Conference on High Energy Physics, Yerevan, Armenia, 11-14 September 2023

Dark matter searches at CMS

Maria Savina, JINR, Dubna

on behalf of the CMS Collaboration

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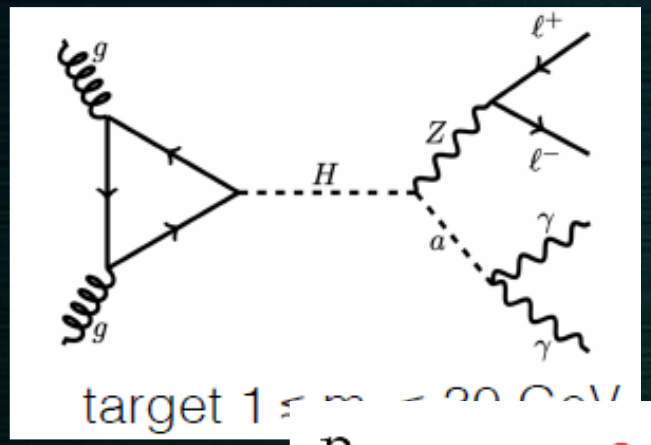
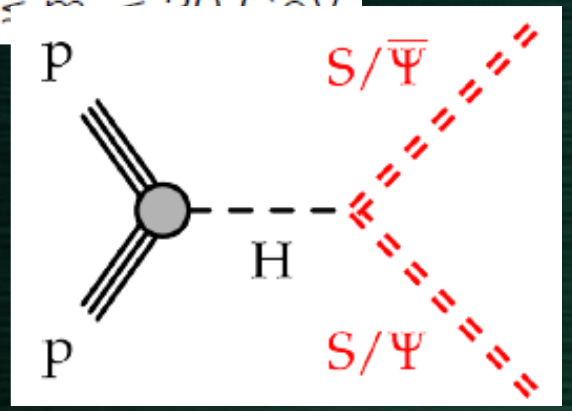
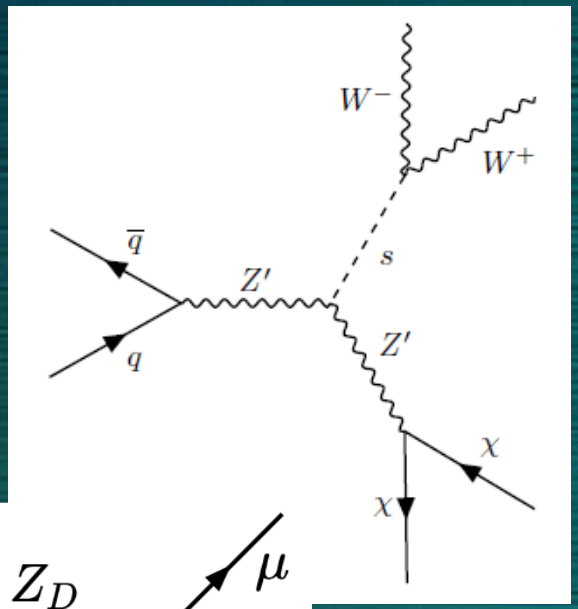
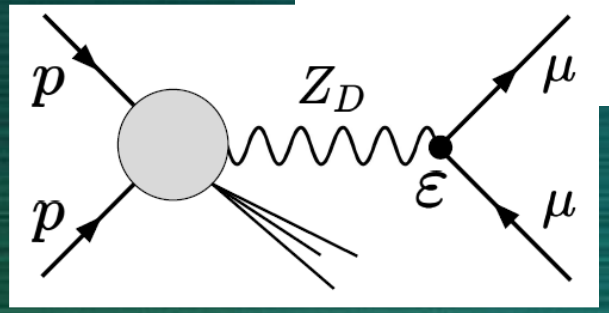








Talk outline

- ✓ 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→ 2 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

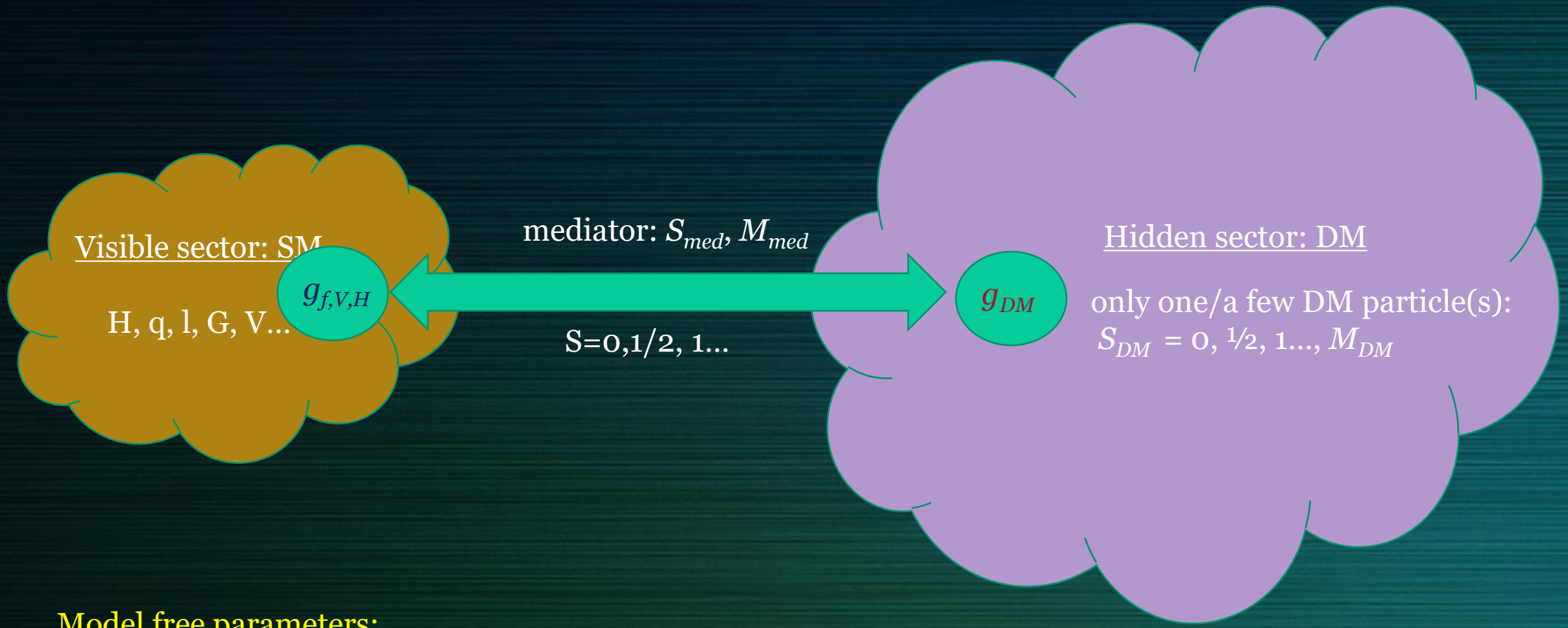
- ✓ LLP signatures:

  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

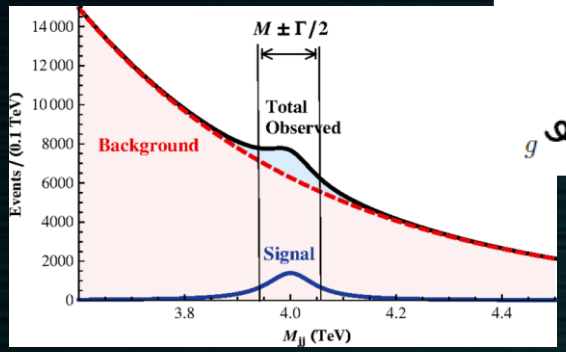
Portals to DM: DM particle(s) + mediator(s)

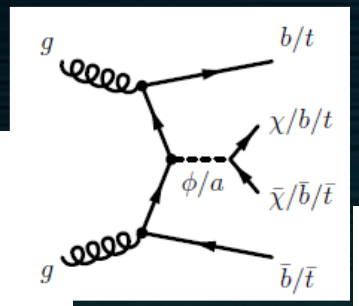


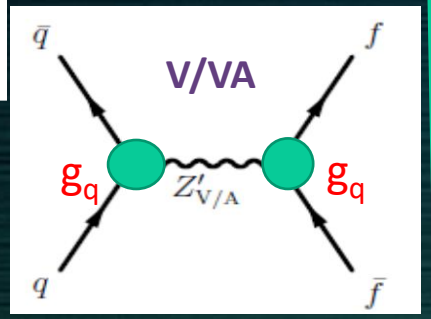
Model free parameters:
a mass of mediator(s) and DM particle(s), couplings to the visible and hidden sector, mixing angle(s)

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

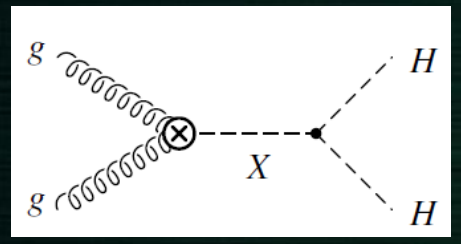
✓ fully visible (a new resonance in dijet/dilepton/diboson etc. spectra)

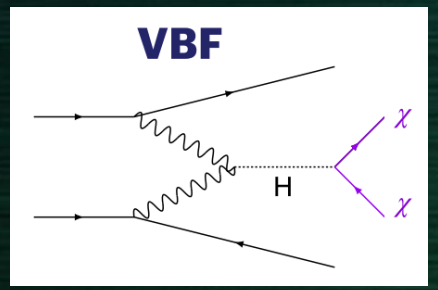


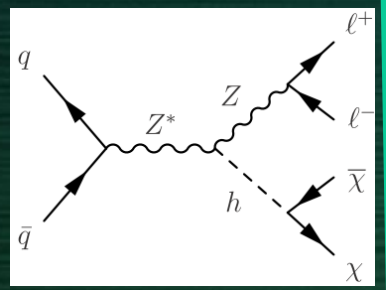




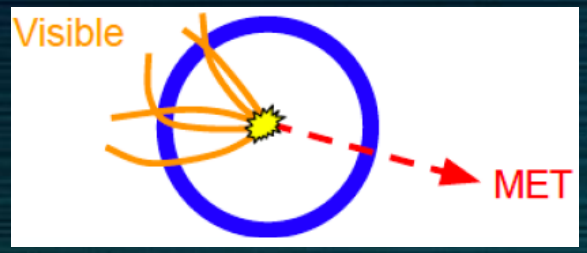
✓ non-standard properties of SM particles (higgs sector – higgs boson pair production, h_{125} to invisible…)

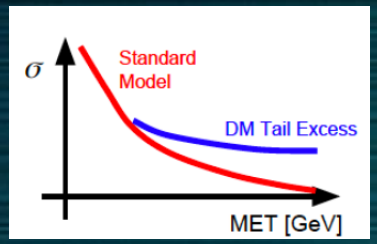


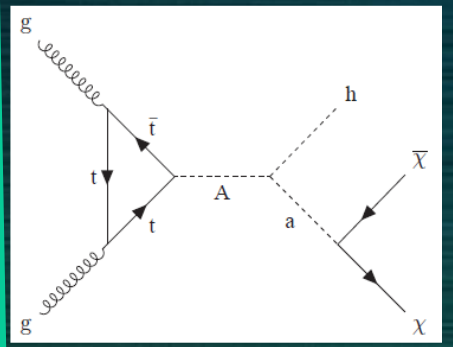


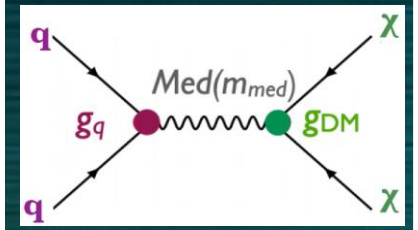


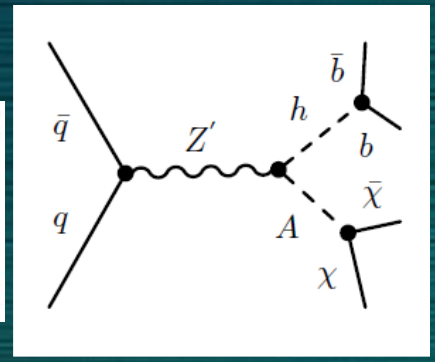
✓ MET - decay to DM particle pair (+ a visible "tag" X(=jet/gamma/Z/H)



