

Search for dark matter produced in association with a pair of bottom quarks

CMS full Run 2 data, 138 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$

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第十二届中国 LHC 物理会议

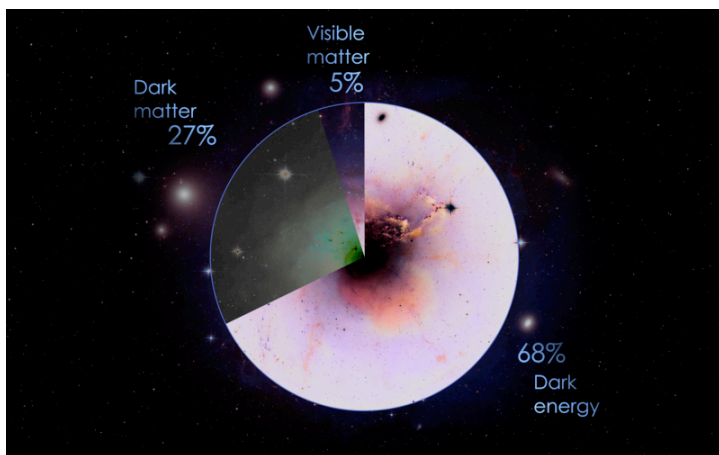
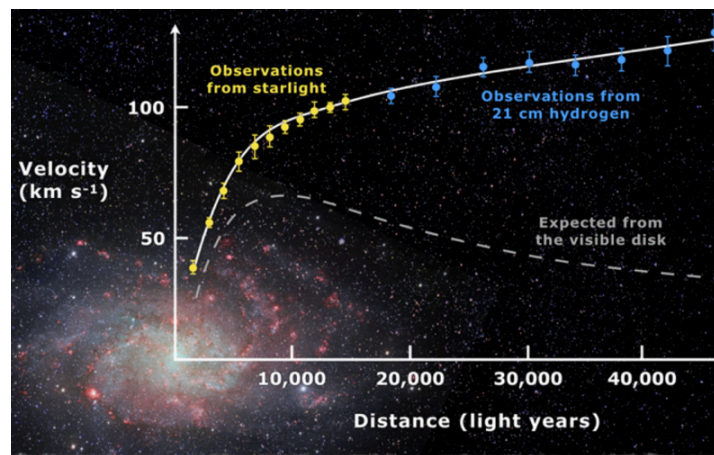
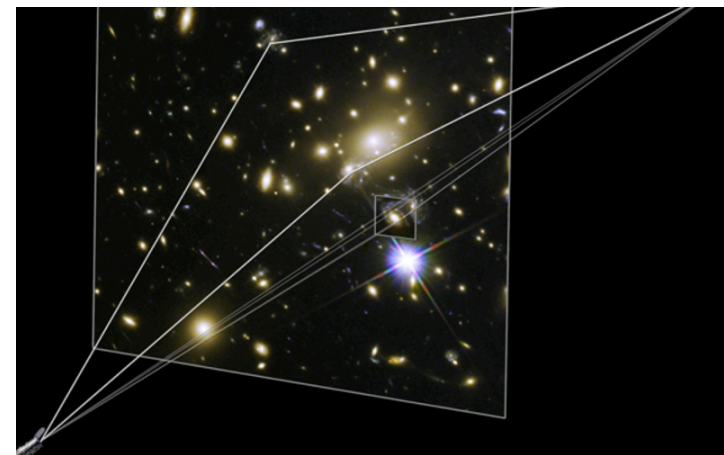
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Outline

1. Motivation: dark matter and the 2HDM+a model
2. Object and event selection
3. Background estimation and signal extraction
4. Results: limits and Run 3 projection
5. Summary

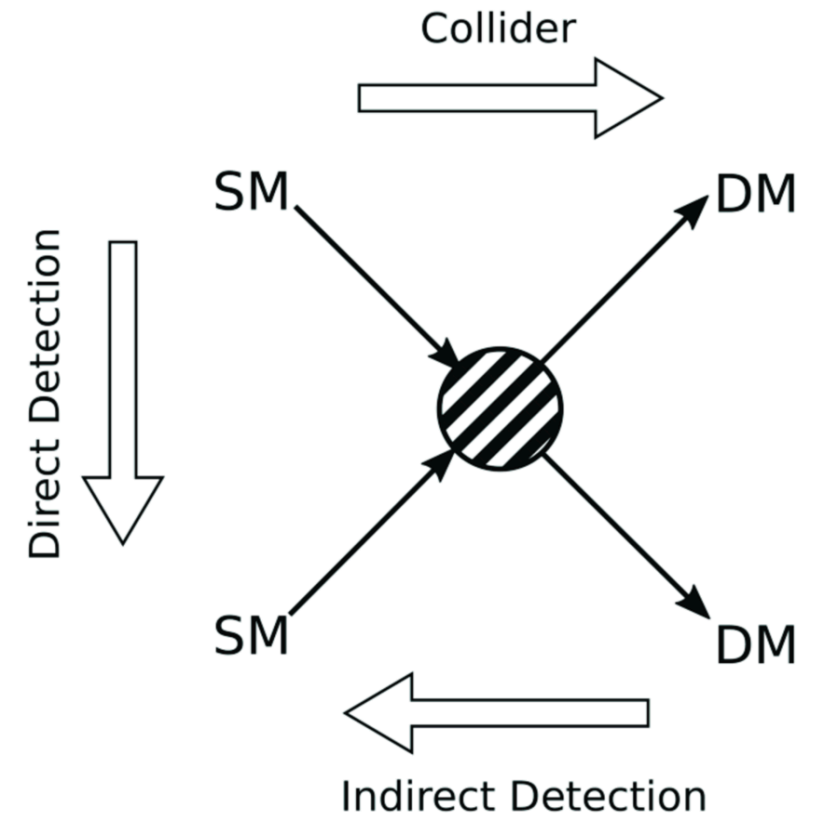
Dark matter



- Dark matter is **27%** of the universe; clear evidence from cosmology, e.g. galaxy rotation curves and gravitational lensing.
- **Goal:** understand the origin and nature of dark matter (DM).

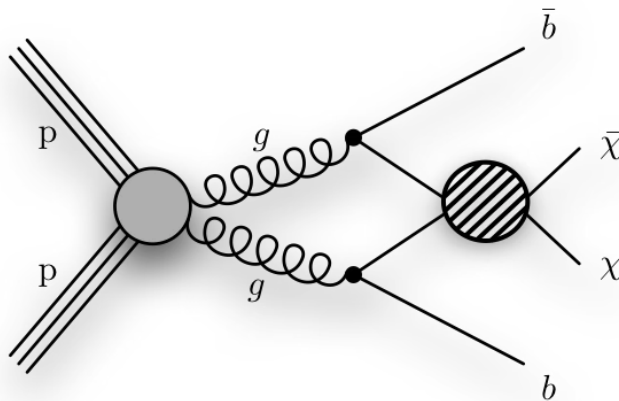
How to search for dark matter

- **Direct**: nuclear recoils from DM passing through the Earth.
- **Indirect**: products of DM annihilation or decay in space.
- **Collider**: produce DM in the lab; it escapes the detector and recoils against SM particles (p_T^{miss}).



Motivation: collider DM searches, from EFT to 2HDM+a

EFT

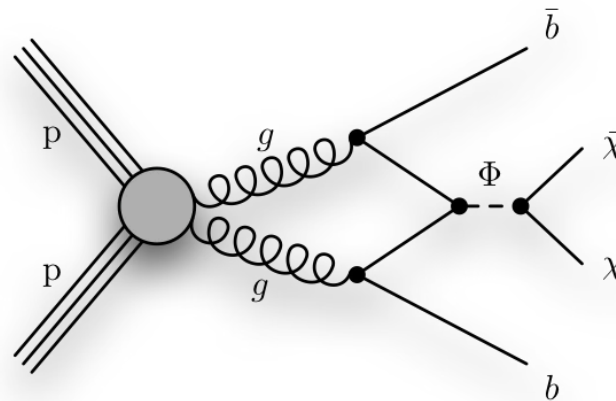


✓ one parameter (Λ)

