An exploration of strongly interacting dark sectors in ATLAS and beyond

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RAL PPD seminar
29/05/2024

Who am I?

Member of ATLAS experiment

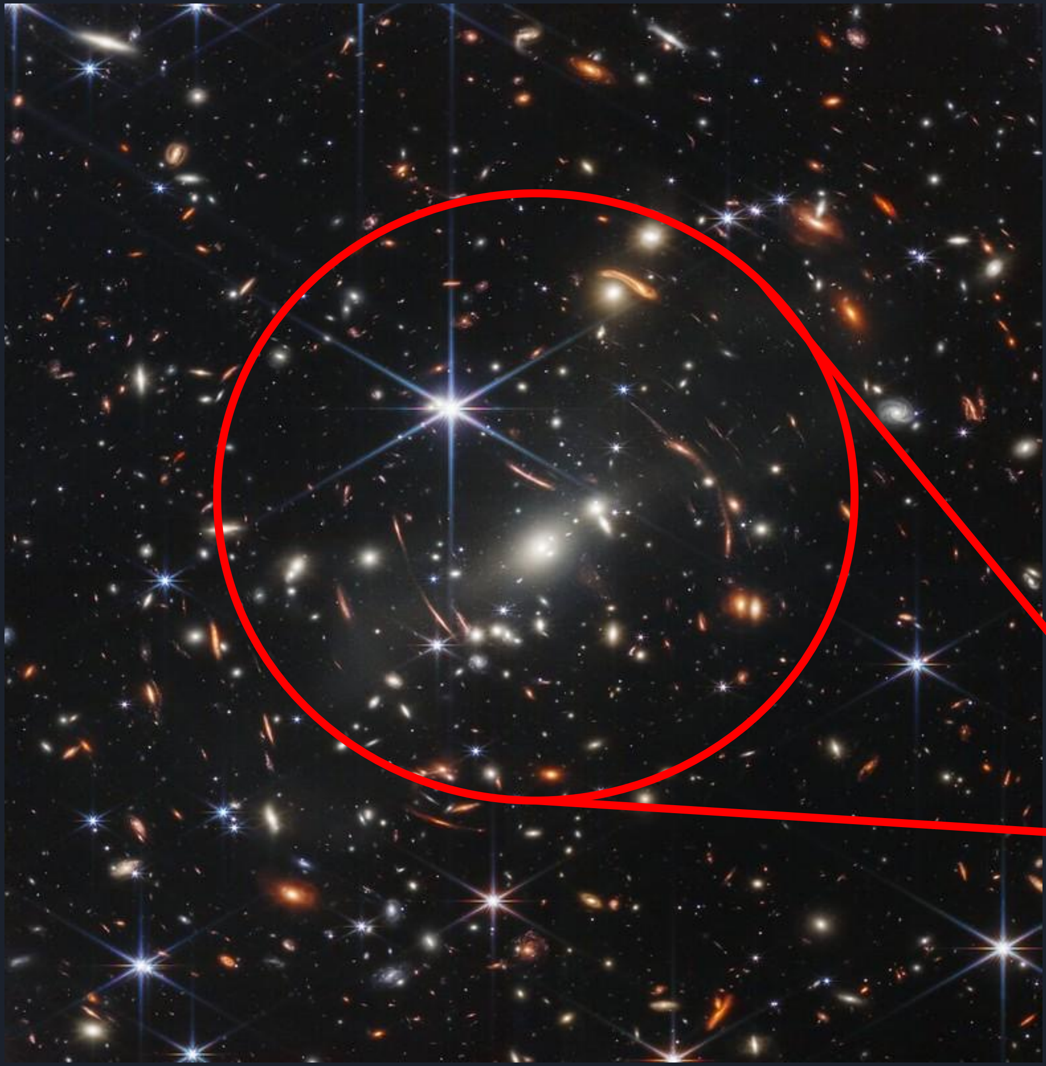
PhD from University of Witwatersrand, South Africa

→ Currently Postdoctoral Researcher at University of Manchester

Marie Curie Early Stage researcher
@ Glasgow University, Scotland

First image from the brand new James Webb Space Telescope, designed by NASA – 11th July 2022

Produced the deepest and sharpest infrared image of the distant universe to date!



