



# TWENTY-FIRST LOMONOSOV CONFERENCE

August, 24-30, 2023  
ON ELEMENTARY PARTICLE PHYSICS  
MOSCOW STATE UNIVERSITY

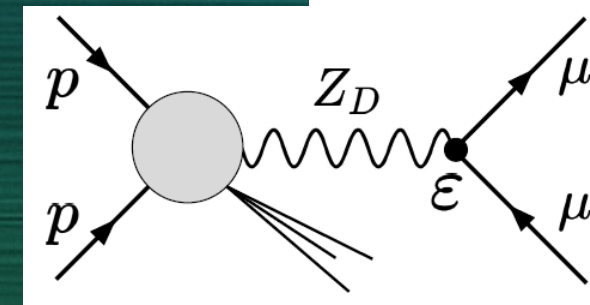
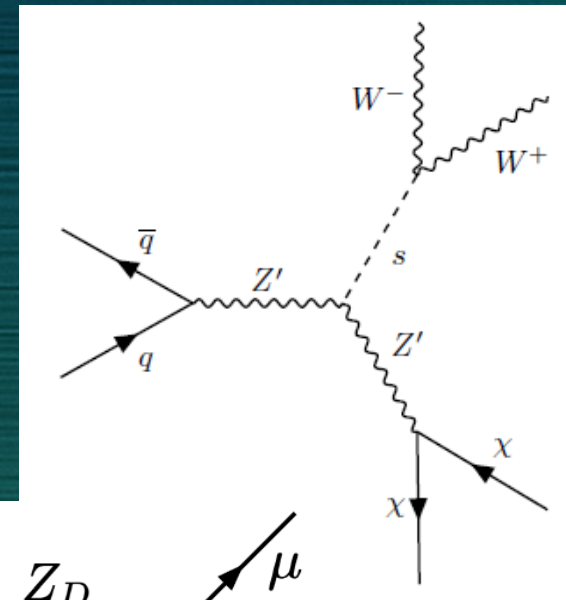
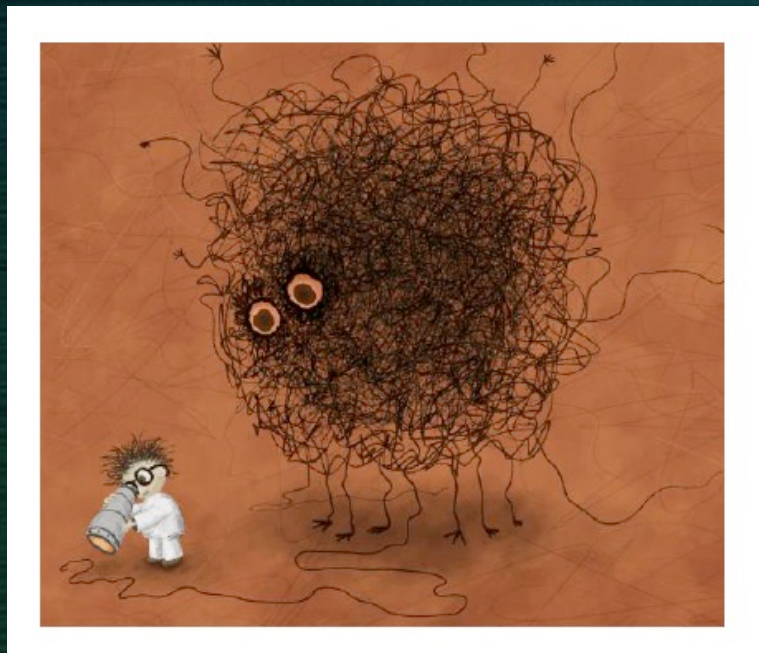
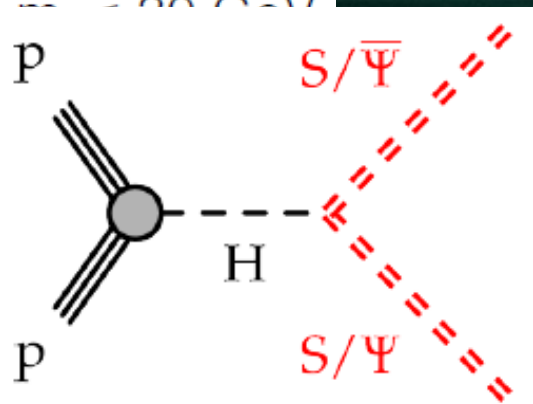
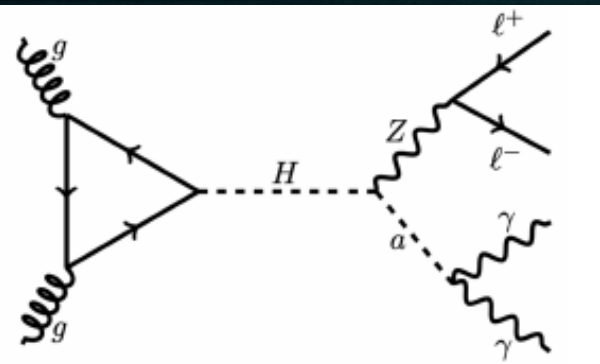


## Dark matter searches at CMS

Maria Savina, JINR, Dubna

on behalf of the CMS Collaboration

[Maria.Savina@cern.ch](mailto:Maria.Savina@cern.ch)



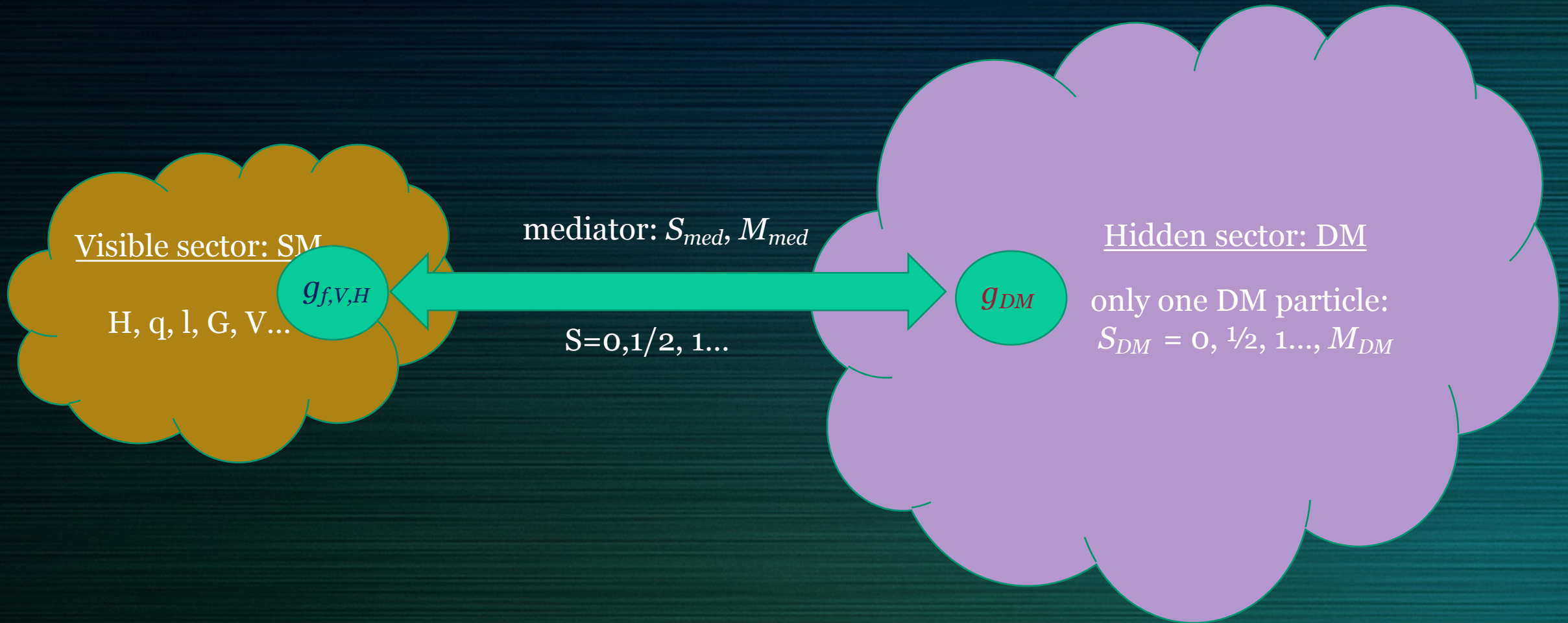


# Talk outline

- ✓ Simplified dark matter models: **DM portals** (DM particles + mediators, “simplified models” of DM/SM interaction)
- ✓ Prompt DM production:
  - CMS HIG-21-007** – invisible Higgs decay
  - CMS PAS HIG-22-003** – exotic Higgs decays into a  $Za(a \rightarrow 2 \text{ gamma})$
  - CMS PAS EXO-21-005** – prompt GeV-scale dimuon resonance
  - CMS EXO-19-020, JHEP 06 (2022) 156** – resonant production of strongly coupled DM with semivisible jets
  - CMS PAS EXO-21-012** – DM production with a  $WW$  pair
- ✓ LLP signatures:
  - CMS PAS EXO-21-008** – long lived decays in the muon system
  - CMS EXO-20-010** – inelastic dark matter with two displaced muons
- ✓ Summary and outlook



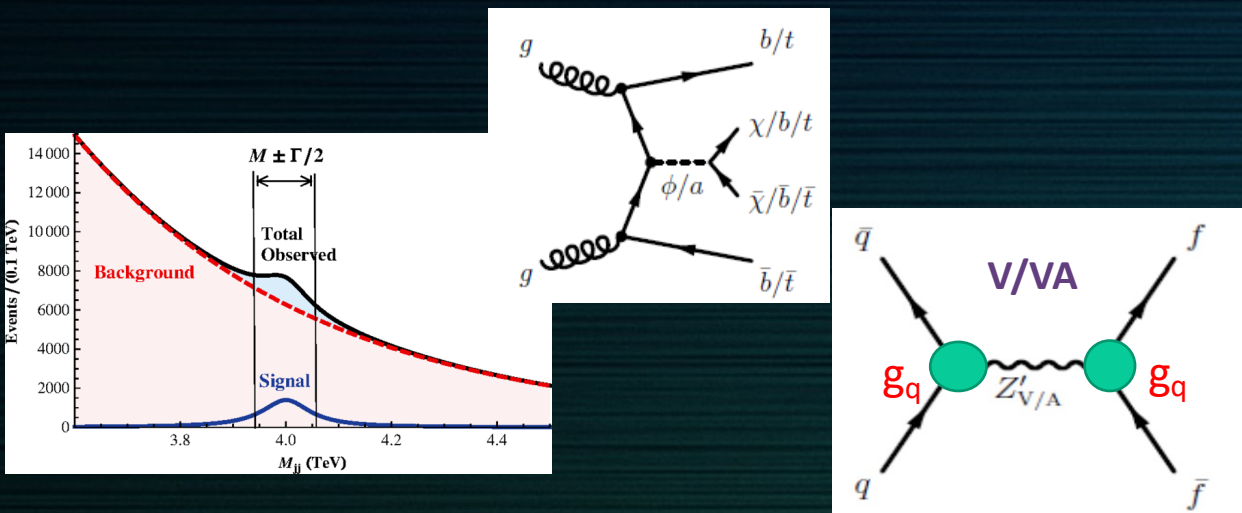
# DM portals: DM particle(s) + mediator(s)



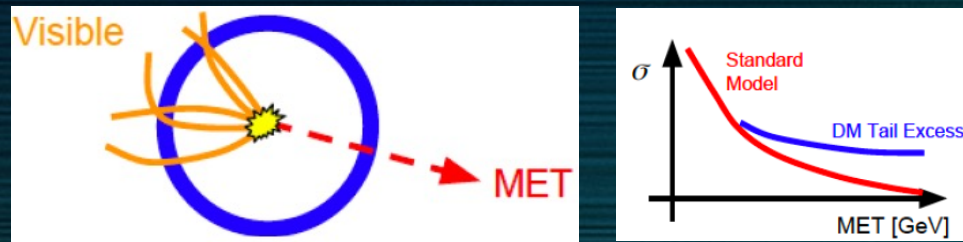
Minimal set of model parameters (the simplest case - masses of mediator and of  $s$  DM particle, couplings)

# Prompt DM signatures, examples (see backup for a full list):

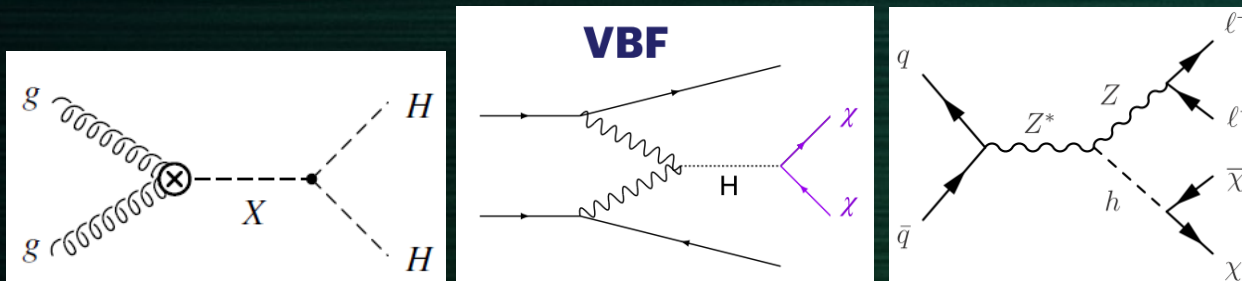
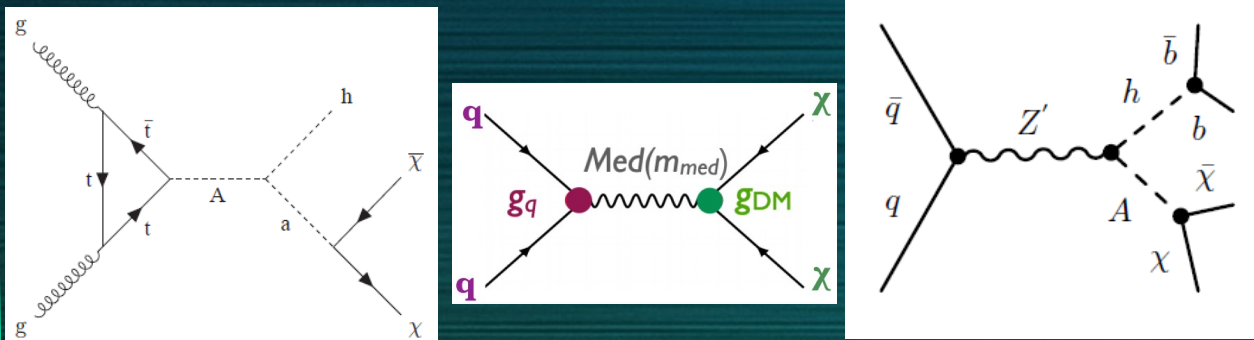
- ✓ fully visible (a new resonance in dijet/dilepton/diboson etc. spectra)



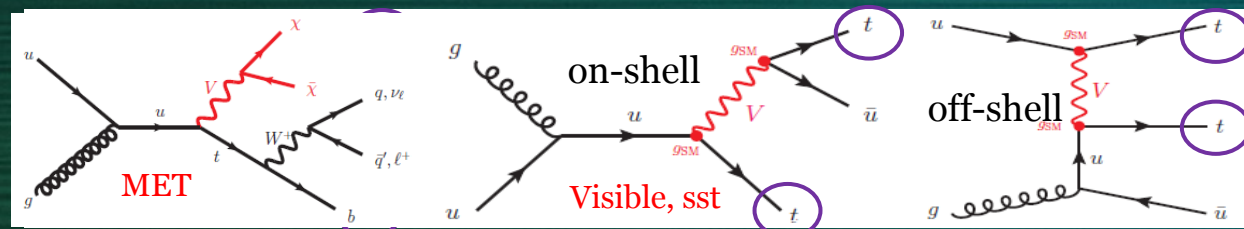
- ✓ MET - decay to DM particle pair (+ a visible “tag”  $X(=jet/gamma/Z/H)$ )



- ✓ non-standard properties of SM particles (higgs sector – higgs boson pair production,  $h_{125}$  to invisible...)



