Searches for Dark Matter with CMS in Mono-X Signatures

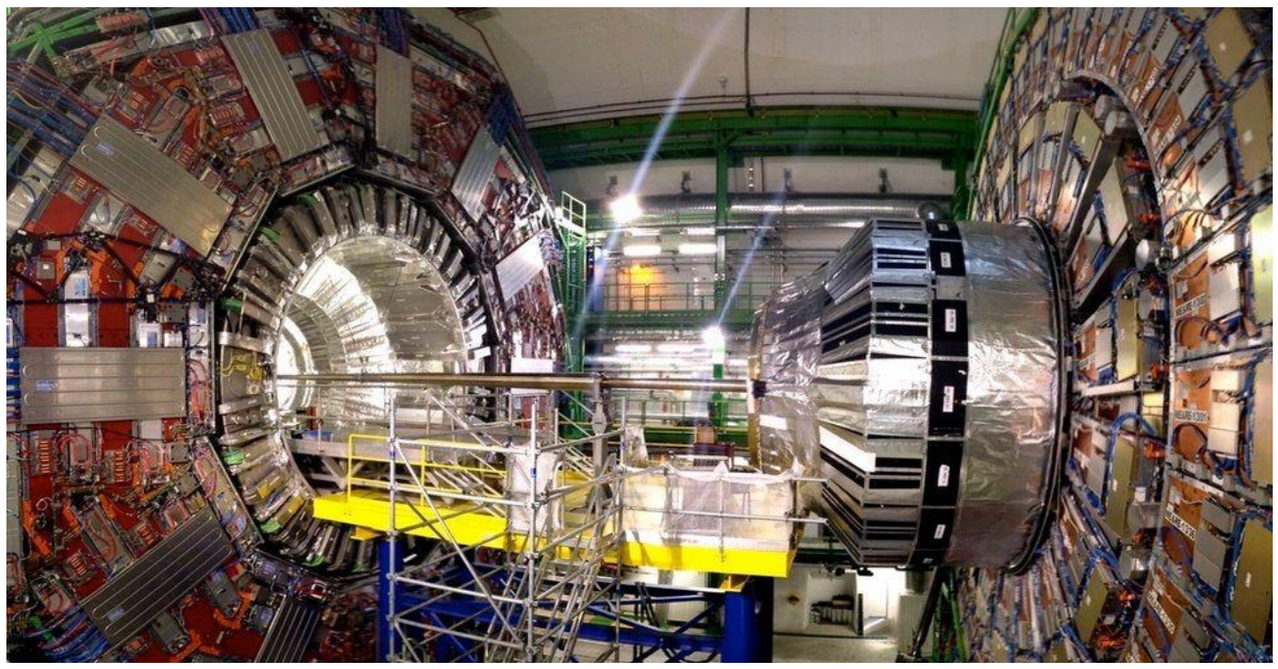
Sushil Singh Chauhan

(Panjab University, Chandigarh, India)

On behalf of

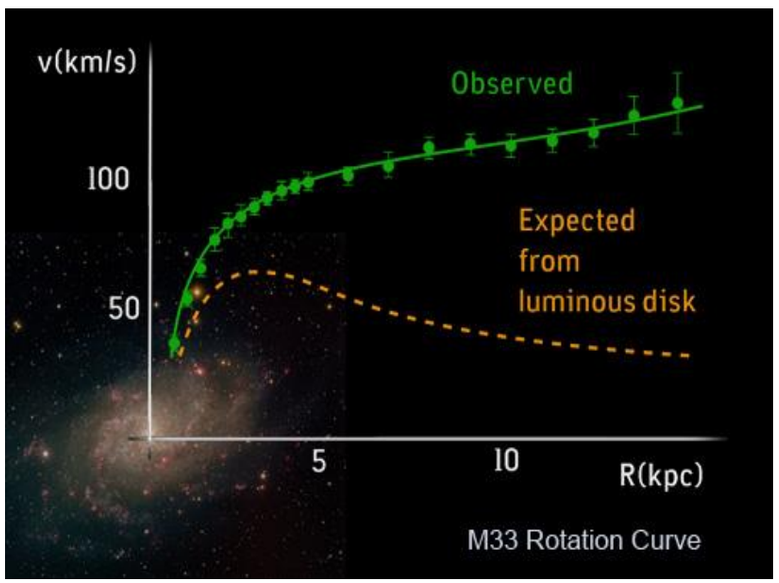
The CMS Collaboration

EPS-HEP, Marseille, France (7-11 July 2025)

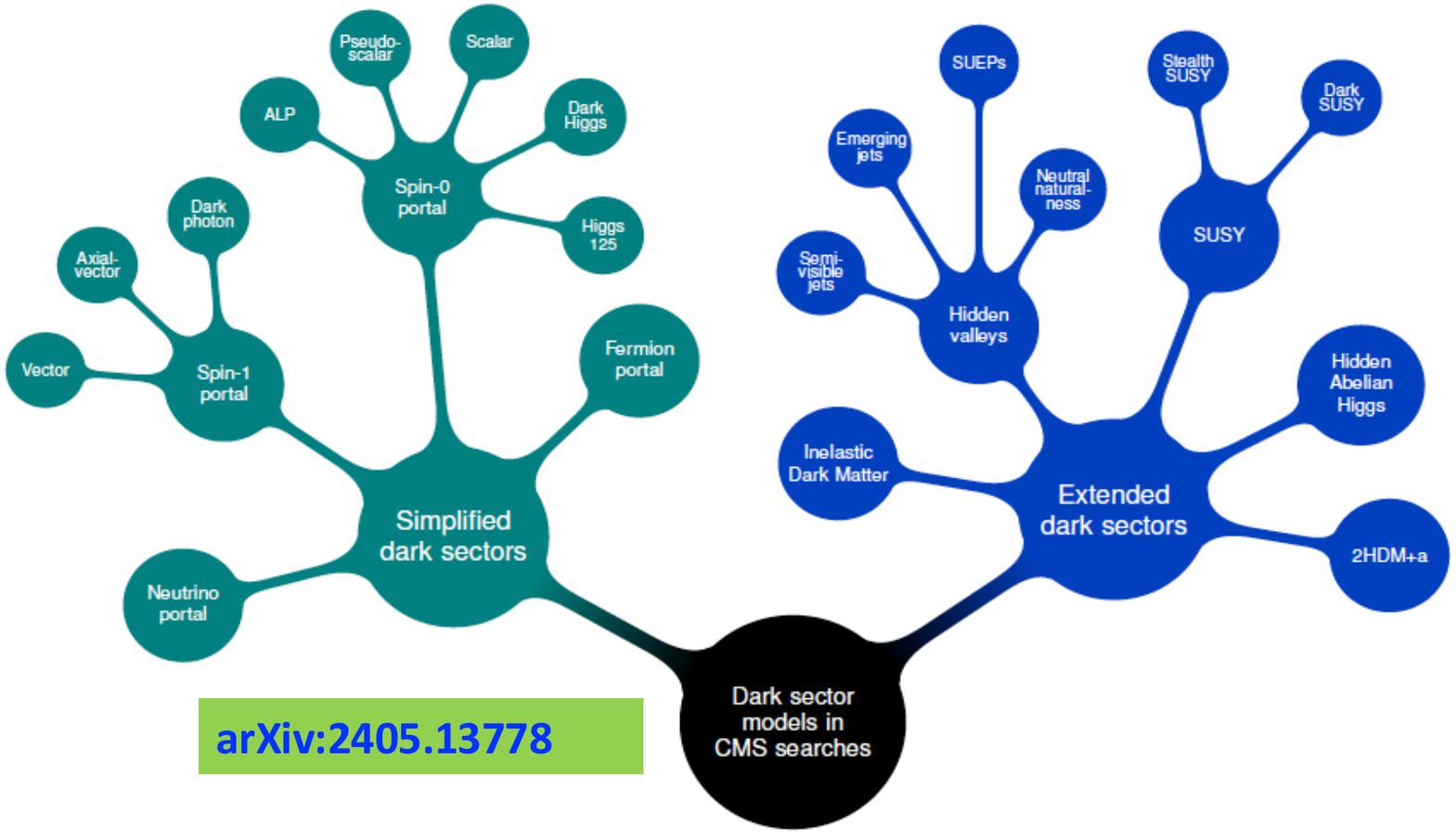


Dark Matter Search & Dark Sector

- **Strong astrophysical evidence for the existences of dark matter**
  - **Rotation curve, CMBR spectrum, Gravitational lensing**
- **Nature of DM is still unknown**

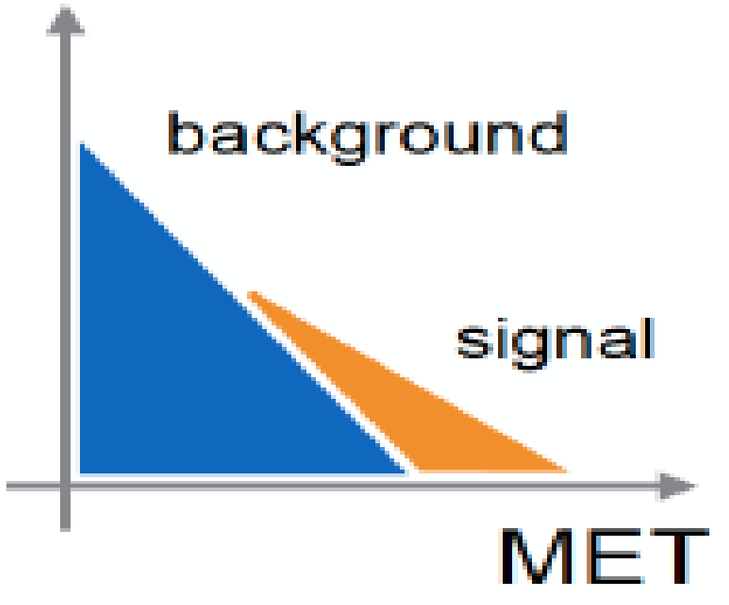


LHC a prime lab for production of DM in pp-collision



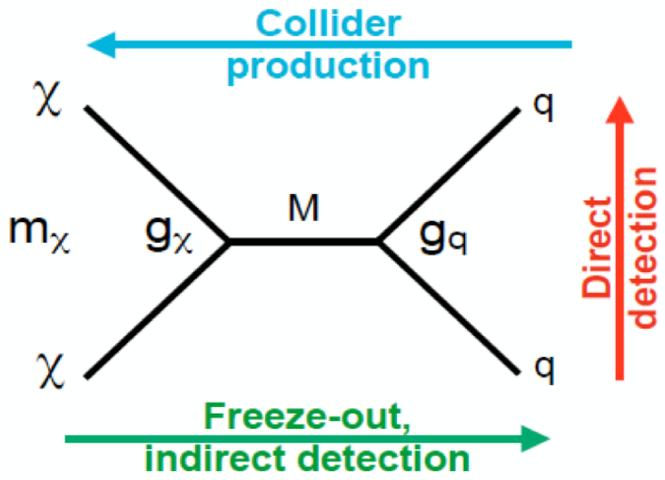
arXiv:2405.13778

This talk: MET+X Signature

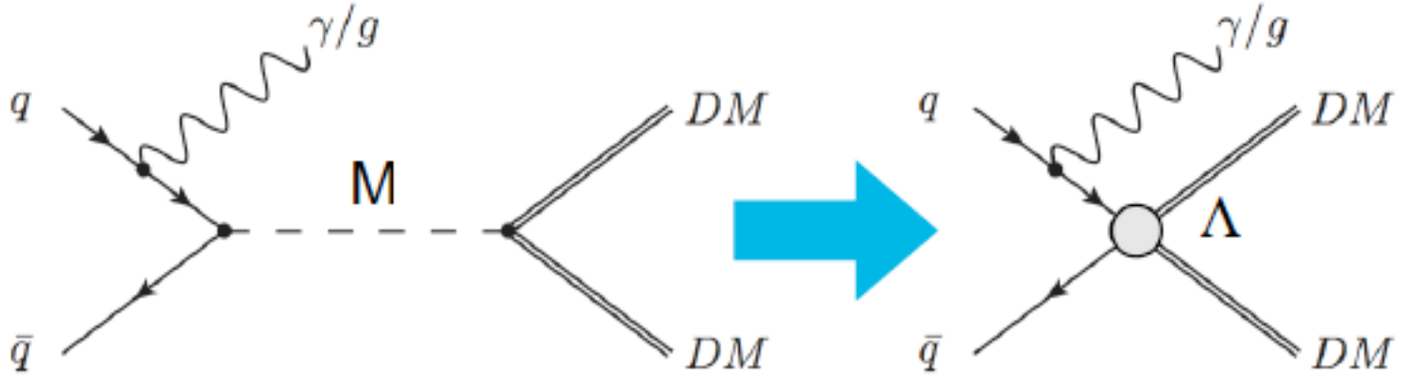


Candidates and Simplified Model

- **Many DM candidates: WIMP, Axion, Neutrino**
  - **WIMP so far most favorable**
  - **Extensive search**



- **Early Searches based on EFT**
- **At collider: mostly focused on Simplified Models**



$$\Lambda = M/\sqrt{g_\chi g_q}$$

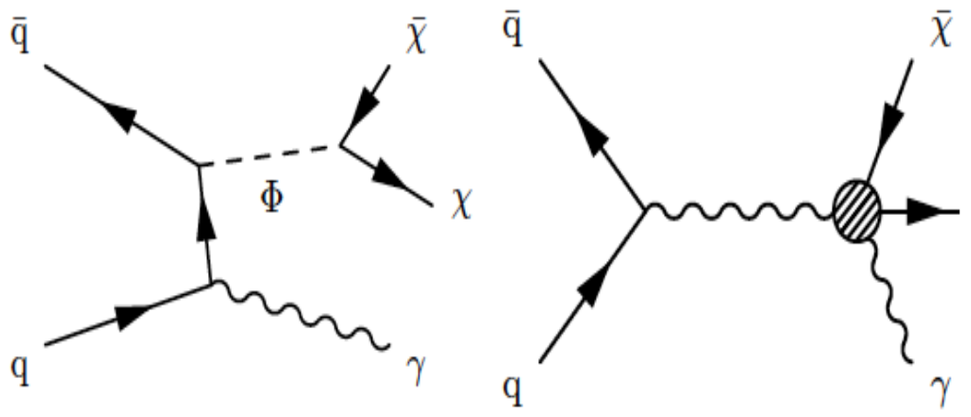
- **Simplified models to interpret results**
  - **DM particle is Dirac fermion ($\chi\chi$)**
  - **Massive mediators (vector, axial-vector, scalar, pseudo-scalars)**
  - **Minimal set of parameters: M_{DM}, M_{MED}, $g_{q=0.25}$, $g_{DM=1.0}$**

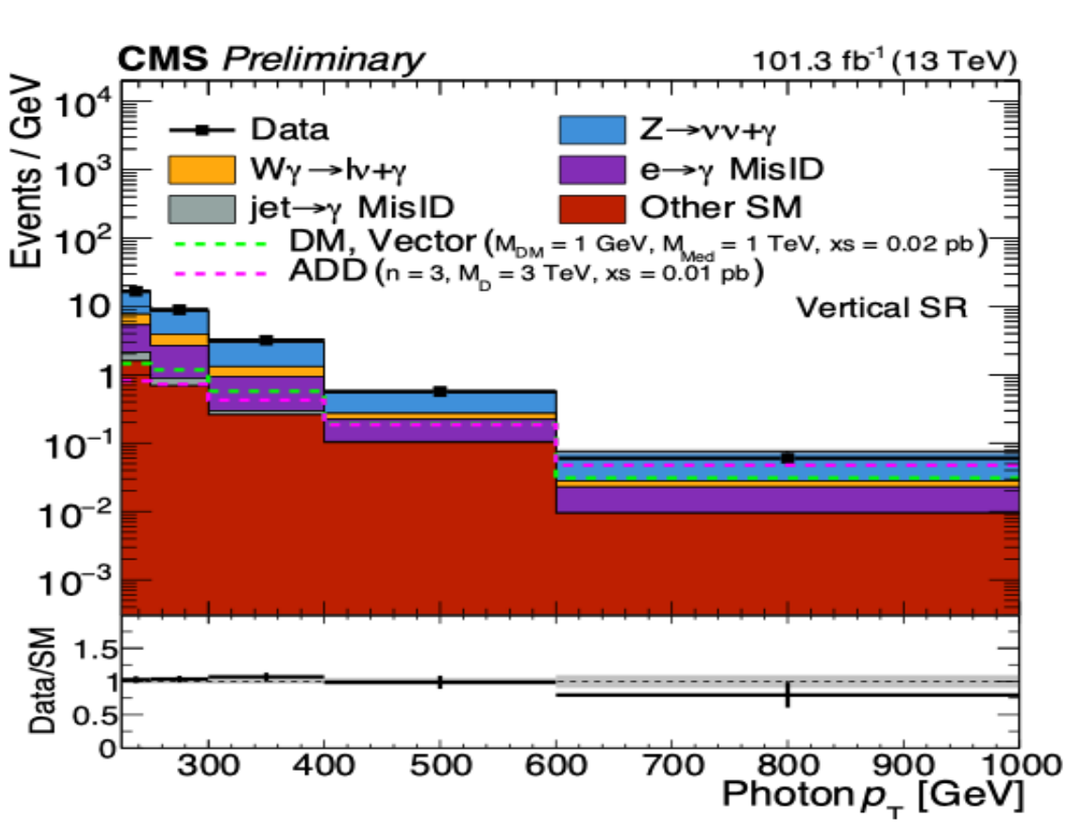
Advantage: Complimentary to Direct Detection(DD) searches

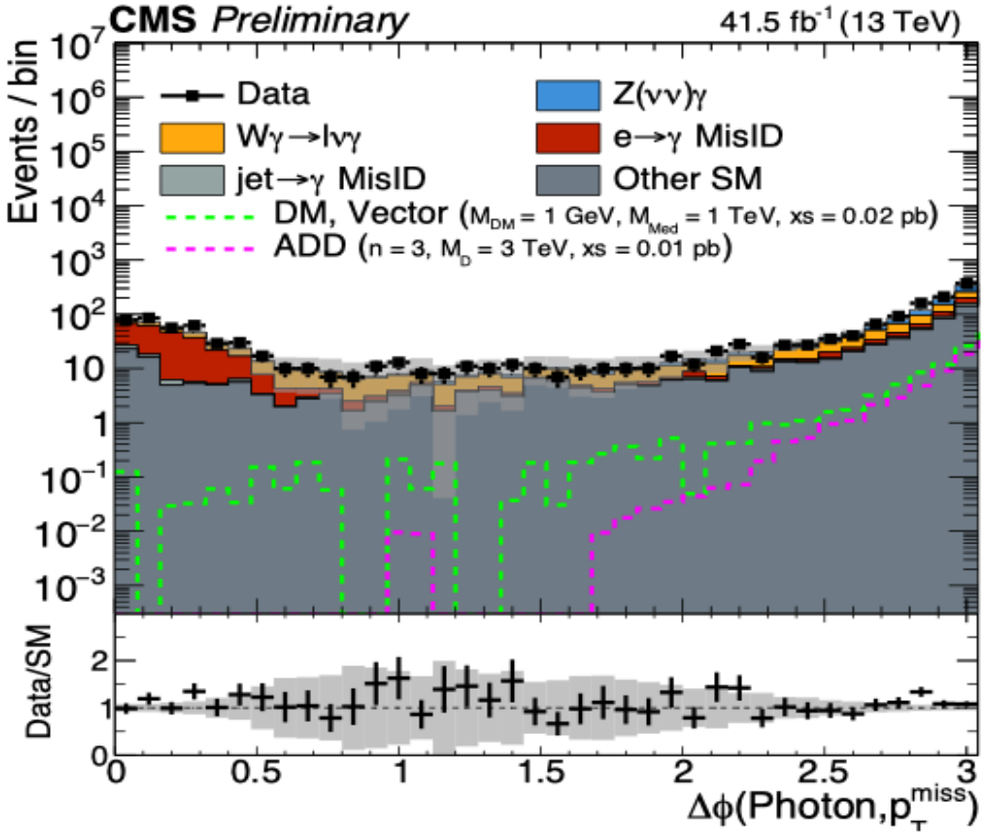
Mono-Photon

SUS-23-016

- **Well known backgrounds**
  - **Z(νν)+γ, W(lν)+γ, instrumental (beam halo), reducible e.g. W+Jets**
- **A lot of state-of the art theoretical work**
  - **NLO EW and NNLO QCD correction to V(W/Z)+jets**
- **Advance analysis techniques using SRs and CRs simultaneous fits**







