Dark Matter Searches at the LHC

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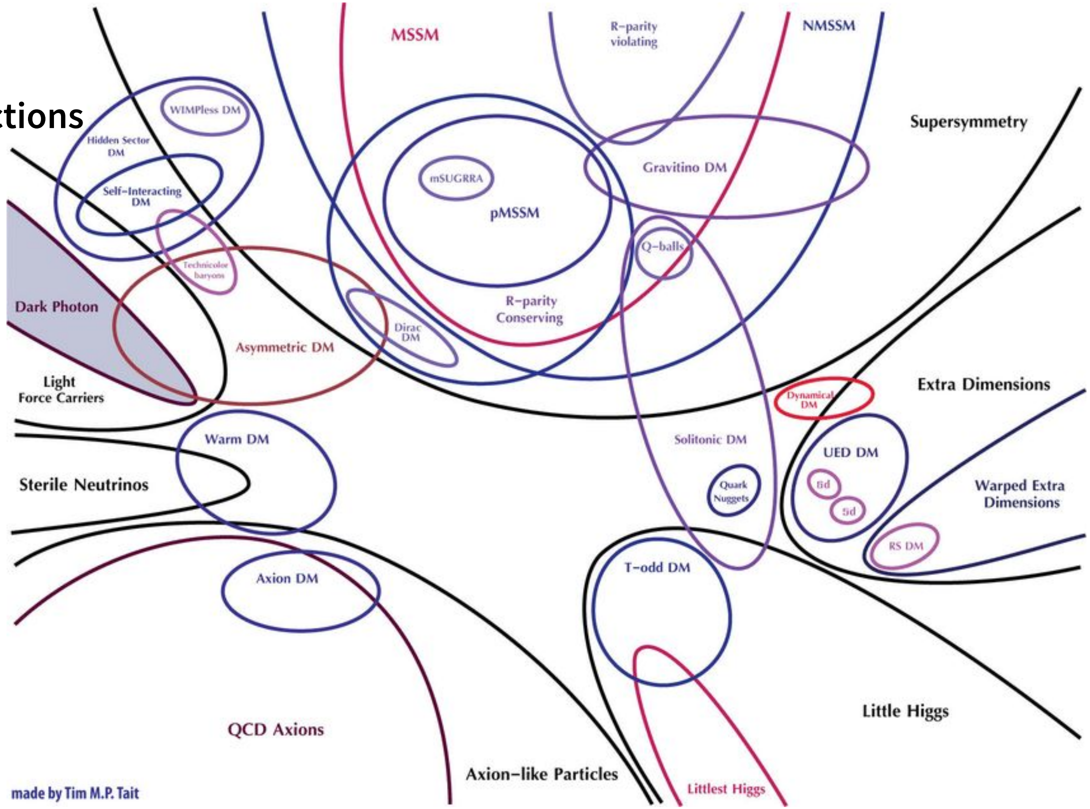
On behalf of the ATLAS & CMS Collaborations

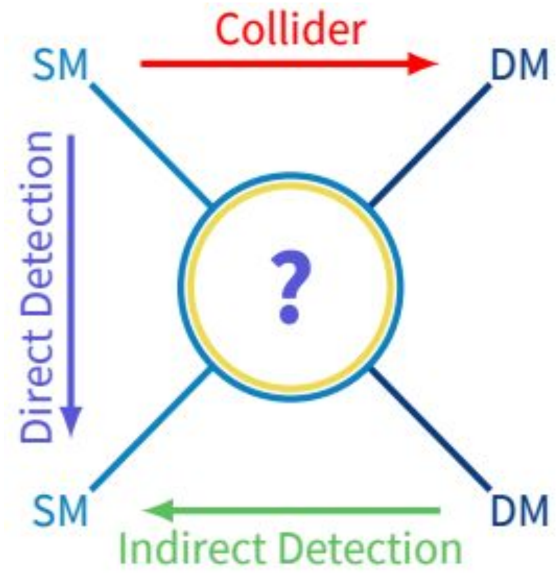
The Nature of Dark Matter

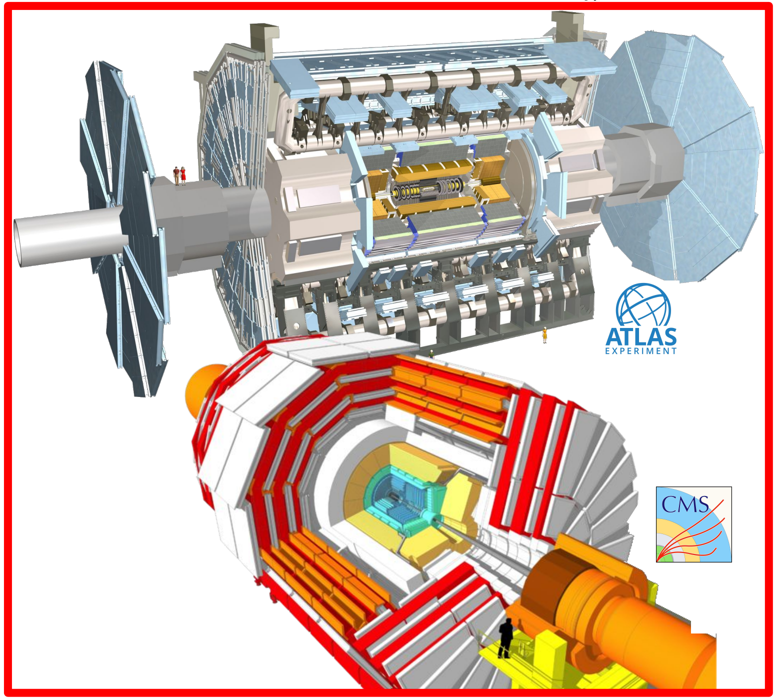
- What could DM be made of?
  - Only observed to have gravitational interactions
  - Has mass
- Non-baryonic?
  - Weakly Interacting Massive Particle (WIMP)
  - Axion-like-particle (ALP)
  - New neutrino (e.g. Majorana)
- Perhaps a whole <u>dark sector</u> consisting of many DM particles!



Collider Searches for Dark Matter

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

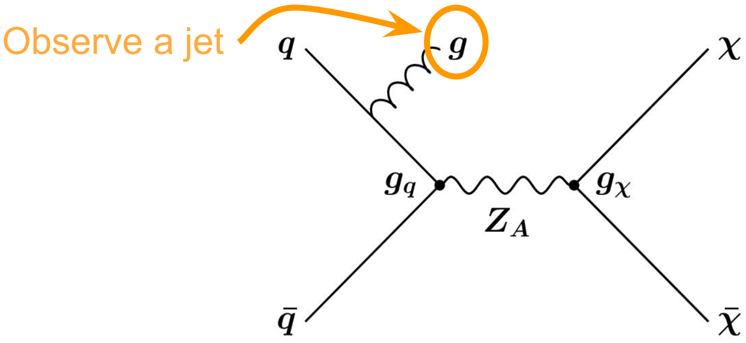


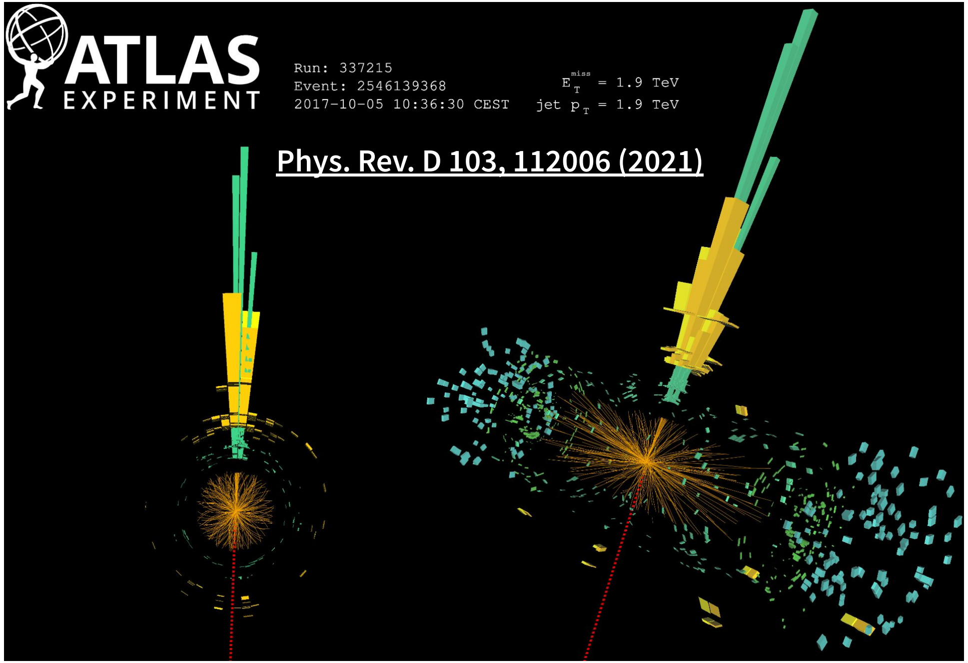


- ➢ Will discuss various <u>recent</u> results from the ATLAS and CMS detectors at the LHC

Dark Matter Detection: Colliders

- Produce DM (χ) in high energy proton collisions





- If DM only interacts through gravity… how do we detect it?
  - Momentum is conserved ∴ can infer missing momentum by measuring all detected particles

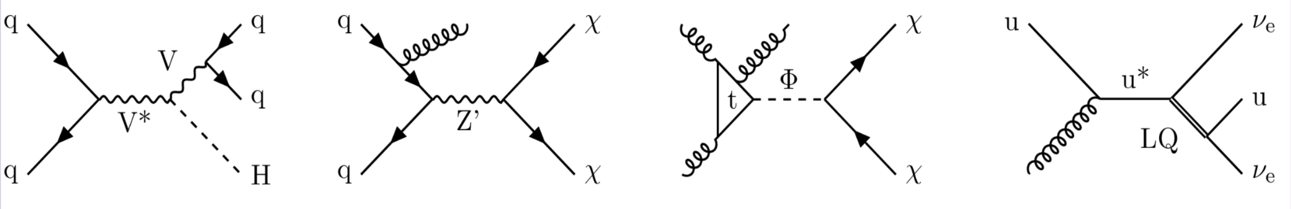
$$E_{\mathrm{T}}^{\mathrm{miss}} = \left| -\sum_{\mathrm{reconstructed}} \vec{p}_T \right| = -\sum_{\mathrm{calo}} \vec{E}_T^{\mathrm{calo}} - \sum_{\mathrm{MS}} \vec{E}_T^{\mathrm{MS}}$$

Missing transverse energy (MET/E_T^{miss})

Mono–jet/V

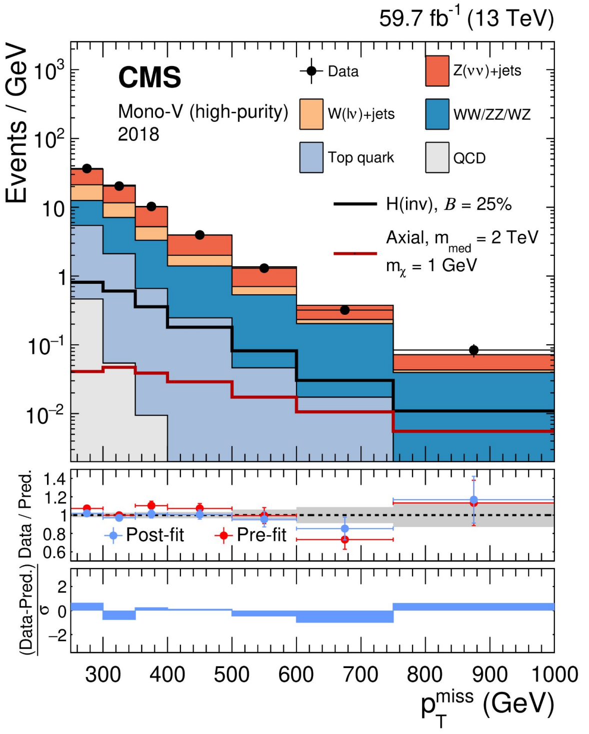
ATLAS: Phys. Rev. D 103, 112006 (2021)
CMS: JHEP 11 (2021) 153

Models



Selection

- Trigger on events with high p_T^{miss}
- Require an energetic jet/V(qq) & large p_T^{miss}, veto events with e/μ/τ/γ
- DEEPAK8 (ML algo) distinguishes between large-R jets from W/Z and narrow ISR jets
- Require large $\Delta\phi(p_T^{jet}, p_T^{miss})$
- Constrain backgrounds by defining 5 enriched control regions (CRs)
  - $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$ (ℓ=e,μ) & γ+jets
- Discriminant: p_T^{miss}