✗ fails at close NP scale

✗ no longer widely used

Simplified

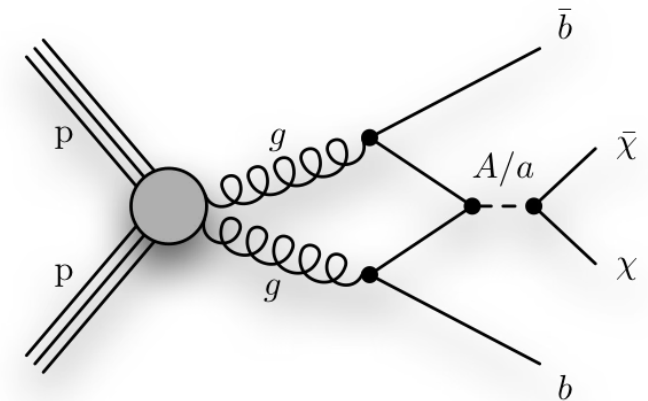


✓ very few parameters

✓ minimal particle content

✗ unitarity violation

2HDM+a



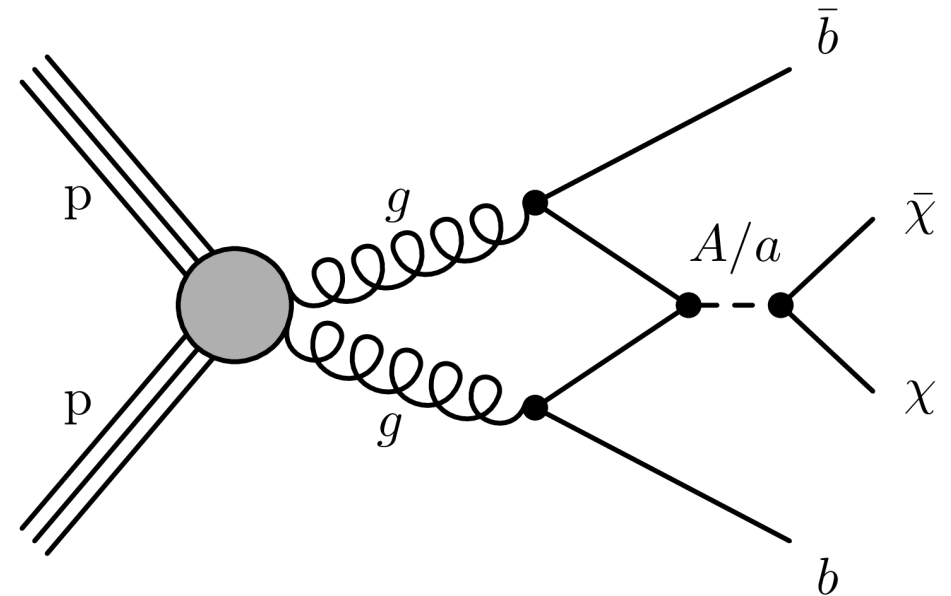
✓ few parameters

✓ minimal particle content

✓ gauge invariant

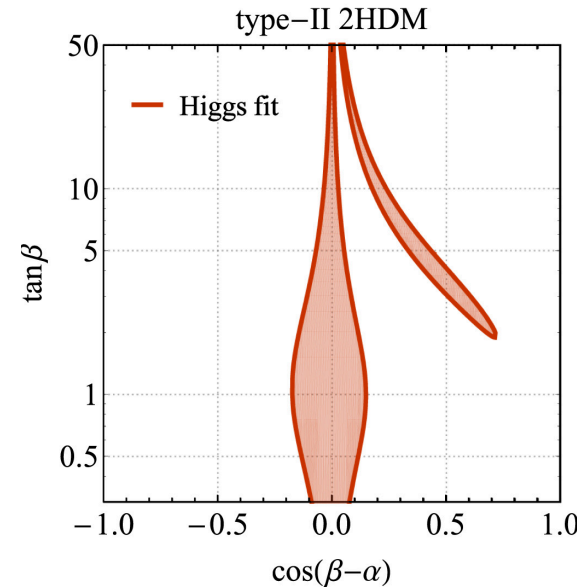
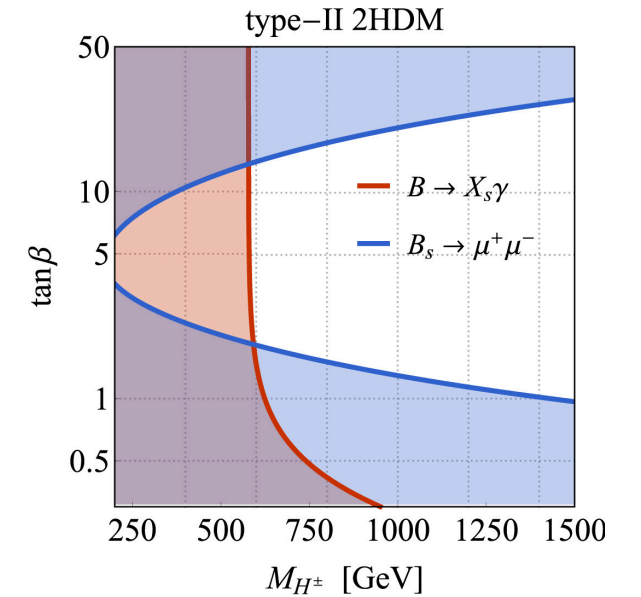
The 2HDM+a model (type-II)

- **Type-II** 2HDM + light pseudoscalar a coupled to DM χ .
- Variety of MET signatures: mono-jet, mono-H, mono- $t\bar{t}$, **mono- $b\bar{b}$** .
- Scalars h (SM), H , $H^\pm$; pseudoscalars A , a ; Dirac DM χ .
- A and a couple to b quarks $\propto \tan \beta$: **enhanced rate at high $\tan \beta$** .

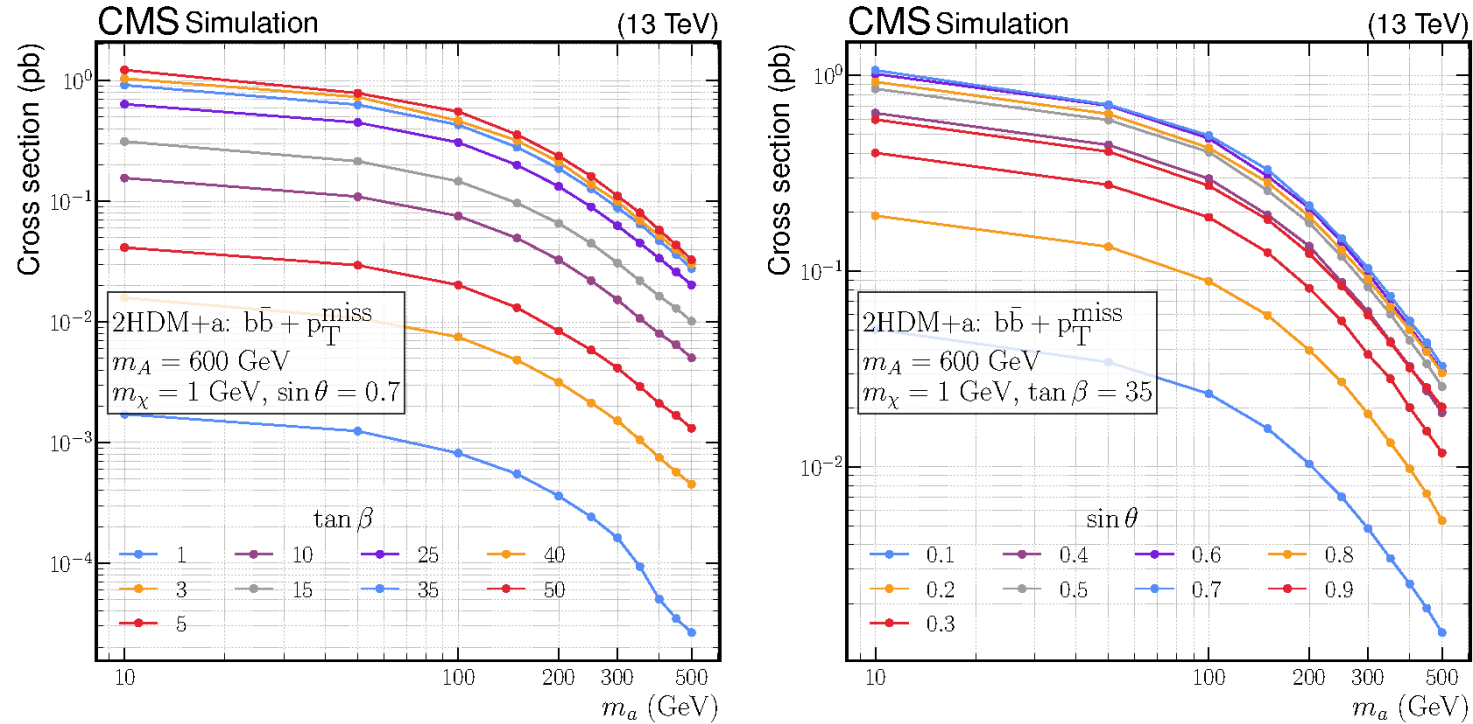


Model parameters

- Mixing angles: α (h - H), θ (A - a); $\tan \beta$ = VEV ratio.
- Higgs fit and flavour constraints: $\cos(\beta - \alpha) = 0$, $\tan \beta < 50$.
- $m_A = m_H = m_{H^\pm}$, $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$, $y_\chi = 1$.
- Free: $\tan \beta$, $\sin \theta$, $m_{A,a,\chi}$.



