SEARCH FOR DARK SECTOR STATES AT THE LHC

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On the behalf of ATLAS and CMS Collaborations

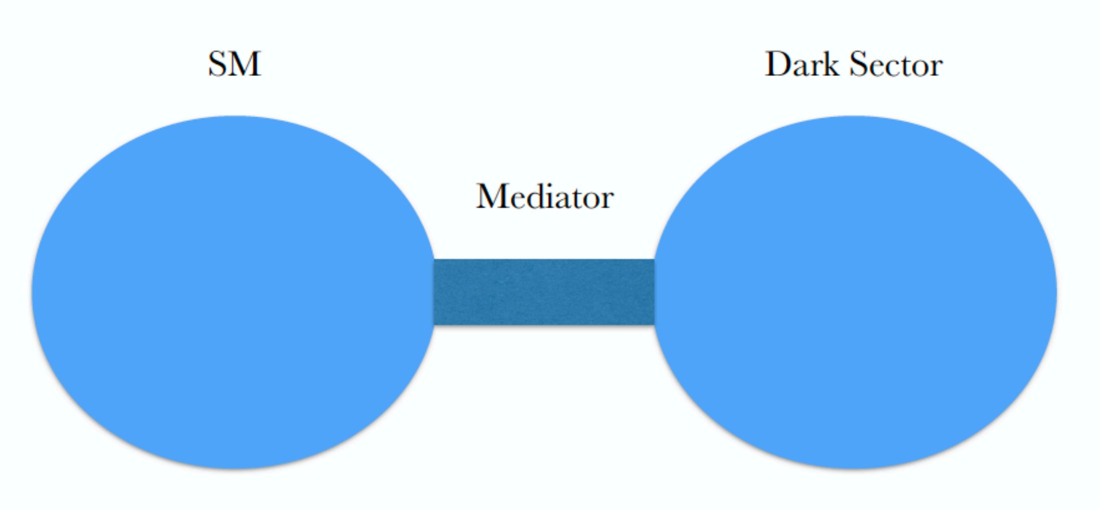
Outline

- Dark Sector States (DS)
- DS → Visible SM particles
- DS → Invisible
- SM Particles → Invisible DS
- Dark matter searches and interpretations

The supersymmetric sector of SUSY is a prime example for a dark sector

Dark Sector

- Dark Sector as "New Physics" beyond the SM



Need new force / interaction
to connect SM to Dark Sector

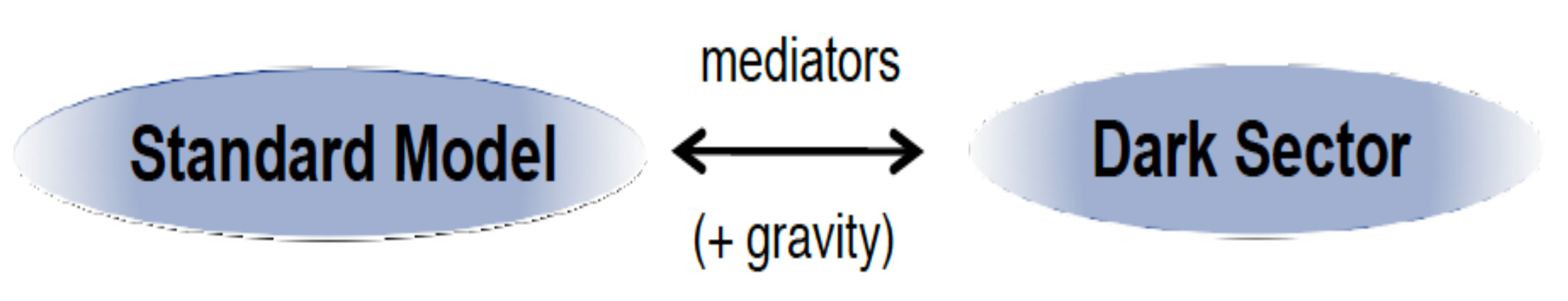
Dark Matter could just be one example of Dark Sector State

- A hidden or dark sector can be introduced with an additional U(1)d dark gauge symmetry
  - *The dark sector could couple to the SM through kinetic mixing with the hypercharge gauge boson*
- Exotic Higgs boson decays have been proposed as a way to search for evidence of new physics
  - *In the decay of the discovered Higgs boson*
  - *To measure the coupling strengths between the SM and the dark sector*
- Such decays predicted in many extensions to the SM to explain
  - *Muon g-2 discrepancy*
  - *Astrophysical observation of positron excess*

ATLAS / CMS Exotics and SUSY results include many Dark Matter searches

Minimal Interactions

- Symmetries of the SM restrict interactions with Dark Sector States



$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j$$

Vector portal [Okun; Galison & Manohar; Holdom; Foot et al]

Higgs portal [Patt & Wilczek]

Neutrino portal

$$+ \frac{1}{f_a} \left(\mathrm{tr}(G\tilde{G}) + c_F F\tilde{F} \right) a + \mathcal{O}(\mathrm{dim} \geq 5)$$

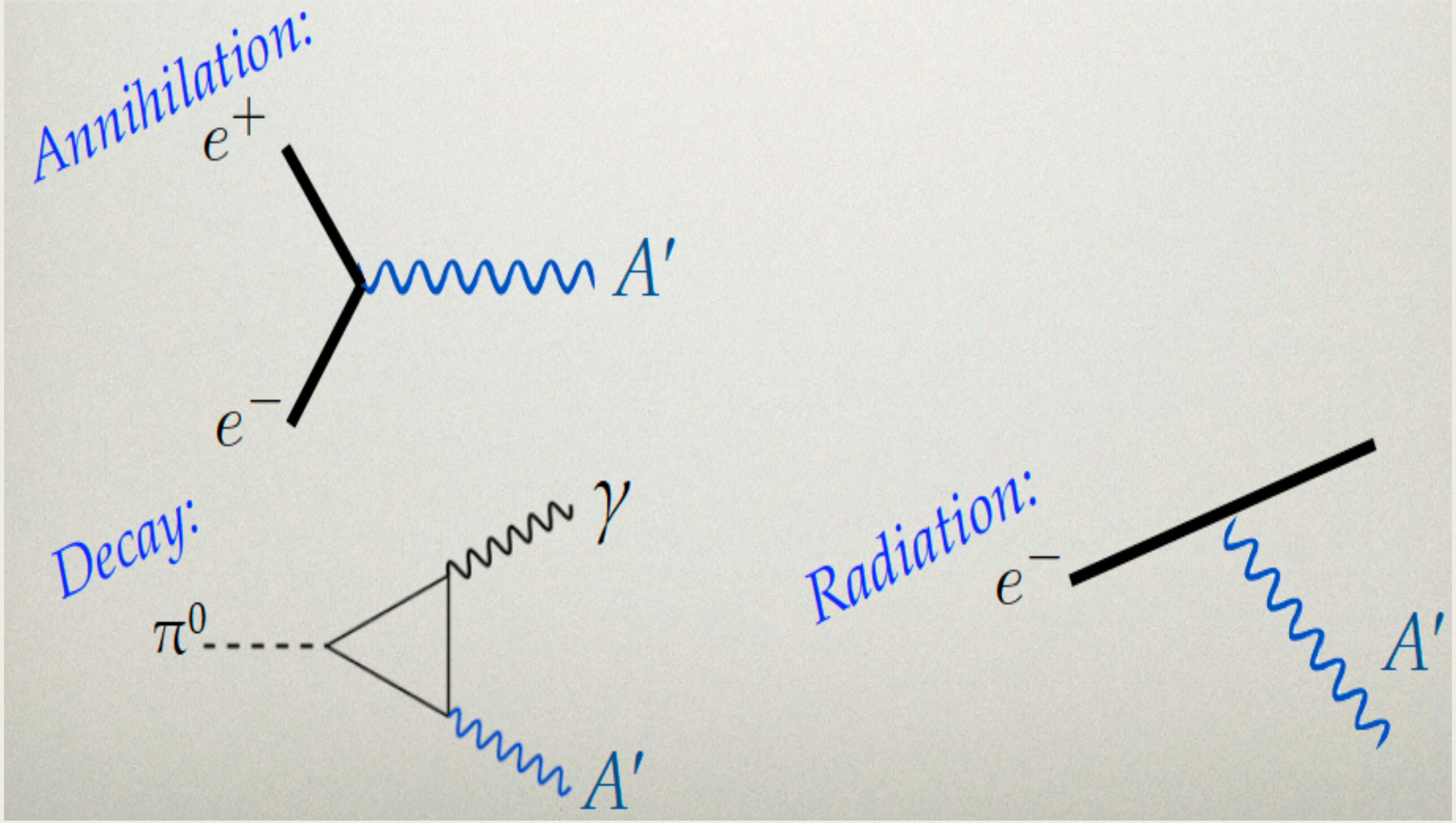
Axion portal [Weinberg, Wilczek, KSVZ, DFSZ]

Vector Portal:

Min. Lagrangian =
SM Lagrangian
+ Dark QED
+ "Kinetic Mixing (ε)"

Dark Photon Production

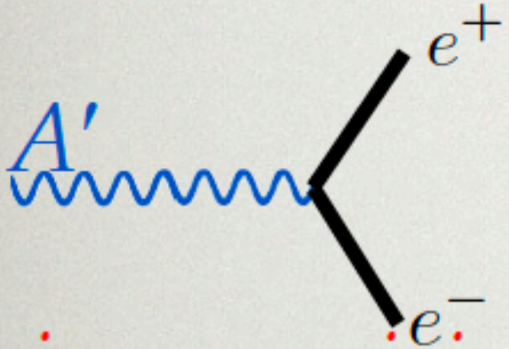
- **Kinetic mixing gives matter of electric charge qe an A' coupling $\propto q\varepsilon e$**



Dark Photon Decays

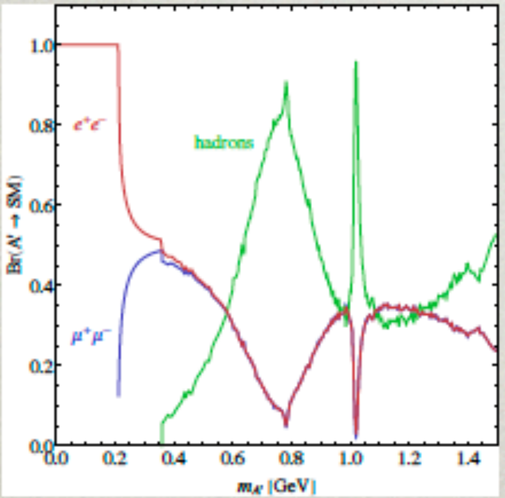
- **Kinetic mixing gives matter of electric charge qe an A' coupling $\propto q\varepsilon e$**

"Minimal" Decay:

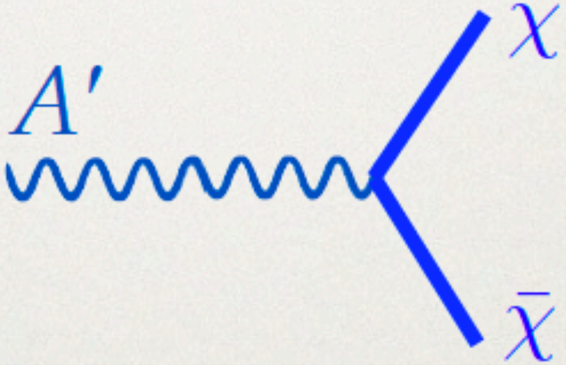


via same mixing operator as production ⇒ tiny width

$$\Gamma \sim \epsilon^2 \alpha m_{A'}$$



"Generic" Decay:



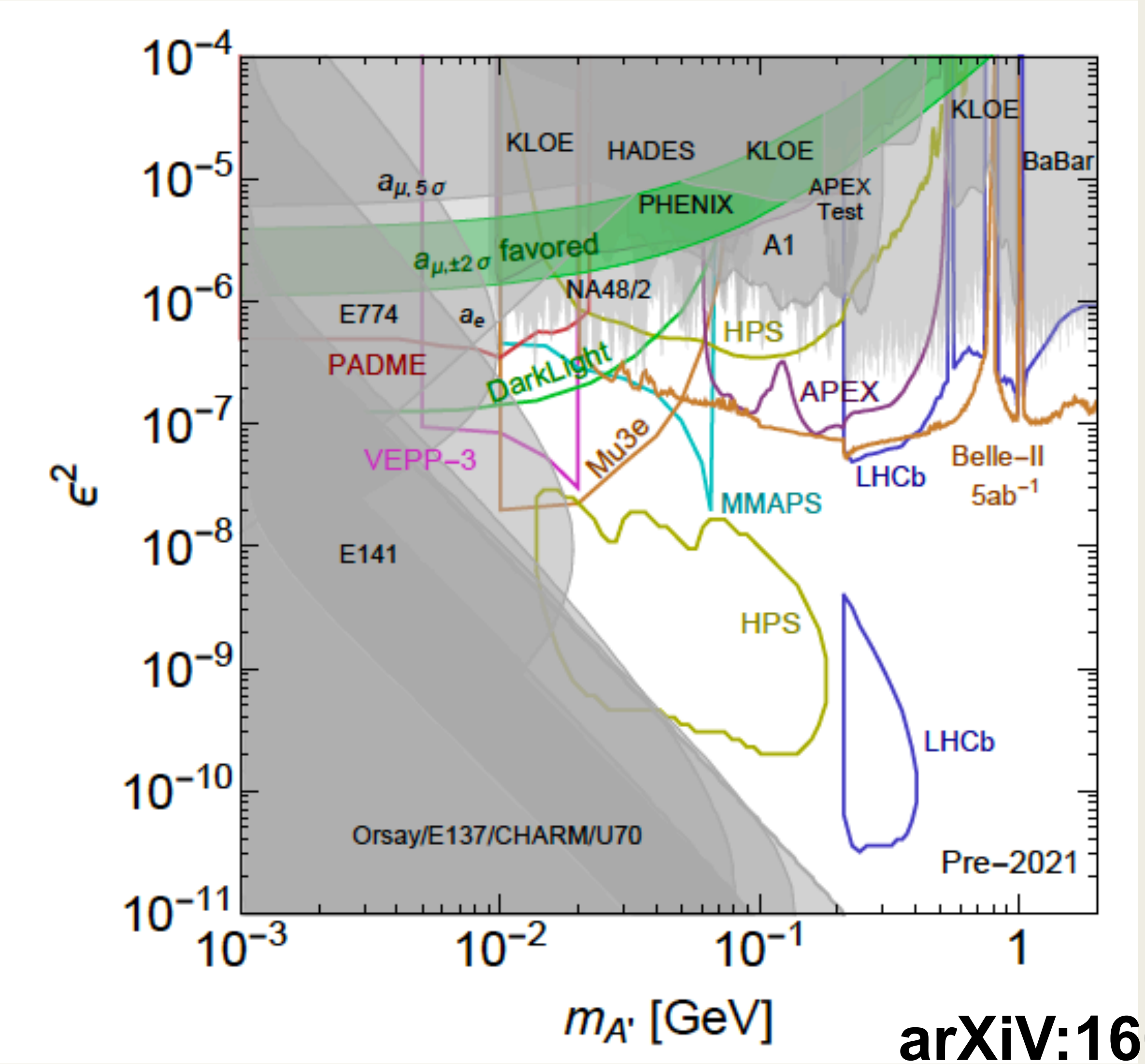
(not ε-supressed!)

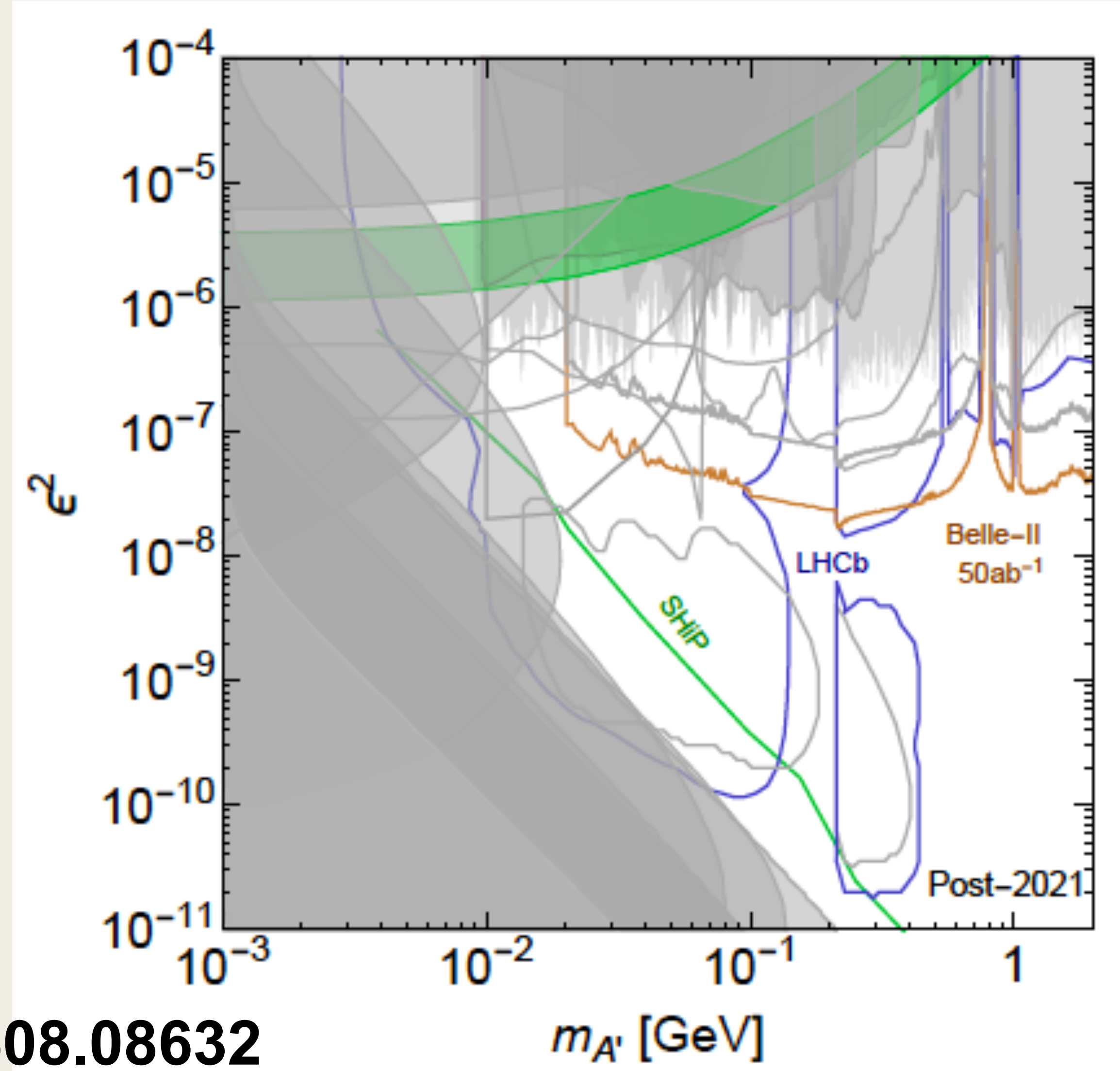
*If **any** dark-sector matter χ has $m_\chi < 2m_{A'}$, this decay dominates*

