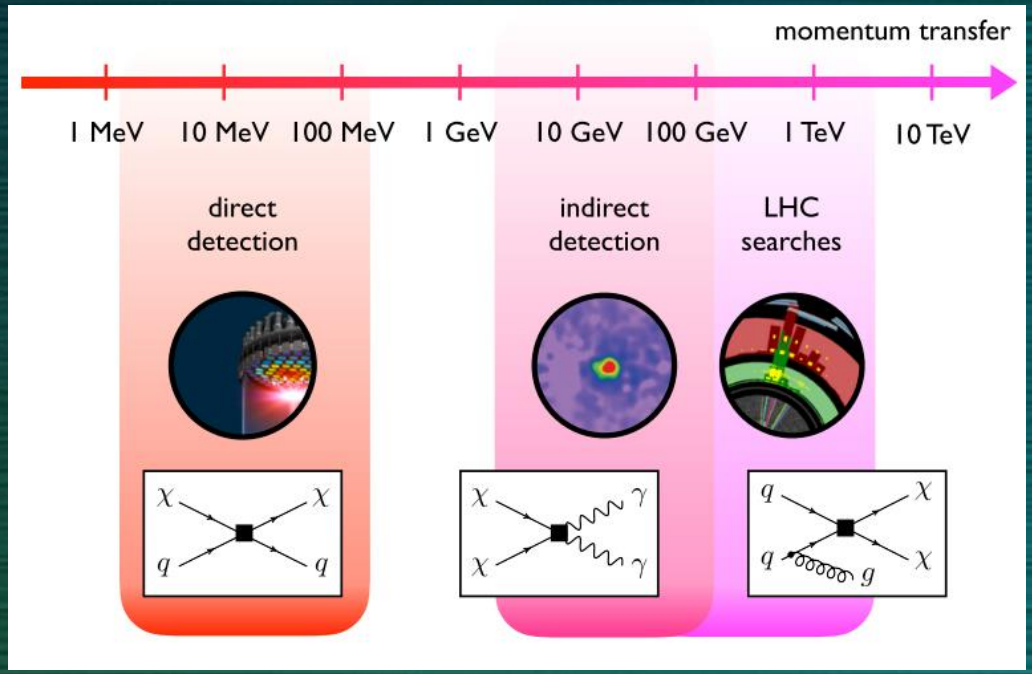
TWENTIETH LOMONOSOV CONFERENCE August, 19-25, 2021 ON ELEMENTARY PARTICLE PHYSICS MOSCOW STATE UNIVERSITY

Dark matter searches at CMS

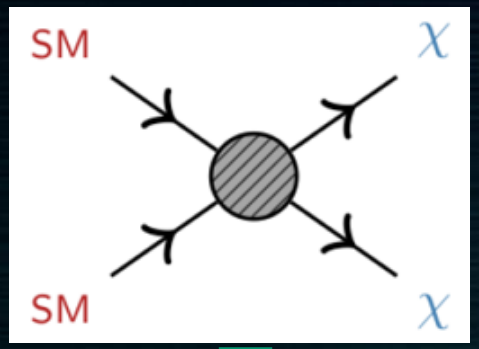
Maria Savina, JINR, Dubna

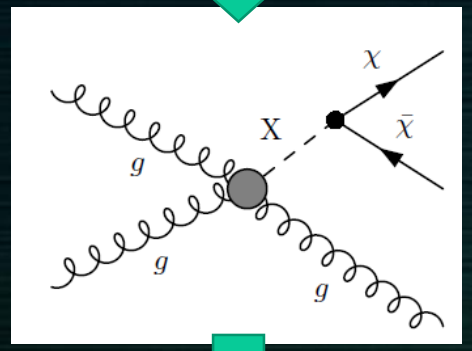
on behalf of the CMS Collaboration

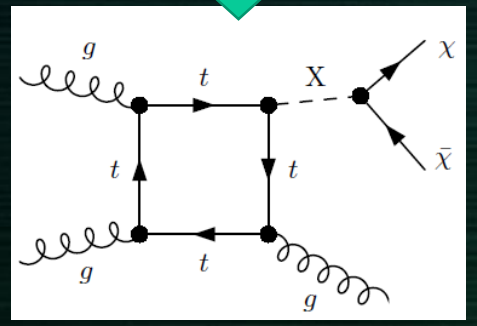
Maria.Savina@cern.ch

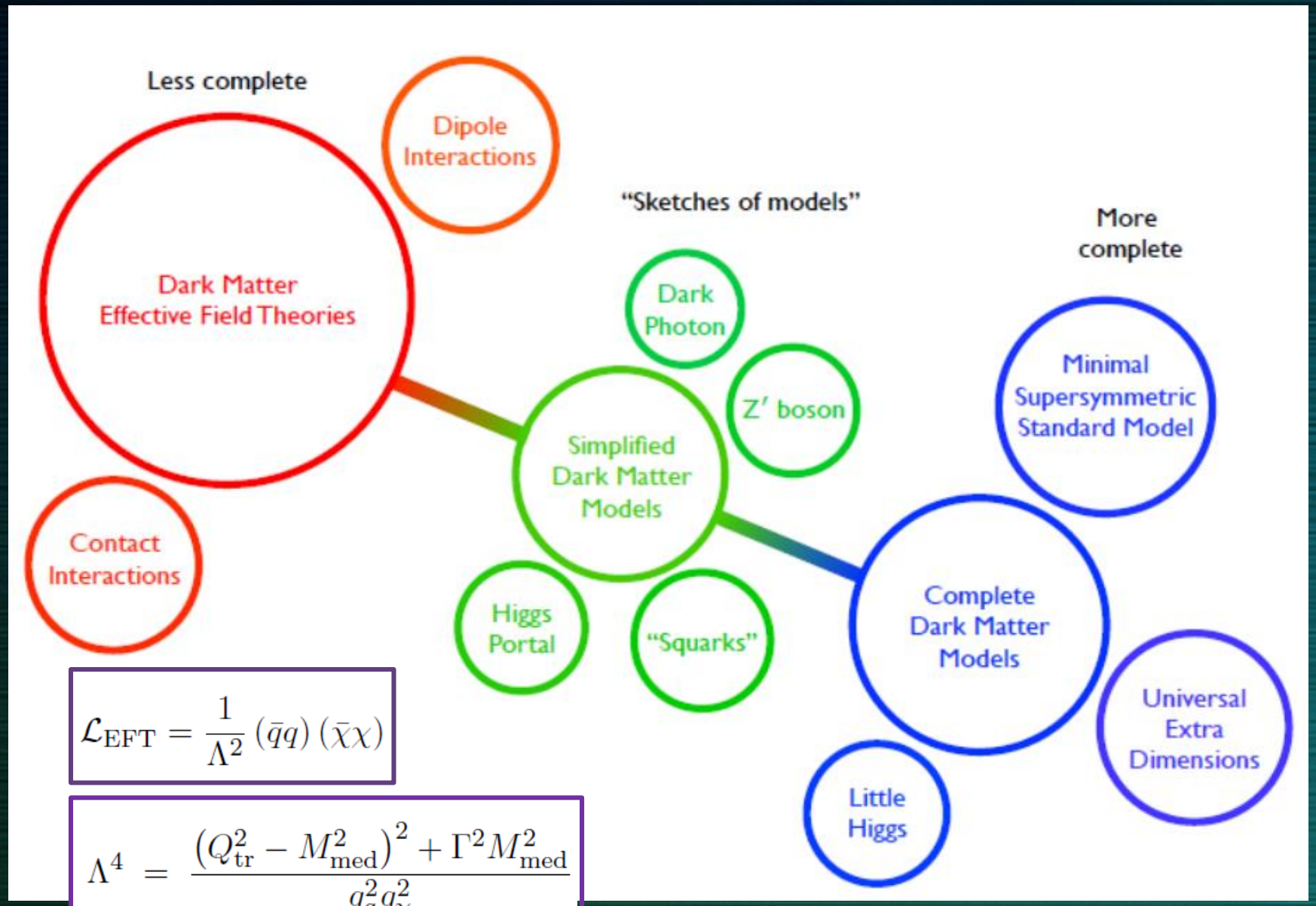


Dark matter approaches: from EFT to complete models









$$\mathcal{L}_{\mathrm{EFT}} = \frac{1}{\Lambda^2}\,(\bar{q}q)\,(\bar{\chi}\chi)$$

$$\Lambda^4 = \frac{\left(Q_{\mathrm{tr}}^2 - M_{\mathrm{med}}^2\right)^2 + \Gamma^2 M_{\mathrm{med}}^2}{g_q^2 g_\chi^2}$$

LHC Dark Matter Working Group documents for RUN 2 analyses

arXiv:1507.00966
arXiv:1603.04156
arXiv:1506.03116

Simplified DM models – main requirements:

1. Minimal set of DM fields, s- and t-channel mediated models
2. Minimal set of physically relevant parameters (couplings, masses and widths)
3. Minimal flavor violation (MVF): new interactions are invariant under global flavor symmetry group or all violating transitions are governed by the CKM matrix (SM FCNC structure, also CPV)

DM mediator(s): spin-0, ½, 1

1. The (axial)vector Z', spin-1
2. The (pseudo)scalar, spin-0 – Higgs portals (special importance of Higgs connected studies).
3. Fermionic portals, spin-1/2 – SUSY, dark SUSY… (often – flavour violation)
4. Double (scalar-vector) portals

DM particle(s): spin-0, ½, 1 (and even spin-2 for Kaluza-Klein DM in TeV-scale gravity models)

Spin-1/2 DM: for fermion case only one DM particle → nonperturbative description for the scalar mediator (see f. e. *arXiv:1903.03616*) → need to extend fermion sector

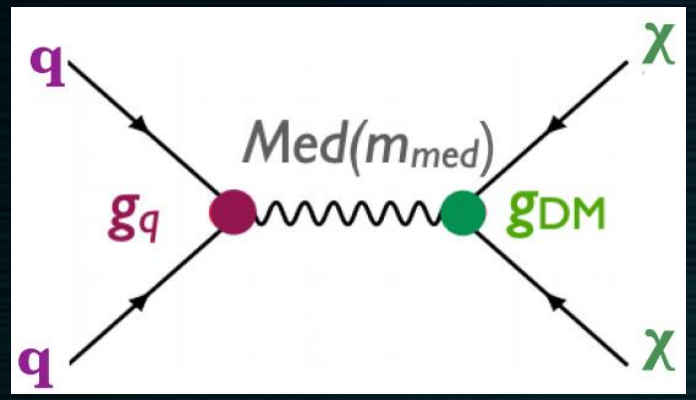
- ✓ Isodoublet-isosinglet model (faces difficulties in imposing collider and astrophysical constraints for minimal mediator models, higgs portals)
- ✓ New vector-like fermion family (VLL, VLQ, VLF in general)

Spin-0 DM: inert higgs doublet

Spin-1 DM: dark photon

The simplest s-channel DM

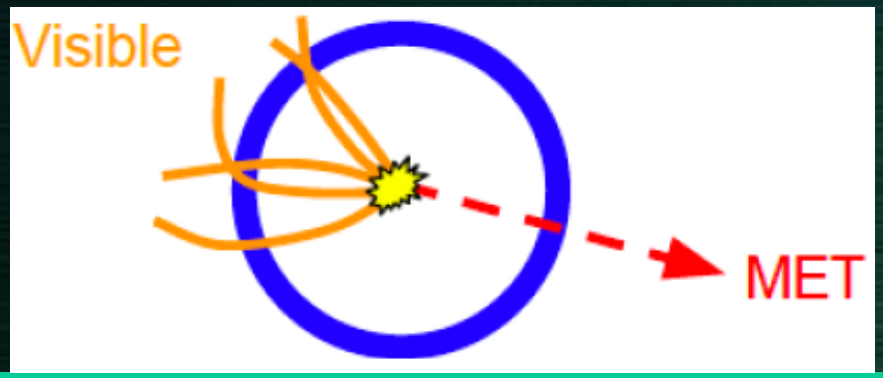
One DM particle, one mediator, plus the SM content. Visible and invisible (MET) FS

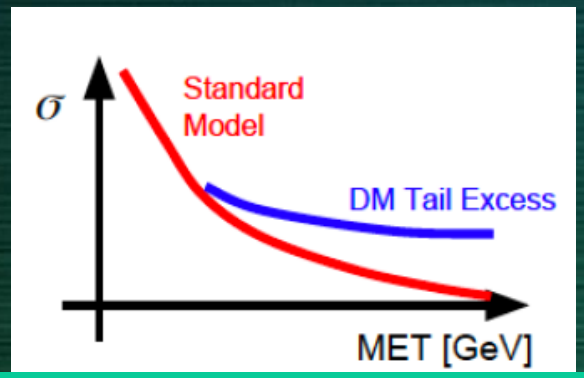


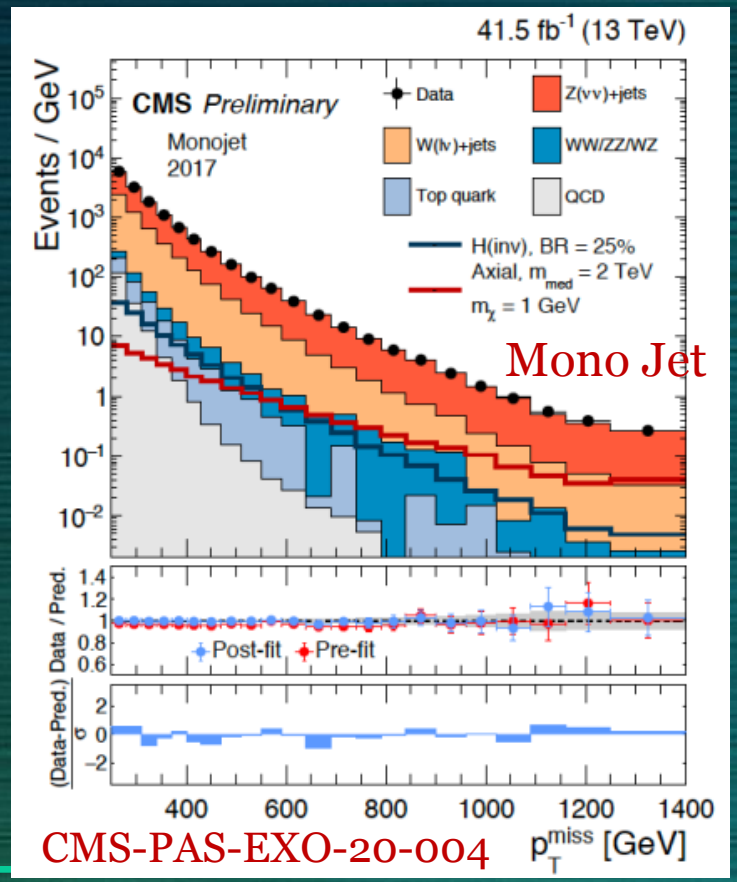
	vector	axial-vector
spin-1	$g_q \sum_q V_\mu \bar{q}\gamma^\mu q$	$g_q \sum_q A_\mu \bar{q}\gamma^\mu\gamma^5 q$
spin-0	scalar: $g_q \frac{\phi}{\sqrt{2}} \sum_f y_f \bar{f} f$	pseudoscalar: $g_q \frac{iA}{\sqrt{2}} \sum_f y_f \bar{f}\gamma^5 f$

A cross section as a function of 5 only model parameters:
m_{med}, g_q, g_l, m_{DM}, g_{DM}

The invisible signature: DM mediator → $\chi\bar{\chi}$ → Mono X + MET;
Mono X = ISR Jet/W(Z)/γ/h_{125}/t/$t\bar{t}$



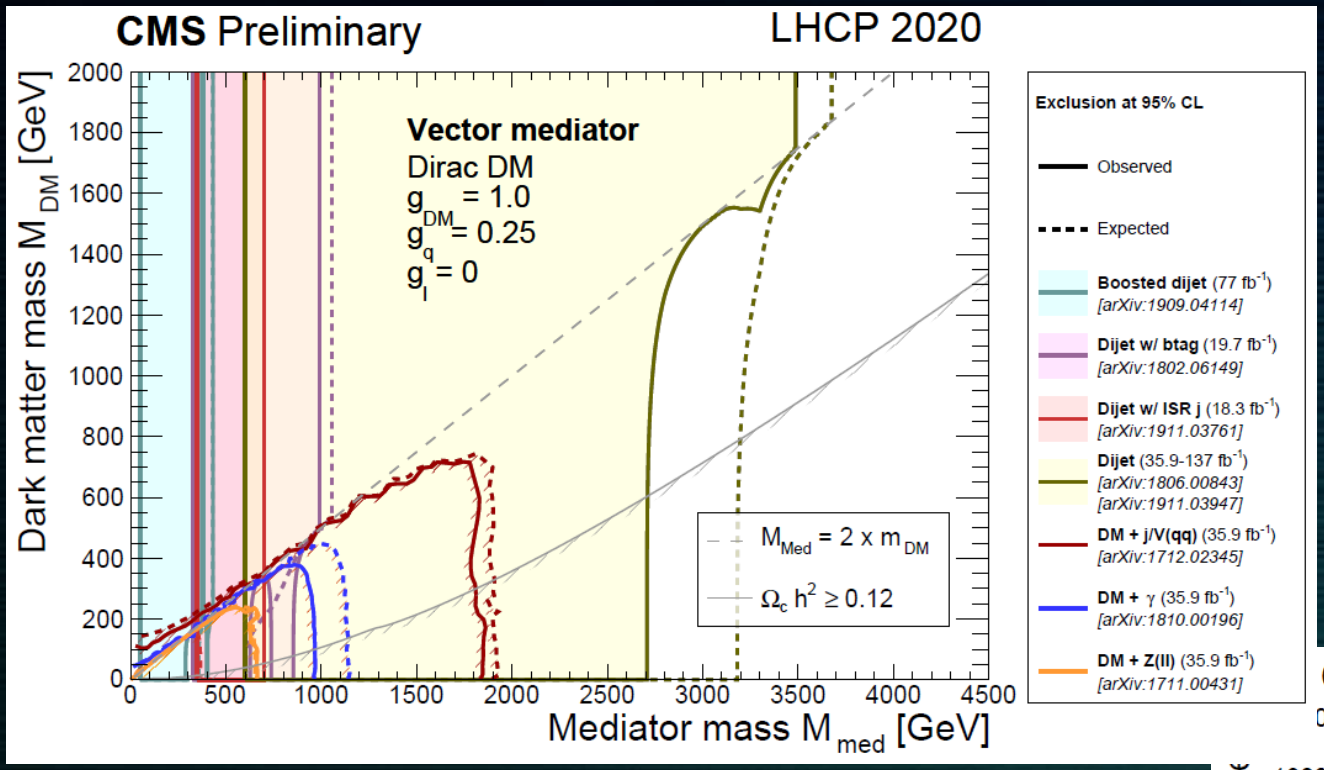




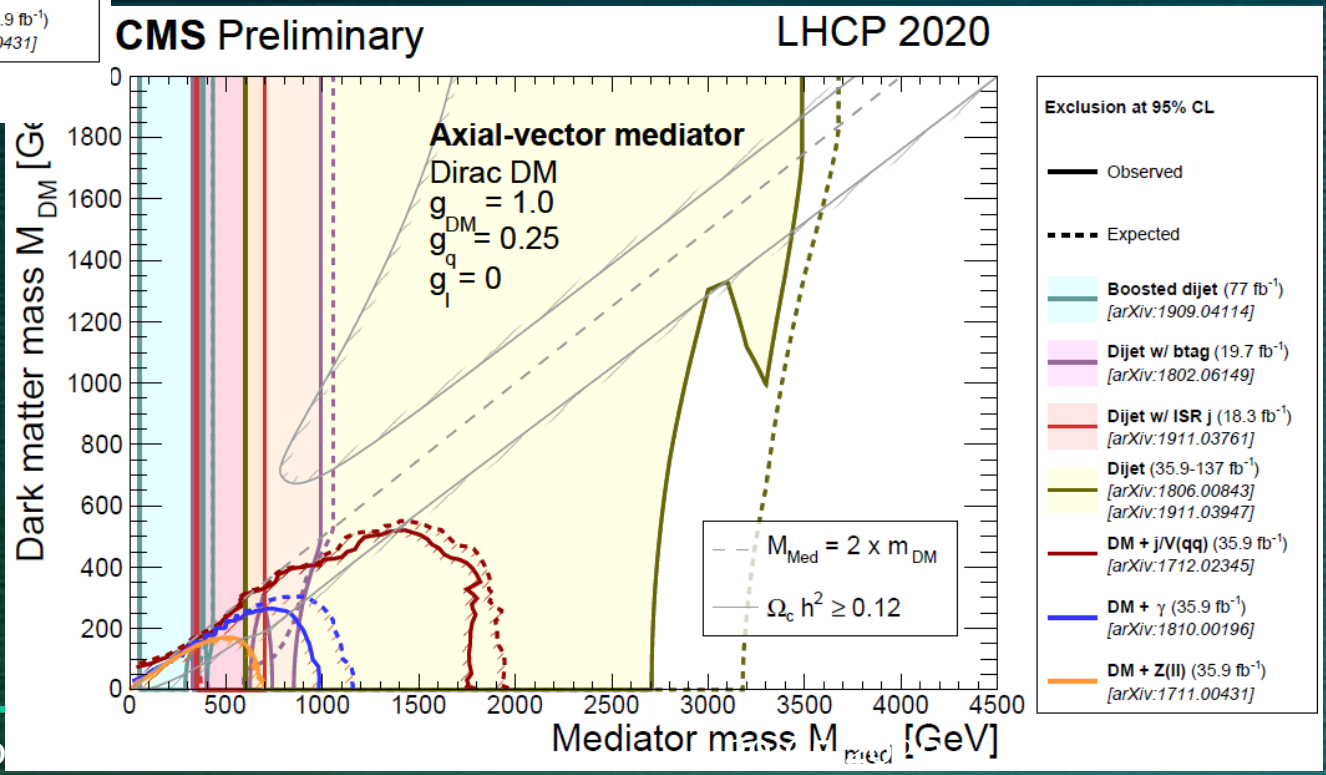
V/AV combined Dijet & Mono X + E_T^{miss}