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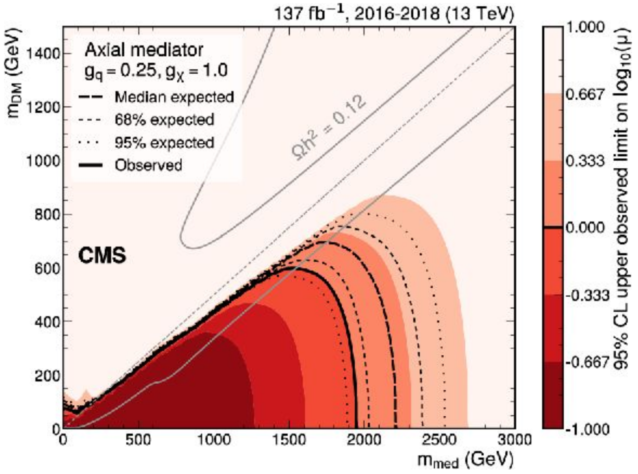
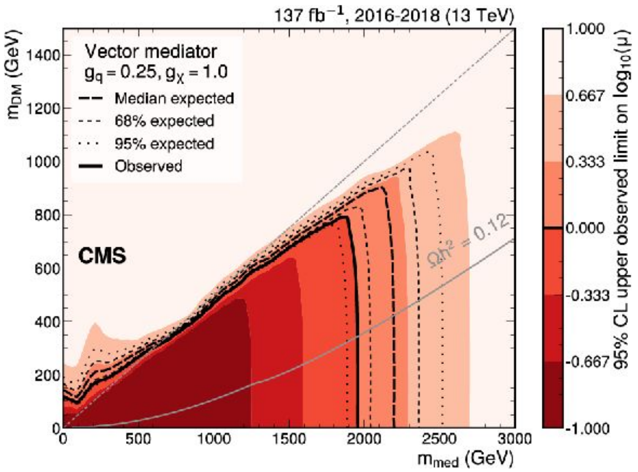
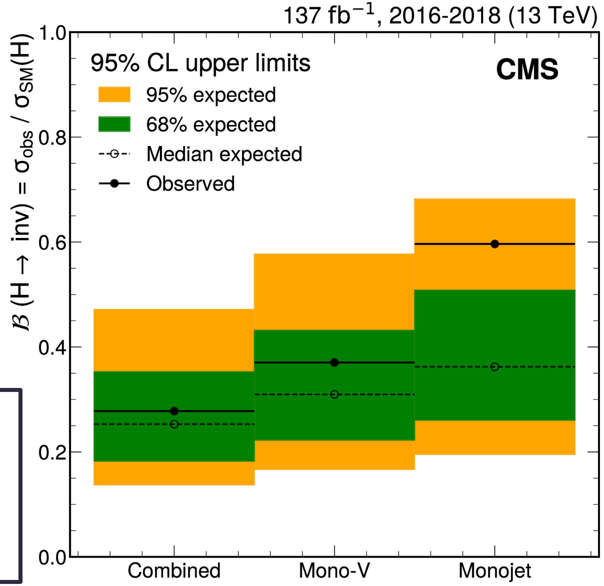




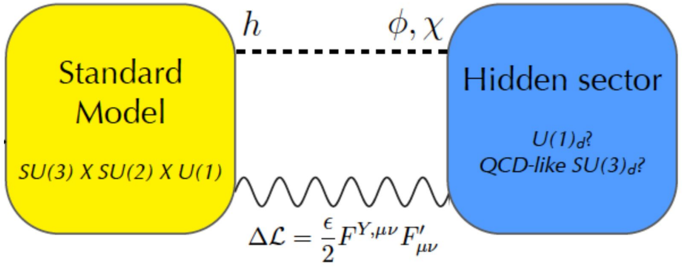


Combined limit:

B(H→inv) < 27.8%

‘Hidden Sectors’

- ➢ **What if new physics, such as 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

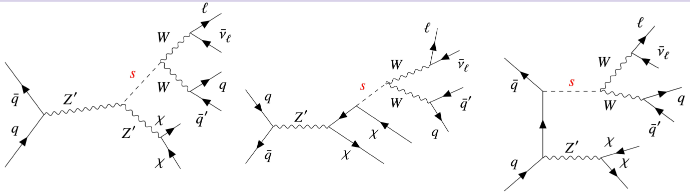
$$\mathcal{L} \supset \begin{cases} -\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H, & \text{Higgs portal} \\ y_n L H N, & \text{neutrino portal} \\ \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}, & \text{axion portal.} \end{cases}$$

- ➢ **Different communication channels between hidden sector & SM, suppressed couplings**
  - ➢ **May lead to unconventional signatures in the detectors**

Dark Higgs

ATLAS: ATLAS-CONF-2022-029
CMS: EXO-20-013

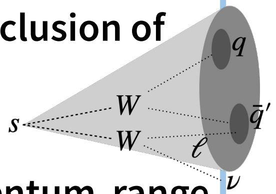
Model

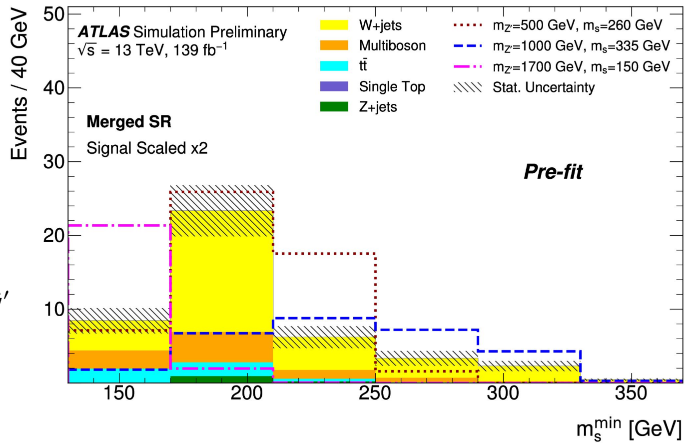


- 2-mediator model with new U(1)′ gauge symmetry
- Yields additional massive spin-1 Z′, complex scalar *s*
- χ obtains mass through Yukawa interactions with *s*

Selection

- Use track-assisted clustering to reconstruct ‘TAR’ jets
  - Better reconstruction of multi-prong s→V(qq)
  - Carefully preselect input tracks to avoid inclusion of the lepton
- Constrain V+jets and tt background using CRs
- Define categories to cover broad VV-pair momentum range
  - ‘merged’ - collimated, ⩾ 1 TAR jet
  - ‘resolved’ - ⩾ 2 small-R jets





Custom minimisation strategy used to approximate *s* mass - discriminant

Dark Higgs

ATLAS: ATLAS-CONF-2022-029
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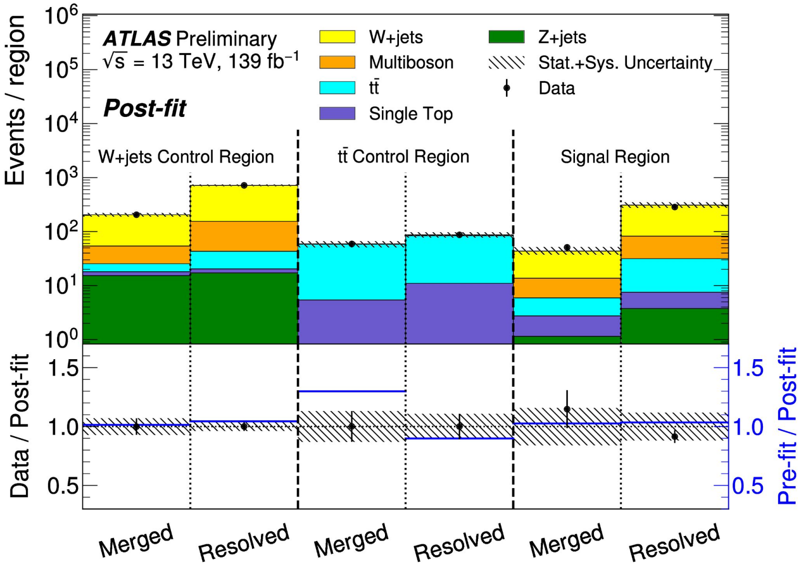
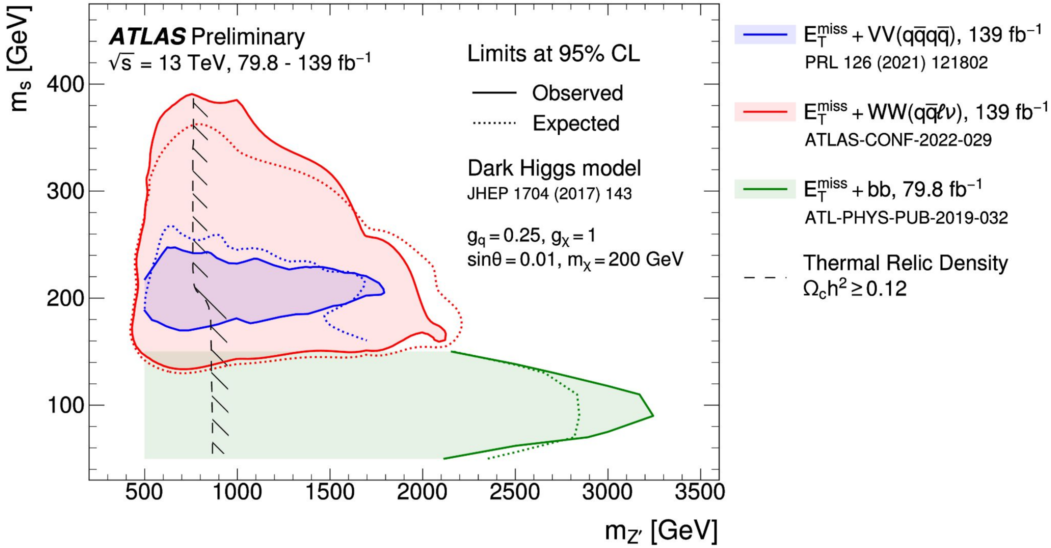


Exclude $m_{Z'}$ up to 1.8 TeV for $150 \lesssim m_s/\text{GeV} \lesssim 250$ @ 95% CL

ATL-PHYS-PUB-2022-036

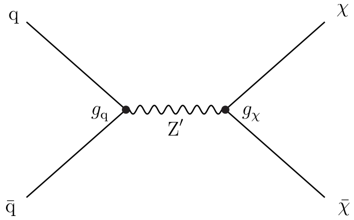
July 2022



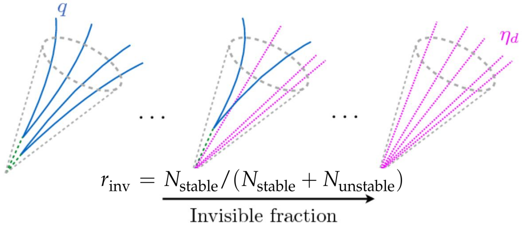
Semi-Visible Jets

ATLAS: ATLAS-CONF-2022-038
CMS: JHEP 06 (2022) 156

Model



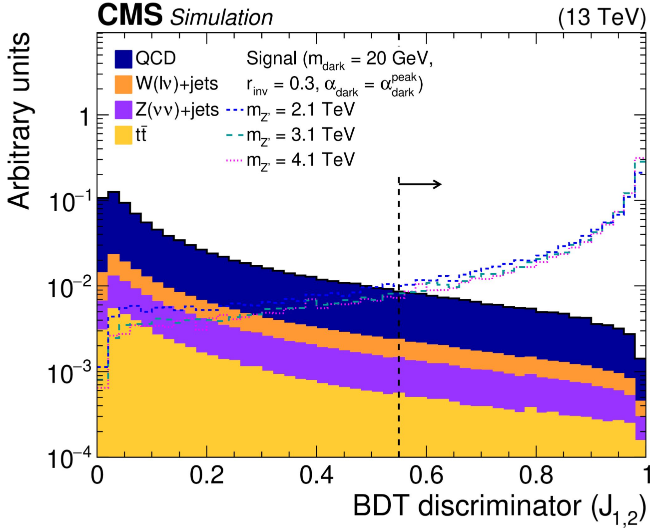
- Dark sector with new SU(N), analogous to QCD
- Dark quarks form bound dark hadron states
- Unstable dark hadrons can decay to SM quarks, others traverse the detector



Selection

- Require ⩾ 2 jets, moderate p_T^{miss} aligned with a jet
- Low $\Delta\phi_{min} = \min[\Delta\phi(\vec{J}_1, \vec{p}_T^{miss}), \Delta\phi(\vec{J}_2, \vec{p}_T^{miss})]$
- High $R_T = p_T^{miss}/m_T$
- Distinguish between semi-visible & SM jets using BDT
- Discriminant: dijet transverse mass, m_T

