



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

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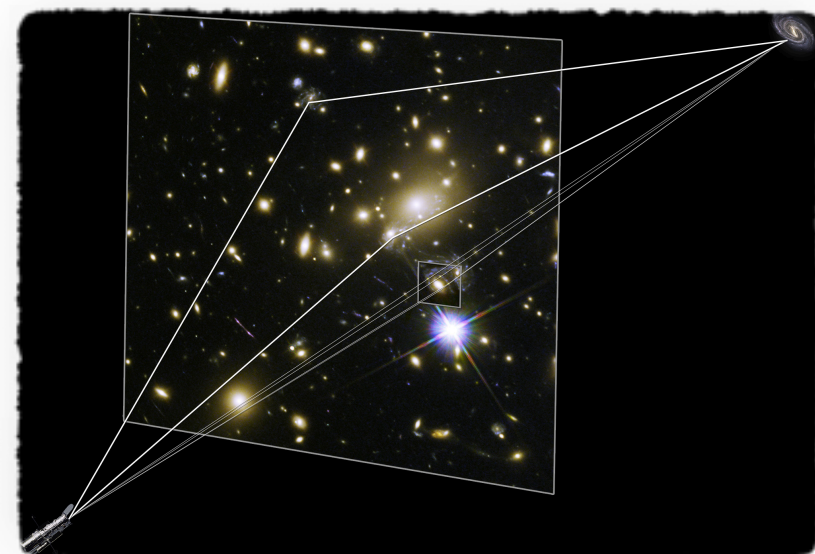
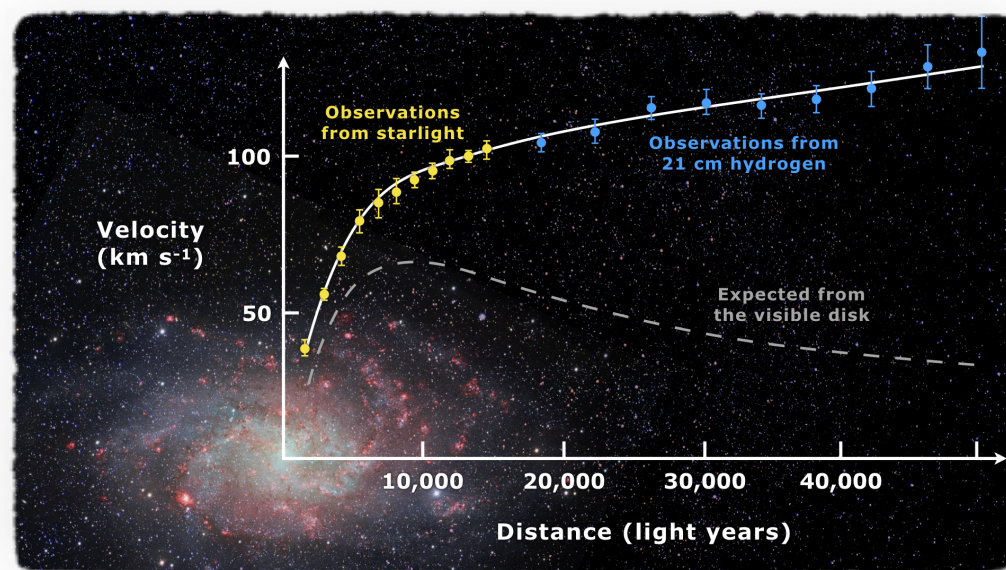
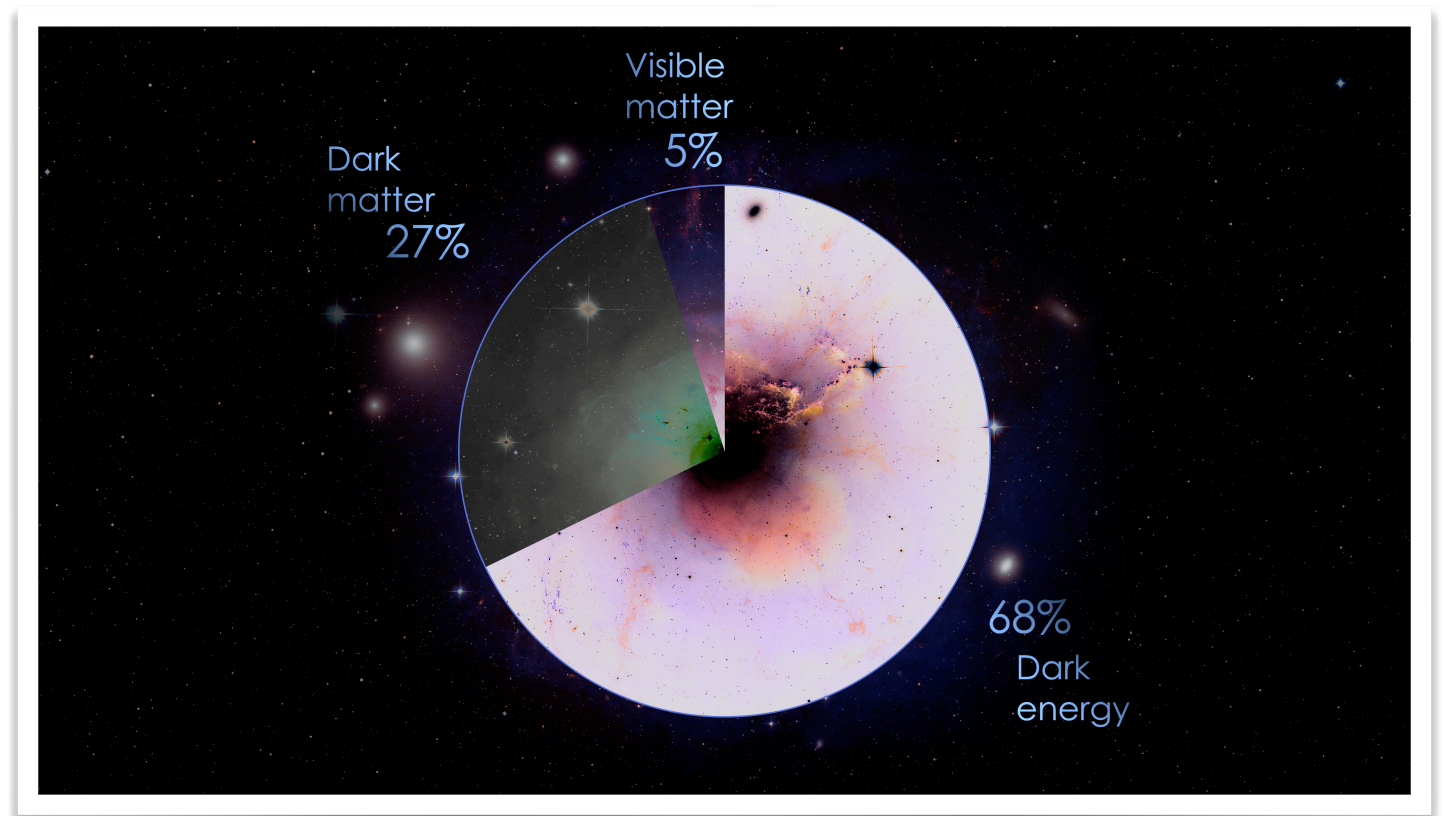
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Outline

- Motivation and Theoretical Overview
- Experimental Setup
- Selection: Object and Event
- Signal Extraction & Limits
- Summary

Dark matter

- 📌 Dark Matter constitute 27% of the Universe
- 📌 There are Clear evidences from Cosmology e.g. rotation curve of Galaxies, gravitational lensing



- 📌 Goal: understand the origin/nature of dark matter (DM)

Dark matter Detection

* Direct detection

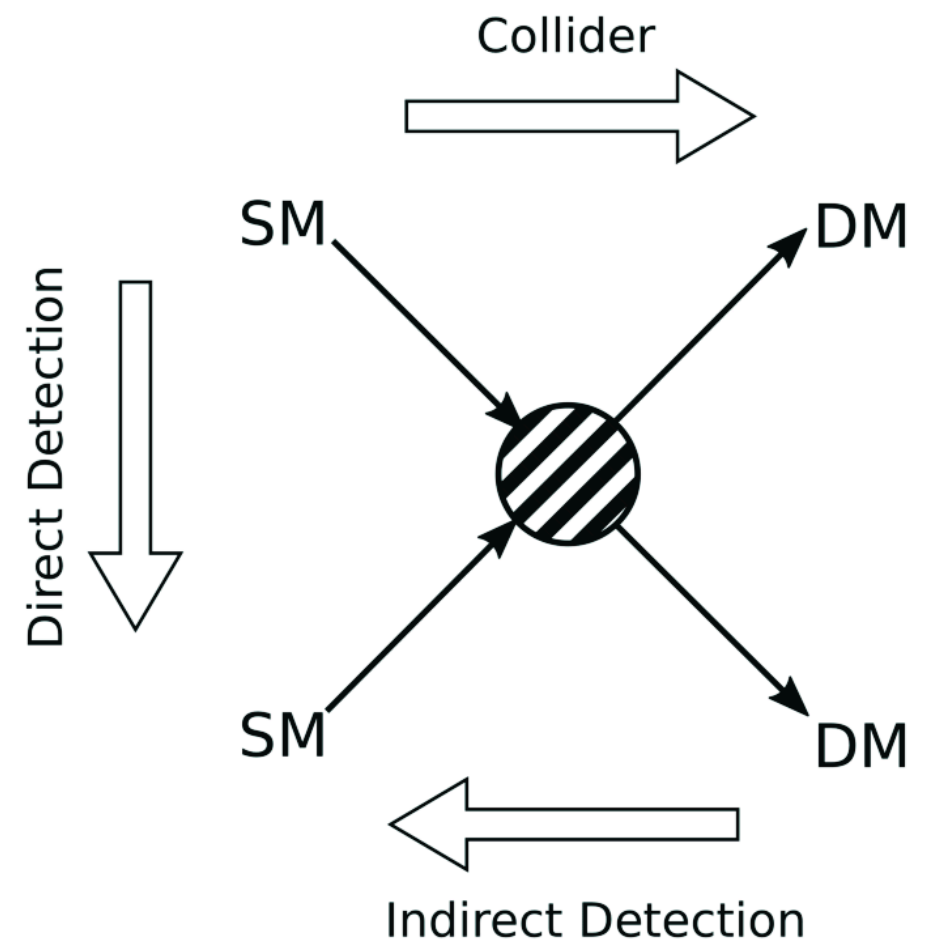
- ◆ To observe low-energy recoils of nuclei induced by interactions with particles of dark matter, which pass through the Earth

* Indirect detection

- ◆ Search for the products of the self-annihilation or decay of dark matter particles in outer space.

* Collider searches

- ◆ Produce DM in laboratory
 - ❖ Dark Matter particles produced that would escape the detector unnoticed and must recoil against the SM particles to become “visible”



Motivation and Theoretical Overview

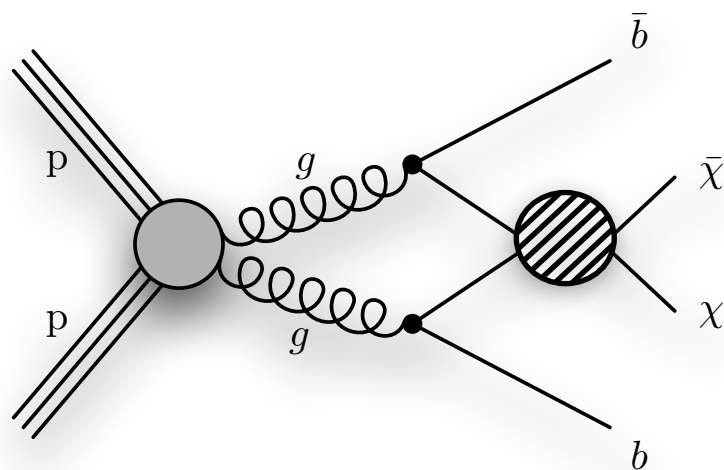
Introduction & Motivation

Search for dark matter produced in association with a pair of bottom quarks in p-p collisions at $\sqrt{s} = 13$ TeV with the CMS detector using full Run2 data

Collider DM searches: From EFT to 2HDM+a Model...

