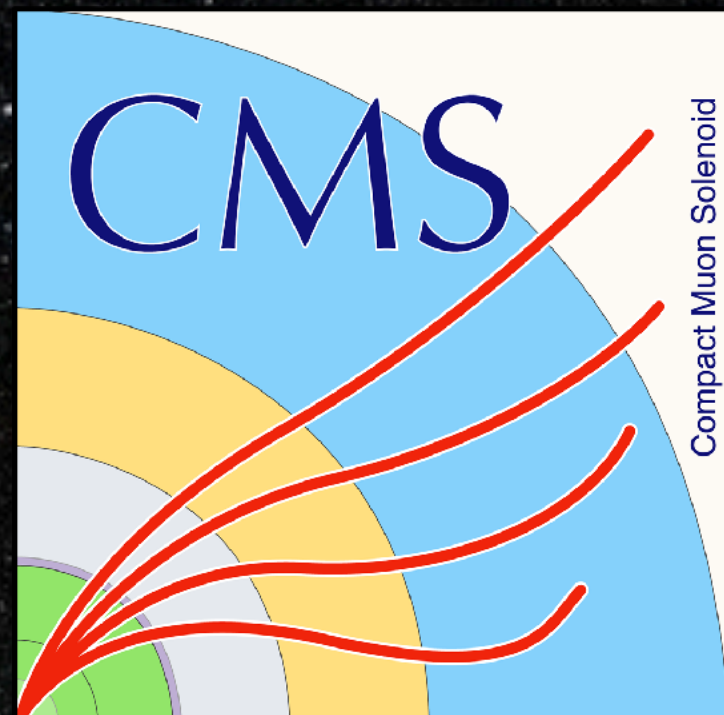




Searches heavy stable neutral particles at the LHC

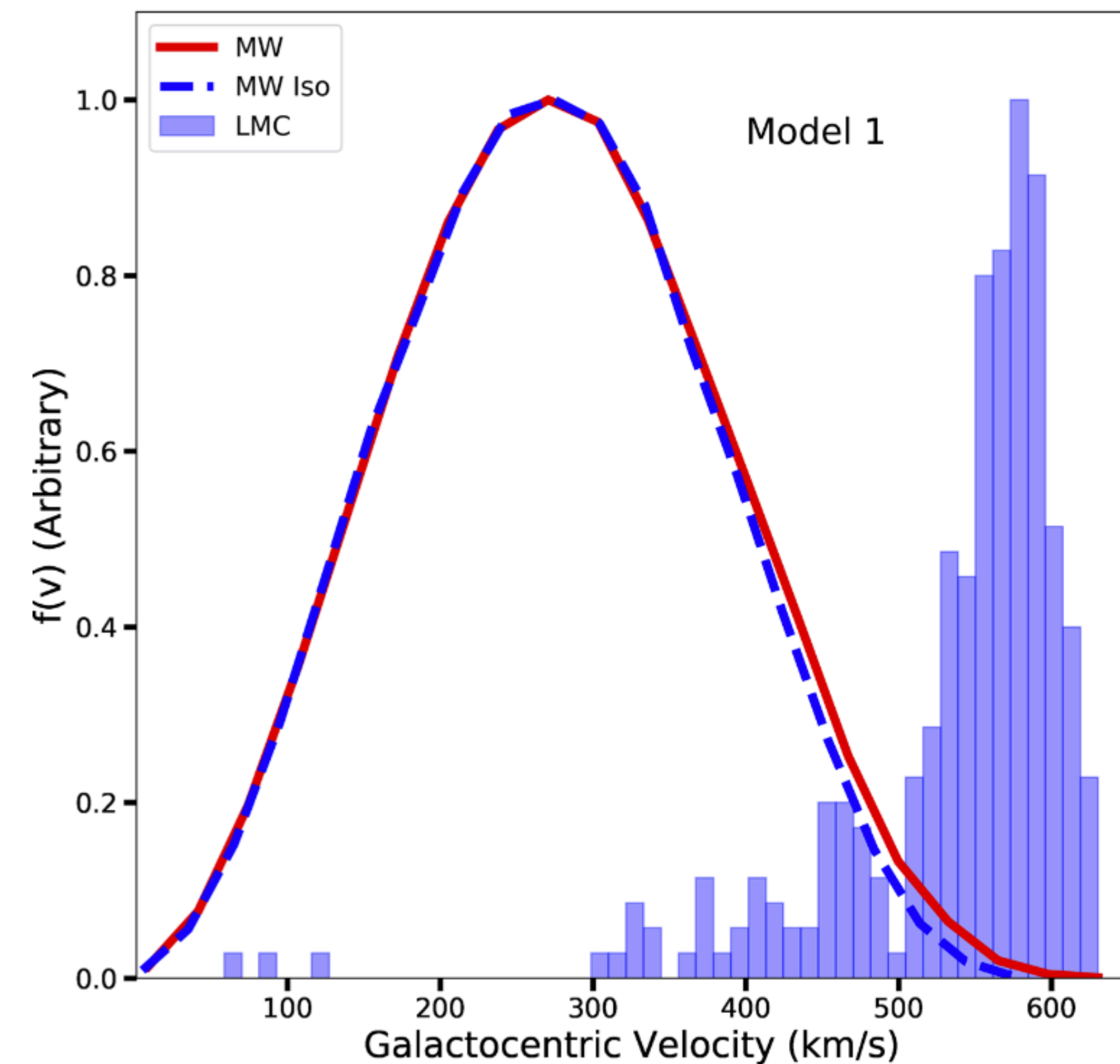
PIC2023: 42nd Symposium on Physics in Collision,
13 Oct 2023, Arica, Chile
Sam Bein, on behalf of ATLAS and CMS



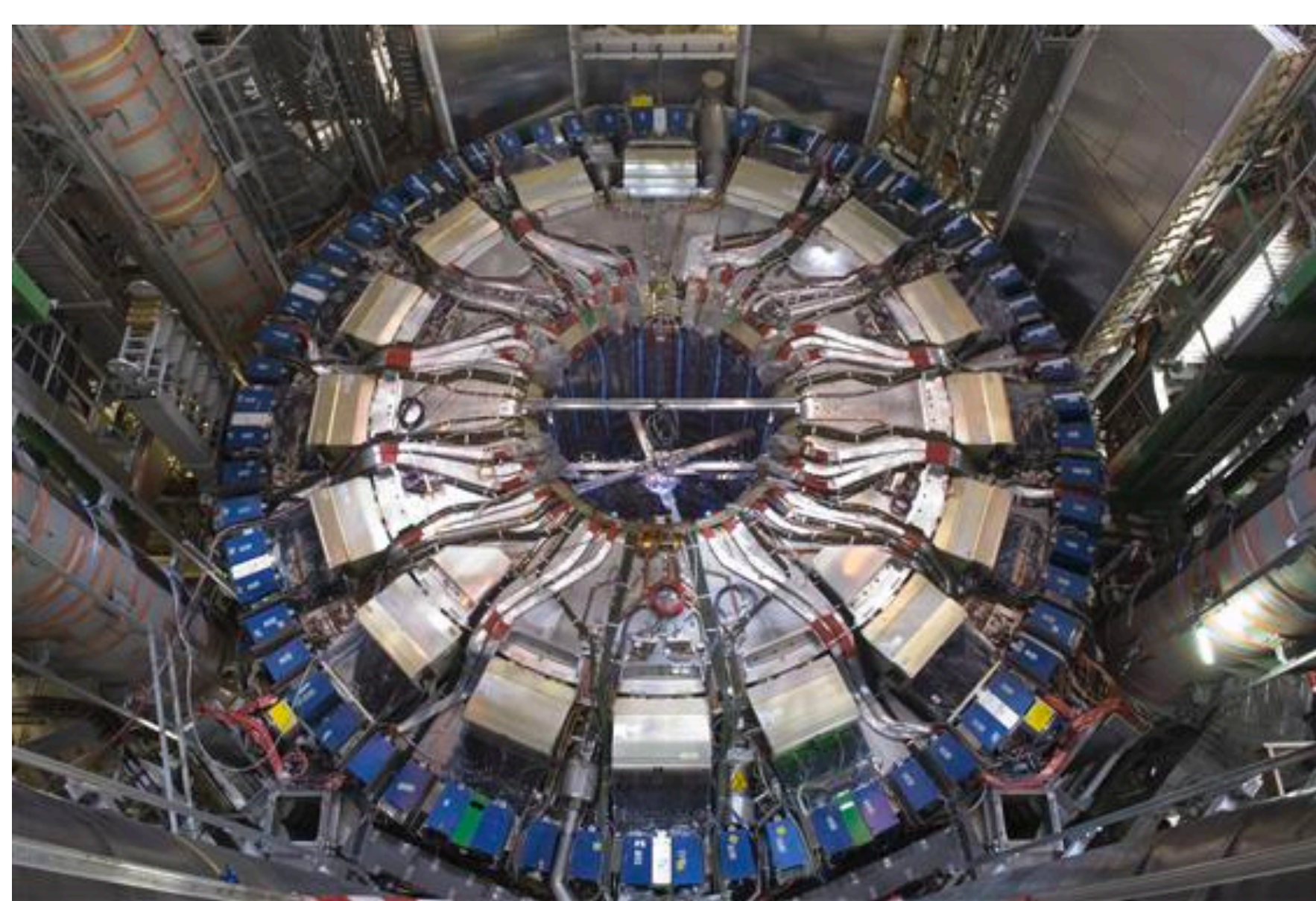


G. Besla *et al* JCAP11(2019) 013

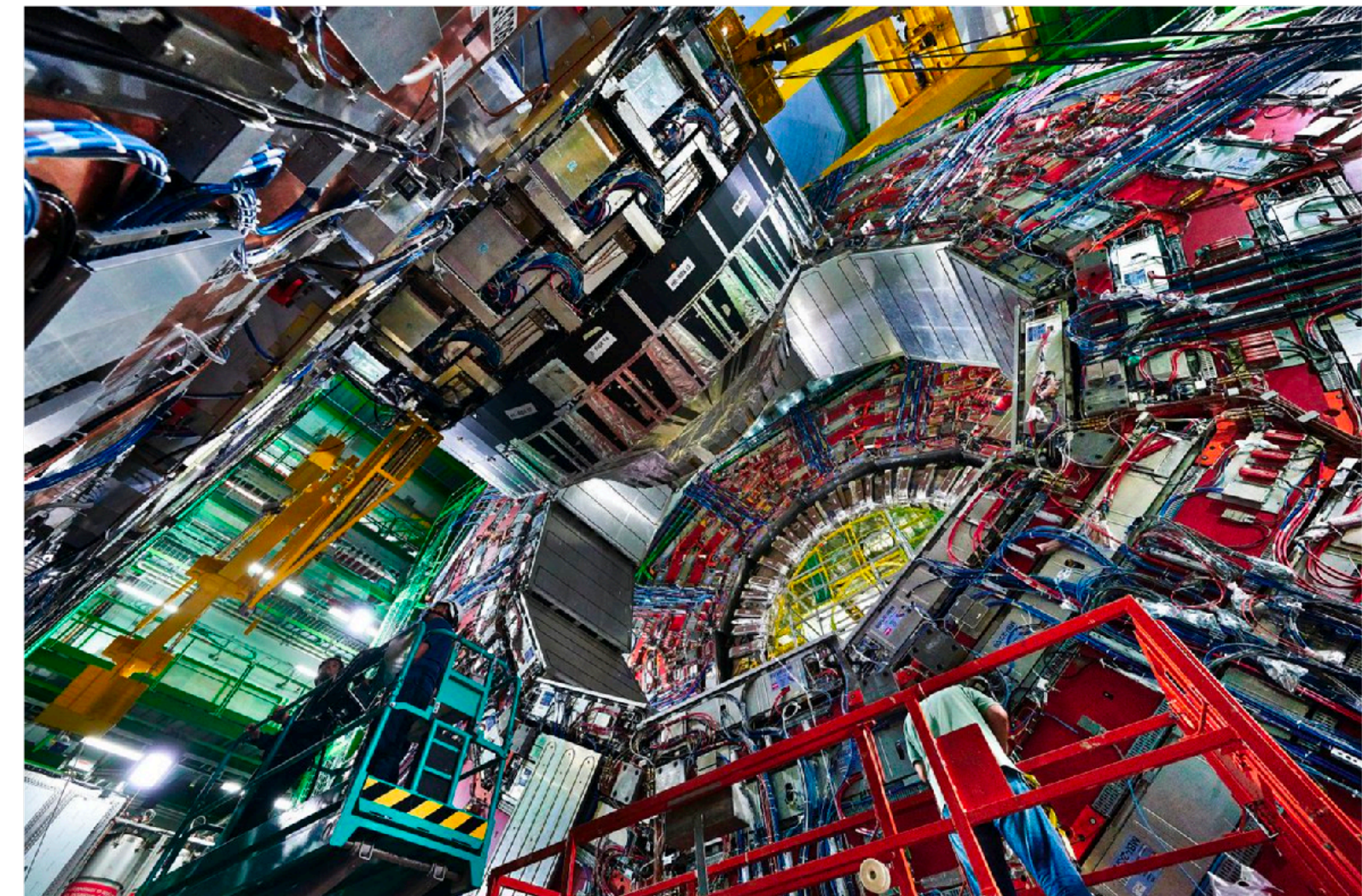
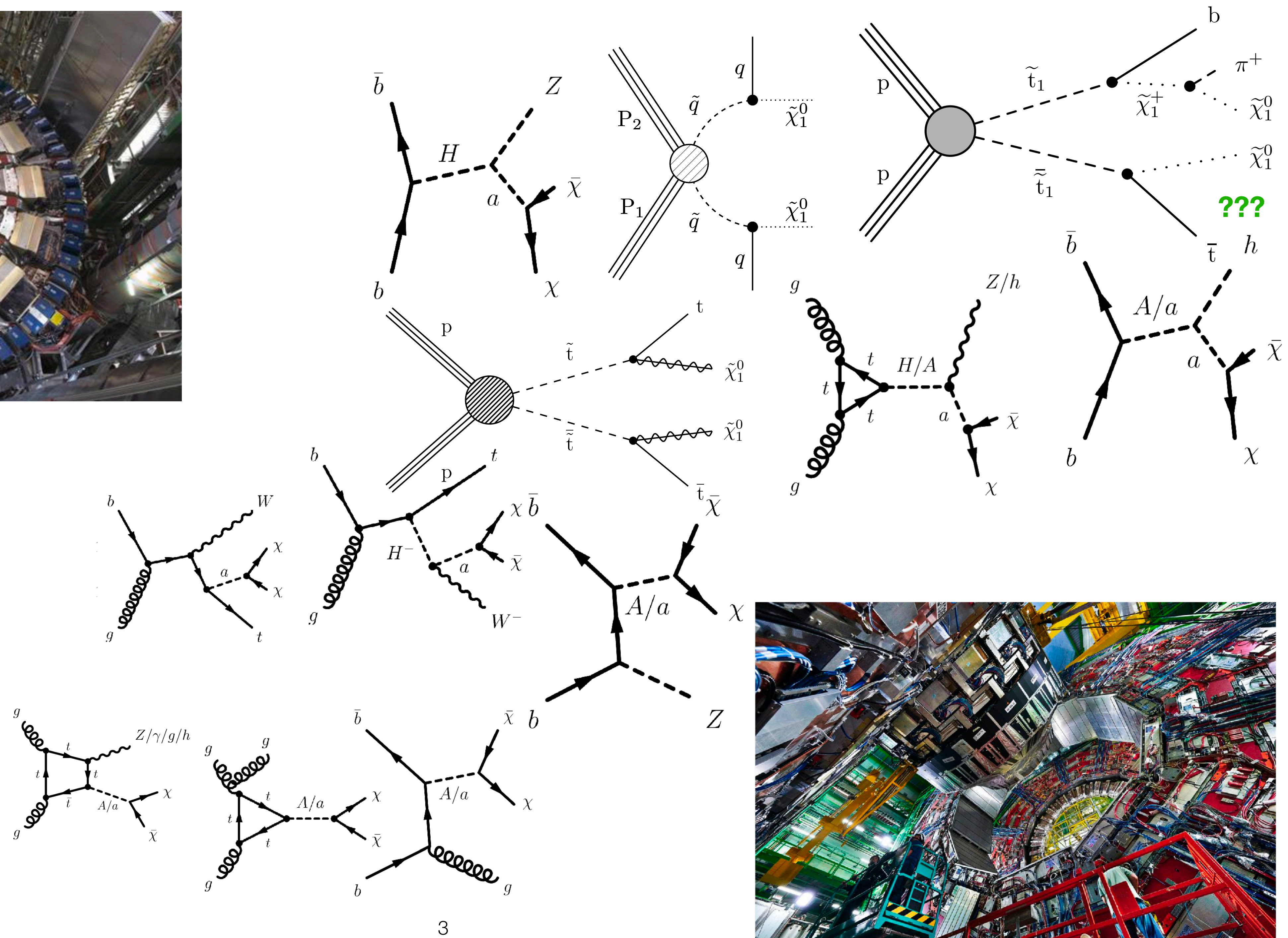
- “[The Large Magellanic Cloud (LMC)] accelerates local MW DM halo particles to high speeds, reaching velocities > 700 km/s”
- “The high-speed tail of the local DM distribution is overwhelmingly of LMC origin”



- “The LMC causes the limits on the spin-independent DM-nucleon scattering cross section σ_{SI} to be significantly lower for low mass WIMPS than expected when the LMC is neglected”



- DM may be produced at the LHC in proton collisions
- But how should we expect it to show up, if it does?



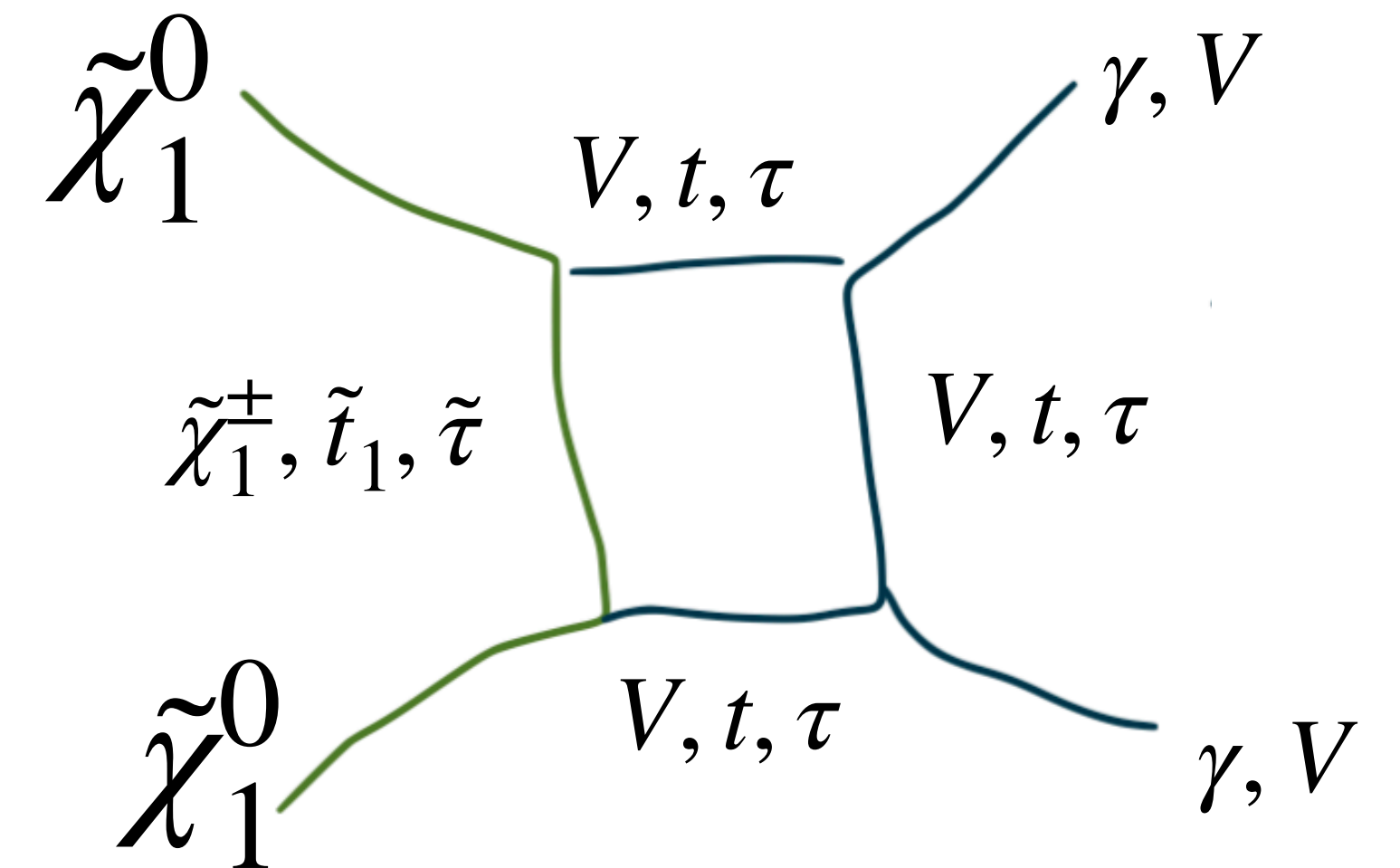
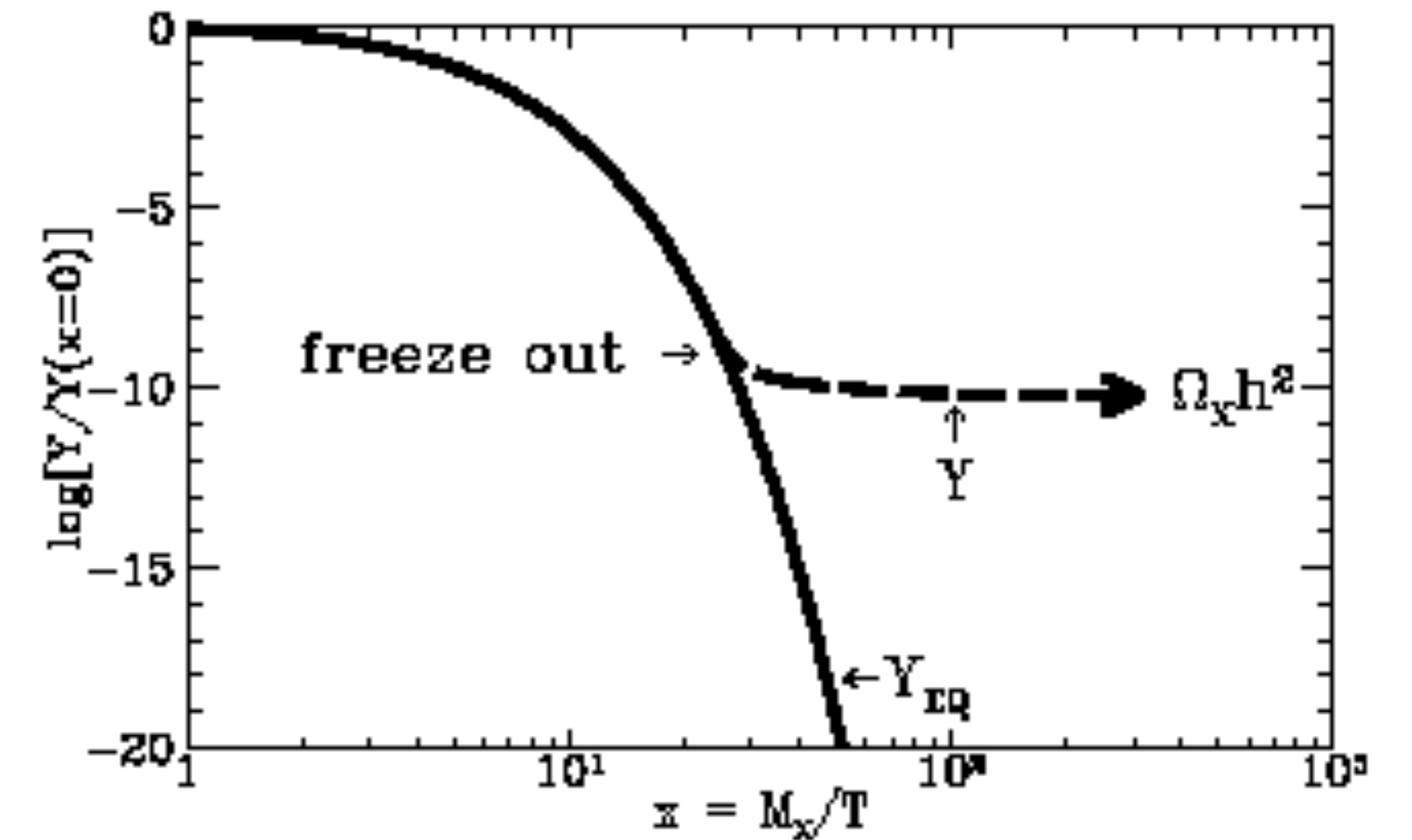
Accounting for relic abundance

Assuming standard cosmology

- BSM scenarios that introduce a new neutral particle

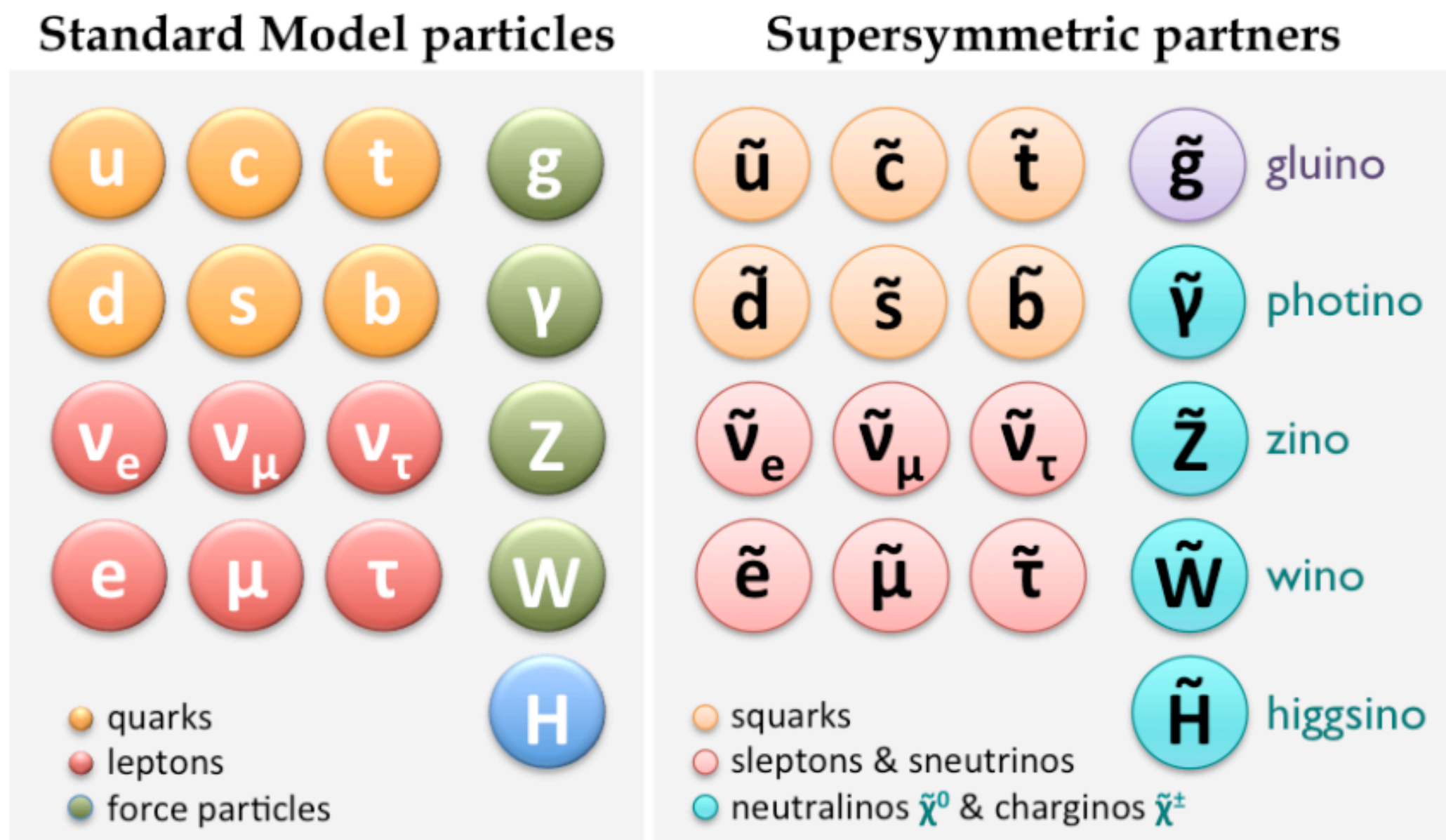
$\tilde{\chi}^0$ can account for dark matter if

- $\tilde{\chi}^0$ is stable
 - $\tilde{\chi}^0$ was produced in abundance in the early universe
 - If enough $\tilde{\chi}^0$ can annihilate before freeze-out - usually requires another particle
- In collider physics, the signature varies depending on annihilation partner/mechanism



Candidate models with annihilation partners

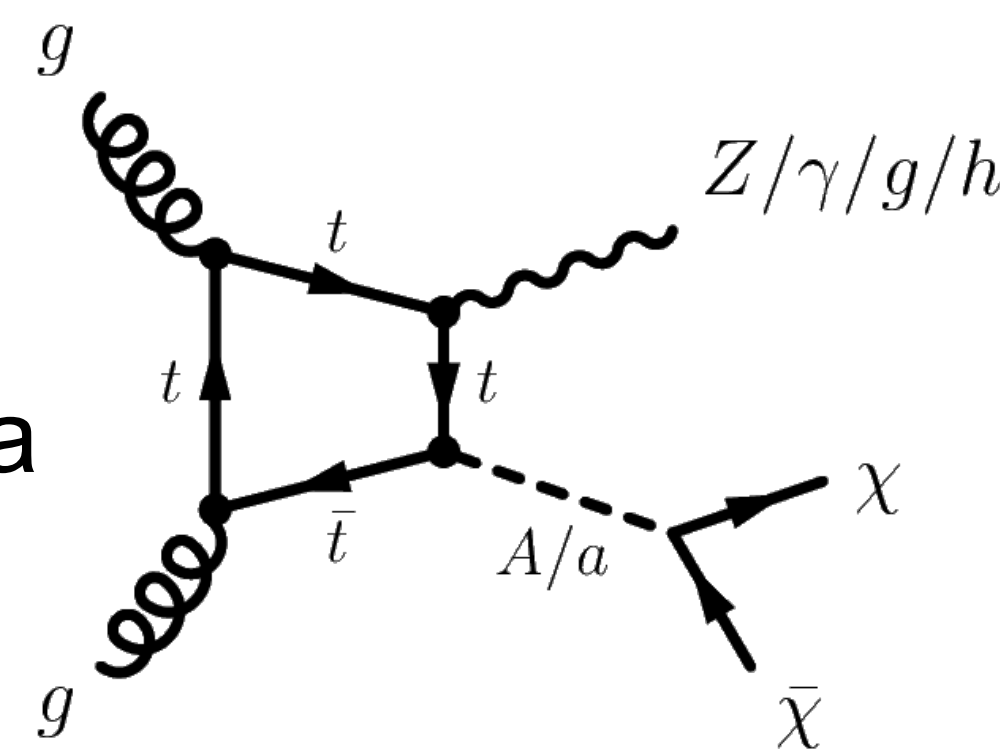
SUSY [Wess, Zumino, ...](#)



- New fermion (boson) partner for each boson (fermion) field if
 - lightest SUSY particle (LSP) is a neutralino $\tilde{\chi}^0$
 - $\tilde{\chi}^0$ is stable (R-parity conserved)
- **MSSM**: model with minimal assumptions
 - 100 free parameters
 - 18 co-annihilation candidates ($\tilde{t}, \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \dots$)
 - annihilation partner needs mass close to LSP

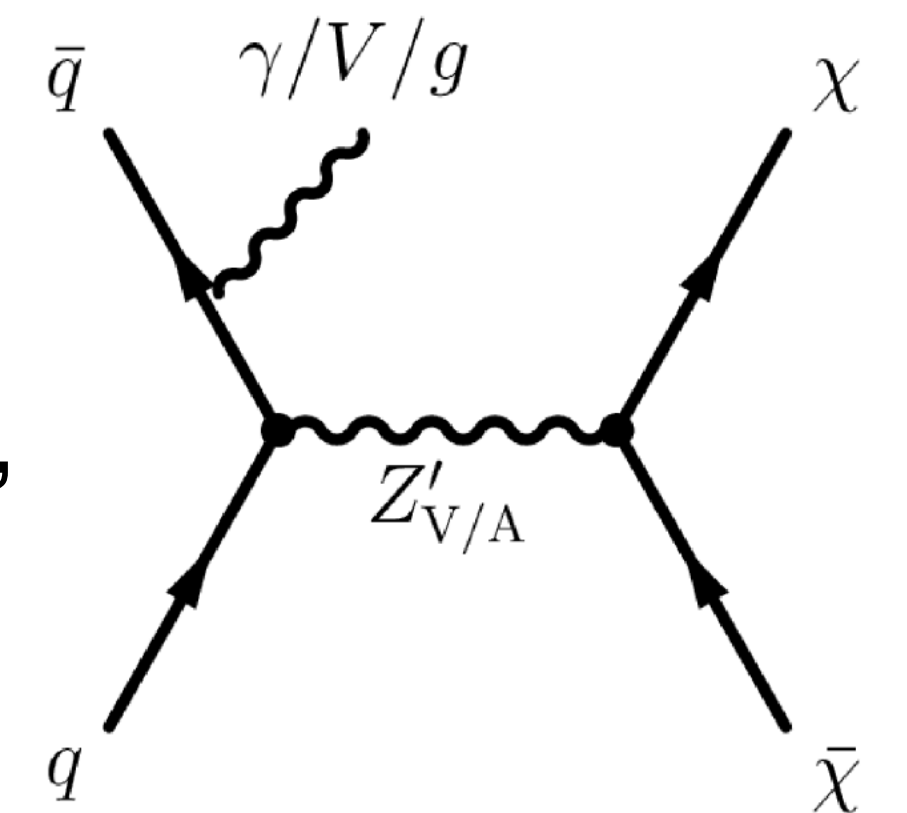
2HDM+a [LHC DM WG](#)

- Second Higgs doublet
- New pseudoscalar mediator a
- Co-annihilation partner: a, A



Simplified models

- Single mediator
- Scalar, pseudoscalar, vector, axial vector,
- Inelastic dark matter



...

