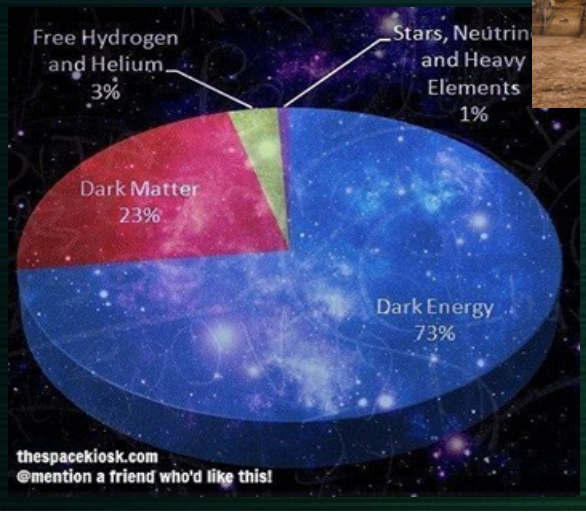
International Conference on Neutrino and Dark Matter
December 14, Cairo, Egypt

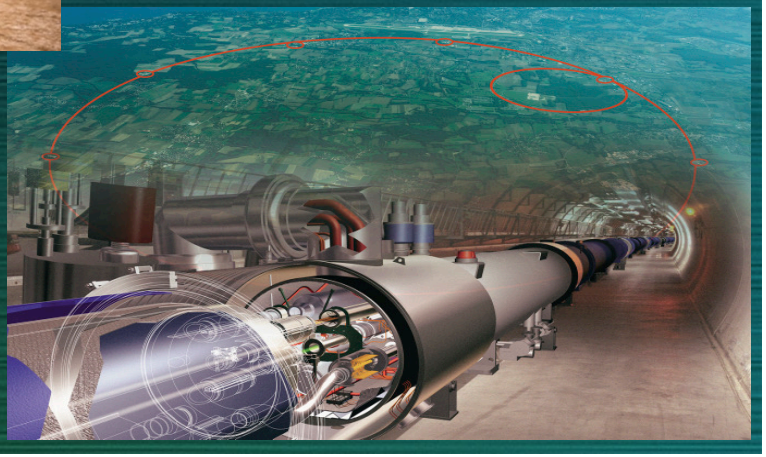
Dark matter searches at the LHC with the CMS



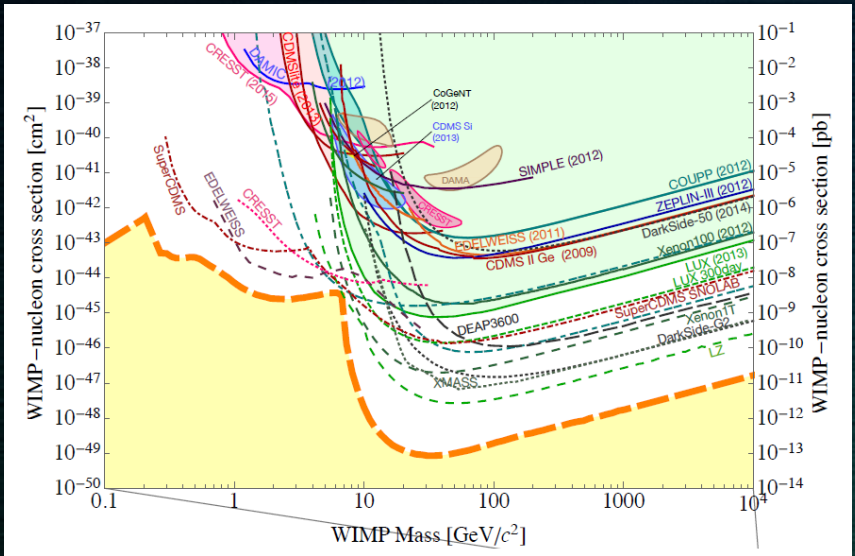
Maria Savina, BLTP JINR, Russia

on behalf of the CMS Collaboration

Maria.Savina@cern.ch



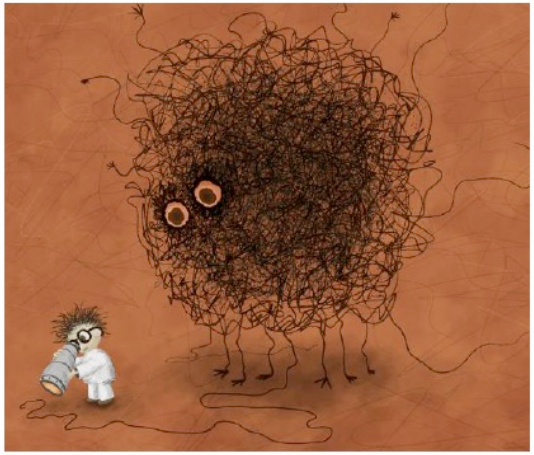
DM searches at the LHC – are you serious about this?



Definitely YES !!

1.Additional search tool to DD, significant contributions in different models in the moderate mass region, where there is a severe loss of DD sensitivity

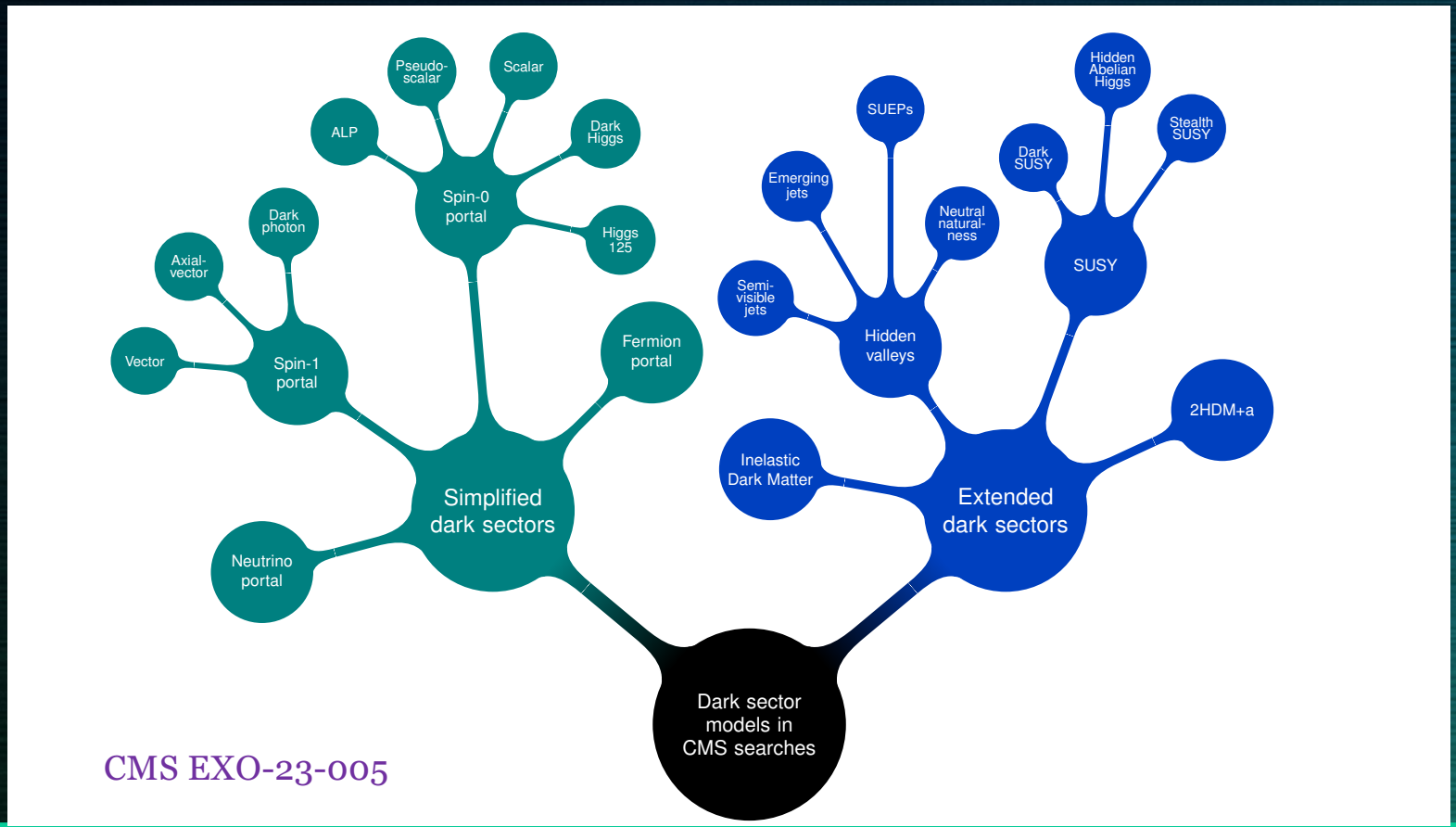
2. A unique opportunity to feel an extended dark sector as opposed to just one DM particle



The long-term LHC search program on DM/DS

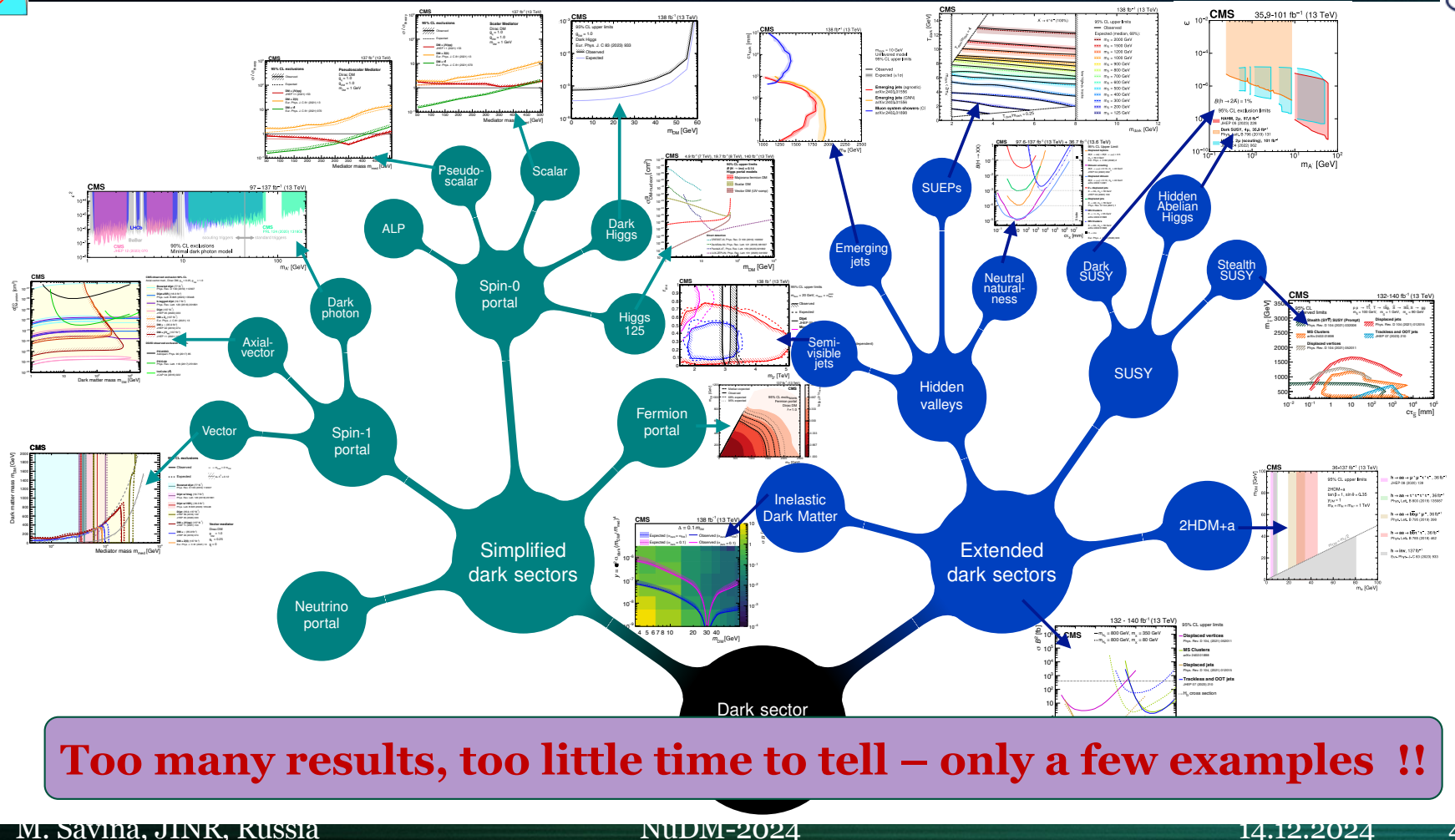
Map of the DM models probed in CMS searches

Portal approaches and simple DS vs “full” theories (or at least an extended DS)



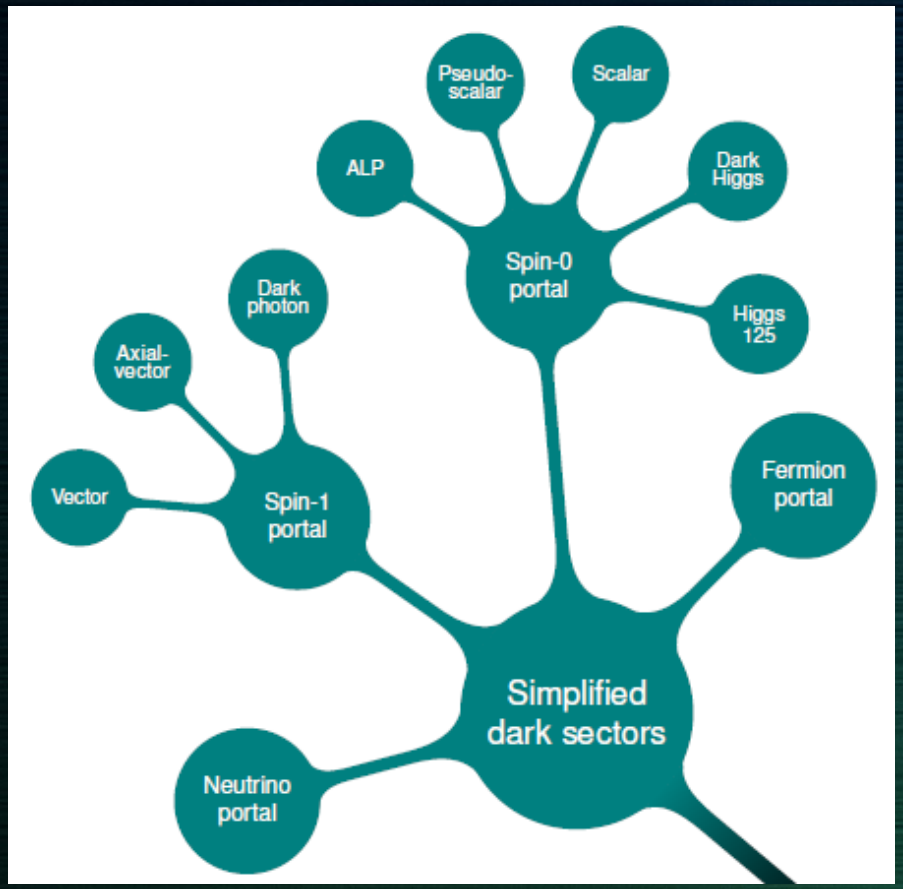
CMS EXO-23-005

Map of the DM models probed in CMS searches



Too many results, too little time to tell – only a few examples !!

Simplified dark sector, portal approaches



Spin-0 portals:

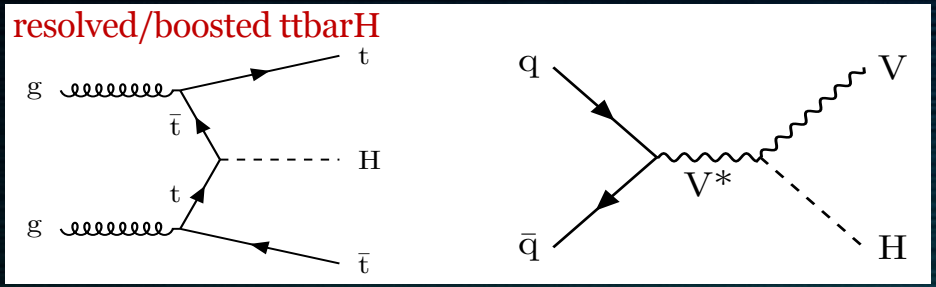
- Higgs → invisible — CMS HIG-21-007
- Axion-like particles — CMS HIG-22-003, CMS EXO-21-018

Spin-1 portals:

- Dark photon — CMS EXO-21-005

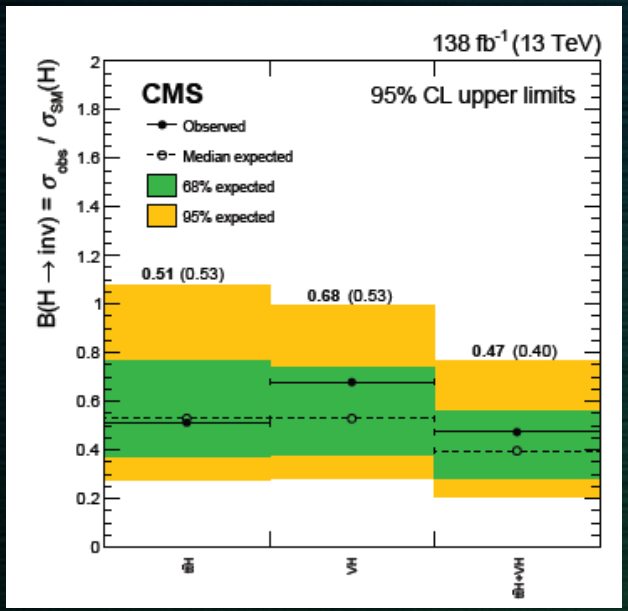
Combination of h_{125} → invisible searches for ttbar and VH