Mono-Photon: Limits

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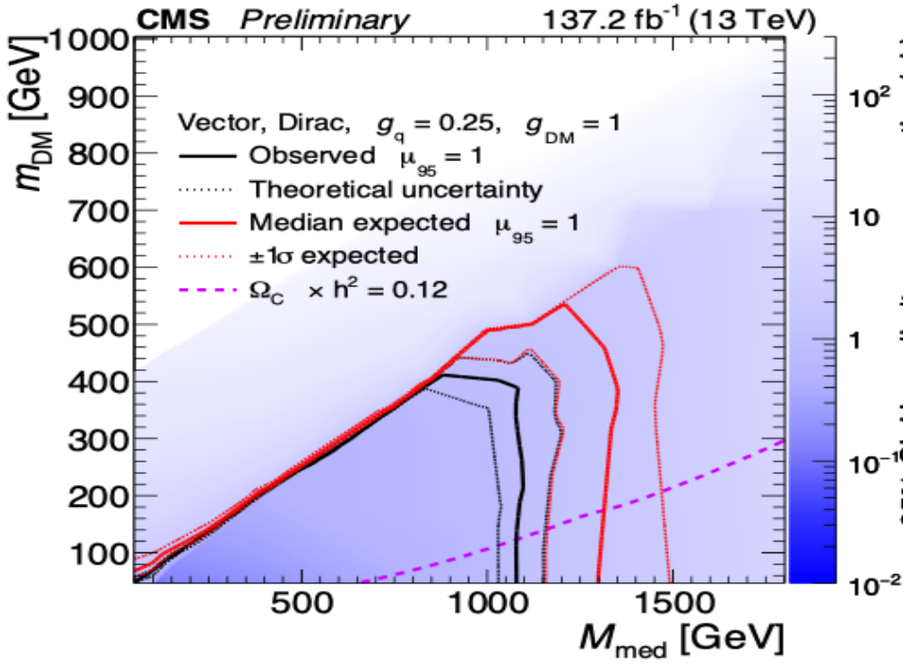
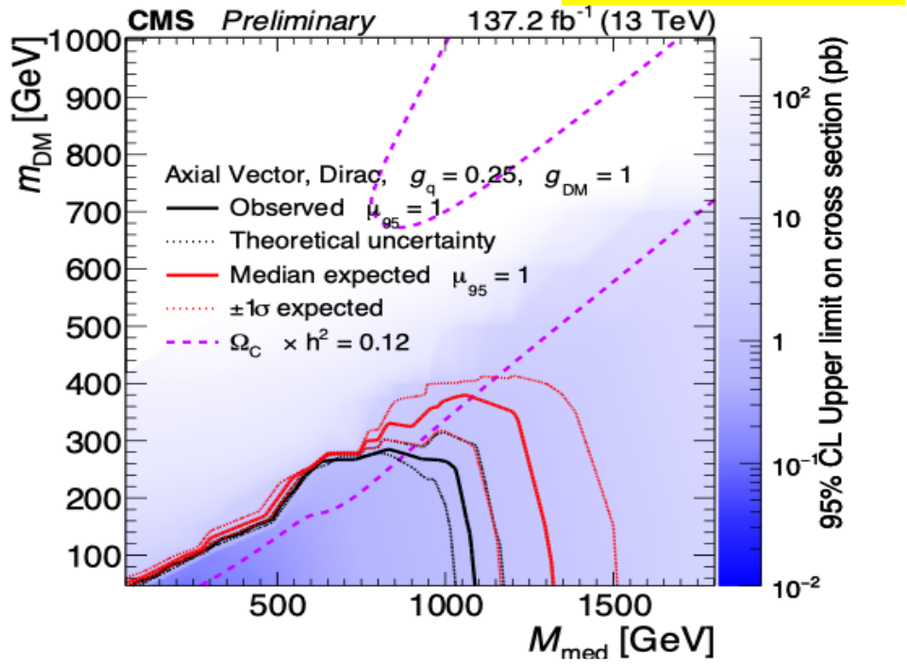
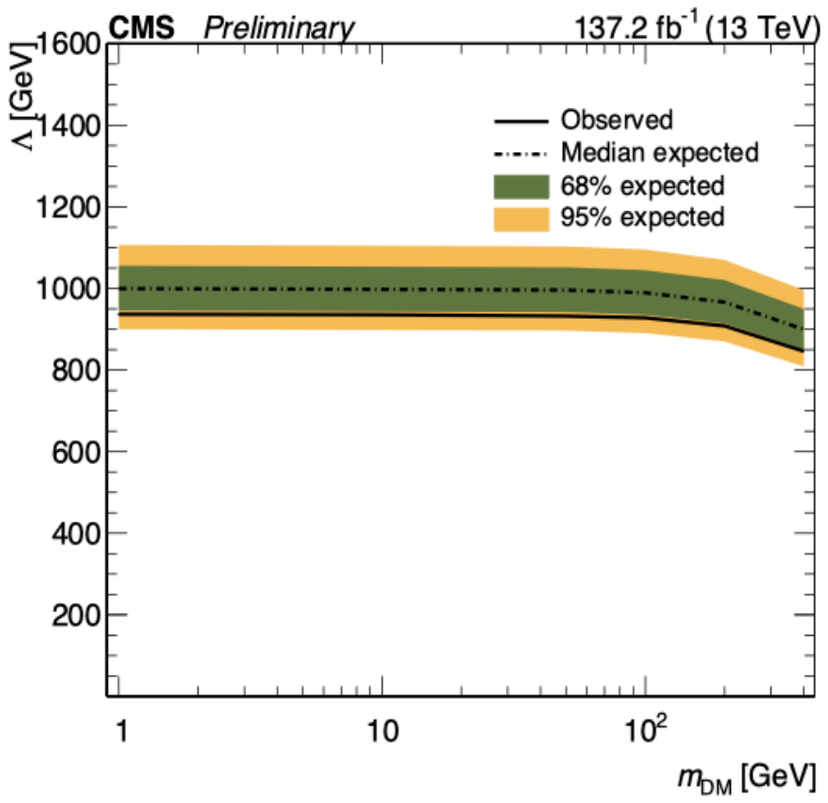
Mediator mass excluded < 1085 GeV for 1 GeV DM mass for both Vector and Axial-Vector case

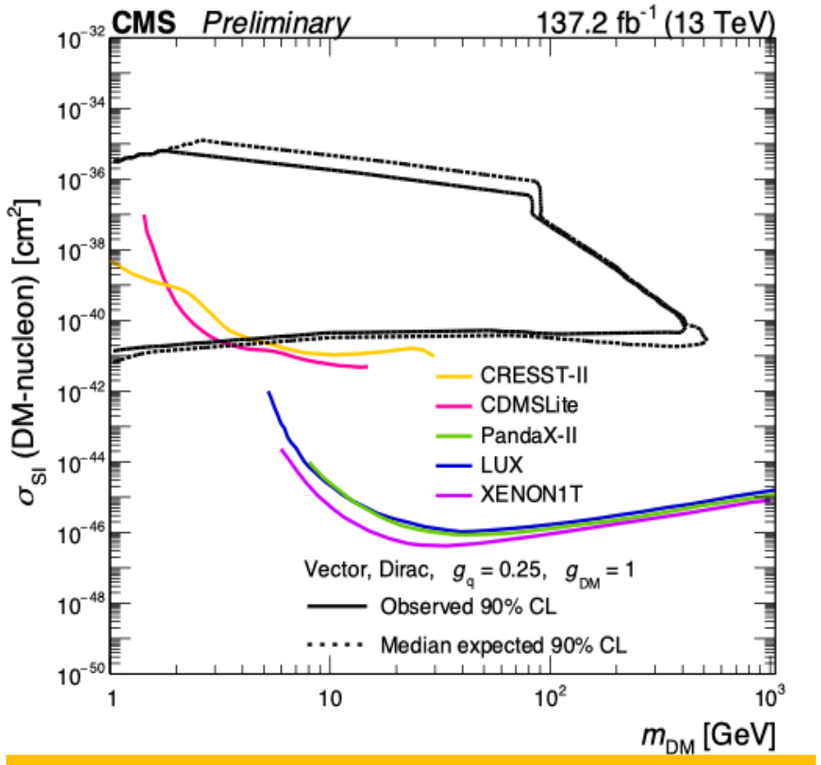




DM-EWK Contact Interaction

Effective Suppression scale Λ excluded up to 937 GeV

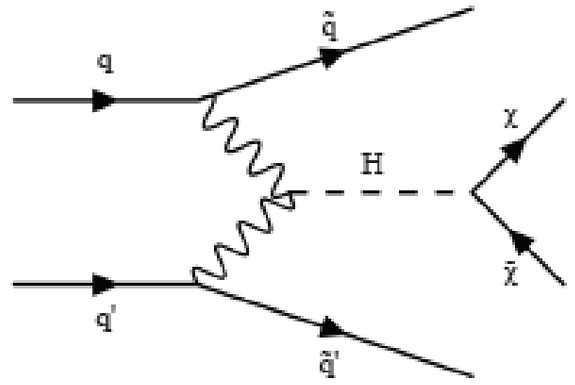




More results in back-up slides

Extended Dark Sector: Higgs + MET

- **Higgs can decay directly to DM particles**
  - **in association of W/Z, or VBF channel**

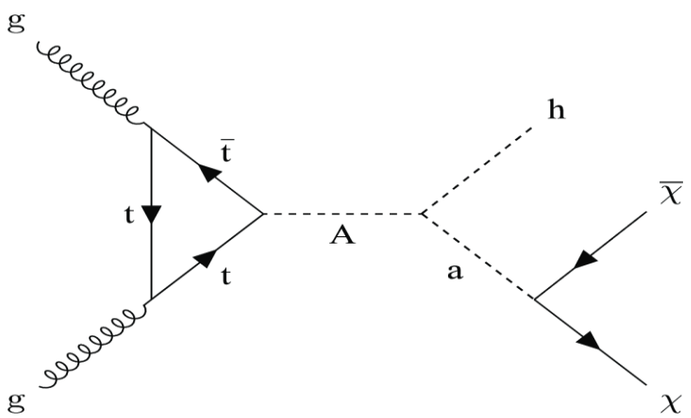


Invisible Higgs decay

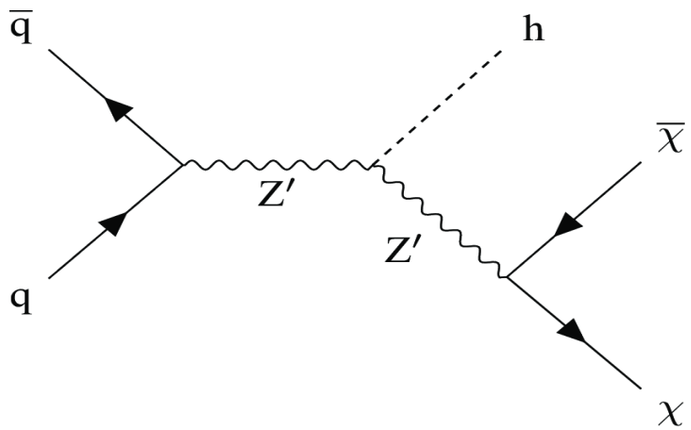
- **Mono-Higgs Searches**
  - **H(bb)+MET** SUS-24-007
  - **H($\tau\tau$)+MET** SUS-23-012

- **Two different processes focused here from extended DS:**
  - **2HDM+a and Baryonic Z' with H → bb/$\tau\tau$**

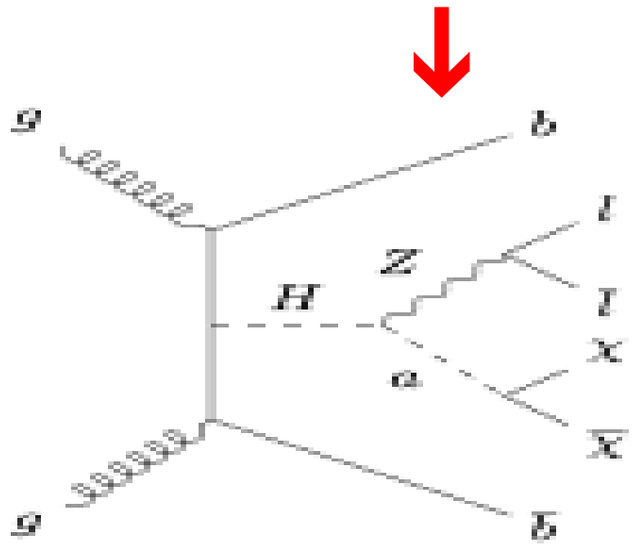
(Not covered here)



2HDM + a pseudo-scalar



Z' Baryonic production



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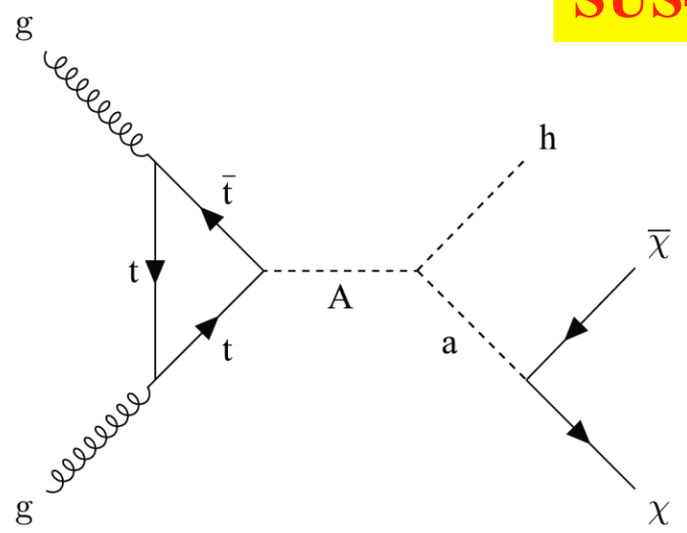
2HDM + a pseudo-scalar

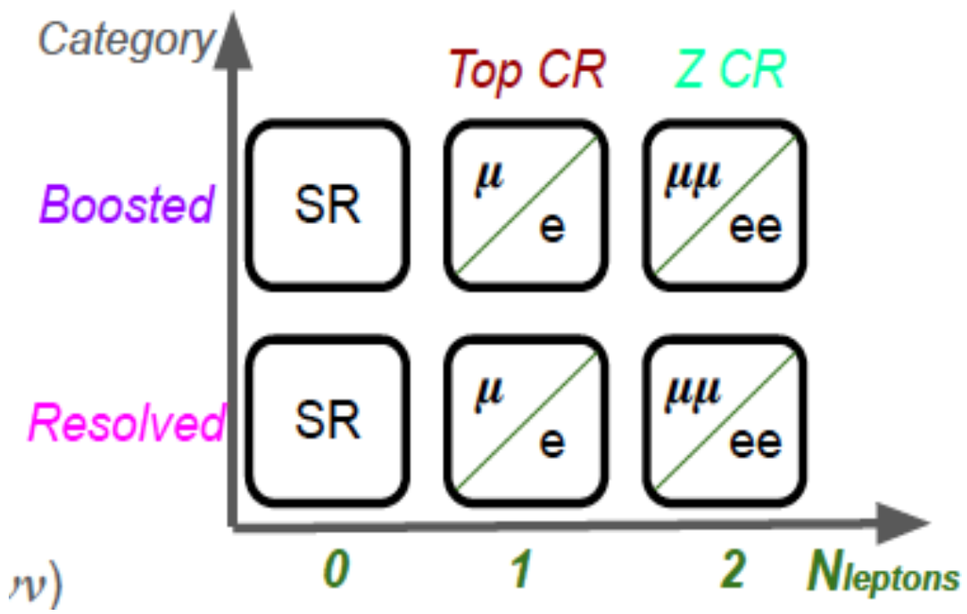
2HDM+a / Z' Baryonic: H(→bb)

SUS-24-007

- **Extension of 2HDM model**
  - **Analysis based on h(bb)+MET final state**
  - **Lepton veto and Photon veto**
- **Main Backgrounds:**
  - **Z+jets, W+jets, ttbar, single top, SM higgs**



- **Dedicated CRs: Bin Likelihood simultaneous fit in SRs and CRs to estimate background**

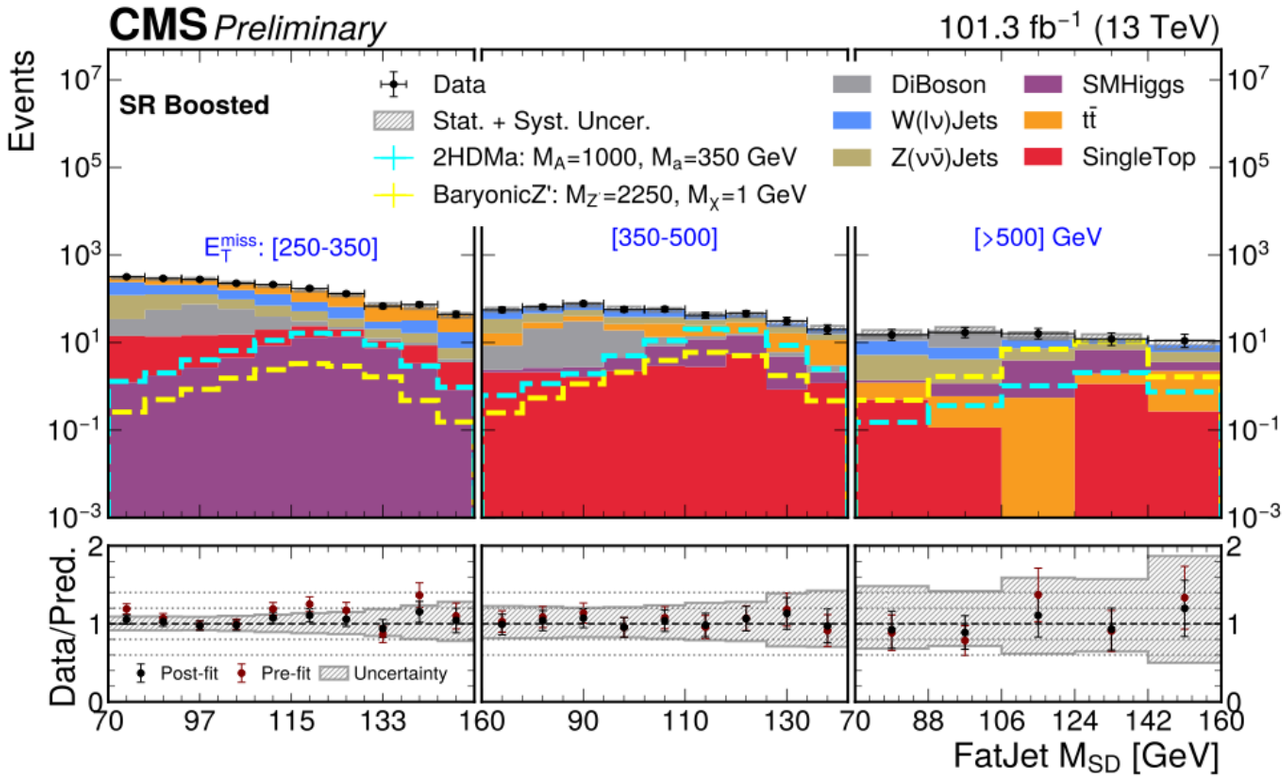


- **Boosted Category**
  - **1 AK8 Jets passing *ParticleNet** with Loose WP**
  - **MET > 250**
- **Resolved Category**
  - **2 AK4 jets with pT> 50 GeV and 30 GeV passing Deep-Jet b-tag discriminator**
  - **MET > 200 GeV, 70 <M_{bb}< 160**

*Phys Rev. D. 101 (2000) 056019 & CMS-BTV-22-001

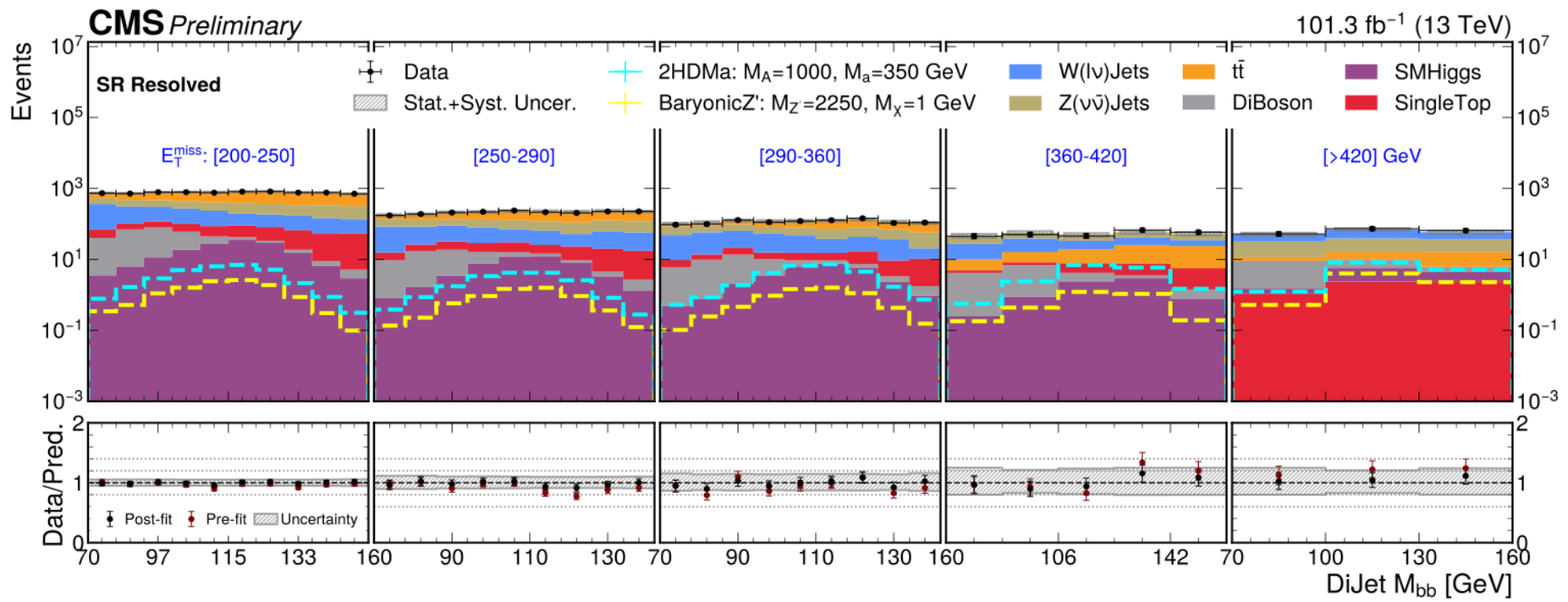
2HDM+a / Z' Baryonic: H(→bb)