Two cases:
- χ stable & invisible
- χ decays into SM particles, A'→ >2 charged particles

searches at BaBar and KLOE

Kinetic Mixing – for experiments seeking $A' \rightarrow ll$



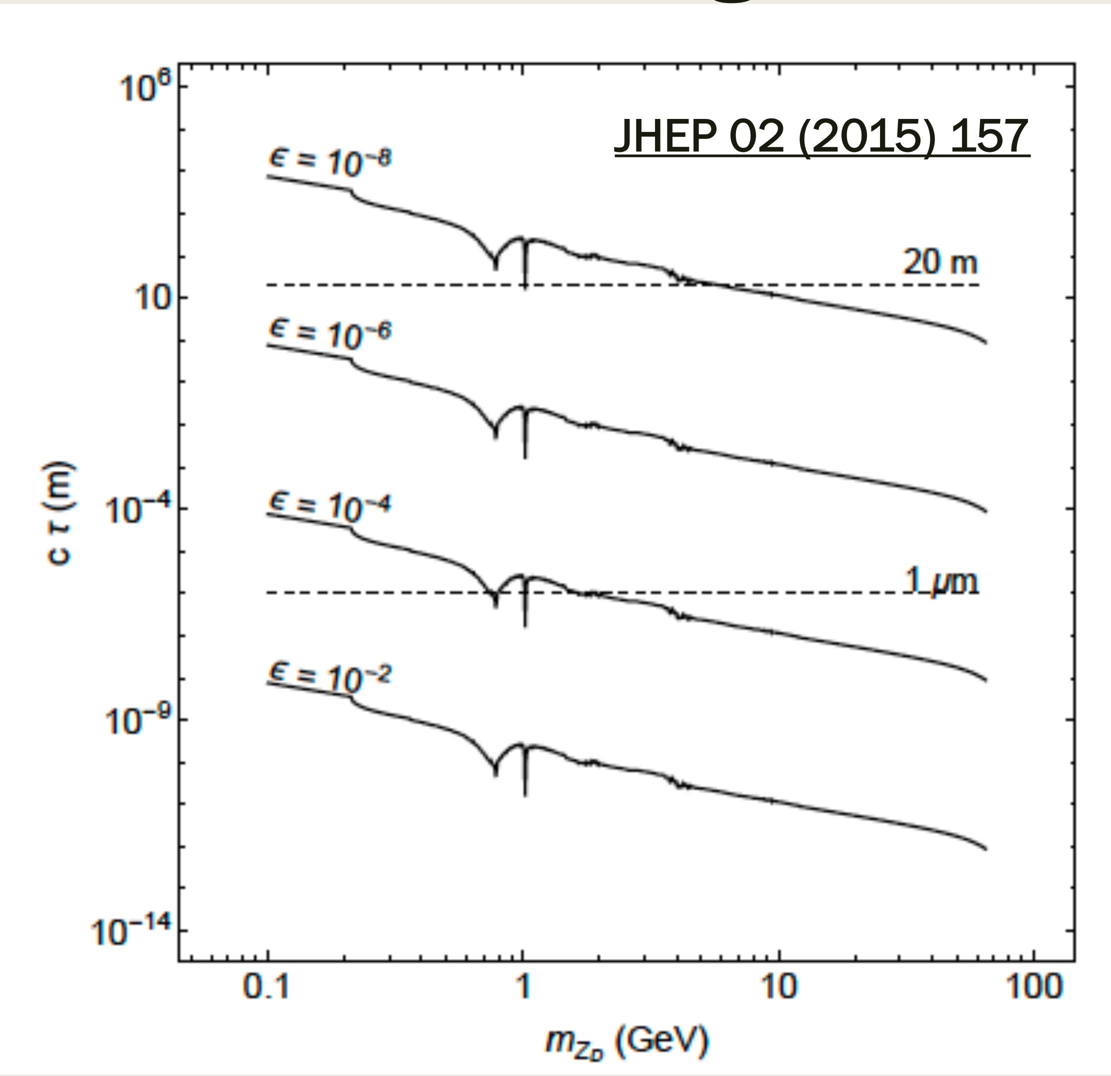


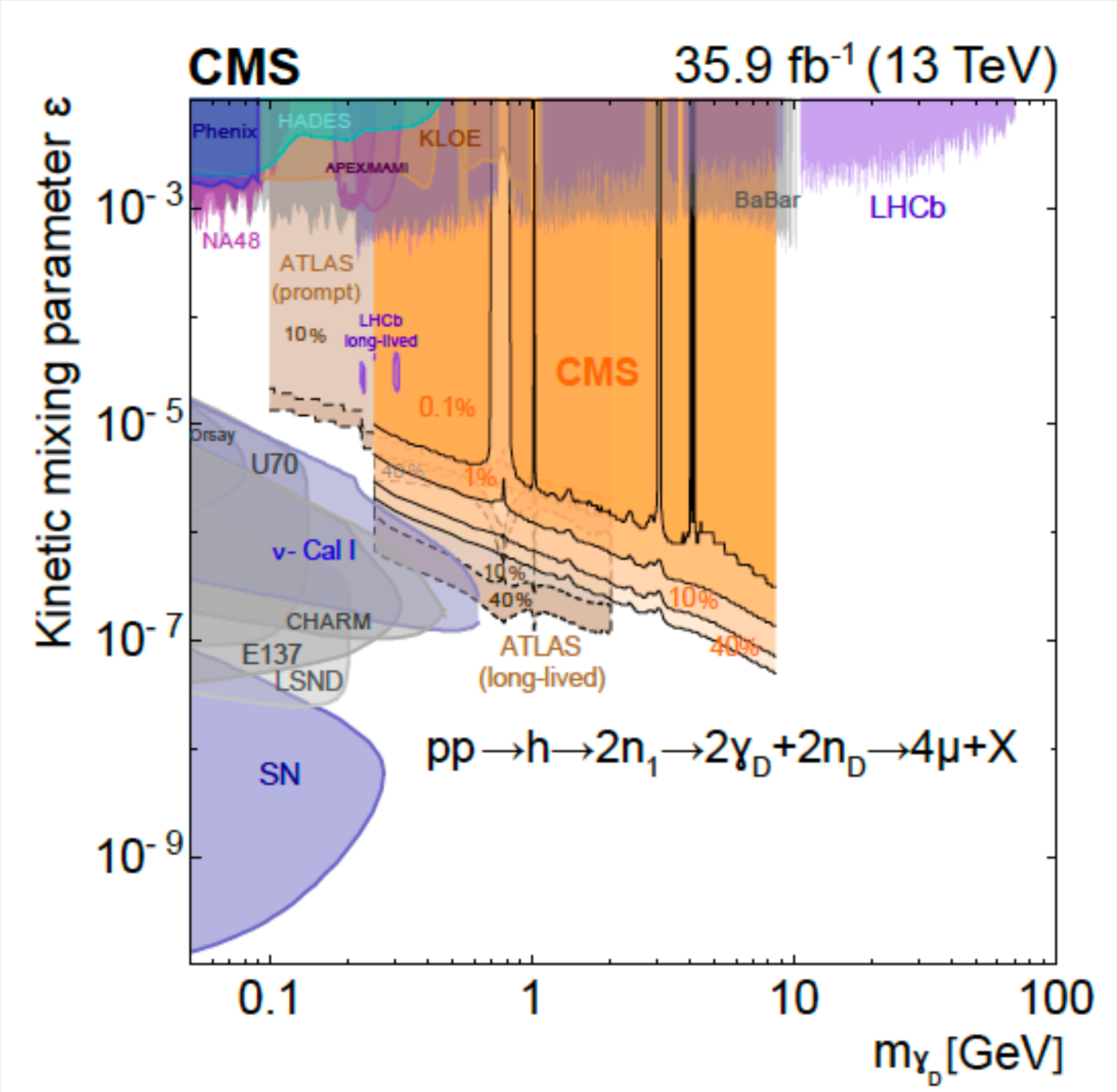
arXiV:1608.08632

Previous constraints

Projections

Kinetic Mixing – ATLAS / CMS Bounds





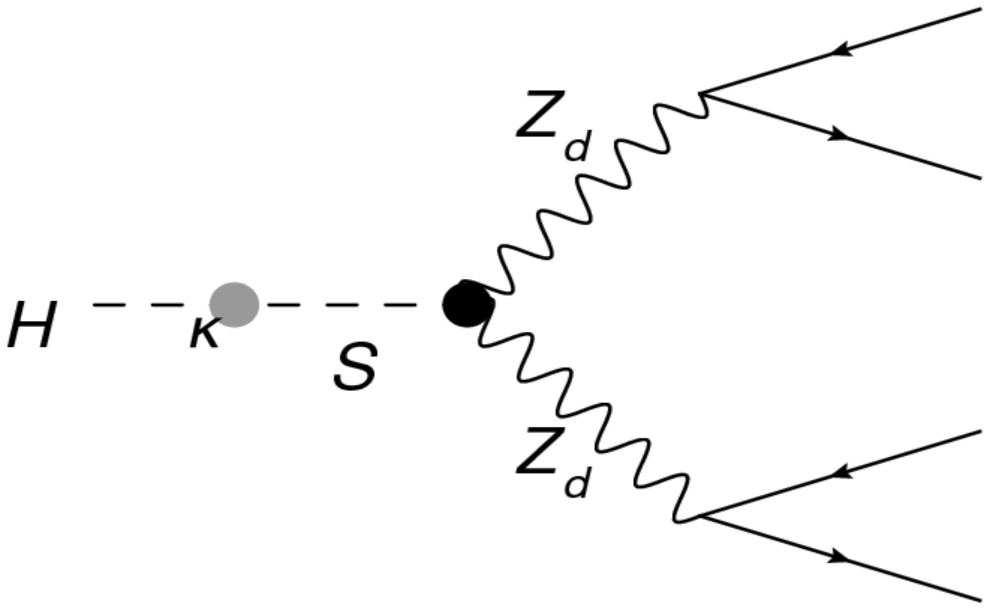
Dark Photon may be prompt or long lived depending of ε and its mass

Phys. Lett. B 796 (2019) 131

The Higgs Portal

Phys. Rev. D 90, 075004 (2014)

$\epsilon_h \, |h|^2 |\phi|^2$ exotic rare Higgs decays
rare meson decays



- If, the U(1)d symmetry is broken by the introduction of a dark Higgs boson, then there could also be a mixing between the SM Higgs boson (H) and the dark sector Higgs boson (S)

Dark Photon (A'), or Dark Z (Zd) same thing …

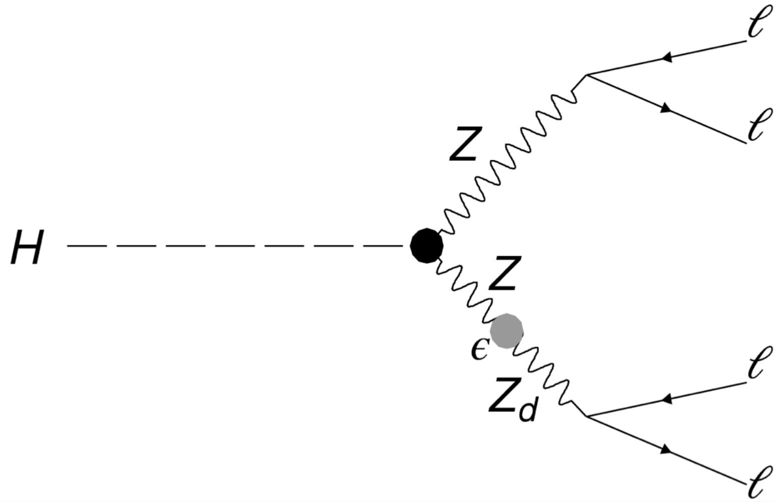
The mixing parameter κ between H and S, can be extracted from H → Zd Zd → 4l, a unique channel to access this parameter

Mass Mixing between SM Z and Zd

Phys.Rev. D 88.1 (2013) 015022

Phys.Rev. D 85 (2012) 115019

- In addition to kinetic mixing, there could be also a mass mixing between SM Z and Zd



$$O_{A,X} = c_{A,X} H X_\mu Z_d^\mu \,, \qquad (2)$$

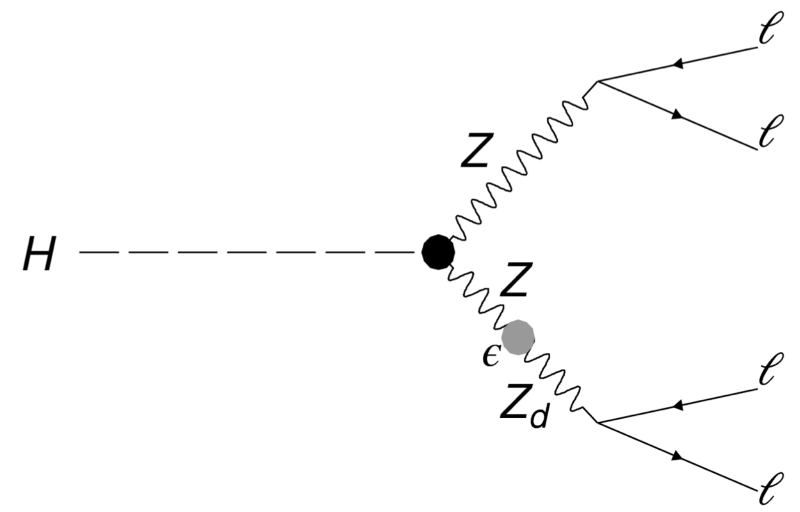
For operators of type $O_{A,X}$ in Eq. (2), we will focus on $X = Z$. Such interactions are typically associated with mixing. For example, the mass term for Z-Z_d mixing can be parametrized as $\varepsilon_Z\, m_Z^2 Z Z_d$, with

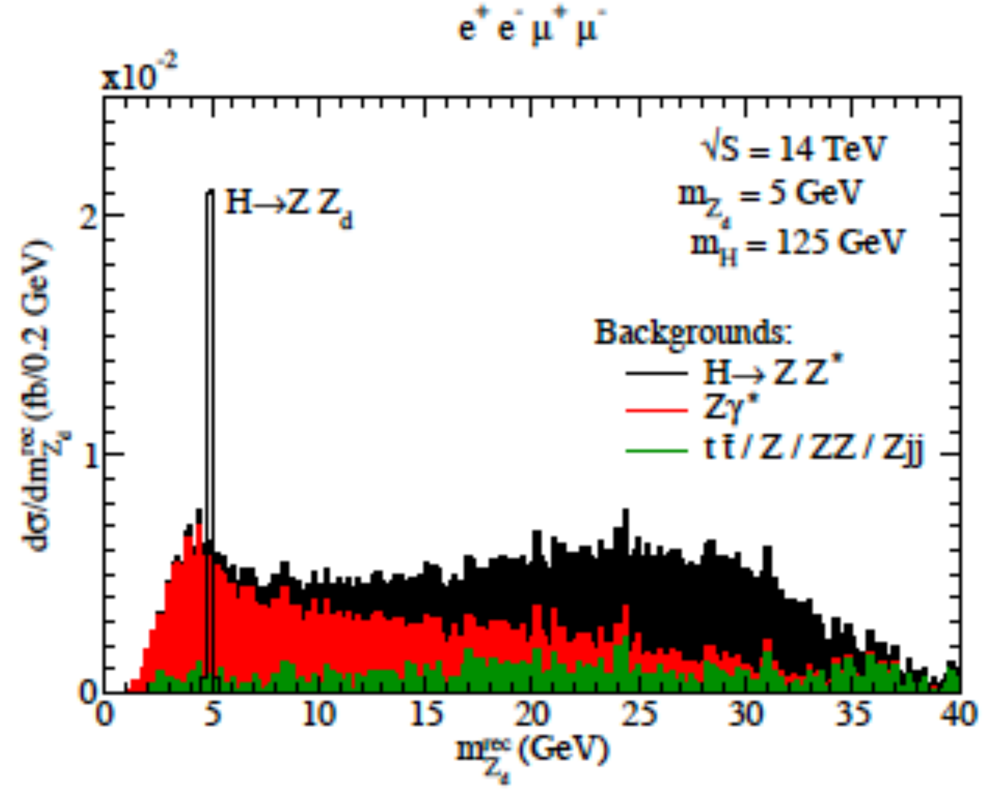
$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta \,, \qquad (4)$$

H → Z Zd → 4l is sensitive to the kinetic mixing parameter ε, and to Z-Zd mixing parameter δ. Unique channel to extract δ

H → Z Zd → 4 leptons

- Search for events with 4 leptons (e, μ) whose invariant masses are consistent with m_H
  - *Lepton-pairs must of opposite signs and same flavor*
  - *One lepton-pair, with mass m_{12} should be consistent with the SM Z-boson*
  - *In the mass distribution, m_{34}, of the other lepton-pair, search for a narrow resonance that might be interpreted as a Z_d signal*