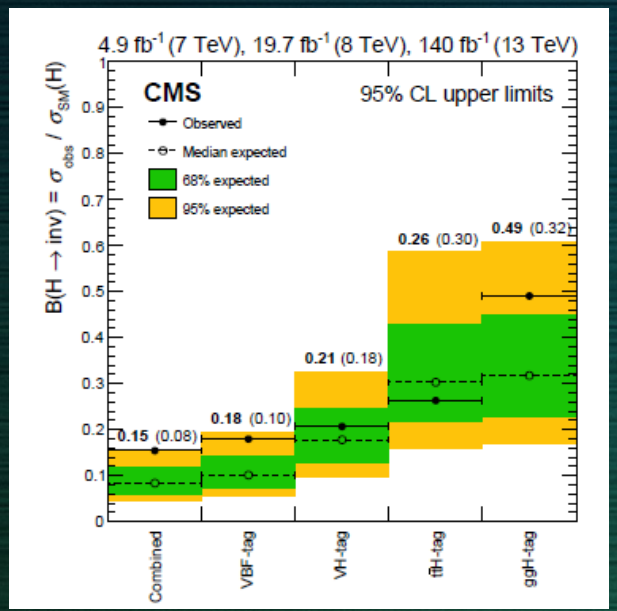
resolved/boosted ttbarH

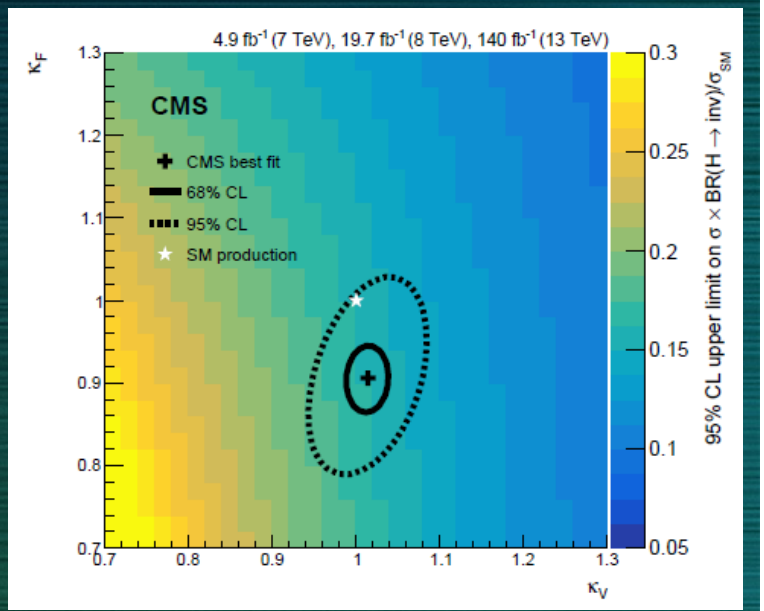


CMS HIG-21-007,
arXiv:2303.01214 [hep-ex]

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

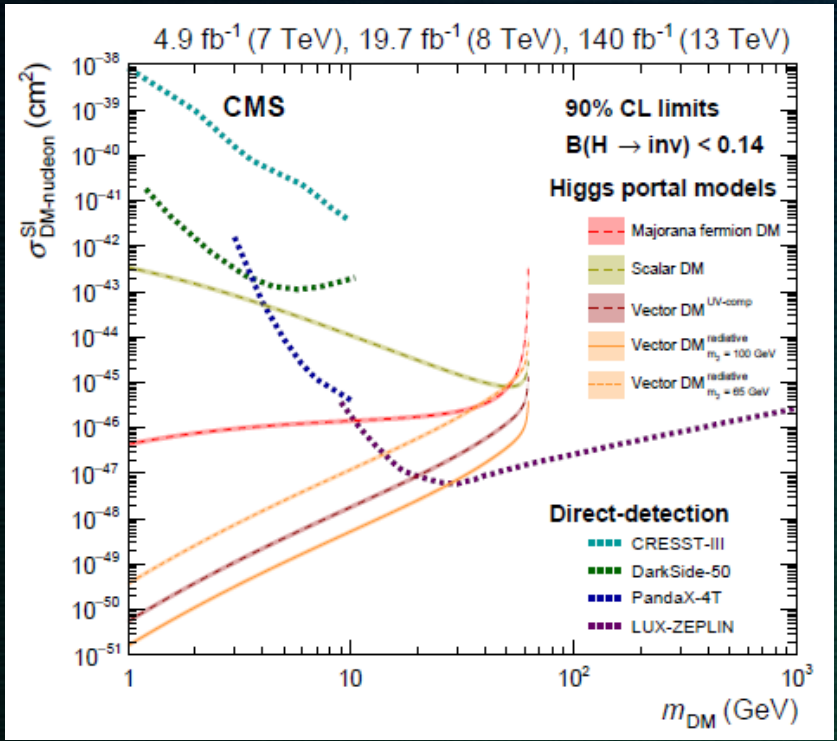


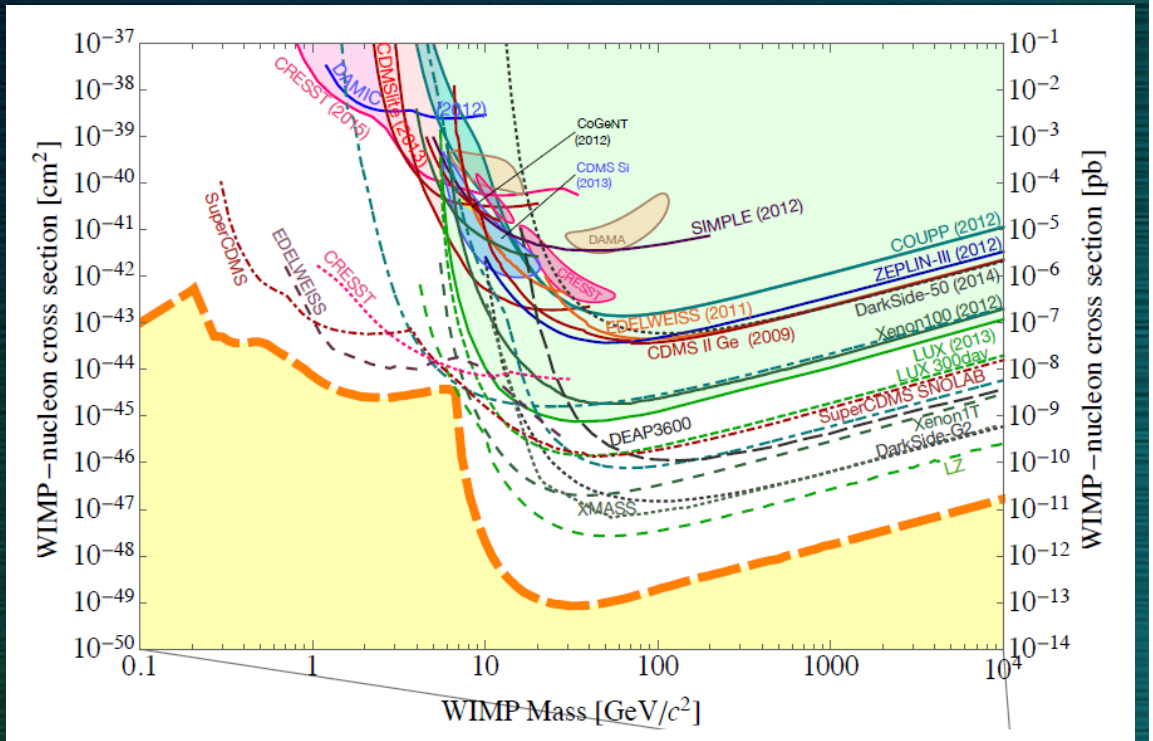




Combination of h_{125} → invisible searches

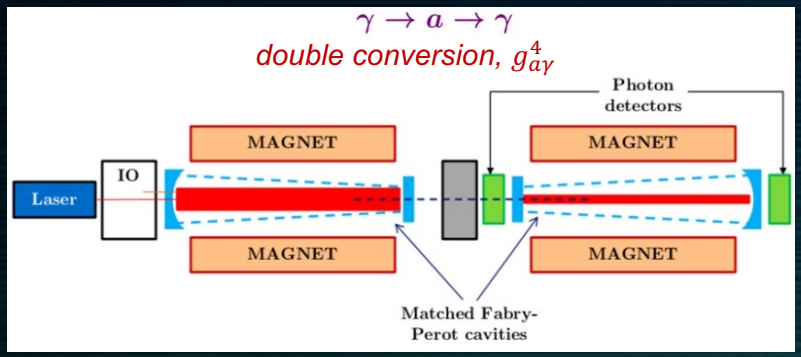
CMS HIG-21-007

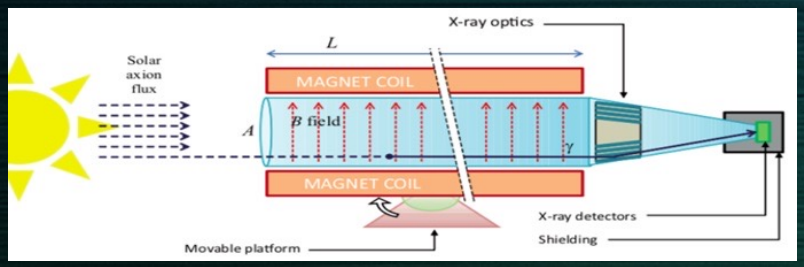




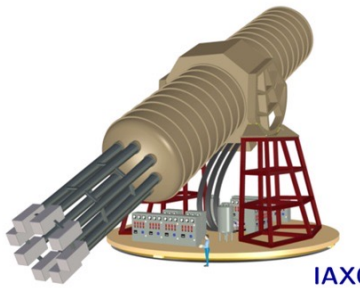
Axion-like particles, 1 – 10 GeV masses

Strong CP problem, axion is a dynamic field which mass after spontaneous symmetry breaking (Peccei-Quinn, Weinberg, Wilczek, 1977)

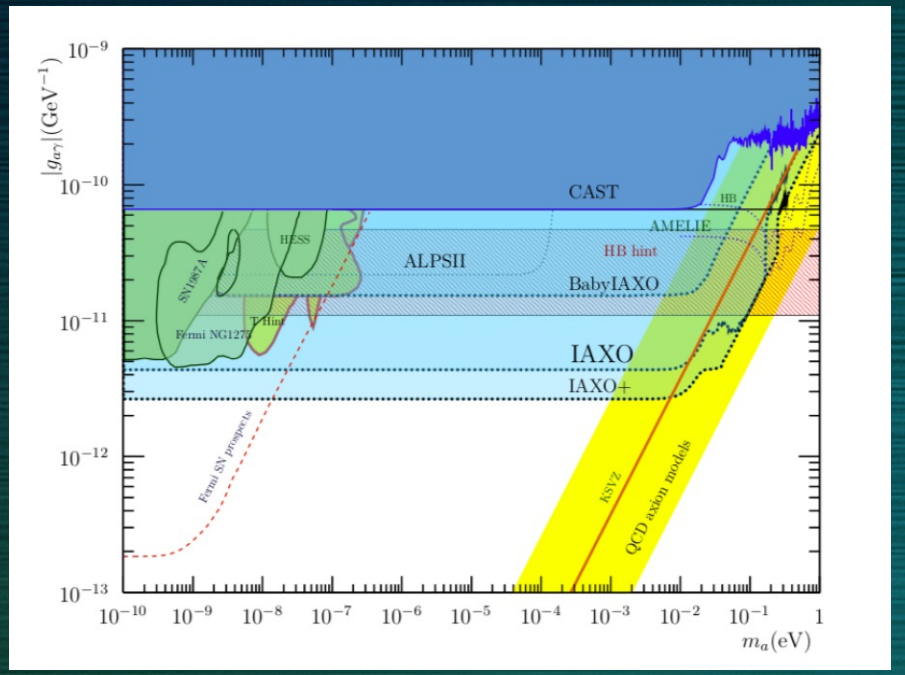




CAST

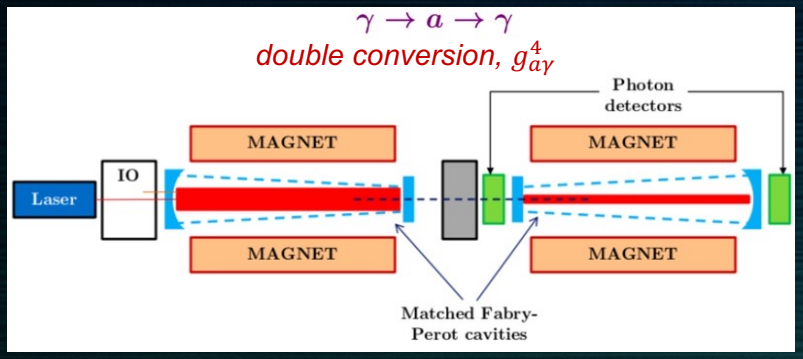


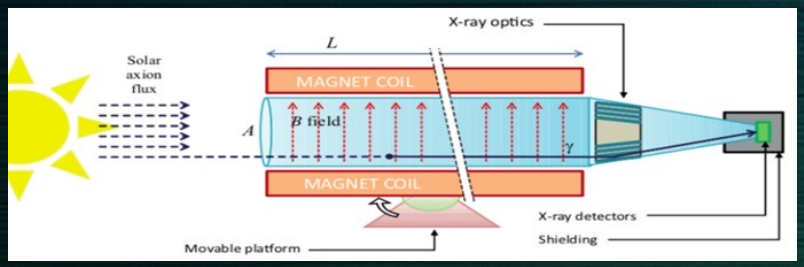
IAXO



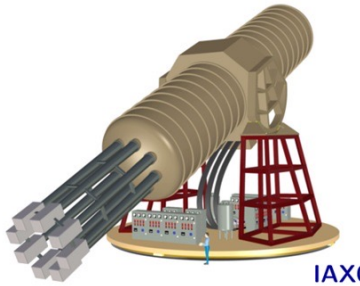
Axion-like particles

Strong CP problem, axion is a dynamic field which mass after spontaneous symmetry breaking (Peccei-Quinn, Weinberg, Wilczek, 1977)





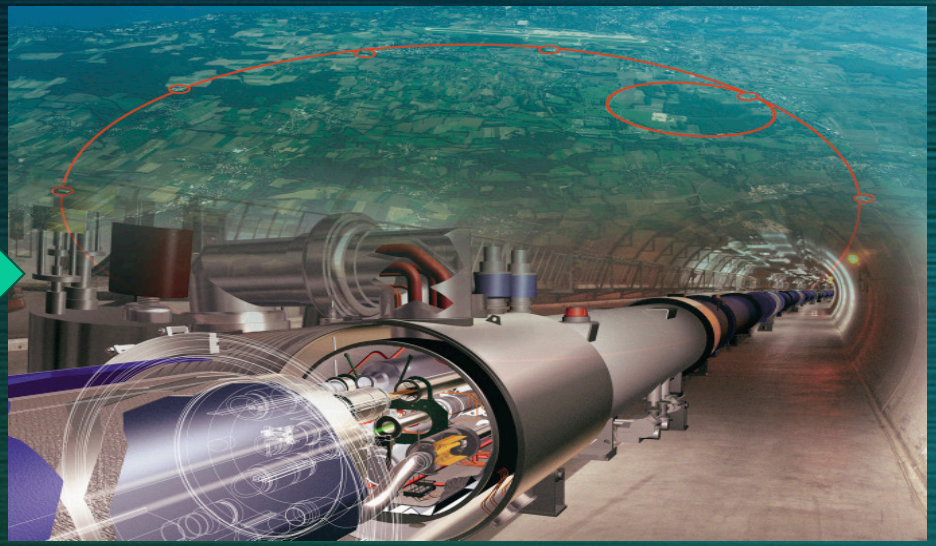
CAST



IAXO

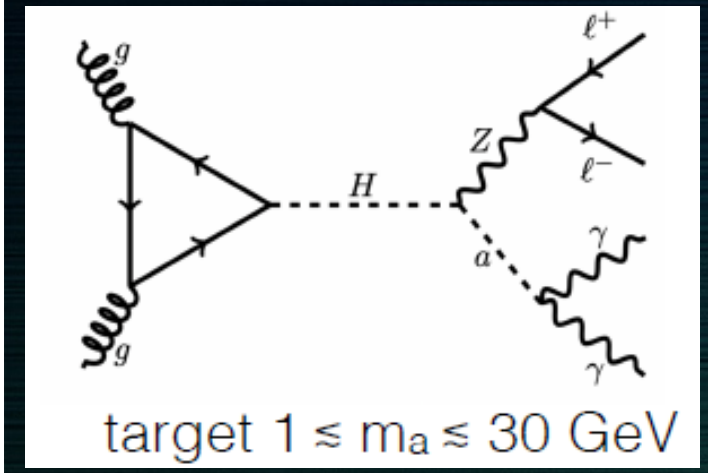
Low masses → moderate masses, axion → ALP

→ possible to search at the LHC

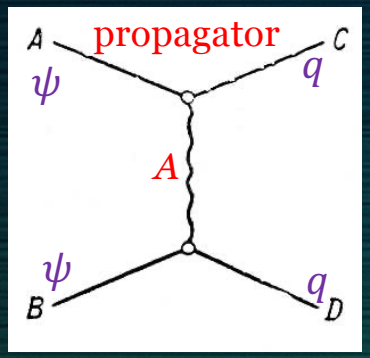


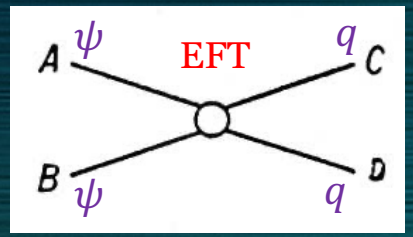
Exotic higgs decays h → Za, Z →ll, a →2 gamma

CMS 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



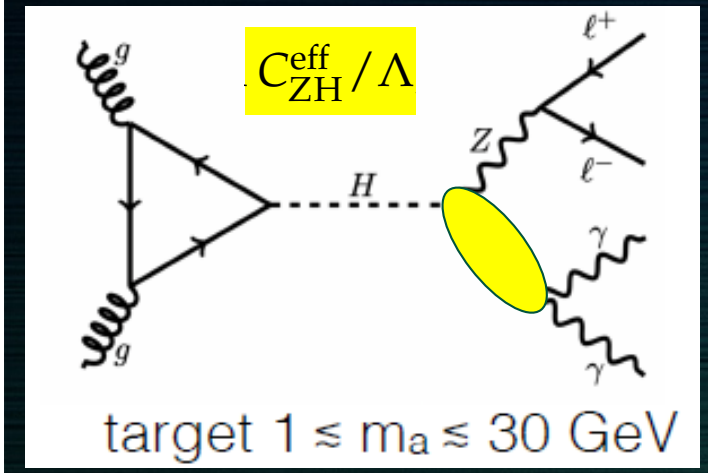


C_i are Wilson coefficients in the EFT approach that describe the ALP/SM couplings

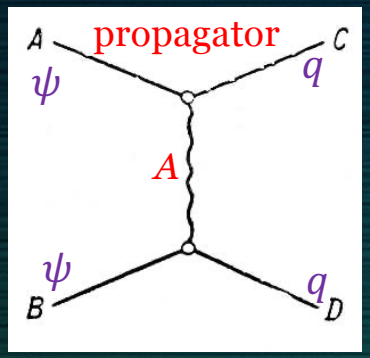
$$\mathcal{L}_{EFT} = \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

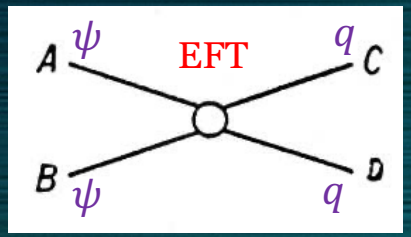
Exotic higgs decays h → Za, Z →ll, a →2 gamma

