University of Victoria

Exploring the Dark Sector with the ATLAS Detector

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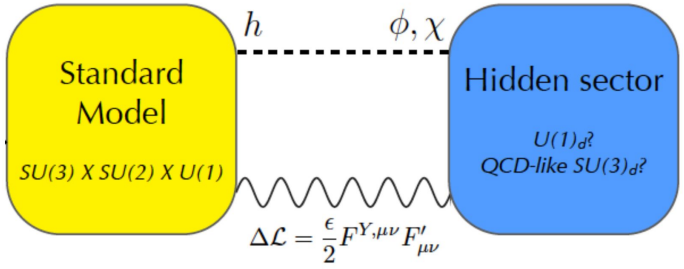
On Behalf of the ATLAS Collaboration

PASCOS 2021

The Dark/Hidden Sector

- What if new physics, such as Dark Matter (DM), exists in a hidden sector, composed of particles which don't undergo SM gauge interactions?
  - Coupling to SM encoded in a mixing term in the Lagrangian
  - May communicate with the SM via mediators, which could be DM candidates OR provide 'portals' to them



1608.08632

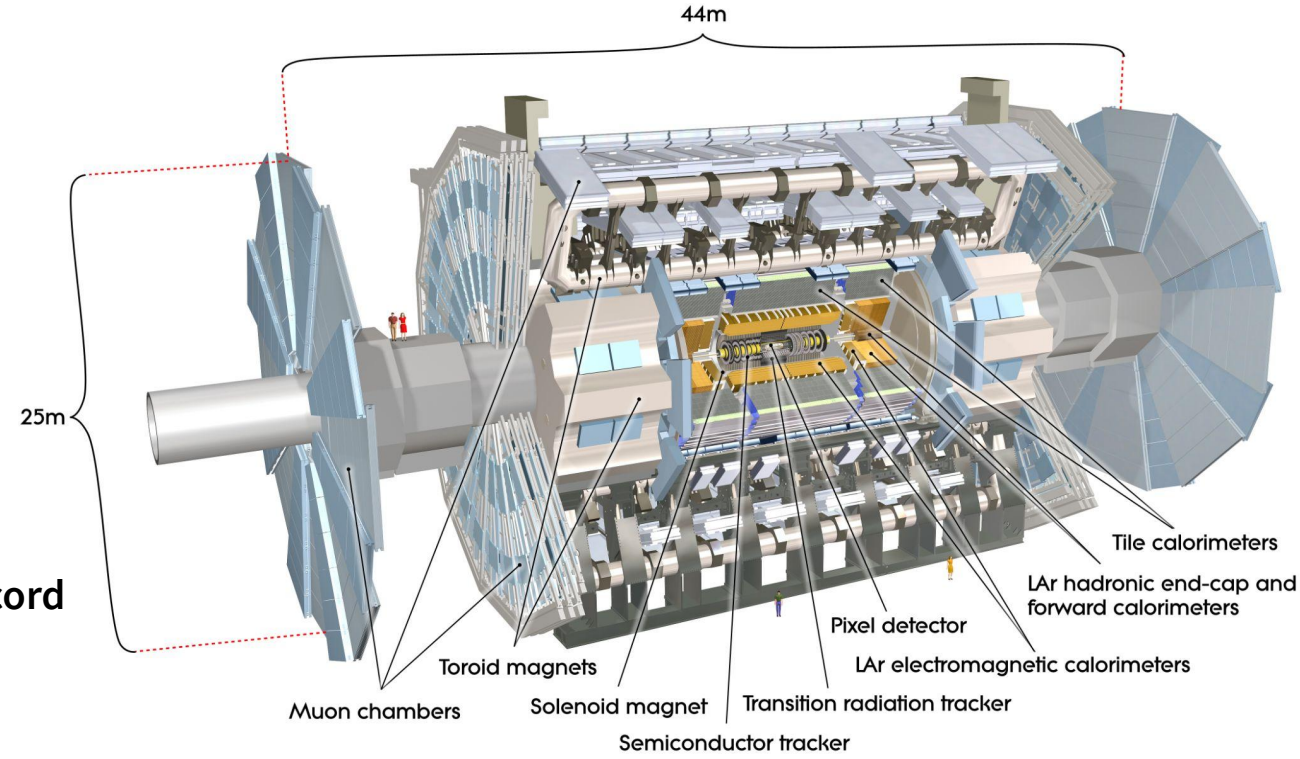
$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}\,, & \text{axion portal.} \end{cases}$$

→ vector A′ → dark Z, dark ɣ
→ scalar ϕ → dark H
→ fermion, N → sterile neutrino
→ pseudo-scalar, α → axion

- Limited ways in which the hidden sector and SM can communicate, many leading to unconventional signatures at the LHC
  - Focus on such signatures in this talk, though many other DM searches out there (e.g. MET+X, SUSY...)

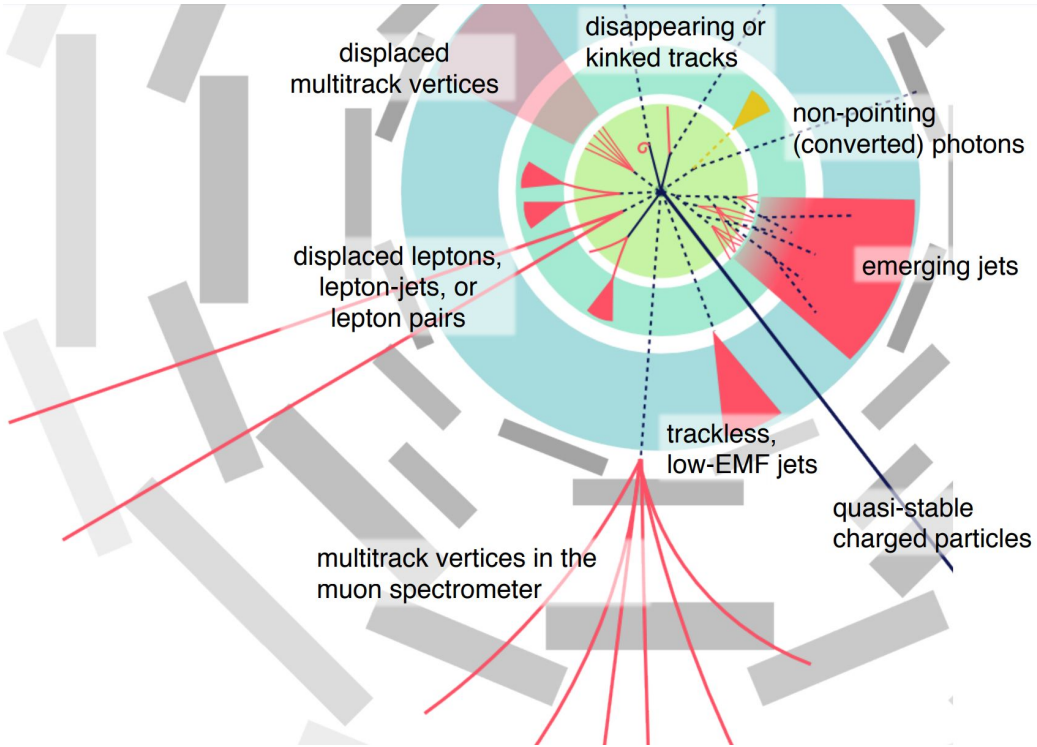
The ATLAS Detector

- General purpose, hermetic detector
- Inner detector (ID), electromagnetic & hadronic calorimeters (ECAL & HCAL), muon spectrometers (MS)
- Two-level trigger system (hardware & software) to record data at 1 kHz (from 40 MHz bunch crossing rate)



Unconventional Signatures

- Weak coupling to the SM leads to long-lived-particles (LLPs)
- Many possible unconventional signatures
- Detecting these can come with experimental challenges
  - Non-standard trigger requirements
  - Decays far from the primary vertex (PV), requiring special tracking
  - Unusual shower shapes in calorimeters, unique fractions of ECal/HCal energy
  - Need for timing information, which is not available in all subdetectors...

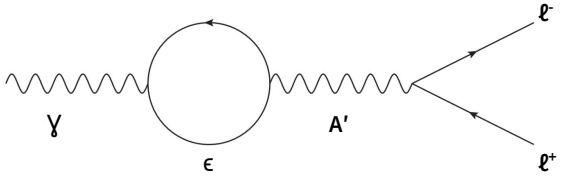


J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

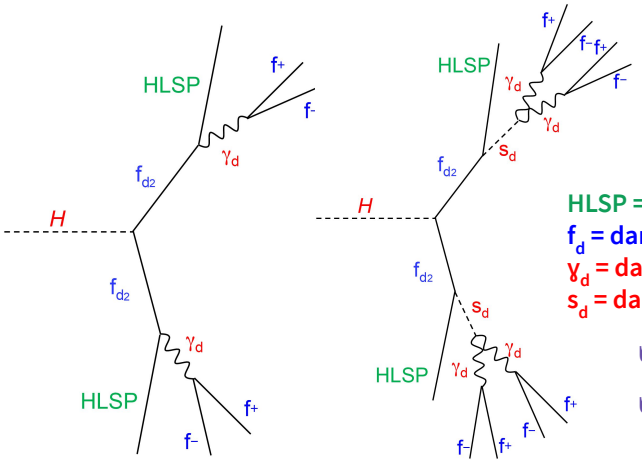
Dark Photons, A′

Eur. Phys. J. C 80 (2020) 450

- U(1) extension of the SM, introducing a hidden gauge boson γ_d, kinetic mixing with SM
  - Benchmark FRVZ model, with Higgs boson decaying to dark fermion pair



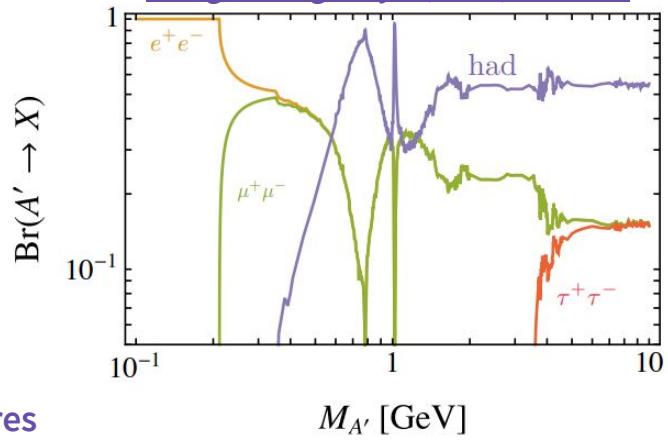
- Low mass A′ could be produced via cascade decays of heavier states
  - Leptonic decays of A′ are prominent in the low-mass range
  - Decay to highly collimated groups of leptons, or ‘lepton-jets’ (LJ)
  - A distinct LHC signature!



