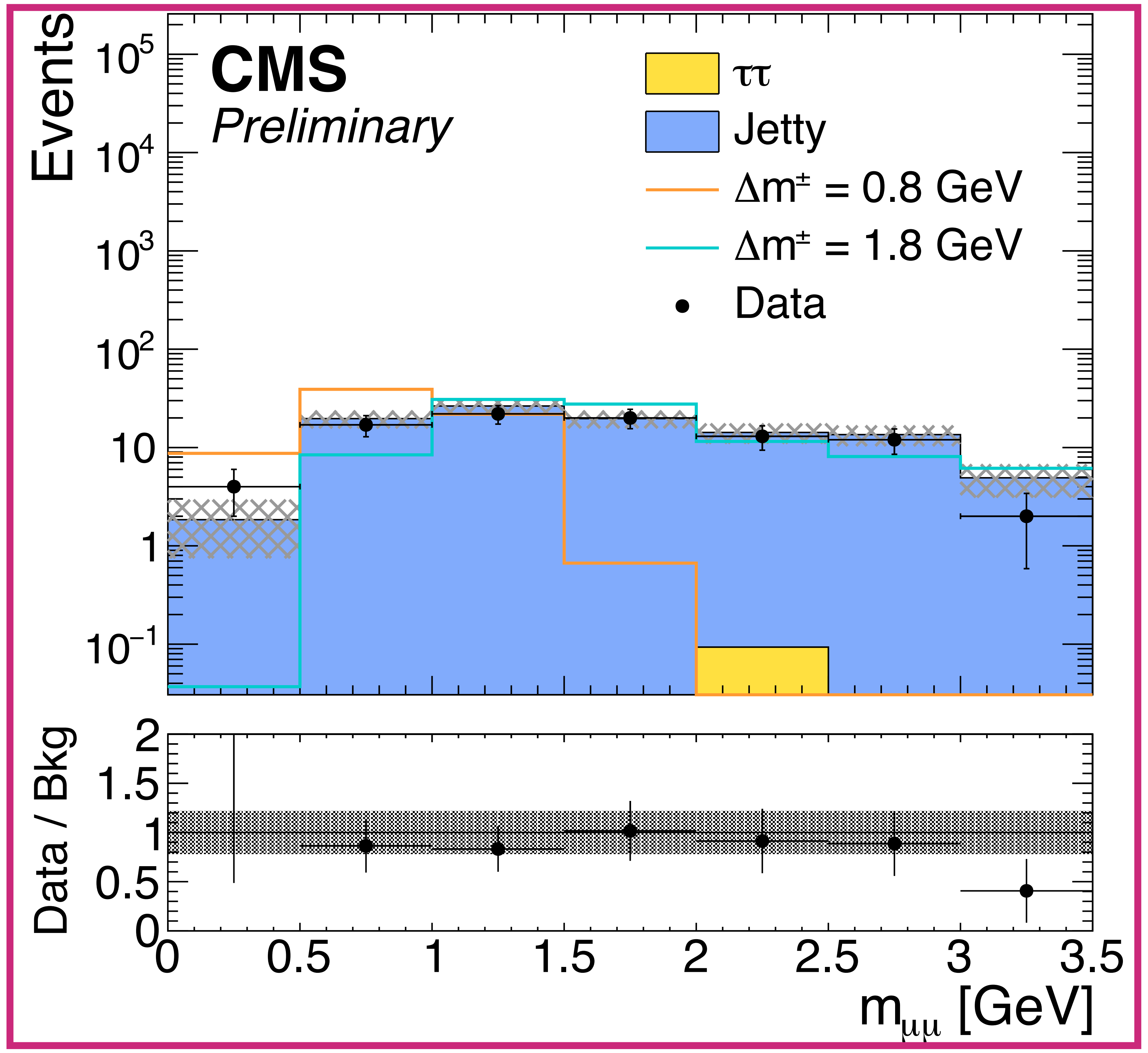


Soft lepton+track results

- Moderate excess worsens the observed limit





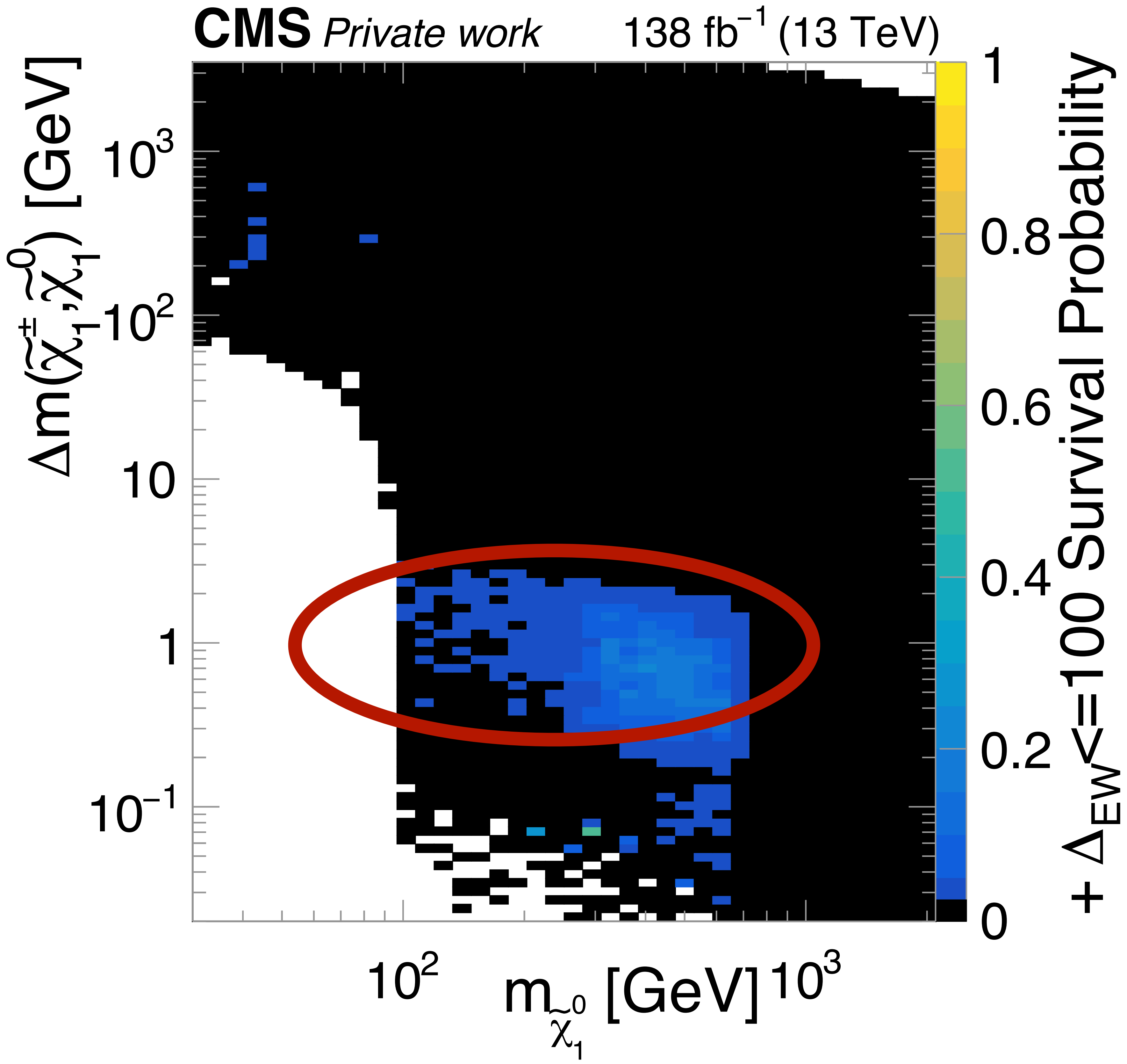


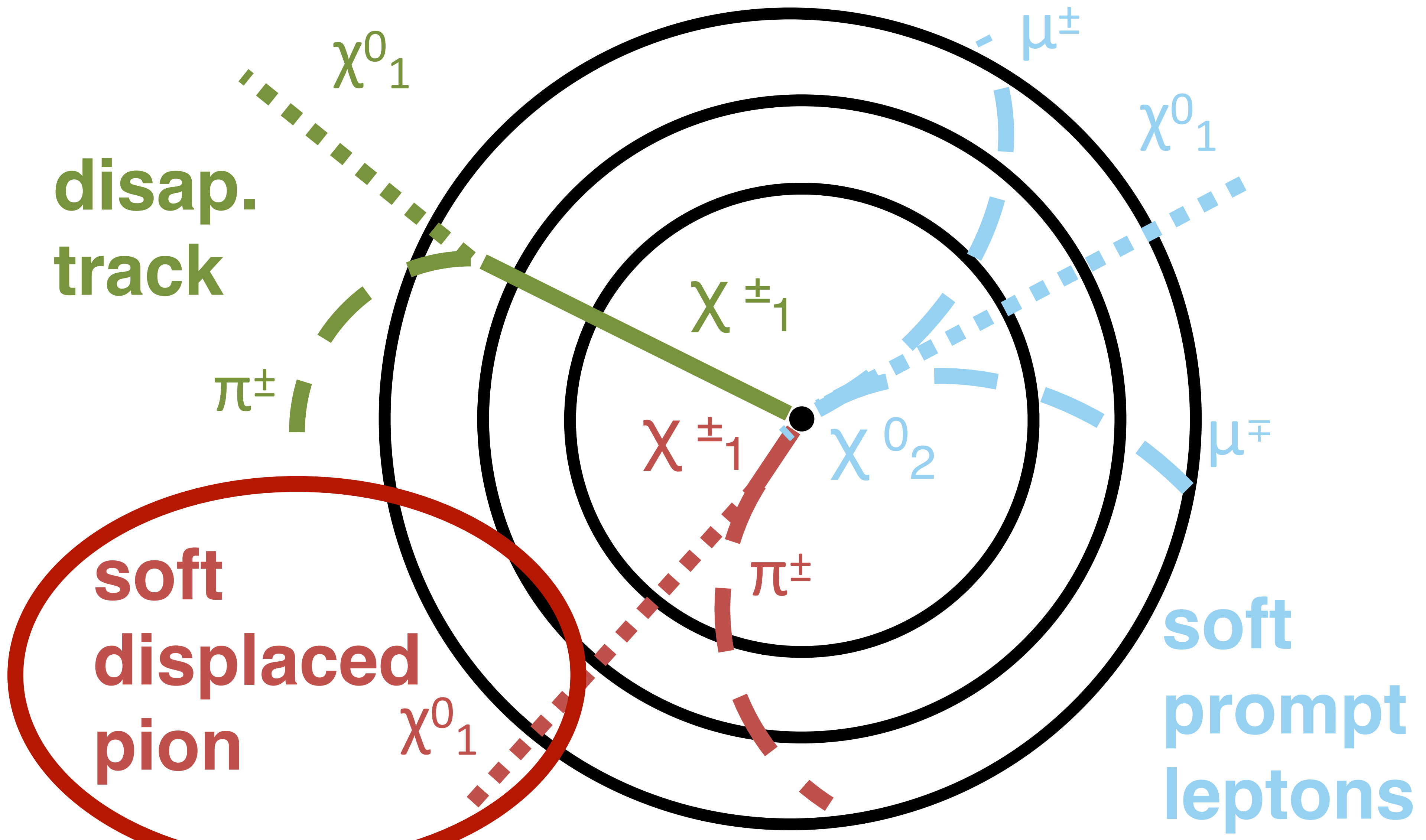
“Search for Higgsinos in final states with low-momentum lepton-track pairs with CMS at 13 TeV,” CMS collaboration; CMS-SUS-24-003.Published: 14 May, 2025.

Soft isolated track $\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm} + \tilde{\chi}_1^0$

"Search for compressed electroweakinos with low-momentum isolated tracks," CMS Collaboration. Report: CMS-PAS-SUS-24-012. Published: 9 April, 2025.

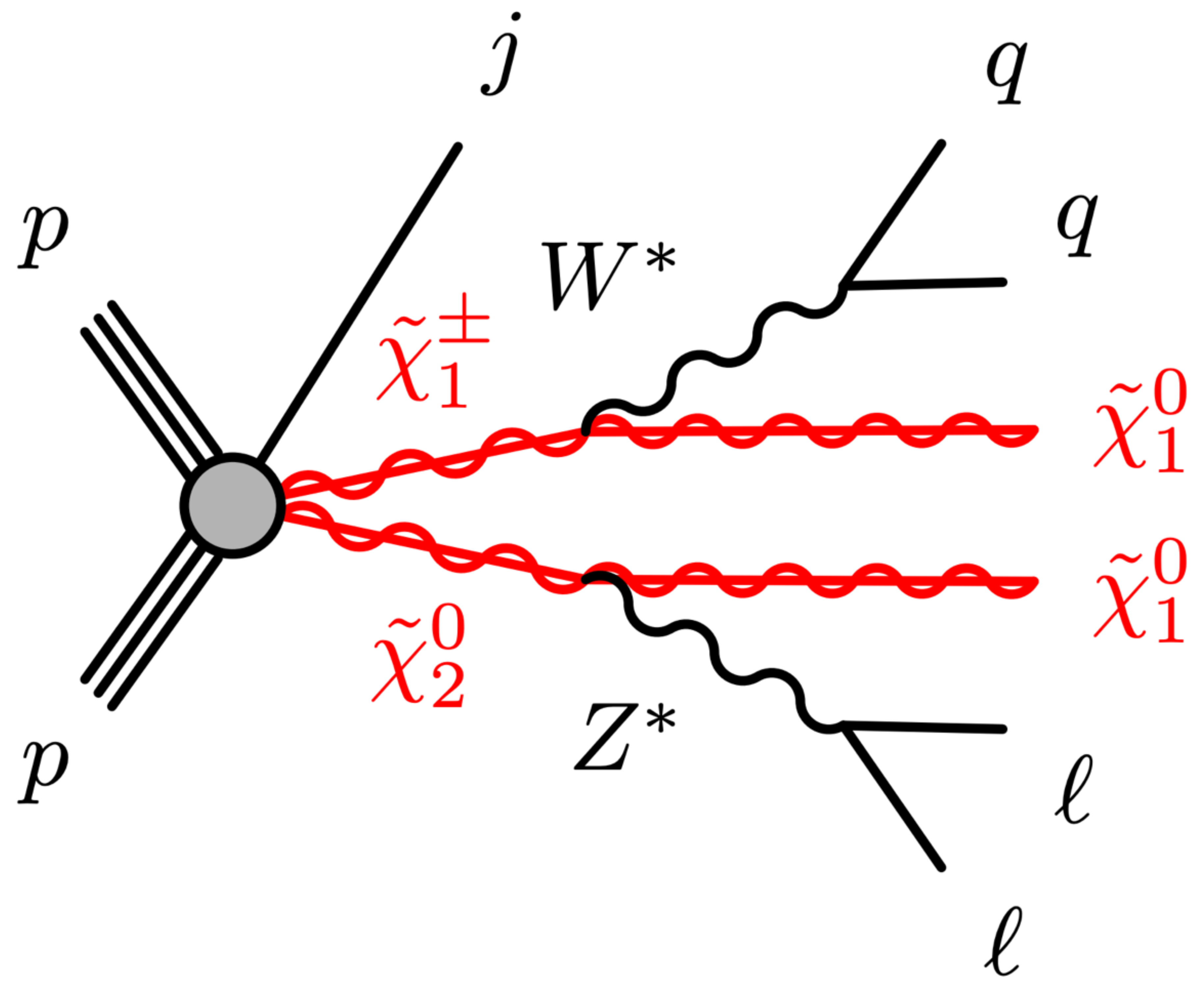
Moritz Wolf

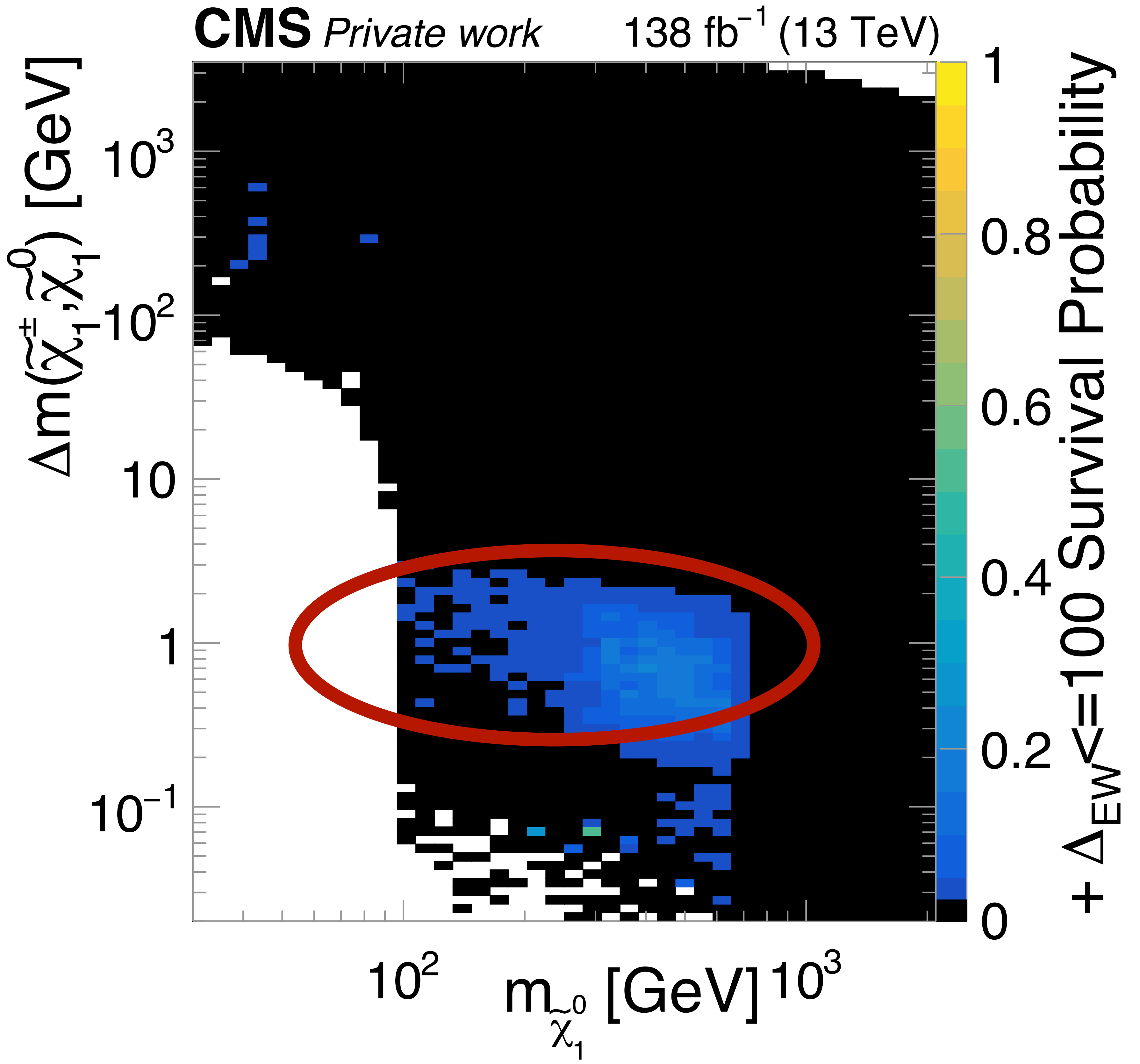


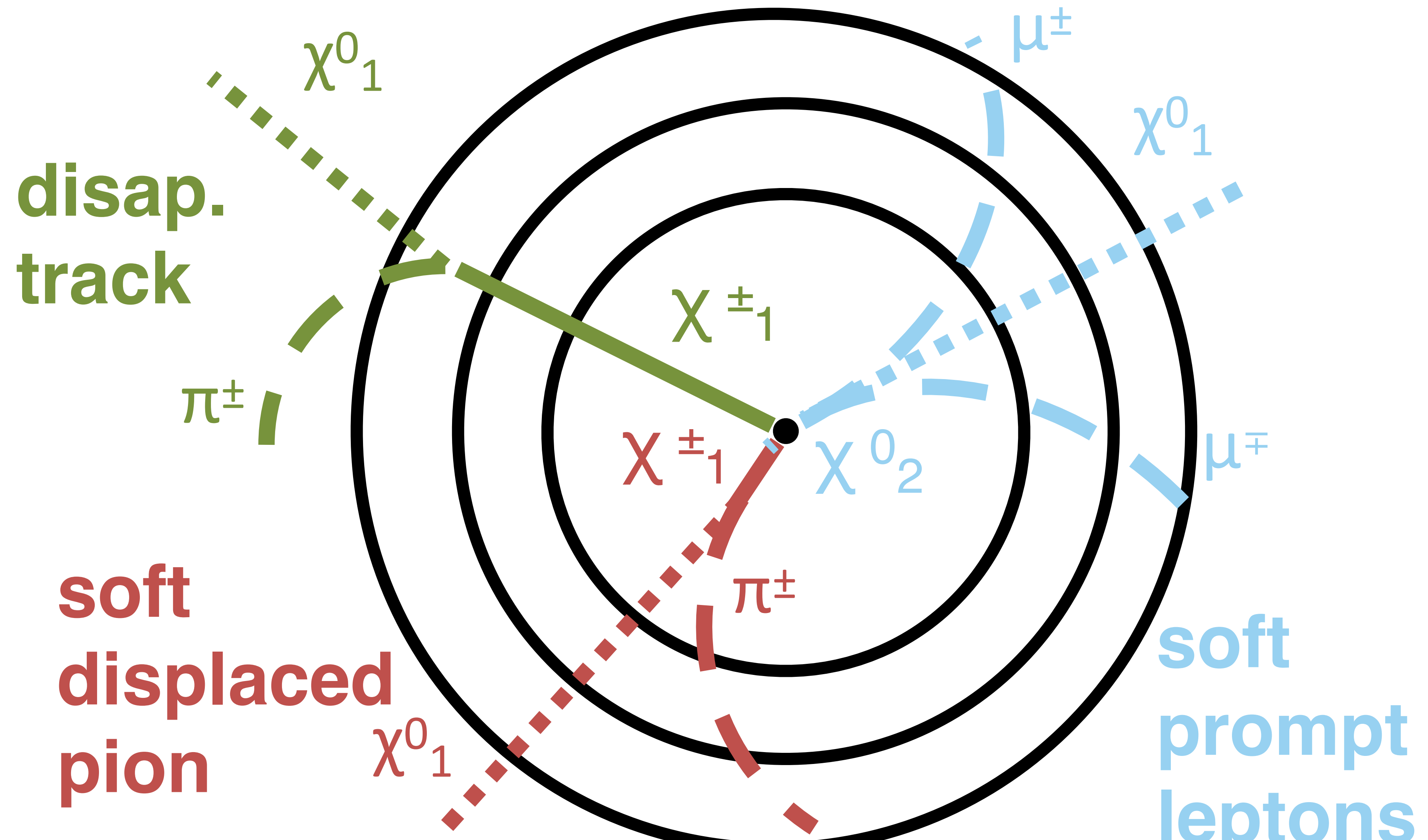


Soft isolated track $\tilde{\chi}_1^{\pm} \to \pi^{\pm} + \tilde{\chi}_1^0$

- ISR trigger loses 90%+signal
- Leptons too soft to be reconstructed
- Chargino doesn't reach the tracker