The leptophobic mediator, $g_l = 0$

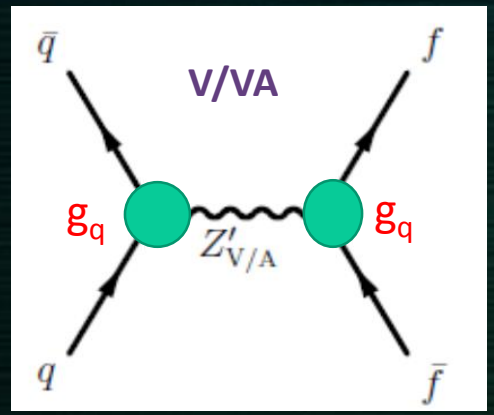
CMS EXO summary plots

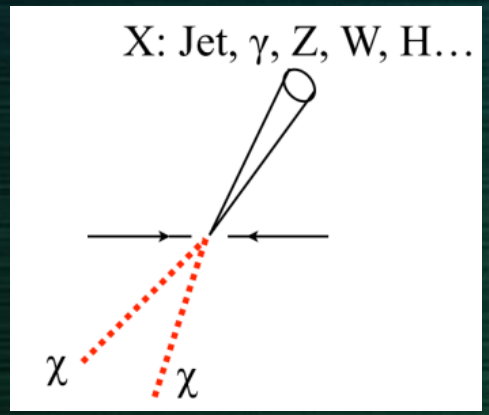


interpretation for the axial-vector mediator



interpretation for the vector mediator

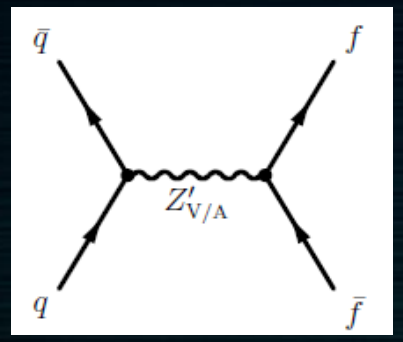




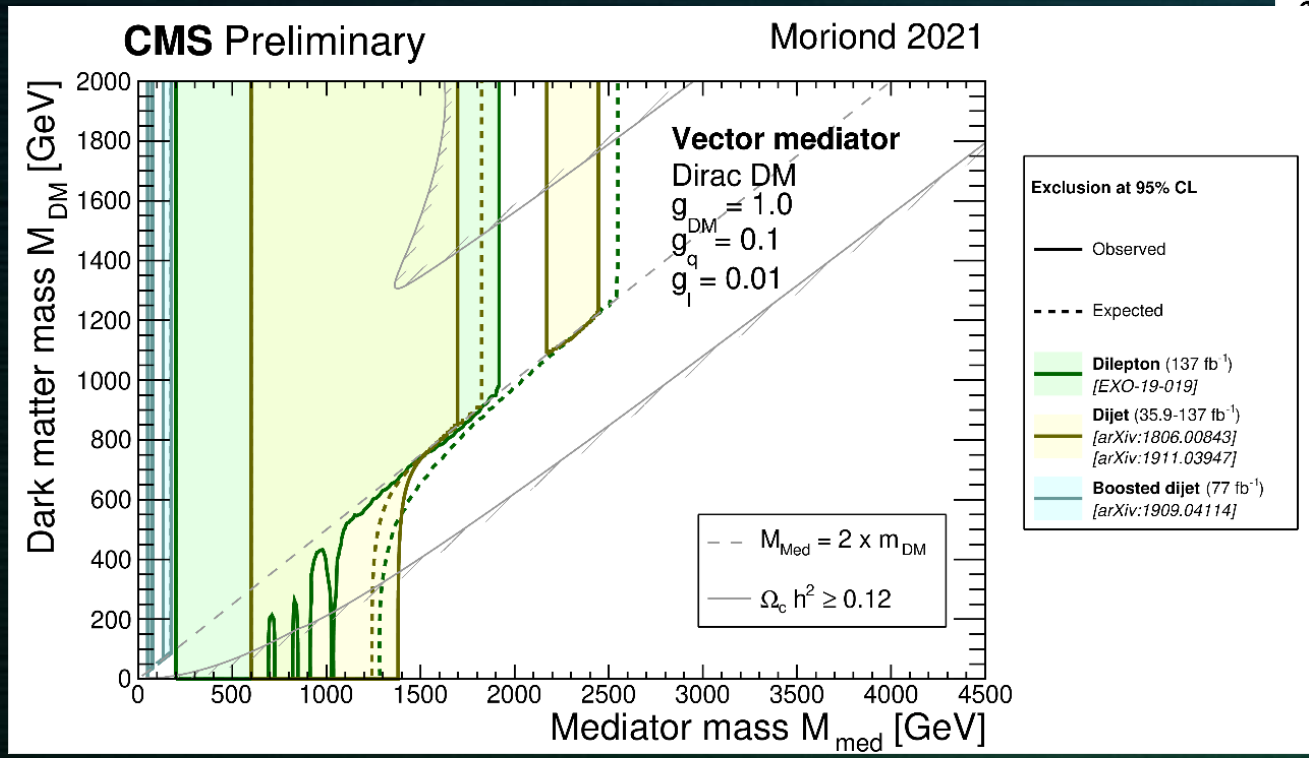
Visible (ffbar) and invisible (X+MET) channels combined

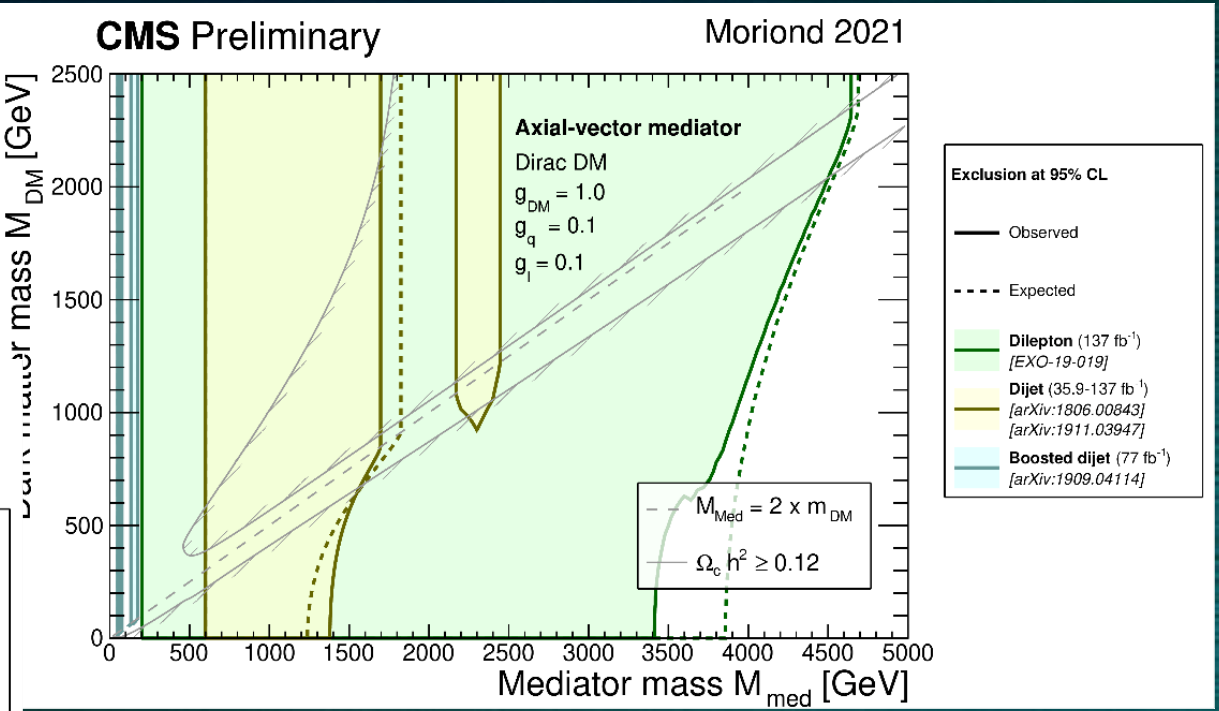
Leptophilic mediator $g_l \neq 0$: dileptons and dijets (combined)

CMS EXO summary plots



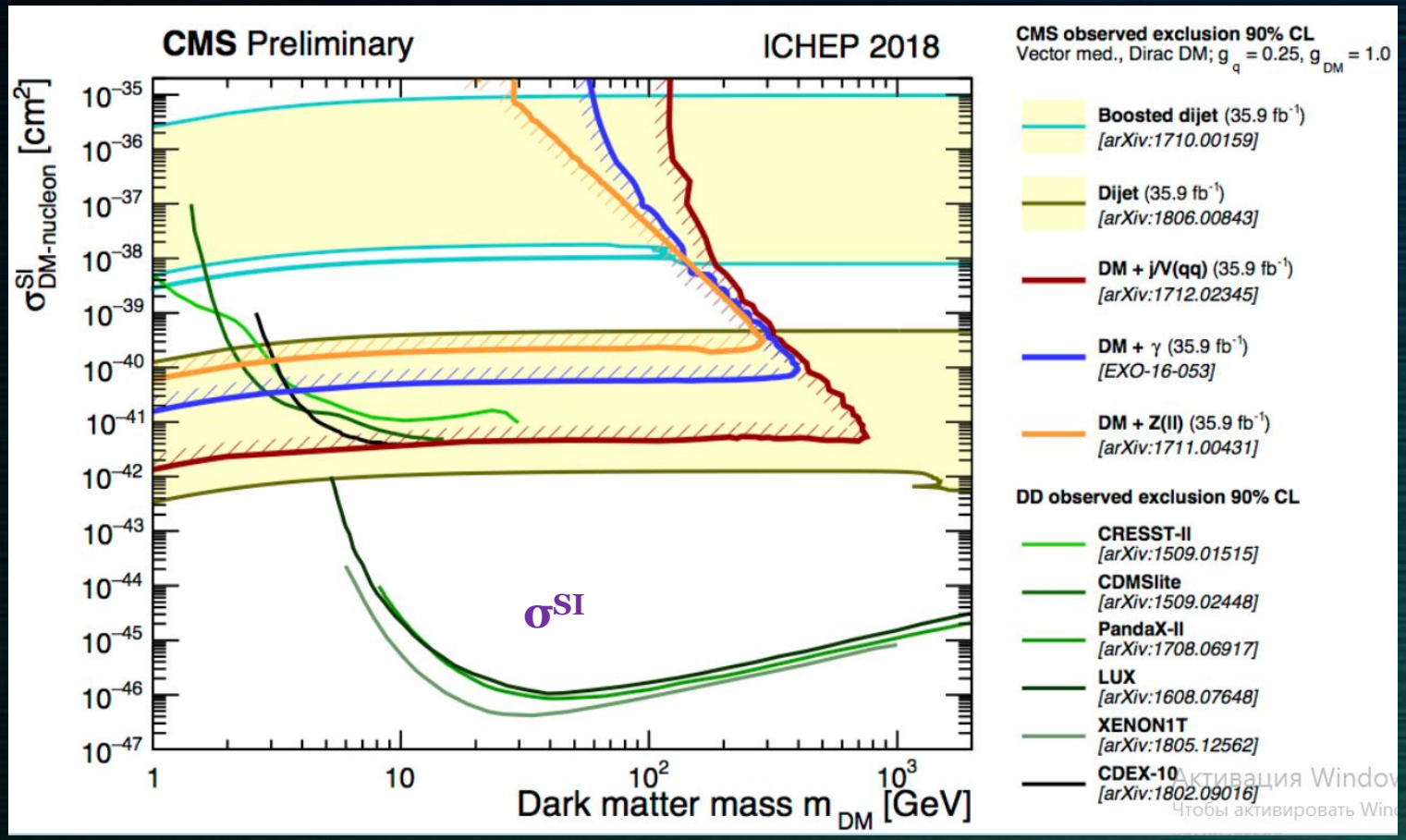
95% CL observed and expected exclusion regions in m_{Med}–m_{DM} plane for dijet and dilepton searches from CMS for the axial-vector and the vector DM mediator





The exclusions are computed for the universal quark coupling of $g_q = 0.1$, lepton coupling $g_l = 0.1$ (0.01 fron DY process) for the VA(V) model, and for the DM coupling of $g_{DM} = 1.0$

Collider and DD constraints on DM: CMS Mono Jet/*V*+ MET, V/AV mediator



Comparison of the inferred limits with the constraints from direct-detection experiments on spin-independent (the V mediator) and spin-dependent (the AV mediator) WIMP-nucleon scattering cross-section

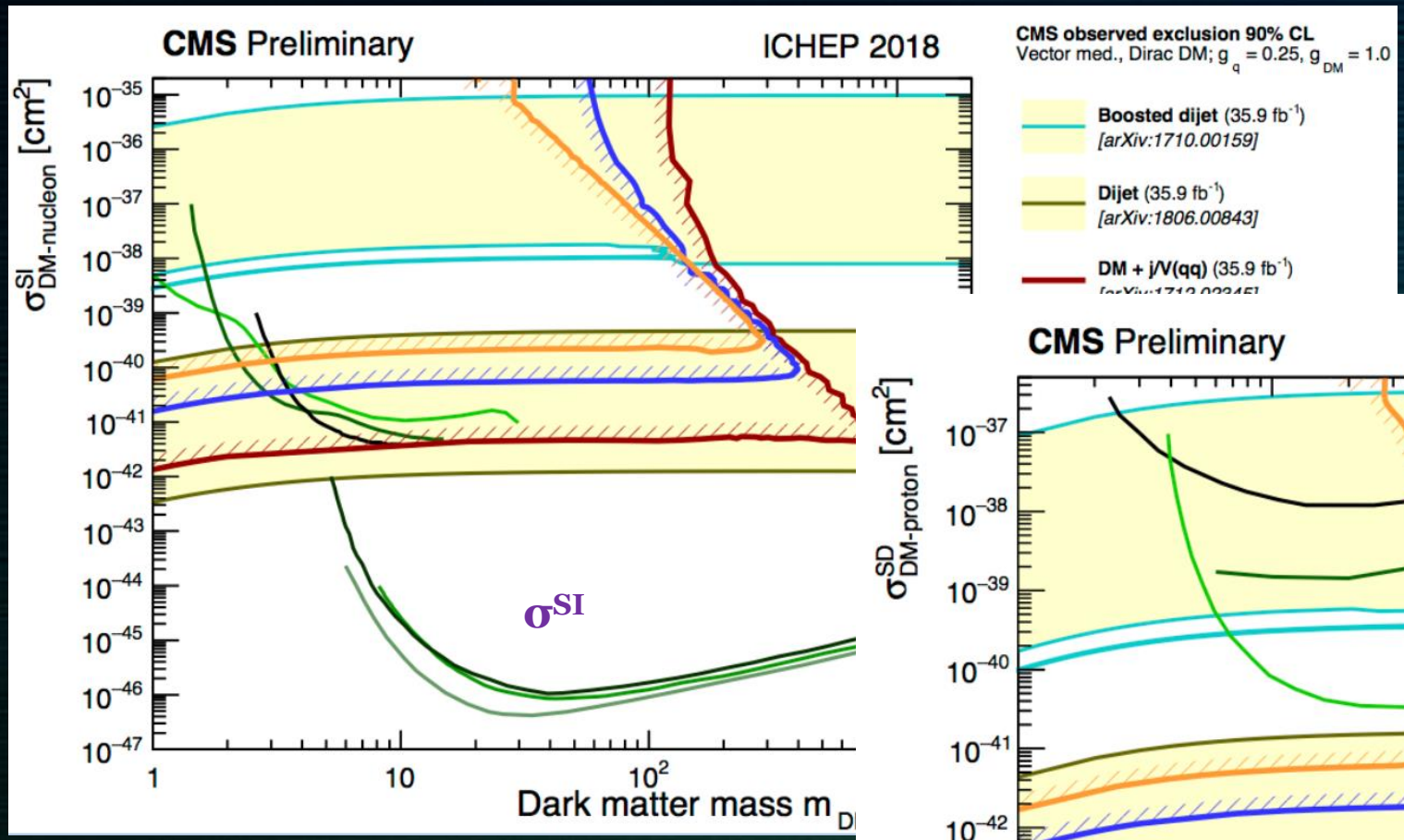
$$\sigma_{\mathrm{SI}} = \frac{f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

Vector

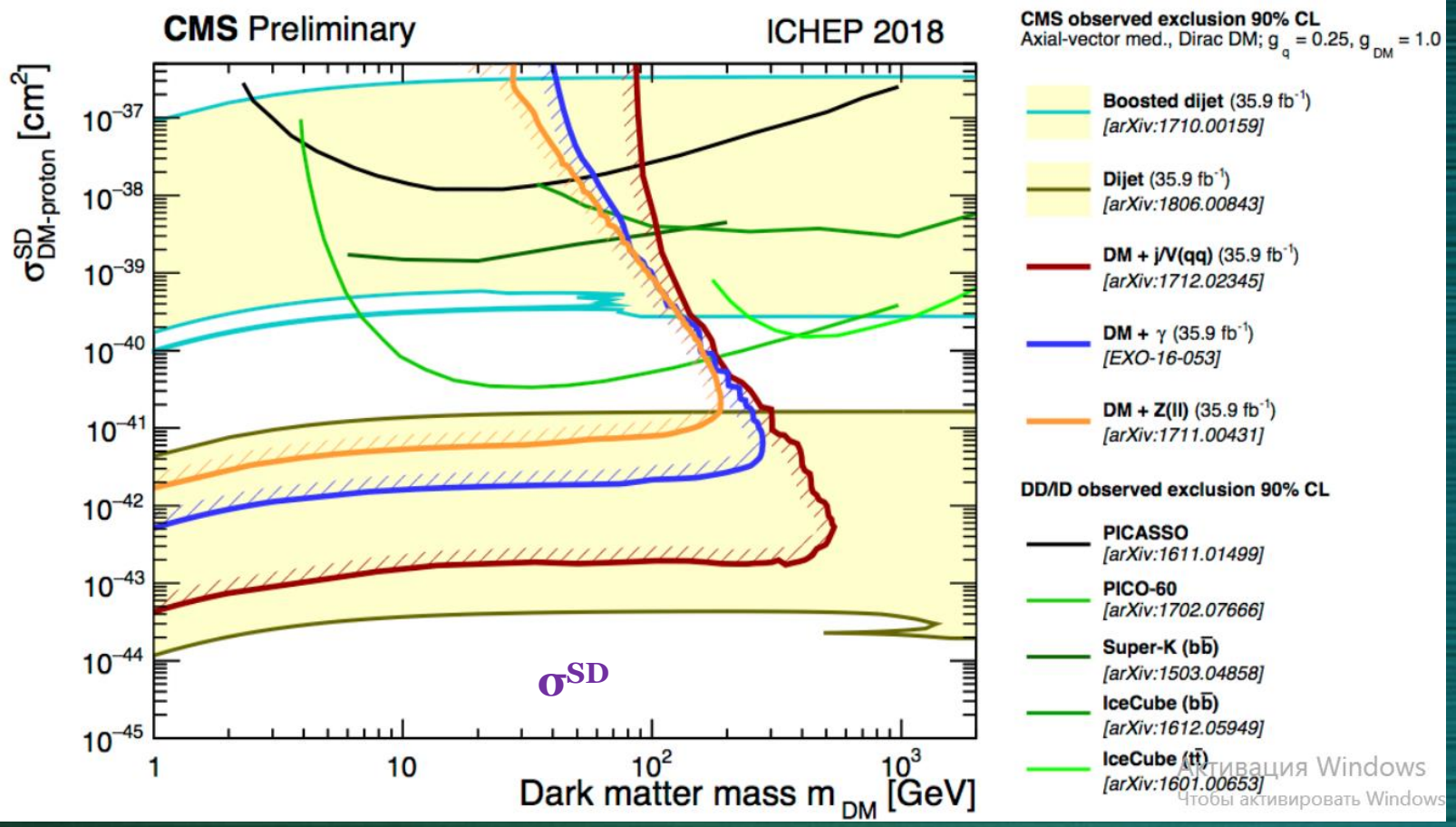
$$f(g_q) = 3 g_q$$

$$\mu_{n\chi} = m_n m_{\mathrm{DM}} / (m_n + m_{\mathrm{DM}})$$

Collider and DD constraints on DM: CMS Mono Jet/*V*+ MET, V/AV mediator



Comparison of the inferred limits with the constraints from direct-detection experiments on spin-independent (the V mediator) and spin-dependent (the AV mediator) WIMP-nucleon scattering cross-section



$$\sigma_{\mathrm{SD}} = \frac{3 f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}$$

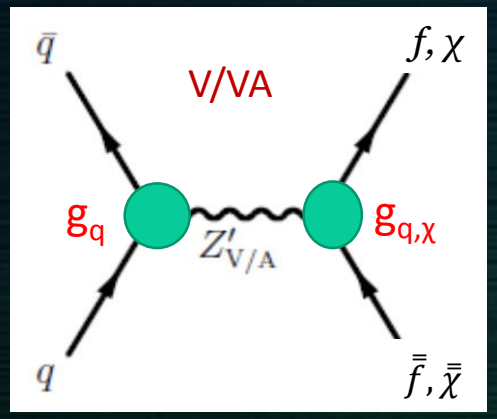
Axial-vector $f(g_q) = 0.32 g_q$

Активация Windows
Чтобы активировать Windows

From the simplest s-channel DM to Simplified Dark matter Model (SDM)