HLSP = Hidden Lightest Stable Particle
f_d = dark fermion
γ_d = dark photon
s_d = dark scalar

- Small mixing → long lifetime
- Prompt or displaced LJ signatures

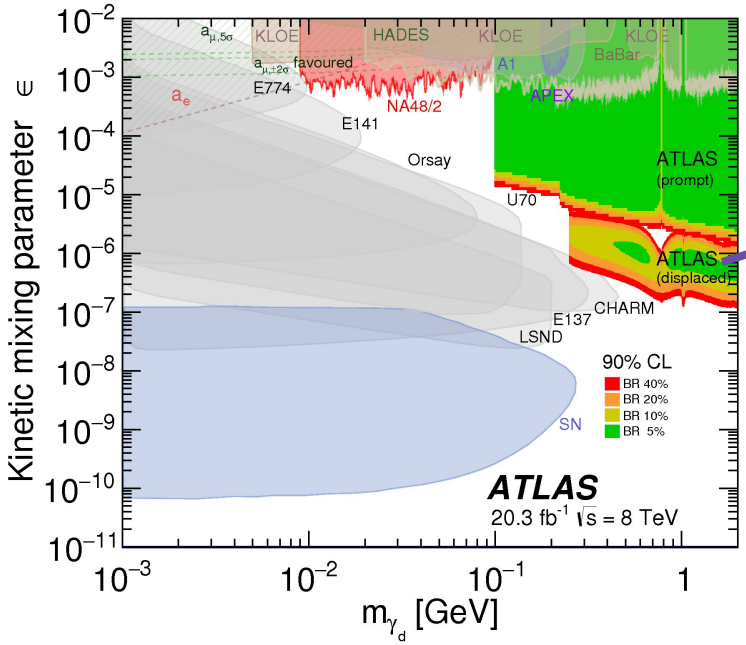
J. High Energ. Phys. (2018) 2018: 94

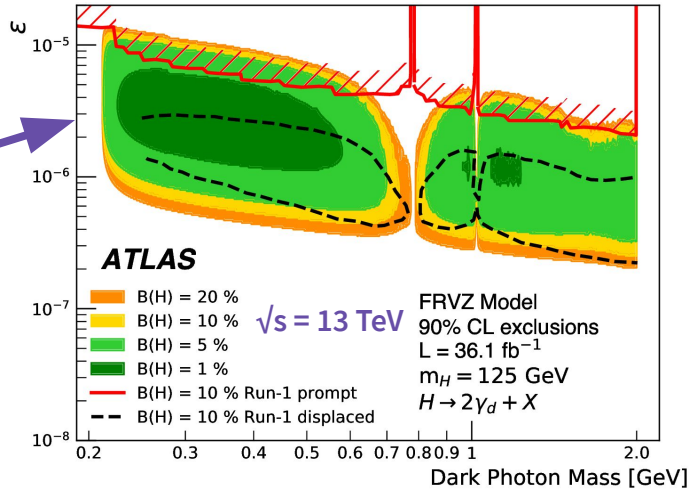


Prompt & Displaced Lepton Jets

Eur. Phys. J. C 80 (2020) 450
JHEP02(2016)062

- Produce limits on the kinetic mixing parameter and $m_{A'}$
  - Limits shown for $10\% \leqslant B(H \to 2\gamma_d + X) \leqslant 20\%$



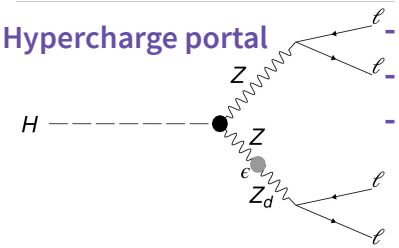


Complementary to fixed target/beam-dump experiments

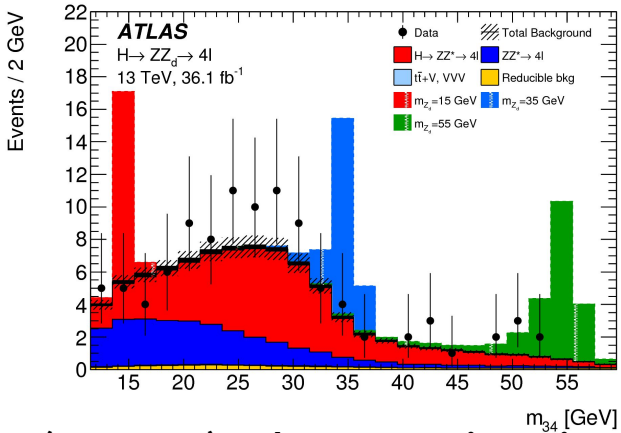
Exotic Higgs Decays

Higgs decays to 4 leptons via PROMPTLY decaying bosons

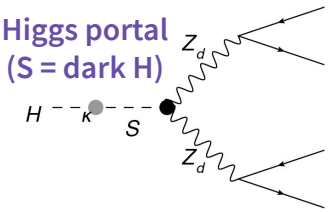
Hypercharge portal



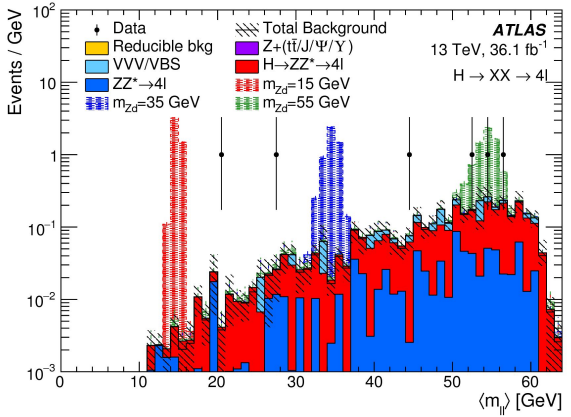
- $H \to ZX \to 4e/4\mu/2e2\mu$
- SR: $m_{4\ell} \in [115, 130]$ GeV
- Constraints on kinetic mixing (ε) and mass-mixing (δ) parameter



Higgs portal (S = dark H)



- High mass: $H \to XX \to 4e/4\mu/2e2\mu$ $15 < m_{ZD} < 62.5$ GeV
- Low mass: $H \to 4\mu$ $1 < m_{ZD} < 15$ GeV
- Veto at quarkonia mass resonances
- Constraints on Higgs mixing parameter (κ)



$\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{12}+m_{34})$, where m_{xy} = invariant masses of dileptons in a quadruplet and $|m_{12} - m_Z| < |m_{34} - m_Z|$

Exotic Higgs Decays

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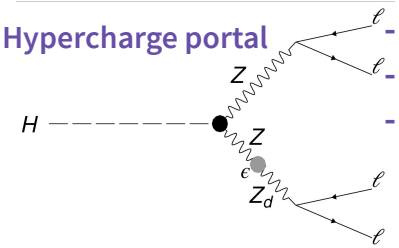

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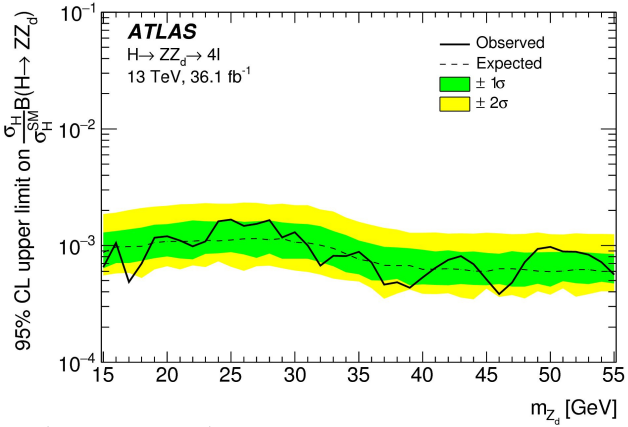

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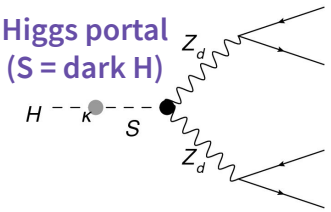

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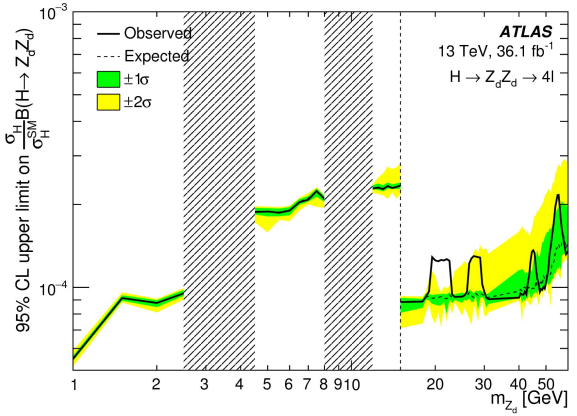

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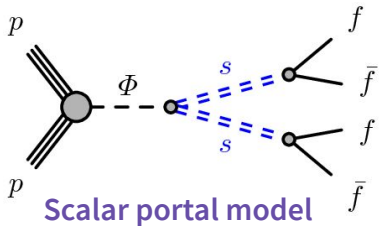
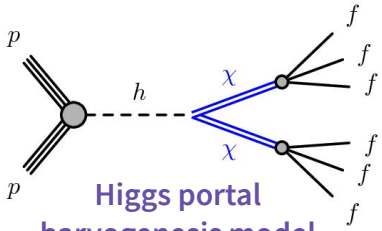
Displaced Vertices / Hadronic Jets

Phys. Rev. D 99, 052005 (2019)
Eur. Phys. J. C 79 (2019) 481
Phys. Rev. D 101, 052013 (2020)