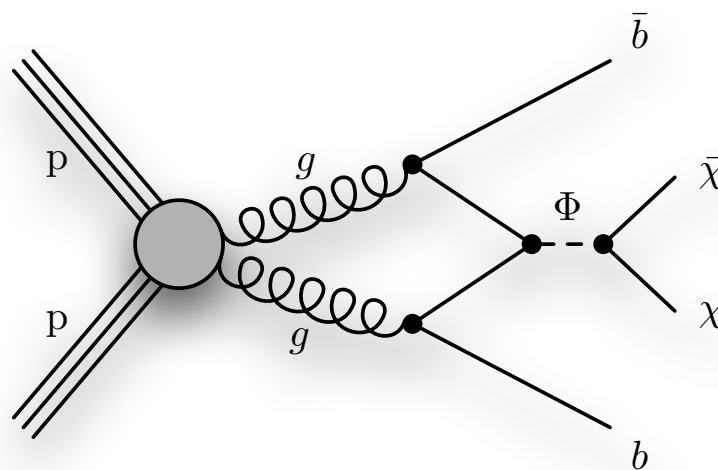
EFT

- ✓ 1 parameter (Λ)
- ✗ problematic at high energies
- ✗ no longer widely used



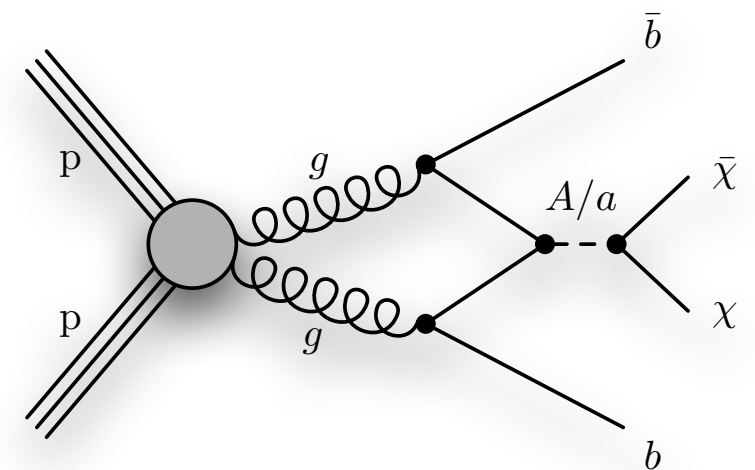
Simplified

- ✓ very few parameters
- ✓ minimal particle content
- ✗ unitarity violation (although often not a problem practically)



2HDM+a

- ✓ few parameters
- ✓ minimal particle content
- ✓ gauge invariant



Introduction & Motivation

Search for dark matter produced in association with a pair of bottom quarks in p-p collisions at $\sqrt{s} = 13$ TeV with the CMS detector using full Run2 data

- **2HDM + a model** [CERN-LPCC-2018-02] (Simplest model with a pseudoscalar mediator to evade DD experiment bounds)

- Minimal particle content and gauge invariant

- Variety of MET signatures

- mono-jet, mono-H, mono-tt, **mono-bb**

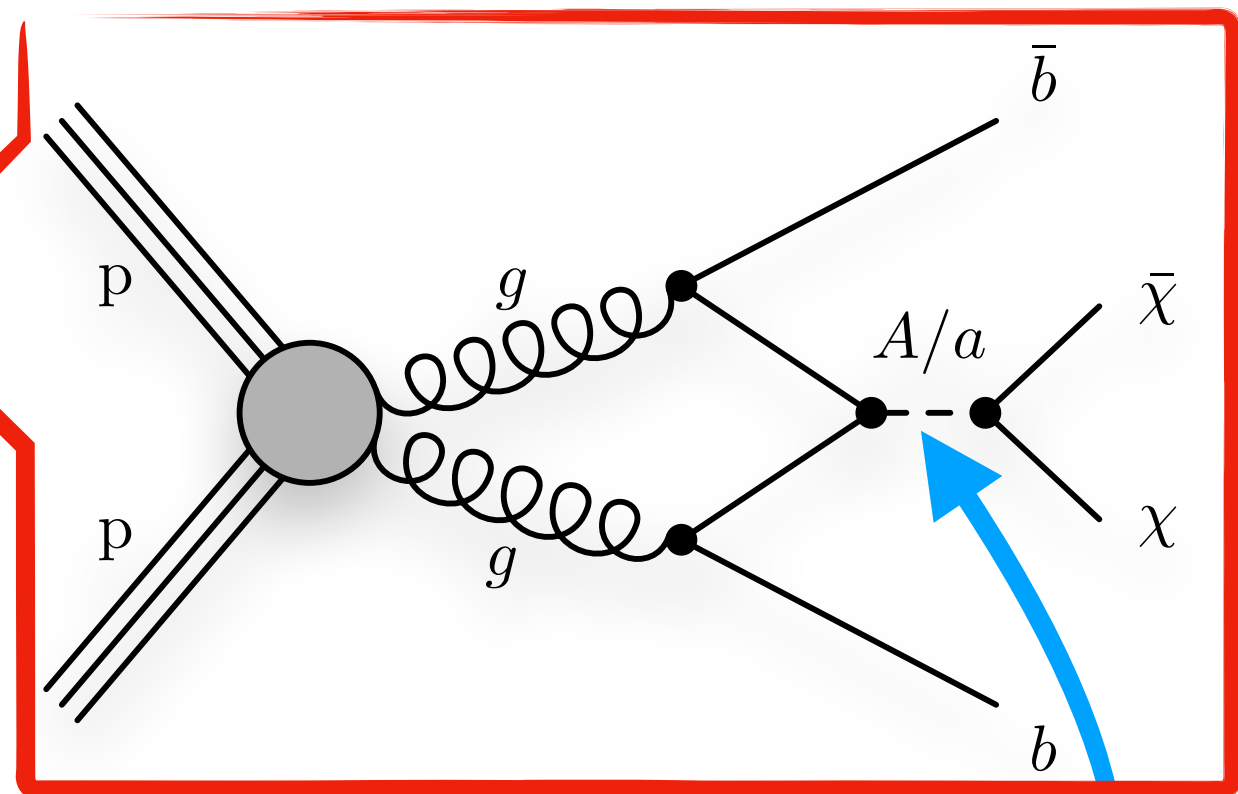
- Particle content:

- Two scalars: h (SM Higgs), H

- Pair of charged scalars: $H^\pm$

- Two pseudoscalars: A, a

- Dirac fermion DM: χ



Model Parameters

Masses

$$m_H = 125 \text{ GeV}$$

$$m_H, m_{H^\pm}, m_A, m_a, m_\chi$$

Quartic

Couplings

$$\lambda_3, \lambda_{P1}, \lambda_{P2}$$

Mixing Angles

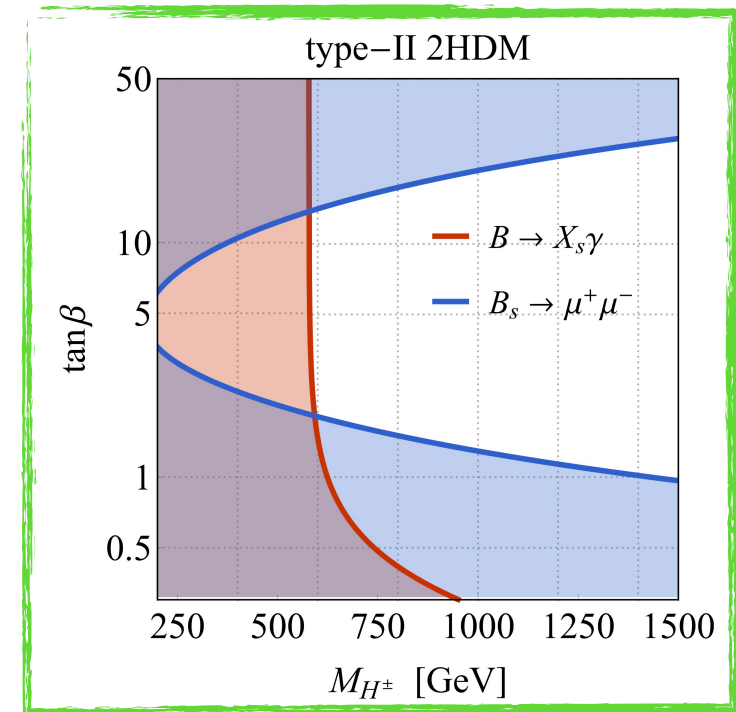
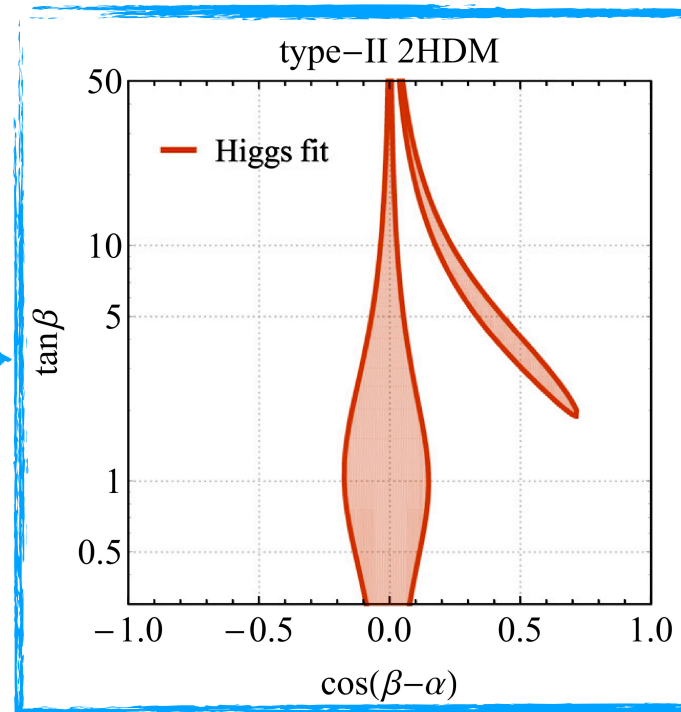
✓ Between h and H : α

✓ Between A and a : θ

✓ VEV ratio of Higgs Doublet: $\tan \beta$

Benchmark Parameters

$$\left\{ \begin{array}{l} m_H = m_{H^\pm} = m_A = 600 \text{ GeV} \\ \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3, m_\chi = 1 \text{ GeV}, \\ \cos(\beta - \alpha) = 0, \tan \beta < 50 \end{array} \right\}$$