SUS-24-007



Boosted Category

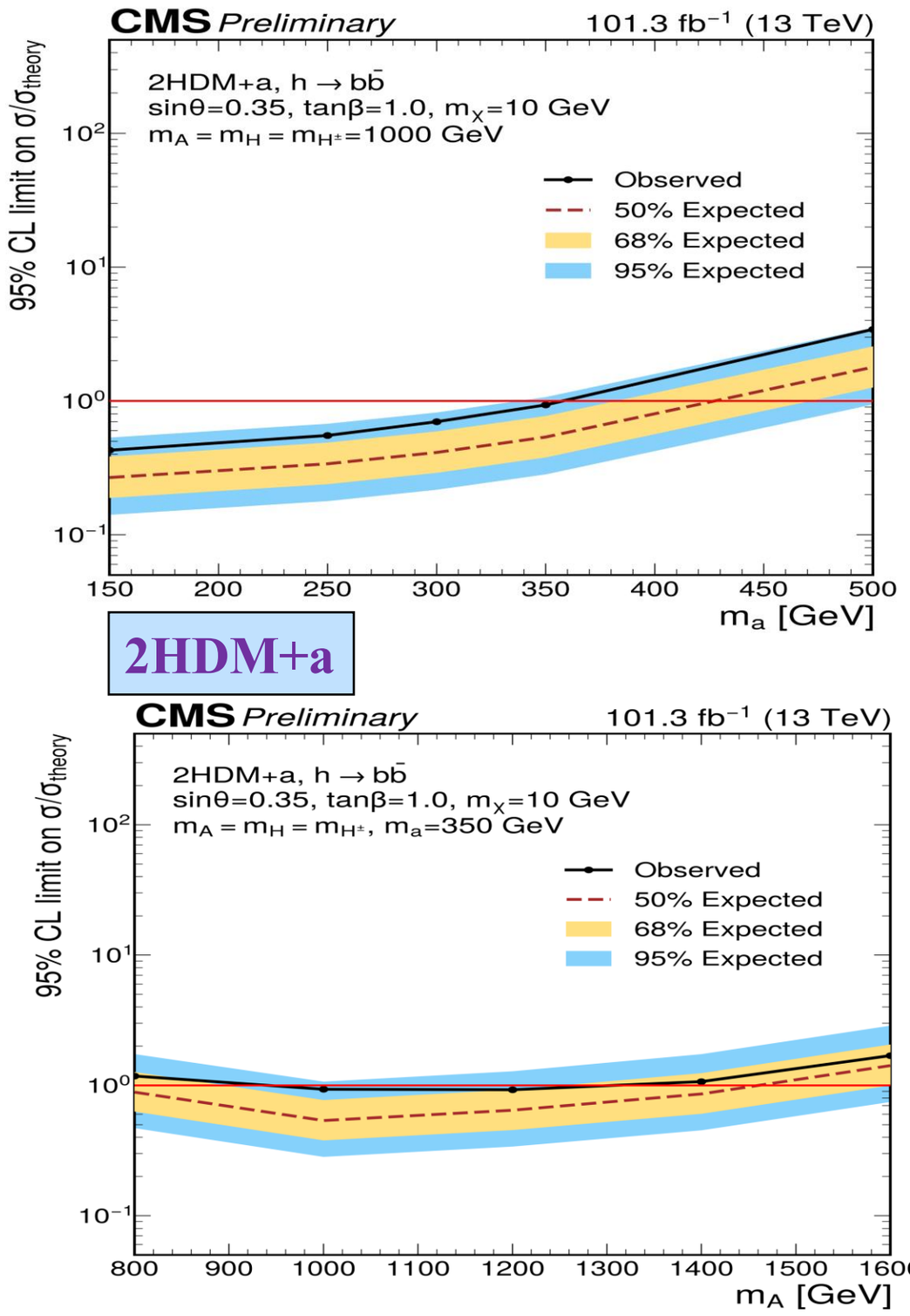
Good agreement of data and background prediction before (pre-fit)and after (post-fit) the simultaneous fit in SRs and CRs



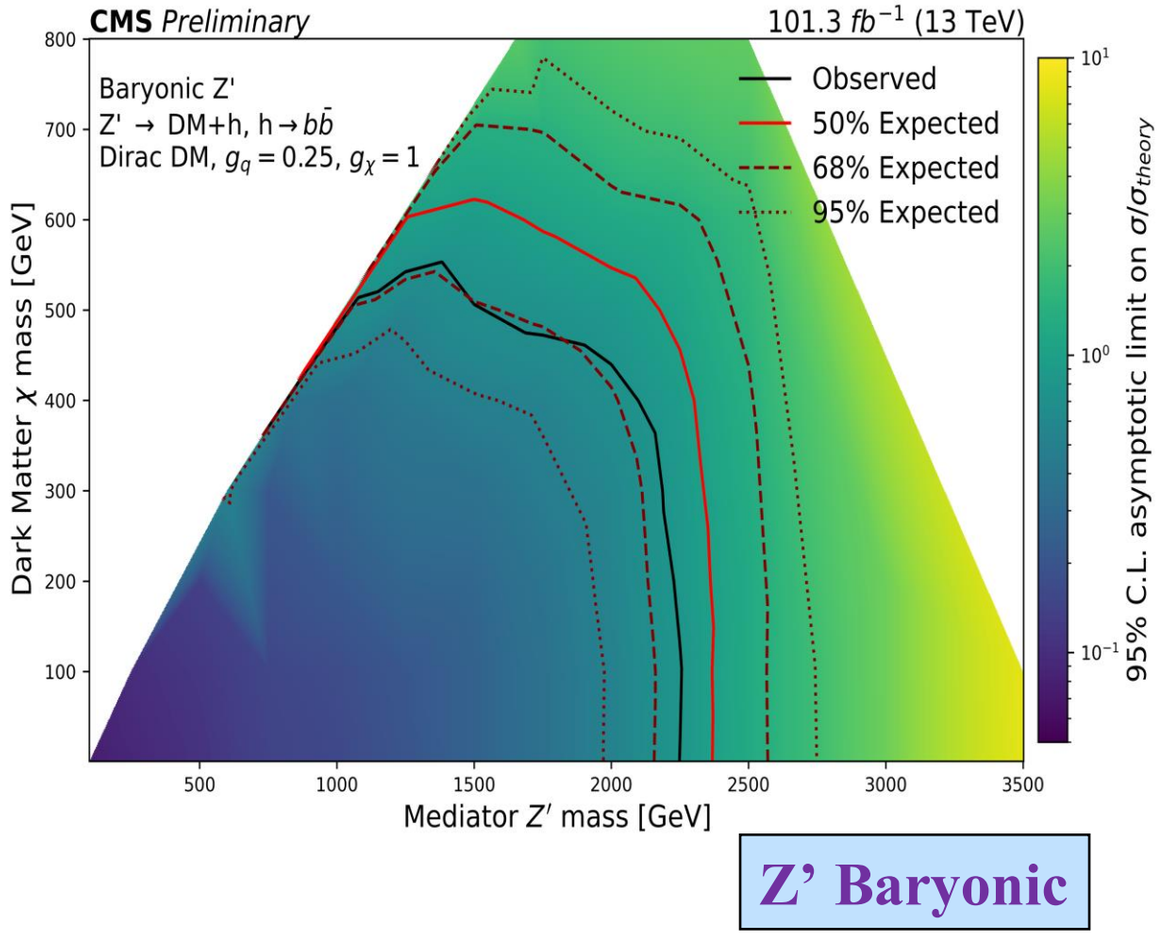
Resolved Category

2HDM+a / Z' Baryonic H(→bb): Limits

SUS-24-007



For 2HDM+a $m_a < 350$ GeV excluded for $m_A = 1$ TeV

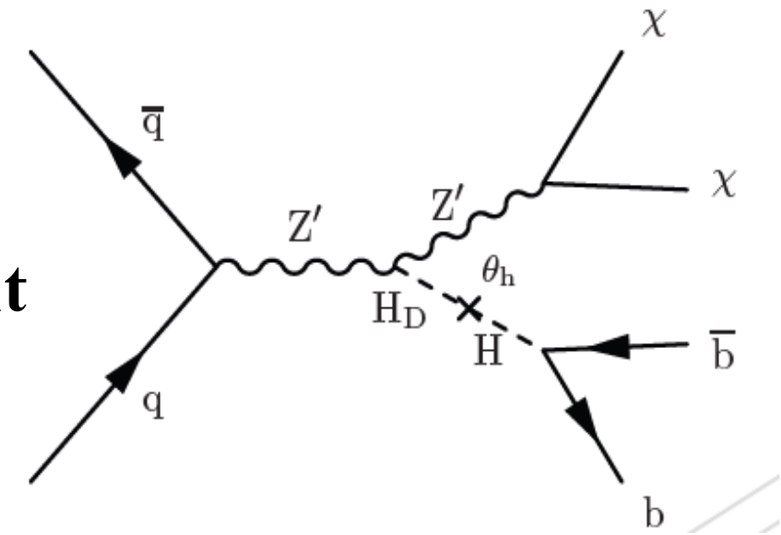


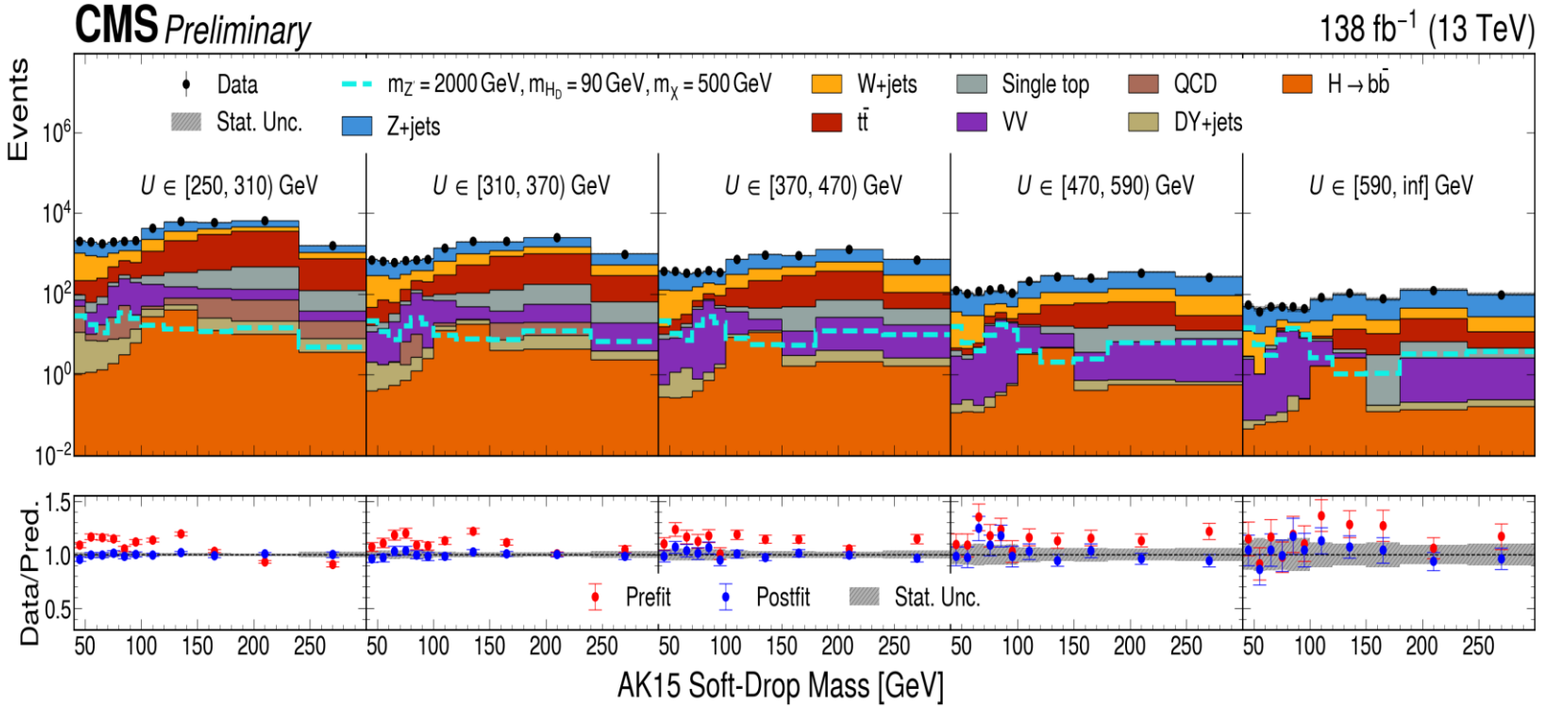
Z' masses are excluded with an observed (expected) limit of 2.10(2.35)TeV for a DM mass of 1 GeV

Dark Higgs: $H_D \rightarrow bb$

SUS-23-013

- **Dark Higgs Model: Lightest state is dark Higgs (H_D)**
  - **H_D mixes with SM Higgs => decay to SM only**
  - **Heavier dark sector particle can radiate H_D**
  - **Focus here m(H_D) < 160 GeV: bb decay dominant**





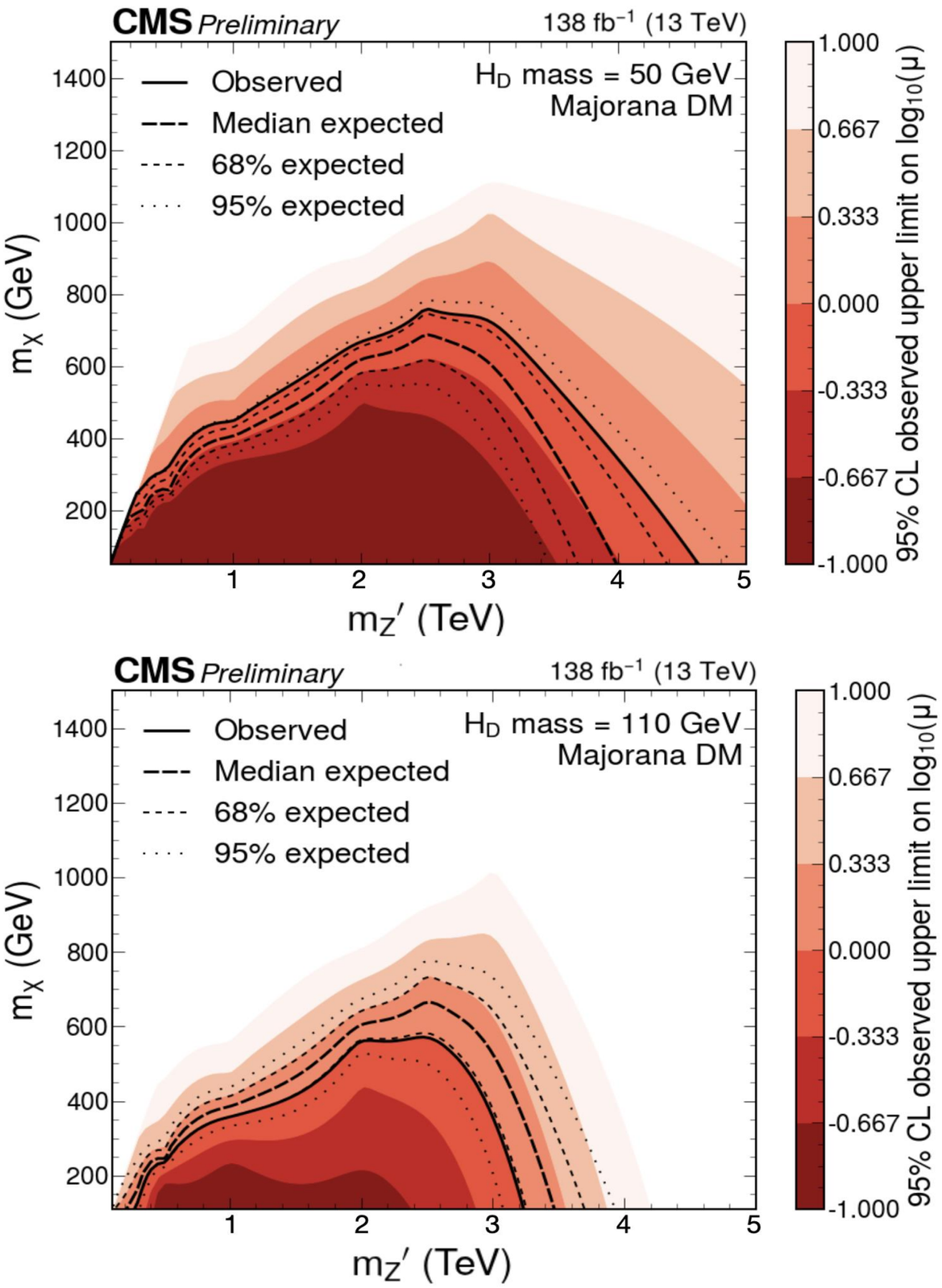
Bins of Hadronic Recoil (U) vs Soft Drop Mass (m_D) is used to extract Signal and background estimation

Analysis Strategy:

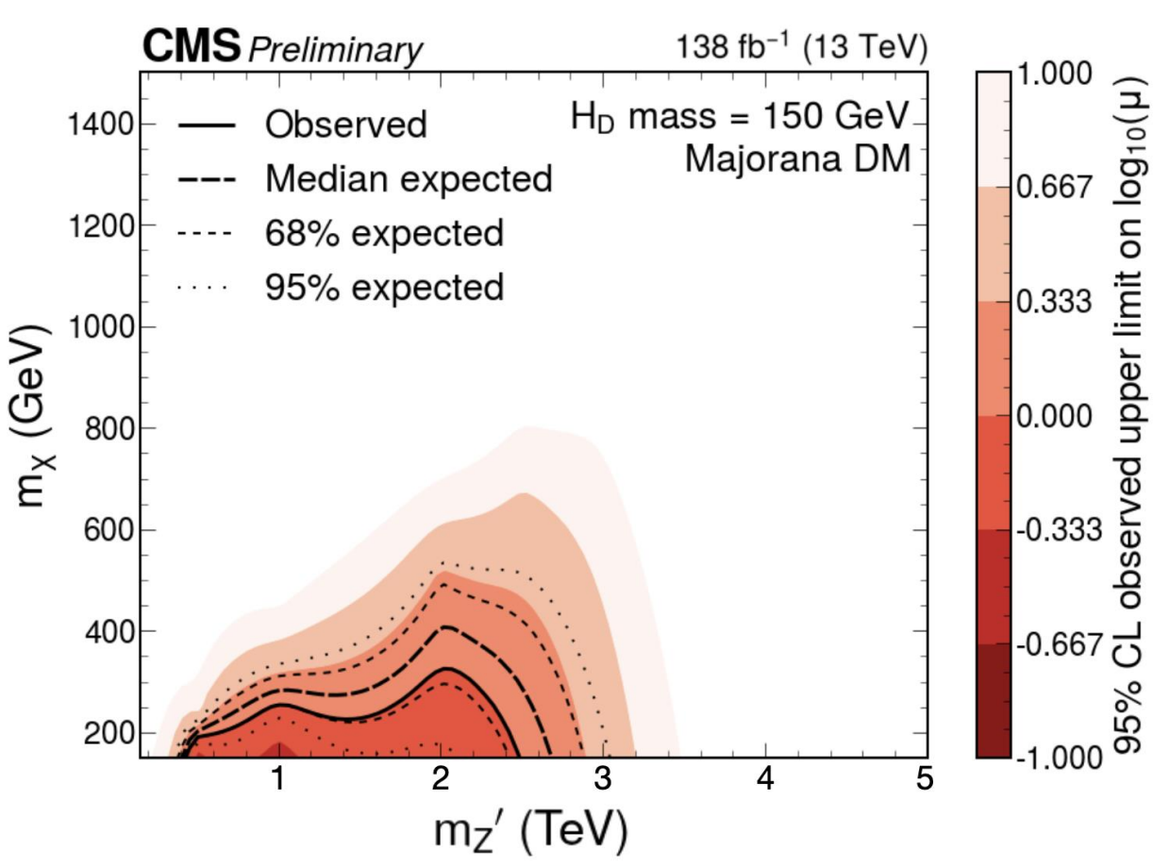
- **AK15 jet with P_T > 160 GeV Identified with deep neural network**
- **Hadronic recoil > 250 GeV**
- **Dedicated CRs to estimate main backgrounds**

Dark Higgs Production: Results

SUS-23-013



Mediator mass up to 2.5 - 4.5 TeV are excluded depending on dark Higgs mass

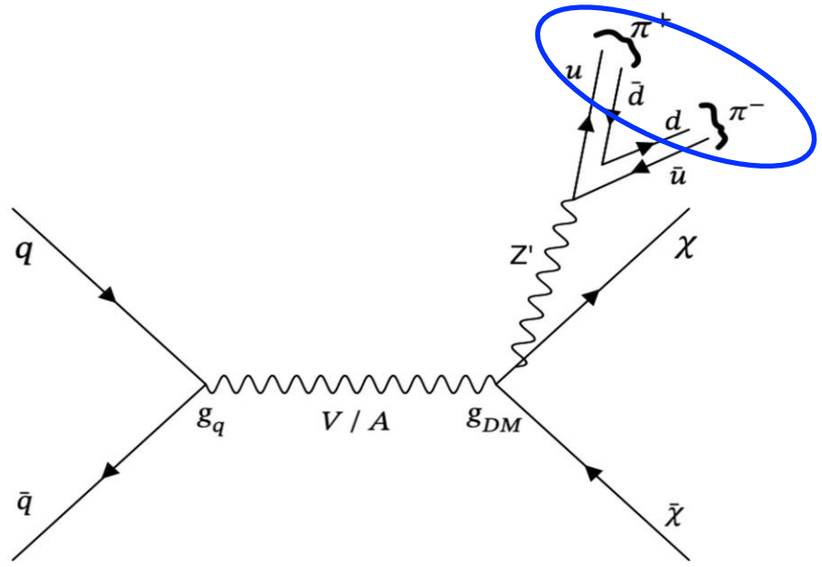


Pencil Jets

SUS-23-017

- Simplified model: DM mass 0.1- 1.0 TeV, ~ 1 GeV scale dark Z decays to light quarks