- Long-lived particles (LLP) may decay to jets far from the interaction point (IP)
  - Standard jet reconstruction assumes ID tracks, common primary vertex…

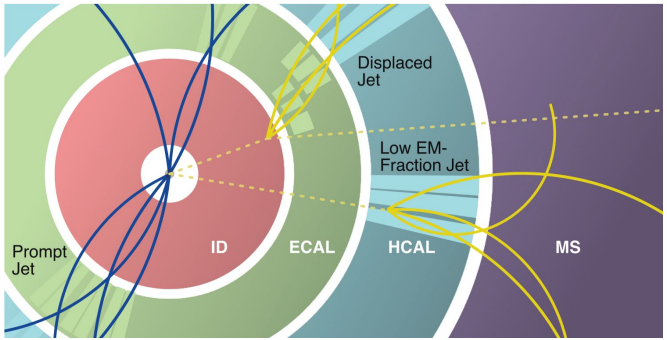


Scalar portal model



Higgs portal baryogenesis model

JPPNP 3695 (2019)



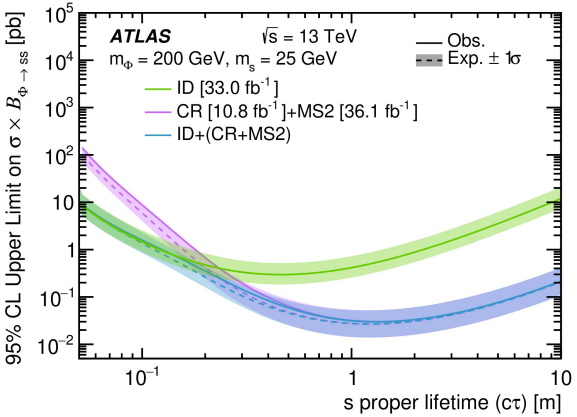
Many possible scenarios:

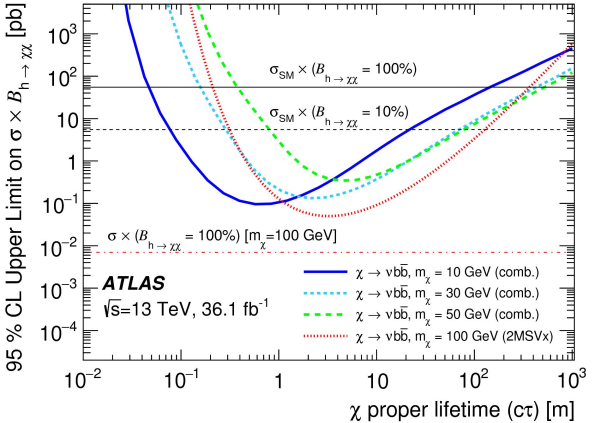
- Particle decays in the ID, but far from the IP / decays in the MS
  - MS-ID: ⩾ 2 jets in the ID and/or MS
  - Dedicated tracking algorithms for MS-only vertexing available (JINST 9 (2014) P02001)
- Particle decays in the middle of the calorimeters
  - CalRatio (CR): jet pair decaying in the HCal with no associated ID tracks
  - Large energy deposit in the HCal, small deposit in the ECal
  - Dedicated CalRatio triggers available (JINST 8 (2013) P07015)

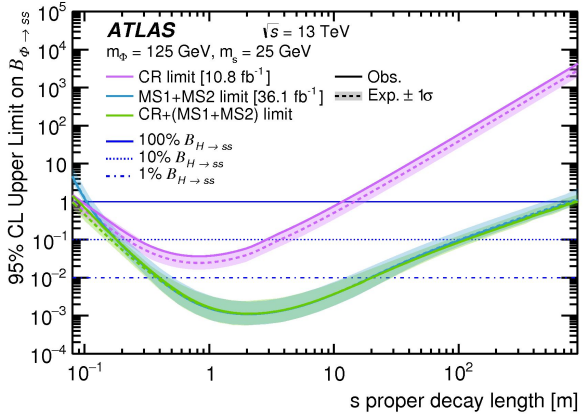
Displaced Vertices/Hadronic Jets

Phys. Rev. D 99, 052005 (2019)
Eur. Phys. J. C 79 (2019) 481
Phys. Rev. D 101, 052013 (2020)

- Search for pair-produced long-lived particles (LLP) produced by a Higgs boson / heavy scalar
  - Set limits on σ x B vs lifetime (cτ)







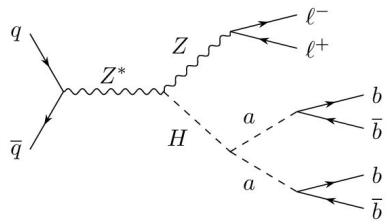
Phys. Rev. D 101, 052013 (2020)
- One LLP decays in ID, the other in MS
- Green = this search (ID)
- MS = Phys. Rev. D 99, 052005 (2019)
- CR = Eur. Phys. J. C 79 (2019) 481

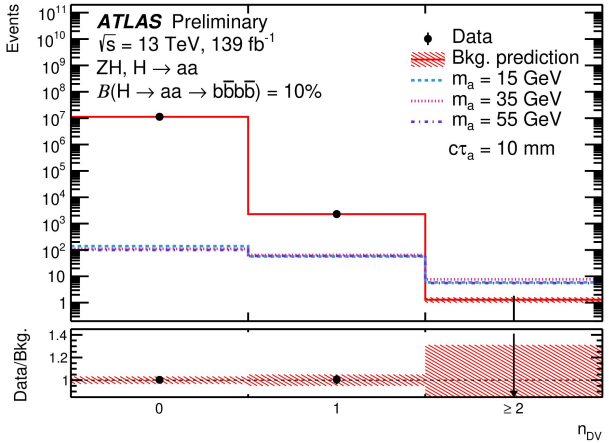
Phys. Rev. D 99, 052005 (2019)
- Two displaced vertices in the MS / one displaced vertex in the MS & some additional detector activity

Eur. Phys. J. C 79 (2019) 481
- LLPs decaying mainly in the HCal or at the outer edge of the ECal
- Use CalRatio

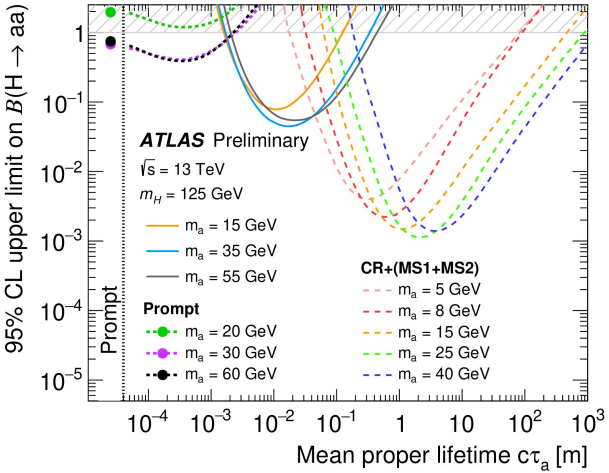
Displaced Vertices/Hadronic Jets

- Many BSM models predict exotic Higgs decays
- Can be difficult to trigger on decay products ∴ helps to look at associated production e.g. ZH mode
- Benchmark model: pseudoscalar with $15 < m_a < 55$ GeV & $10\ \text{mm} < c\tau_a < 1$ m
- Signature: 2 leptons & 2 displaced vertices (DV) in the ID
- Dedicated Large Radius Tracking (LRT) ATL-PHYS-PUB-2017-014 & secondary vertex reconstruction optimised for LLPs ATL-PHYS-PUB-2019-013





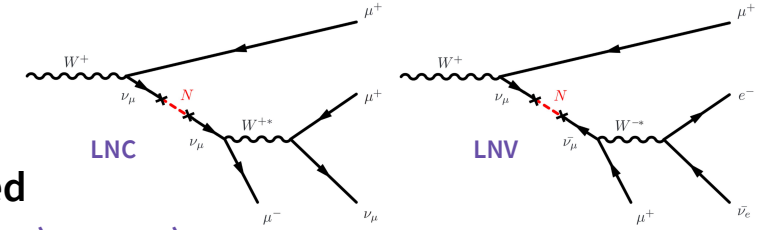
- Zero events observed in signal region
- Limits set on BR(H→aa→bbbb)
  - Most stringent limits in this lifetime regime for $m_a < 40$ GeV

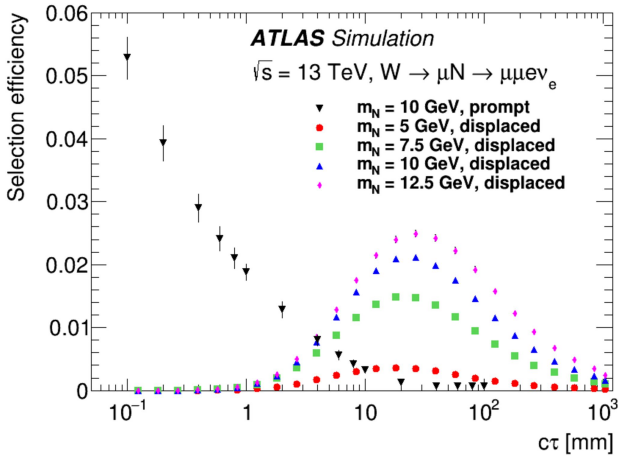


Heavy Neutral Leptons

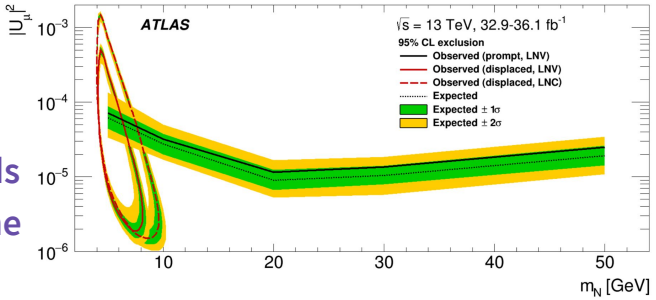
JHEP 10 (2019) 265

- Postulate new right-handed neutrinos with Majorana masses below the EW scale
  - Explain neutrino masses, matter-antimatter asymmetry, DM…
  - Decays may be lepton number violating (LNV) or conserving (LNC), depending on nature of neutrinos
- Both prompt & displaced leptonic decay signatures studied
  - Displaced vertex reconstruction algorithm (Phys. Rev. D 97 (2018) 052012)