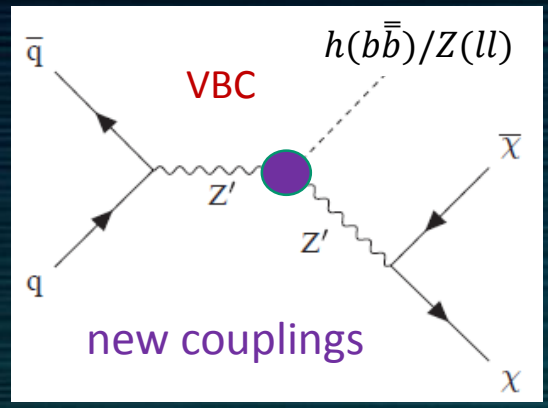
Extended simplified DM:

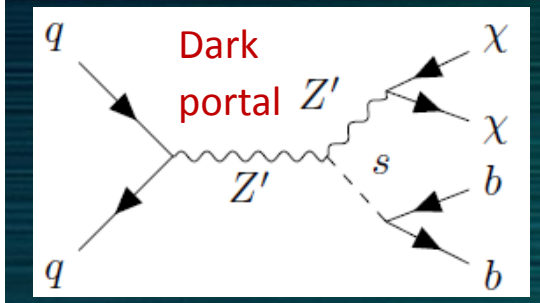
- ✓ 2HDM-based DM
- ✓ Dark portal
- ✓ t-channel VFC SDM…

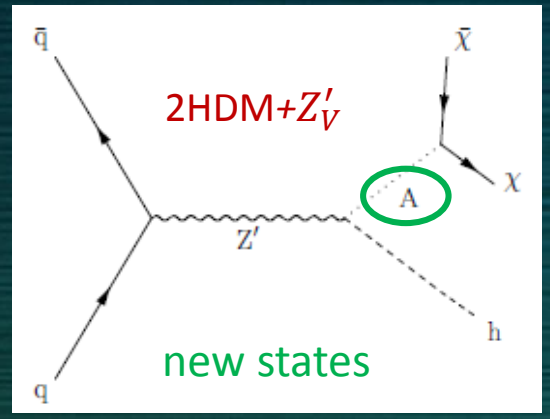


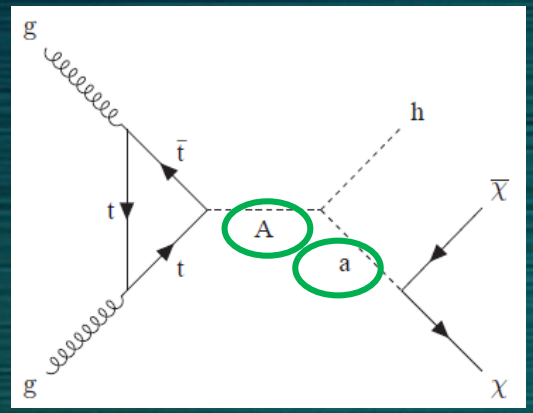
one DM particle,
one mediator + SM

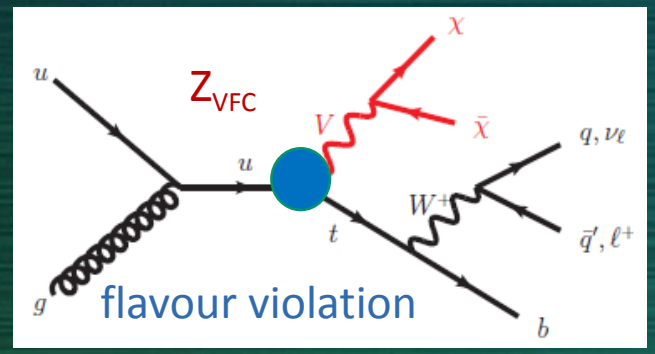
extended higgs/gauge sector:
extra states = extra graphs











SDM models and 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

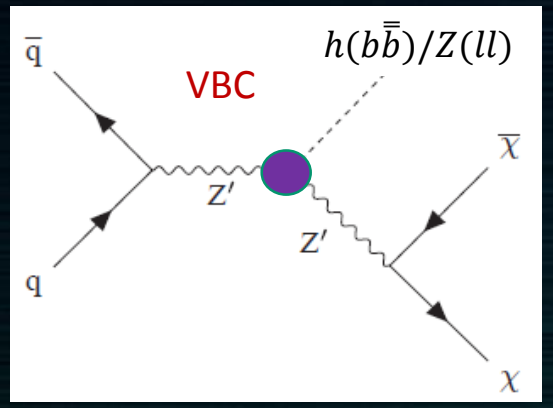
S(calar)/PS(eudoscalar)	$jet/V/h+E_T^{miss}$, $t\bar{t}(b\bar{b})$ resonance, $t\bar{t}(b\bar{b})+E_T^{miss}$, $h \rightarrow inv$, $X \rightarrow hh$
S(calar)C(olor)C(harged)$_b$	$b(b\bar{b}) + E_T^{miss}$
SCC$_t$	$t(t\bar{t}) + E_T^{miss}$
2HDM+a (pseudoscalar 2HDM based)	$h+E_T^{miss}$, $Z(ll)/V(qq')/Z(q\bar{q})+E_T^{miss}$,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

Mono h($b\bar{b}$) + E_T^{miss}, SDM Z'_V interpretations

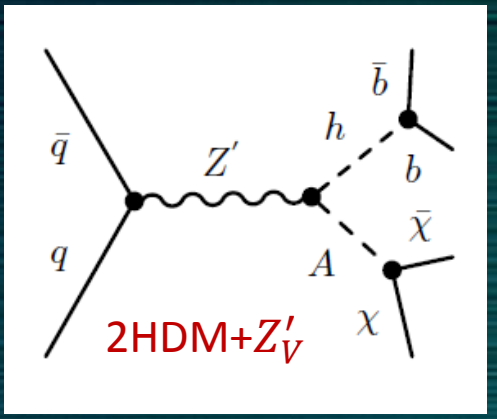
EPJC 79 (2019) 280

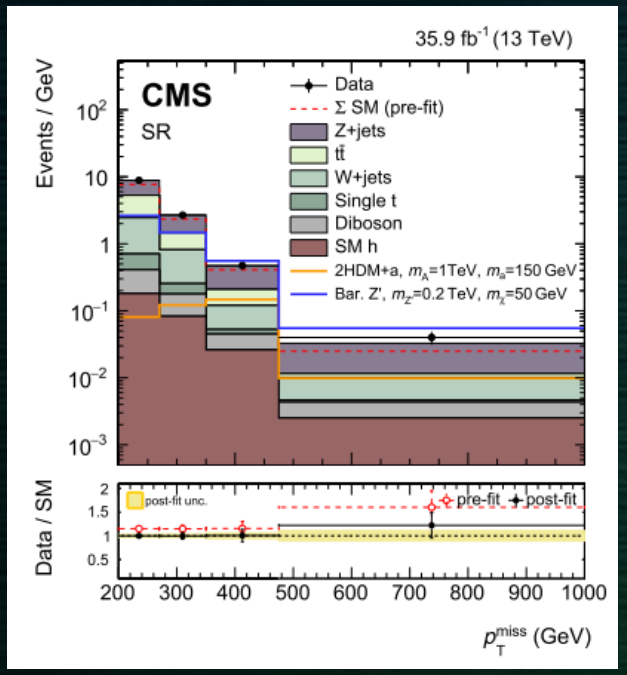
Decay h→ $b\bar{b}$, new vector/pseudoscalar in invisible mode

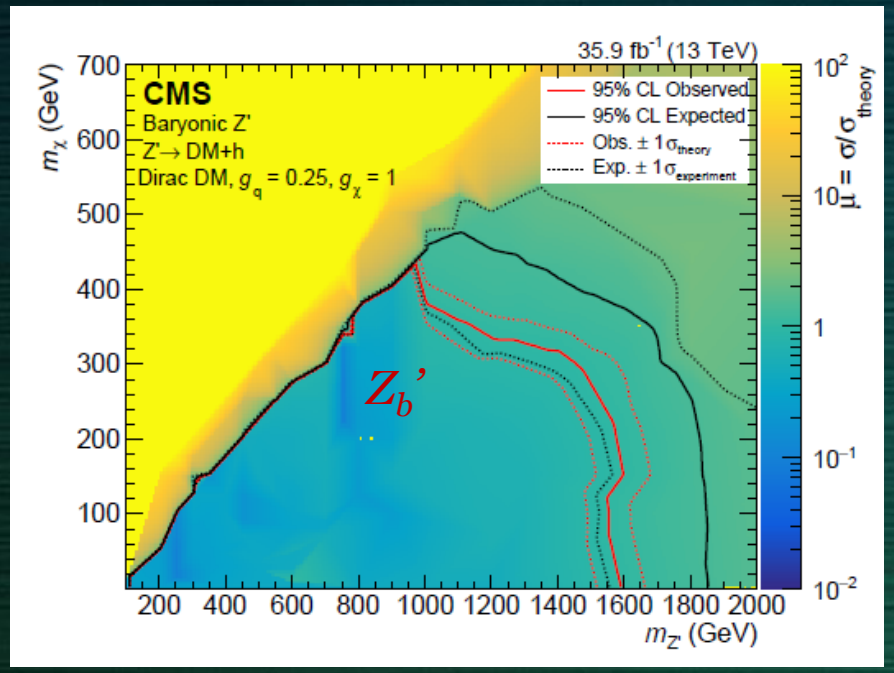


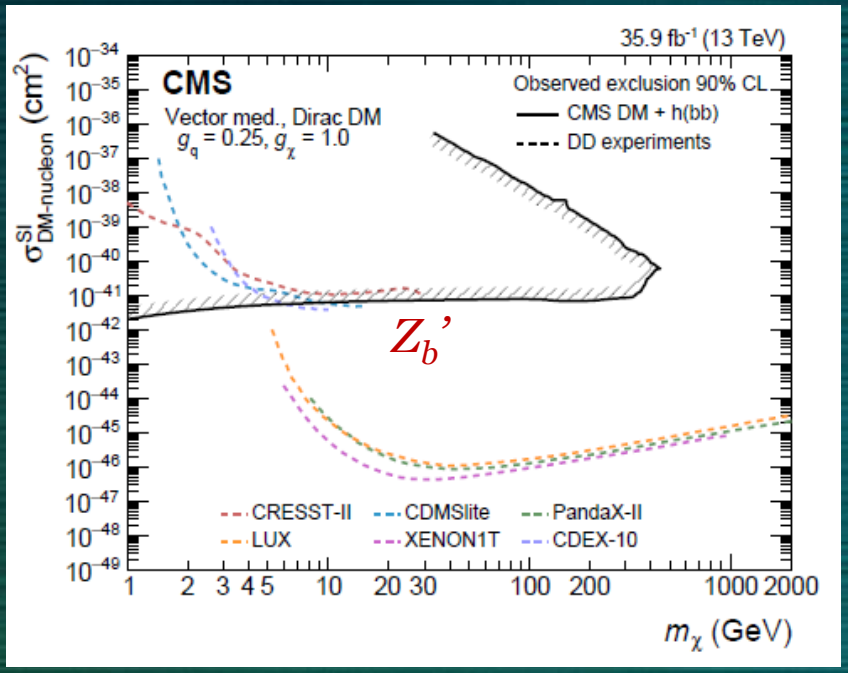
Z_b': Vector Baryon-number-Charged mediator (VBC)
Free parameters of the SDM used in the analyses: m_A, m_H, $m_{Z'}$, m_χ, coupling Z'_V to SM matter $g_{Z'}$ (=0.25), coupling to DM g_χ(=1.0)

2HDM+Z'_V: m_A, m_H, $m_{Z'}$, m_χ(=100 GeV), coupling Z'_V to SM matter $g_{Z'}$ (=0.8), coupling to DM g_χ(=1.0), $tan\beta$=1

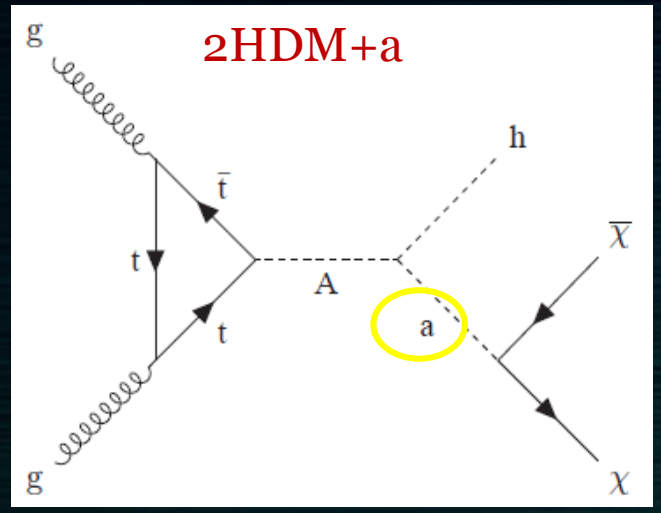








Mono h($b\bar{b}$) + E_T^{miss}, SDM 2HDM+a interpretations

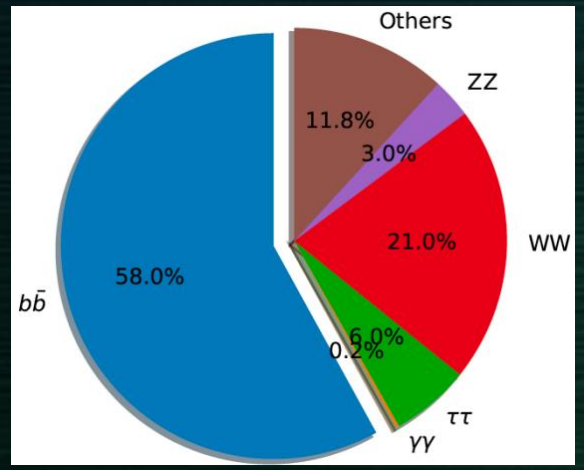


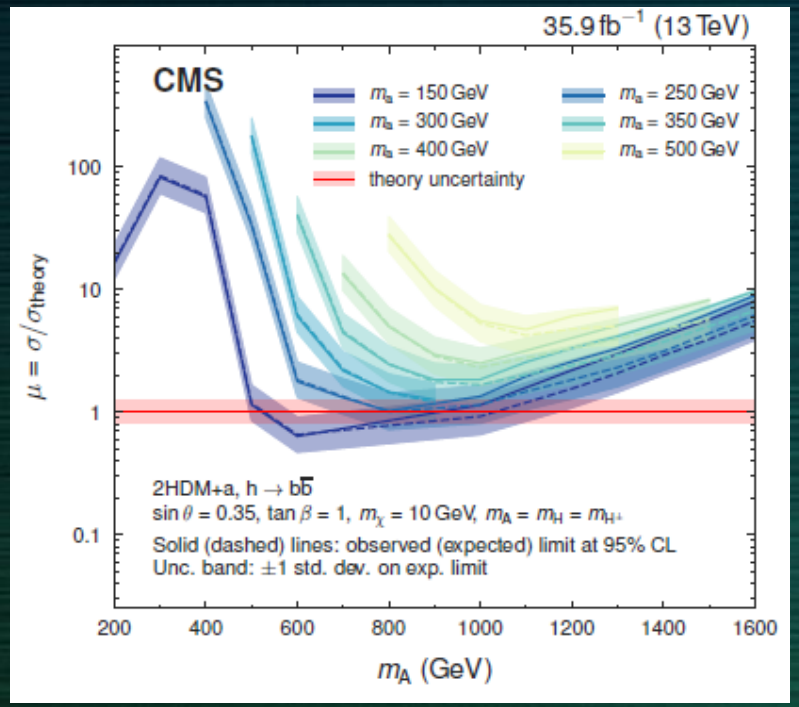
Decay h→ $b\bar{b}$, new pseudoscalar in invisible mode

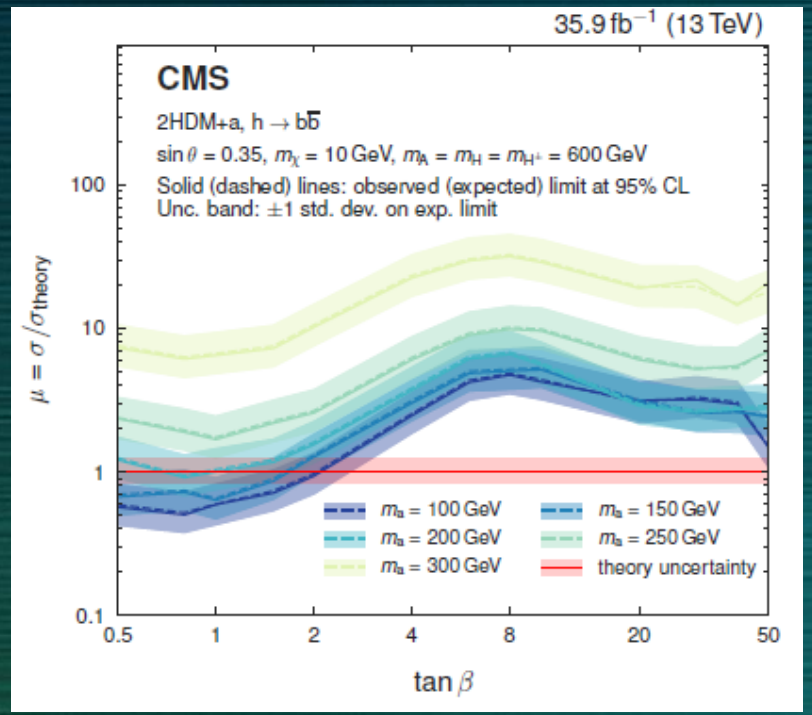
EPJC 79 (2019) 280

Free parameters of a simplified description used in an analyses: m_A, m_H, m_S, mixing angle between a and A $sin\theta$, VEV ratio for two higgs doublets $tan\beta$, couplings to SM and DM particles

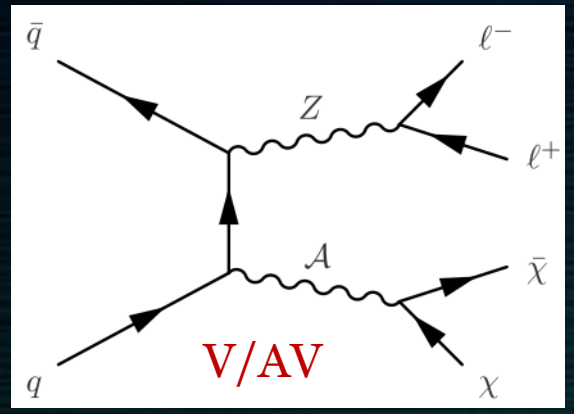
See also JHEP 03 (2020) 25 for combined h → $b\bar{b}$ /WW/ZZ/γγ/ττ



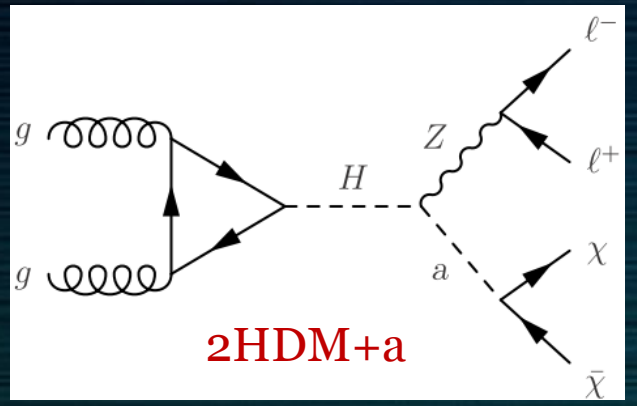




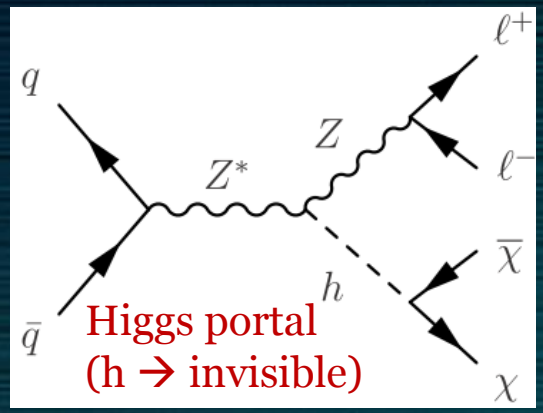
Mono $Z(ll) + E_T^{miss}$, different SDM interpretations