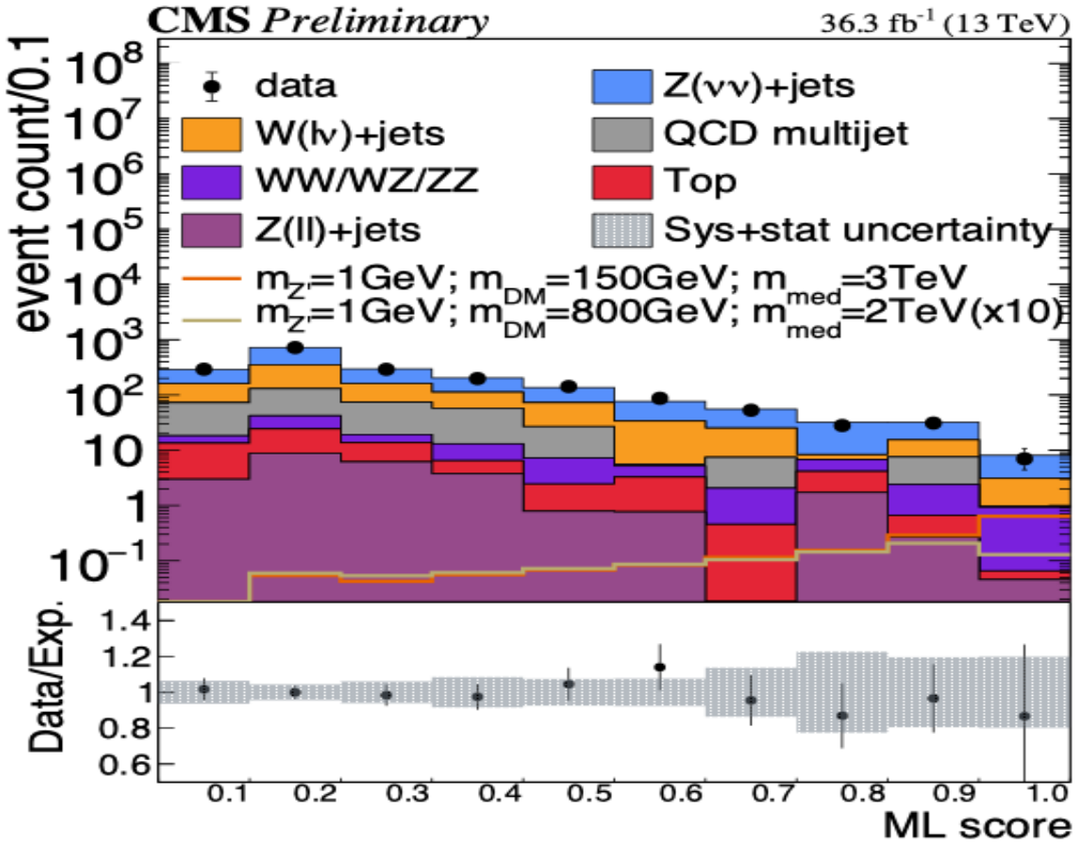
- Pencil Jet: Narrow cone (size < 0.1) with small multiplicity (< 5) of charged hadrons



- $Z(\nu\nu)$+jets, $W(l\nu)$+jets, QCD are main backgrounds

- Supervised ML used to gain sensitivity

- Leading pencil jet P_T > 120 GeV
- Recoil > 250 GeV



Pencil Jets: Limits

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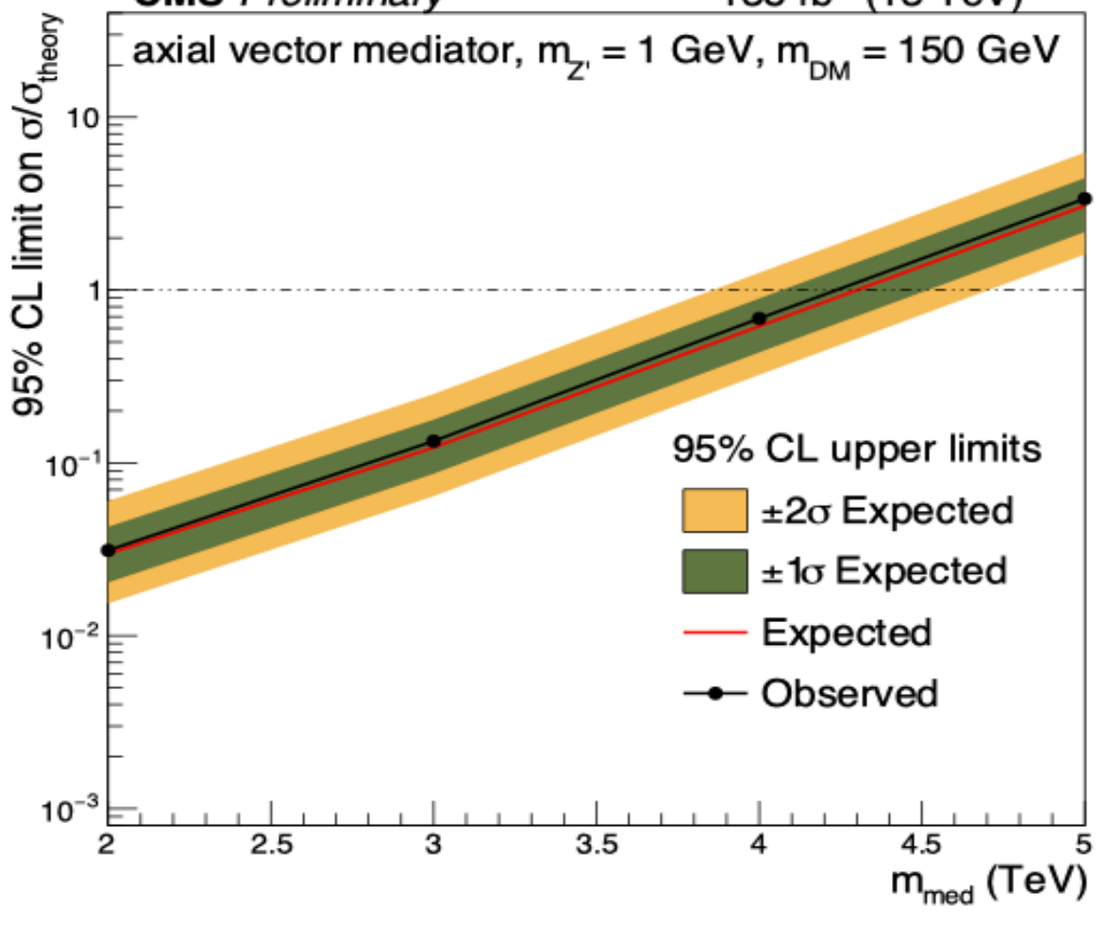
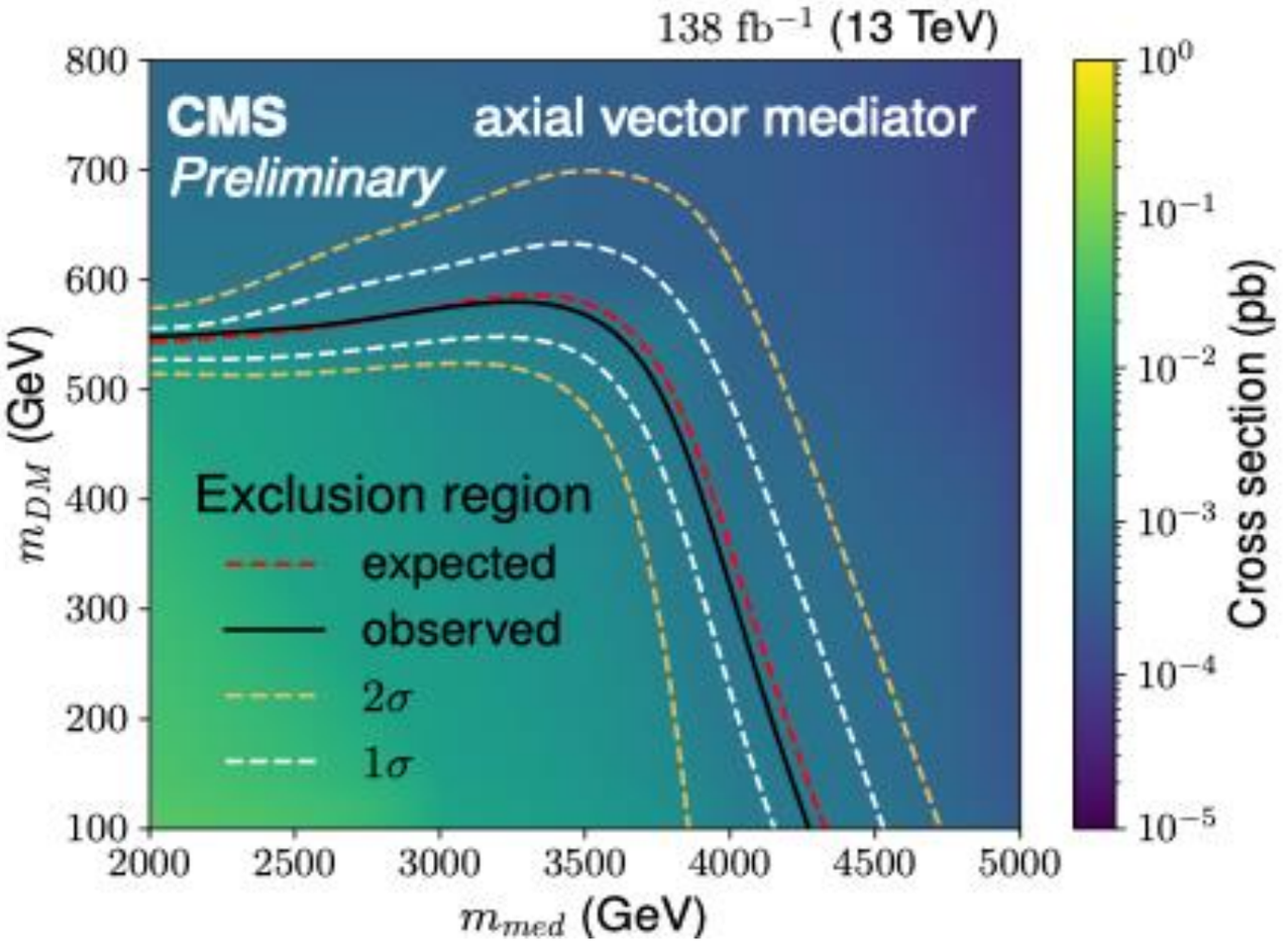
95% CL limits are placed on upper cross section for range of DM and Mediator masses





Mediator masses up to 4250 (3500) GeV are excluded for DM mass of 100 (550) GeV

More results in back-up slides

Summary & Outlook

- **Extensive and broad Dark Matter search program at the CMS experiment**
- **Update with full Run-2 data on conventional searches**

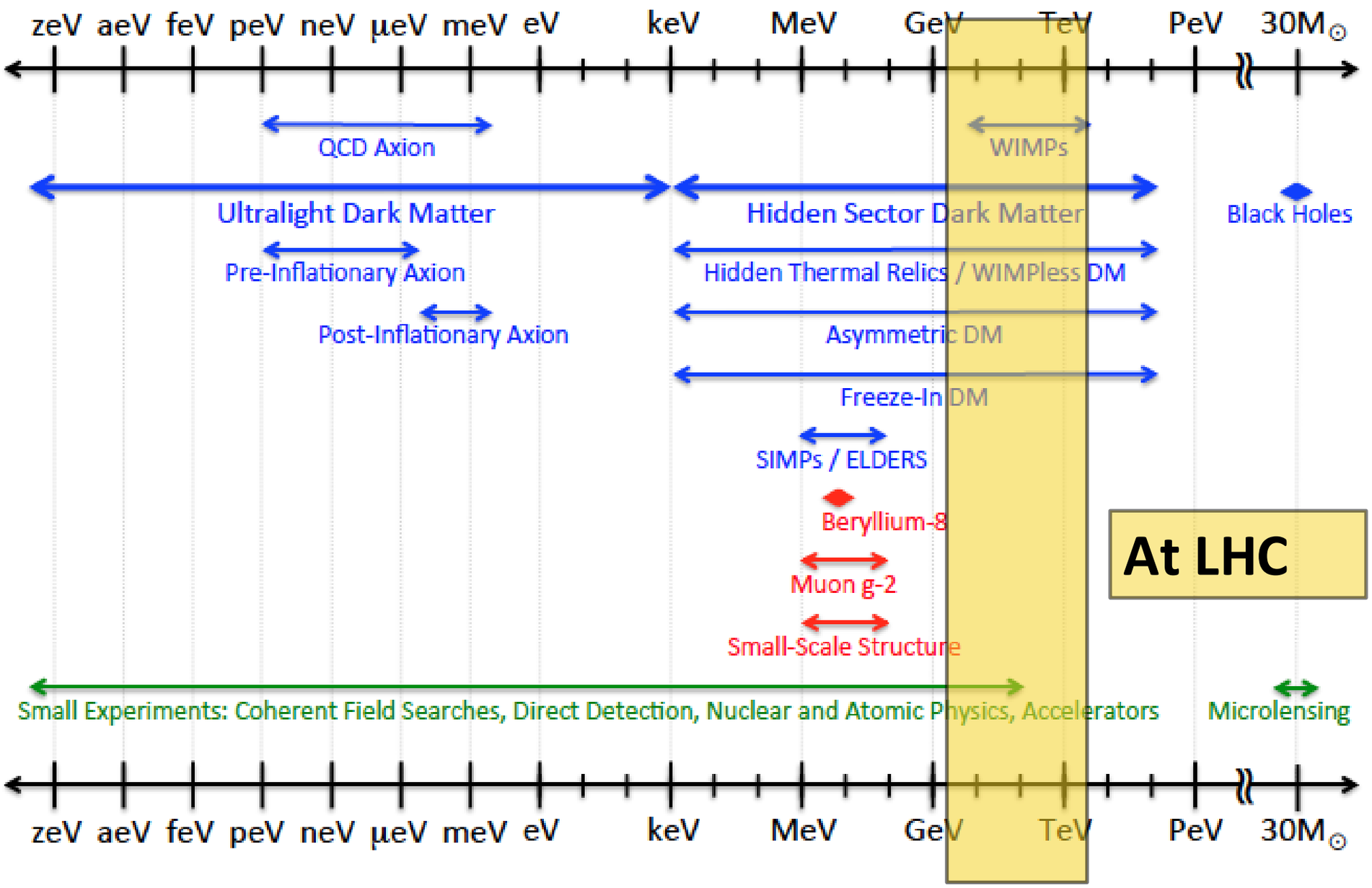
- **Top and Higgs are being further explored with additional final states particles**

- **Stay tuned for new results from CMS Run-3, and full Run-2 data**


Thank You!!

Dark Matter Search: Big Picture

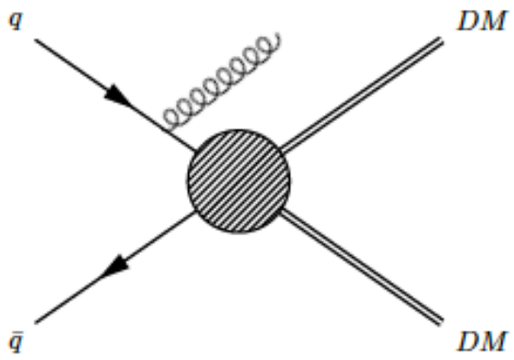
arXiv:1707.04591

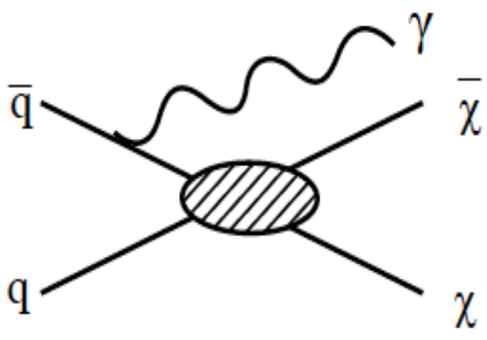


LHC a prime lab for production of DM in pp collision

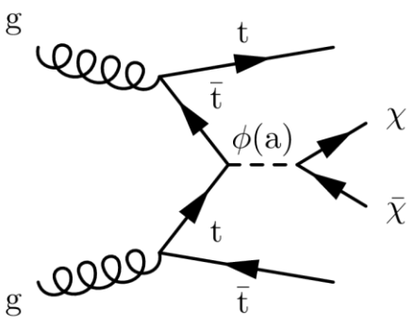
Large MET+X (photon, jet, leptons)

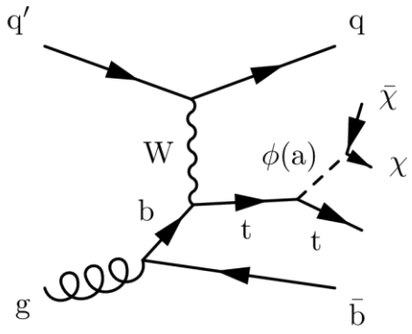
Mono-X(X=γ/jet/W….)