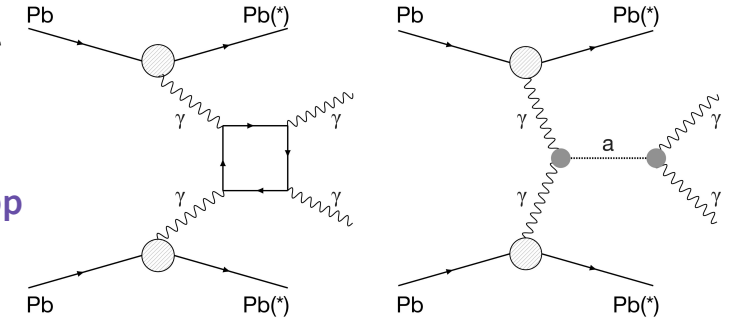
- Set limits on mass and coupling strength for prompt & displaced
- Displaced limit contour oblique ellipse approximately corresponds to HNL proper decay lengths in the range 1-30 mm

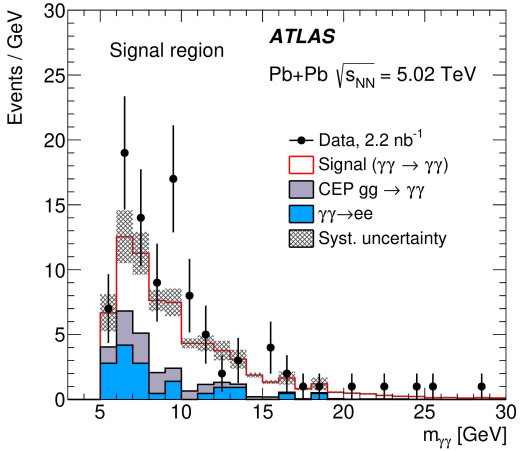


Axion-Like-Particles

JHEP 03 (2021) 243

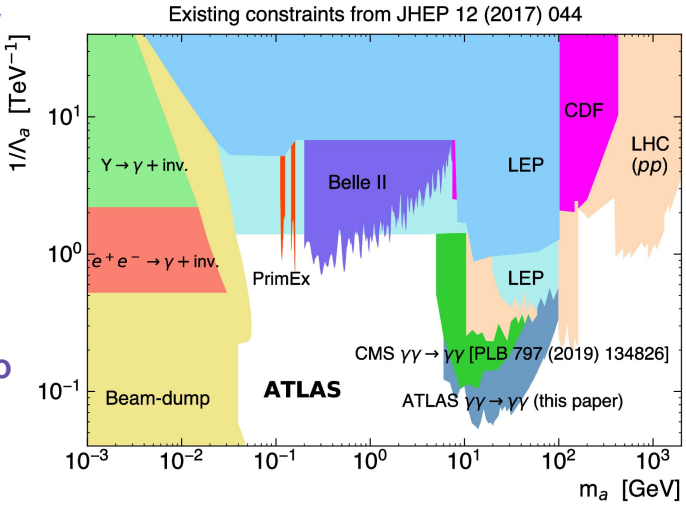
- Relativistic Pb nuclei can be treated as a beam of quasi-real photons
- Photon flux associated with each nucleus scales with Z^2
  - Light-by-light scattering cross-section strongly enhanced w.r.t pp collisions
  - This scattering may arise from SM QED box diagram OR an ALP
  - Look for narrow diphoton resonances in EM calo, little ID activity





Measured mass spectrum used to set limits on ALP mass

Exclusion limits in ALP-photon coupling vs ALP mass compared to other experiments



Conclusion & Outlook

- The Dark Sector search programme at ATLAS covers a diverse range of unconventional signatures

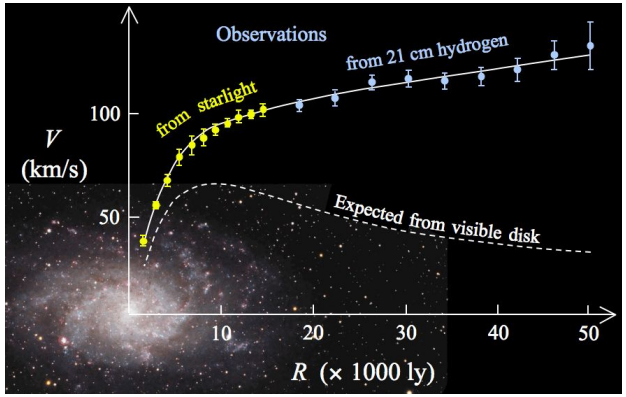
- These analyses hone our experimental techniques in the face of complicated final states
  - Using our detector in ways that were not considered in its design
  - Requiring non-standard triggers and reconstruction
  - Involving complex backgrounds, often requiring data-driven methods
  - Often left with small statistics to work with

- Still lots of potential to improve and cover more phase-space and models
  - Analyse existing data or re-interpret other studies (e.g. ATL-PHYS-PUB-2020-007)
  - Run-3 data taking starting next year, with an upgraded detector

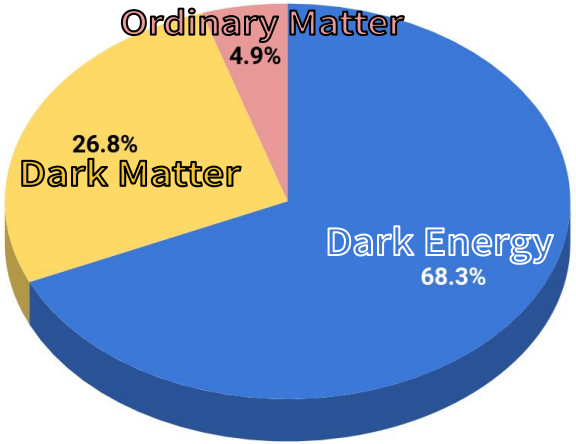
https://www.symmetrymagazine.org/article/voyage-into-the-dark-sector

Backup Slides

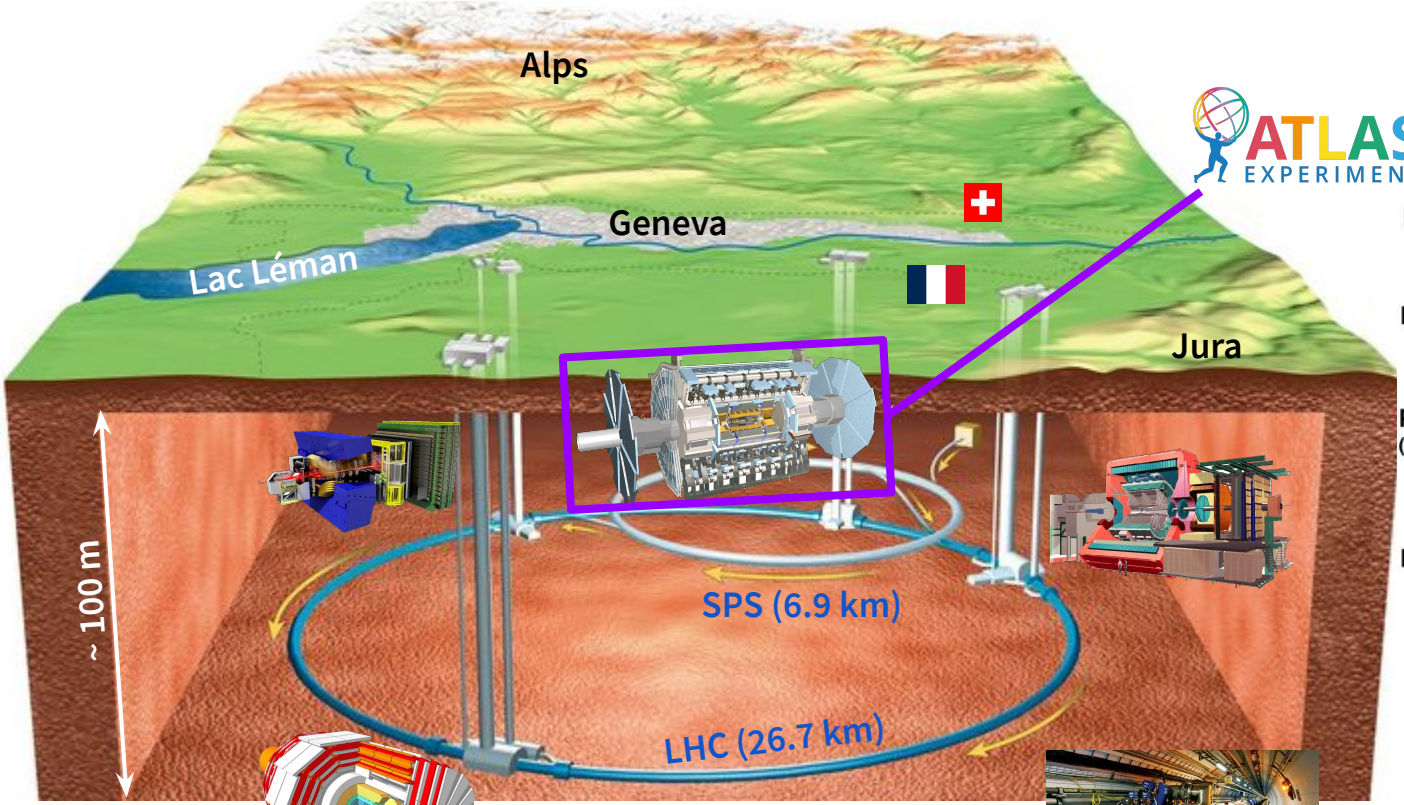
Hints at Dark Matter

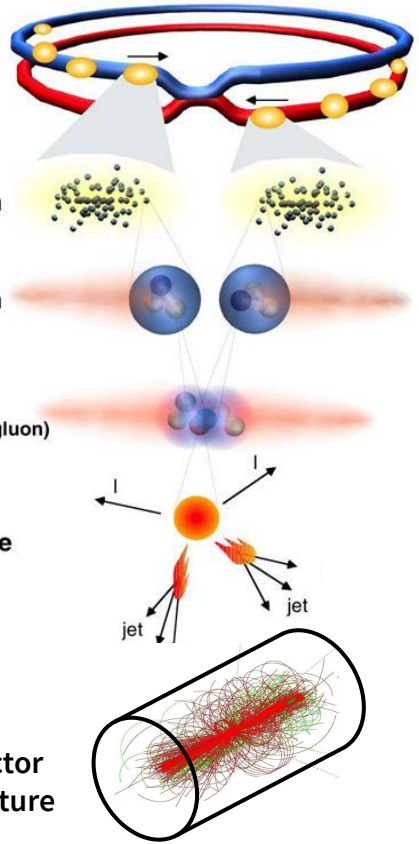


- A range of astrophysical measurements point to the existence of a non-baryonic form of matter (Phys.Rept.405:279-390,2005)
  - Galaxy rotation curves, gravitational lensing, colliding galaxy clusters…
- Weakly Interacting Massive Particles (WIMPs) are an attractive Dark Matter (DM) candidate, especially for the LHC
  - Lead to the correct relic density of non-relativistic matter
  - Non-gravitational interactions with the SM ∴ could be seen at colliders!!