- ✓ flavor violating processes

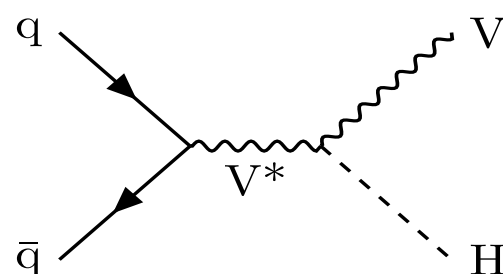
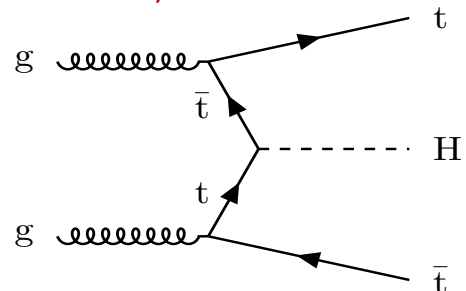




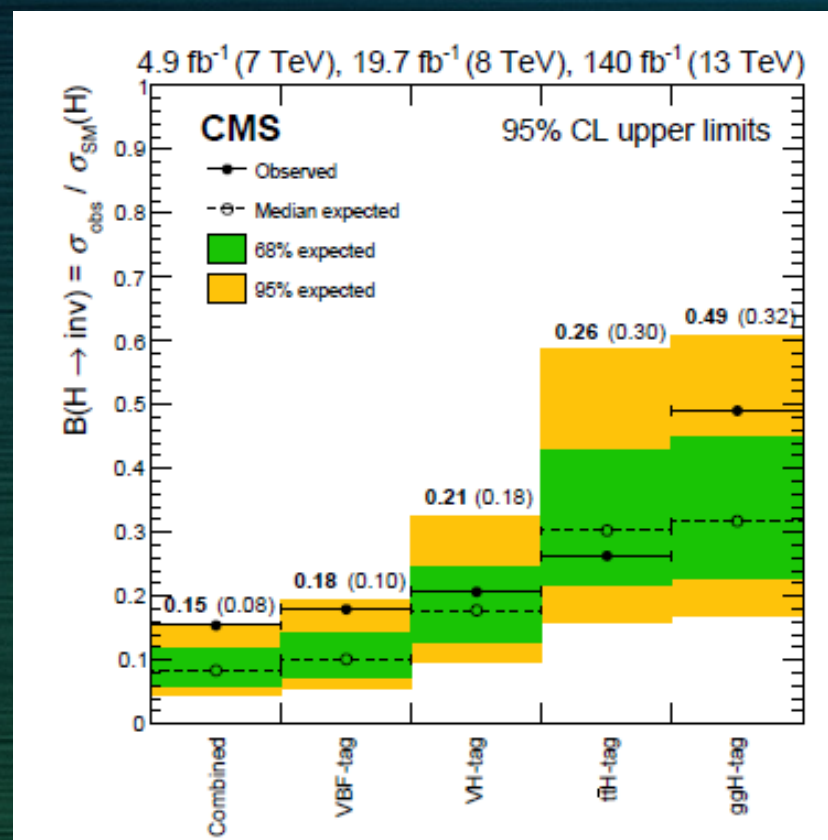
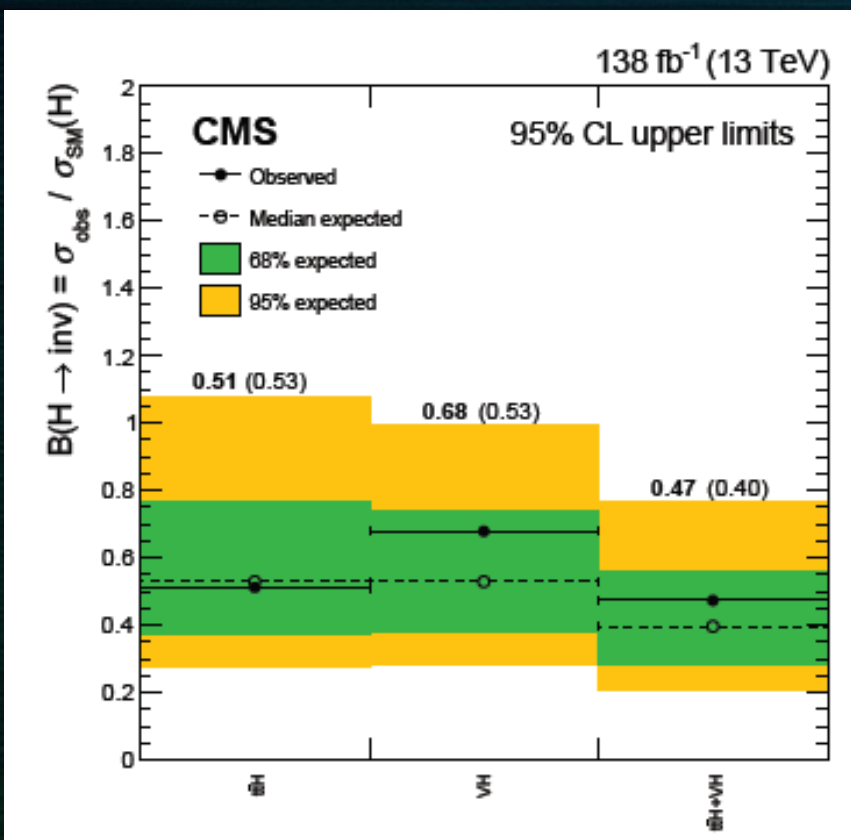


# Combination of $h_{125} \rightarrow$ invisible searches for $t\bar{t}H$ and $VH$

resolved/boosted  $t\bar{t}H$



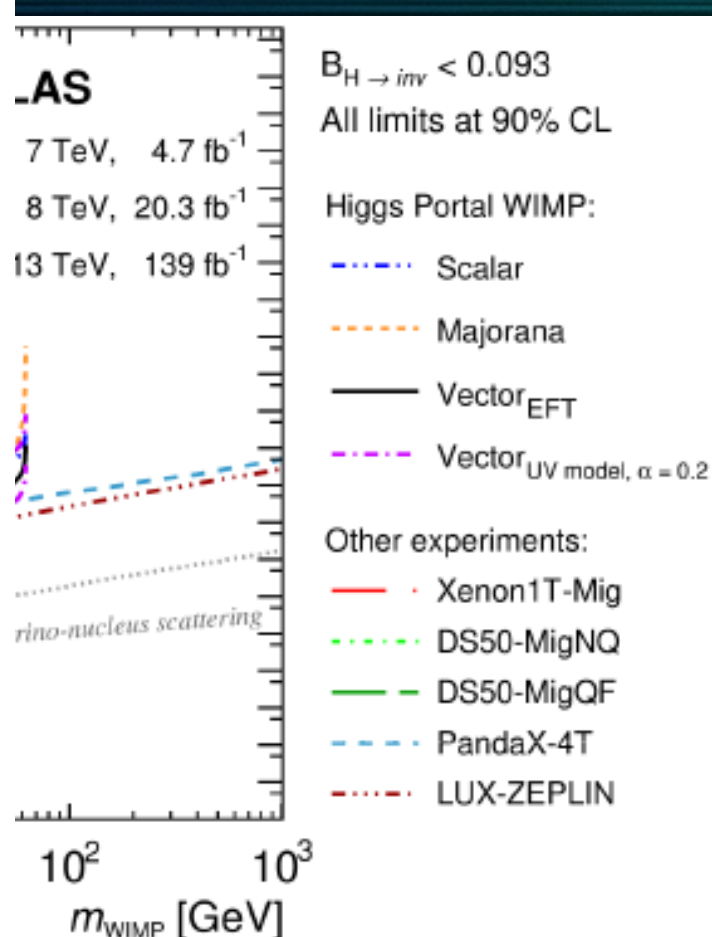
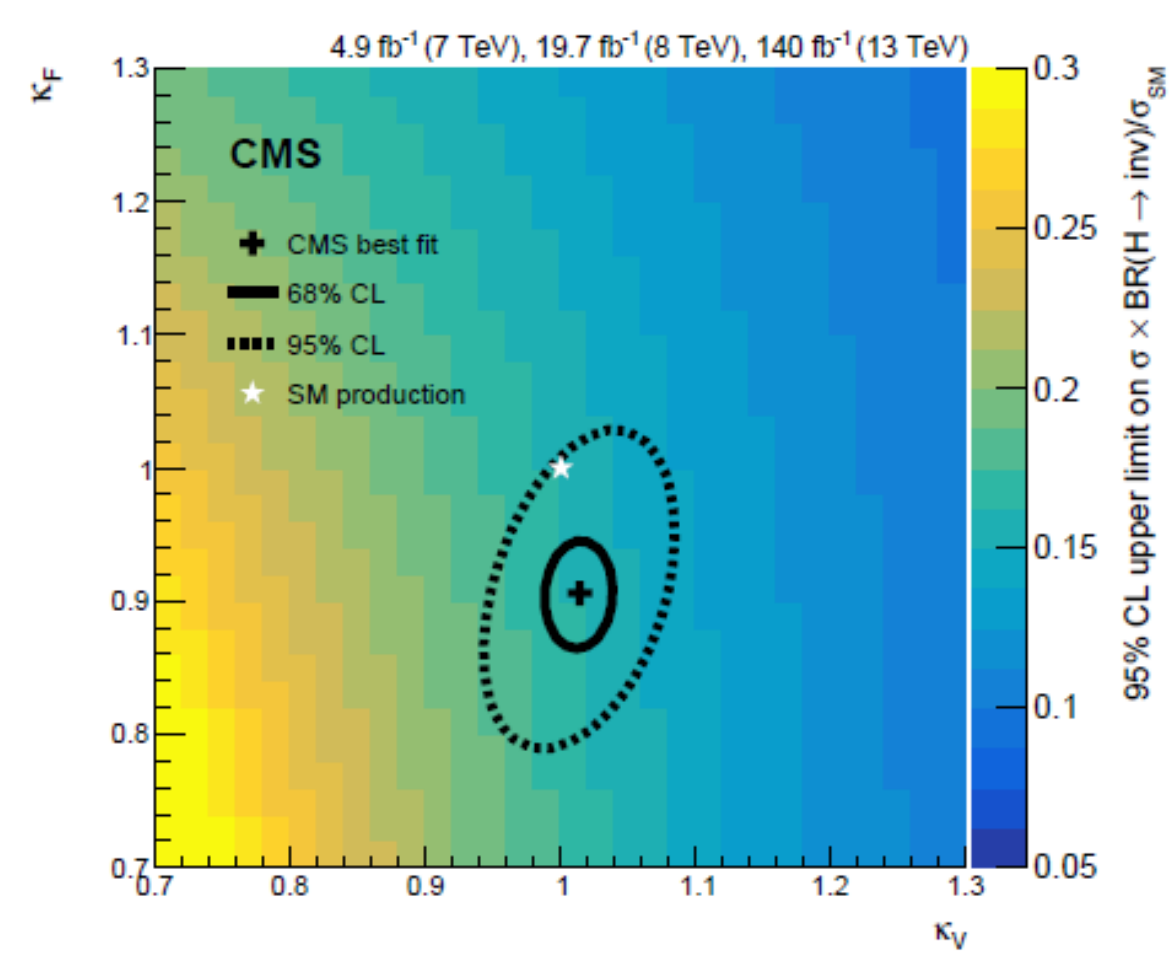
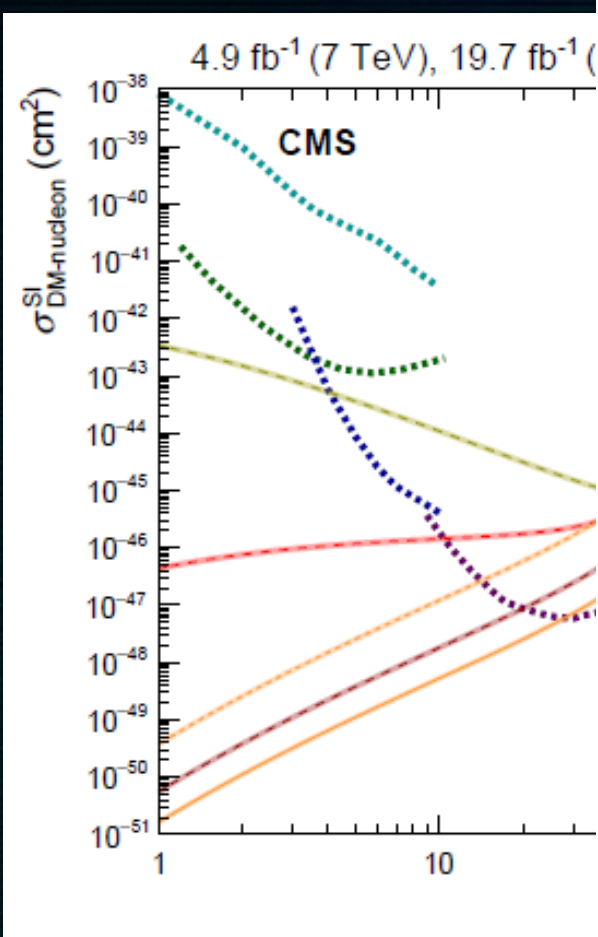
CMS HIG-21-007,  
arXiv:2303.01214 [hep-ex]