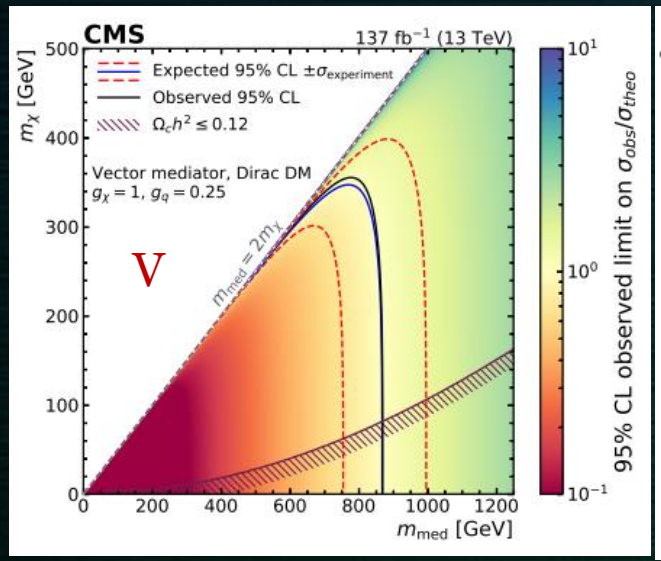
V/AV

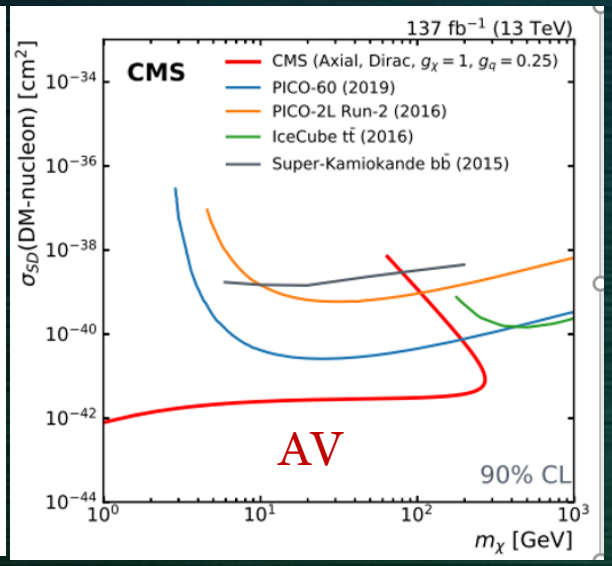


2HDM+a

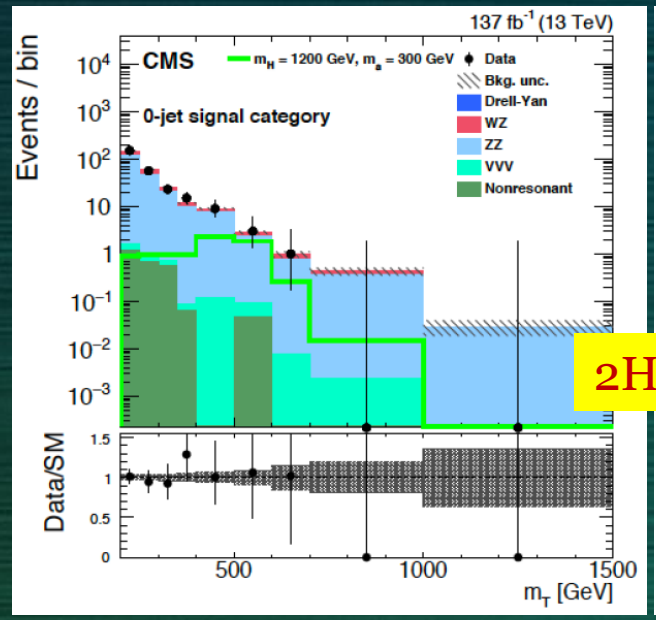


Higgs portal
(h → invisible)

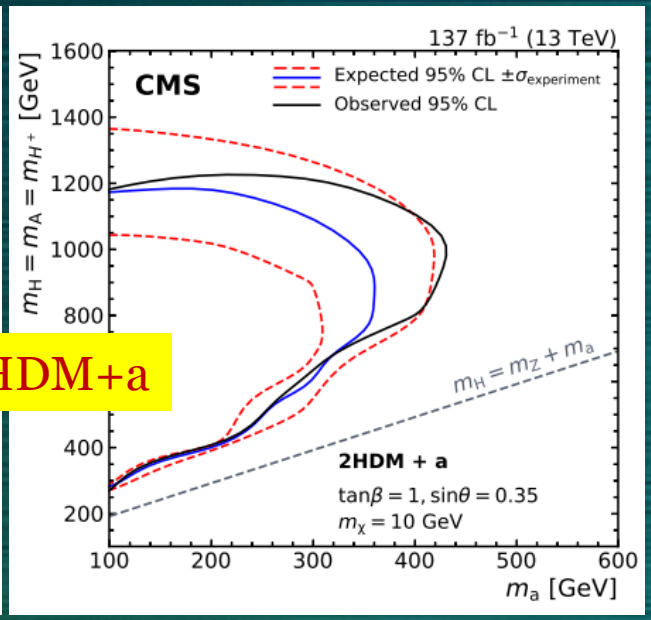




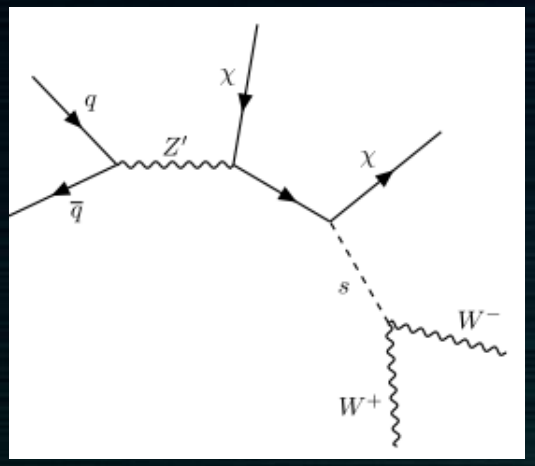
EPJC 81 (2021) 13



2HDM+a

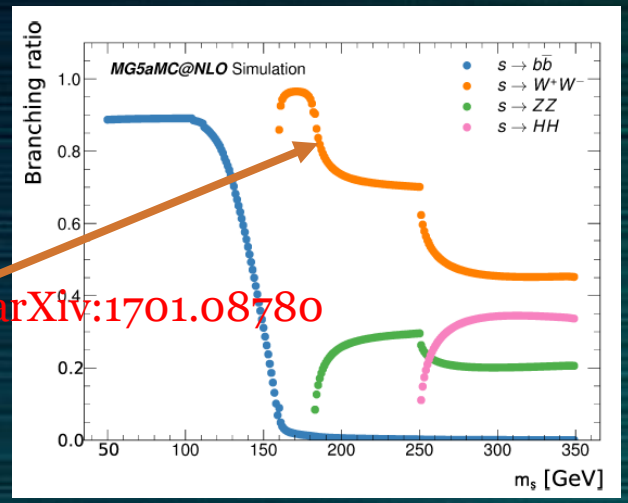


Dark Higgs model, resolved decay of s(W⁺W⁻) + E_T^{miss}

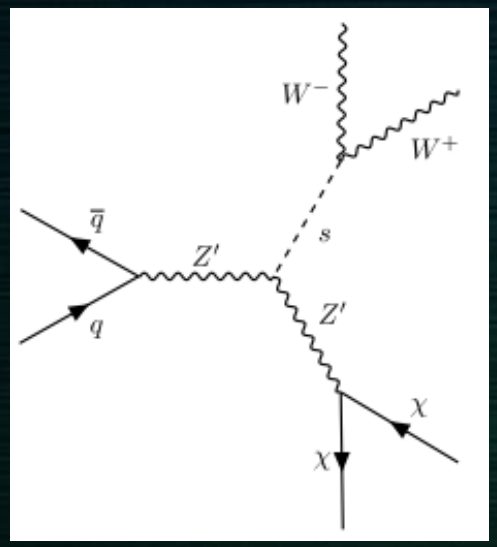


- ✓ "Double portal": both "dark higgs" s and massive Z'_V coupled to SM.
- ✓ A new higgs state is weakly mixed with SM h, a new U(1)' → SSB(s) → massive Z'_V coupled to quarks only
- ✓ s → W⁺W⁻ decay dominates at large s mass values

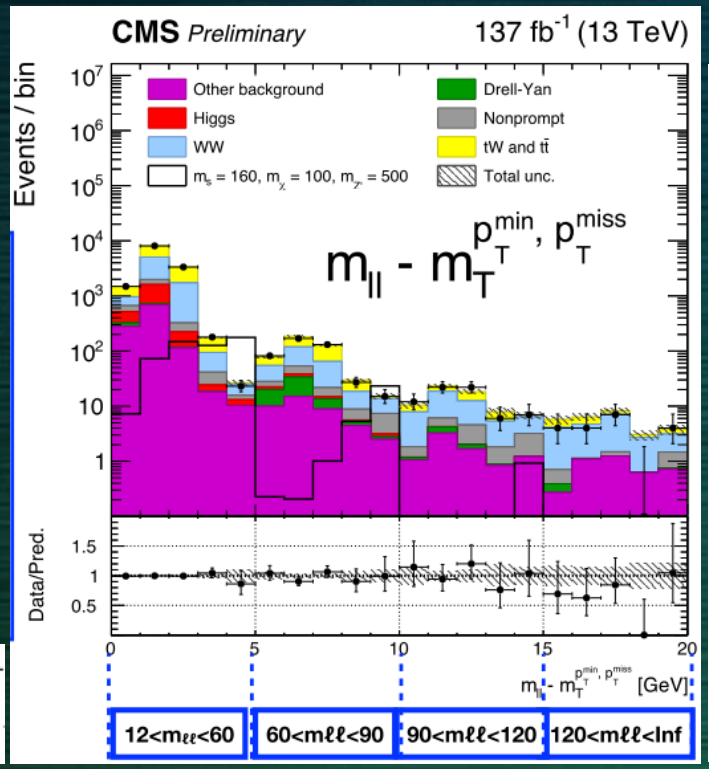
Model parameters : m_s, $m_{Z'}$, m_χ, g_q, g_χ, $\sin\theta$ (h–s mixing)

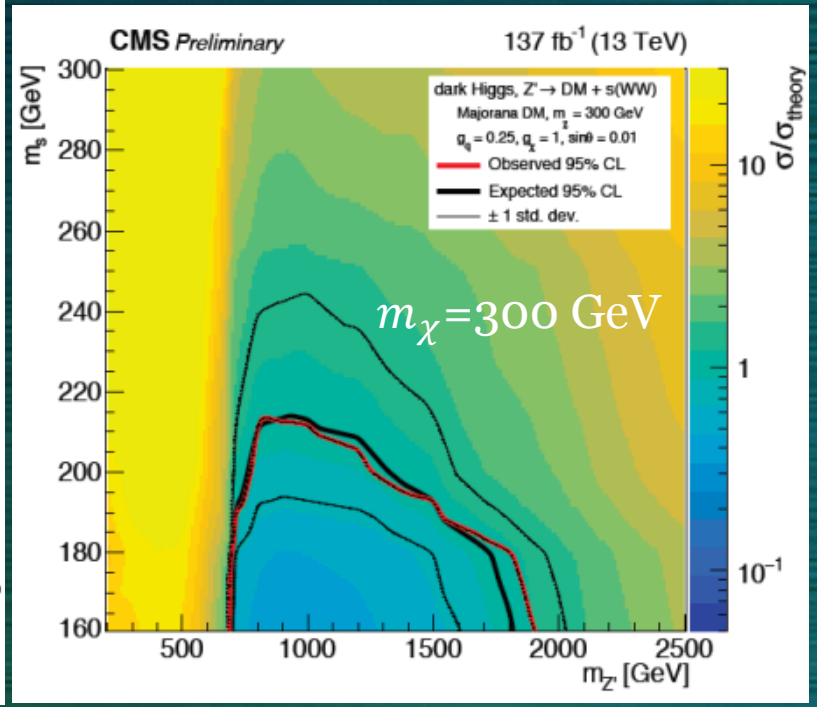


arXiv:1701.08780



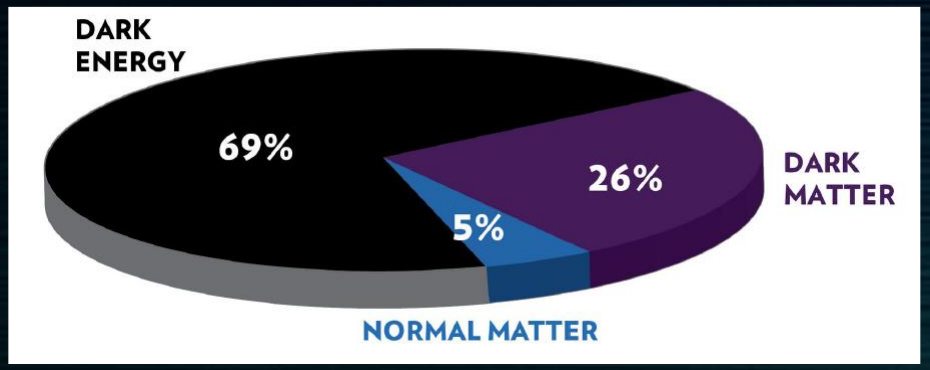
CMS-PAS-EXO-20-013





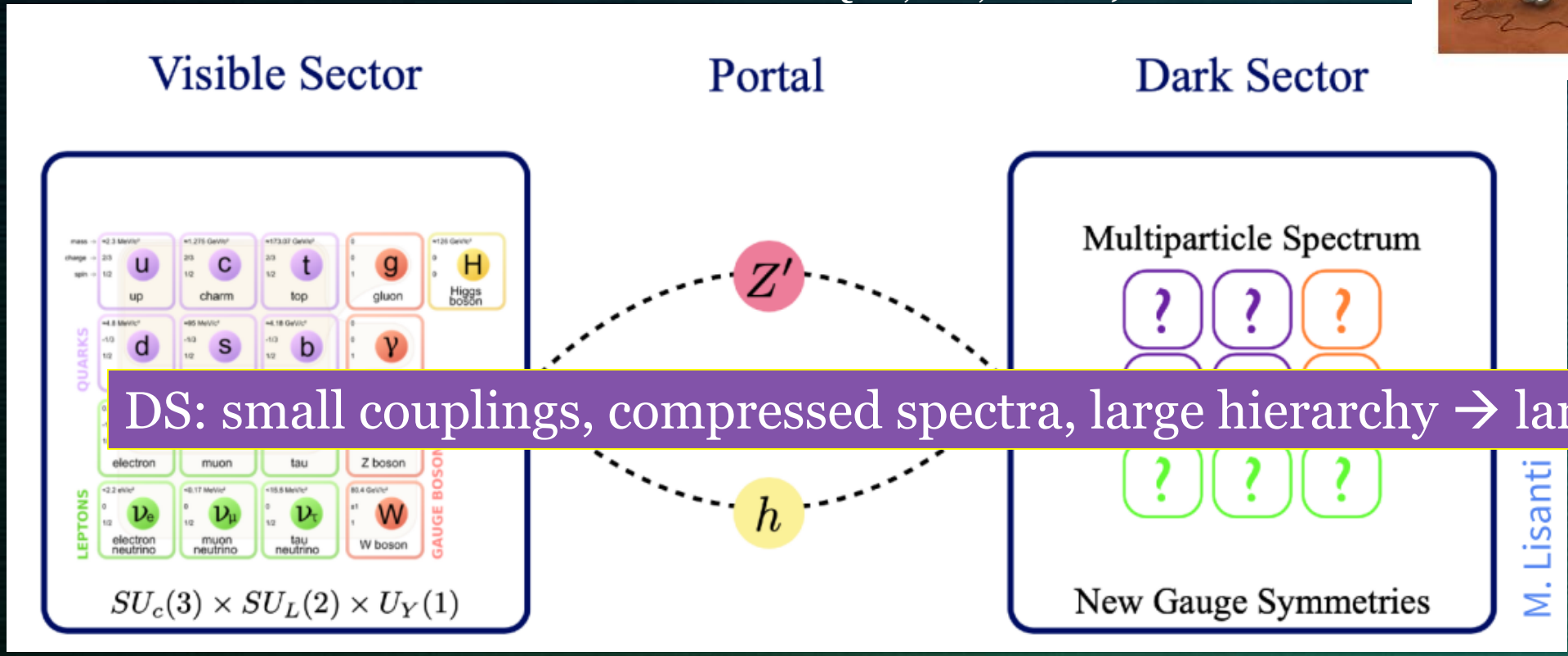
$$m_{\mathrm{T}}^{\ell\,\mathrm{min},p_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2p_{\mathrm{T}}^{\ell\,\mathrm{min}}\,p_{\mathrm{T}}^{\mathrm{miss}}\left[1-\cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\,\mathrm{min}},\vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right]}$$

Dark sector, how might it look?



DS might be extended and rich

- ✓ presence of new "dark" particles that manifests itself through SM-dark interactions (portals)
- ✓ new symmetries (new "dark" QCD, EW, SUSY…)



NB: not only dark sector: see Backup slides for full list of models that give LLP signatures

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

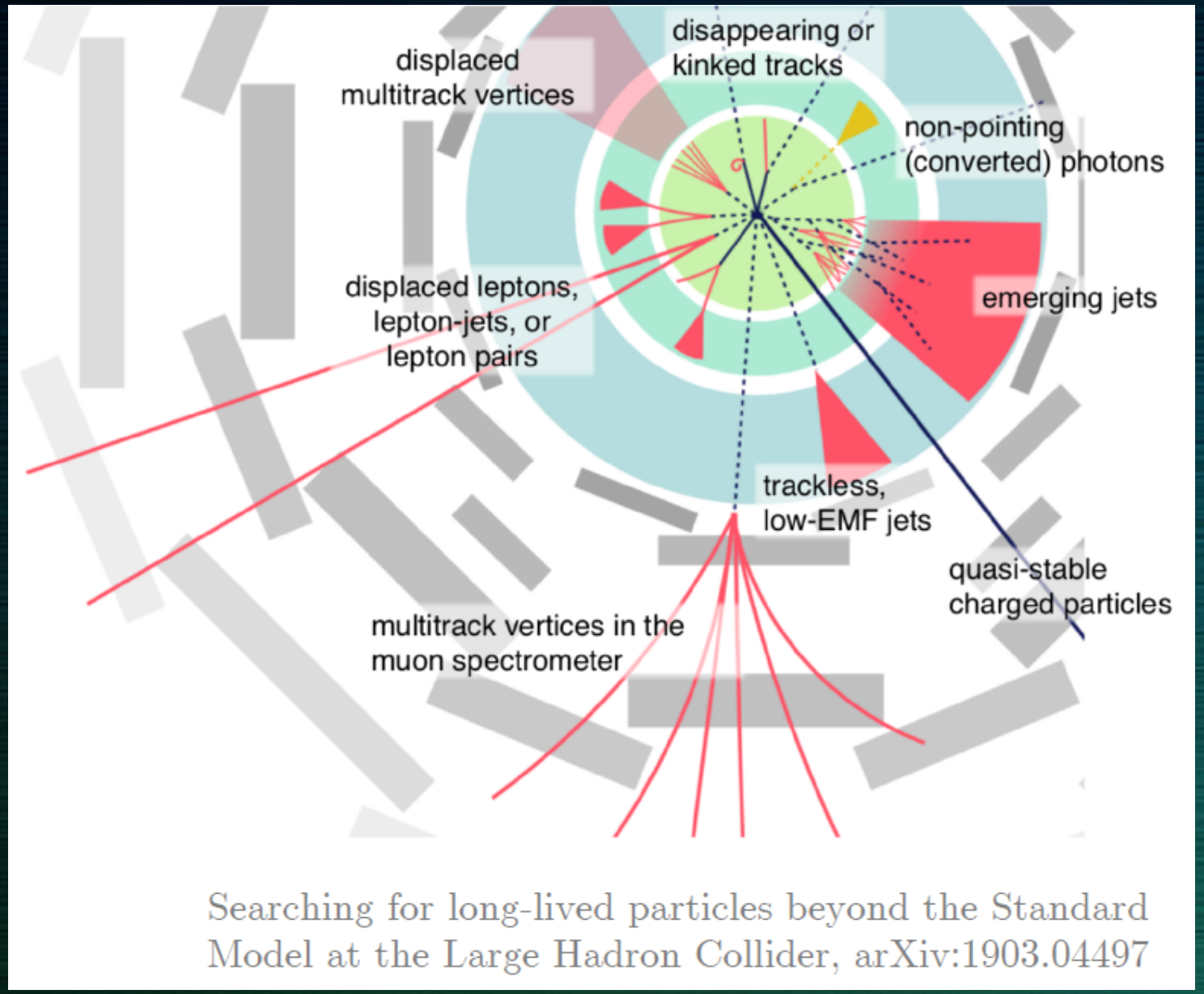
Dark sector with Long-Lived Particles at the LHC

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

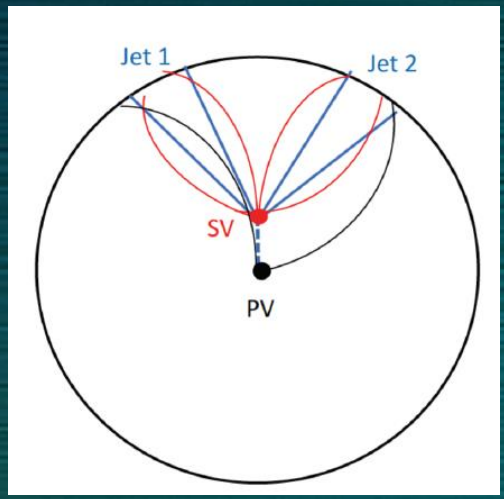


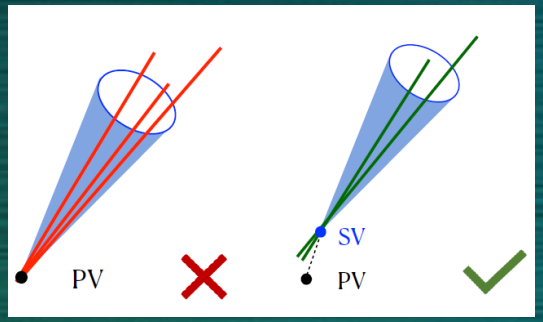
Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497

