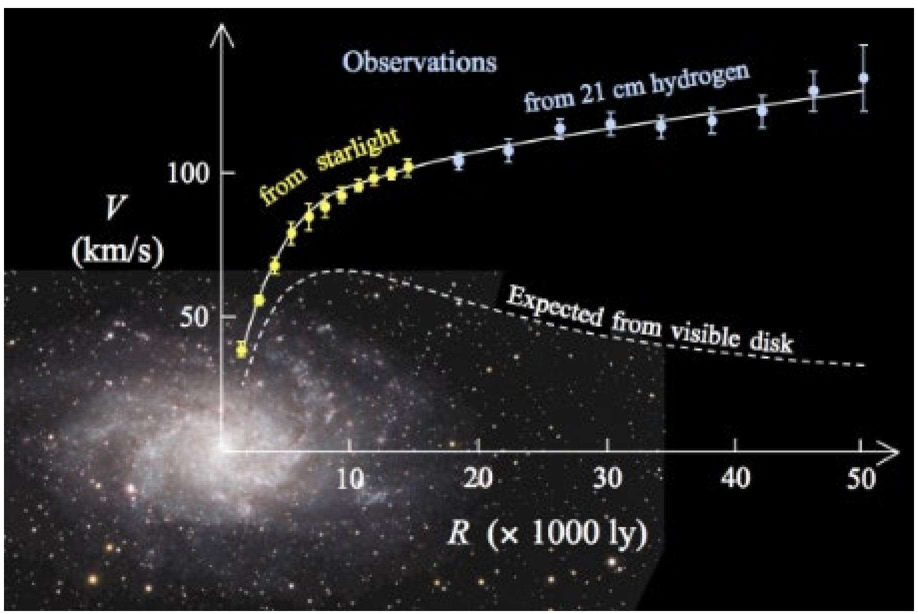
Searches for Dark Matter with CMS

Deep Inelastic Scattering (DIS)
8 - 12 Apr 2024, Grenoble

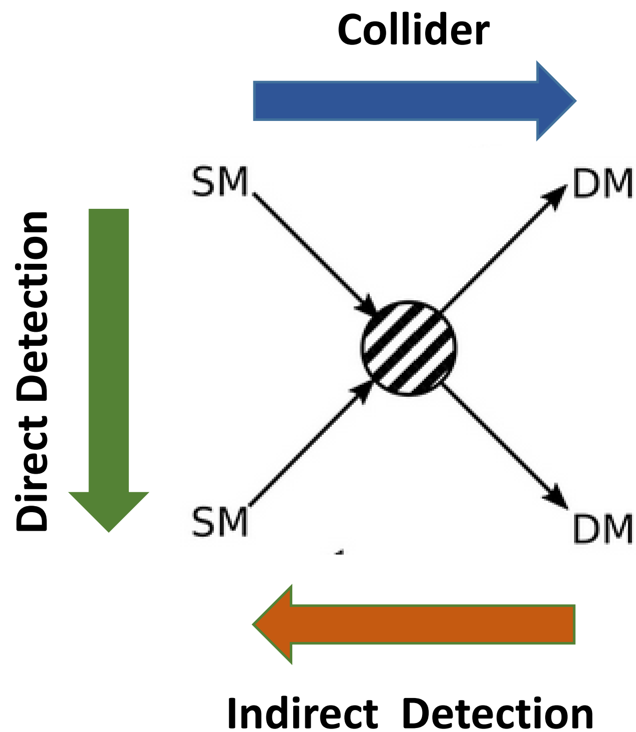
Jesús Vizán on behalf of the CMS Collaboration
Universidad de Cantabria – Instituto de Física de Cantabria

Dark Matter

- DM inferred from astrophysical observations
  - Galaxy rotation curves
  - Strong gravitational lensing
  - Bullet cluster
  - ...



- Hunt for DM with complementary approaches: **Collider searches**, **direct**, and **indirect** detection



Dark Matter Searches at CMS

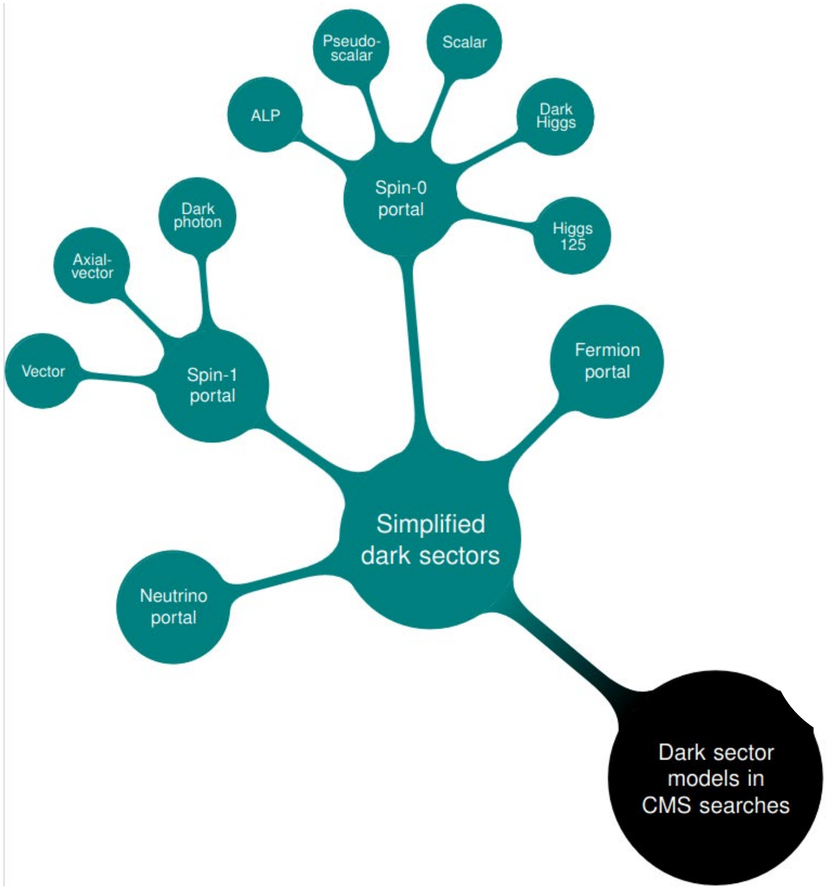
- At LHC, many BSM models considered in order to cover as much DM theory as possible [**see CMS briefing on Dark Matter**]

Dark Matter Searches at CMS

- At LHC, many BSM models considered in order to cover as much DM theory as possible [see CMS briefing on Dark Matter]
  - Simplified Models / Dark Sectors

Involve a single mediator

- **spin 1** *portal :* Vector, Axial-vector, Dark Photon
- **Spin 0**: Scalar, Pseudoscalar, Dark Higgs, …
- …

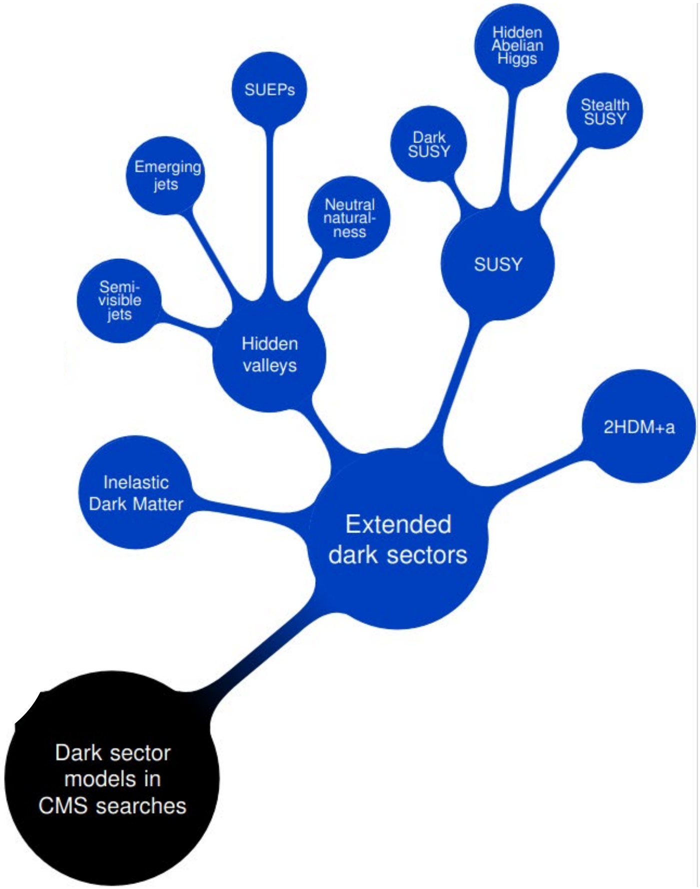


Dark Matter Searches at CMS

- At LHC, many BSM models considered in order to cover as much DM theory as possible [see CMS briefing on Dark Matter]
  - Extended Dark sectors

More complex dynamics of Dark Sector

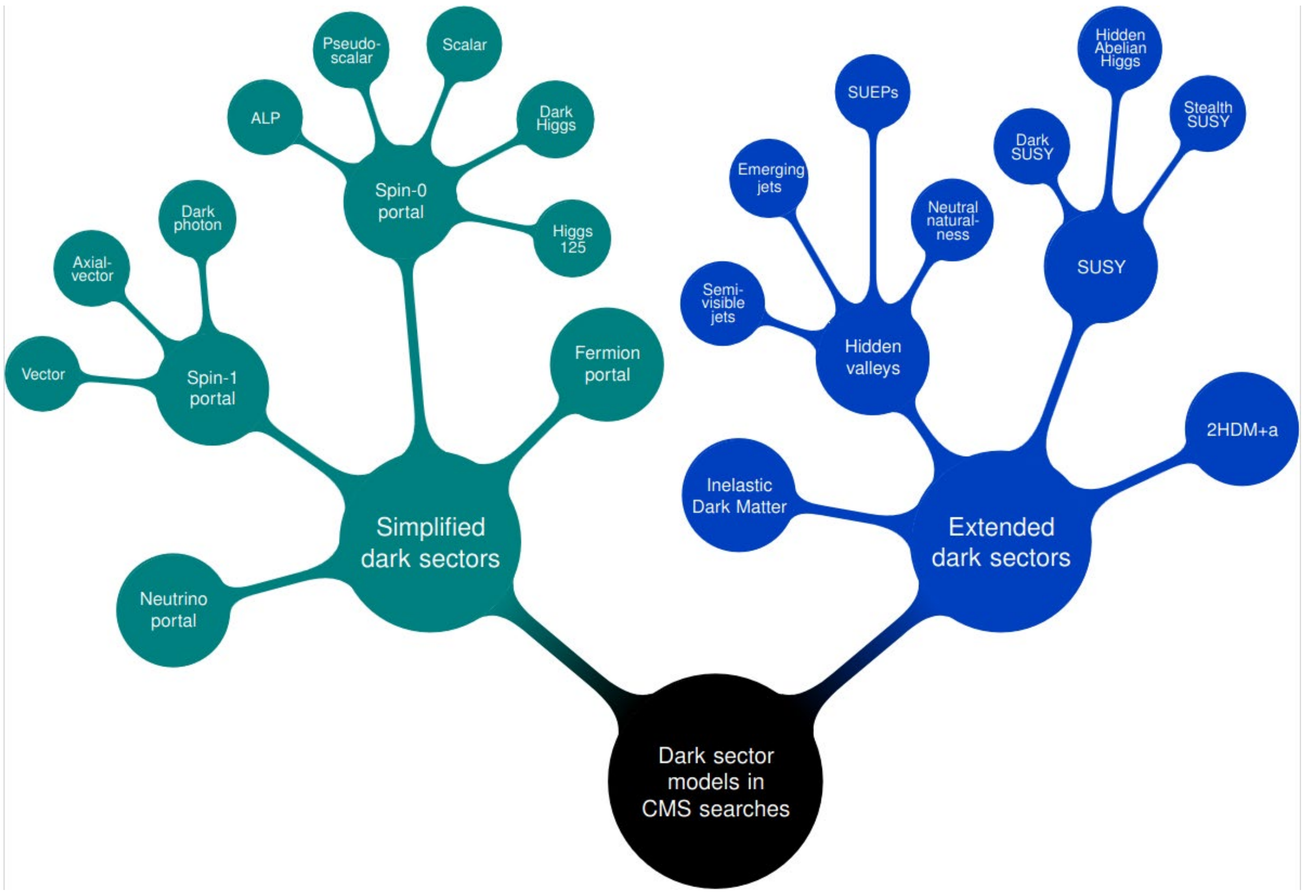
- Supersymmetry, Hidden Valleys, 2HDM+a, Inelastic Dark Matter