◆ With various constraints

- $m_A, m_a, m_\chi, \sin \theta, \tan \beta$

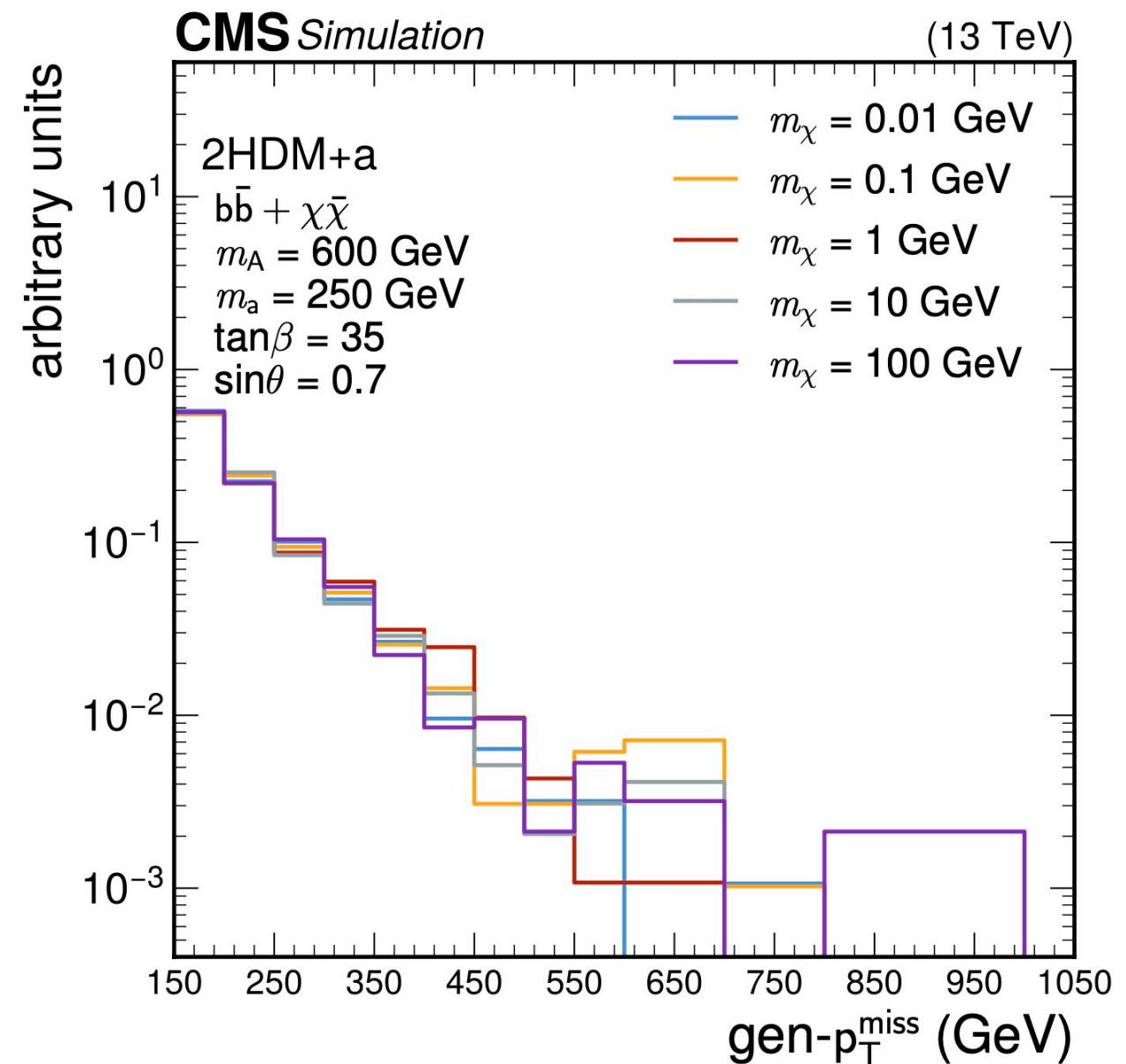
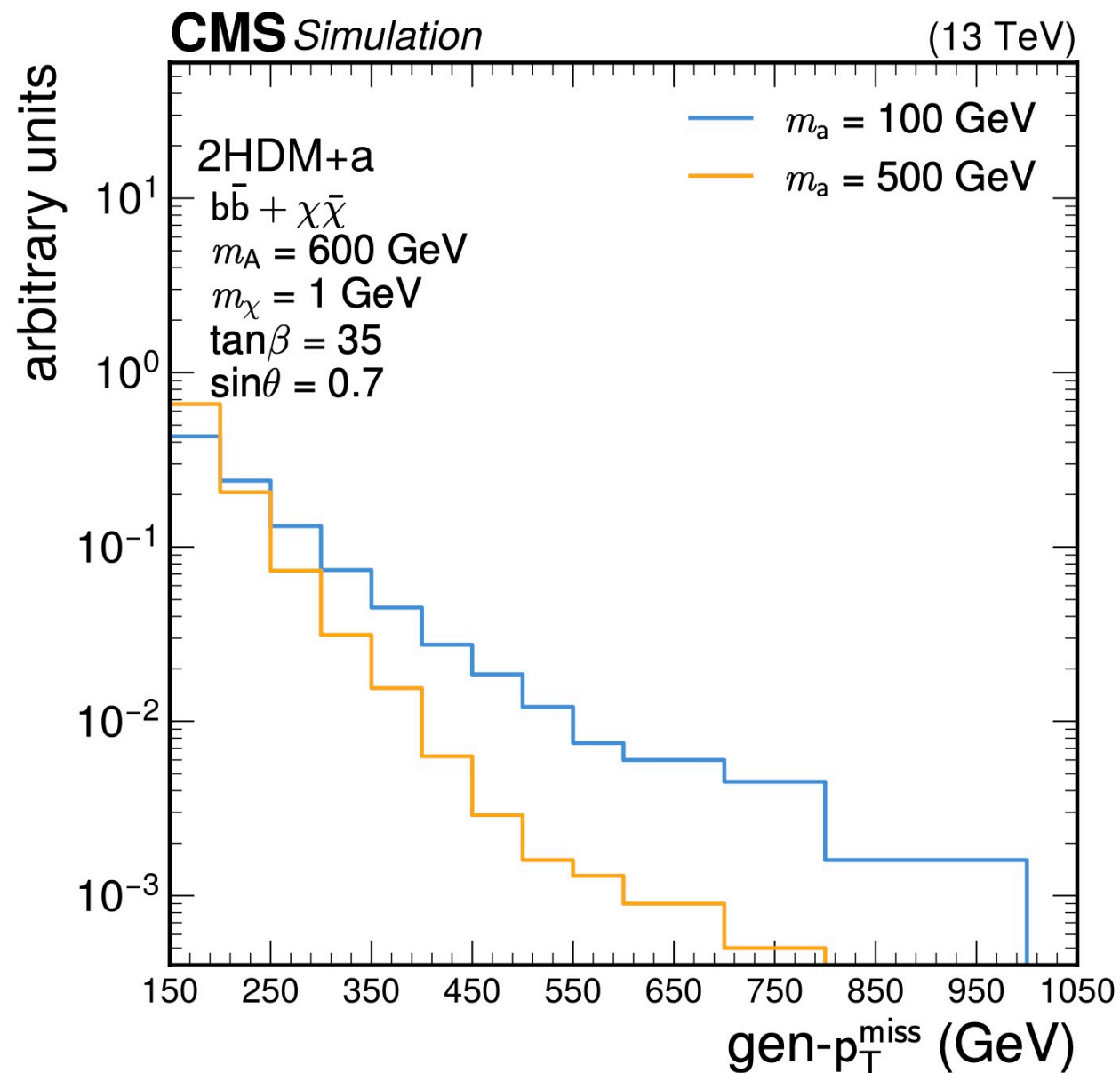
◆ The heavier (A) and lighter (a) pseudo-scalar couple to SM and DM particles

- $-iy_\chi(A\sin\theta + a\cos\theta)\bar{\chi}\gamma_5\chi$

◆ $g_{b\bar{b}A}$ and $g_{b\bar{b}a}$ couplings are $\tan\beta$ -enhanced

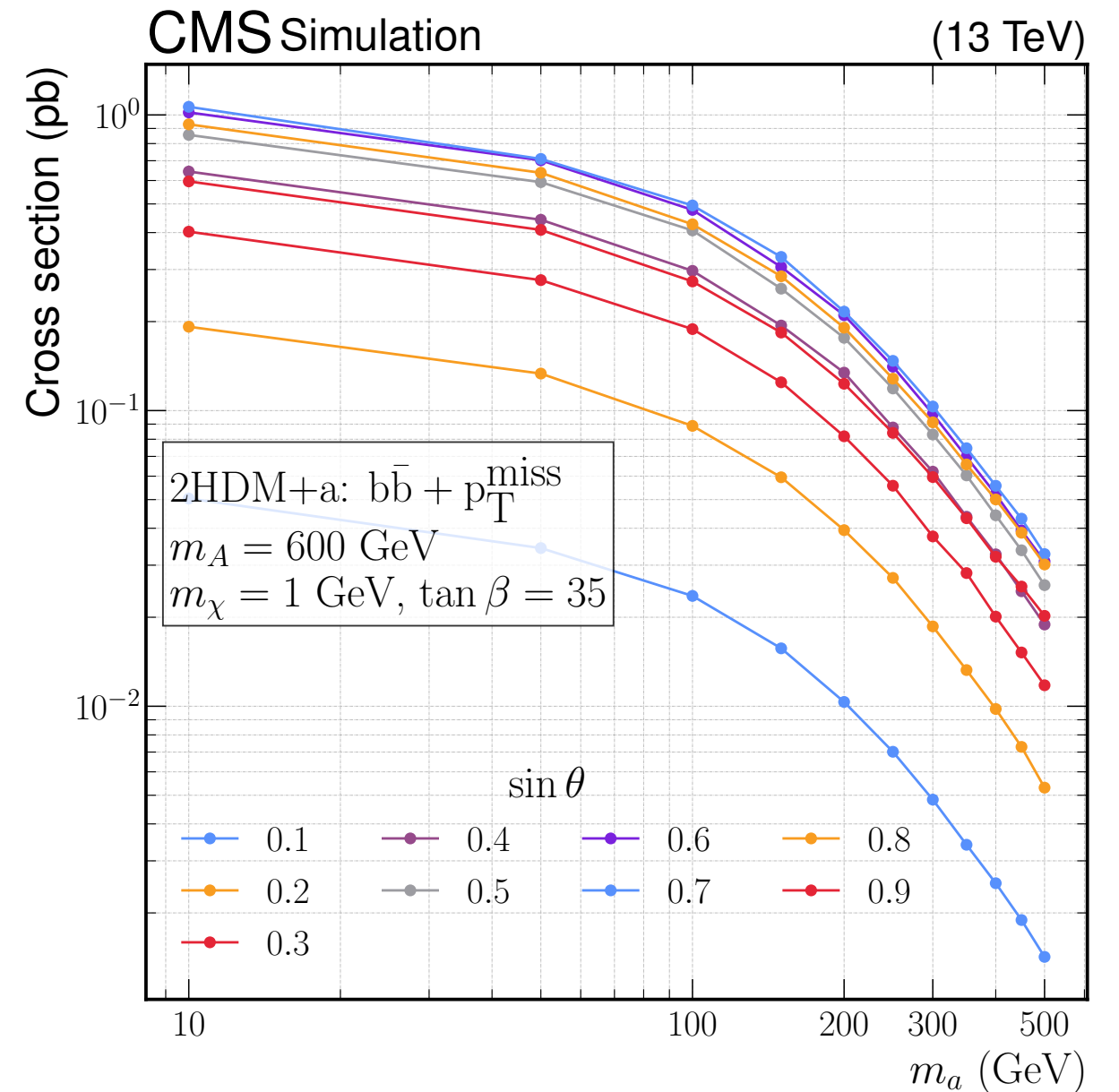
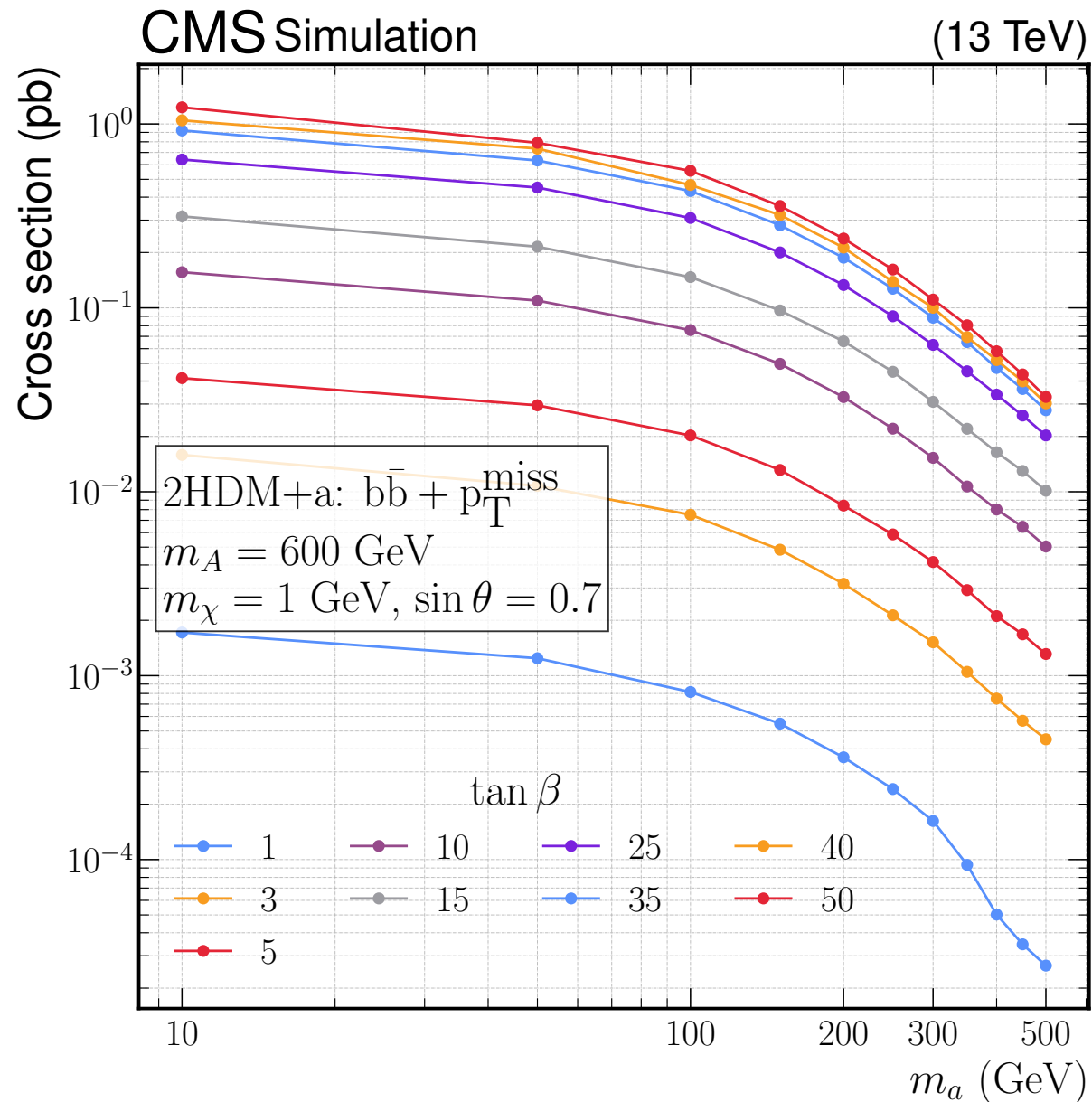
Model Parameters

◆ Dependence of parameters on the kinematics



Model Parameters

◆ Cross-section scan on $\tan \beta$, $\sin \theta$:



Experimental Setup

LHC and CMS Detector

◆ The Experiment starts with the Large Hadron Collider (LHC):

- ✓ 1232 dipole magnets
- ✓ 392 quadrupole magnets
- ✓ 27 km at 1.9 K (superfluid He)
- ✓ Vacuum $\sim 10^{-13}$ Atm.