LLP White Paper: arXiv:1903.04497

LLP theory motivations: arXiv:1806.07396

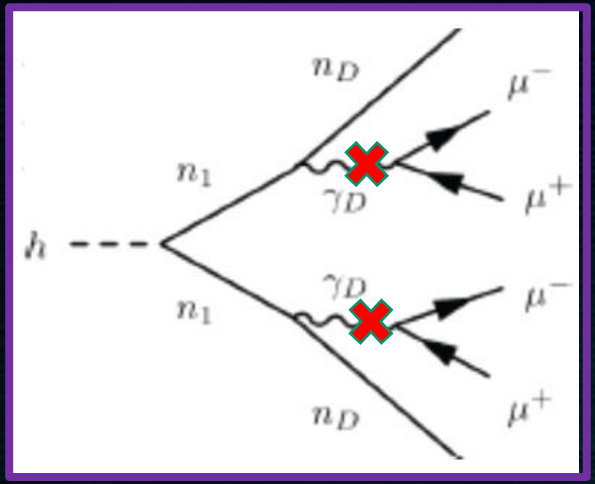
displaced jets





Dark photon from dark SUSY, displaced LJ

Phys. Lett. B 796 (2019) 131
13 TeV, 35.9 fb^{-1}



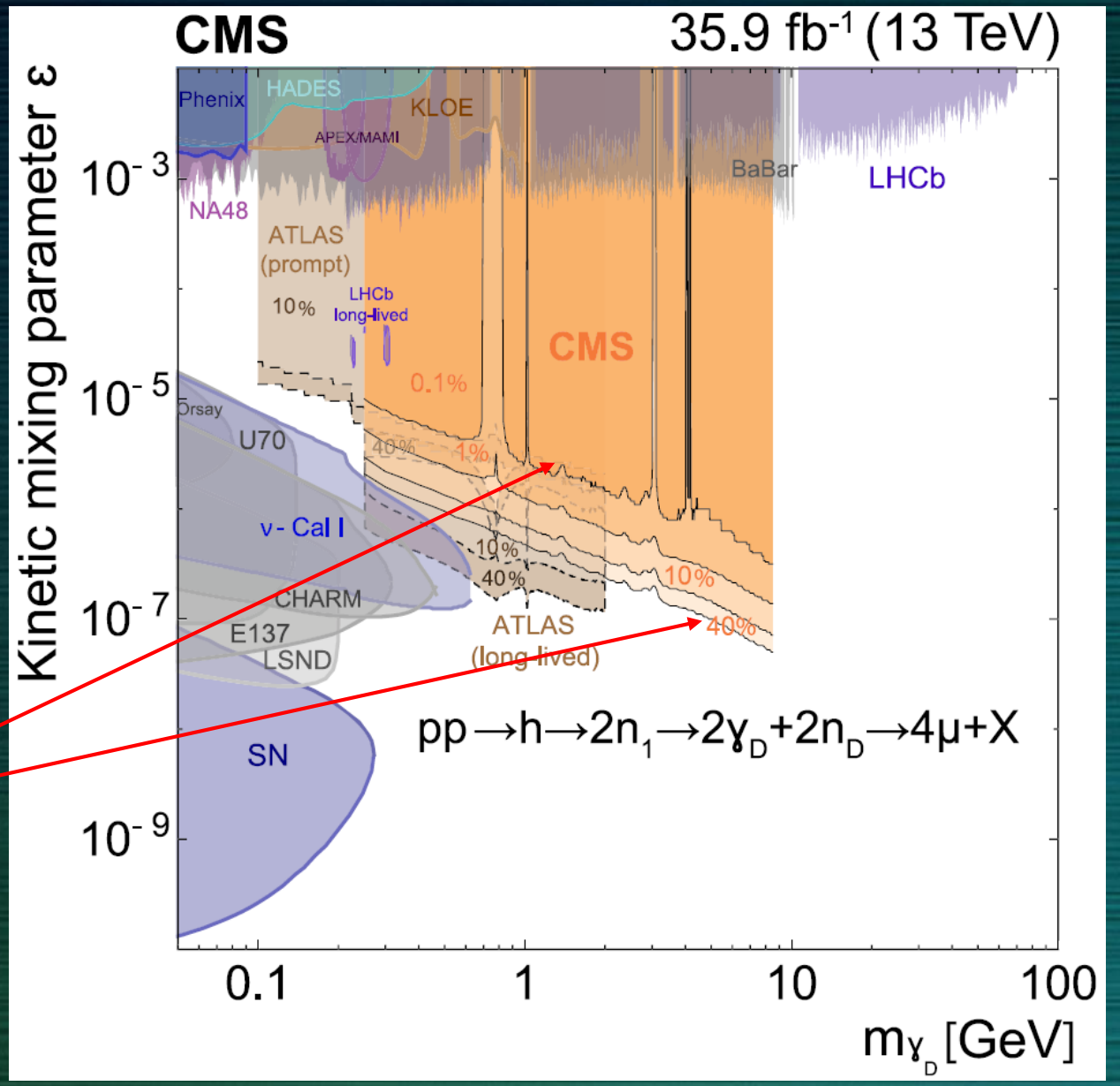
SUSY portal
h – Higgs boson (visible)
n_1 – neutralino,
n_D – dark neutralino
$\gamma_D \rightarrow \gamma$ conversion, ε

Upper limits set on product of H production cross section and BR of Higgs boson (cascade) decay to a pair of dark photons:

$$\sigma(pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D) \times B(\gamma_D \rightarrow 2\mu)$$

Interpreted in terms of limits on the kinetic mixing parameter, ϵ, and $m_{A'}$.

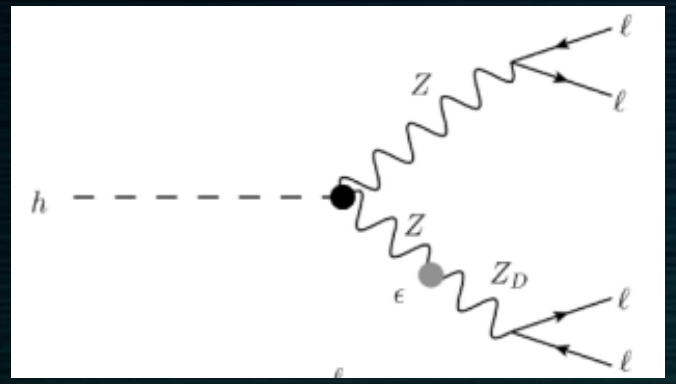
Limits are shown for $B(h \rightarrow 2\gamma_D + X)$ in the range 0.1–40%.



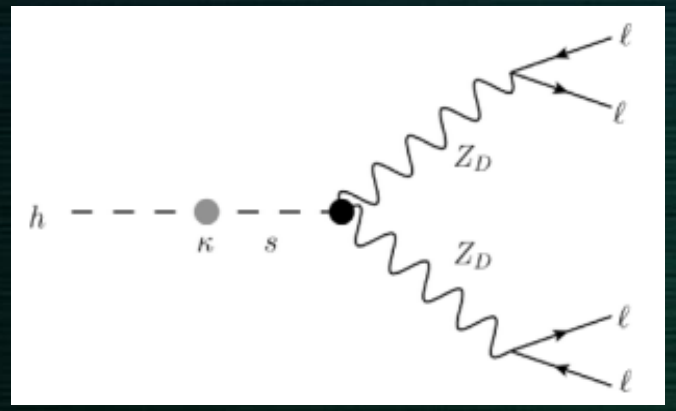
See also full RUN 2 statistics of 137 fb^{-1} analyses for γ_D in VBF and ZH associated prod. and for the light narrow vector resonance Z_D -> $\mu\mu$ in Backup slides

Higgs decay to dark photons: displaced muon jets

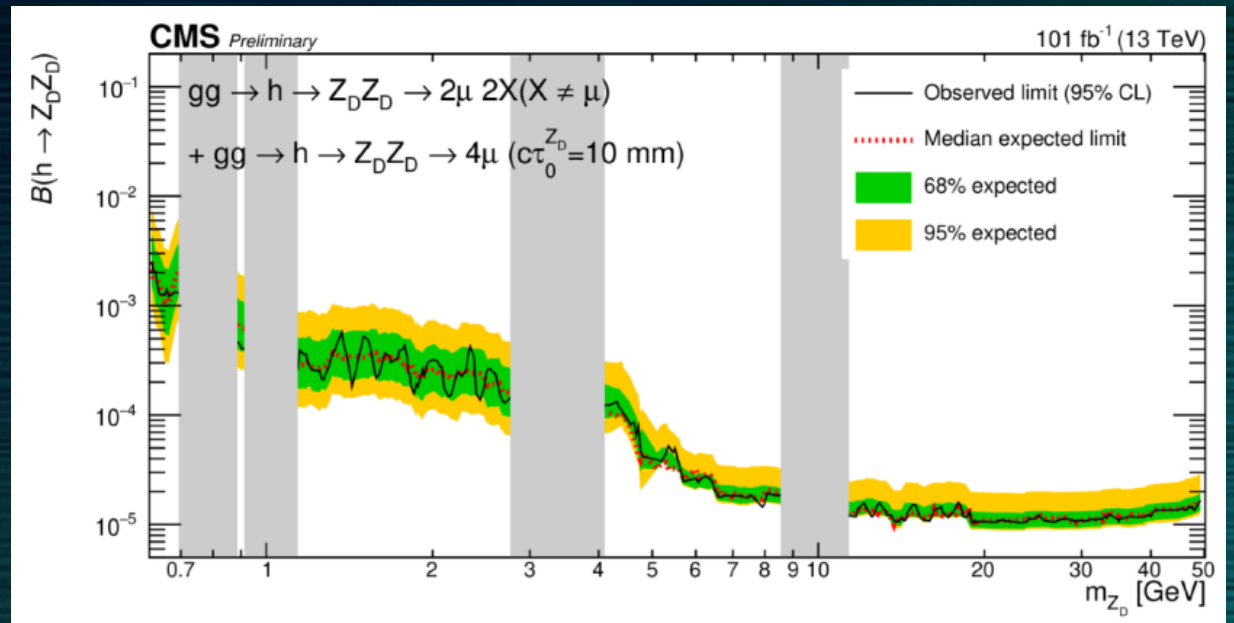
CMS-PAS-EXO-20-014

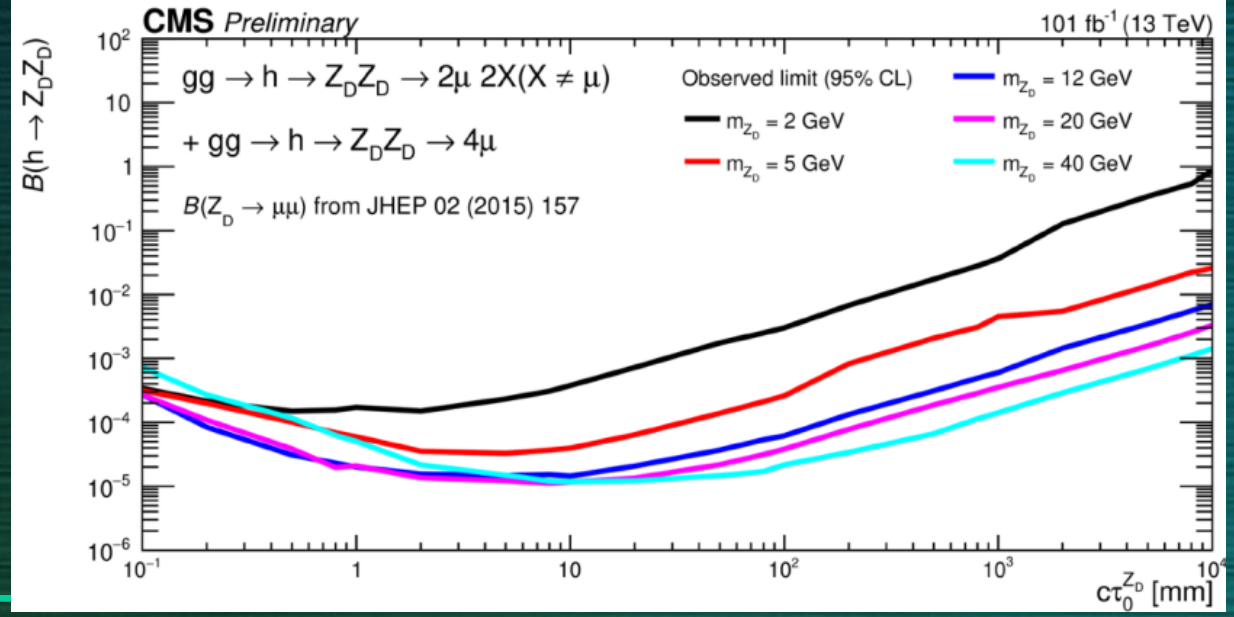


Z–Z_D conversion, ε^2

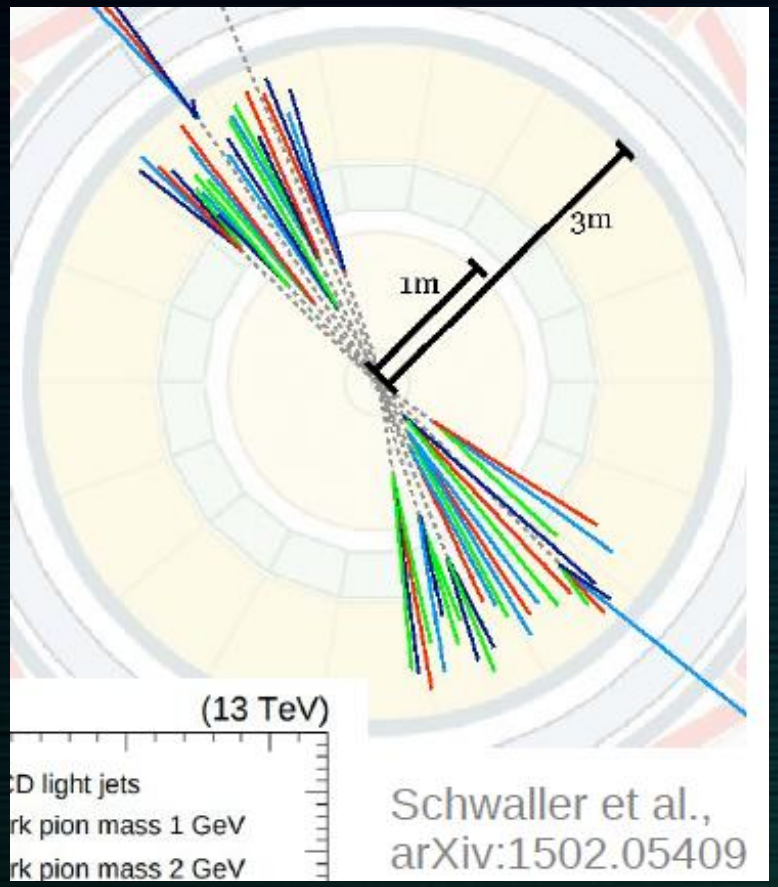


Higgs – dark higgs conversion, κ

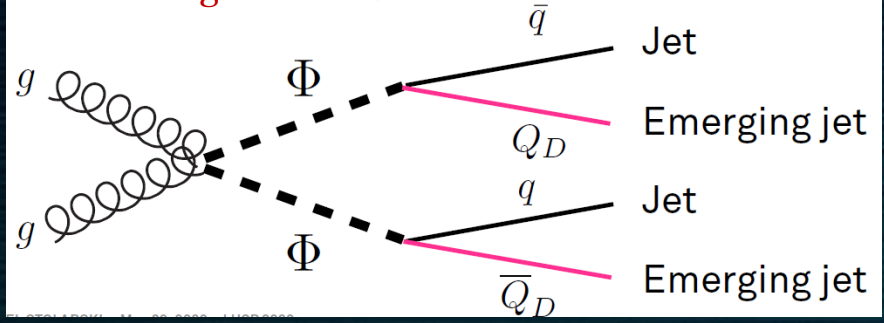


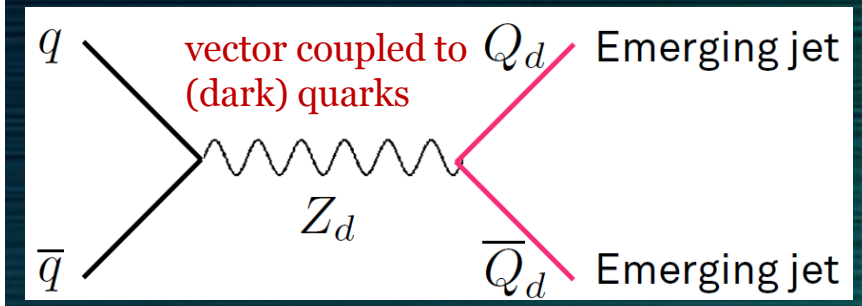


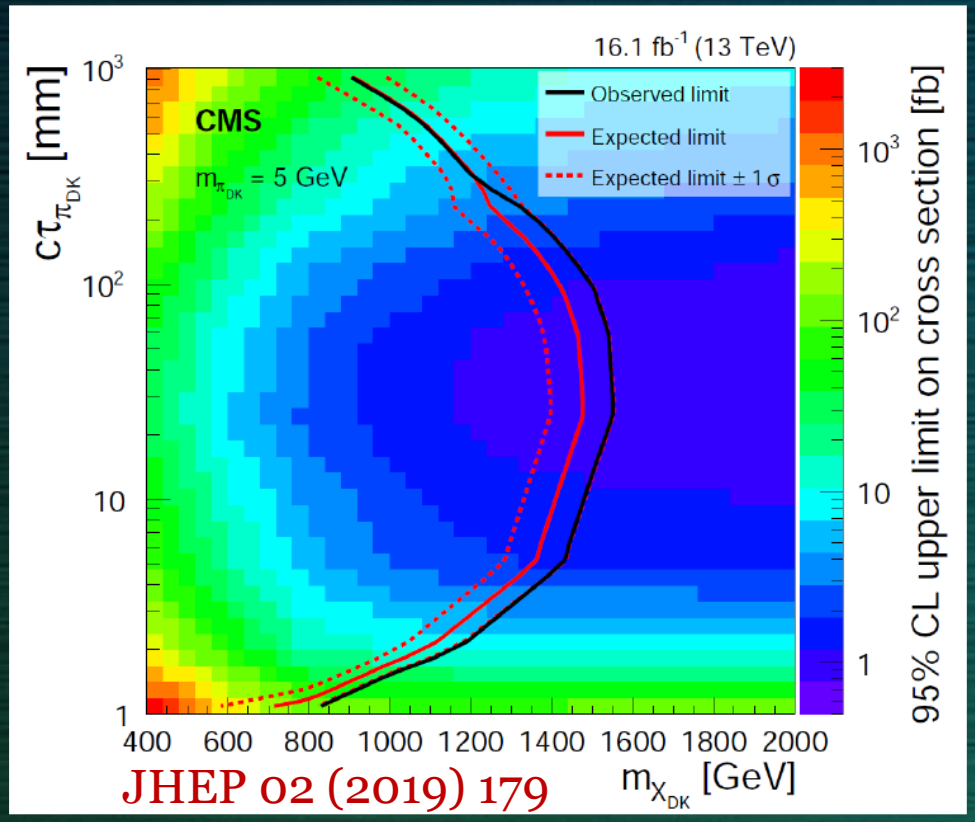
Emerging jets/dark showers from dark QCD



scalar charged under both colour and dark colour

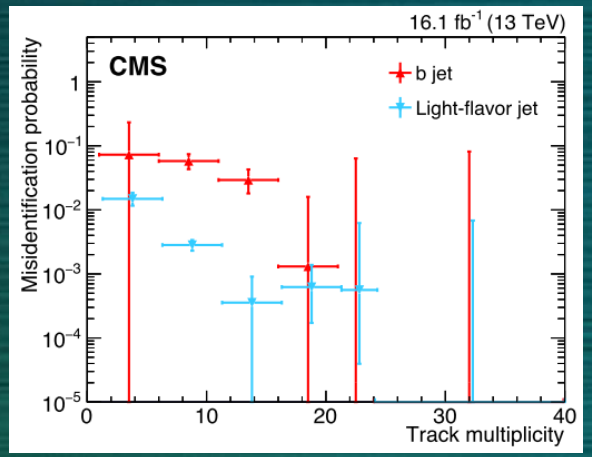






JHEP 02 (2019) 179

background from QCD multijet dominates



- ✓ 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

Summary and outlook on DM searches

- ✓ Wide variety and an extensive list of analyses on DM at CMS, simplified s-channel DM model and slightly beyond it
- ✓ Model specific/non-specific signatures, reinterpretation of common to many models, separation through special signatures
- ✓ Still no signals of new DM particles/mediator
- ✓ Further development of an analysis and related theory/simplified model approaches, new interaction channels, new frameworks:
  - ➢ t-channel studies
  - ➢ LHC Dark Matter Working Group: Next generation spin-0 dark matter models (in the 2HDM+a framework)

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 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.)…

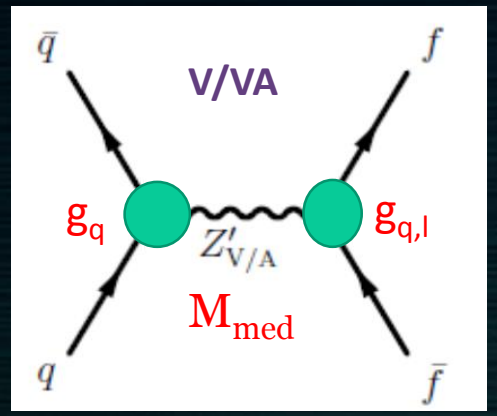
Bright experimental signatures: extra Higgs states, neutral and (doubly)charged, CP-odd and CP-even ones, lighter and heavier than the SM Higgs h_{125}