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



Semi-Visible Jets

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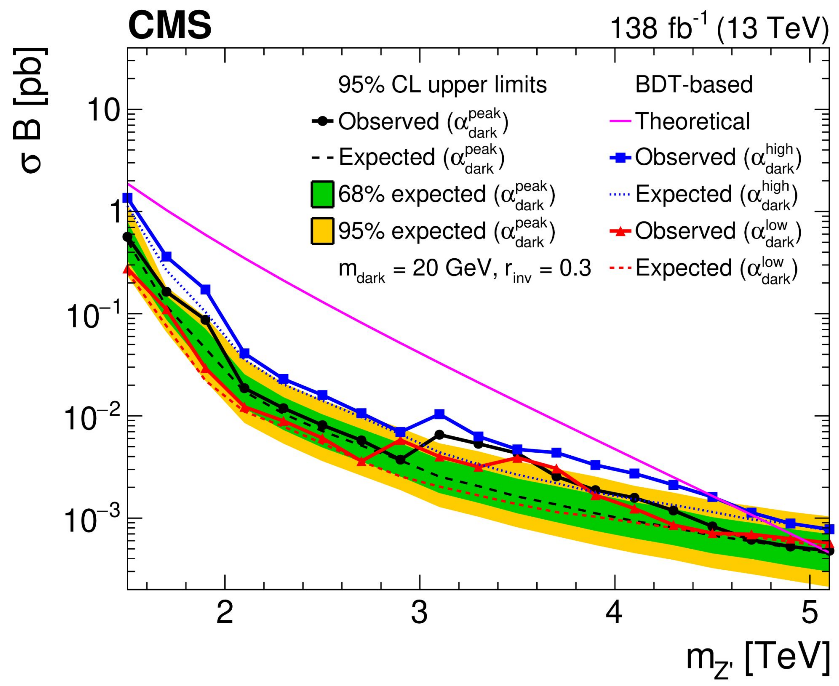
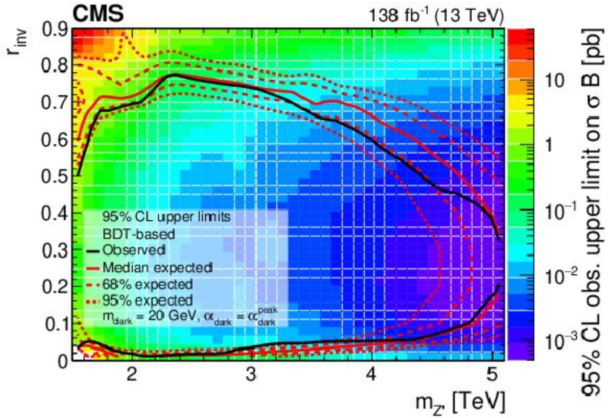
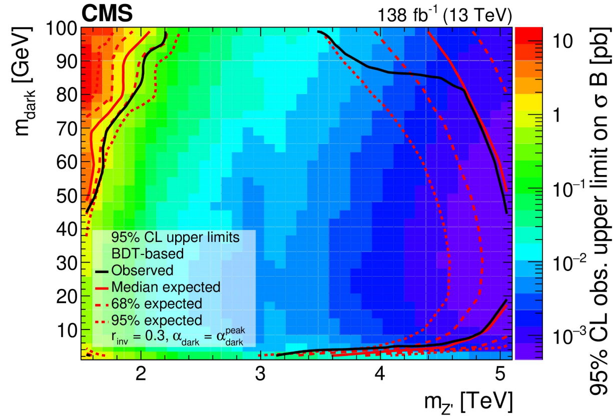


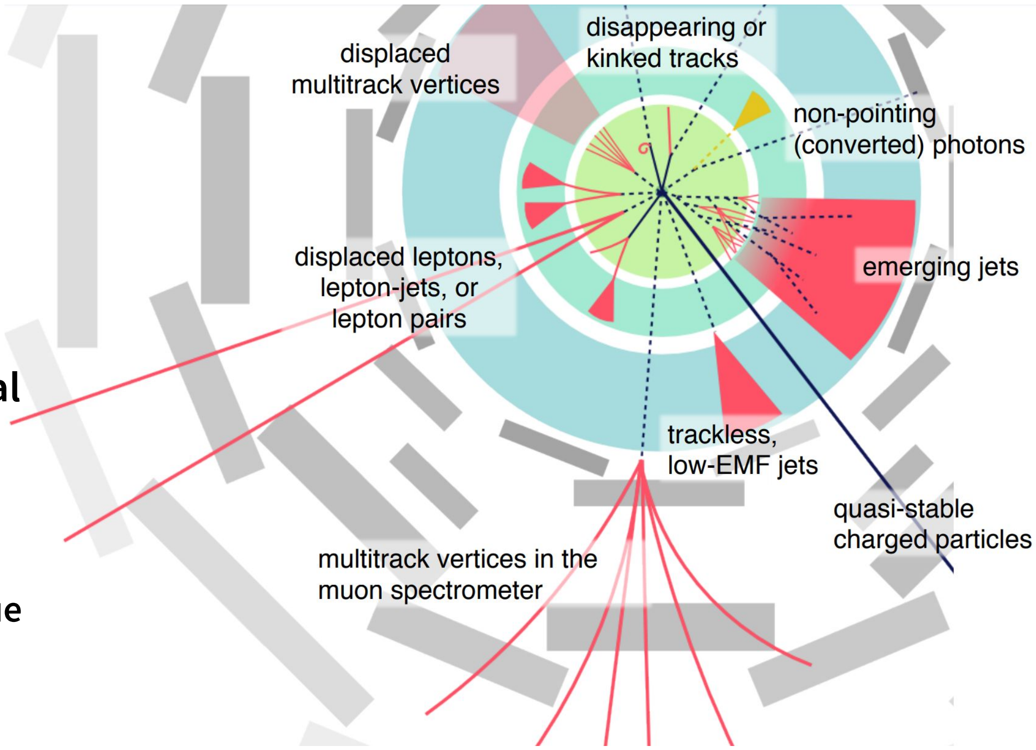




Exclude 1.5 ⩽ $m_{Z'}$ ⩽1 TeV for r_{inv} = 0.3
Exclude 0.01 ⩽ r_{inv} ⩽ 0.77 for m_{dark} = 20 GeV

Unconventional Signatures

- ➢ Weak coupling to the SM leads to long-lived-particles (LLPs)
- ➢ Many possible unconventional signatures
- ➢ Detecting these can come with experimental challenges
  - ➢ Custom triggers required
  - ➢ 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...

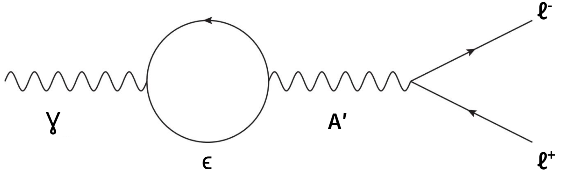


J. Phys. G: Nucl. Part. Phys. 47 090501 (2020)

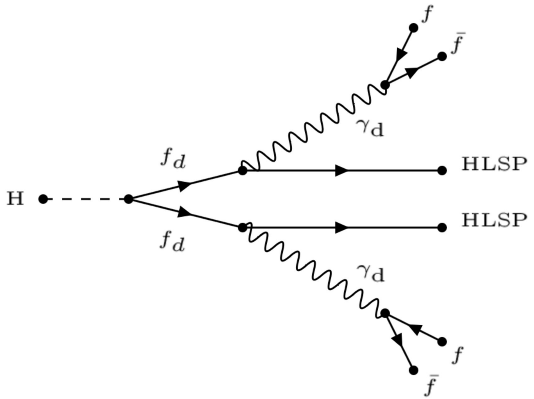
Dark Bosons

2206.12181
See also: 2203.00587, JHEP 03 (2022) 041 , ATL-PHYS-PUB-2022-007

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

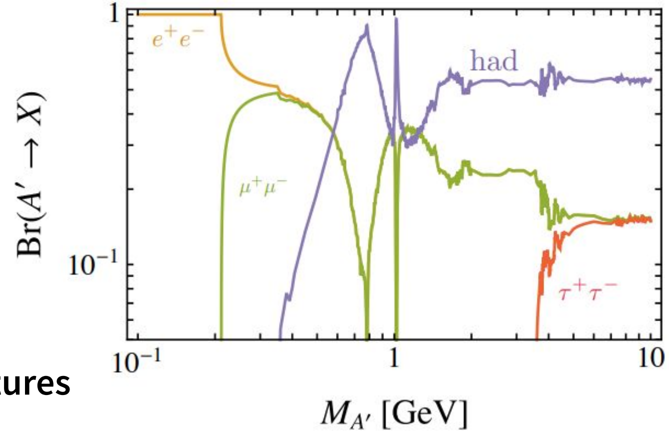


- Low mass γ_d could be produced via cascade decays of heavier states
  - Leptonic decays of γ_d are prominent in the low-mass range
  - Decay to highly collimated groups of leptons, or ‘lepton-jets’ (LJ)
  - A distinct LHC signature!



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

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



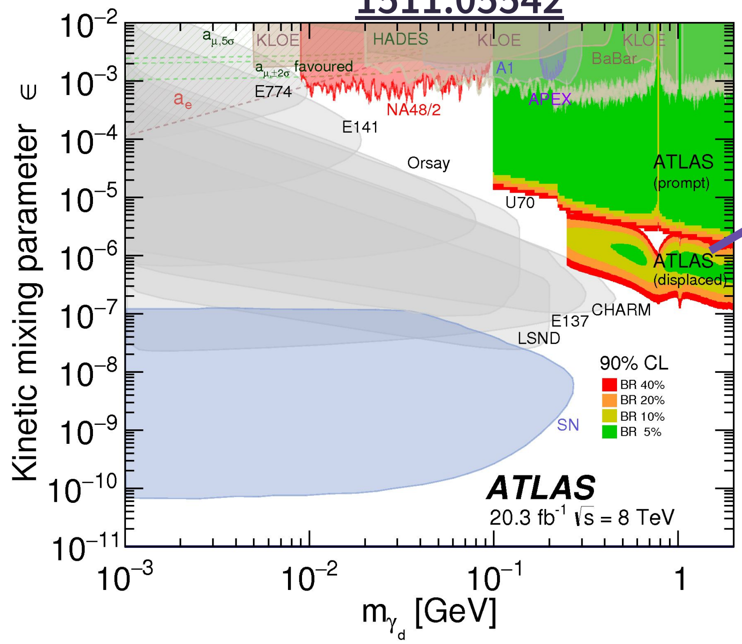
- Small mixing → long lifetime
- Prompt or displaced LJ signatures

Dark Bosons

2206.12181
See also: 2203.00587, JHEP 03 (2022) 041 , ATL-PHYS-PUB-2022-007

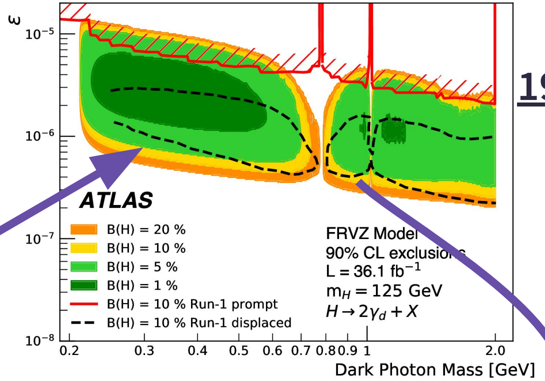
- ➢ Produce limits on the kinetic mixing parameter and $m_{\gamma d}$
  - ➢ Limits shown for various $B(H \rightarrow 2\gamma_d + X) \leqslant 20\%$

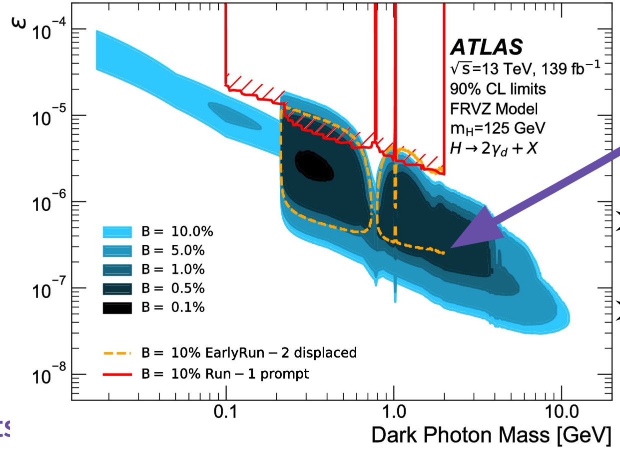
1511.05542



Complementary to fixed target/beam-dump experiments

1909.01246





- ➢ NN-based tagger for displaced jet ID
- ➢ Including ggH & WH production modes

Conclusions & Outlook

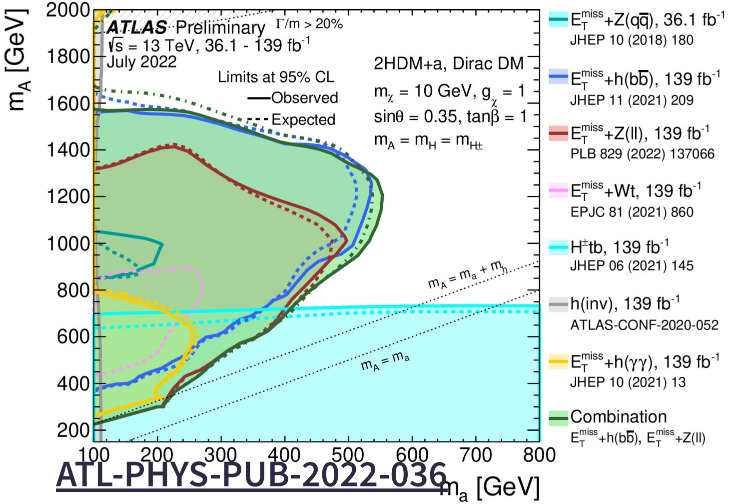
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://twiki.cern.ch/twiki/bin/view/CMSPublic