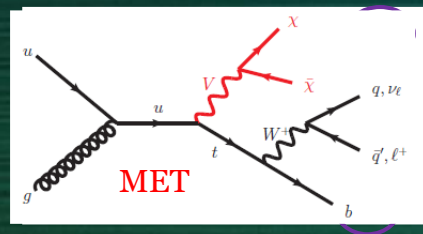


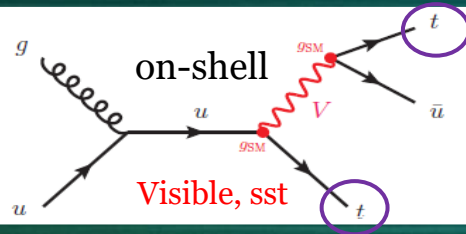


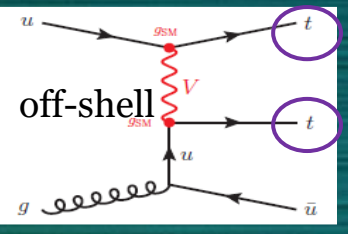




✓ flavor violating processes

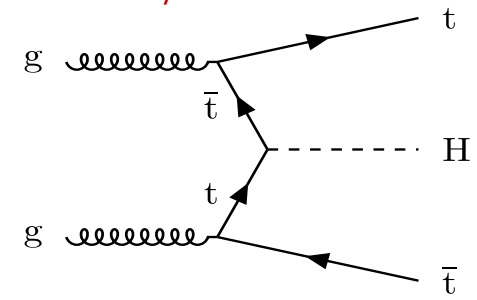


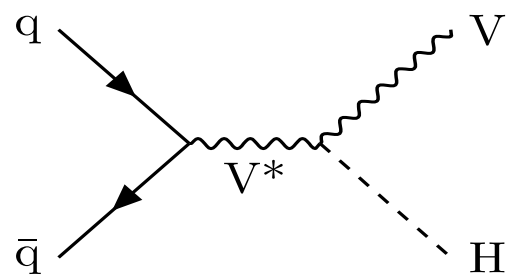




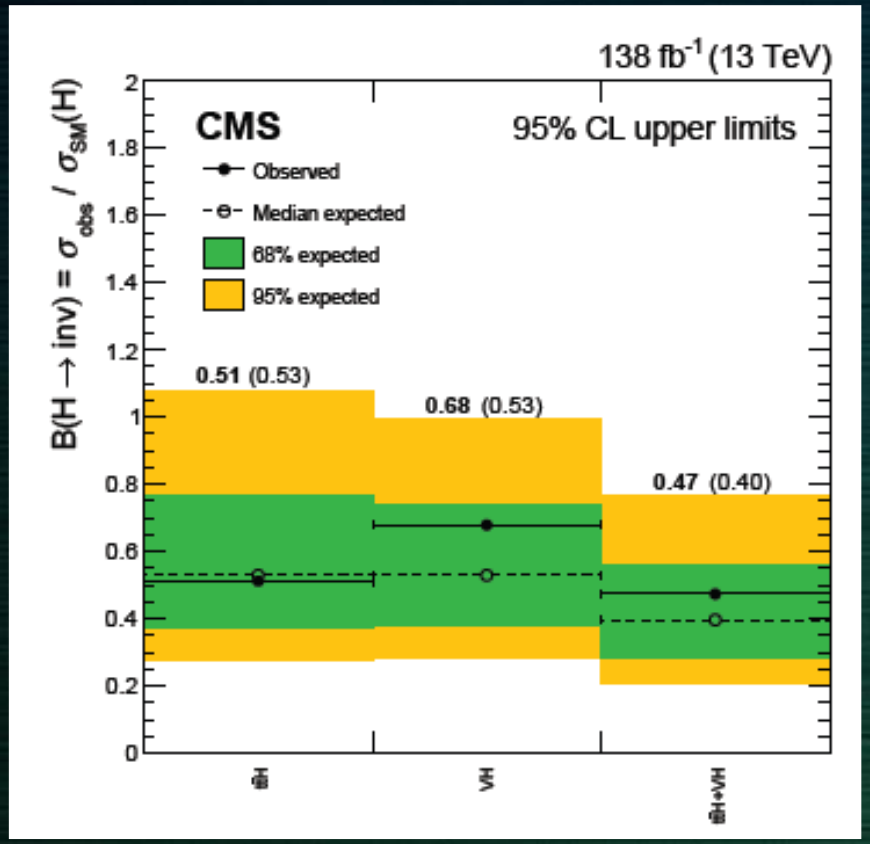
Combination of h_{125} → invisible searches for ttbar and VH

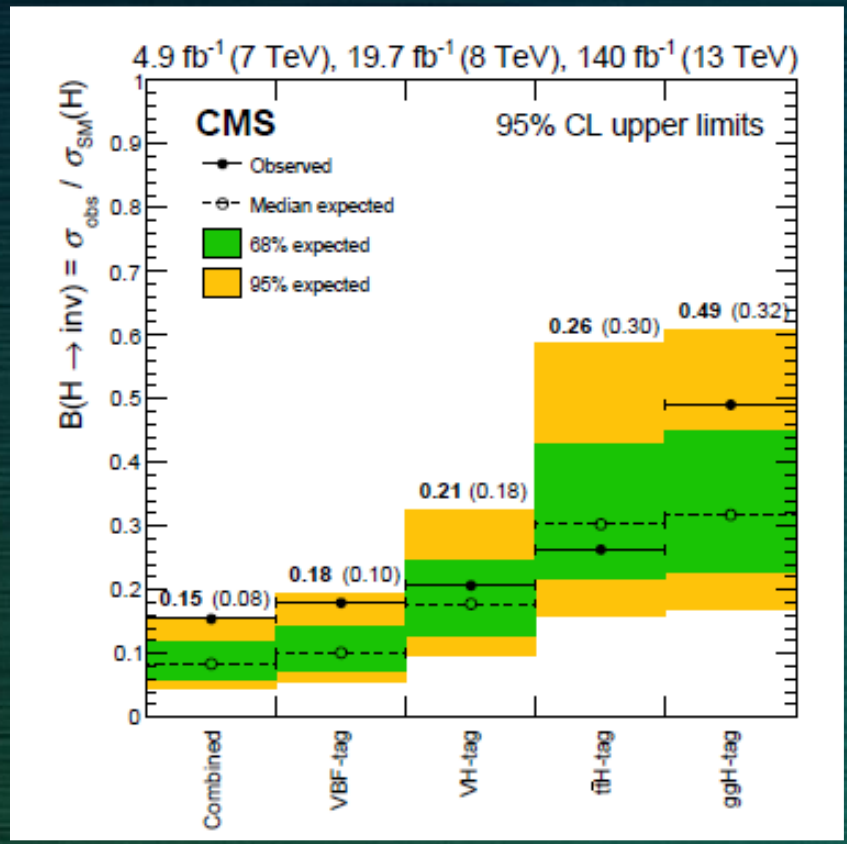
resolved/boosted ttbarH





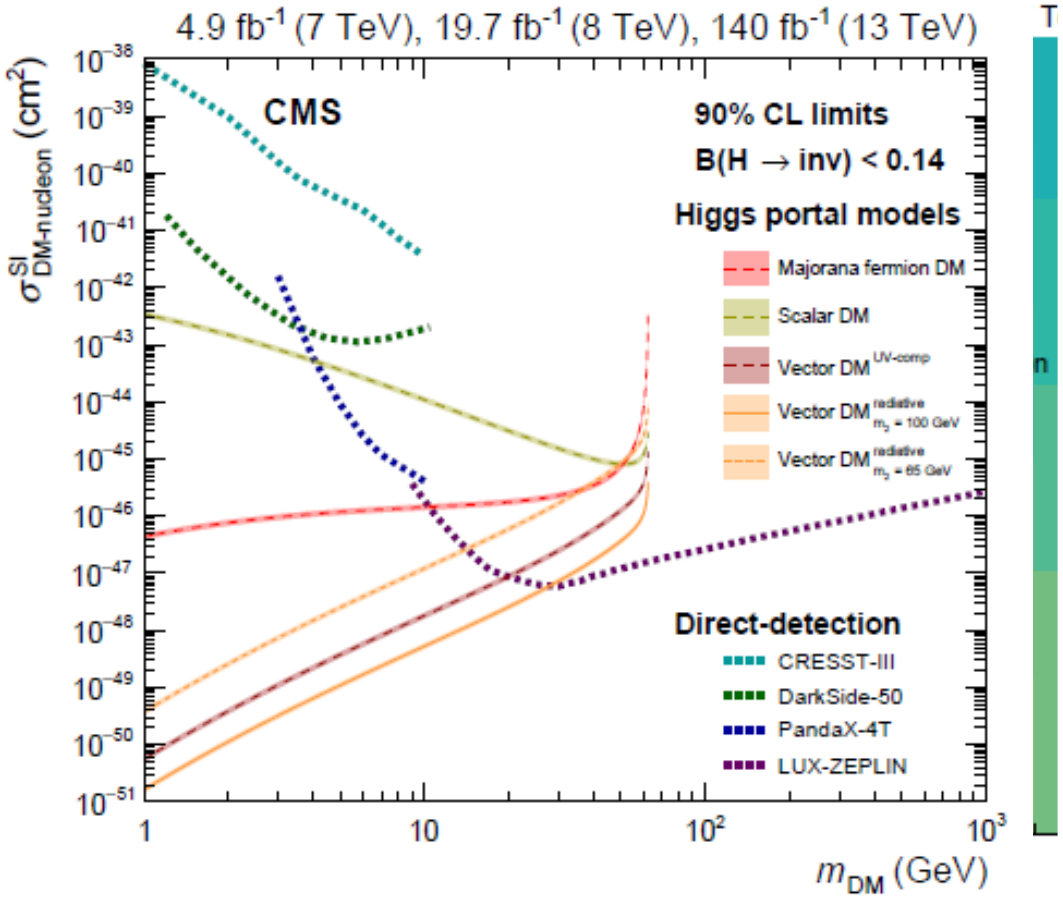
CMS HIG-21-007,
arXiv:2303.01214 [hep-ex]

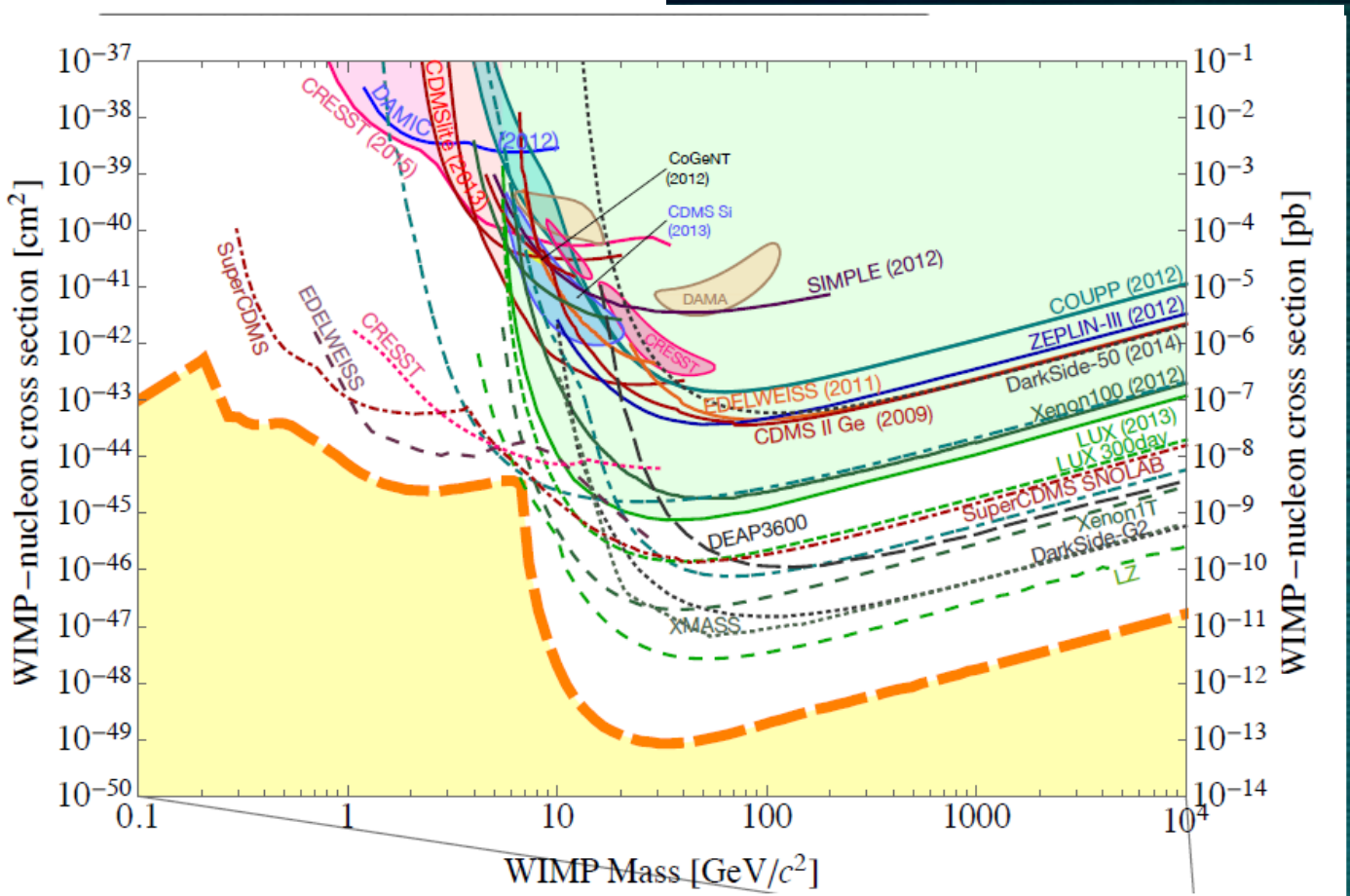




Combination of h_{125} → invisible searches

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

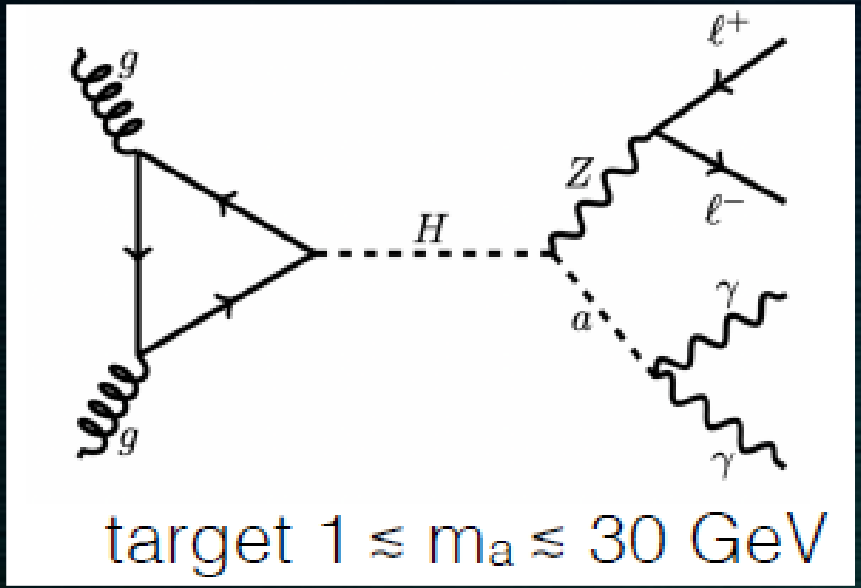




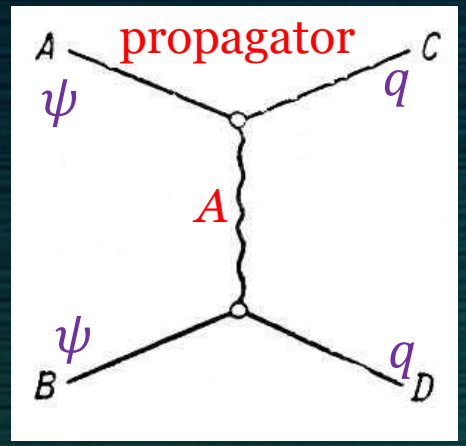
CMS: BR(H→inv.) < 15% (8% expected)
ATLAS: BR(H→inv.) < 10.7% (7.7% expected)