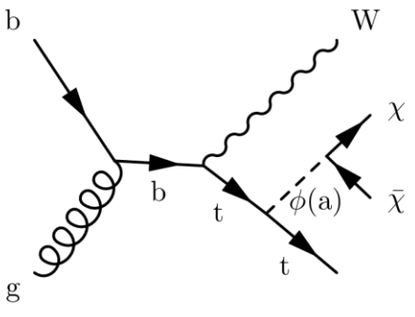


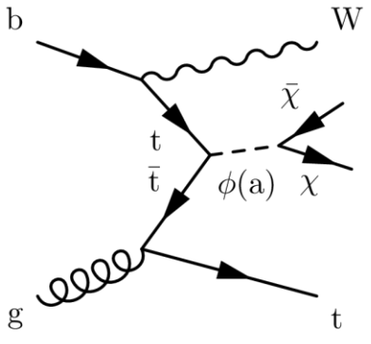


Mediated by virtual t-channel and virtual s-channel

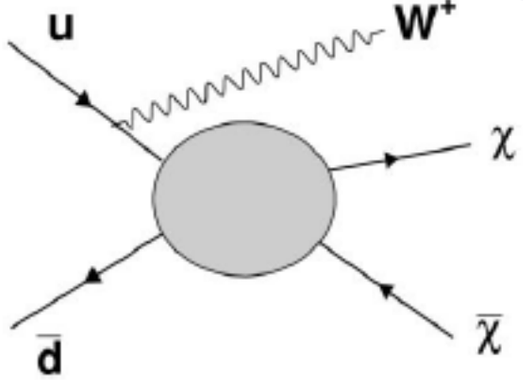


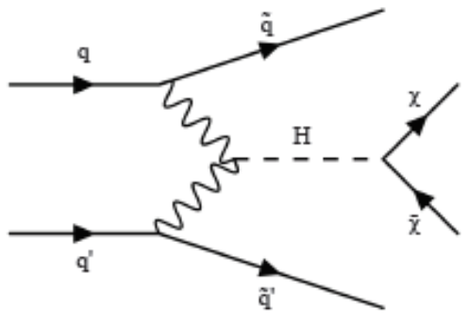


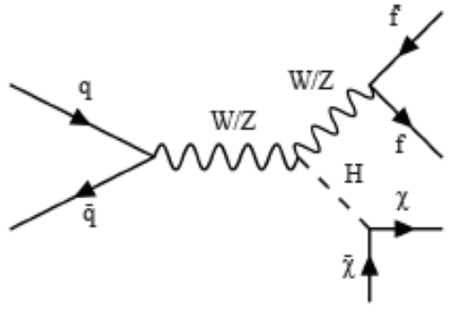




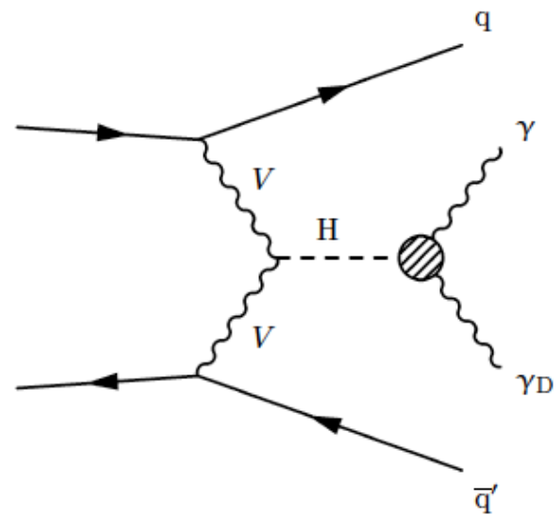
Higgs -> Invisible



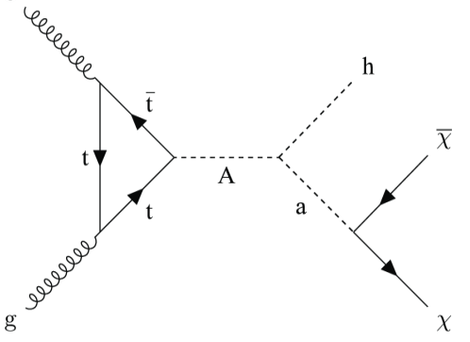




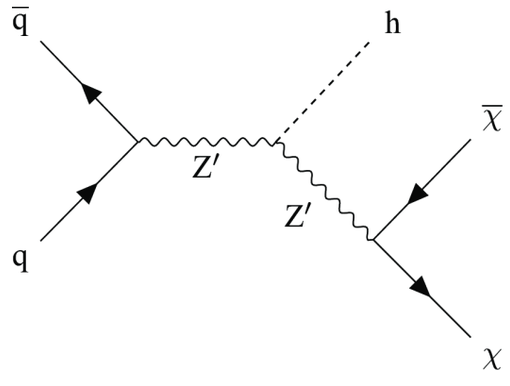
Dark Photon



2HDM + a pseudo-scalar

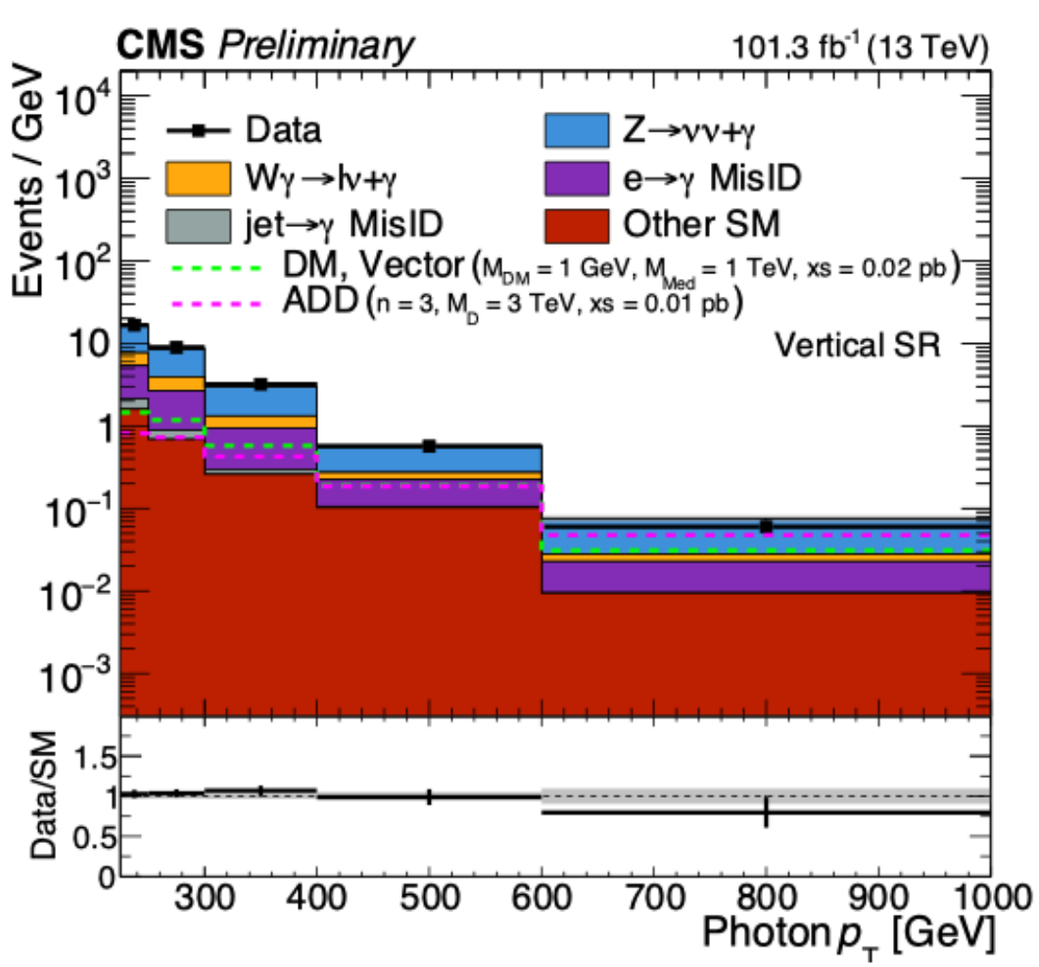


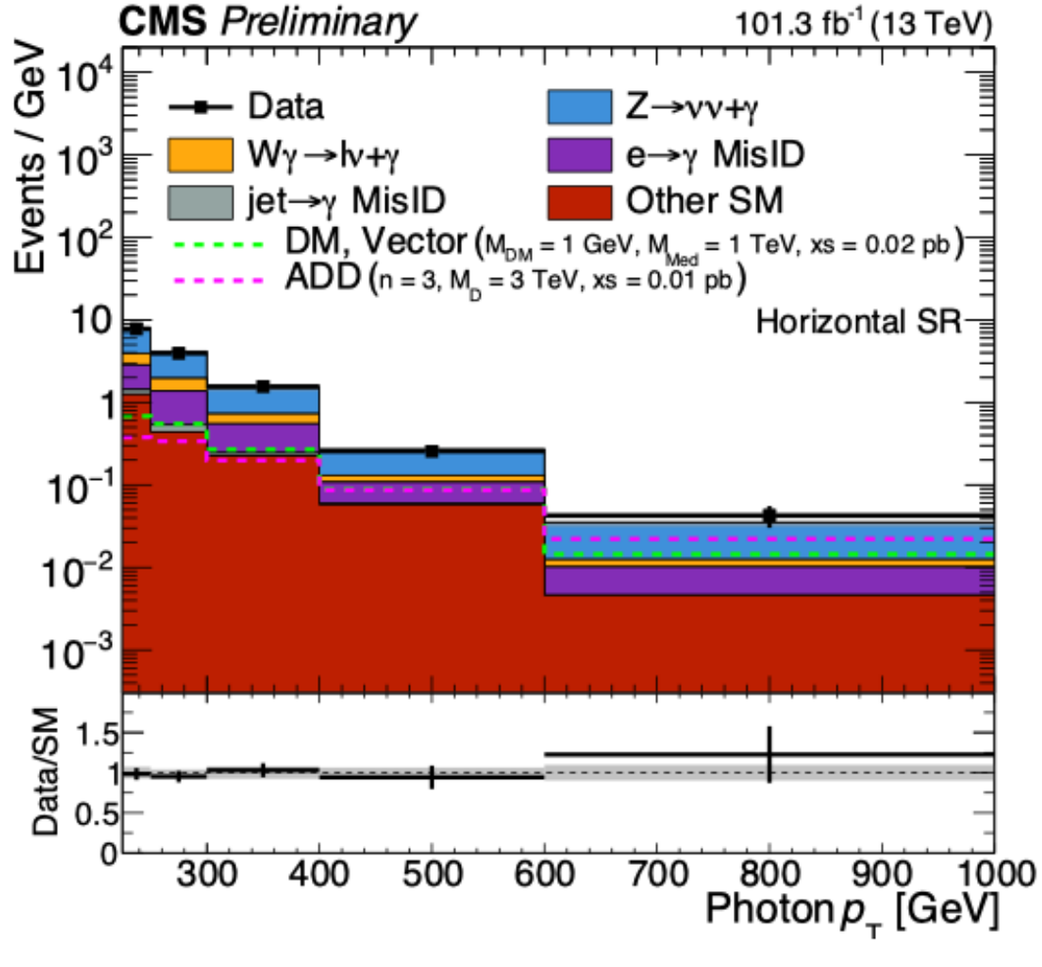
Z’ Baryonic production



Mono-Photon: Phase Space

Category	SR
Trigger	$E_T^\gamma > 200$ GeV
Photon Requirement	$E_T^\gamma > 225 GeV$, $\lvert\eta\rvert < 1.4442$
MET Requirement	$p_T^{miss} > 200$ GeV
Angular Separation	$\Delta\phi(\gamma, p_T^{miss}) > 0.5$
Jet Requirement	$\Delta\phi(jet, p_T^{miss}) > 0.5$
γ+Jets Suppression	Photon E_T^γ / $p_T^{miss} < 1.4$





Mono-Photon: Limits

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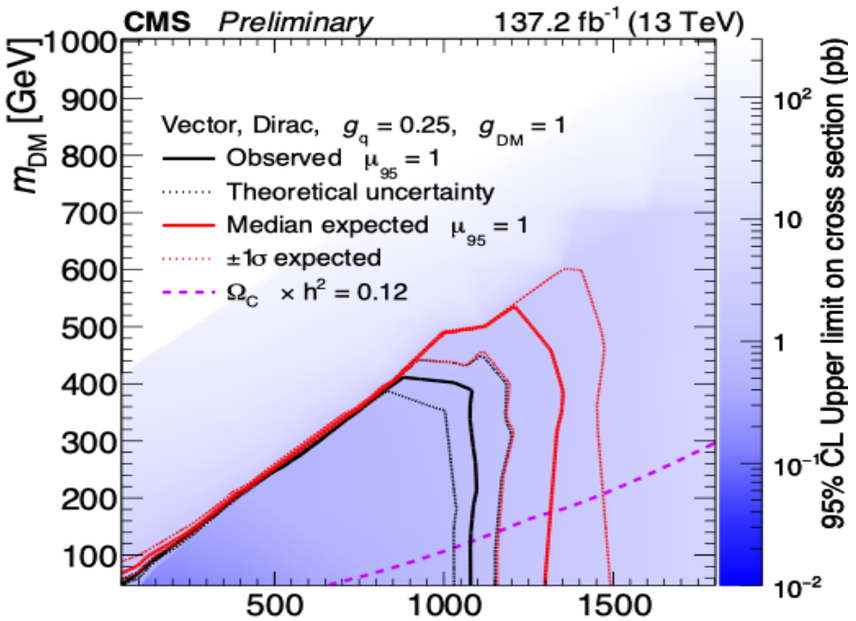
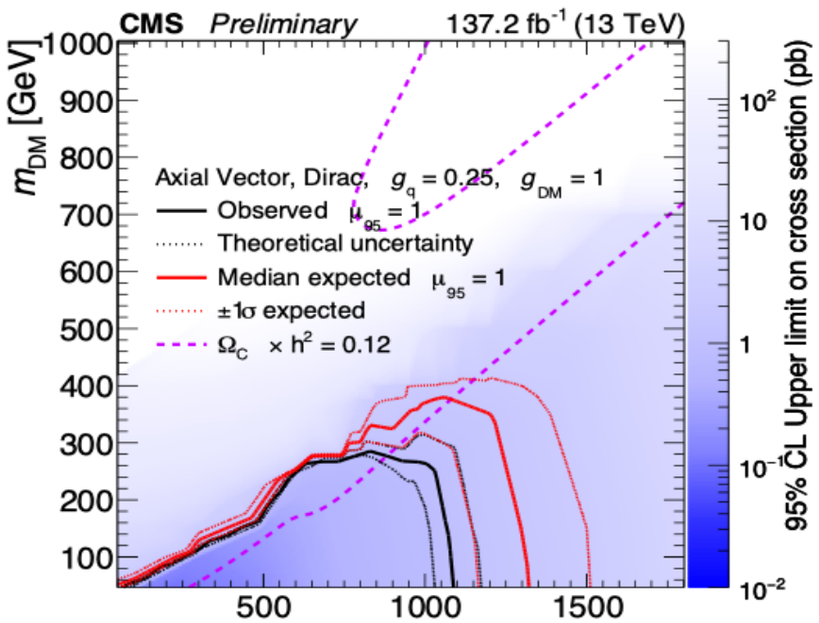
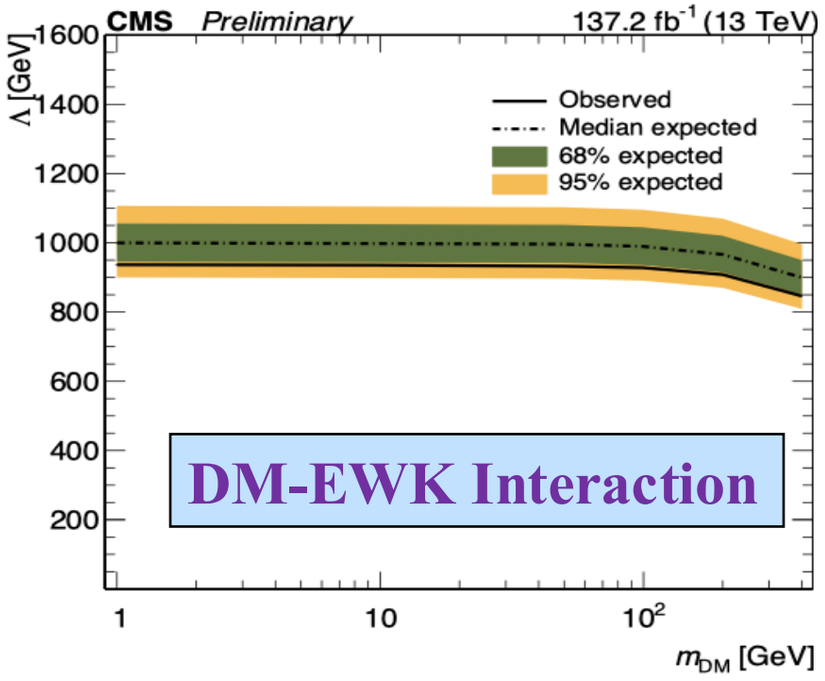
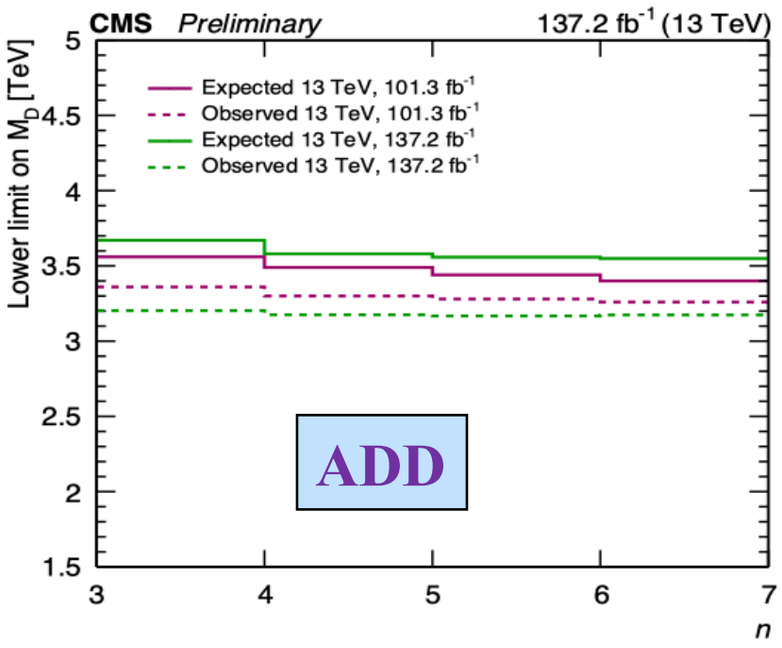




SUS-23-016

Additional interpretation for ADD Model and Contact Interaction between EWK and DM sector





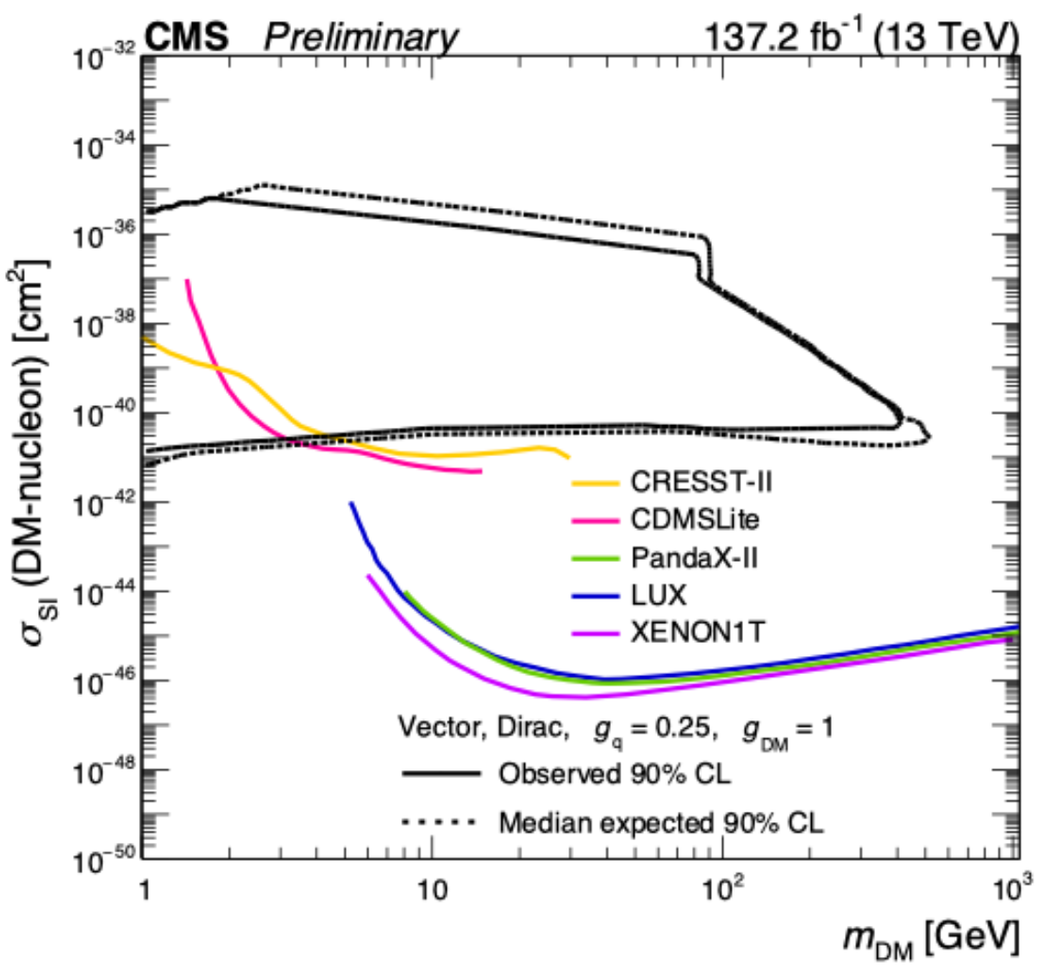
Effective EWK-DM contact interaction: Suppression scale excluded up to 937 GeV

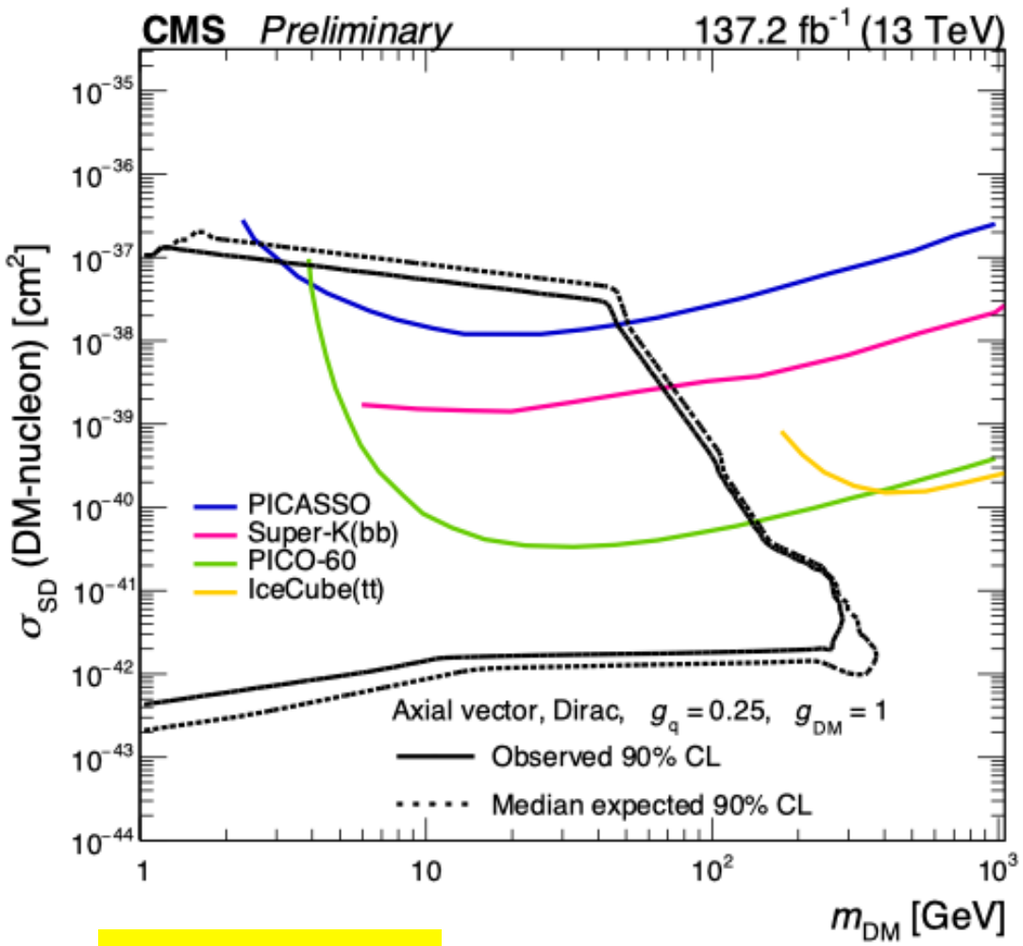
ADD Model: Effective Plank scale excluded up to 3.17-3.20 TeV (for n=3-6)

Mono-Photon: Complementarity with DD

Collider experiment and DD

- **Complement each other as phase space explored are not exactly same**
- **Contour on the upper and to the left of curve are excluded for collider**





SUS-23-016

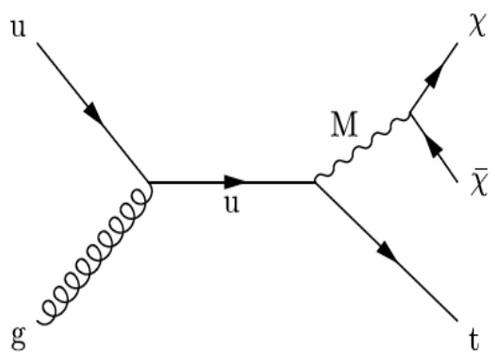
top +MET

arXiv:2503.20033

SUS-23-004

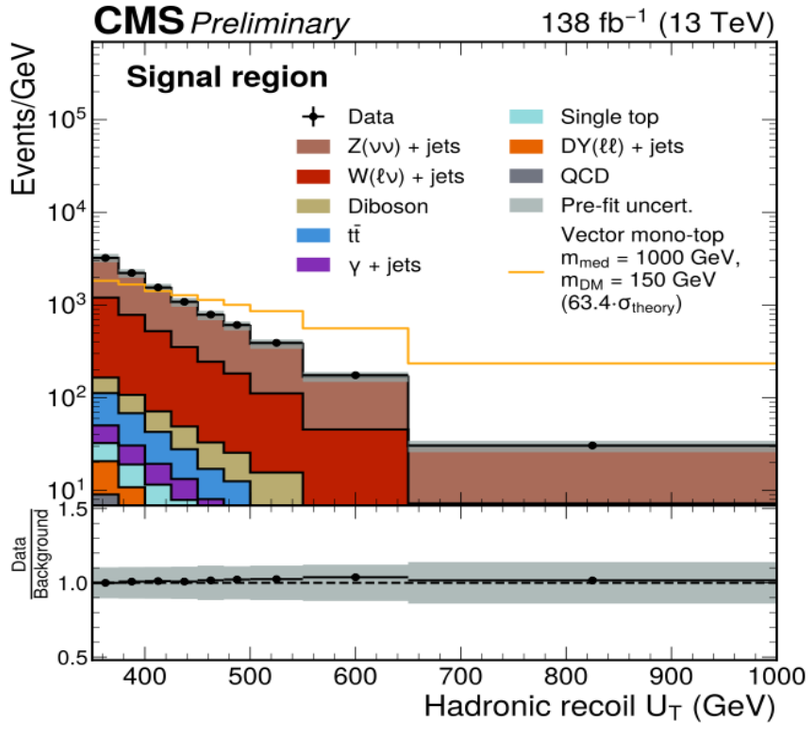
- Simplified model: Mono-top production at tree level via FCNC
- Neutral spin-1 Mediator M decays to DM candidate

- Z($\nu\nu$)+jets, Z(ll)+jets, and W(lν)+jets most prominent background. Other includes t-tbar, QCD di-boson
- At least one AK15 fat-jet are used with pT > 250 GeV
- Hadronic recoils > 350 GeV
- $\Delta\varphi$ >1.5 between hadronic recoil and AK15 fat-jet



Discriminator based on *ParticleNet is used to distinguished between AK15 jet from hadronic decay of top and QCD jet**

- Many CRs to estimate yields for different background processes based on top tagger pass/fail
- Transfer factor are used to determine major background in SRs