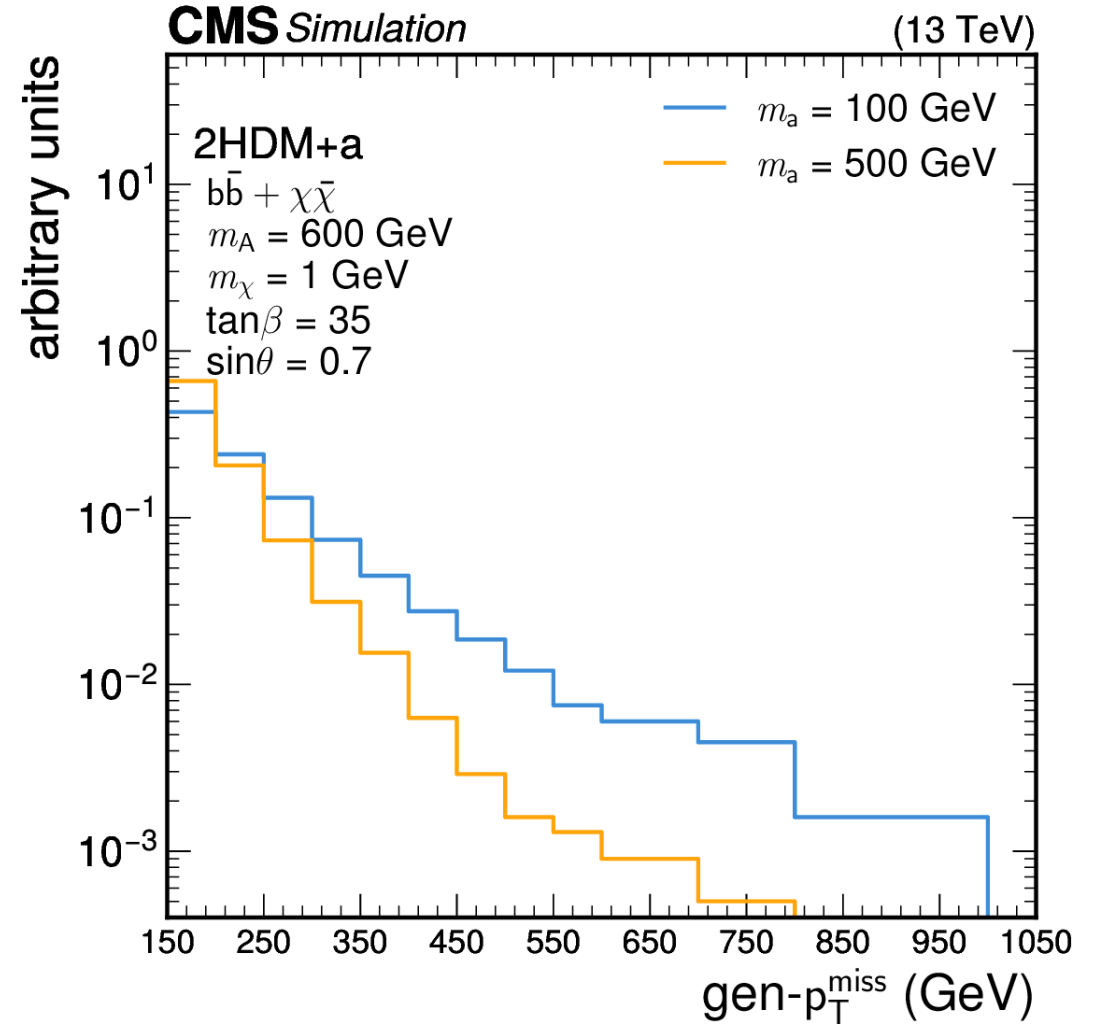
Cross-section scan: $\tan \beta$ and $\sin \theta$



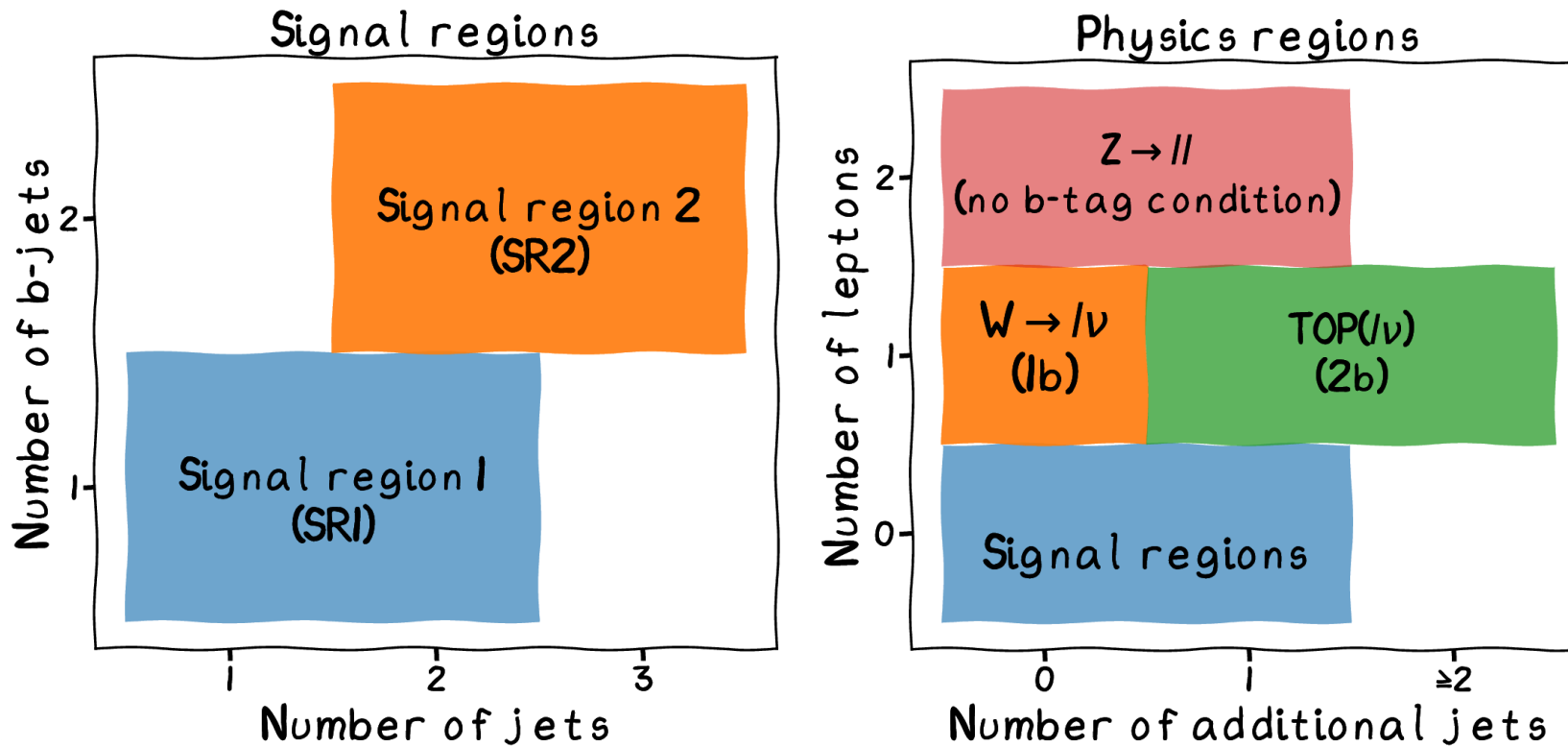
- $m_A = 600$ GeV, $m_\chi = 1$ GeV. Benchmark: $\tan \beta = 35$, $\sin \theta = 0.7$.

Signal kinematics and benchmark

- Cross section driven by m_a , $\tan \beta$, $\sin \theta$; **weak m_A dependence**.
- p_T^{miss} shape depends strongly on m_a , marginally on $\tan \beta$, $\sin \theta$, m_χ .
- Benchmark: $m_A = 600$ GeV, $\tan \beta = 35$, $\sin \theta = 0.7$, $m_\chi = 1$ GeV.
- Generator cut: $p_T^{\text{miss}} > 150$ GeV.



Analysis strategy: signal and control regions



- 1b or 2b b-tagged jets + large p_T^{miss} ; SR1 and SR2 each have two CRs.
- Backgrounds: $Z(\nu\nu)$ +jets, $t\bar{t}$, $W(\ell\nu)$ +jets, DIBOSON, SMH, QCD.