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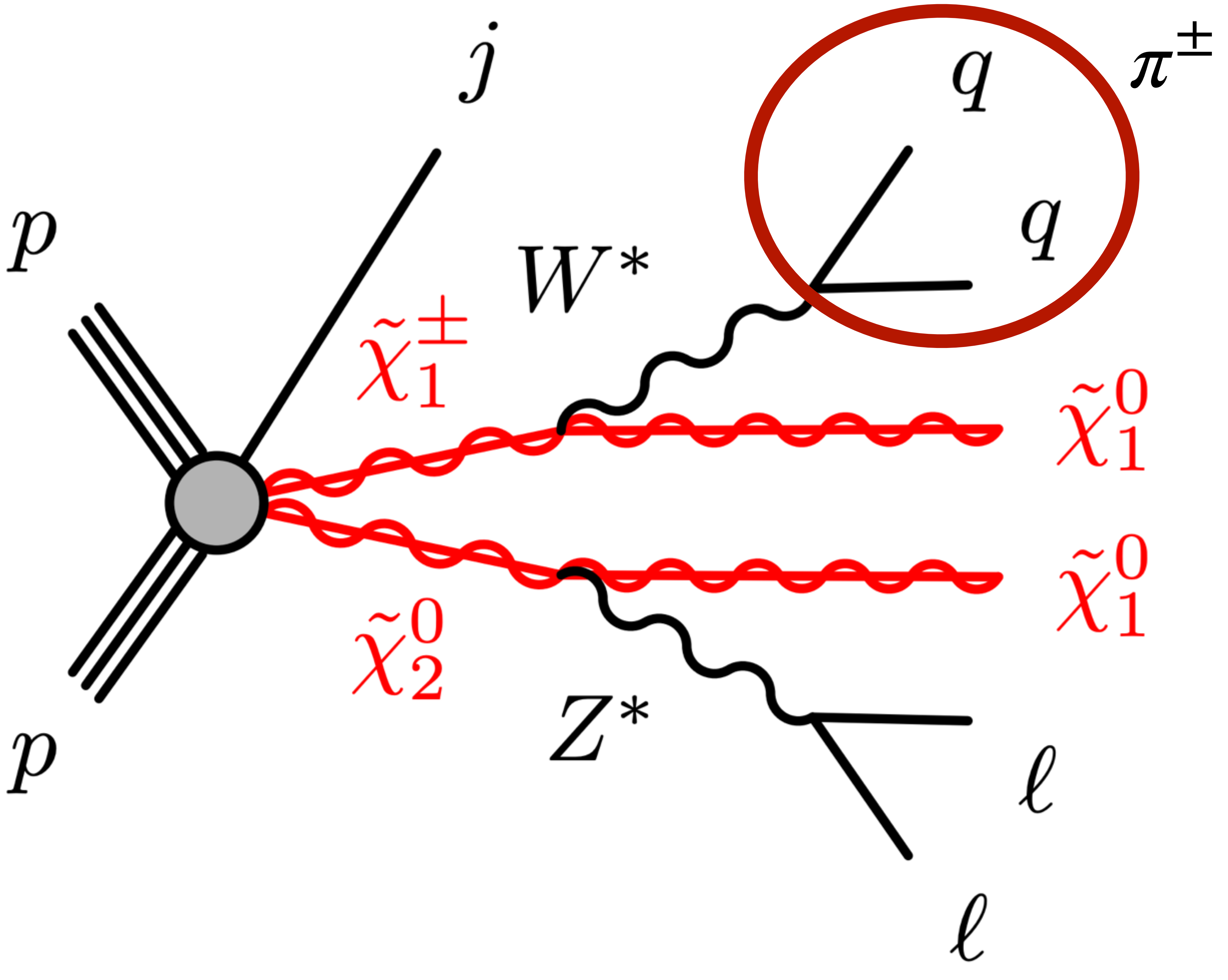

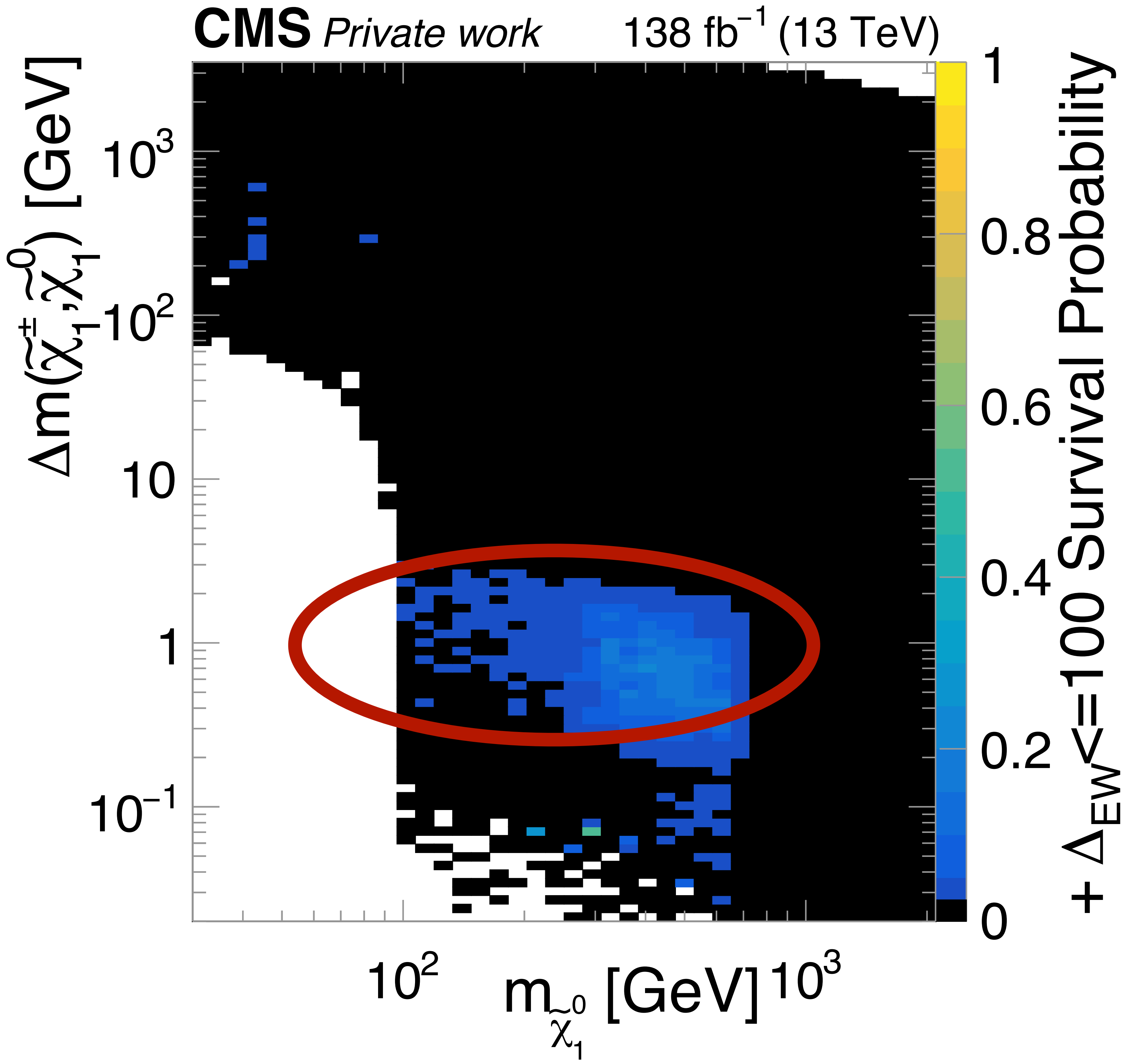

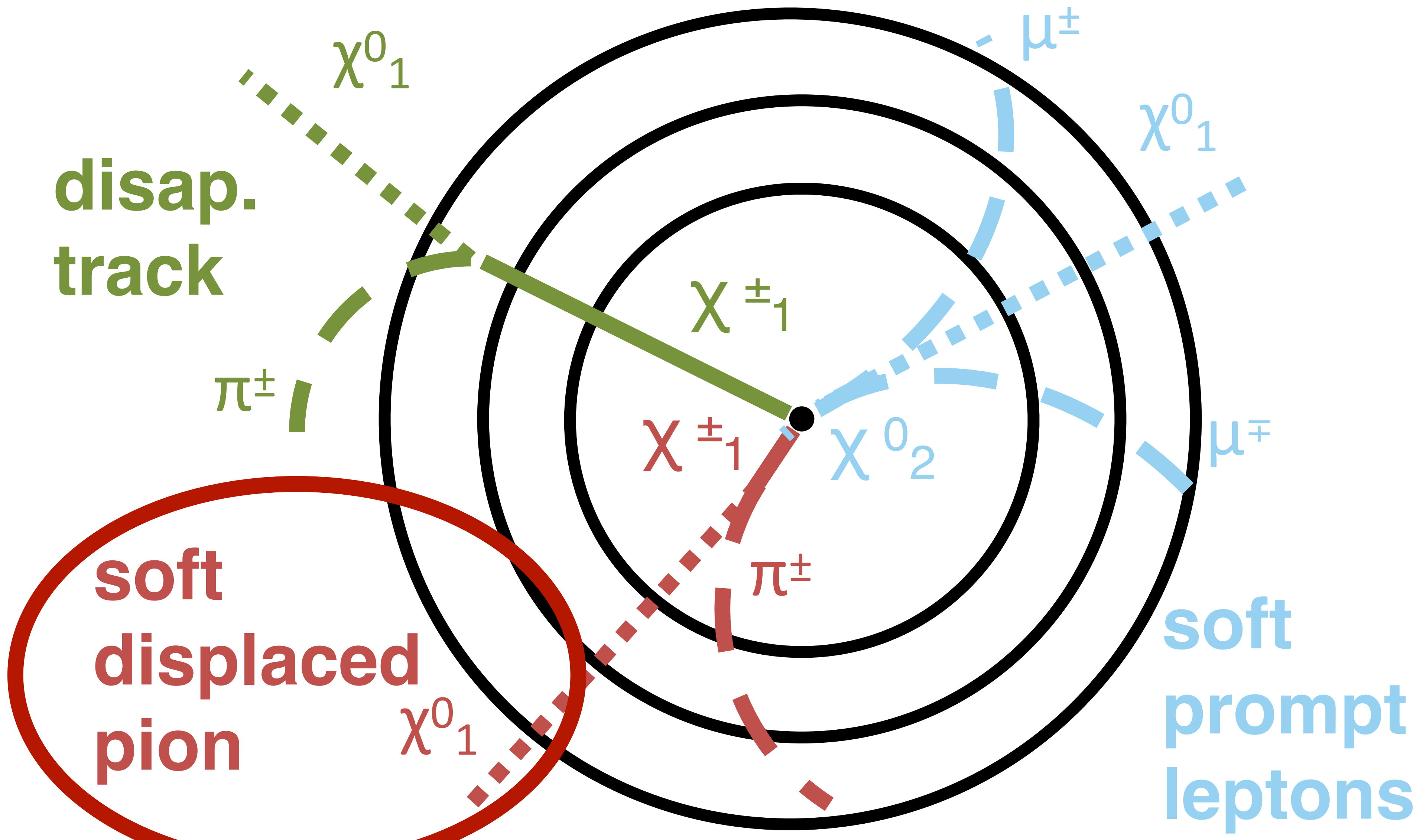

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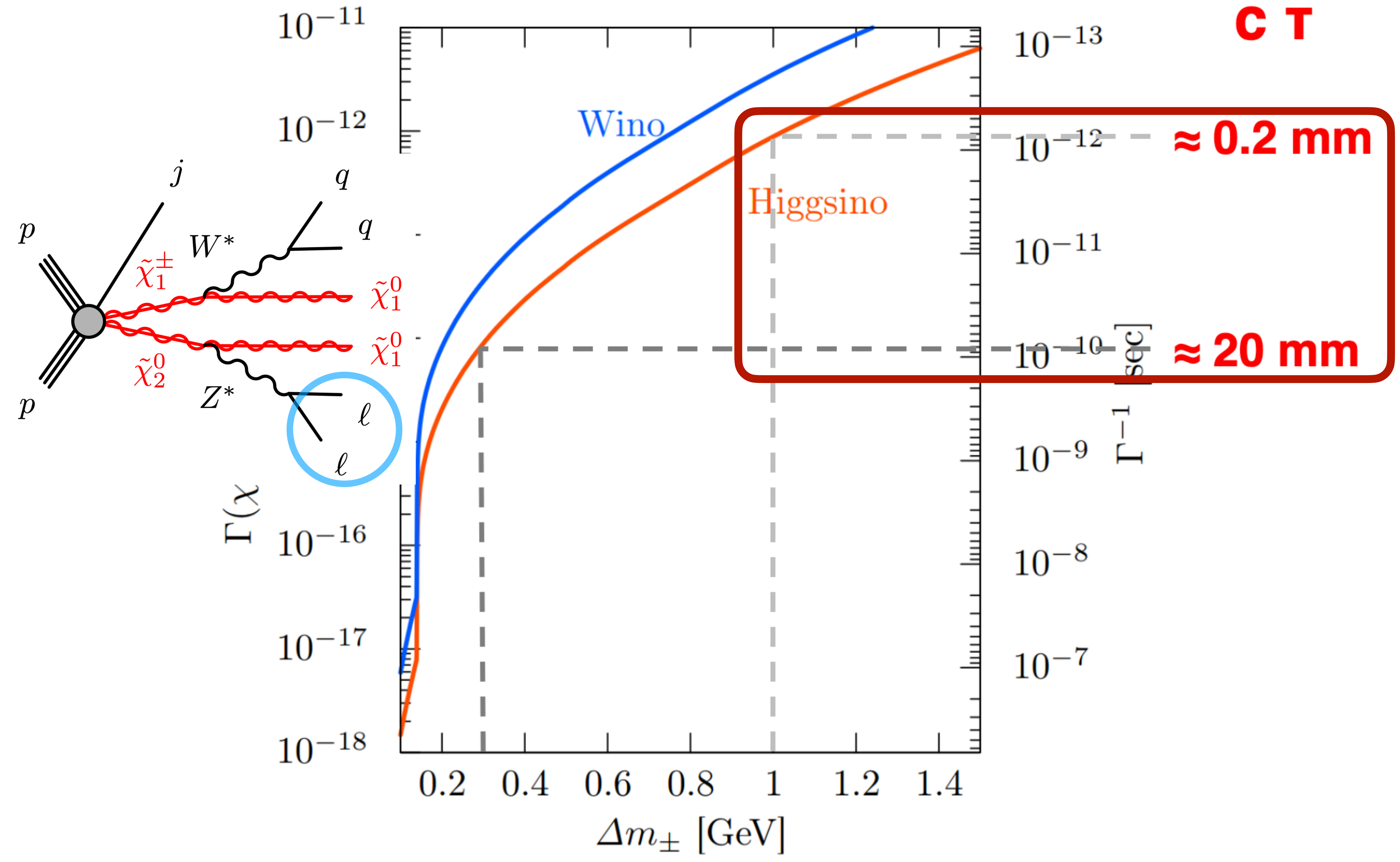
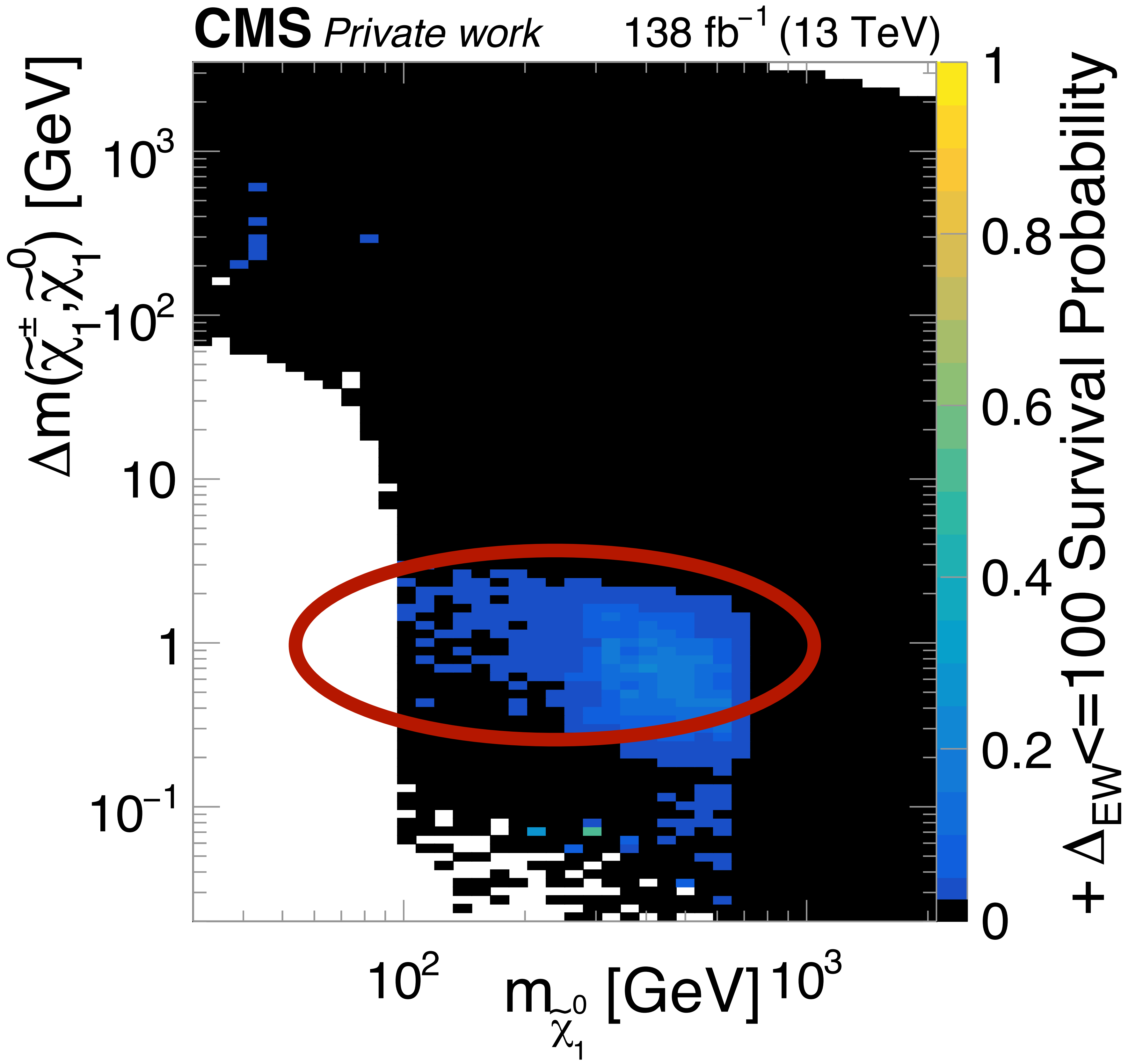
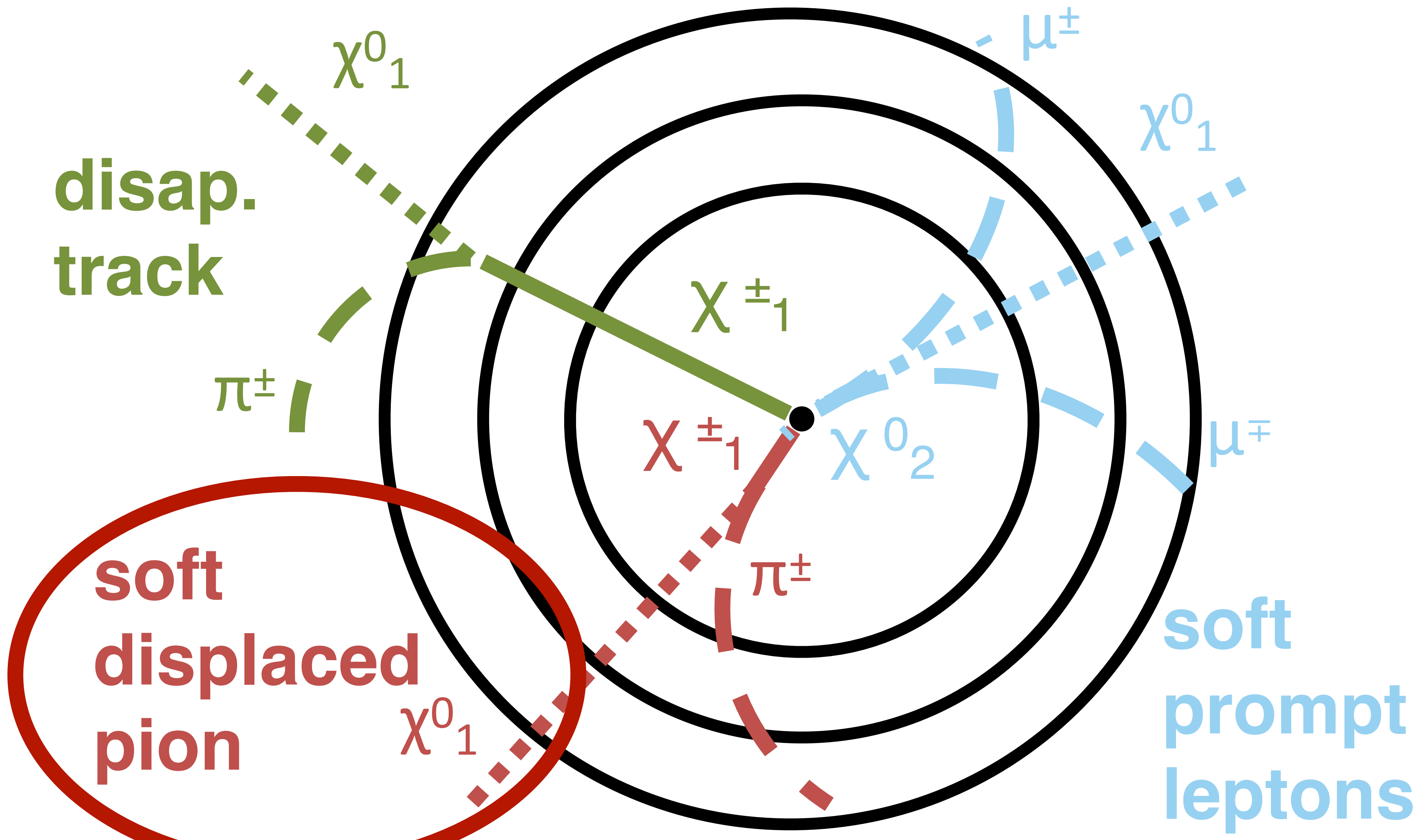
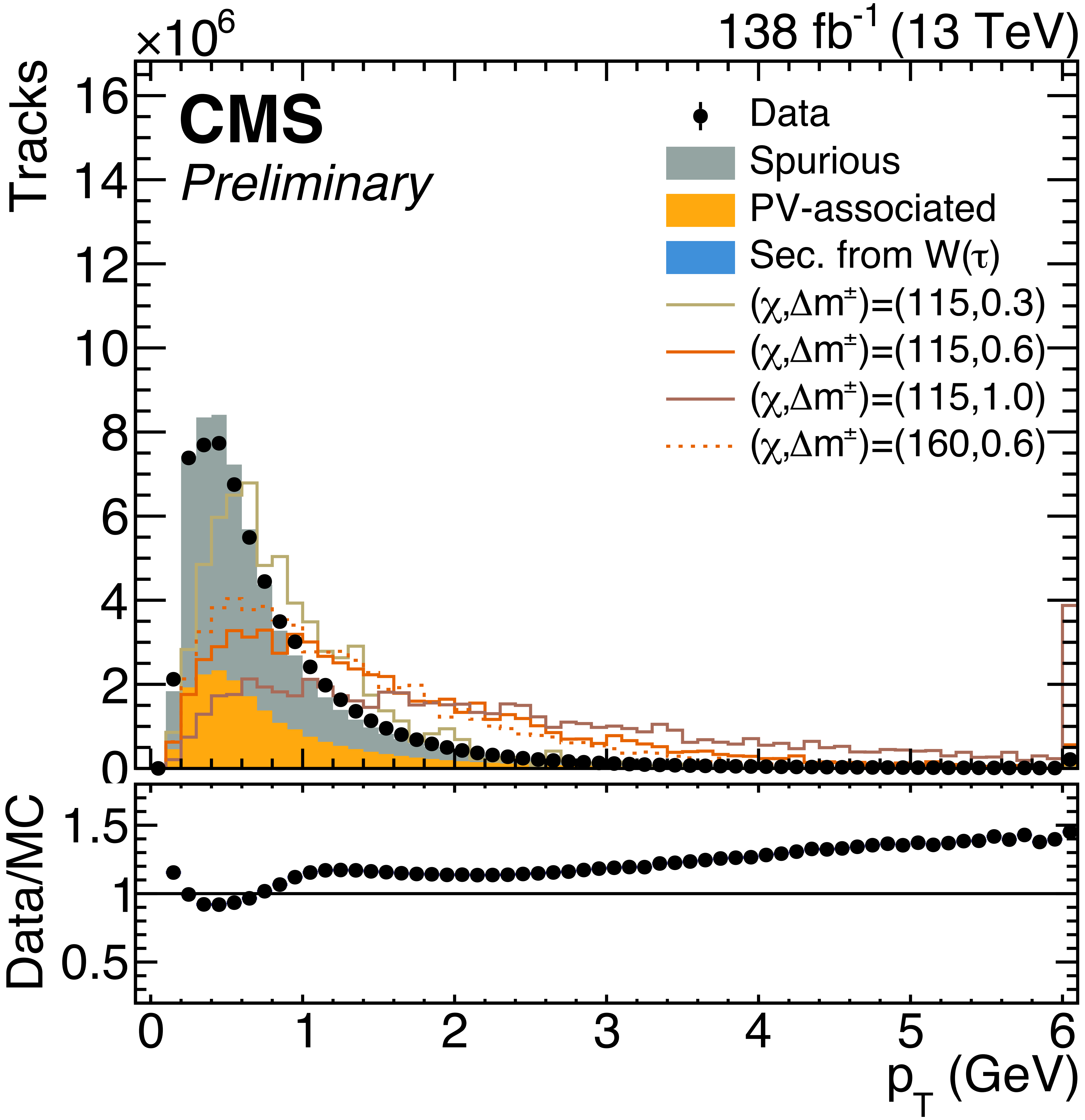
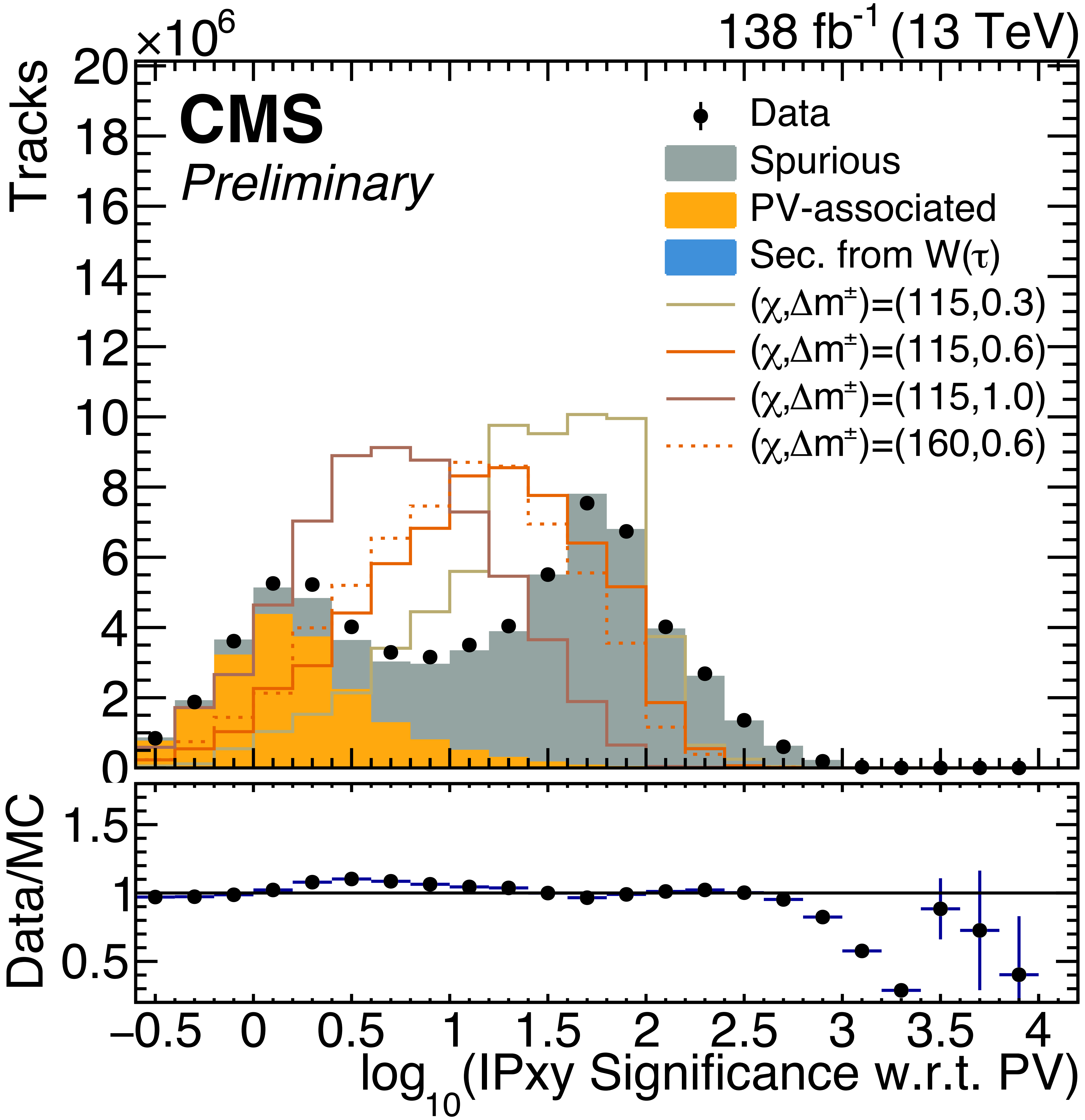