Dark Matter Searches at CMS

- At LHC, many BSM models considered in order to cover as much DM theory as possible [see CMS briefing on Dark Matter]

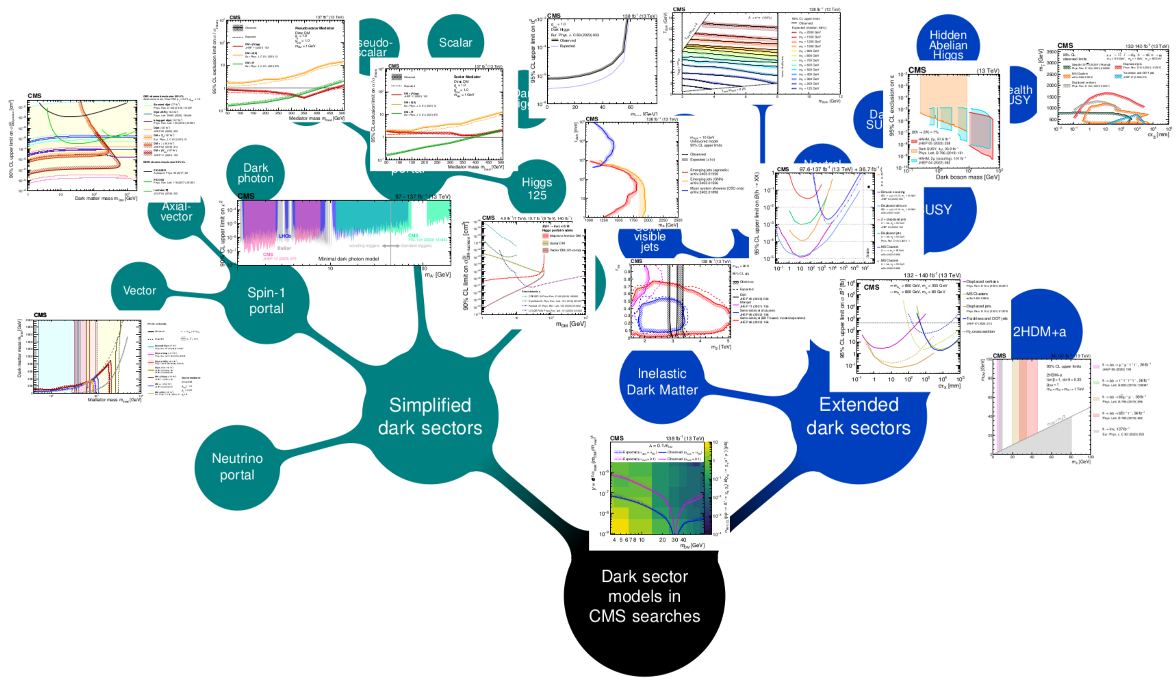
- Experimental challenges and a wide variety of experimental signatures
  - Missing Transverse Energy **(MET) + X**
  - **Displaced** particles
  - **Semivisible** jets, **Emerging** jets, Soft Unclustered Energy Patterns (**SUEPS**)
  - Other unconventional signatures



Dark Matter Searches at CMS

- At LHC, many BSM models considered in order to cover as much DM theory as possible [see CMS briefing on Dark Matter]

- This talk will briefly overview:
  - New Summary Plots (full list in this link)
  - Some recent searches that will serve as an example (impossible to cover everything)

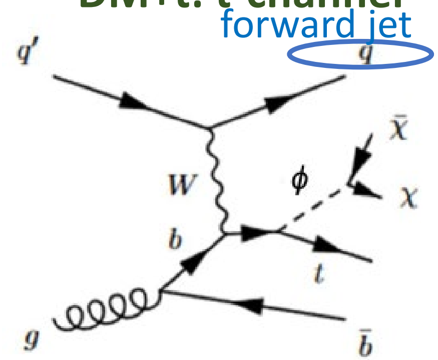


DM + t/tt

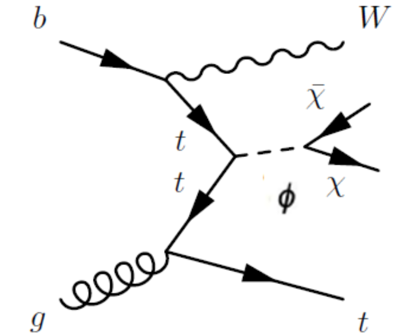
NEW:
CMS-PAS-EXO-22-014

- X + p_T^{miss} signatures (mono-X: mono-jet/H/tt)
  - mono-t/tt: DM associated with **Single top** or **tt**
- Simplified model with a **scalar (ϕ)** or **pseudoscalar (a)** mediator that interacts with SM and **Dirac χ DM**
  - Preferential couple to third-generation

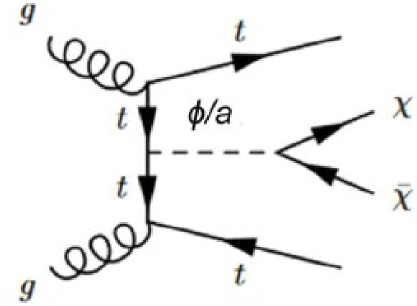
DM+t: t-channel



DM+t: tW channel



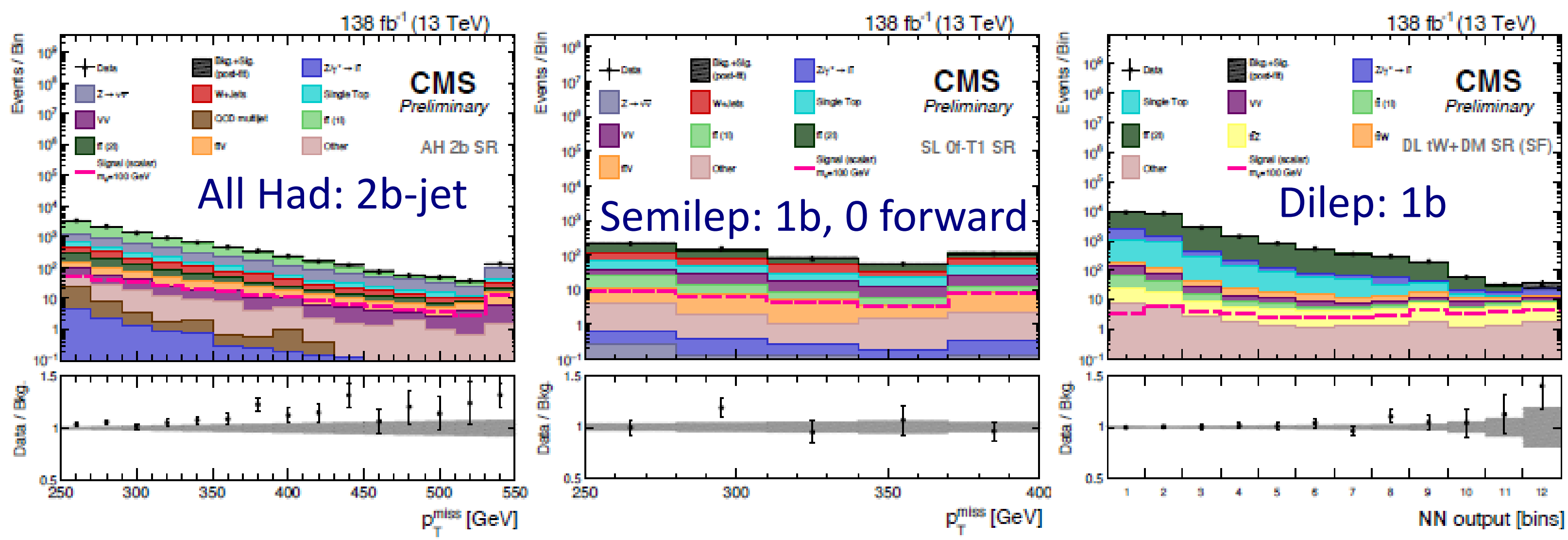
DM+tt



All Hadronic
- leptons veto: e,μ
- ≥ 3 jets
- =1, ≥ 2 b-tagged jets
- **MET > 250 GeV**
- +0, ≥1 forward jets (|η|>2.4)

Semileptonic
- 1 lepton: isolated e,μ
- ≥ 2 jets (j small-cone)
- =1, ≥ 2 b-tagged jets
- **MET > 250 GeV**
- +0, ≥1 forward jets

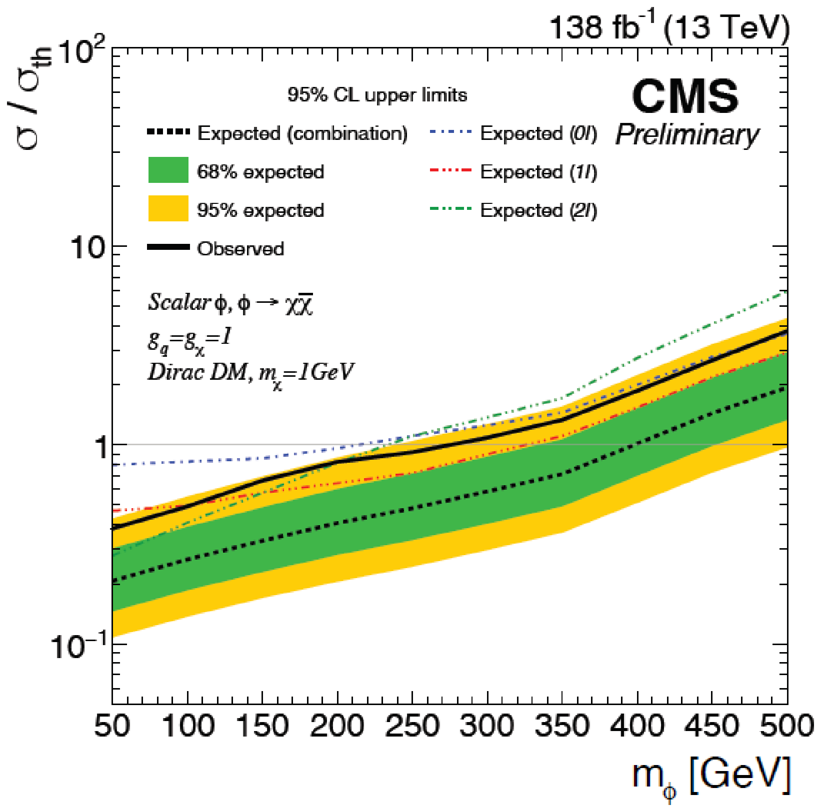
Dileptonic
- 2 lepton: isolated e,μ (opposite sign)
- ≥ 1 jets
- =1, ≥ 2 b-tagged jets
- **MVA techniques** to improve sensitivity