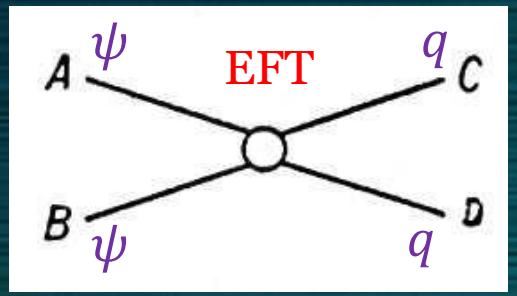
Exotic higgs decays h → Za, Z →ll, a →2 gamma

CMS PAS HIG-22-003



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



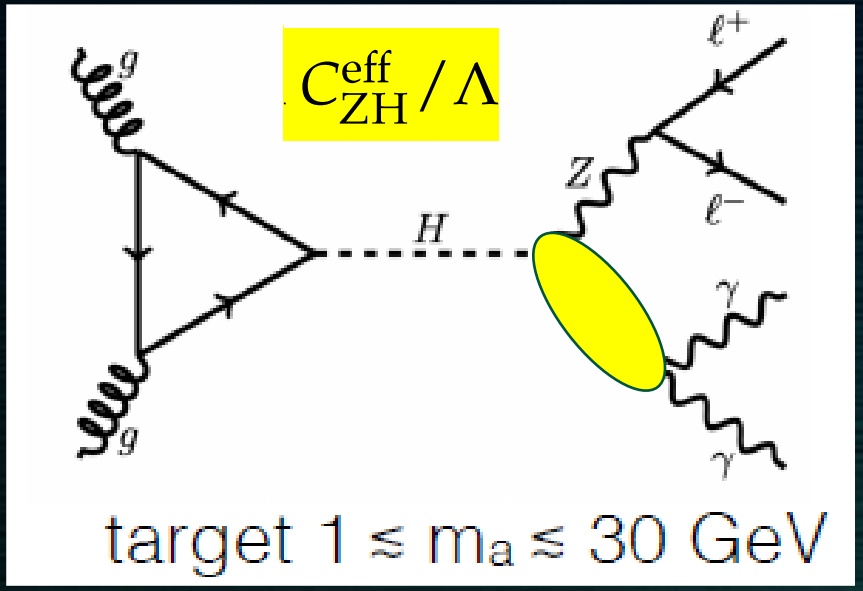


C_i are Wilson coefficients in the EFT approach that describe the ALP/SM couplings

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

Exotic higgs decays h → Za, Z →ll, a →2 gamma

CMS PAS HIG-22-003



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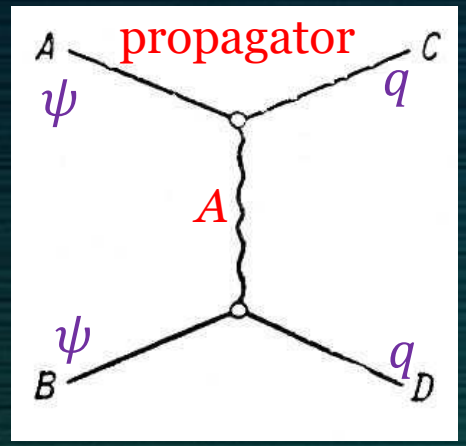

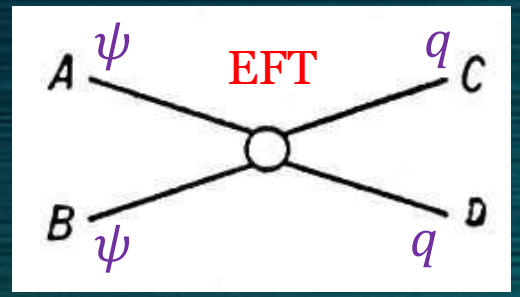

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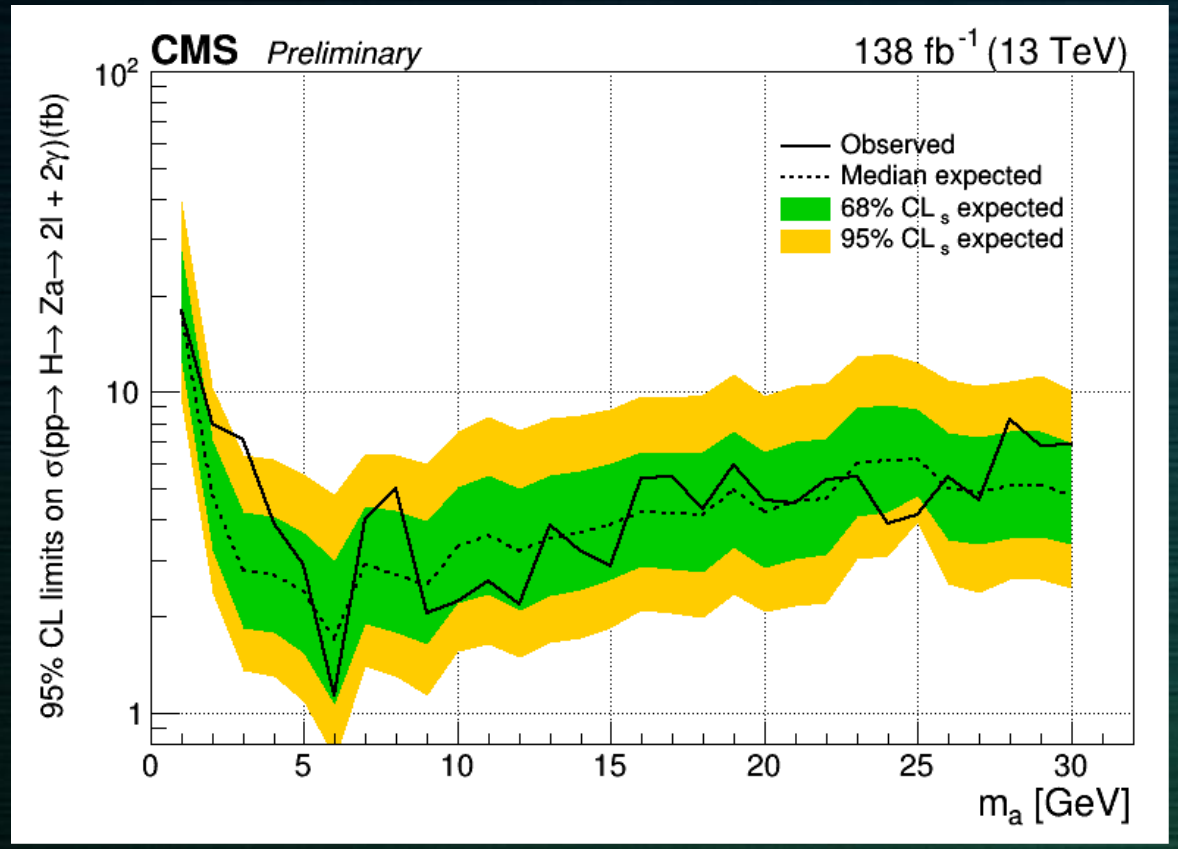
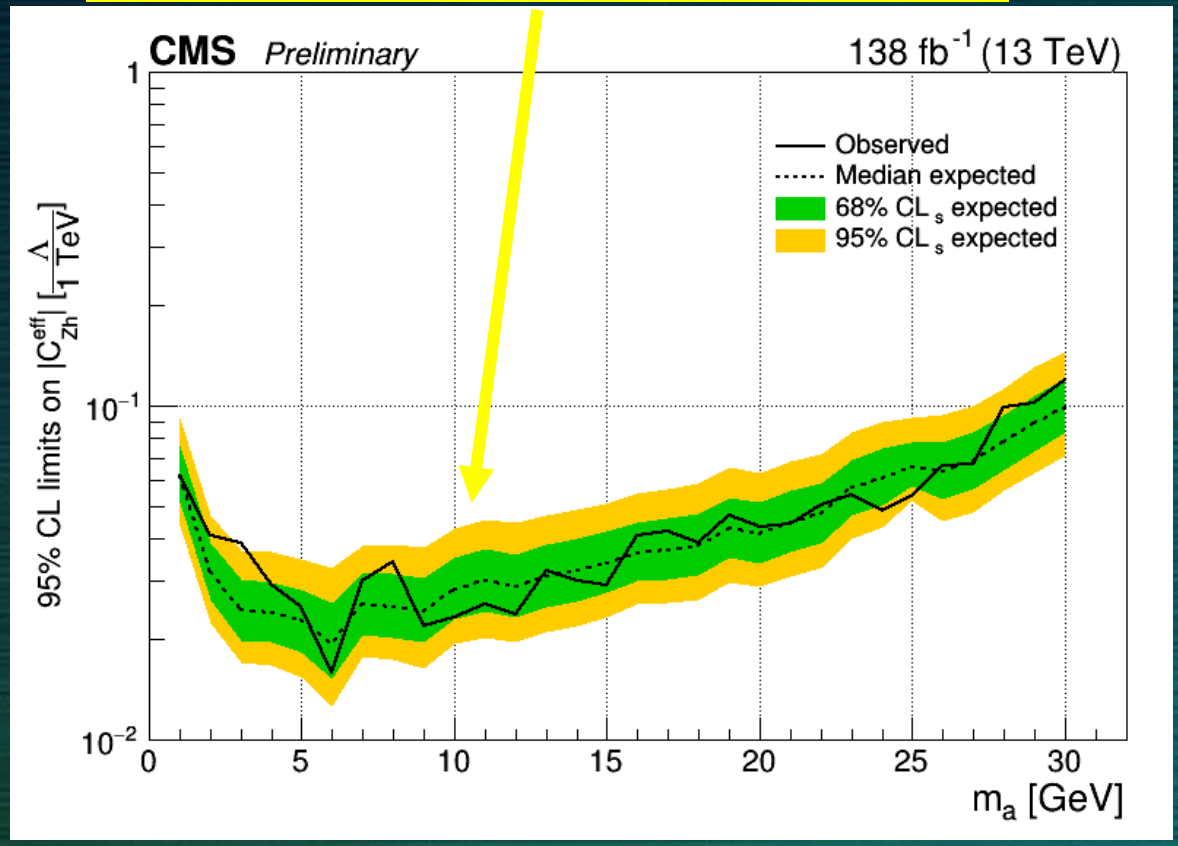
Exotic higgs decays h → Za, Z →ll, a →2 gamma

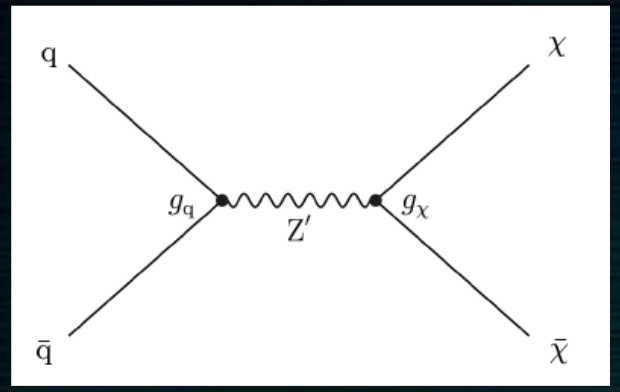
CMS PAS HIG-22-003

Limit on C_{ZH}^{eff} / Λ, when ALP decays exclusively in a diphoton, Λ 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

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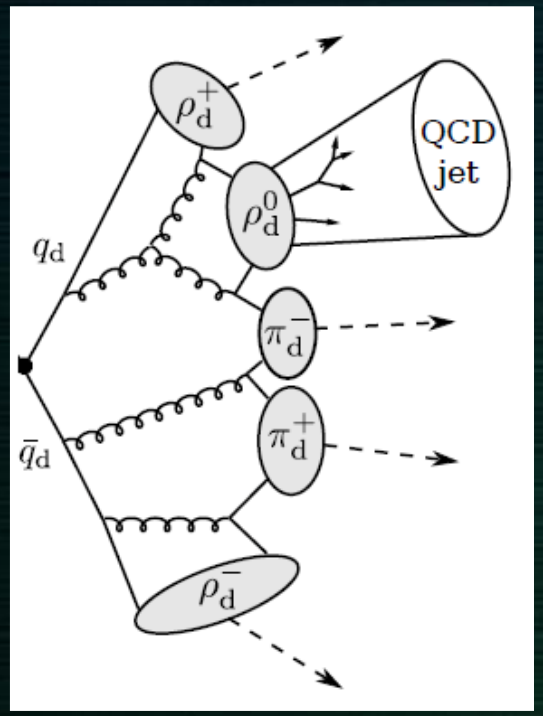
CMS EXO-19-020