First image from the brand new James Webb Space Telescope, designed by NASA – 11th July 2022

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Why does the light from distant galaxies look all squiggly and bending?

First image from the brand new James Webb Space Telescope, designed by NASA – 11th July 2022

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Why does the light from distant galaxies look all squiggly and bending?

Gravitational lensing!

Gravitational lensing occurs when a massive celestial body — such as a galaxy cluster — causes a sufficient curvature of spacetime for the path of light around it to be visibly bent, as if by a lens

First image from the brand new James Webb Space Telescope, designed by NASA – 11th July 2022

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Why does the light from distant galaxies look all squiggly and bending?

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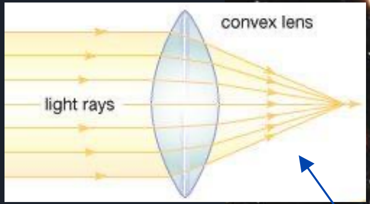

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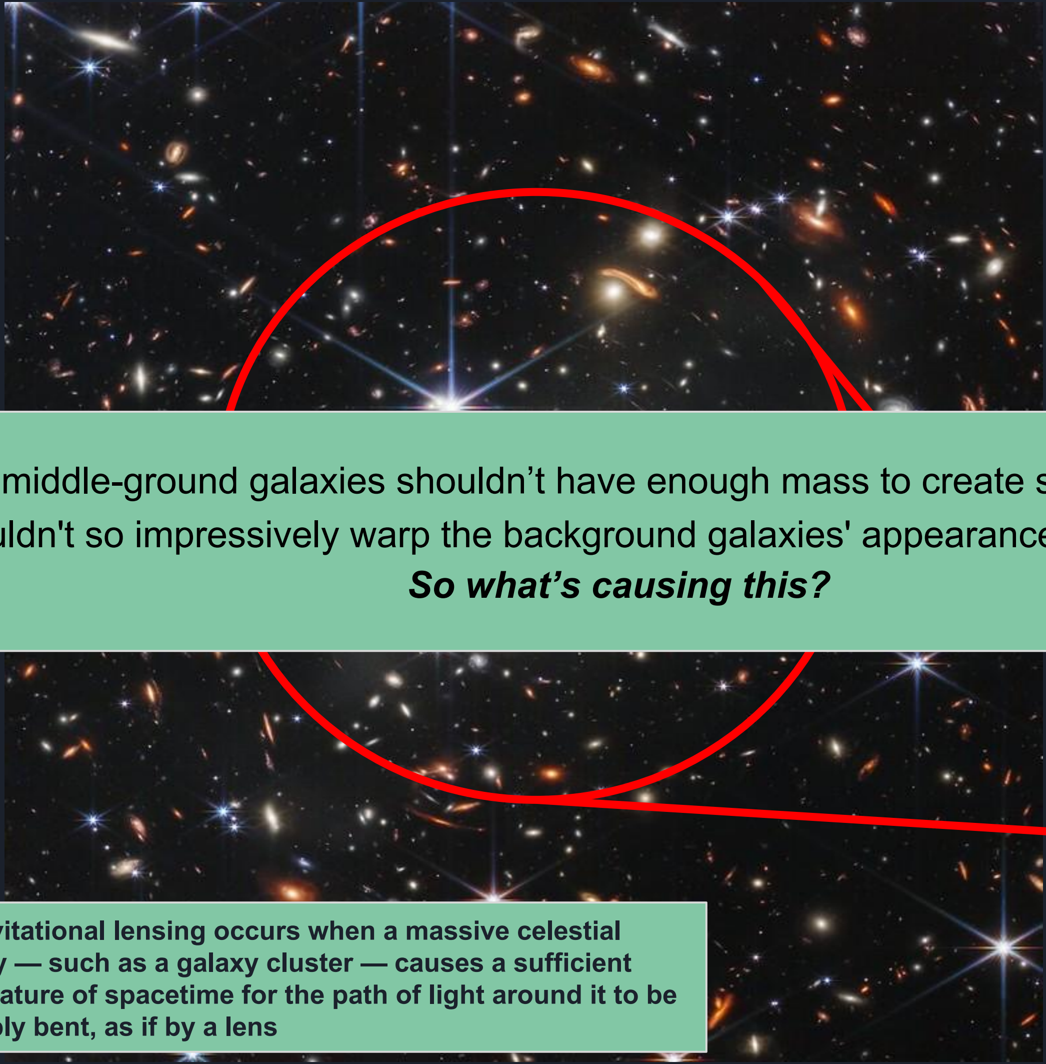