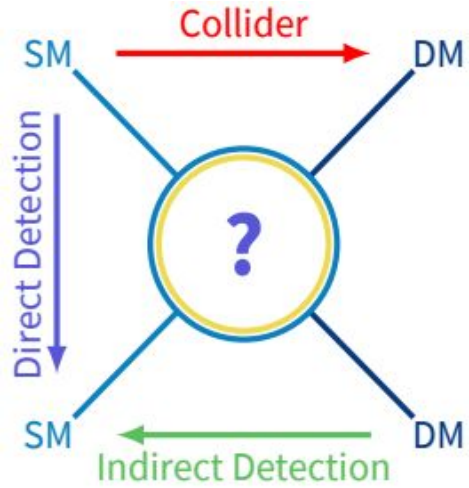
The Large Hadron Collider





Methods for Detecting Dark Matter

Various methods exist for detecting DM, covering different ranges of DM mass, m_χ



Direct Detection (DD):

➟ Nuclear recoil from elastic scattering

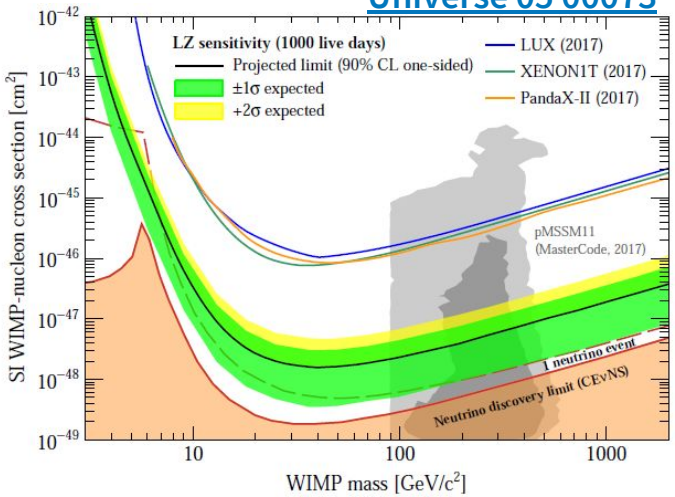
Indirect Detection (ID):

➟ DM annihilation

Collider Searches:

➟ DM production in high energy particle interactions

Universe 05 00073

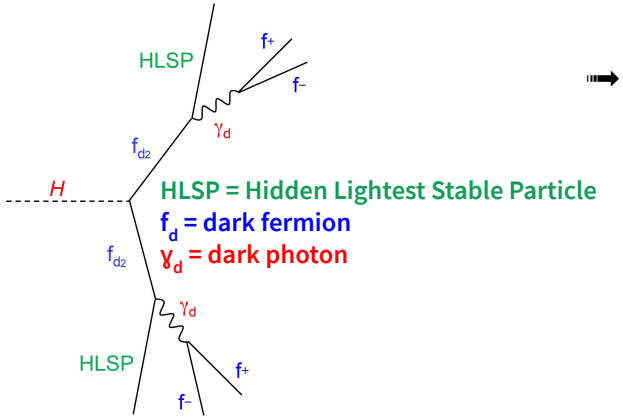


All three complementary methods continue to put mounting pressure on the WIMP hypothesis...

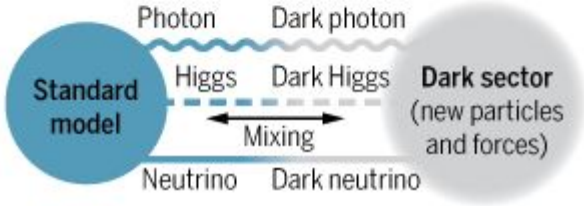
Dark Sector Searches

e.g. ATLAS: CERN-EP-2019-140 (dark γ)

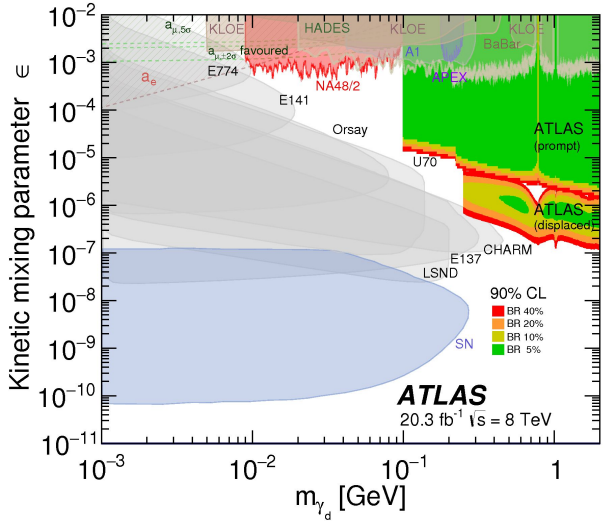
- What if DM exists in a hidden sector, composed of particles which don't undergo SM gauge interactions?
- Dark mediators could couple to SM via portal interactions
  - Coupling to SM encoded in a mixing term in the Lagrangian
  - Look for SM particles from DM decays via these portals
  - Set limits on coupling strength to SM… ε^2 (dark γ), f_a (ALPs)…
  - Small mixing → long lifetime



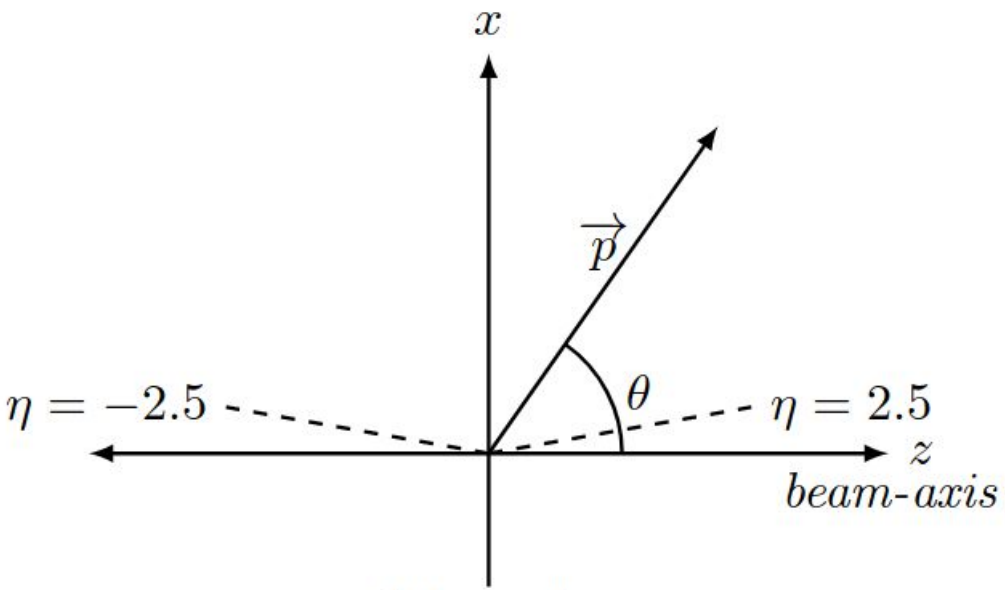
- LHC detectors can extend to high masses and low couplings
  - Complementary to fixed target/beam-dump experiments (JHEP02(2016)062)