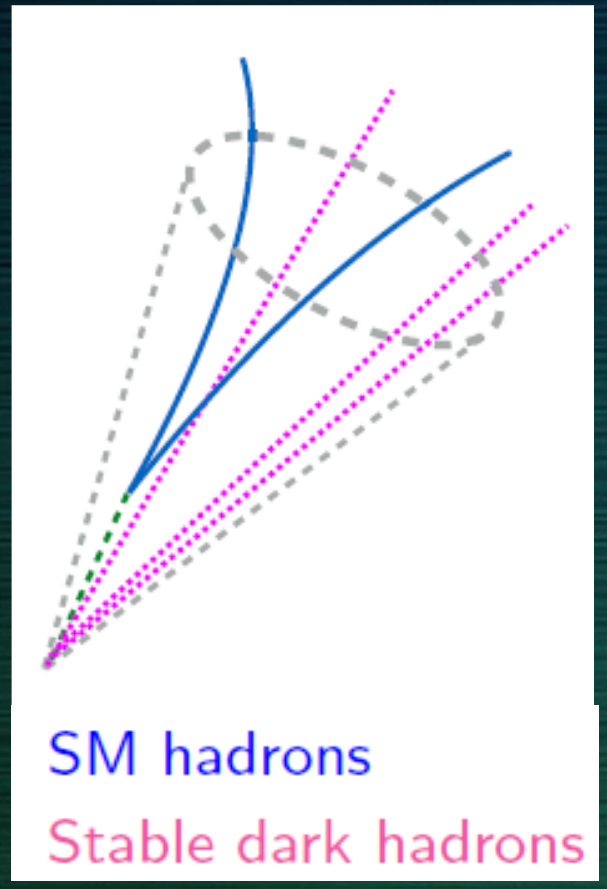


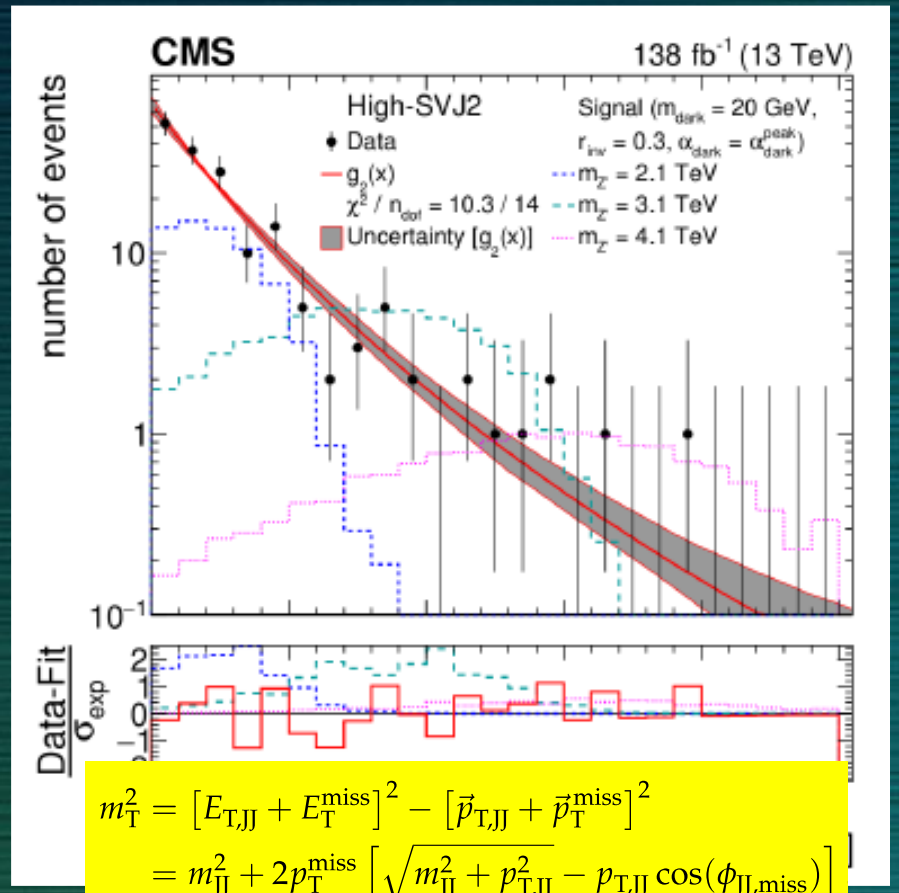
semi-visible jets

DM part (visible) +

SM part (invisible)

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





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

Resonant production of strongly coupled DM for semivisible jets

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

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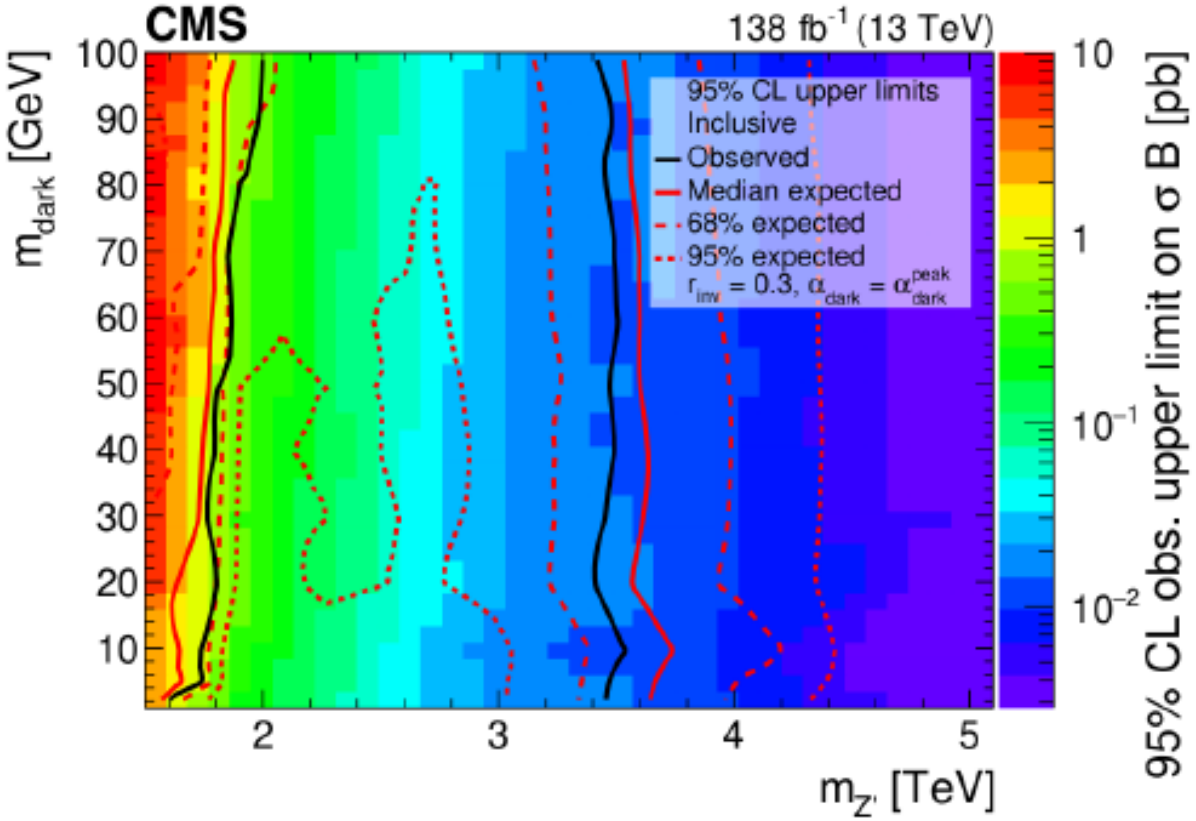
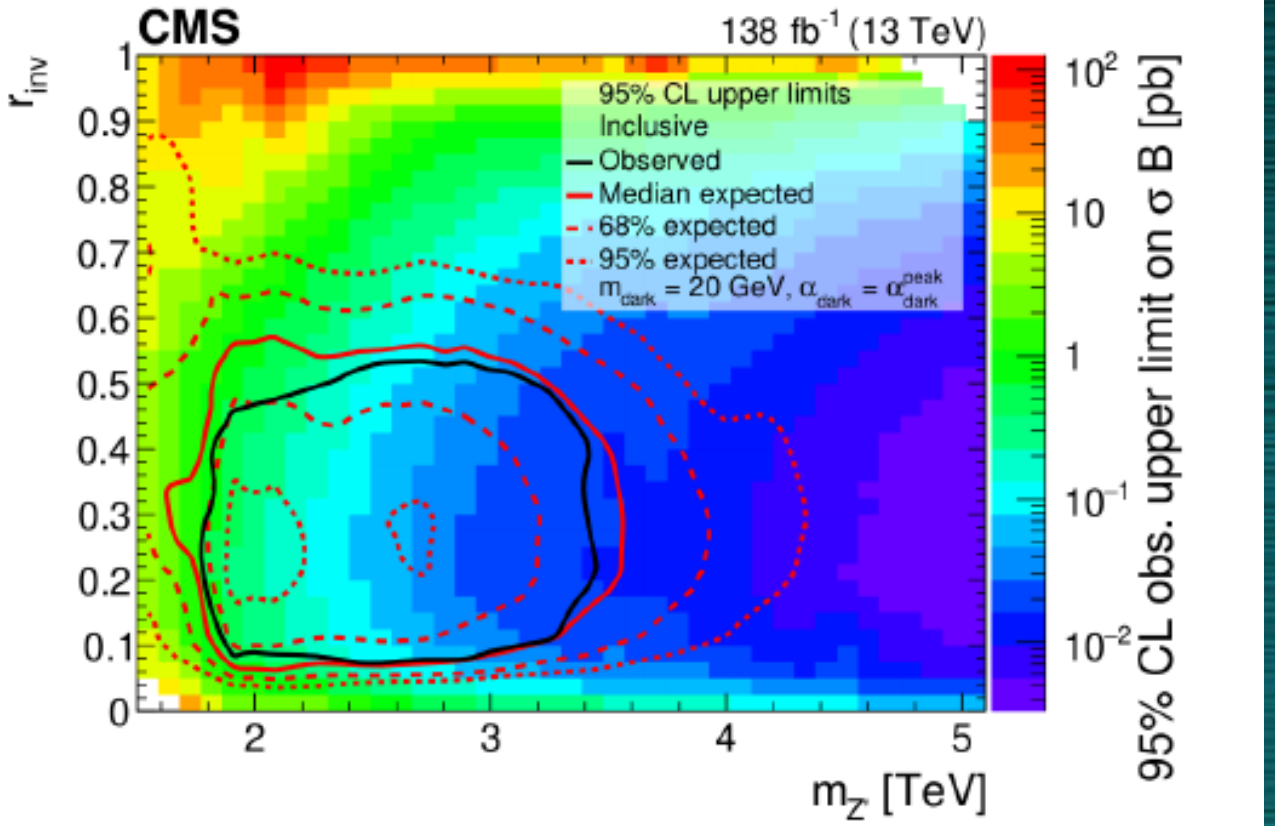
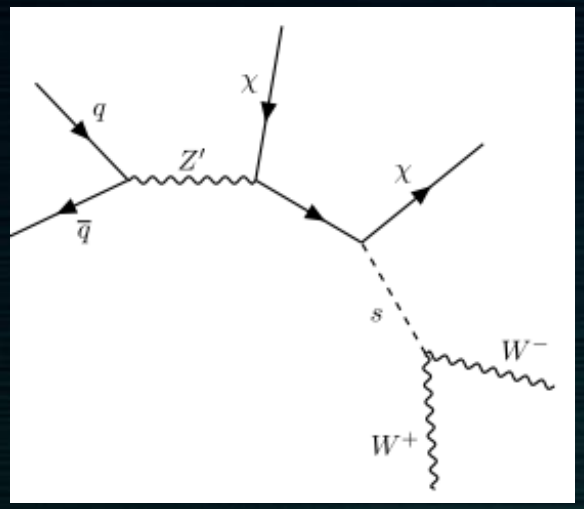
CMS EXO-19-020

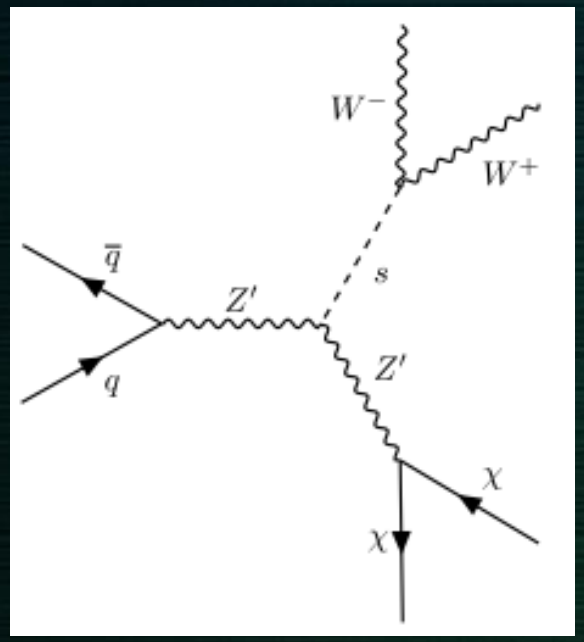




See also backup for LLP dark showers – emerging jet signature

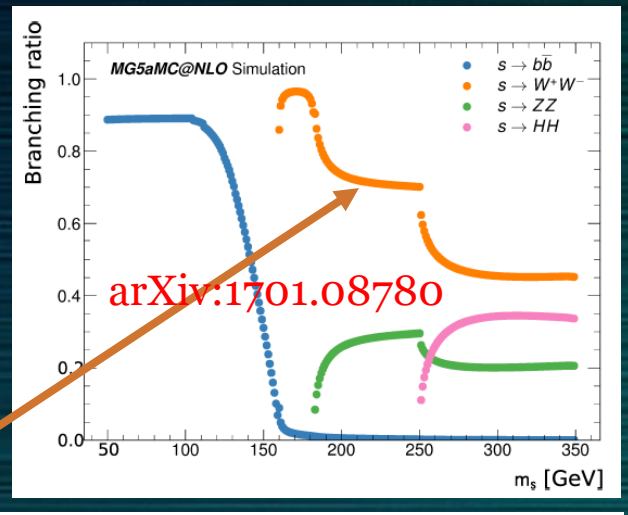
Dark Higgs model, resolved decay of s(W⁺W⁻) + E_T^{miss}