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1 \text{ m}^2 \sim 66\text{M}$ channels
Microstrips ($80\text{--}180 \mu\text{m}$) $\sim 200 \text{ m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000 \text{ A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER

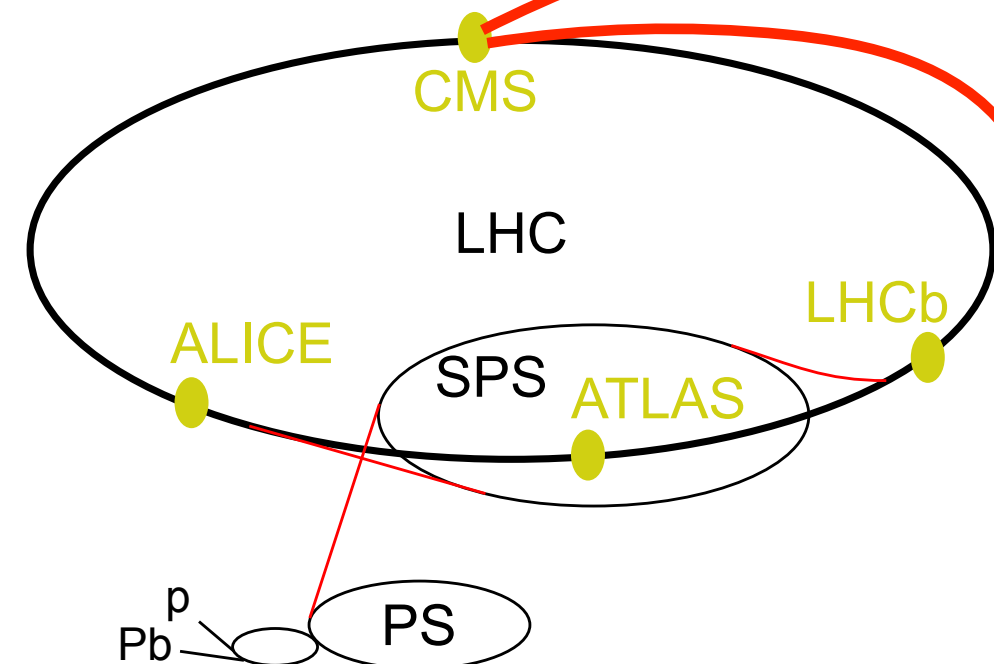
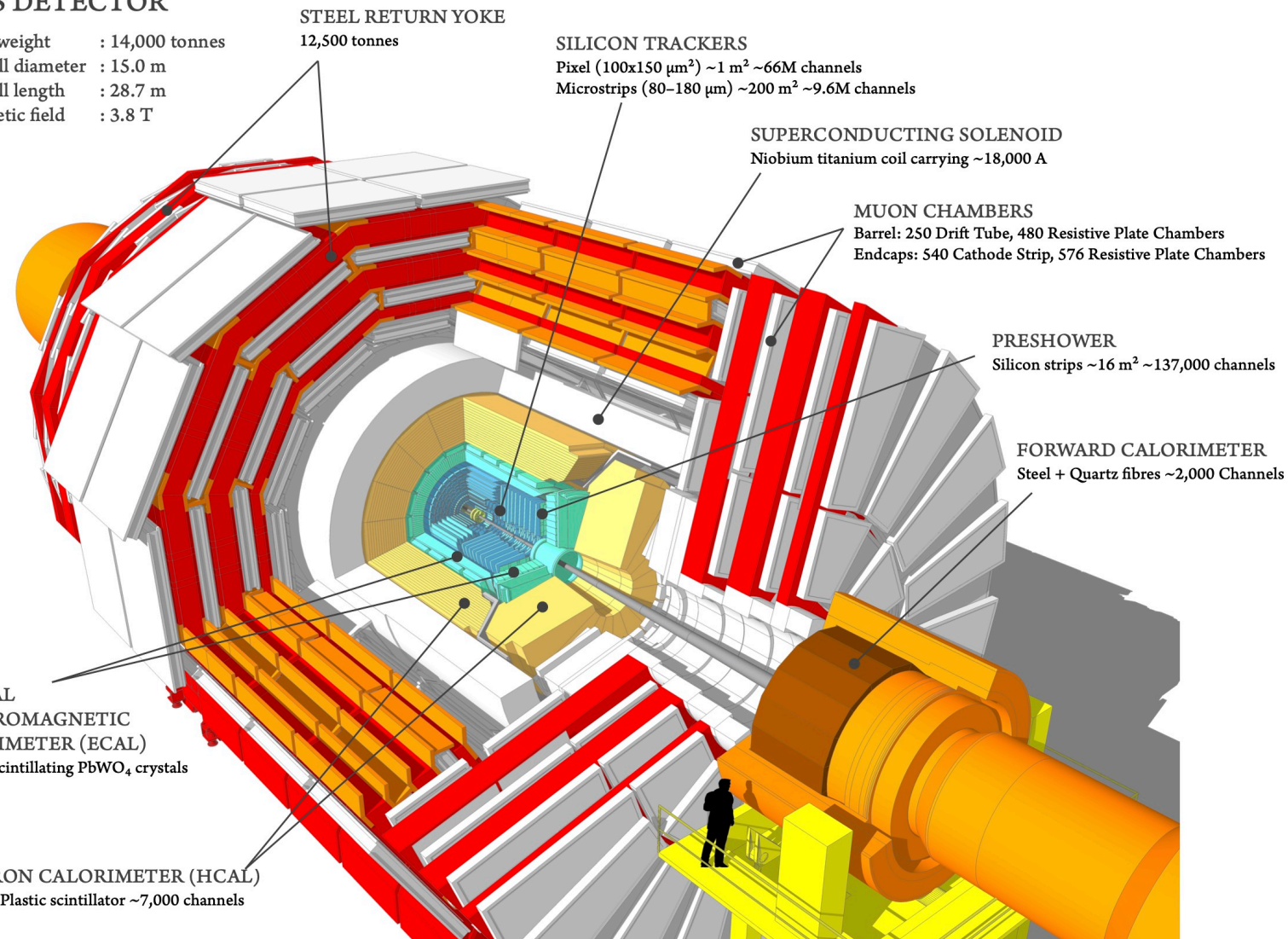
Silicon strips $\sim 16 \text{ m}^2 \sim 137,000$ channels

FORWARD CALORIMETER

Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

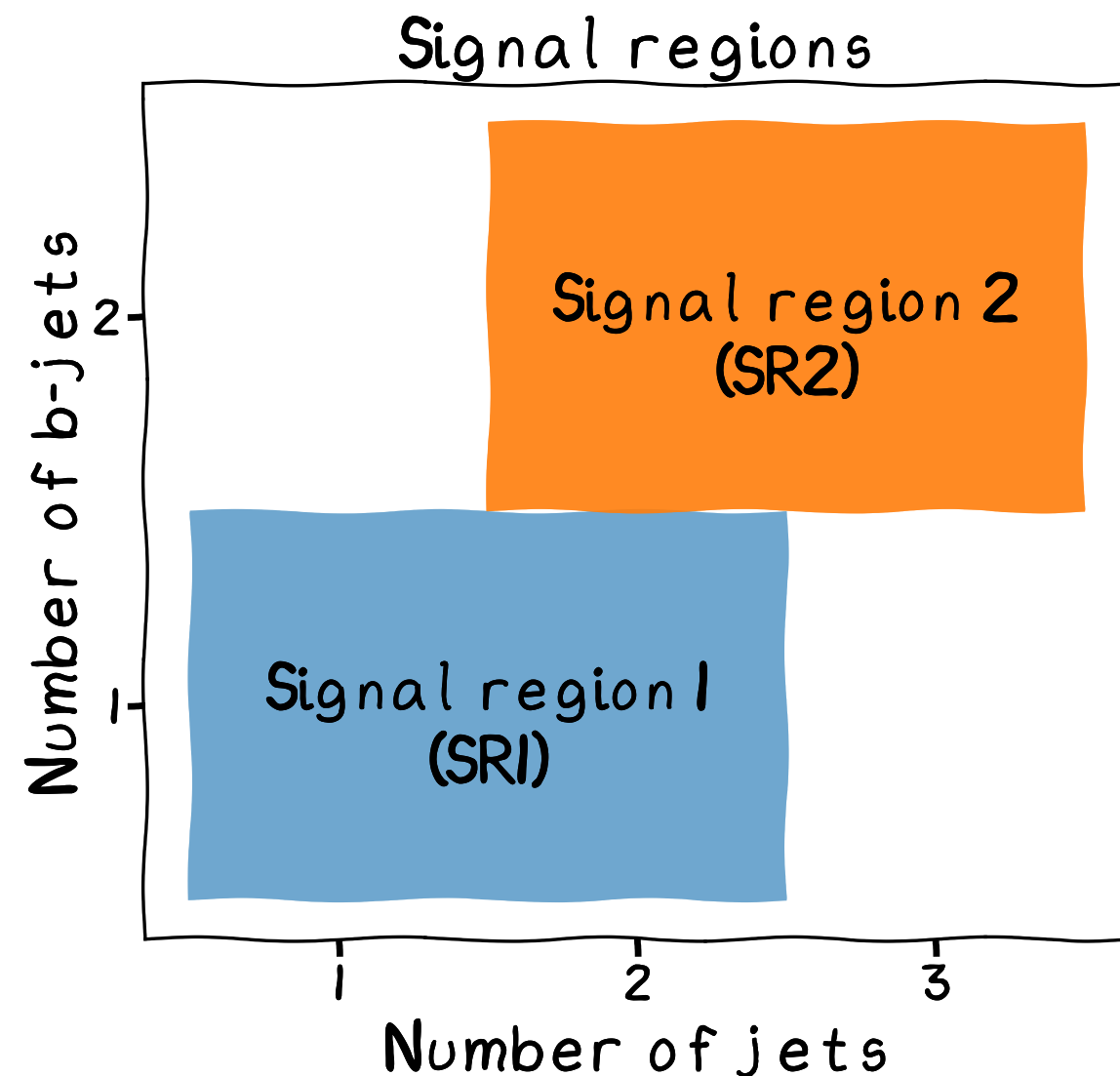


Selection: Object and Event

Event Selection

Signal Region

- Two categories based on
 - Number of b-jets
 - Lepton veto



	SR1	SR2
E_T^{miss}	$> 250 \text{ GeV}$	
Jet1	$p_T > 100 \text{ GeV}$	
Jet2	$p_T > 30 \text{ GeV}$ (if present)	$p_T > 30 \text{ GeV}$
Jet3	veto	$p_T > 30 \text{ GeV}$ (if present)
# b-Jets	1	2
Leptons (e/μ)	veto	
Hadronic τ	veto	
$\min\left(\Delta\phi\left(\text{jet}, E_T^{\text{miss}}\right)\right)$	> 0.5	
$\frac{\left(pf E_T^{\text{miss}} - \text{calo} E_T^{\text{miss}}\right)}{pf E_T^{\text{miss}}}$	< 0.5	

With main observable:

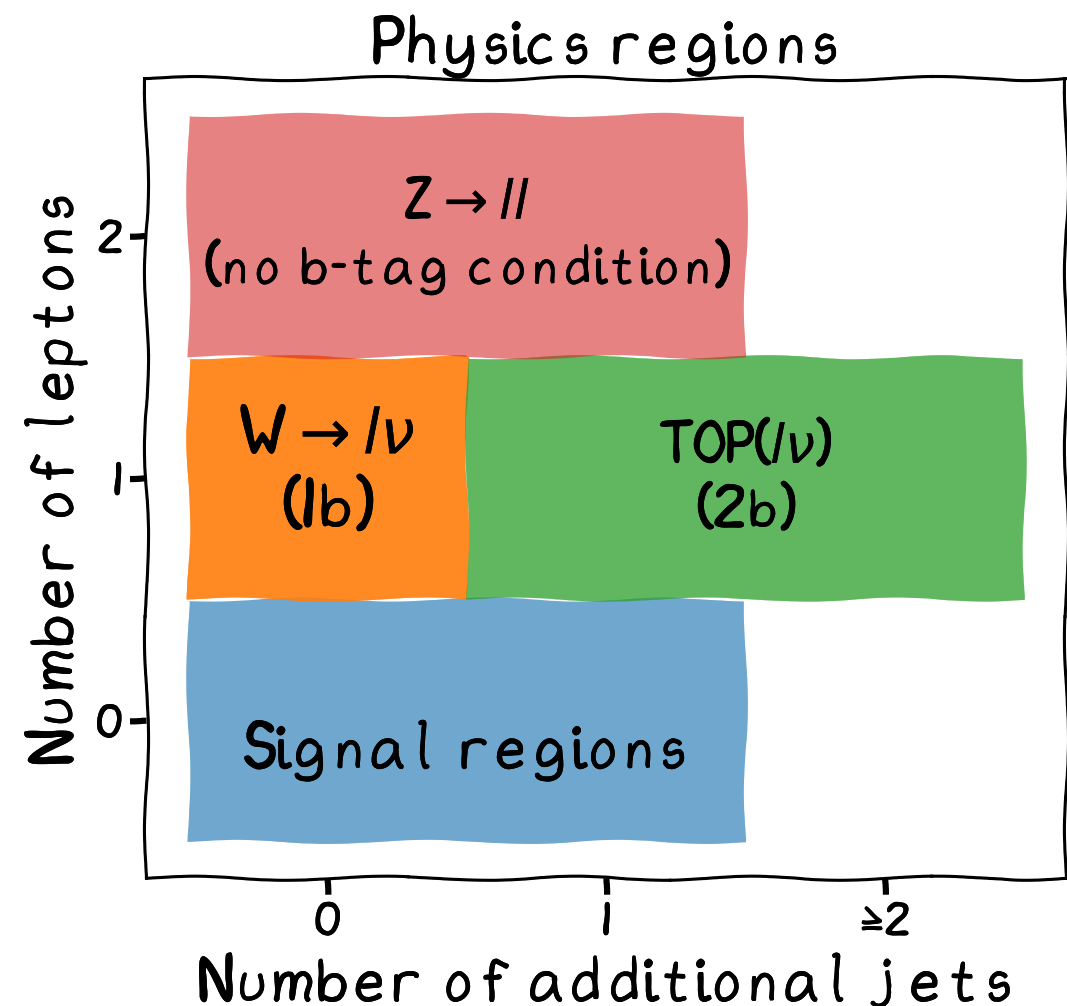
◦ 1b: p_T^{Miss}

◦ 2b: $\cos\Theta^* = \left| \tanh\left(\frac{\eta_{\text{Jet1}} - \eta_{\text{Jet2}}}{2}\right) \right|$