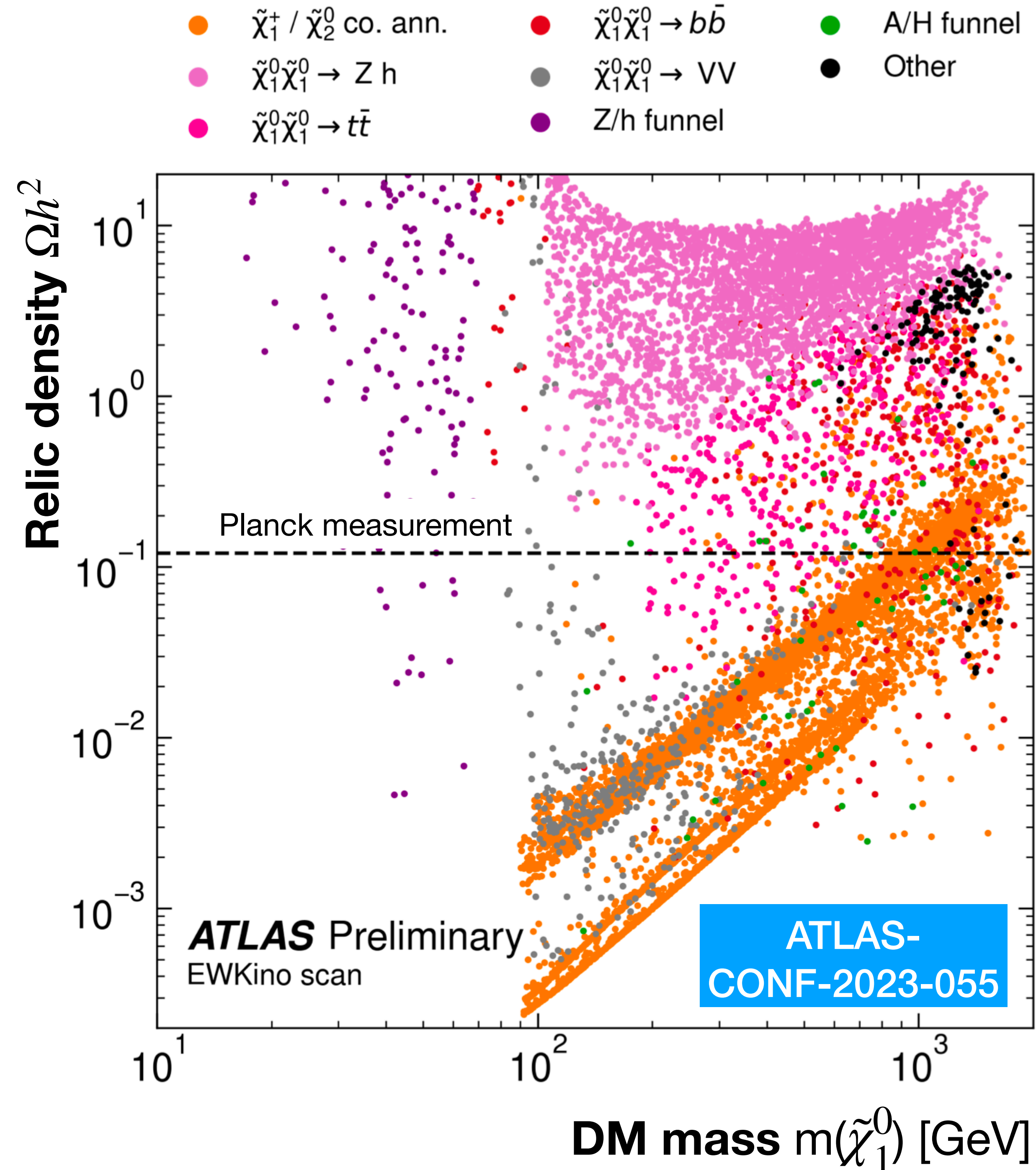
various sources

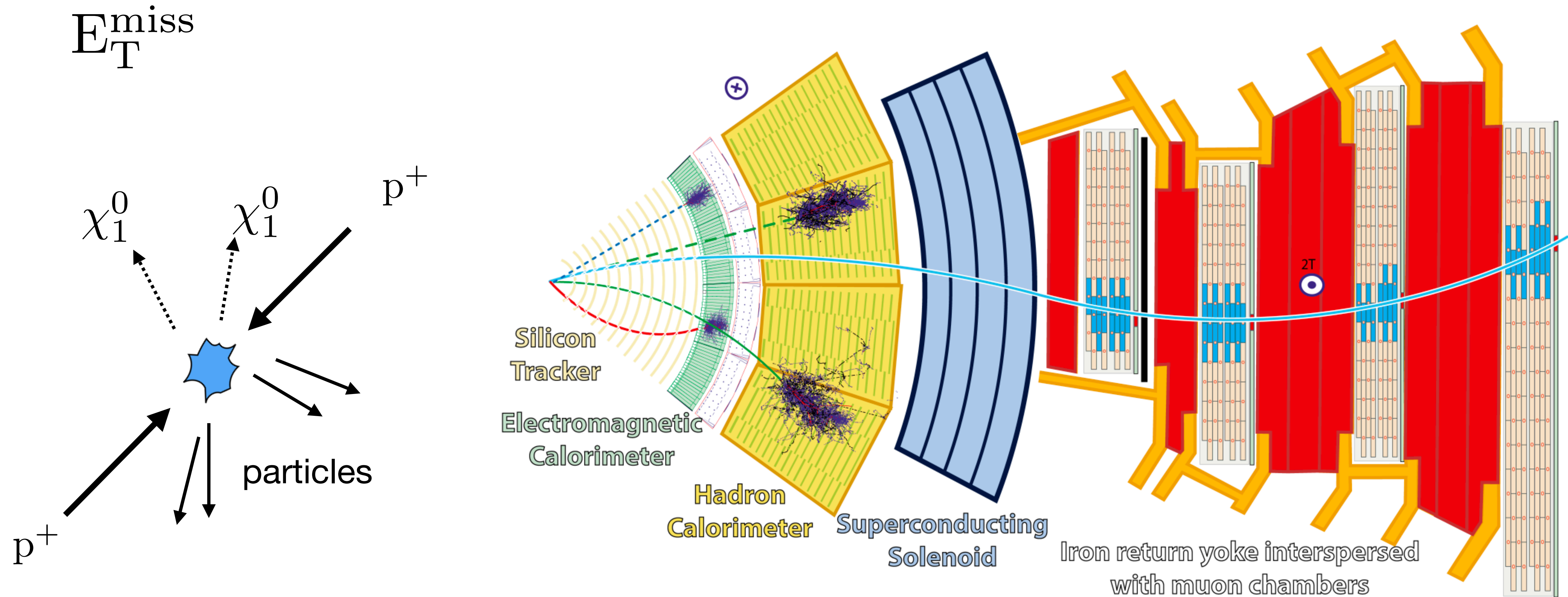
Others...axions, wisps, large extra dimensions

Mapping out SUSY DM

Phenomenological MSSM (pMSSM)

- ATLAS Run 2 MSSM study
- Two 12-parameter random scans considering electroweak states
- 20,000 considered model points total
- Possible annihilation partners:
 - EWKino: $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$
 - 4 funnels: Z, h, A, H
- Impact of 8 searches: 0L, 1Lbb, 2L0J, 2L2J, 3L, 4L, compressed, disappearing track
- compare with direct detection, relic density



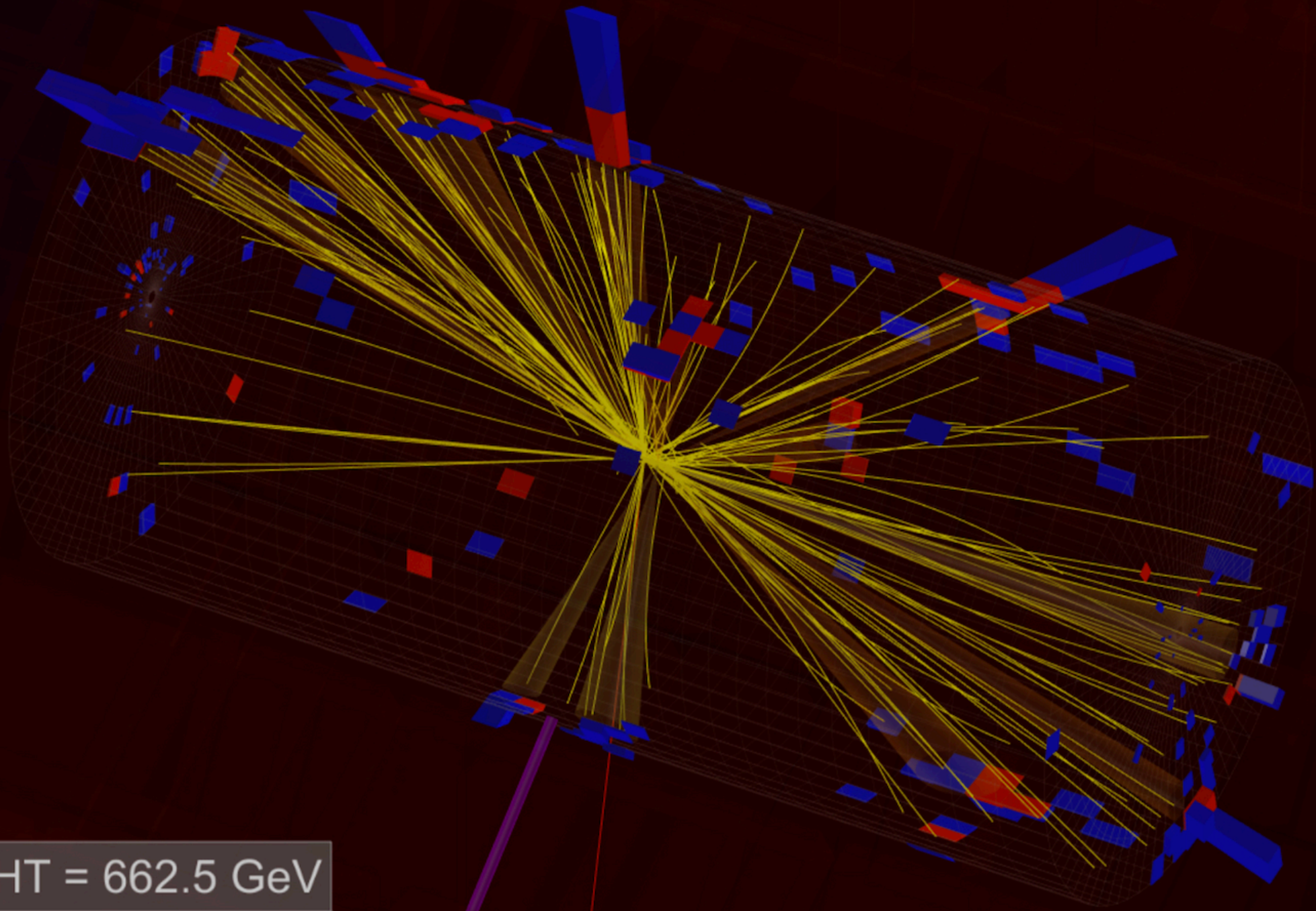


- Run 2
 - $\sim 140 \text{ fb}^{-1}$ @ $\sqrt{s} = 13 \text{ TeV}$
- Run 3
 - ongoing at 13.6 TeV

Missing transverse momentum E_T^{miss}



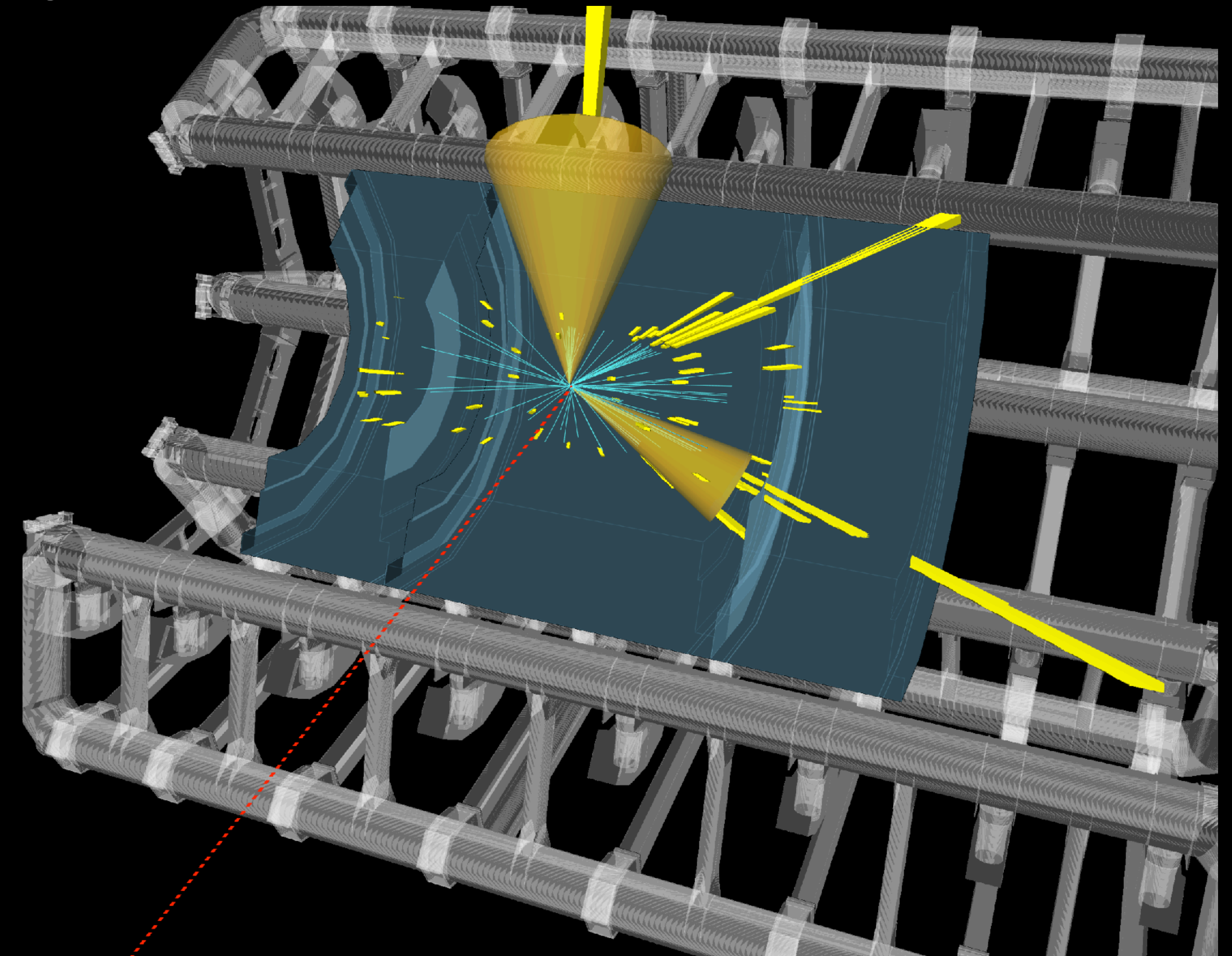
CMS Experiment at LHC, CERN
Data recorded: Sat May 14 21:35:27 2011
Run/Event: 273447 / 291867669
Lumi section: 179
Orbit/Crossing: 46782411 / 396



MHT = 662.5 GeV



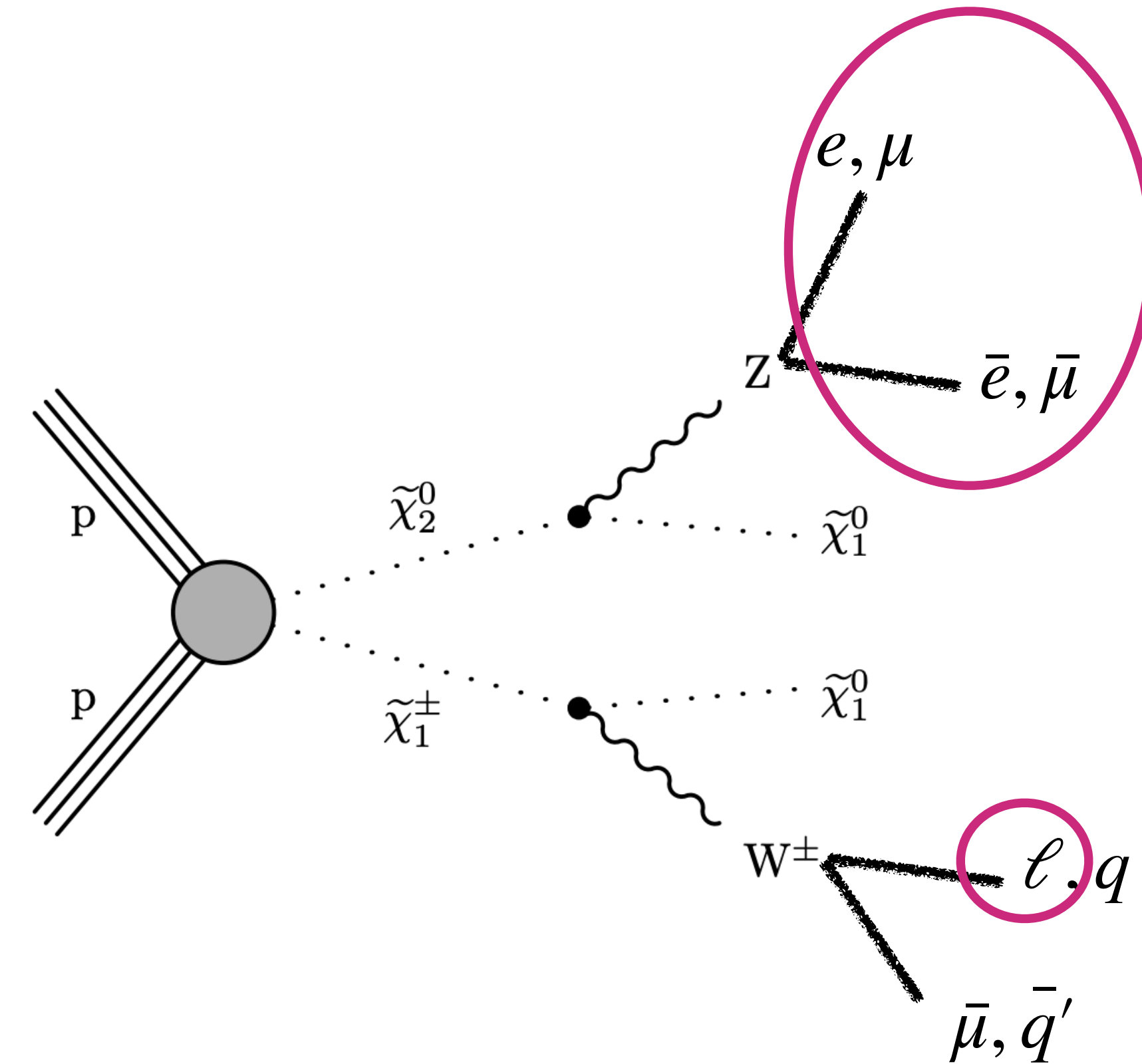
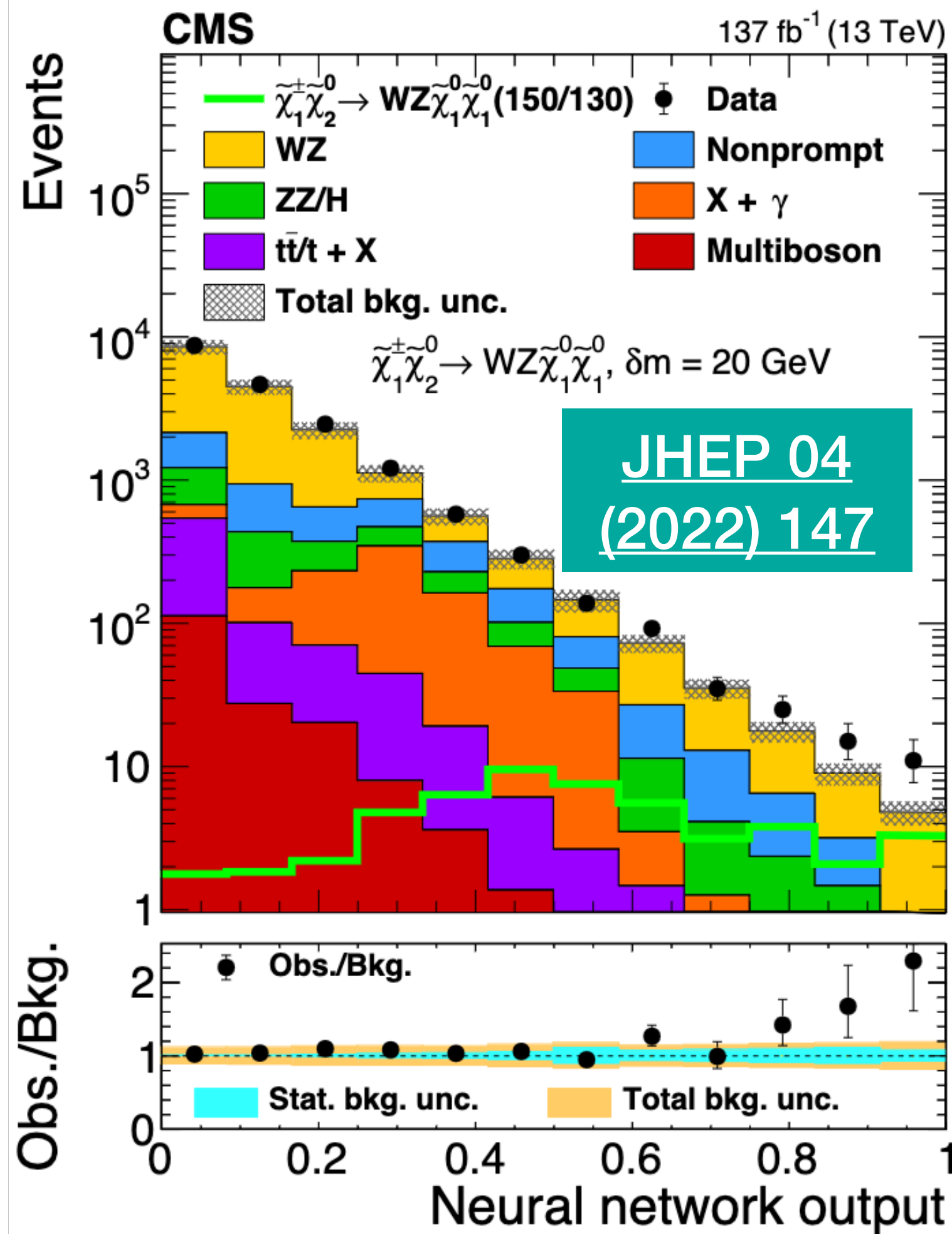
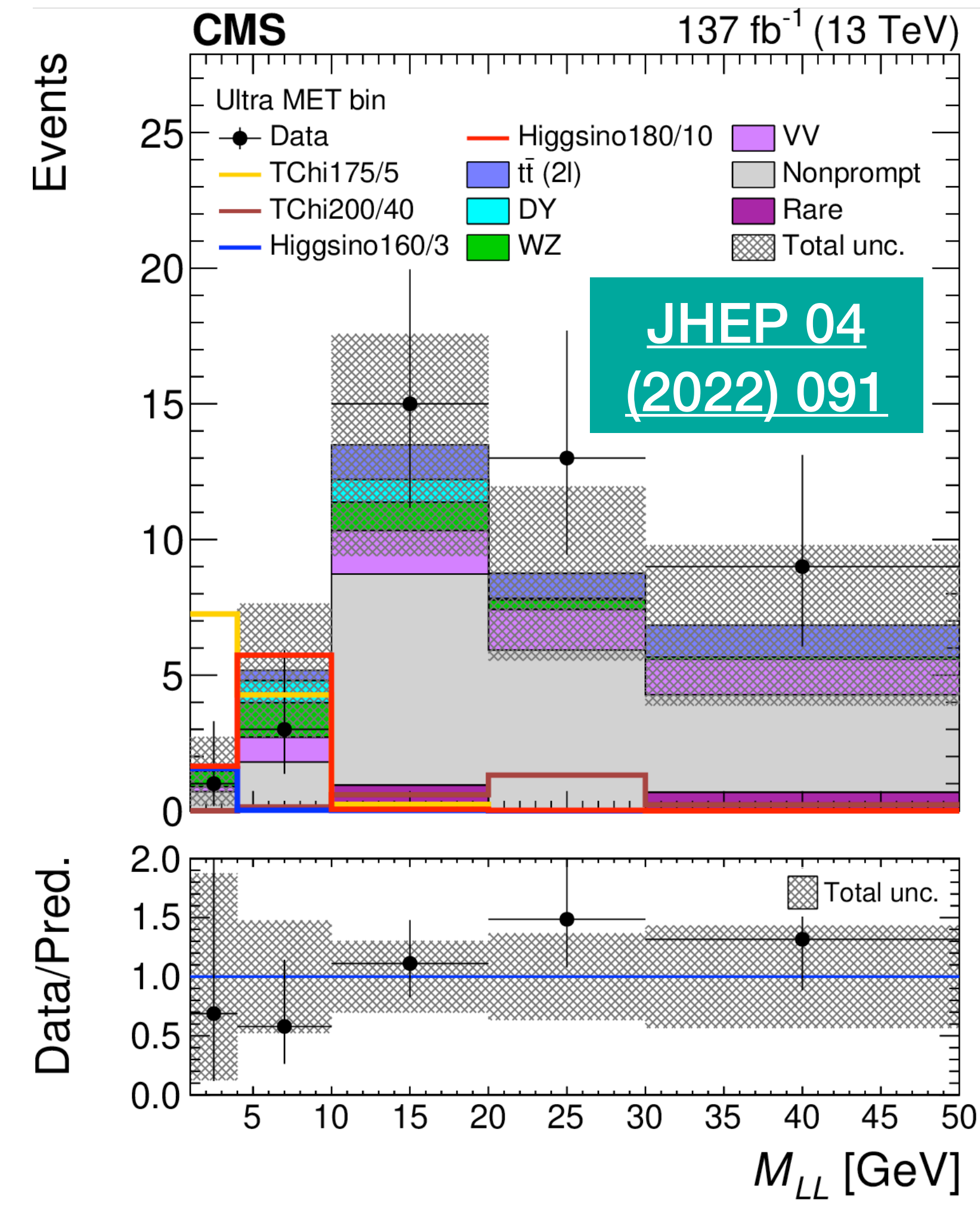
Run: 356205
Event: 1558935601
2018-07-22 11:48:40 CEST