Soft isolated track $\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm} + \tilde{\chi}_1^0$



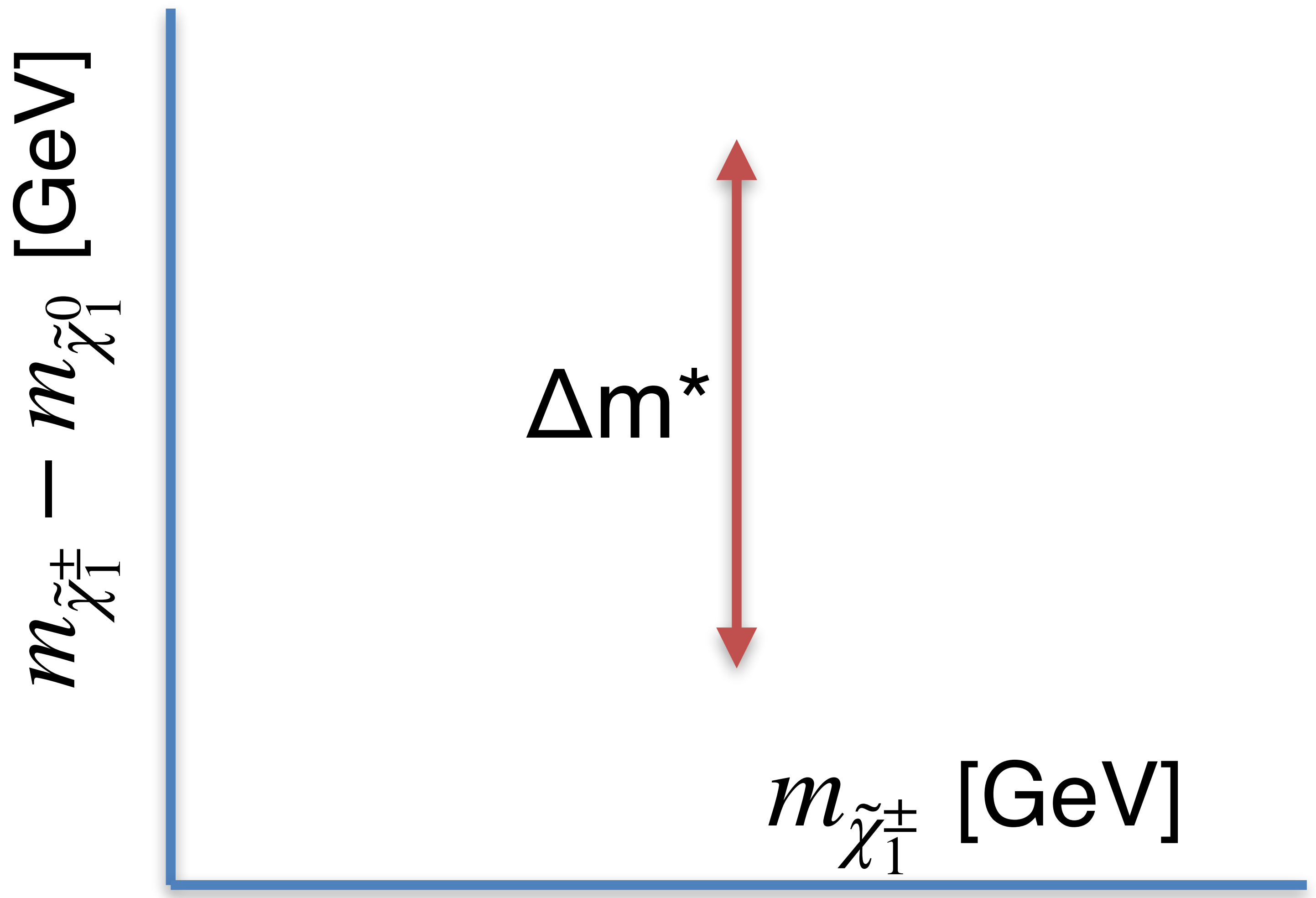


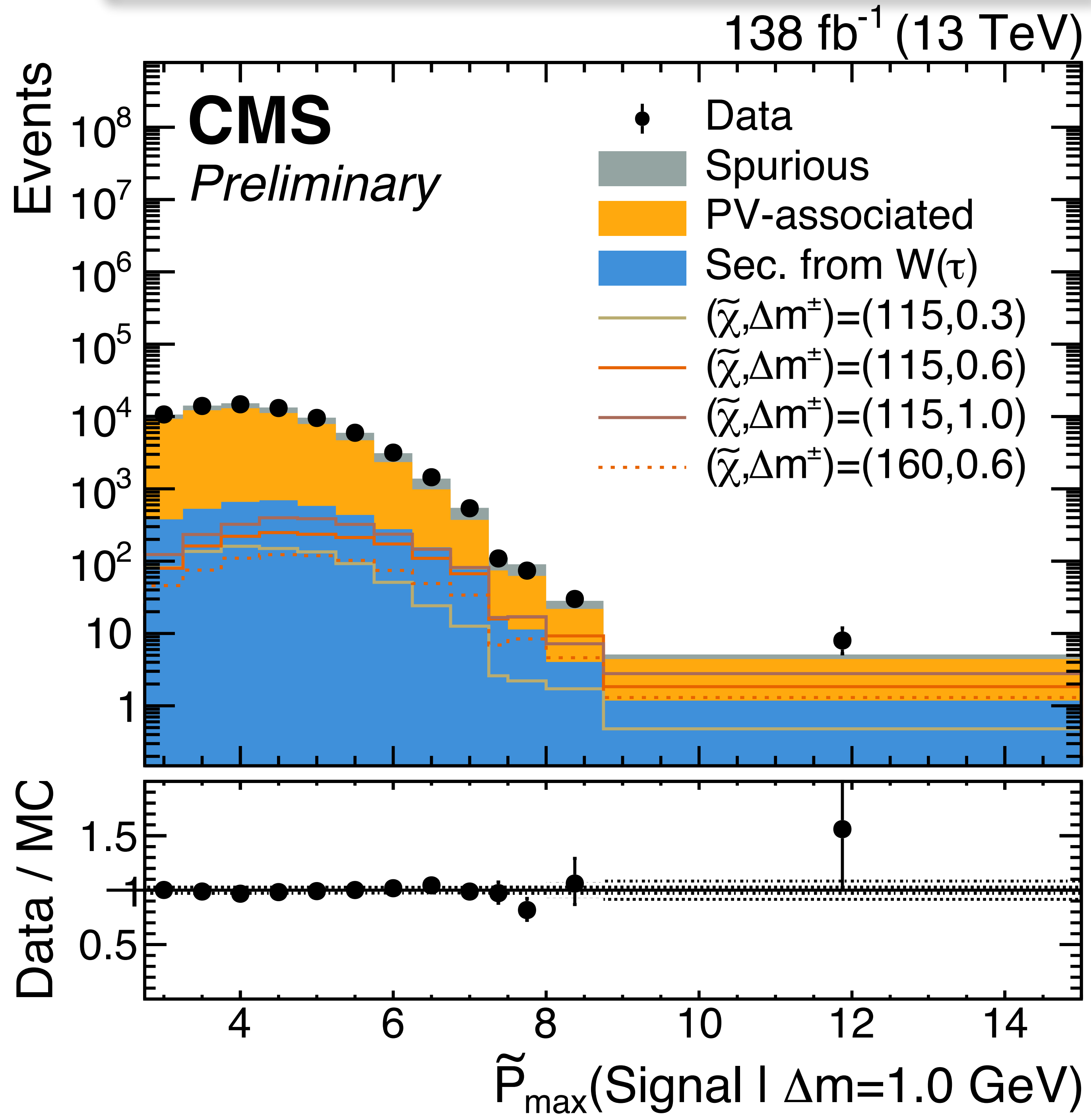
Signal properties trade off usefulness

low Δm: $p_T \downarrow$ and displacement $\uparrow$, high Δm: $p_T \uparrow$ and displacement $\downarrow$

Soft isolated track - parametrized neural network (NN)

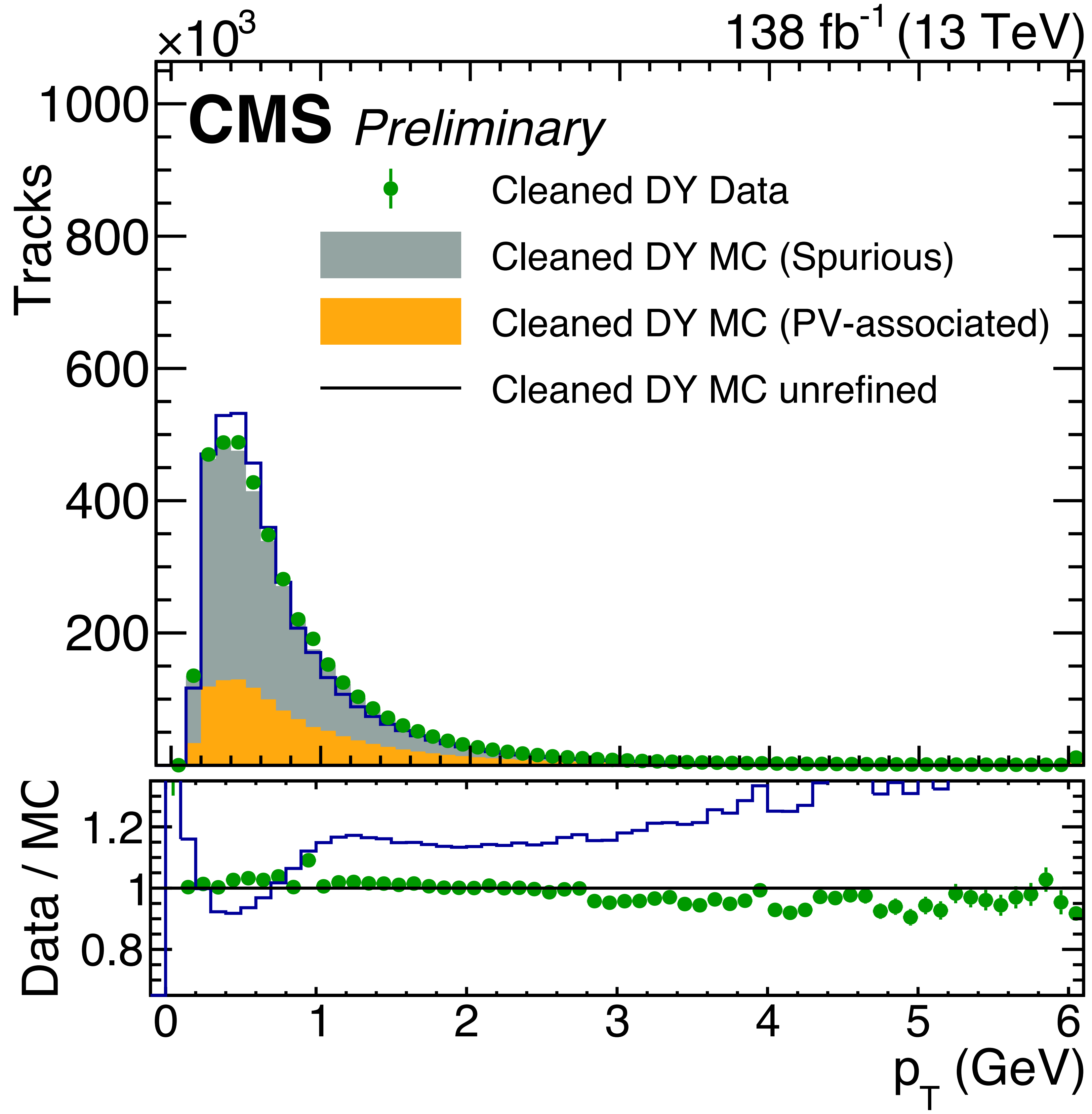
- Use NN classifier to find the most signal-like track in event
- 37 inputs: 36 **track-level** observables, e.g., p_T, η, $d_{xy/z}$, IP significance, isolation, $\Delta\varphi(p_T^{miss}$, track$)$,… + **event-level** $|p_T^{miss}|$
  - **Parametrize** NN with Δm to expand sensitivity range (choose certain Δm^* when evaluating)
- 5 output nodes (softmax-activated): 5 track classes
  - Signal (tracks matched to pion from chargino decay)
  - Fakes, Prompt, Secondary, tau

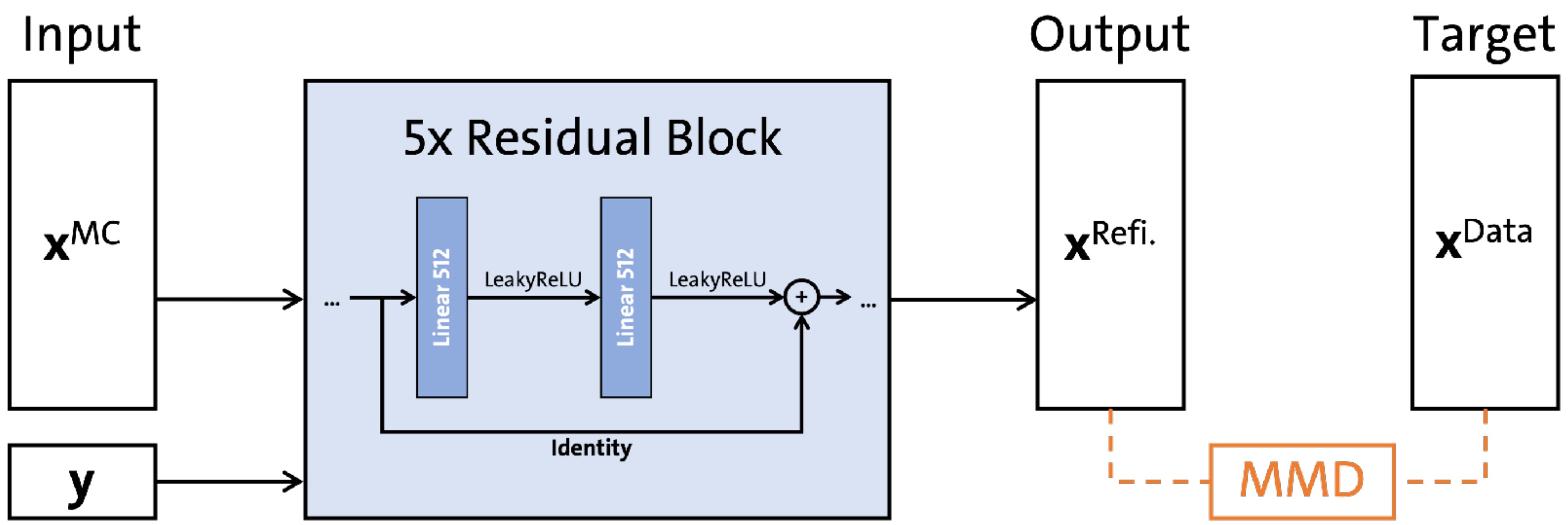




Simulation corrections

- Normalization and correction factors
- MC shape correction
  - Transformation $x^{MC} \rightarrow x^{MC\ refined}$ to better match x^{Data}
  - Refine track variables: $x = (p_T, dz^{Error}, dxy^{Error})$
  - Additional SR-specific weights from residual discrepancies in cl. DY
- Signal **FastSim correction** (from comparison with FullSim in sub-space of all simulated model points