CMS 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





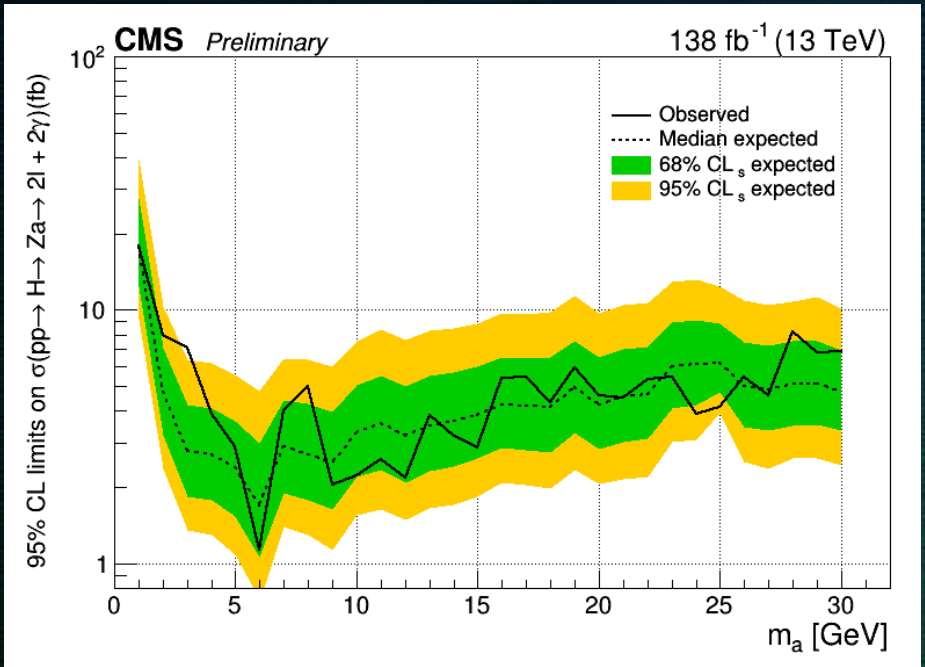
C_i are Wilson coefficients in the EFT approach that describe the ALP/SM couplings

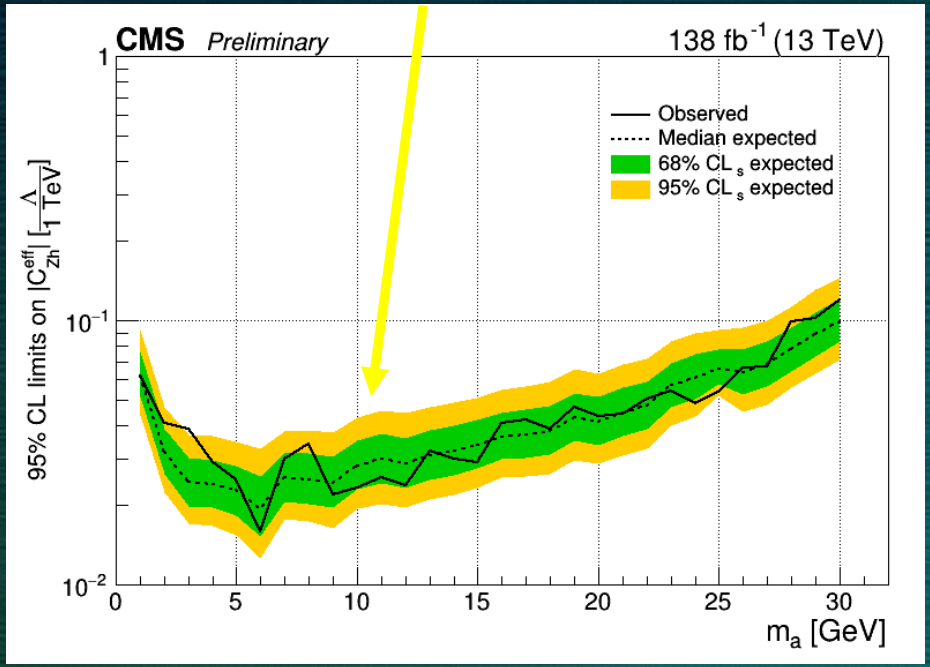
$$\mathcal{L}_{EFT} = \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

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

CMS HIG-22-003

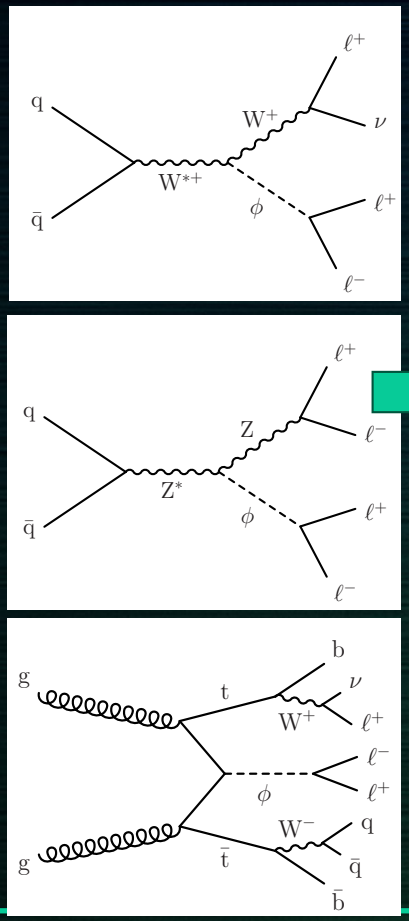
Limit on C_{ZH}^{eff} / Λ, when ALP decays exclusively in a diphoton, Λ is large

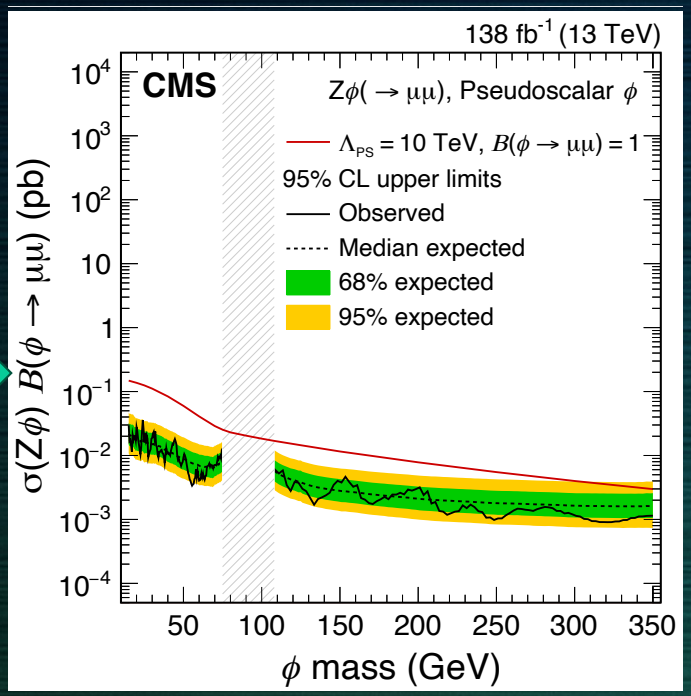




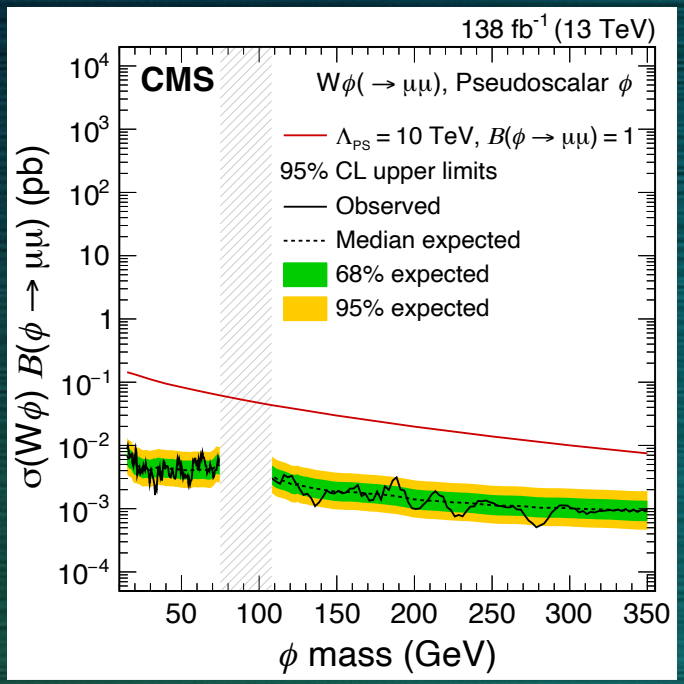
(Pseudo)scalar dilepton resonance in association with V/$t\bar{t}$-pair

Scalar, pseudoscalar (axion-like) and Higgs-like Vφ int.



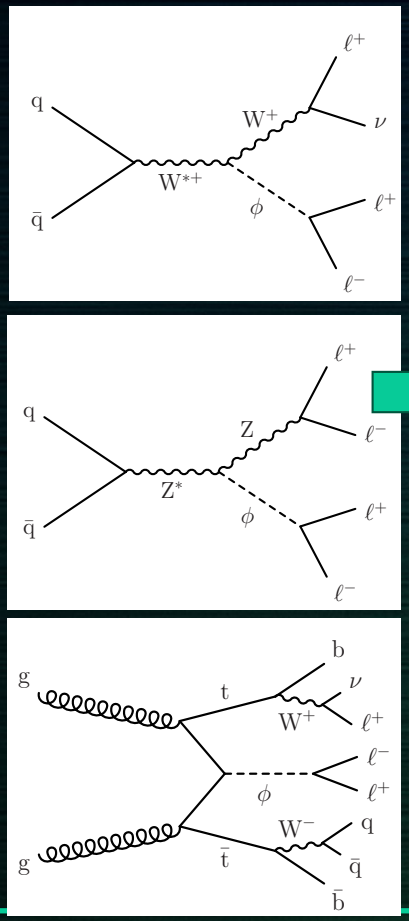


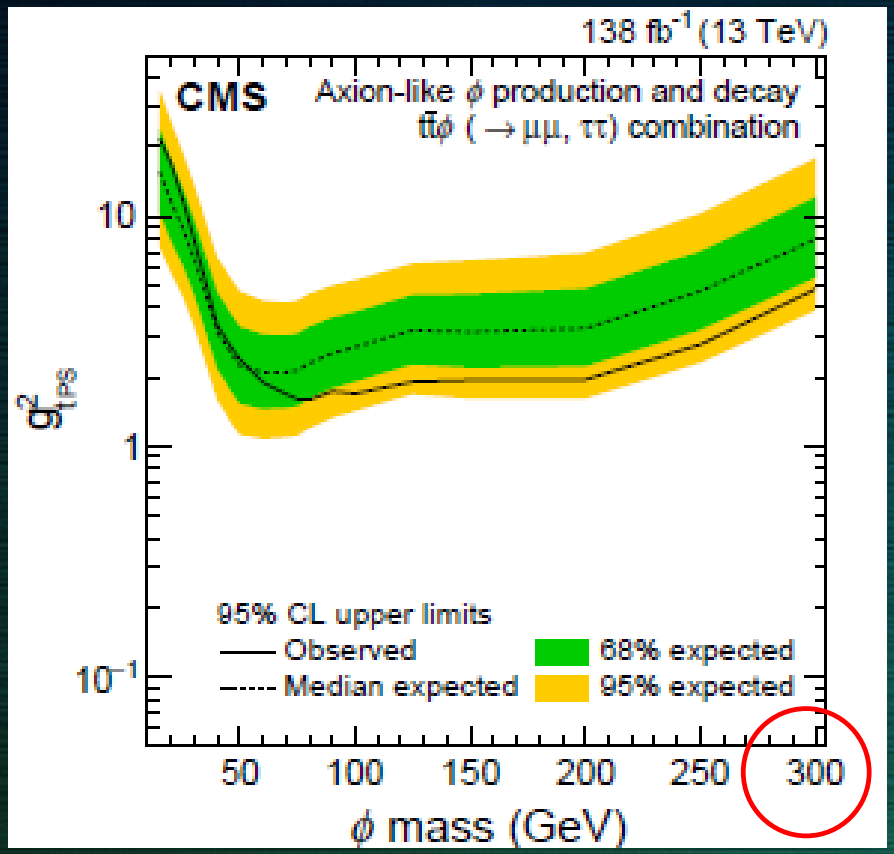
CMS EXO-21-018,
arXiv:2402.11098 [hep-ex]



(Pseudo)scalar dilepton resonance in association with V/$t\bar{t}$-pair

Scalar, pseudoscalar (axion-like) and Higgs-like Vφ int.



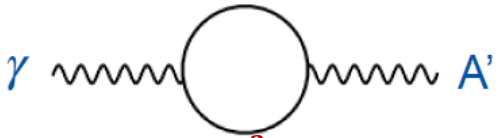


CMS EXO-21-018, arXiv:2402.11098 [hep-ex]

Higher mass limit of about 300 GeV is because of non-negligible axion branching to top-antitop pair

Search for dark photons, prompt/LLP

The coupling to SM particles proportional to electric charge

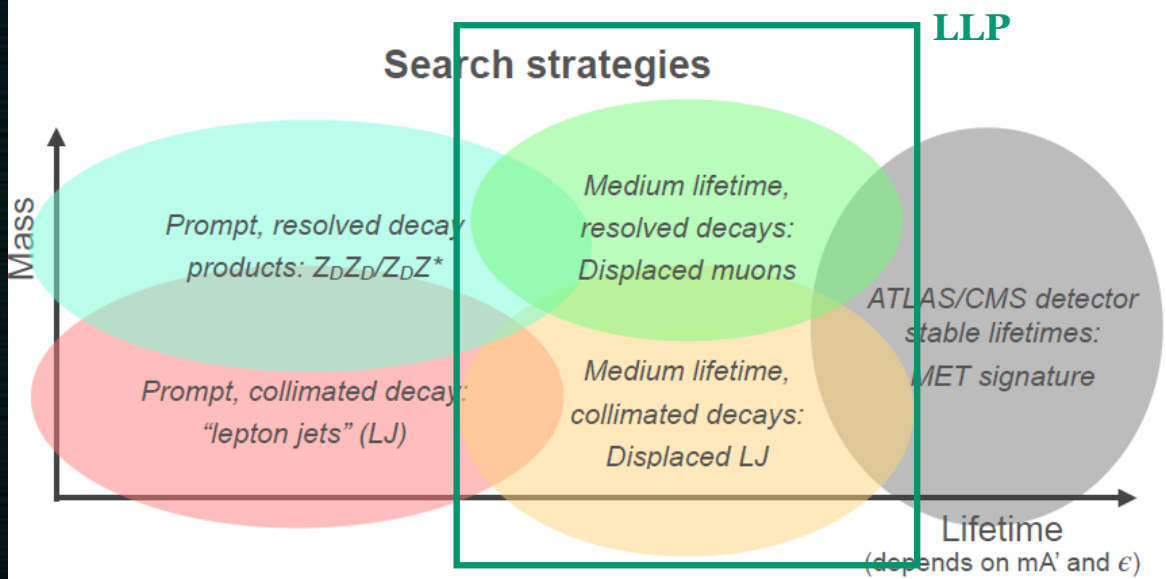


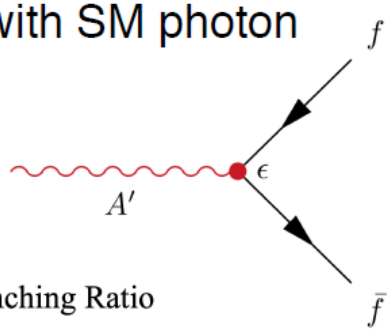
$\alpha' = \epsilon^2 \alpha_{EM}$

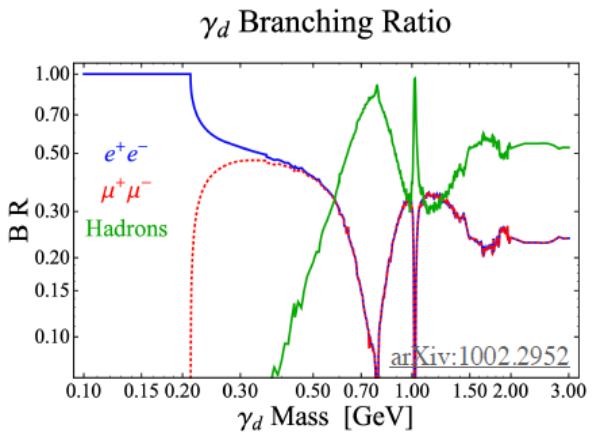
1 or 2 loops: naively $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

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

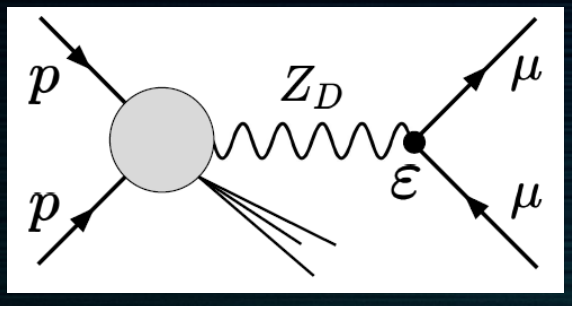
Parameters: kinetic mixing term, ϵ, and $m_{A'}$





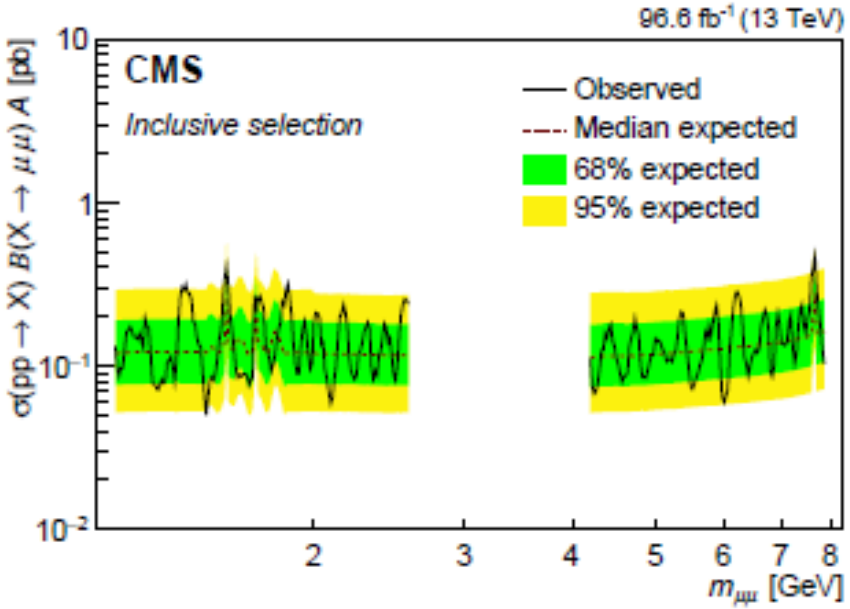


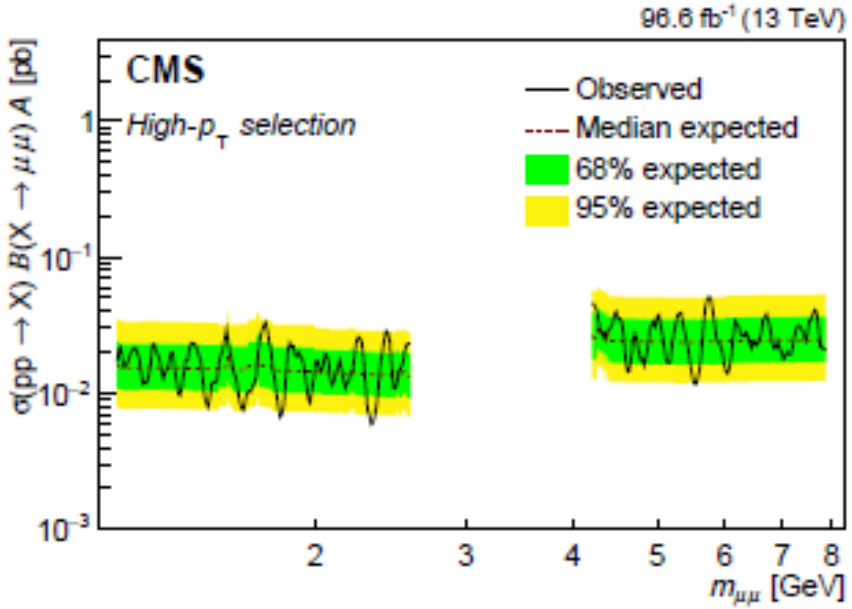
Search for prompt GeV-scale dimuon resonance