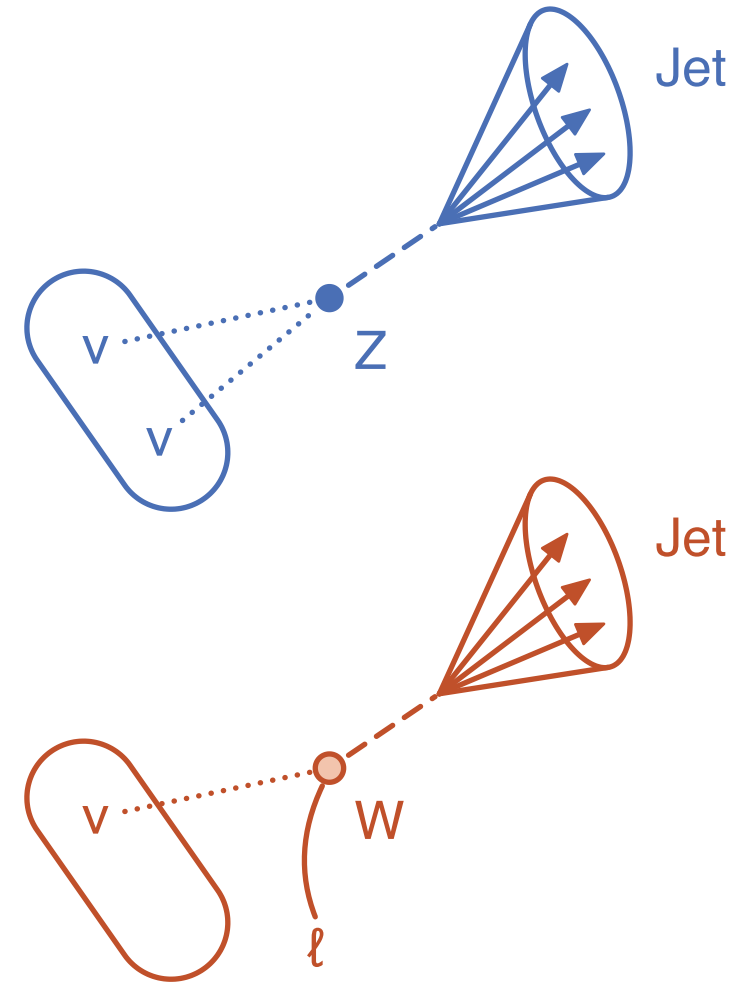
Event selection

Selection	Cut
Trigger	p_T^{miss} (SR, muon CR); single e (electron CR)
p_T^{miss} (U in CR)	> 250 GeV
Jets	≥ 1 , $p_T > 30$ GeV, $ \eta < 2.5$; leading $p_T > 100$ GeV
$\min \Delta\phi(\text{jet}, p_T^{\text{miss}})$	> 0.5 (QCD suppression)
Photon / e / μ / τ_h	vetoed in SR

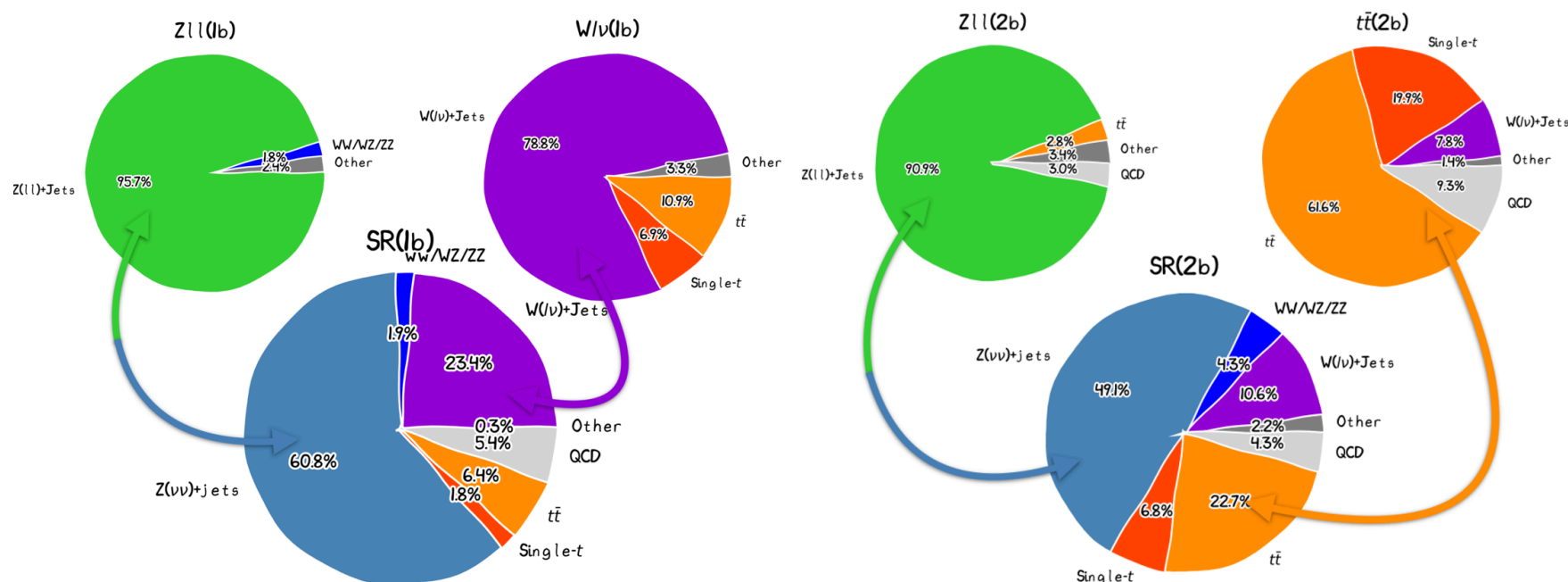
- Recoil in CRs: $U = \left| - \left(\vec{p}_T^{\text{miss}} + \sum \vec{p}_T^{\text{lep}} \right) \right|$.
- 2b discriminant: $\cos \theta^* = \left| \tanh \frac{\eta_{\text{jet1}} - \eta_{\text{jet2}}}{2} \right|$.

Background estimation

- $Z(\nu\nu)$ +jets (60-70%): $Z(ee)$, $Z(\mu\mu)$ CRs, lepton $p_T > 30$ GeV, 70-110 GeV mass.
- $W(\ell\nu)$ (1b), $t\bar{t}$ (2b): single-lepton CRs.
- Recoil U replaces p_T^{miss} in CRs.
- Single top, diboson, Vh : simulation.
- QCD: data-driven (backup).