# Combination of $h_{125} \rightarrow$ invisible searches

CMS HIG-21-007  
ATLAS HIGG-2021-05

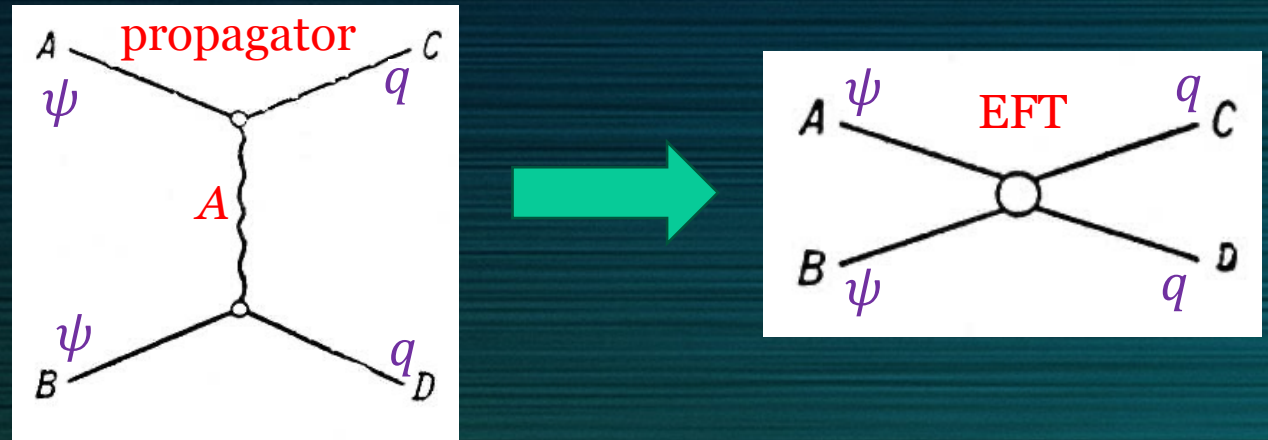
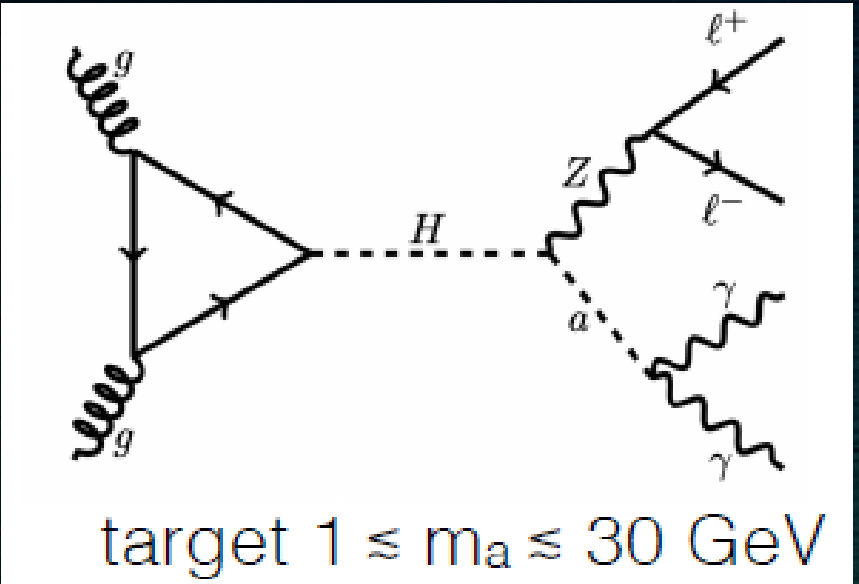


CMS:  $\text{BR}(H \rightarrow \text{inv.}) < 15\%$  (8% expected)  
 ATLAS:  $\text{BR}(H \rightarrow \text{inv.}) < 10.7\%$  (7.7% expected)



# Exotic higgs decays $h \rightarrow Za, Z \rightarrow ll, a \rightarrow 2 \text{ gamma}$

The first search of such type for axion-like particles (ALPs) at the LHC.  
Pseudoscalar portal, the light enough ALP,  $Z^0$ -ALPs interactions



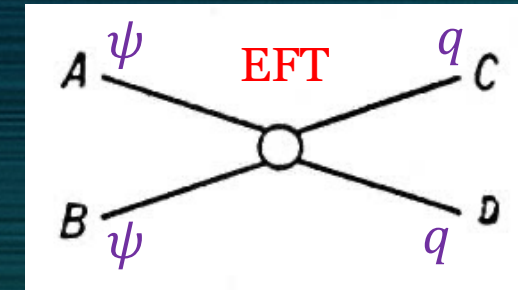
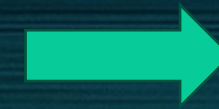
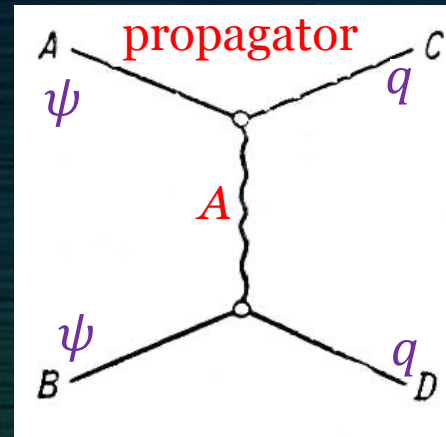
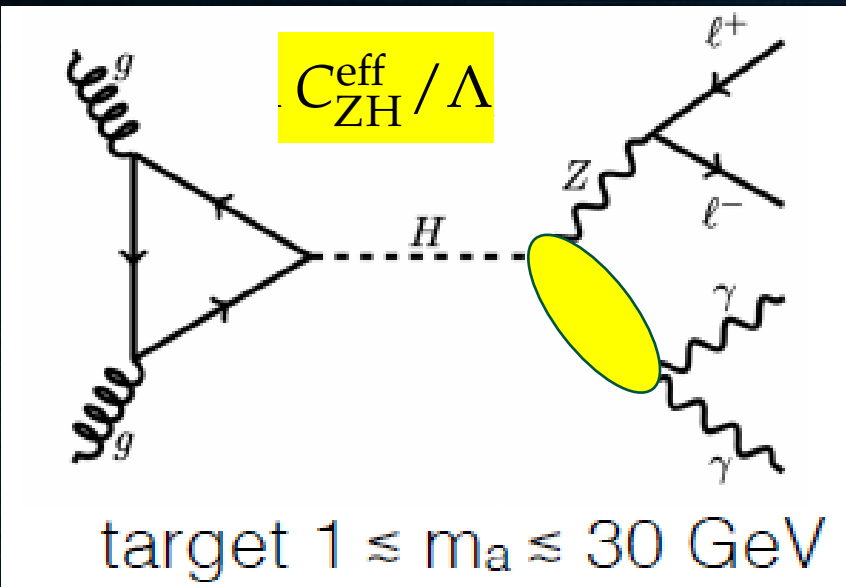
$C_i$  are Wilson coefficients in the EFT approach that describe the ALP/SM couplings

$$\mathcal{L}_{EFT} = \sum_i \frac{C_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$



# Exotic higgs decays $h \rightarrow Za, Z \rightarrow ll, a \rightarrow 2 \text{ gamma}$

The first search of such type for axion-like particles (ALPs) at the LHC.  
Pseudoscalar portal, the light enough ALP,  $Z^0$ -ALPs interactions



$C_i$  are Wilson coefficients in the EFT approach that describe the ALP/SM couplings

$$\mathcal{L}_{EFT} = \sum_i \frac{C_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \dots$$

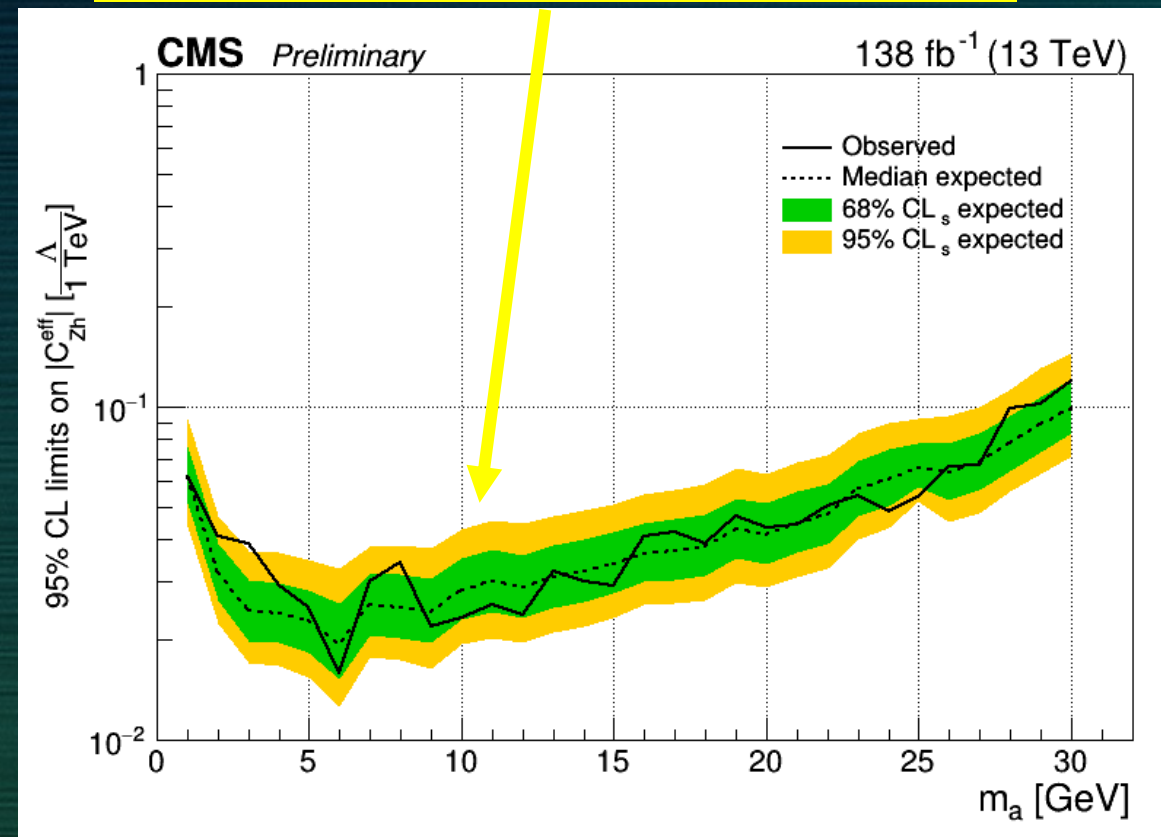
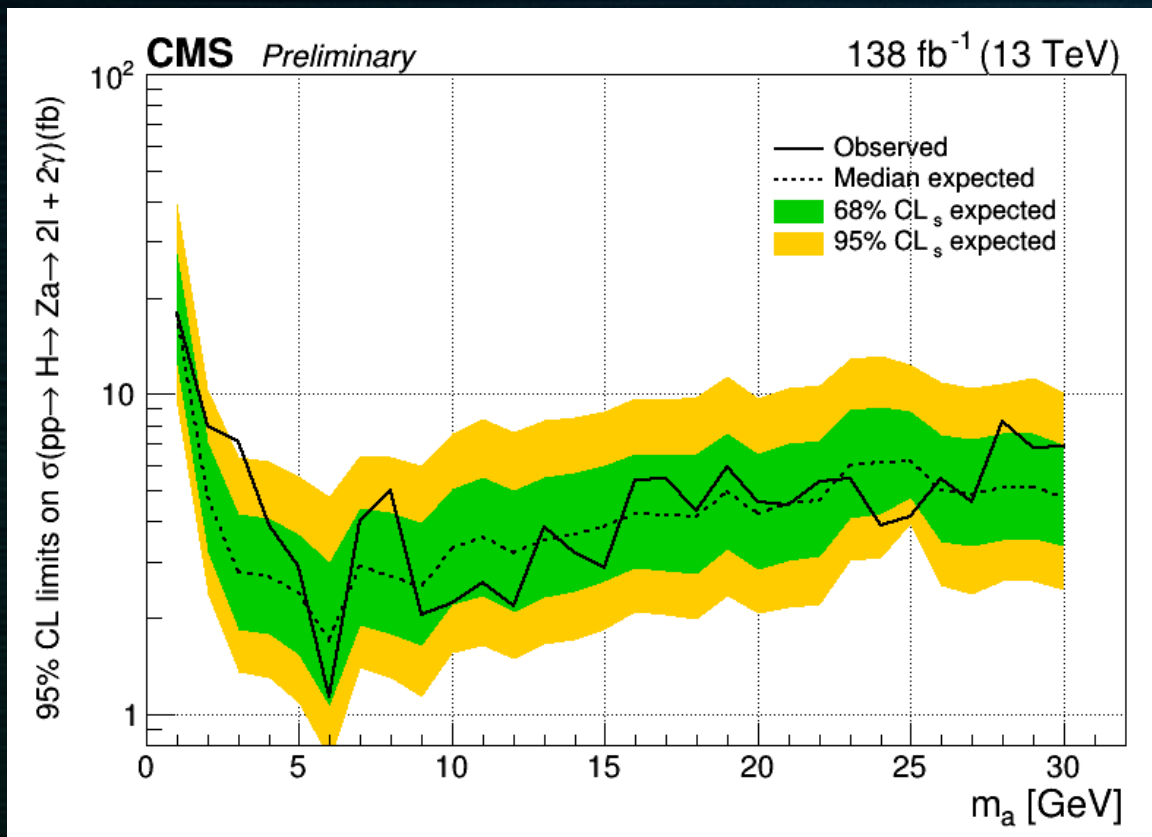




# Exotic higgs decays $h \rightarrow Za, Z \rightarrow ll, a \rightarrow 2 \text{ gamma}$

CMS PAS HIG-22-003

Limit on  $C_{ZH}^{\text{eff}} / \Lambda$ , when ALP decays exclusively in a diphoton,  $\Lambda$  is large