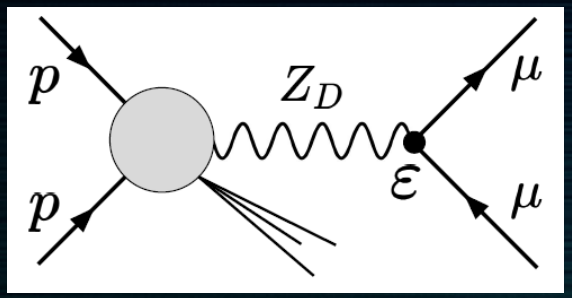
- ✓ minimal dark photon model and
- ✓ light scalar decay to dimuon (2HDM+S) interpretations

CMS EXO-21-005,
arXiv:2309.16003 [hep-ex]



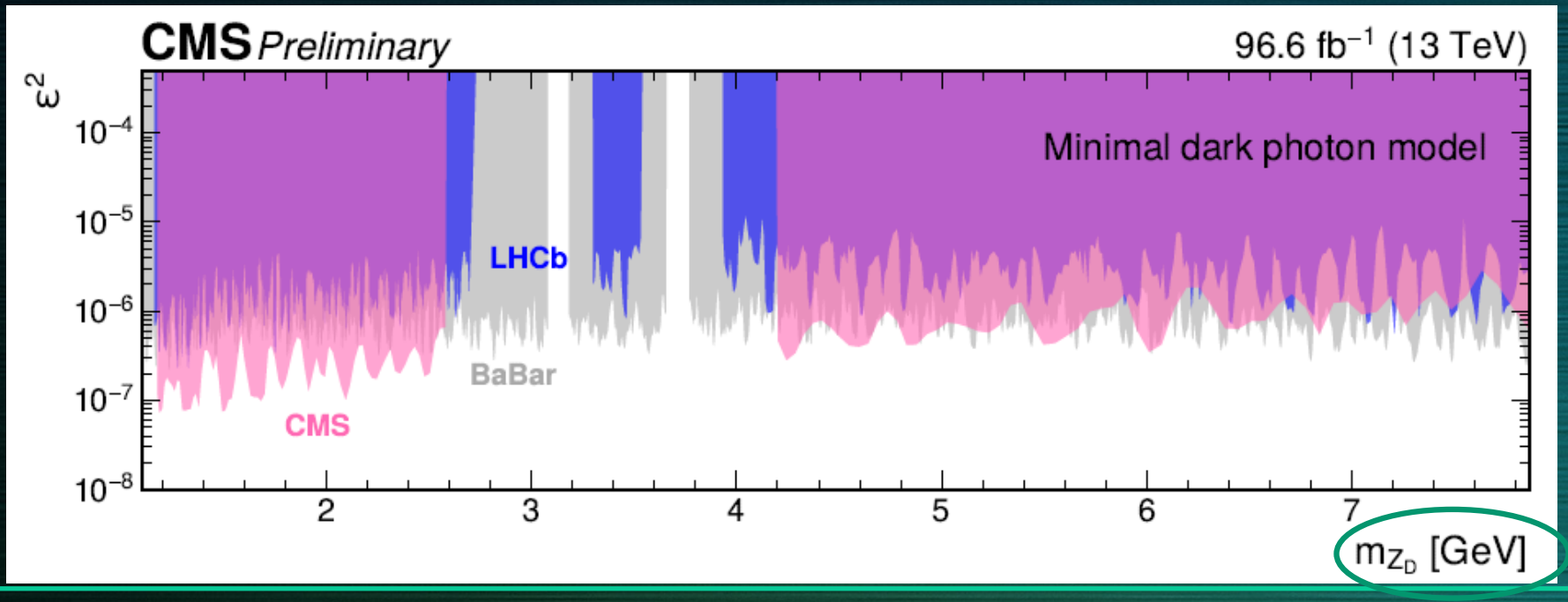


Search for prompt GeV-scale dimuon resonance

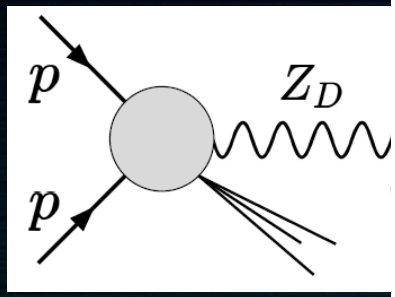


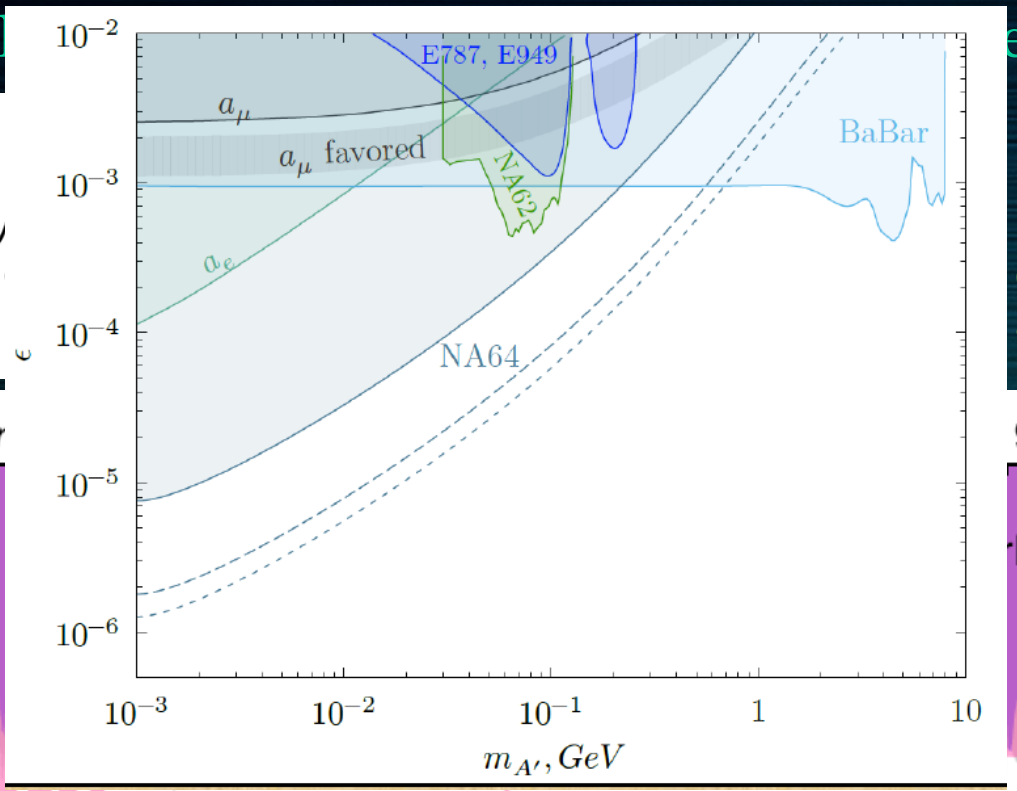
- ✓ minimal dark photon model and
- ✓ light scalar decay to dimuon (2HDM+S) interpretations

CMS EXO-21-005,
arXiv:2309.16003 [hep-ex]



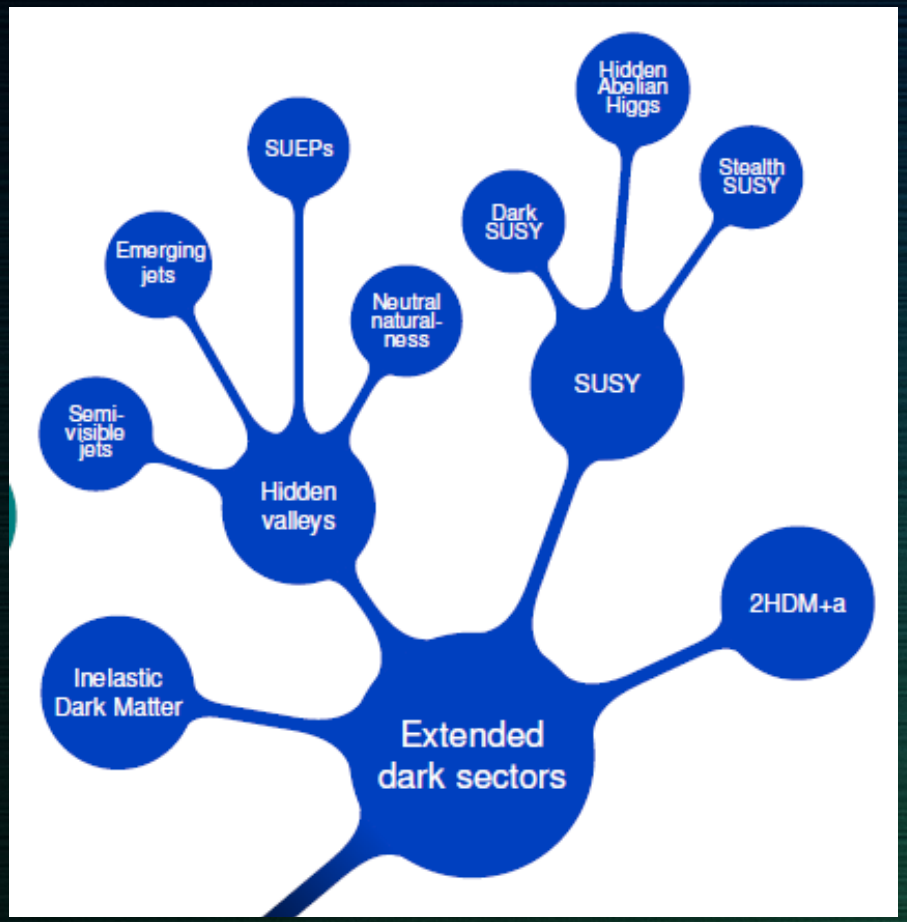
Searc e





CMS EXO-21-005,
arXiv:2309.16003 [hep-ex]

Extended dark sector and "full" theories



RPC/PRV SUSY

- GMSB SUSY — CMS SUS-16-046
- Stealth SUSY — CMS SUS-19-001
- RPV SUSY — CMS SUS-23-015

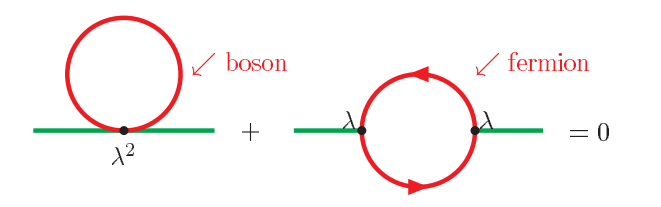
Strongly coupled DM, dark showers

- LLP dark showers — CMS EXO-22-015, CMS EXO-21-008
- SUEP — CMS EXO-23-002

Weakly coupled DM

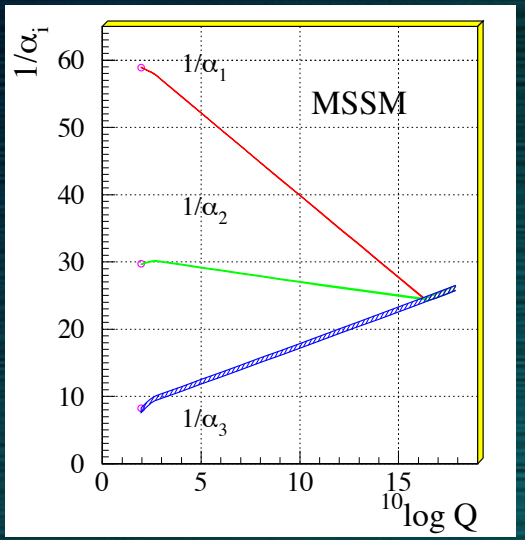
- Twin higgs — CMS EXO-23-013
- Higgs/Z' HAHM. — CMS EXO-23-014

MSSM as a natural SUSY



$$\sum_{bosons} m^2 - \sum_{fermions} m^2 = M^2_{SUSY}$$

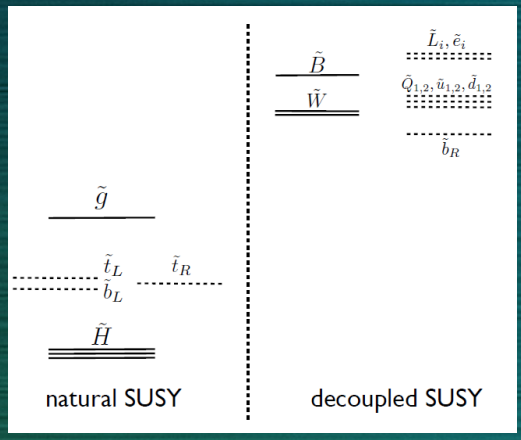
$$\delta M_h^2 \sim g^2 M^2_{SUSY} \sim M_h^2.$$



- Natural SUSY: weak-scale supersymmetric masses for neutralino (at least for the lightest two ones), for stops and gluino
- SUSY breaking, soft mass terms – ambiguity of spectrum arrangement
- R-parity preserved (RPC SUSY) – pair SP production/decays

$$R = (-1)^{3(B-L)+2s}$$

- Natural DM candidate – LSP/gravitino
- Cascade decays up to LPS, hard multijet / SS leptons / 2 gamma … + large MET (to reduce SM background)



GMSB, low scale SSB: a basis

SM+SP, ~~SUSY~~

messenger sector
$(\Phi_i, \overline{\Phi_i}, ..., i = 1,..N_f)$

$X, \qquad \langle X \rangle = M + \theta^2 F$

one(two)loop suppressed interactions with MS , soft SP masses, no flavor violation enhancement from soft terms, LSP – gravitino!

Masses are depend on *F, M, N*

chiral scalar superfield(s), fund. rep. 5+anti-5 (also 10+anti-10) of SU(5) or 16+anti-16 of SO(10) for the GUT group

tree level interaction goldstino-MS

$$W = \lambda_{ij} \bar{\Phi}_i X \Phi_j$$

$$\delta\alpha_{GUT}^{-1} = -\frac{N}{2\pi} \ln \frac{M_{GUT}}{M} \qquad N \lesssim 150/\ln \frac{M_{GUT}}{M}$$

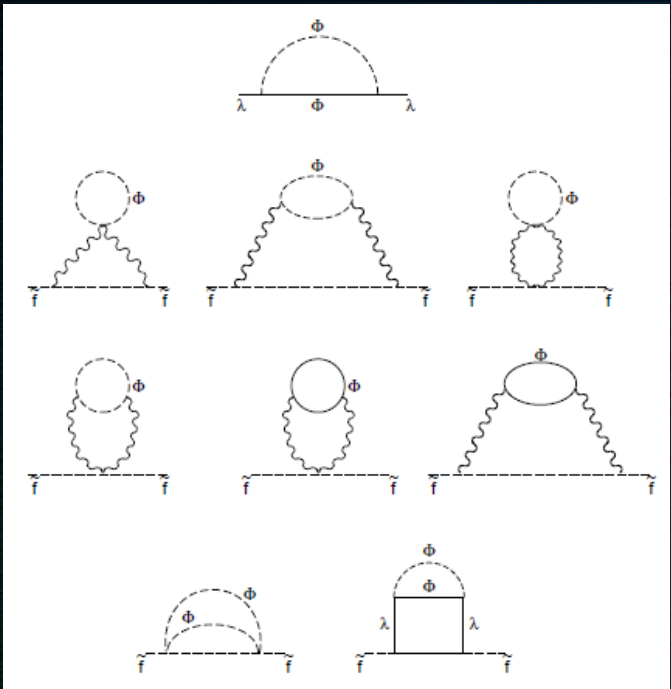
physical scalar states : $\frac{(\Phi \pm \bar{\Phi})}{\sqrt{2}}$ ➡ $M_{\Phi\tilde{\Phi}} \sim (\lambda M)^2 \pm (\lambda F)$

M – SUSY mass scale, F – SSB energy scale !!