Event Selection

Control Regions

- Hadronic Recoil > 250 GeV
 - $-\left(p_T^{\text{Miss}} + \sum p_T^{\text{Lepton}}\right)$
- **Z+Jets CR**
 - $\mu\mu/ee$ with $70 < M_{ll} < 110$,
 - leading lep $p_T > 30$ GeV
with tight ID ISO
- **Top+Jets CR**
 - μ/e with tight ID ISO,
 $M_T < 160$ GeV
 - ≥ 1 additional jets



- **W+Jets CR**
 - μ/e with tight ID ISO, $M_T < 160$ GeV
 - No additional jets
 - $p_T^{\text{miss}} > 100$ GeV

Signal Extraction & Limits

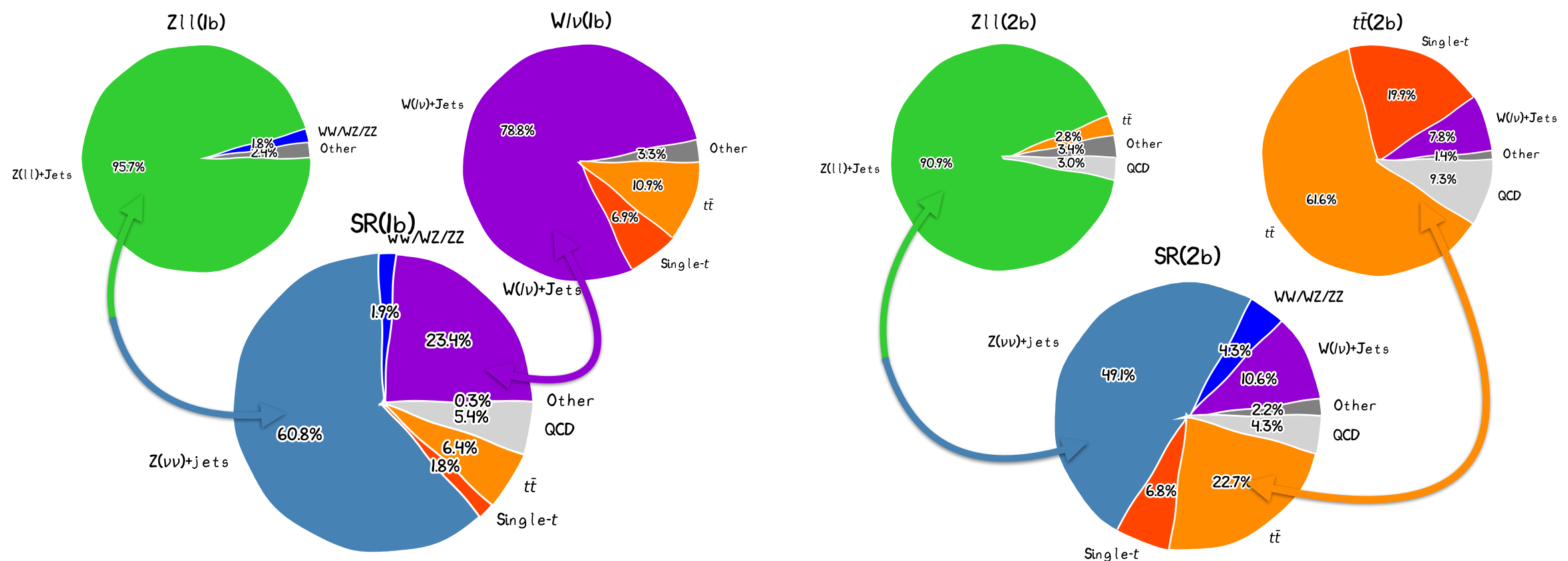
Systematic Uncertainties

Table 2: Systematic uncertainties affecting the shape and normalization (lnN) of the signal and background predictions with an impact greater than 0.5%.

Systematics	Type	Size
Pileup reweighting	shape	3%
b tag efficiency	shape	3–8%
Incorrectly b-tagged jets	shape	1–7%
Electron identification	shape	5–7%
Electron reconstruction efficiency	shape	3–5%
Muon identification	shape	<1%
Muon isolation	shape	<1%
Electron trigger	shape	1%
p_T^{miss} trigger	shape	1%
Jet energy correction	shape	3%
L1 prefiring	shape	0.5%
Muon prefiring	lnN	0.5%
τ_h veto	lnN	6%
Integrated luminosity	lnN	2.5%
Cross section diboson	lnN	20%
Cross section Drell–Yan	lnN	5%
Cross section Higgs boson	lnN	20%
Cross section single top quark	lnN	10%
QCD normalization	lnN	20%
Renormalization and factorization scales	shape	16–42%
PDF	shape	25–50%

Signal Extraction

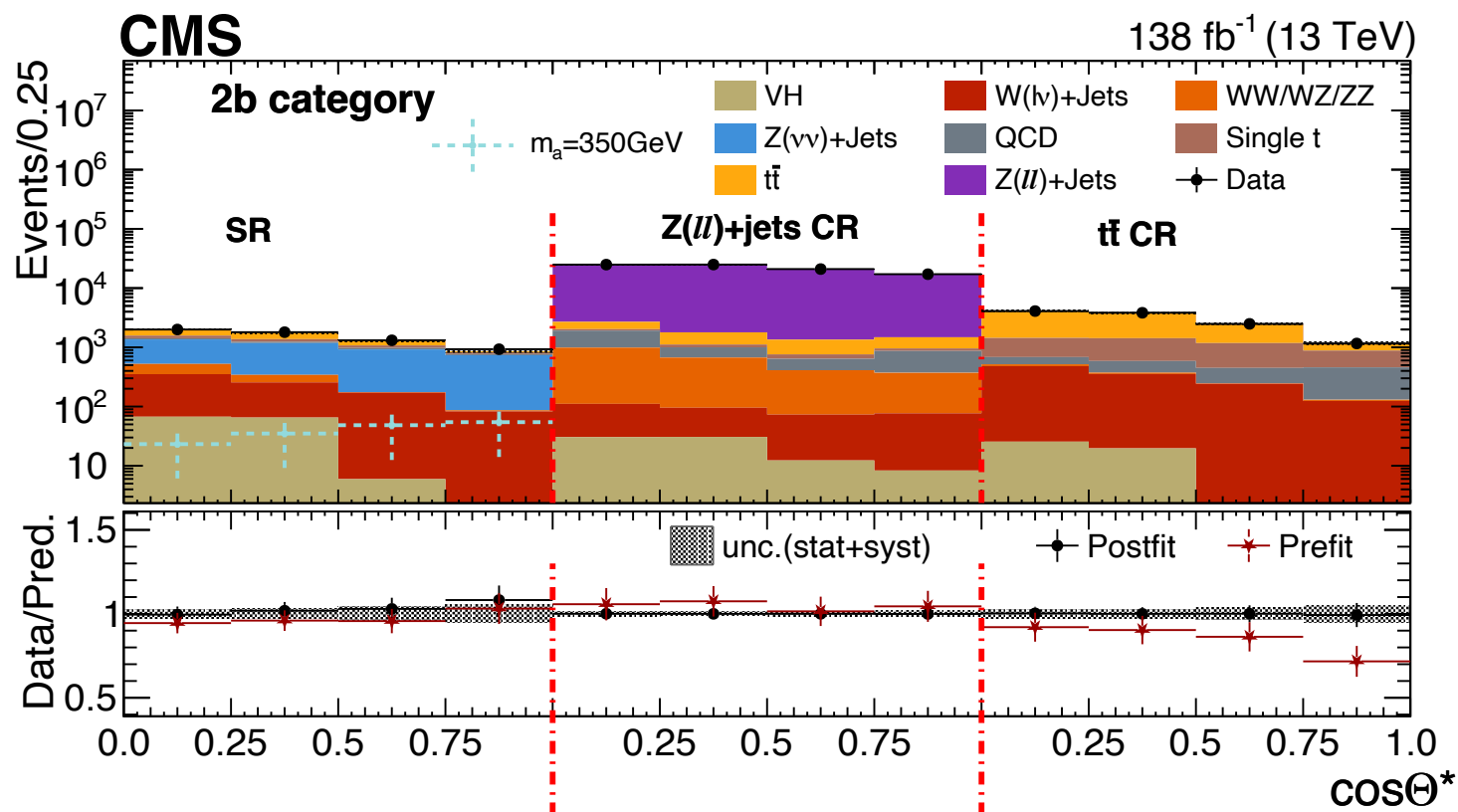
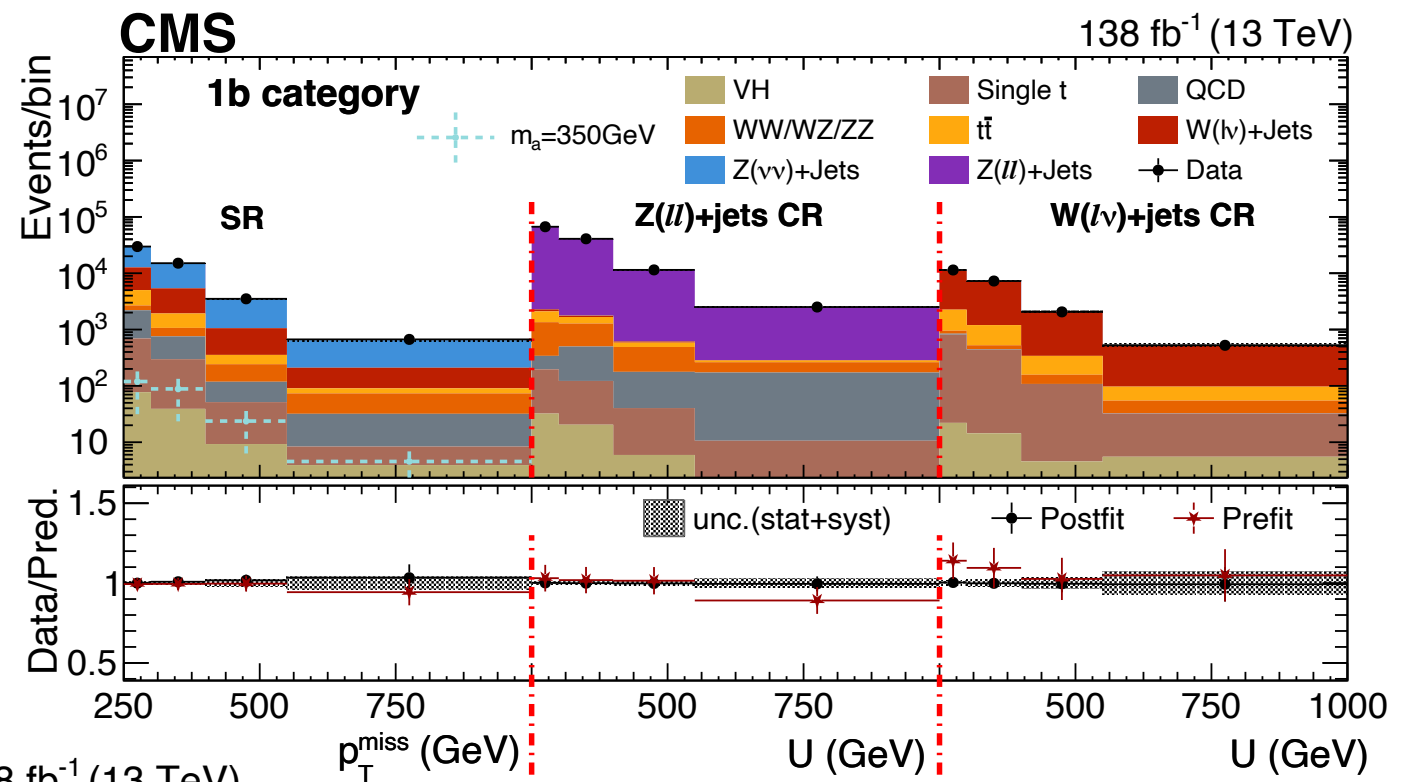
- Z+Jets and $t\bar{t}$ have the largest contribution in the 1b (2b) SR
- Combining electron and muon channel then linking SR and CR through rateParam will all the systematics taken as nuisance parameters
- One rateParam for each bin and for each region
- A simultaneous binned profile likelihood fit is performed in Signal and Control Region
- On $p_T^{\text{Miss}}(\cos \Theta^*)$ variable