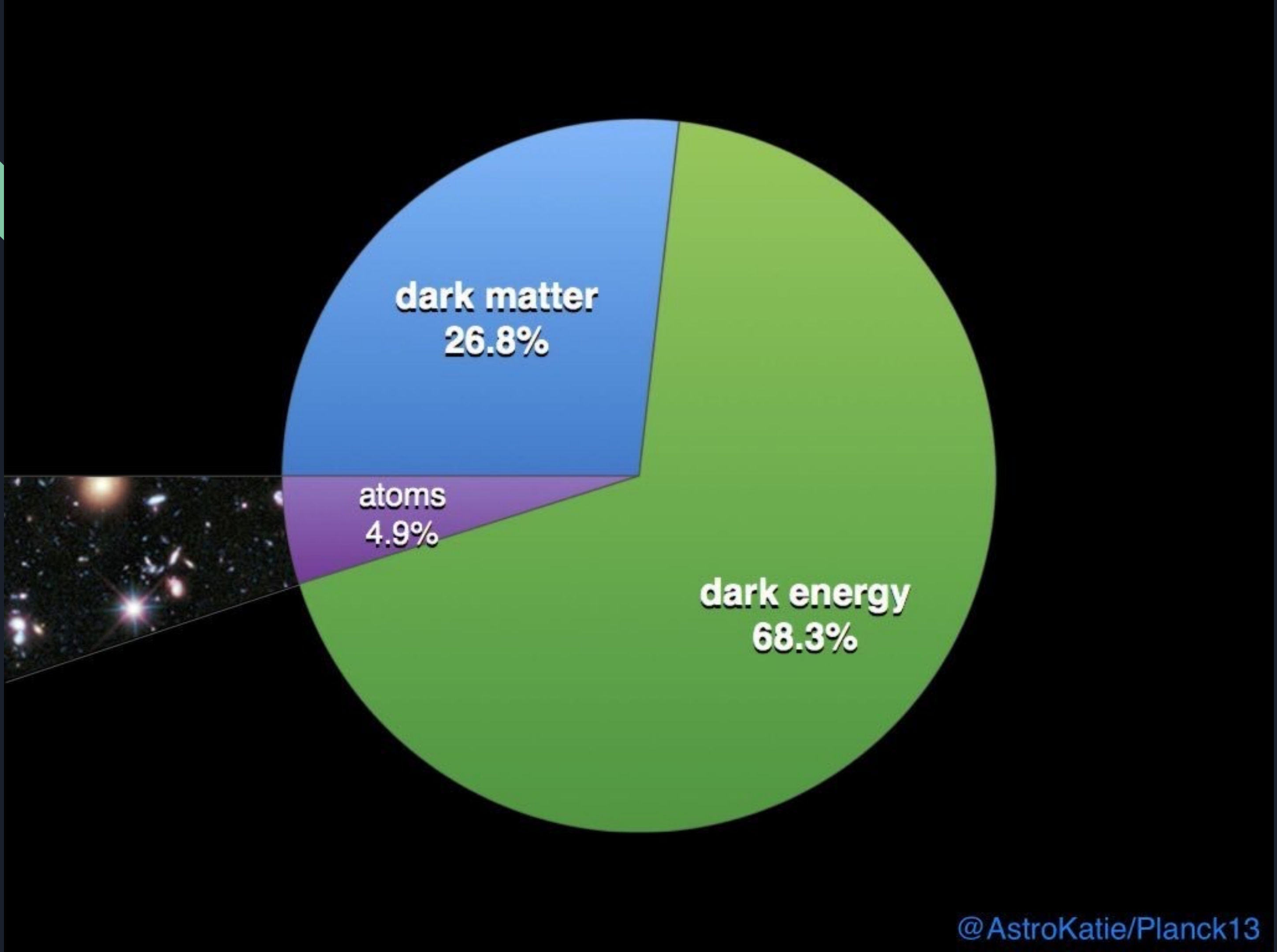
The middle-ground galaxies shouldn’t have enough mass to create such a powerful lens, and shouldn't so impressively warp the background galaxies' appearances.