(limits:
F ~ M or F << M)

GMSB SUSY, soft mass terms and universal spectrum

1-loop for gauginos, 2-loops for squarks



$$\mathcal{L}_{\text{soft}} = -\frac{1}{2}\left(\tilde{M}_\lambda \lambda_g \lambda_g + \text{h.c.}\right) - m^2_{\tilde{Q}} Q^\dagger Q - \left(\sum_i A_i Q_i \partial_{Q_i} W(Q) + \text{h.c.}\right)$$

$$\tilde{M}_\lambda(t) = -\frac{1}{2}\frac{\partial \ln S(X,t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M} ,$$

$$m^2_{\tilde{Q}}(t) = -\frac{\partial^2 \ln Z_Q(X,X^\dagger,t)}{\partial \ln X\, \partial \ln X^\dagger}\bigg|_{X=M} \frac{FF^\dagger}{MM^\dagger} ,$$

$$A_i(t) = \frac{\partial \ln Z_{Q_i}(X,X^\dagger,t)}{\partial \ln X}\bigg|_{X=M} \frac{F}{M} .$$

$$t = ln\, M^2/Q^2$$

F<<M

$$\tilde{M}_{\lambda_r}(t) = k_r \frac{\alpha_r(t)}{4\pi} \Lambda_G \qquad (r = 1,2,3) ,$$

$$\Lambda_G = \sum_{i=1}^{N_f} n_i \frac{F_i}{M_i} \left[1 + \mathcal{O}(F_i^2/M_i^4)\right] ,$$

$$m^2_{\tilde{f}}(t) = 2\sum_{r=1}^{3} C_r^{\tilde{f}} k_r \frac{\alpha_r^2(0)}{(4\pi)^2} \left[\Lambda_S^2 + h_r \Lambda_G^2\right] ,$$

$$h_r = \frac{k_r}{b_r}\left[1 - \frac{\alpha_r^2(t)}{\alpha_r^2(0)}\right] ,$$

$$\Lambda_S^2 = N\frac{F^2}{M^2}\left[1 + \mathcal{O}(F^2/M^4)\right]$$

All soft masses are proportional to *NF/M*

GMSB, DM candidates

S. Dimopoulos, G. F. Guidice, and A. Pomarol , arXiv:hep-ph/9607225

Three variants:

- **HS neutral scalar** (global symmetry prevented hidden scalar interaction with MSSM sector, stable state – no DD of DM)

$$\Omega_{B_\varphi} h^2 \gtrsim (m_{B_\varphi}/300\ \mathrm{TeV})^2$$

cold unobservable DM

superheavy DM

- **MS neutral scalar**

$$\sum_{i=1}^{n} m_{\varphi_i}^2 \lesssim (5\ \mathrm{TeV})^2$$

cold observable DM

overestimated DM density !! (But – the LMSS can decay into gravitino)

- **SSB MSSM gravitino** (very light neutral fermion)

Gravitino mass

$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^2 2.4\ \mathrm{eV}$$

$$\kappa = \frac{F}{F_0} < 1 \quad \Rightarrow \quad m_{3/2} \geq keV$$

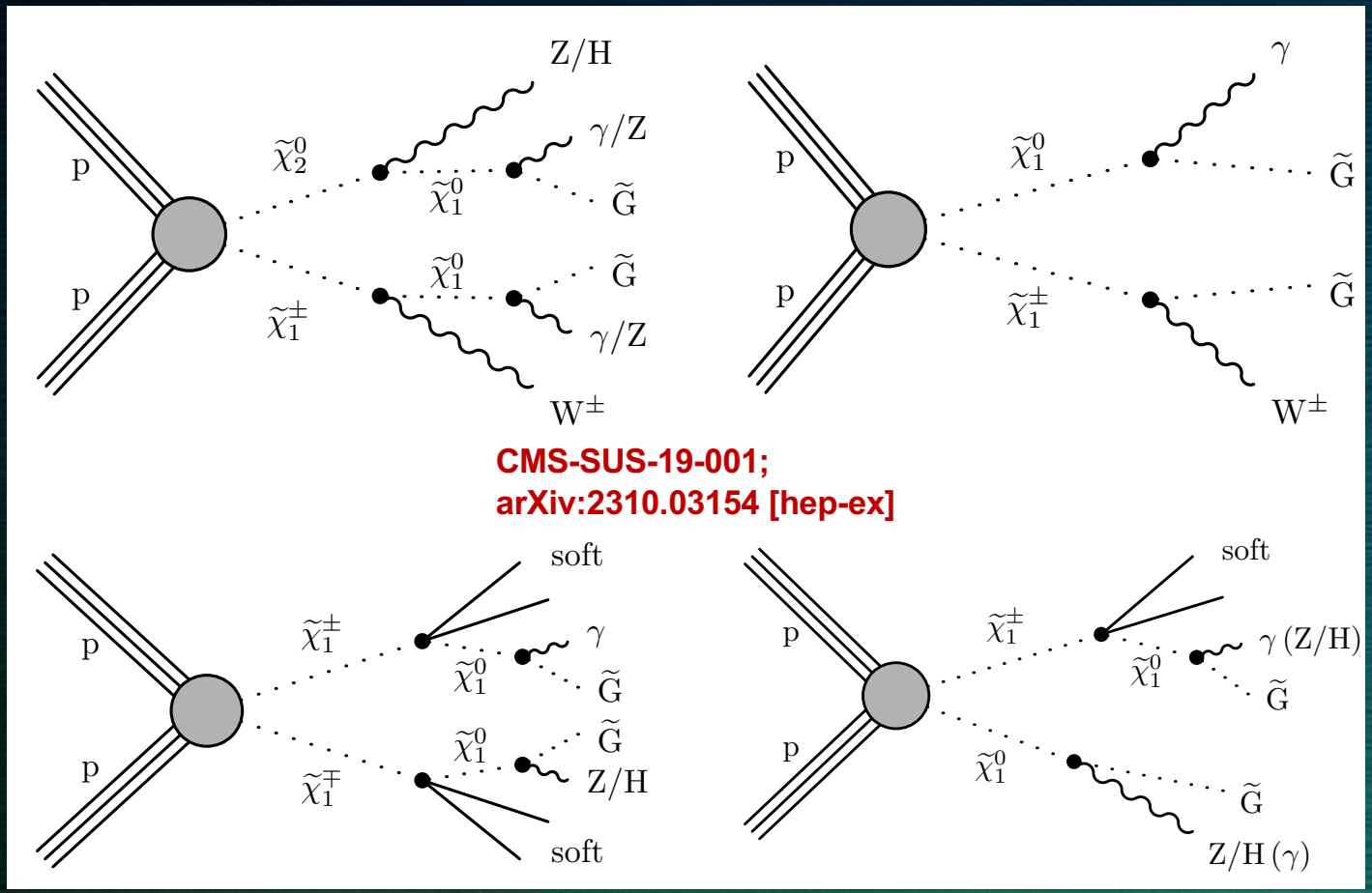
"warm" DM - OK

no direct search – not OK

GMSB at the LHC, CMS RUN 2, prompt decays

EWK production, neutralino as the NLSP, general GMSB

CMS SUS-16-046;
arXiv:1711.08008 [hep-ex]

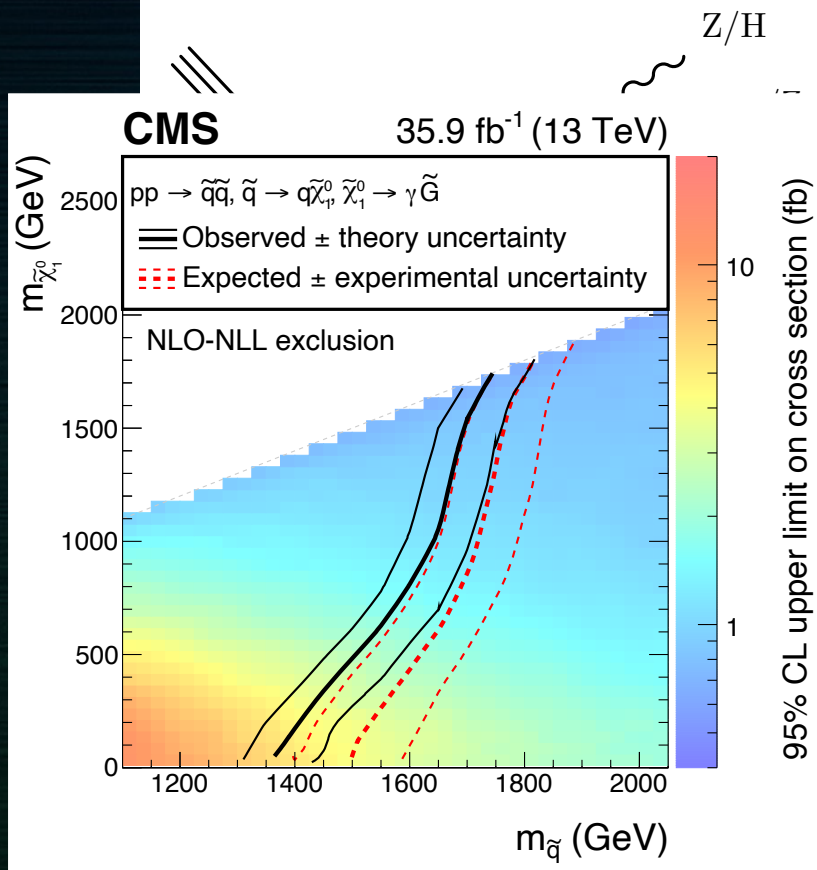


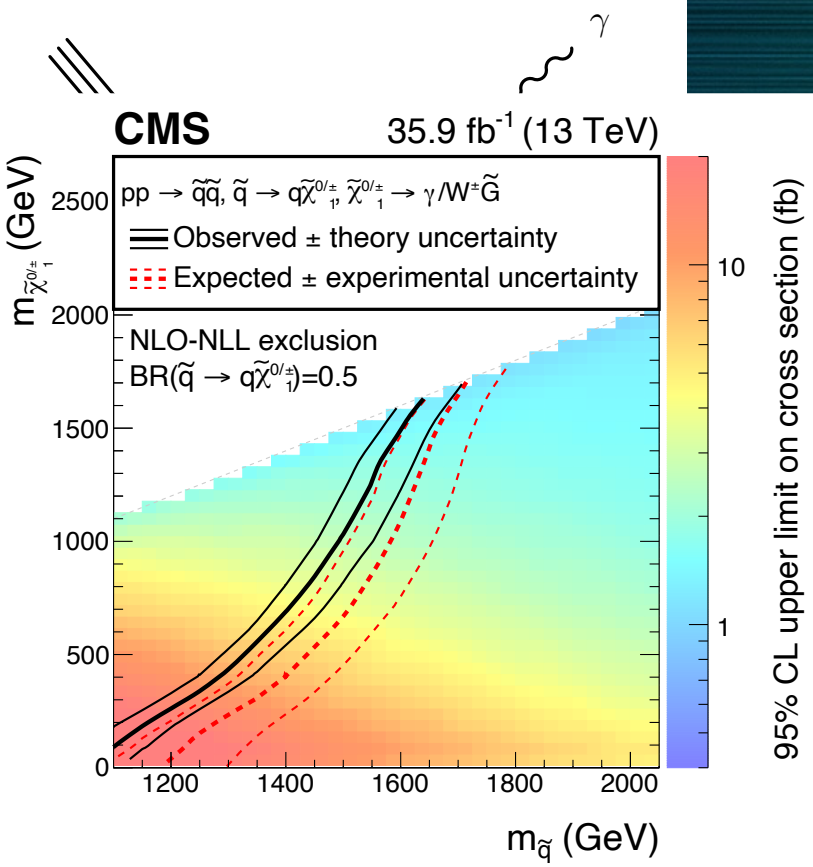
CMS-SUS-19-001;
arXiv:2310.03154 [hep-ex]

GMSB at the LHC, CMS RUN 2, prompt decays

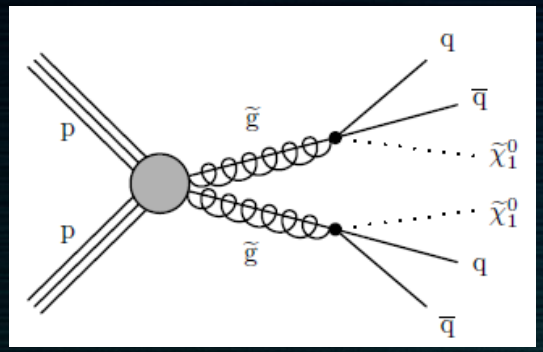
EWK production, neutralino as the NLSP, general GMSB

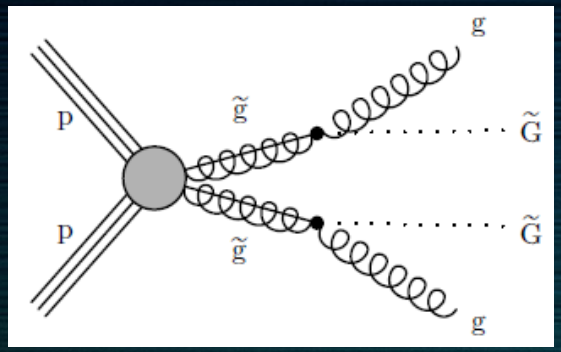
CMS SUS-16-046;
arXiv:1711.08008 [hep-ex]





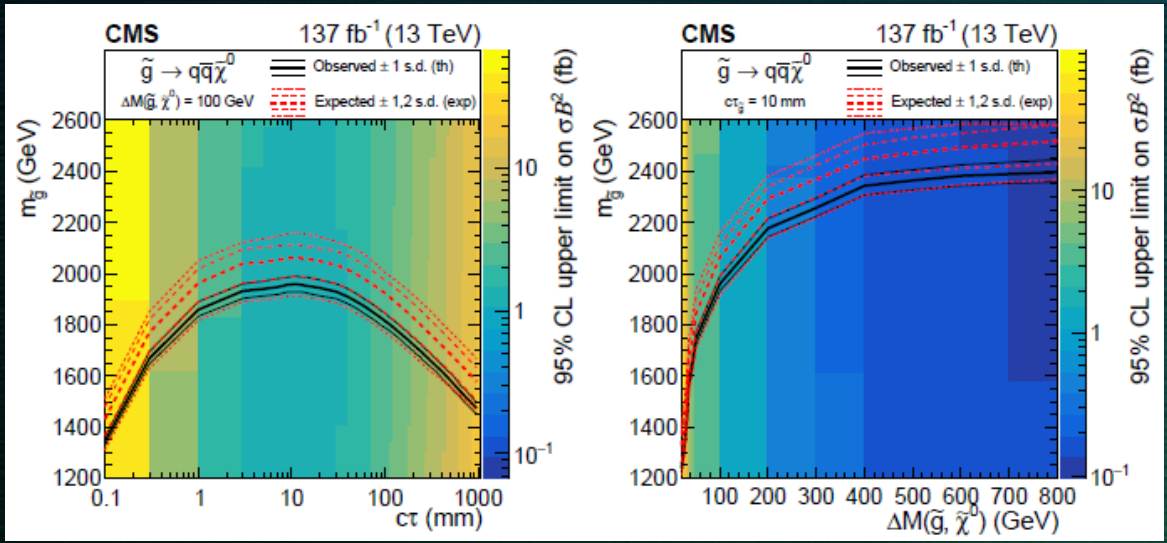
Split/GMSB SUSY in LLP decays with displaced vertices plus MET

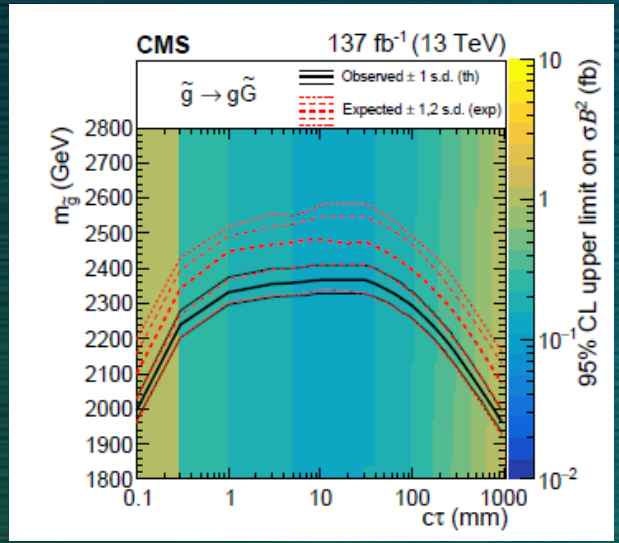




CMS EXO-22-020;
arXiv:2402.15804 [hep-ex]

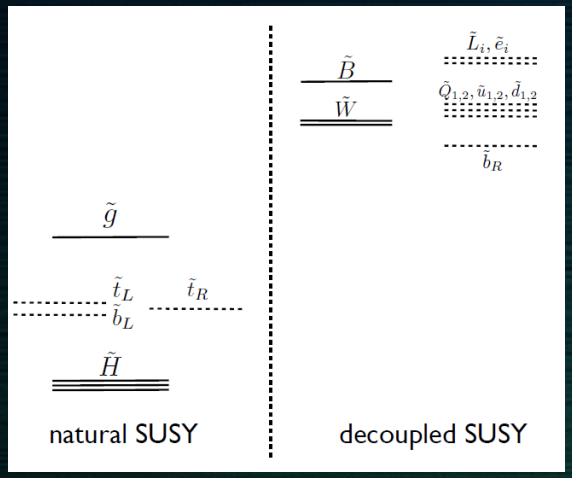
$$\tau \simeq 8 \left(\frac{m_{\mathrm{SUSY}}}{10^6\ \mathrm{TeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_{\tilde{g}}}\right)^5 \mathrm{s},$$



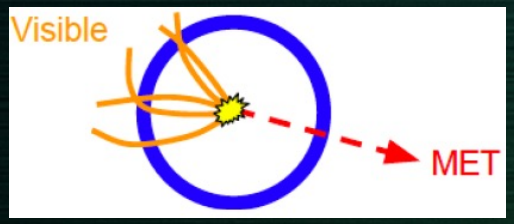


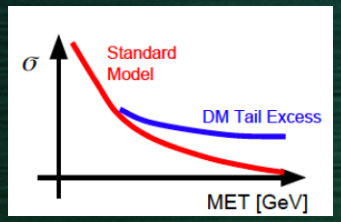
SUSY beyond MSSM: low(zero) p_T^{mis} signatures

"natural" mass spectrum



typical experimental signature: high p_T^{mis}





From prompt production to LLP:

1. Stealth SUSY

   JiJi Fan, Matthew Reece, Joshua T. Ruderman

   arXiv:1105.5135 [hep-ph]

   arXiv:1201.4875 [hep-ph]

   arXiv:1512.05781 [hep-ph]

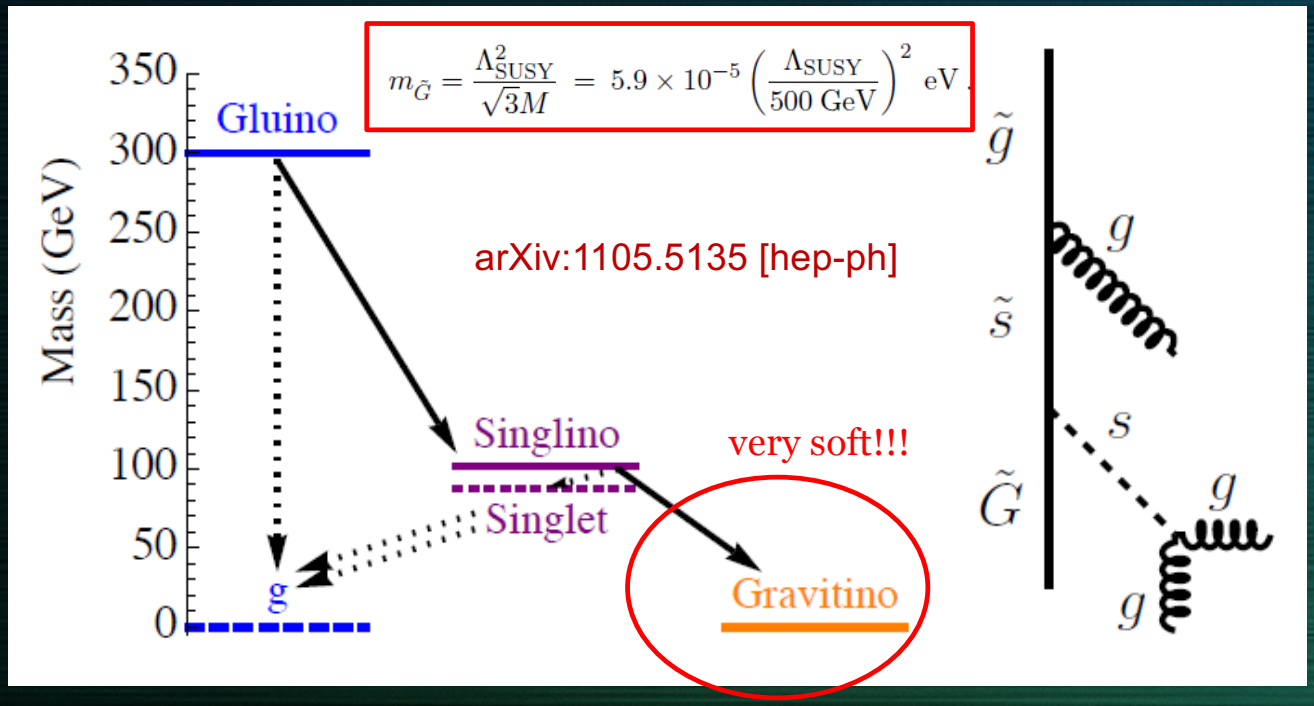
2. RPV SUSY

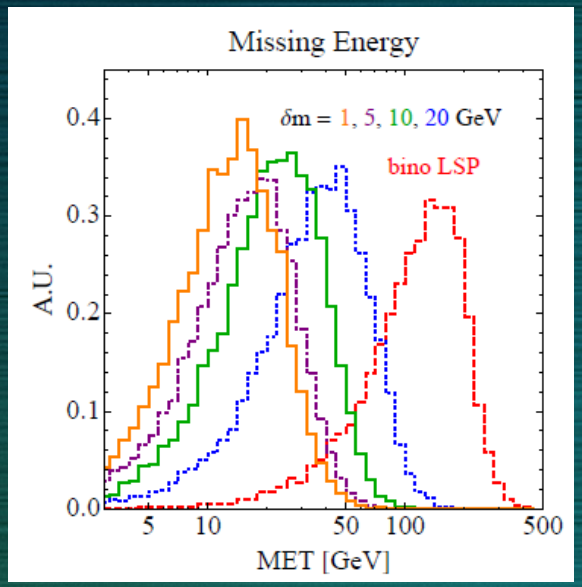
   Csaba Csaki, Yuval Grossman, and Ben Heidenreich

   arXiv:1111.1239 [hep-ph]

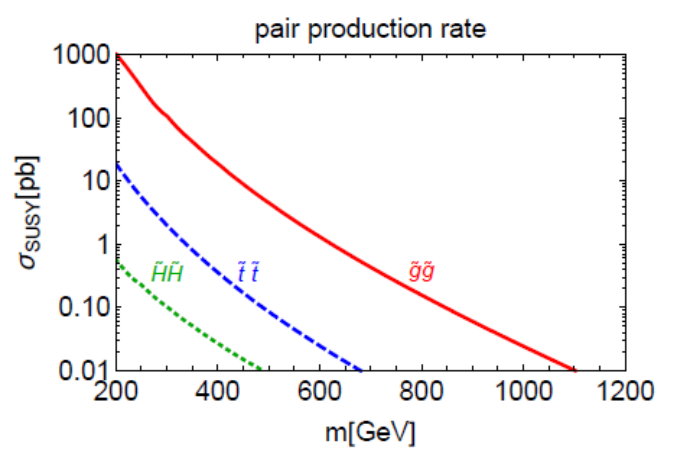
Stealth SUSY basis

SUSY is natural, low-scale SUSY breaking, hidden sector with (at least) one chiral singlet supefield (R-odd singlino, R-even singlet). LSP – gravitino (GMSB),
NLSP decays to gravitino through a hidden sector.
HS states of order the EW scale, states approximately supersymmetric (F << M) – closely degenerated by masses.
Suppression of large missing E_T at the end of decay chain (gravitino assosiated).