Postfit Distributions

The postfit distribution have good performance

- With p_T^{Miss} observable in 1b

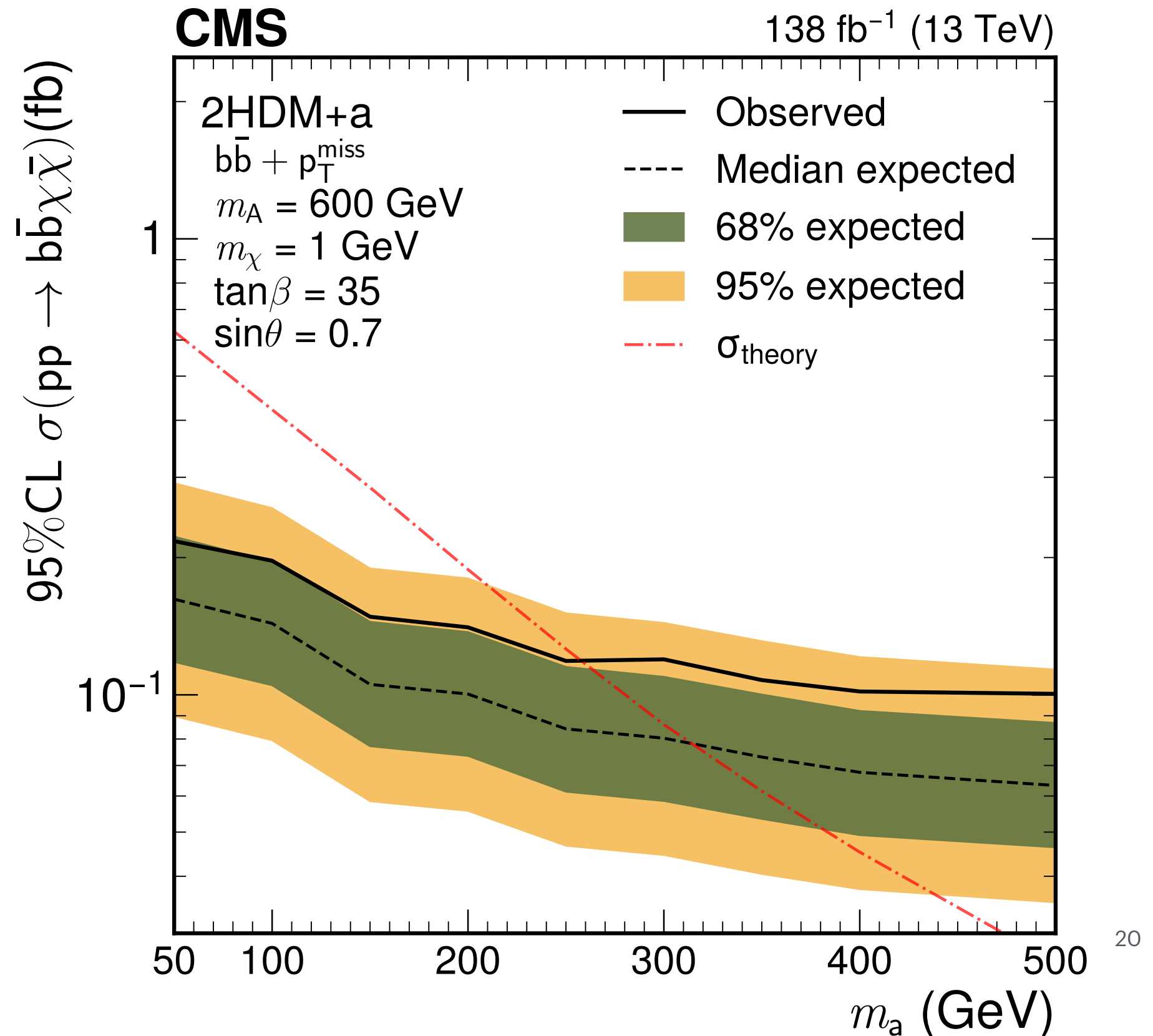


- With $\cos\Theta^*$ observable in 2b

Run2 Results

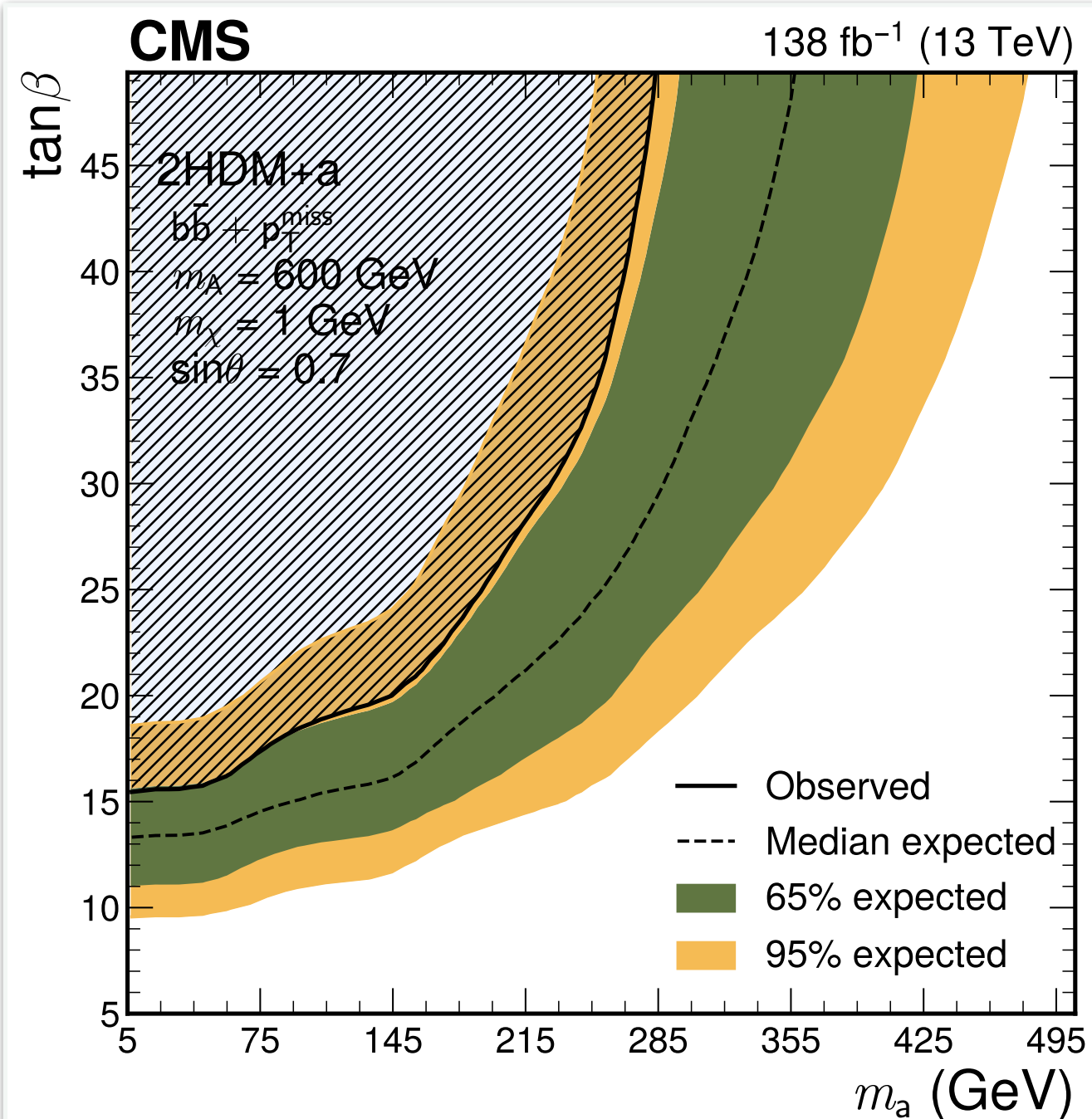
1D Limits

- Full Run 2 Limit with p_T^{Miss} (1b) and $\cos \Theta^*$ (2b)
- No Excess has been observed