Signal extraction

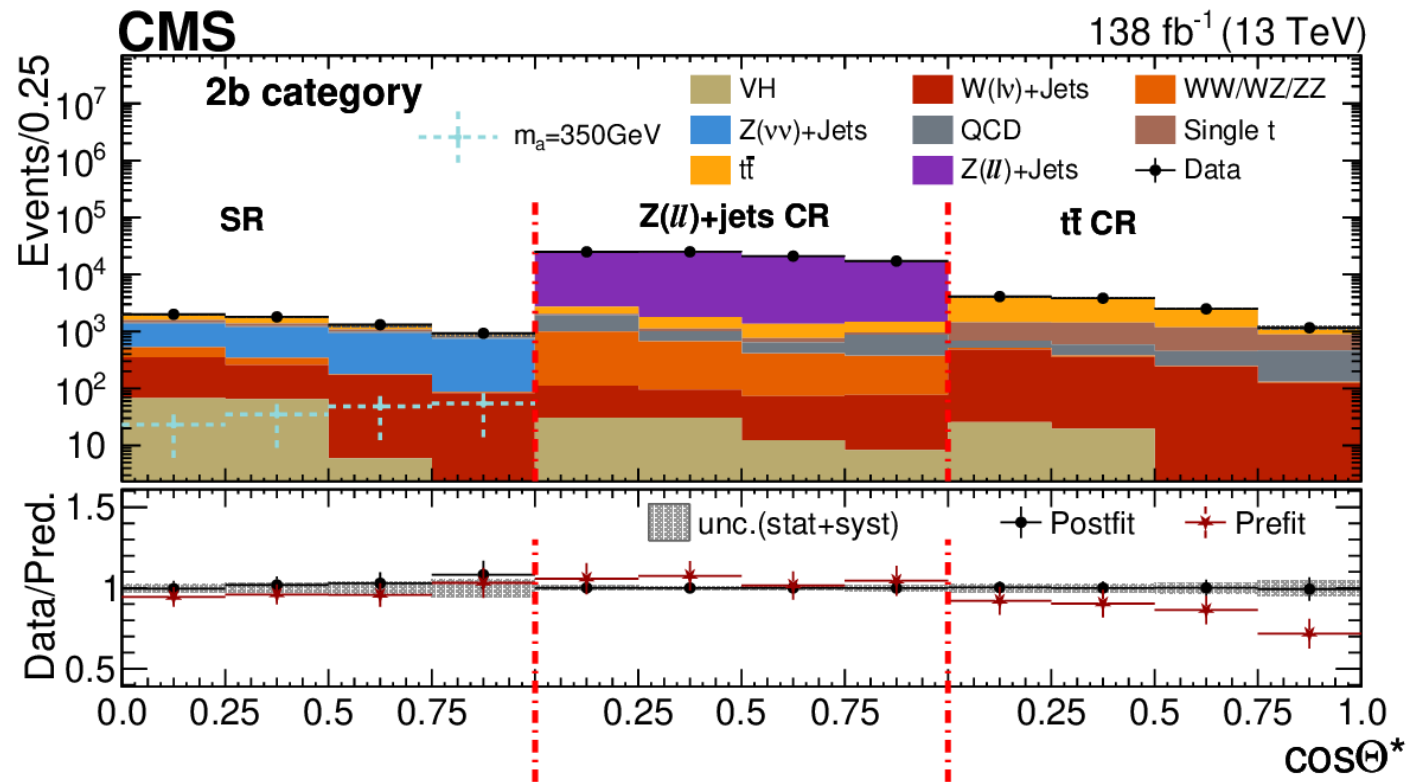


- Simultaneous binned profile-likelihood fit of SR and CRs; e and μ CRs combined.
- 1b: p_T^{miss} (SR1), U (CRs). 2b: $\cos \theta^*$, 4 bins.
- **Per-bin rate parameter** ties each SR bin to its CR; systematics are nuisances.

Systematic uncertainties

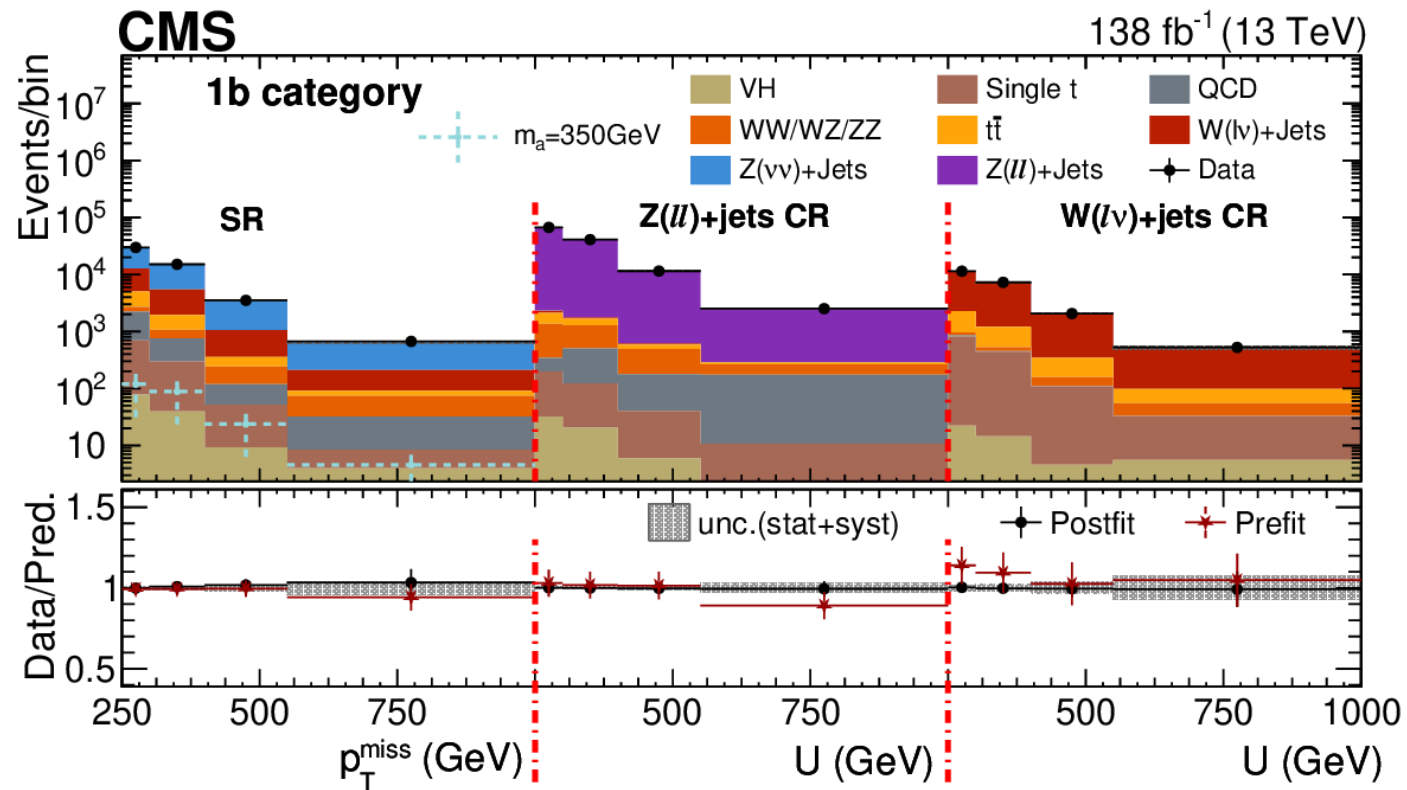
Source	Type	Size
b tagging efficiency / mistag	shape + norm	8% / 7%
Electron ID / reconstruction	shape + norm	7% / 5%
τ_h veto	norm	6%
Jet energy corrections, pileup	shape + norm	3% each
p_T^{miss} and electron triggers	shape + norm	1%
Integrated luminosity	norm	1.2-2.5% per year (1.6% combined)
Diboson, Vh / single top / DY cross sections	norm	20% / 10% / 5%
QCD normalization	norm	50%
Renormalization and factorization scales / PDF	shape	<42% / <50%

Post-fit distributions: 2b



- $\cos\theta^*$ in SR2, $Z(\nu\nu)$ CR and $t\bar{t}$ CR: good agreement, **no excess** over the SM.