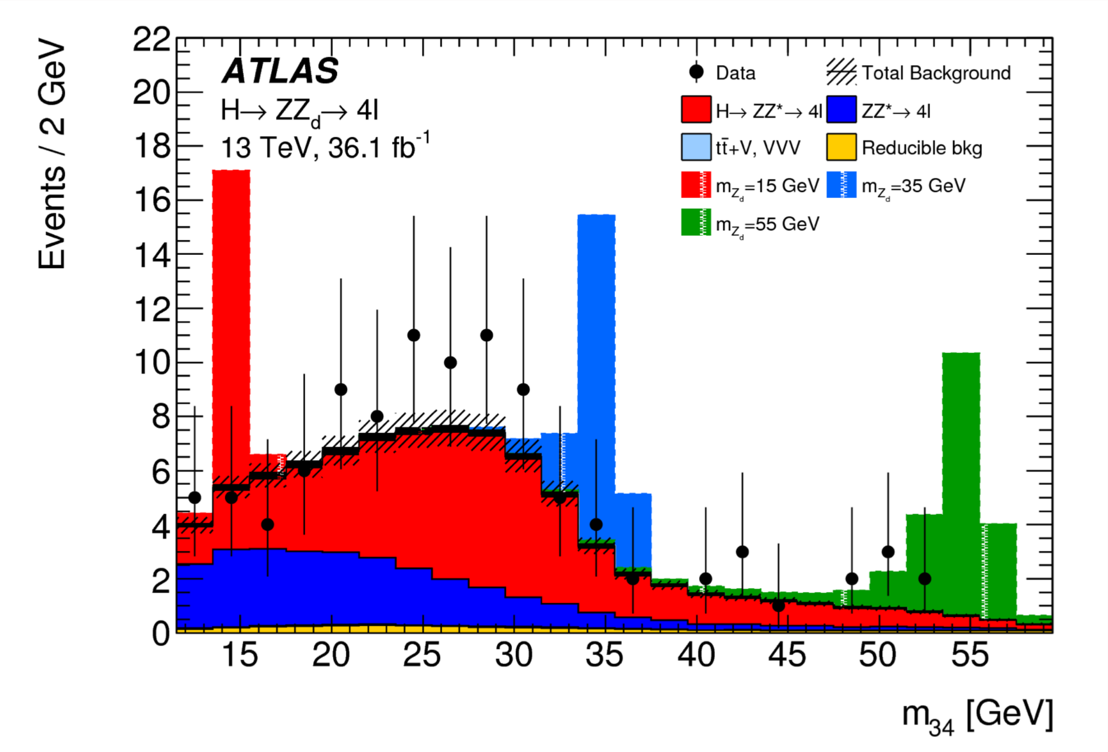


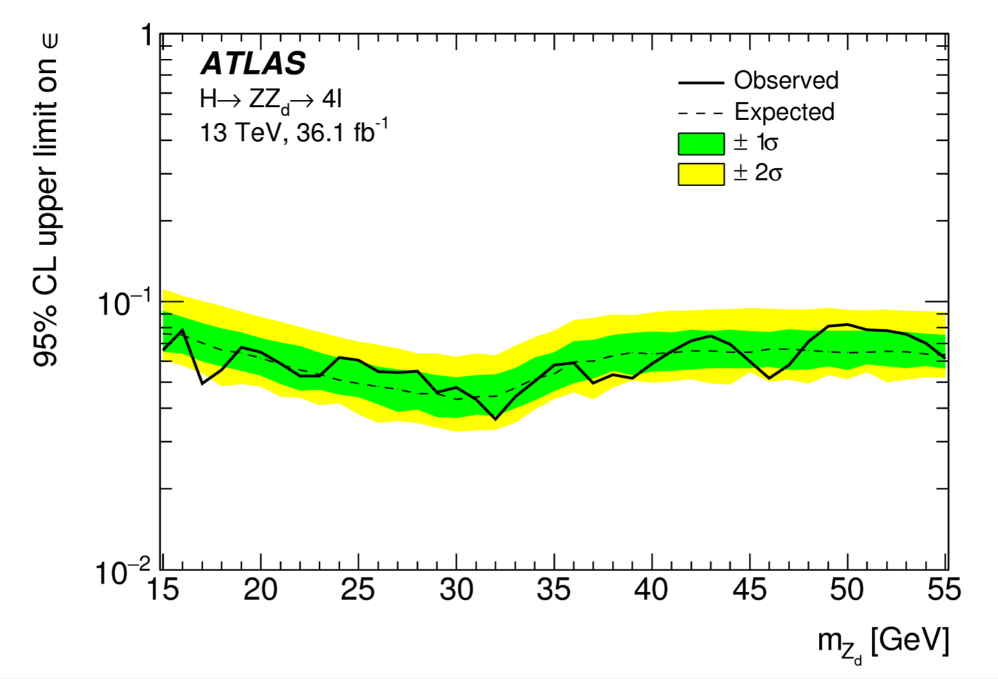


Phys. Rev. D 88, 015022 (2013

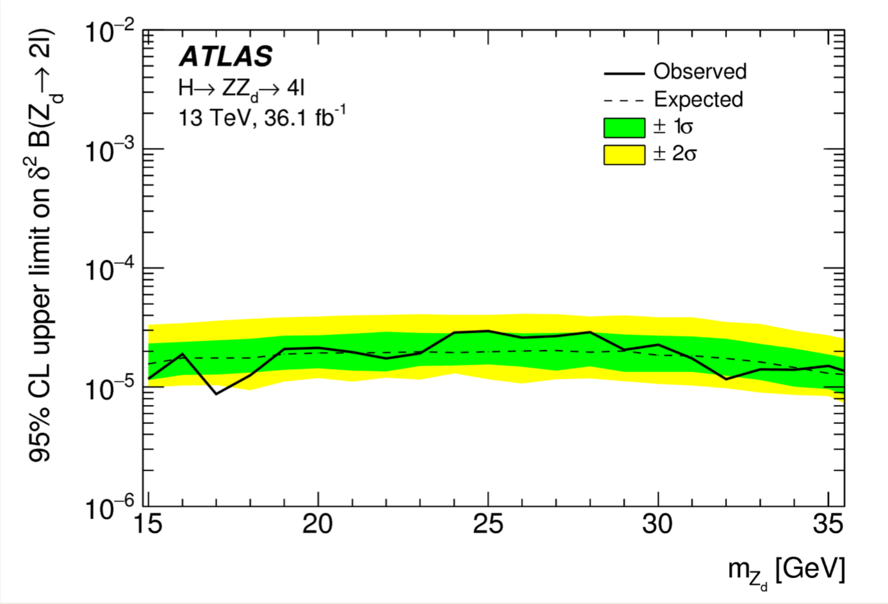
H → Z Zd → 4 leptons

JHEP 06 (2018) 166





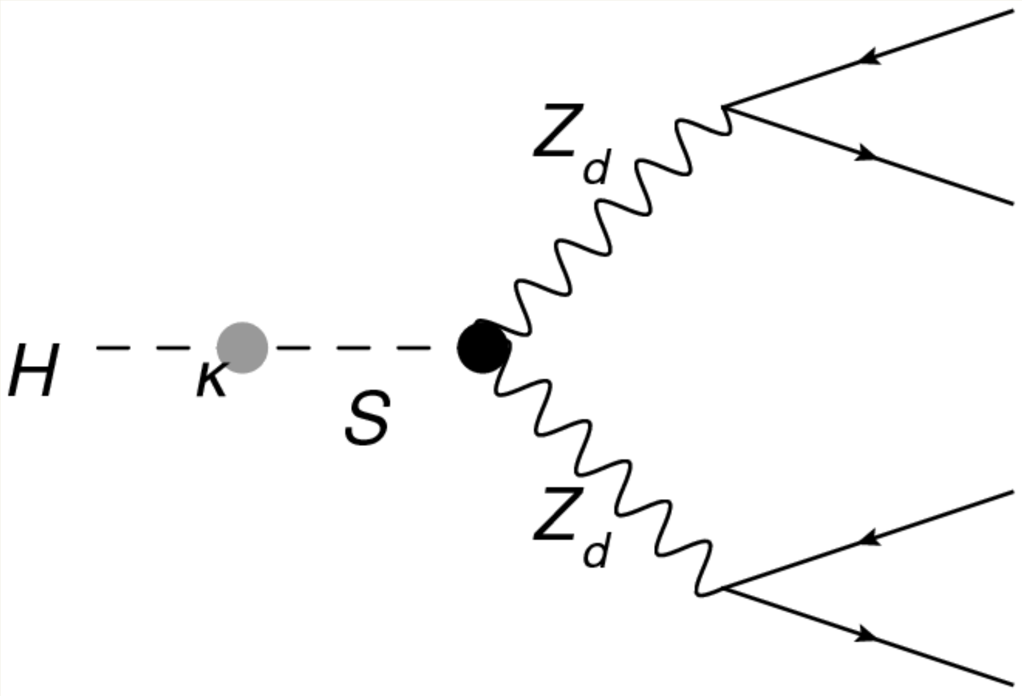
Bound on ε from H → ZZd not competitive. However, this channel is unique to get Z-Zd mixing parameter δ



- No excess of events found
- A constraint on the kinetic mixing parameter between the SM and the dark sector, and on the Z-Zd mass mixing parameter could be derived

H → Zd Zd → 4l (4e, 2e2μ, 4μ)

JHEP 06 (2018) 166



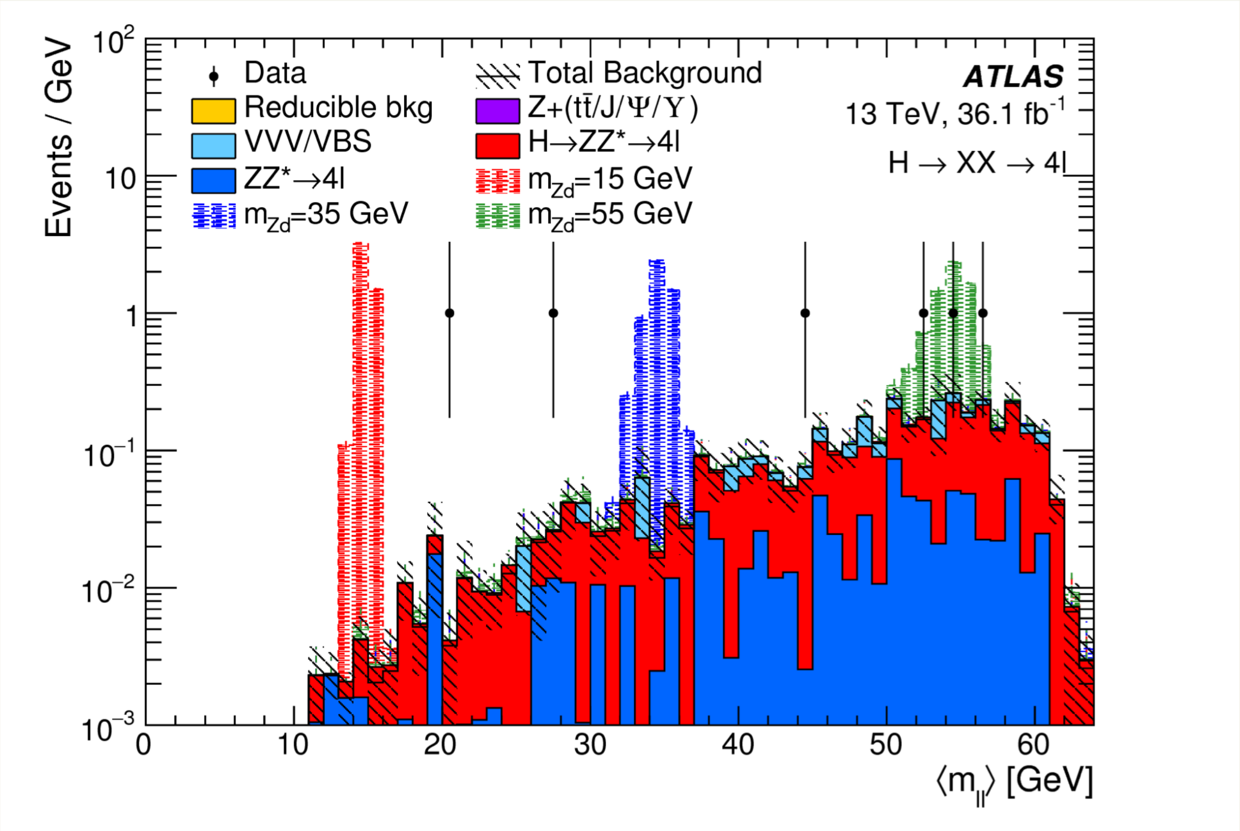
- Search for events with 4 leptons (e, μ) whose invariant masses are consistent with m_H
  - *Lepton-pairs must of opposite signs and same flavor*
  - *Both lepton-pairs, with masses m_{12} and m_{34}, must be consistent in mass, $\Delta m = |m_{12} - m_{34}|$ minimal*
  - *Veto events where m_{12} or m_{34} is consistent with Z-boson, J/psi or Upsilon*

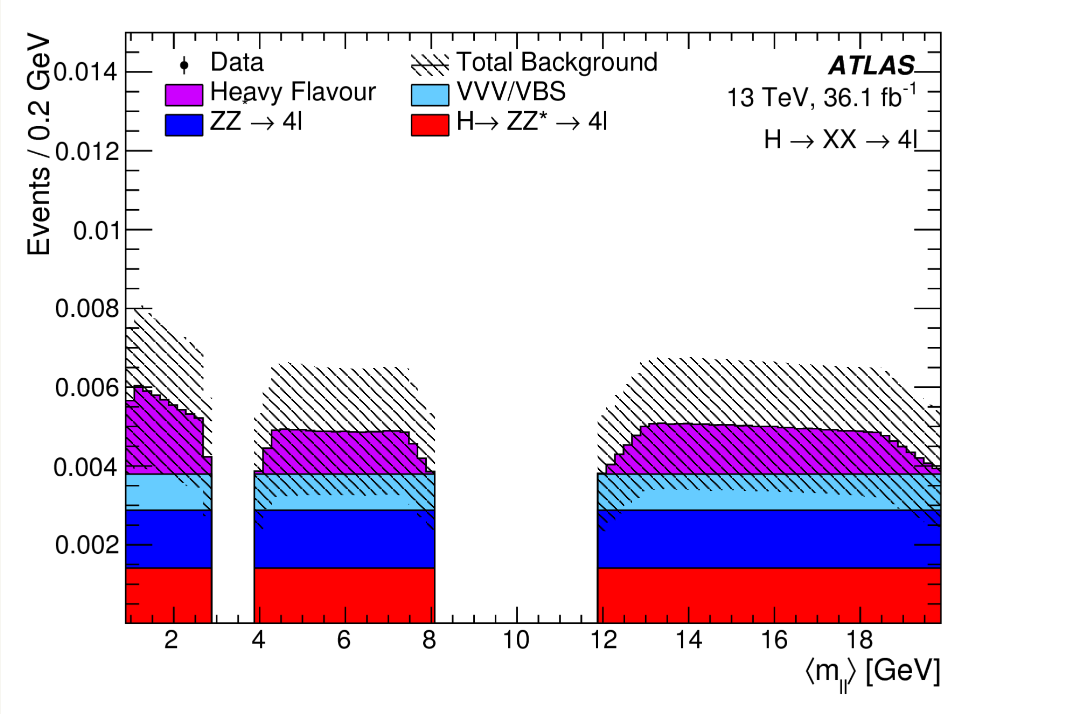
ATLAS:

Search range, high mass: $15 < m_{Zd} < 60$ GeV

Low mass ($m_{Zd} < 15$ GeV) search: with only the 4μ channel

H → Zd Zd → 4 leptons



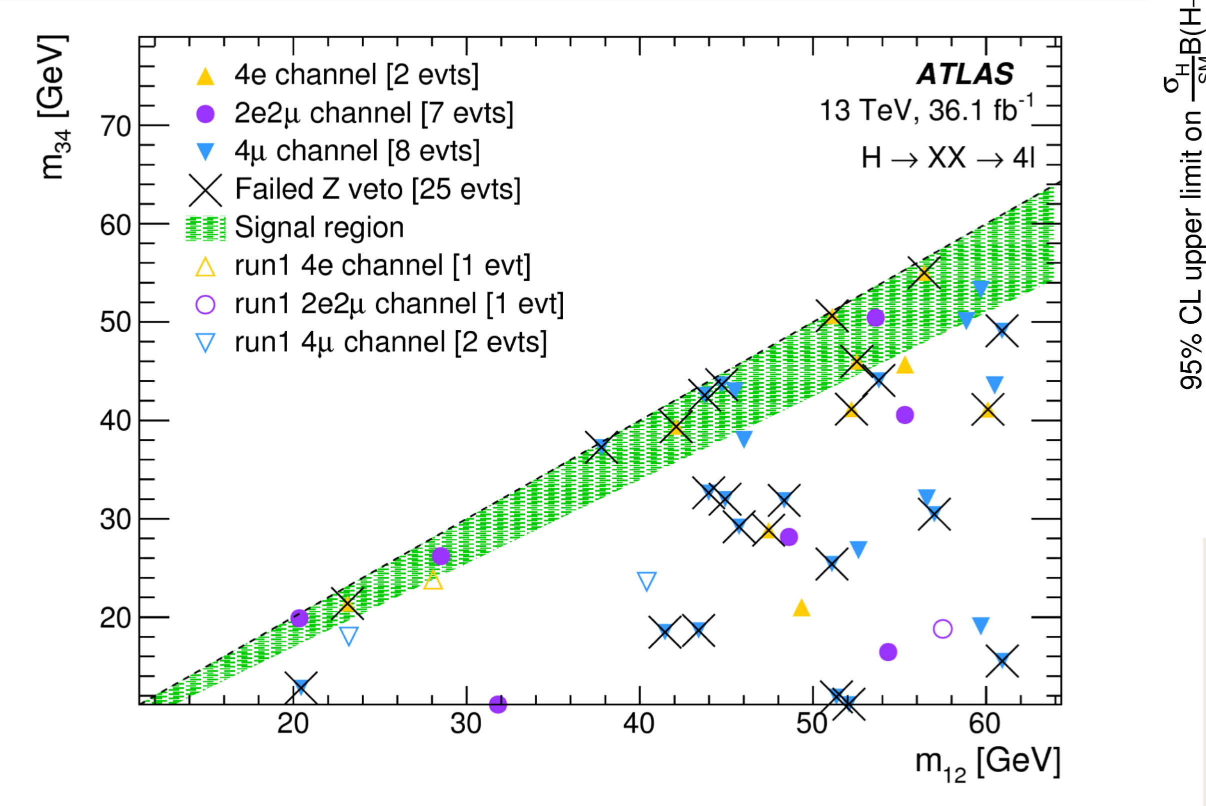


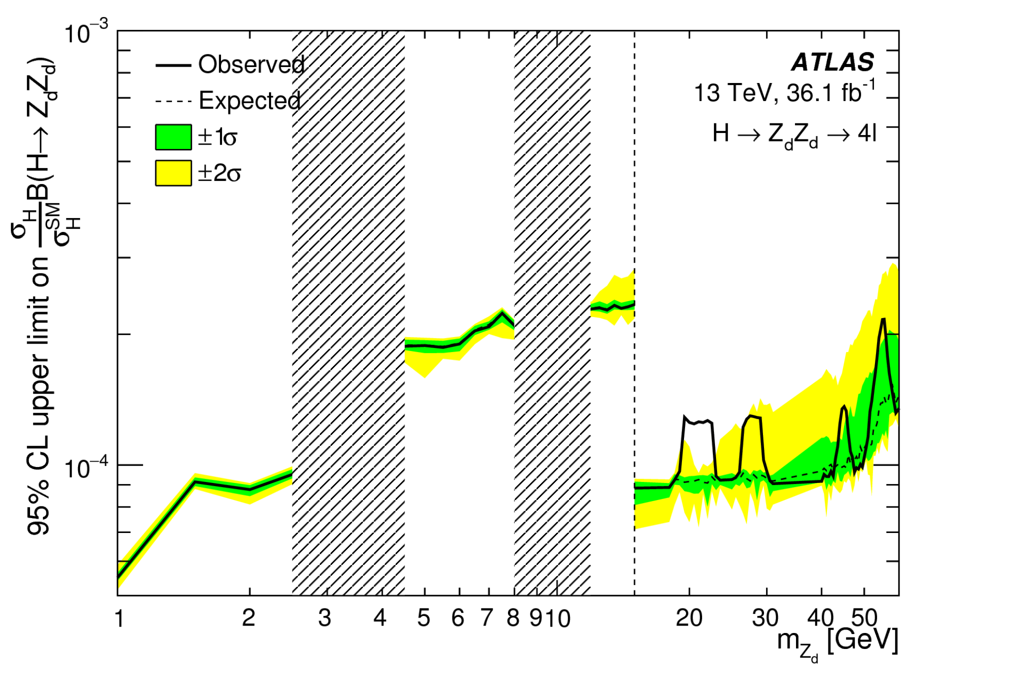
- No excess of events found
- A constraint on the mixing parameter between the SM Higgs boson and the dark sector Higgs boson could be derived