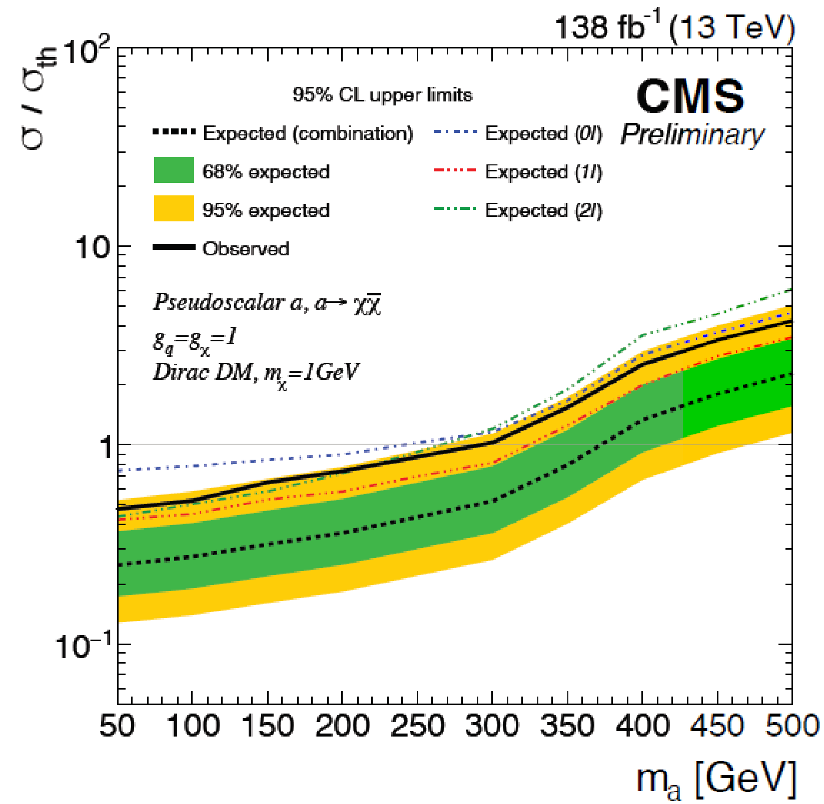


- p_T^{miss} /MVA used for fit in signal and several control regions

DM + t/tt

NEW:
CMS-PAS-EXO-22-014

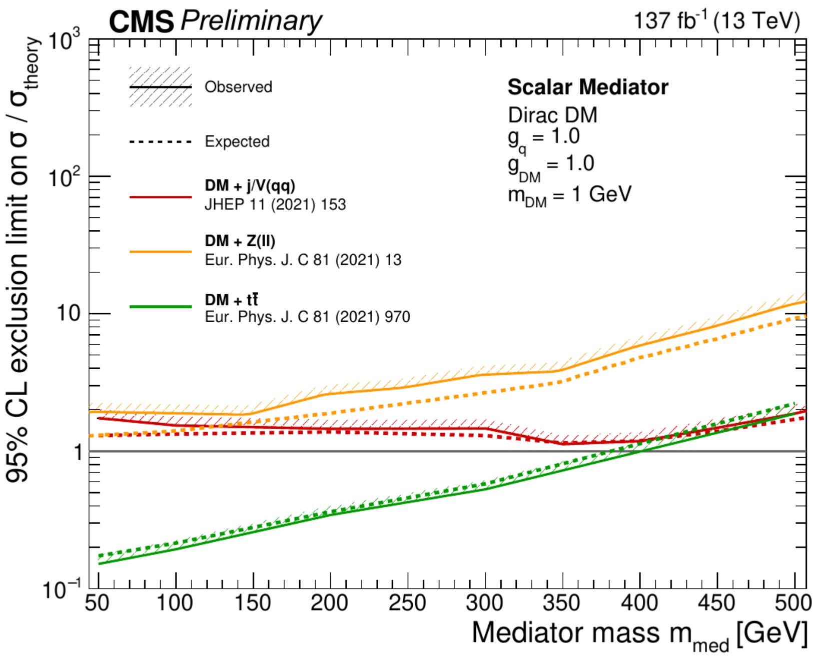


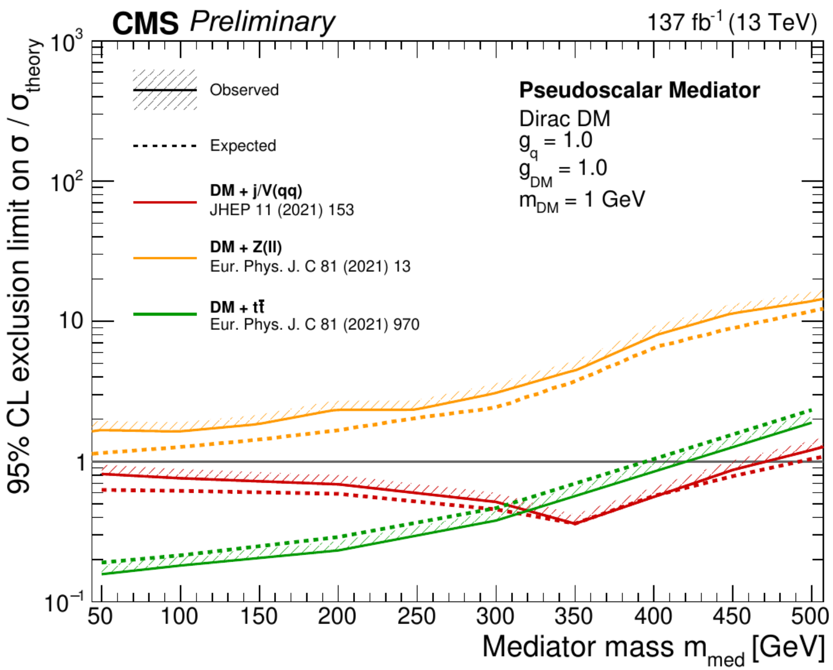


- 95% CL limits on production cross section vs mass of scalar or pseudoscalar
  - Exclusion for benchmark model up to ~400 GeV

Scalar / Pseudoscalar Summary

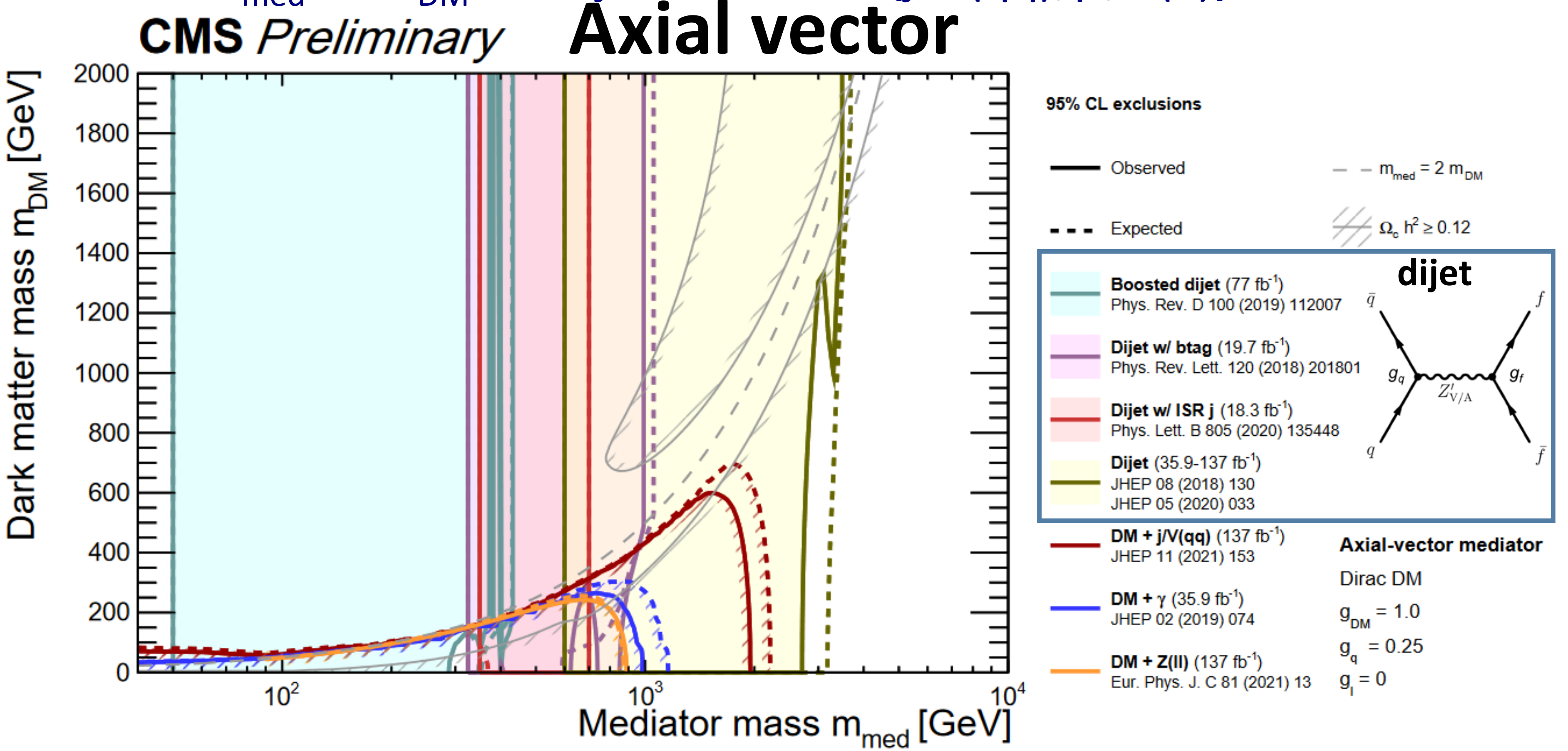
- Production vs mediator mass from DM + {j/V(qq); Z(ll); tt} analyses