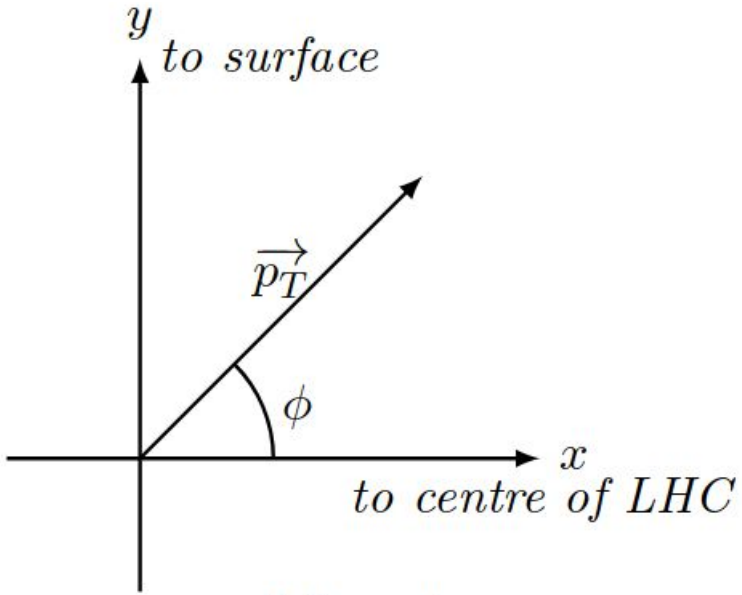
C.BICKEL/SCIENCE



LHC Coordinate System



(a) xz-plane

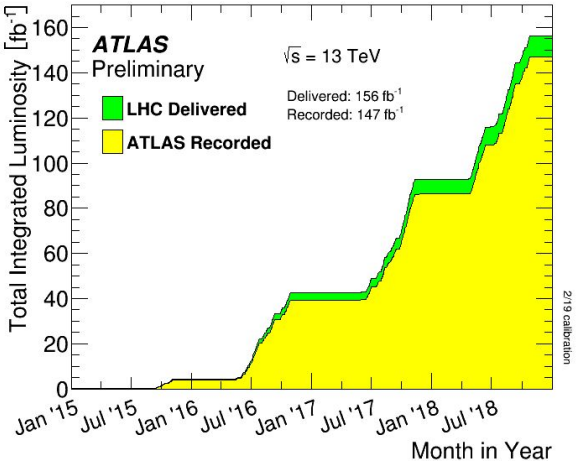


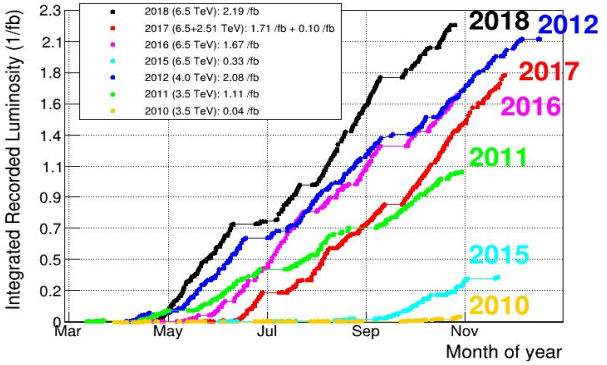
(b) xy-plane

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right)$$

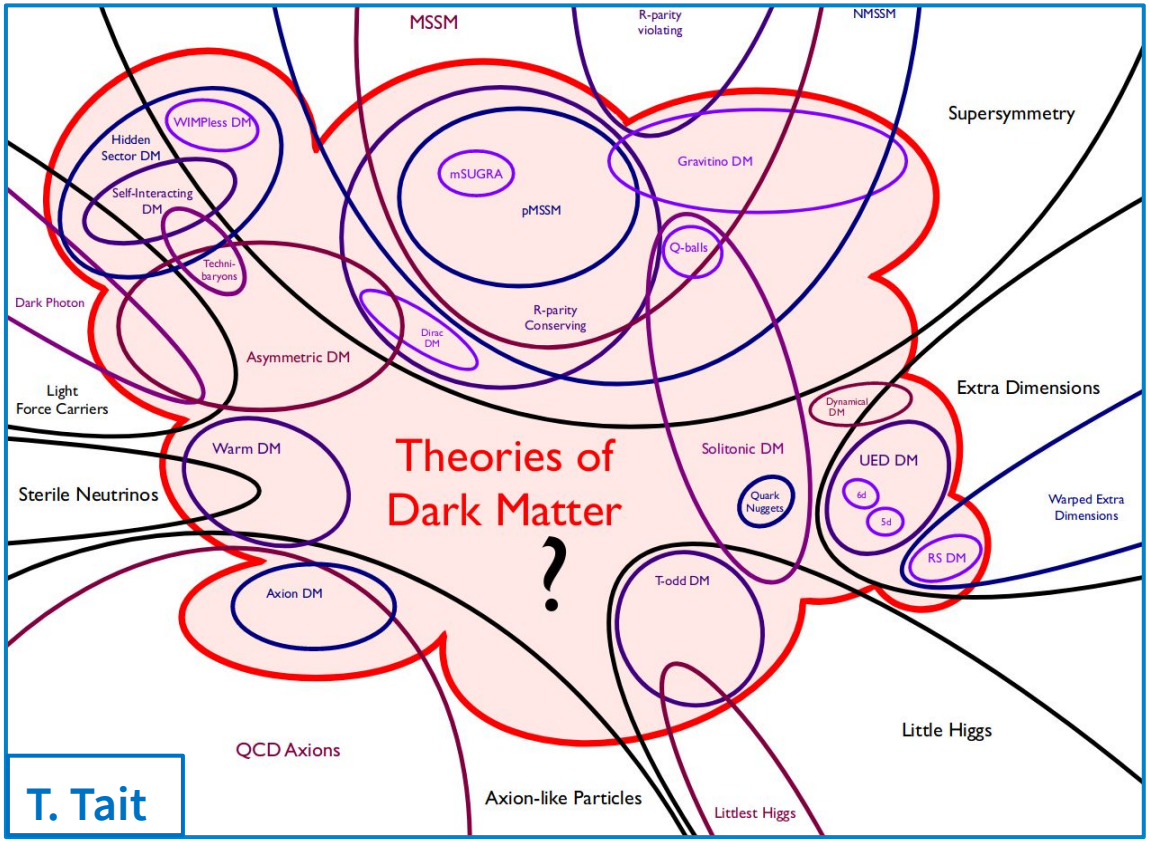
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

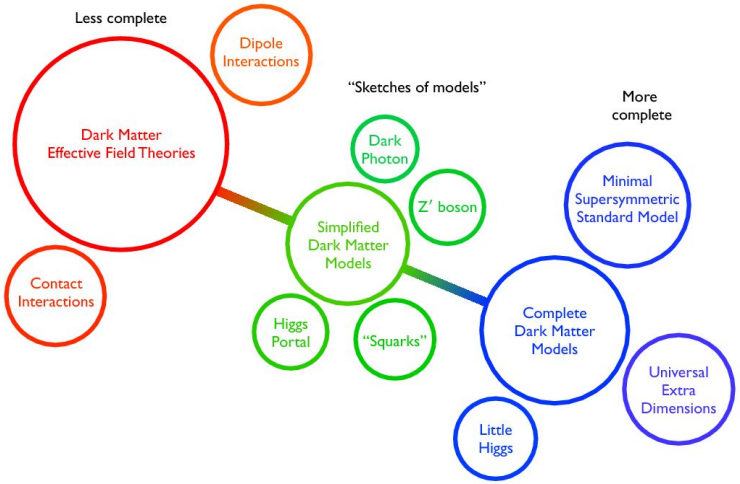
Recorded Integrated Luminosity





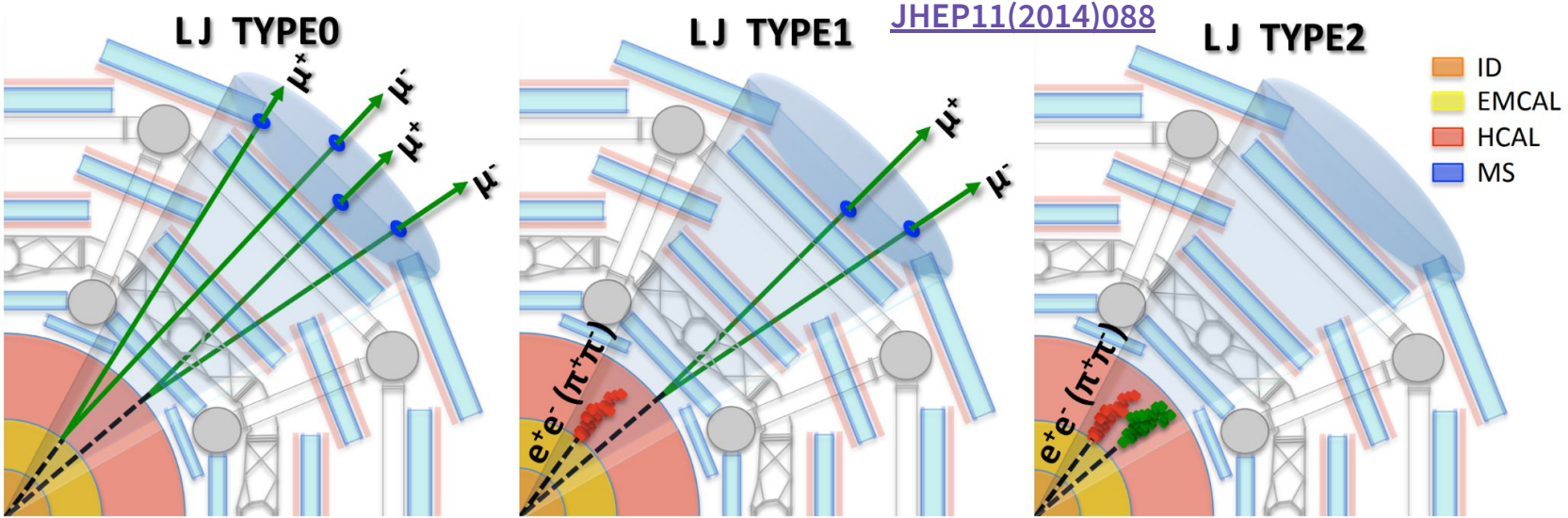
Theoretical Landscape of Dark Matter





Phys. Dark Univ. 9-10 (2015) 8-23

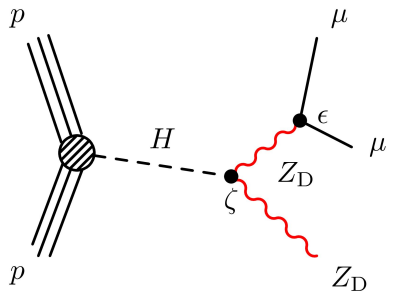
Prompt & Displaced Lepton Jets

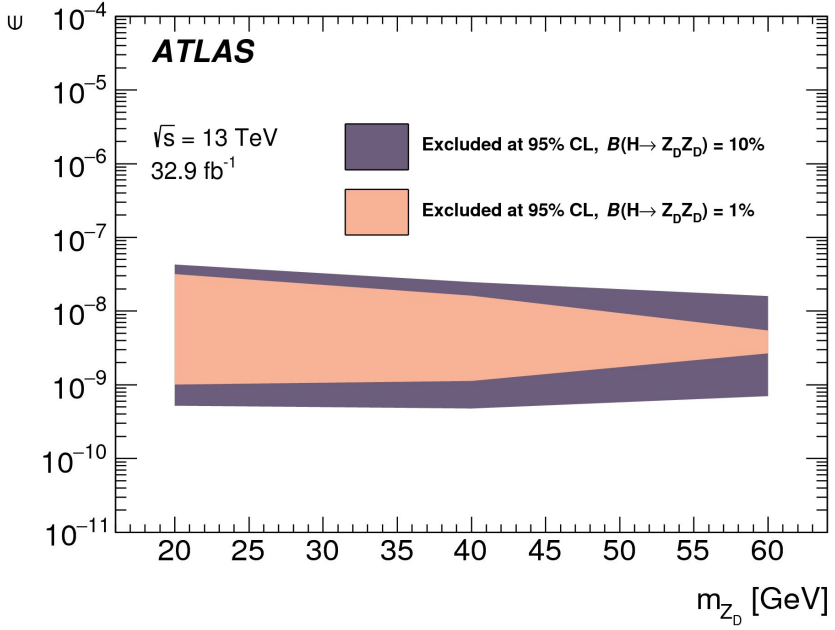


Displaced Muons

Phys. Rev. D 99, 012001 (2019)