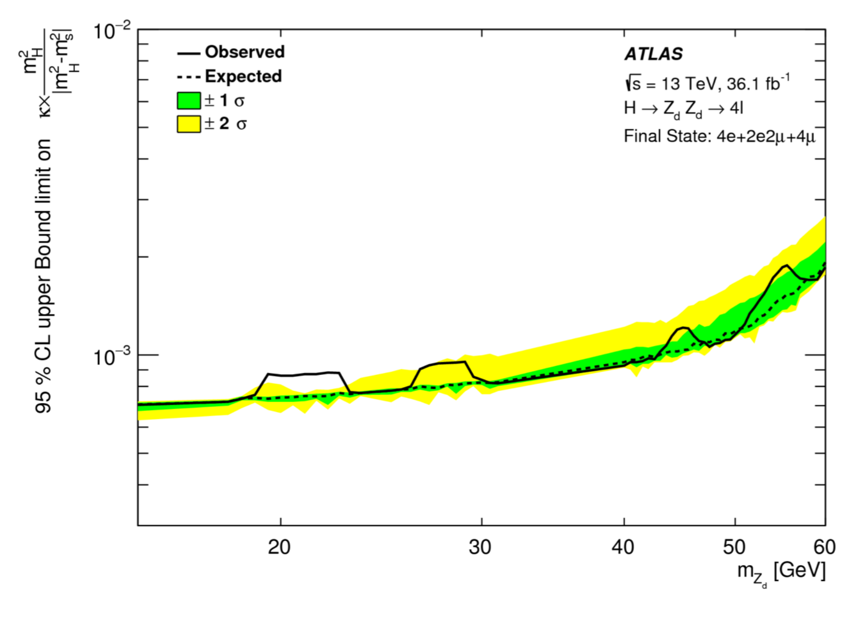
Analysis continues with searches for generic scalar of mass up to 1 TeV decaying into 4l, with dark vector bosons in the intermediate state

JHEP 06 (2018) 166

H → Zd Zd → 4l







A constraint on the effective Higgs mixing parameter

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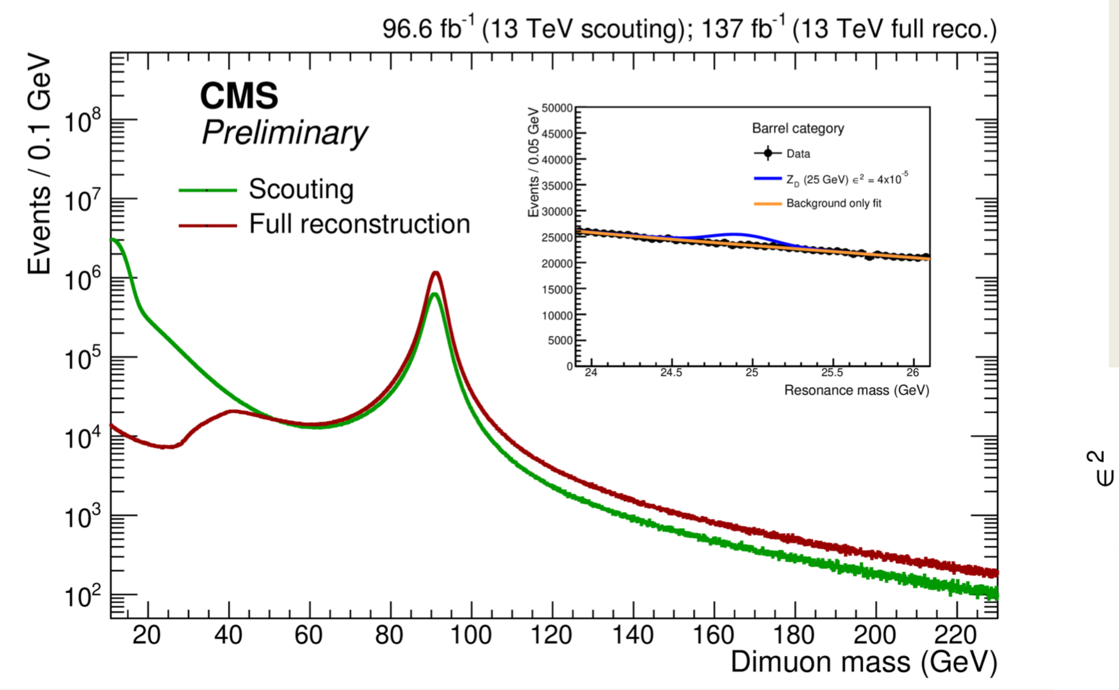
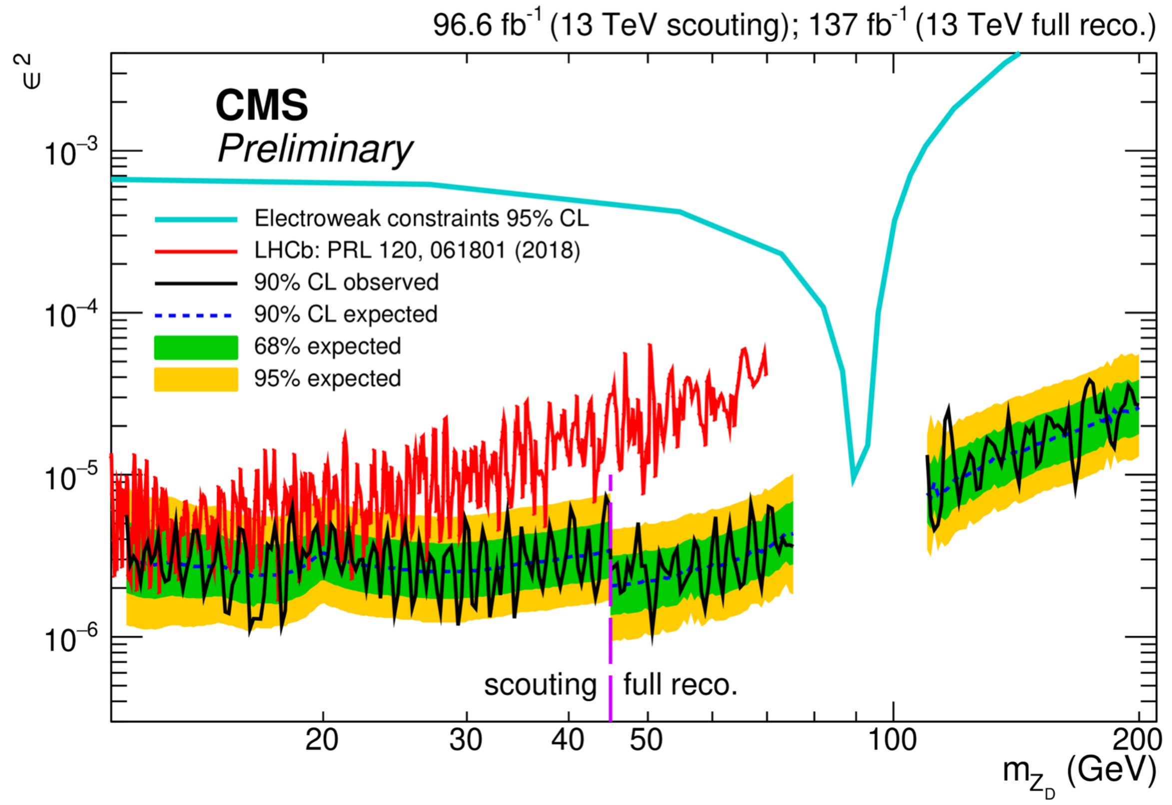
Narrow resonance decaying in a pair of muons



The search in the 45-75 and 110-200 GeV uses 137 fb^{-1}. The search in the 11.5-45.0 GeV mass range uses 96.6 fb^{-1} of data collected using scouting.



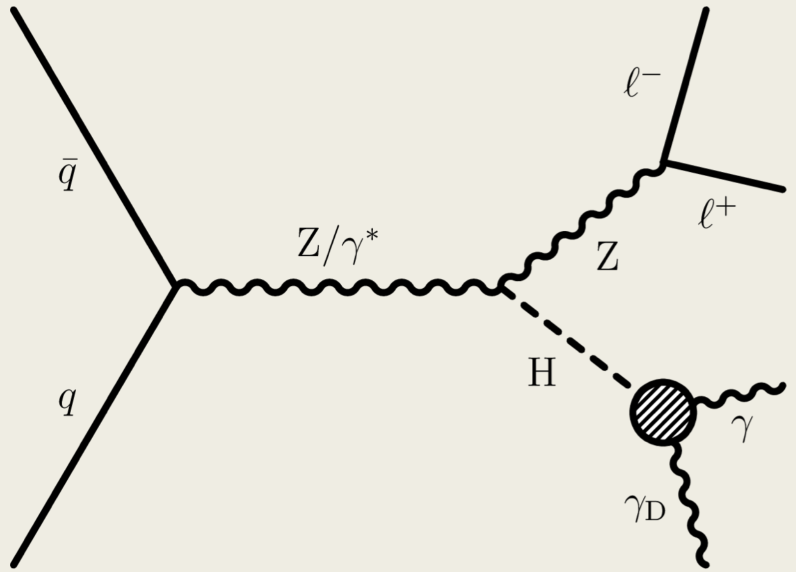
No significant resonant peaks are observed. The search sets the strongest constraints on a hypothetical dark photon heavier than 11.5 GeV.

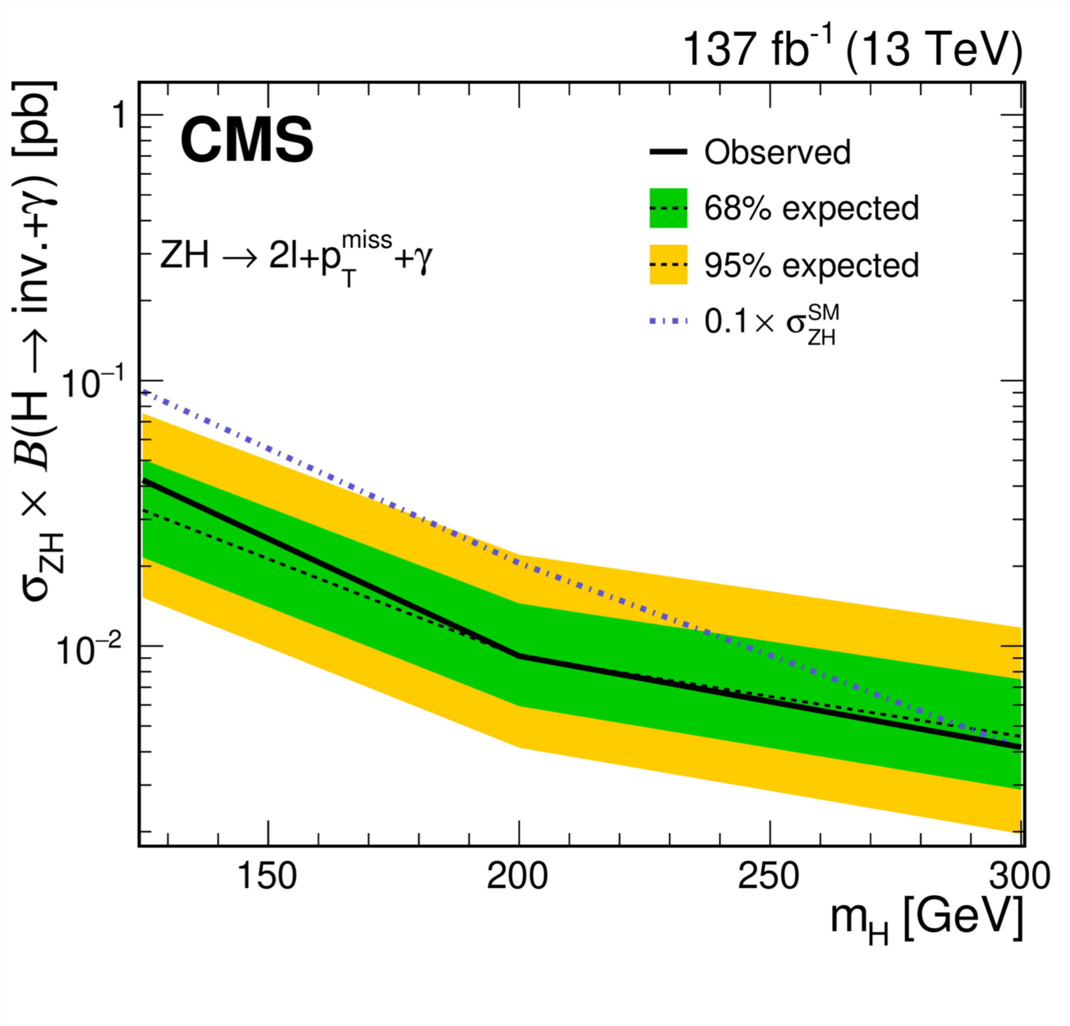
CMS-PAS-EXO-19-018

H → γ γ_d

arXiv:1908.0269
submitted to JHEP

Massless dark photon in ZH production mode



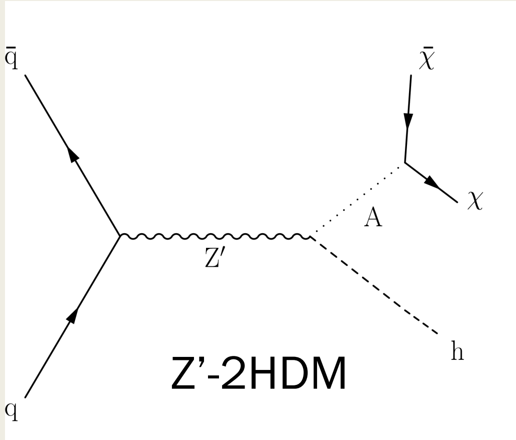


- ❑ **Lower cross section compared to VBF mode.**
- ❑ **Cleaner signal with highly efficient online lepton trigger**

ATLAS analysis in progress by a group from Mohammed V University, Morocco. Thesis work of Hassnae El Jarrari, currently spending 3 months at BNL to work with KAA on this

Dark Matter Produced in Association with a Higgs Boson

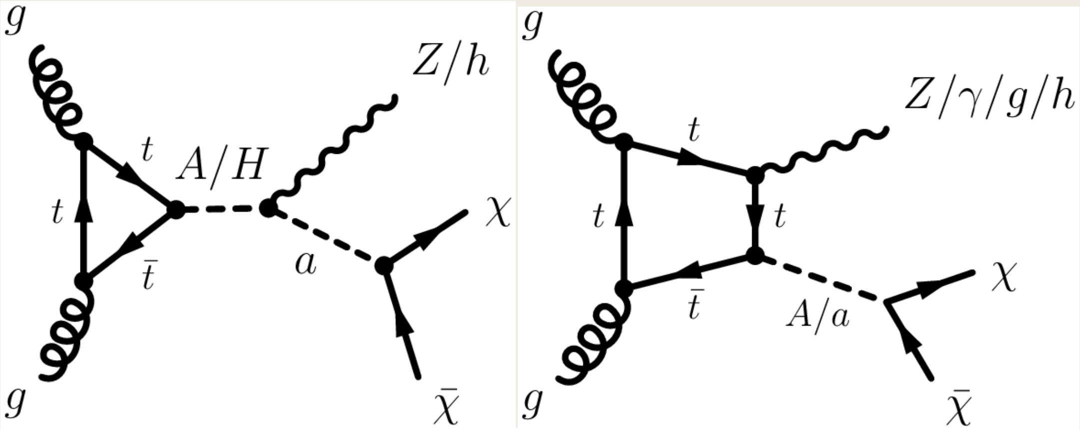
2HDM+a

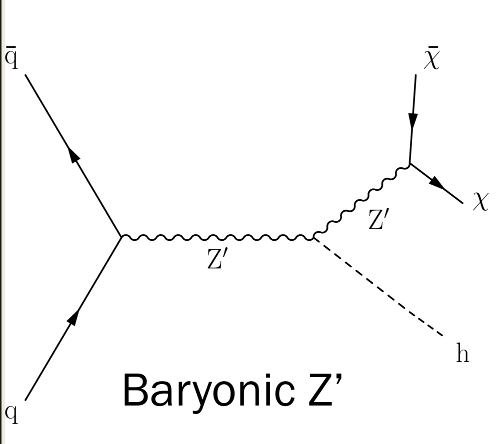


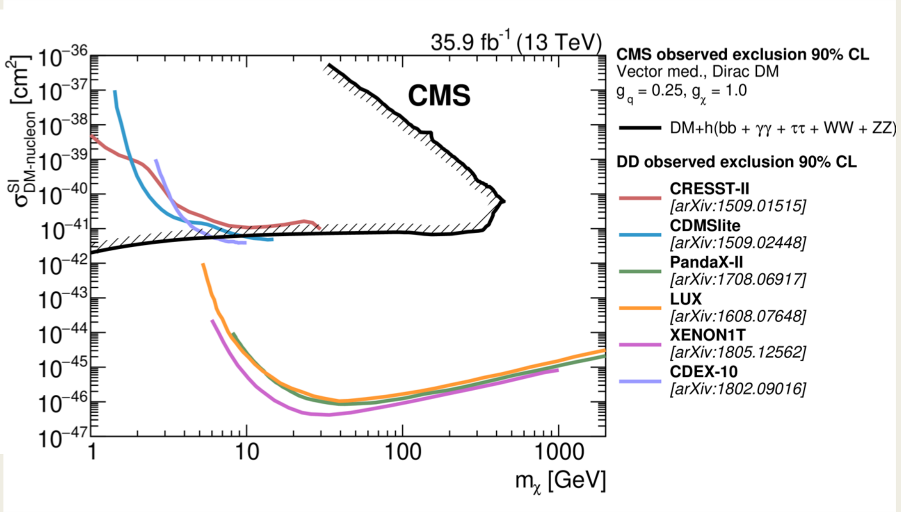
arXiv:1908.01713

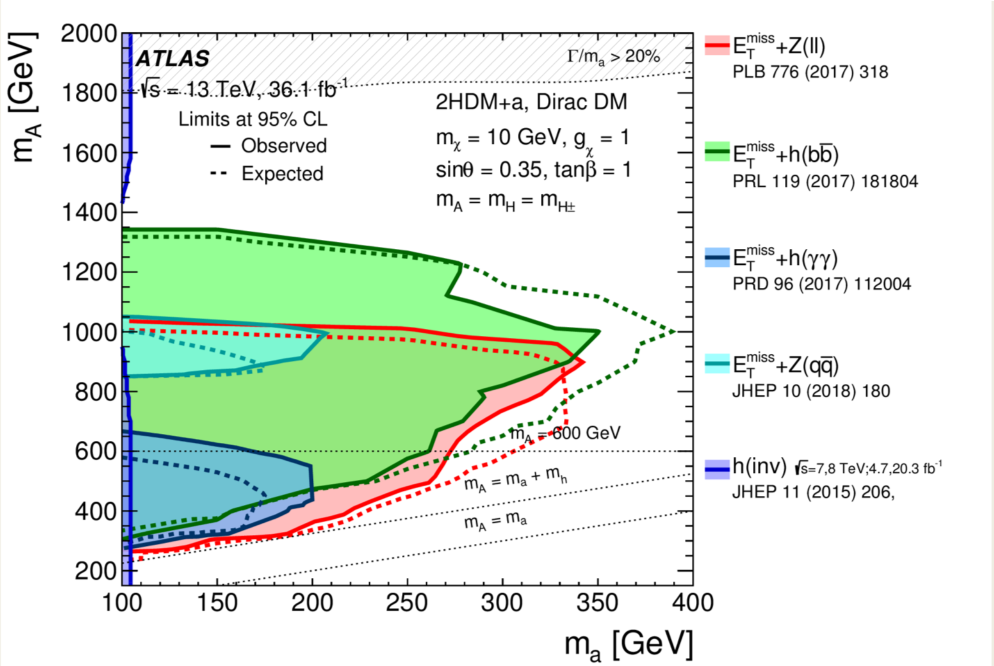
Submitted to JHEP

The search is performed in five Higgs boson decay channels: $h \to b\bar{b}$, $\gamma\gamma$, $\tau^+\tau^-$, W^+W^-, and ZZ, and combined.