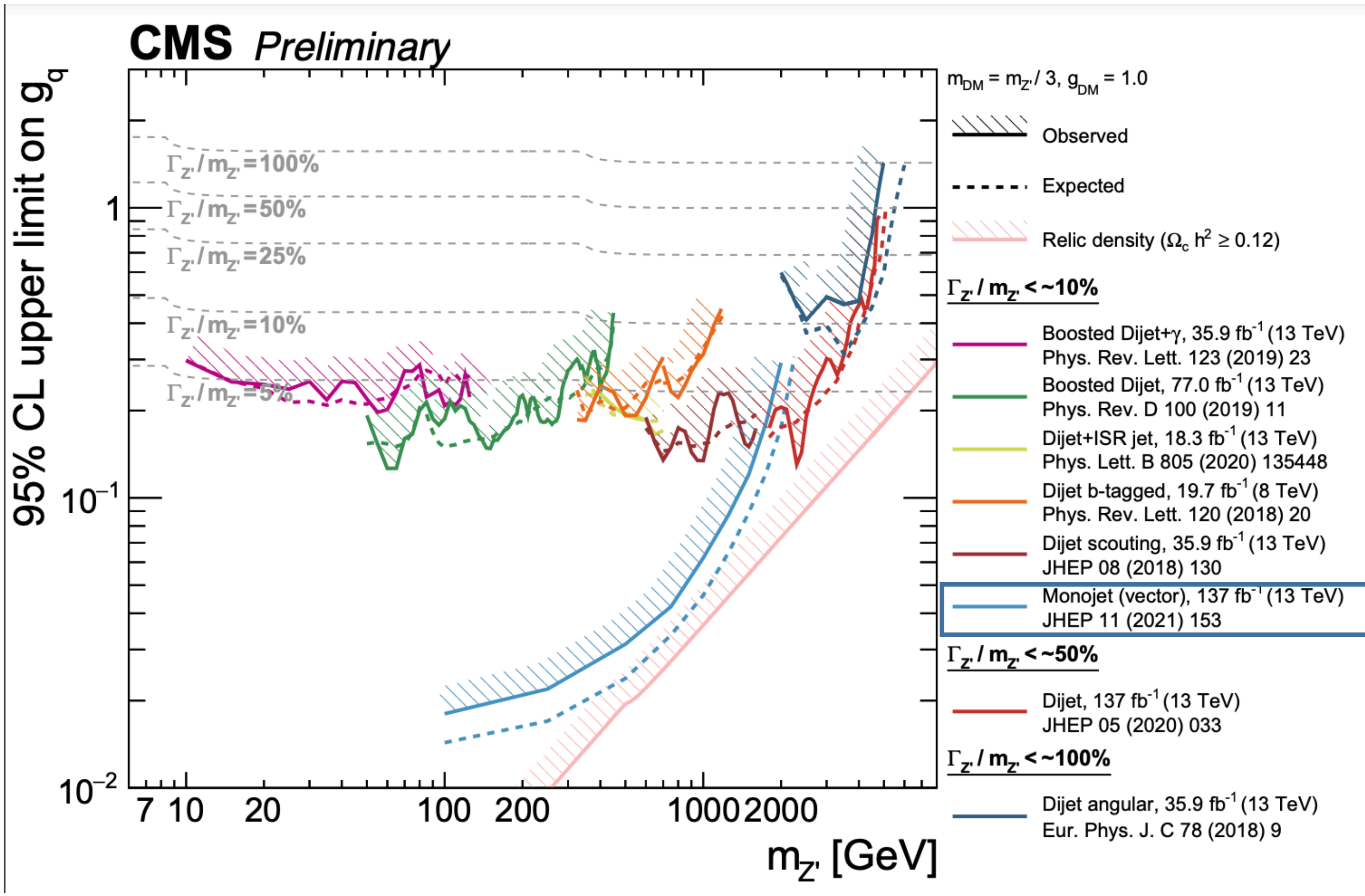
$Z'_{V/A}$ mediator: m_{med} vs m_{DM}

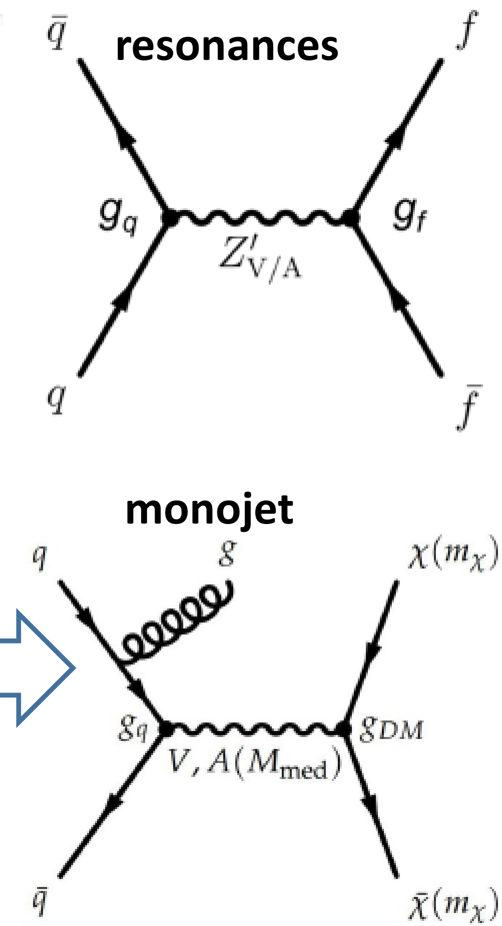
- Consider spin 1 mediator: **vector** (Z_V)or **axial vector** (Z_A)
- Limits on m_{med} vs m_{DM} for dijet and DM + {j/V(qq);γ ; Z(ll)}



$Z'_{V/A}$ mediator: dijet resonance and monojet

- Consider spin 1 mediator: **vector** (Z_V)or **axial vector** (Z_A)
- Limits on universal quark coupling g_q

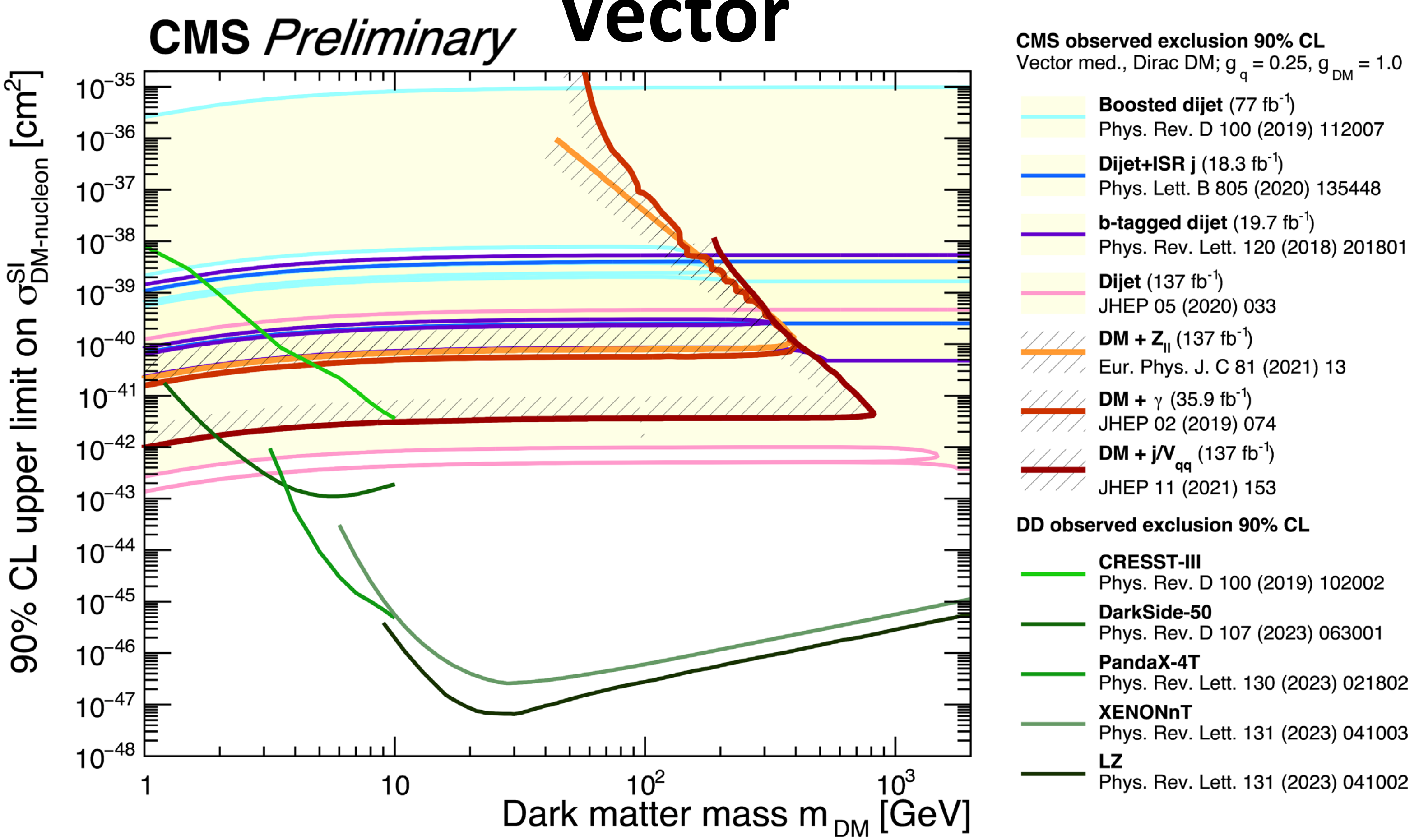




Z’$_{V/A}$ mediator: comparison with Direct Detection

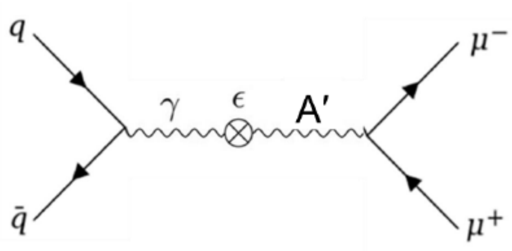
- Consider spin 1 mediator: **vector** (Z_V)or **axial vector** (Z_A)
- 90% CL Limits on scattering DM-Nucleon cross section

Vector



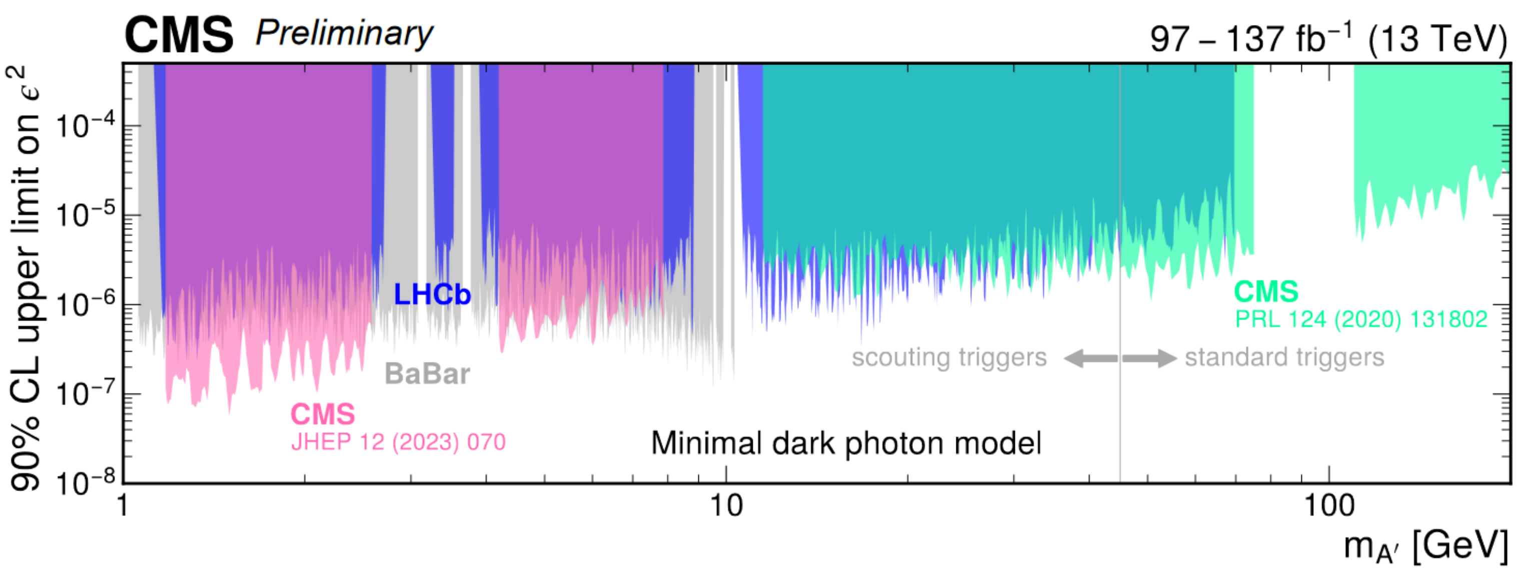
Dark photon with dimuon resonances

- Dark photon A':
  - spin1 mediator
  - mixing with SM photon



NEW: Enriching the physics program of the CMS experiment via data scouting and data parking
2403.16134