Stealth SUSY simplified, prompt/LLP



JiJi Fan, Matthew Reece, Joshua T. Ruderman

arXiv:1105.5135 [hep-ph]

arXiv:1201.4875 [hep-ph]

arXiv:1512.05781 [hep-ph]

Field set: LOSP – gluino, stop, higgsino only
The lightest R-odd SUSY particle – gravitino/axino

NLSP neutralino decay width

$$\Gamma(\chi_1^0 \to \gamma\tilde{G}) = \frac{k^2\,\kappa_\gamma m_{\chi_1^0}^5}{16\pi F^2} = k^2\,\kappa_\gamma \left(\frac{m_{\chi_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{TeV}}{\sqrt{F}}\right)^4 2\times 10^{-3}\ \mathrm{eV}$$

NLSP gluino decay width

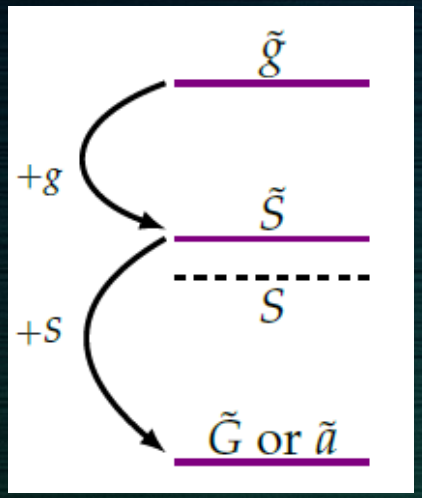
$$\Gamma(\tilde{g} \to g\tilde{G}) = \frac{m_{\tilde{g}}^5}{48\pi M^2 m_{\tilde{G}}^2} = 1.1\times 10^{-9}\ \mathrm{GeV} \left(\frac{m_{\tilde{g}}}{250\ \mathrm{GeV}}\right)^5 \left(\frac{m_{\tilde{G}}}{1\ \mathrm{eV}}\right)^{-2}$$

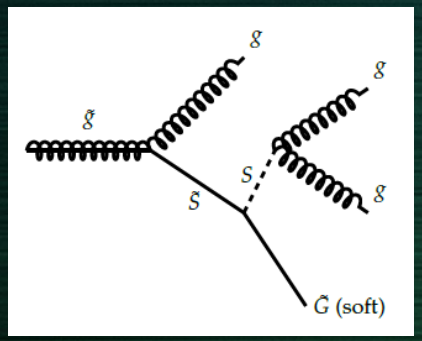
Typically LLP signatures in a wide parameter space region!! ($c\tau_0 > 8\ mm$ for F ~ 10 GeV)

Stealth SUSY, gluino pair production, gluino/stop as NLSP

$SY\bar{Y}$: GMSB-like: messengers in $5, \bar{5}$ of SU(5), $m_S \sim 100$ GeV, $m_Y \sim$ TeV – supersymmetric soft masses

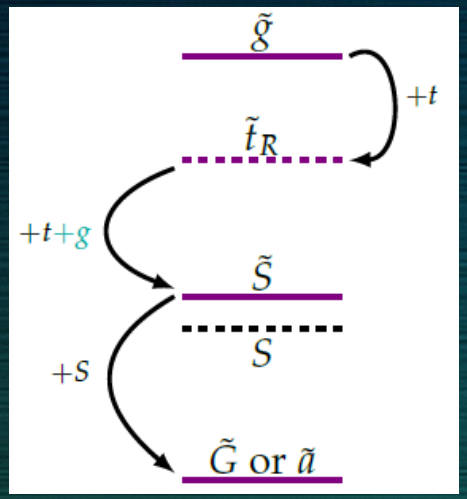
$\tilde{g} \to \tilde{S} \to \tilde{G}$

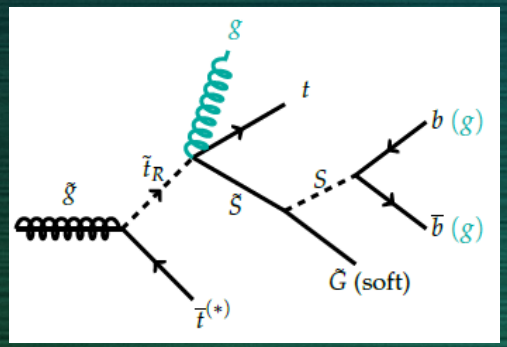




3g → 6 jets FS (mostly light flavors for small m_S)

$\tilde{g} \to \tilde{t} \to \tilde{S}S\tilde{G}$



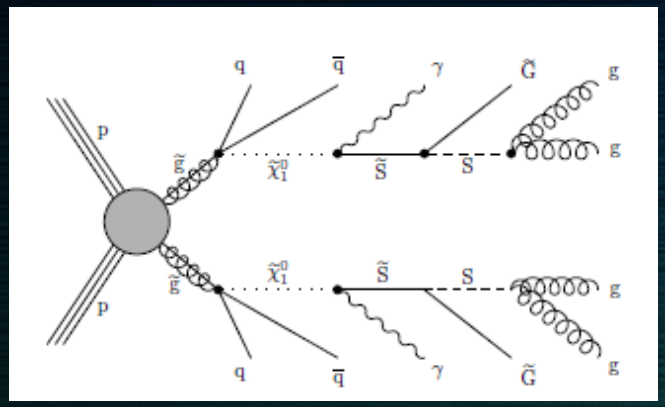


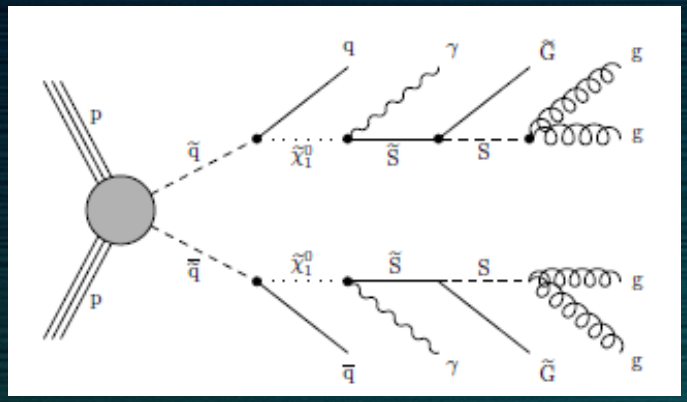
SS leptons or 3 leptons plus >4 jets (3 jets b-tagged)

Gluino/stop PP, neutralino as NLSP, prompt, 2gamma + jets + low E_T^{mis}

$150\ GeV < M < m_{\tilde{g}}(m_{\tilde{q}}) - 100\ GeV$; $m_{\tilde{q}}, m_{\tilde{g}}: 1250 < M < 2350\ GeV, 1100 < M < 2000\ GeV$

$SY\bar{Y}$





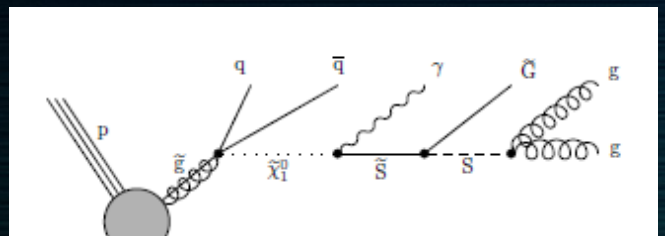
CMS SUS-19-001;
arXiv:2310.03154 [hepex];

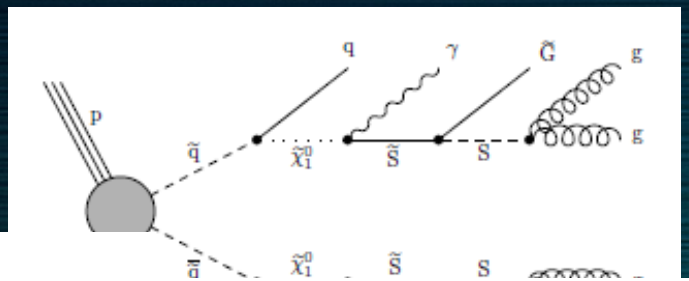
See also:
CMS SUS-23-001
for stealth /RPV SUSY
with DNN

Gluino/stop PP, neutralino as NLSP, prompt, 2gamma + jets + low E_T^{mis}

$150\ GeV < M < m_{\tilde{g}}(m_{\tilde{q}}) - 100\ GeV$; $m_{\tilde{q}}, m_{\tilde{g}}: 1250 < M < 2350\ GeV, 1100 < M < 2000\ GeV$

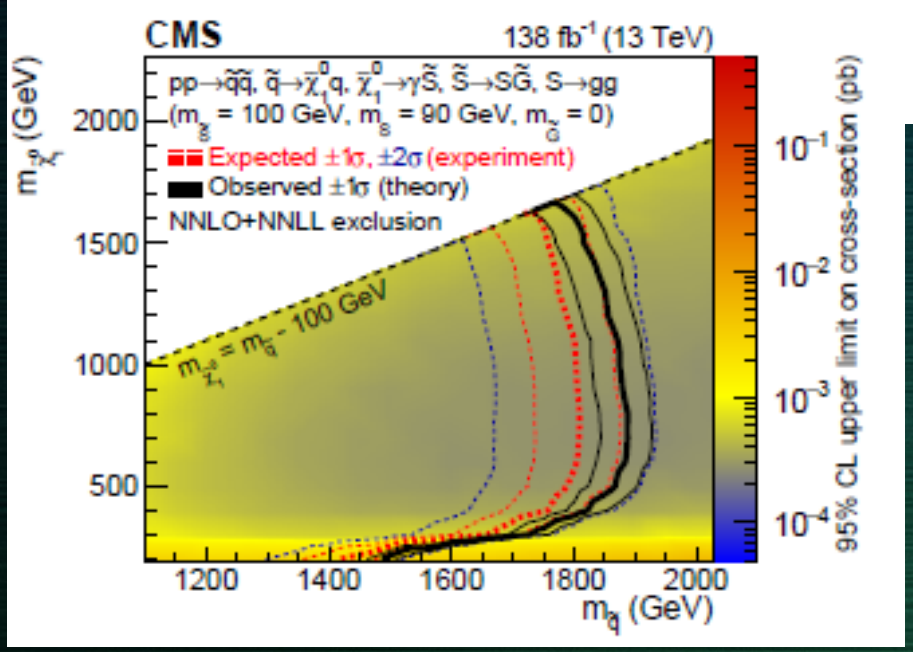
$SY\bar{Y}$

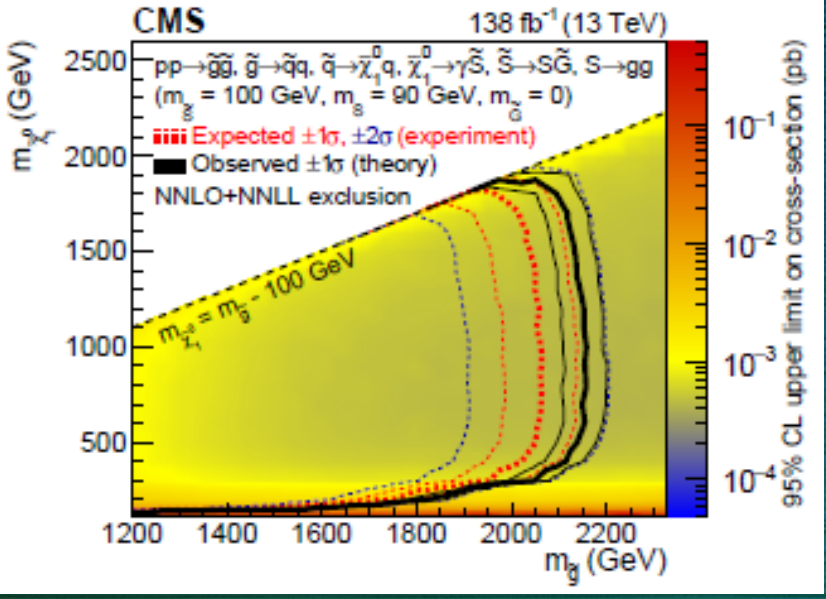




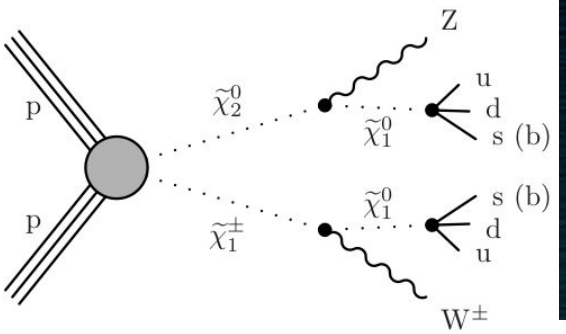
CMS SUS-19-001;
arXiv:2310.03154 [hepex];

See also:
CMS SUS-23-001
for stealth /RPV SUSY
with DNN





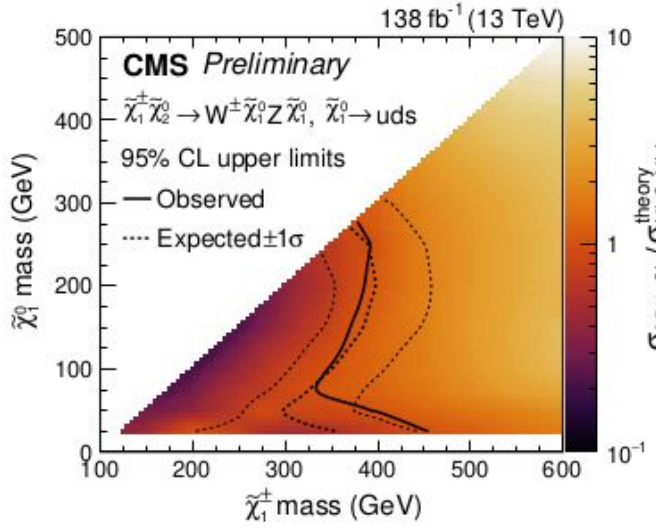
RPV SUSY in three-lepton plus jets FS



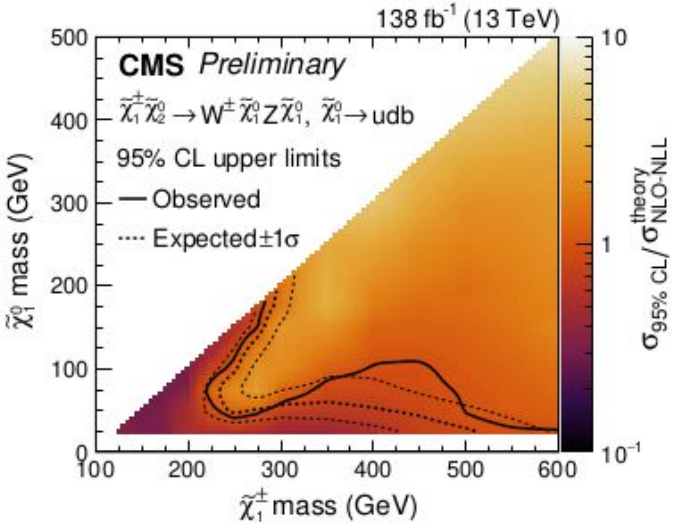
Degenerated by mass gaugino-like neutralino/chargino production with LSP (neutralino) RPV decay. FS with light/heavy quarks

CMS SUS-23-015

$$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0;\ \tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$$
$$\tilde{\chi}_1^0 \to \text{uds}$$
$$\tilde{\chi}_1^0 \to \text{udb}$$



RPVq



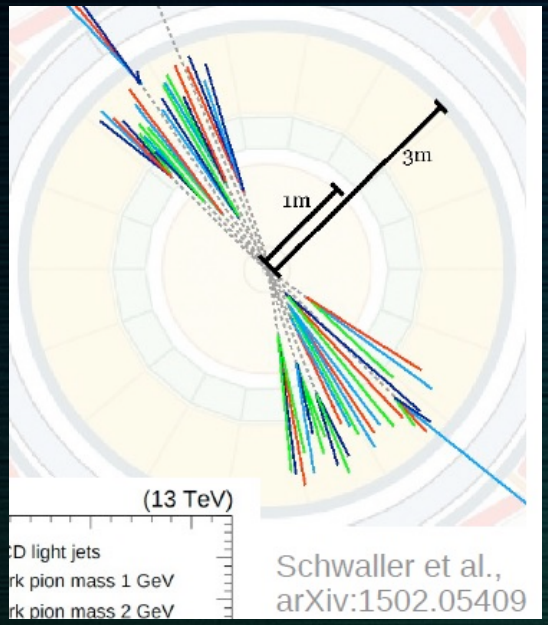
RPVb

See also:

CMS-EXO-21-004; arXiv:2402.02992 RPV SUSY in pair-produced multijet resonances

Strongly coupled DS, dark showers, prompt/LLP

Hidden valleys , dark QCD

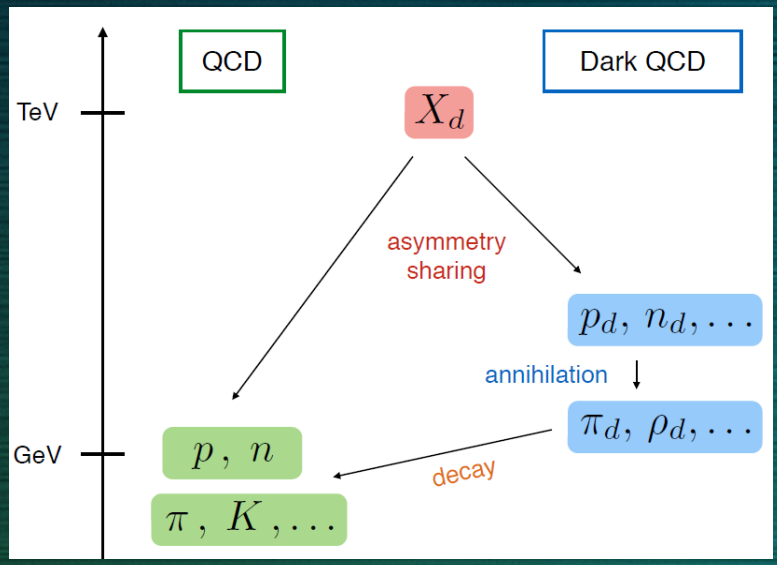


$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \bar{q}_{\rm d} i \not{D} q_{\rm d} - \bar{q}_{\rm d} M_q q_{\rm d}$$

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

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

M_q: quark mass matrix

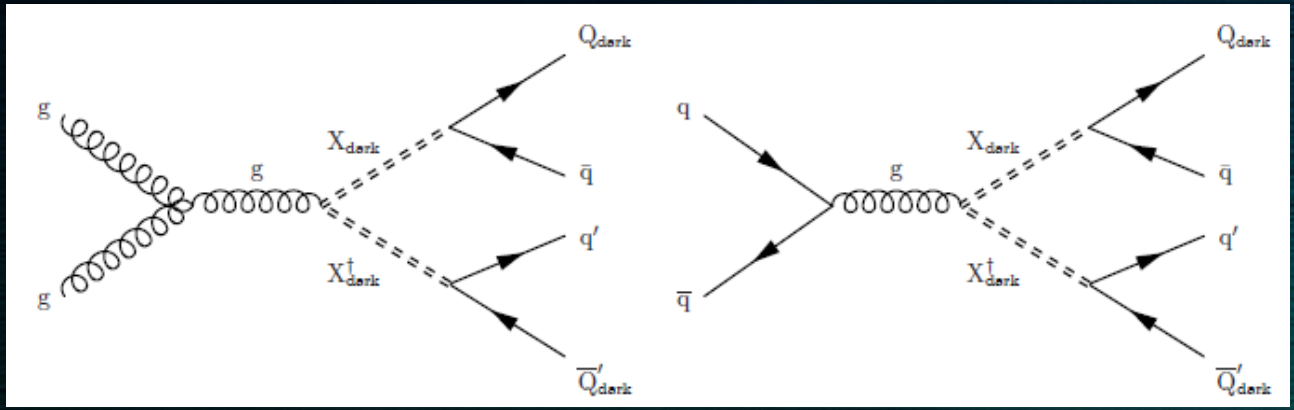


- ✓ One of the most striking DM-targeted signatures (Dark QCD → dark showers, emerging jets)
- ✓ Tracks start near the edge of the tracker, in the ECAL and HCAL and even in the inner muon stations

LLP dark showers with emerging jets

CMS EXO-22-015;
arXiv:2403.01556 [hep-ex]

HV dark QCD, scalar mediator,
dark meson LLP decays, b-quark FS

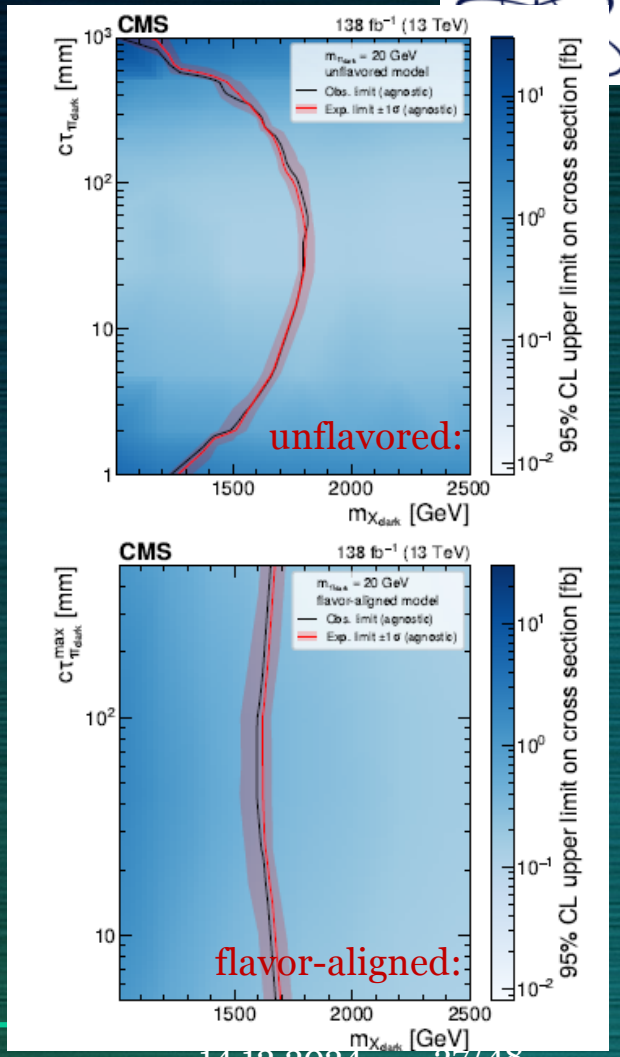


unflavored:

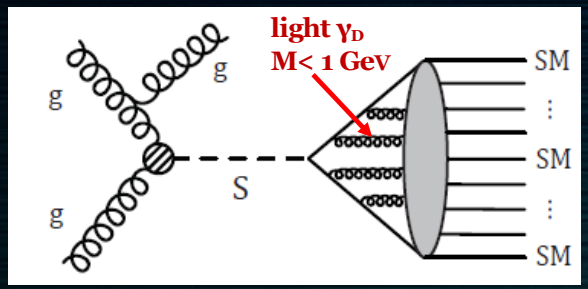
$$c\tau_{\pi_{dark}} = 80\,\text{mm}\left(\frac{1}{\kappa^4}\right)\left(\frac{2\,\text{GeV}}{f_{\pi_{dark}}}\right)^2\left(\frac{100\,\text{MeV}}{m_d}\right)^2\left(\frac{2\,\text{GeV}}{m_{\pi_{dark}}}\right)\left(\frac{m_{X_{dark}}}{1\,\text{TeV}}\right)^4$$

flavor-aligned:

$$c\tau^{\alpha\beta}_{\pi_{dark}} = \frac{8\pi m^4_{X_{dark}} c\hbar}{N_c m_{\pi_{dark}} f^2_{\pi_{dark}} \sum_{i,j}|\kappa_{\alpha i}\kappa^*_{\beta j}|^2 \left(m_i^2 + m_j^2\right)\sqrt{\left(1-\frac{(m_i+m_j)^2}{m^2_{\pi_{dark}}}\right)\left(1-\frac{(m_i-m_j)^2}{m^2_{\pi_{dark}}}\right)}},$$



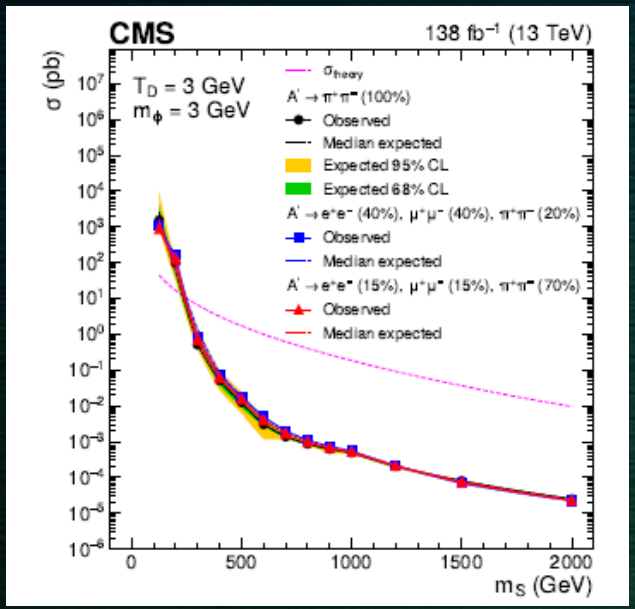
Soft Unclustered Energy Patterns (SUEPs)

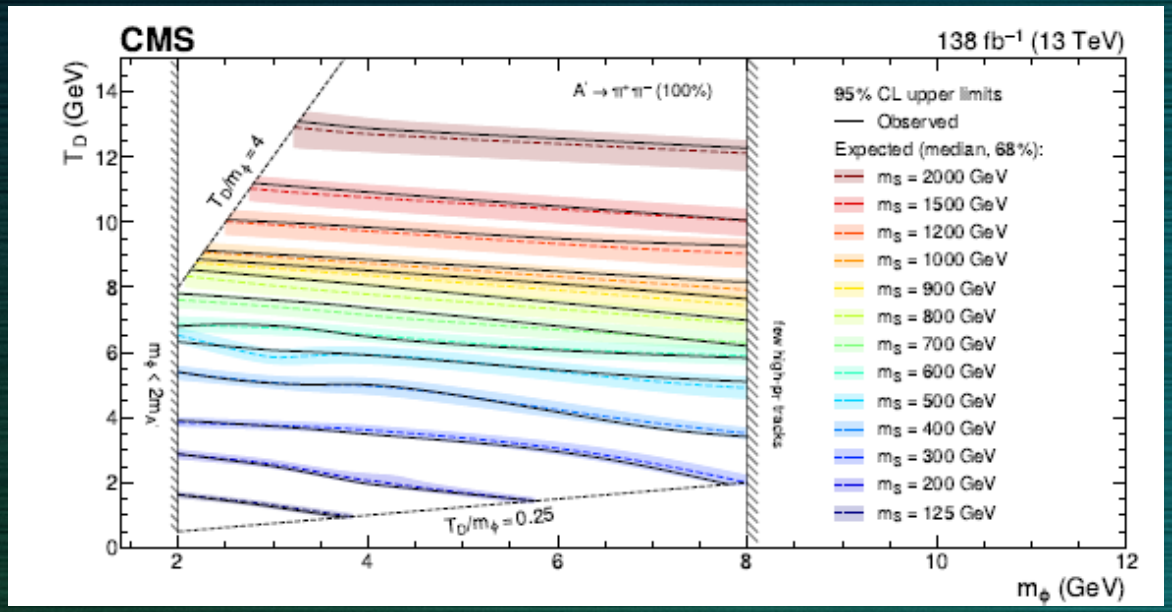


$m_{q_D} < \Lambda_D$, $\Lambda_D \ll \sqrt{s}$

CMS EXO-23-002;
arXiv:2403.05311 [hep-ex]

- HV concept, quasi-conformal DS, dark mesons masses much smaller than S mediator mass. S charged under both SU(3) and $SU(3)_D$
- Spherically symmetric FS distributions, high multiplicity of soft PS
- Boltzmann distr. for pseudoscalar p_T, depending on T_D (Λ_D) and m_φ
- Decay $\varphi \rightarrow \gamma_D\gamma_D$, $\rightarrow$ SM FS trough γ - γ_D mixing, prompt decays



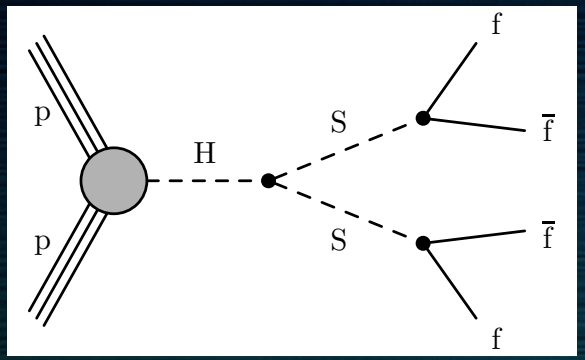


Light LLP decays in displaced jets

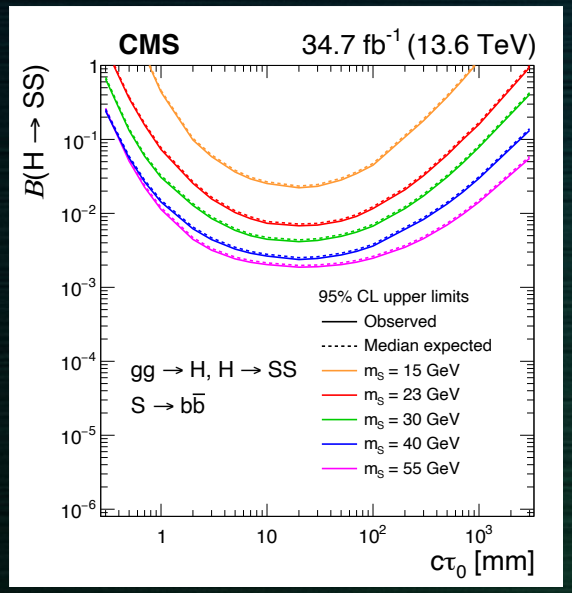
CMS EXO-23-013;
arXiv:2409.10806 [hep-ex]

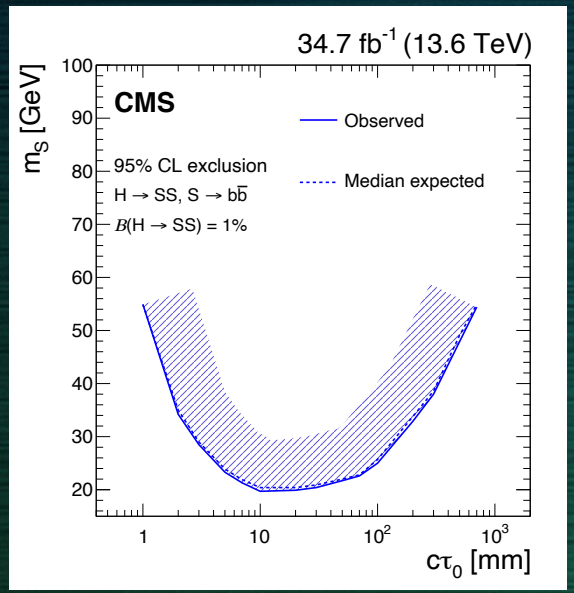
Neutral naturalness – a global SM-DS symmetry, protecting m_H

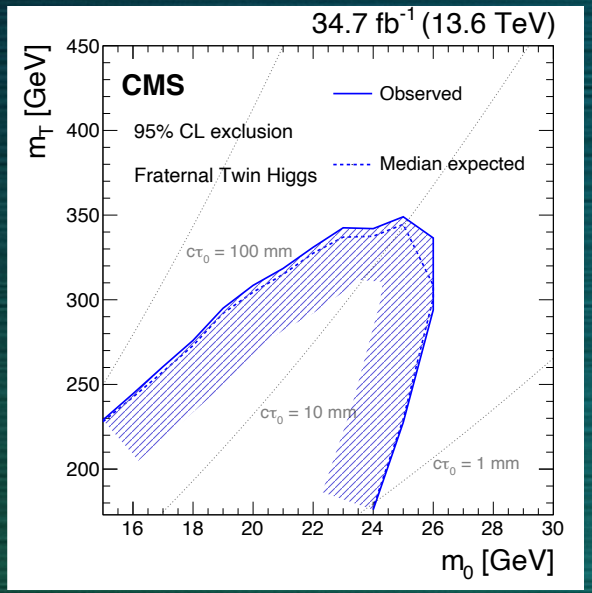
Fraternal twin higgs model and folded SUSY interpretations



- the lightest DS state – dark glueball with strongly suppressed decays to SM
→ LLP
- light LLP with masses < 60 GeV
- LLP decays to b-/d- quarks and τ-leptons



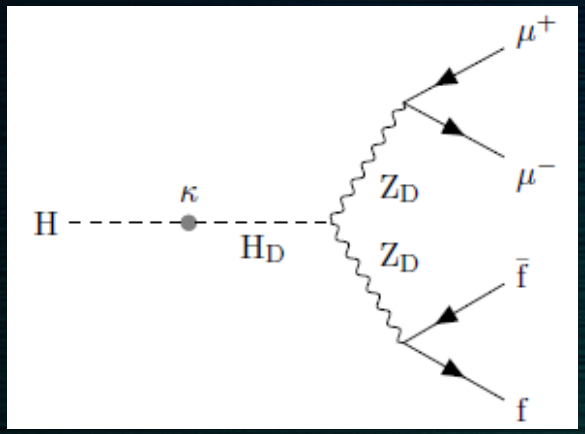




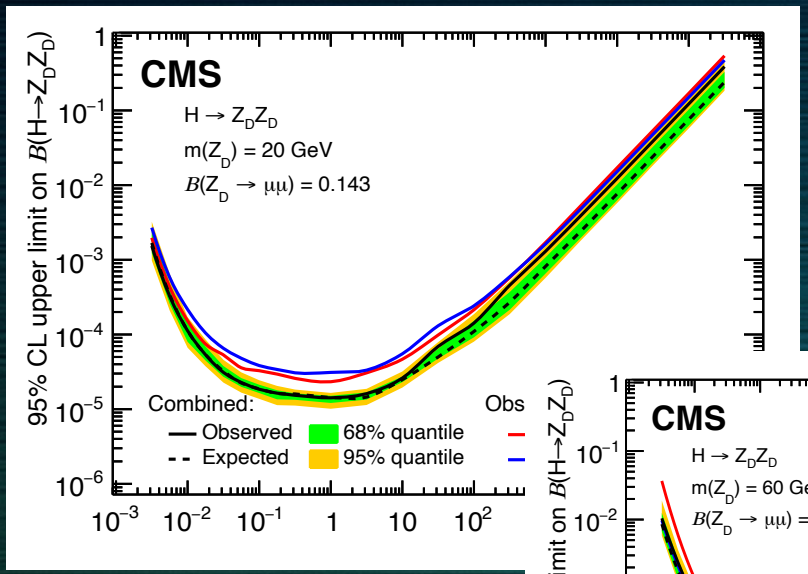
LLP decays to muon pairs

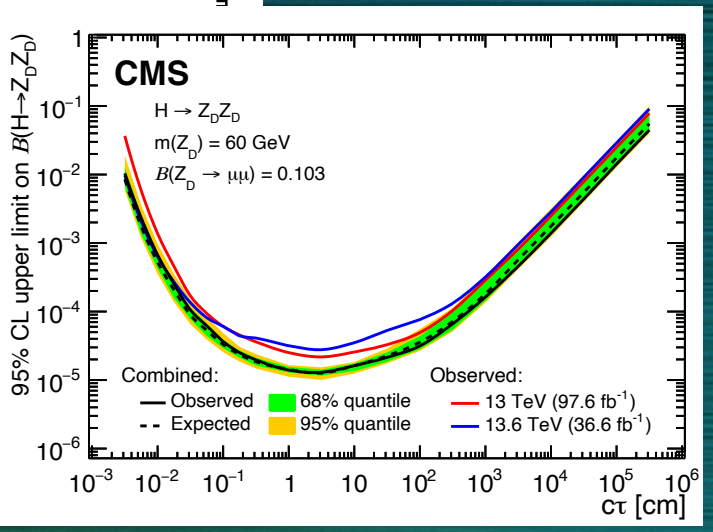
Dark higgs-photon double portal (HAHM) and SUSY interpretations

CMS-EXO-23-014;
arXiv:2402.14491 [hep-ex]



- Dark $U(1)_D$ with Z_D charged under SM group hypercharge
- Mass of Z_D comes from H_D
- Mixing in gauge and higgs sectors ("double portal")
- Dark photon decays dominantly to SM leptons ← no light DS states with masses lower then m_{Z_D}





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

GMSB, gravitino as DM

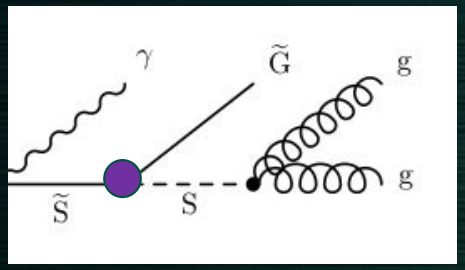
Gravitino mass

$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^2 2.4\ \text{eV}$$

$$\kappa = \frac{F}{F_0} < 1 \quad \Rightarrow \quad m_{3/2} \geq keV$$

- “warm” DM - OK
- no direct search – not OK

Gravitino effective action



$$\mathcal{L} = -\frac{1}{F_0} J_Q^\mu \partial_\mu \tilde{G}$$

$$\partial_\mu J_Q^\mu = -F_0 \gamma^\mu \partial_\mu \tilde{G}$$

$$\Rightarrow \quad \mathcal{L} = \frac{k}{F}\left[(m_\psi^2 - m_\phi^2)\bar{\psi}_L \phi + \frac{M_\lambda}{4\sqrt{2}}\bar{\lambda}^a \sigma^{\nu\rho} F^a_{\nu\rho}\right]\tilde{G} + \text{h.c.}$$

1/F suppressed !