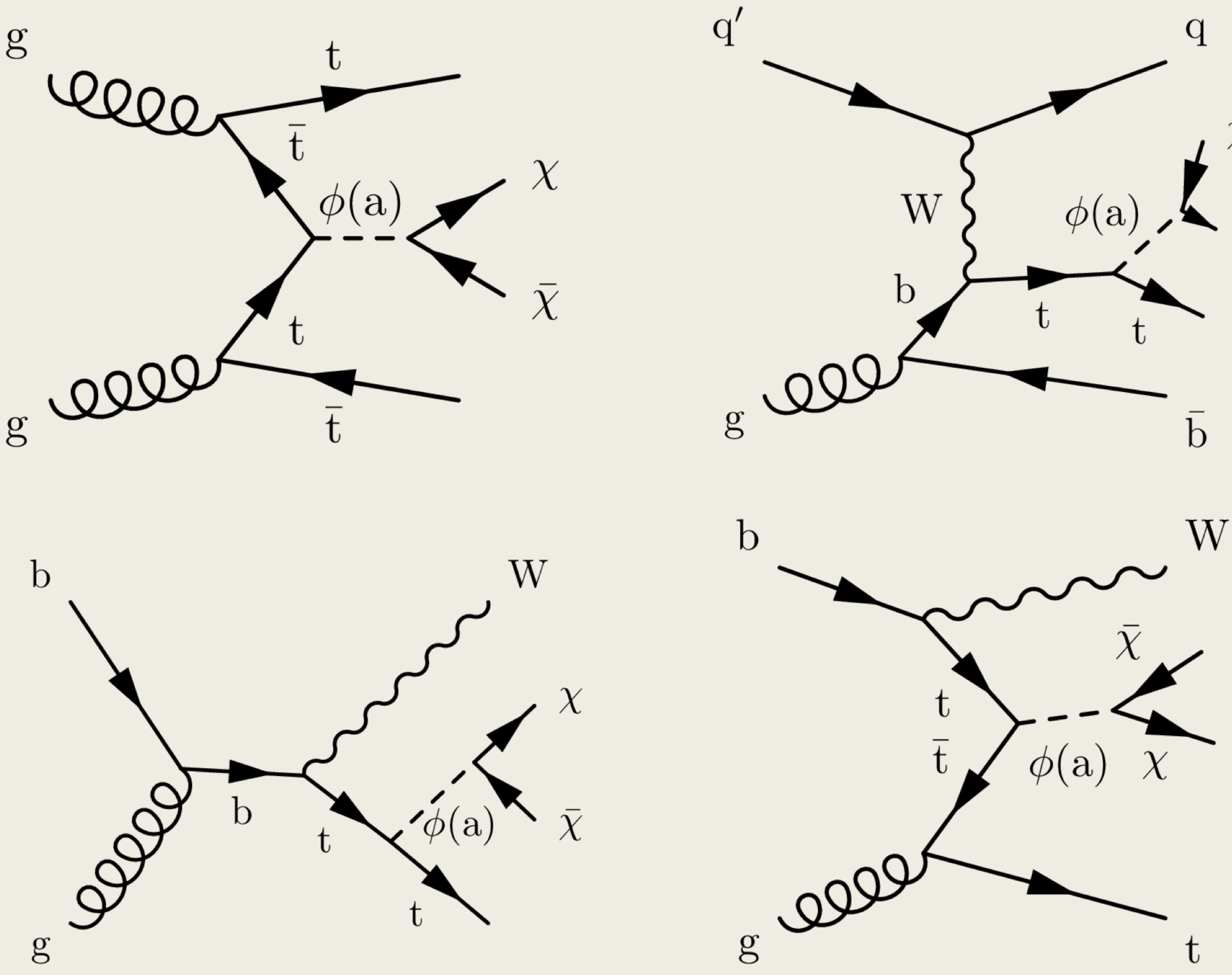


The upper limits at 90% CL on the DM-nucleon spin-independent scattering cross section σ_{SI}, as a function of m_χ

Dark Matter Produced in Association with top-quark(s)

JHEP 03 (2019) 141

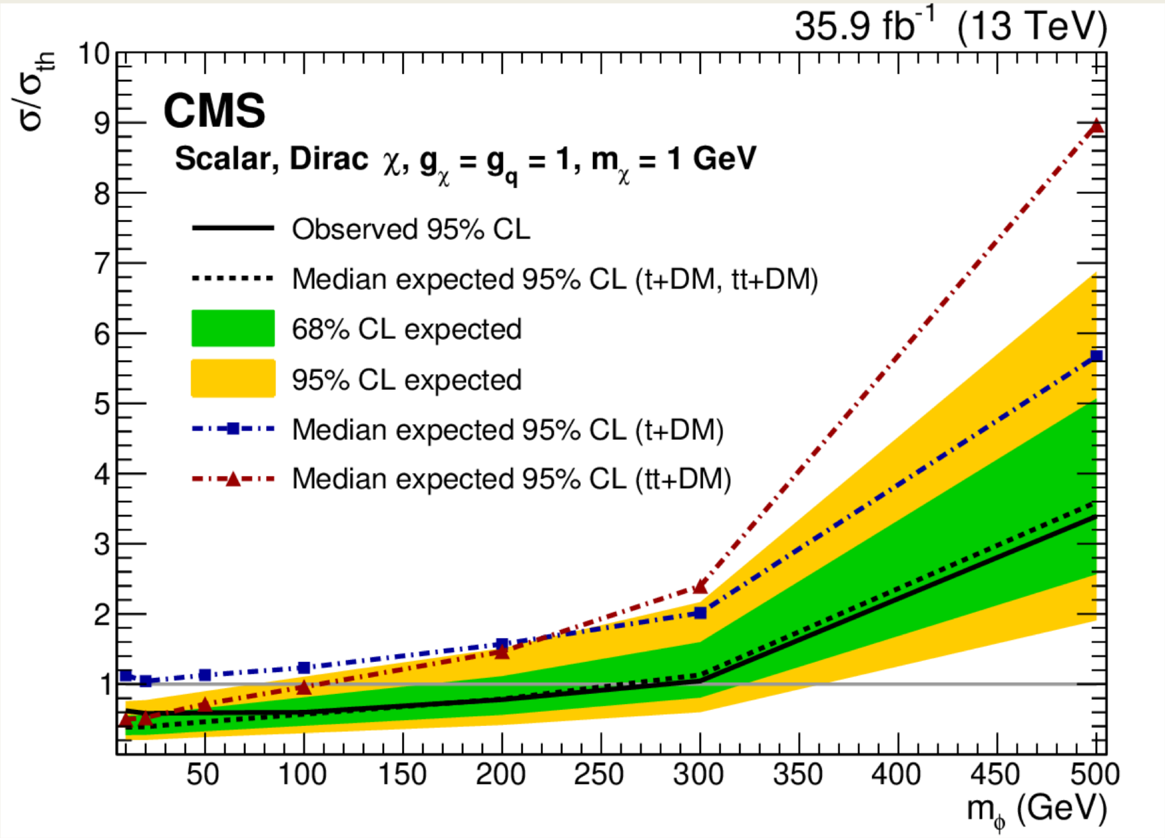
Principal production diagrams for the associated production at the LHC of dark matter with a top quark pair (upper left) or a single top quark with associated *t* channel W boson production (upper right) or with associated tW production (lower left and right).

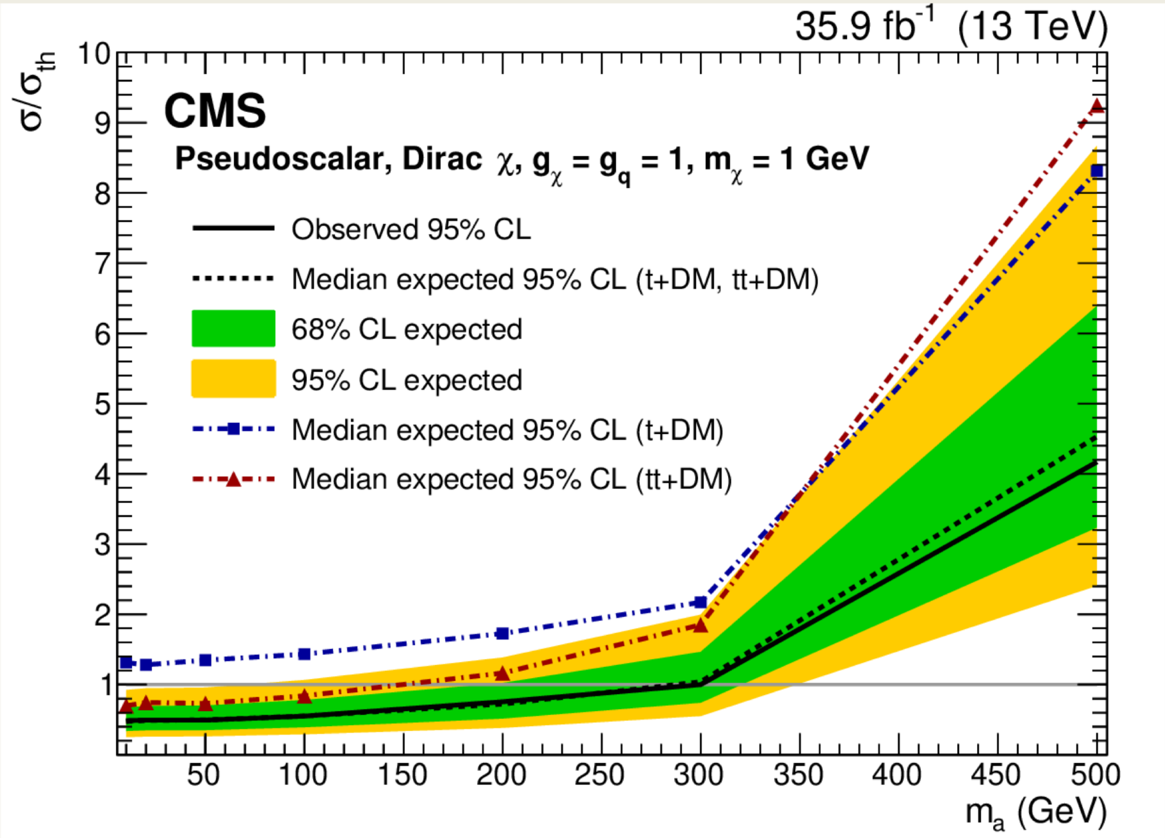


ϕ(a): a scalar or pseudoscalar mediator particle couples to a top quark and subsequently decays into dark matter particles

Dark Matter Produced in Association with top-quark(s)

JHEP 03 (2019) 141



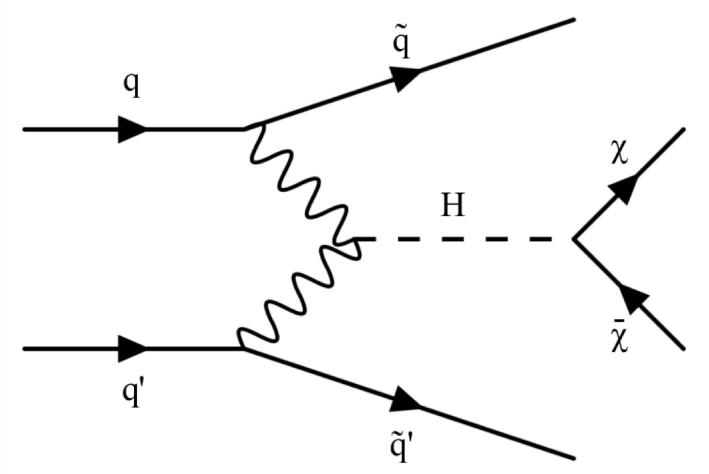


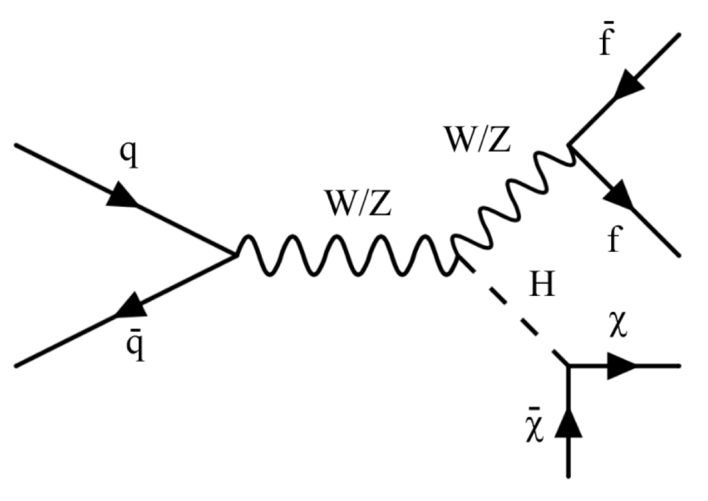
Interpretation in a simplified model where scalar and pseudoscalar mediator particles with masses below 290 and 300 GeV, respectively, are excluded at 95% confidence level, assuming a dark matter particle mass of 1 GeV and mediator couplings to fermions and dark matter particles equal to unity

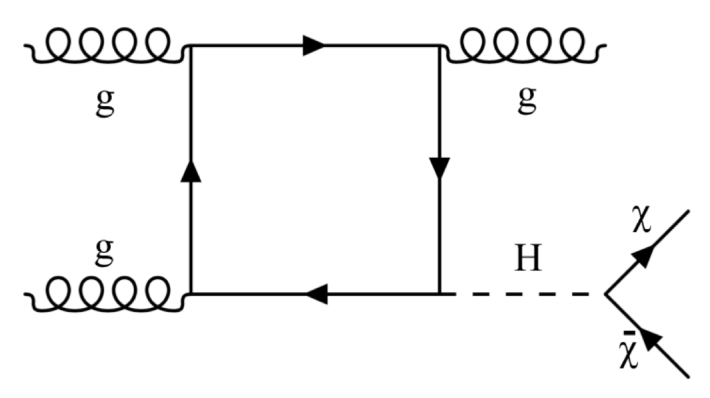
ATLAS results (Eur. Phys. J. C78 (2018) 18, JHEP 05 (2019) 142)