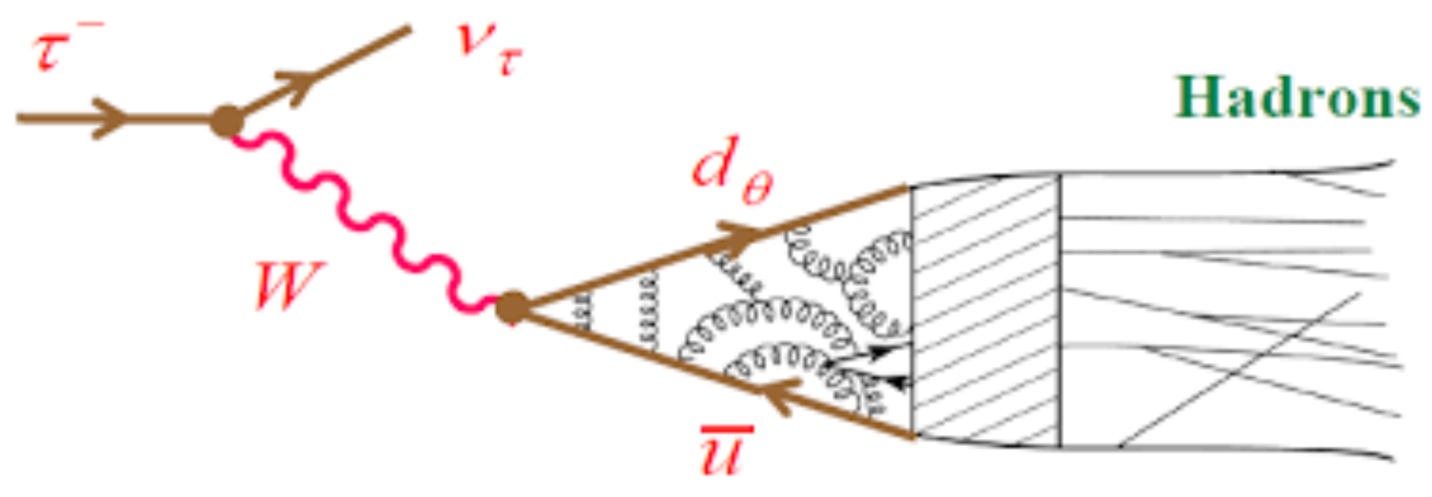




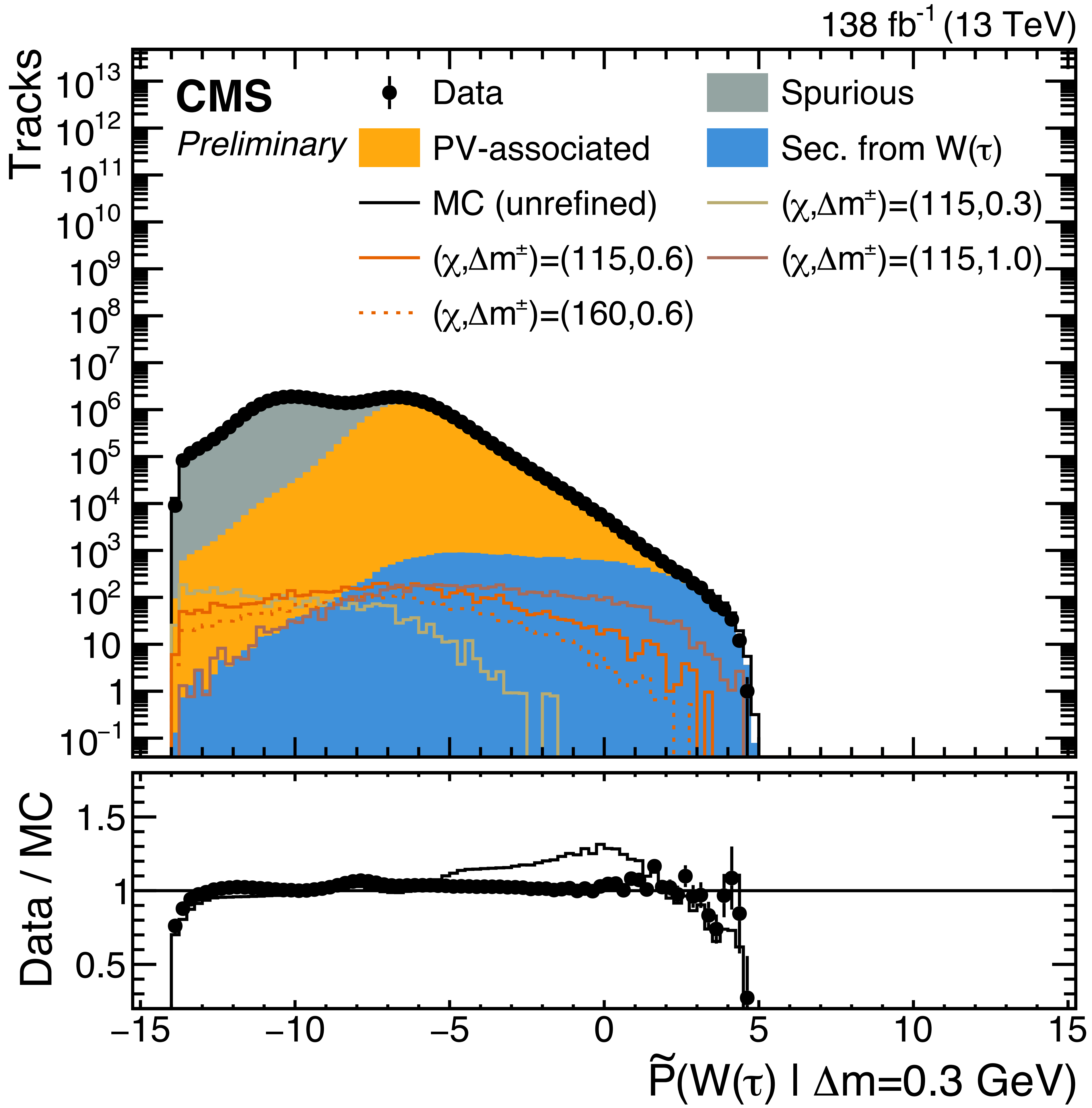
"Fast Perfekt: Regression-based refinement of fast simulation," Moritz Wolf, Lars O. Stietz, Patrick Connor, Peter Schleper, and Samuel Bein; arXiv:2410.15992

Soft isolated track - signal proxy

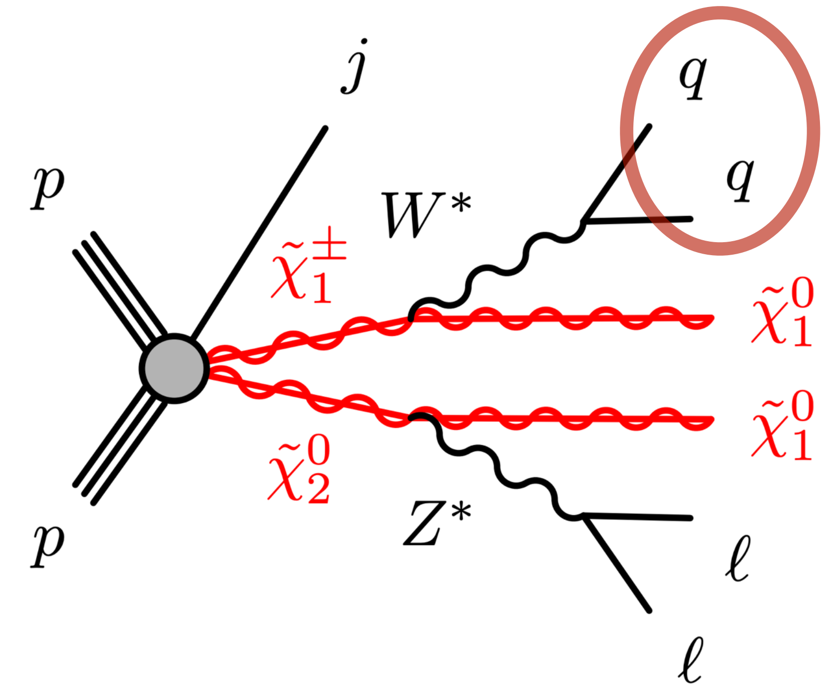
- Tau as proxy for soft electroweak decays

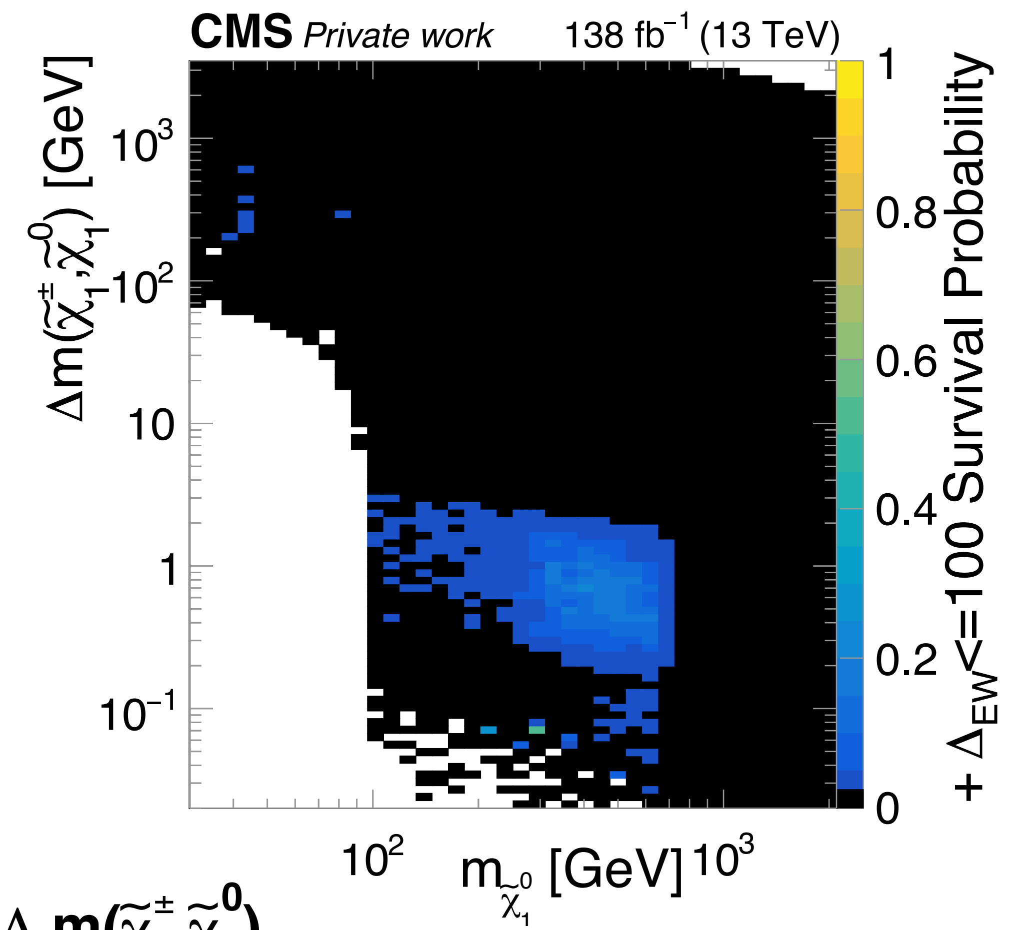


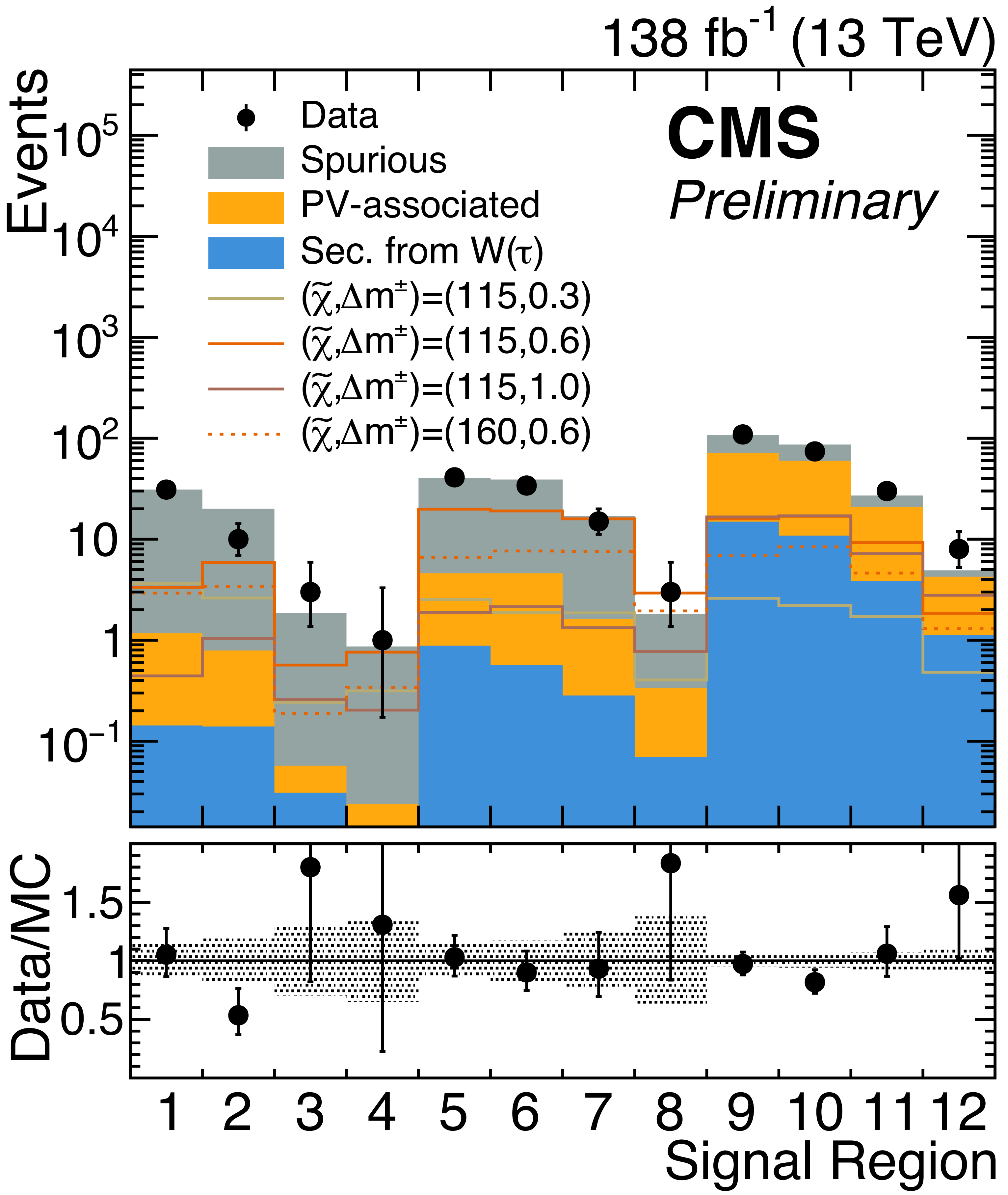
- Select tracks with lower threshold on on signal node
- Isolated signal-like tau decays
- Assess 10% signal systematic uncertainty

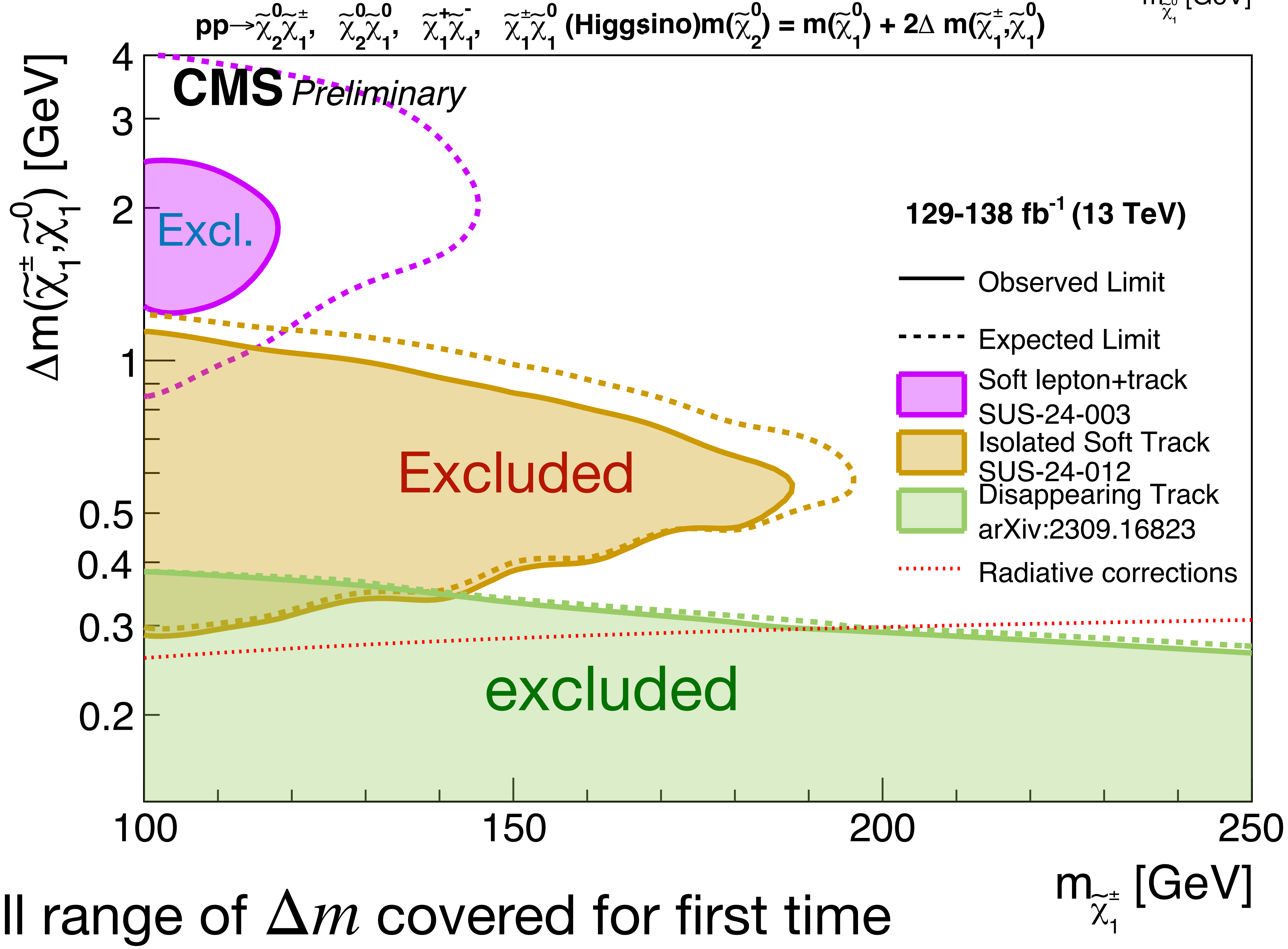


Soft isolated track - results





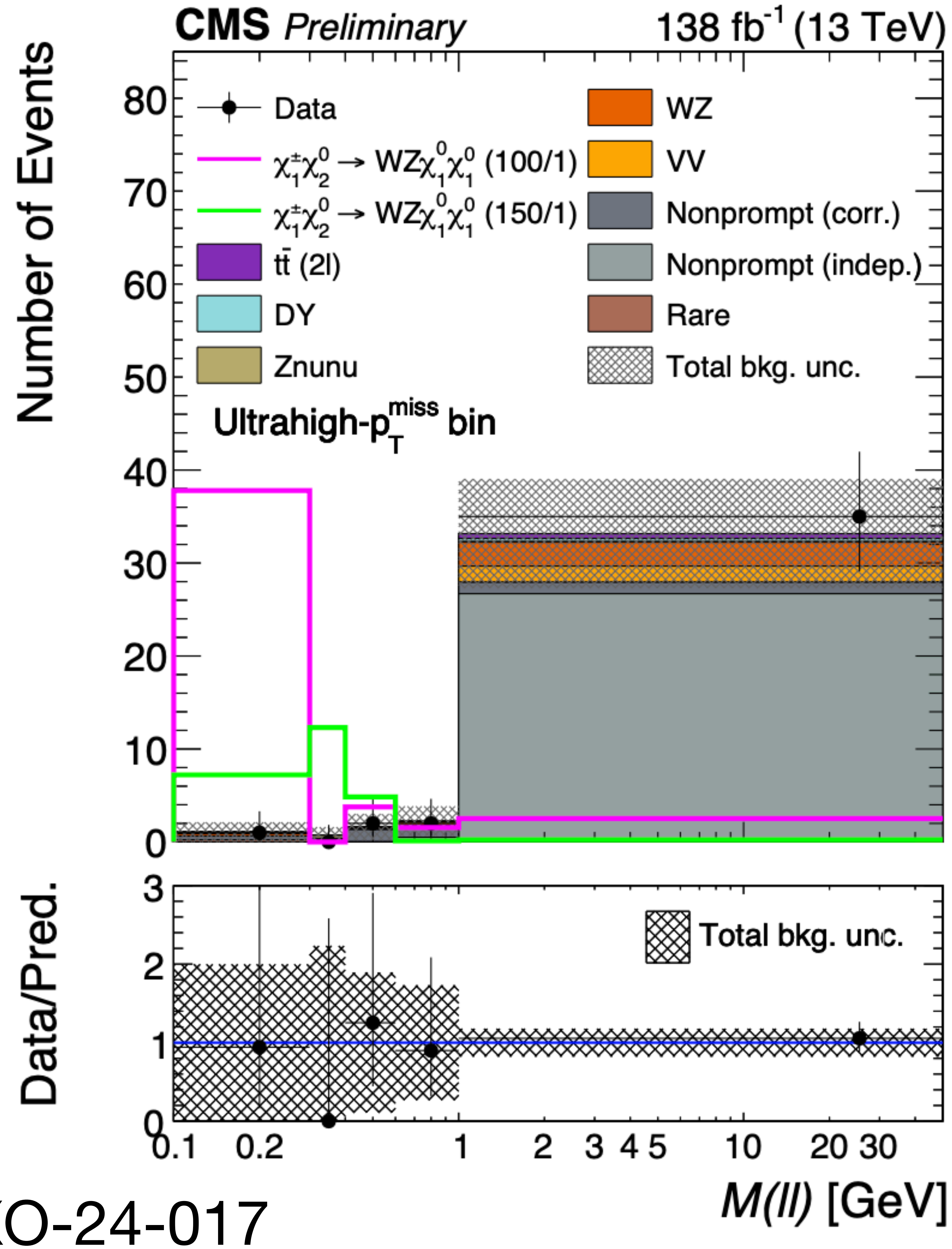




Full range of Δm covered for first time

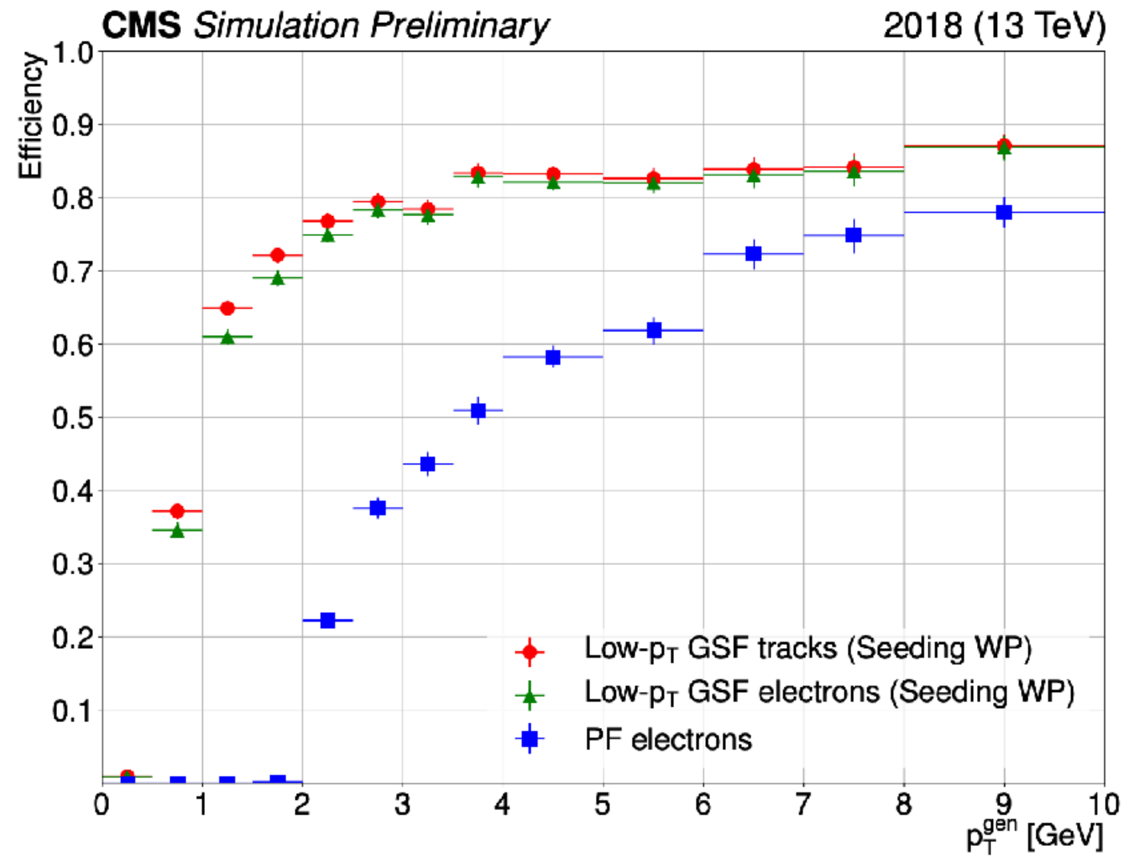
Joined by soft and displaced di-electron