So what’s causing this?

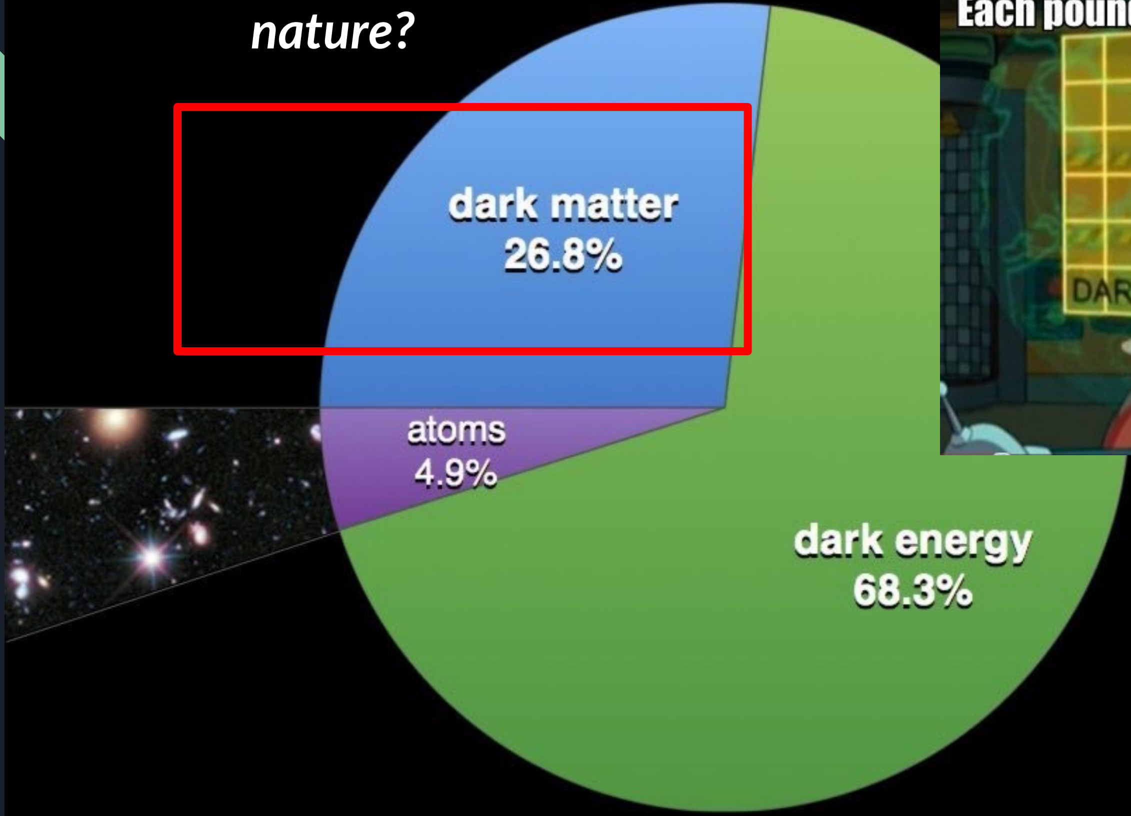
from
k all
squiggly and bending?