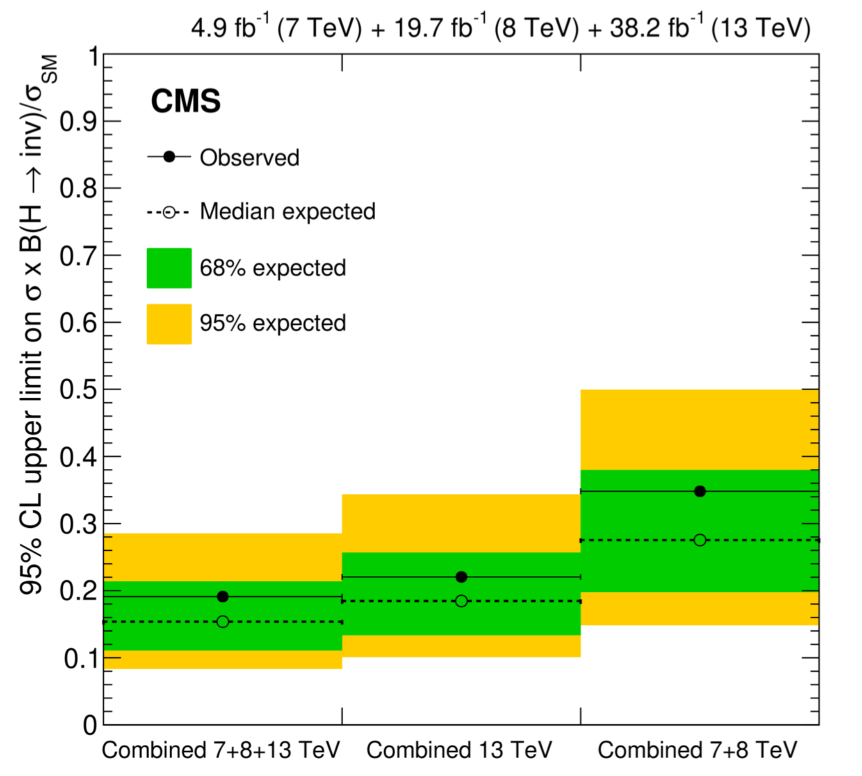
CMS H → inv. combination

Phys. Lett. B 793 (2019) 520

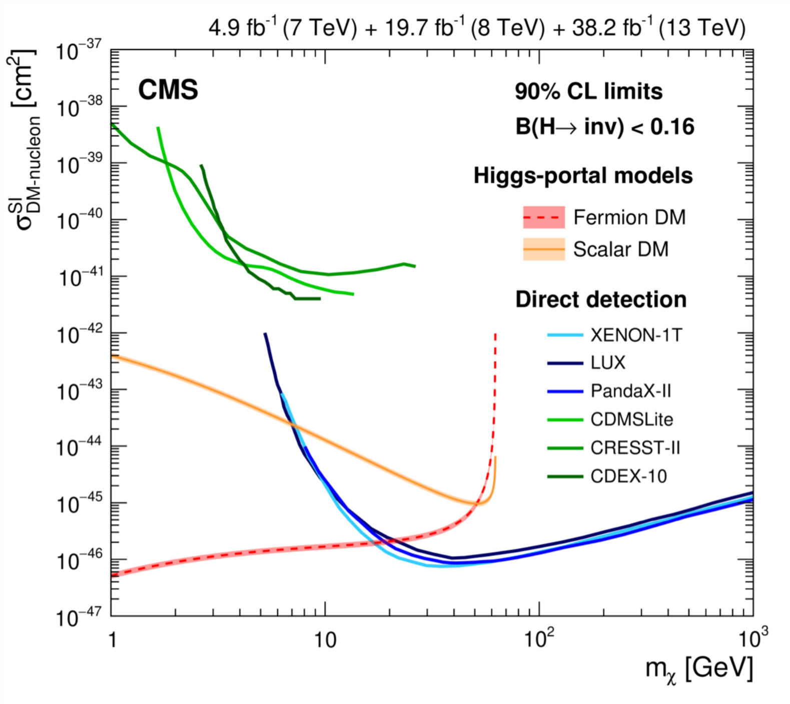






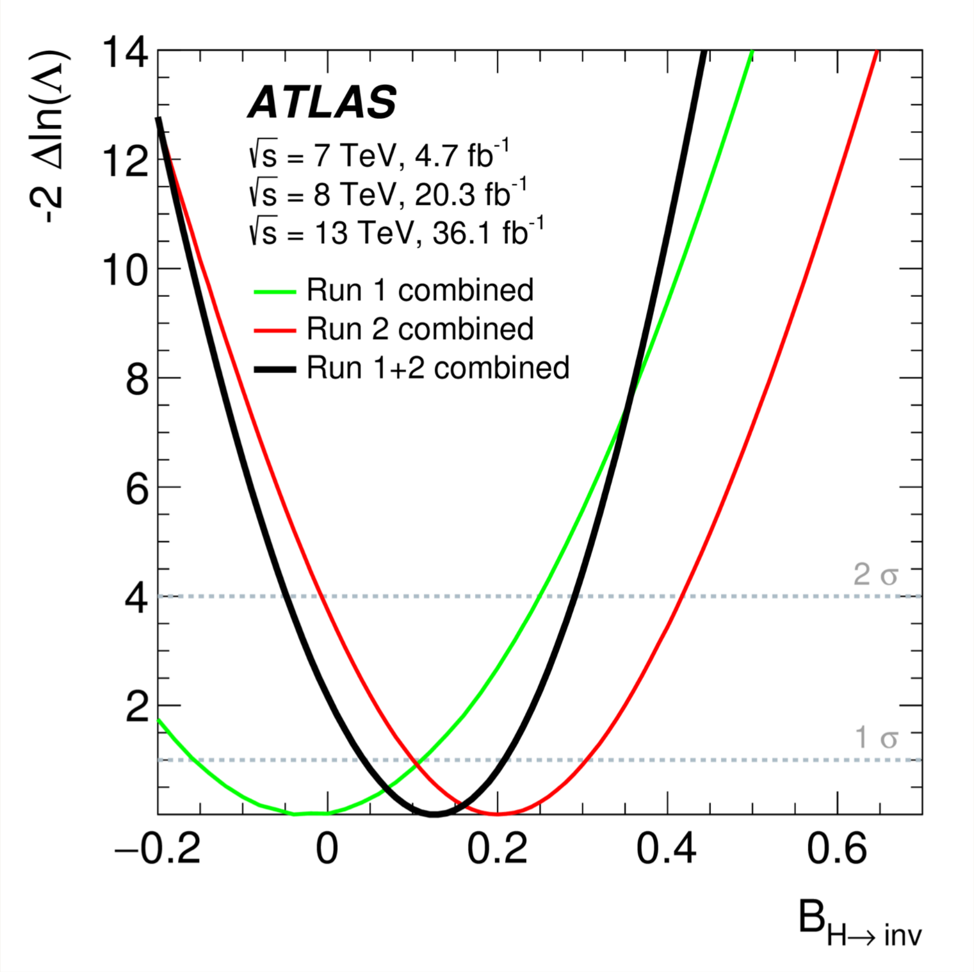


- VBF Only: observed (expected) upper limit of 0.33 (0.25), at 95% CL
- Combination of VBF, VH and ggF: observed (expected) upper limit of 0.19 (0.15), at 95% CL
- A constraint on the spin-independent WIMP-nucleon scattering cross section as a function of the WIMP mass

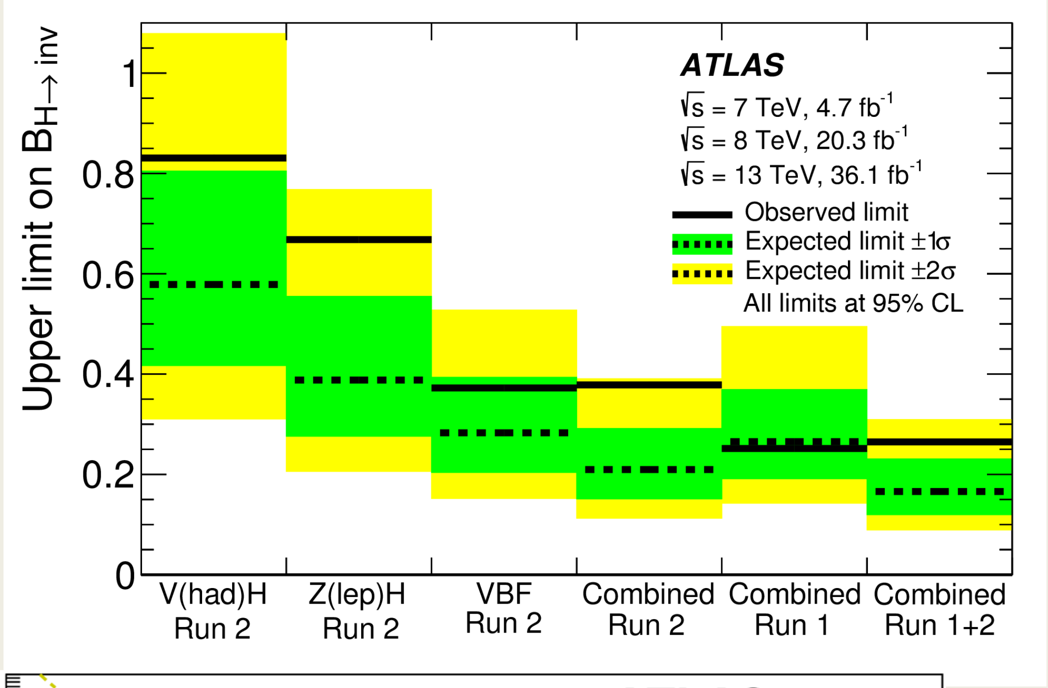


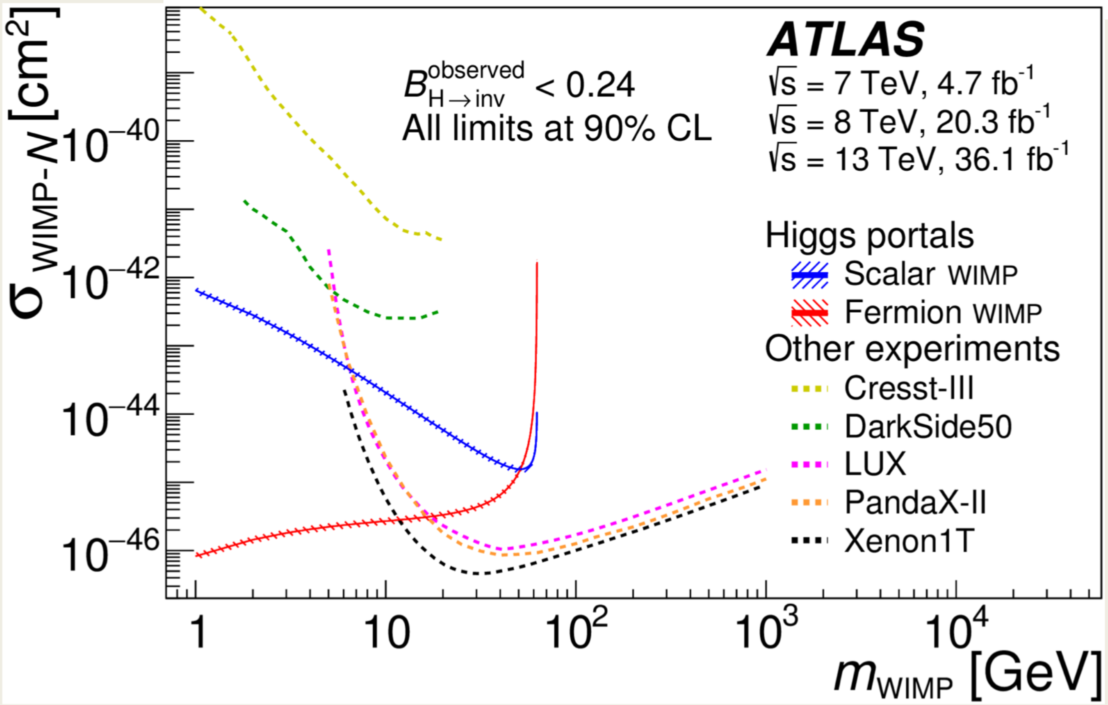
ATLAS H → inv. combination

$H\rightarrow$**invisible** branching ratio (ATLAS) of **0.26 (0.17+0.07−0.05)** at 95%



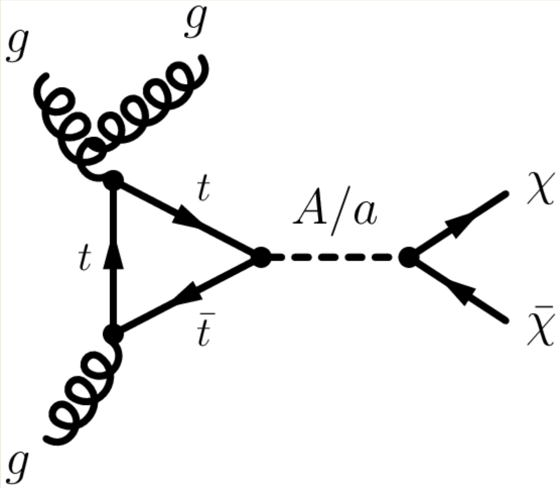
Phys. Rev. Lett. 122, 231801 (2019)

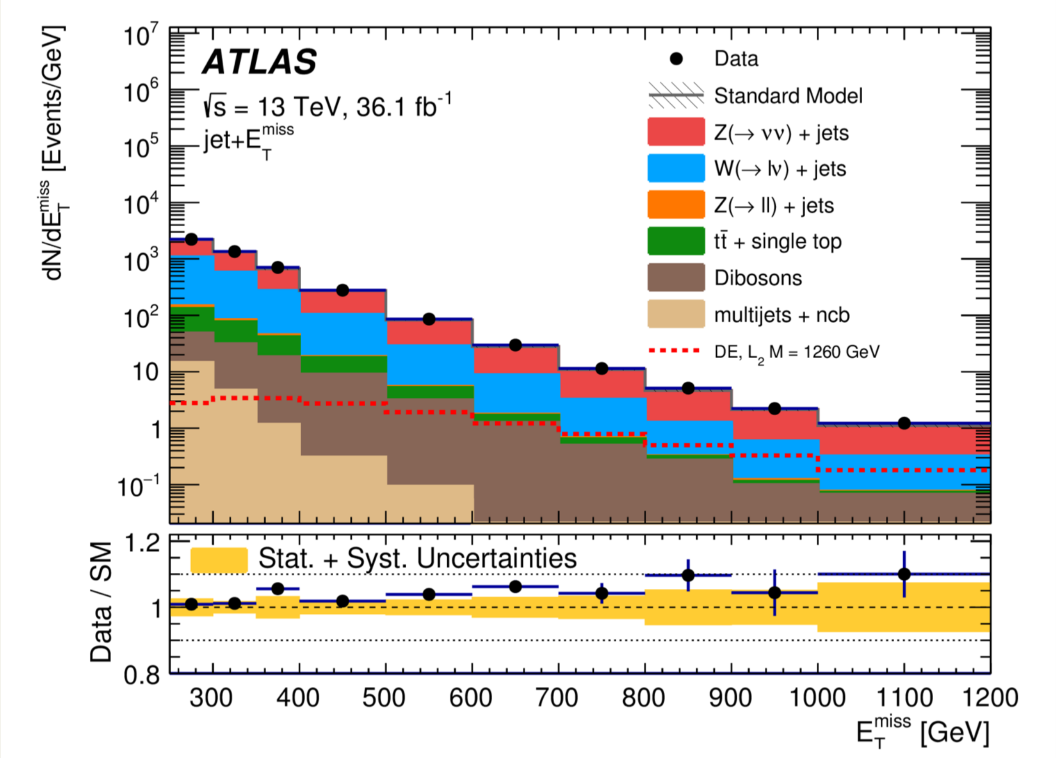




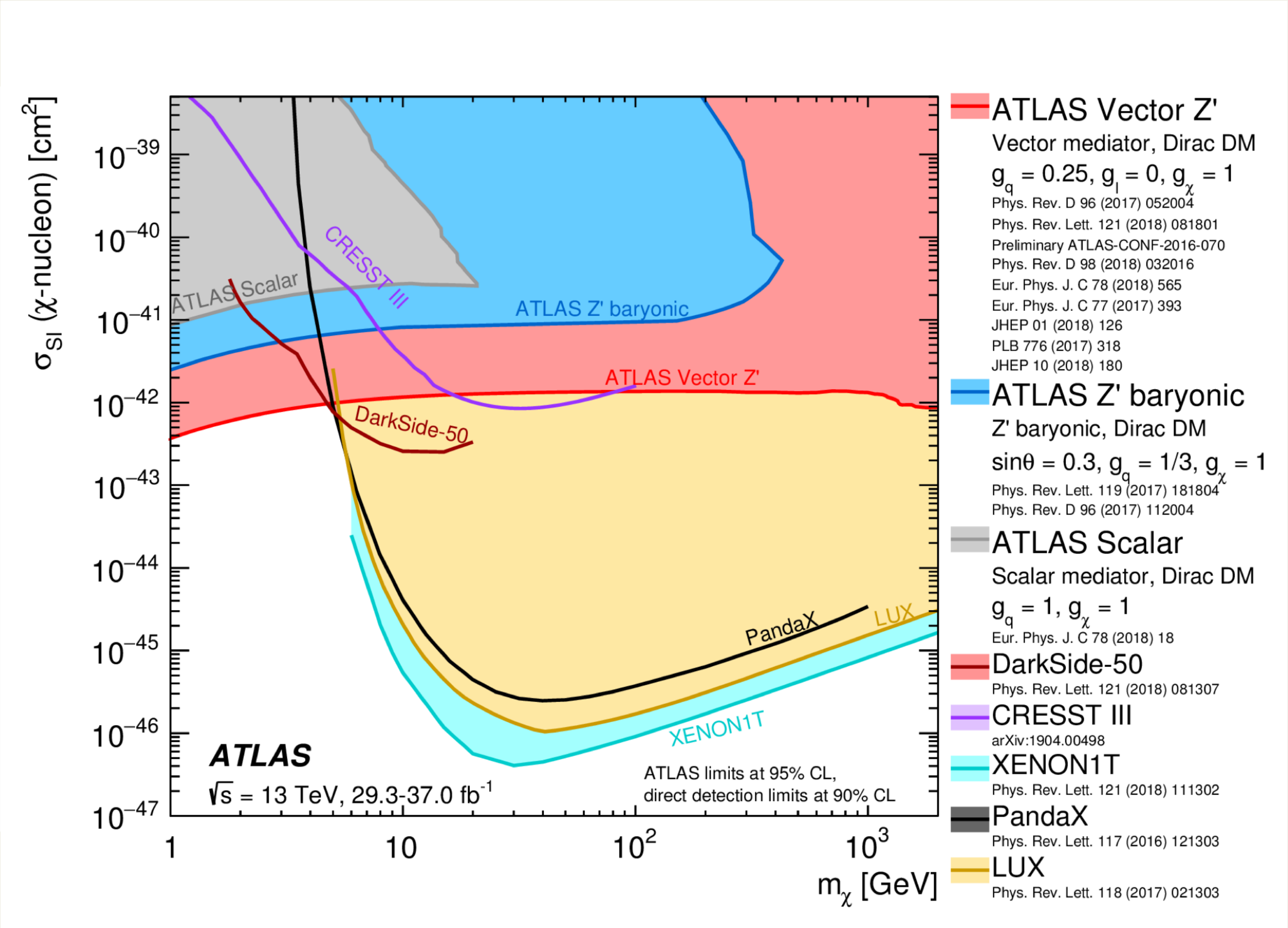
Constraints on selected mediator-based dark matter models and a scalar dark energy model