Neutralino as annihilation partner

- 2, 3 soft leptons
- signal regions in E_T^{miss} , $m_{\ell\ell}$

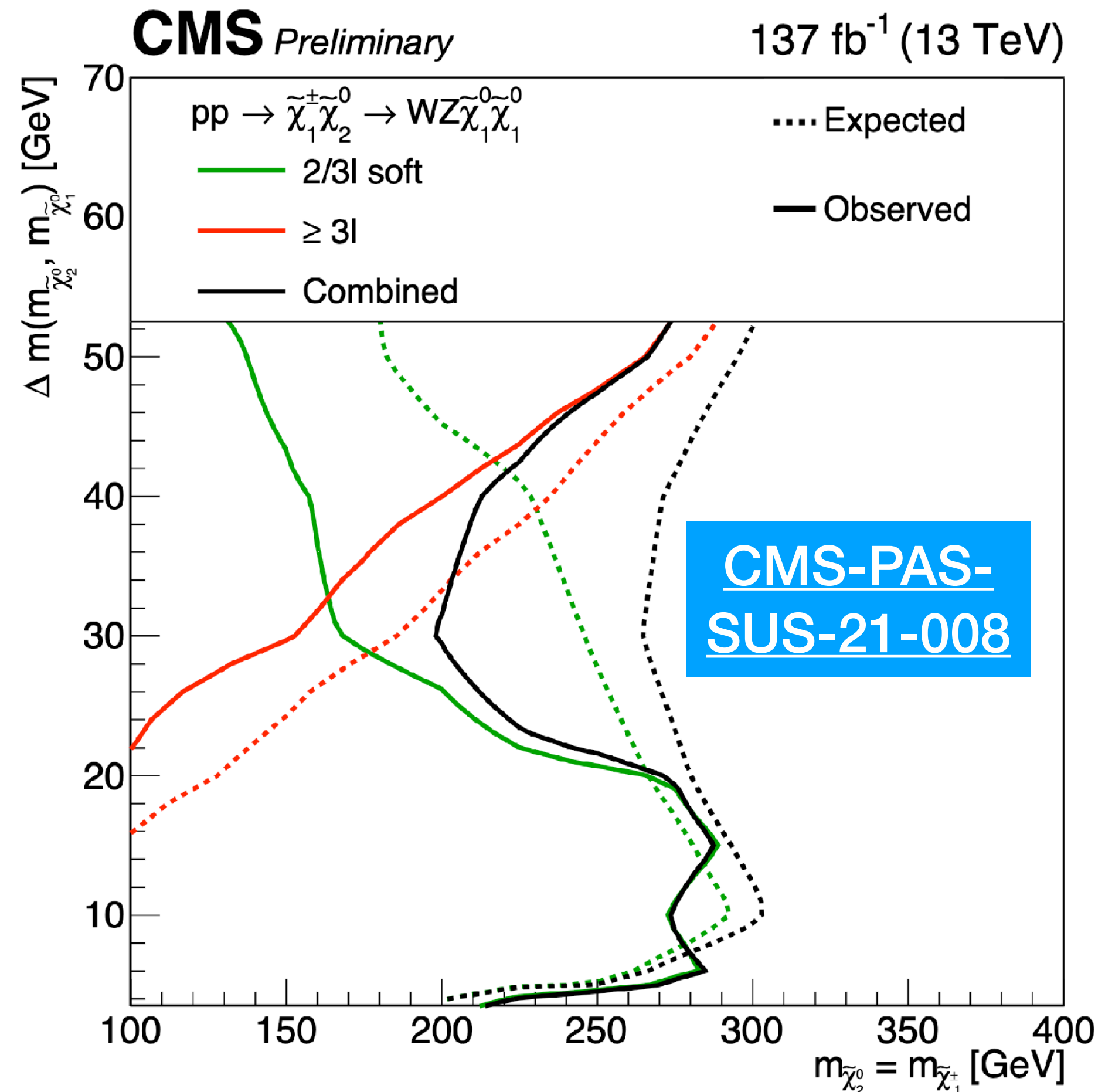
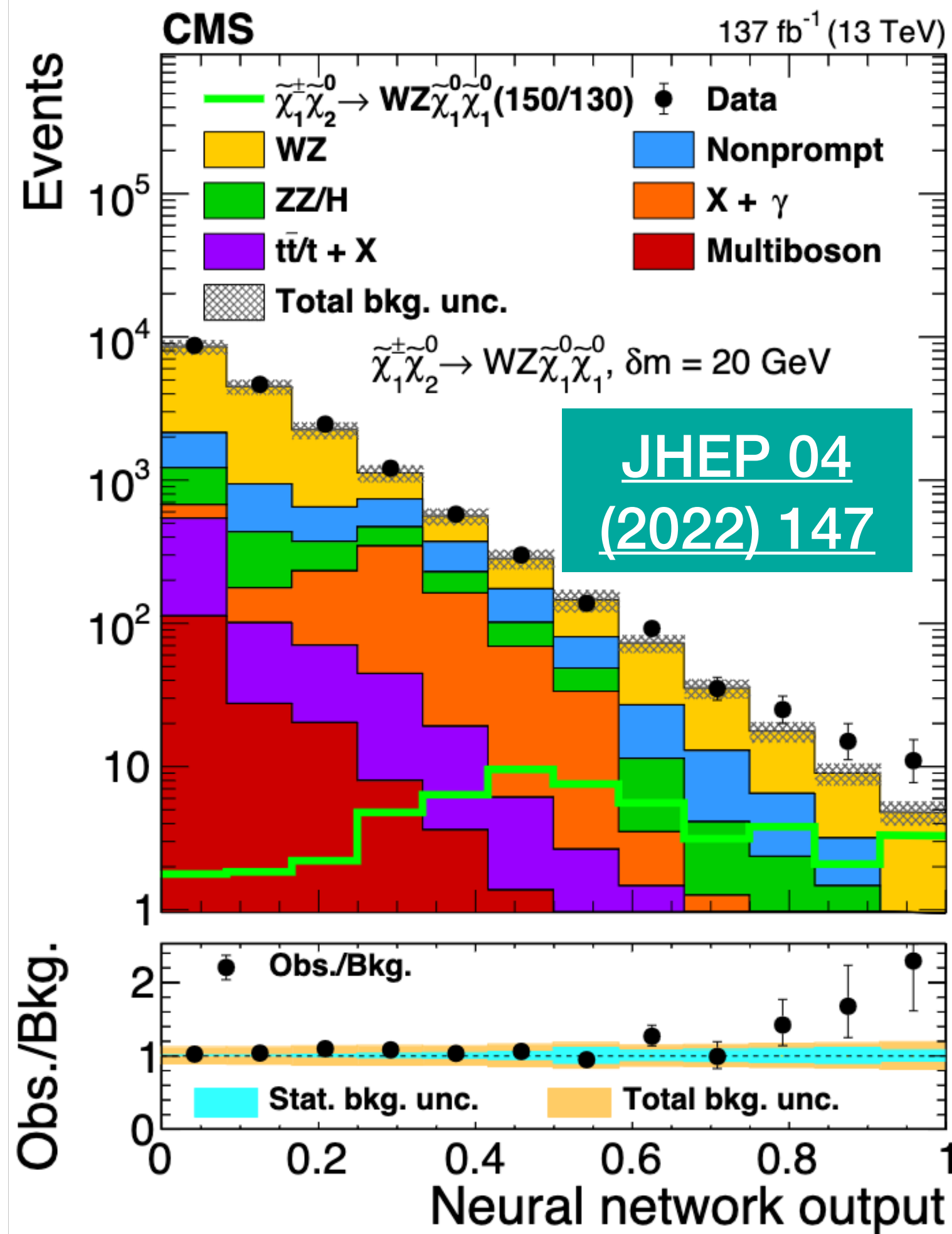
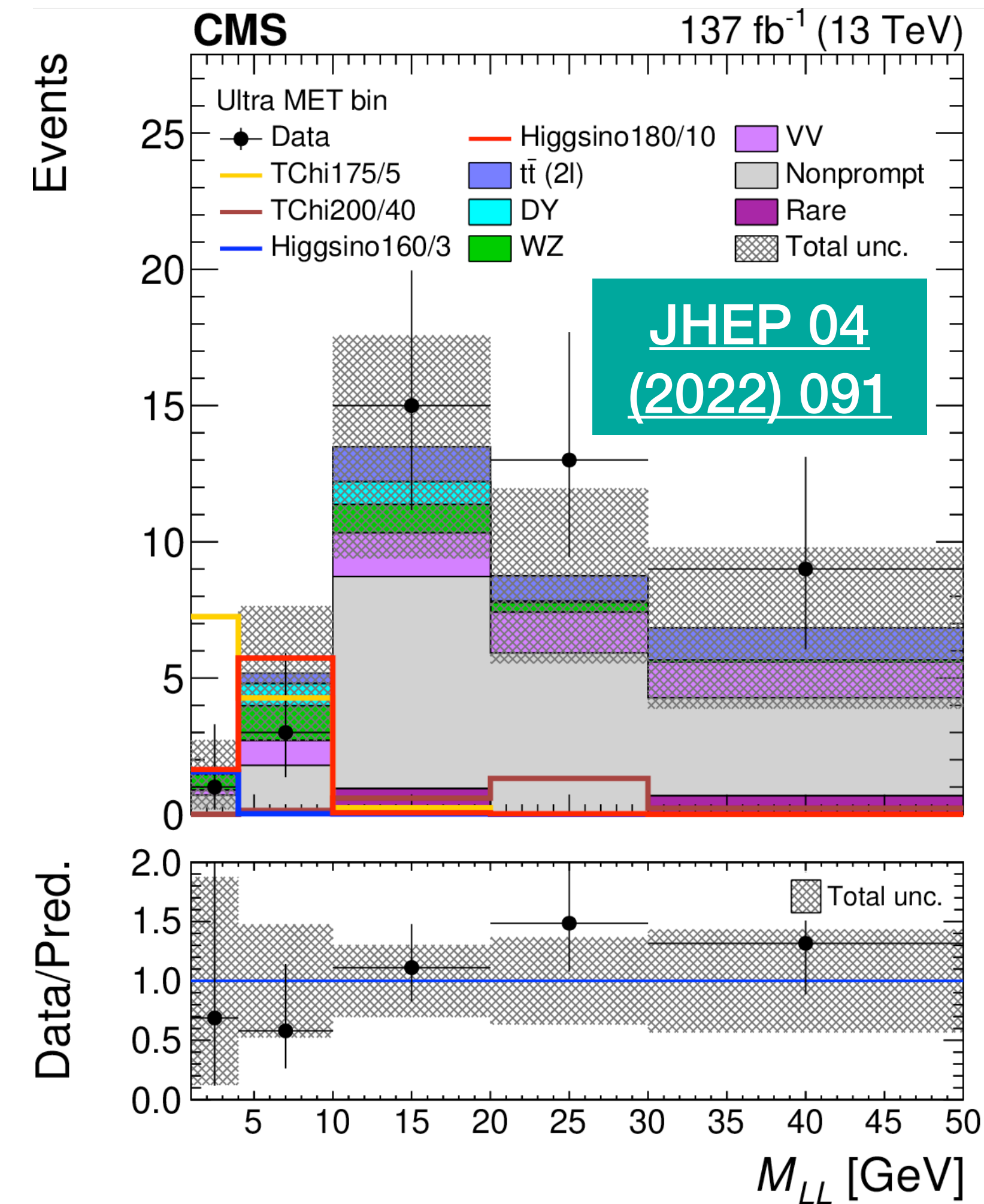
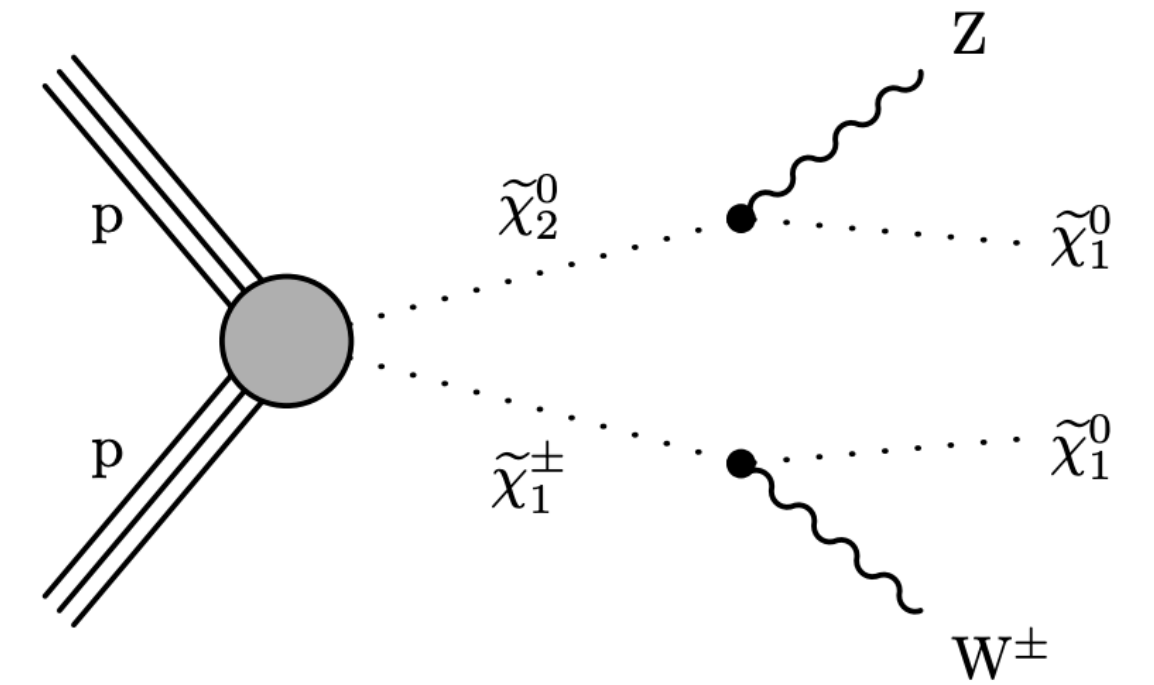
- 3 or more leptons
- NN event classifier to reject backgrounds



Neutralino as annihilation partner

- 2, 3 soft leptons
- signal regions in E_T^{miss} , $m_{\ell\ell}$

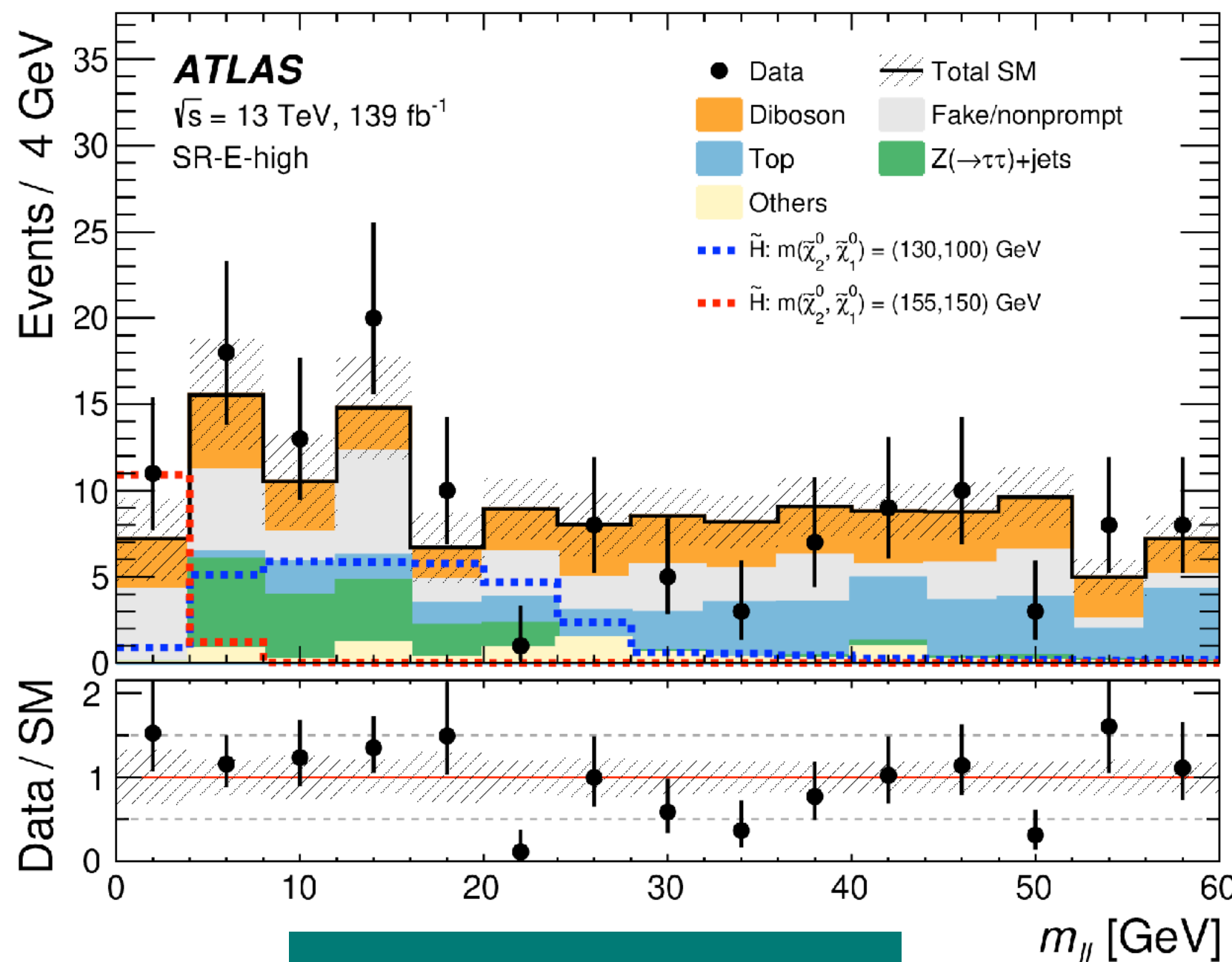
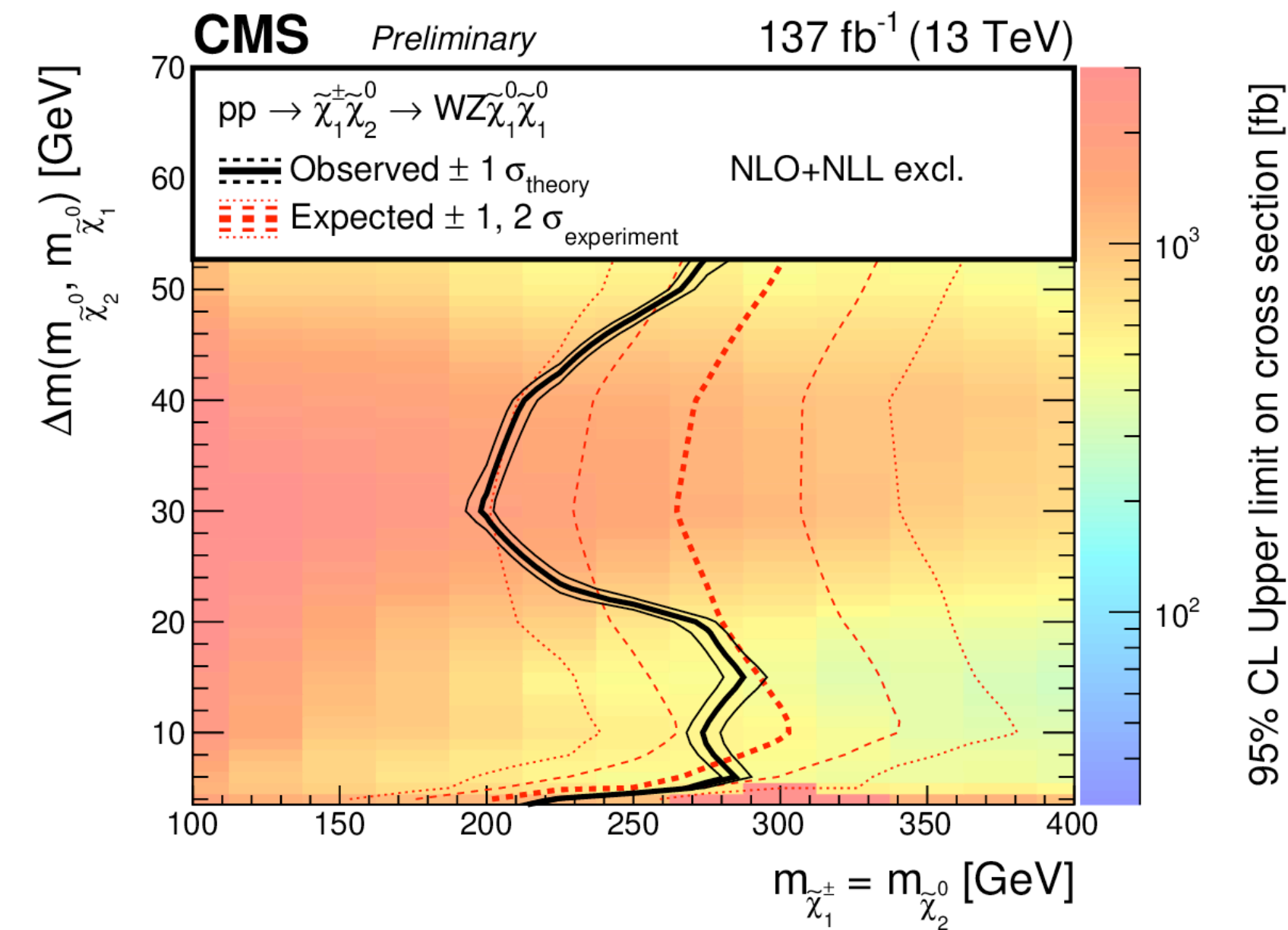
- 3 or more leptons
- NN event classifier to reject backgrounds



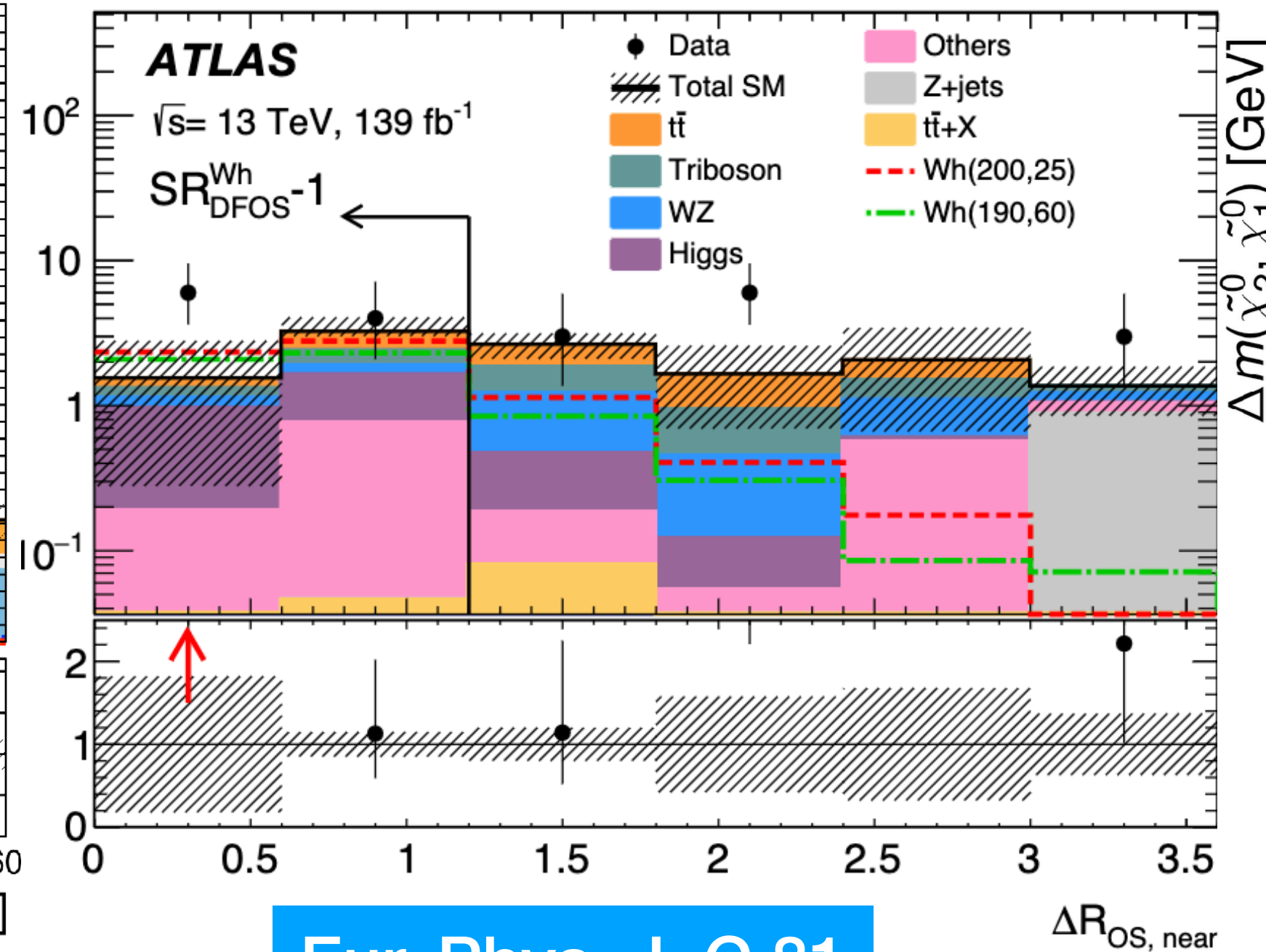
CMS EWK combination - small excess
2- σ consistent with $\delta m = 25-35$ GeV

Neutralino as partner

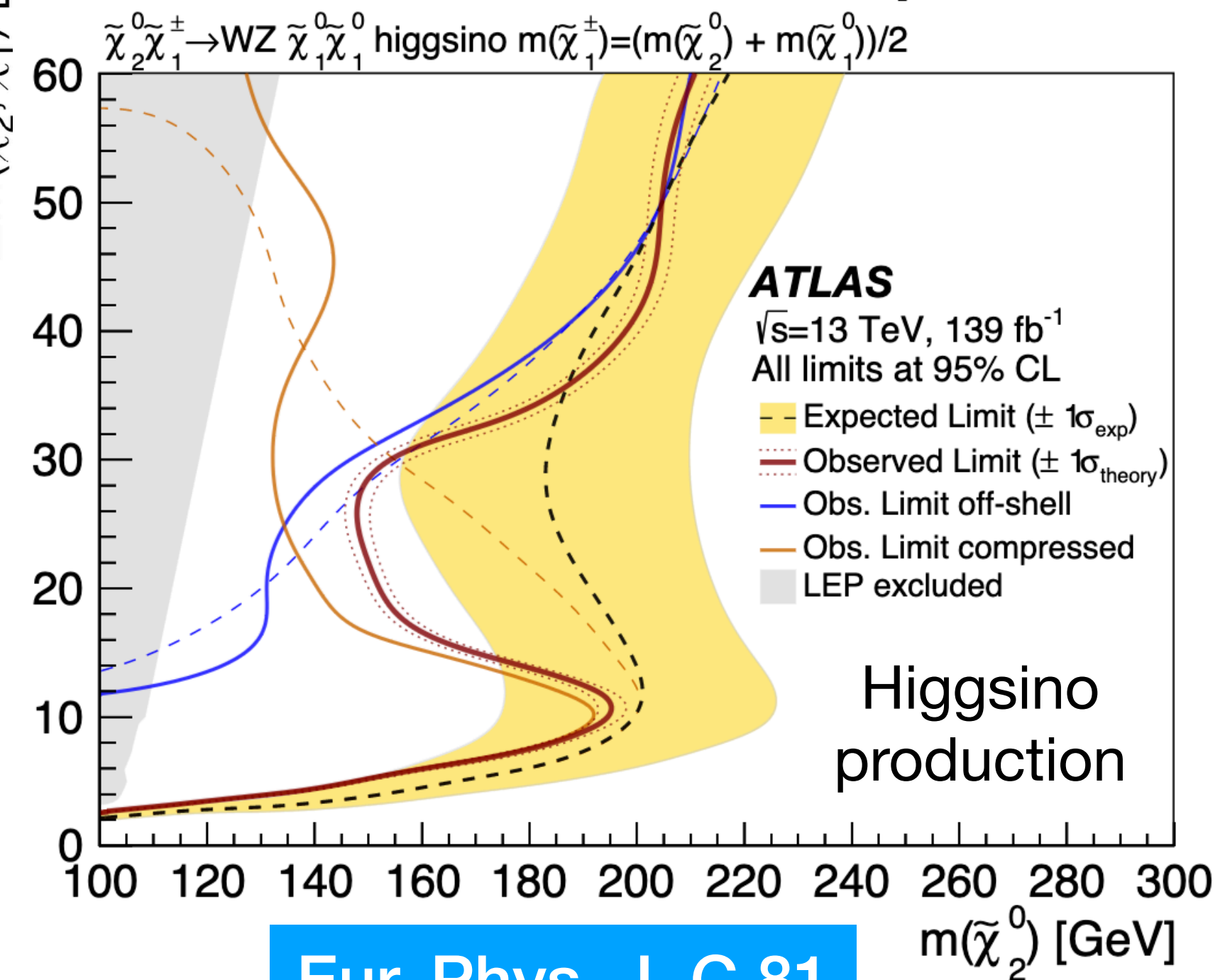
- 2 soft, opposite-sign leptons + jet + E_T^{miss}
- Search in bins of $m_{\ell\ell}$
- 3 or more leptons, opposite-sign pair
- Recursive Jig Saw method: SUSY decay systems
- Search in $m_{\ell\ell}, \Delta R_{\ell\ell}$