GMSB, the lightest neutral partner from messenger sector as DM

$$\langle \sigma(\varphi\varphi^* \to \text{anything})v \rangle = \frac{1}{m_\varphi^2}\left(A + \frac{B}{x}\right)$$

– total annihilation cross section

$$\Omega_\varphi h^2 = \frac{8.5 \times 10^{-5}}{\sqrt{g_*}} \left(\frac{m_\varphi}{\text{TeV}}\right)^2 \frac{x_f}{A + \frac{B}{2x_f}};$$

$$x = m_\varphi / T$$

$$\sum_{i=1}^{n} m_{\varphi_i}^2 \lesssim (5\ \text{TeV})^2$$

overestimated DM density !!

(But – the LMS can decay to gravitino)

Basically two cases:

F << M :

F < (350 GeV)² general GMSB setup

M – F ~1 :

$$\frac{F}{M}\sqrt{nf(F/M^2)} > 20\ \text{TeV}$$

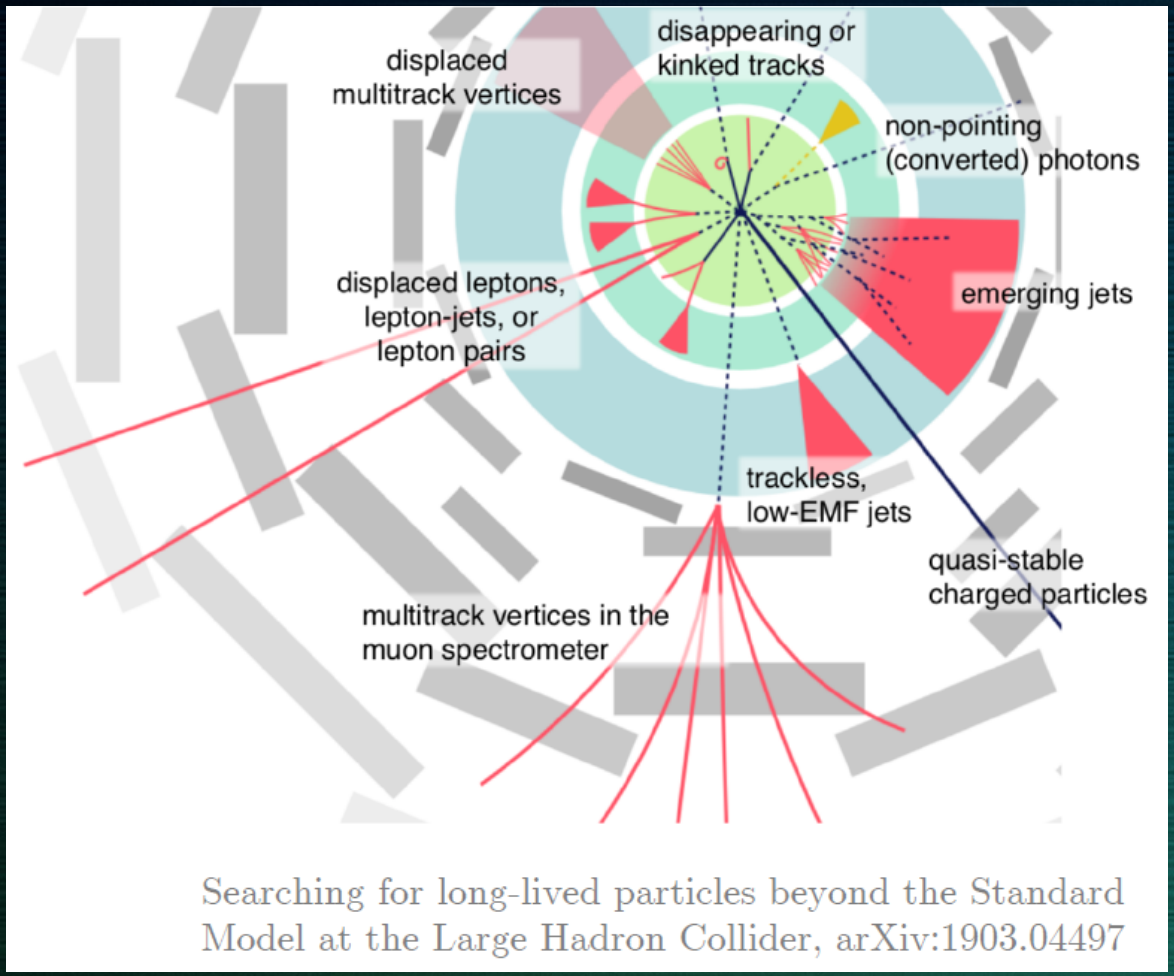
Dark sector with Long-Lived Particles at the LHC

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

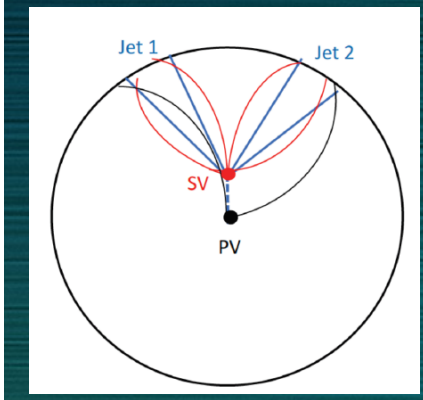


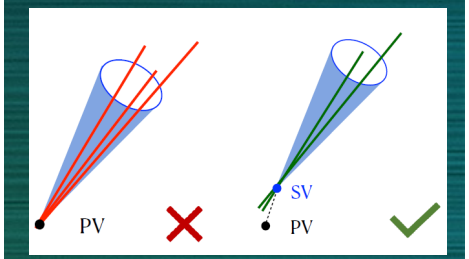
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

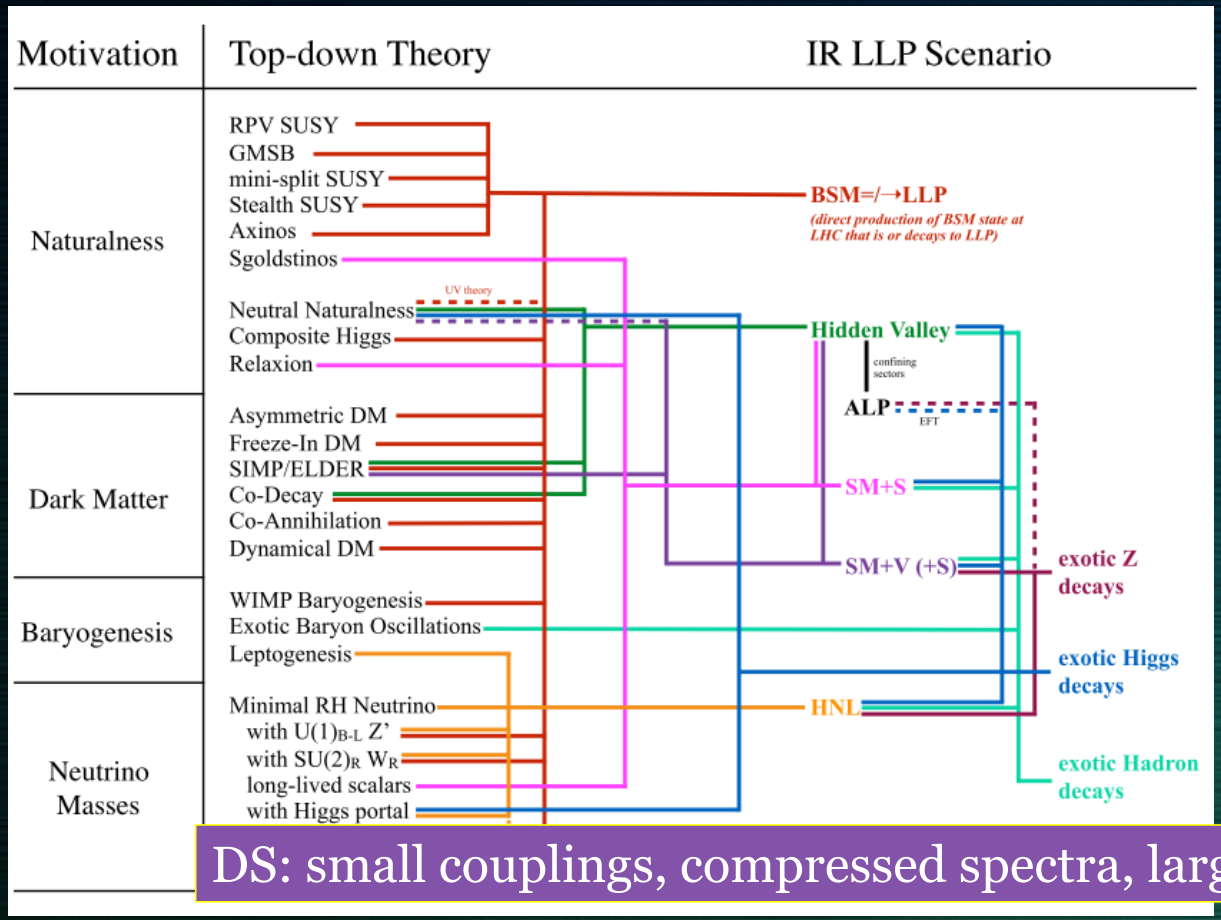
LLP theory motivations: arXiv:1806.07396

displaced jets





Inelastic dark matter at the LHC/LLP

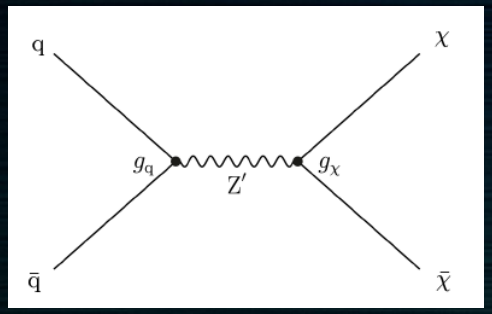


https://arxiv.org/abs/1901.04040

- ✓ 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

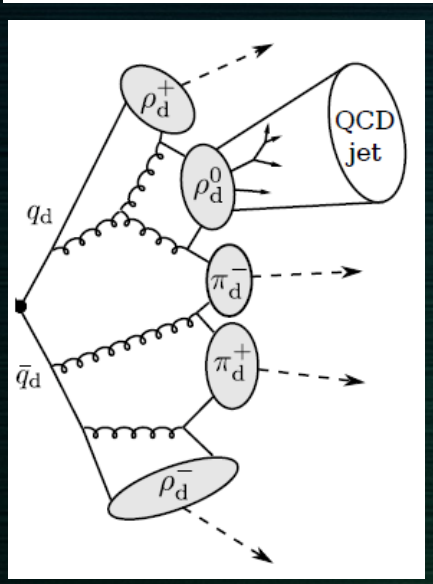
DS: small couplings, compressed spectra, large hierarchy → large cτ

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

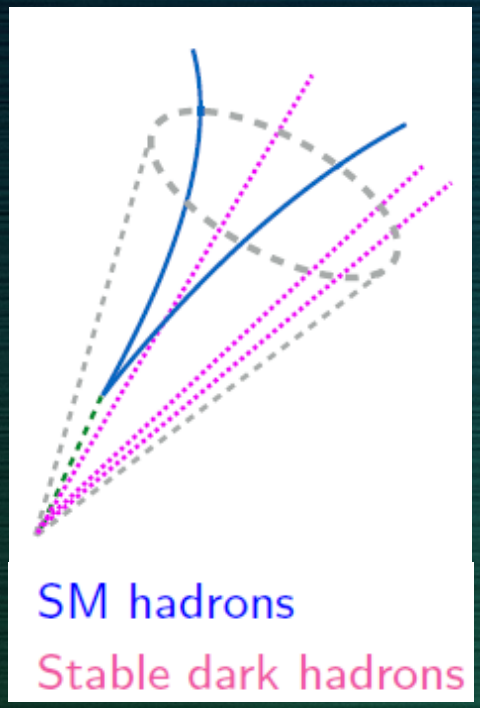


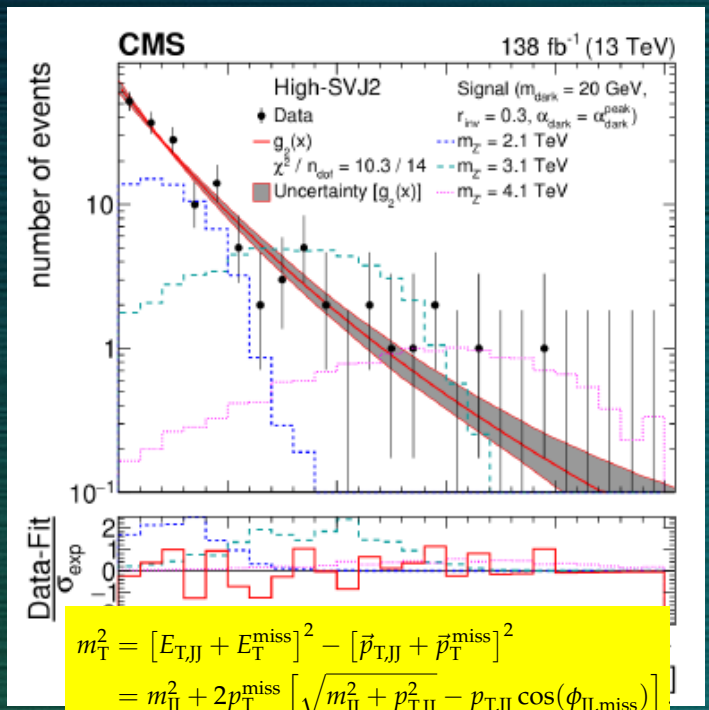
semi-visible jets

DM part (visible) +

SM part (invisible)

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



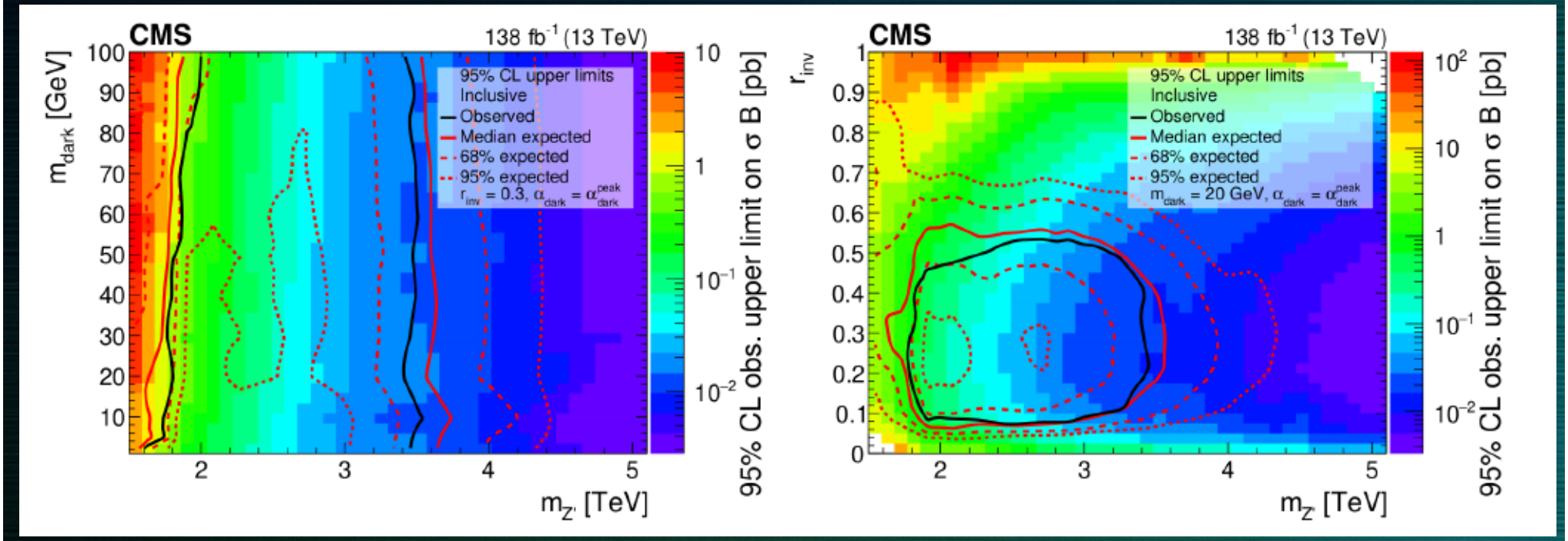


$$m_T^2 = \left[E_{T,JJ} + E_T^{miss}\right]^2 - \left[\vec{p}_{T,JJ} + \vec{p}_T^{miss}\right]^2$$
$$= m_{JJ}^2 + 2p_T^{miss}\left[\sqrt{m_{JJ}^2 + p_{T,JJ}^2} - p_{T,JJ}\cos(\phi_{JJ,miss})\right]$$

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)

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



LLP summary plots, CMS, 2023