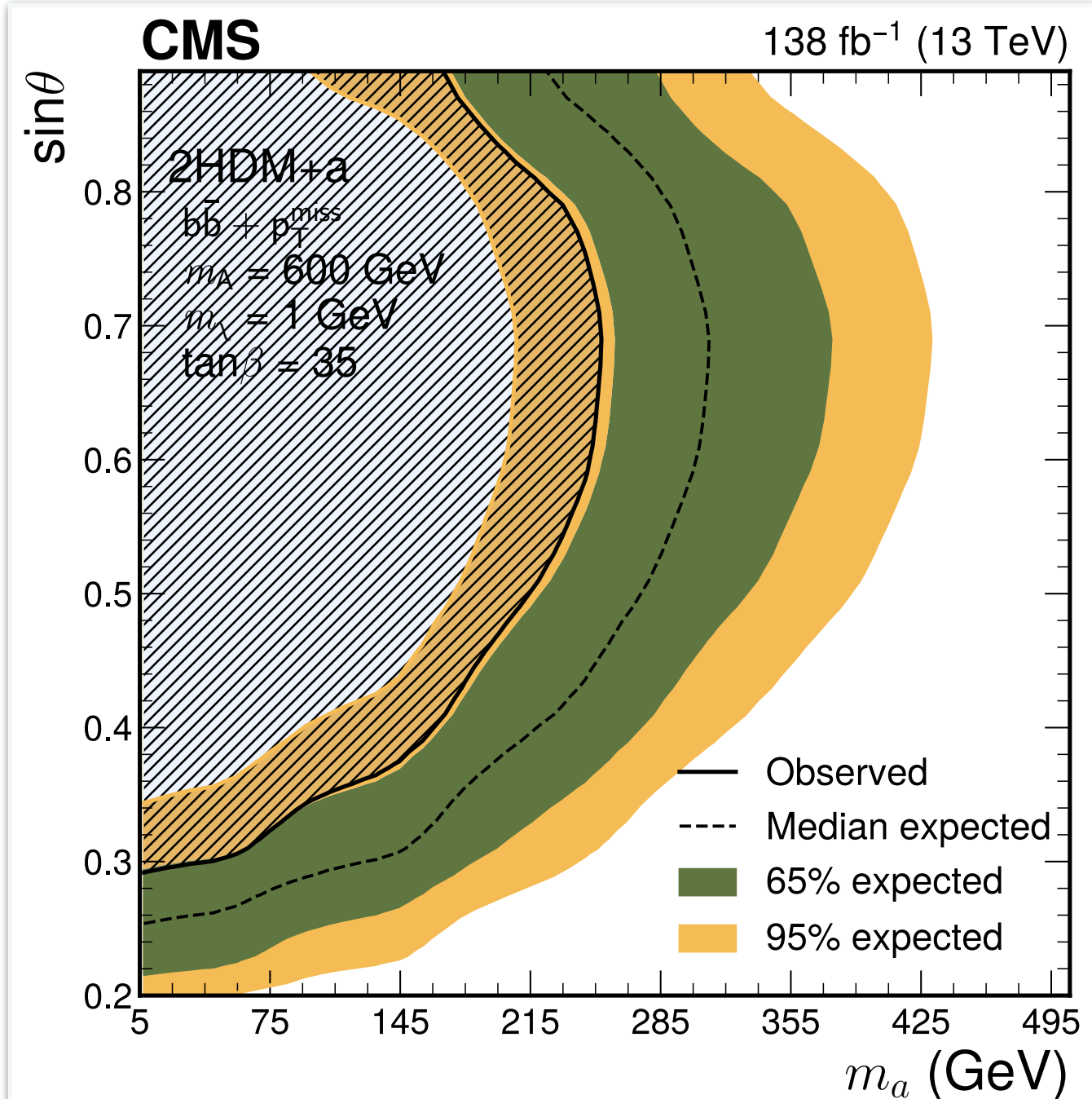


Run2 Results

2D Limits

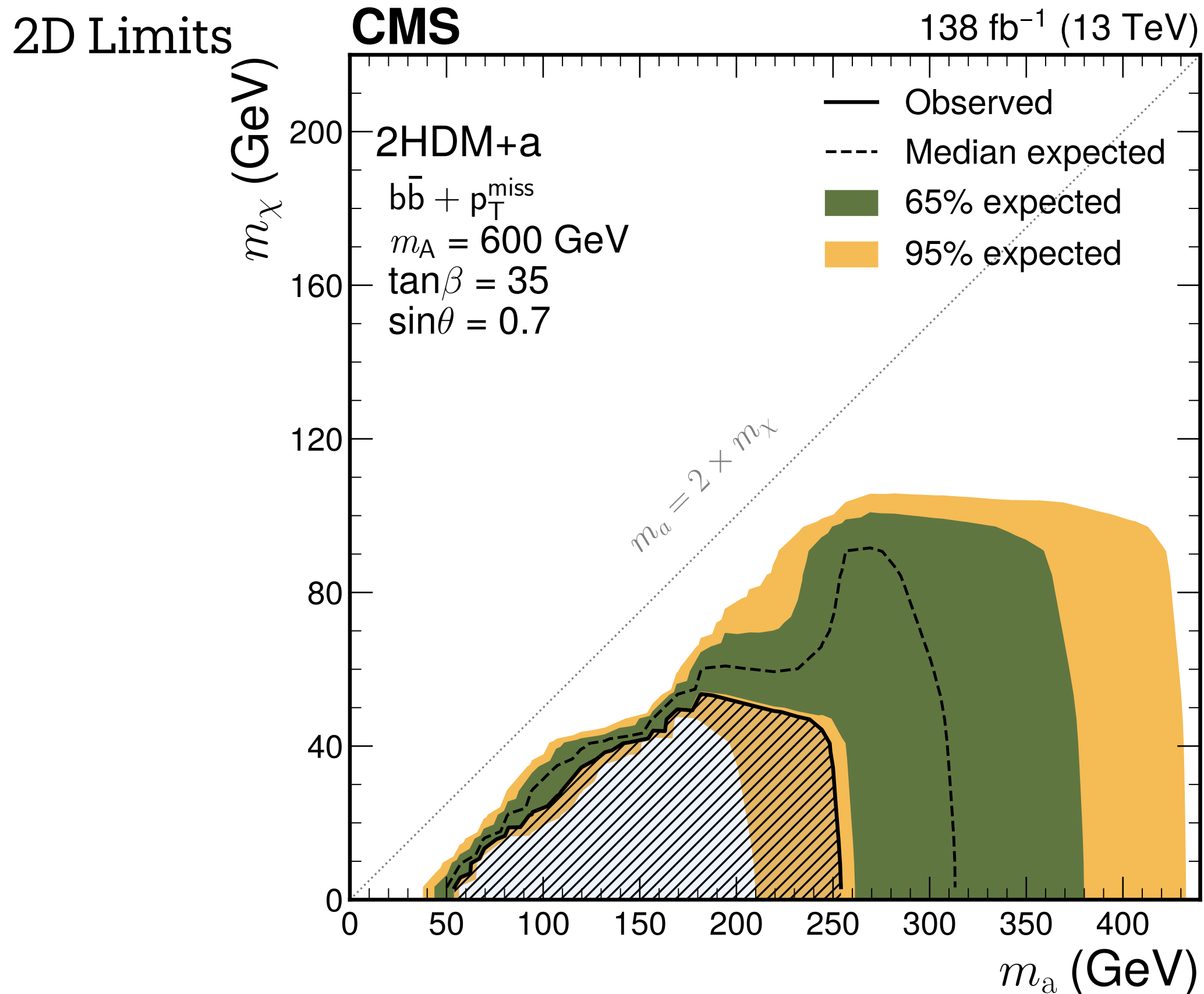


$m_a - \tan \beta$



$m_a - \sin \theta$

Run2 Results

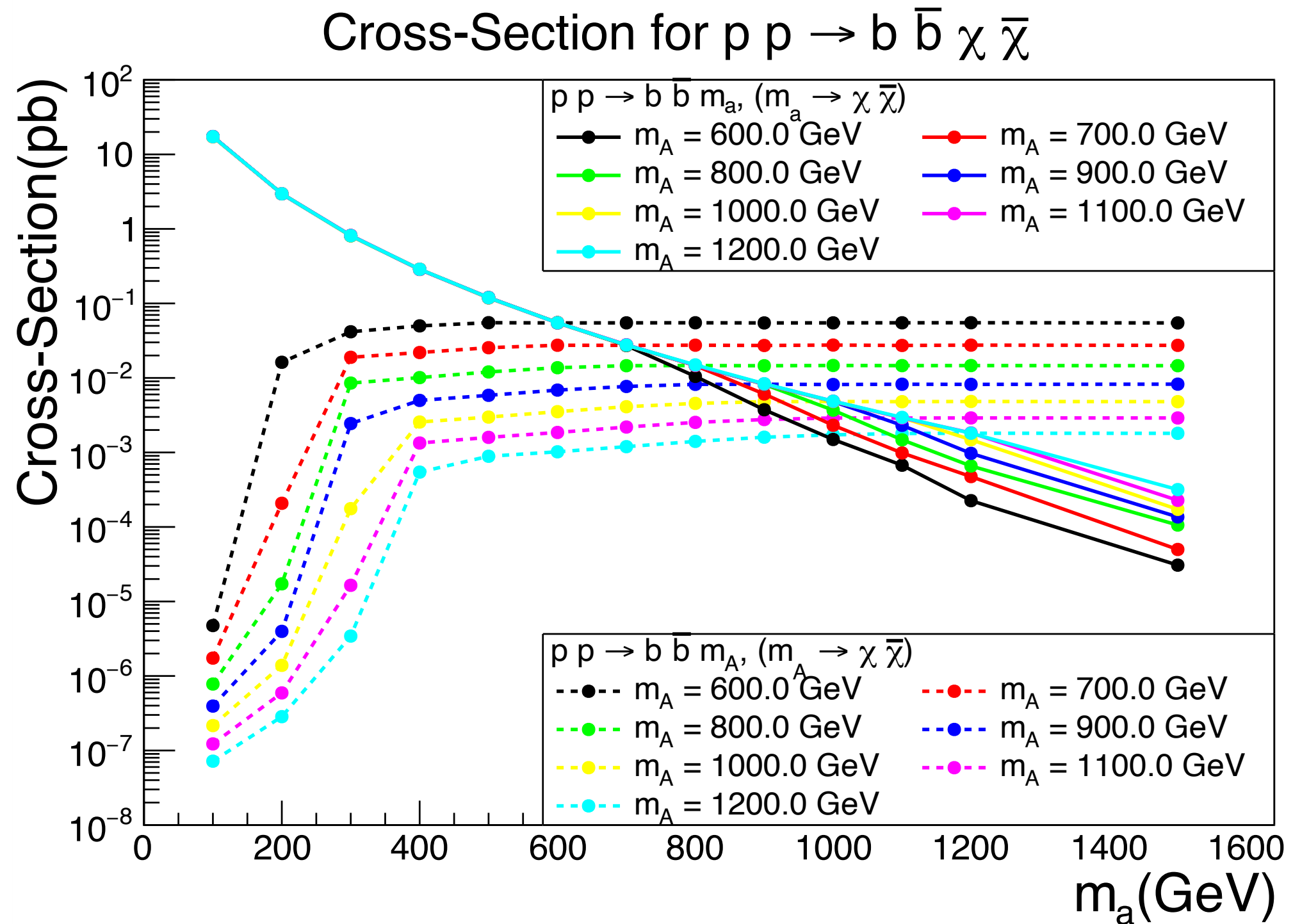


Summary

- Search for DM in the bb+MET channel using RunII CMS data is presented
- The results are interpreted with type-II 2HDM+a model
- Full Run 2 limit is calculated covering large phase space of the model
 - Complementary to most of the mono+X searches
- Published in JHEP
 - DOI: [https://doi.org/10.1007/JHEP02\(2025\)050](https://doi.org/10.1007/JHEP02(2025)050)
- Started LHC Run 3 Analysis
 - Leveraging higher luminosity and improved detector performance for the bbMET dark-matter search in the 2HDM+a model.
 - Employing advanced ML techniques to enhance signal-background separation and fit modeling.

Thank You

$b\bar{b}$ production with a and A

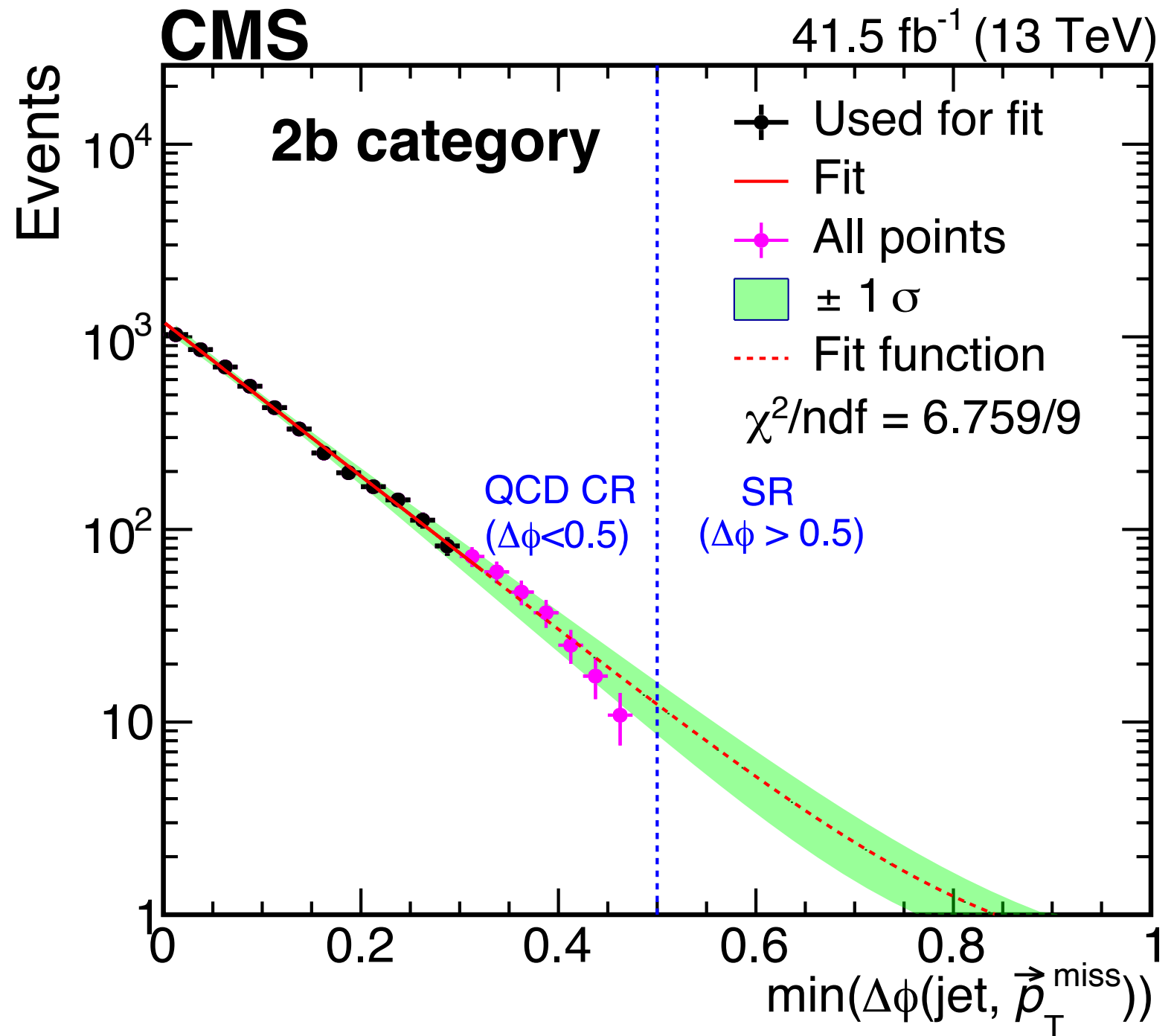


Estimating QCD

2017

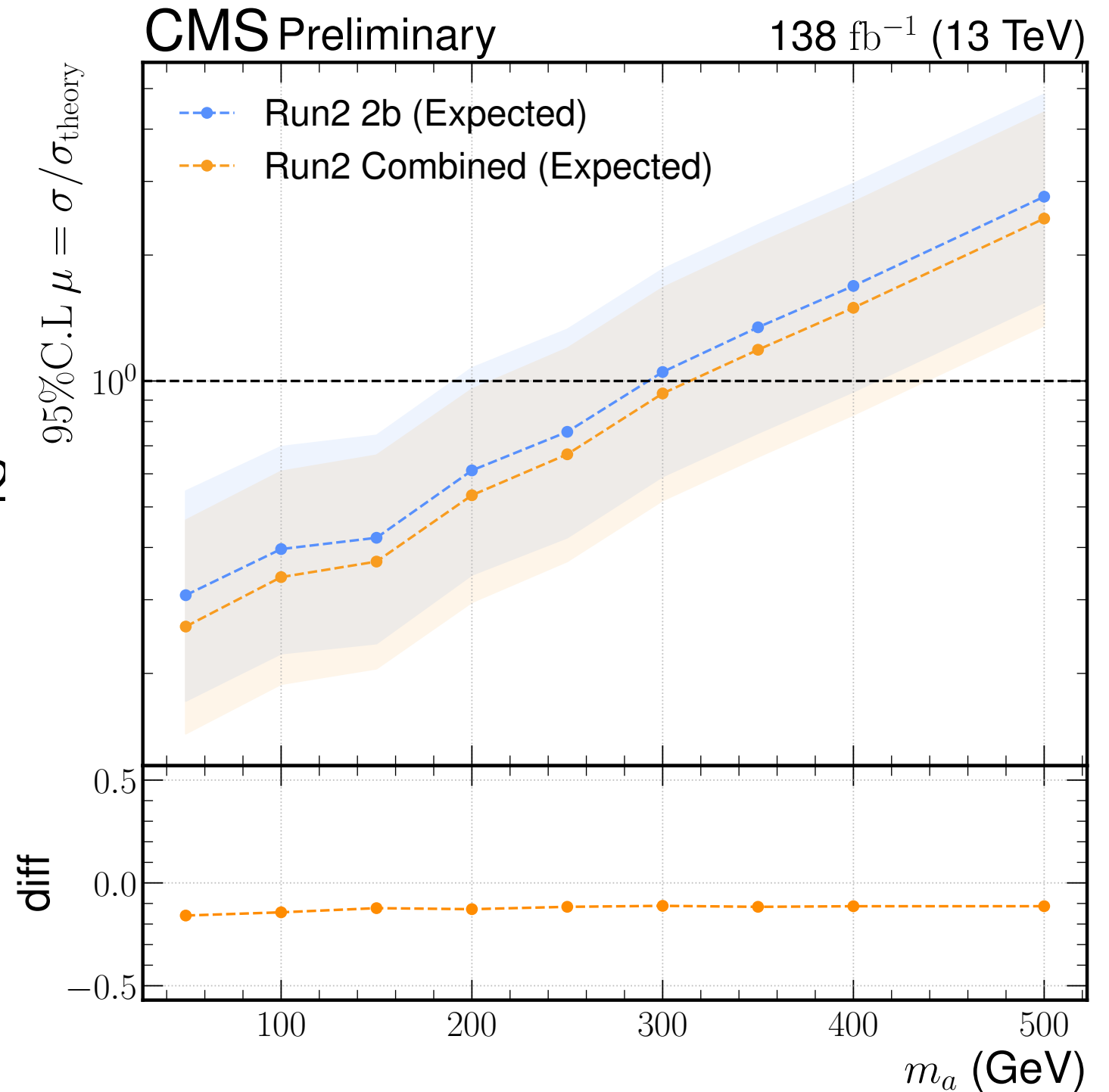
- Using QCD as the difference of DATA and total background except QCDCMC in a dedicated qcdCR for each region ($\Delta\phi < 0.5$)