JHEP 05 (2019) 142





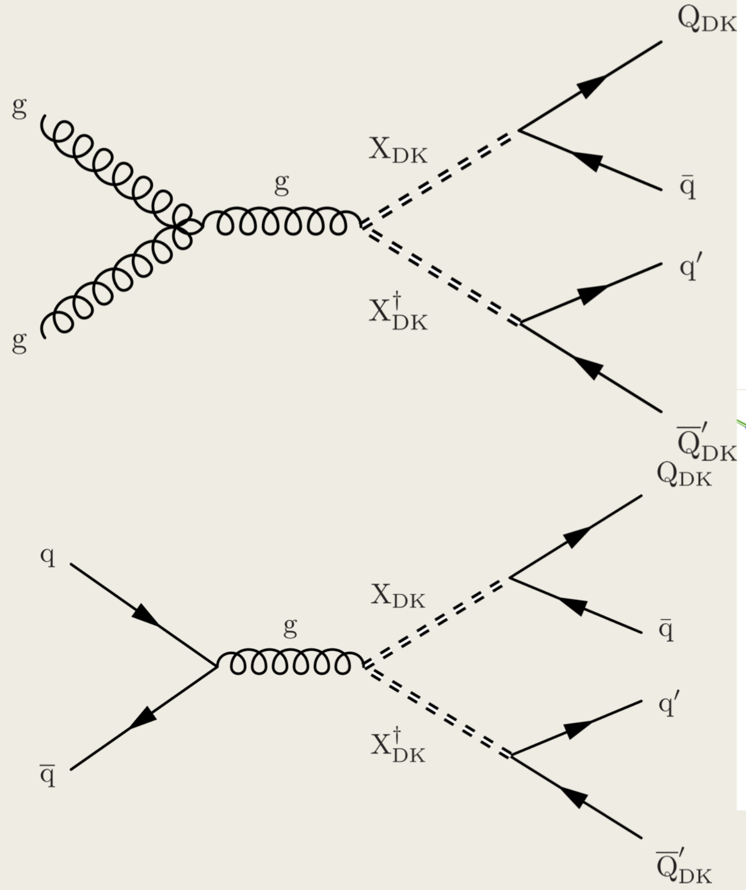
Jet + Missing Energy Analysis

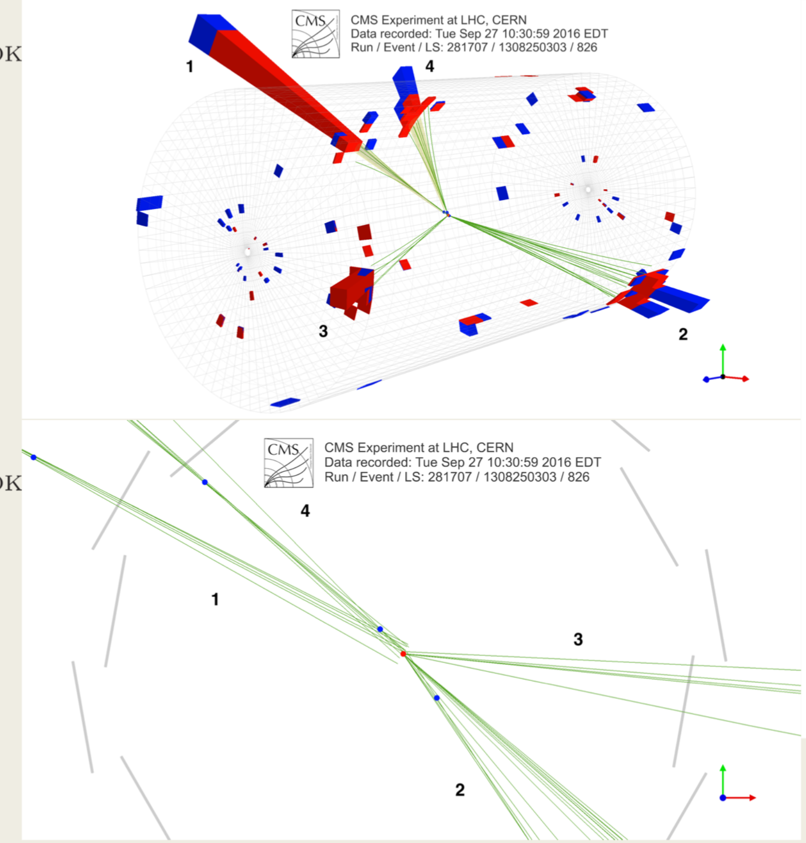


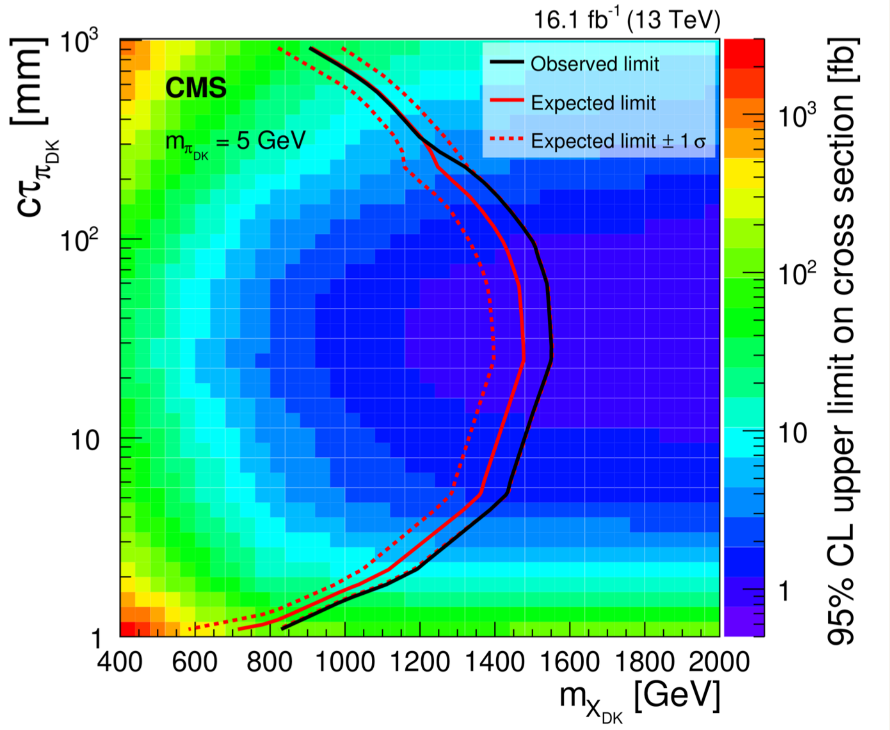
New particles decaying to a jet and an emerging jet

JHEP 02 (2019) 179

- Search for pair production of a new heavy particle that acts as a mediator between a dark sector and normal matter, and that decays to a light quark and a new fermion called a dark quark



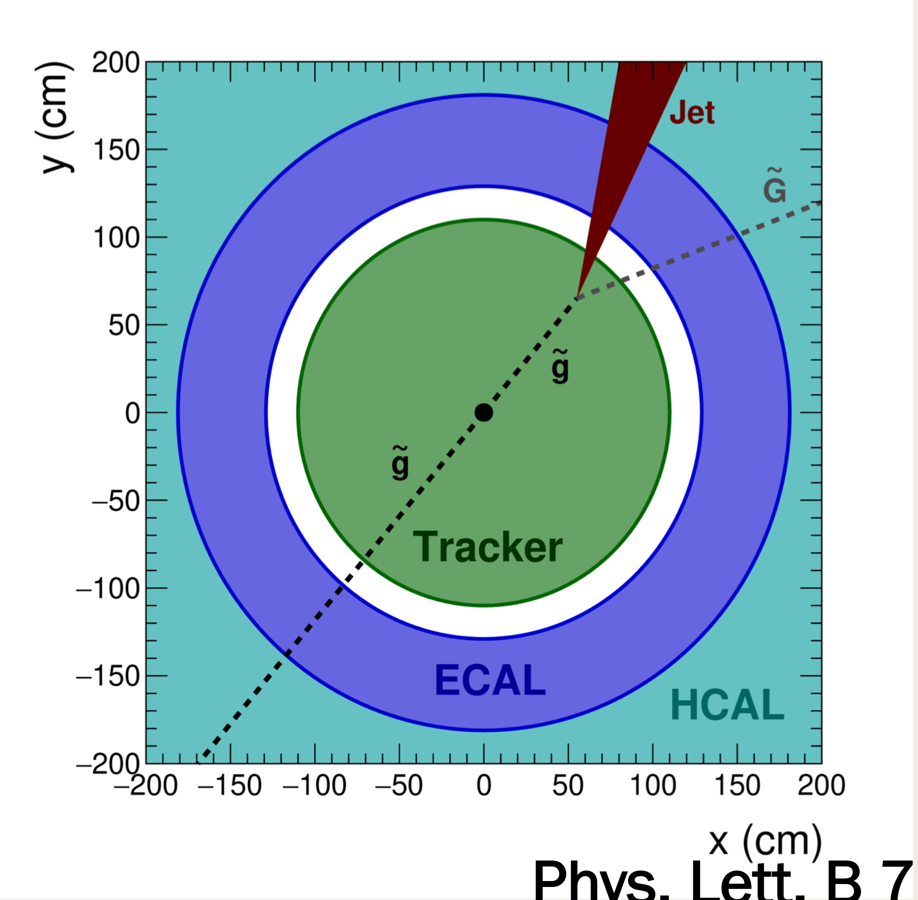


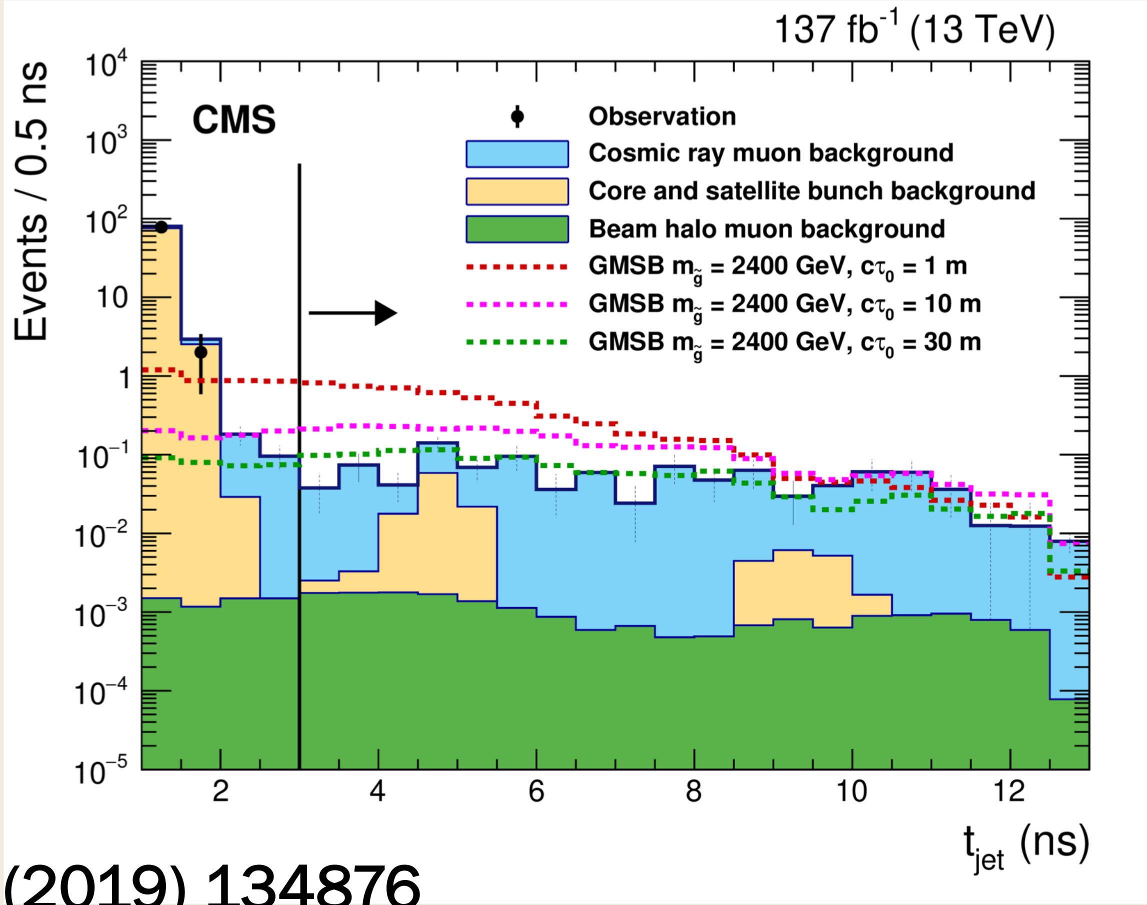


The data are consistent with the expectation from standard model processes

Non-prompt Jet + Missing Energy Analysis

Many models for physics beyond the SM predict long-lived particles that may be produced at the LHC and decay into final states containing jets with missing transverse momentum. These include SUSY GMSB, split and stealth SUSY, and hidden valley models

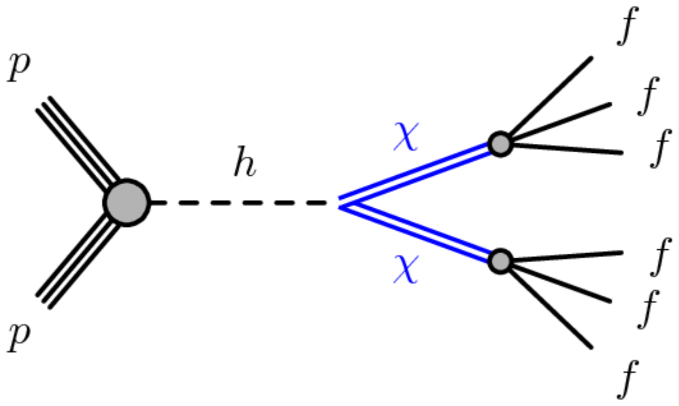


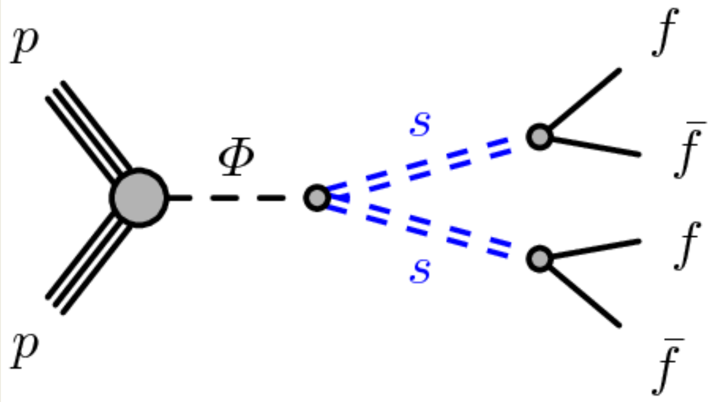


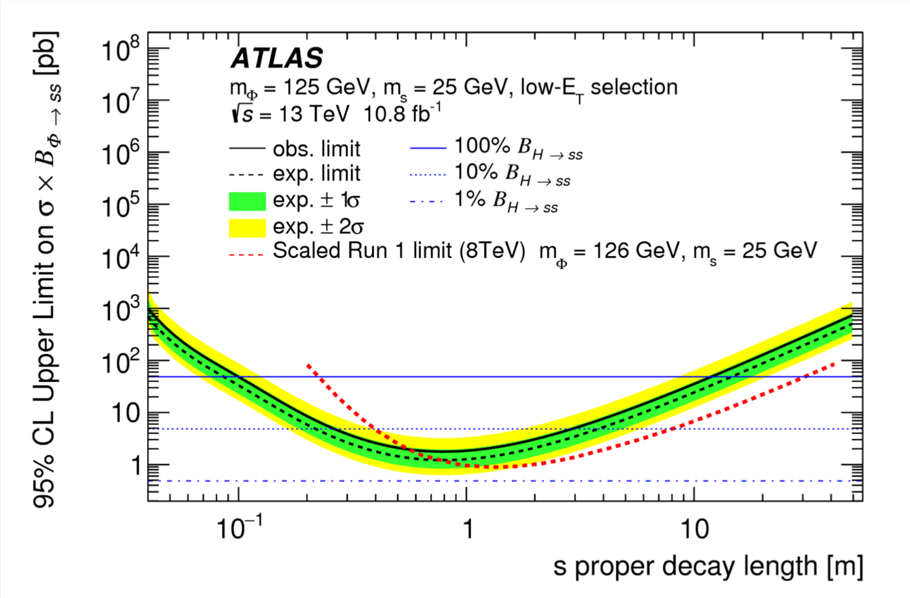
Phys. Lett. B 797 (2019) 134876

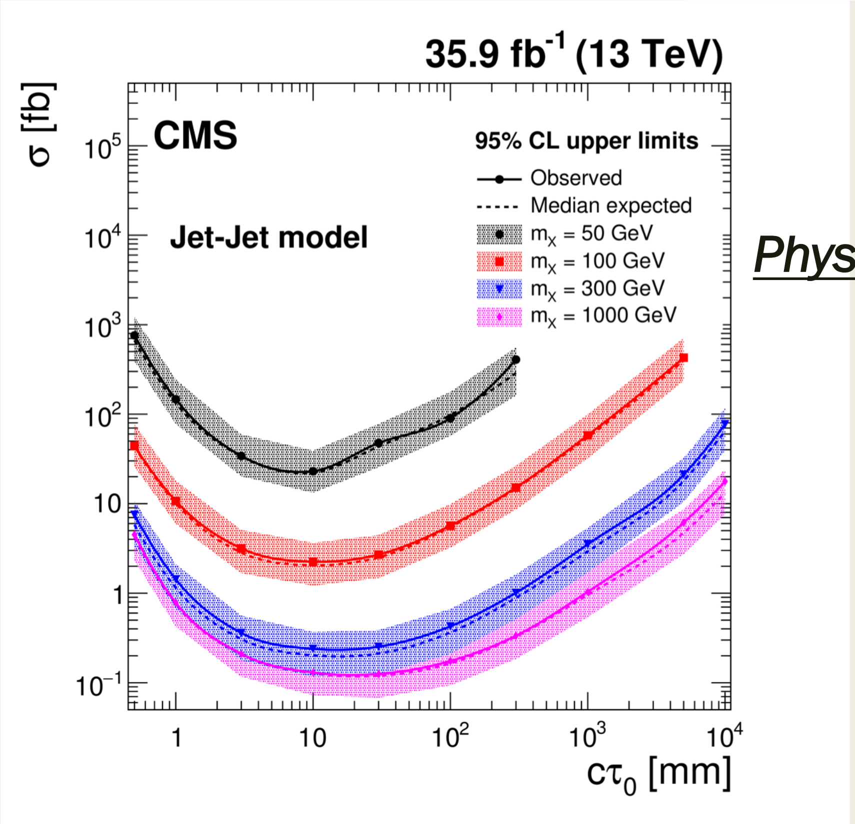
The search uses the timing of energy deposits in the EM calorimeter to select delayed jets from the decays of heavy long-lived particles. Results consistent with the background prediction.

Long-lived particles decaying into displaced jets









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For a simplified model in which long-lived neutral particles are pair produced and decay to two jets, pair production cross sections larger than 0.2 fb are excluded at 95% confidence level for a long-lived particle mass larger than 1000 GeV and proper decay lengths between 3 and 130 mm.