Phys. Rev. D 101
(2020) 052005



Eur. Phys. J. C 81
(2021) 1118



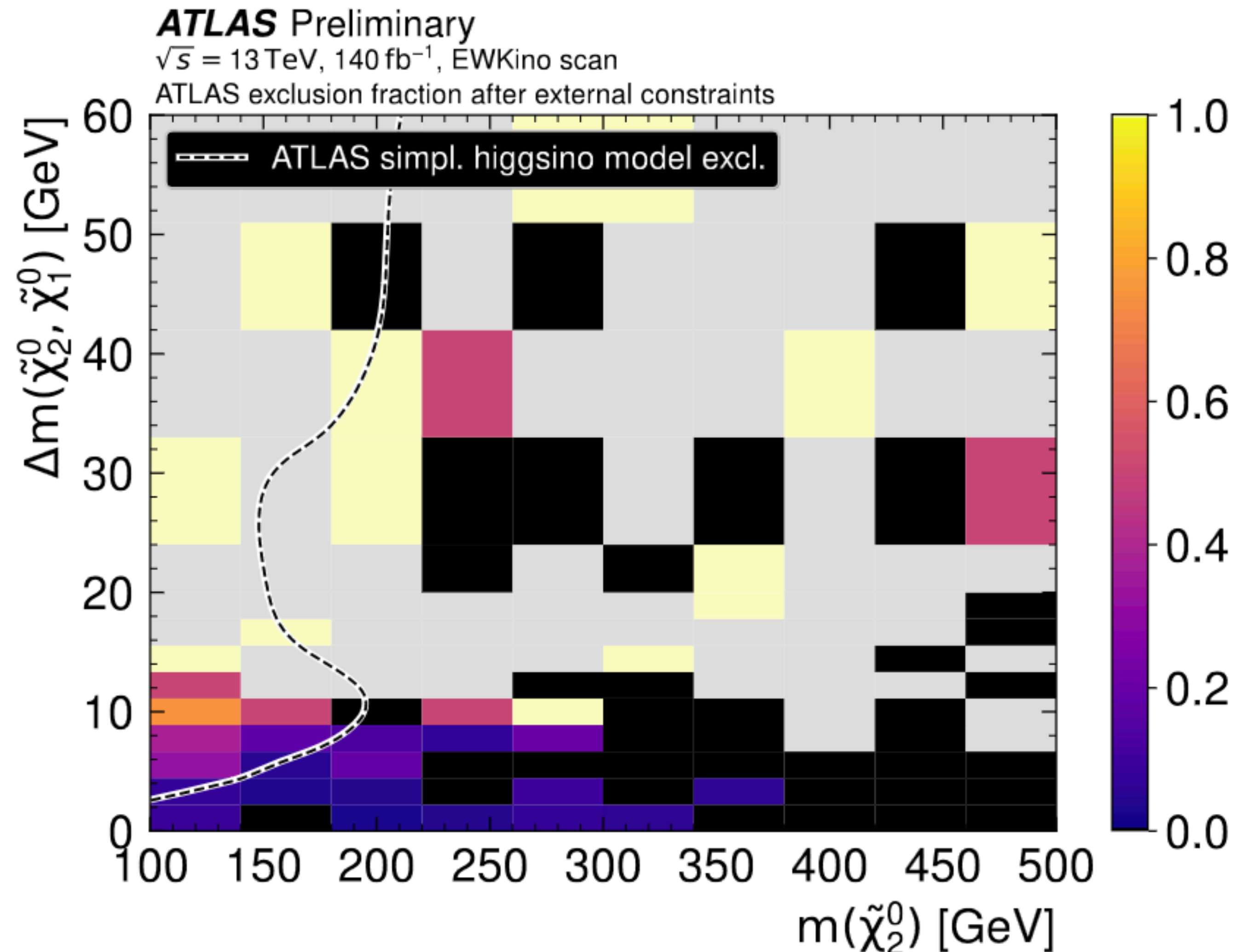
Eur. Phys. J. C 81
(2021) 1118

ATLAS EWK combination - small excess
~2- σ consistent with $dm=25-35$ GeV

Neutralino as annihilation partner

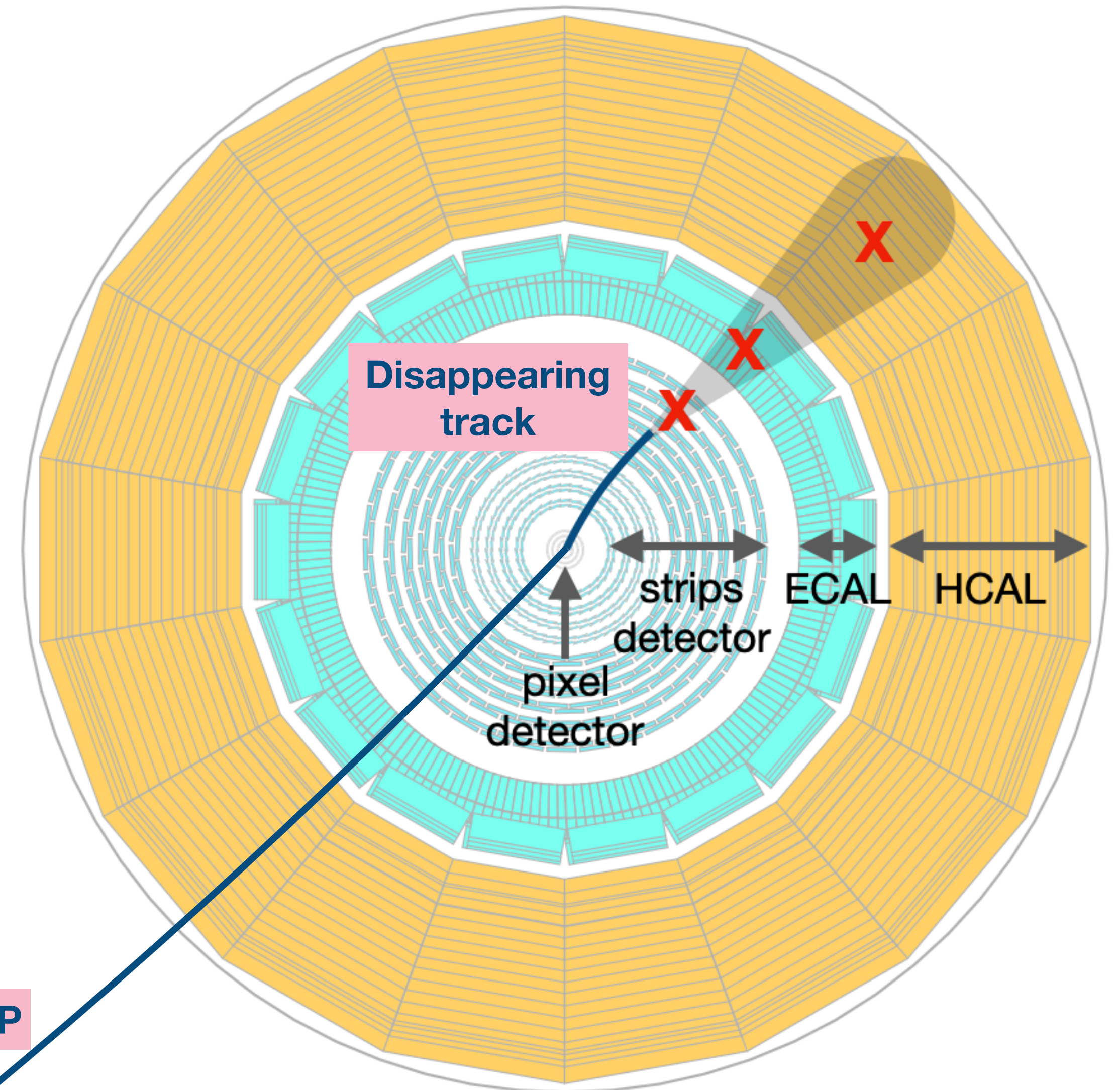
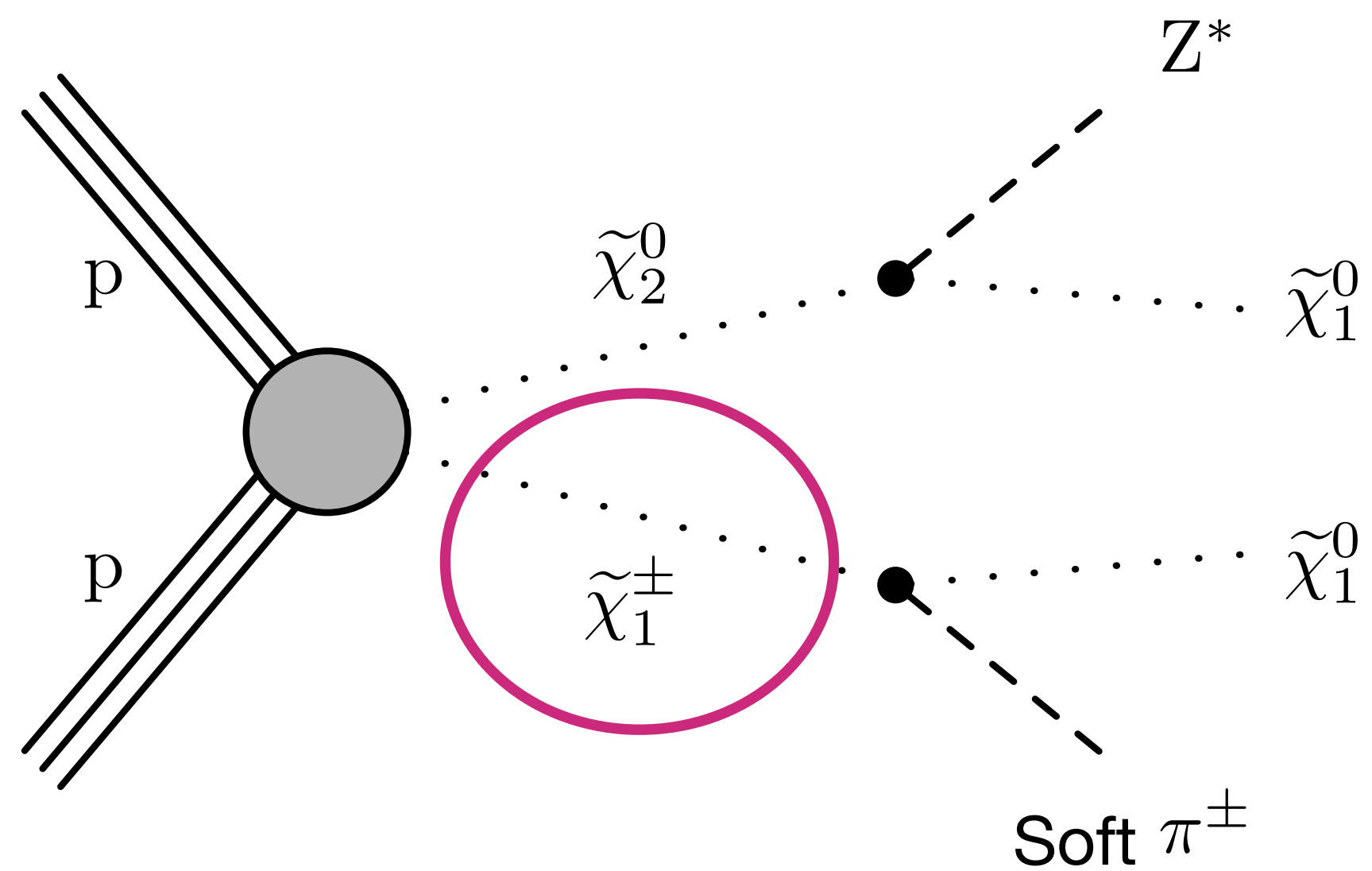
- Contrasting with pMSSM (ATLAS sensitivity)
- Fraction of excluded models; each bin
 - (numerator): # of models excluded by ATLAS
 - (denominator): # allowed by DM, precision measurements
- Gray: no models
- Creme: all excluded
- Black: none excluded

Models consistent with the excess seem to be excluded
—surprisingly low sensitivity to compressed!



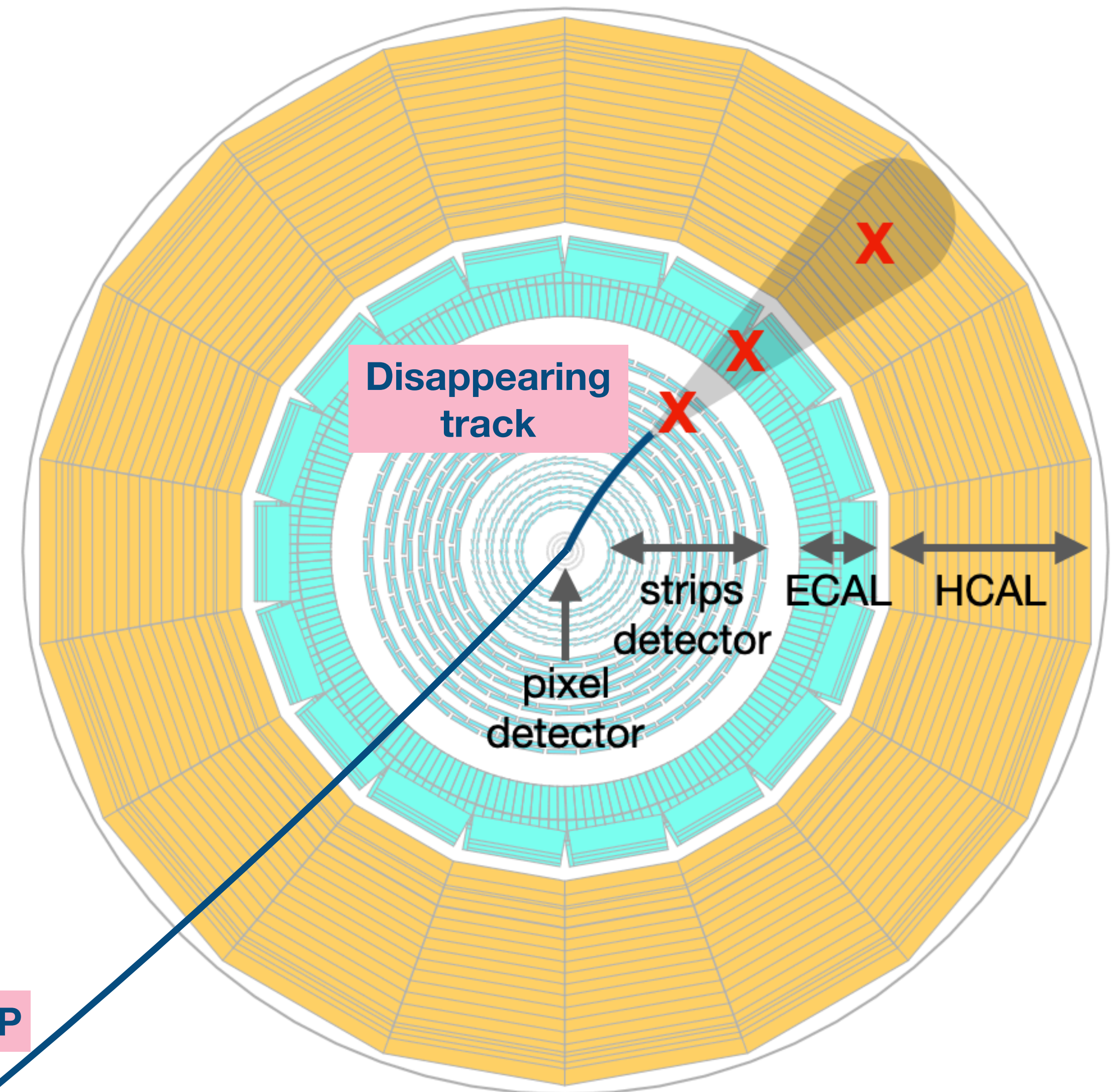
Chargino, stau or gluino partner

- Semi-stable chargino $\tilde{\chi}^\pm$
 - traverses part of detector, decays “invisibly”
- Gluino or squark partner
 - LL gluino or squark becomes R-hadron, can traverse all or part of detector



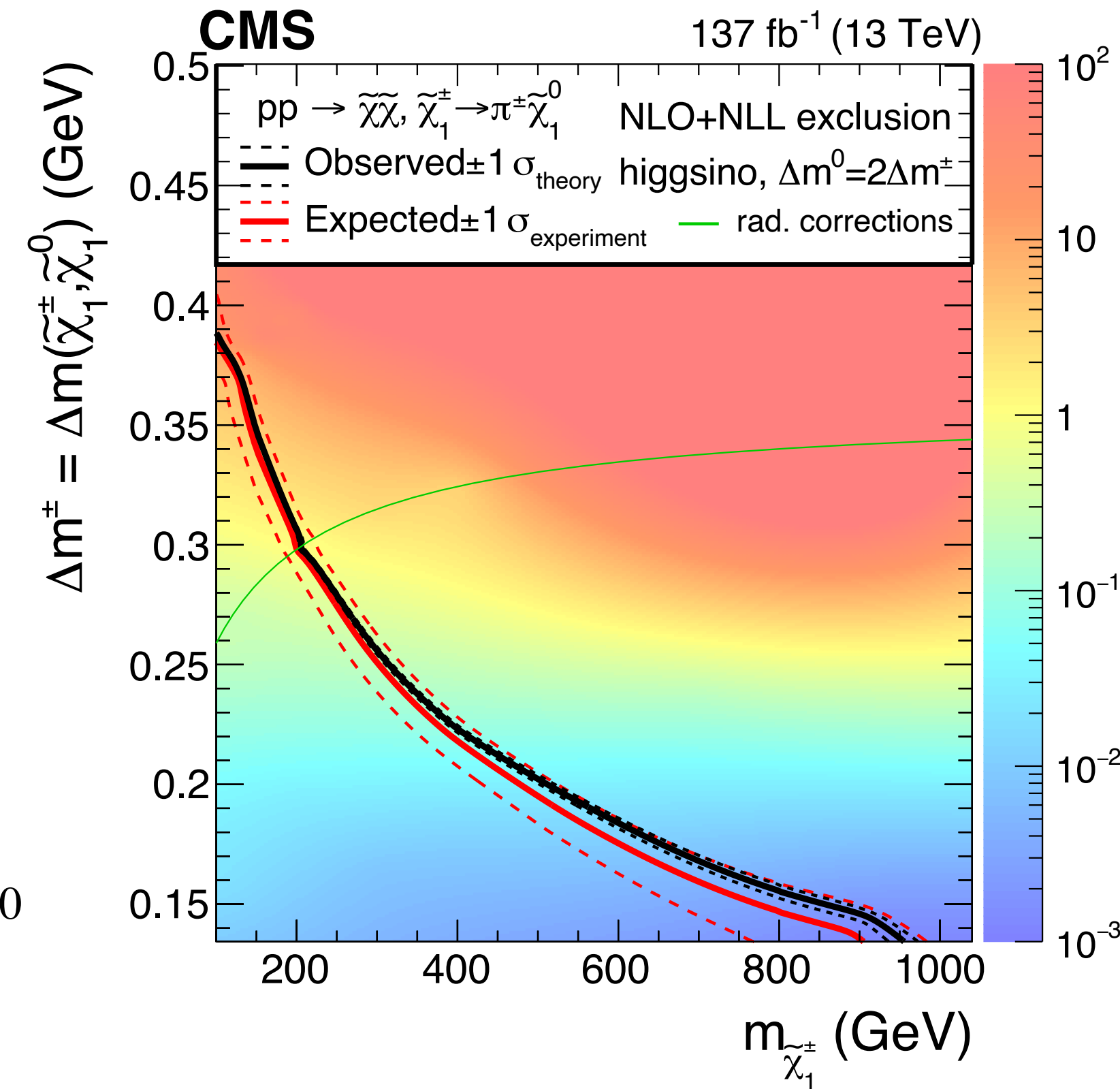
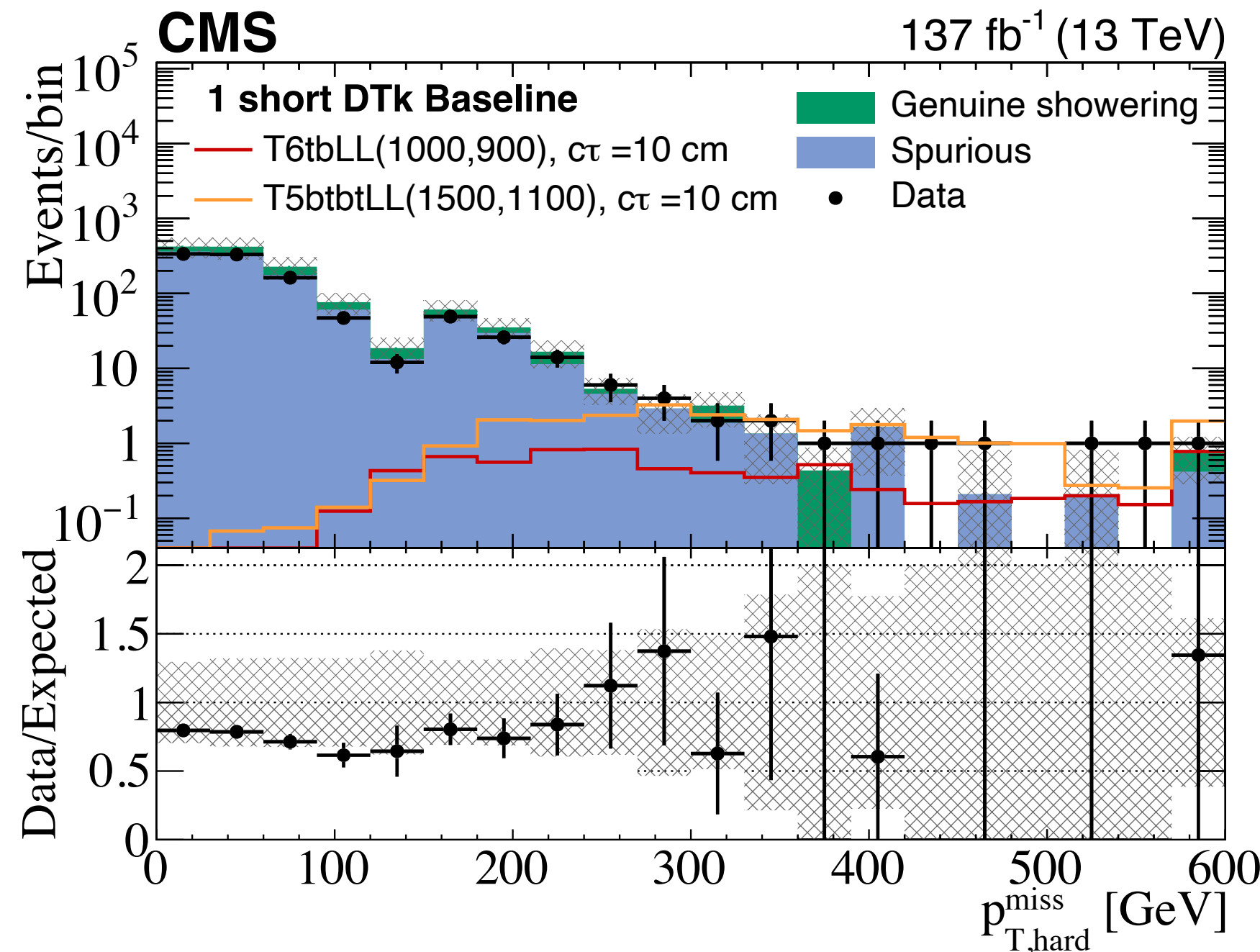
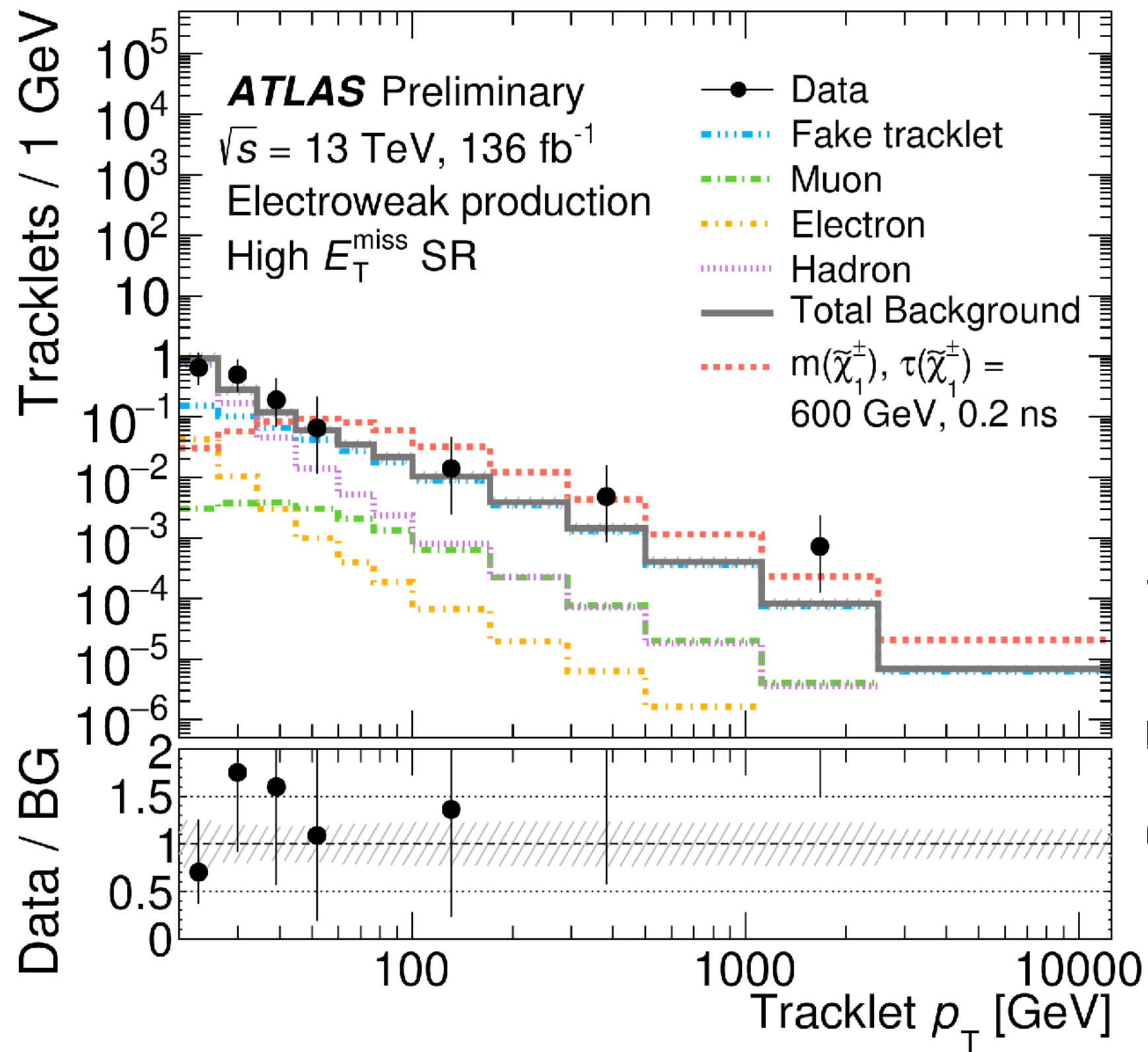
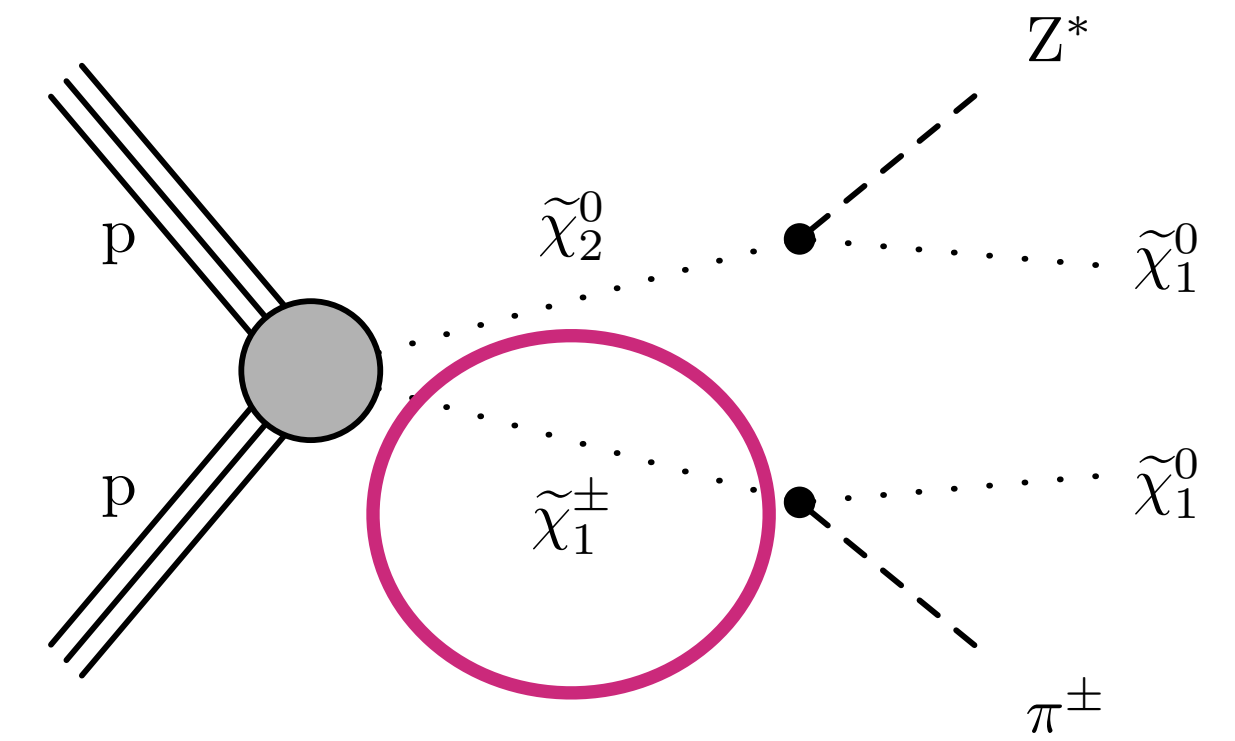
Chargino, stau or gluino partner

- Semi-stable chargino $\tilde{\chi}^{\pm}$
 - traverses part of detector, decays “invisibly”
- Gluino or squark partner
 - LL gluino or squark becomes R-hadron, can traverse all or part of detector
- Signatures:
 - Track points to primary vertex
 - Disappears!
 - Large dE/dx ionization in the tracker
 - Out-of time muon candidate



Chargino, stau or gluino partner

- ATLAS disappearing track search
- CMS disappearing track search
- Final state: short “tracklets”
- Final state: short, long tracks
- Additional jets, leptons



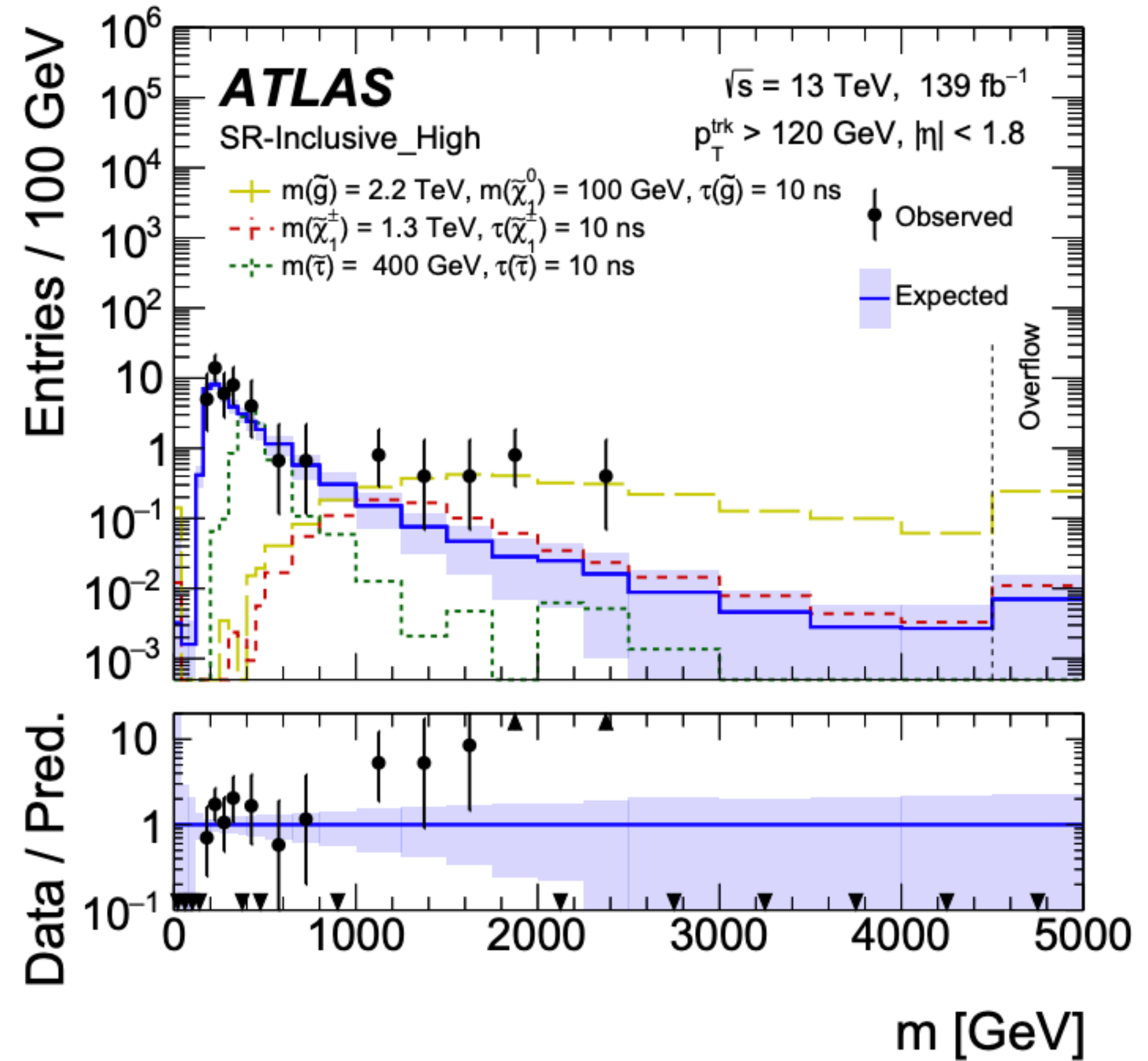
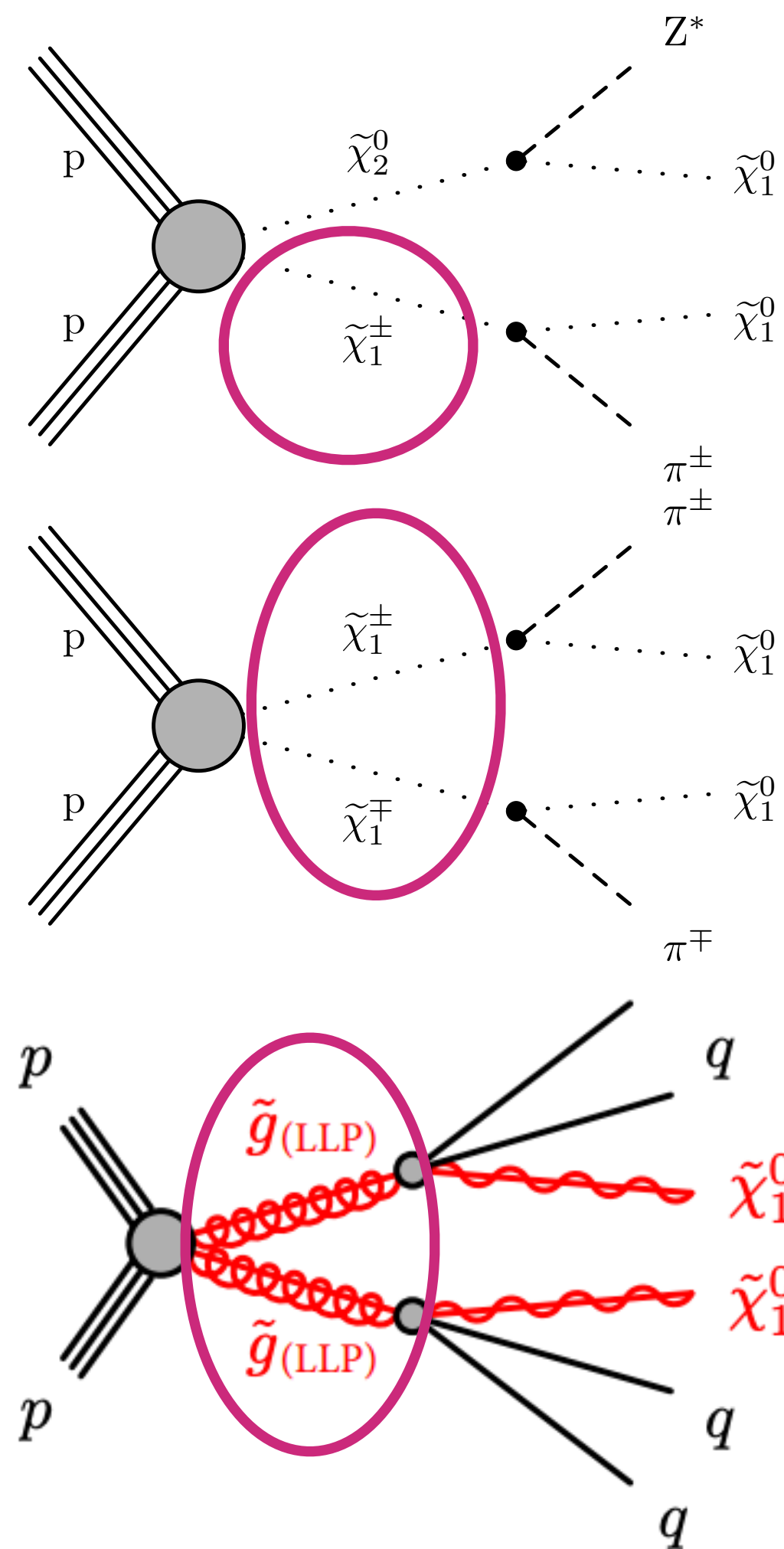
arXiv:2309.16823: sub
 to PRD 28.09.2023