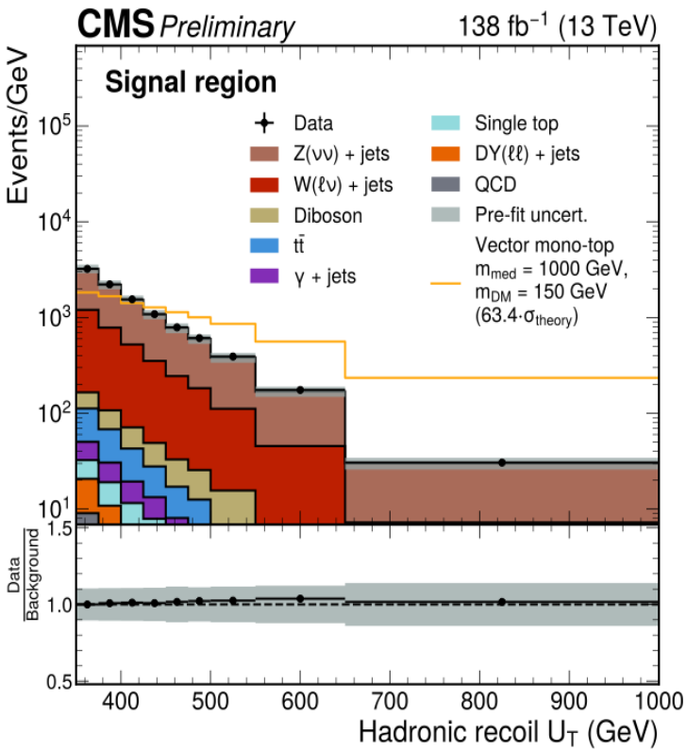
*Phys Rev. D. 101 (2000) 056019 & CMS-BTV-22-001

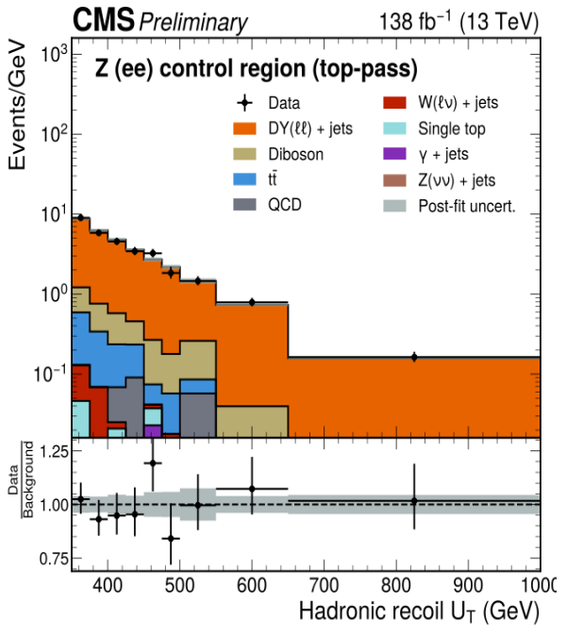
top +MET: SRs and CRs

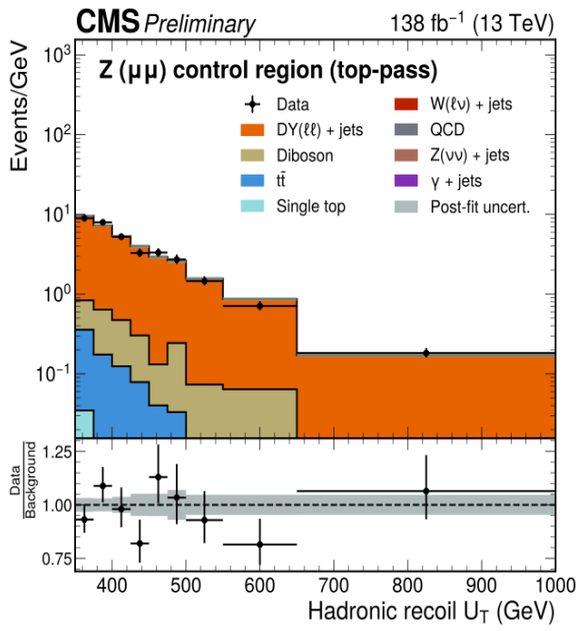
SUS-23-004

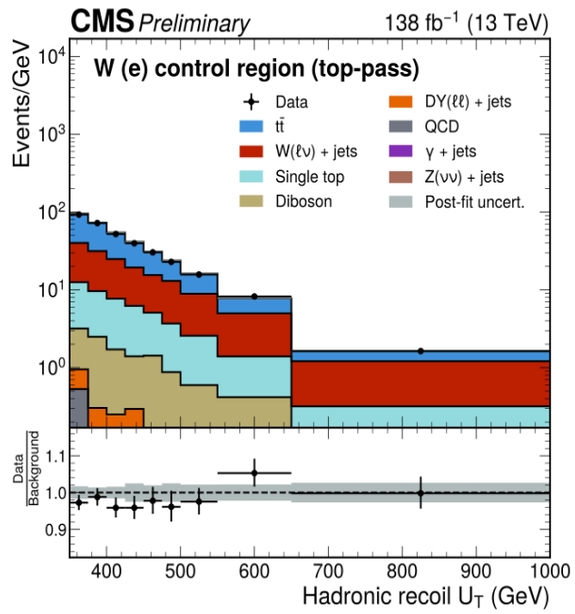
arXiv:2503.20033

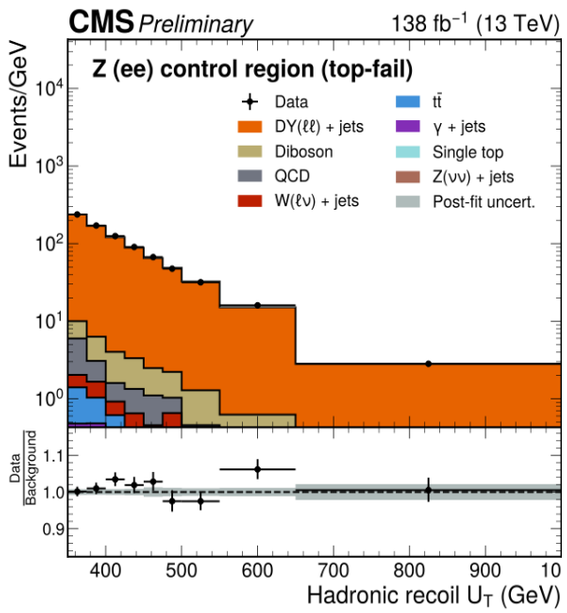
Good agreement between data and prediction in all CRs and SR

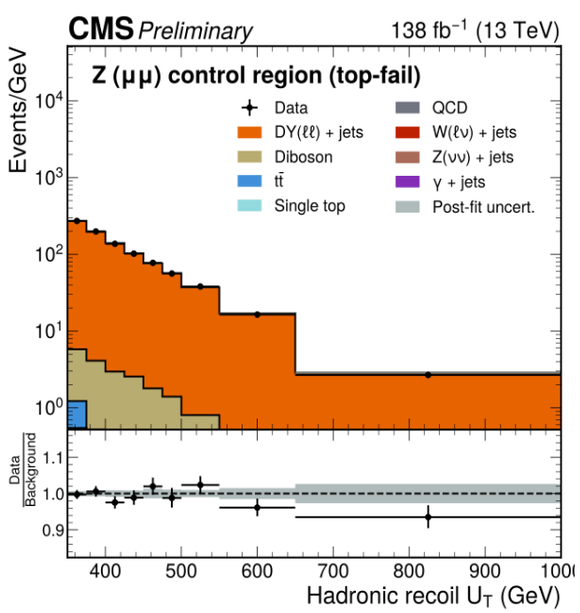


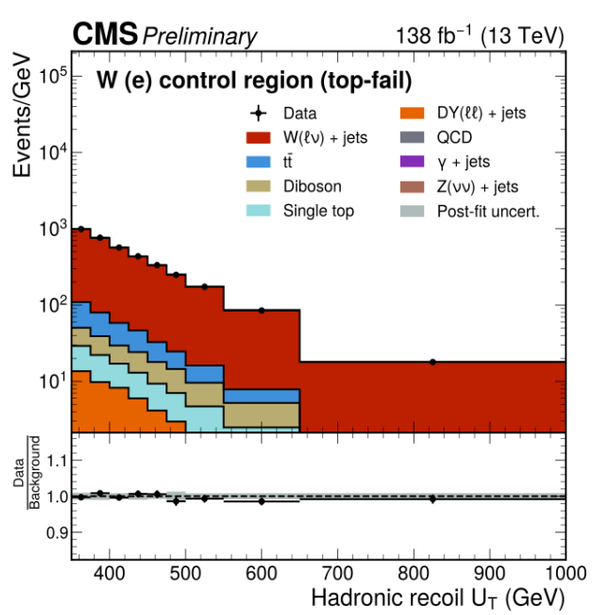












SRs

CRs

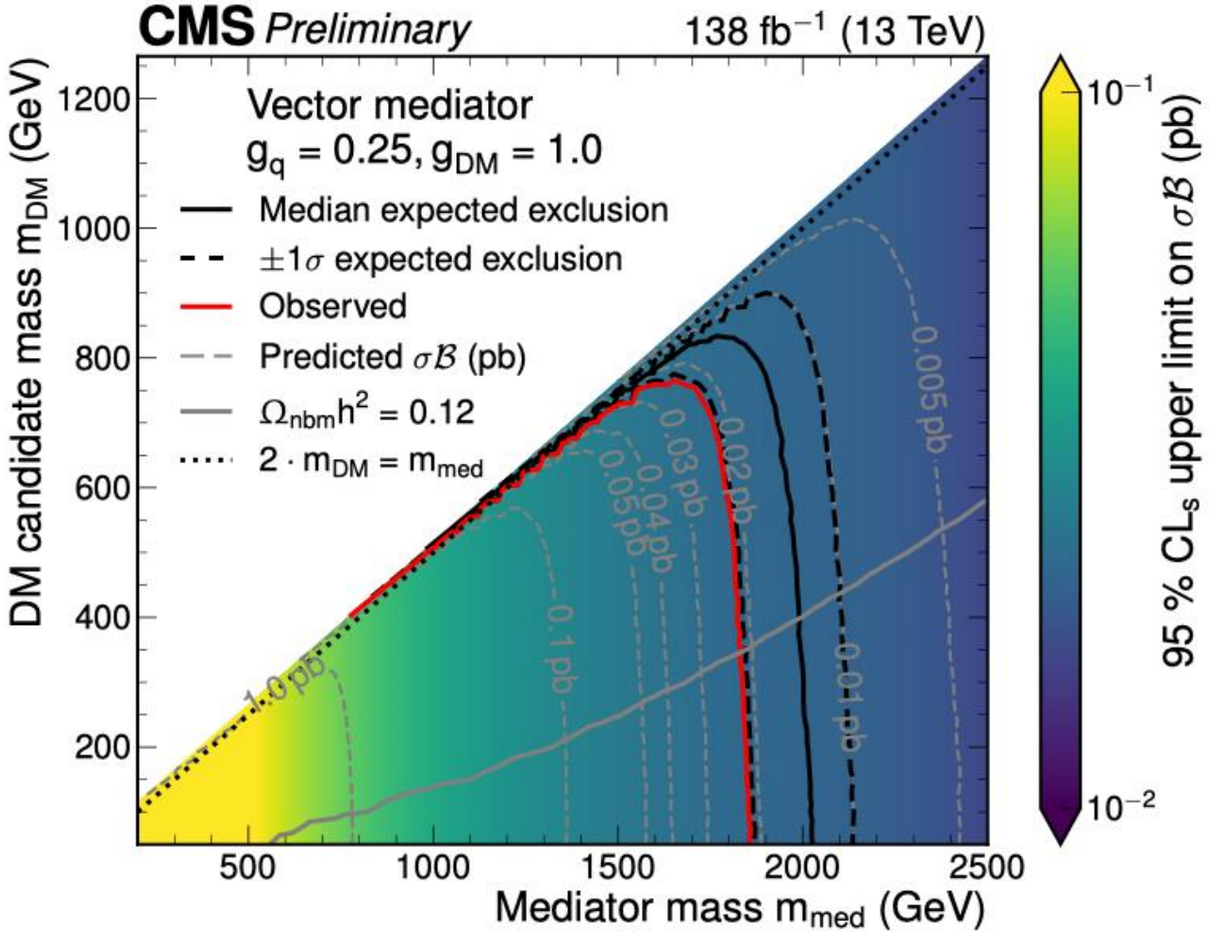
top +MET: Limits

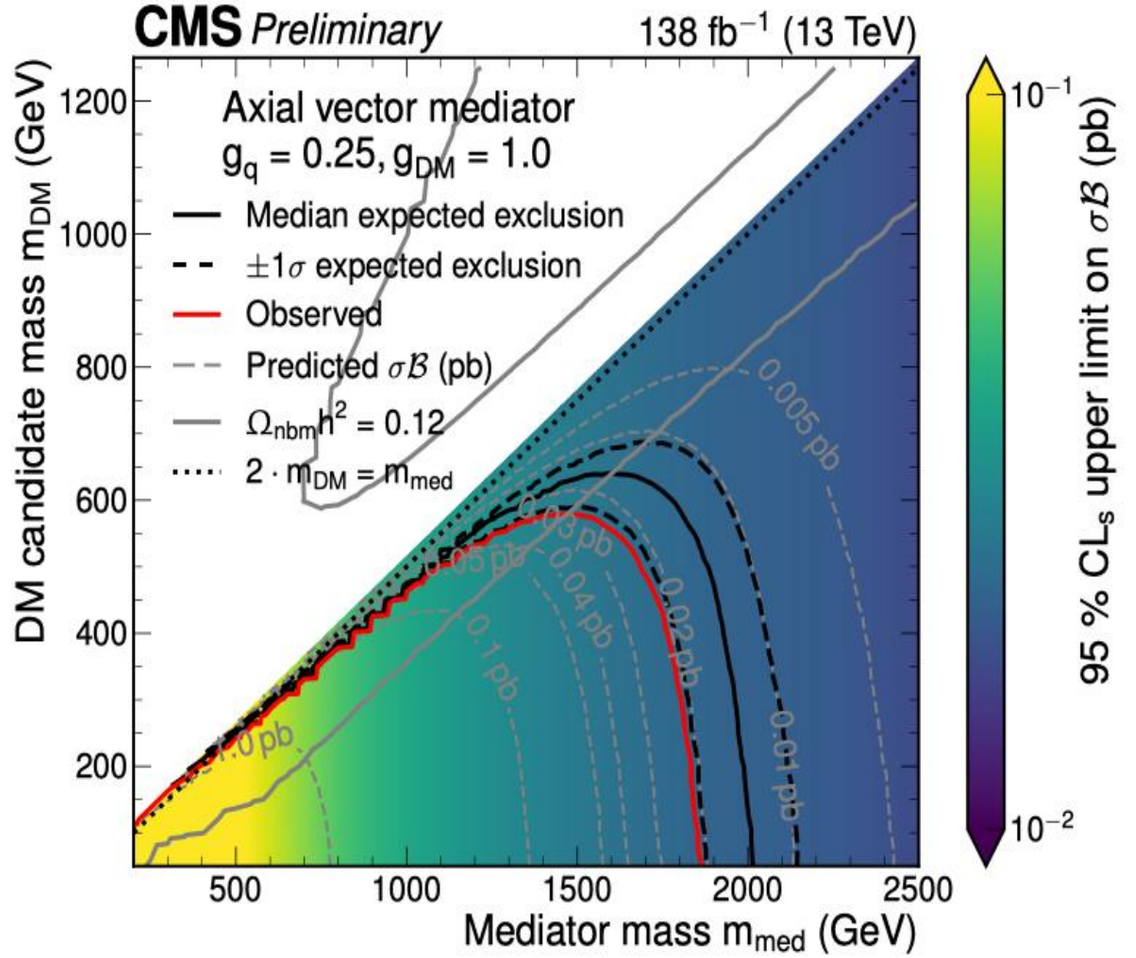
arXiv:2503.20033

SUS-23-004

- **Vector (Axial Vector) Mediator are excluded up to 1.85(2.0)TeV with an expectation of 2.0 (2.0) TeV**

- **Dark Matter masses are excluded up to 750(550) GeV for Vector (Axial-Vector) case with an expectation of 850(650) GeV**