- **There is a growing DM search programme at the LHC, with many interesting signatures covered by ATLAS and CMS**
  - Looking at simplified & complex models

- **Both experiments have started to look at more complex final states, which present experimental challenges, using our detectors in ways that they were not originally designed for**
  - Novel triggering/tracking techniques
  - Use of machine learning to distinguish between objects

- **Expect more analyses from the Run-2 (2015-2018) dataset, including combinations of results**

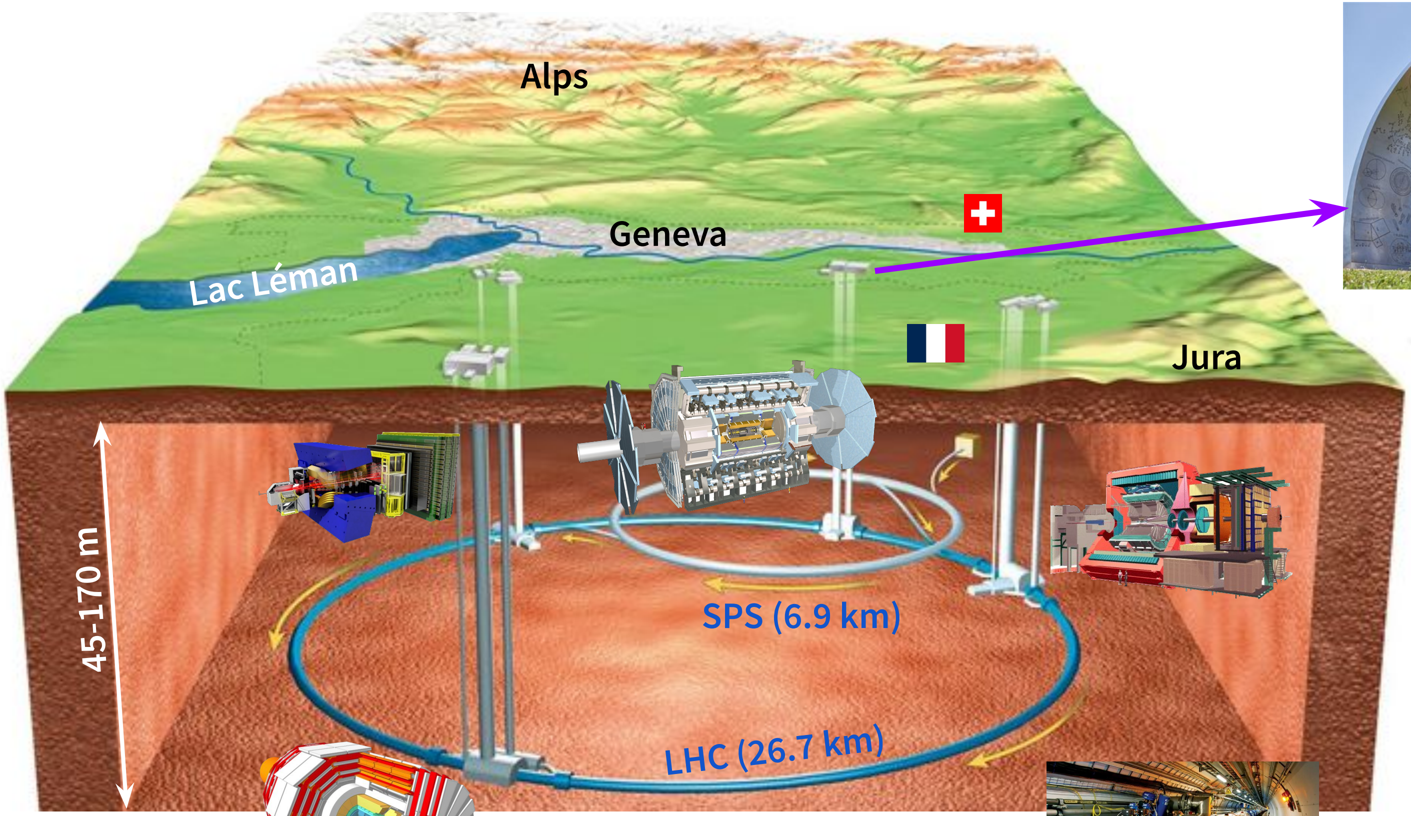
- **The LHC has now entered Run-3! Providing 13.6 TeV collision data with hardware & software upgrades!**

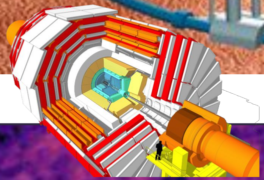


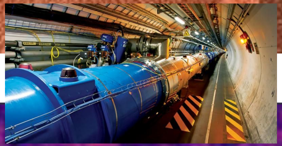
ATL-PHYS-PUB-2022-036

Backup

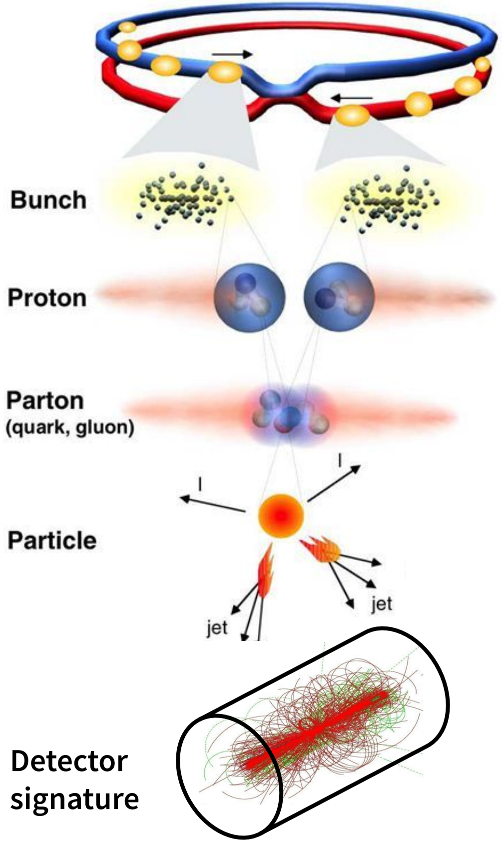
The Large Hadron Collider



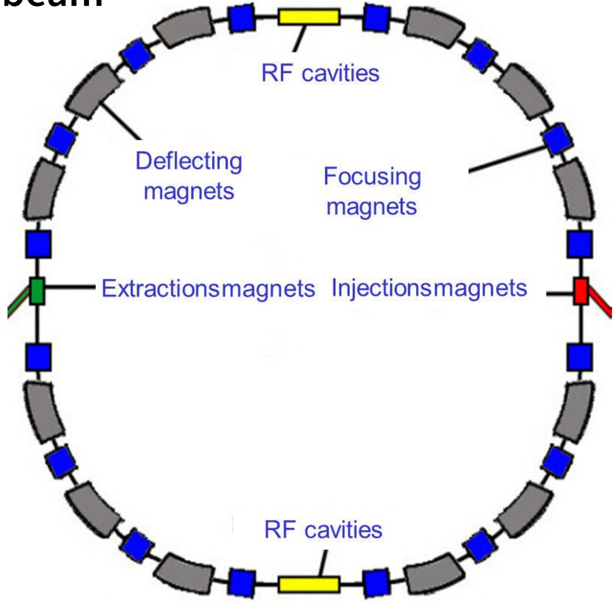




LHC Proton Beams

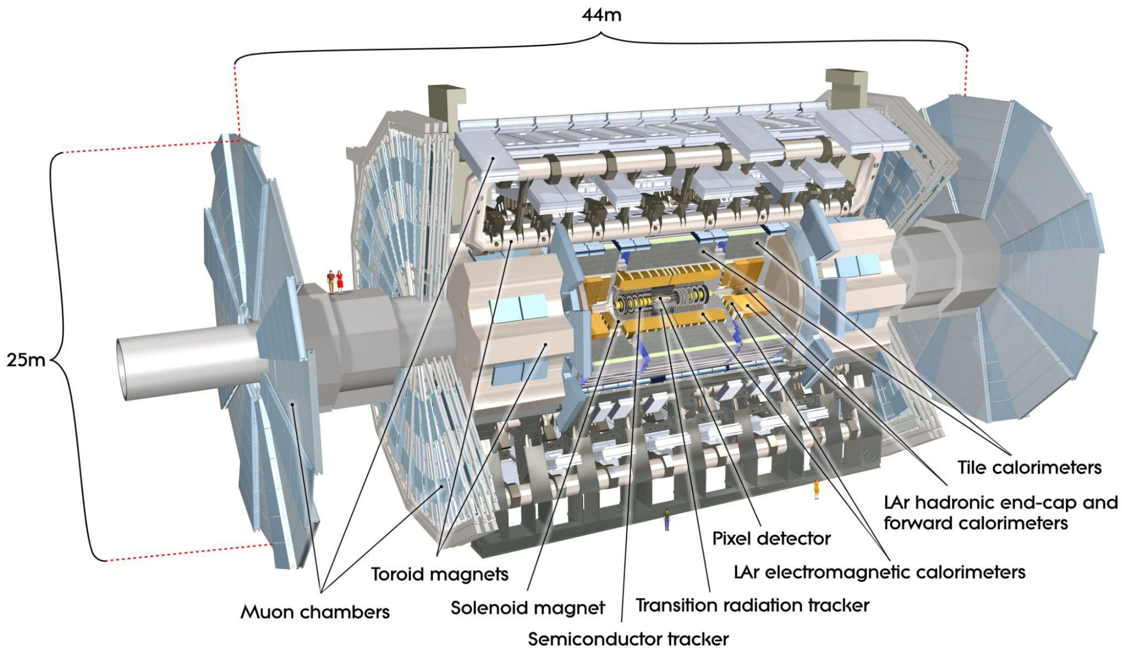


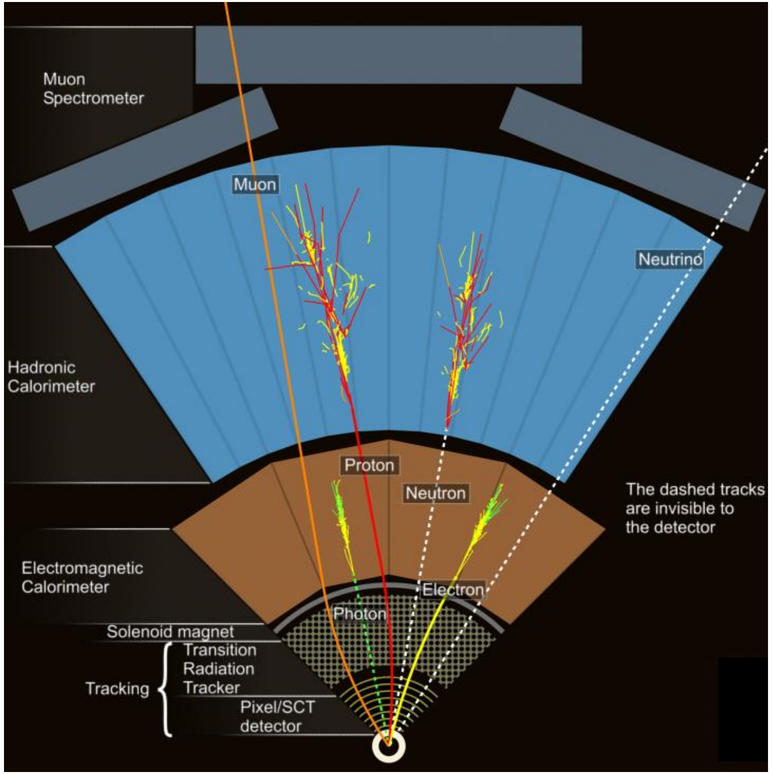
- > 50 kinds of magnets
- 1232 superconducting dipole magnets operating at -271.3°C
  - Sextupole, octupole & decapole magnets correct the beam
- 8 RadioFrequency (RF) cavities per beam