ATLAS-CONF-2021-015

CMS, ATLAS each set upper
 limit on pure Higgsino dark
 matter $m(\tilde{\chi}^\pm) > 210 \text{ GeV}$

Chargino, stau, gluino partner

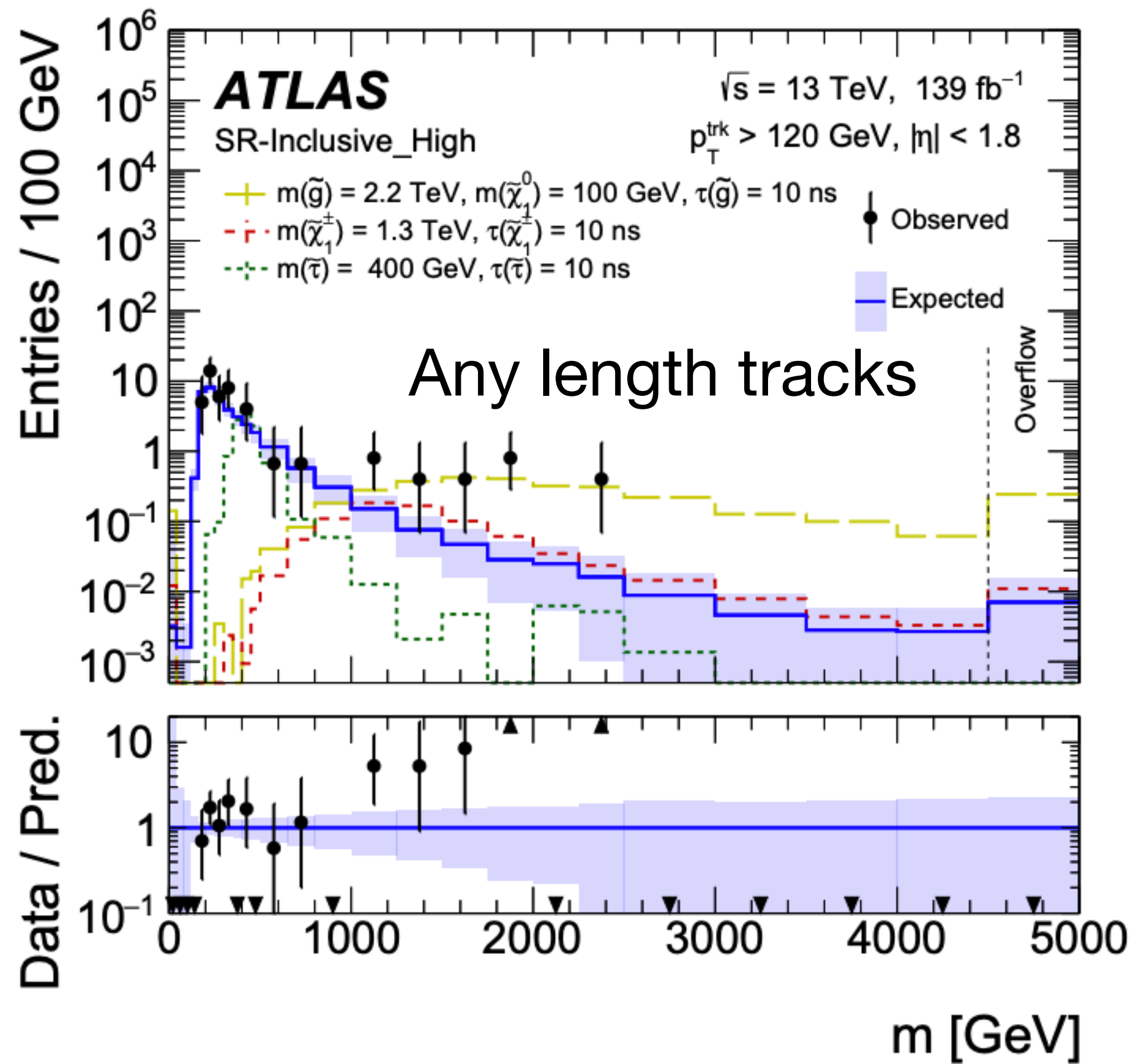
- ATLAS search for massive, charged, long-lived particle, with high ionization
- Final state: high pT track with high pixel dE/dx
- Binning in mass(dE/dx)
- 3.6 local (3.4 global)- σ excess seen in mass(dE/dx) distribution
- Time-of-flight cross check not compatible with excess



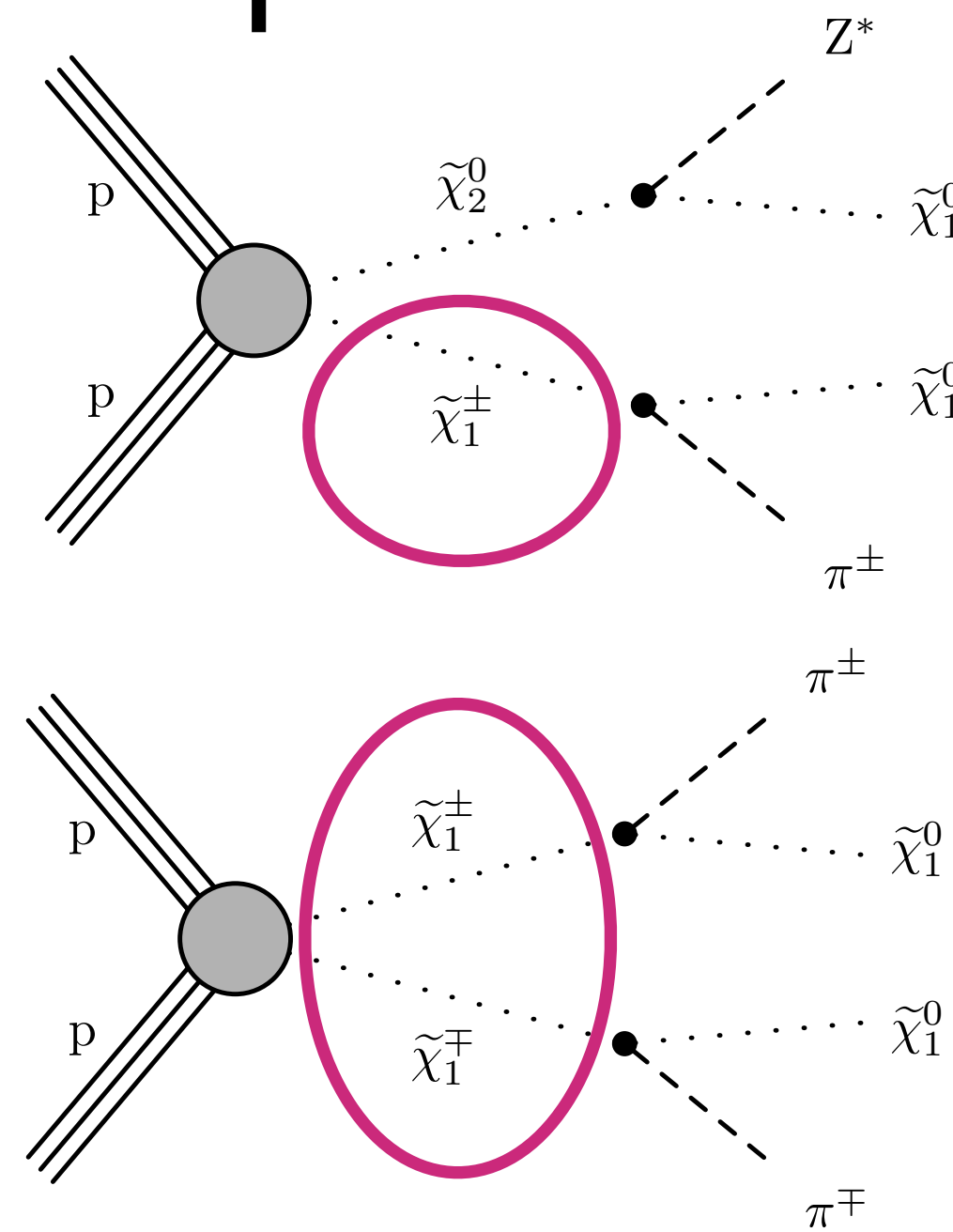
ATLAS SUSY-2018-42,
JHEP (2023)

$$\frac{1}{16} \left\langle \frac{dE}{dx} \right\rangle = K_Z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Chargino, stau, gluino partner



ATLAS SUSY-2018-42,
JHEP (2023)

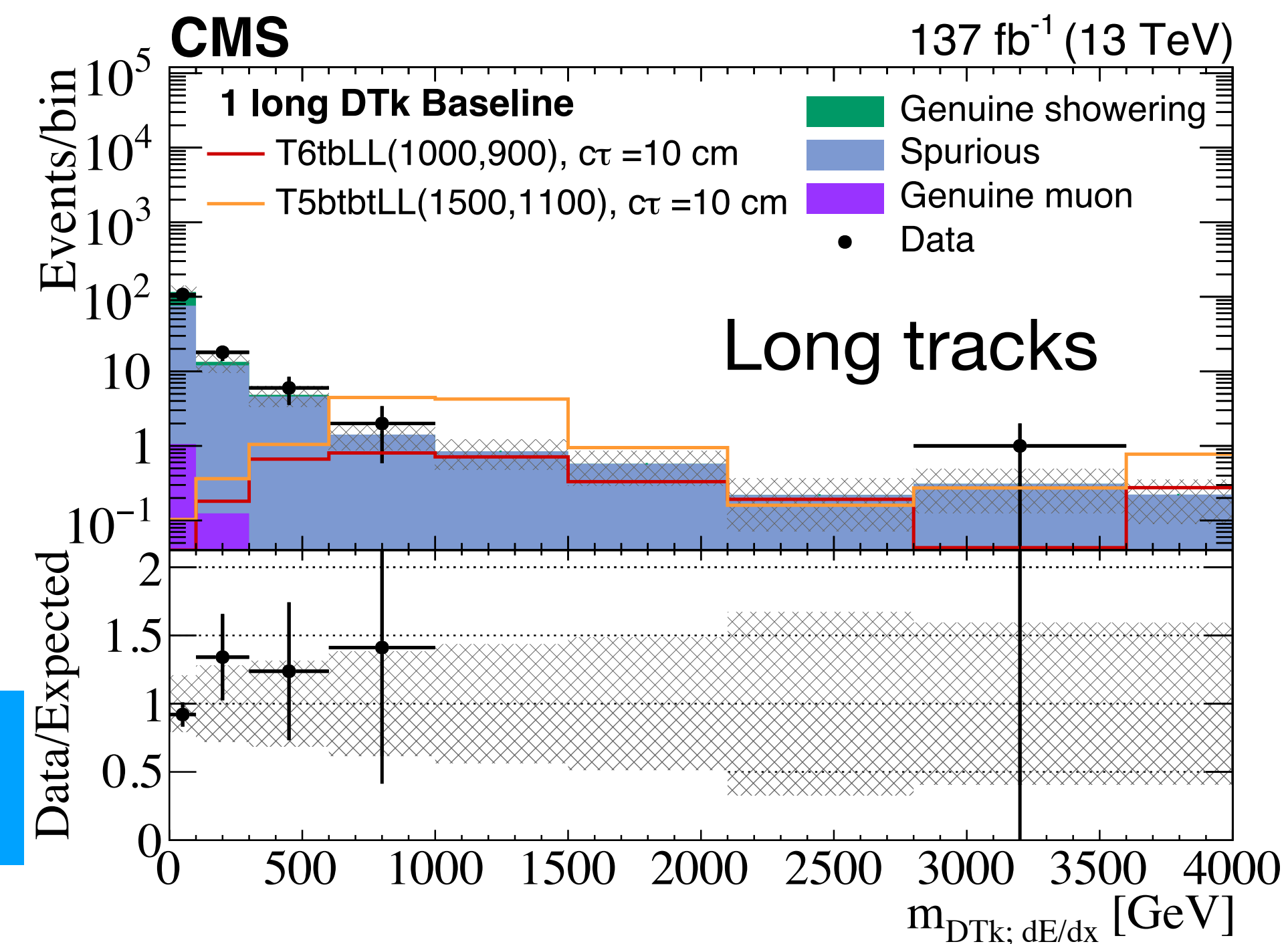
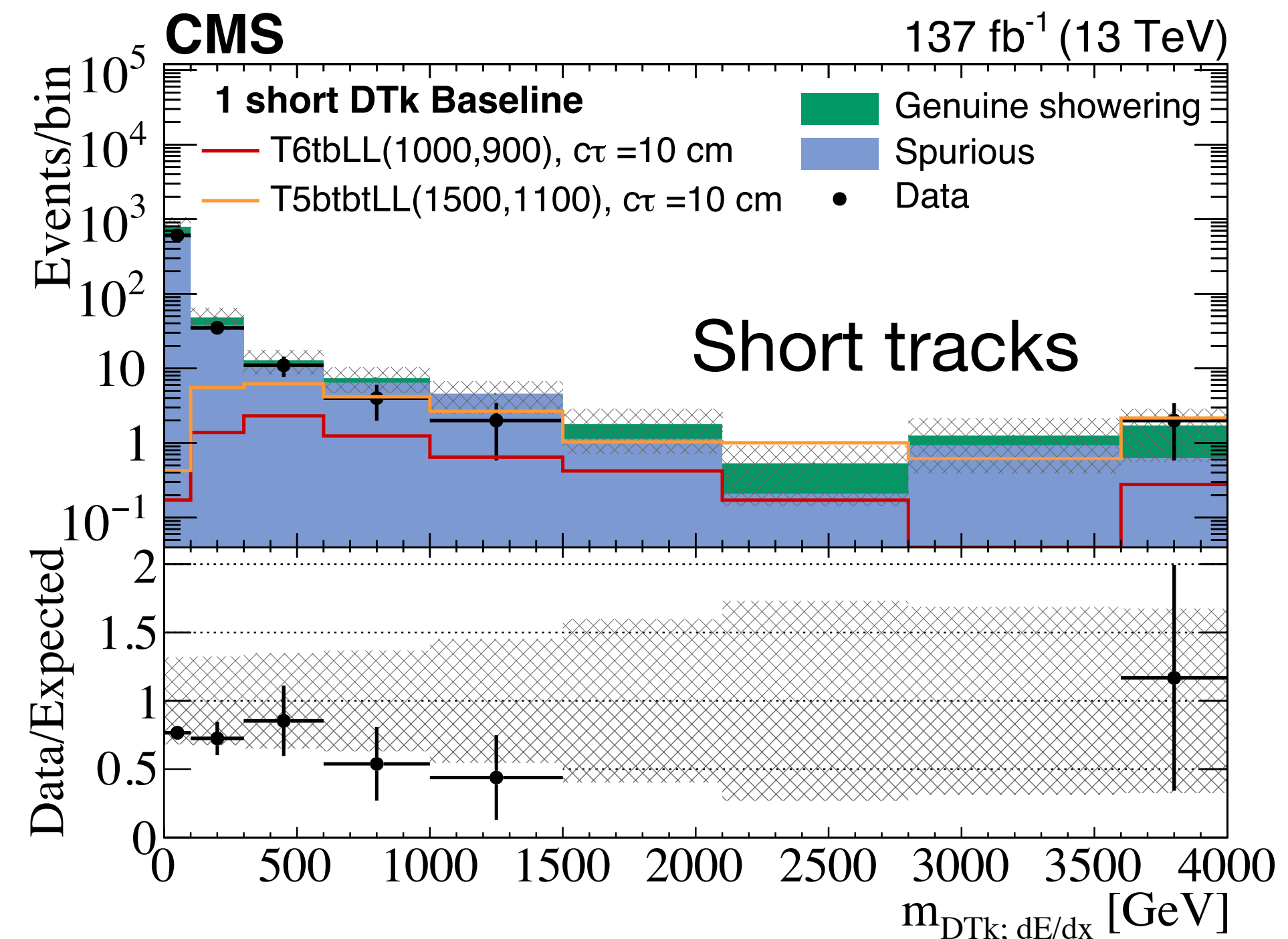


No consistent
signal feature

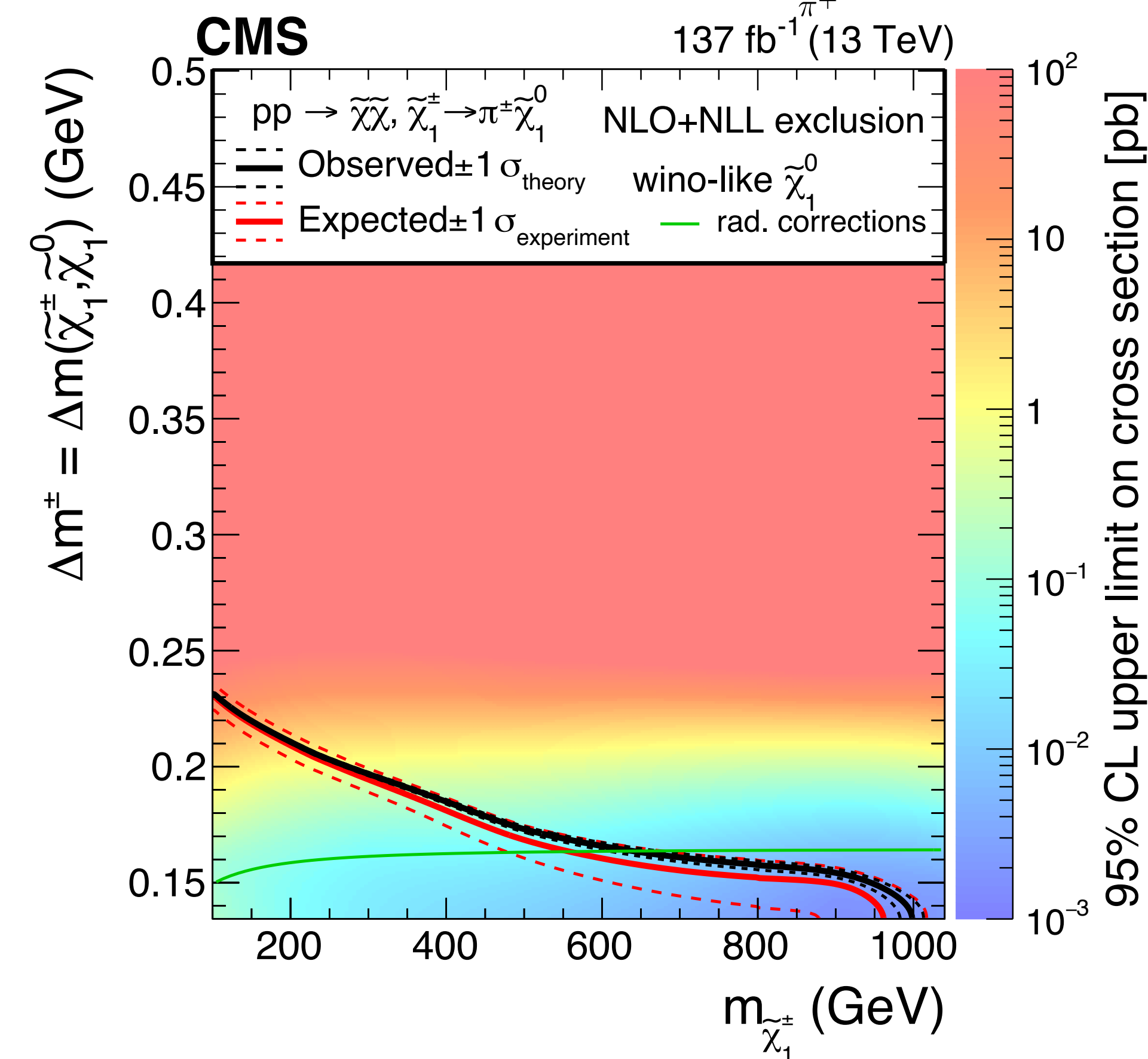
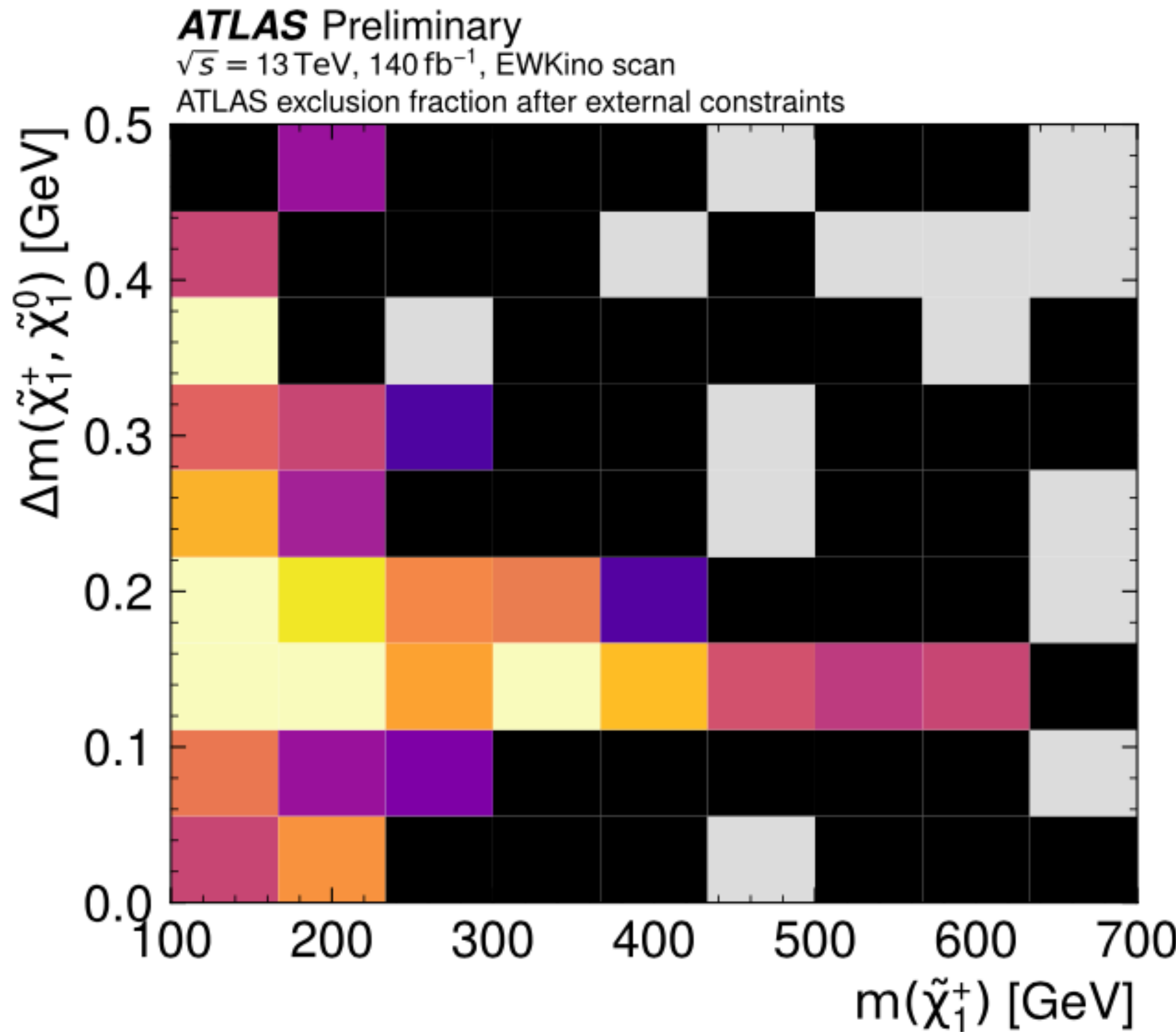
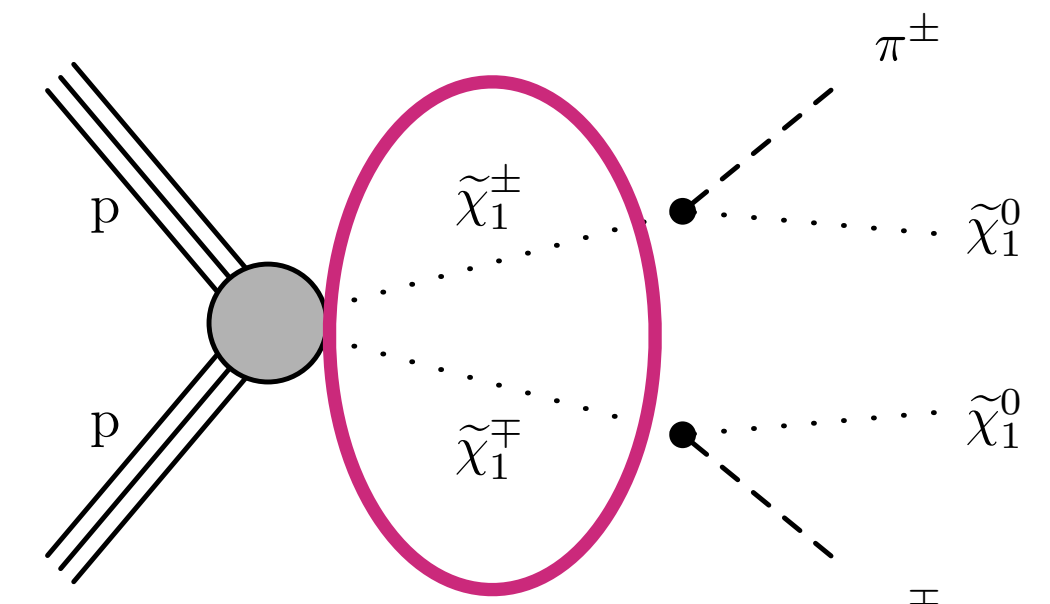
Mass from dE/dx

$$dE/dx = K \frac{m^2}{p^2} + C$$

arXiv:2309.16823: sub
to PRD 28.09.2023



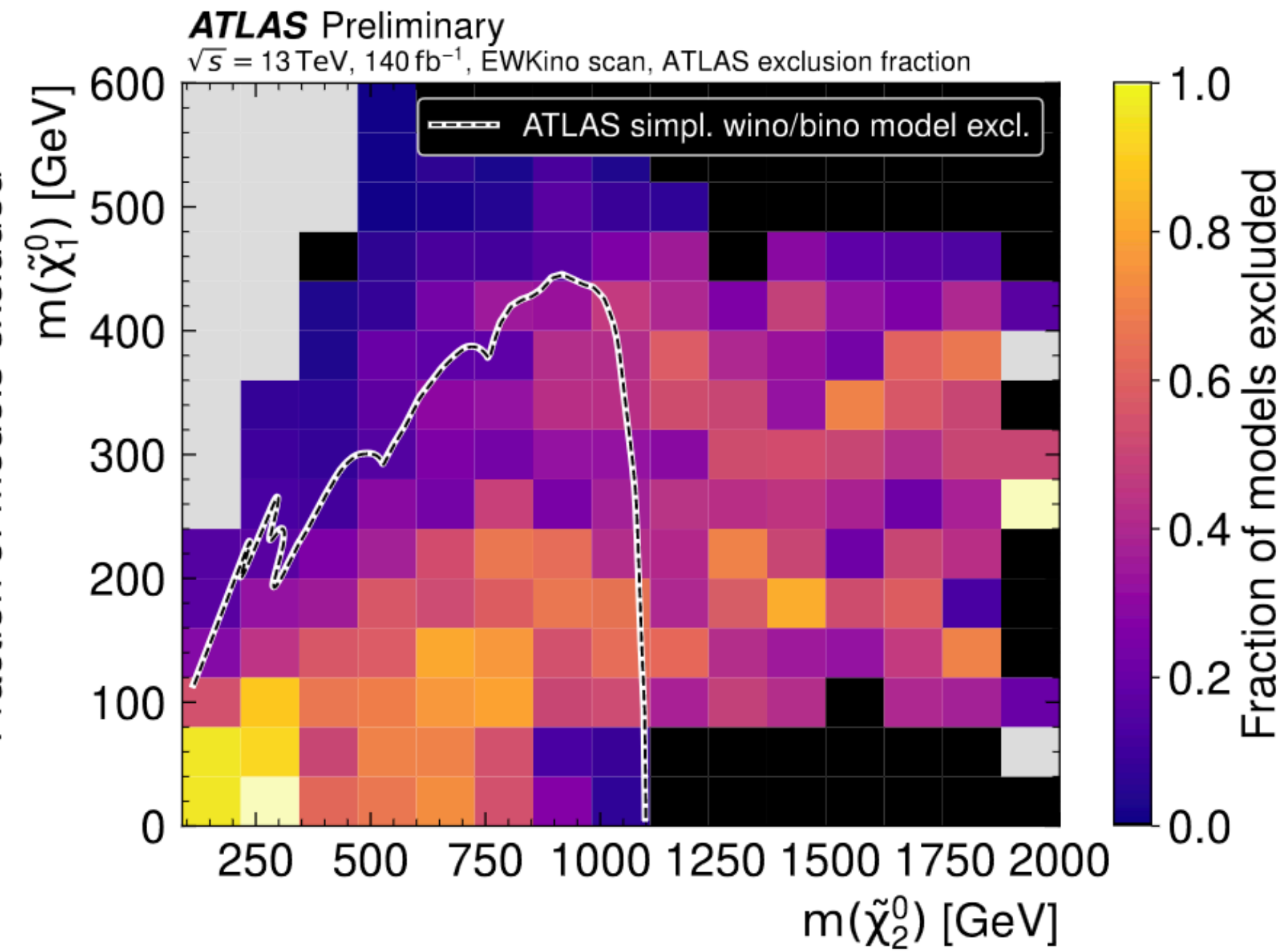
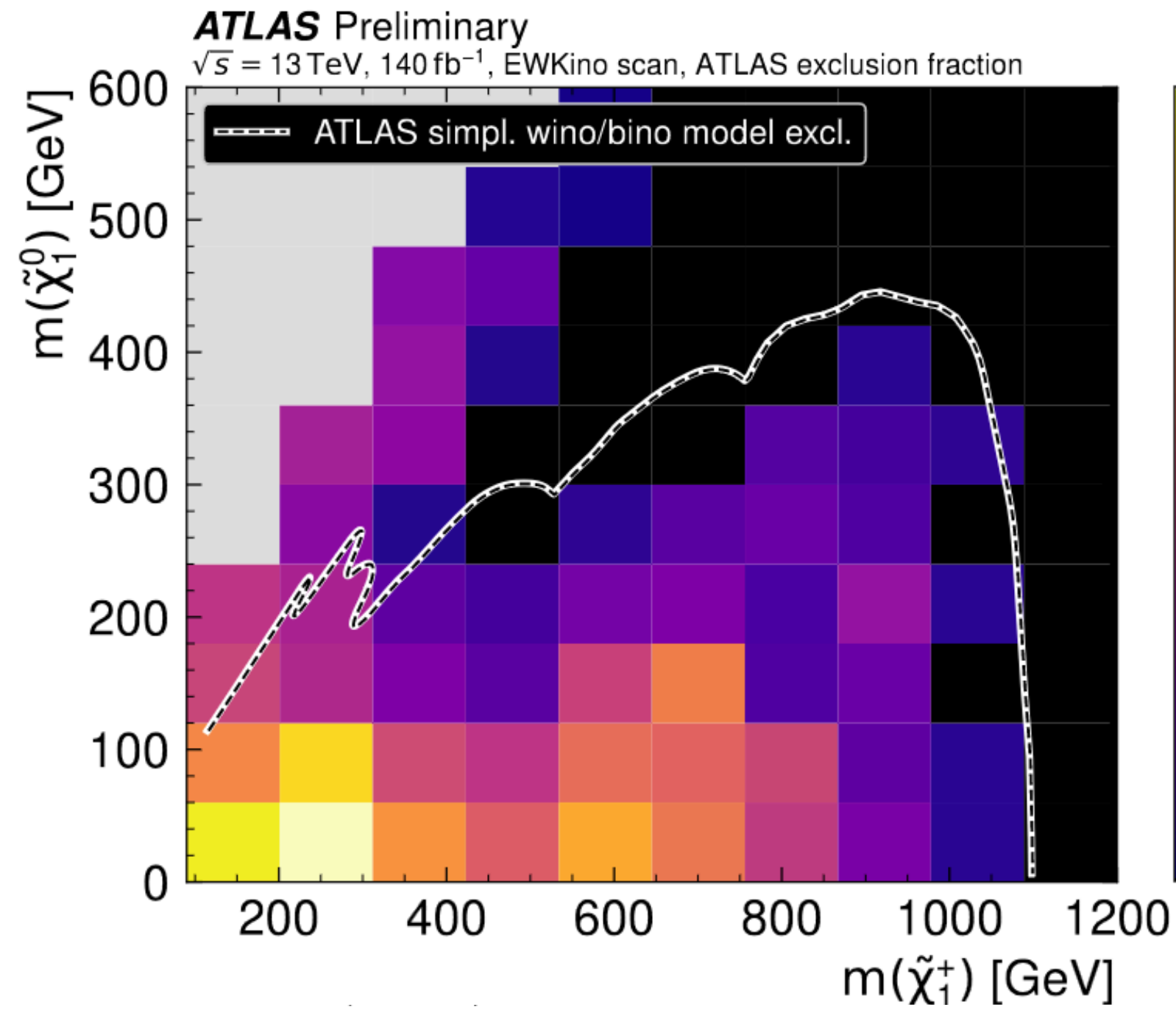
Chargino partner