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

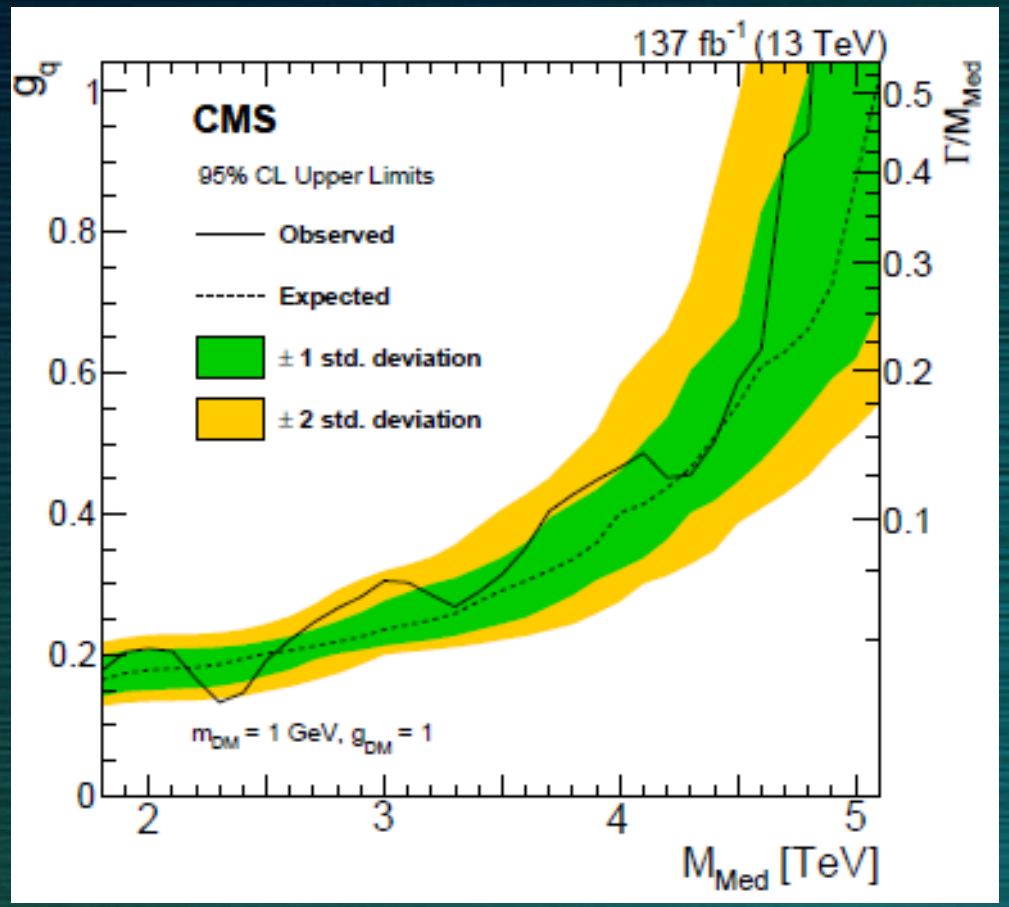
The simplest s-channel DM: (axial)vector mediator V/AV

JHEP 05 (2020) 033

One DM particle (spin-1/2), one mediator + SM, fully visible decay



$$\Gamma_{med} = \frac{3(g'_q)^2 M_{med}}{2\pi} \simeq \frac{(18g_q^2 + 1)M_{med}}{12\pi}$$



mediator on/off-shell production, dijet/dilepton FS

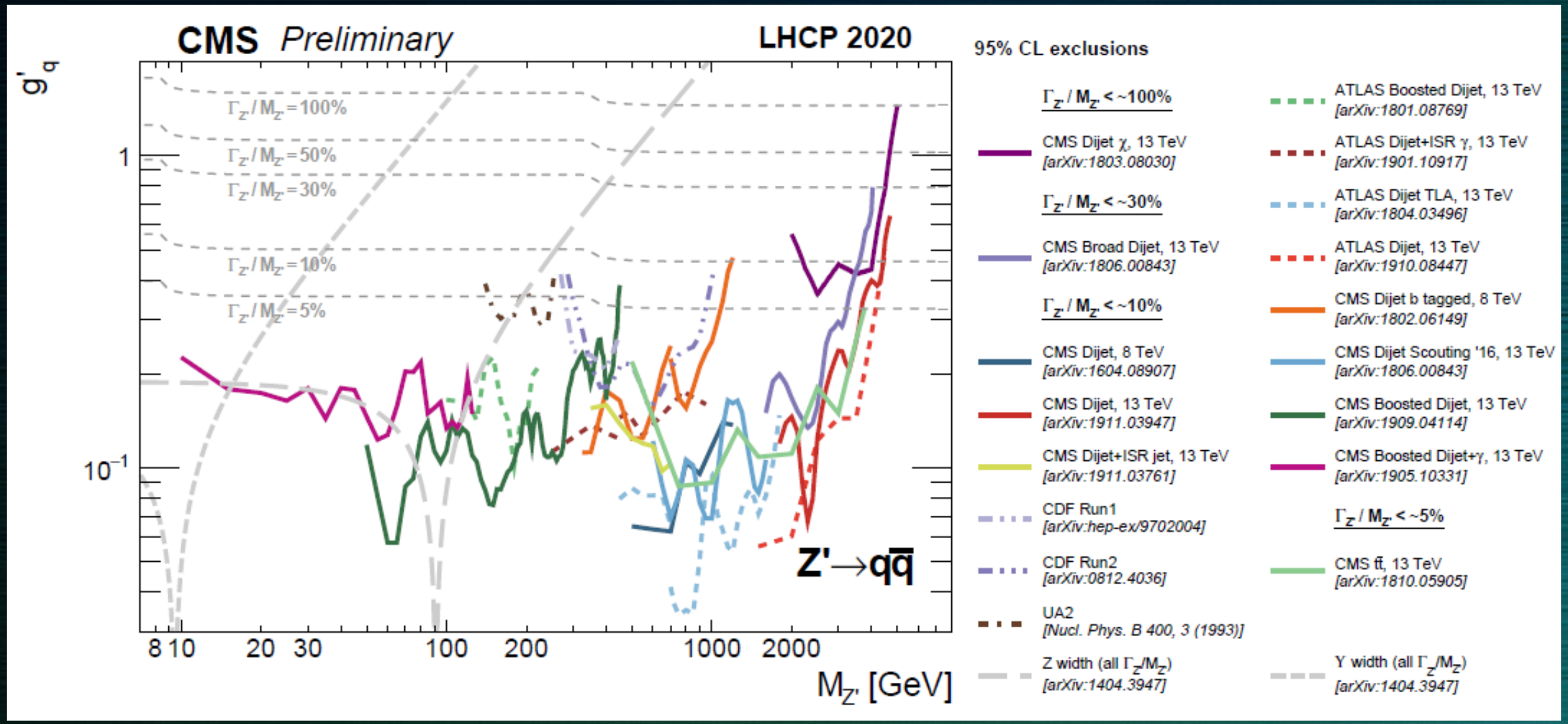
- ✓ A cross section as a function of the 3 parameters : M_{med}, g_q, g_l
- ✓ m_{DM} = 1 GeV (can differ)
- ✓ limits on g_l from DY (the V mediator): $g_l \leq 0.01$
- ✓ Universal quark coupling: $g'_q = \frac{g_B}{6}$

$$g'_q = \frac{g_q}{\sqrt{1 + 1/(3N_q(M_{med})q_q^2)}}$$

$$N_q(M_{med}) = \sum_q \left(1 - 4\frac{m_q^2}{M_{med}^2}\right)^{1/2} \left(1 + 2\frac{m_q^2}{M_{med}^2}\right)$$

General dijet results: CMS + ATLAS (also CDF, UA2, precision Z^0 and Y widths)

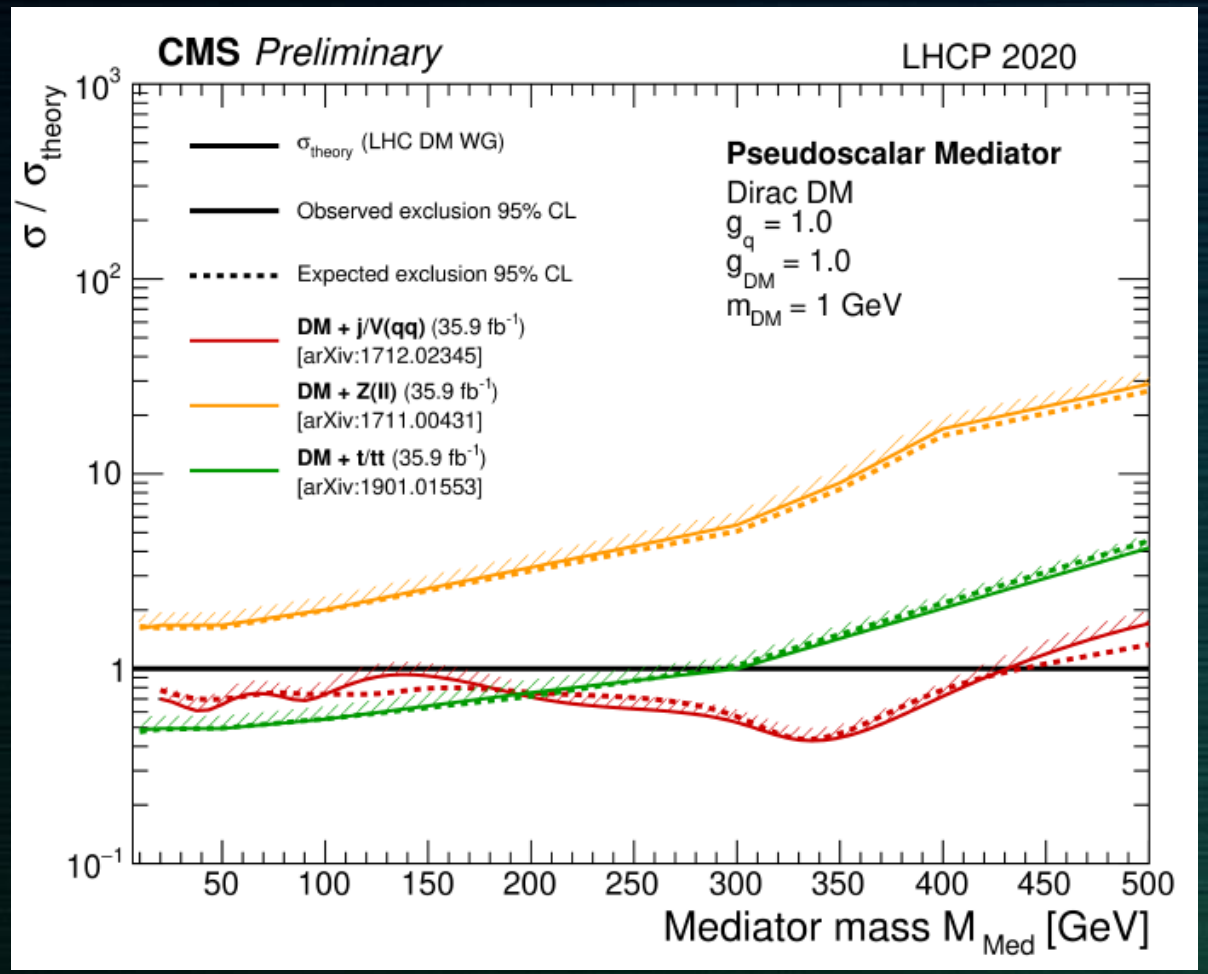
CMS EXO summary plots

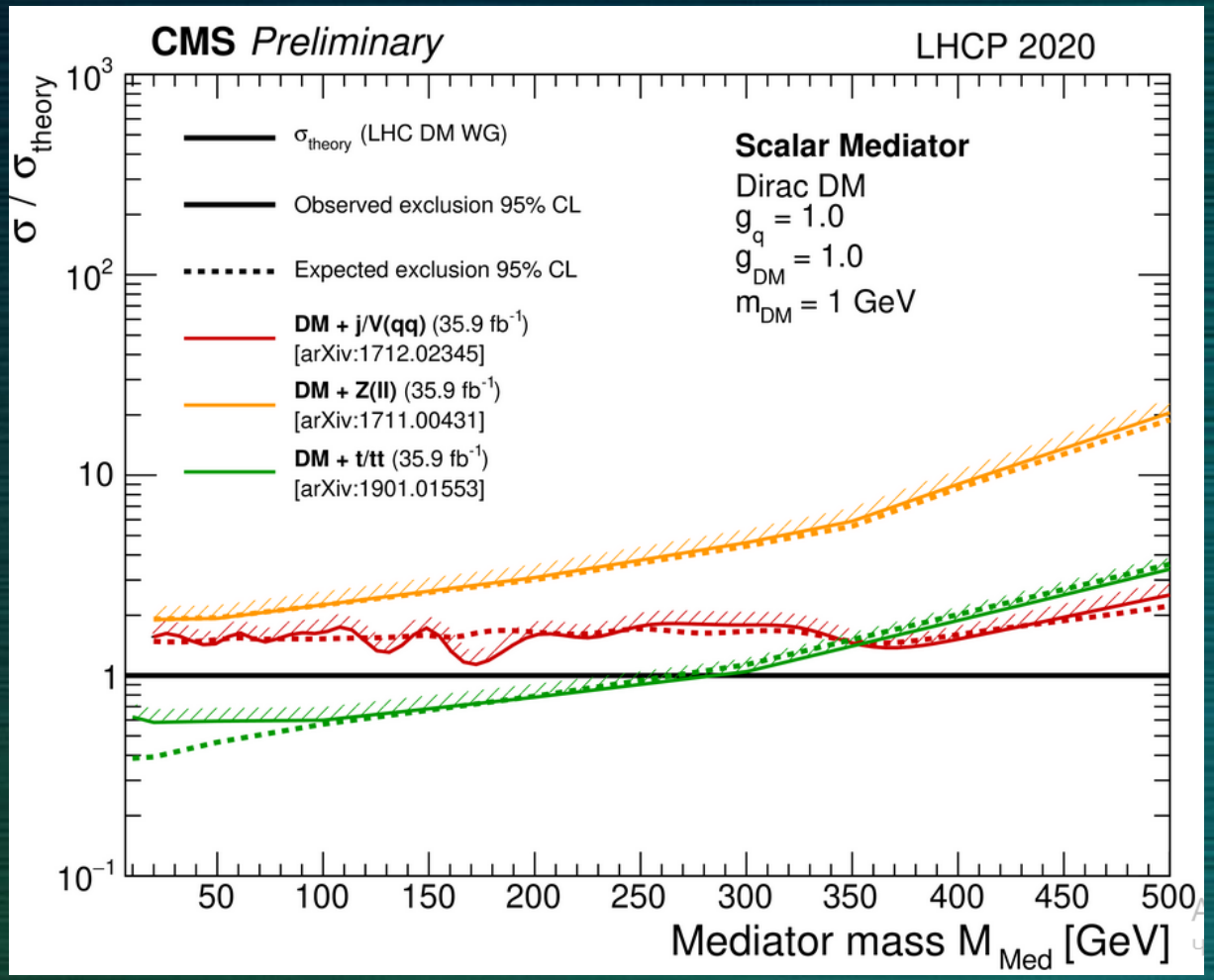


S/PS limits combined: Jet/$V(qq)/Z(ll)/t(t\bar{t})$ + E_T^{miss}

Model non-specific interpretation

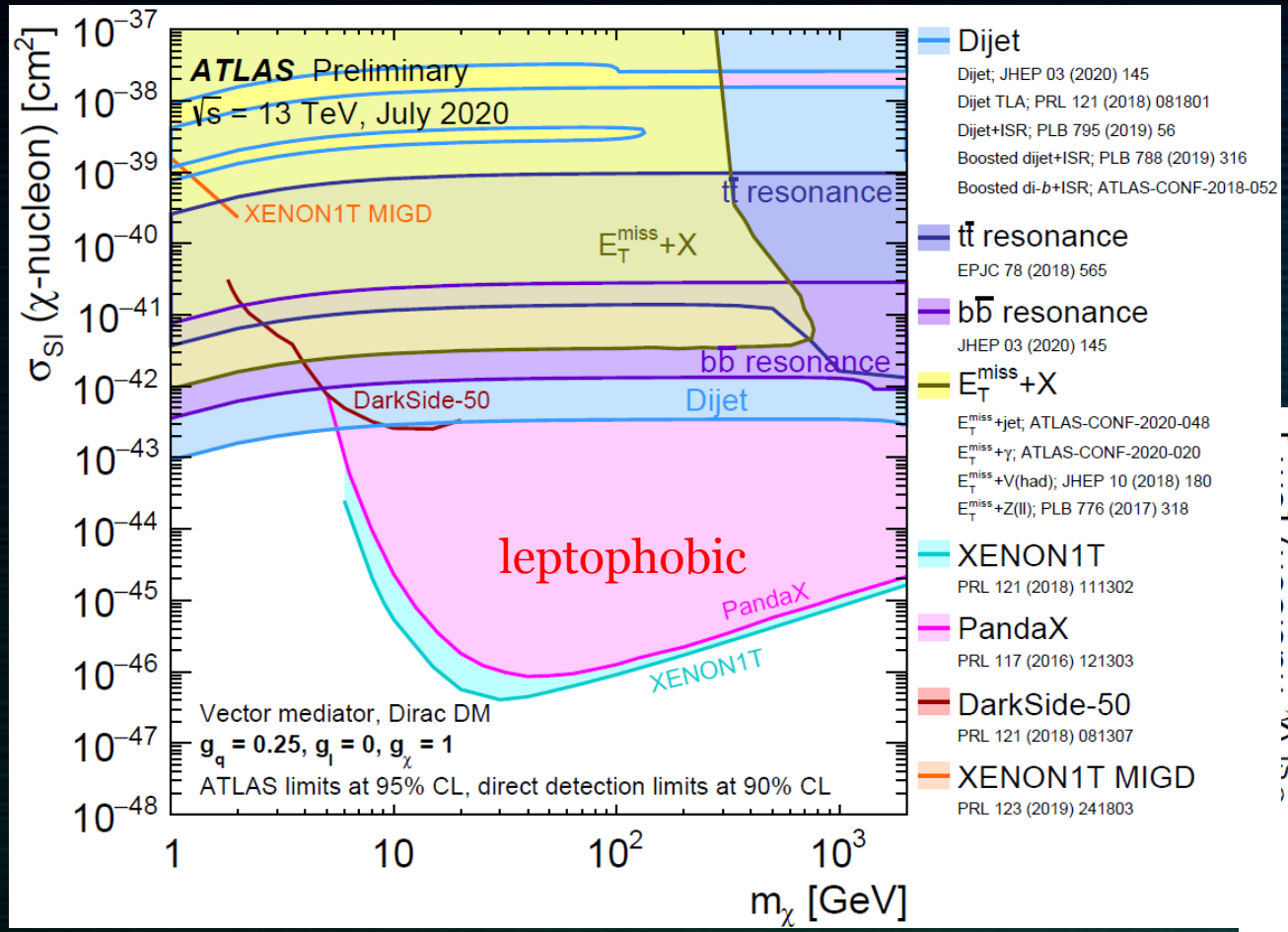
CMS EXO summary plots

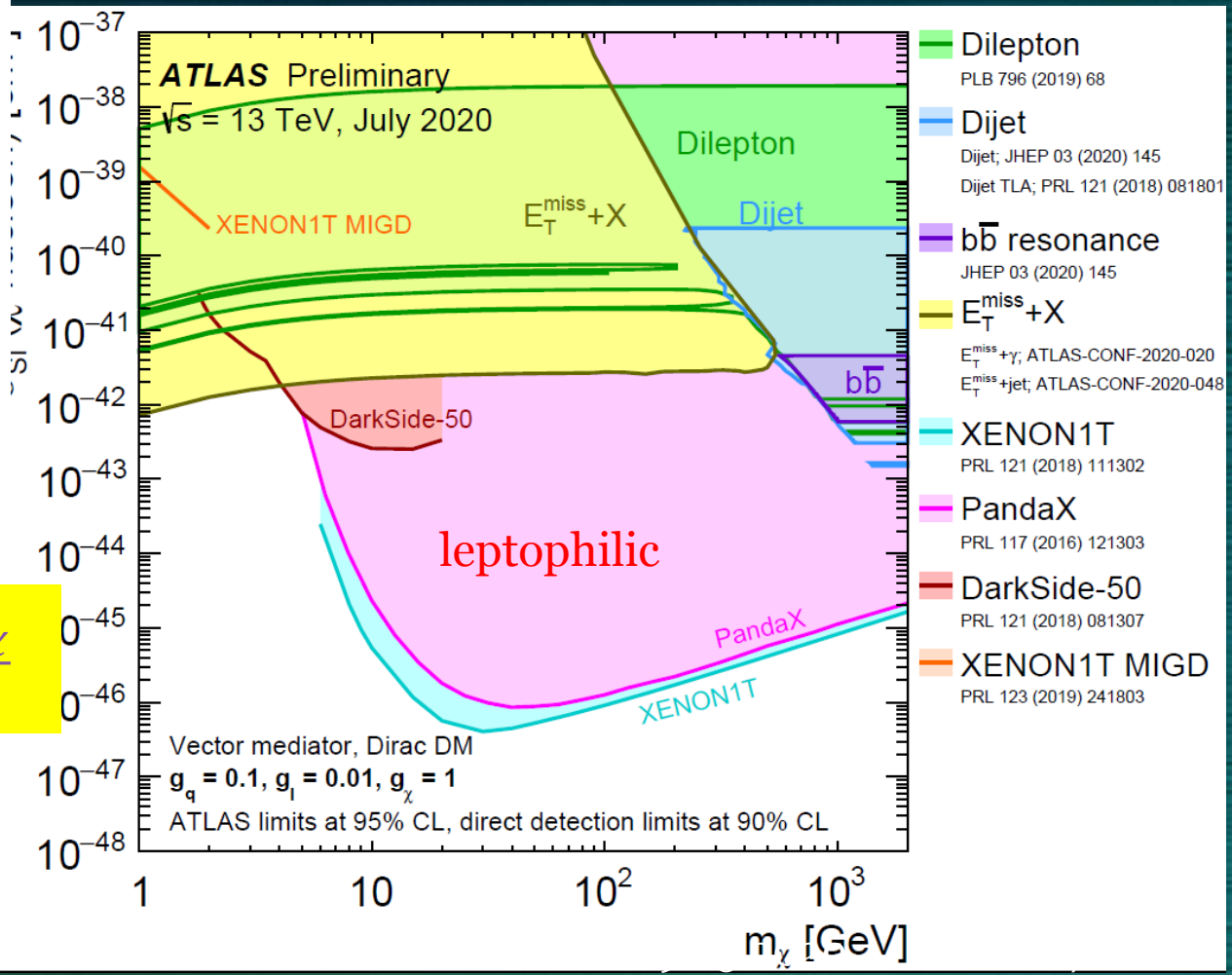




ATLAS: combination of collider and DD constraints on DM (LHCP 2020)