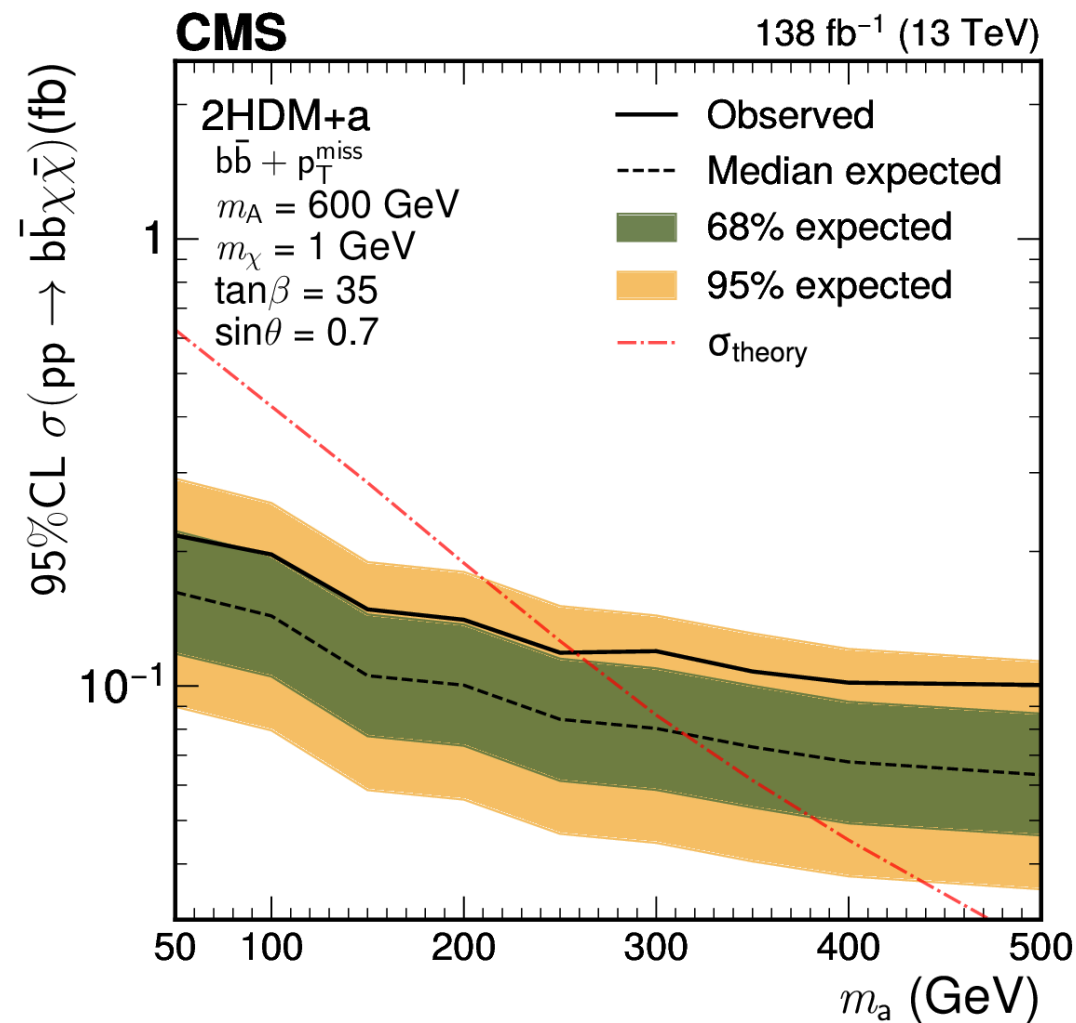
Post-fit distributions: 1b



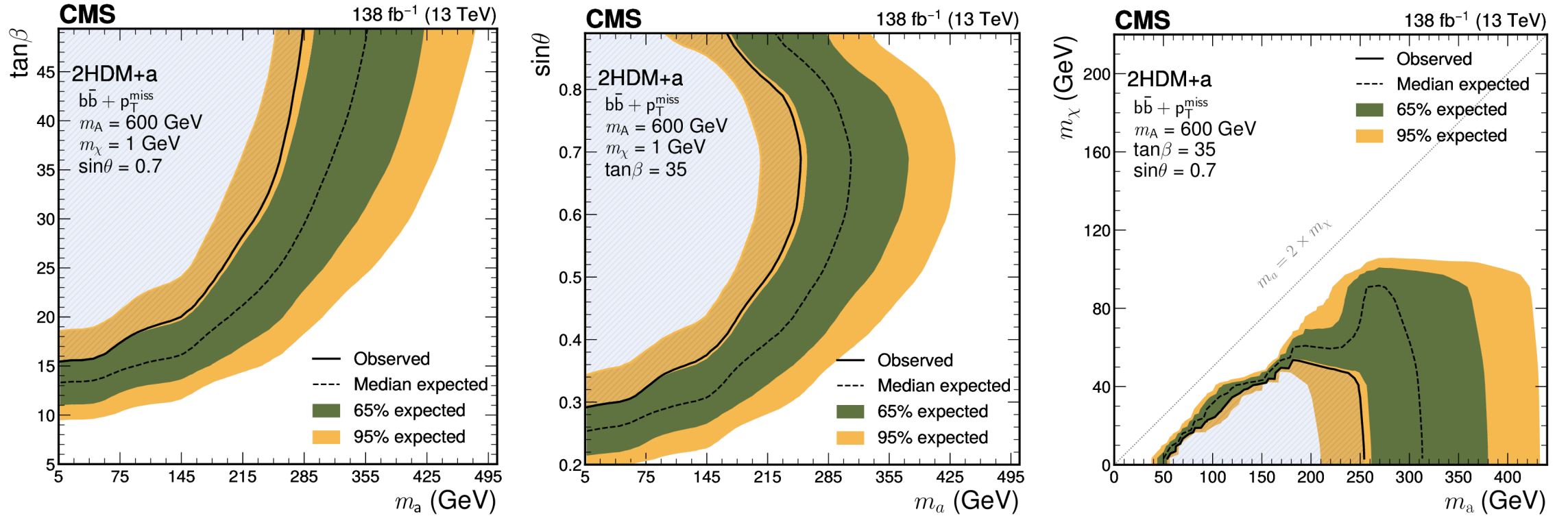
- p_T^{miss} in SR1, U in $Z(\ell\ell)$ and $W(\ell\nu)$ CRs: good agreement, **no excess**.

Result: 1D limit

- 95% CL limit on $\sigma/\sigma_{\text{theory}}$, SR1 + SR2.
- $m_A = 600 \text{ GeV}$, $\tan \beta = 35$, $\sin \theta = 0.7$, $m_\chi = 1 \text{ GeV}$.
- Observed exclusion up to $m_a \approx 260 \text{ GeV}$.
- Points below the red line are excluded.



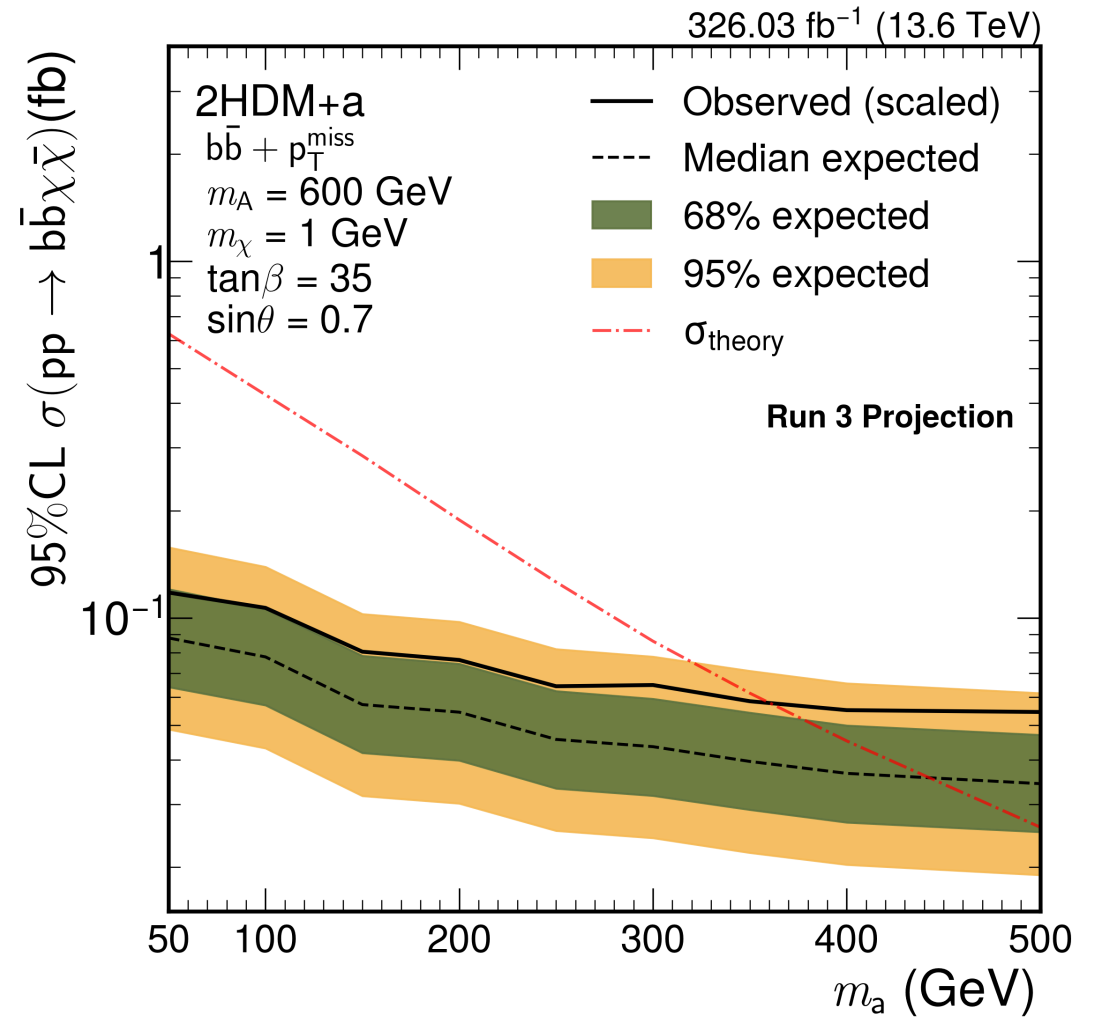
Result: 2D limits



- $m_A = 600$ GeV. Left: m_a - $\tan\beta$ ($\sin\theta = 0.7$); middle: m_a - $\sin\theta$ ($\tan\beta = 35$); right: m_a - m_χ (dotted: $m_a = 2m_\chi$). Tables on [HEPData](https://hepdata.net).

Run 3 projection

- Run 2 limit scaled to **326 fb⁻¹** at **13.6 TeV**.
- Benchmark: $m_A = 600$ GeV, $\tan \beta = 35$, $\sin \theta = 0.7$.
- Observed (scaled) reach: $m_a \approx$ **360 GeV** (Run 2: 260 GeV).
- Expected reach: about 440 GeV.