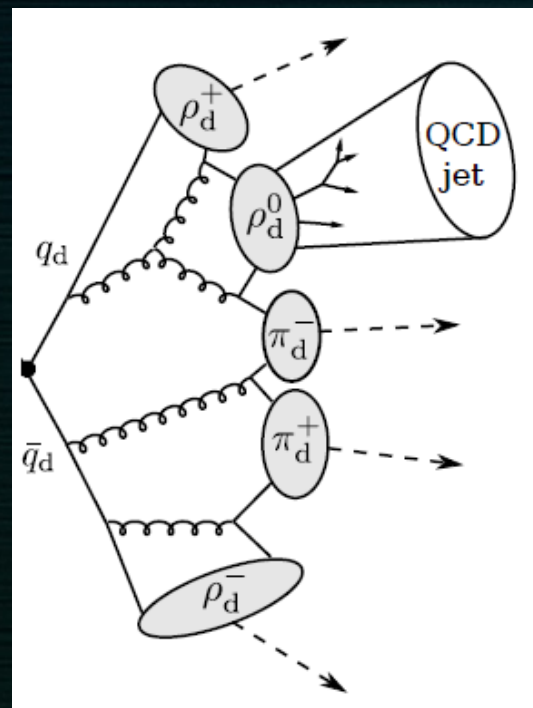
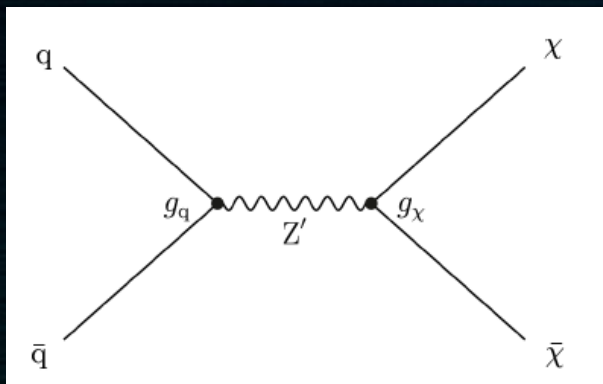




# Resonant production of strongly coupled DM for semivisible jets

Hidden valley concept, hidden sector, new non-abelian symmetries in DS, strongly interacting DM (“dark QCD”), vector mediator  $Z'$ . A large-scale suppression of SM/DM interactions, “semivisible” jet substructure

JHEP 06 (2022) 156  
CMS EXO-19-020

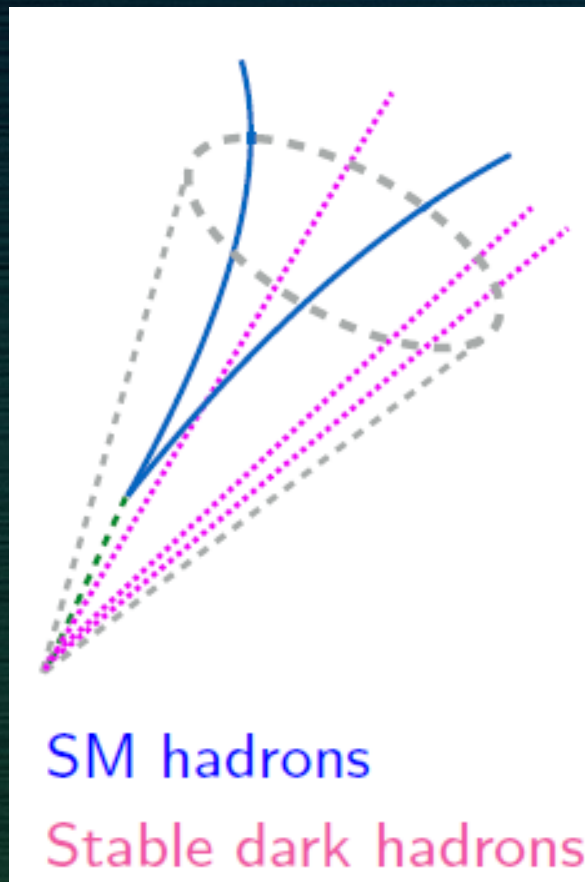


semi-  
visible jets



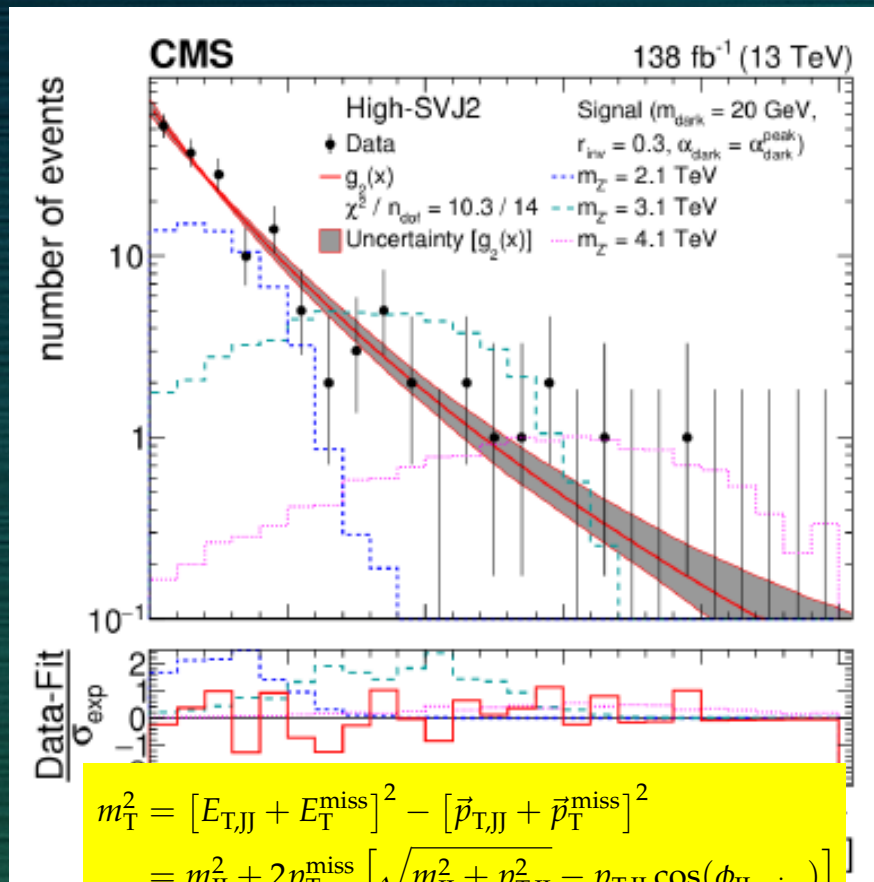
DM part  
(visible) +  
SM part  
(invisible)

$x_{sec.}$ ,  $m_{Z'}$ ,  
 $m_{dark}$ ,  $g_{dark}$ ,  
 $r_{inv}$



SM hadrons

Stable dark hadrons



$$m_T^2 = [E_{T, JJ} + E_T^{miss}]^2 - [\vec{p}_{T, JJ} + \vec{p}_T^{miss}]^2$$
$$= m_{JJ}^2 + 2p_T^{miss} \left[ \sqrt{m_{JJ}^2 + p_{T, JJ}^2} - p_{T, JJ} \cos(\phi_{JJ, miss}) \right]$$

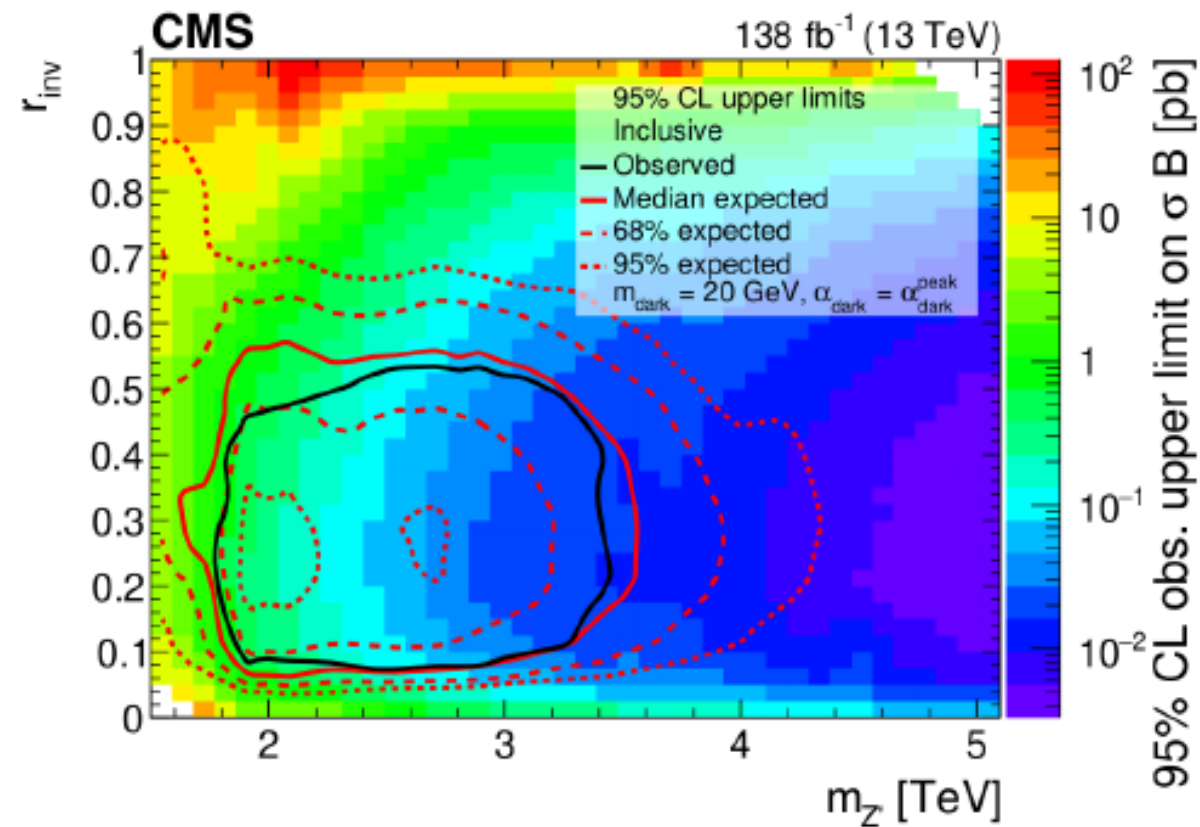
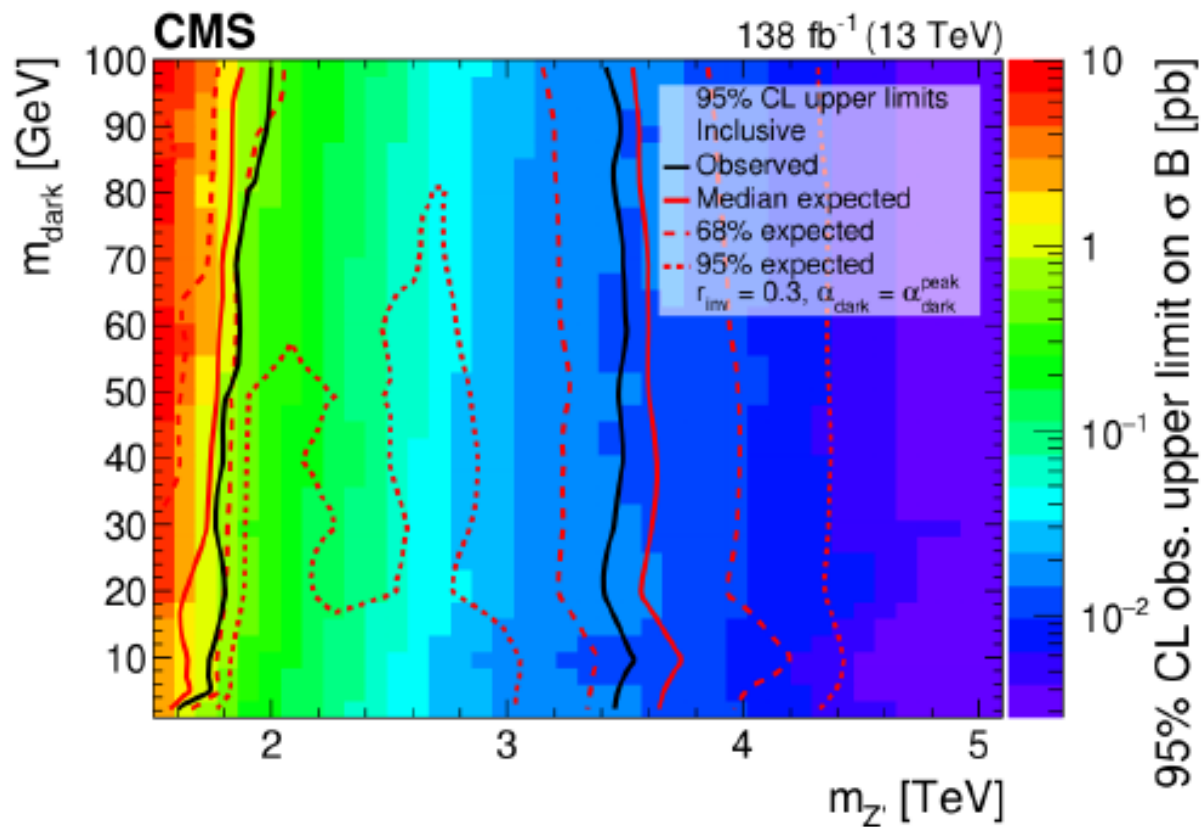




# Resonant production of strongly coupled DM for semivisible jets

The first CMS study of jet invisible contribution with dark sector I interpretation. The fraction  $r_{inv}$  of stable invisible dark hadrons in between 0 (dijet, small MET) and 1 (large MET)

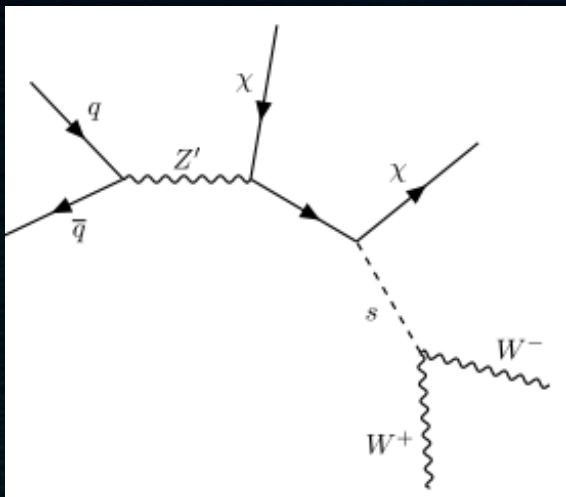
JHEP 06 (2022) 156  
CMS EXO-19-020



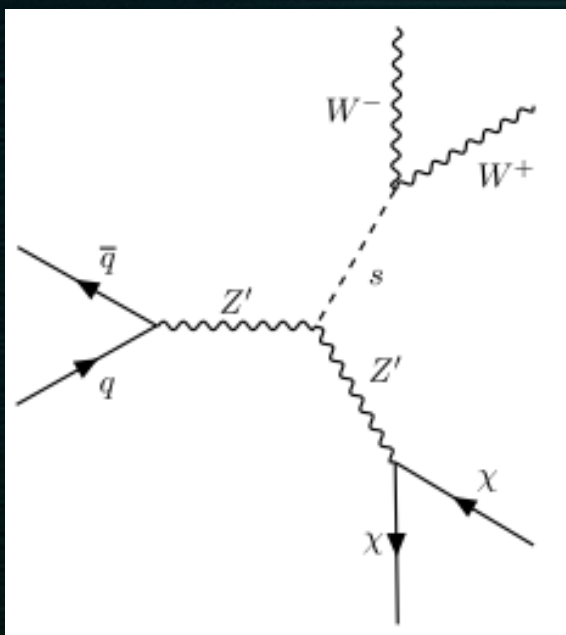
See also backup for LLP dark showers – emerging jet signature