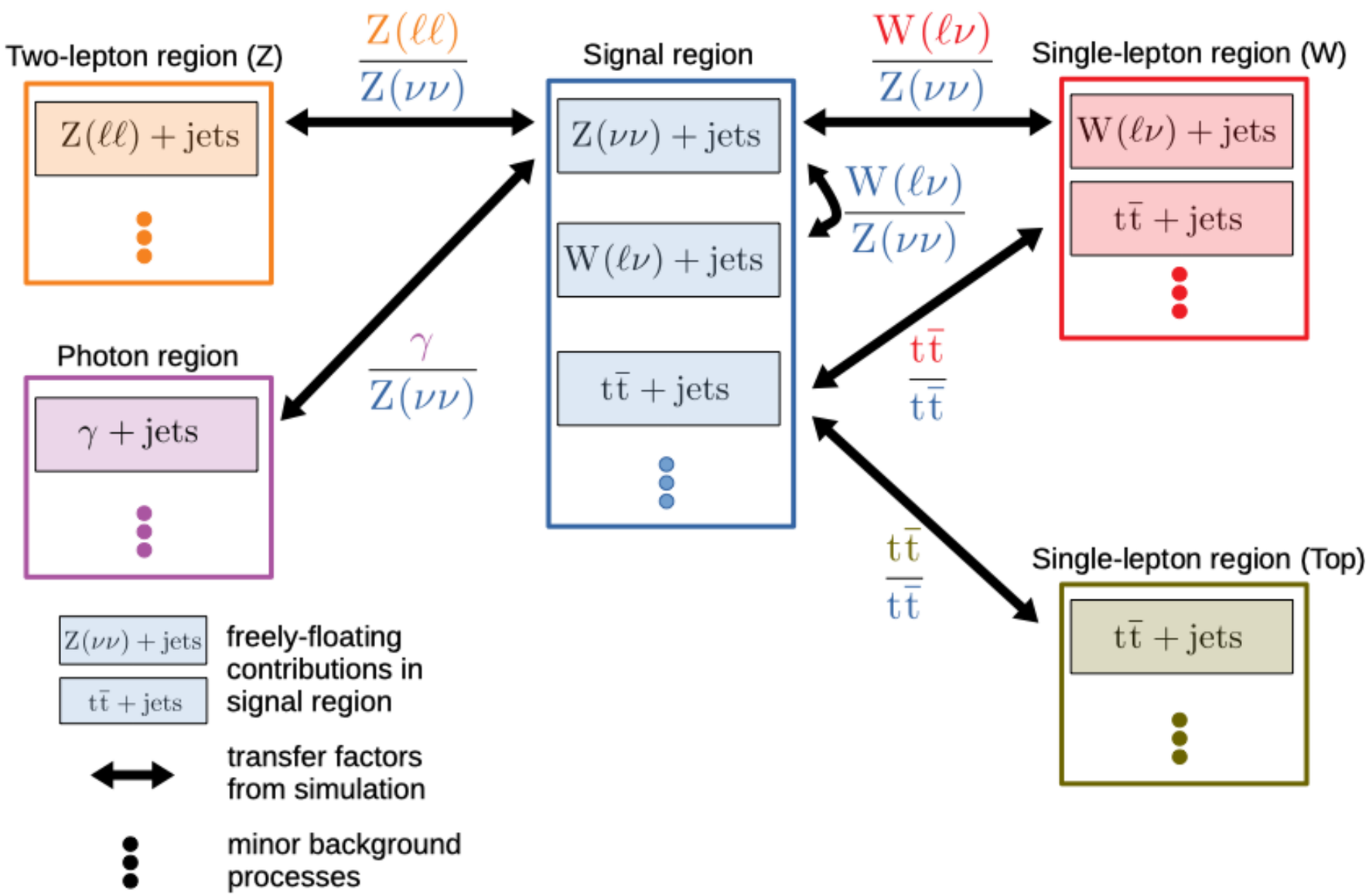




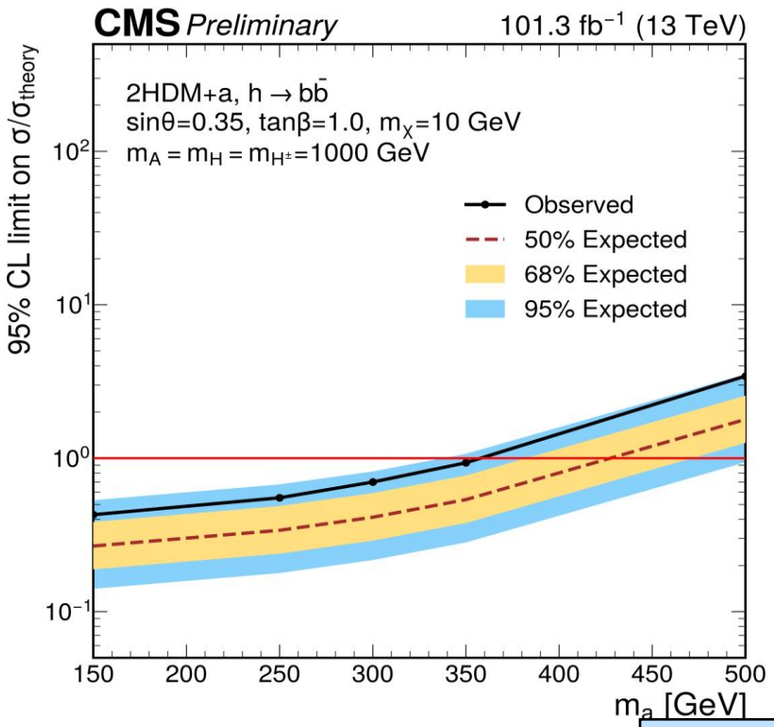
top +MET: SRs and CRs

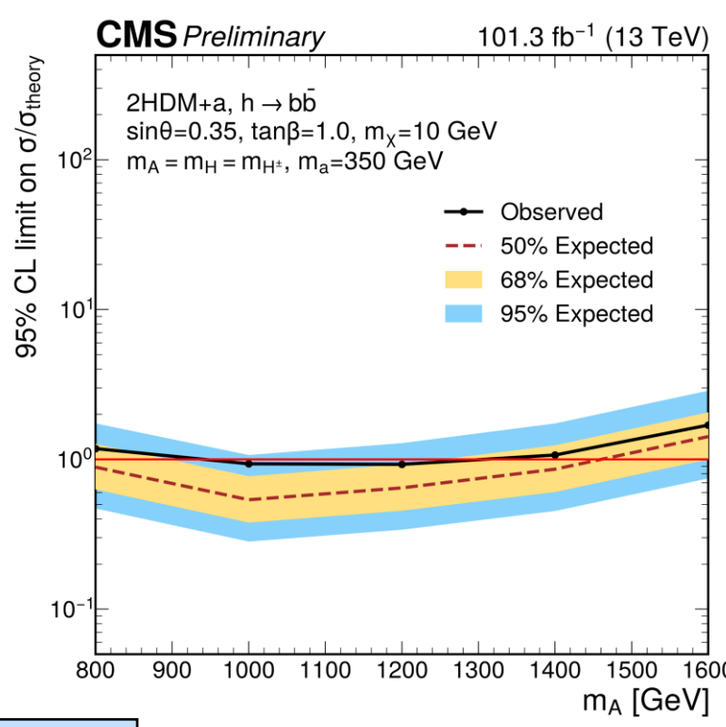
arXiv:2503.20033

SUS-23-004

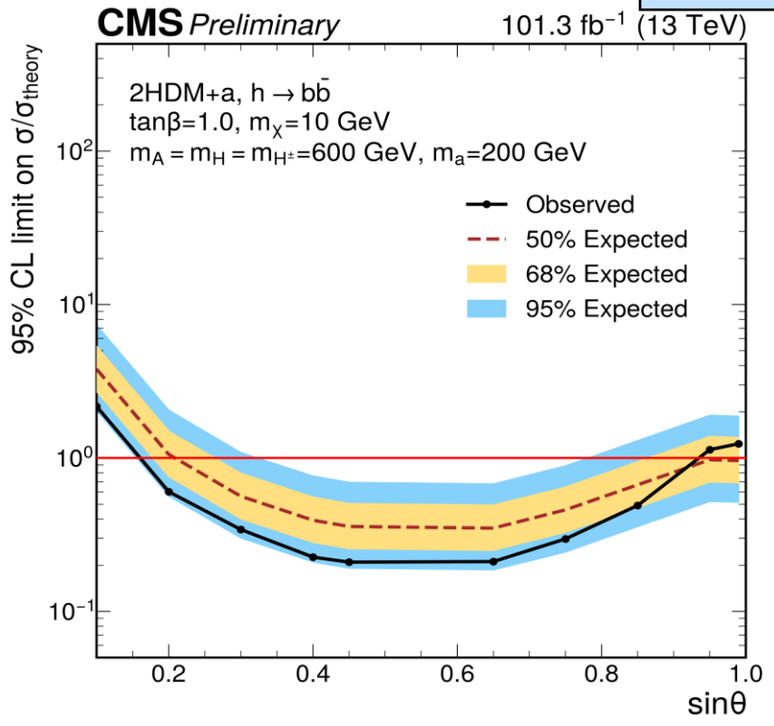


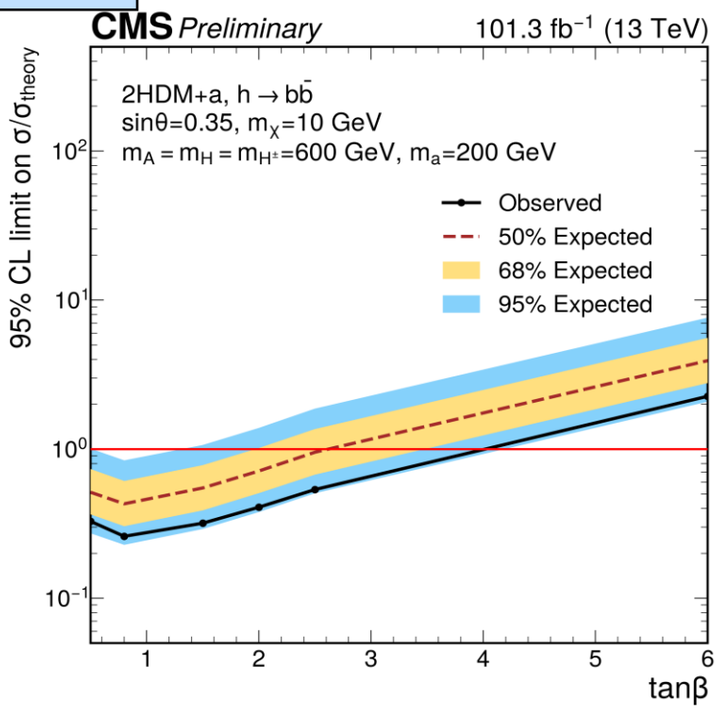
2HDM+ a / Z' Baryonic, H(→bb): Limits





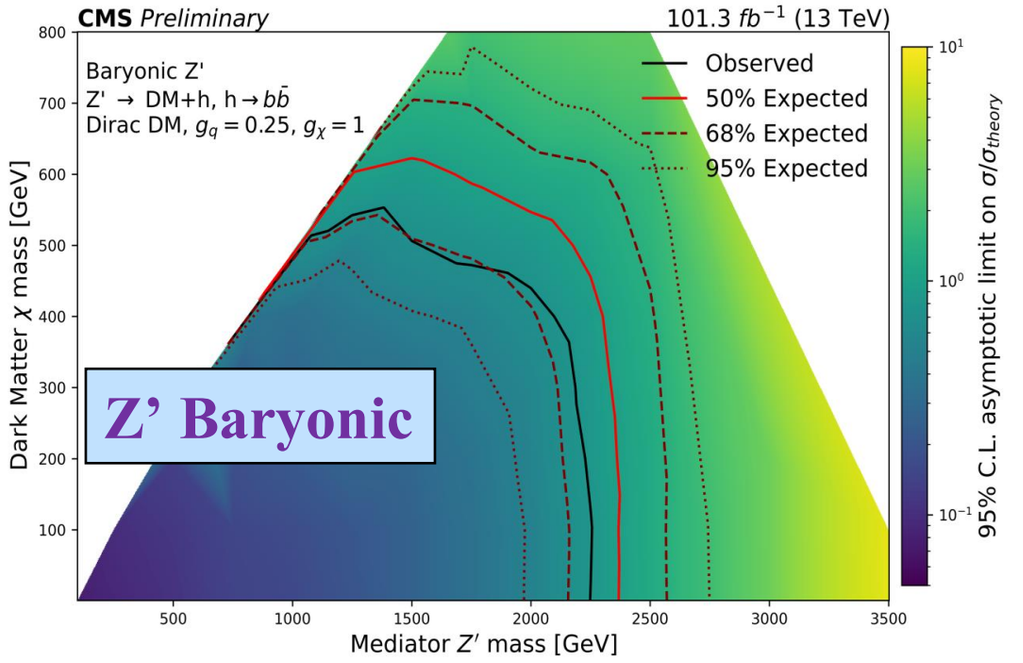
2HDM+a





For 2HDM+a $m_a < 350$ GeV excluded for $m_A = 1$ TeV

For $m_a = 350$ GeV, $960 < m_A < 1300$ GeV is excluded



Z' Baryonic

Mediator masses are excluded with an observed (expected) limit of 2.10(2.35)TeV for a DM mass of 1 GeV

DM Masses up to 500 GeV are excluded for Mediator mass of 1.25 TeV

2HDM+ a / Z' baryonic with H(→ττ)

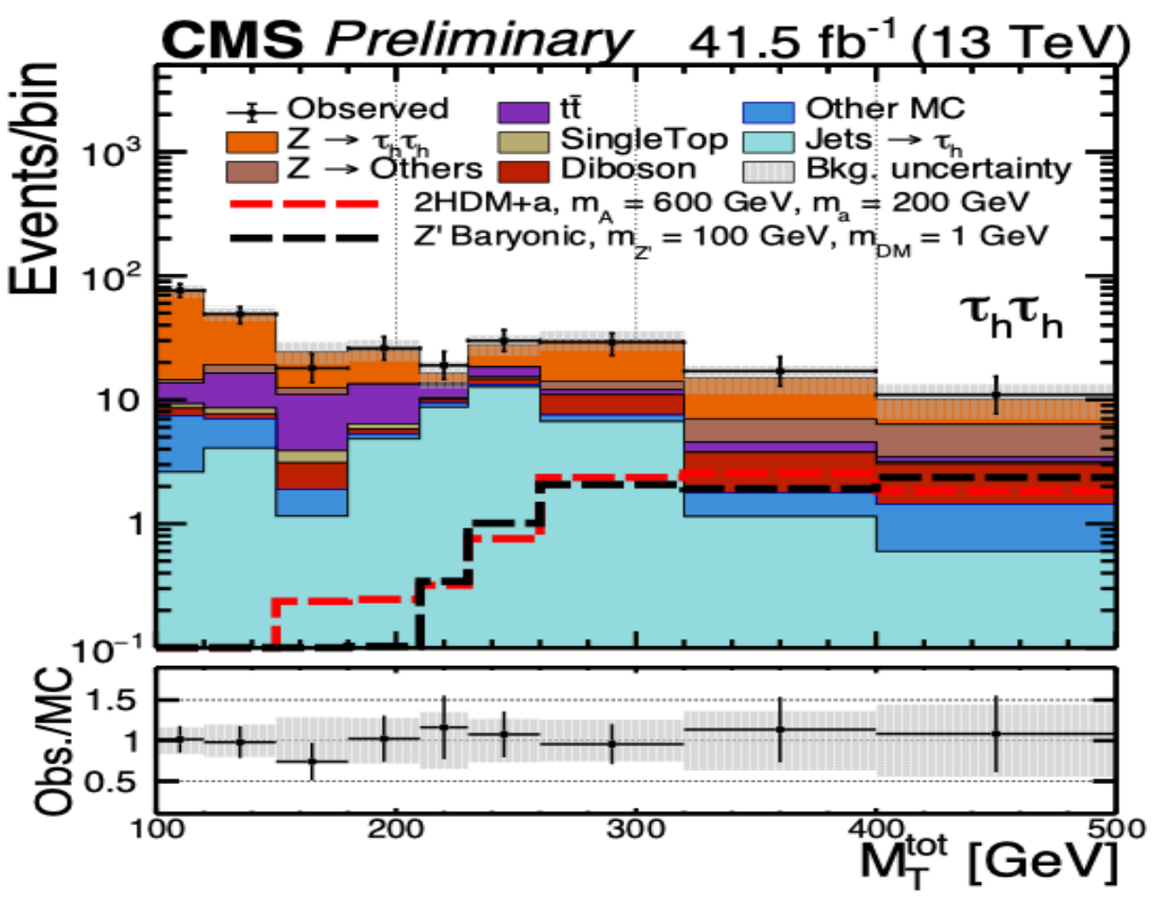
arXiv: 2506.04431

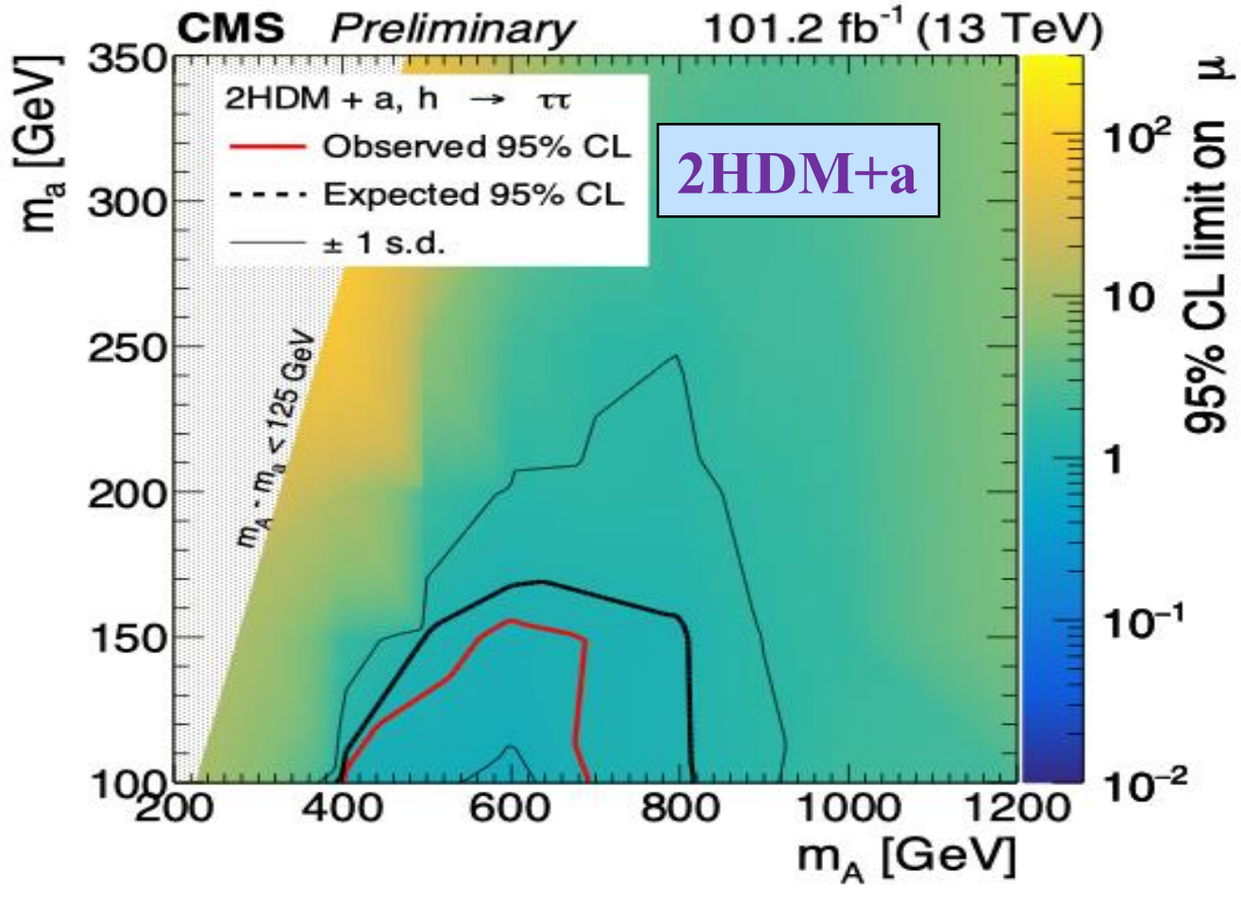
SUS-23-012

- **Main Backgrounds:**
  - **Z(ll)+Jets, from MC scaled to NNLO cross section**
  - **QCD and W+Jets: fake factor method from data**
- **Selected eτ, μτ and ττ events with opposite sign, third lepton and b-jet veto applied**
  - **Higgs P_T > 65 GeV**
  - **MET > 105 GeV and M_T > 100 GeV**

Signal extraction: likelihood fit on the total transverse mass variable in SR

Baryonic Z': 400 < m_A < 700 GeV excluded for m_a = 100 GeV



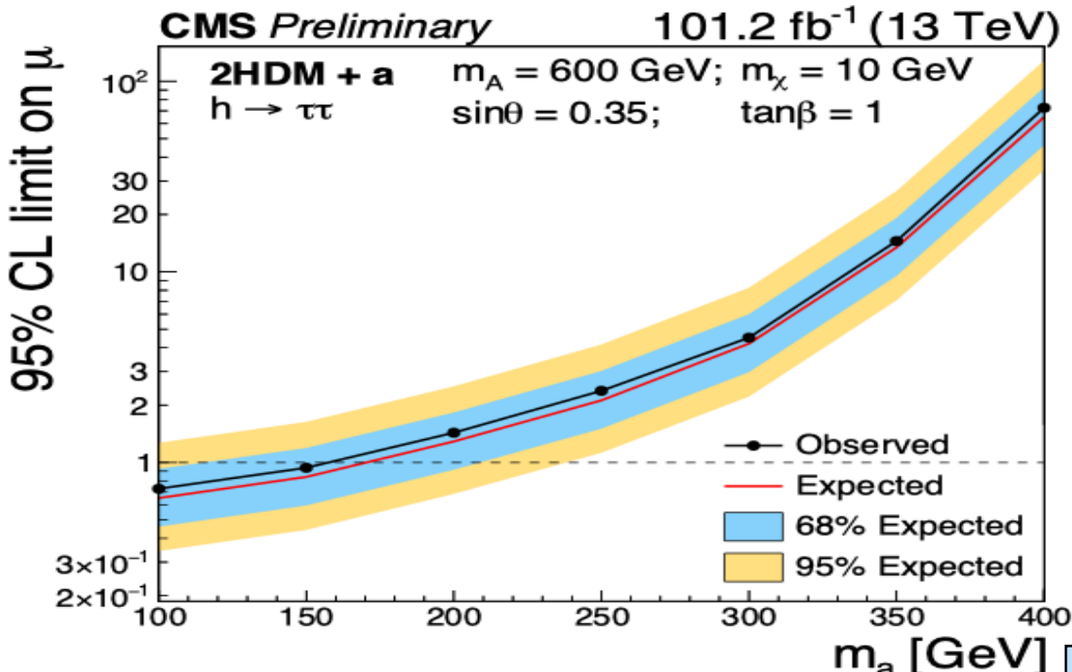


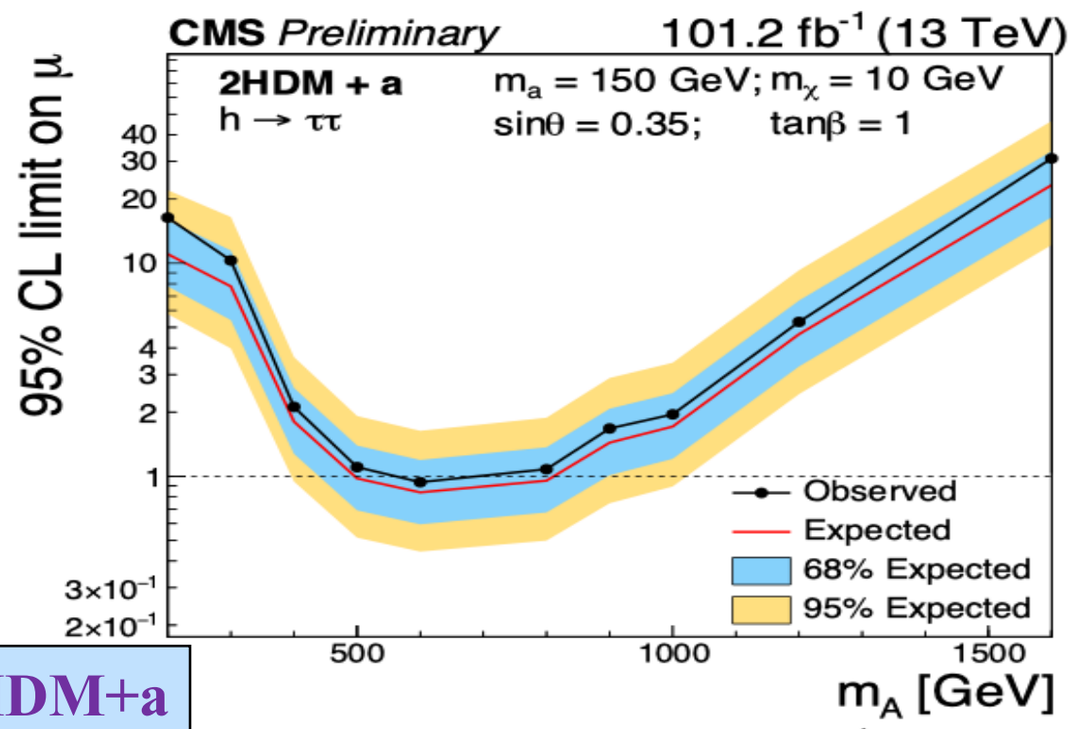
2HDM+ a with H(→ττ): Parameters Scan

arXiv: 2506.04431

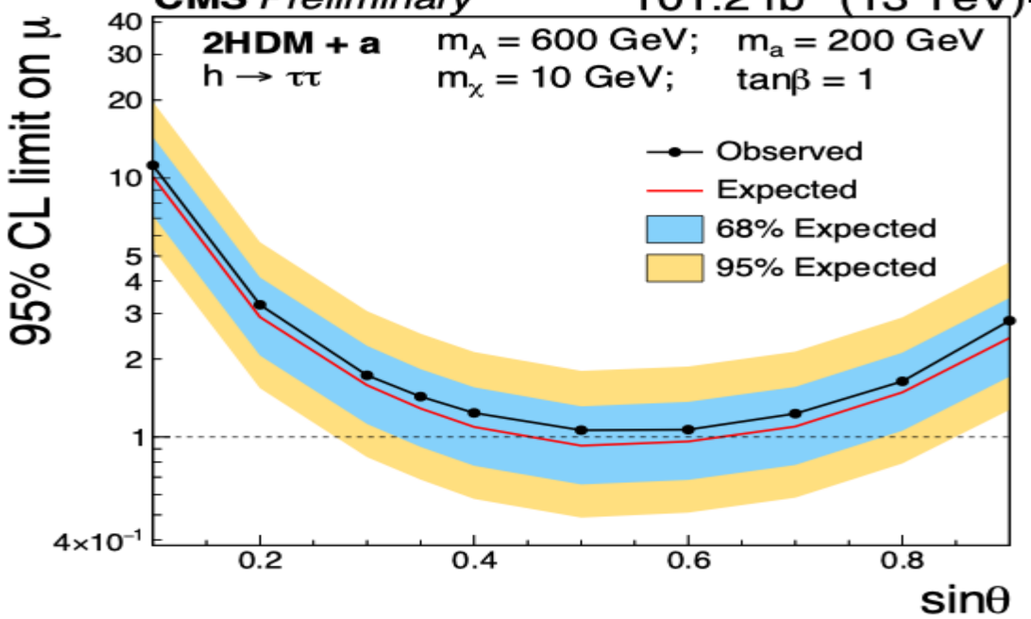
SUS-23-012

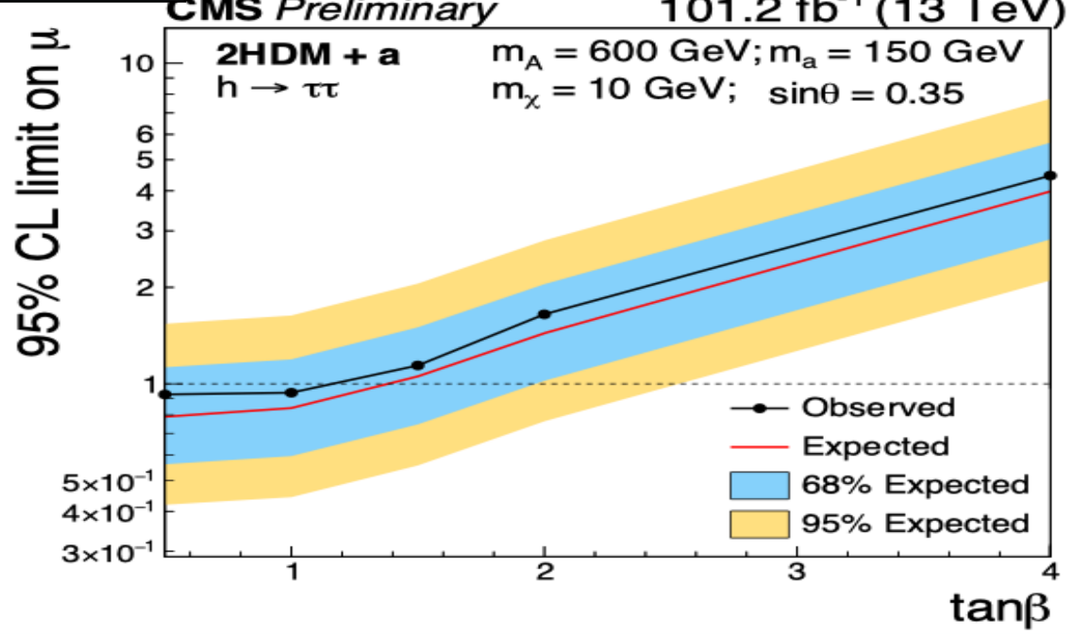
95%CL limits on signal modifier (μ) as a function for different parameters of the model