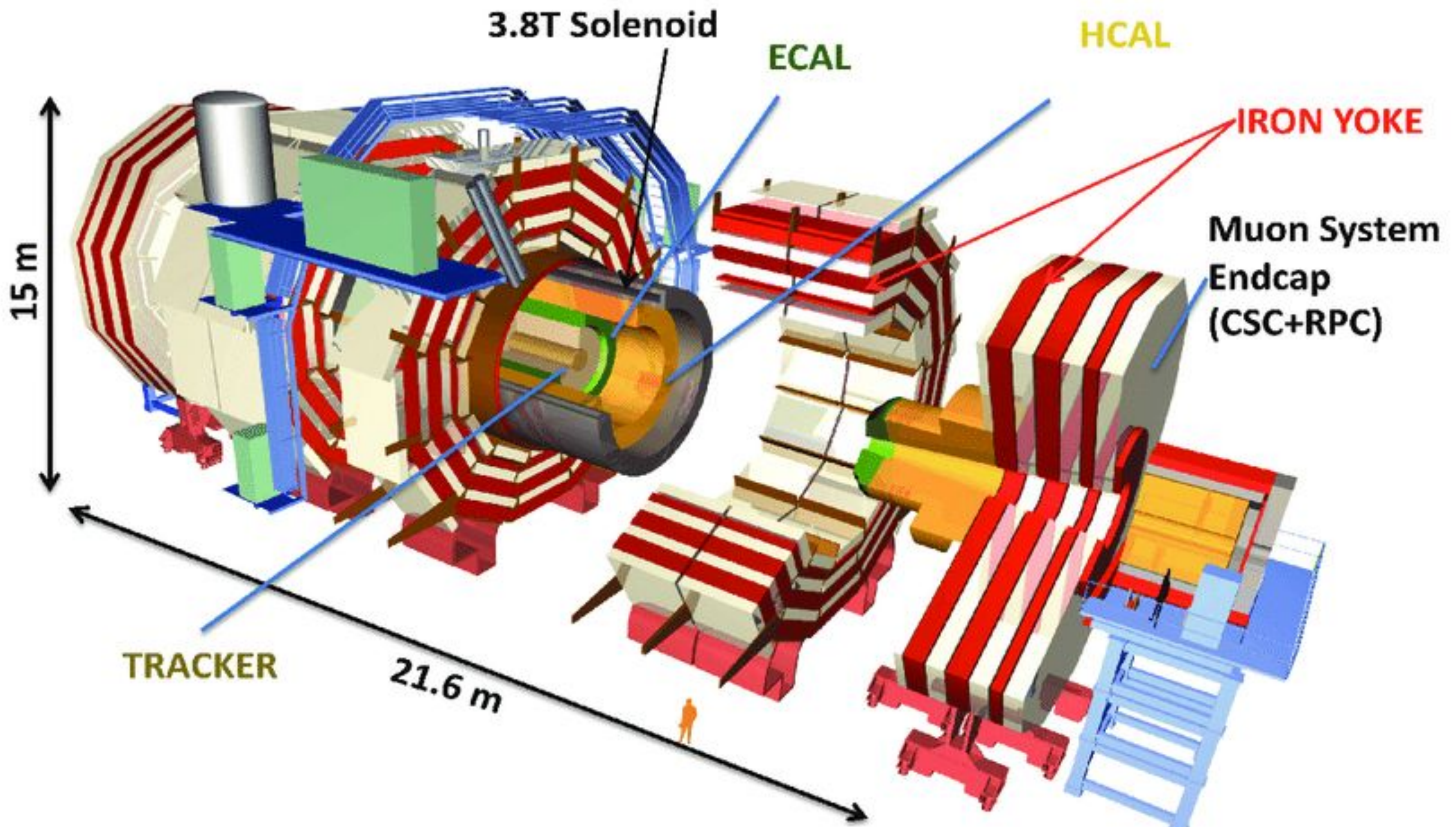
- Proton beam energy = 6.5 TeV
- 1.2 x 10^{11} protons/bunch
- ~ 2800 bunches/beam
- 25ns bunch spacing
  - 40,000,000 collisions per second

The ATLAS Detector

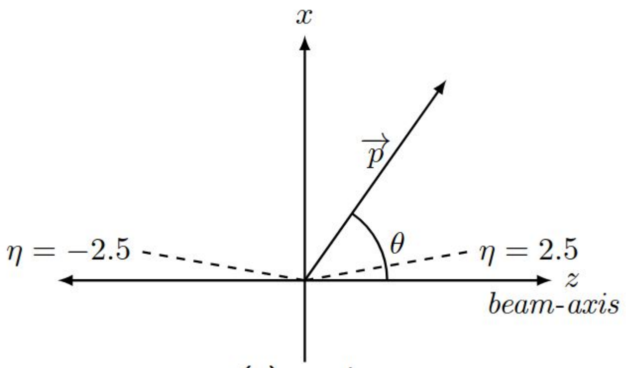




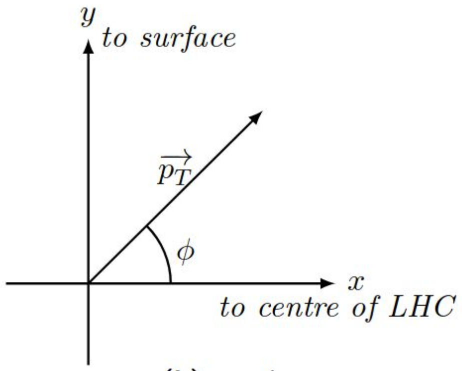
CMS


3.8T Solenoid
ECAL
HCAL
IRON YOKE
Muon System
Endcap
(CSC+RPC)
15 m
TRACKER
21.6 m

The LHC Coordinate System



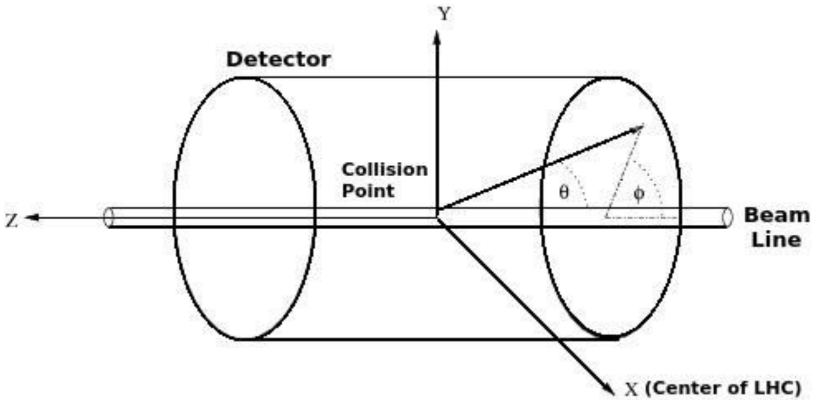
(a) xz-plane



(b) xy-plane

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

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



Dark Matter Search Methods

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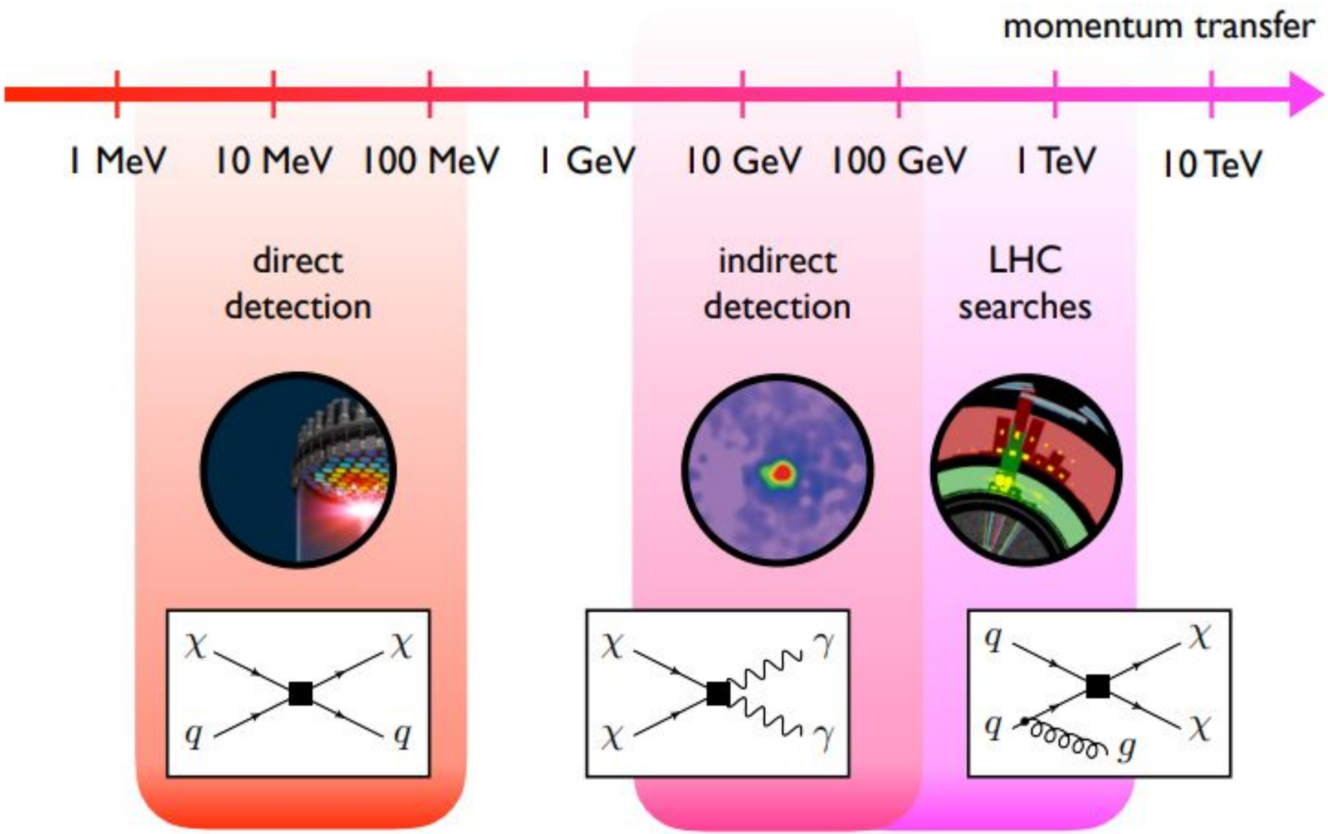
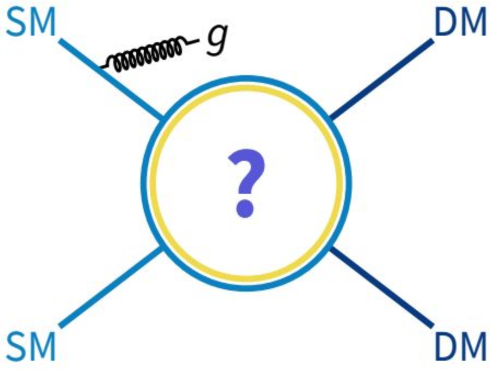


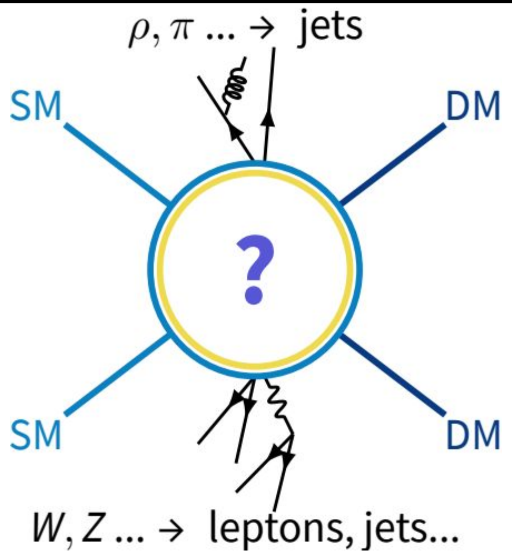
Types of LHC DM Searches

See Phys. Dark Univ. 26 (2019) 100371
& LHC DM Working Group

Dark matter is invisible to our detectors → look for associated production of visible (SM) particles

Generic Searches & Simpler Models ⟷ Specific Searches & More Complete Models



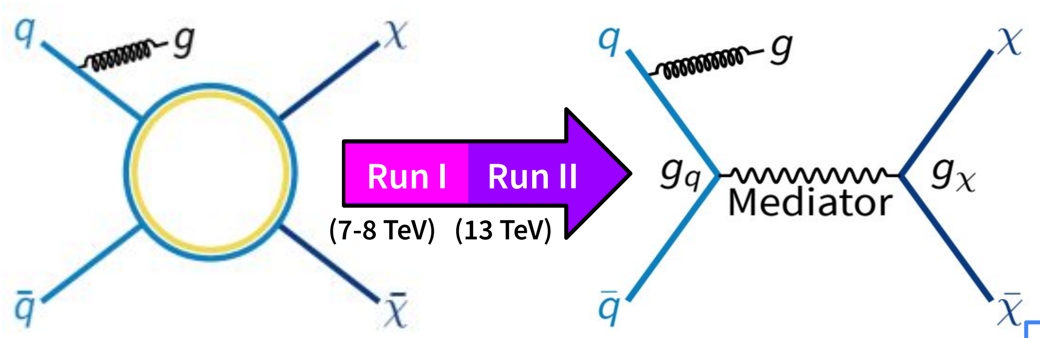


- ➢ Simple signals e.g. a single mediator
- ➢ Sizeable cross-sections
- ➢ Fewer assumptions on specific model parameters