Dark Interactions workshop series at BNL

- Started in 2014
- It is biennial
- 70-80 experts in the field gather for 3.5 days
  - *Talks and discussions*
  - *Exchanges of ideas*
  - *Networking and scientific collaboration*
- 4th in the series planned for 2020
- Organized at BNL
  - *In collaboration with BNL theory group and other institutes*

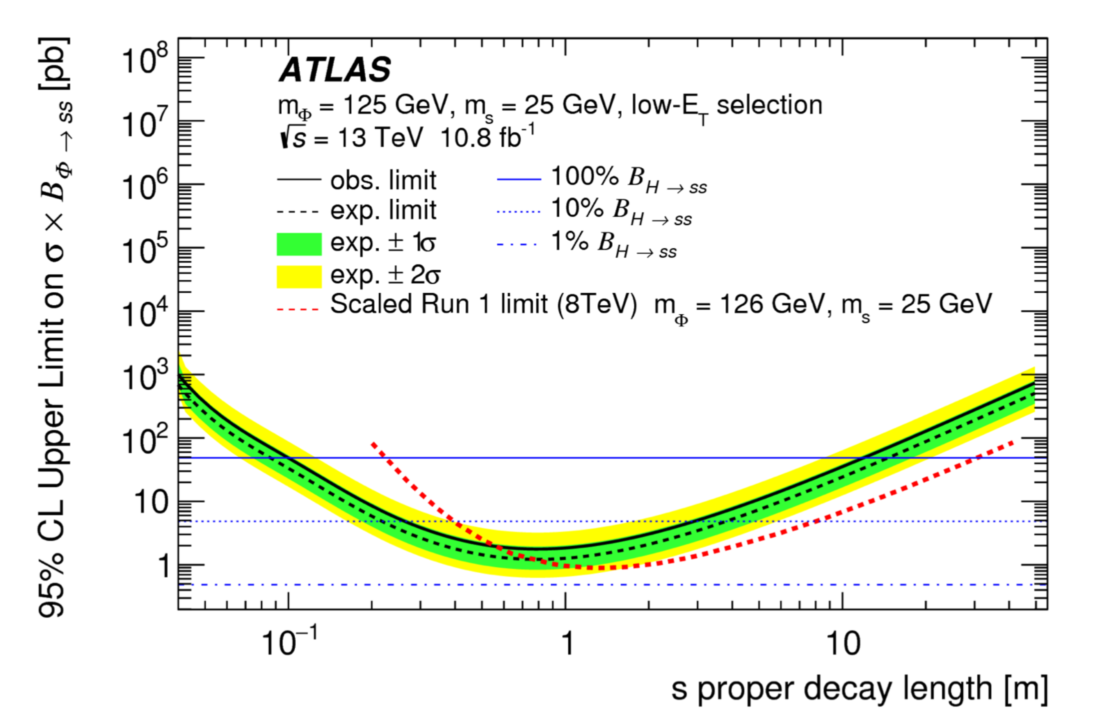
Conclusions

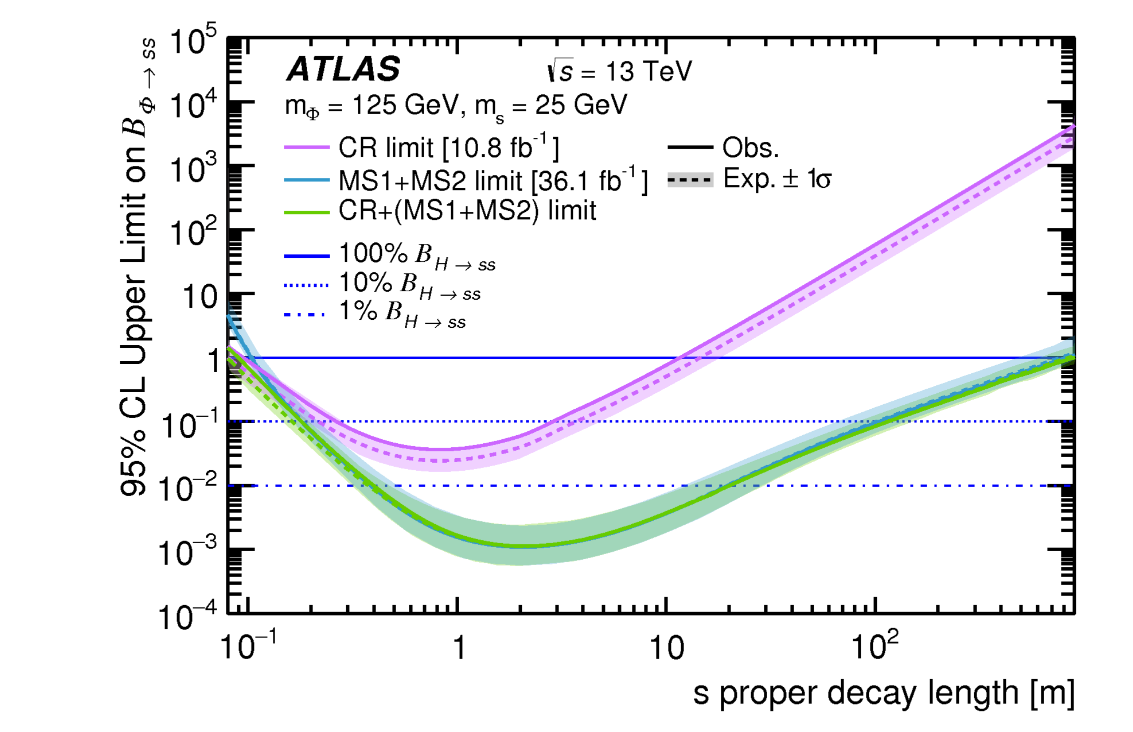
- Many searches for dark sector states have been performed at the LHC
- No significant signals have been observed
- Upper bounds placed on cross sections times branching ratios
- Results interpreted in various models to constrain model parameters
- The searches for dark sector states continue

Additional Materials

Long-lived particles decaying in the ATLAS calorimeter

- Long-lived particles occur in many extensions to the SM and may elude searches for new promptly decaying particles. The analysis considers neutral, long-lived scalars with masses between 5 GeV and 400 GeV, produced from decays of heavy bosons with masses between 125 GeV and 1000 GeV, where the long-lived scalars decay into Standard Model fermions





Trigger efficiency of simulated signal events as a function of the LLP p_T

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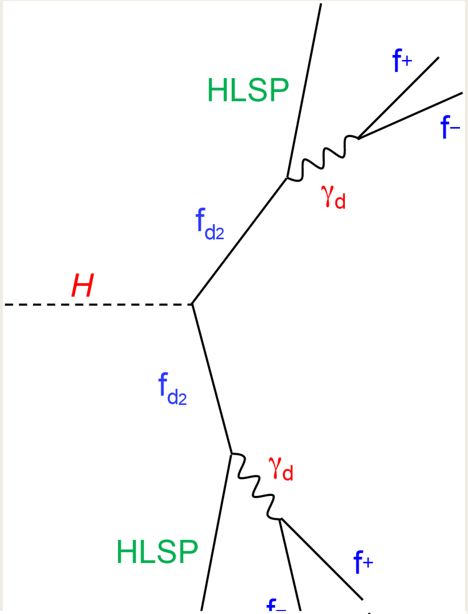
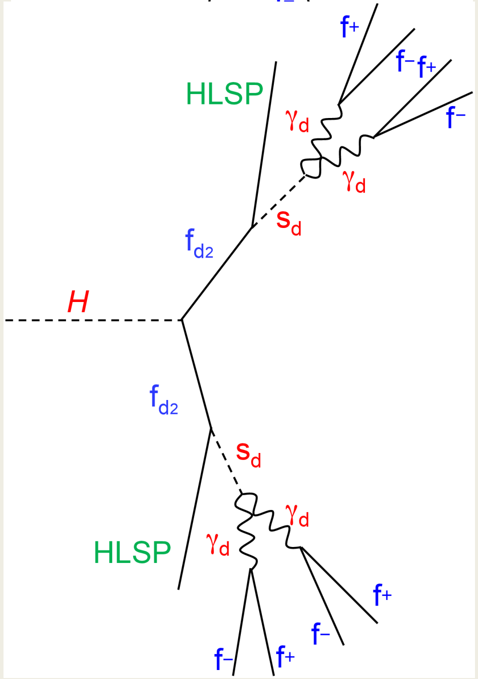
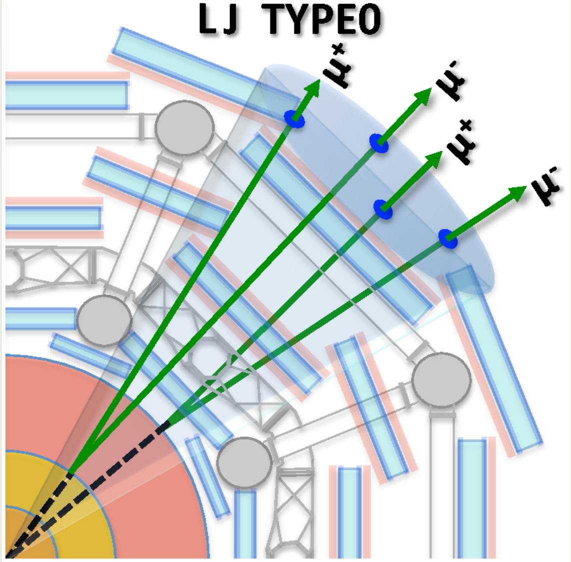
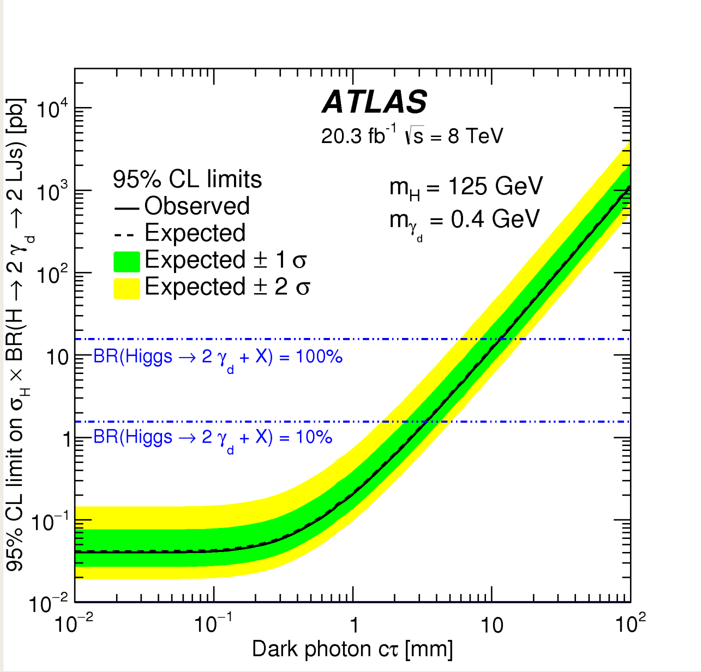
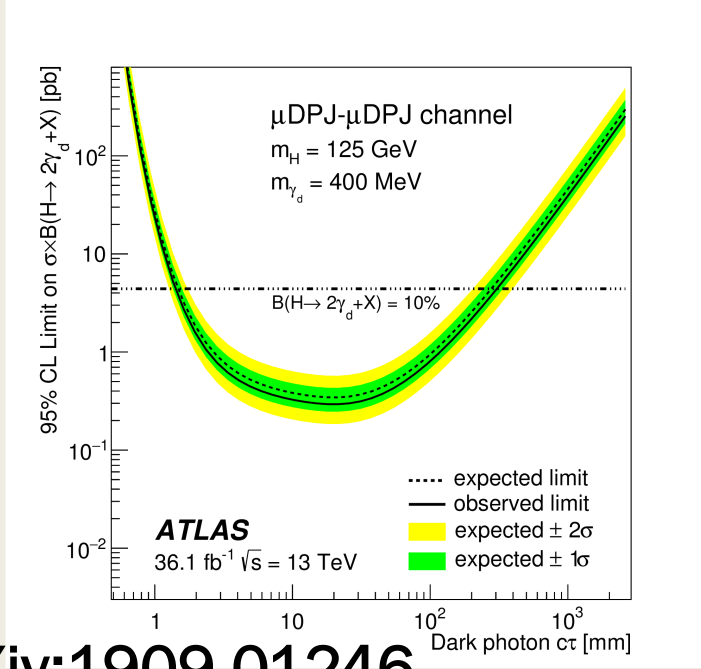
Prompt or displaced Lepton-jets





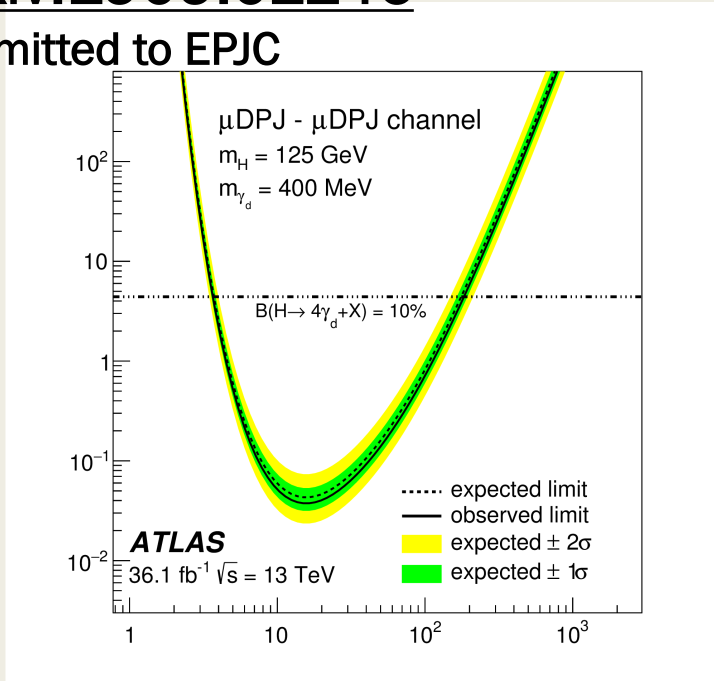






arXiv:1909.01246

submitted to EPJC



H → invisible particles – coupling combination

ATLAS BR(h⟶invisible) direct search in VBF channel (8 TeV)

Results	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ	Observed
SR1	0.35	0.49	0.25	0.67	0.19	0.30
SR2	0.60	0.85	0.43	1.18	0.32	0.83
Combined Results	0.31	0.44	0.23	0.60	0.17	0.28

VBF

JHEP 01 (2016) 172

VBF + VH (Z→ll, V→jj): BR_{INV} < 0.25. The use of the measured visible decay rates in a more general coupling fit improves the upper limit to 0.23

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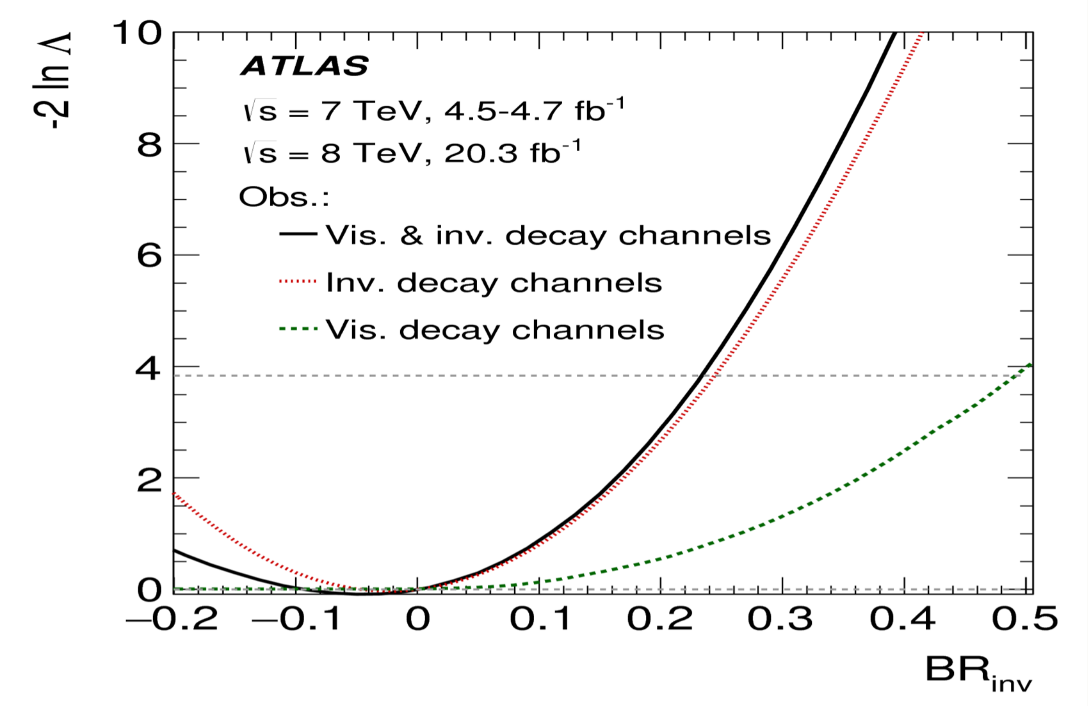
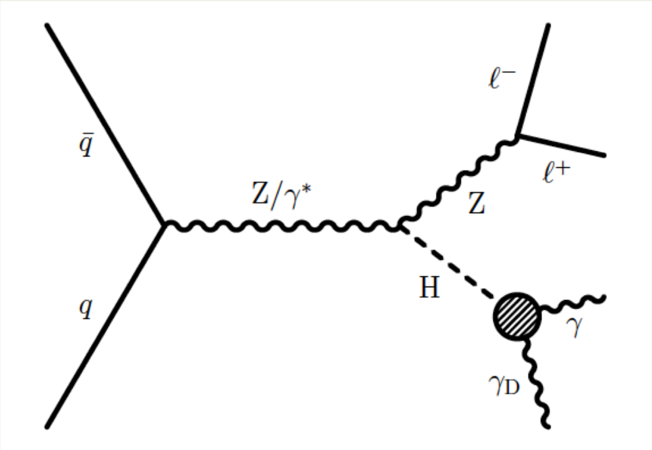


Search for massless dark photons in resonant monophoton signatures from Higgs boson decays

Motivations to Dark Photon searches	Analysis overview	Plans
❑ Dark sector might contain light or massless gauge bosons mediating long-range interactions between dark particles. ❑ Many dark photon proposals were introduced to improve astroparticle and cosmology models ❑ Massless dark photons provide a unique signature to test the dark sector and its possible connection to the Standard Model.	Looking for massless dark photon in ZH production mode:  ❑ Lower cross section compared to VBF mode. ❑ Cleaner signal with highly efficient online lepton trigger.	❑ Ongoing analysis with full LHC Run 2 data of ~150 fb-1 ❑ The aim is to provide the best limit on the branching ratio of H->γ+γ_d using an model independent search. ❑ Prospect of theoritical interpretation combining ATLAS DM searches and dark photon results.

Hassnae El Jarrari, Mohammed V University, Rabat Morocco, on a 3-month visit to BNL