2HDM+a





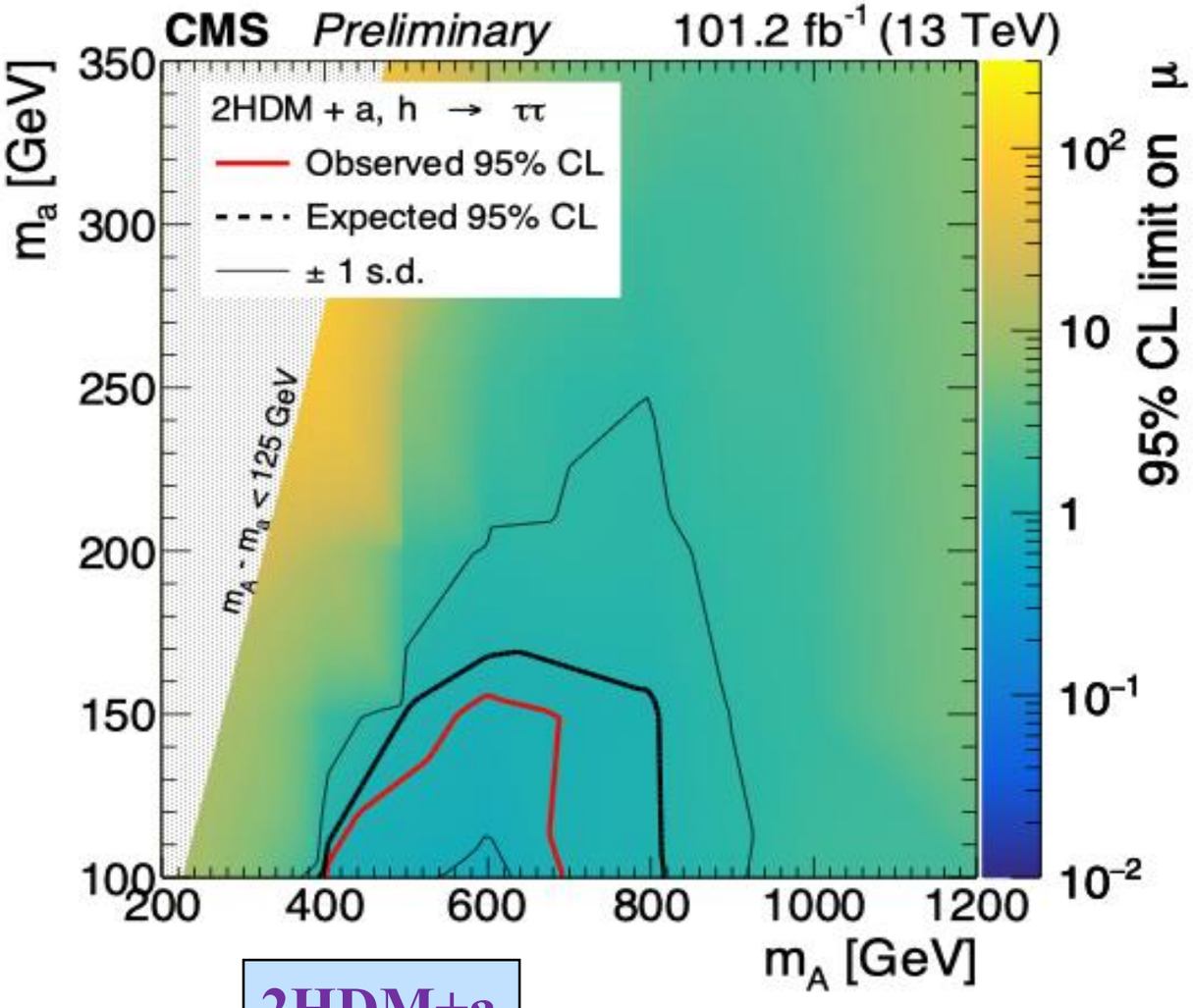
2HDM+ a / Z' baryonic with H(→ττ)

arXiv: 2506.04431

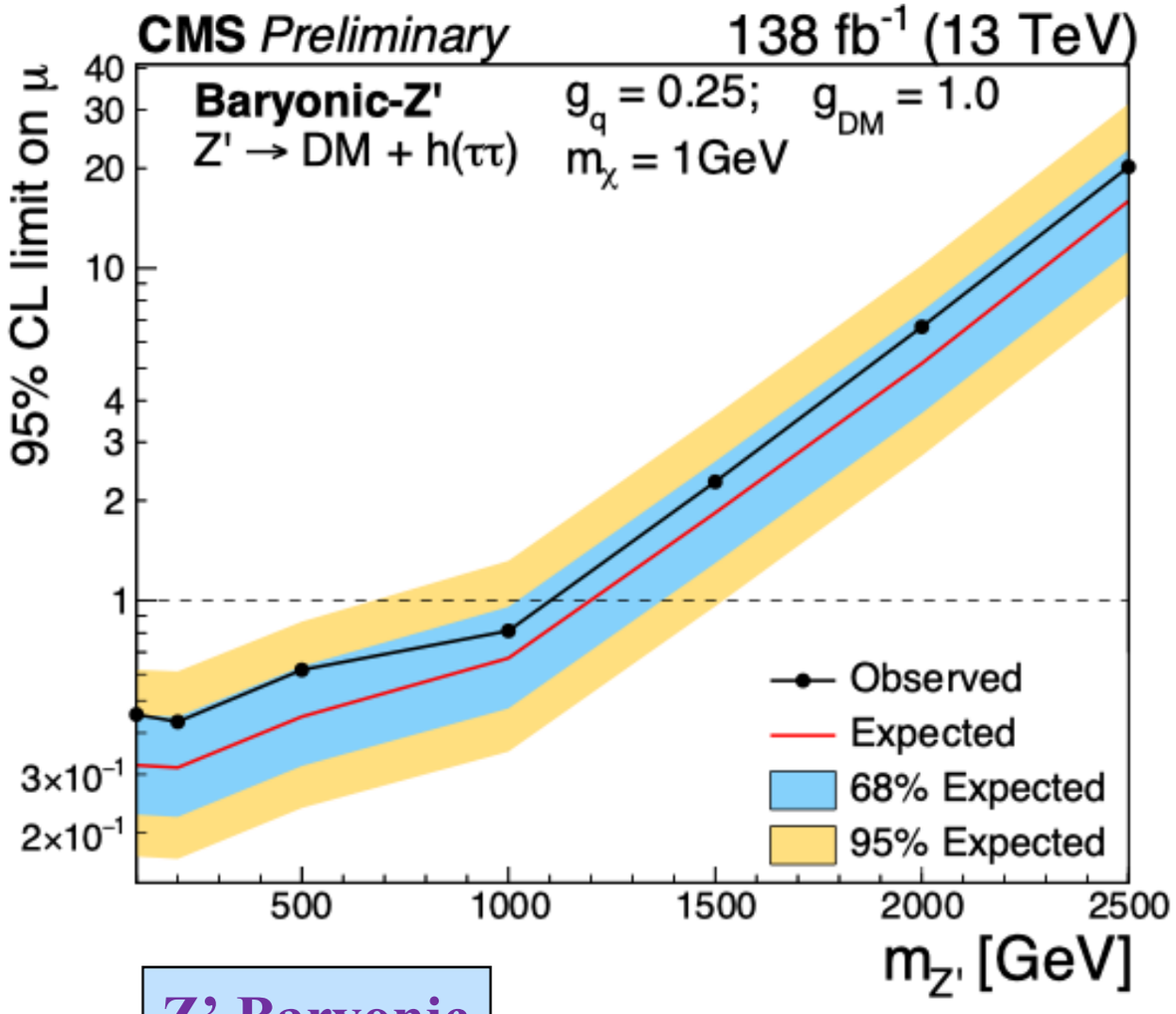
SUS-23-012

Heavy pseudoscalar mass between 400-700 GeV are excluded for light pseudoscalar mass around 100 GeV

Z' mass excluded < 1050 GeV for 1 GeV DM mass

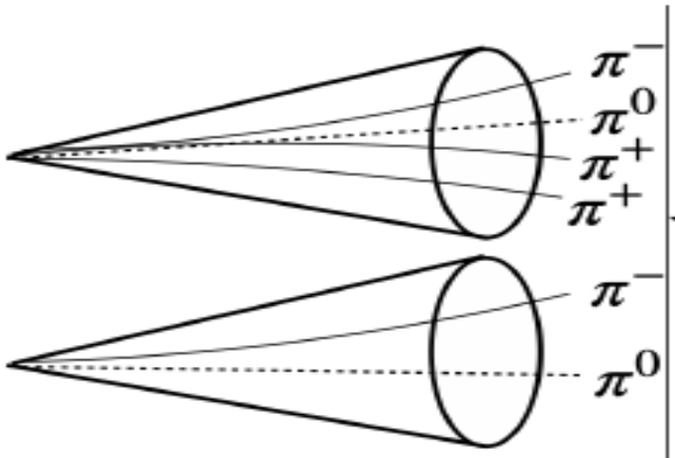


2HDM+a



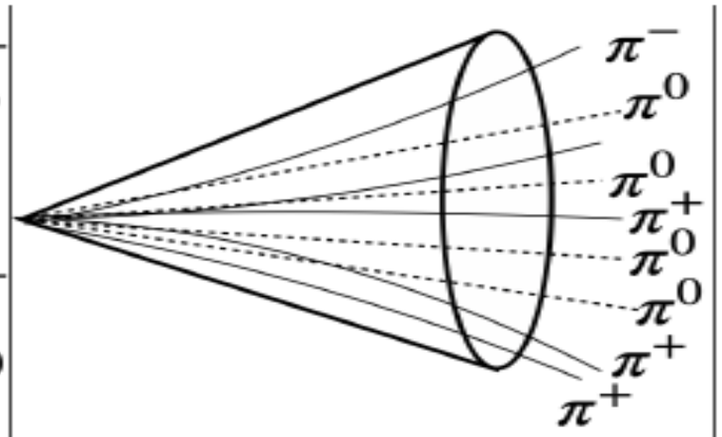
Z' Baryonic

Pencil Jets



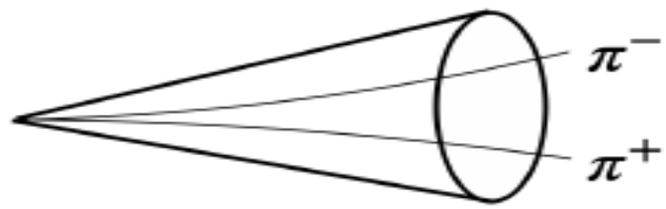
Standard Model τ

- Typically 1 or 3 pronged
- Jet radius < 0.4
- Smaller number of particles in Jet
- $\pi^0(->\gamma\gamma)$ present in decay



QCD Jet

- Many tracks
- Jet radius ~ 0.4
- Large number of particles in Jet
- $\pi^0(->\gamma\gamma)$ present in decay



Pencil Jet

- Typically 2 pronged
- Jet radius < 0.4
- Smaller number of particles in Jet
- $\pi^0(->\gamma\gamma)$ not present in the decay

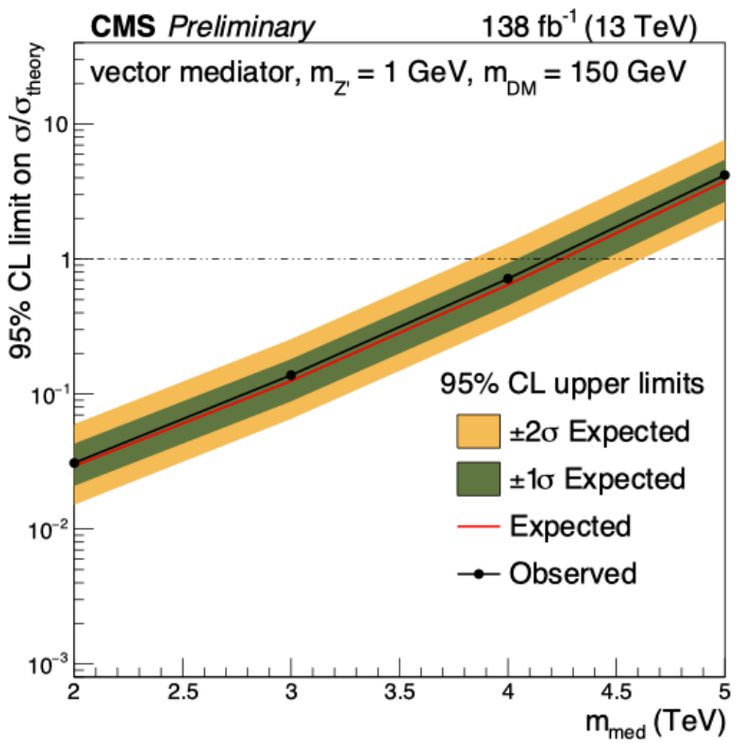
*This is how an "ideal" jet from these 3 different sources looks like. Real Jets are messy and there are all kinds of overlap

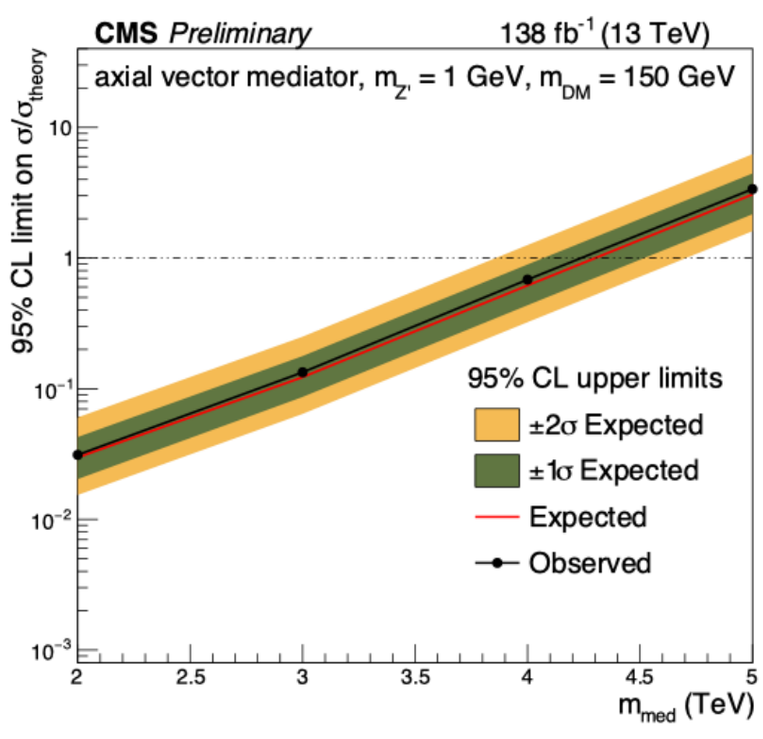
Final state	Observable	First lepton	Second lepton
$e\tau_h$	$p_T >$	25	30
	$\lvert\eta\rvert <$	2.1	2.3
	$I^e_{rel} <$	0.15	–
$\mu\tau_h$	$p_T >$	29	30
	$\lvert\eta\rvert <$	2.4	2.3
	$I^\mu_{rel} <$	0.15	–
$\tau_h\tau_h$	$p_T >$	55	45
	$\lvert\eta\rvert <$	2.1	2.1

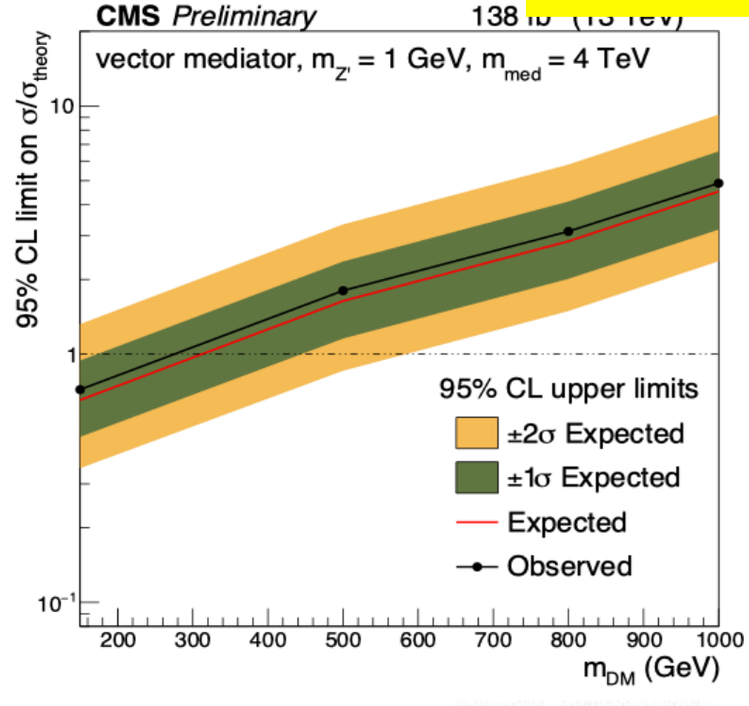
$$M_T^{tot} = \sqrt{(E_T^{\tau_1} + E_T^{\tau_2} + p_T^{miss})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{miss})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{miss})^2},$$

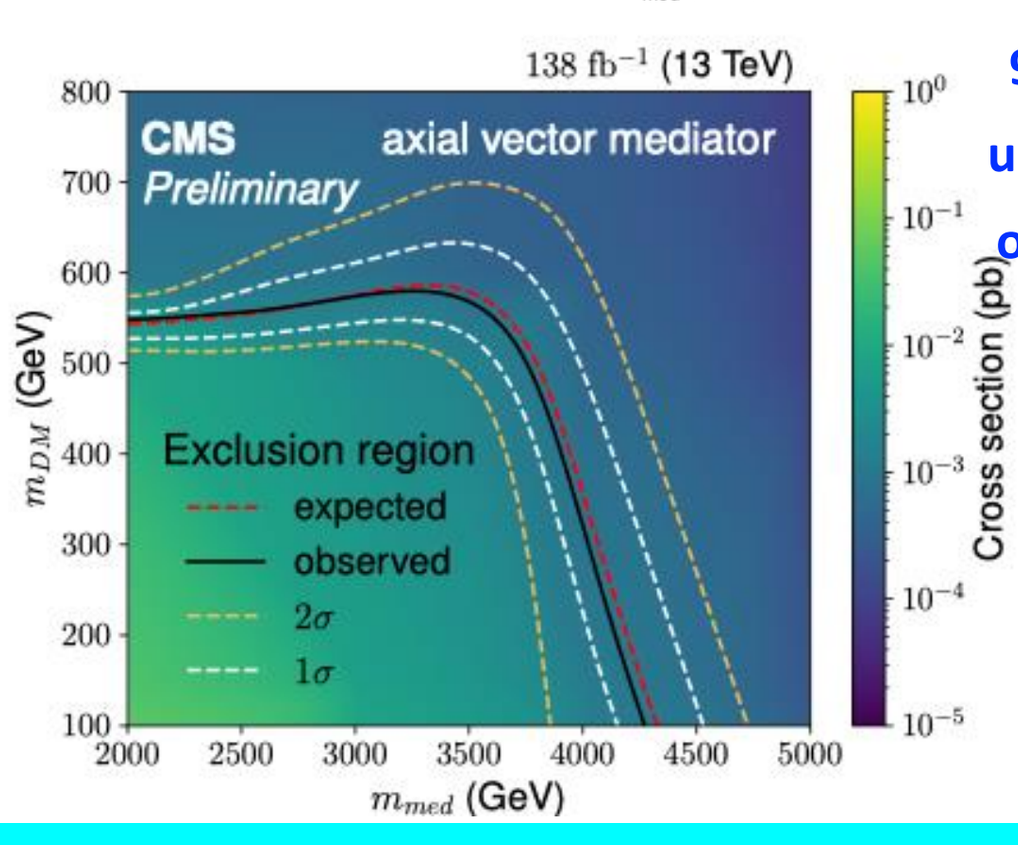
Pencil Jets: Limits

SUS-23-017









95% CL limits are placed on upper cross section for range of DM and Mediator masses

Mediator masses up to 4250(3500) GeV are excluded for DM mass of 100(550) GeV