# Dark Higgs model, resolved decay of $s(W^+W^-) + E_T^{\text{miss}}$



- ✓ “Double portal”: both “dark higgs”  $s$  and massive  $Z'_V$  coupled to SM.
- ✓ A new higgs state is weakly mixed with SM  $h$ , a new  $U(1)'$   $\rightarrow$  SSB( $s$ )  $\rightarrow$  massive  $Z'_V$  coupled to quarks only
- ✓  $s \rightarrow W^+W^-$  decay dominates at large  $s$  mass values

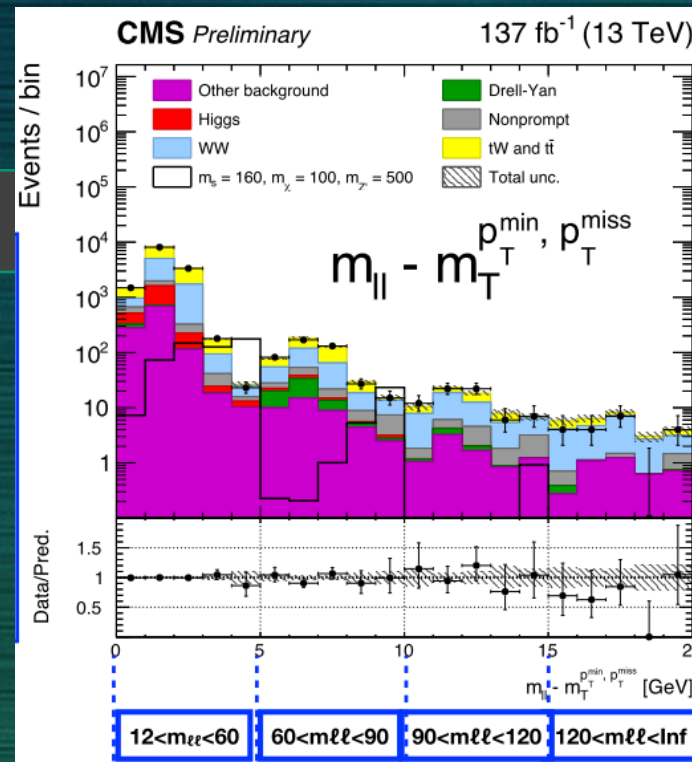
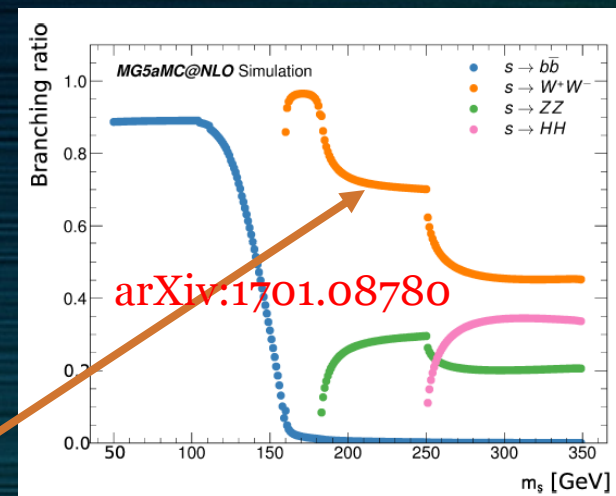


Model parameters :  $m_s, m_{Z'}, m_\chi, g_q, g_\chi, \sin\theta$  ( $h-s$  mix.)



CMS-PAS-EXO-20-012

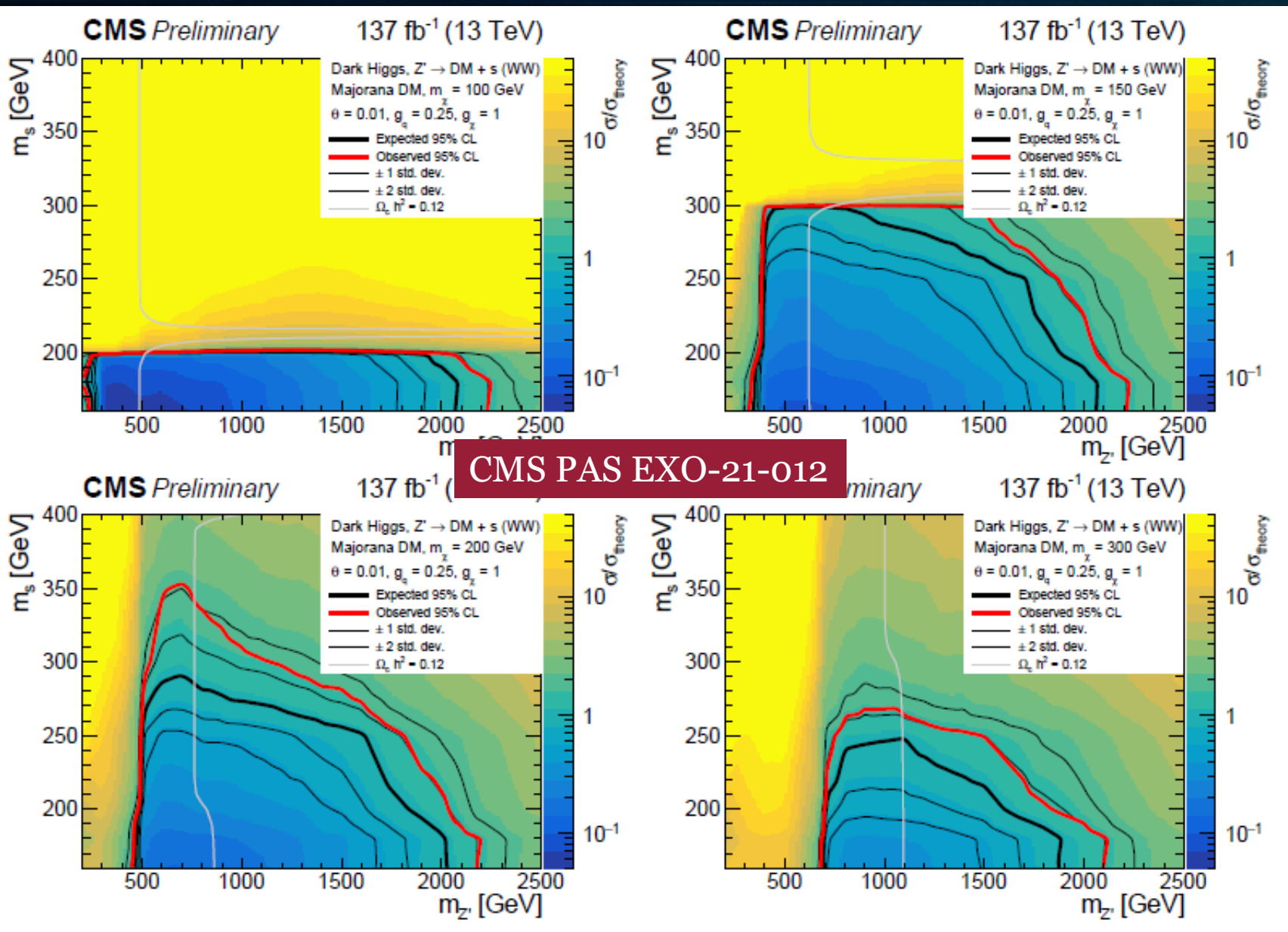
$$m_T^{\ell \text{ min}, p_T^{\text{miss}}} = \sqrt{2p_T^{\ell \text{ min}} p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_T^{\ell \text{ min}}, \vec{p}_T^{\text{miss}})]}$$





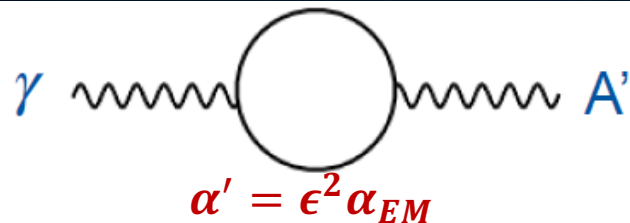


# Dark Higgs model, resolved decay of $s(W^+W^-) + E_T^{miss}$



# Search for dark photons, prompt/LLP

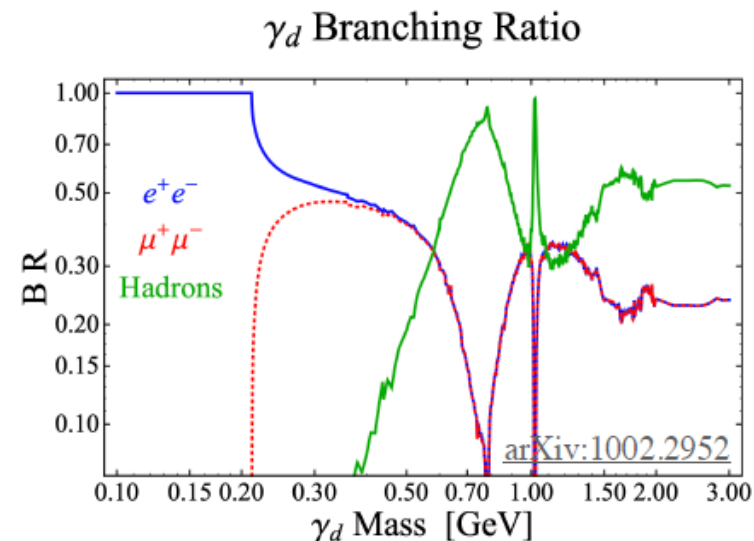
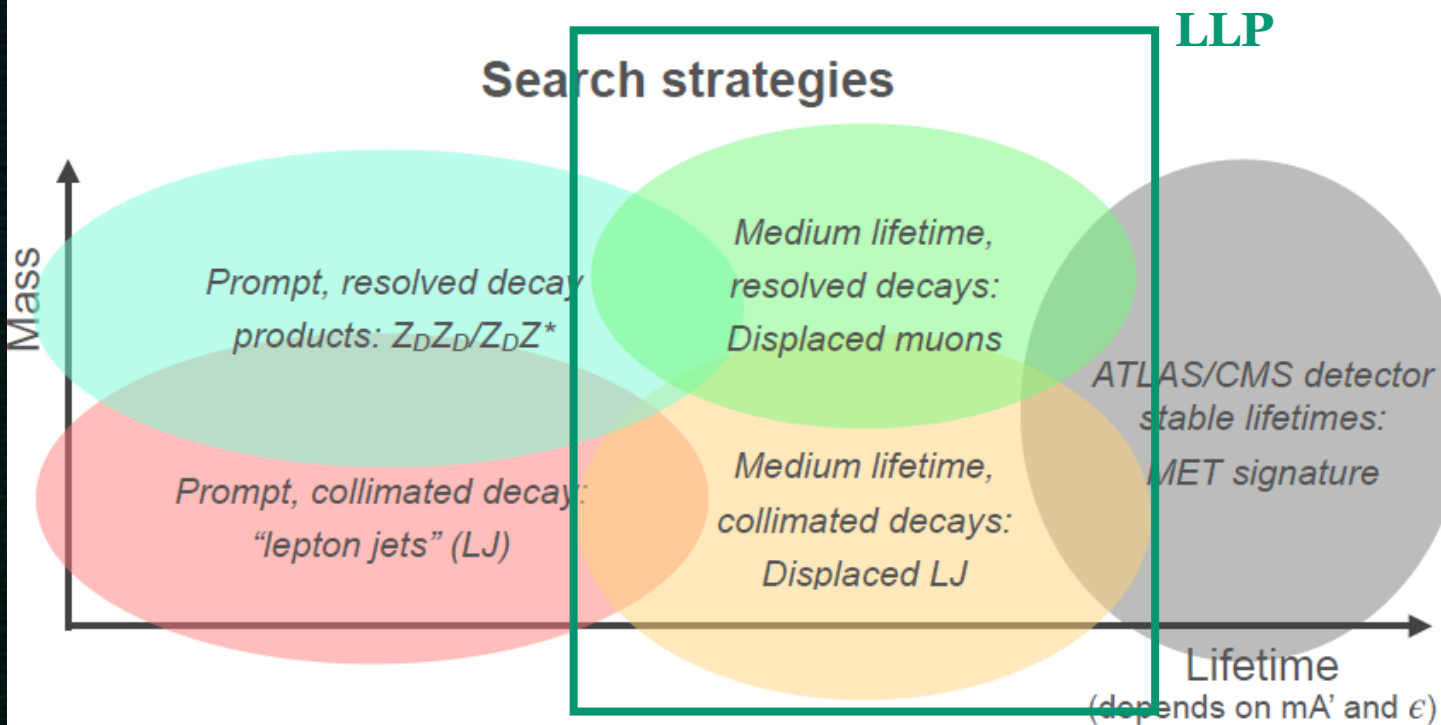
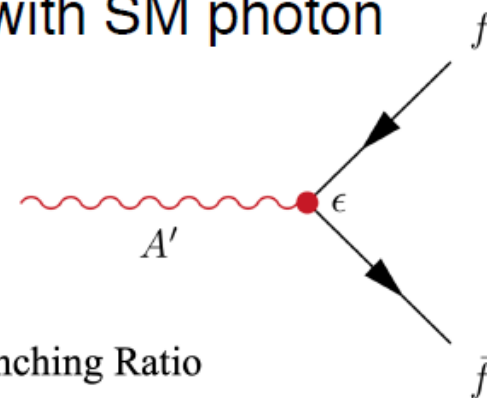
The coupling to SM particles proportional to electric charge



1 or 2 loops: naively  $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

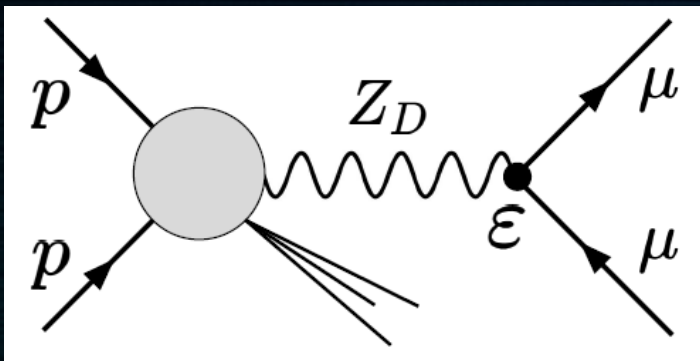
Add a  $U(1)_D$  where massive dark gauge boson ( $A'/Z_D/\gamma_D$ ) kinetically mix with SM photon