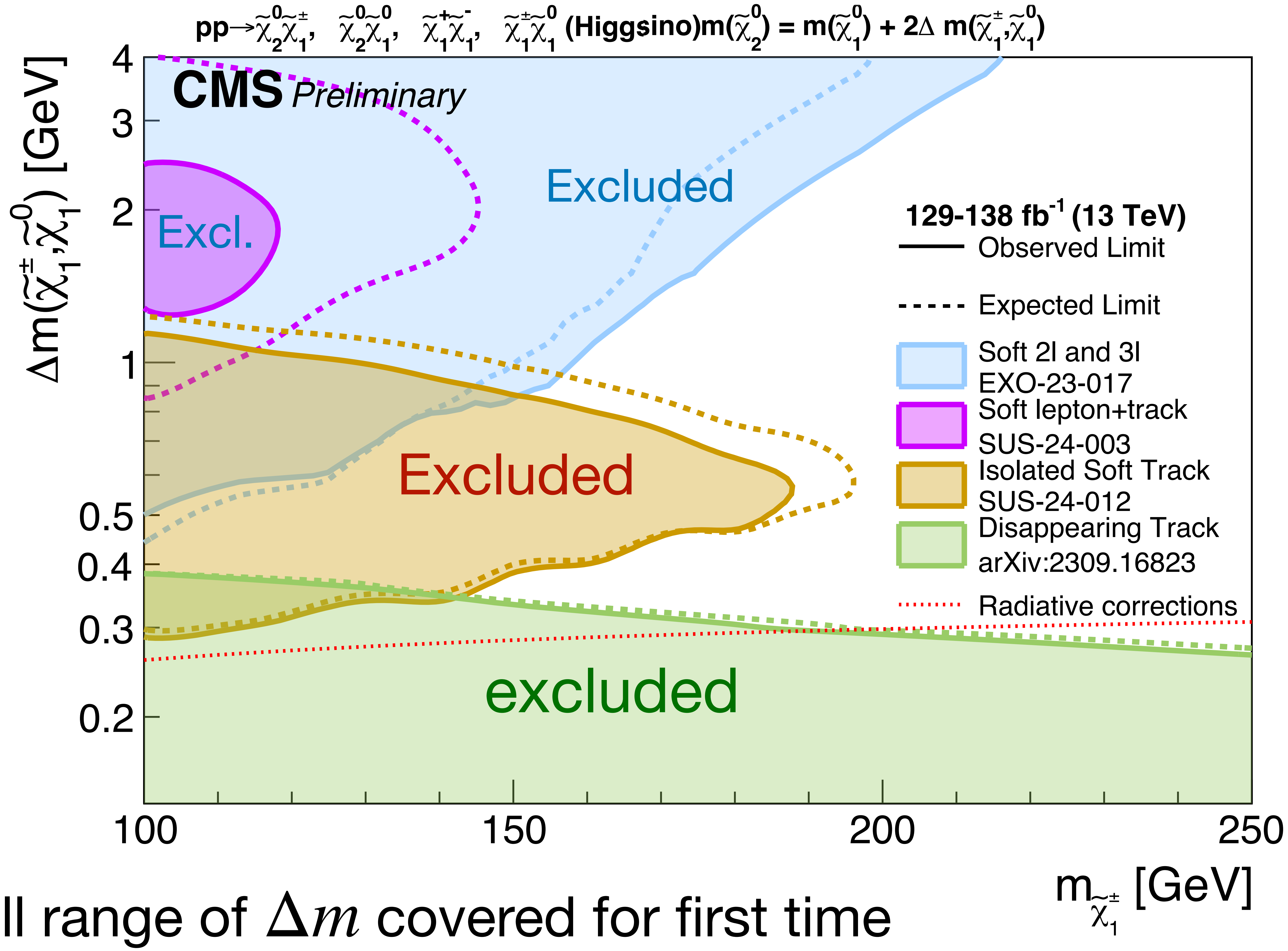
EXO-24-017



EXO-24-017

“Recording and reconstructing 10 billion unbiased b hadron decays in CMS;” Rob Bainbridge (CDS)





Full range of Δm covered for first time

Putting it all together

Iso track and dilepton not yet in pMSSM interpretation, but expected put pressure on natural SUSY

Simulation Corrections

- Normalization and correction factors
- MC shape correction
  - Transformation $x^{MC} \rightarrow x^{MC\ refined}$ to better match x^{Data}
  - Refine track variables: $x = (p_T, dz^{Error}, dxy^{Error})$
  - Refiner trained in cleaned DY region
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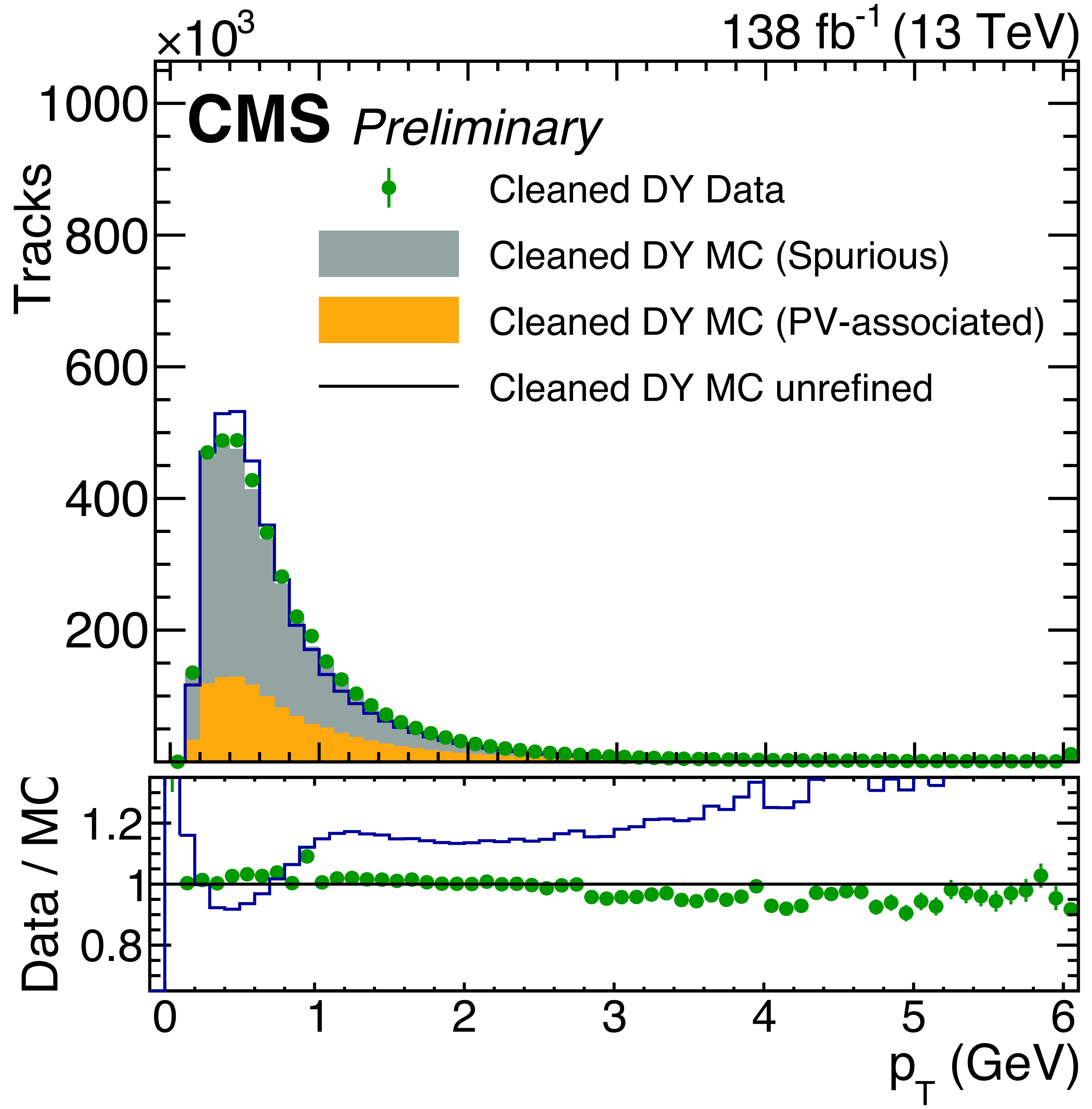
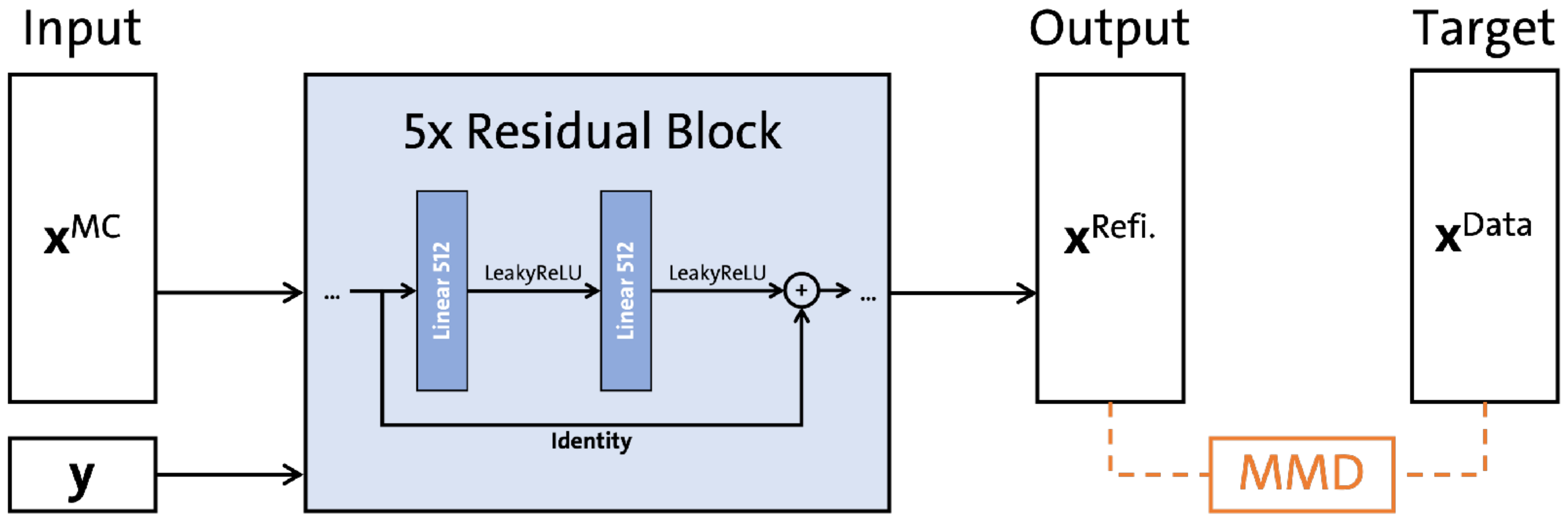
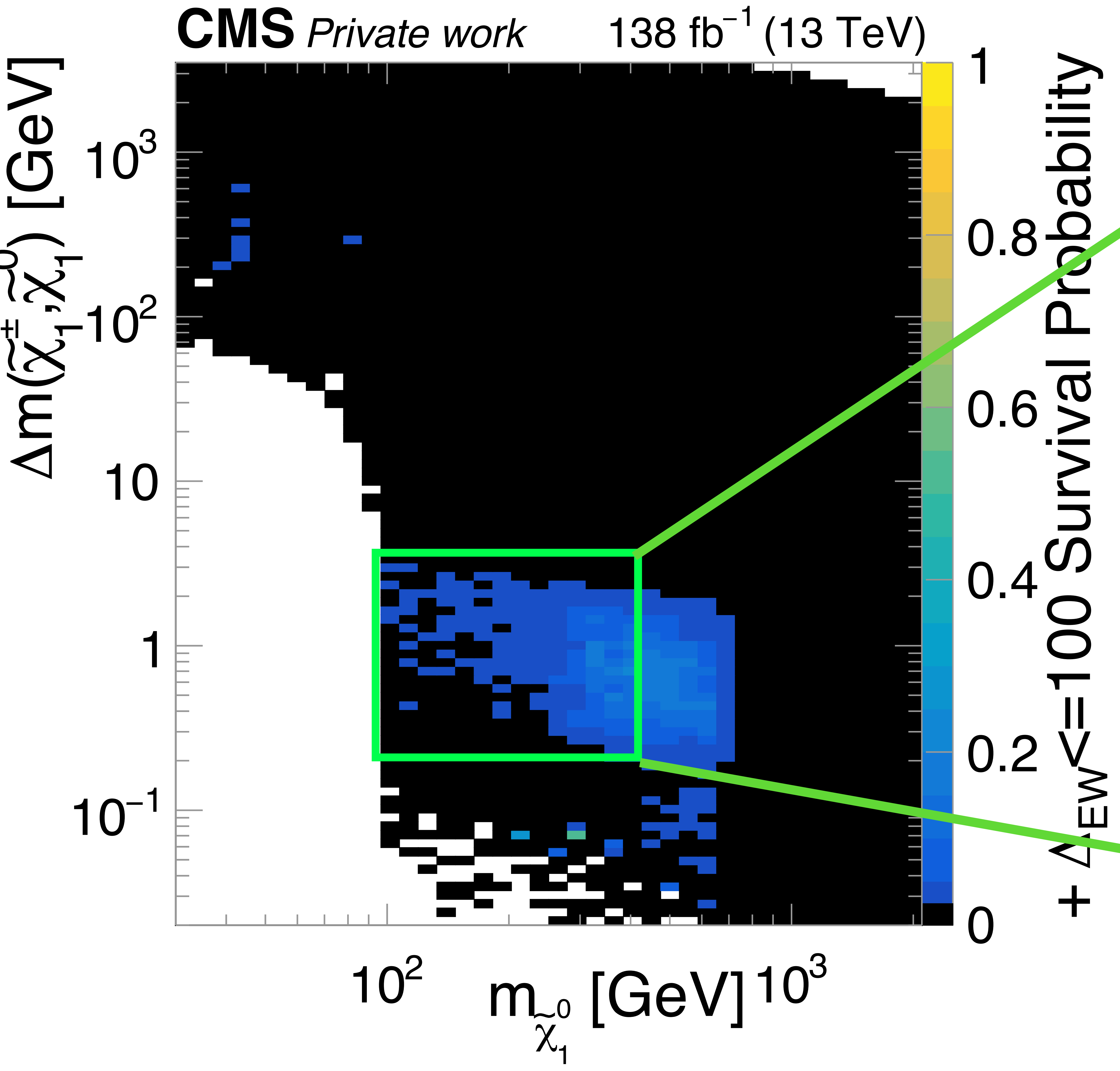


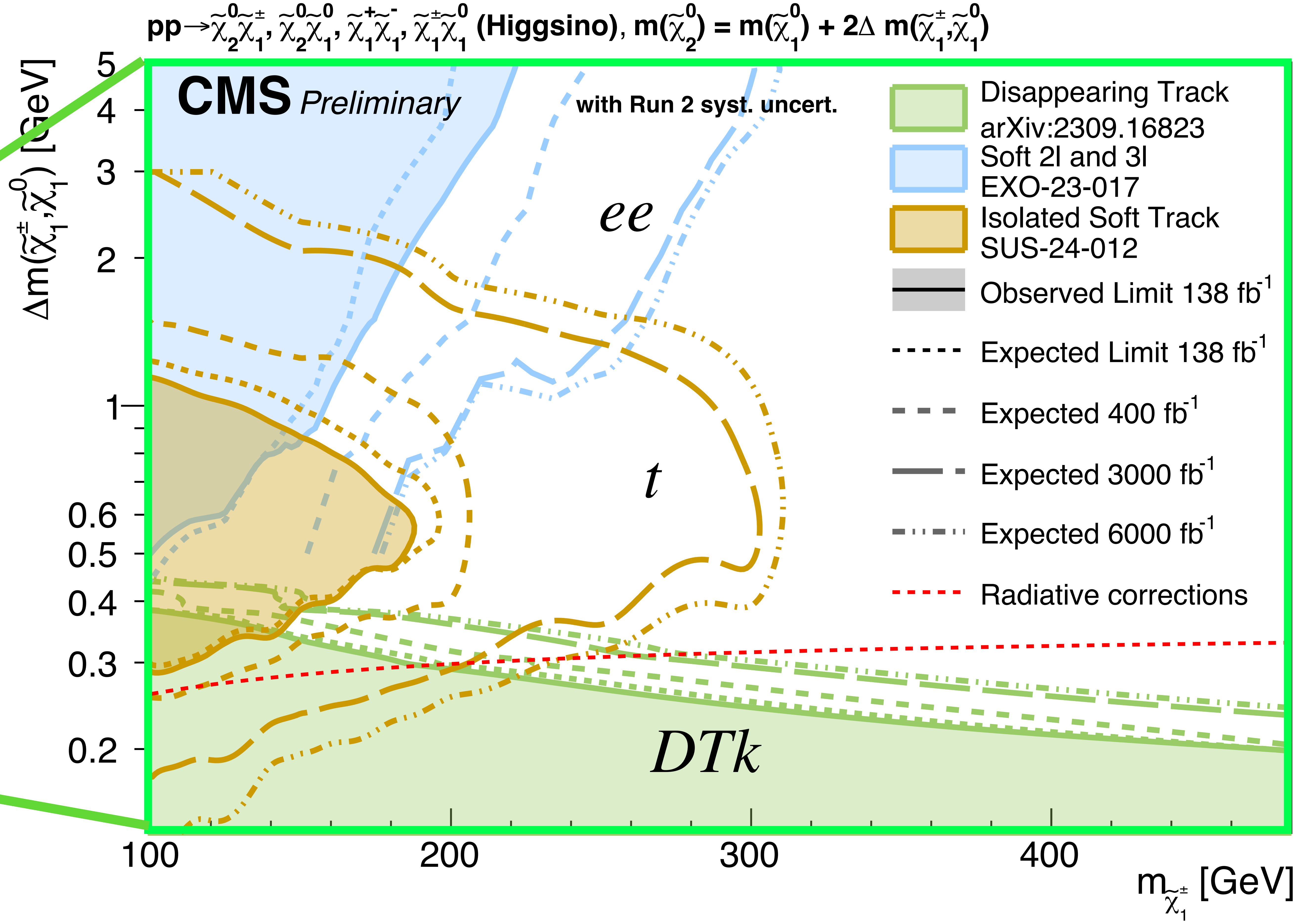


“Fast Perfekt: Regression-based refinement of fast simulation,” Moritz Wolf, Lars O. Stietz, Patrick Connor, Peter Schleper, and Samuel Bein; arXiv:2410.15992

Part 3

Compressed searches at HL-LHC

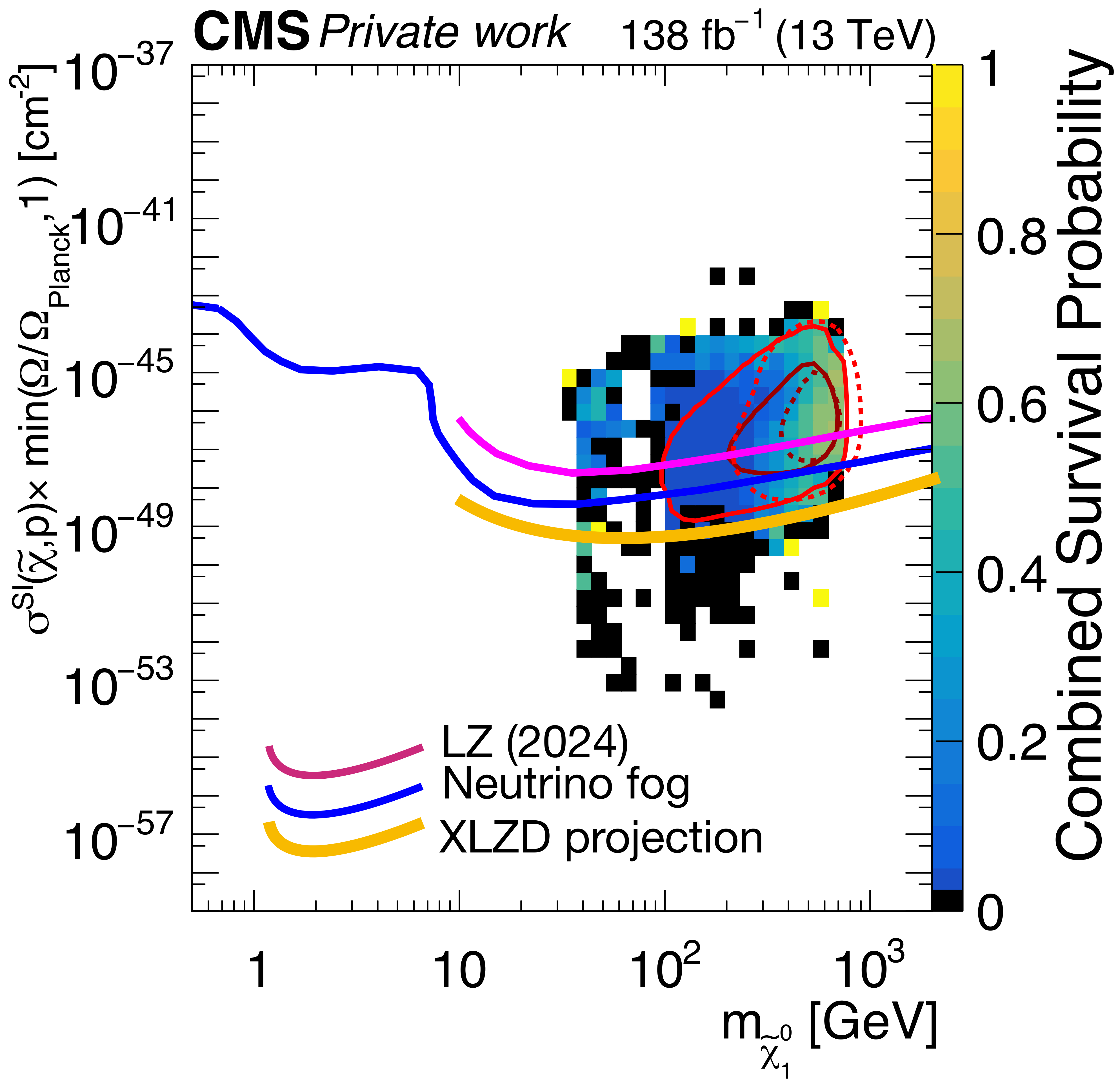




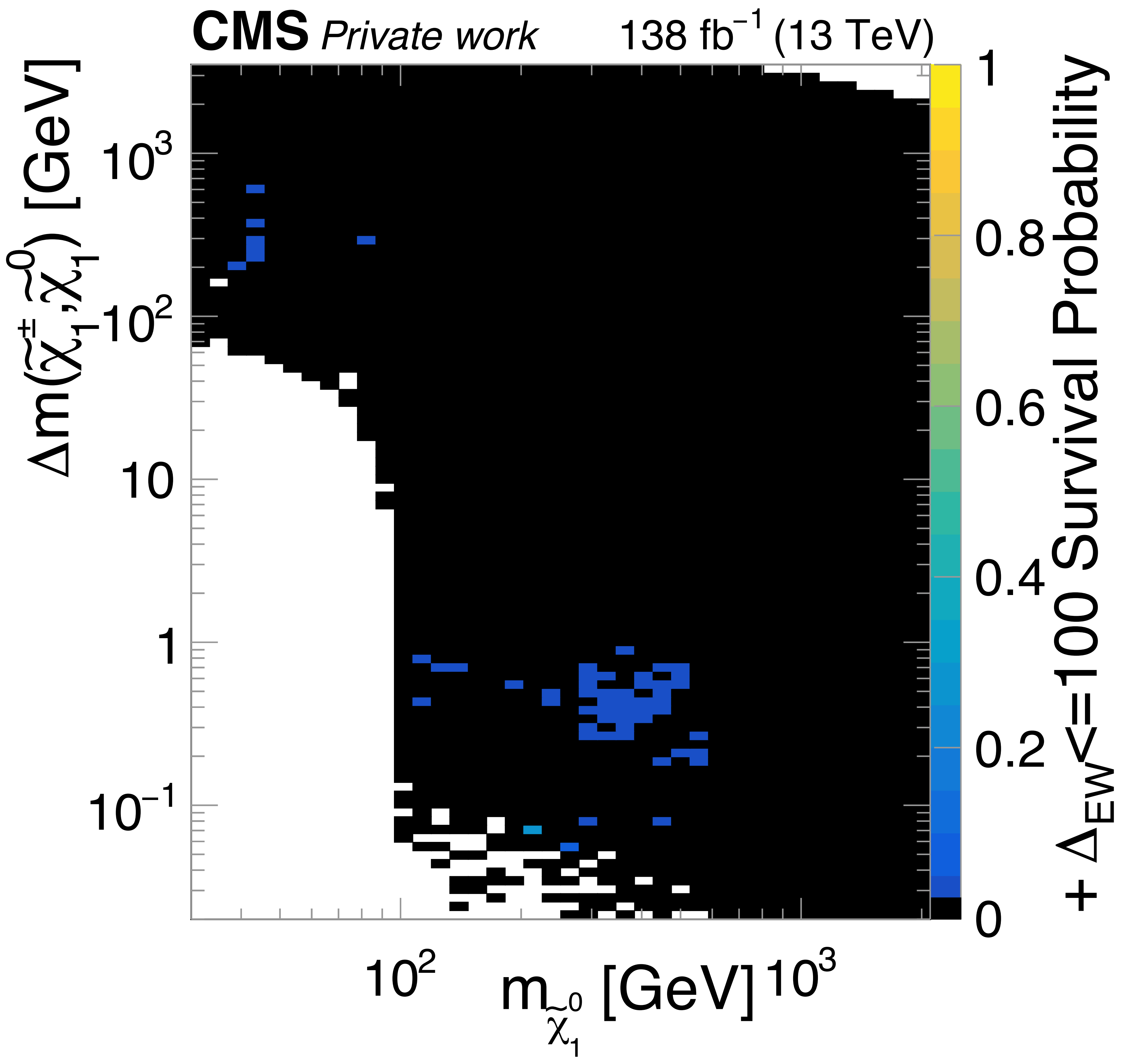
HL-LHC to significantly extend reach into natural SUSY DM stronghold - but existing methods won't conquer the beast