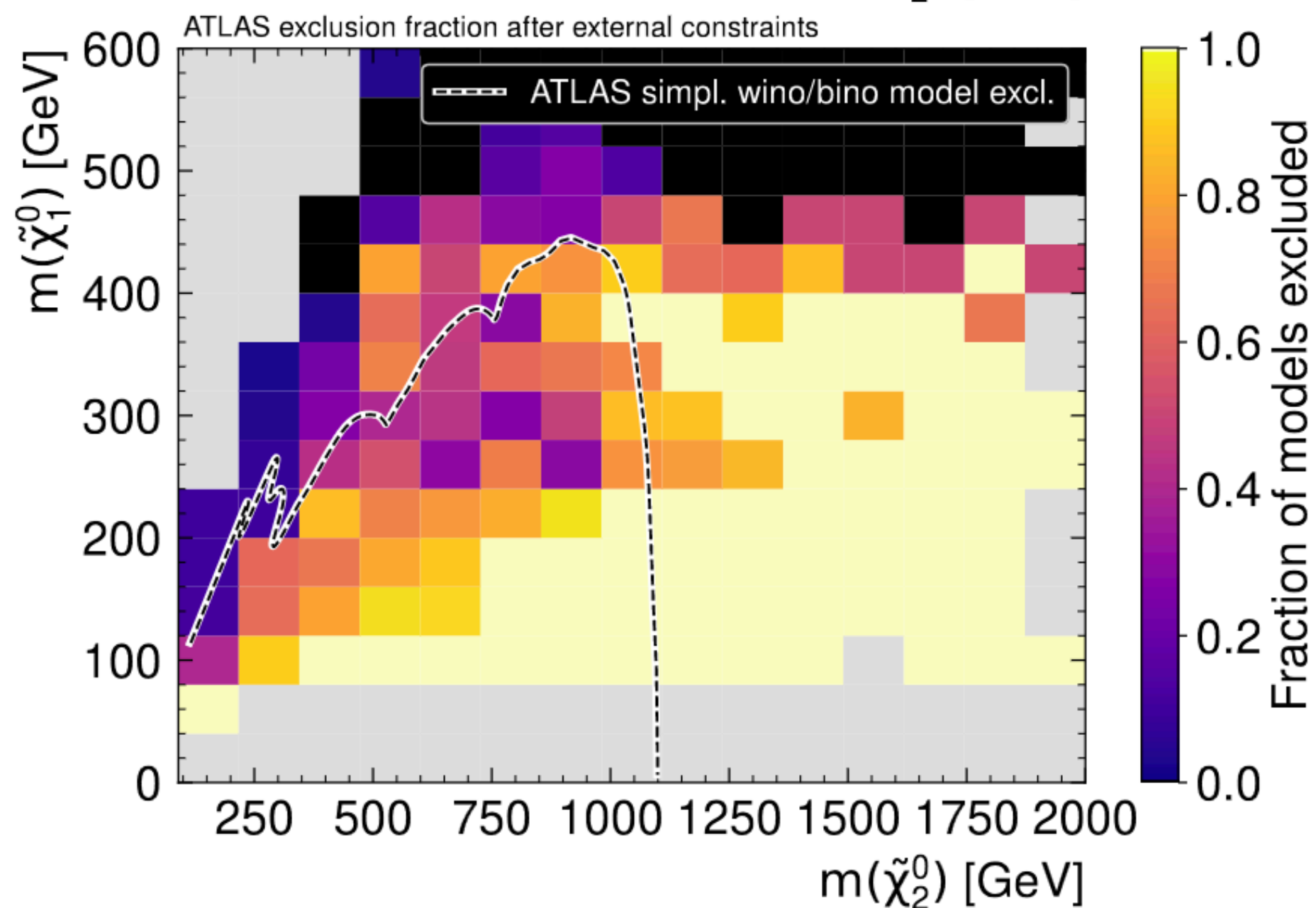
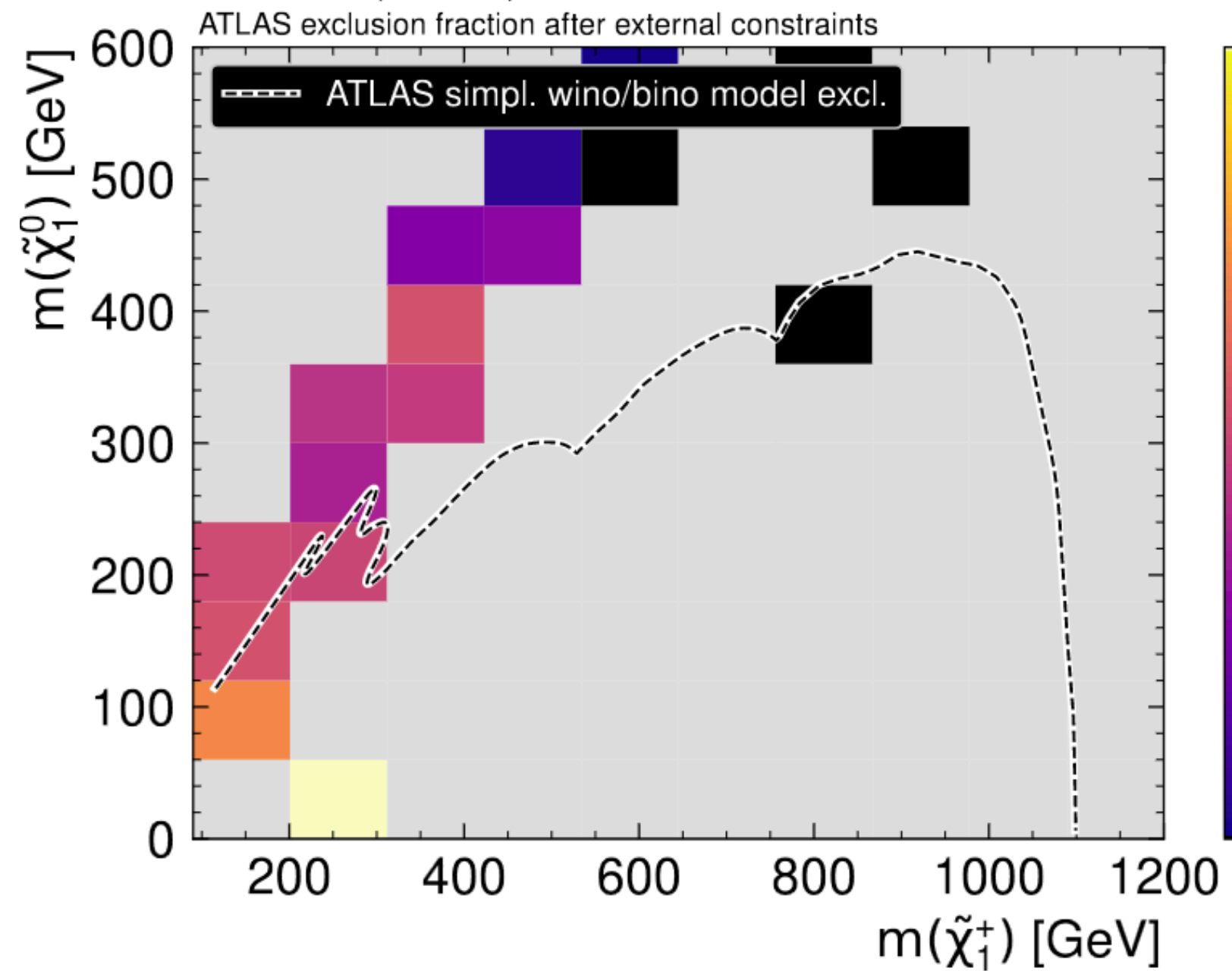
- pMSSM shows more (less) sensitivity to higher (lower) $\Delta m(\tilde{\chi}^\pm, \tilde{\chi}^0)$
- Disappearing tracks search -> big impact beyond non-LHC constraints!

CMS, ATLAS each set upper limit on pure Wino dark matter $m(\tilde{\chi}^\pm) > 625 \text{ GeV}$

LHC impact



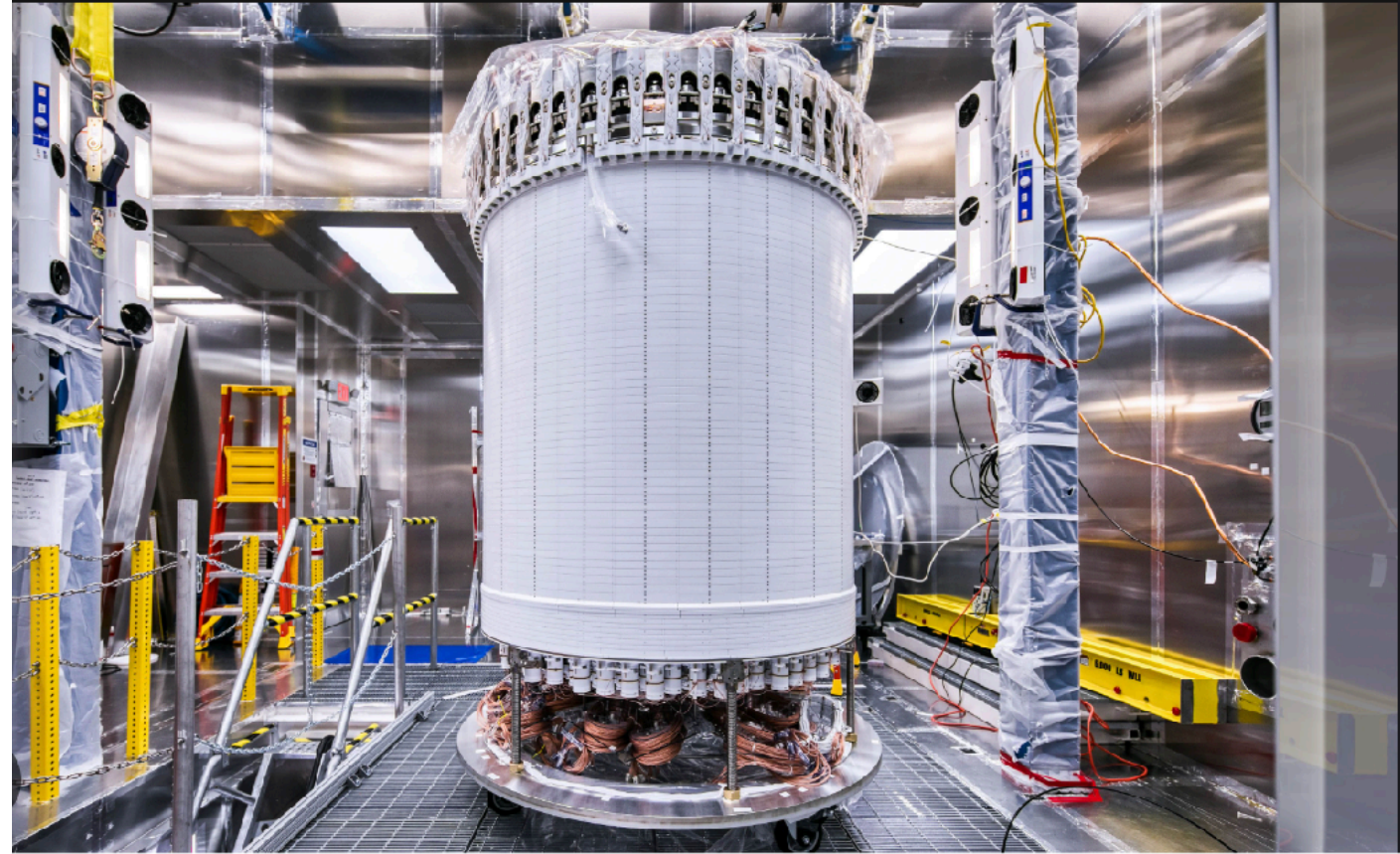
Unique LHC impact



- $m(\tilde{\chi}_2^0)$ constrained from above - interesting!

- Cream: high impact (total exclusion); black: no exclusion; gray: excluded by other experiments

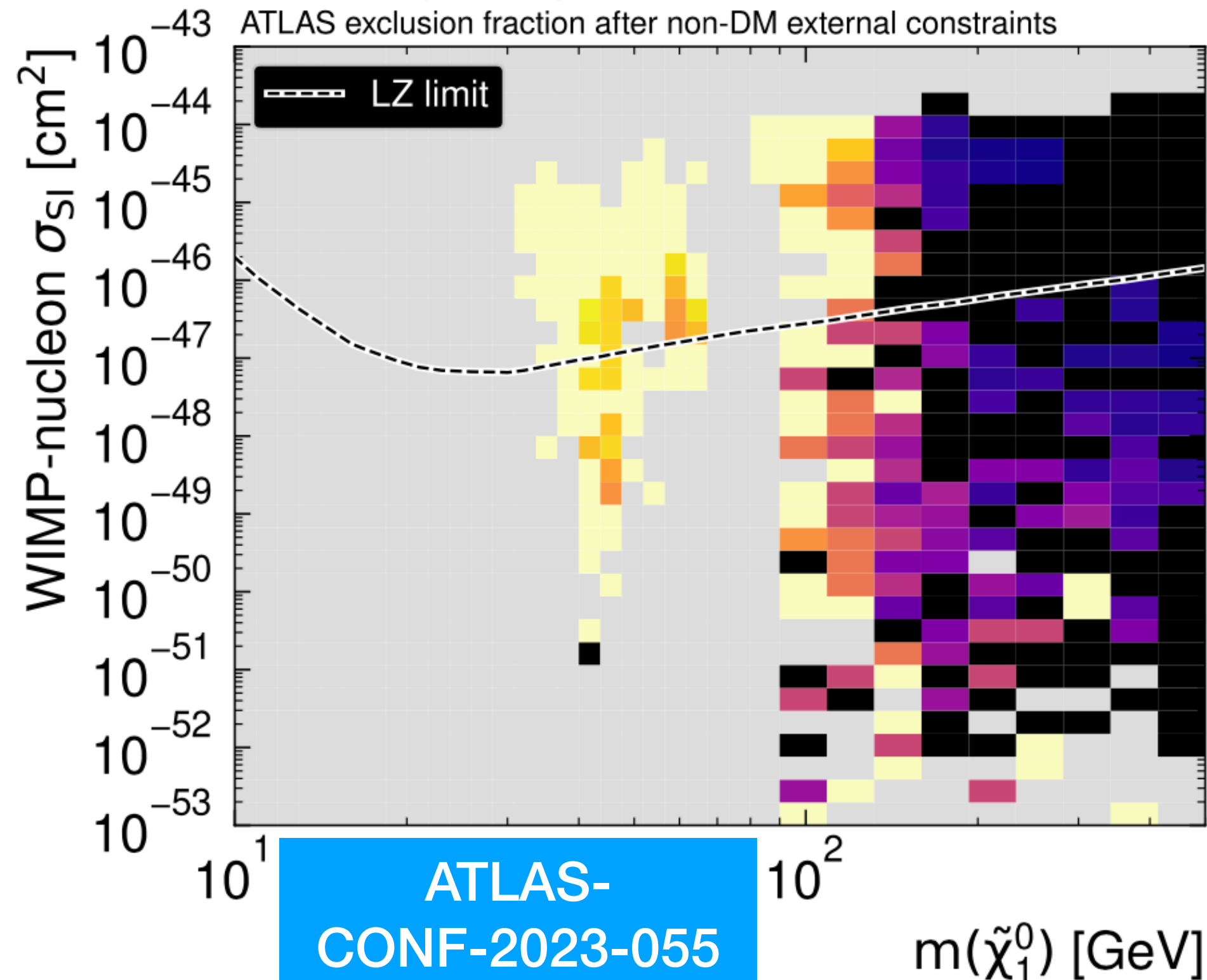
- Spin-independent WIMP-nucleon cross section.
 - - - LUX/ZEPLIN first results



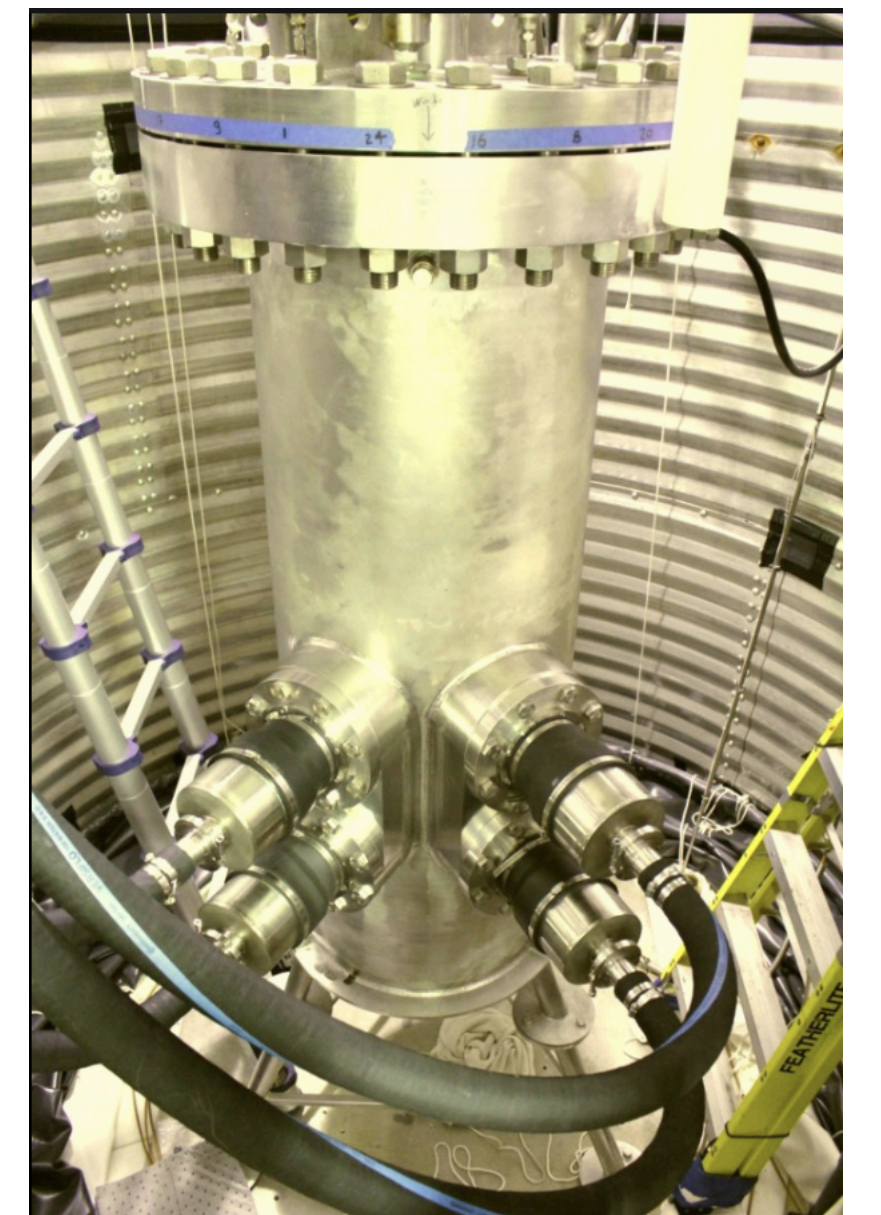
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$, 140 fb^{-1} , Bino-DM scan

ATLAS exclusion fraction after non-DM external constraints



- Spin-dependent WIMP-nucleon cross section
 - - - PICO-60 Complete exposure

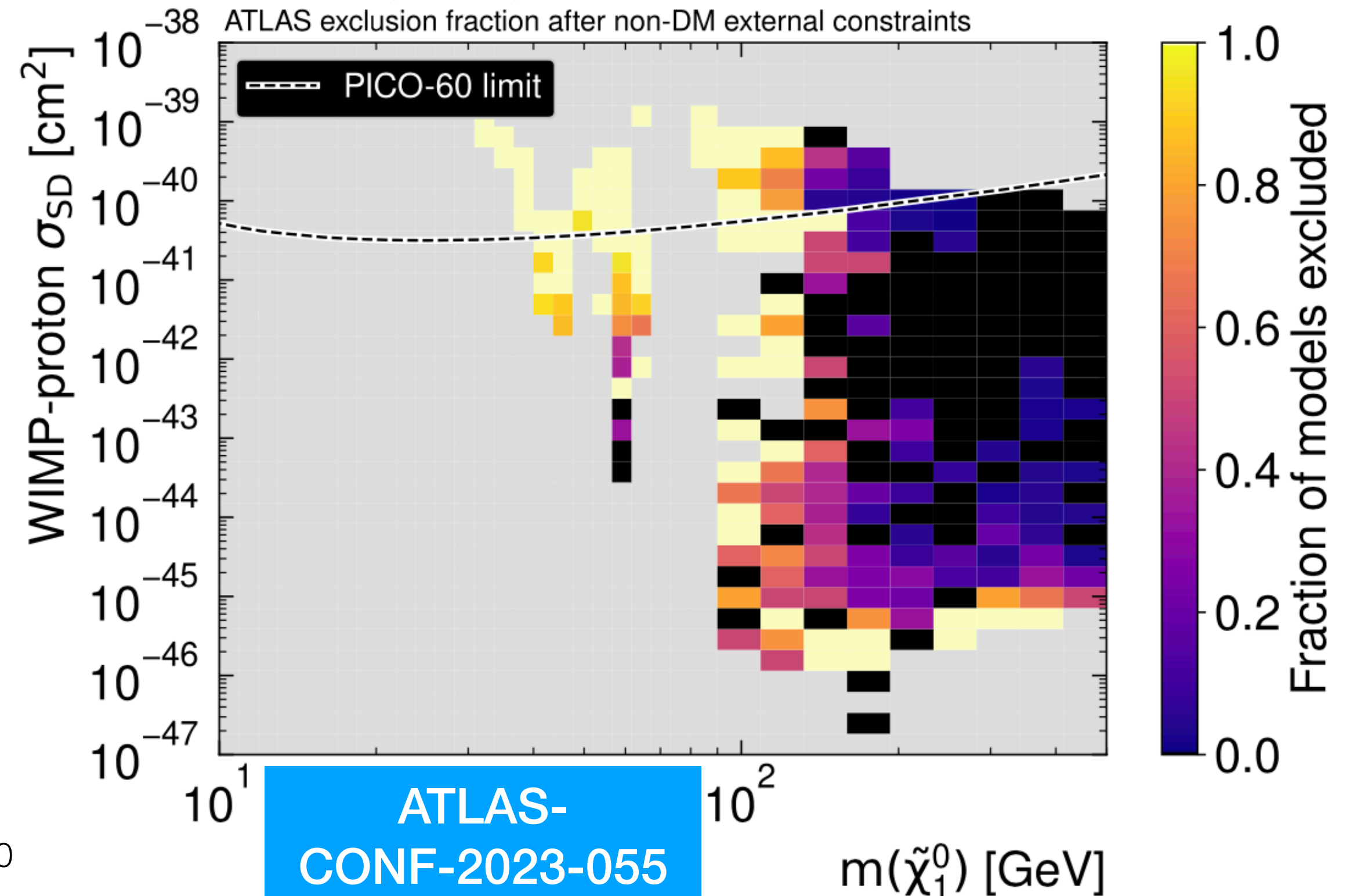


Good complementarity between collider, direct detection experiments!

ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$, 140 fb^{-1} , Bino-DM scan

ATLAS exclusion fraction after non-DM external constraints



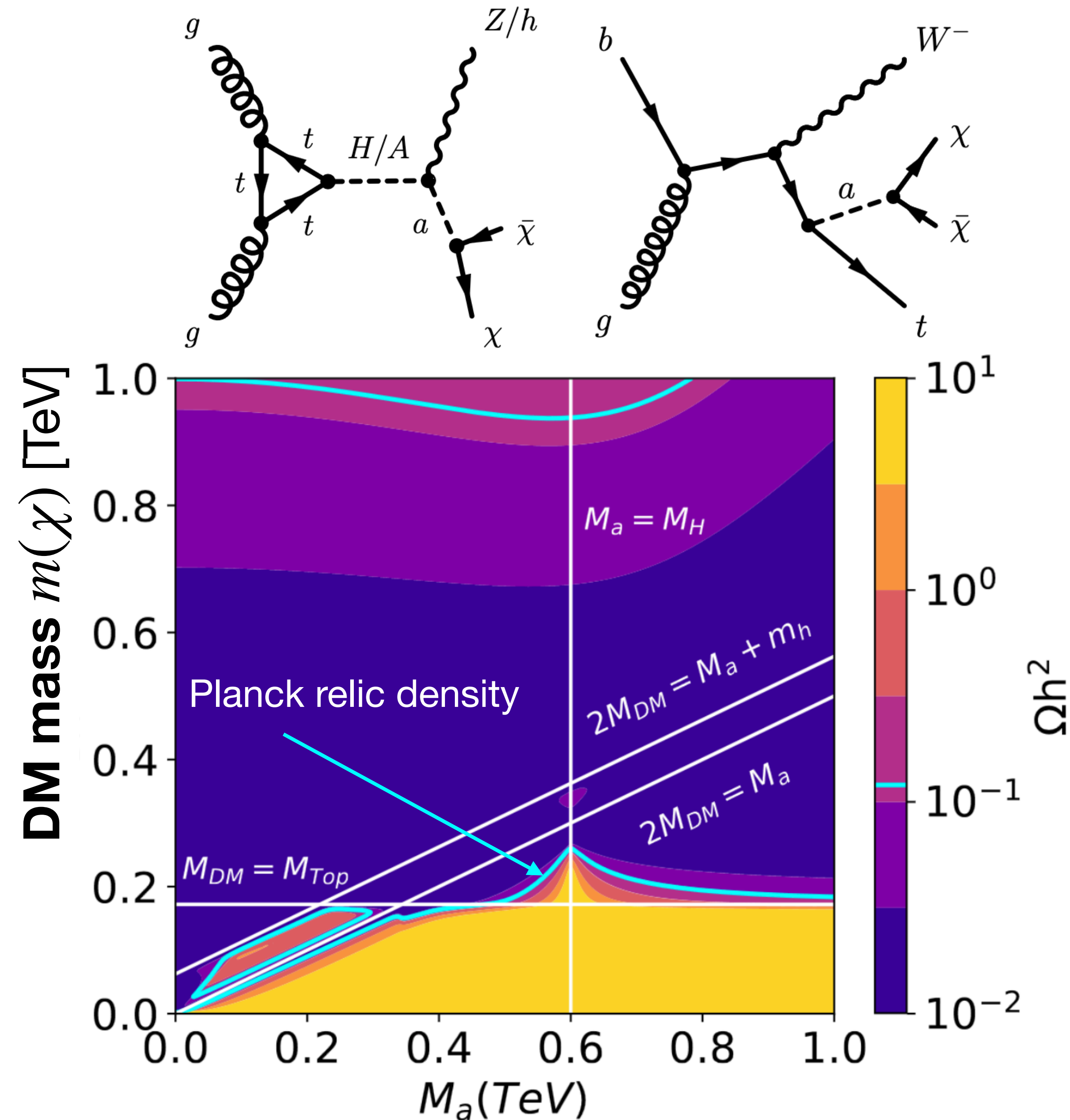
Community white paper

Two Higgs Doublet+pseudo-scalar mediator

- LHC Dark matter working group put forward candidate model for collider searches for DM:
 - 2HDM+a: 14 free parameters
 - Avoids direct detection - LHC impact important
- ATLAS DM combination
 - 6 scans: 2D-planes in 5-parameter subspace:
 - Dark matter mass: m_χ
 - Heavy Higgs Boson mass: $m_A = m_H = m_{H^\pm}$
 - Pseudo-scalar mediator mass: m_a
 - CP-odd mixing: θ , VEV ratio: $\tan\beta$
- Impact of 8 searches: $E_T^{\text{miss}}+$
 - $Z, h, tW, j, b\bar{b}, t\bar{t}, t\bar{t}t\bar{t}$