**Parameters:** kinetic mixing term,  $\epsilon$ , and  $m_{A'}$





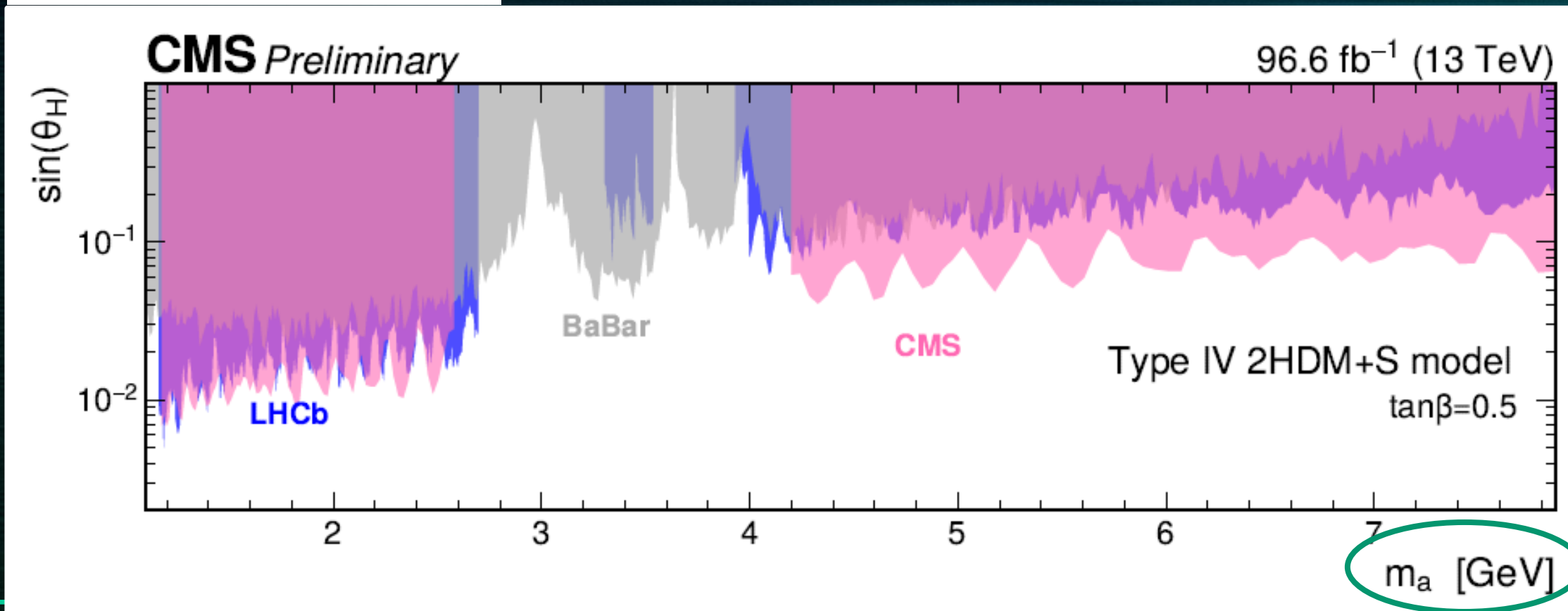
# Search for prompt GeV-scale dimuon resonance



- ✓ minimal dark photon model and
- ✓ light scalar decay to dimuon (2HDM+S) interpretations

CMS PAS EXP-21-005

See also backup for Higgs → displaced muon pair analyses, CMS PAS EXO-20-014





# Dark sector with Long-Lived Particles at the LHC

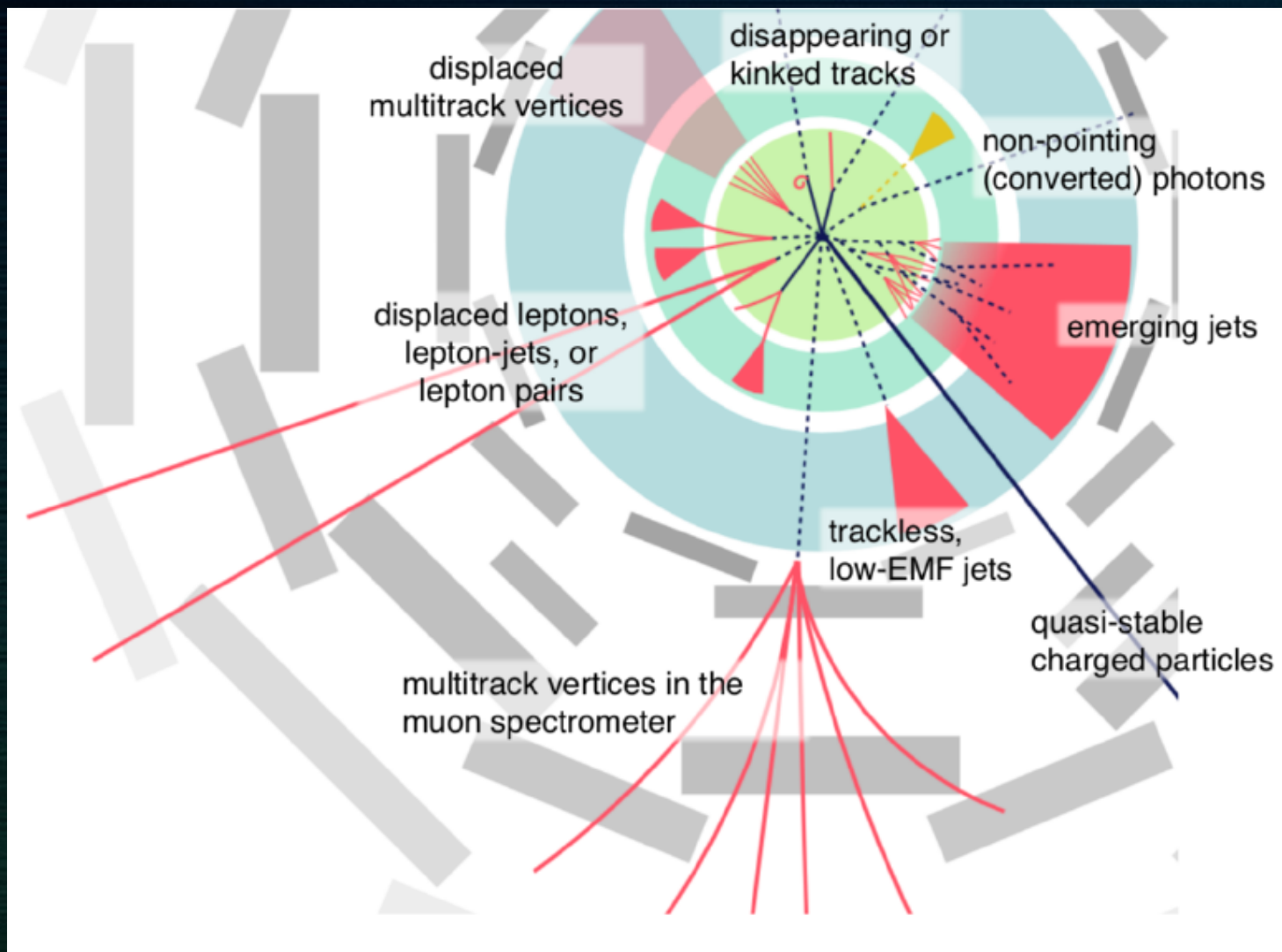
## LLP:

a proper lifetime  $\tau_0$  is greater than or comparable to the characteristic size of the (sub)detectors

✓ small  $\tau_0$  that comparable to the inner tracker size, no displaced tracks  $\rightarrow$  “standard” prompt decay

✓ intermediate  $\tau_0 \rightarrow$  LLP

✓ very large/infinite large  $\tau_0 \rightarrow$  stable particles, “standard” MET signatures

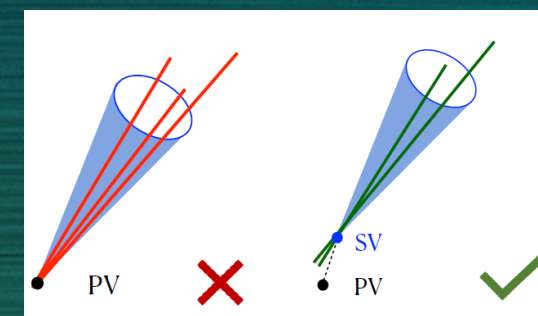
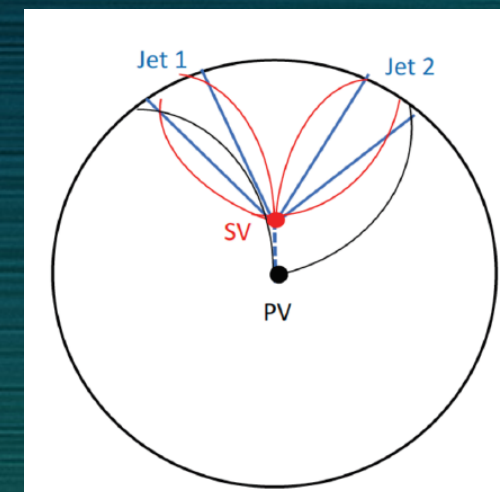


Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper:  
arXiv:1903.04497

LLP theory motivations:  
arXiv:1806.07396

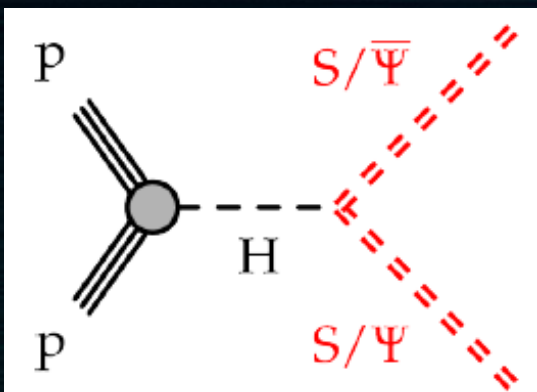
## displaced jets





# LLP decays in the CMS Muon system

CMS PAS EXO-21-008



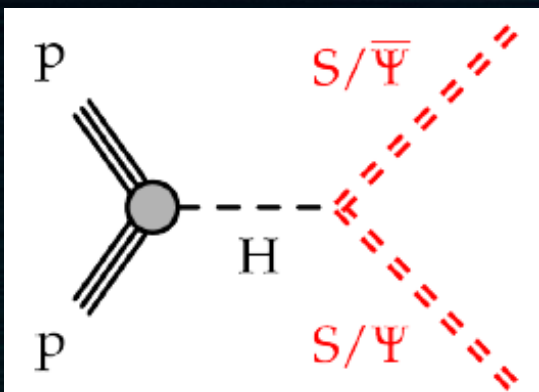
- A unique technique for LLP decays reconstruction in the muon system
- Sensitivity to long lived scalars with masses between 0.4 and 55 GeV
- Decays in hadronic showers ( $b\bar{b}$ ,  $d\bar{d}$ ,  $K^+K^-$ ,  $K^0\bar{K}^0$ ,  $2\pi$ ,  $2\tau$ ,  $2\gamma$  etc.)
- Interpretations for dark showers and twin Higgs models



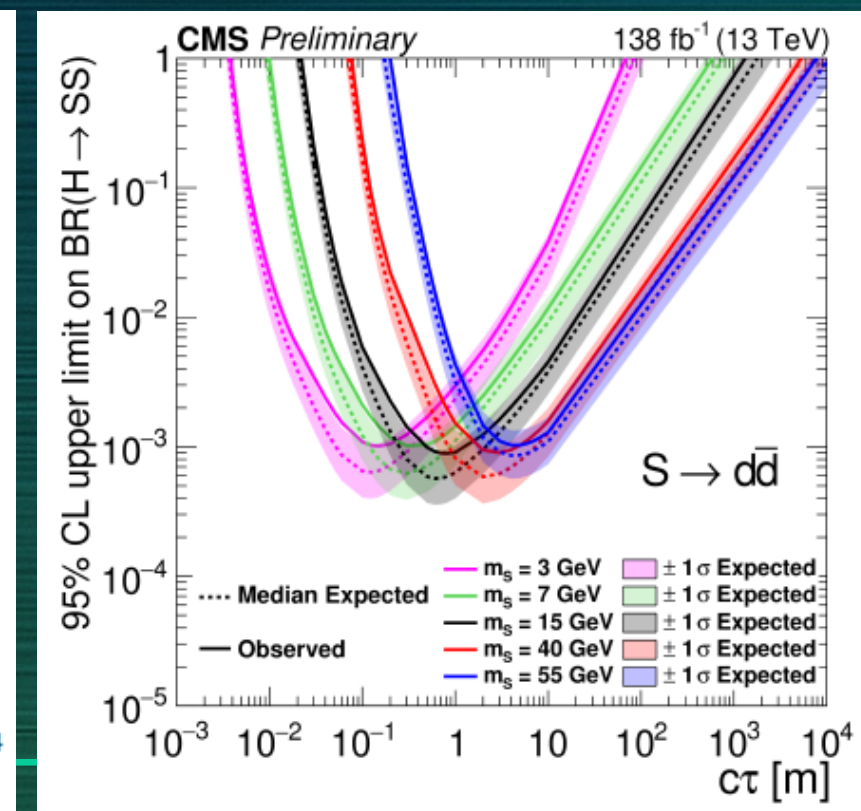
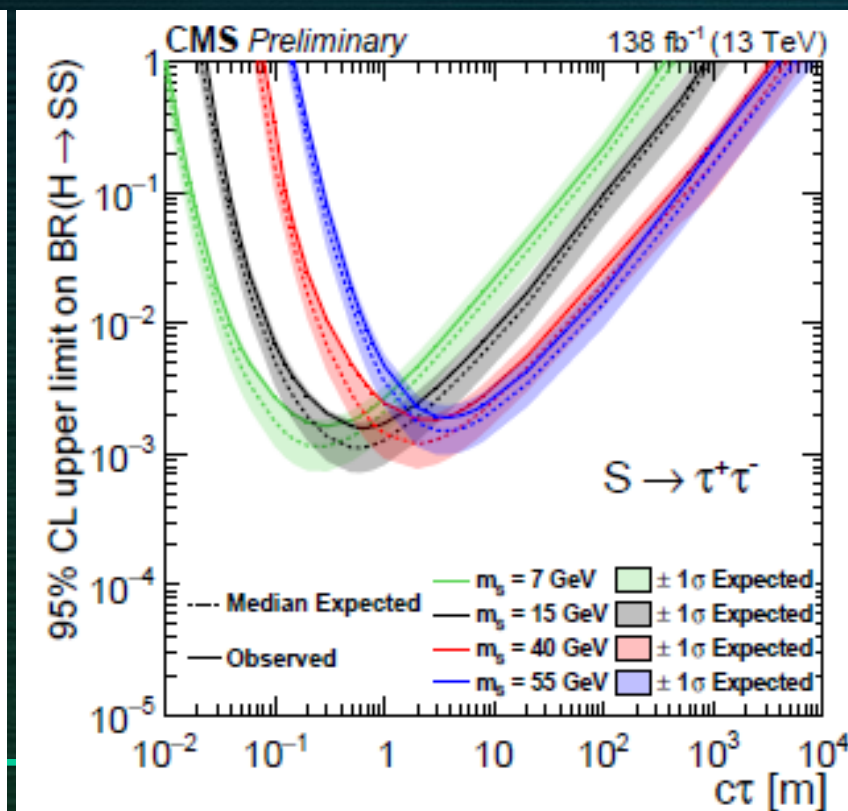
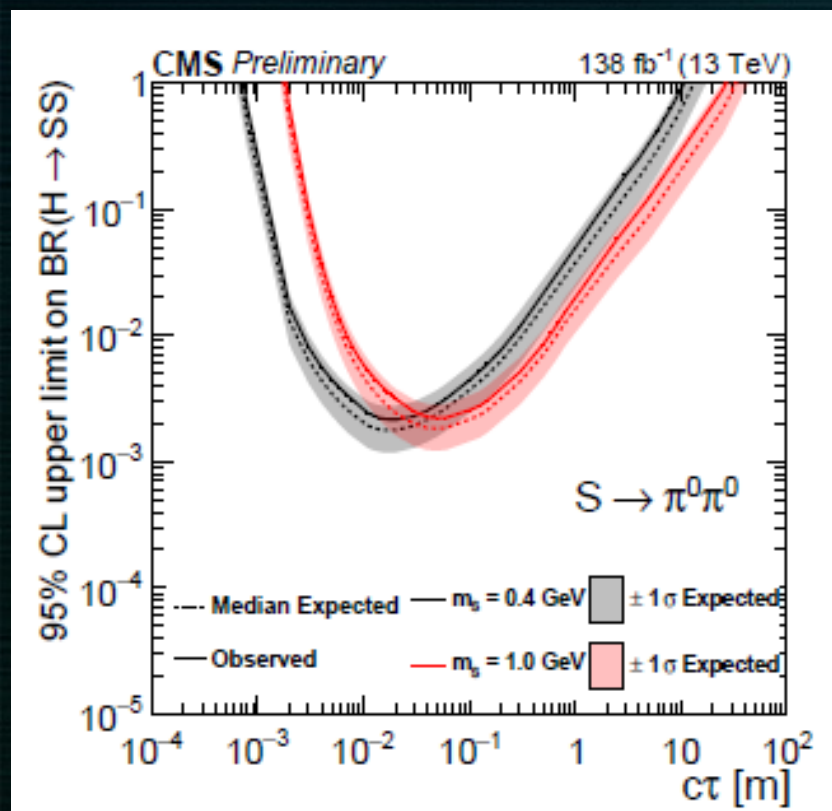