Summary

- First CMS full Run 2 search for DM + $b\bar{b}$ in the type-II **2HDM+a**.
- 1b and 2b categories; SR+CR fit with per-bin rate parameters.
- **No excess** over the SM.
- 95% CL limits in m_a - $\tan \beta$, m_a - $\sin \theta$, m_a - m_χ .
- For $m_A = 600$ GeV, $\tan \beta = 35$, $\sin \theta = 0.7$: m_a **excluded up to ~ 260 GeV**.
- Complementary to mono- X searches. Published in JHEP02(2025)050.
- **Run 3 underway**: more data, better detector, ML-based analysis, new interpretations (t-channel DM, type-I 2HDM+a).

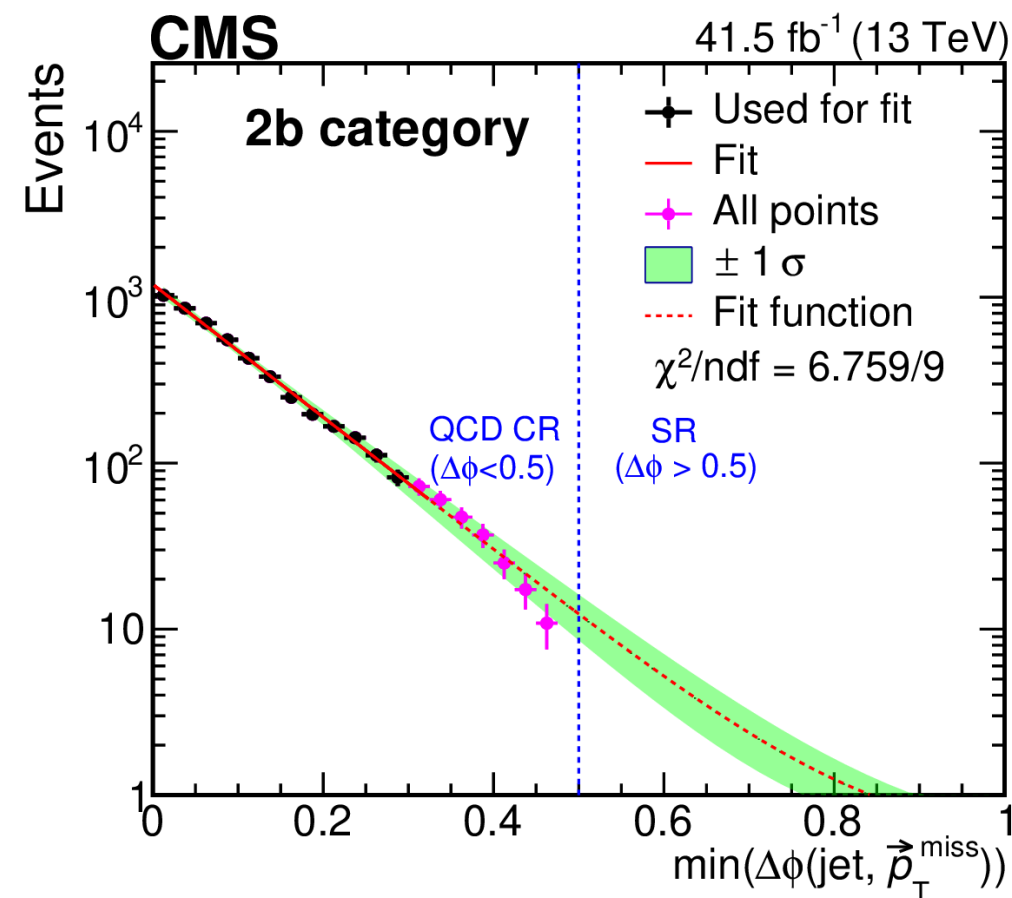
Backup

Backup: object selection

Object	Algorithm	Selection
Jets	anti- k_T ($R = 0.4$), PF, CHS	$p_T > 30$ GeV, $ \eta < 2.5$; removed within $\Delta R = 0.4$ of leptons
b jets	DeepCSV, medium WP	68% efficiency, 1% mistag
Electrons	PF; shower shape + isolation	$p_T > 10$ GeV, $ \eta < 2.5$
Muons	PF; tracker-muon hits + track quality	$p_T > 10$ GeV, $ \eta < 2.4$
Photons	PF; shower shape + isolation	$p_T > 15$ GeV, $ \eta < 2.5$
τ_h	hadron-plus-strips + DeepTau	$p_T > 18$ GeV, $ \eta < 2.3$ (vetoed)
p_T^{miss}	$-\sum \vec{p}_T$ of PF candidates, JEC applied	event filters remove >90% of anomalous events

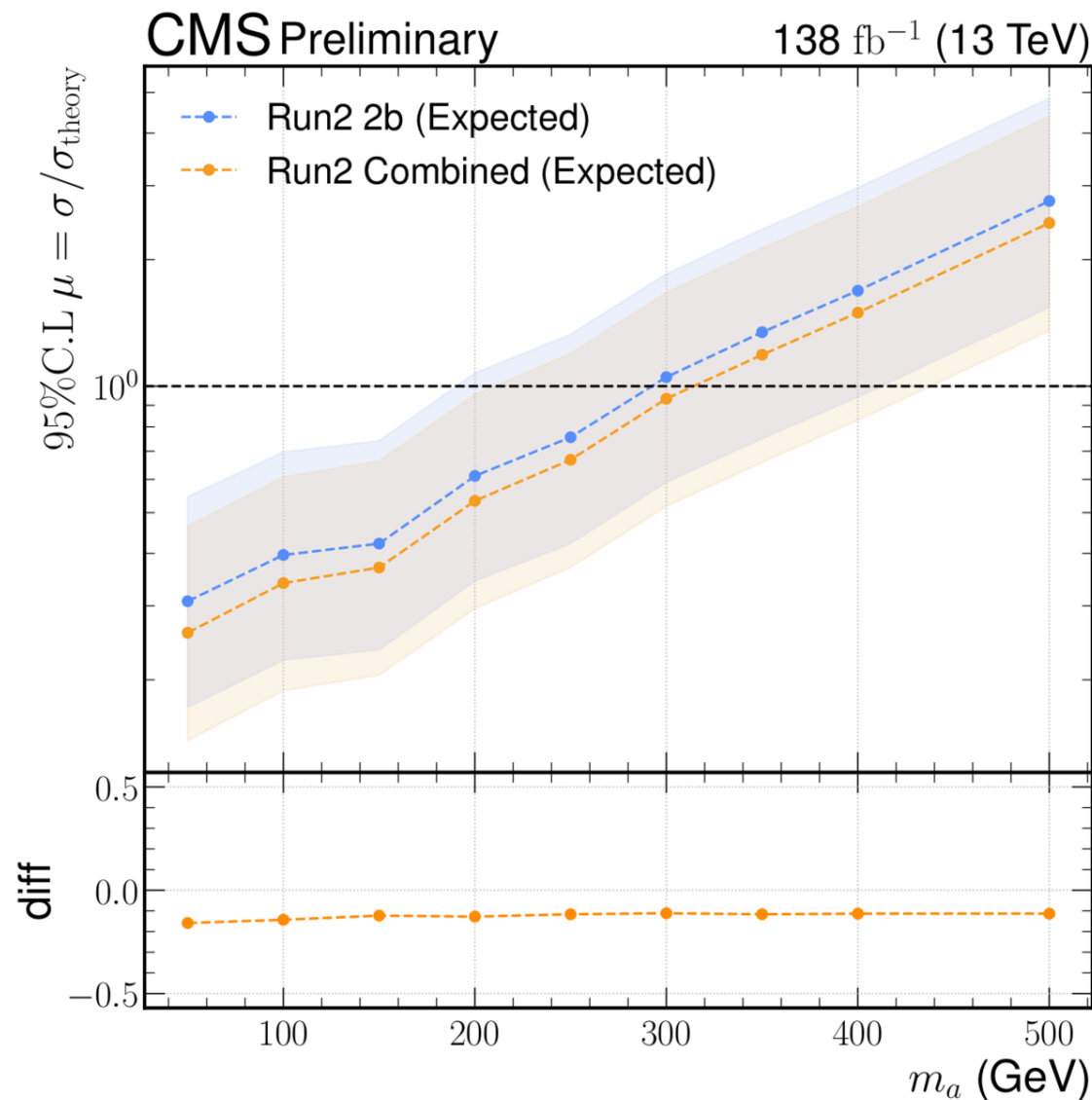
Backup: QCD multijet estimation

- QCD CR: SR selection with $\min \Delta\phi < 0.5$.
- QCD in the CR = data minus all other backgrounds.
- Exponential fit in $\min \Delta\phi$ 0-0.3, validated in 0.3-0.5.
- SR yield: integral of the fit above 0.5.
- Total uncertainty about 50%.
- Plot: 2b category, 2017.