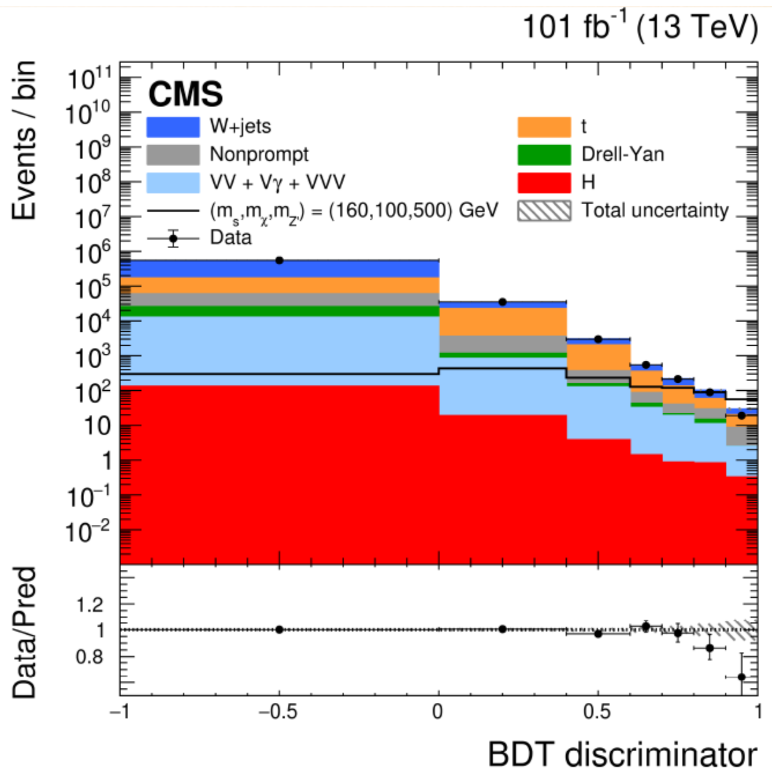
- Minimal dark photon model
- Low mass resonances with scouting triggers
- 90% CL limits on squared mixing coefficient vs dark photon mass

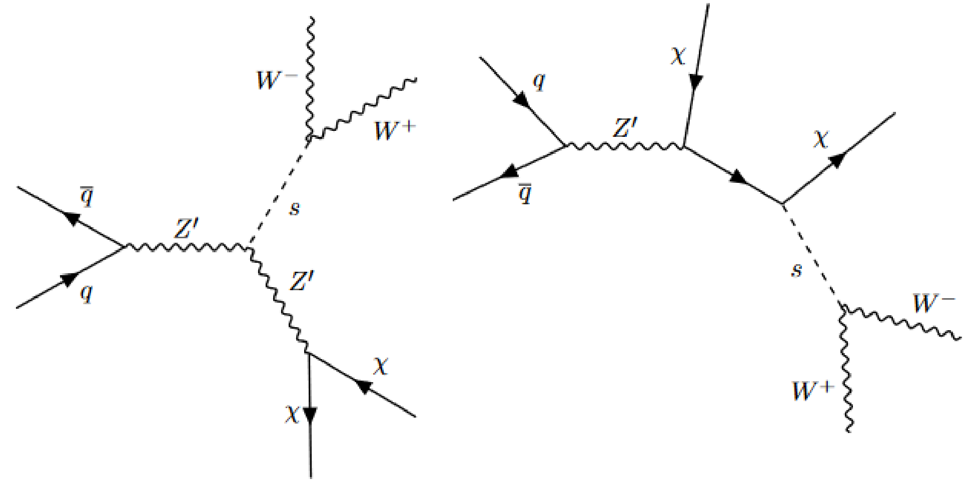


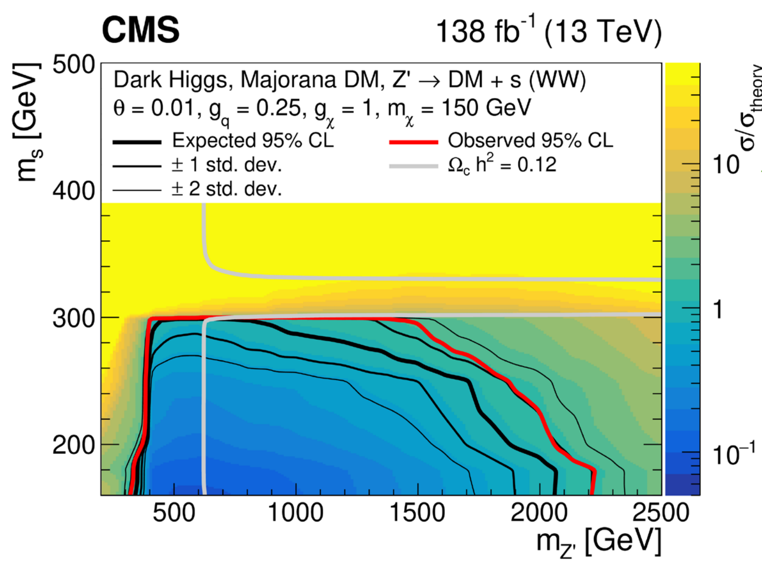
Dark Higgs in WW

2310.12229
JHEP 03 (2024) 134

- Introduces vector boson Z' and a new physical Higgs boson *s*
  - Semileptonic and fully leptonic





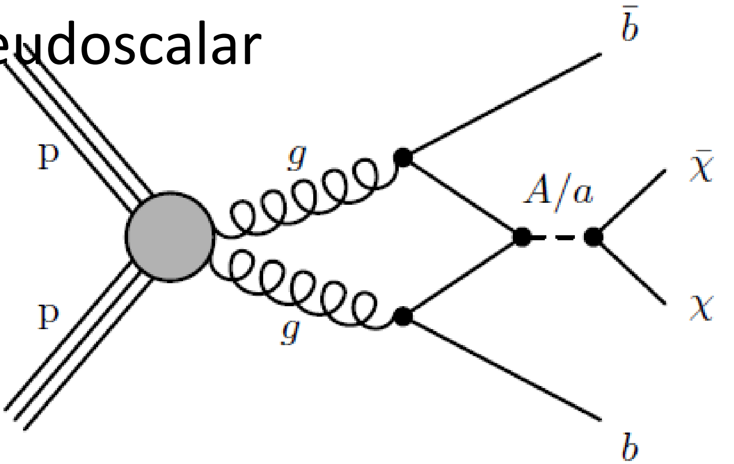


- Sharp drop of sensitivity for $m_s > 2\, m_\chi$ (s predominantly decays to $\chi\chi$)

DM + bb (non-resonant)

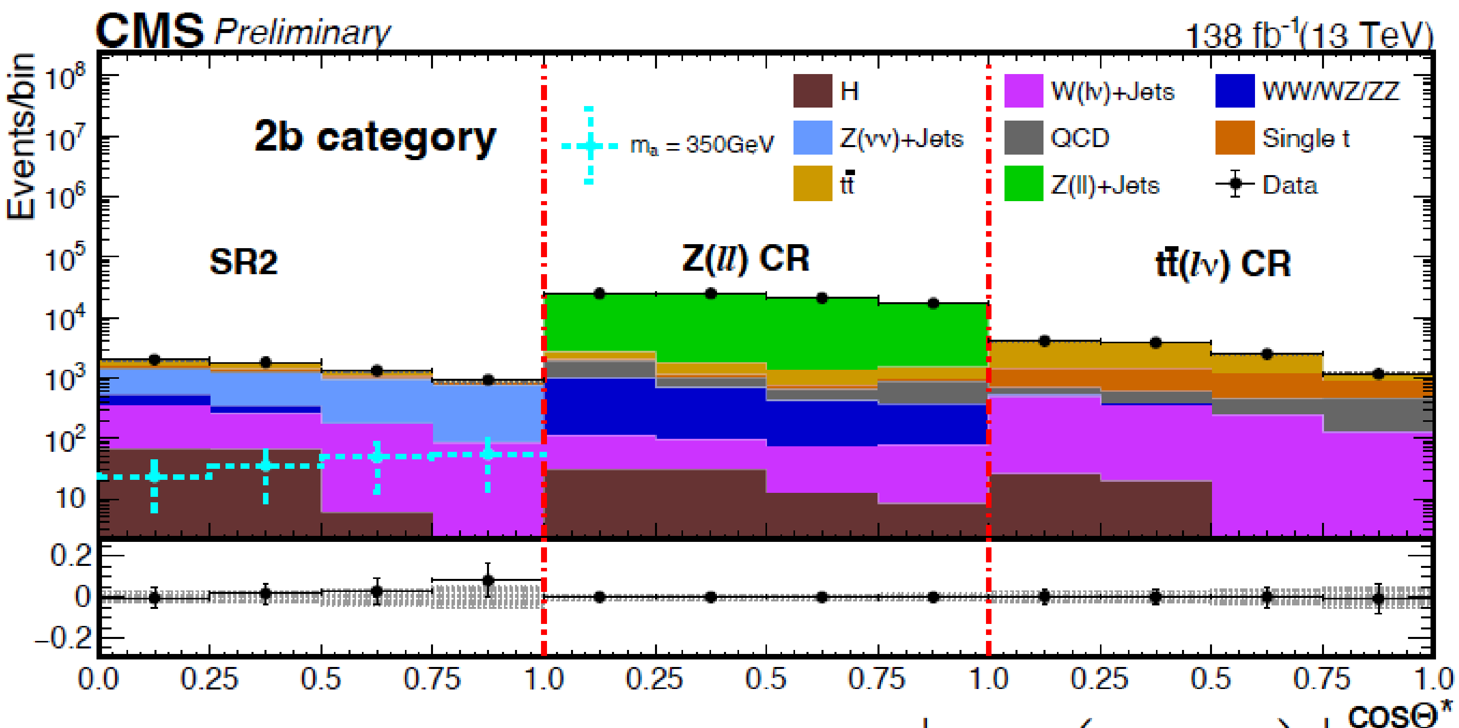
NEW:
CMS-PAS-SUS-23-008

- Targeting 2HDM+a model [CERN-LPCC-2018-02]
  - χ:Dirac DM fermion; ***a:*** addional light pseudoscalar
- mono-bb: **bb + high** p_T^{miss} signature