Future of direct detection DM Experiments

- XLZD and PandaX to venture into neutrino fog
  arXiv:2410.17137



XLZD extrapolation
(Assuming no signal)



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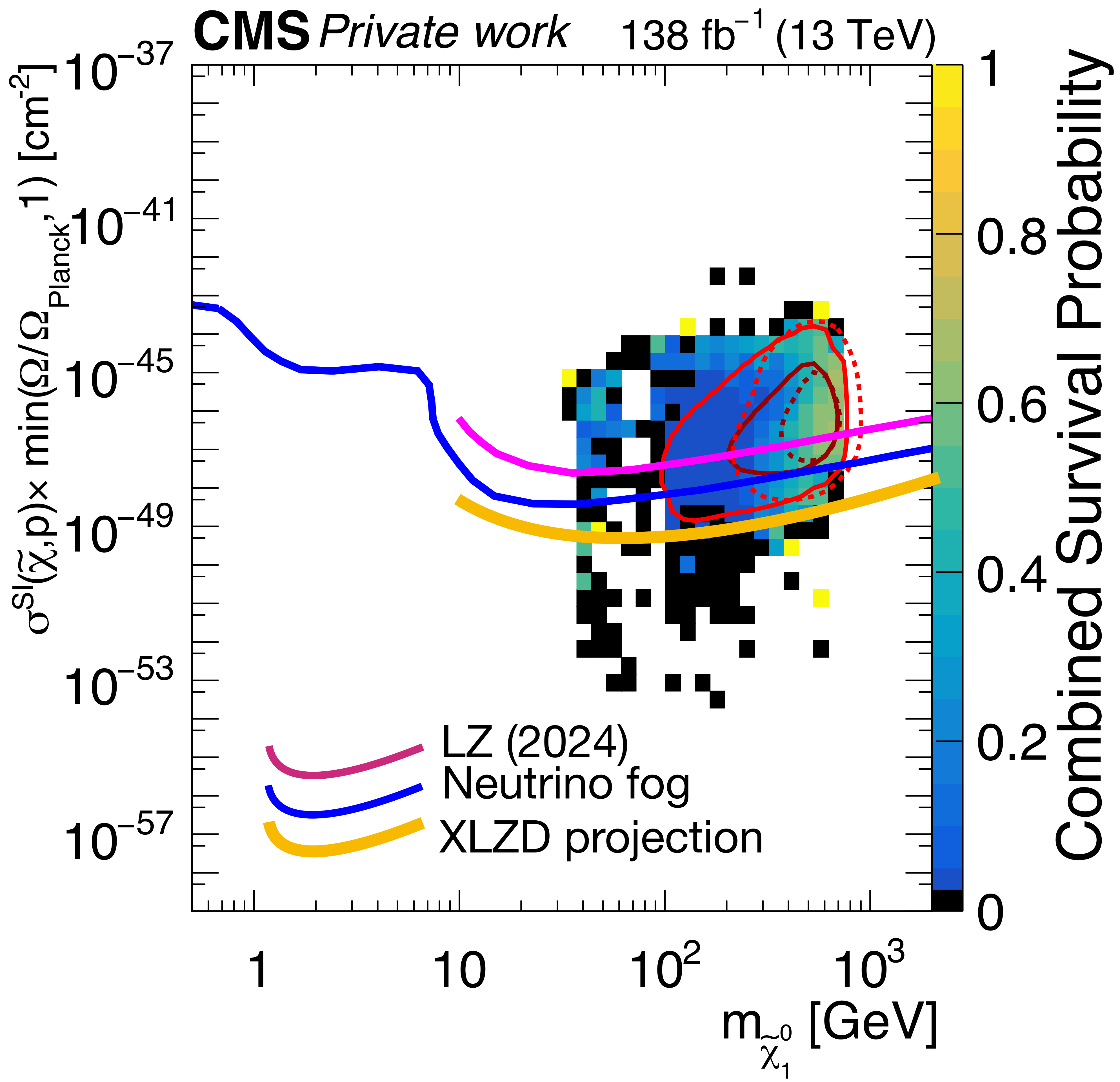

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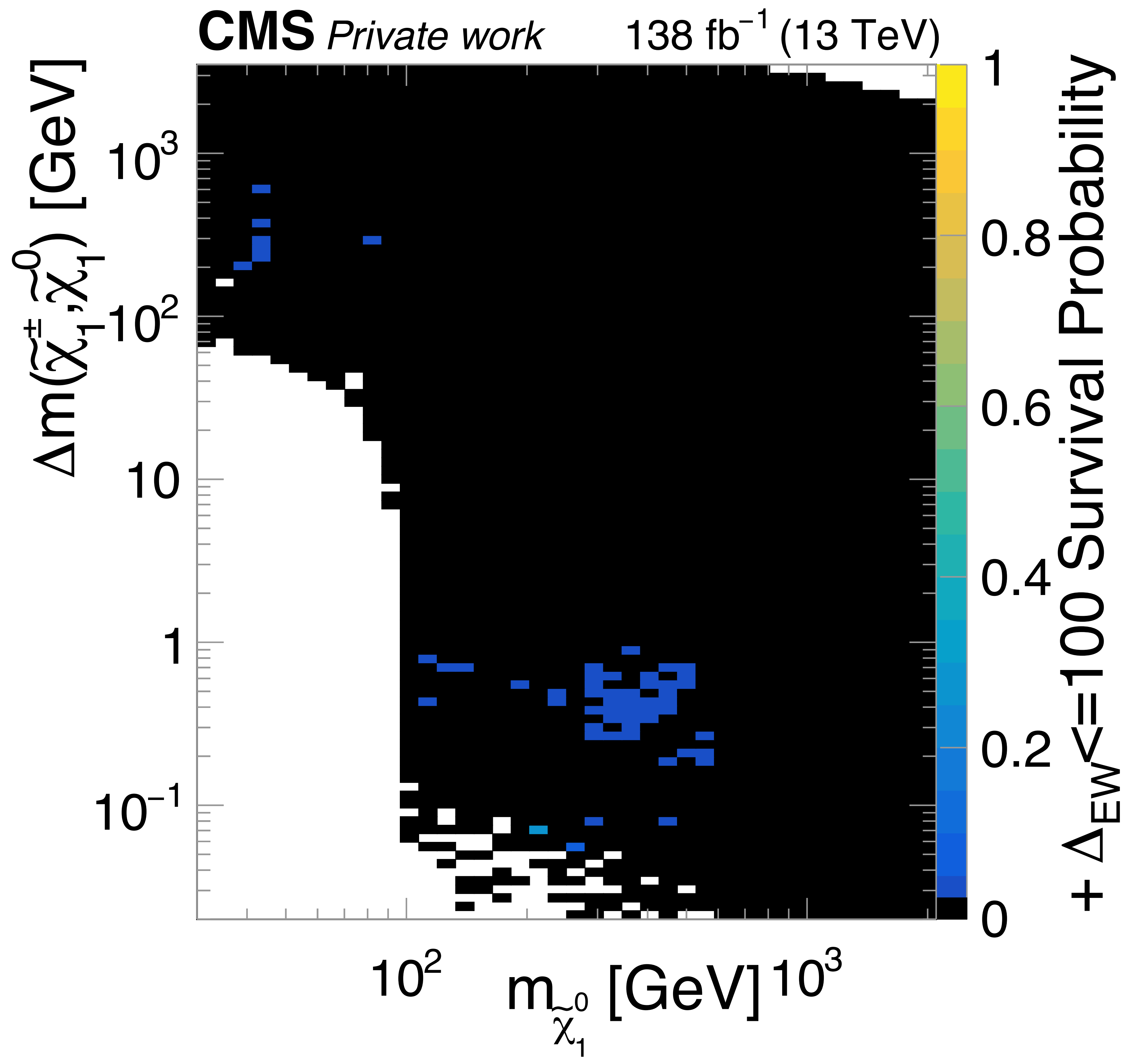

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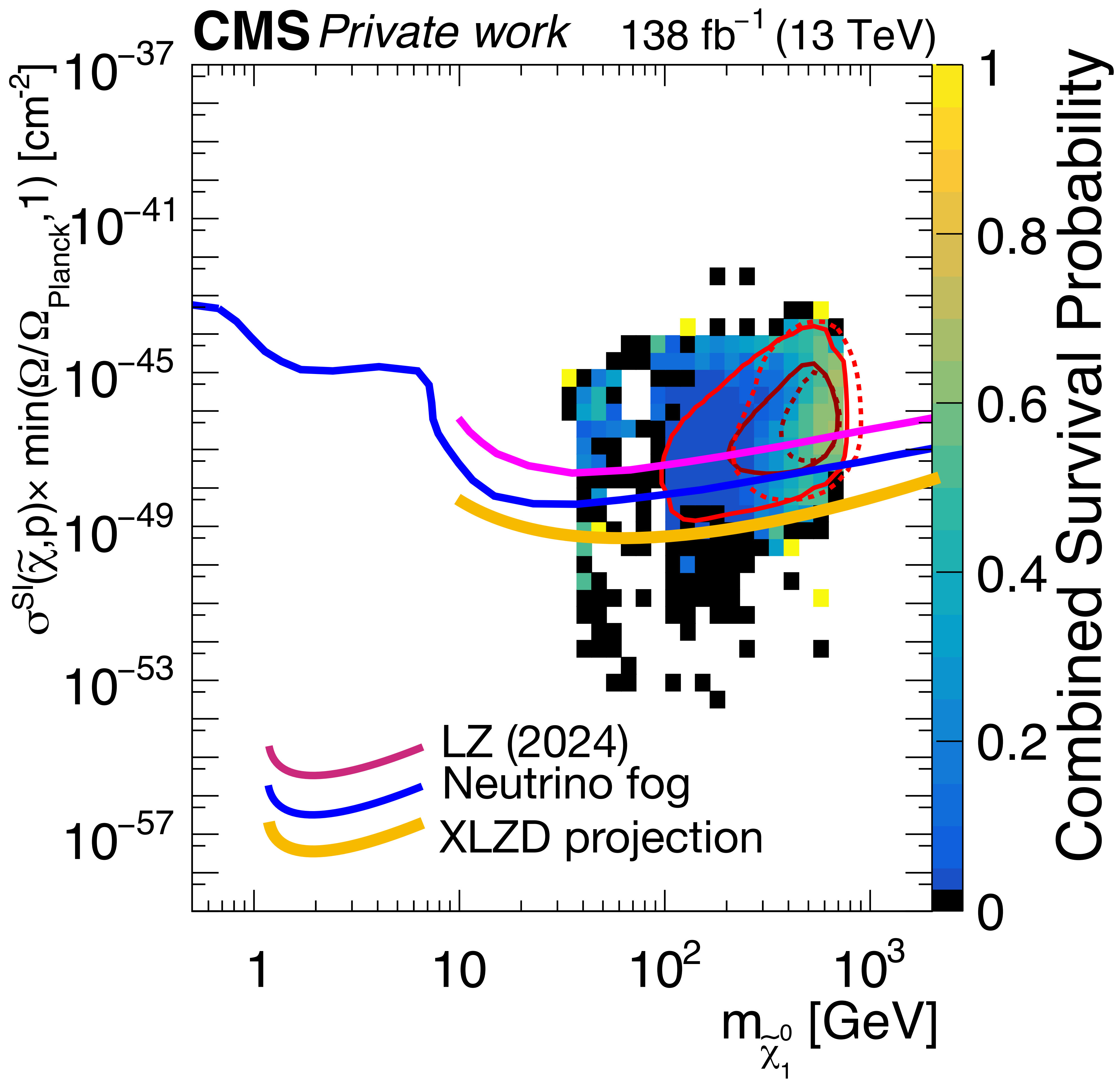

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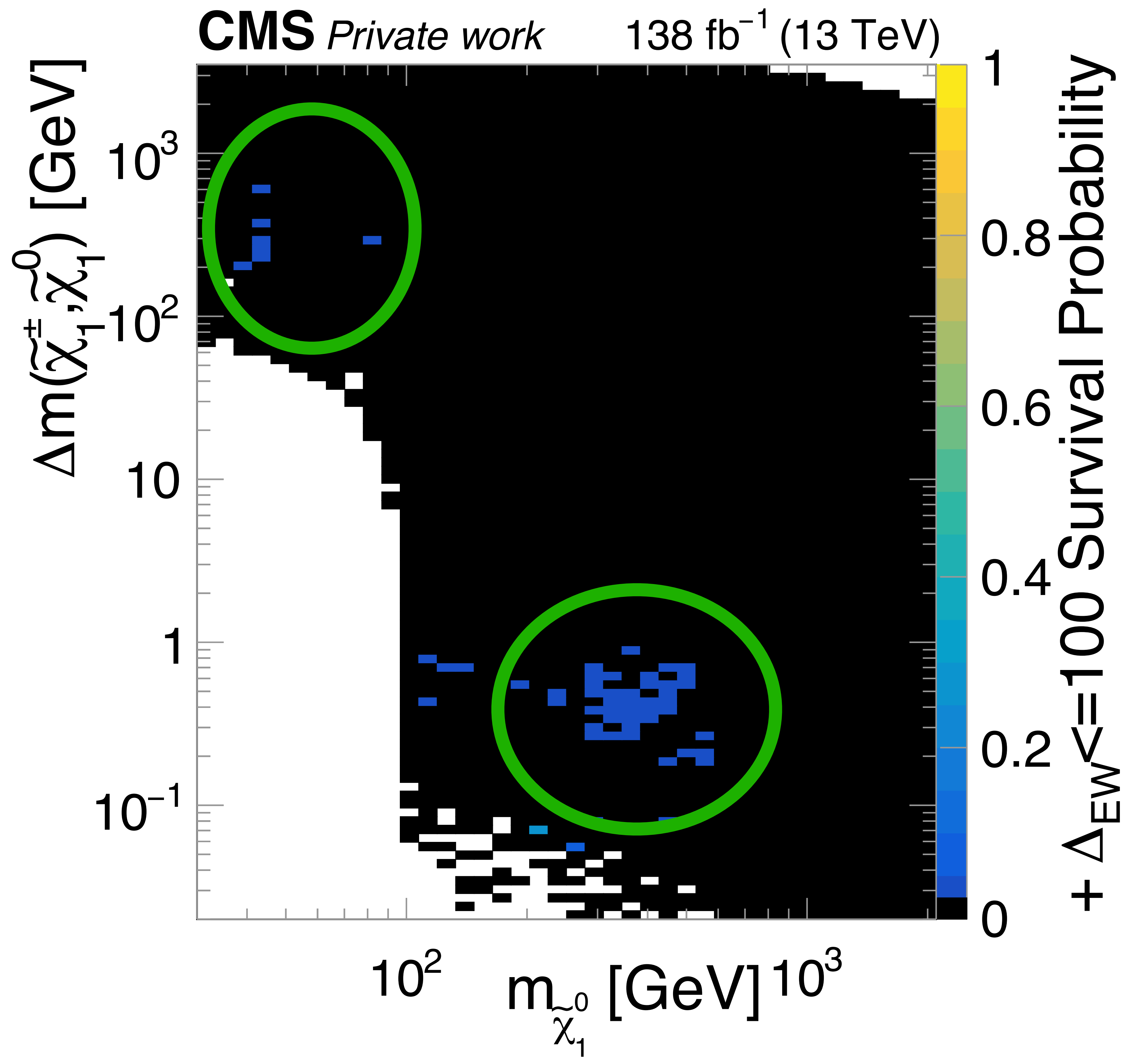
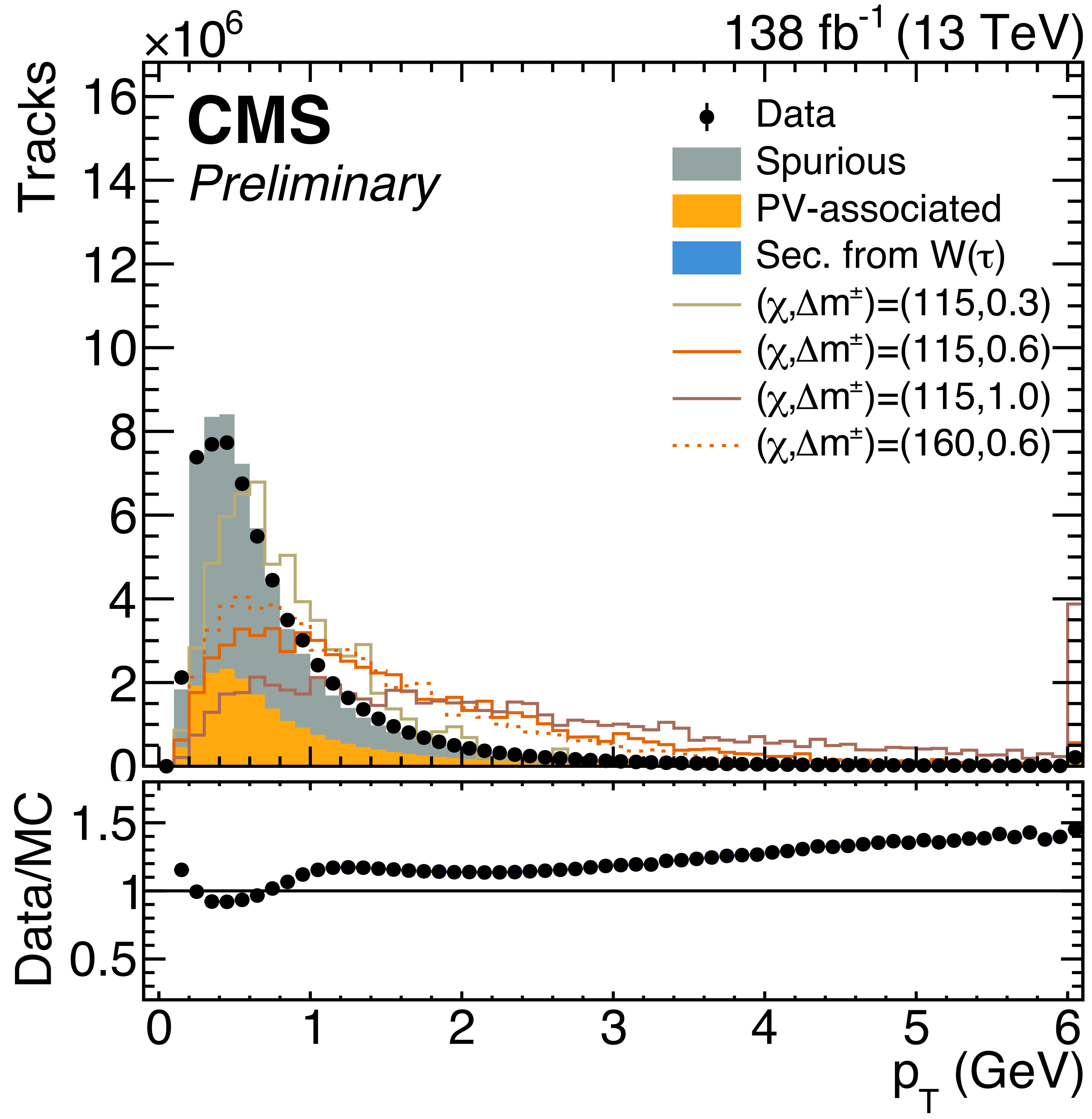


For us to contemplate

CMS Phase 2 Upgrade: L1 track trigger

- The Phase-2 Upgrade of the CMSLevel-1 Trigger
  CMS-TDR-017
- Double-layered silicon modules with 2 mm gap

- Hardware-level track triggers with pT > 2 GeV threshold



- Current iso track analysis loses 90% of events due to MET trigger
- For slightly larger Δm, could pick up 10x more signal
  - But need to design trigger paths!

Summary

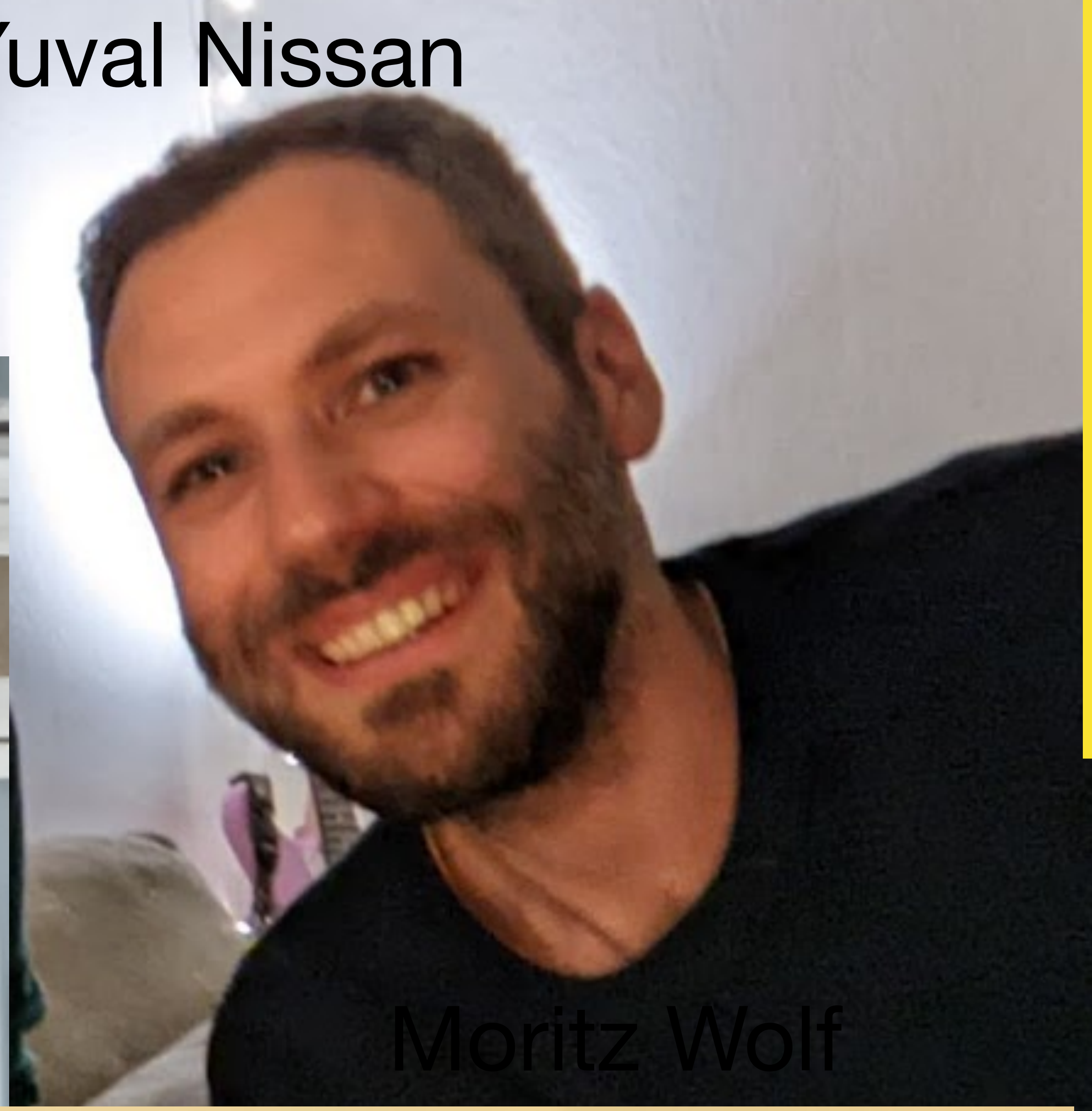
- Incredible fruits borne from efforts of Hamburg+DESY community in constraining SUSY
- SUSY is still very much an area of investigation in CMS and ATLAS
- Natural SUSY is under pressure from LHC, but not excluded
  - Some of the most interesting phase space of natural SUSY DM just beyond current reach
  - A focused and systematic approach is needed to target remaining regions
    - Development of disruptive measures, such as targeted soft isolated track triggers, *could* open up falsifiability possibility for some classes, or *something more exciting*
- Models that can explain most of DM are a farther off prize, but we'll keeping chipping
- Establishing reasonable milestones based on pMSSM studies seems like a promising approach

Thank you!