- QCD contribution in the region is the integral of the FIT () from $\Delta\phi > 0.5$
- Fit Function:
 - $a \cdot \exp(b \cdot x) + c$

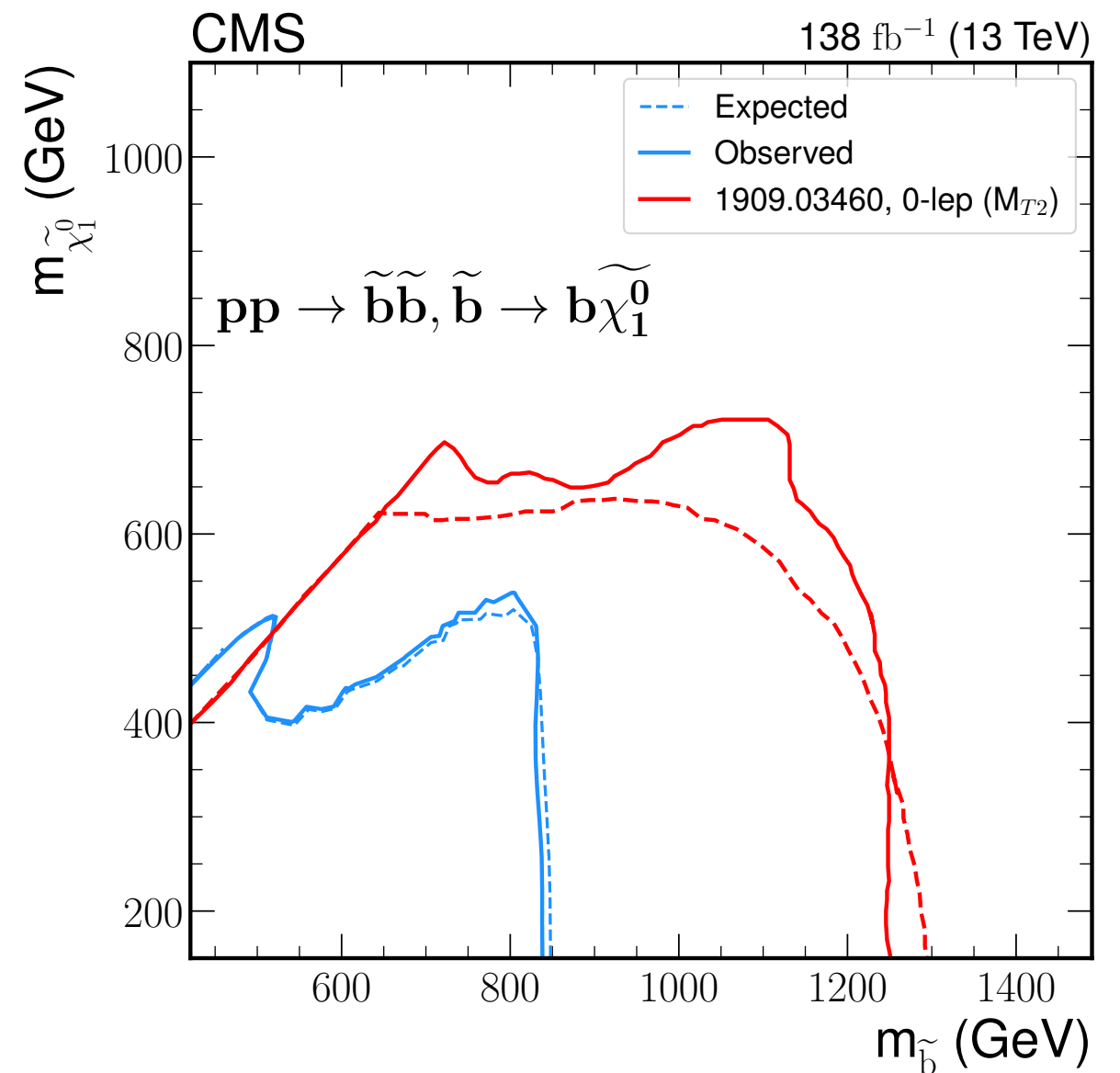
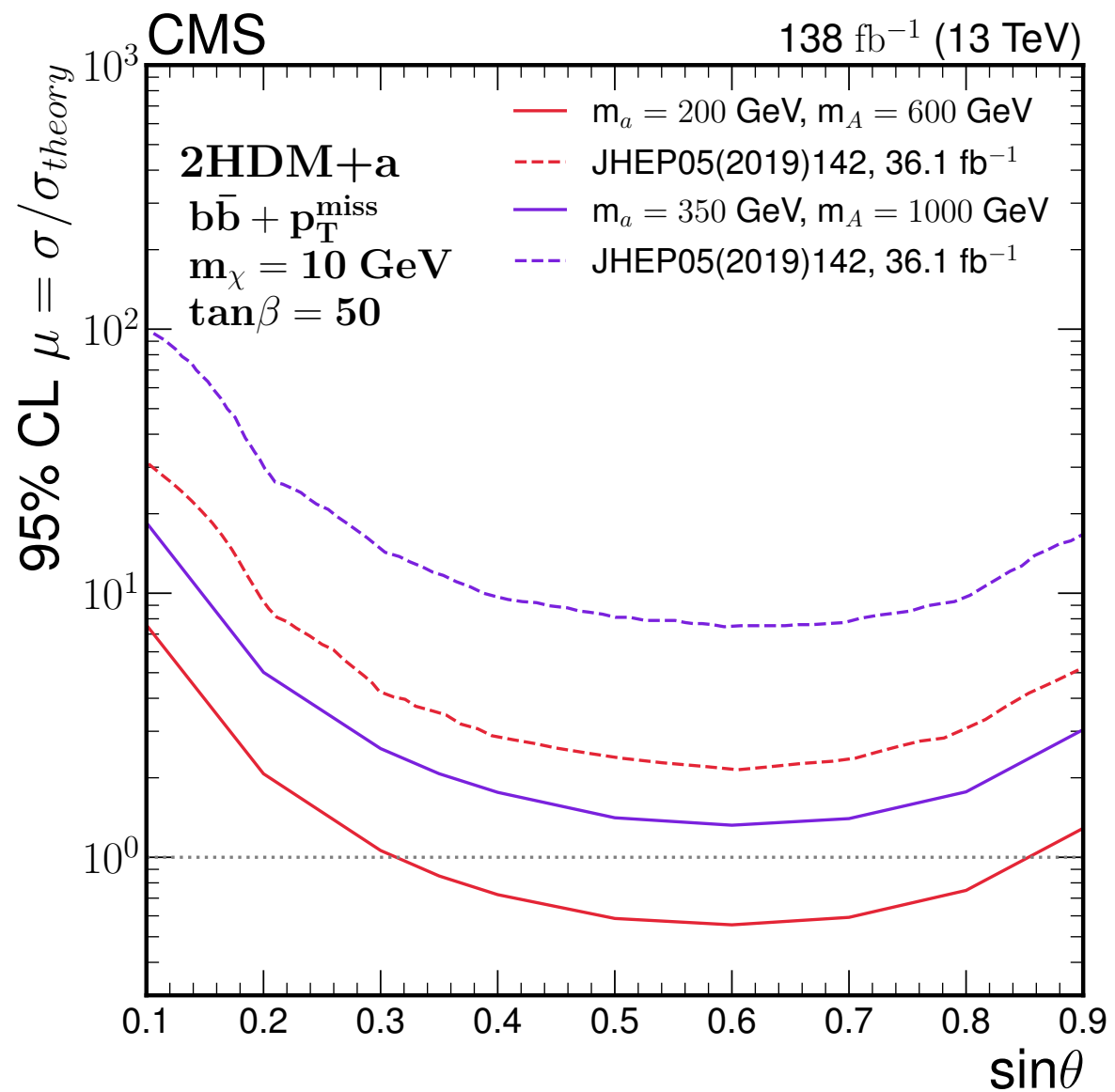


1b Category Contribution

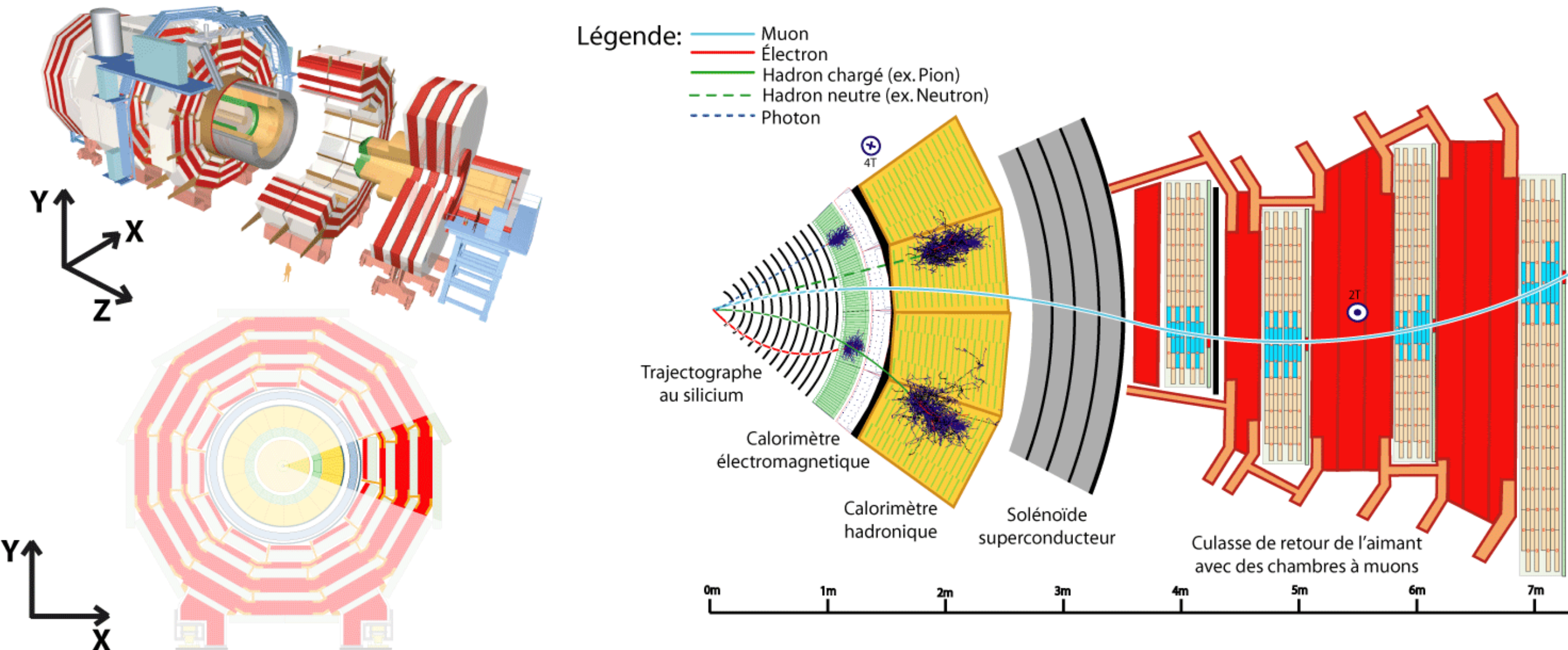
- 1b category contributes up-to 10% in the Full Run 2 Limit (expected) with $p_T^{\text{Miss}(1b)}$ and $\cos(\theta)^*(2b)$



Limits comparisons



Object Selection



Electron

* $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$

Muon

* $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$

Tau

* $p_T > 18 \text{ GeV}$ and $|\eta| < 2.3$

p_T^{Miss}

* $> 250 \text{ GeV}$

Jets

- * AK4PF jets, $p_T > 30 \text{ GeV}$, $|\eta| < 2.5$
- ◆ Cleaned against electron and muon using $\Delta R (\text{lepton, jet}) < 0.4$
- ◆ b-jets with $|\eta| < 2.5$ DeepCSV Medium working point