- 1 and 2 b-jet categories
  - **DY(ll)/tt/W(lv) Control Regions (CR) with events with leptons**

- Signal extraction from **fit to** $\cos\Theta^*$ in Signal and Control Regions

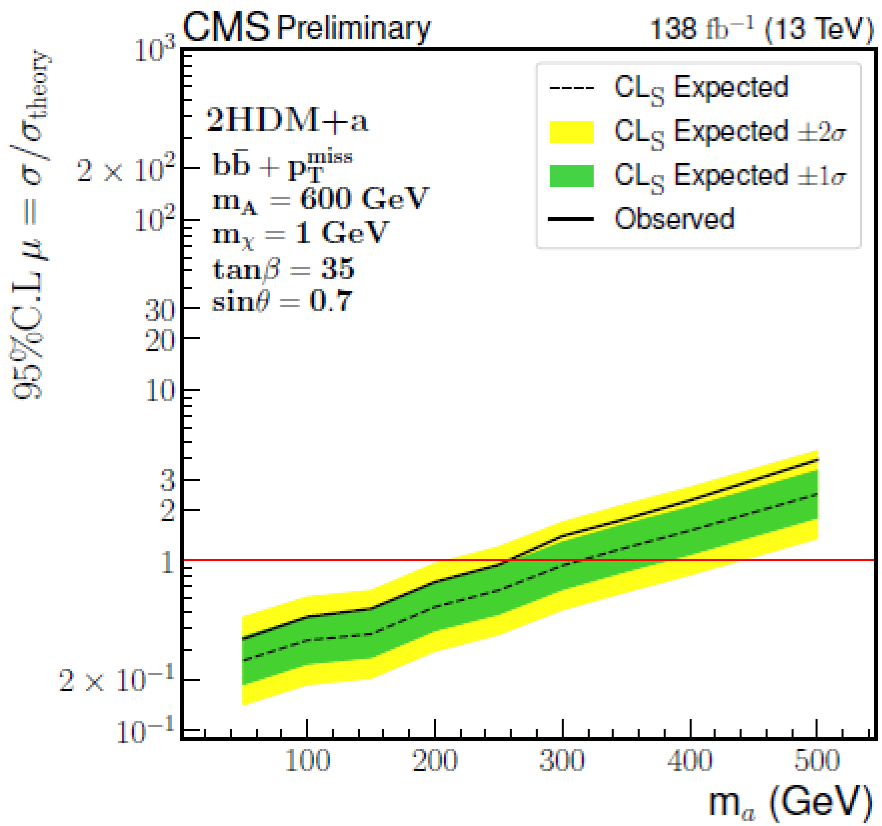


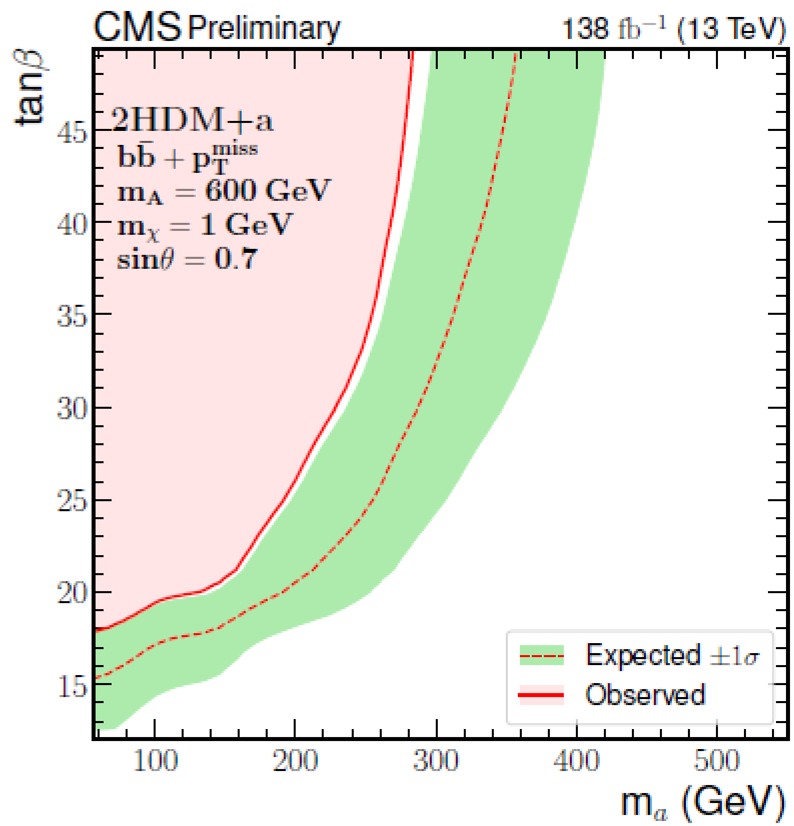
$$\cos\Theta^* = \left|\tanh\left(\frac{\eta_1 - \eta_2}{2}\right)\right|$$

DM + bb (non-resonant)

NEW: CMS-PAS-SUS-23-008

- No significant excess. 95% CL limits:





▲ **m_a up to ~260 GeV** ▲ m_a - tanβ plane

Better sensitivity at high tan β ($g_{b\bar{b}A}, g_{b\bar{b}a}$ couplings are tanβ-enhanced)

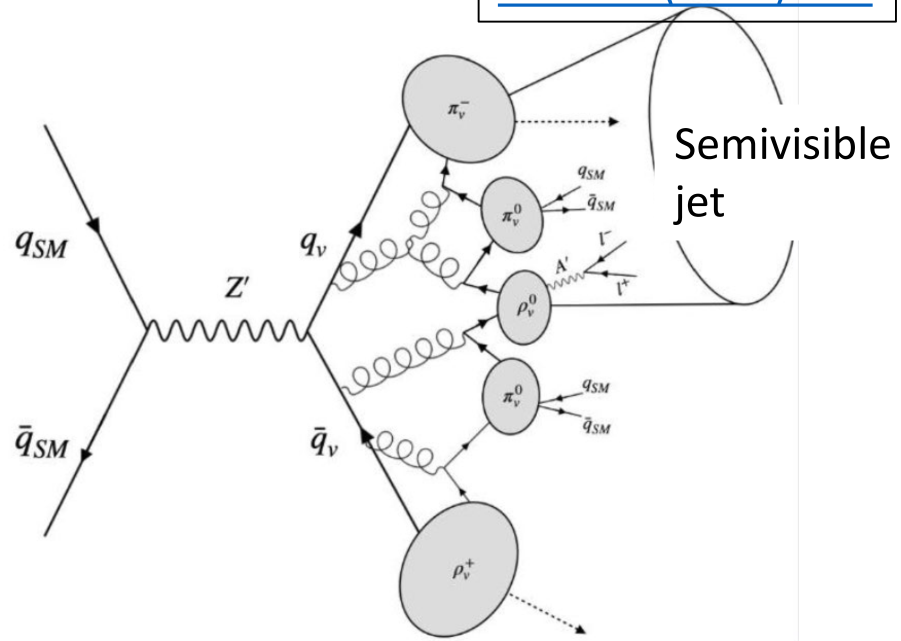
Dark QCD

- Non-minimal Dark Sectors may have multiple new particles and interactions decoupled from SM (Hidden Valley theories)
- **Dark QCD:** strongly coupled dark sector
  - N_f^{dark} flavors of dark quarks
  - Accessible via collider at high energy corresponding to the mass of the mediator between DS and SM
  - Numerous phenomenological signatures depending on parameters of model
- Distinctive signatures such as **semivisible** jets, **emerging** jets or **SUEPs** (Soft Unclustered Energy Patterns)

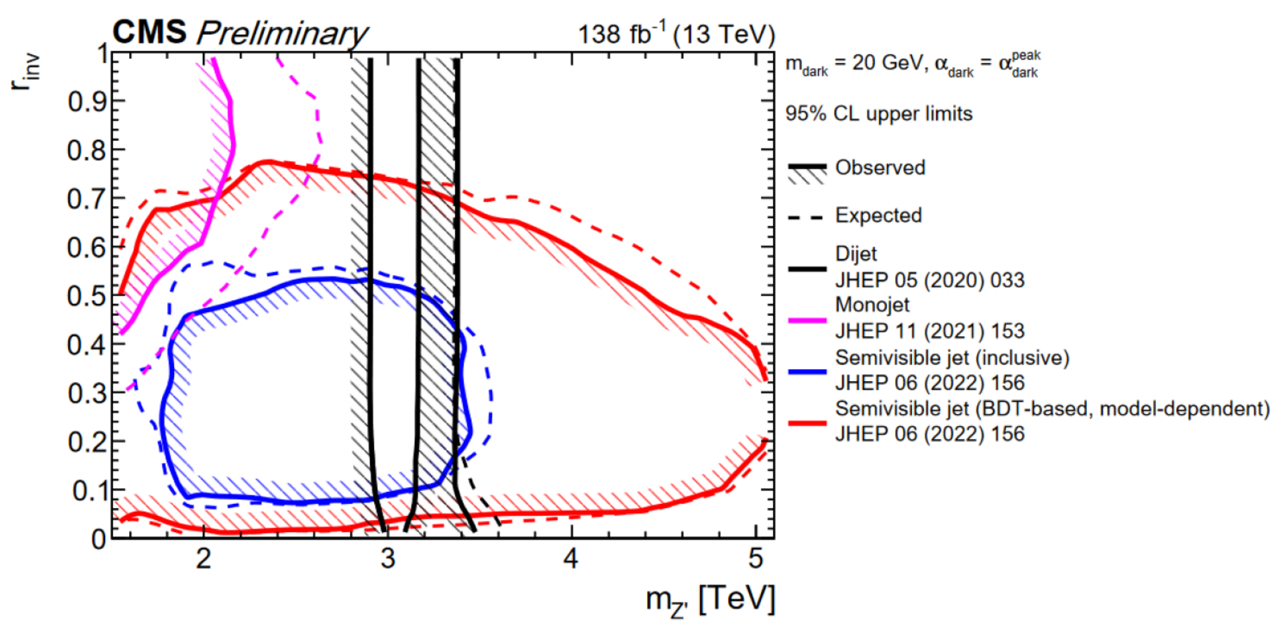
Semivisible jets

[2112.11125](#)
JHEP 06 (2022) 156

- Dark quarks could shower and hadronize forming dark jets
  - Stable dark hadrons become DM candidates
  - Unstable dark hadrons decay to SM
- Characterized by r_{inv}
  - Fraction of energy carried by invisible DM particles