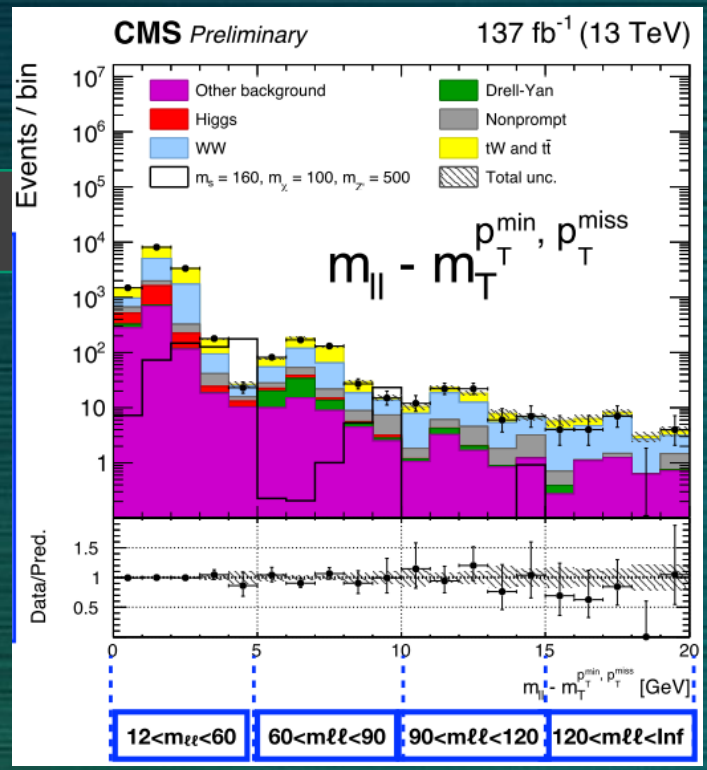




- ✓ "Double portal": both "dark higgs" s and massive Z'_V coupled to SM.
- ✓ A new higgs state is weakly mixed with SM h, a new U(1)' → SSB(s) → massive Z'_V coupled to quarks only
- ✓ s → W⁺W⁻ decay dominates at large s mass values

Model parameters : m_s, $m_{Z'}$, m_χ, g_q, g_χ, $sin\theta$ (*h–s mix.*)

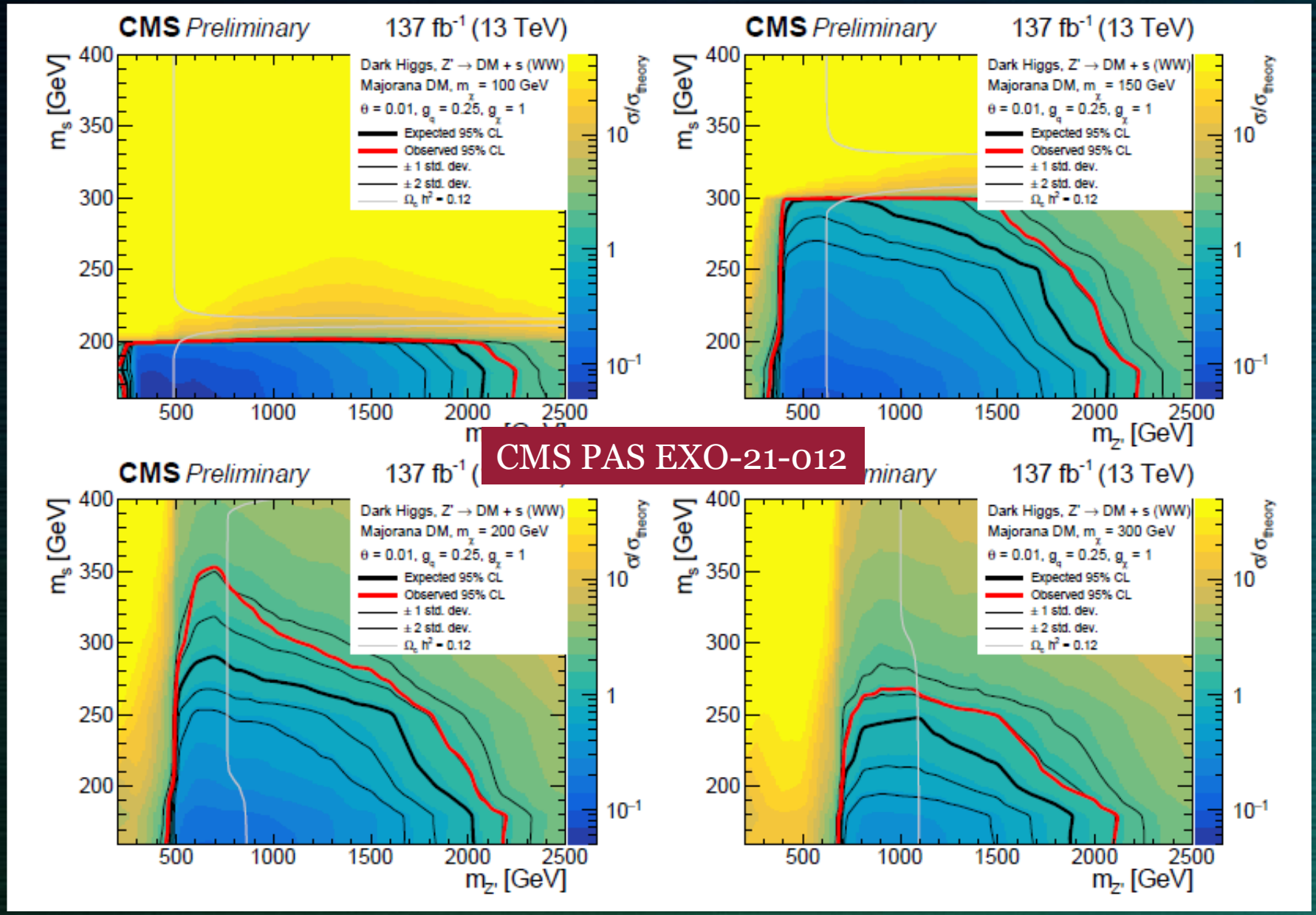




CMS-PAS-EXO-20-012

$$m_{\mathrm{T}}^{\ell\ \mathrm{min}, p_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 p_{\mathrm{T}}^{\ell\ \mathrm{min}} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\ \ell\ \mathrm{min}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]}$$

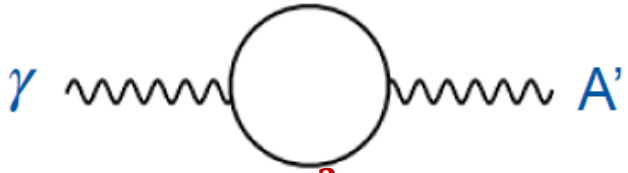
Dark Higgs model, resolved decay of s(W⁺W⁻) + E_T^{miss}



CMS PAS EXO-21-012

Search for dark photons, prompt/LLP

The coupling to SM particles proportional to electric charge

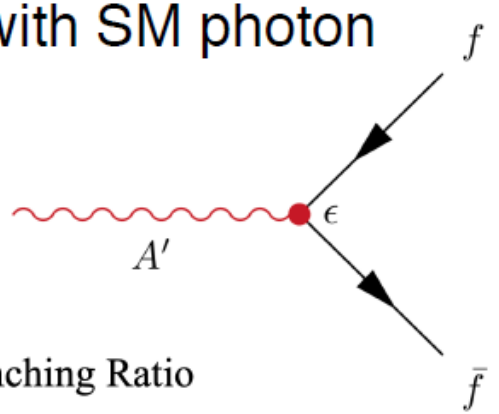


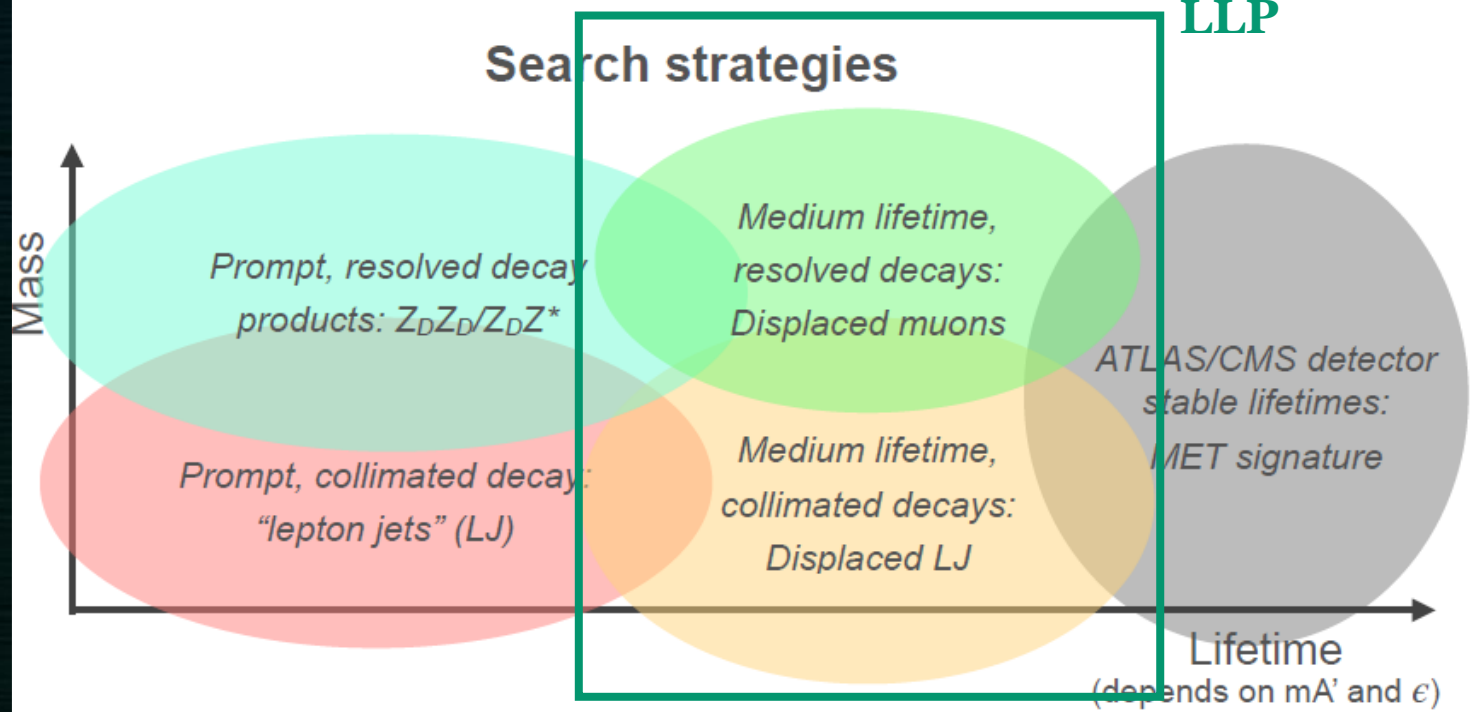
$\alpha' = \epsilon^2 \alpha_{EM}$

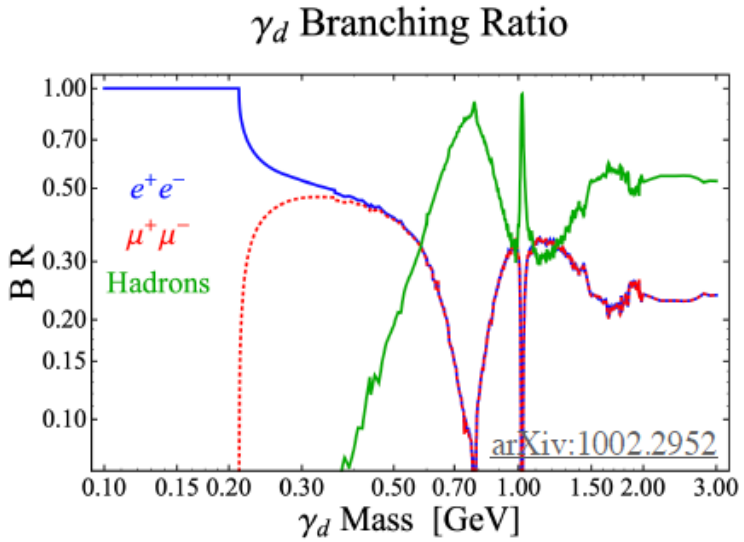
1 or 2 loops: naively $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

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

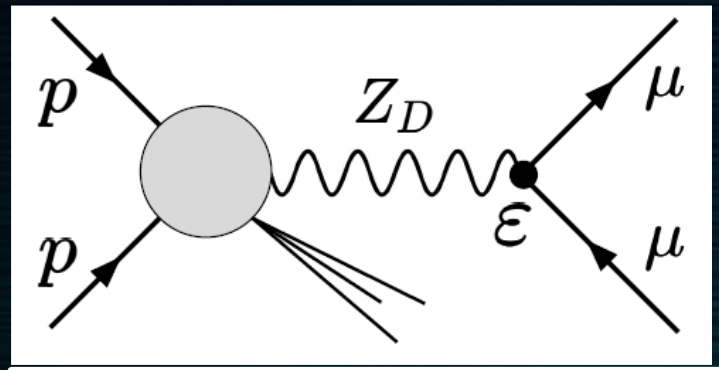
Parameters: kinetic mixing term, ϵ, and $m_{A'}$