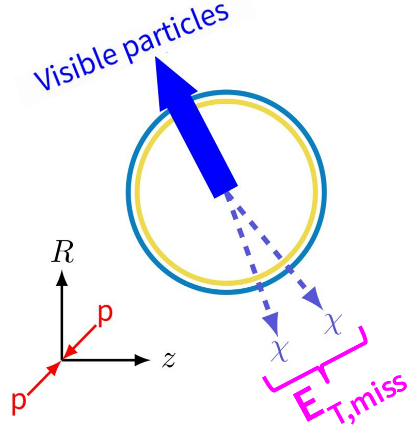
- ➢ More reliant on model assumptions
- ➢ E.g. supersymmetry, UV complete models

Simplified Models - ‘Mono-X’

- The most general models involve contact interaction operators in Effective Field Theories (EFTs)
- These become invalid at large momentum transfer, Q^2, which is problematic for Run-II
  - Favour ‘simplified’ models with a mediator, introducing m_χ, m_{med}, g_q and g_χ



CERN-TH-2017-102



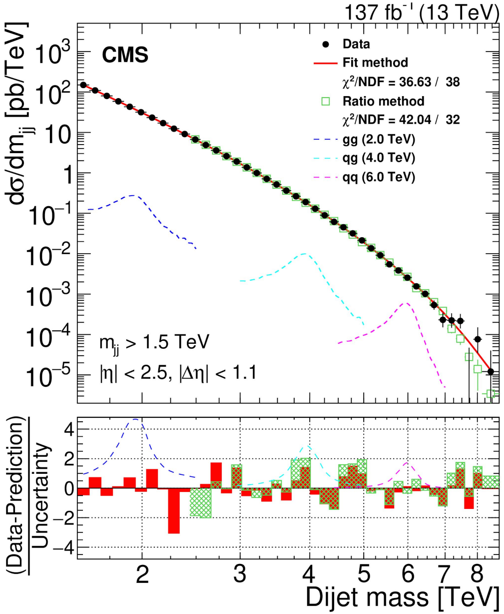
- Look for ‘mono-X’ signatures
  - Select events with ‘X’ (jet/γ/W/Z/t/H), veto other objects, precisely model backgrounds, check E_T^{miss}
  - Fix g_q, g_χ and exclude m_χ, m_{med} → CERN-LPCC-2016-001
- Also look for visible decays of the mediator to complement these searches → CERN-LPCC-2017-01
  - Re-interpret other analyses as mediator searches

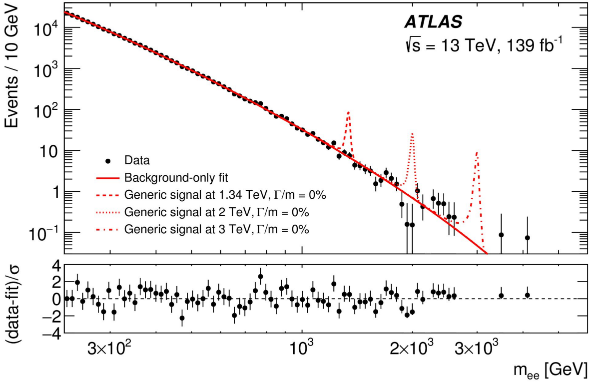
Visibly Decaying Mediator Searches

- DM cannot be produced on-shell if $2m_{DM} > m_{med}$
  - Mediator decays back to SM
  - Need to probe visible signatures to see DM interactions off-shell
- The LHC is a “mediator machine”!
- Probe high masses in search of BSM mediators.
- Look for bumps on the smoothly falling di-object distribution, which is modeled by a parameterized function.
- In absence of bump, set limits for different physics scenarios.

Dijet

- ATLAS: CERN-EP-2019-1
- CMS: CERN-EP-2019-222





Dilepton

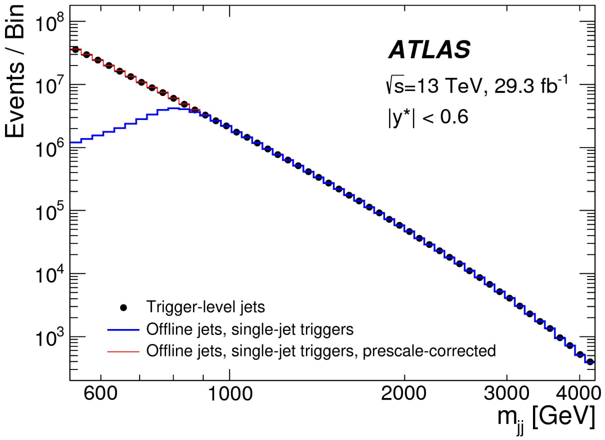
- ATLAS: PHYS. LETT. B 796 (2019) 68
- CMS: JHEP 06 (2018) 120

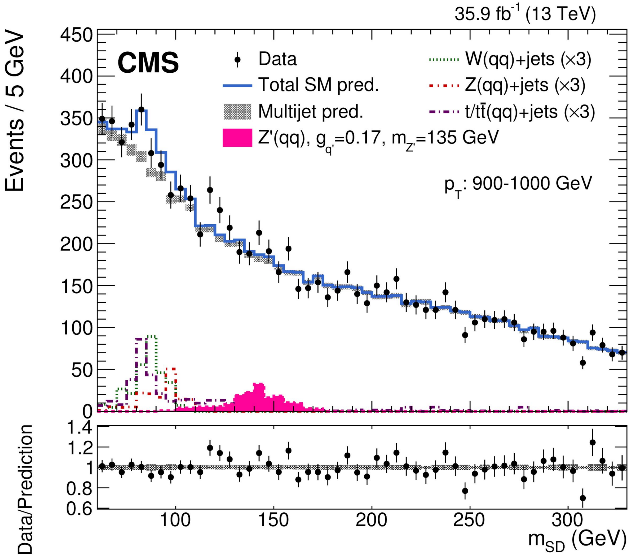
Low Mass Di-jet Searches

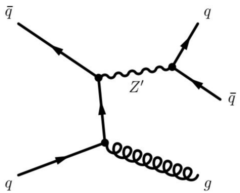
ATLAS: PHYS. LETT. B 795 (2019) 56
CMS: JHEP 01 (2018) 097

- ➢ Sensitivity at low (< 1 TeV) m_{jj} is limited by jet triggers
  - ➢ Data collection rates for inclusive single-jet triggers << SM multijet production rate
- ➢ "Data-scouting" / "Trigger-object Level Analysis" (TLA)
  - ➢ Use reduced data format to allow high trigger rate with low bandwidth

PHYS. REV. LETT. 121, 081801 (2018)





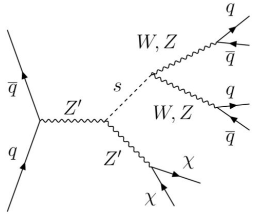


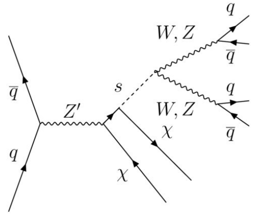
- ➢ Introduce hard Initial-State Radiation (ISR) requirement
  - ➢ Require ≥ 1 high p_T ISR jet in association with the *qq* resonance
  - ➢ Provides enough energy to satisfy trigger
  - ➢ Min p_T high enough that hadroisation from *qq* gives a large-R jet
  - ➢ Achieve sensitivity to even lower mediator masses
  - ➢ ATLAS: 225 - 1100 GeV, CMS: < 100 GeV!

Dark Higgs

ATLAS: Phys. Rev. Lett. 126, 121802 (2021)
CMS: EXO-20-013

Model

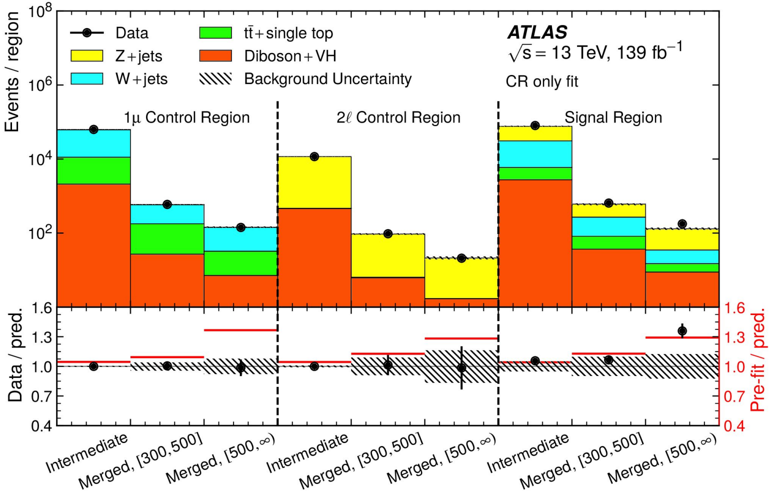




- 2-mediator model with new U(1)′ gauge symmetry
- Yields additional massive spin-1 Z′, complex scalar *s*
- χ obtains mass through Yukawa interactions with *s*

Selection

- Novel track-assisted clustering to reconstruct ‘TAR’ jets
  - Better reconstruction of multi-prong s→V(qq)V(qq)
- Define categories to cover broad VV-pair momentum range
  - ‘merged’ - collimated, ⩾ 1 TAR jet
  - ‘intermediate’ - 1 TAR jet with up to 2 small-R jets
- Constrain V+jets backgrounds with 1μ + 2ℓ CRs
- Discriminant: *s* invariant mass, m_{VV}



Dark Higgs

ATLAS: Phys. Rev. Lett. 126, 121802 (2021)
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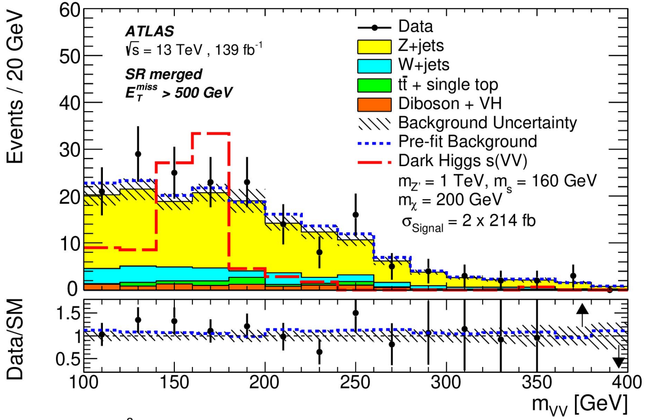
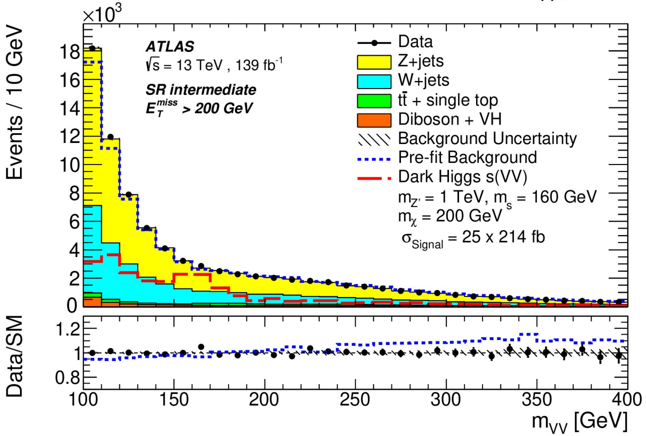
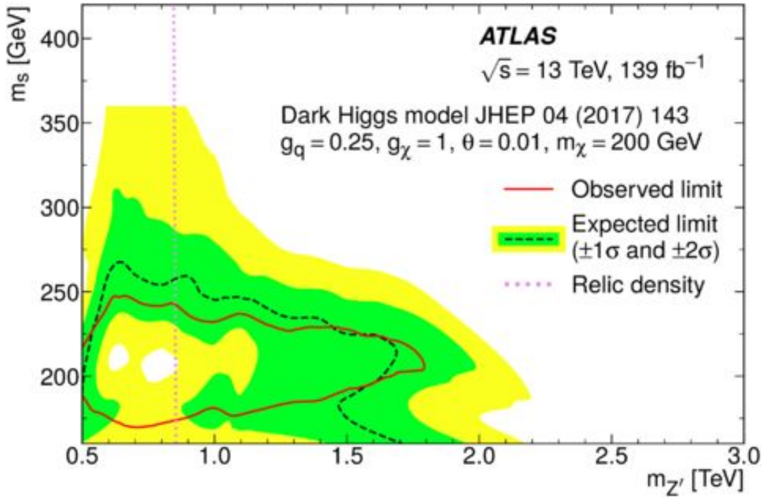




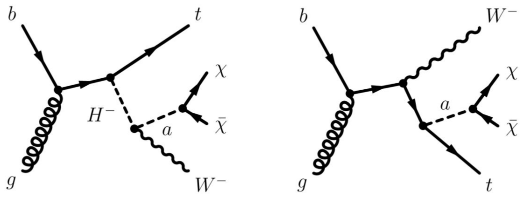


exclude $m_{Z'}$ up to 1.8 TeV for m_s = 210 GeV @ 95% CL

Heavy Flavour + DM

ATLAS-CONF-2022-012

Model



- ➢ Two Higgs-doublet model with additional pseudo-scalar mediator (a), 2HDM+a
- ➢ tW+DM is the dominant single-top production mode