interpretation for the leptophobic and leptophilic V mediator, σ^{SI}





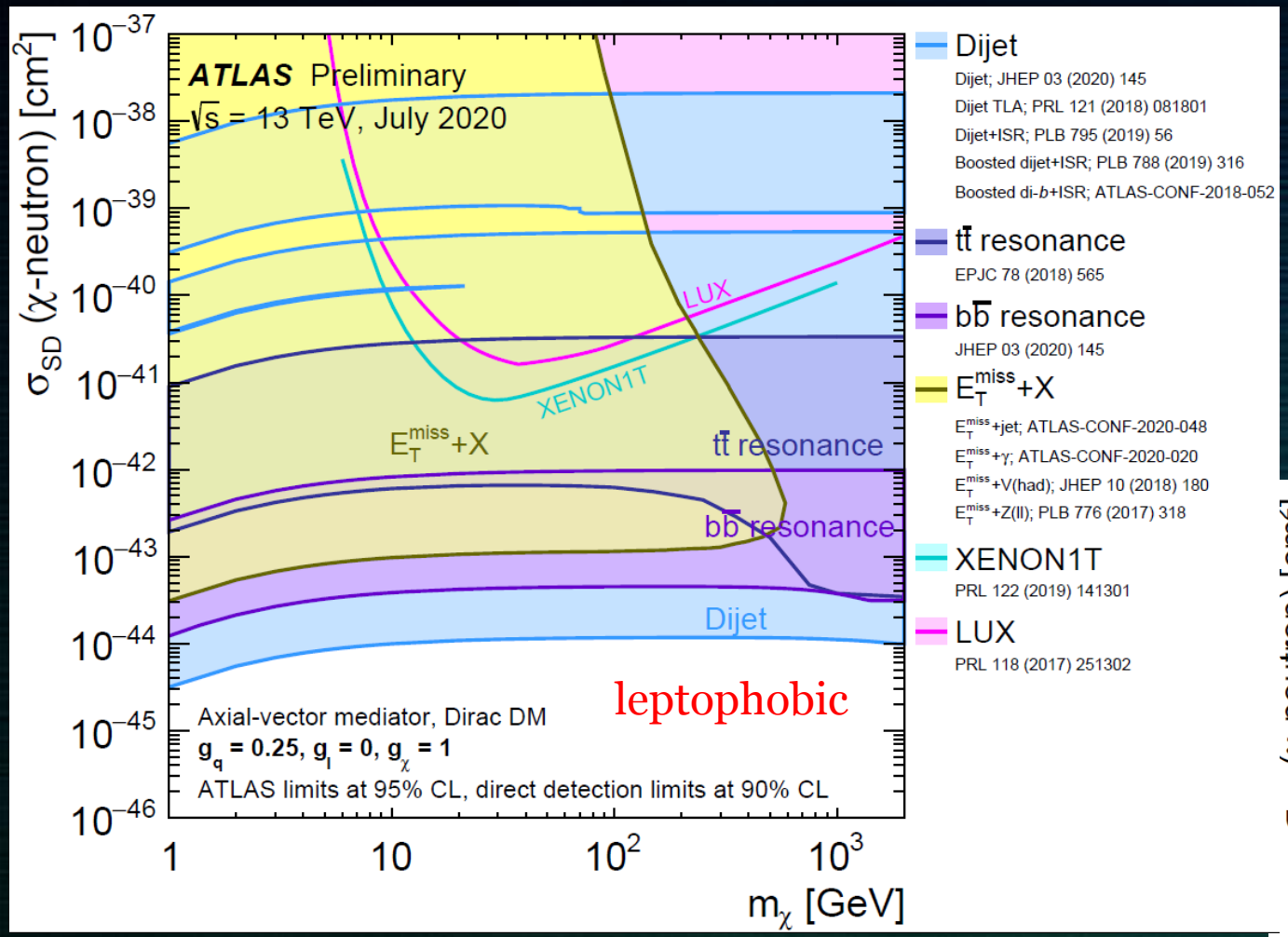
A comparison of the inferred limits with the constraints from direct-detection experiments on spin-independent WIMP-nucleon scattering cross- section

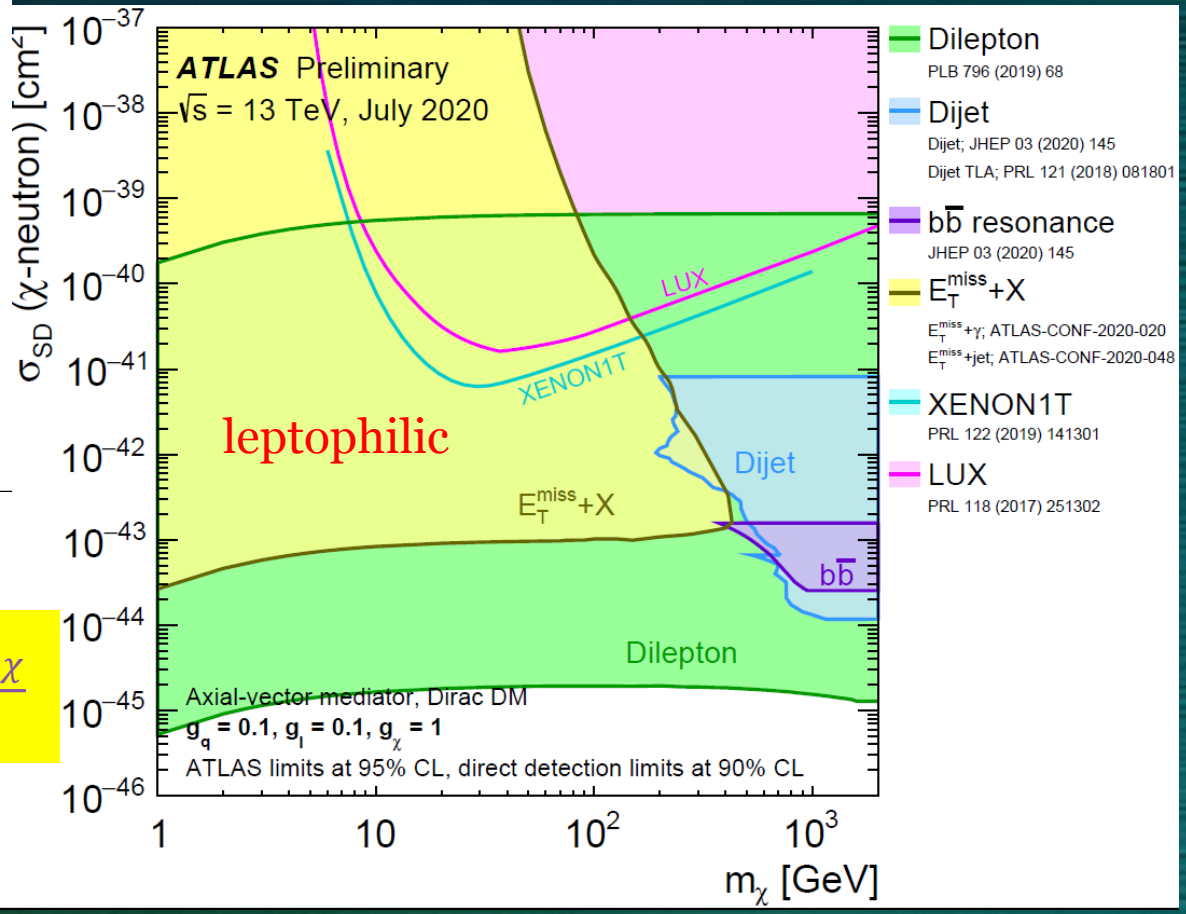
$$\sigma^{SI} = \frac{f^2(g_q) g_\chi^2 \mu_{n\chi}^2}{\pi m_{med}^4}$$

See a talk by Fady Bishara on EFT for DD experiments and collider data decoding!

ATLAS: combination of collider and DD constraints on DM (LHCP 2020)

interpretation for the leptophobic and leptophilic AV mediator, σ^{SD}





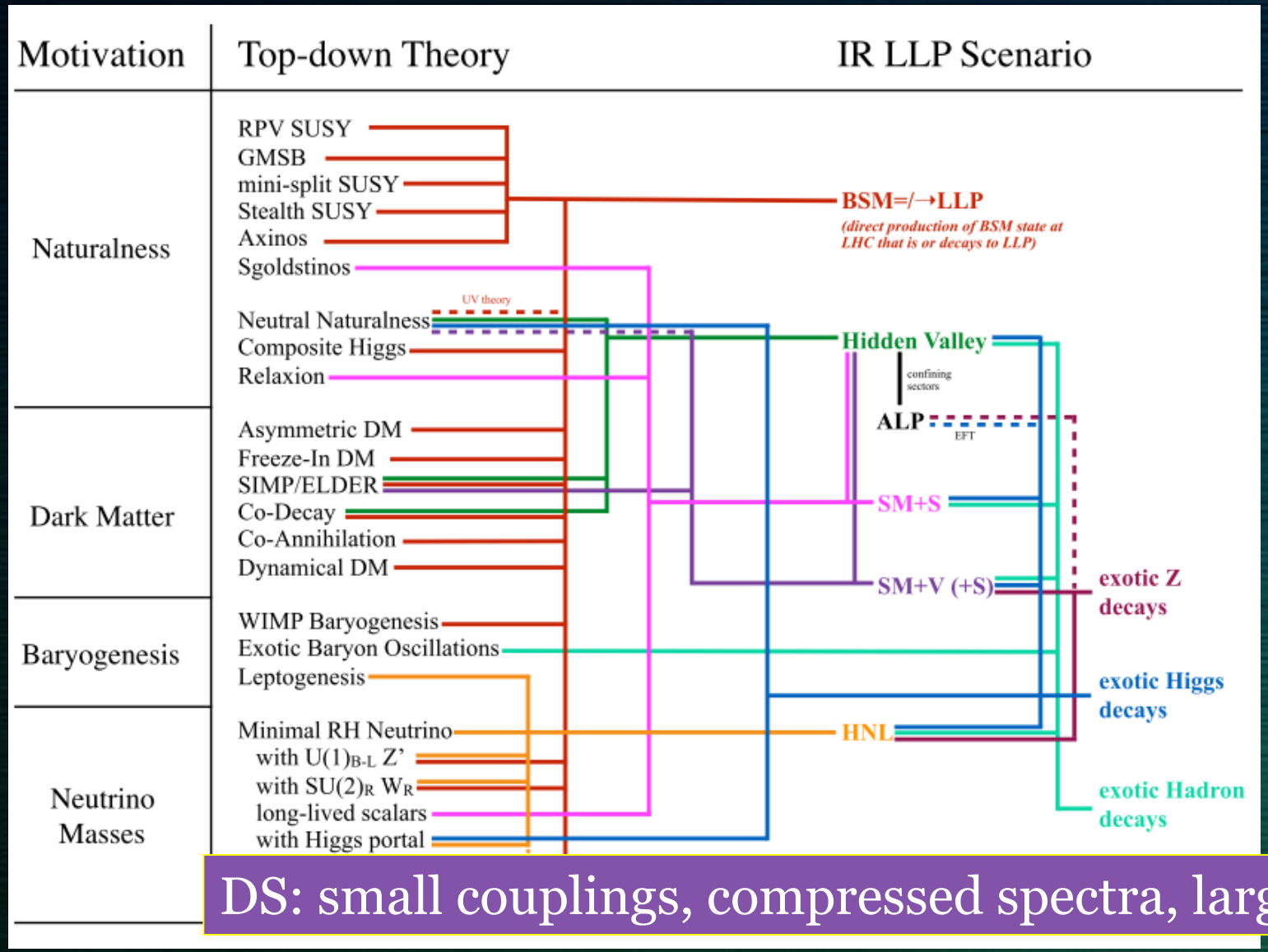
A comparison of the inferred limits with the constraints from direct-detection experiments on spin-dependent WIMP-nucleon scattering cross- section

$$\sigma^{SD} = \frac{3f^2(g_q)g_\chi^2\mu_{n\chi}^2}{\pi m_{med}^4}$$

See a talk by Fady Bishara on EFT for DD experiments and collider data decoding!

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)…

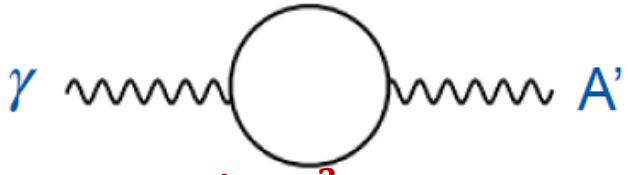
- ✓ Higgs/GB/gluon/SUSY portals

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

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

Dark photon, prompt/displaced jets

The coupling to SM particles proportional to electric charge

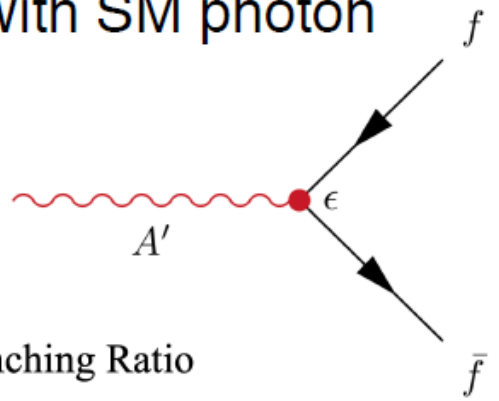


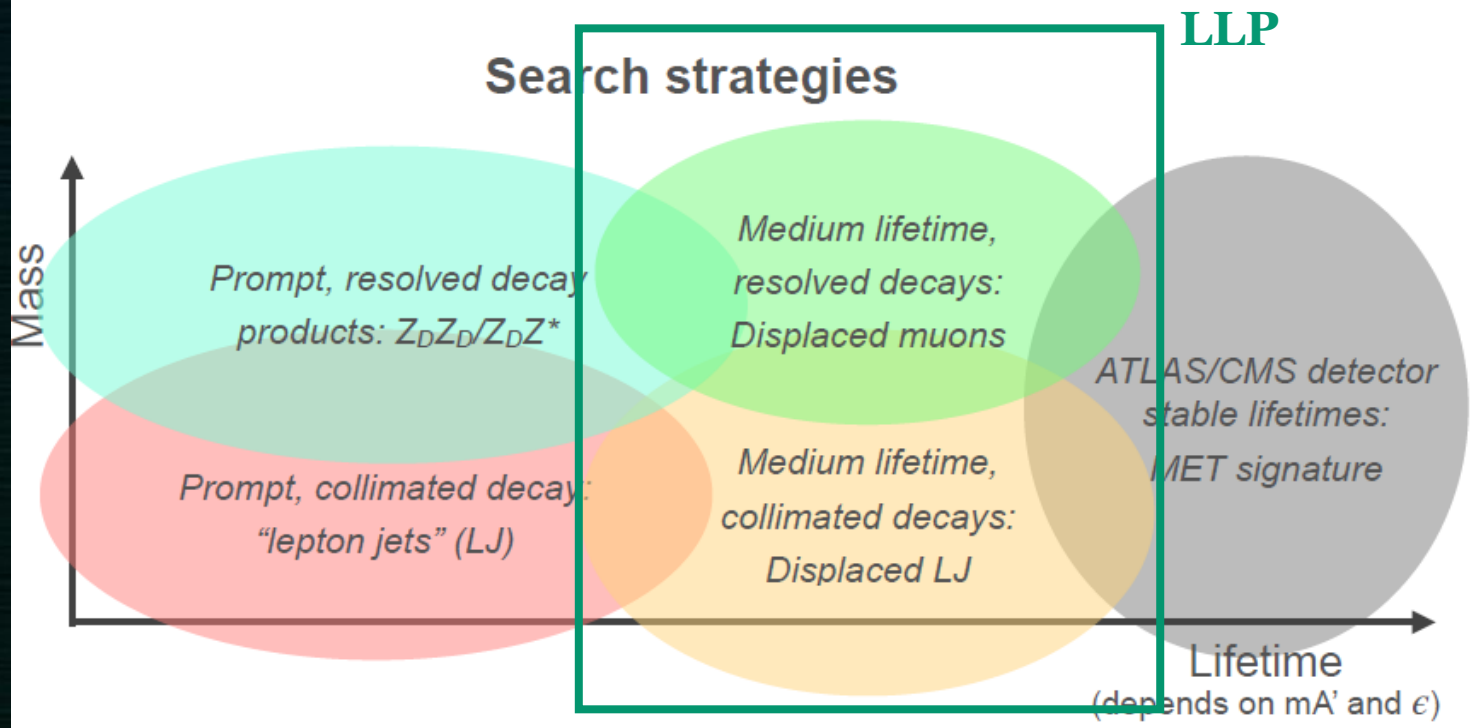
$\alpha' = \epsilon^2 \alpha_{EM}$

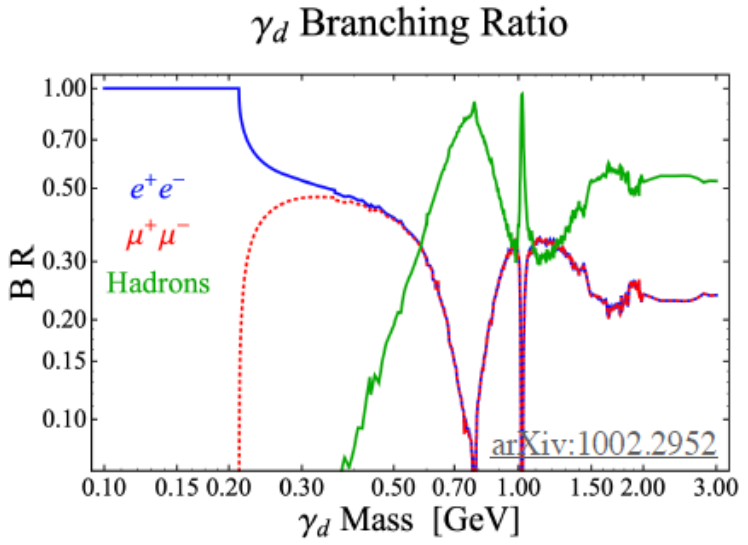
1 or 2 loops: naively $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$

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

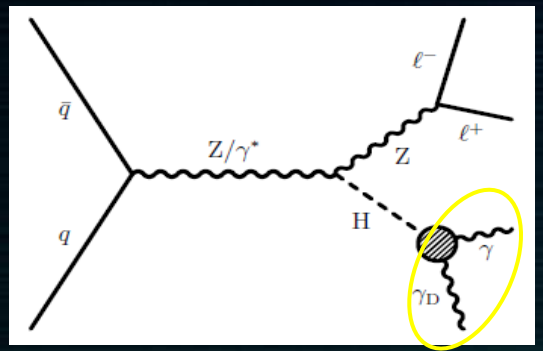
Parameters: kinetic mixing term, ϵ, and $m_{A'}$