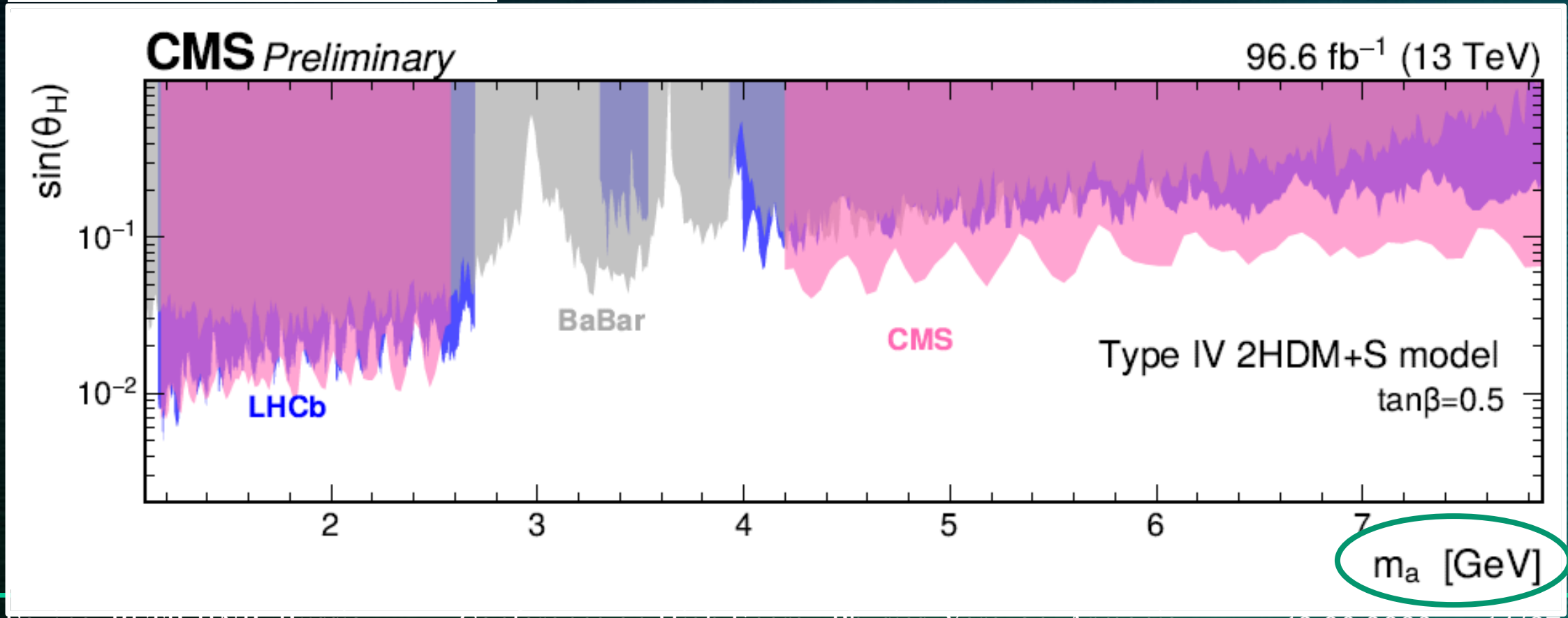
Search for prompt GeV-scale dimuon resonance



- ✓ 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



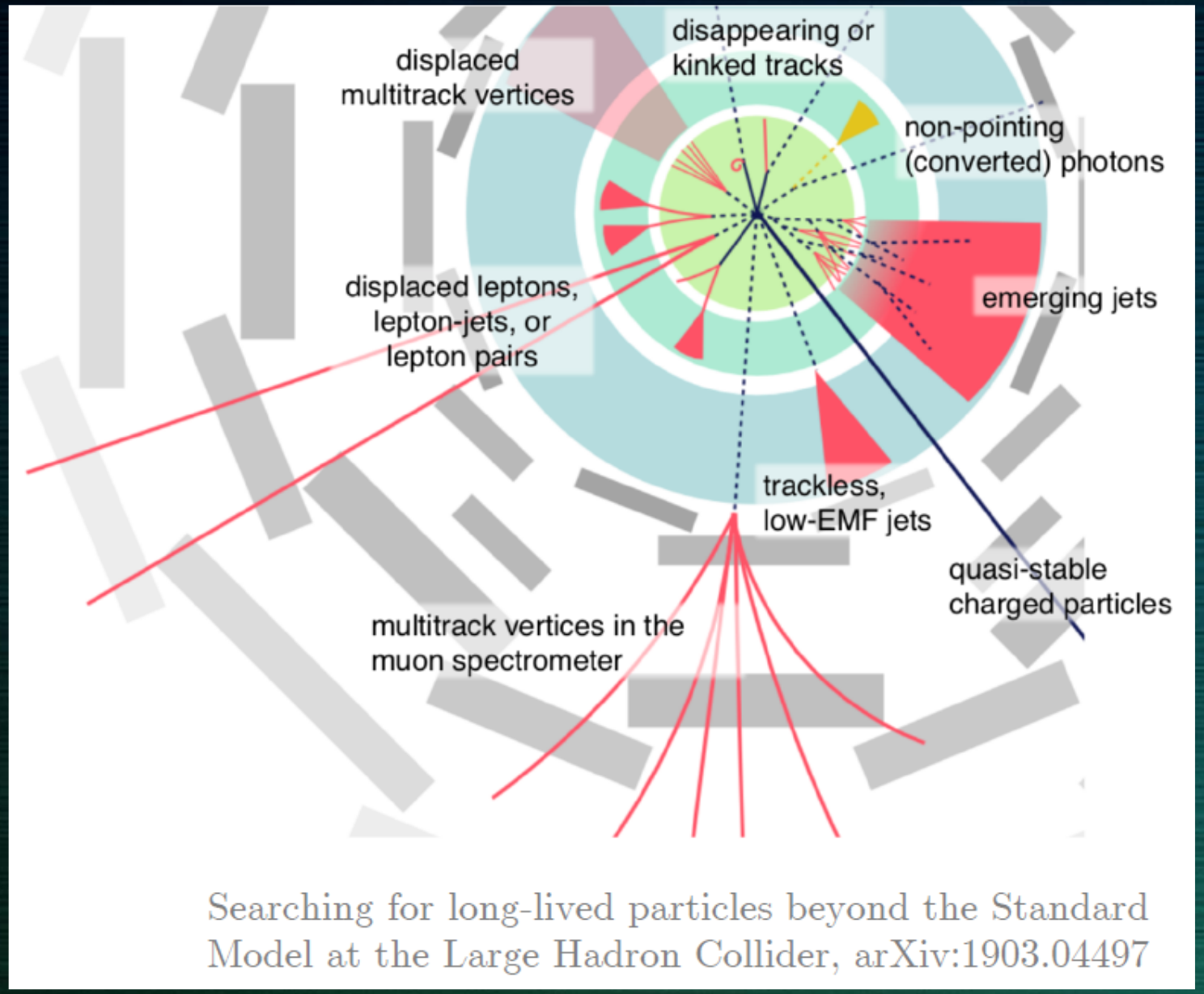
Dark sector with Long-Lived Particles at the LHC

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

✓ small $c\tau_0$ that comparable to the inner tracker size, no displaced tracks → "standard" prompt decay

✓ intermediate $c\tau_0$ → LLP

✓ very large/infinite large $c\tau_0$ → stable particles, "standard" MET signatures

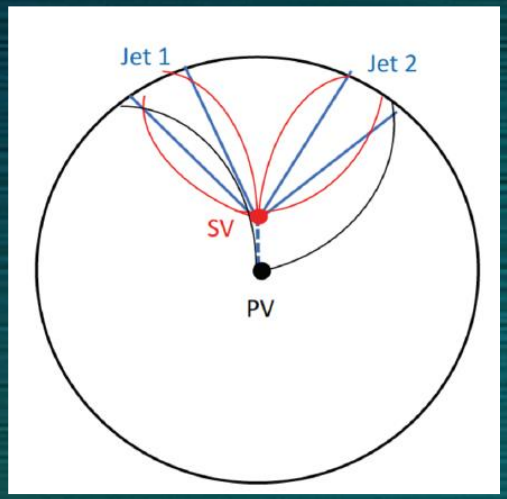


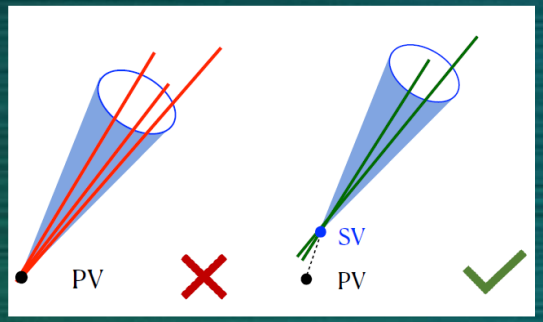
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

LLP theory motivations: arXiv:1806.07396

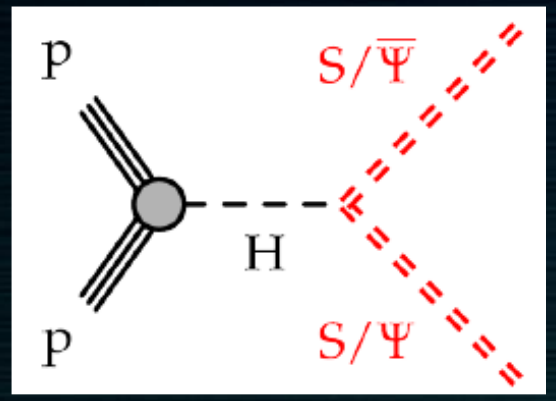
displaced jets





LLP decays in the CMS Muon system

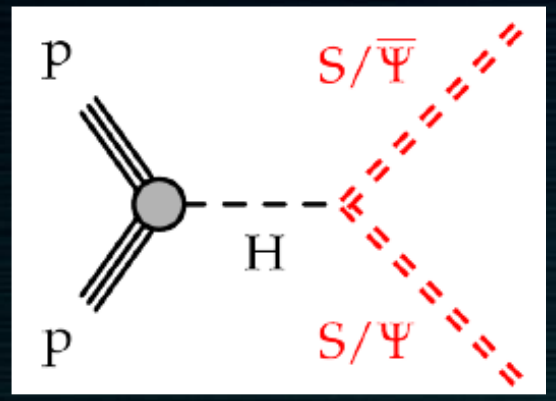
CMS PAS EXO-21-008



- 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 (bbbar, ddbar, K^+K^-, K^0K^0 , 2π, 2τ, 2γ etc.)
- Interpretations for dark showers and twin Higgs models