# LLP decays in the CMS Muon system

CMS PAS EXO-21-008



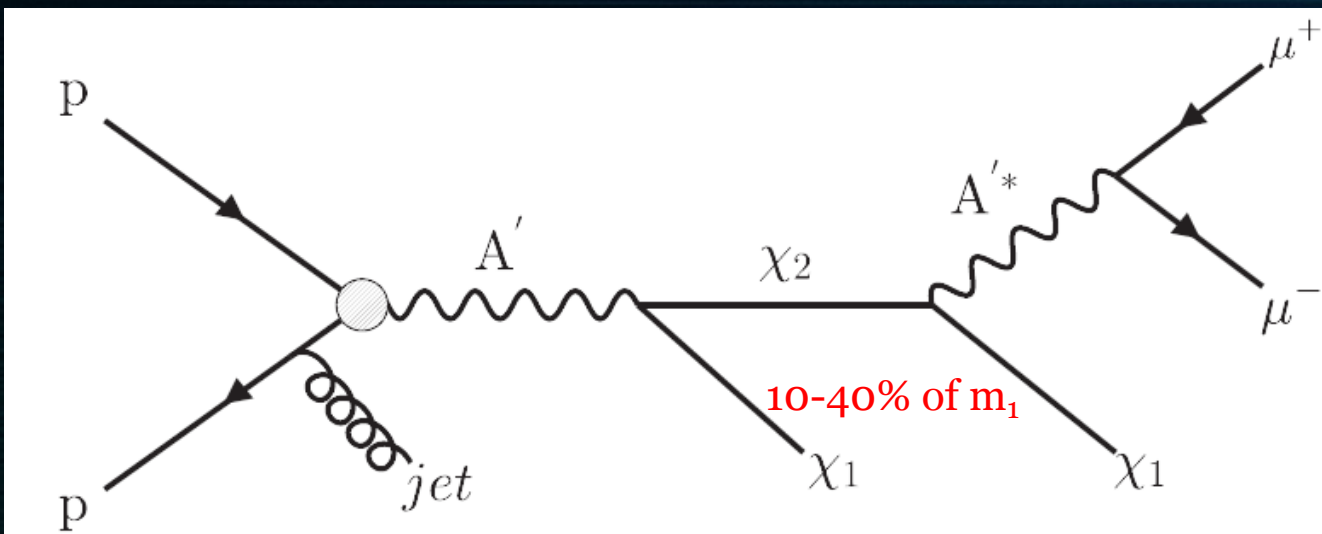
- A unique technique for LLP decays reconstruction in the muon system
- Sensitivity to long lived scalars with masses between 0.4 and 55 GeV
- Decays in hadronic showers ( $b\bar{b}$ ,  $d\bar{d}$ ,  $K^+K^-$ ,  $K^0\bar{K}^0$ ,  $2\pi$ ,  $2\tau$ ,  $2\gamma$  etc.)
- Interpretations for dark showers and twin Higgs models





# Search for inelastic DM with two displaced muons + MET

CMS EXO-20-010



- Inelastic DM – dark photon  $A'$  ( $m_{A'}$ , kinematic mixing  $\epsilon$ ), and two closely degenerated by mass DM states (mass splitting  $\Delta$ , mass of  $\chi_1$   $m_1$ ), LLP  $\chi_2$  (lifetime  $c\tau$ ), dark gauge-fermion coupling  $\alpha_D$

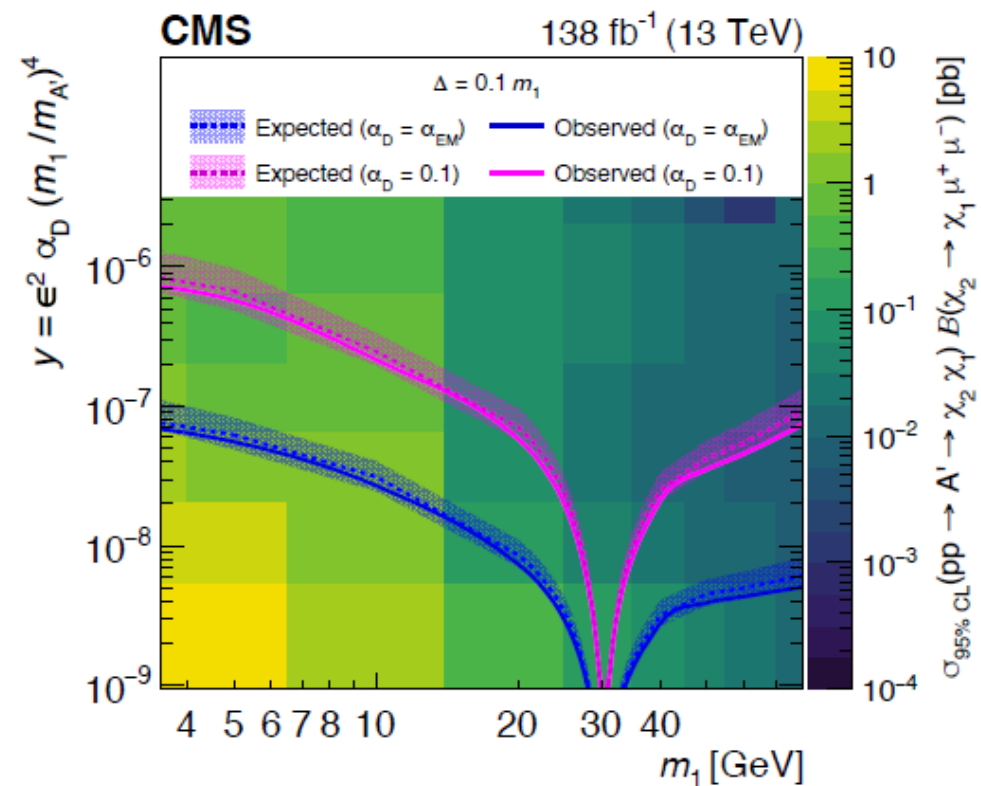
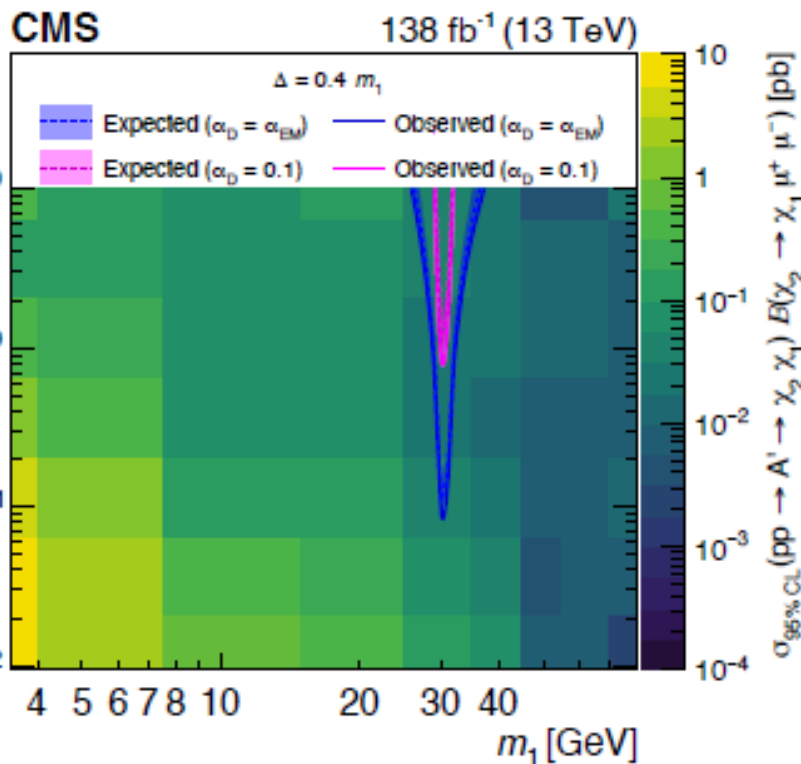
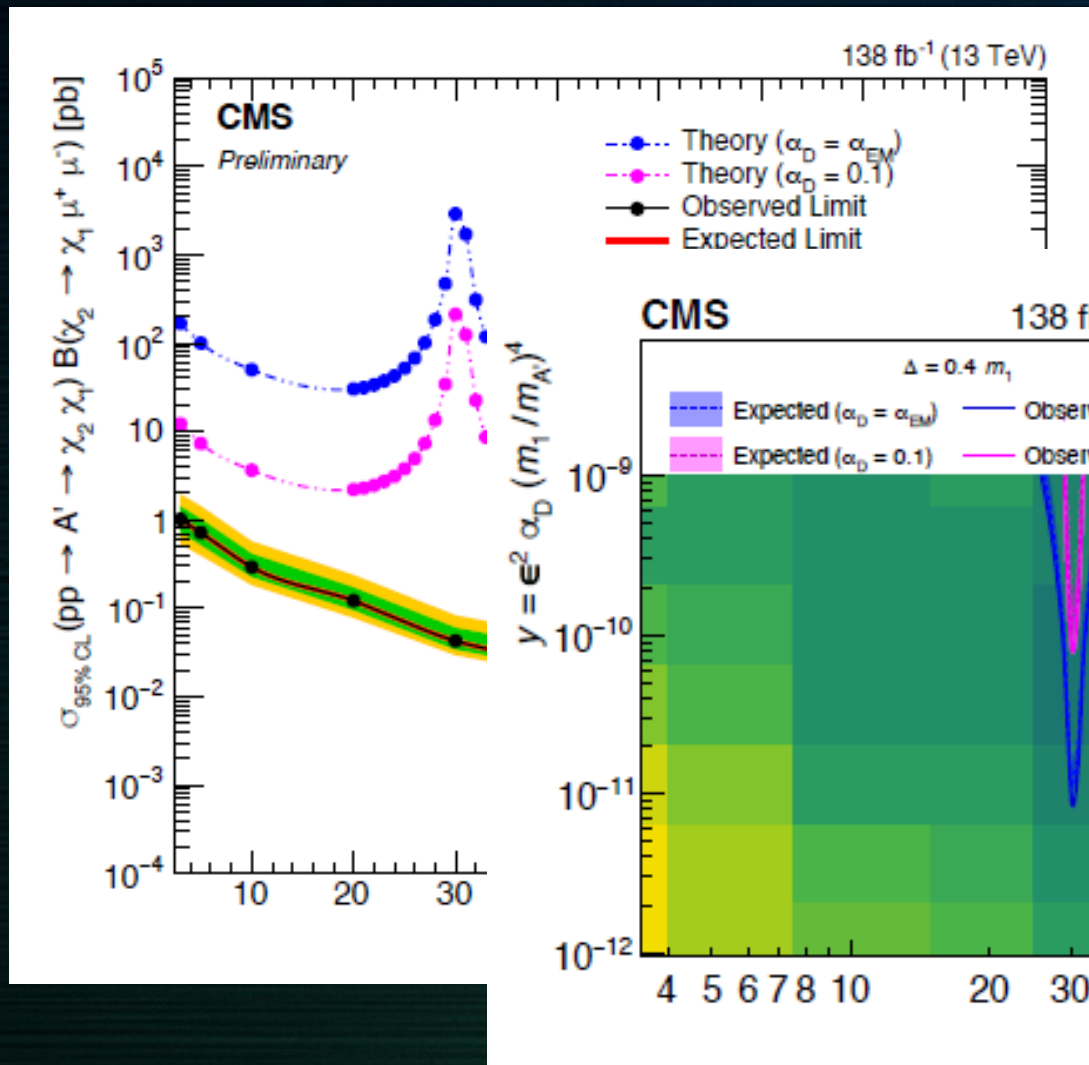
- The interaction strength  $y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{A'}\right)^4$

- The first LHC search of such a type – mixed LLP + MET signature
- A pair of displaced muons (soft, collimated)
- Large MET collimated with muons
- IS energetic jet as a tag



# Search for inelastic DM with two displaced muons + MET

CMS EXO-20-010







# Summary and outlook on DM searches

- ✓ Wide variety and an extensive list of analyses on DM and hidden sector at CMS
- ✓ Still no signals of new DM particles/mediator
- ✓ Further development of an analysis (scouting triggers , new signatures like semivisible jets, novel prompt/LLP reconstruction algorithms) and related theory/simplified model approaches, new interaction channels, new frameworks

CMS analyses summary on DM search and much more:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>





Thank you for your attention!