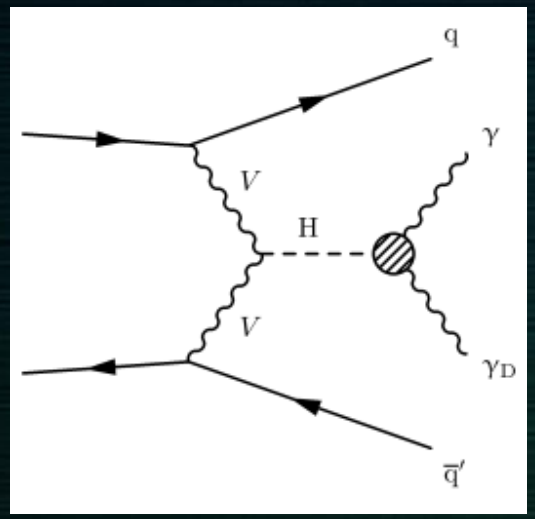


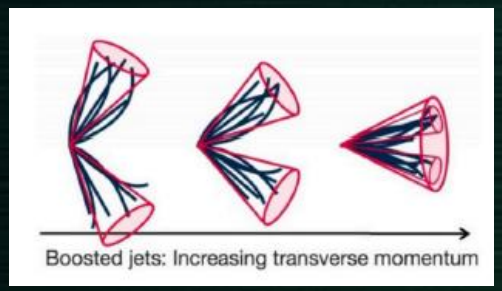




Not only LLP (1): dark photon in VBF and $Z(ll)H(\gamma\gamma_D)$

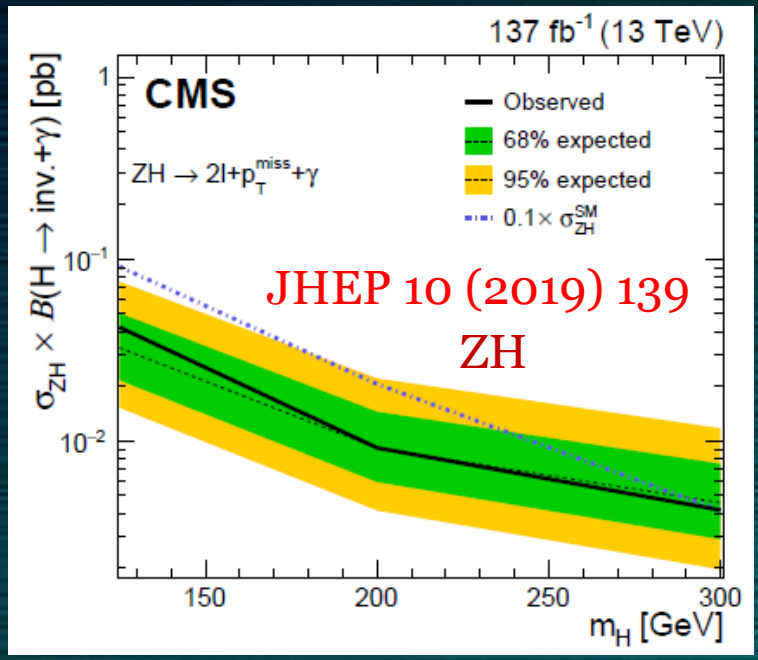


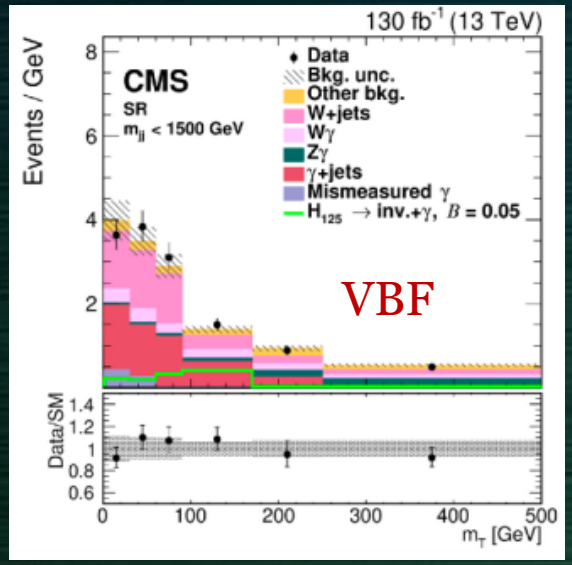


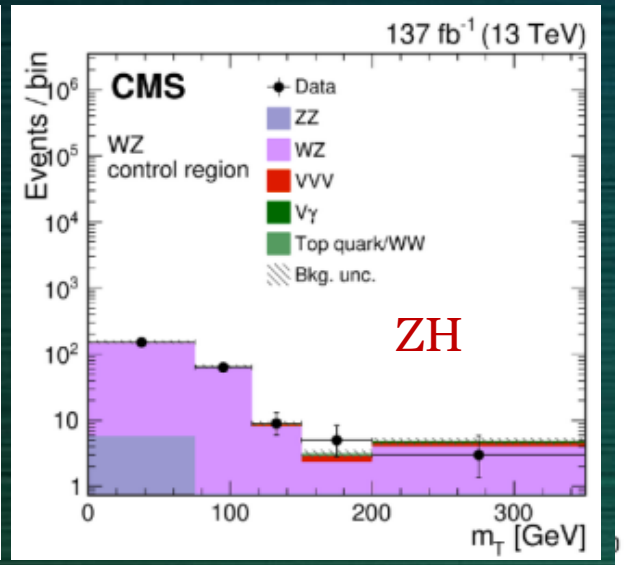


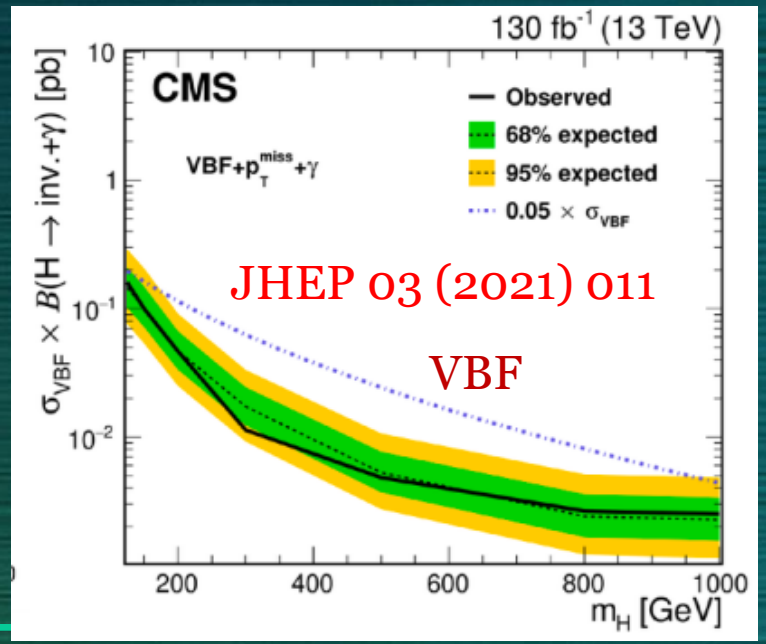
"Standard" (non-LLP) analyses:

- ✓ Prompt, resolved decay, γ + MET
- ✓ Associated ZH production and partially invisible (semi-invisible) H decay
- ✓ $\mathcal{B}(H \to invisible + \gamma) \leq 5\%$
- ✓ in SM $\mathcal{B}(H \to Z\gamma \to \nu\bar{\nu}\gamma) = 3 \times 10^{-4}$
- ✓ Bckgr. from WZ, ZZ, WW, t





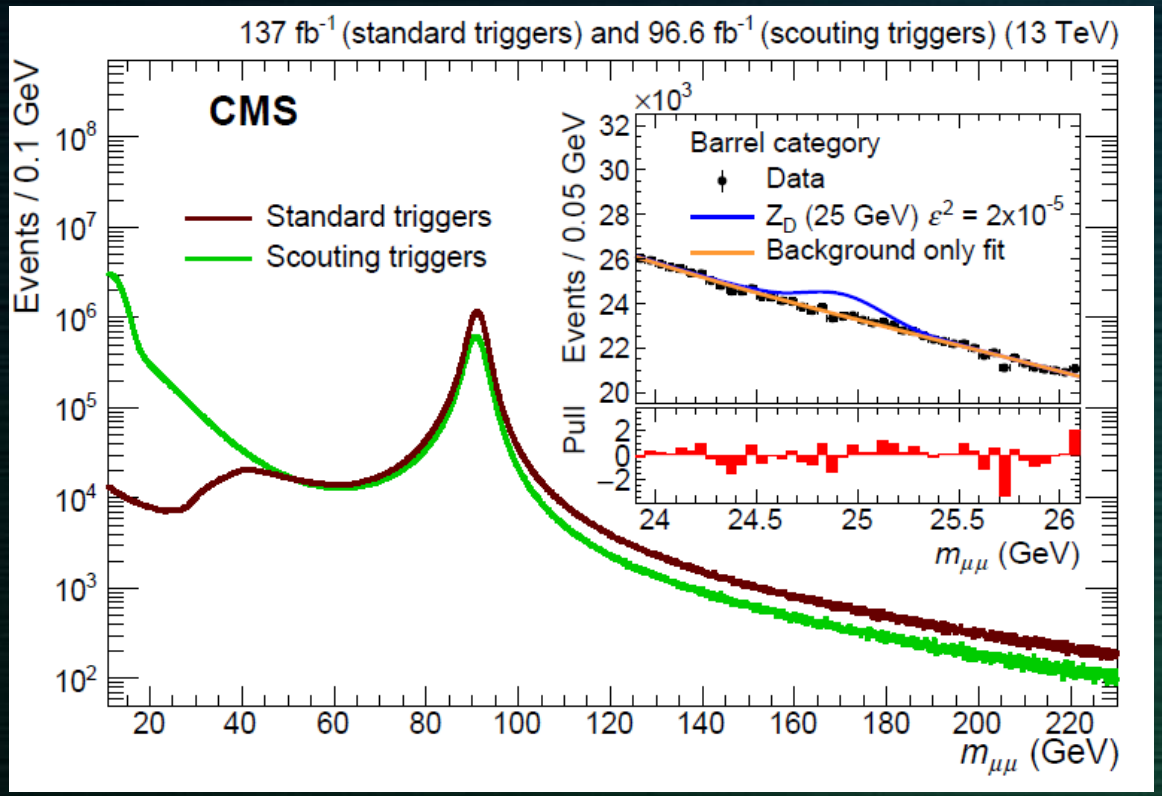


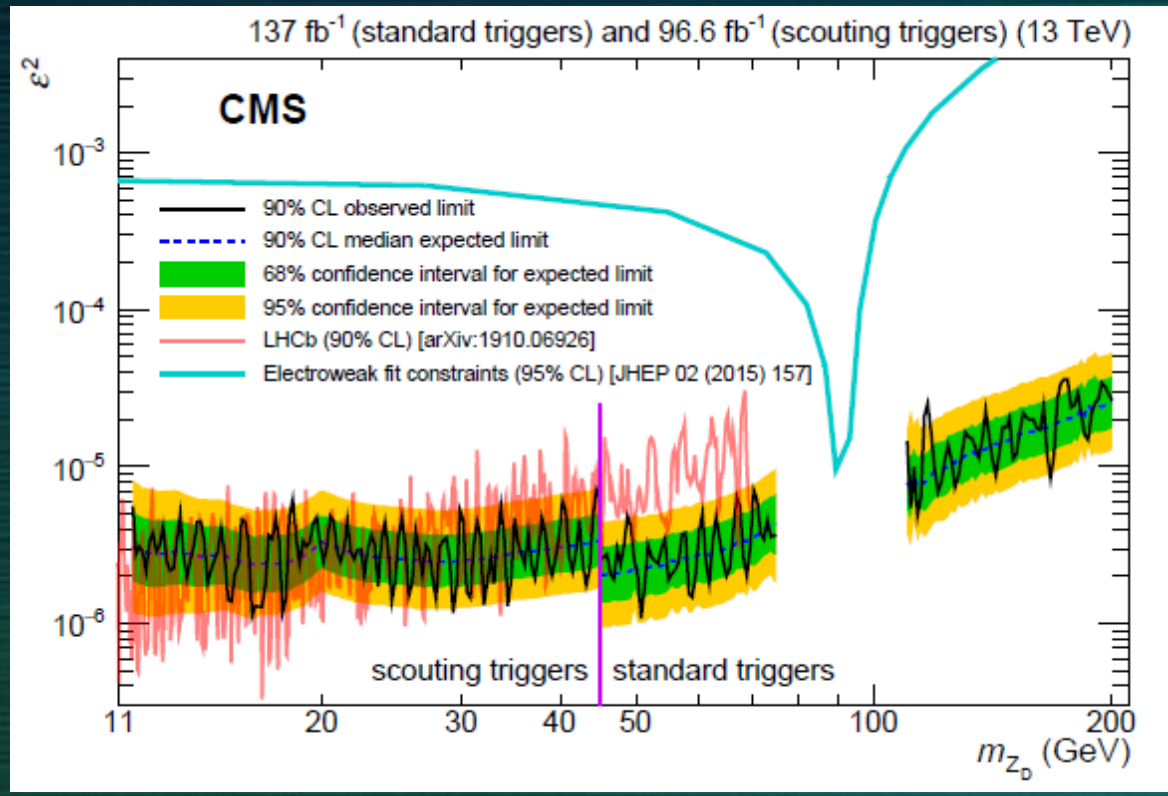


Not only LLP (2): light narrow vector resonance Z_D -> $\mu\mu$

$U(1)_D \times U(1)_Y$, mixing in a gauge sector with a parameter ε: $\mathcal{L}_{gauge\ mixing} = \frac{\varepsilon}{2} B_{\mu\nu} b^{\mu\nu}$

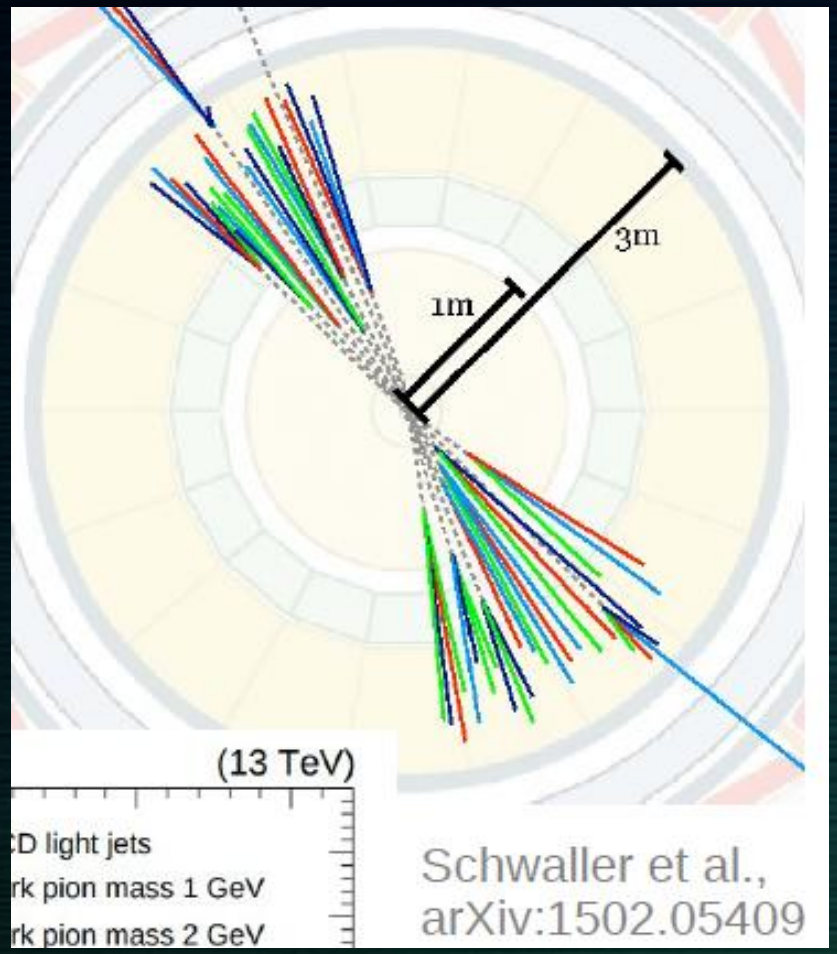
- ✓ Search for new light spin-1 resonance Z_D produced on the LHC via mixing with ordinary SM weak bosons.
- ✓ Prompt, collimated decay, LJ





Phys. Rev. Lett. 124, 131802 (2020)

Emerging jets/dark showers



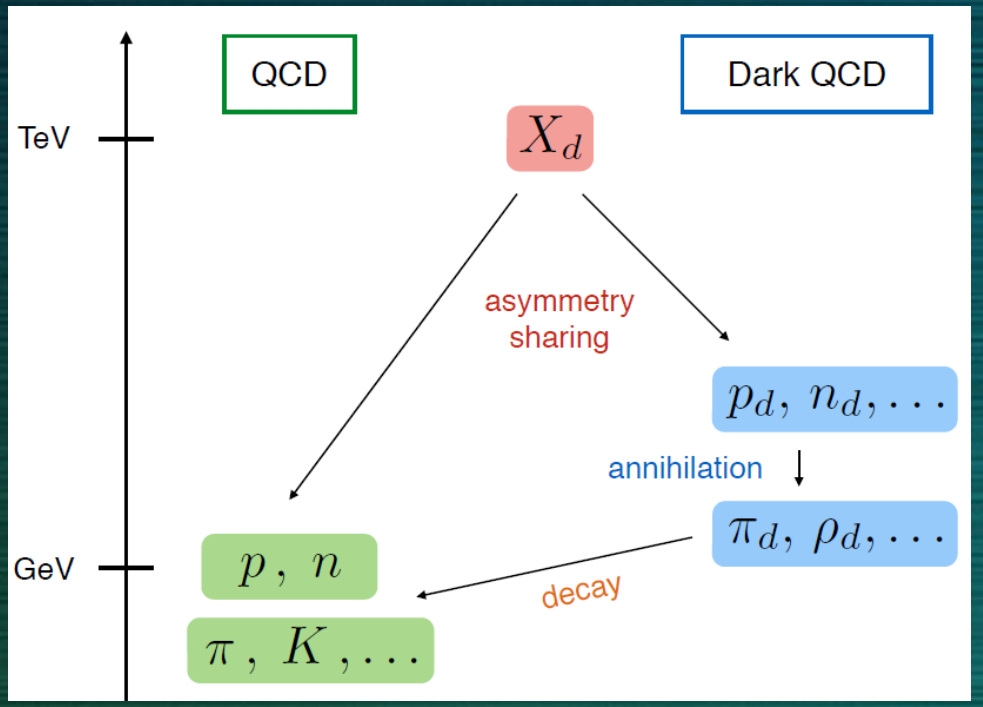
Dark QCD

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

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

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

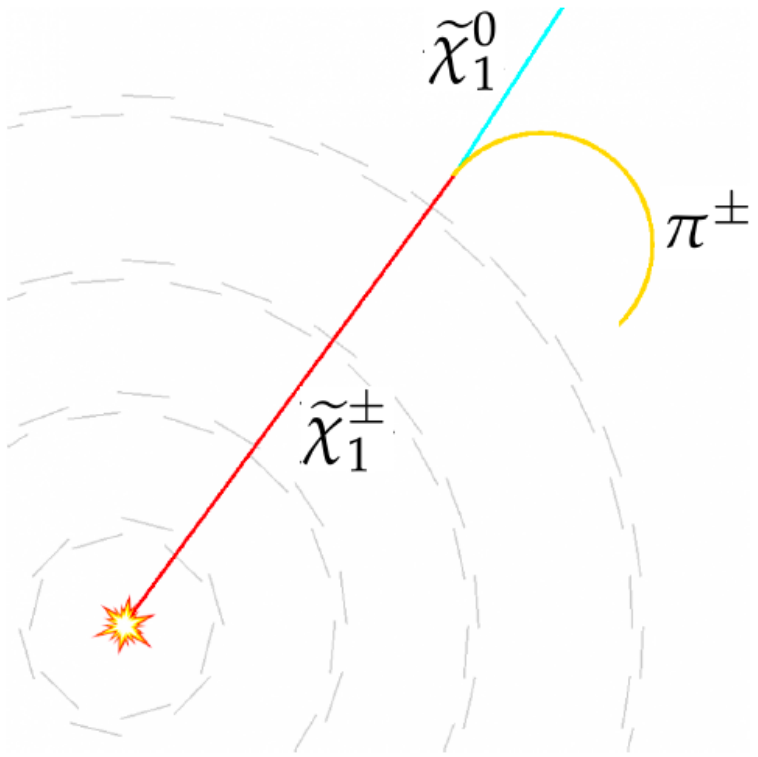
M_q: quark mass matrix



- ✓ 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

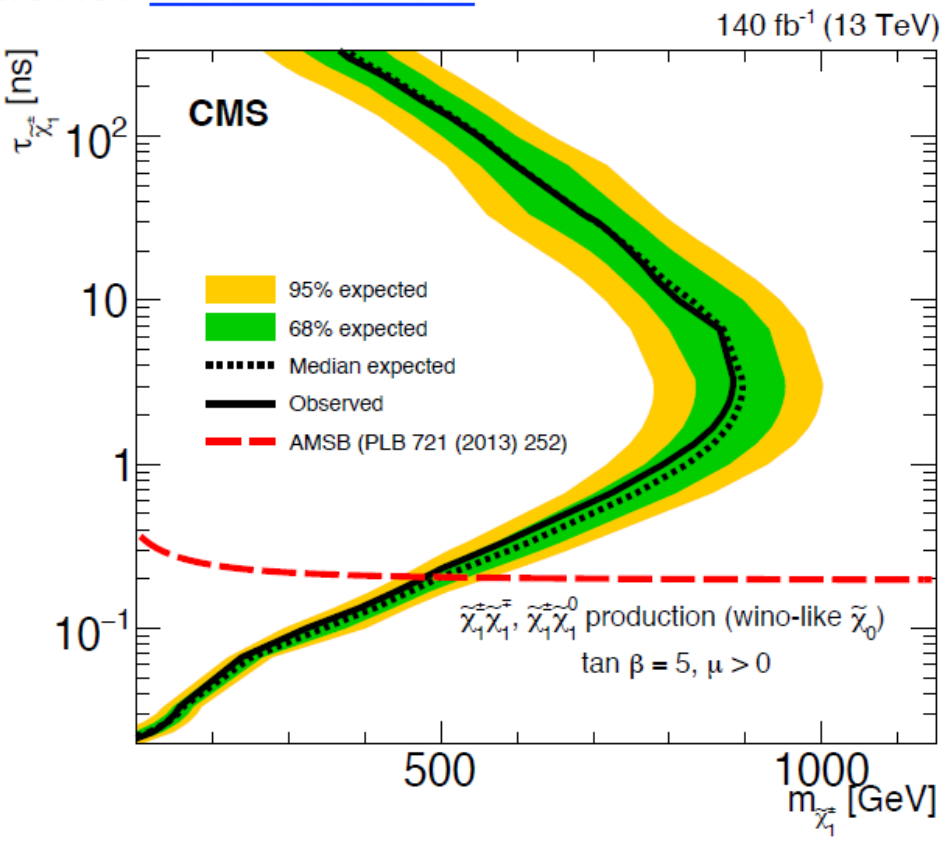
Disappearing tracks

Disappearing Tracks: 2004.05153



Distinct signature!

Arises naturally in AMSB and compressed SUSY scenarios with $\mathcal{O}$(100 MeV) splittings



Charginos excluded for pure $\tilde{W}$ LSP scenarios up to 474 GeV and 0.2 ns (175 GeV and 0.05 ns for $\tilde{H}$ LSP)

LLP7 slides from B. Francis