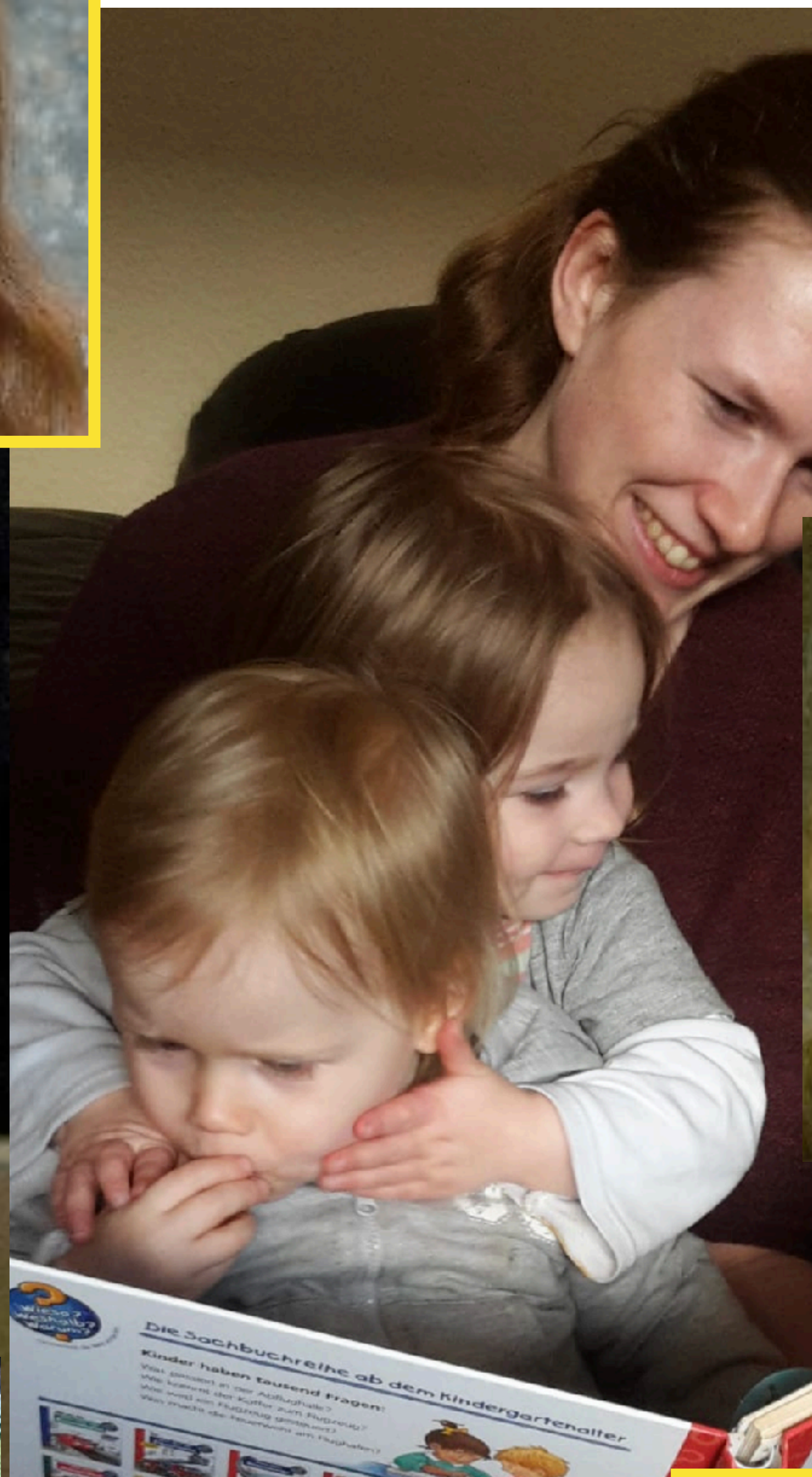
Viktor Kutzner

Malte Mrowietz

Yuval Nissan



Gudrid
Moortgat-Pick



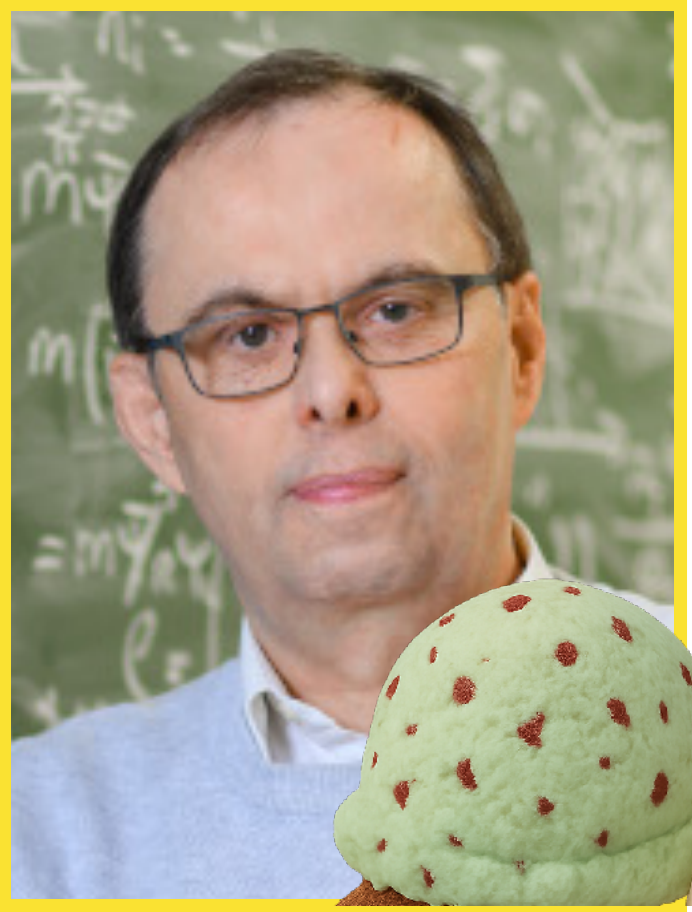
Moritz Wolf

Akshansh Singh

Isabell Melzer-Pellmann

Peter Schleper

Sam Bein



Muon collider

- https://arxiv.org/abs/2405.08858

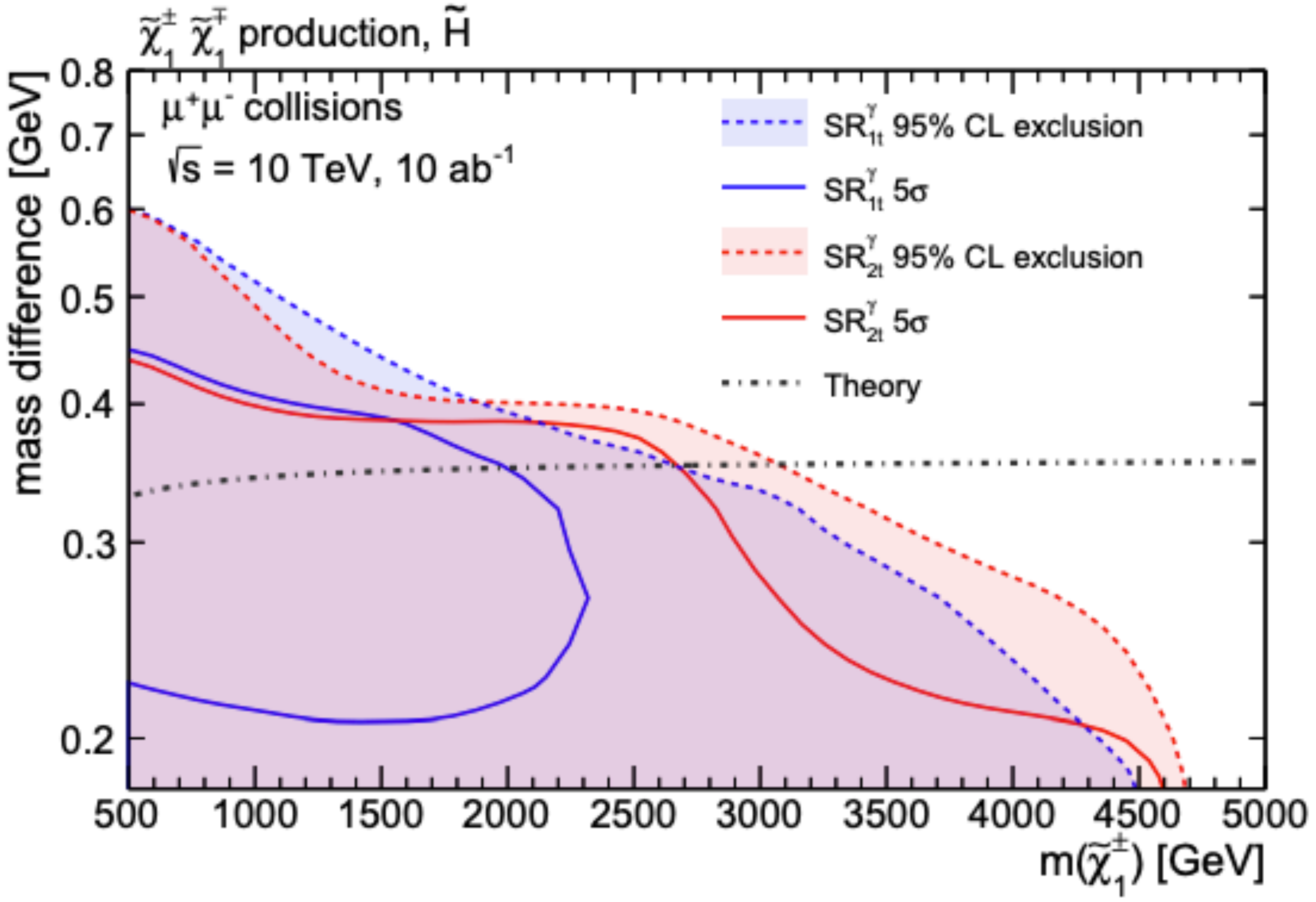
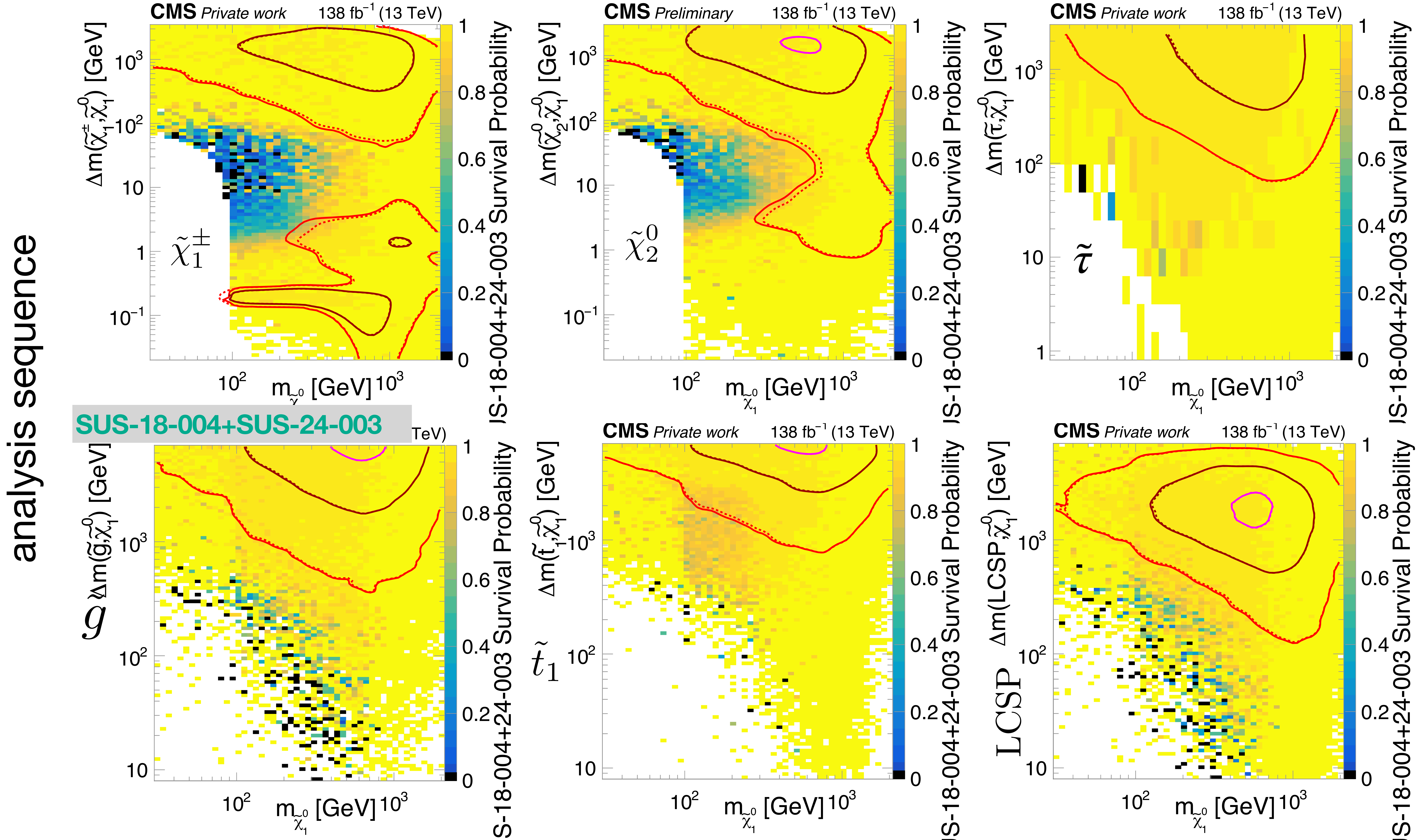


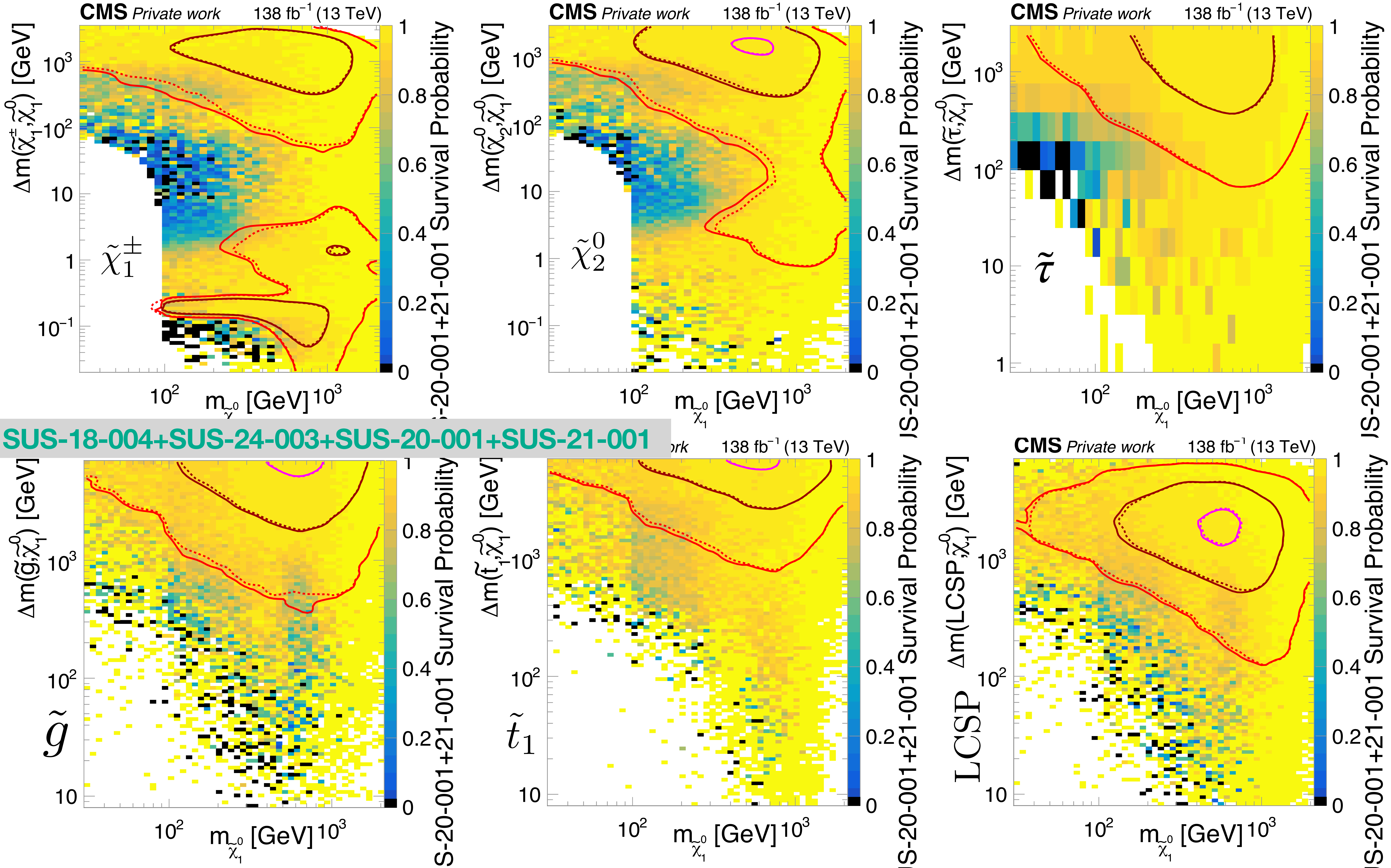
Figure 15: Expected sensitivity using 10 ab^{-1} of 10 TeV $\mu^+\mu^-$ collision data as a function of the $\tilde{\chi}^\pm$ mass and mass difference with the lightest neutral state, assuming a pure-higgsino scenario. The mass splitting as a function of the $\tilde{\chi}^\pm$ mass is shown by the dashed grey line and was calculated at the one-loop level [28, 62].



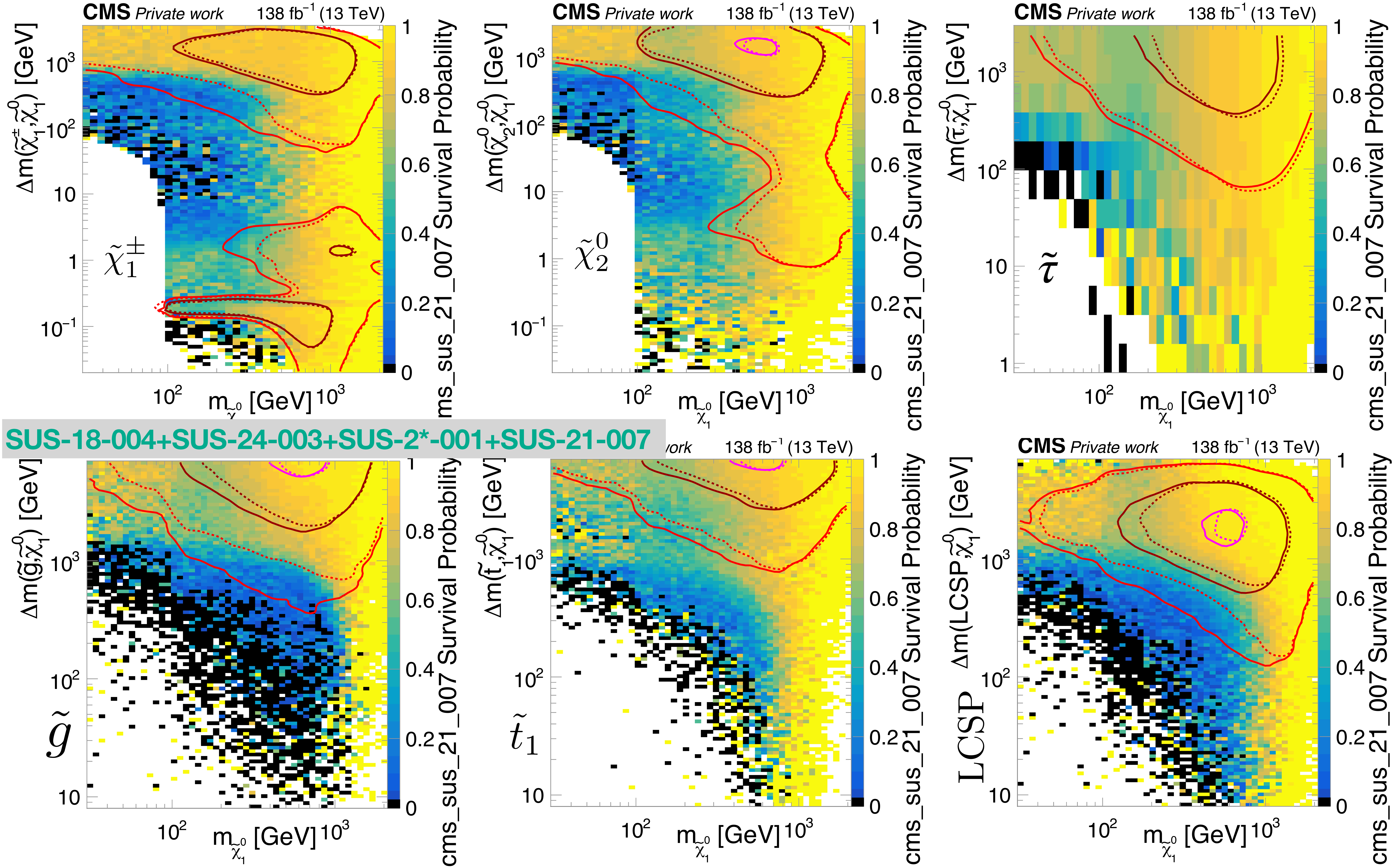
analysis sequence
SUS-18-004+SUS-24-003
CMS Private work
CMS Preliminary
138 fb^{-1} (13 TeV)
Survival Probability
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
$\tilde{\tau}$
g
$\tilde{t}_1$
LCSP
$m_{\tilde{\chi}_1^0}$ [GeV]