LLP decays in the CMS Muon system

CMS PAS EXO-21-008



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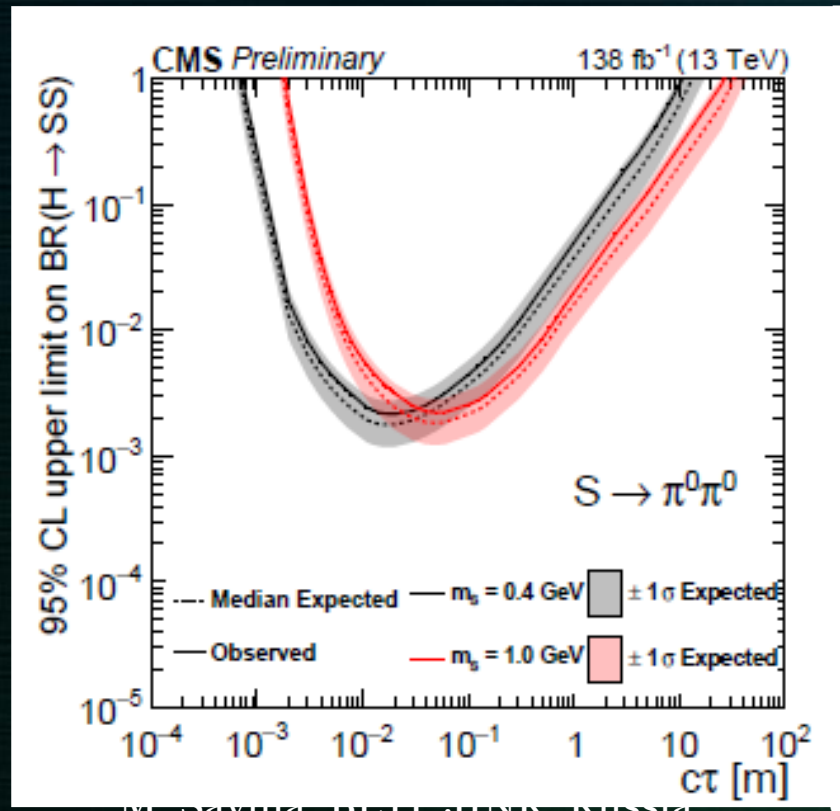
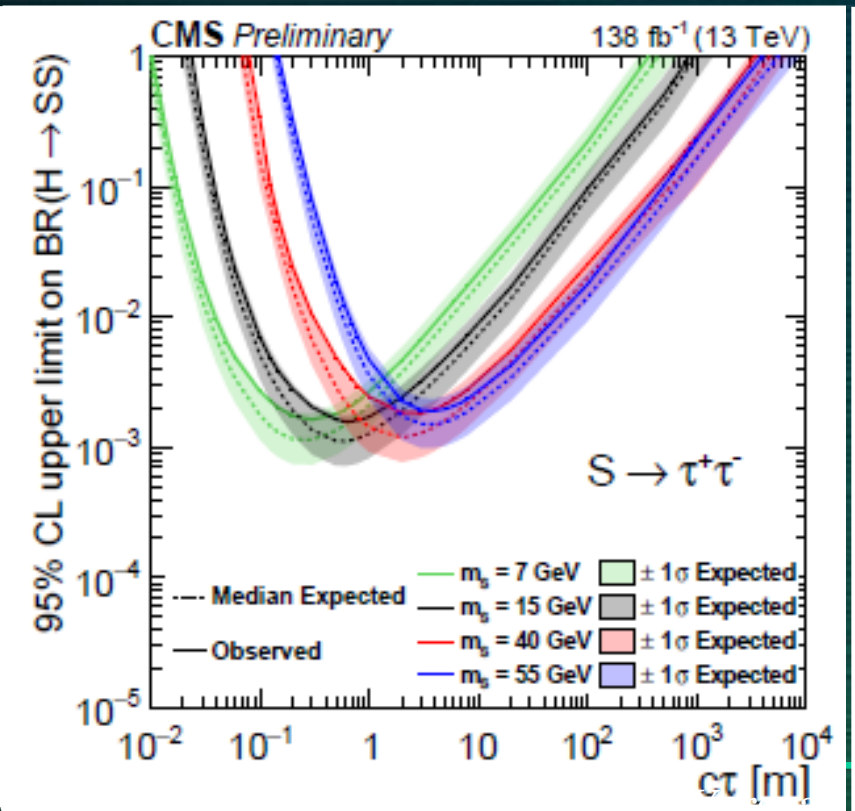
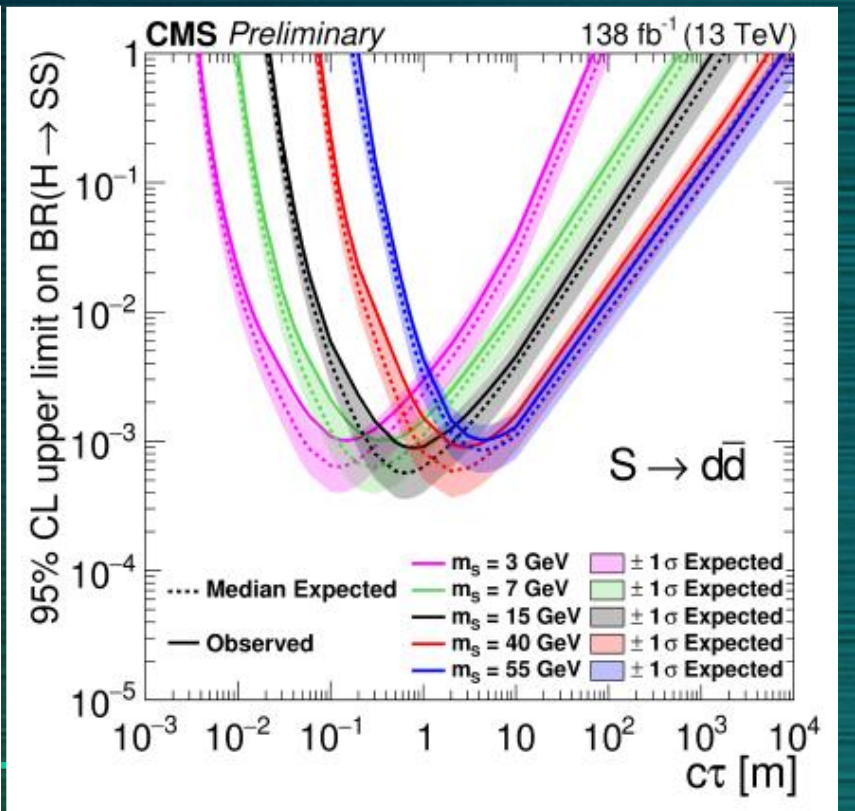
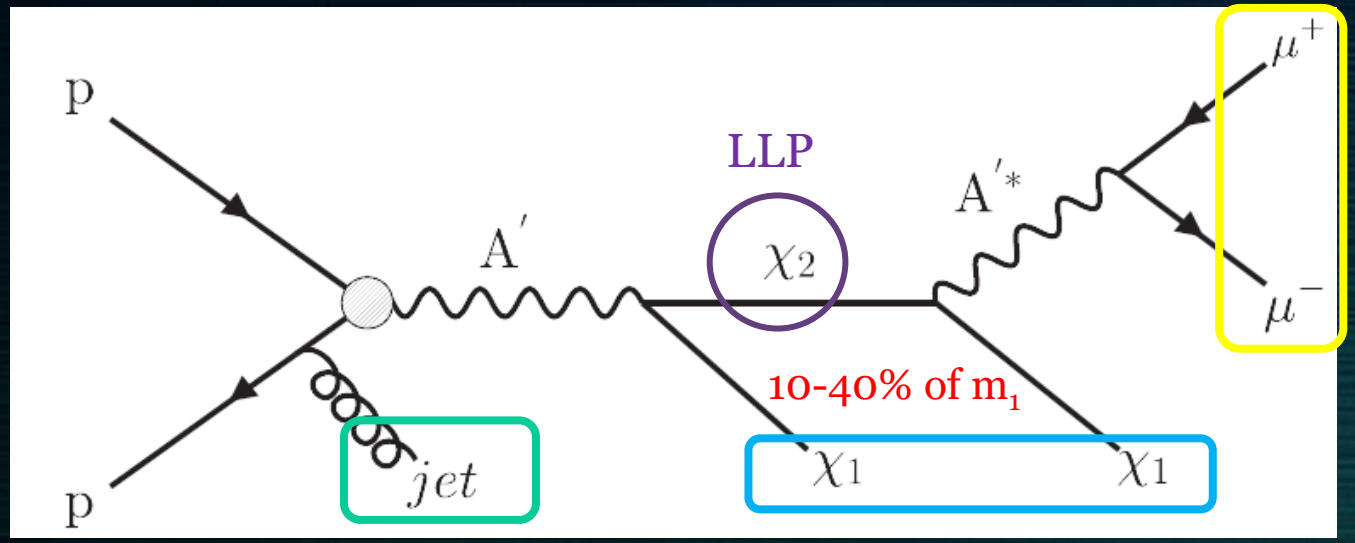






Search for inelastic DM with two displaced muons + MET

CMS EXO-20-010

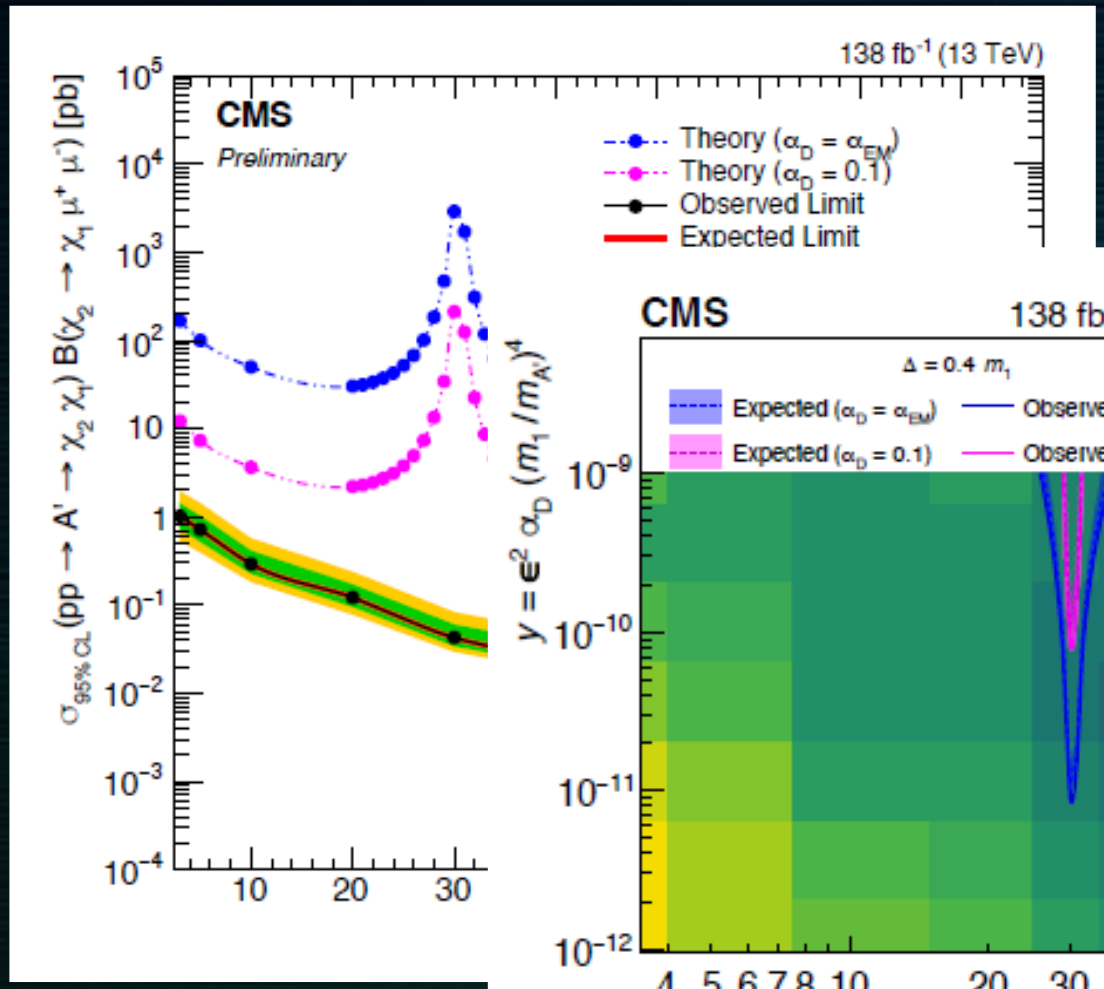


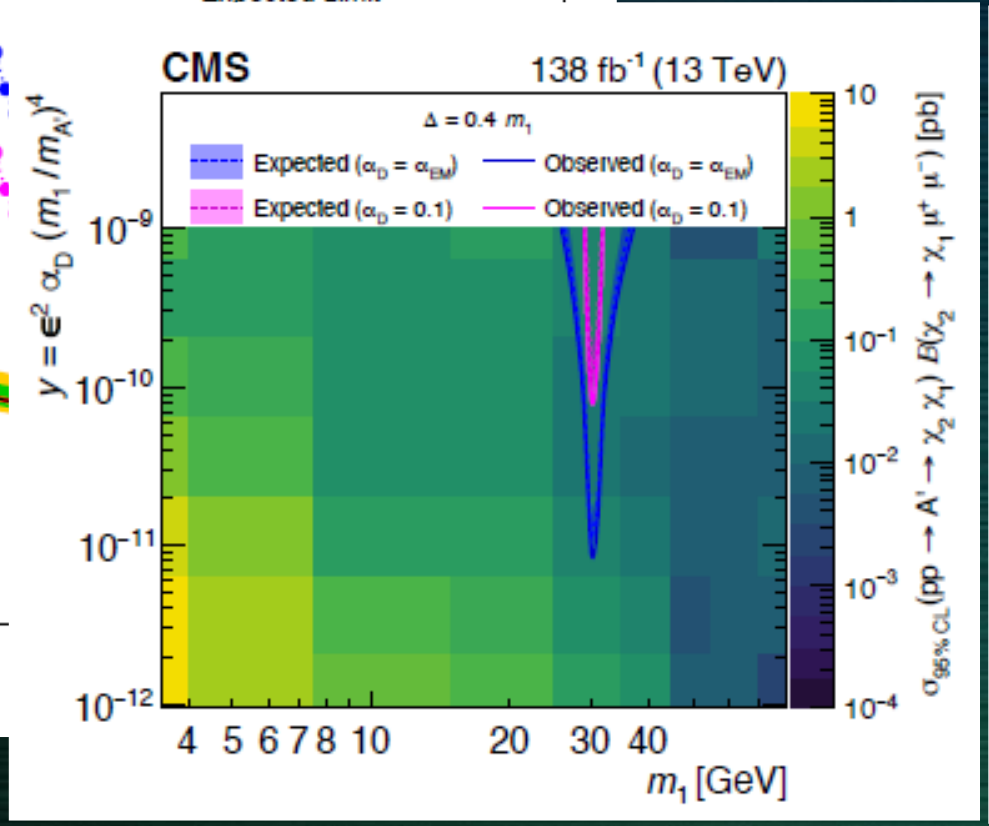
- Inelastic DM – dark photon A' ($m_{A'}$, kinematic mixing ε), and two closely degenerated by mass DM states (mass splitting Δ, mass of χ_1 m_1), LLP χ_2(lifetime $c\tau$), dark gauge-fermion coupling α_D
- The interaction strength $y \equiv \epsilon^2 \alpha_D \left(\frac{m_1}{A'}\right)^4$