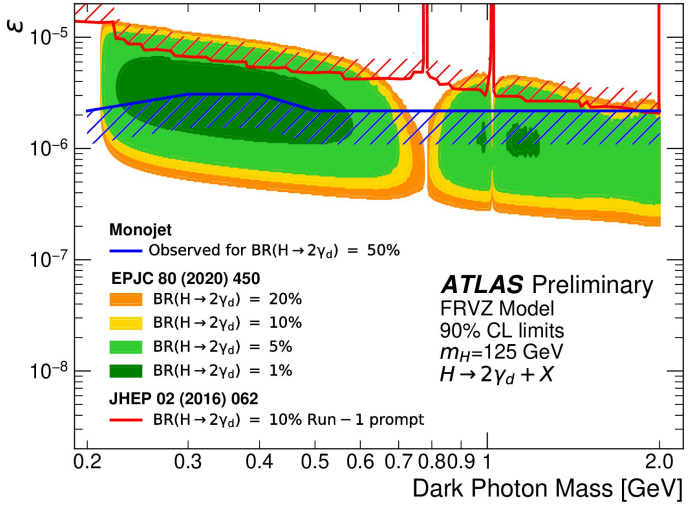
- Long-lived dark bosons produced from Higgs decay
  - Low mass search for OS di-muon not originating from IP
  - Exclude $\varepsilon < 10^{-8}$ for $20\ \text{GeV} < m^{Z_D} < 60\ \text{GeV}$

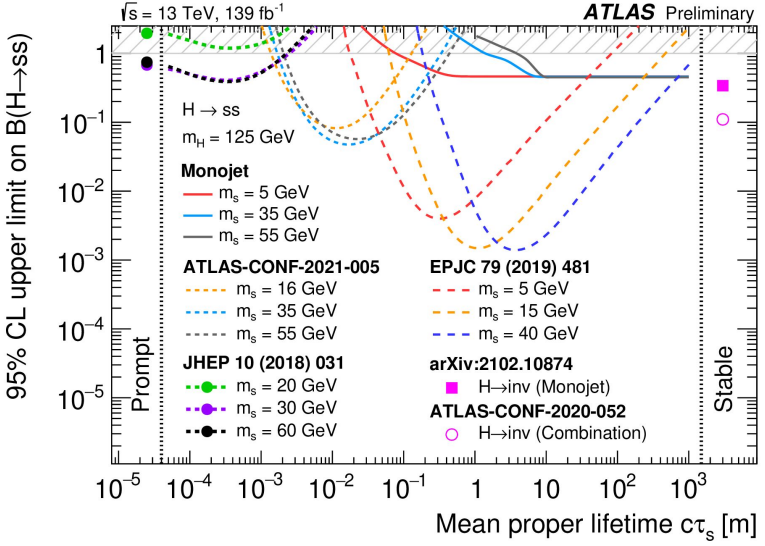




Re-Interpretations

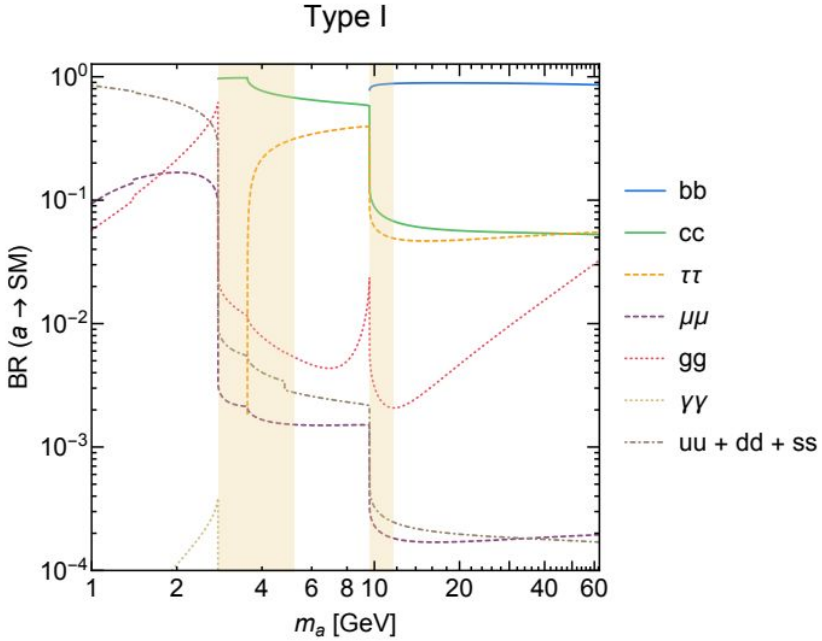
- Re-interpretation of full run-2 mono-jet search (Phys. Rev. D 103 (2021) 112006) using RECAST (JHEP04(2011)038)

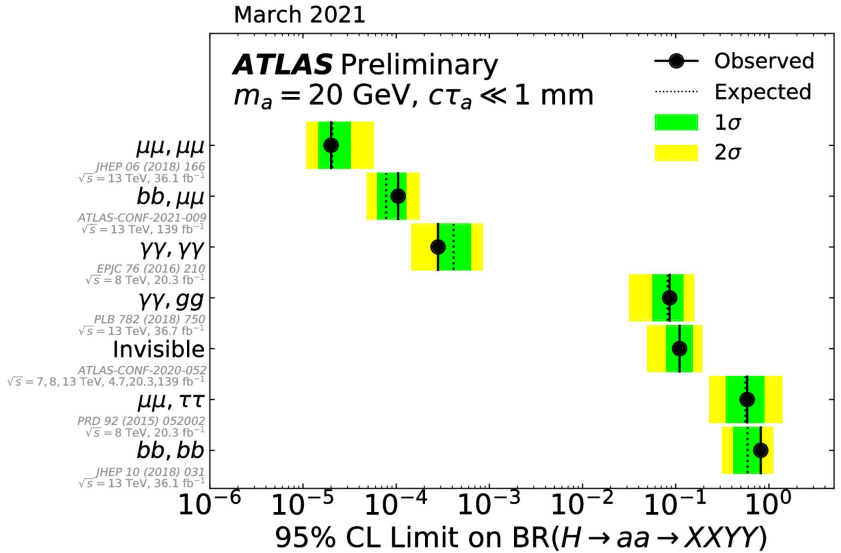




Exotic Higgs Decays to Pseudoscalars

➟ H → aa → XXYY could be a promising window to the dark sector

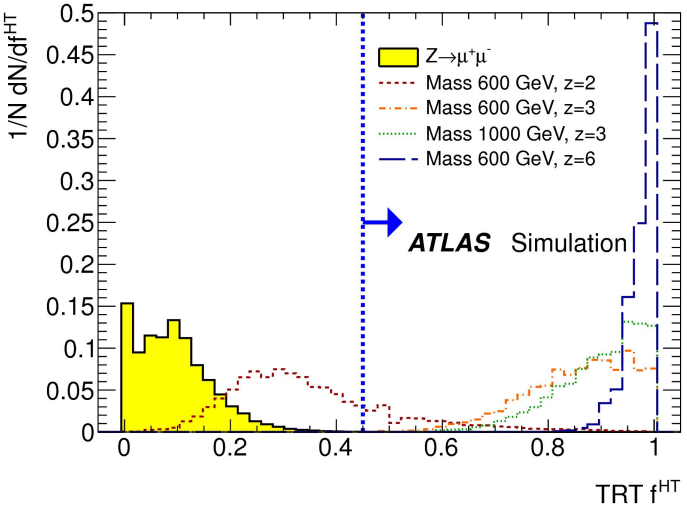


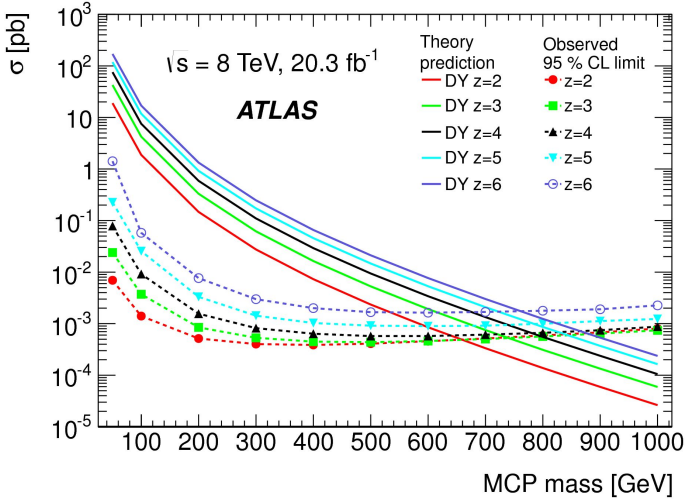


Phys. Rev. D 90, 075004 (2014)