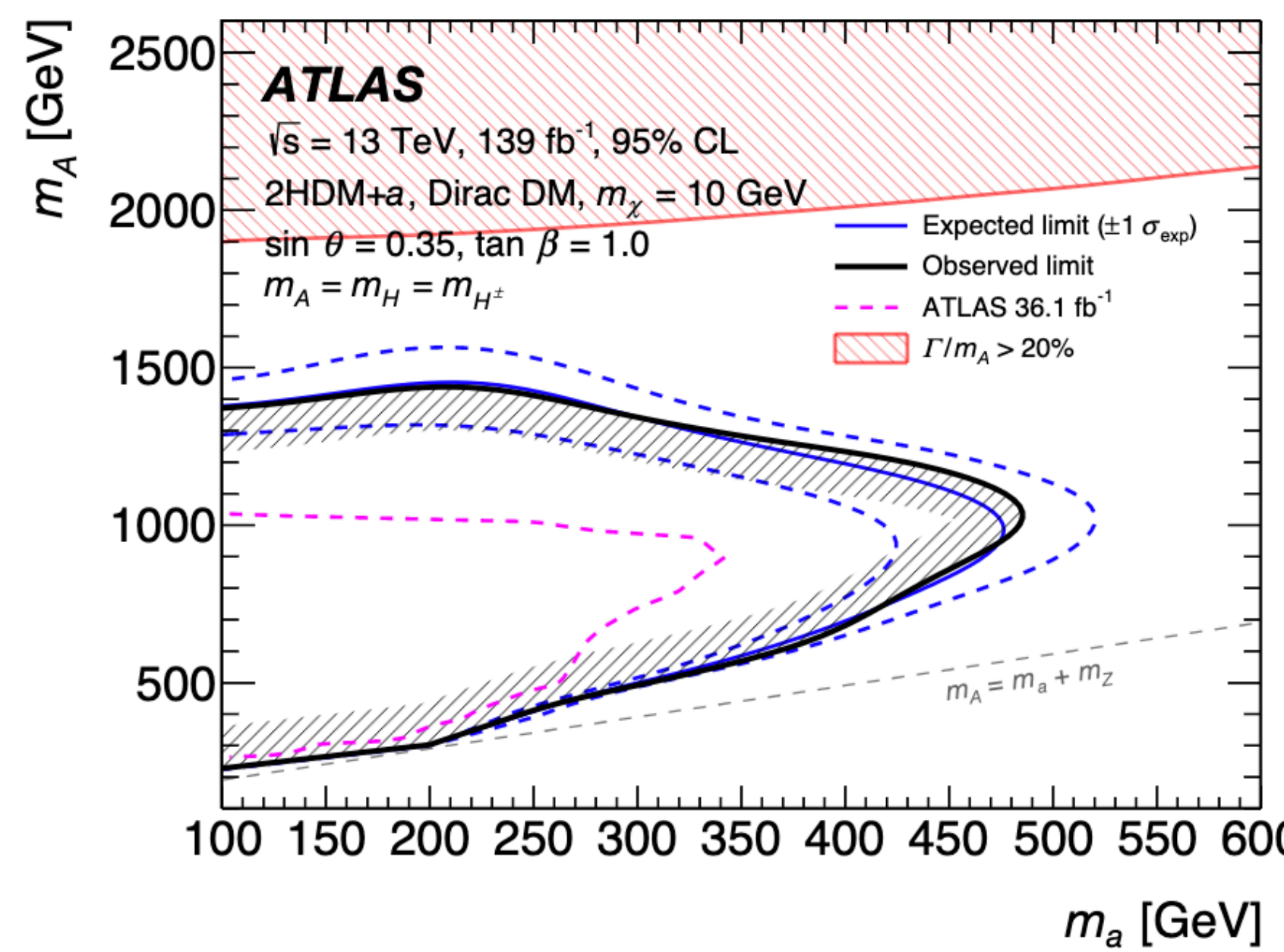
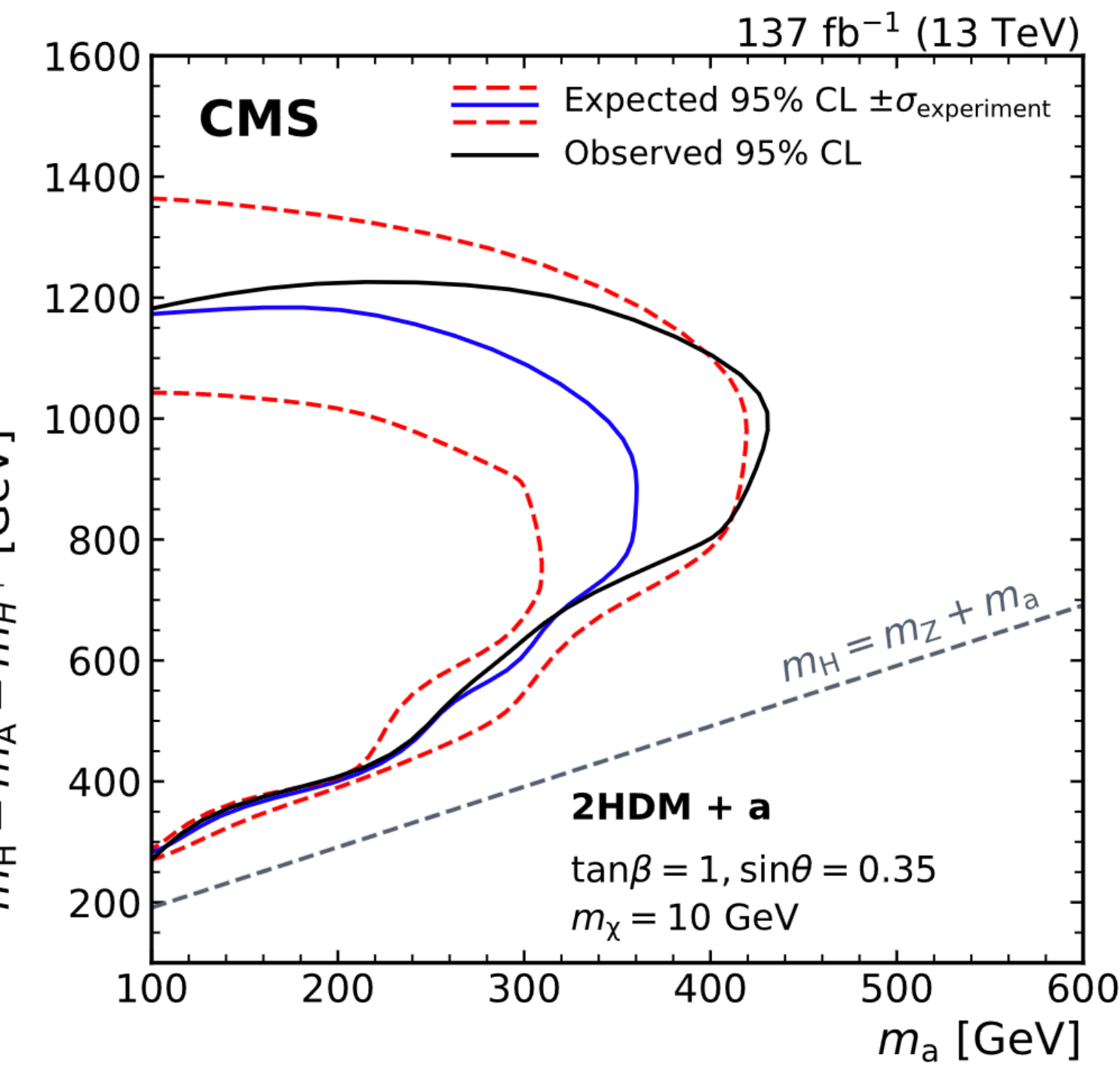
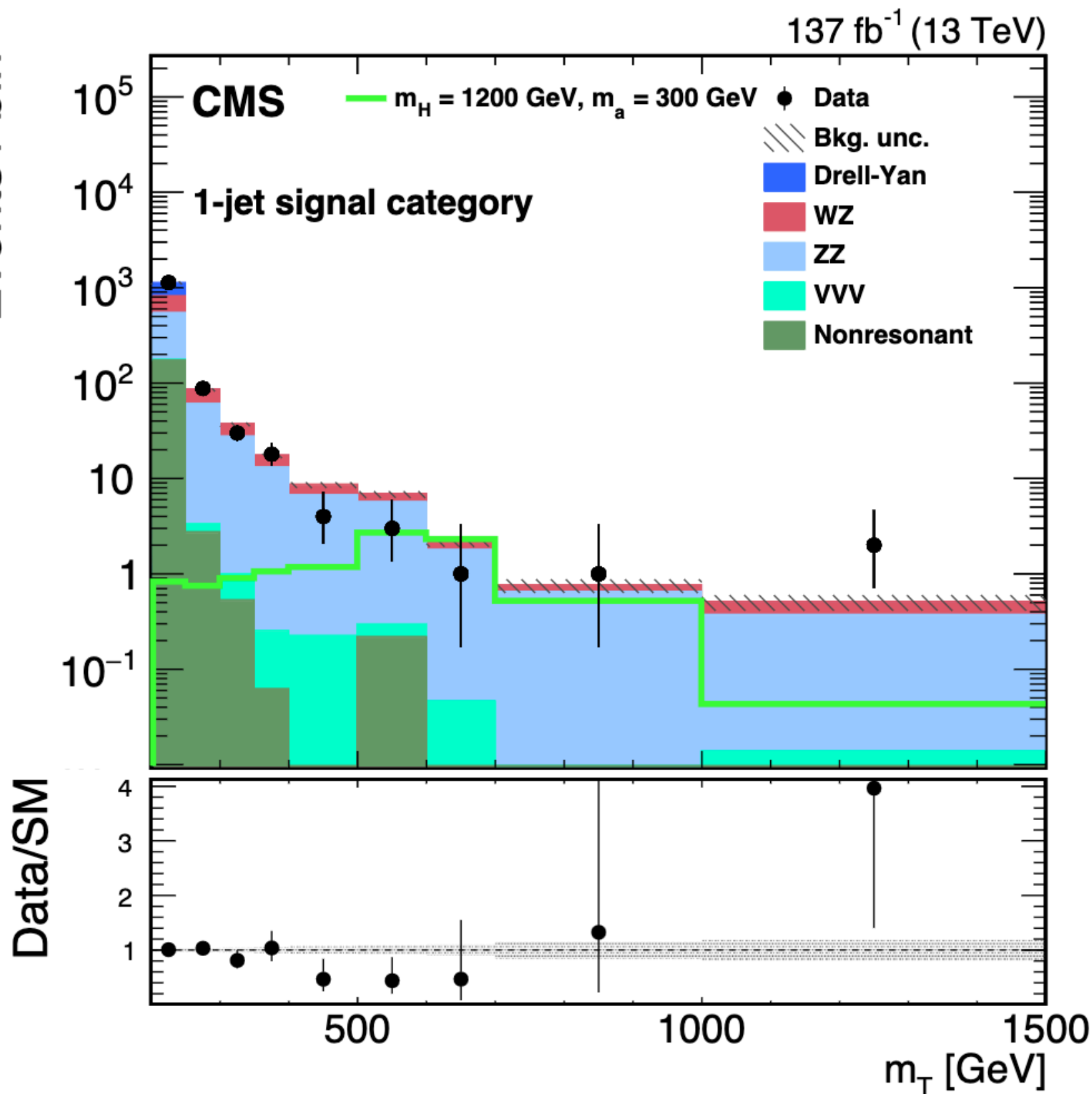
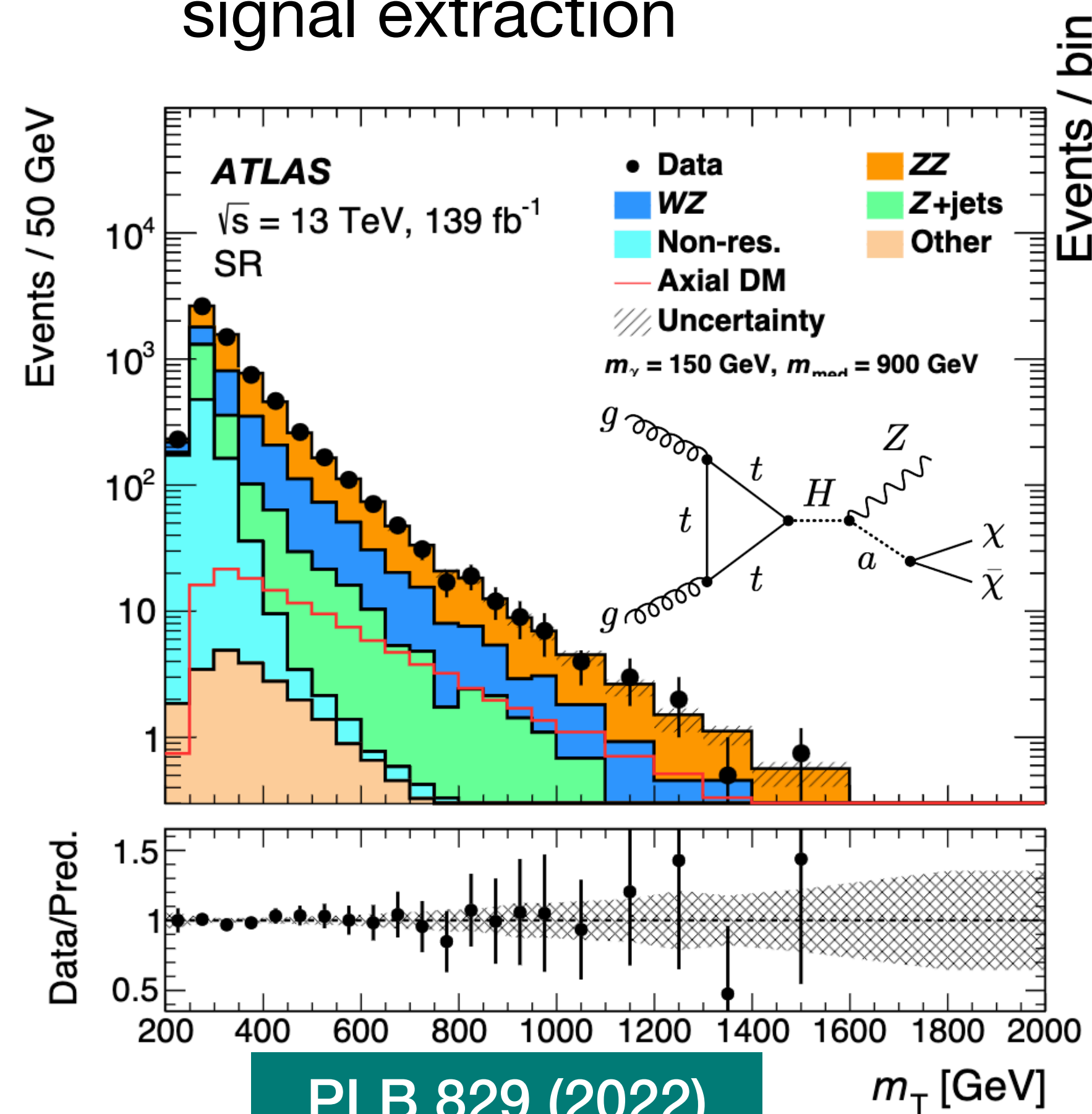
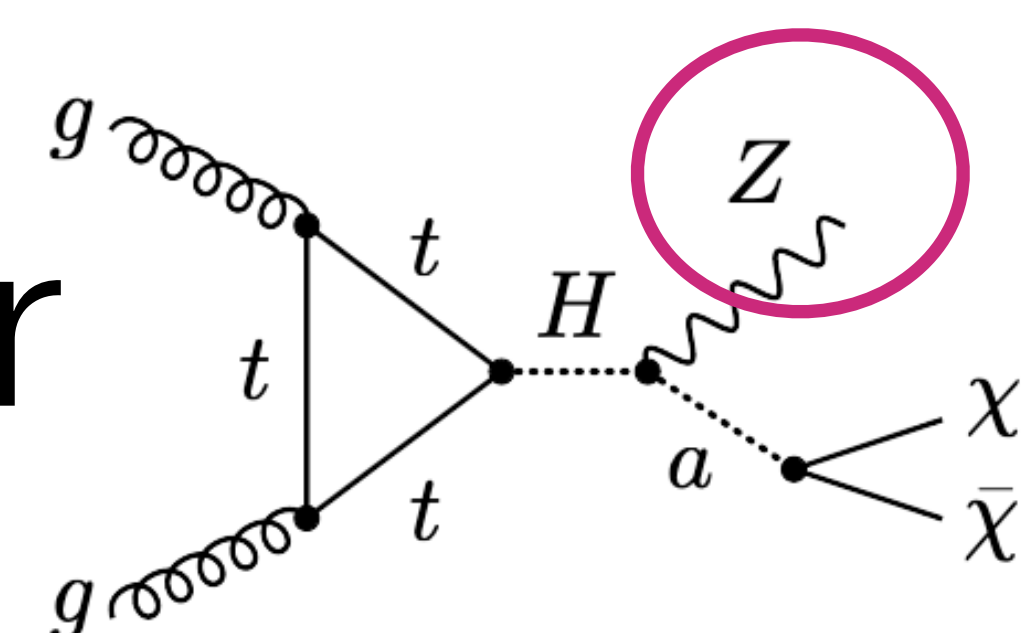
[arXiv:2306.00641](https://arxiv.org/abs/2306.00641) Sub to Science bulletin

21



Pseudoscalar as partner

- 2-OSSF lepton final state: $Z \rightarrow \ell\ell + E_T^{\text{miss}}$
- Transverse mass $m_T[\vec{p}_T(\ell\ell), \vec{E}_T^{\text{miss}}]$ for signal extraction

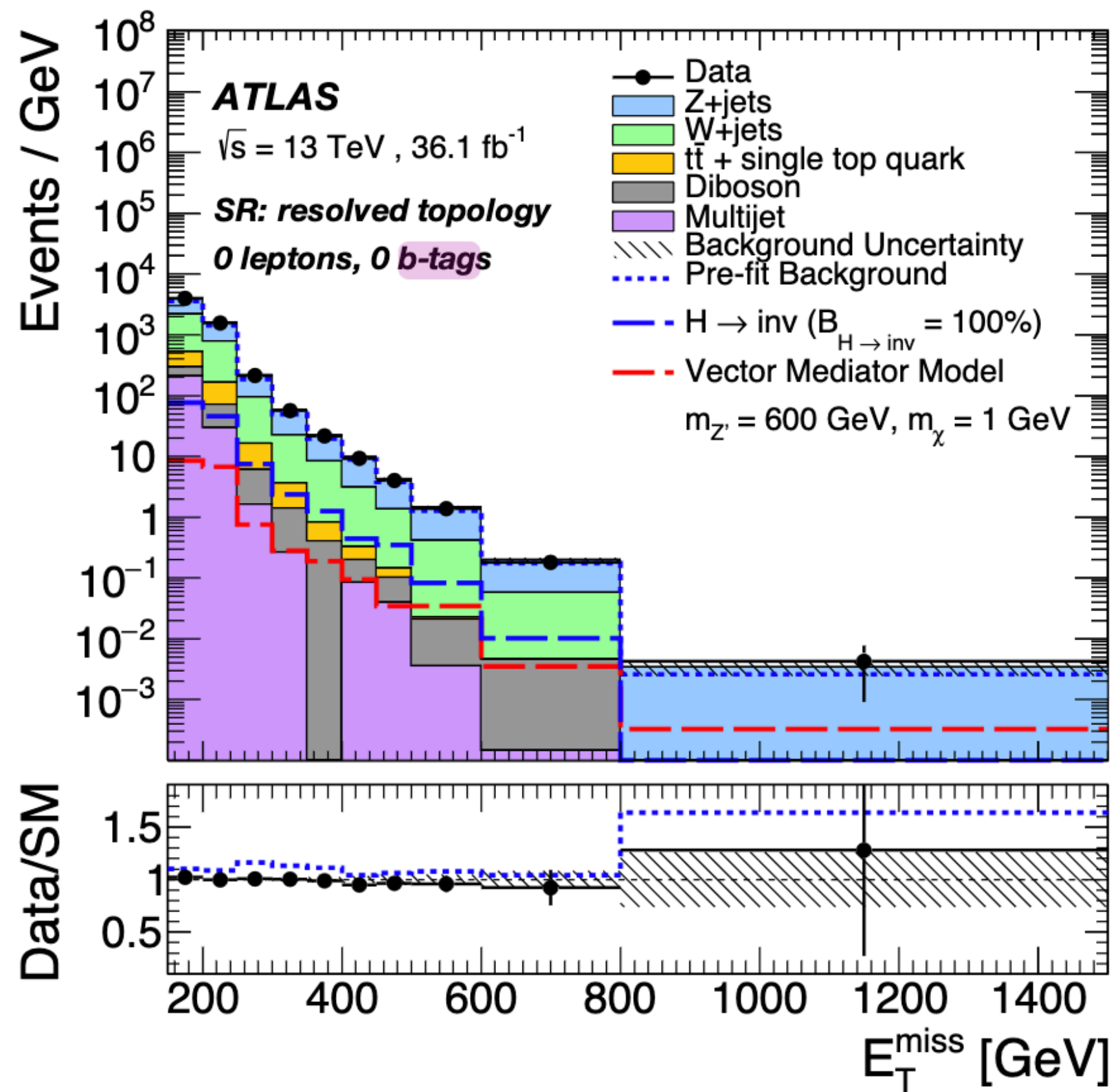
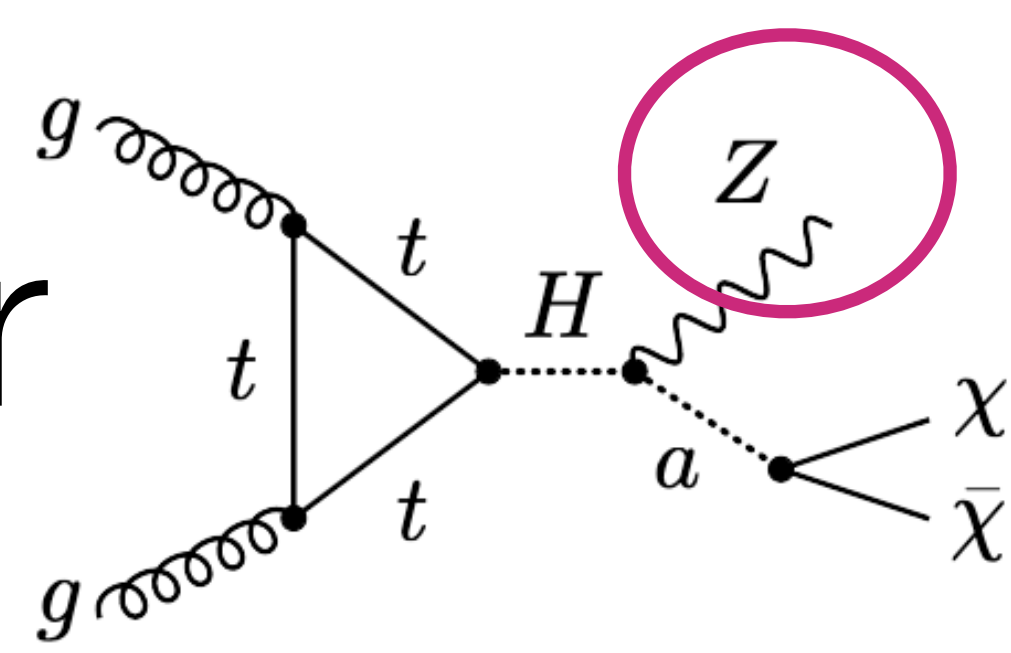


PLB 829 (2022)
137006

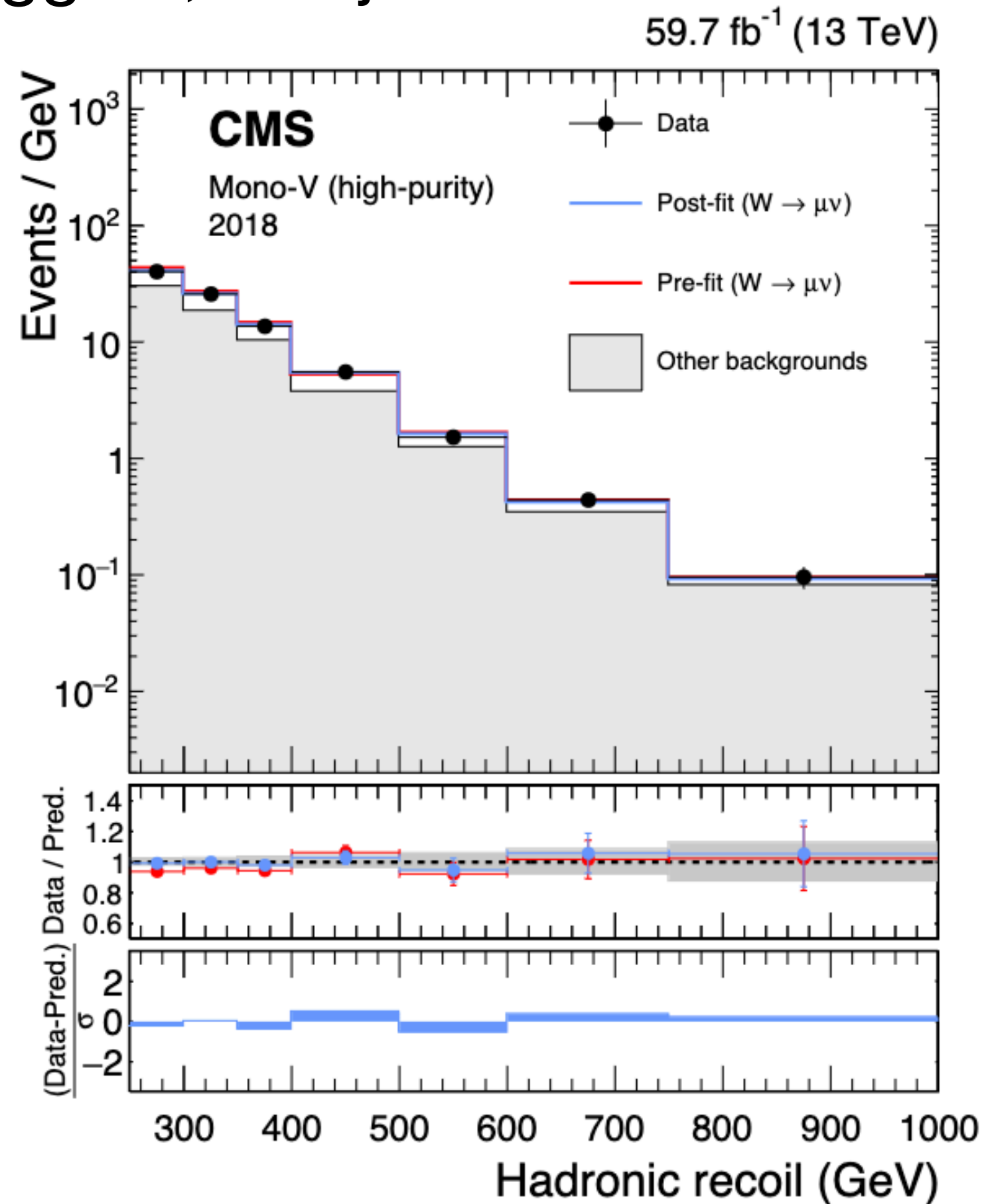
Eur. Phys. J. C 81 (2021)

Pseudoscalar as partner

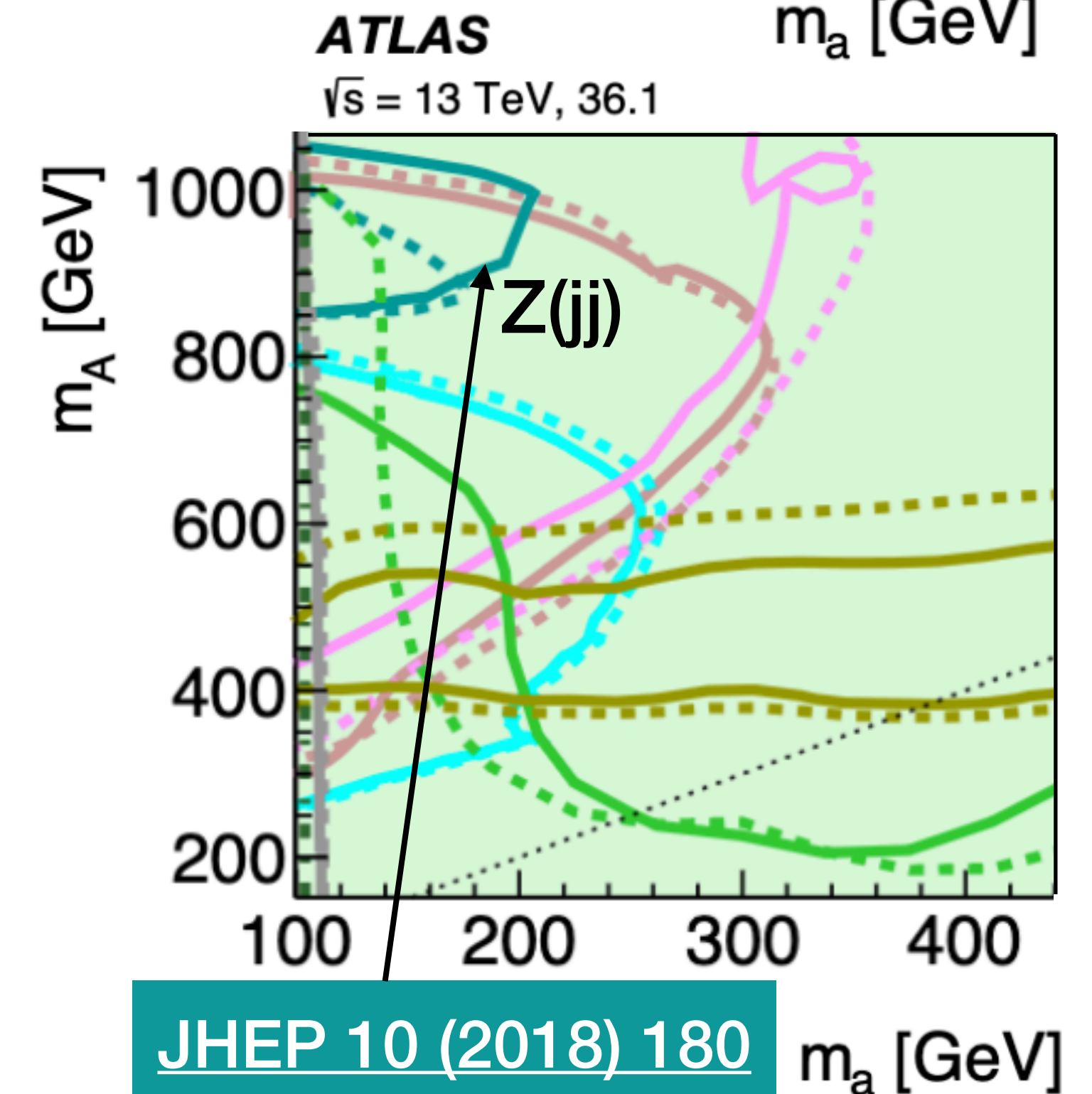
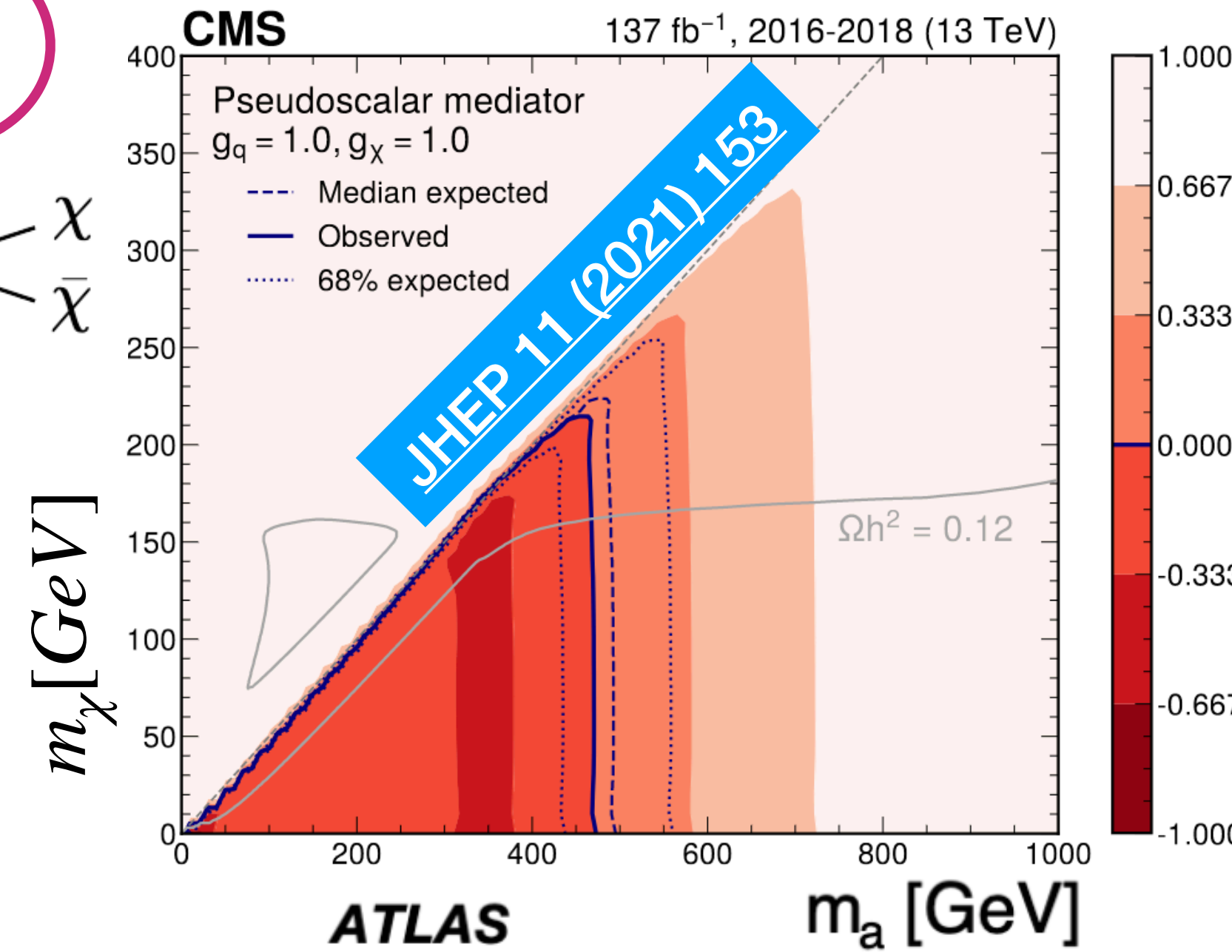
- Hadronic final state: $Z \rightarrow qq + E_T^{\text{miss}}$
- Large-radius jet (merged jet) V-taggers, ak8 jet