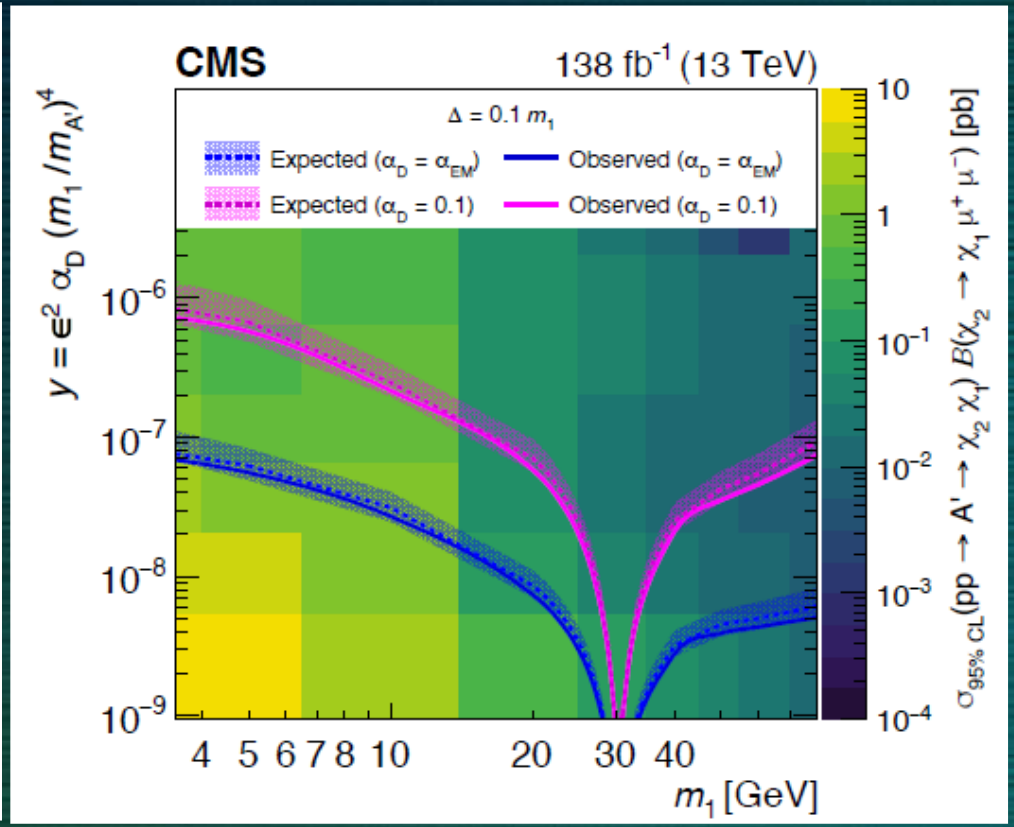
- The first LHC search of such a type – mixed LLP + MET signature
- A pair of displaced muons (soft, collimated)
- Large MET collimated with muons
- IS energetic jet as a tag

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

There’s no point in describing what’s happening,
so I’ll just write: we’re fine

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 aligment (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	$s(b\bar{b})+E_T^{miss}$

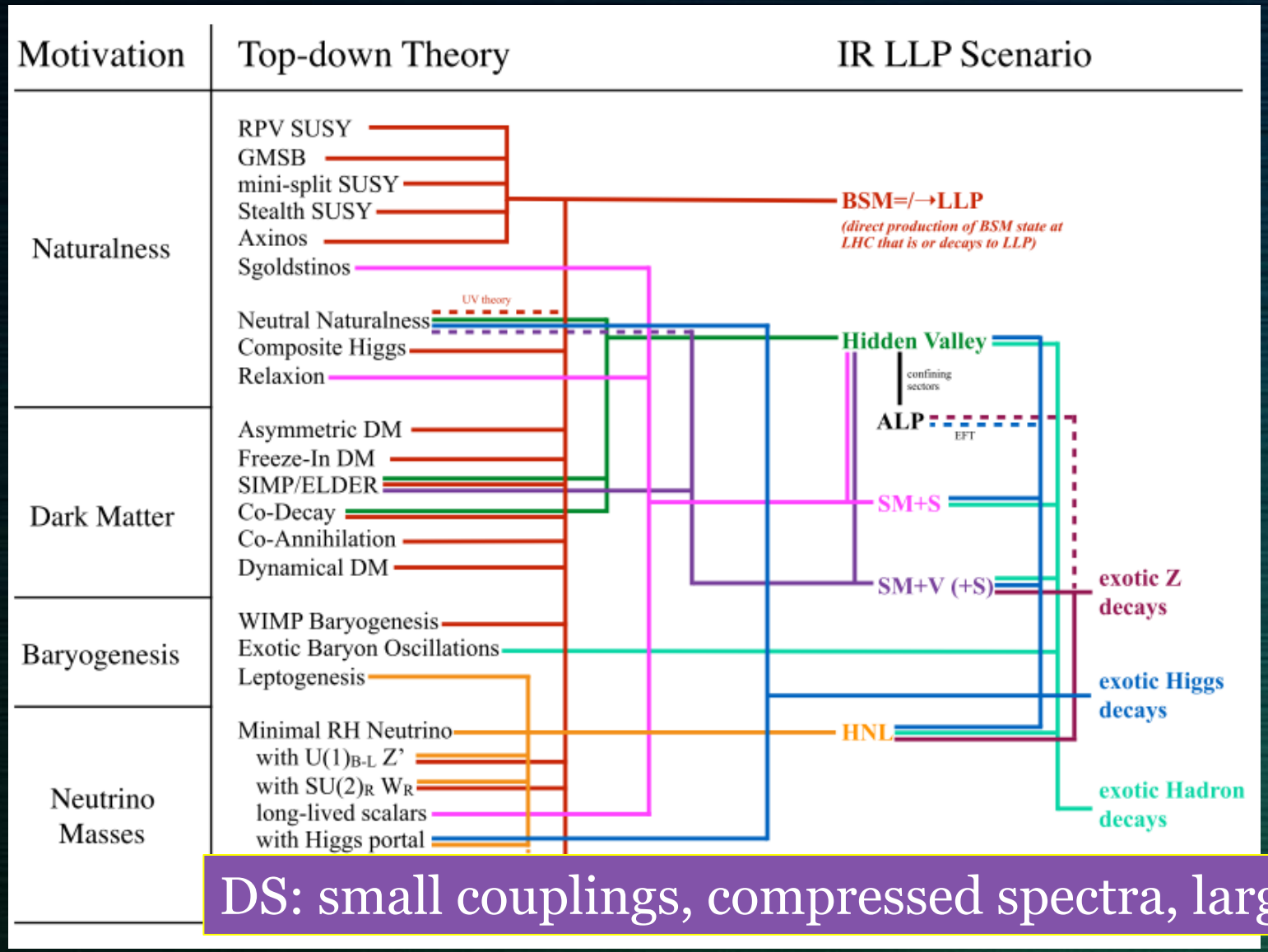
The (pseudo)scalar mediator

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)	$h+E_T^{miss}$, $Z(ll)/V(qq')/Z(q\bar{q})+E_T^{miss}$, $h\rightarrow inv$, $X\rightarrow hh$, 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



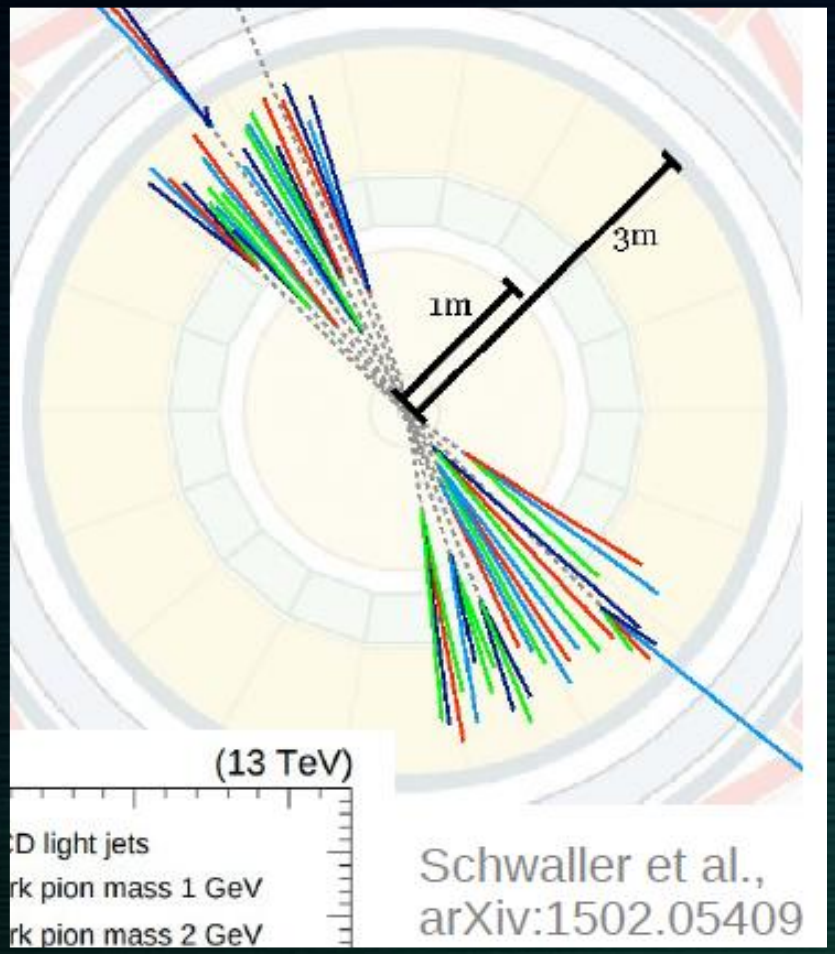
- ✓ Dark photon
- ✓ Heavy neutral leptons (quarks)
- ✓ Dark GB and/or Higgs(es)…

- ✓ Higgs/GB/gluon/SUSY portals

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

DS: small couplings, compressed spectra, large hierarchy → large cτ

Emerging jets/dark showers



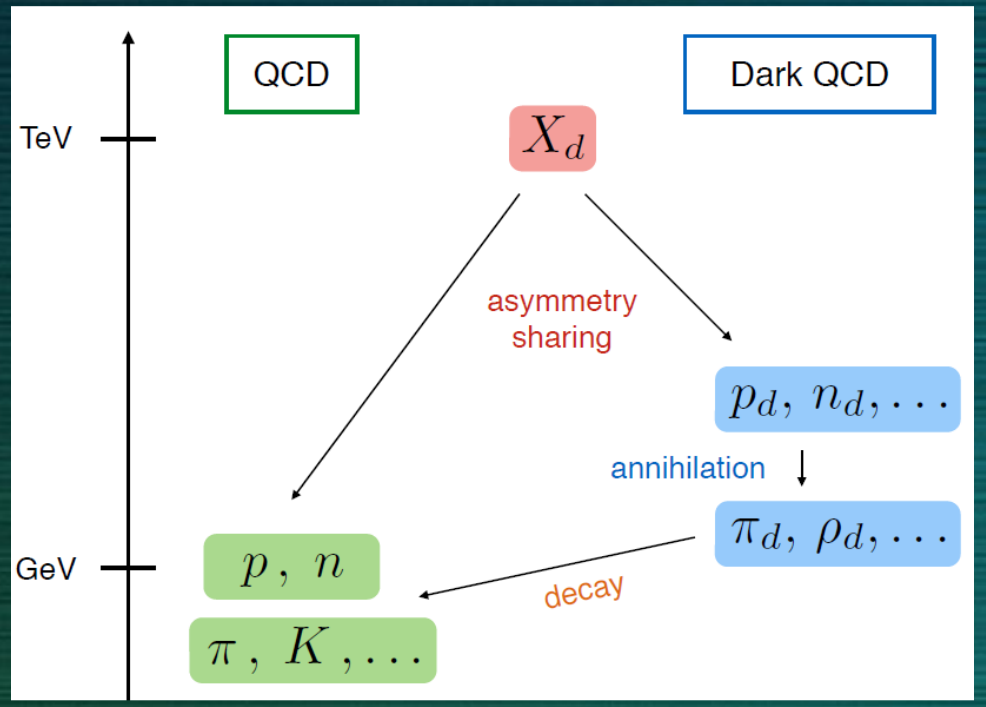
Dark QCD

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \bar{q}_{\mathrm{d}} i \not{D} q_{\mathrm{d}} - \bar{q}_{\mathrm{d}} M_q q_{\mathrm{d}}$$

F^a: dark gluons (N_{d} colours)

q_{d}: dark quarks (N_{f} flavours)

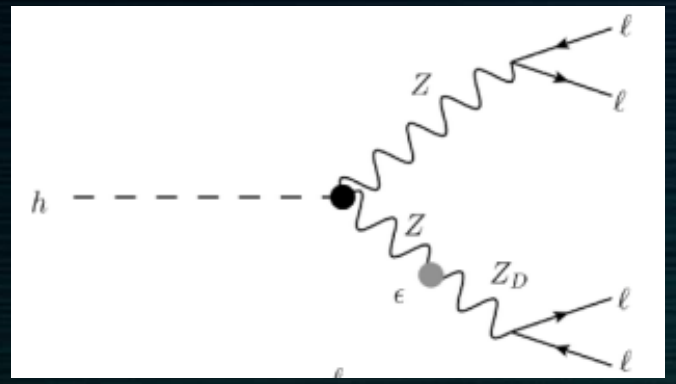
M_q: quark mass matrix



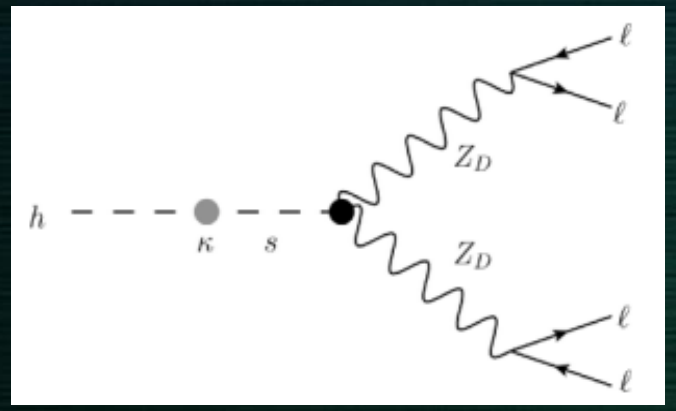
- ✓ One of the most striking DM-targeted signatures (Dark QCD → dark showers)
- ✓ Tracks start near the edge of the tracker, in the ECAL and HCAL and even in the inner muon stations

Higgs decay to dark photons: displaced muon jets

CMS-PAS-EXO-20-014



$Z–Z_D$ conversion, ε^2



Higgs – dark higgs conversion, κ