Multi-Charged Particles

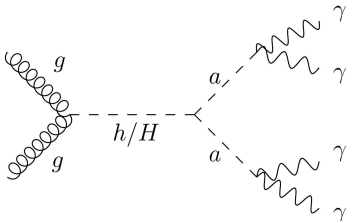
Eur. Phys. J. C (2015) 75:362

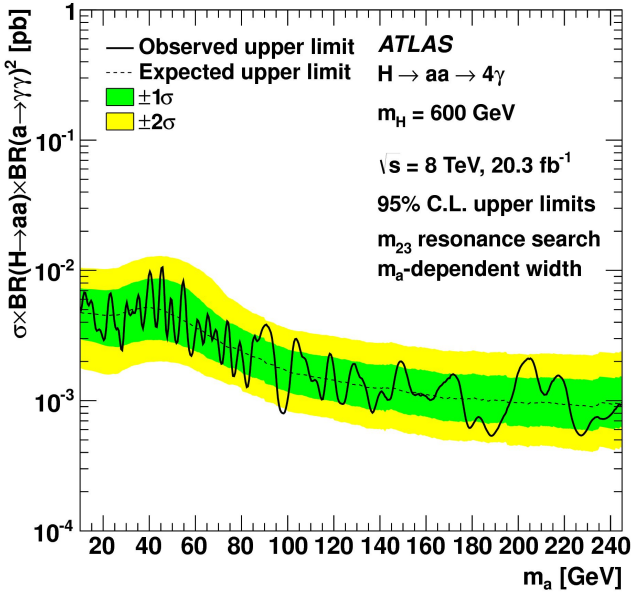


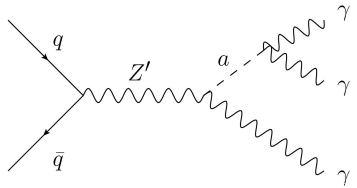


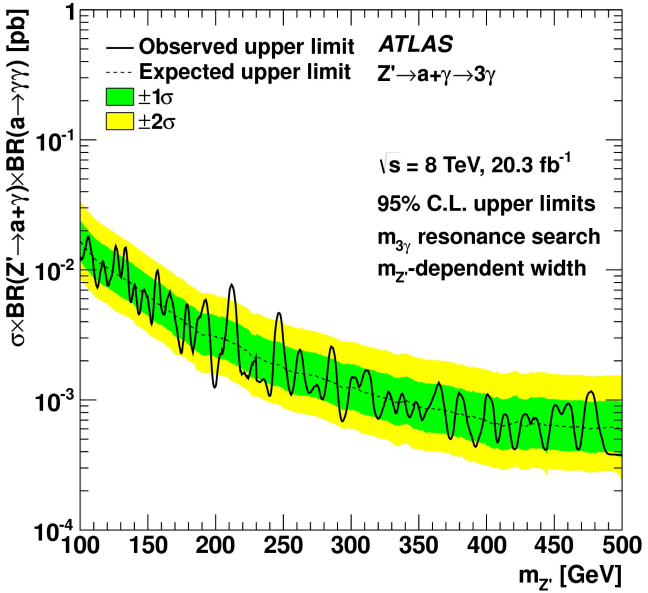
Multi-Photon Signatures

Eur. Phys. J. C 76(4) , 1-26 (2016)

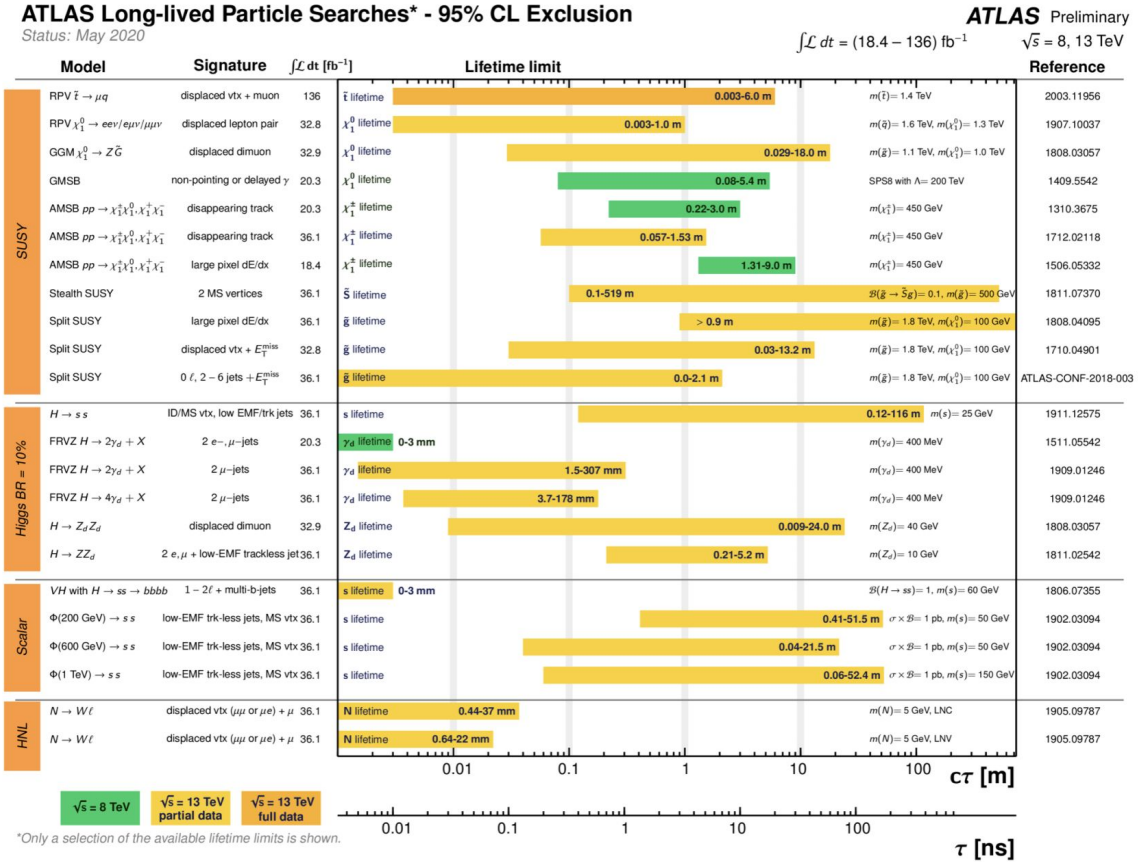








Summary of ATLAS Displaced Searches



Dark Energy

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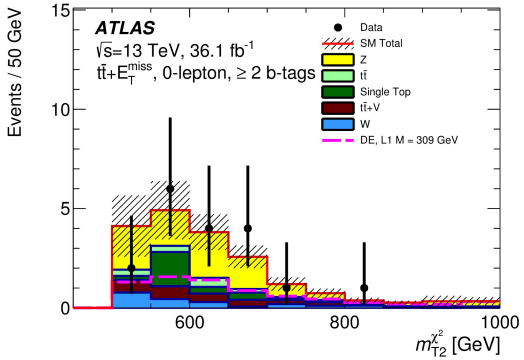
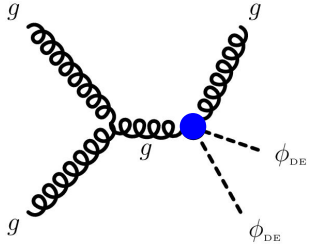
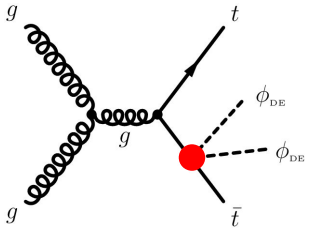


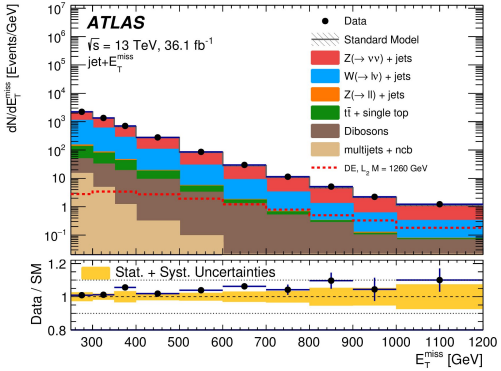
- Horndeski model in EFT
  - Introduce DM scalar, creating MET signature in colliders

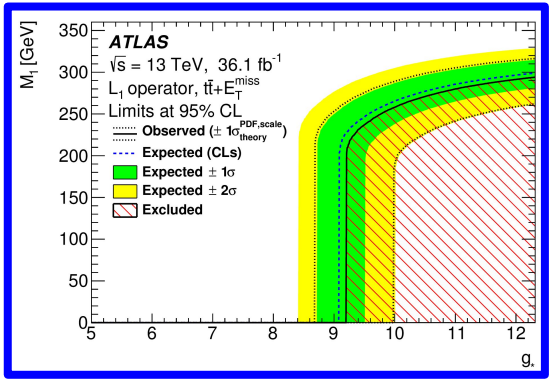


Disformal coupling $\mathcal{L}_1$

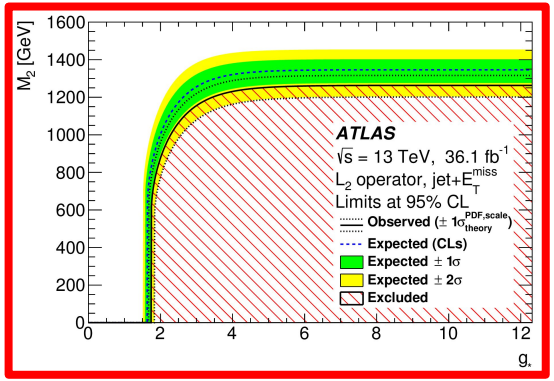


Conformal coupling $\mathcal{L}_2$





- Limits set on suppression scale (M) for least suppressed operators:
  - $\mathcal{L}_1$: coupling proportional to fermion mass, tt̄+MET
  - $\mathcal{L}_2$: coupling scales with momentum transfer, jet+MET
- g_* = effective coupling, UV completion



Dark Energy

- New mono-jet results with full run-2 data
- Set 95% CL limits on suppression scale
  - Horndeski DE with $m_\phi = 0.1$ GeV, $c_i \neq 2 = 0$, $c_2 = 1$
  - Suppression scales $M_2 \lesssim 1.5$ TeV excluded

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{9} c_i \mathcal{L}_i = \mathcal{L}_{\rm SM} + \sum_{i=1}^{9} \frac{c_i}{M_i^{d-4}} O_i^{(d)}, \qquad \mathcal{L}_1 = \frac{\partial_\mu \phi_{\rm DE} \partial^\mu \phi_{\rm DE}}{M_1^4} T^\nu_\nu$$

$$\mathcal{L}_2 = \frac{\partial_\mu \phi_{\rm DE} \partial_\nu \phi_{\rm DE}}{M_2^4} T^{\mu\nu},$$

d = operator dimension, c_i = Wilson coefficients, M = energy scale