JHEP 10 (2018) 180



JHEP 11 (2021) 153

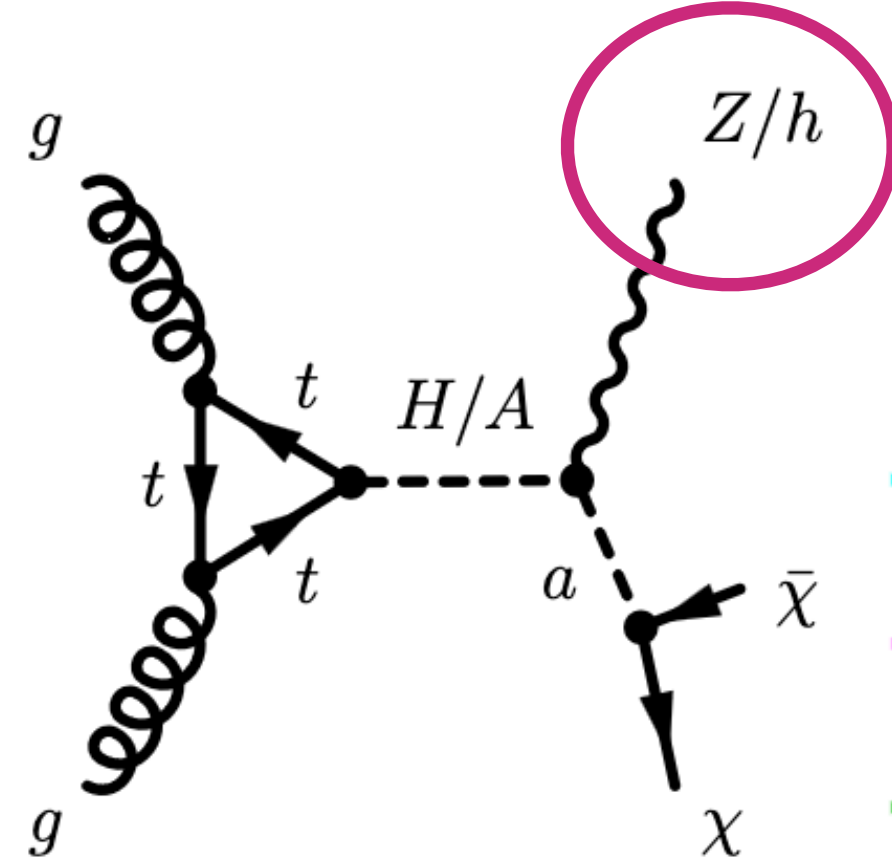


JHEP 10 (2018) 180

m_a [GeV]

Pseudoscalar as partner

- ATLAS combination 2HDM+a
- Combine best three searches:
 $h(b\bar{b}), E_T^{\text{miss}} + Z(\ell\ell), tbH^\pm(tb)$

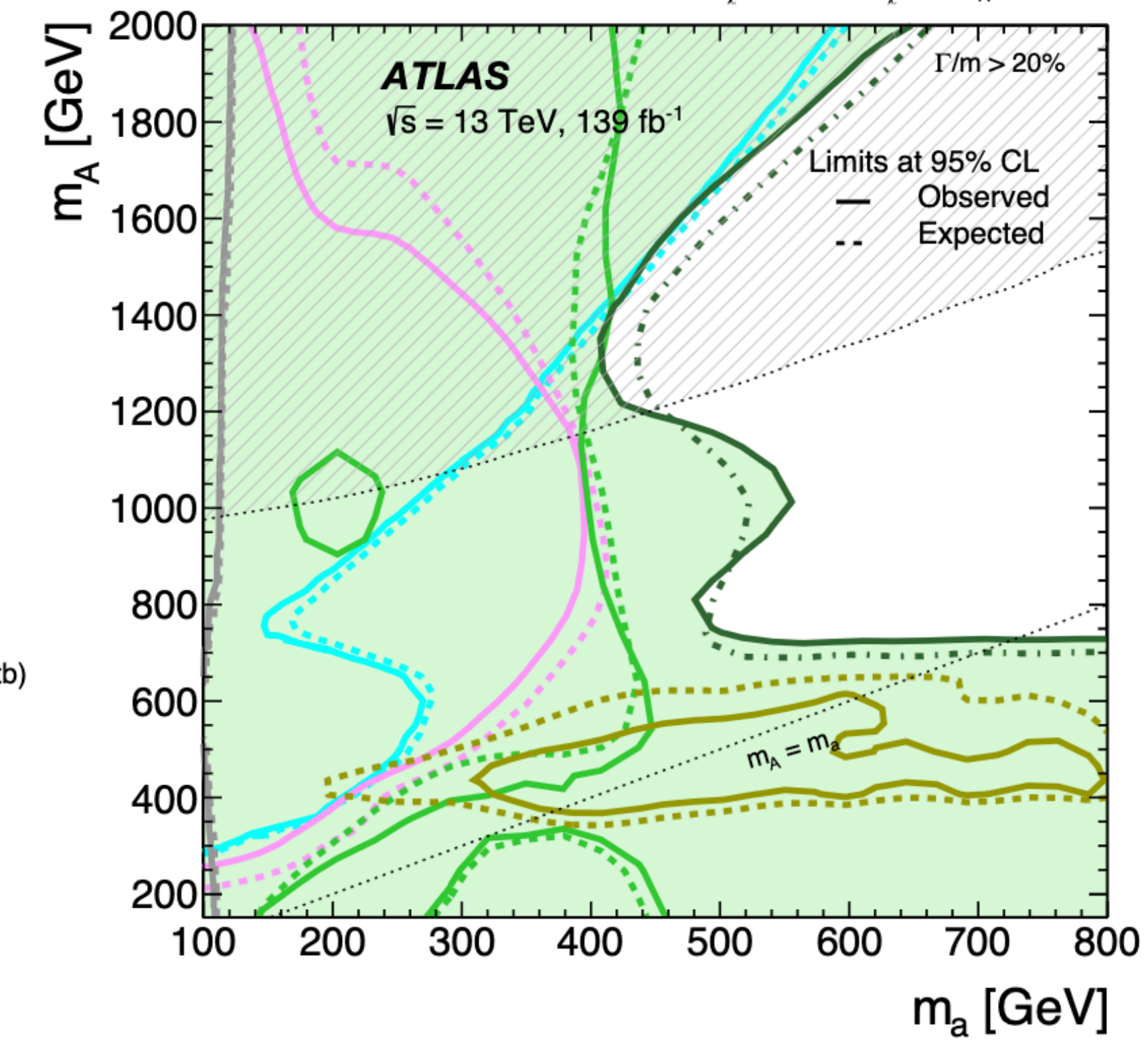
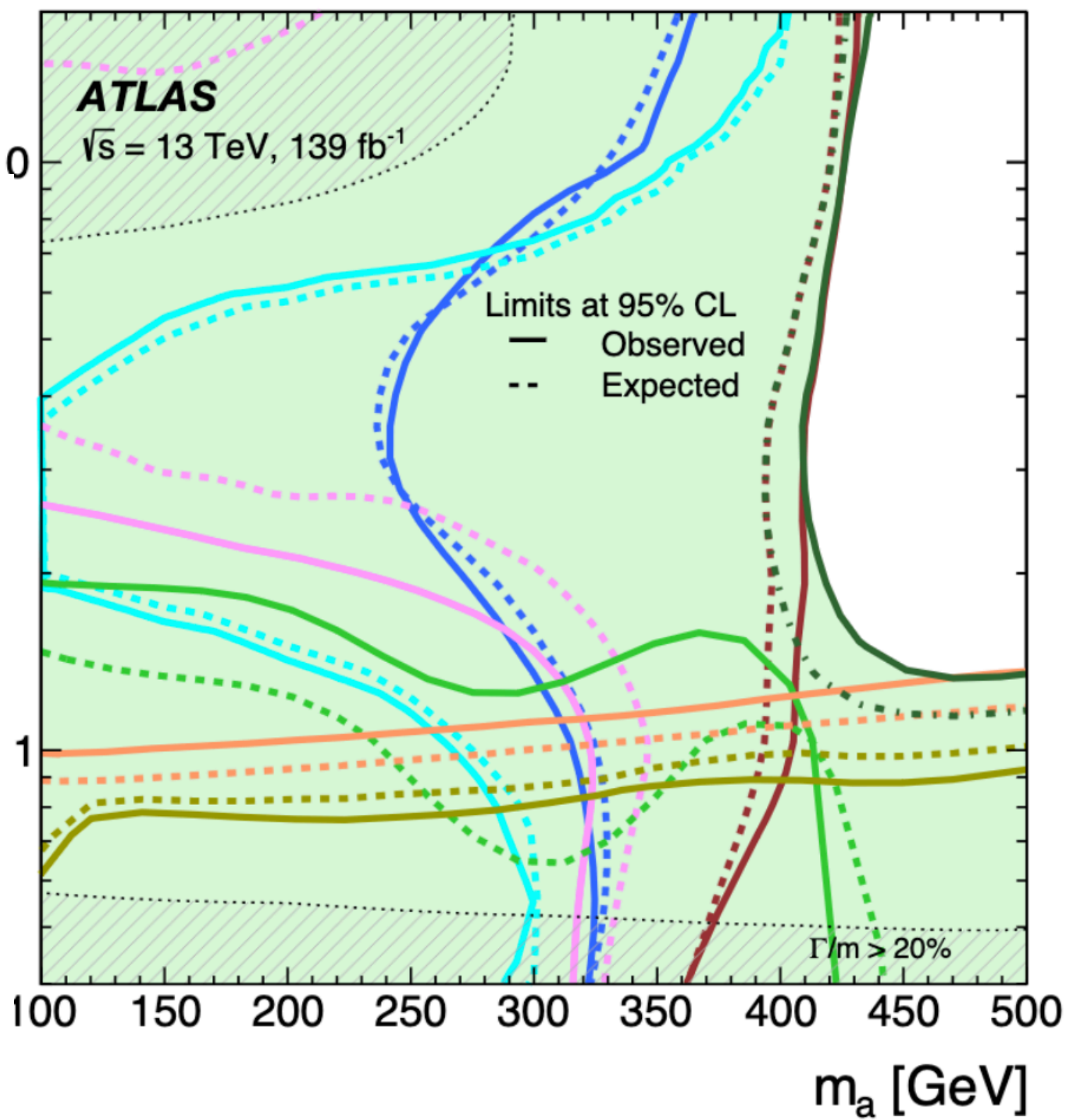
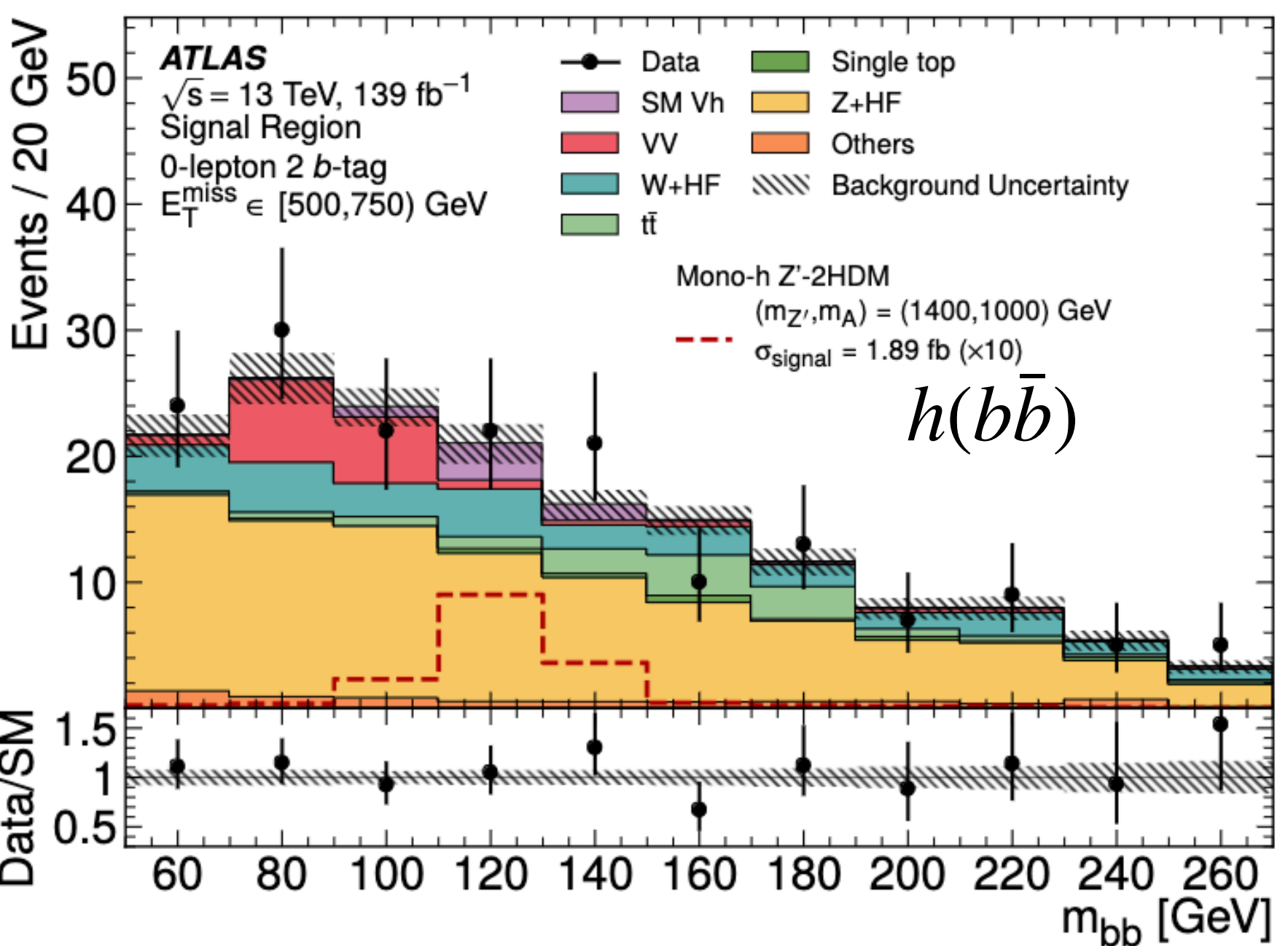


arXiv:2306.00641 Sub to Science bulletin

- $E_T^{\text{miss}} + h(\gamma\gamma), 139 \text{ fb}^{-1}$ (JHEP 10 (2021) 13)
- $E_T^{\text{miss}} + tW, 139 \text{ fb}^{-1}$ (arXiv:2211.13138)
- $E_T^{\text{miss}} + j, 139 \text{ fb}^{-1}$ (PRD 103 (2021) 112006)
- $t\bar{t}t, 139 \text{ fb}^{-1}$ (arXiv:2211.01136)
- $h \rightarrow \text{invisible}, 139 \text{ fb}^{-1}$ (arxiv:2301.10731)
- Combination $E_T^{\text{miss}} + h(b\bar{b}), E_T^{\text{miss}} + Z(\ell\ell), tbH^\pm(tb)$

2HDM+a, Dirac DM, $\sin\theta = 0.7, m_\chi = 10 \text{ GeV}, g_\chi = 1, m_A = m_H = m_{H^\pm} = 600 \text{ GeV}$

2HDM+a, Dirac DM, $\sin\theta = 0.7, \tan\beta = 1, m_\chi = 10 \text{ GeV}, g_\chi = 1, m_A = m_H = m_{H^\pm}$

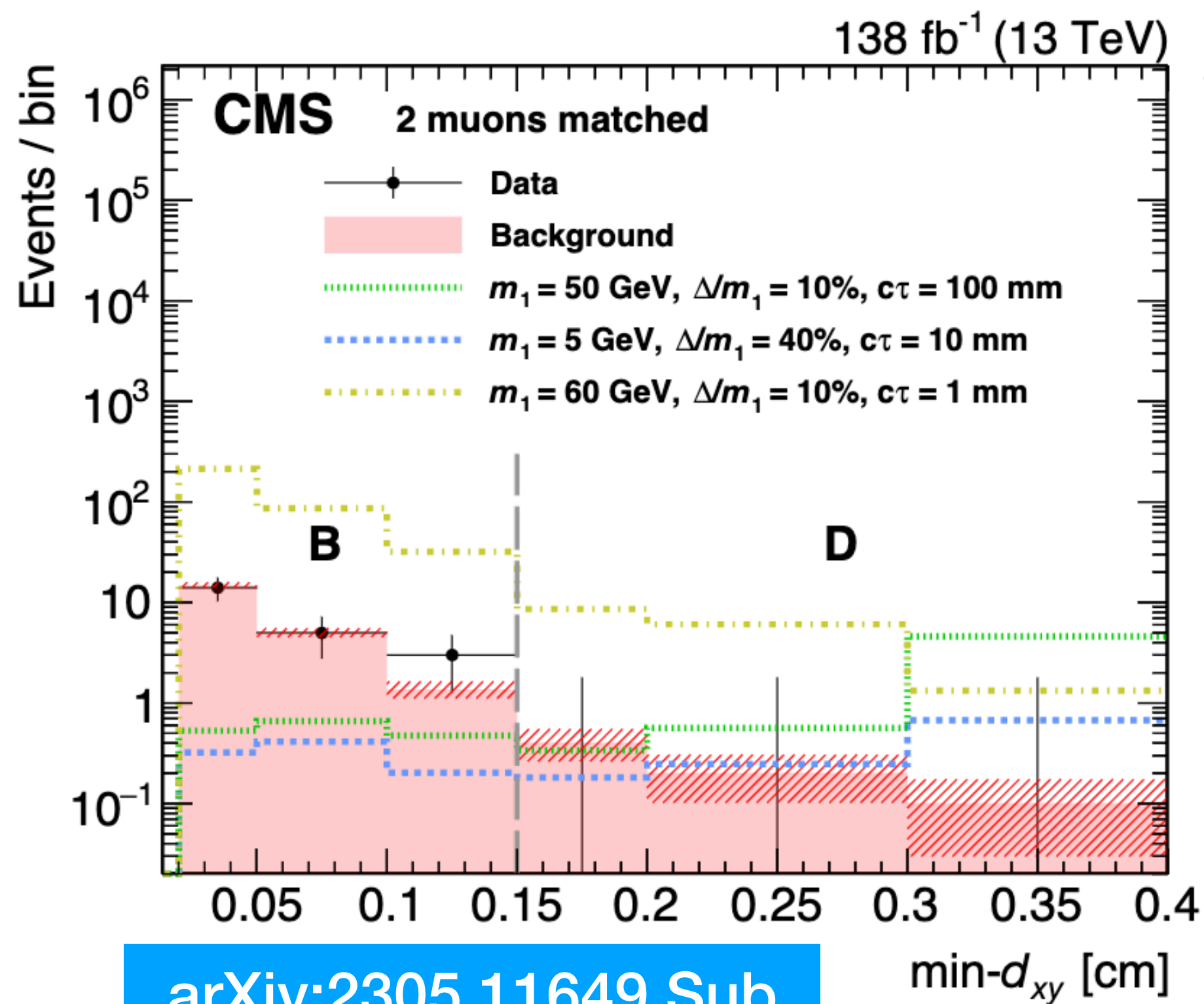
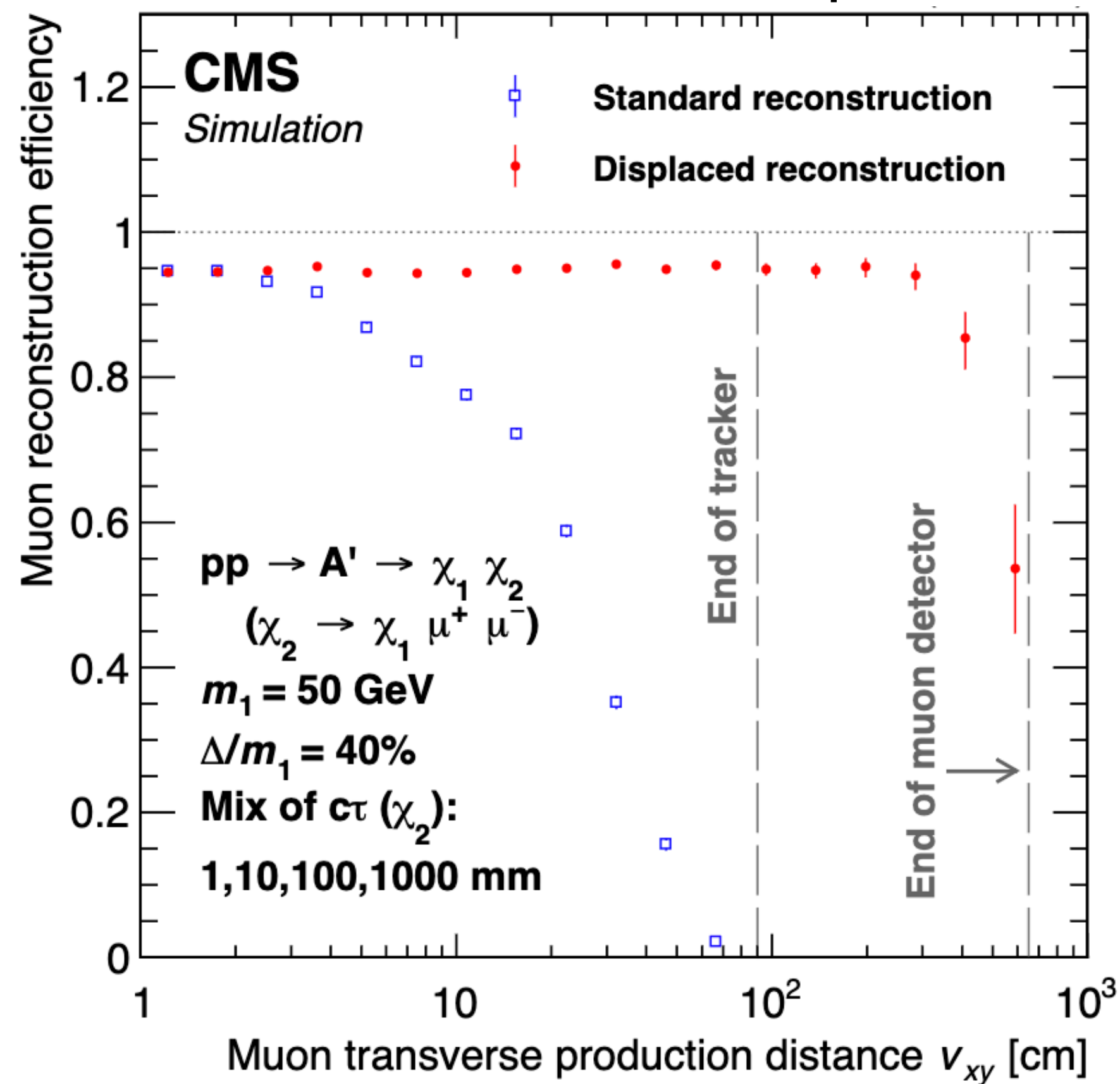
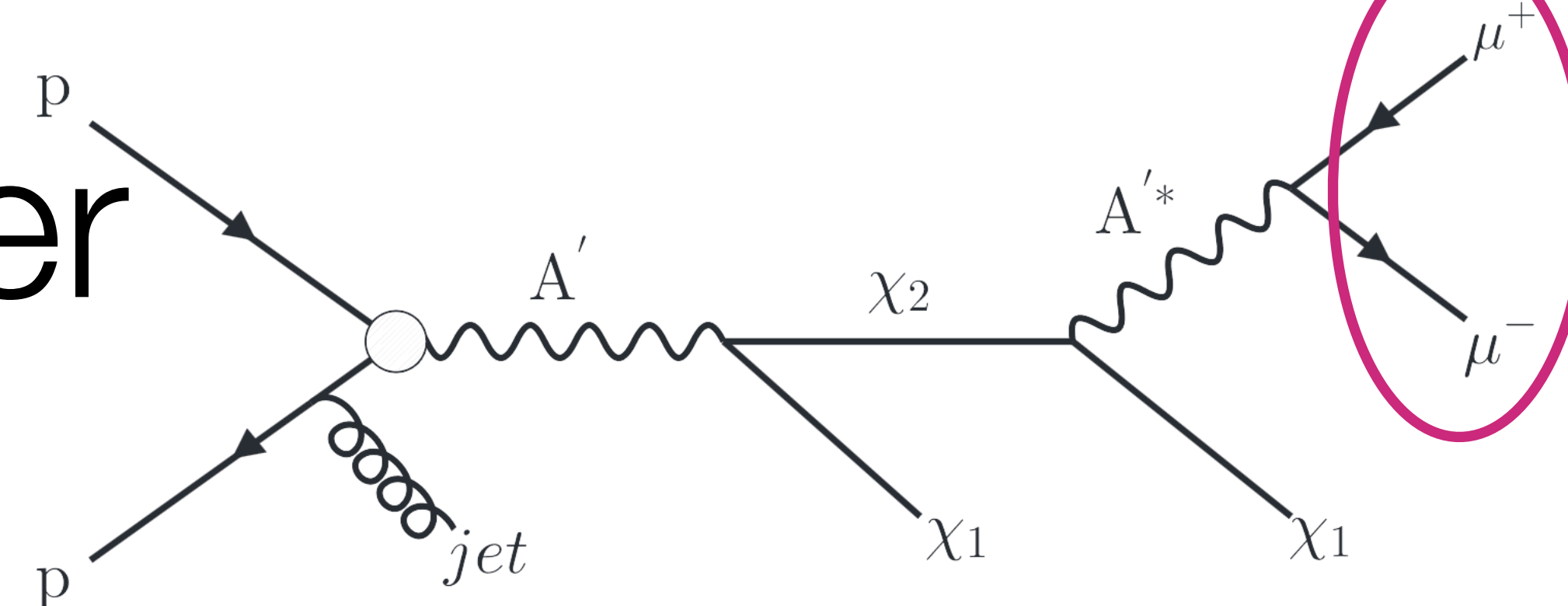


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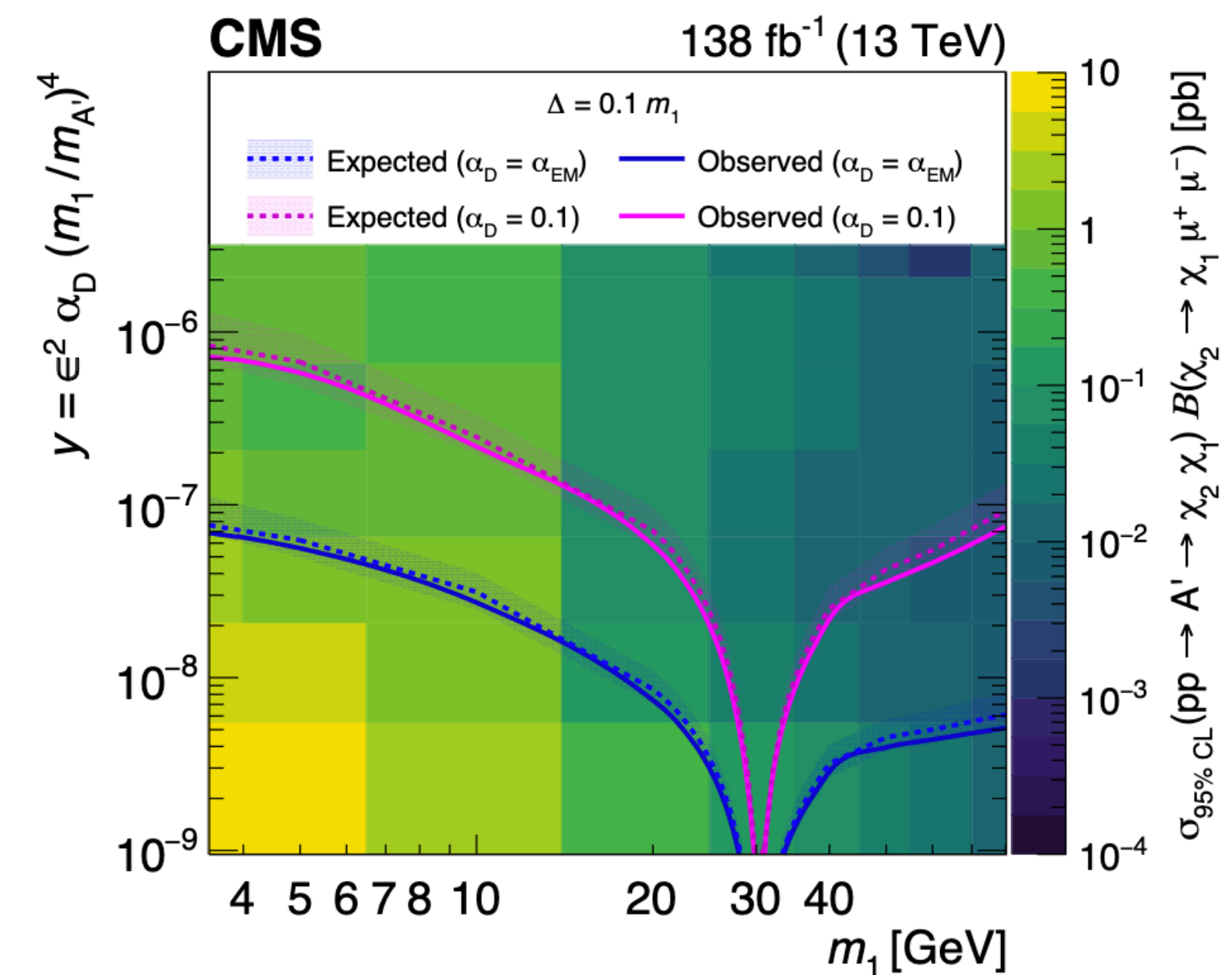
Combination of top 3 greatly outperforms other analyses

Dark photon (DP) as partner

- First LHC search for elastic dark matter
- Small $\Delta m(\chi_1, DP)$ avoids direct detection constraints
- Displaced di-muon signatures - dedicated reconstruction developed!



[arXiv:2305.11649](https://arxiv.org/abs/2305.11649) Sub
to PRL 19.04.2023



Limits on DM mass and
coupling to DP mediator

The search is on

- LHC is making a unique impact on the search for dark matter
- Searches are guided by models as well as signatures
- Often these models cure other problems - gauge unification, fine tuning puzzles,...
- We will try to leave no stone unturned

Thank you!