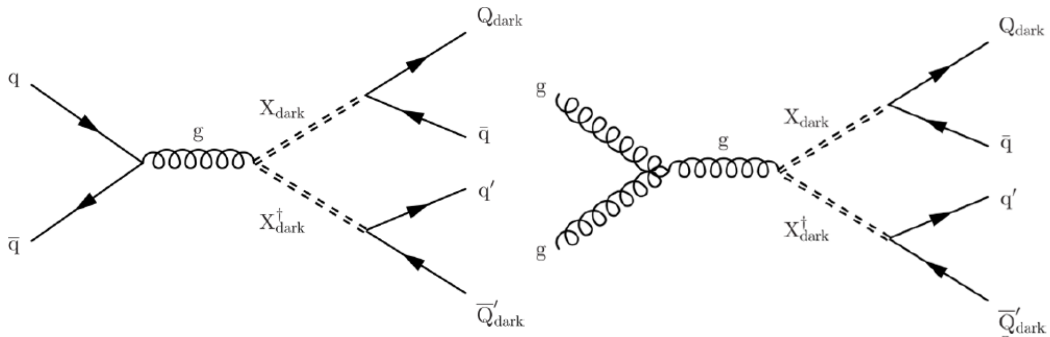
- 95% CL limits on mass of mediator vs r_{inv} (comparison with dijet and monojet analyses)



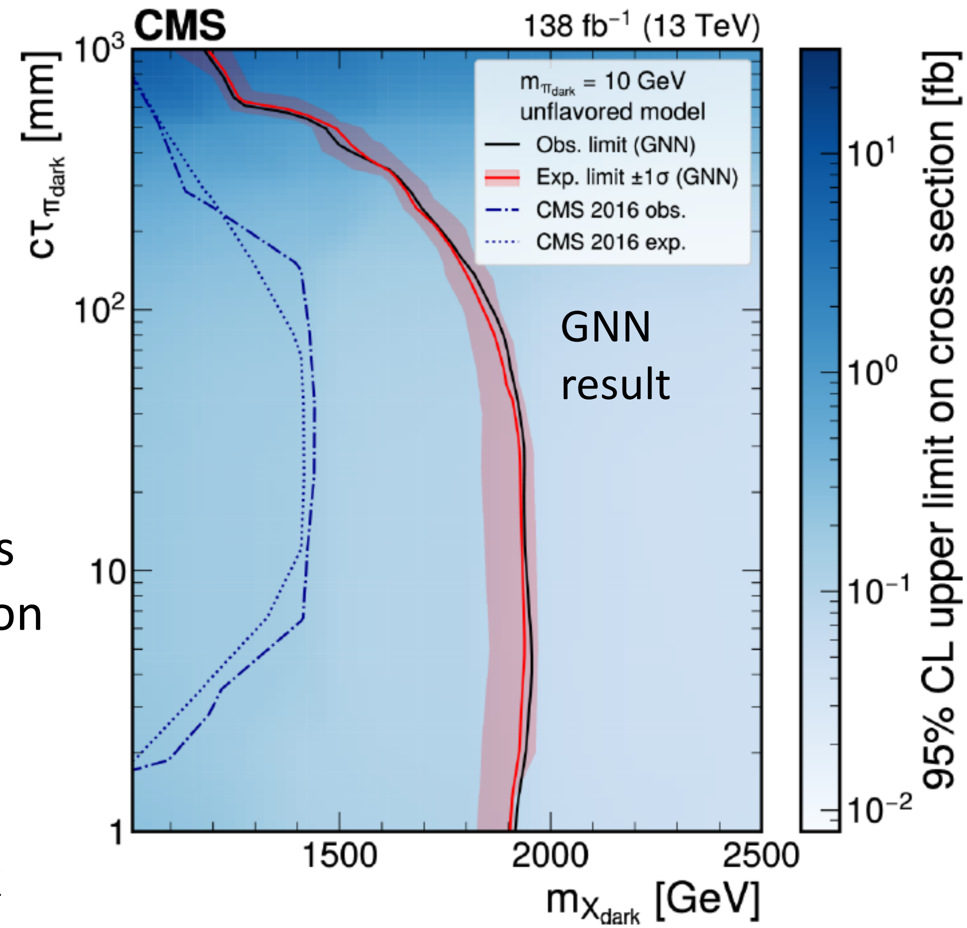
Emerging jets

NEW:
[2403.01556](https://arxiv.org/abs/2403.01556)
Submitted to JHEP

- Parton shower and hadronization on dark sector shorter timescale than dark meson decay to SM particles
- Long-lived dark mesons: Emerging jets
- Analysis signature



  - 2 emerging jets with multiple displaced tracks (at various distances depending on dark meson lifetimes)
  - 2 SM jets
- 2 Emerging jet tagging approaches
  - Selection on jet-level variables based on track displacement (model agnostic)
  - Graph NN trained on specific signal model
- Model depends on mass and lifetime of dark pion, π_{dark}, and the mass of the scalar mediator, X_{dark}

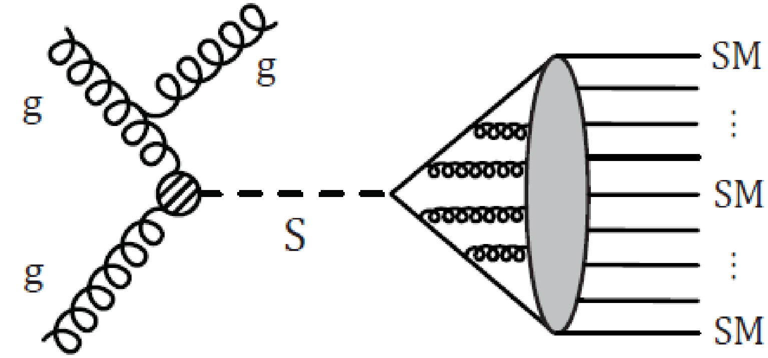


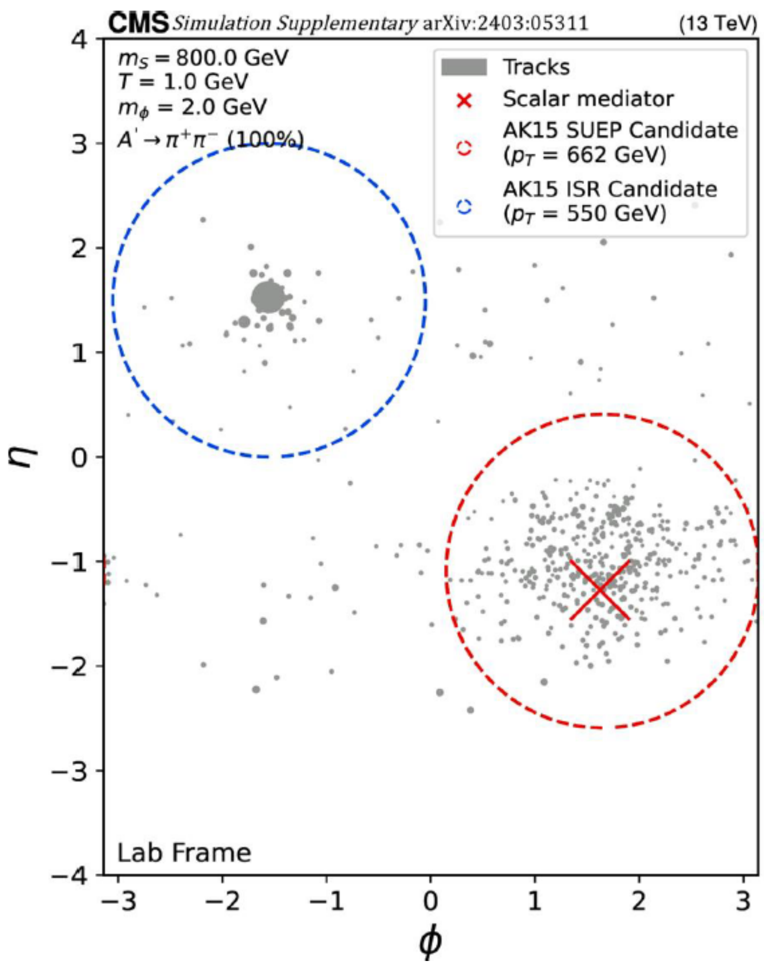
- 95% CL limit on cross section for mass of dark pion = 10 GeV

SUEP

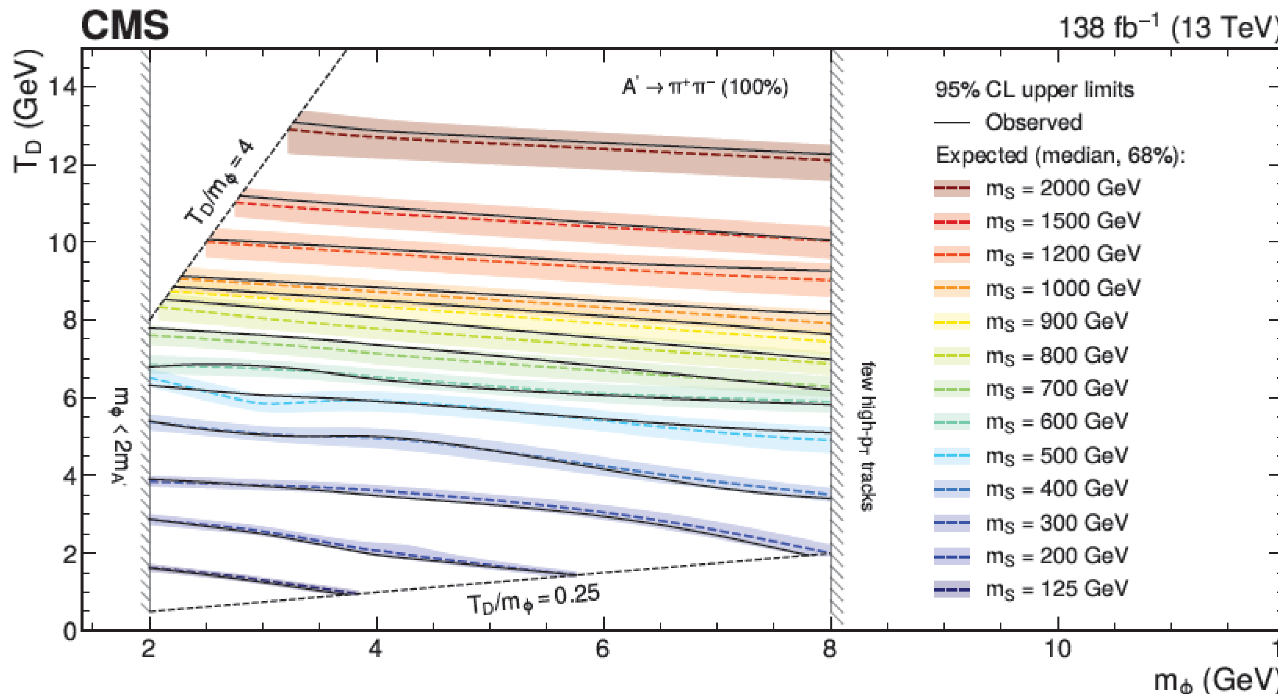
NEW:
2403.05311
Submitted to PRL

- Instead of collimated jets, Dark showers can result in a **large multiplicity** of **spherically- distributed** **low-momentum** charged particles





- Model depends on cascade temperature (T_D), masses of scalar mediator (m_S) and dark meson (m_ϕ)