Selection

- ➢ Require events with high p_T^{miss} & ⩾ 1 b-tagged jet
- ➢ 0/1 ℓ selections, for leptonic/hadronic W decays

$tW_{0\ell}$

- ℓ veto
- ⩾ 4 standard jets
- 1 energetic large-R jet

$tW_{1\ell}$

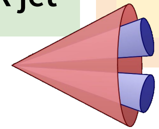
- 1 ℓ (e/μ)

t(→ℓνb)W(→qq)

- ⩾ 2 standard jets
- 1 energetic large-R jet

t(→qqb)W(→ℓν)

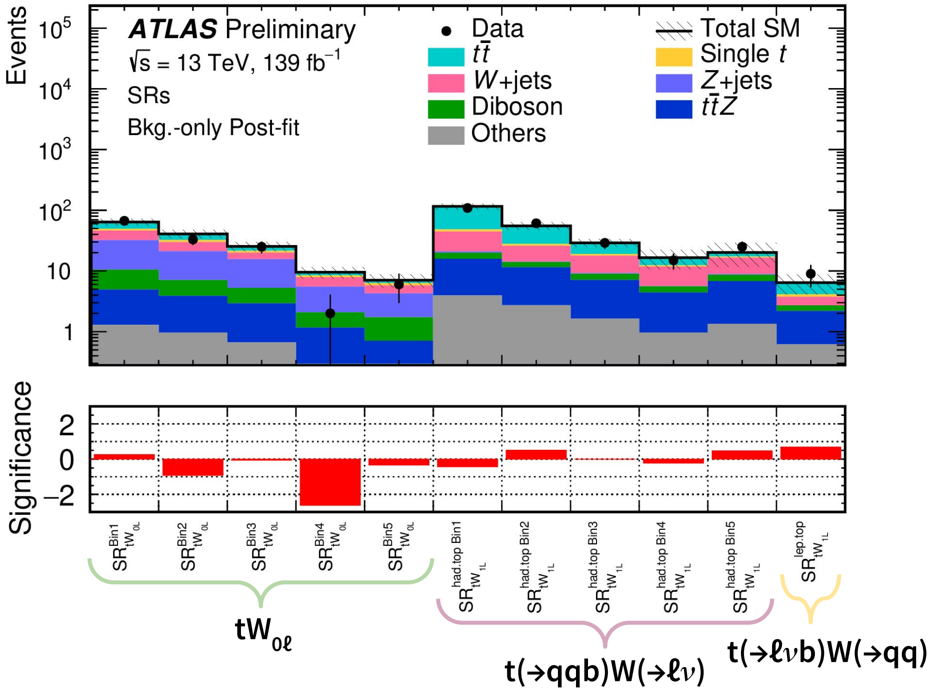
- ⩾ 3 standard jets



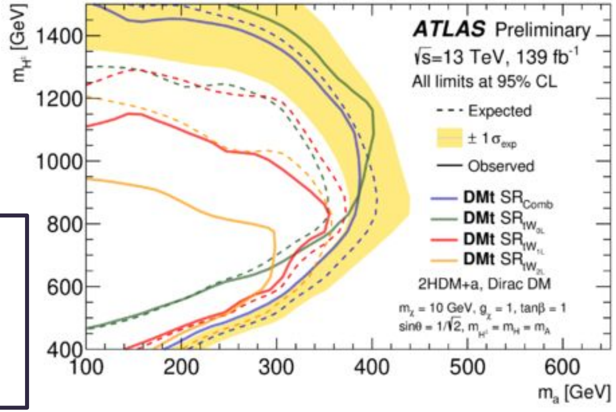
- ➢ Five dominant SM BG sources, Z+jets, W+jets, tt, ttZ, single top constrained using 6 CRs
- ➢ Discriminant: p_T^{miss}

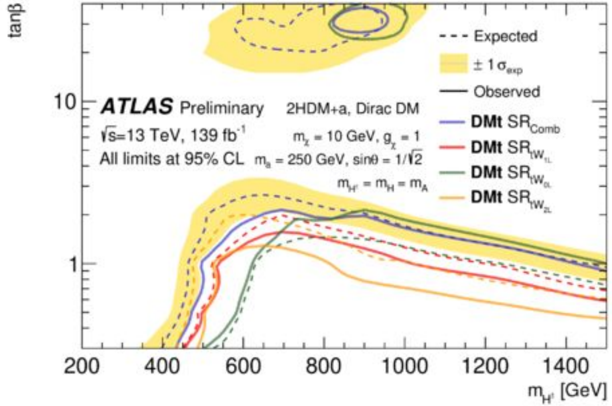
Heavy Flavour + DM

ATLAS-CONF-2022-012



Statistical combination with 2ℓ from 2011.09308

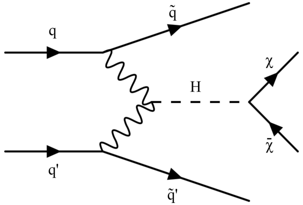




Invisible Higgs Decays

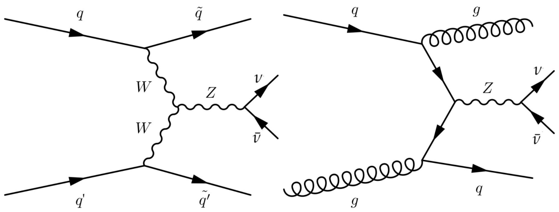
ATLAS: JHEP 03 (2022) 041
CMS: Phys. Rev. D 105 (2022) 092007

Model



- ➢ Most sensitive production mode, thanks to large production cross-section & distinctive topology

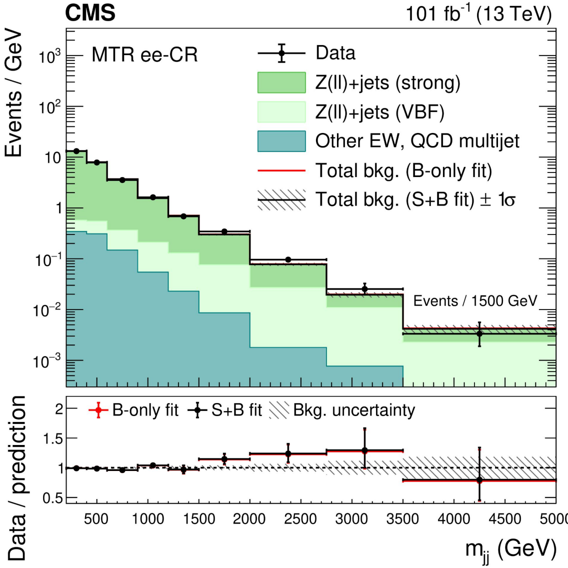
Dominant Backgrounds



& equivalent W processes

Selection

- ➢ Define 2 trigger strategy categories:
  - ➢ p_T^{miss} triggers (MTR) for ptmiss > 250 GeV
  - ➢ p_T^{miss} + jet property triggers (VTR) for $160 < p_T^{miss} < 250$ GeV
- ➢ Select VBF-like events
  - ➢ 2 jets in opposite detector hemispheres ($\eta_{j1} \cdot \eta_{j2} < 0$)
  - ➢ Large $\Delta\phi(p_T^{miss}, p_T^{jet})$
- ➢ Veto e, μ, γ, τ_h, b-jets
- ➢ Constrain irreducible backgrounds with V+jets & γ+jets CRs
- ➢ Discriminant: m_{jj}



Invisible Higgs Decays

ATLAS: JHEP 03 (2022) 041
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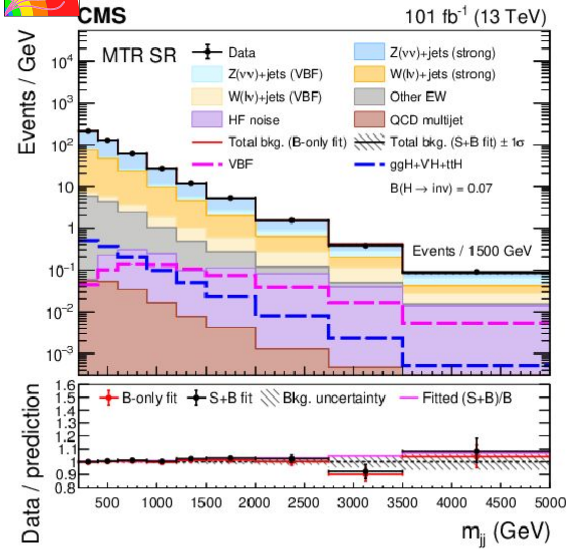
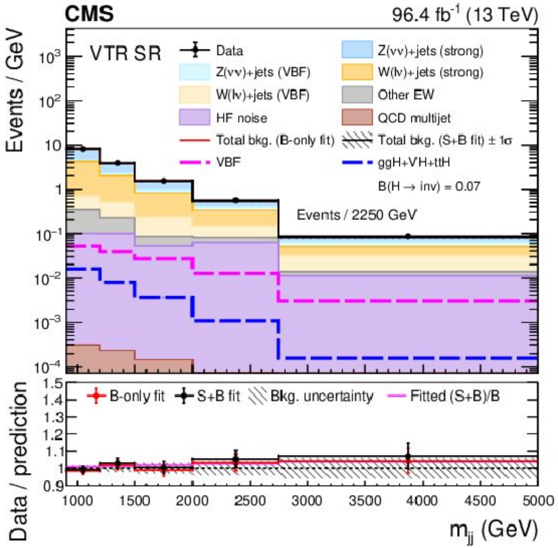
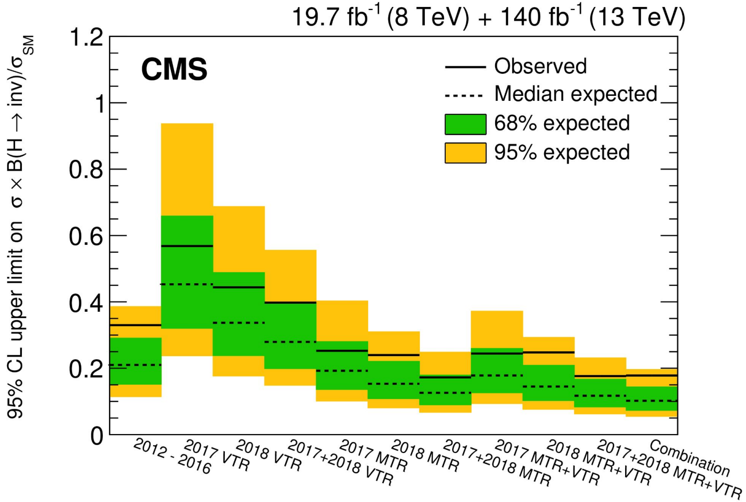




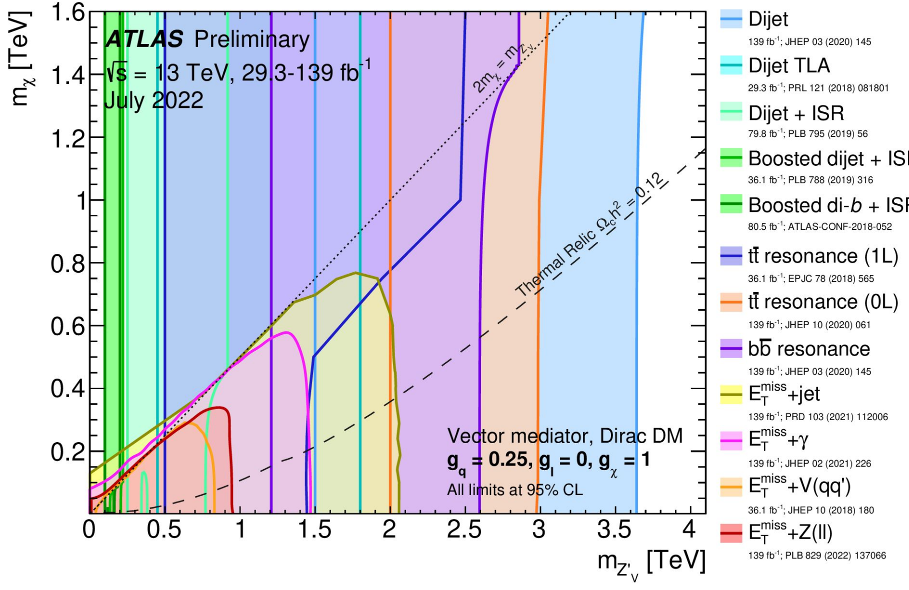
B(H→inv) < 18%

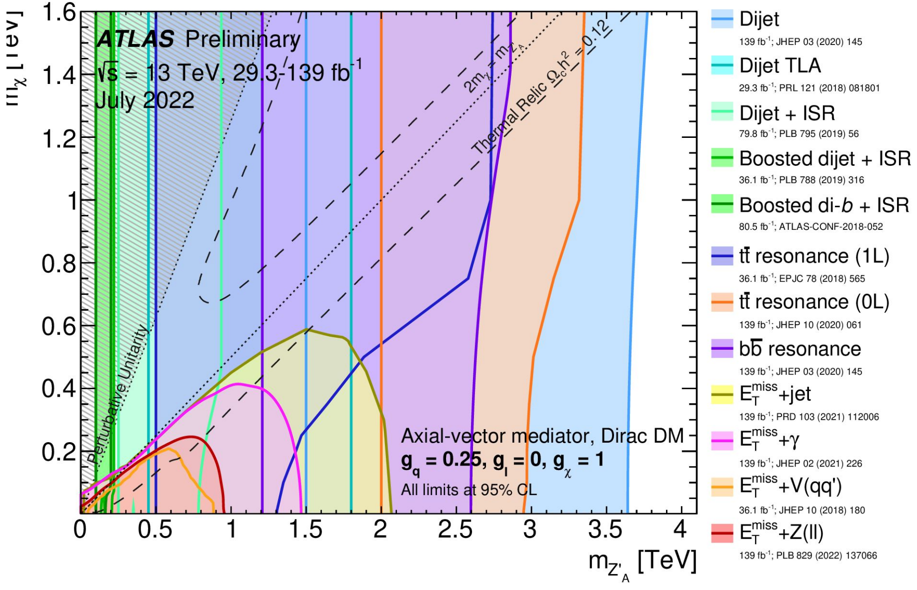


Combined Results

ATL-PHYS-PUB-2022-036

➢ **Vector/Axial-vector mediator, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$**