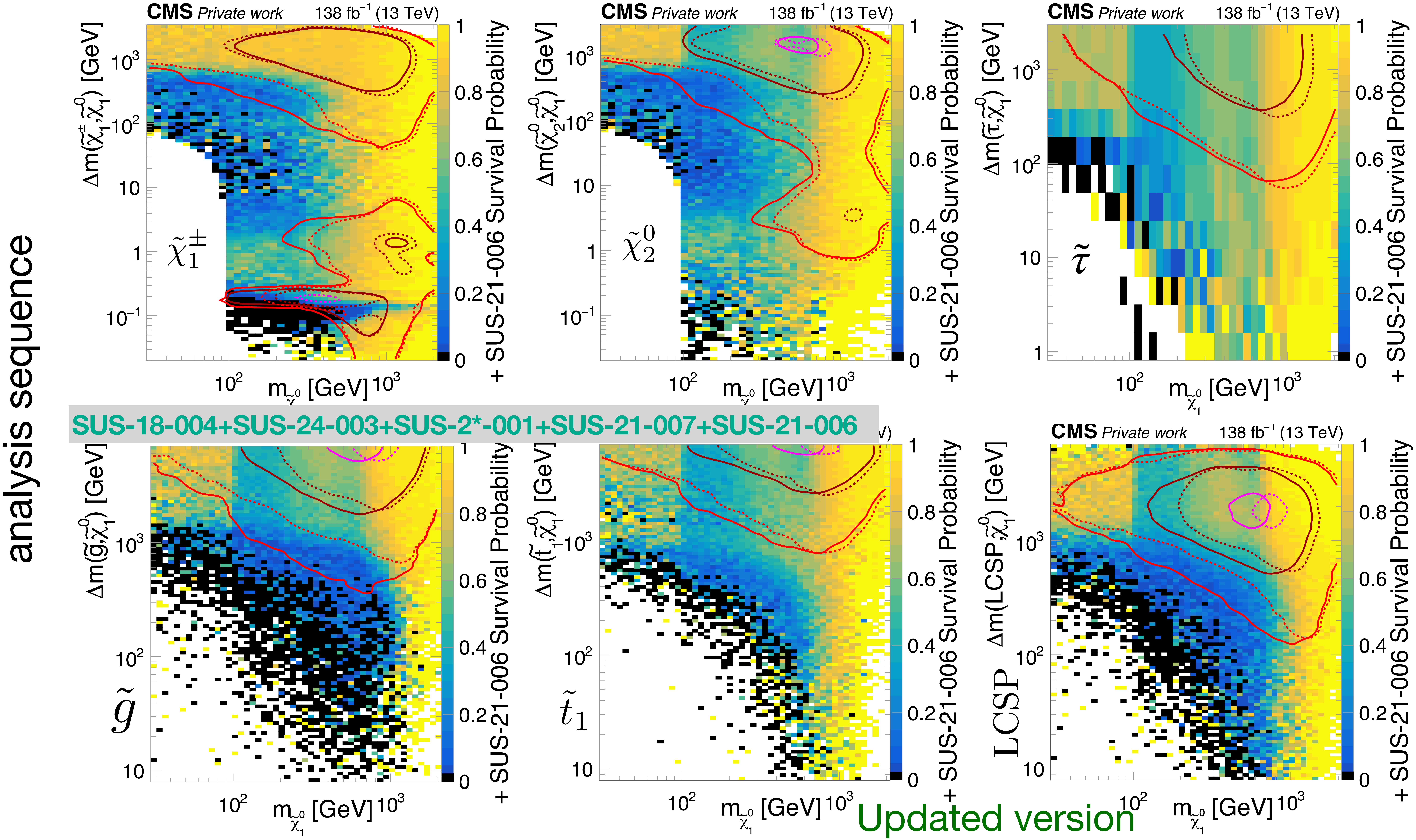
analysis sequence

SUS-18-004+SUS-24-003+SUS-20-001+SUS-21-001



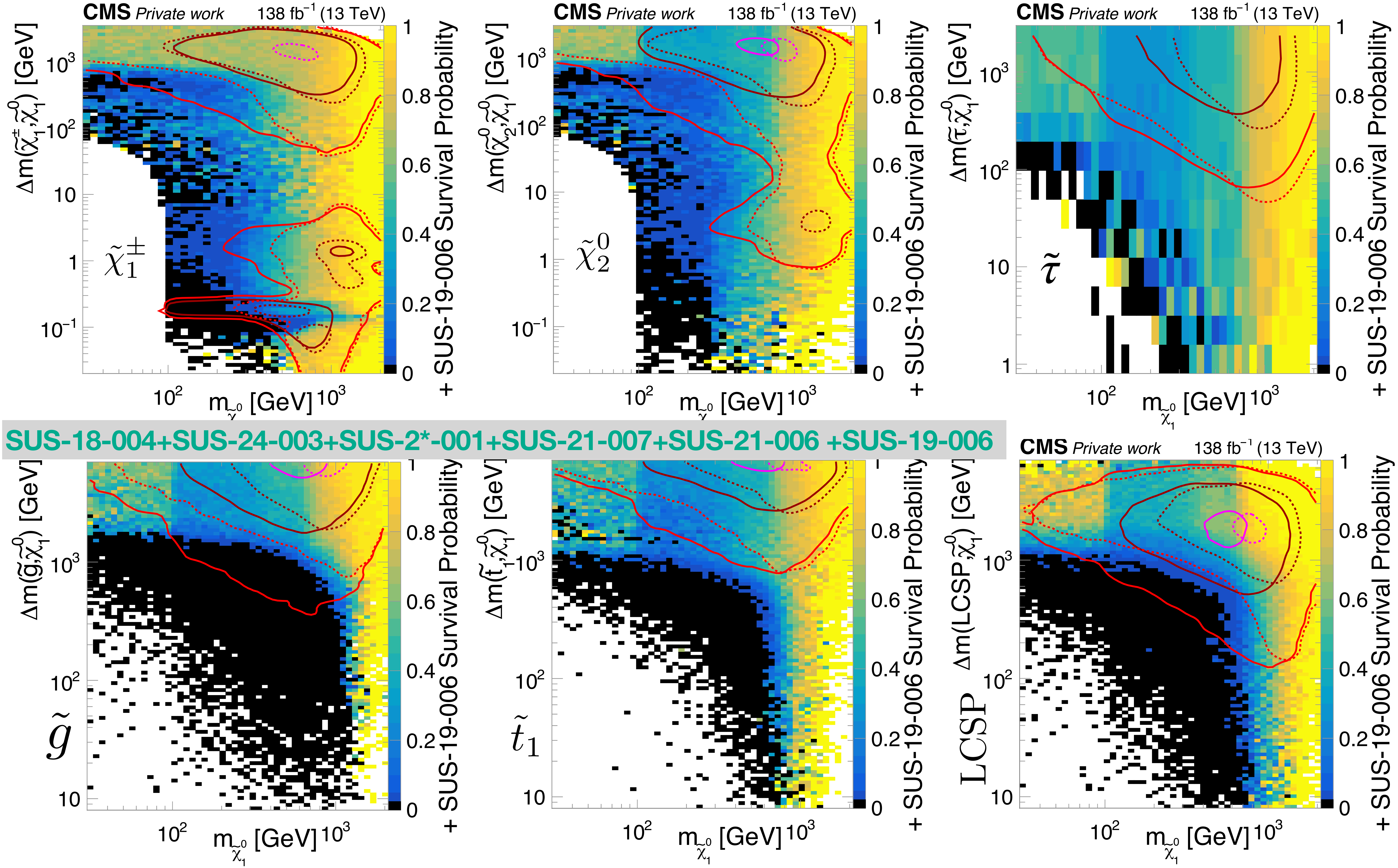
analysis sequence



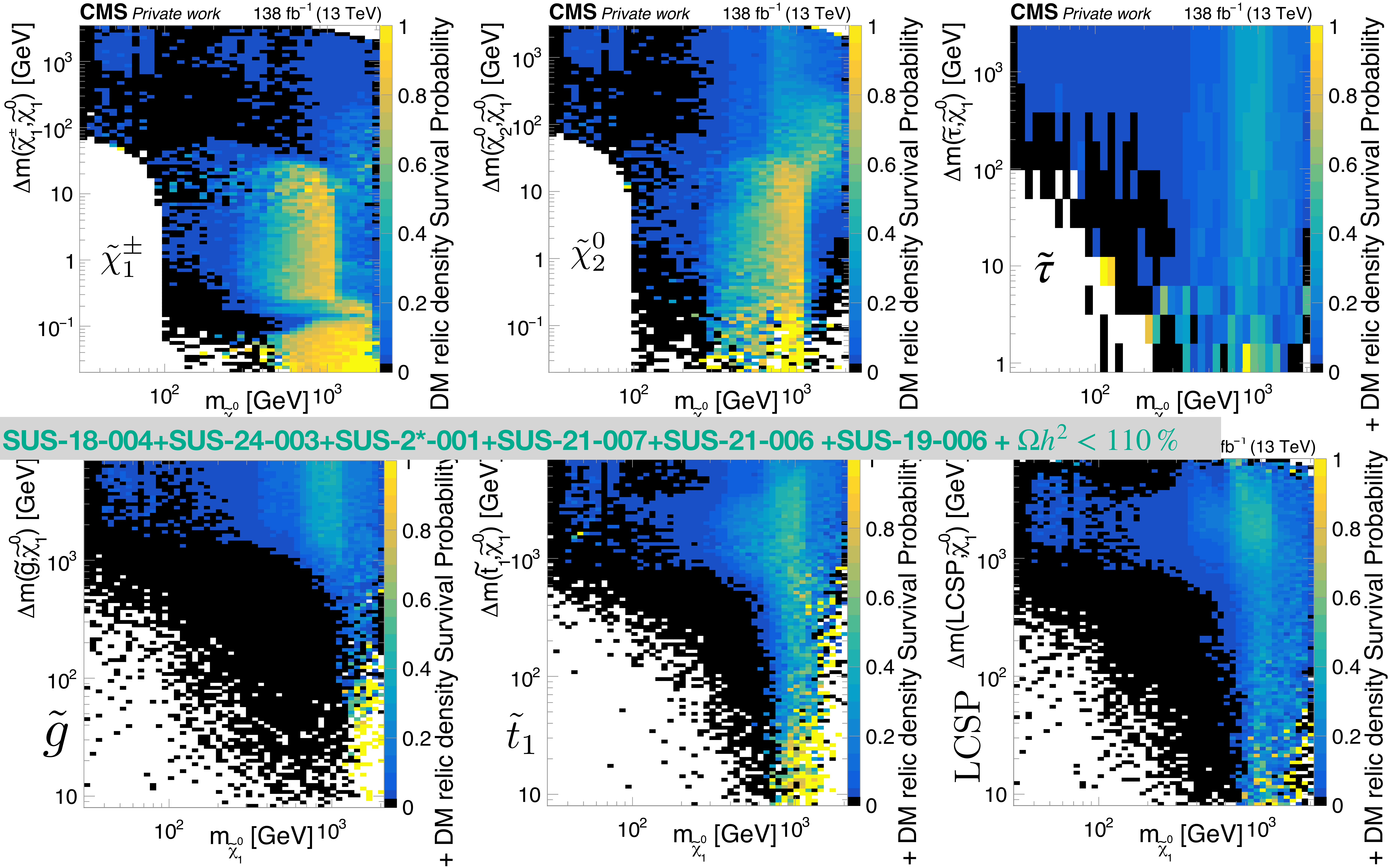


analysis sequence
CMS Private work
138 fb^{-1} (13 TeV)
SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006
+ SUS-21-006 Survival Probability
$\tilde{\chi}_1^{\pm}$
$\tilde{\chi}_2^0$
$\tilde{\tau}$
$\tilde{g}$
$\tilde{t}_1$
LCSP
Updated version

analysis sequence

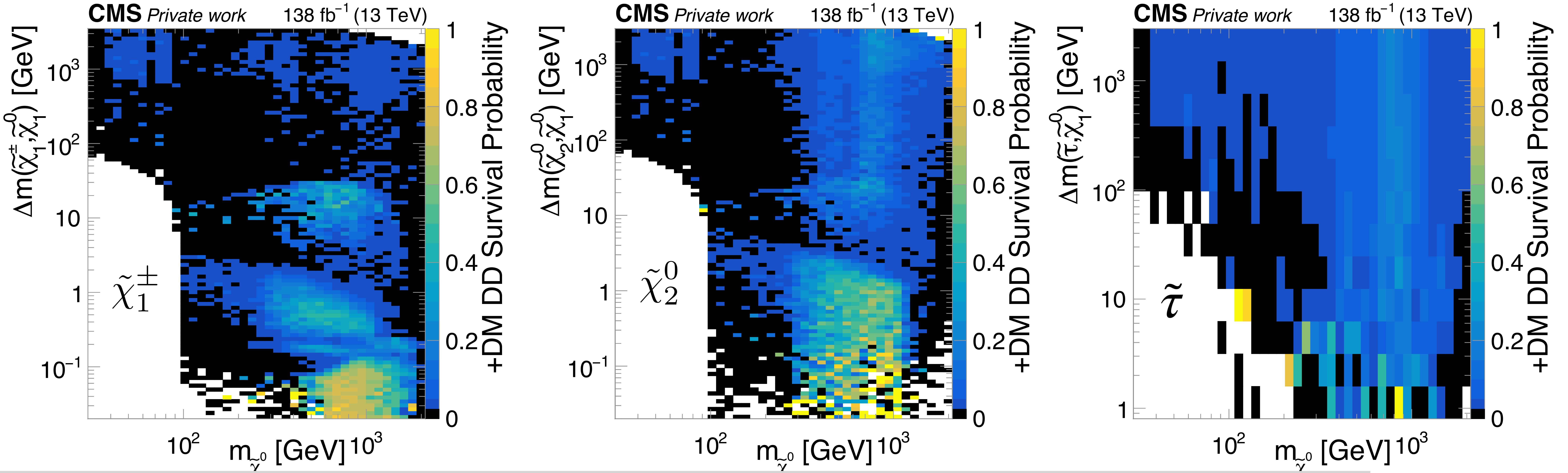


analysis sequence

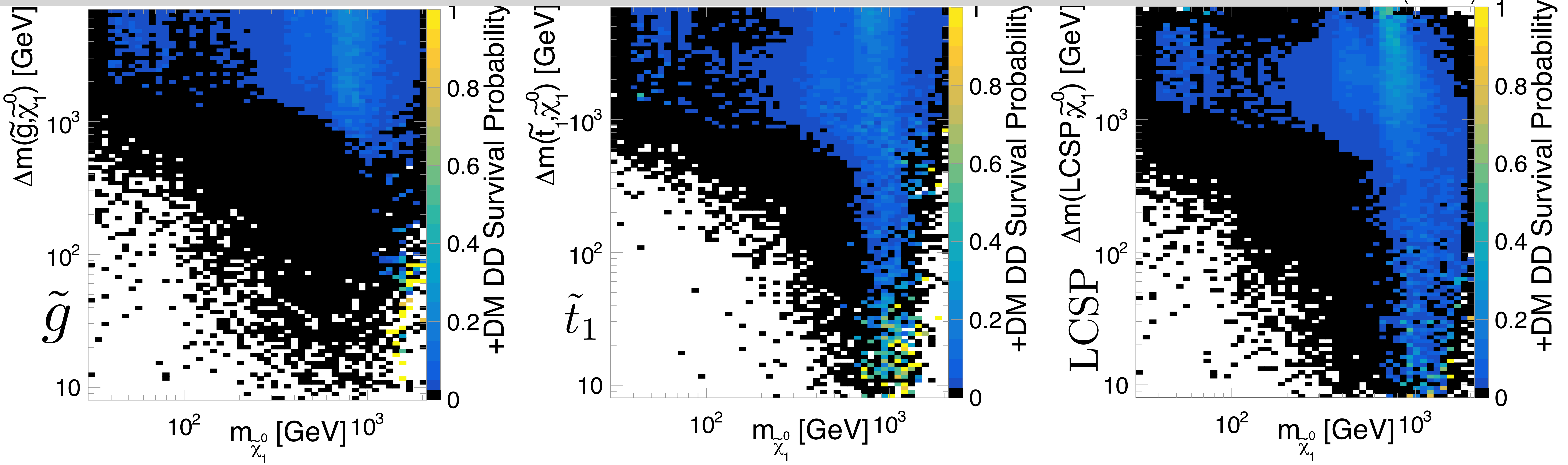


SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006 + $\Omega h^2 < 110\,\%$

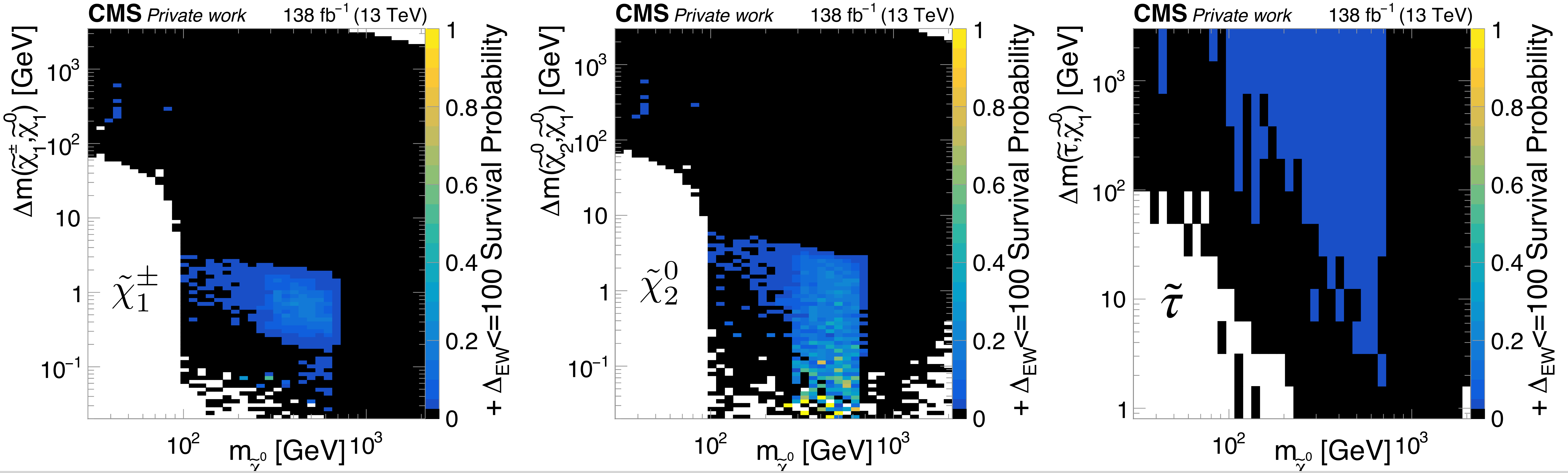
pMSSM impact analysis sequence



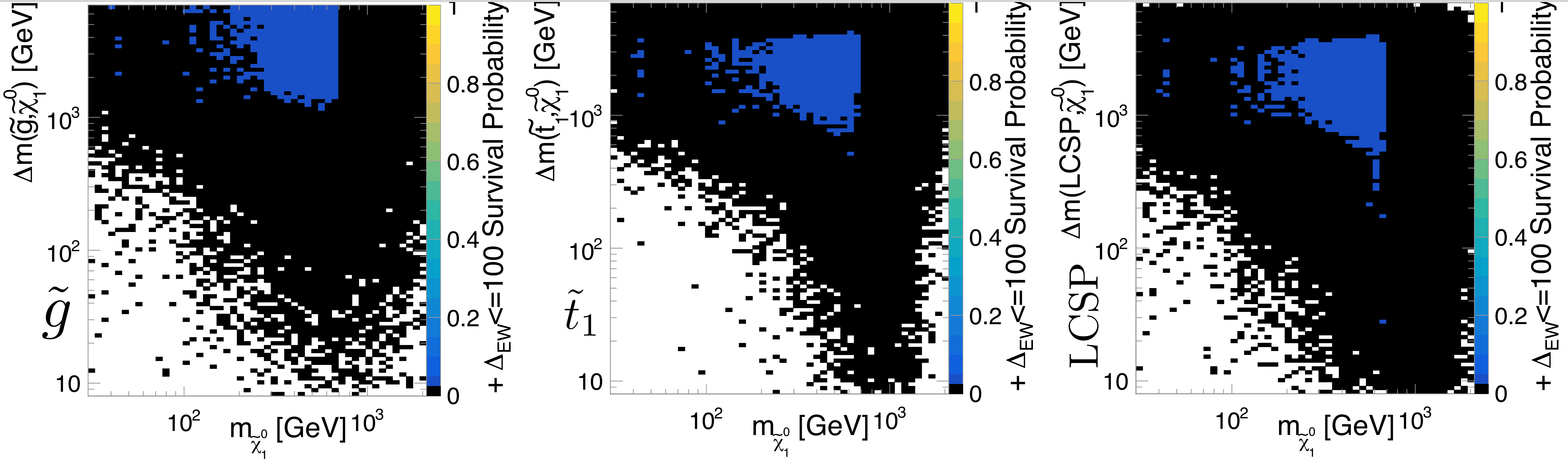
SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006 + DM constraints



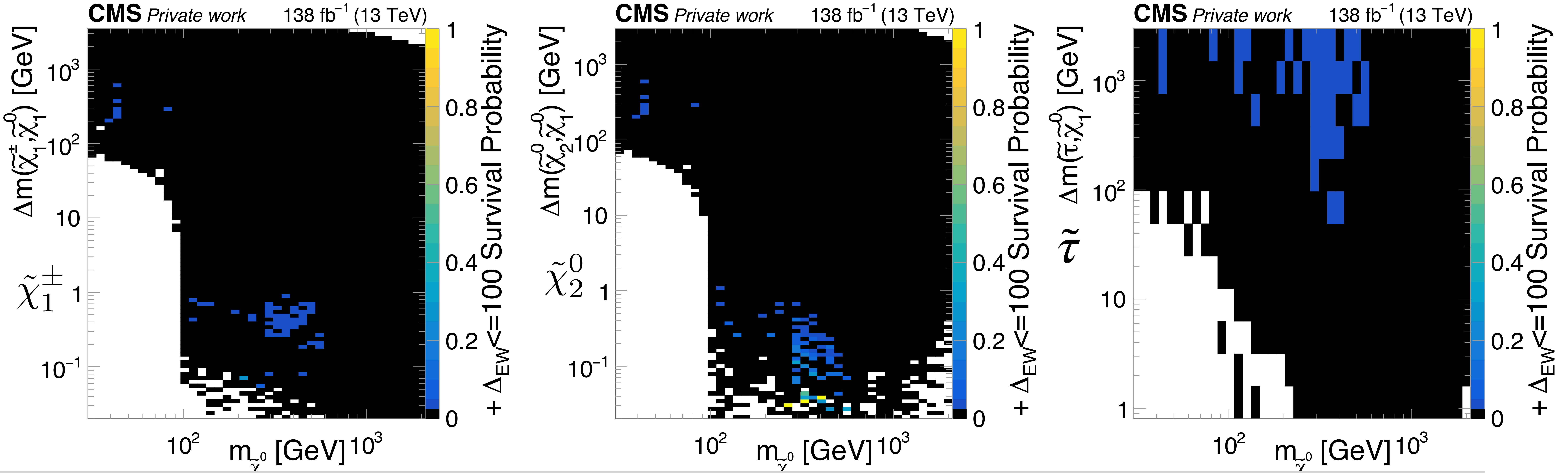
pMSSM impact analysis sequence



SUS-18-004+SUS-24-003+SUS-2*-001+SUS-21-007+SUS-21-006 +SUS-19-006 + DM constraints + deltaEW<100



pMSSM impact analysis sequence



SUS-18-004+SUS-24-003+SUS-20-001+SUS-21-007+SUS-21-006 +SUS-19-006 + XLZD! + deltaEW<100