- 95% CL limit on cross section for various model parameters

Summary

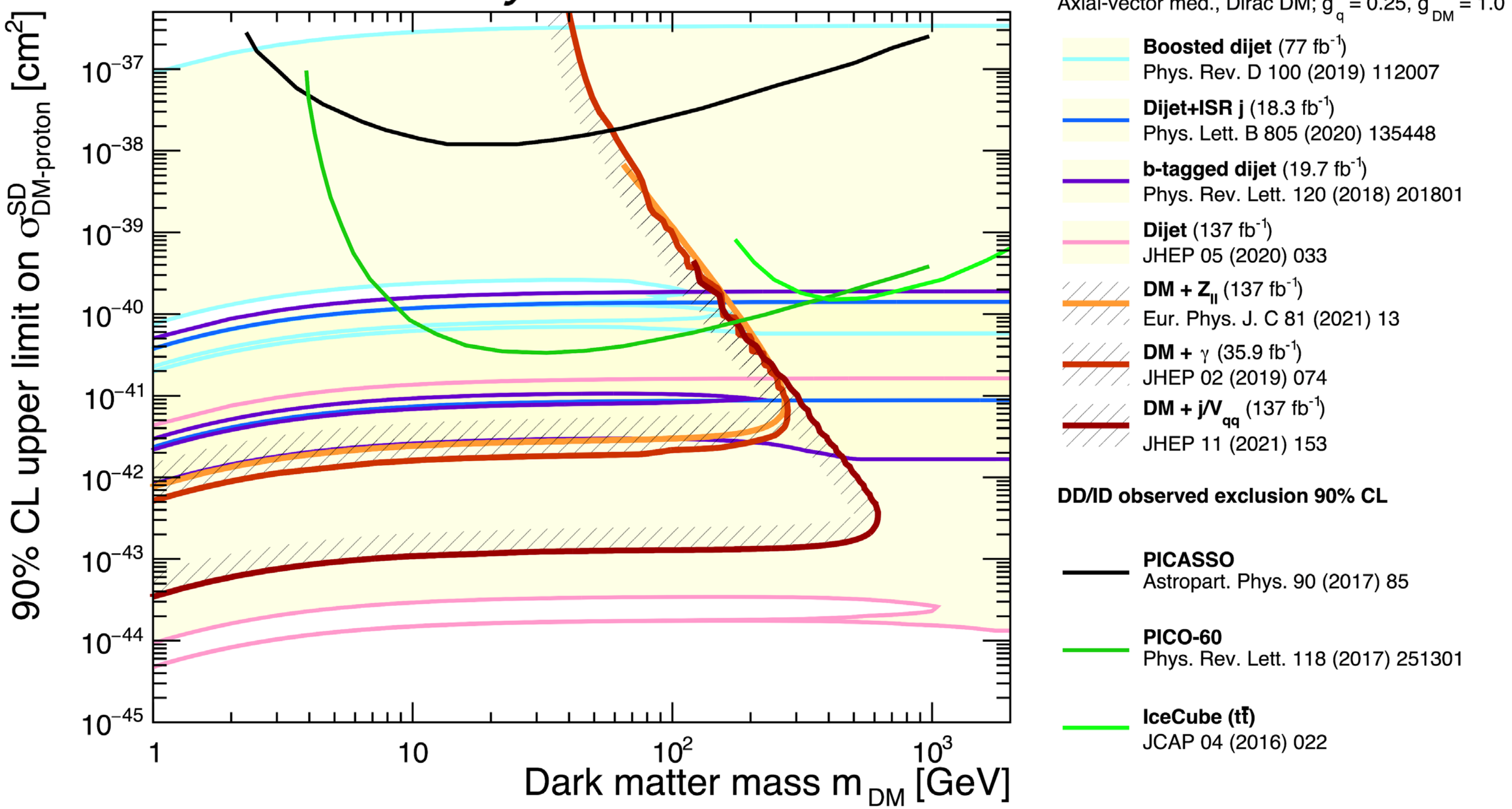
- Explored a wide-variety of DM models making use of the full Run 2 CMS dataset
- Complementary approaches using **simplified** and **extended** dark sector models
- Considered various mediators and broad model-parameter phase space
- From simpler **MET + X** signature to very **unconventional signatures**

Back-up

Z'$_{V/A}$ mediator: comparison with Direct Detection

- 90% CL Limits on scattering DM-Nucleon cross section

Axial - Vector



DM + bb (non-resonant)

NEW:
CMS-PAS-SUS-23-008

- Particle content:
  - Two scalars: h (SM Higgs), H
  - Pair of charged scalars: $H^{\pm}$
  - Two pseudoscalars: A , a
  - Dirac fermion DM

Benchmark Parameters

$$m_H = m_{H^\pm} = m_A = 600\,\text{GeV},$$

$$\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3, m_\chi = 1\,\text{GeV},$$

$$\cos(\beta - \alpha) = 0,\ \tan\beta < 50$$

Parameters

Mixing angles

Between h and H : α

Between A and a : θ

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

Quartic couplings

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

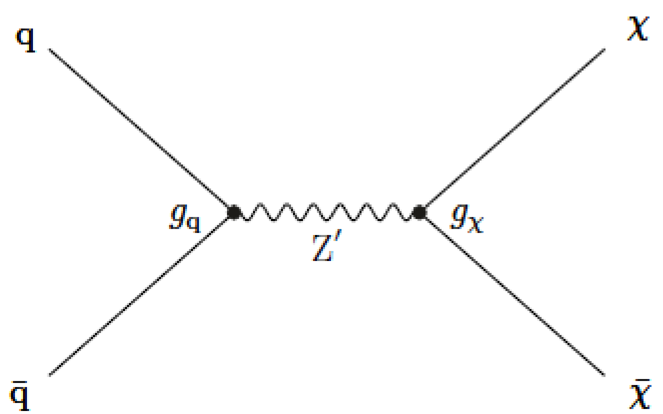
Masses

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

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

Semivisible jets

- Resonant Production



Preselection requirements
$p_T(J_{1,2}) > 200\,\text{GeV},\ \eta(J_{1,2}) < 2.4$
$R_T > 0.15$
$\Delta\eta(J_1, J_2) < 1.5$
$m_T > 1.5\,\text{TeV}$
$N_\mu = 0$
$N_e = 0$
p_T^{miss} filters
$\Delta R(j_{1,2}, c_{nonfunctional}) > 0.1$

Final selection requirements
veto $f_\gamma(j_1) > 0.7$ & $p_T(j_1) > 1.0\,\text{TeV}$
veto $-3.05 < \eta_j < -1.35$ & $-1.62 < \phi_j < -0.82$ *
$\Delta\phi_{min} < 0.8$

- Model parameters

$N_c^{dark} = 2,\ N_f^{dark} = 2$

$m_{Z'}$, m_{dark}, α_{dark}, and r_{inv}.

$0.15<R_T<0.25$ $R_T>0.25$

$R_T = \not{E}_T/M_T$

- Fit mT(JJ, MET) distribution in each signal region

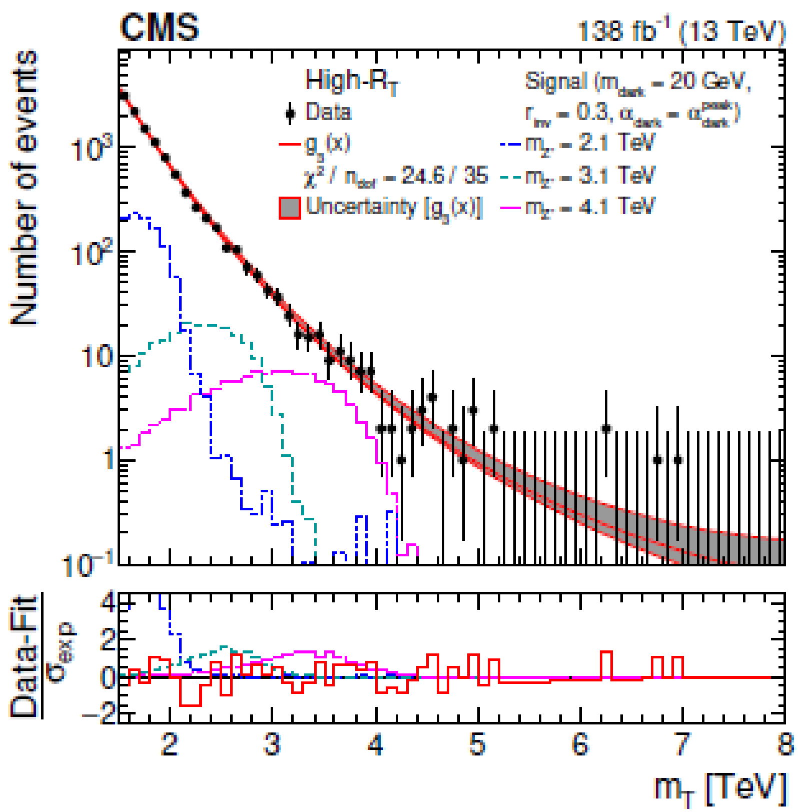
$$g(x) = \exp(p_1 x)x^{p_2[1+p_3 \ln(x)]}$$

$x = m_T/\sqrt{s}$ (with $\sqrt{s} = 13\,\text{TeV}$) and p_1, p_2, and p_3 are free parameters in the fit

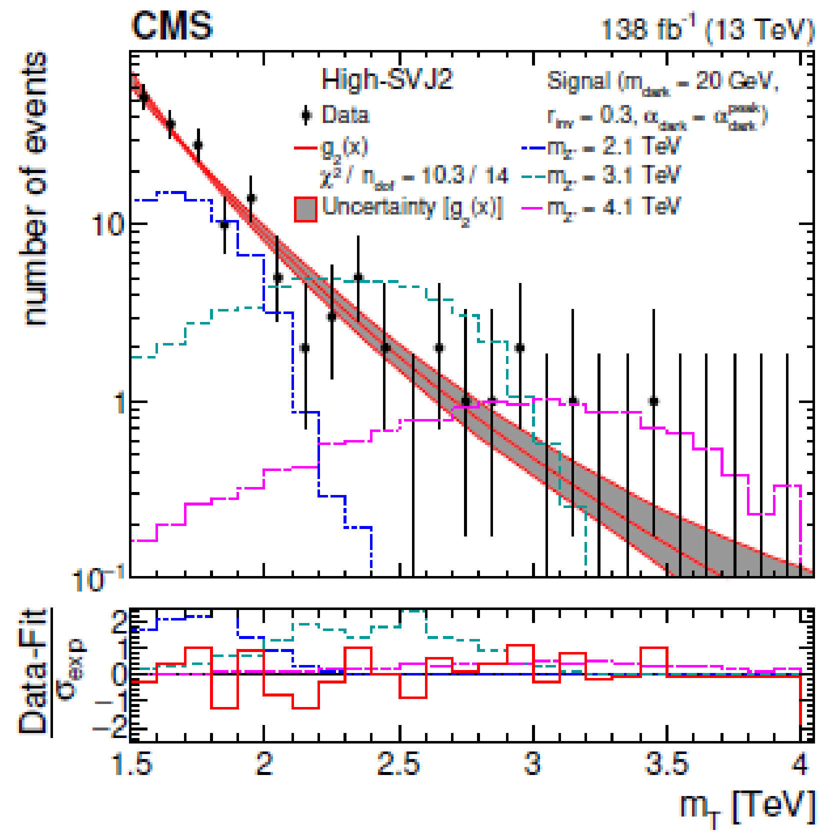
Semivisible jets

- SVJ Tagger (BDT)

Trained used a combination of signal models against a combination of tt and QCD



Cut-based



BDT