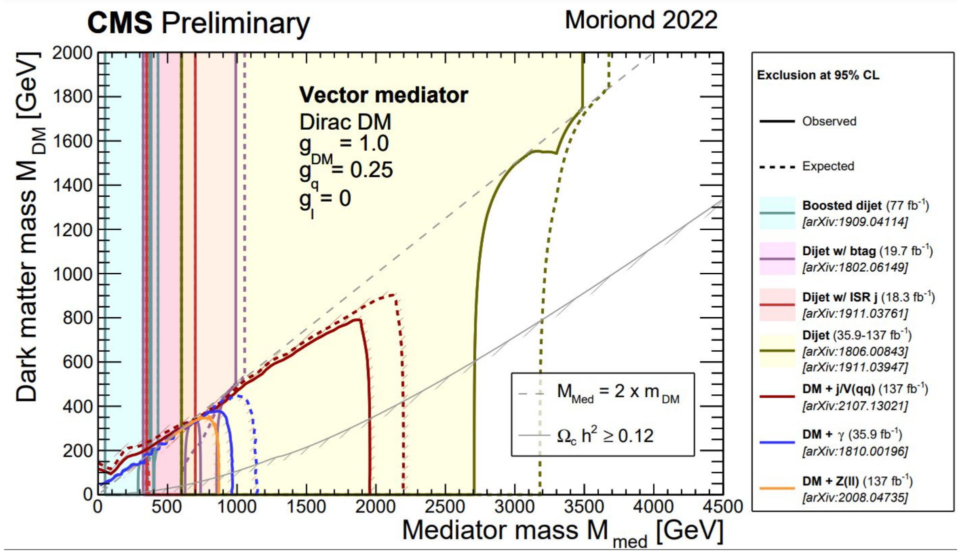


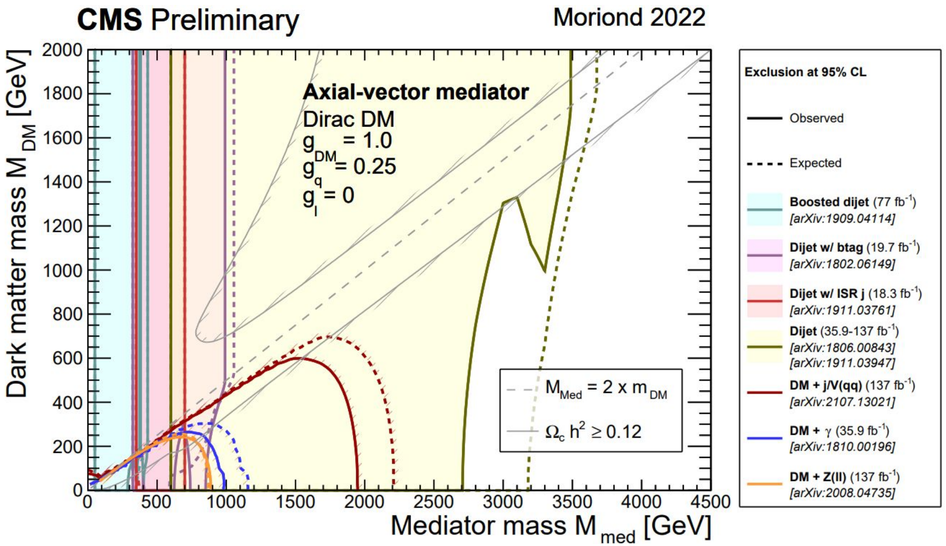
m_{med} ~ 3.6 TeV reach from mediator searches

Combined Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

- ➢ Vector/Axial-vector mediator, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$



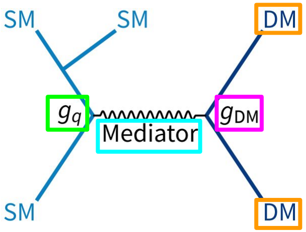


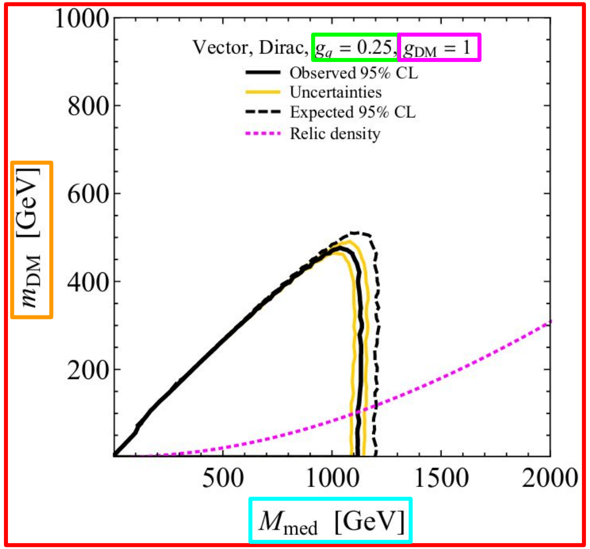
Comparing Results to DD/ID

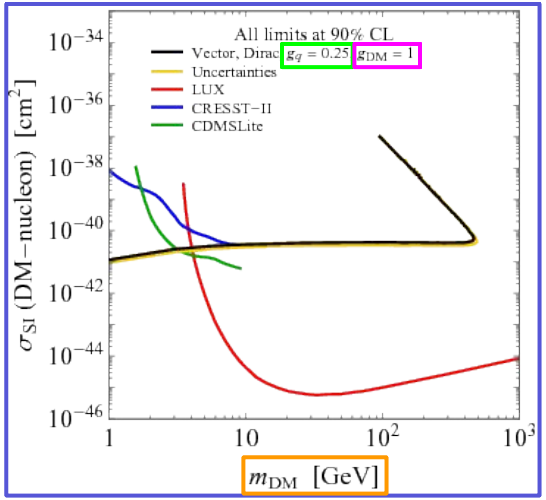
CERN-LPCC-2016-001

➢ Comparisons to other experiments / channels are possible only in the context of a benchmark - need to fully specify model/parameters and be aware of any limitations

➢ Advised prescriptions exist for translating LHC limits (m_{DM} vs. m_{med}) to ID/DD limits.





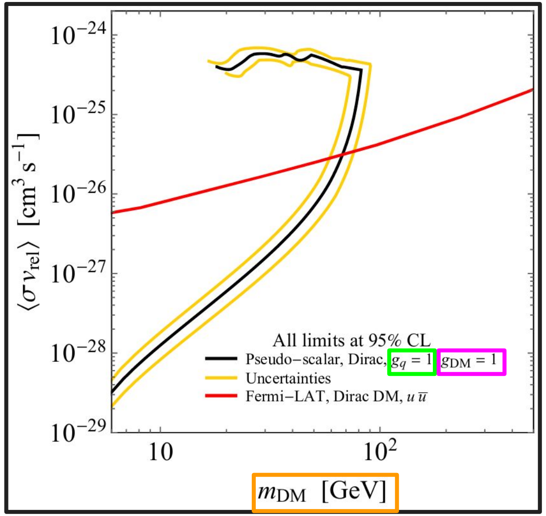


DD: spin (in)dependent DM-nucleon cross-section

σ_{SI} / σ_{SD}

ID: DM annihilation cross-section

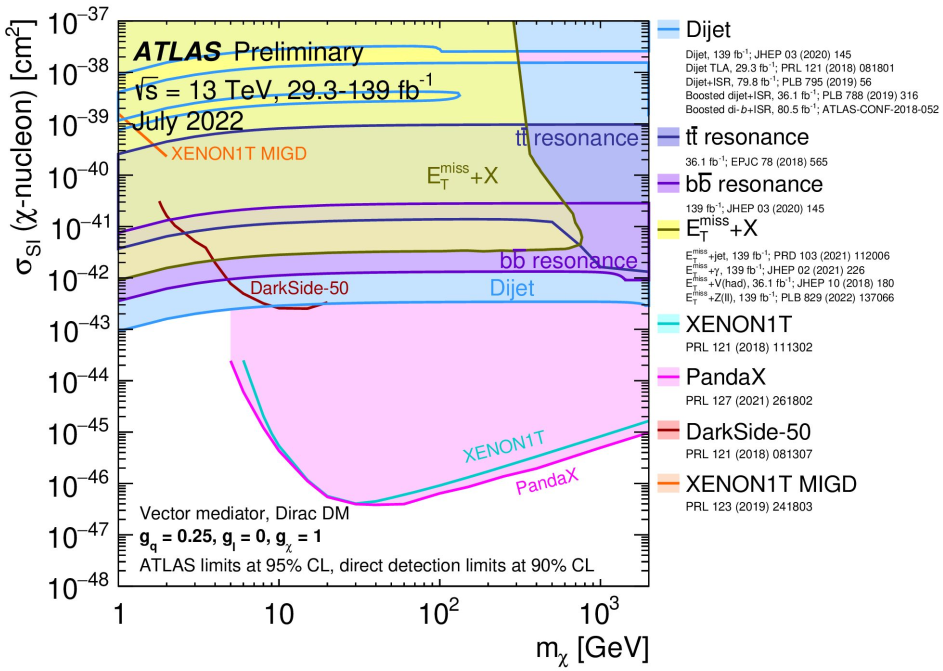
$\langle \sigma v_{rel} \rangle$

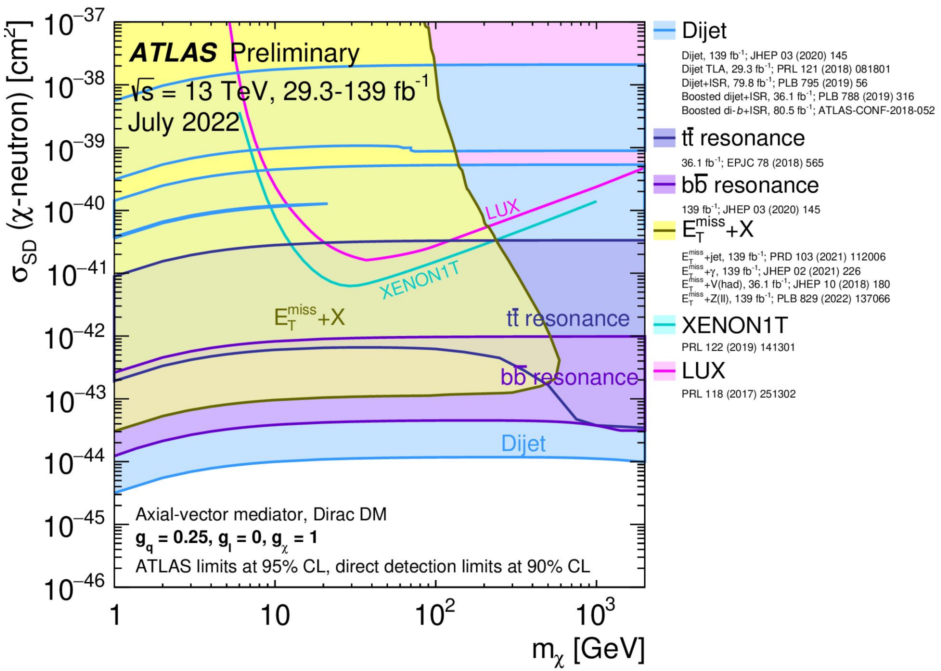


Combined Results

ATL-PHYS-PUB-2022-036

- SI & SD WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.25$, $g_l = 0$
  - Strong SD limits compared to DD for these couplings in this model!





Combined Results

ATL-PHYS-PUB-2022-036

- SI WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.1$, $g_l = 0.01$
  - For <u>these couplings in this model</u>, the mono-jet search has higher sensitivity than DD at low m_χ!