# Backup slides



# Spin of DM mediator: Higgs/gauge (or both) portals to dark matter

**Higgs portal:** DM interacts with our world only through coupling with the Higgs sector → special importance of Higgs connected studies

Additional higgs bosons needed to accommodate DM → **an extended Higgs sector**. How to extend?

**SM style...**

- ✓ SM + one singlet (real/complex) – **SM + S**, the simplest singlet-doublet model (the doublet corresponds to the SM)
- ✓ SM + one doublet (real/complex) – **2H(iggs)D(oublet)M(odel)**, flavor conserving 4 types (type II – MSSM), 5 physical states: **h, H (CP-even), A (CP-odd),  $H^{+/-}$** ; h–H mixing, “the alignment (decoupling) limit” →  $h_{125} = h$
- ✓ SM + doublet + scalar singlet (r/c) – **2HDM+S** or **N(ext/non-minimal)2HDM**, flavor conserving 4 types (type II – NMSSM), 7 physical states, one is the pseudoscalar → 2HDM+a in the simplified description
- ✓ SM + 2 doublets – 3HDM etc.

**and non-SM style** (SM: isosinglet and isodoublet reps. under SU(2) weak symmetry group). Then how?

- ✓ isotriplet representations of SU(3) for Higgs fields (Georgi-Machacek model etc.)...

**Bright experimental signatures:** extra Higgs states, neutral and (doubly)charged, CP-odd and CP-even ones, lighter and heavier than the SM Higgs  $h_{125}$

Also: gauge portal → the (axial)vector mediator and double portal → both vector + scalar mediators





# SDM models and prompt DM signatures

Generalized or model specific search, combinations of visible and MET signatures

## The (axial)vector mediator

$V^{(ector)}/A^{(xial)}V^{(ector)}$	dijet (dilepton), diboson $hW/Z$ pair, $t\bar{t}$ resonance
$V^{(ector)}F^{(lavour)}C^{(changing)}$	$t+E_T^{miss}$ , same-sign $tt$
$V^{(ector)}B^{(aryon-number)}C^{(harged)}$	$h(b\bar{b}/\gamma\gamma/\tau\tau) + E_T^{miss}$
2HDM+ $Z'_V$ (vector 2HDM based)	$h(b\bar{b}/\gamma\gamma/\tau\tau) + E_T^{miss}$ , diboson $W/Z/h$ pairs, $t\bar{t}$ resonance
Dark higgs $Z'_V+s$	$s(b\bar{b}) + E_T^{miss}$

## The (pseudo)scalar mediator

$S^{(calar)}/PS^{(eudoscalar)}$	$jet/V/h+E_T^{miss}$ , $t\bar{t}(b\bar{b})$ resonance, $t\bar{t}(b\bar{b})+E_T^{miss}$ , $h \rightarrow inv$ , $X \rightarrow hh$
$S^{(calar)}C^{(olor)}C^{(harged)}_b$	$b(b\bar{b}) + E_T^{miss}$
$SCC_t$	$t(t\bar{t}) + E_T^{miss}$
2HDM+a (pseudoscalar 2HDM based)	$h+E_T^{miss}$ , $Z(l\bar{l})/V(qq')/Z(q\bar{q})+E_T^{miss}$ , $h \rightarrow inv$ , $X \rightarrow hh$ , diboson $Zh(+b\bar{b})$ , $t\bar{t}(b\bar{b})$ resonance, $t\bar{t}(b\bar{b})+E_T^{miss}$ , $t\bar{t}t\bar{t}$

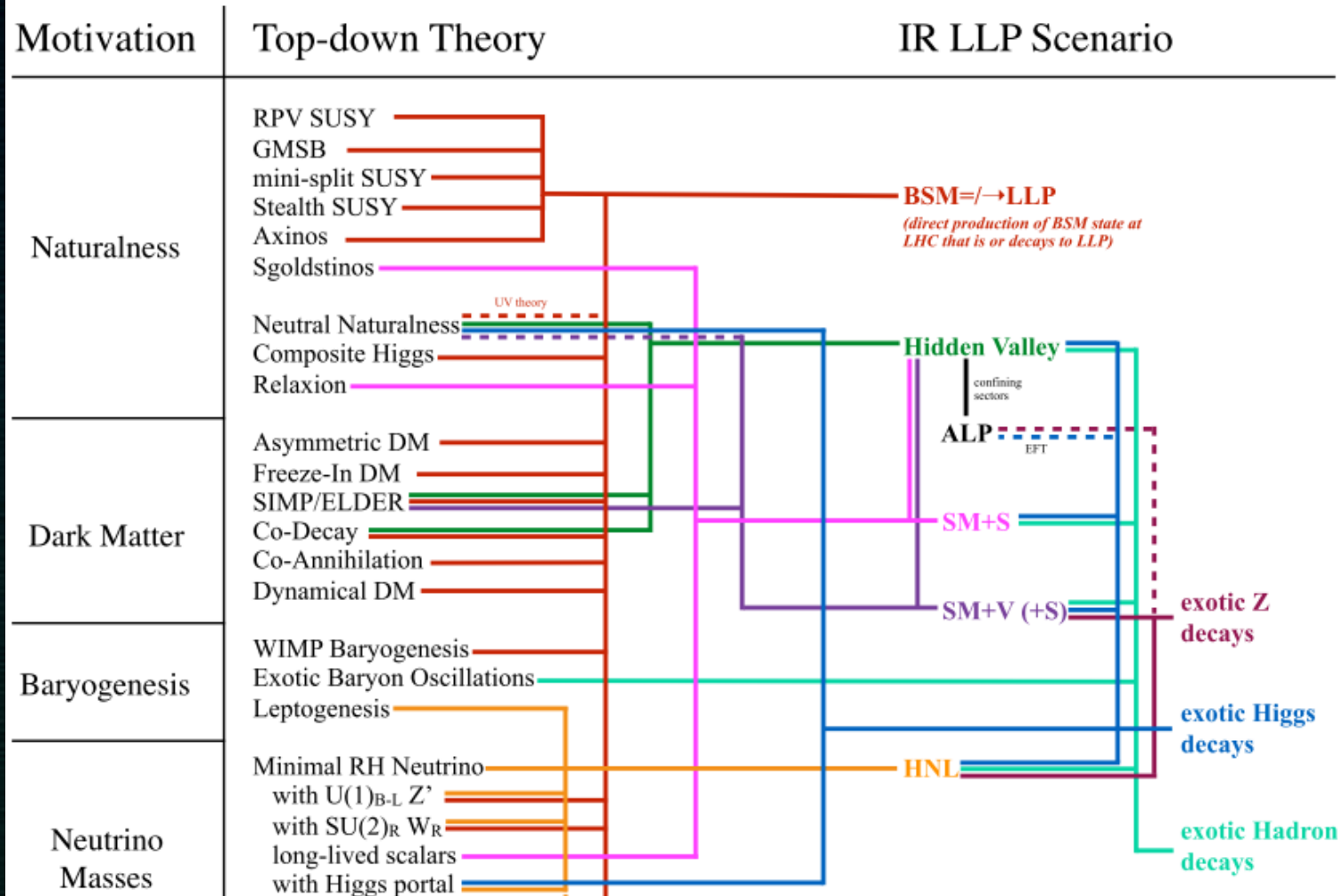
A key: separation/reinterpretation and a wide complementary search with all available signatures





# Inelastic dark matter at the LHC/LLP

<https://arxiv.org/abs/1901.04040>



- ✓ Dark photon
- ✓ Heavy neutral leptons (quarks)
- ✓ Dark GB and/or Higgs(es)...

- ✓ Higgs/GB/gluon/SUSY portals

- ✓ (Asymmetric DM/  
Baryogenesis)
  - Dark SUSY
  - Dark QCD
- ✓ Twin Higgs

DS: small couplings, compressed spectra, large hierarchy → large  $\sigma$



# Emerging jets/dark showers

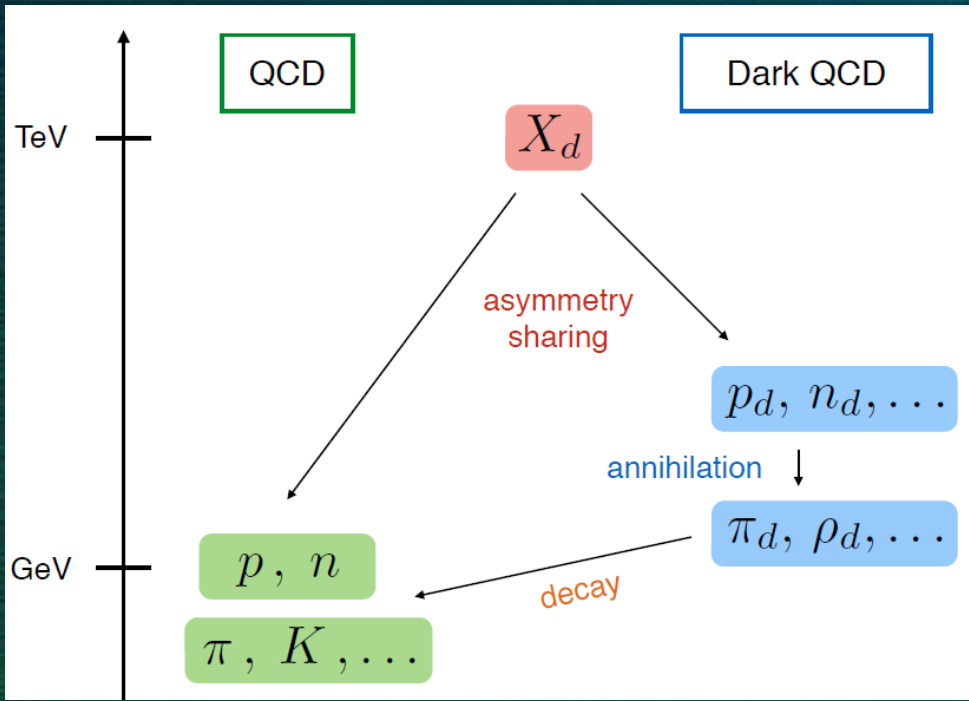
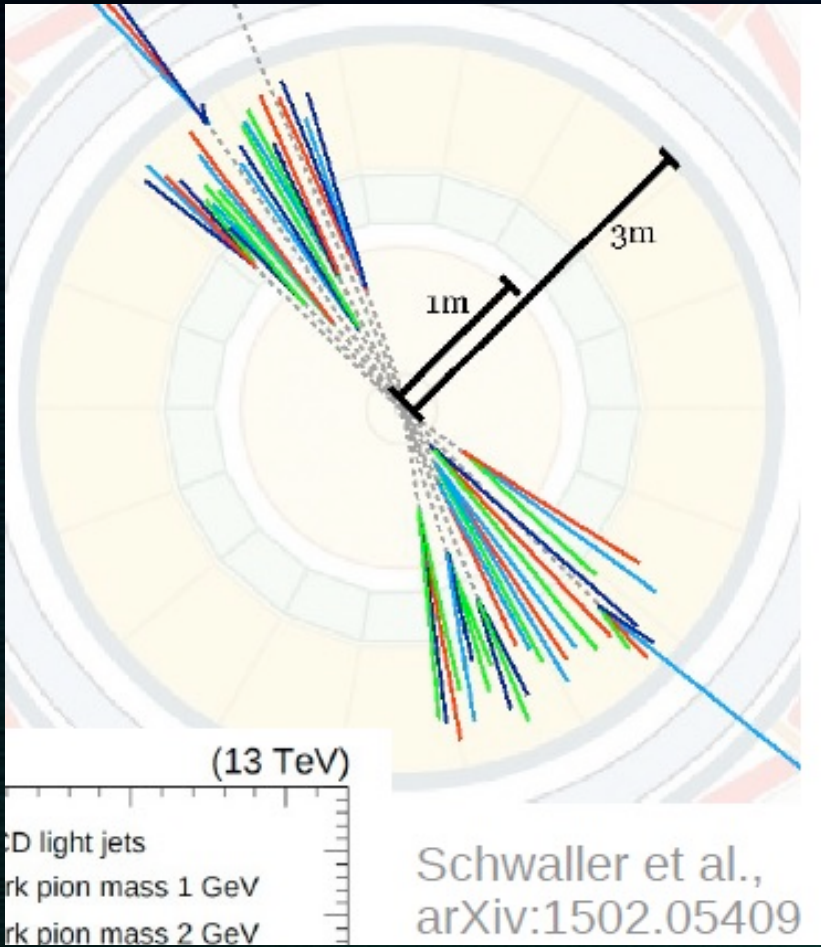
## Dark QCD

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a} + \bar{q}_d i \not{D} q_d - \bar{q}_d M_q q_d$$

$F^a$ : dark gluons ( $N_d$  colours)

$q_d$ : dark quarks ( $N_f$  flavours)

$M_q$ : quark mass matrix

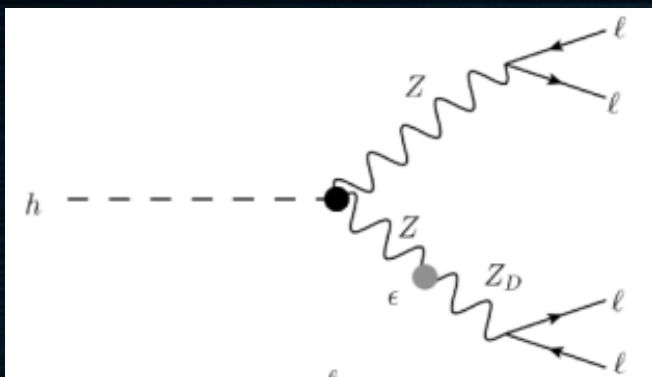


- ✓ One of the most striking DM-targeted signatures (Dark QCD → dark showers)
- ✓ Tracks start near the edge of the tracker, in the ECAL and HCAL and even in the inner muon stations

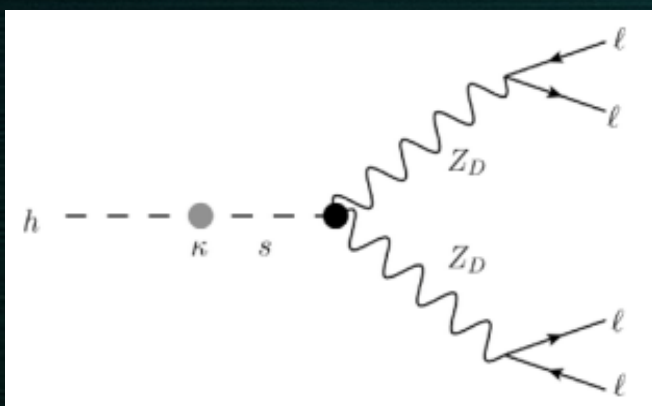


# Higgs decay to dark photons: displaced muon jets

CMS-PAS-EXO-20-014



Z-Z<sub>D</sub> conversion,  $\epsilon^2$



Higgs – dark higgs conversion,  $\kappa$