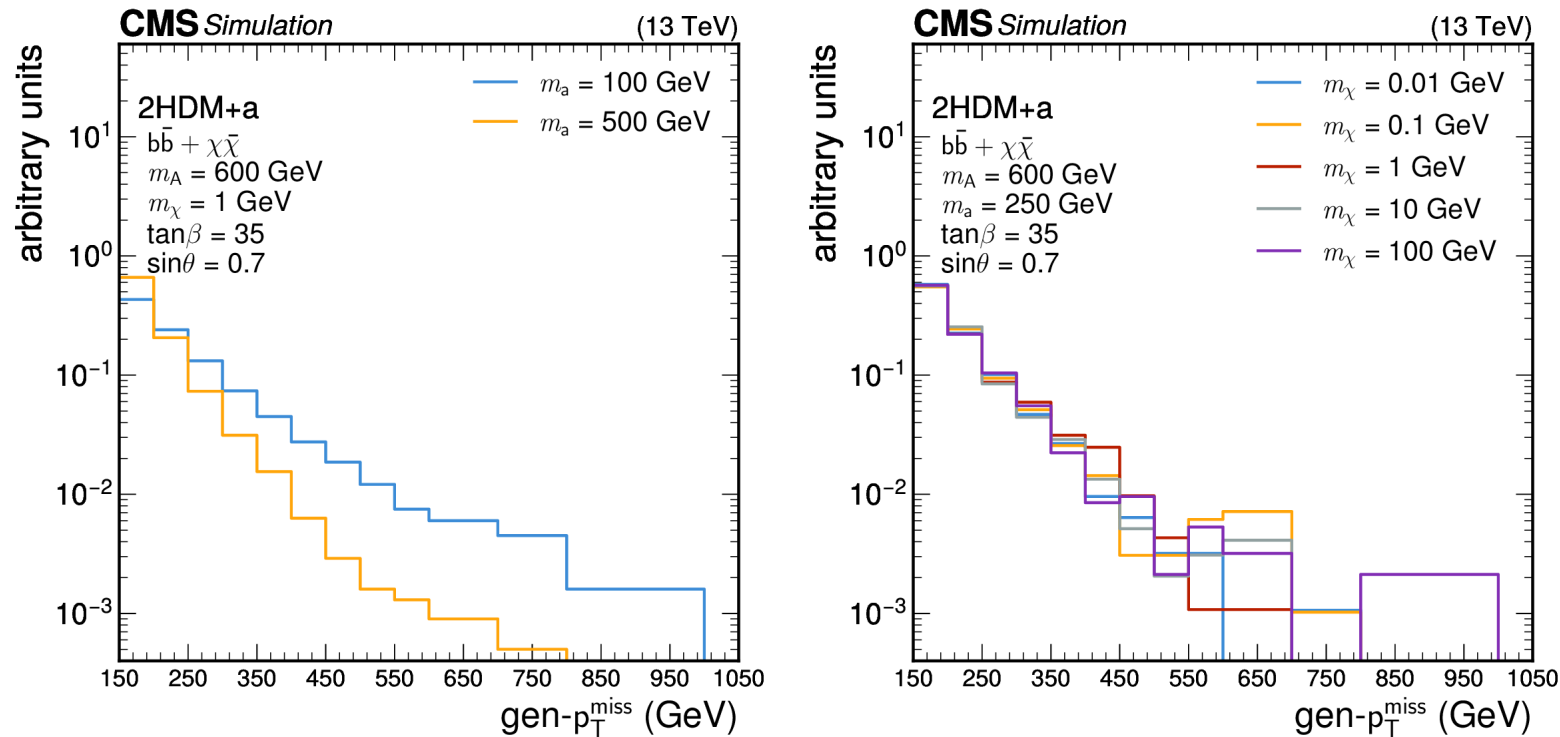


Backup: 1b category contribution

- 2b only vs 1b+2b combined, expected limit.
- 1b adds up to **10%** to the full Run 2 expected limit.
- Observables: p_T^{miss} (1b), $\cos \theta^*$ (2b).

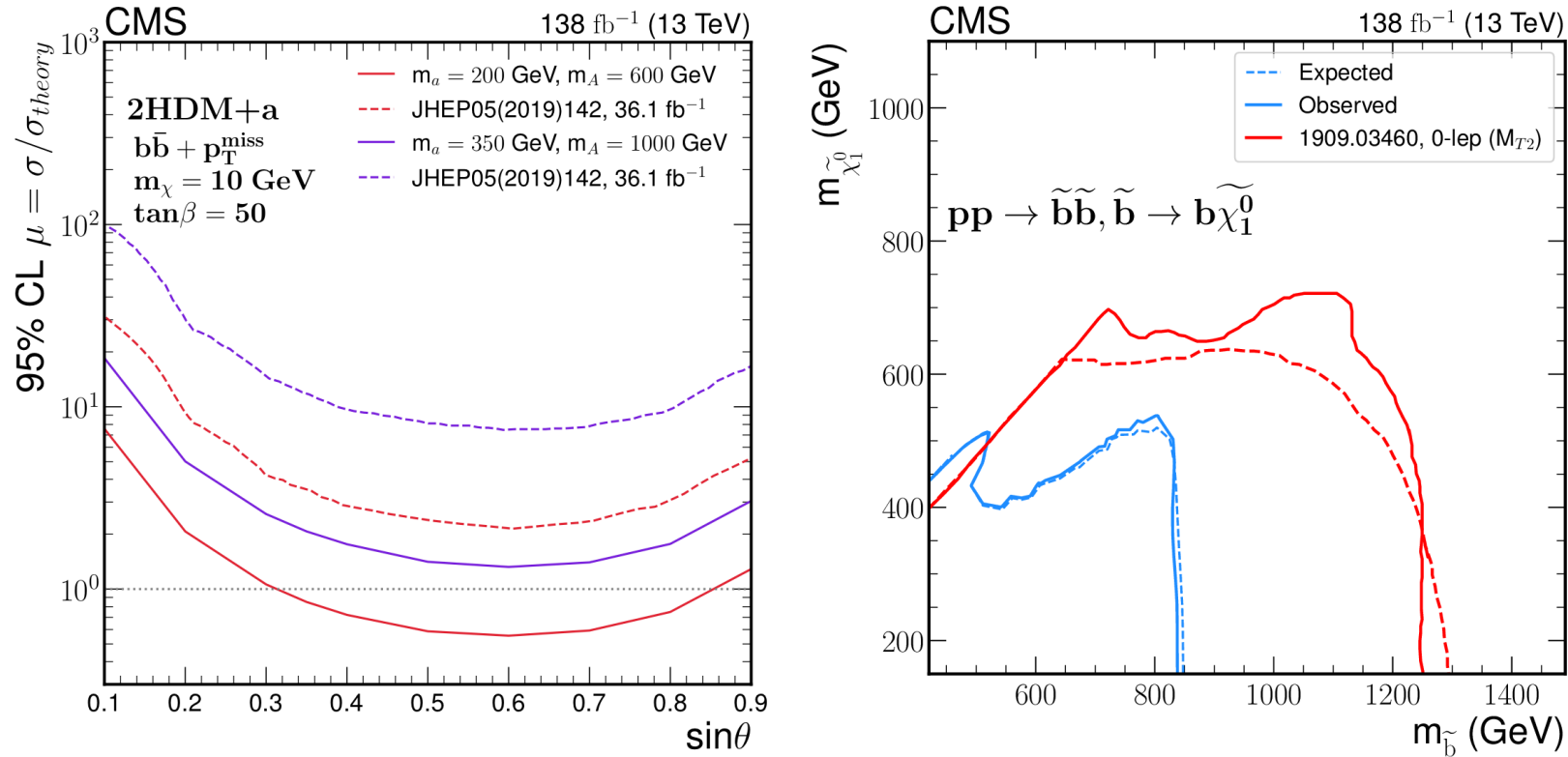


Backup: signal p_T^{miss} shapes



- Normalized generator-level p_T^{miss} : two m_a values (left), five m_χ values (right).

Backup: comparison with earlier results



- Left: μ vs $\sin \theta$ ($m_\chi = 10$ GeV, $\tan \beta = 50$) vs JHEP05(2019)142, 36.1 fb⁻¹. Right: sbottom interpretation vs 0-lepton M_{T2} .

Backup: SUSY interpretation

- Same selection reinterpreted for $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\tilde{\chi}_1^0$.
- 95% CL limit, 138 fb^{-1} .
- Observed exclusion reaches $m_{\tilde{b}} \approx 840 \text{ GeV}$ at low $m_{\tilde{\chi}_1^0}$.
- Red: CMS 0-lepton M_{T2} search (arXiv:1909.03460).