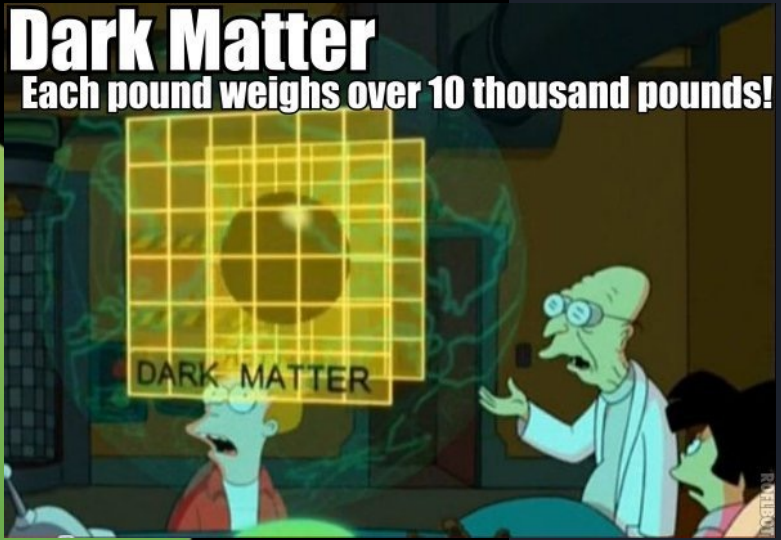
Gravitational lensing!

Gravitational lensing occurs when a massive celestial body — such as a galaxy cluster — causes a sufficient curvature of spacetime for the path of light around it to be visibly bent, as if by a lens

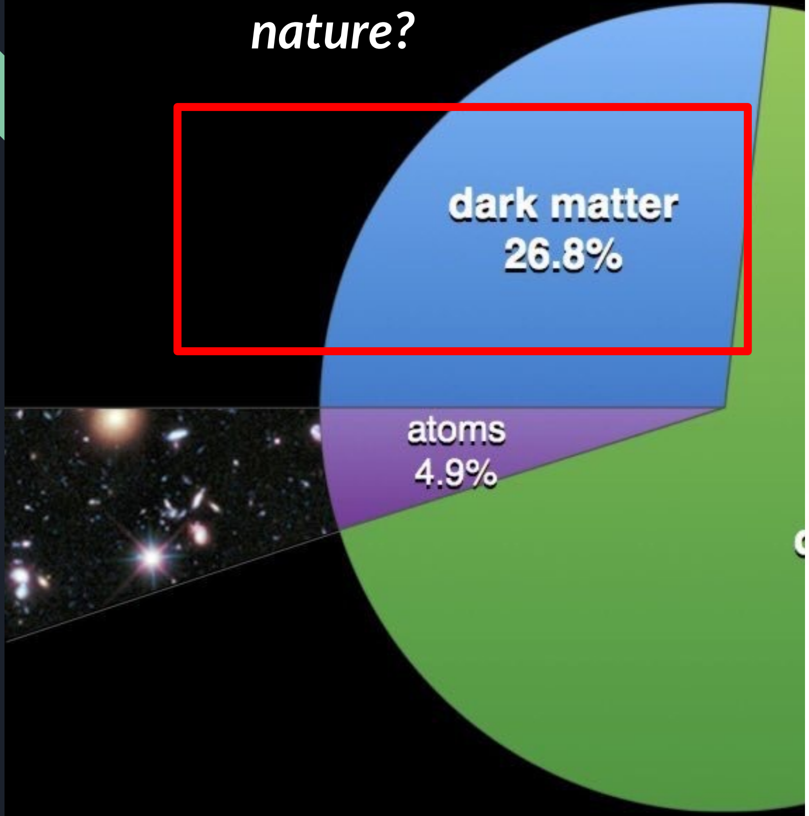

dark matter
26.8%
atoms
4.9%
dark energy
68.3%
@AstroKatie/Planck13

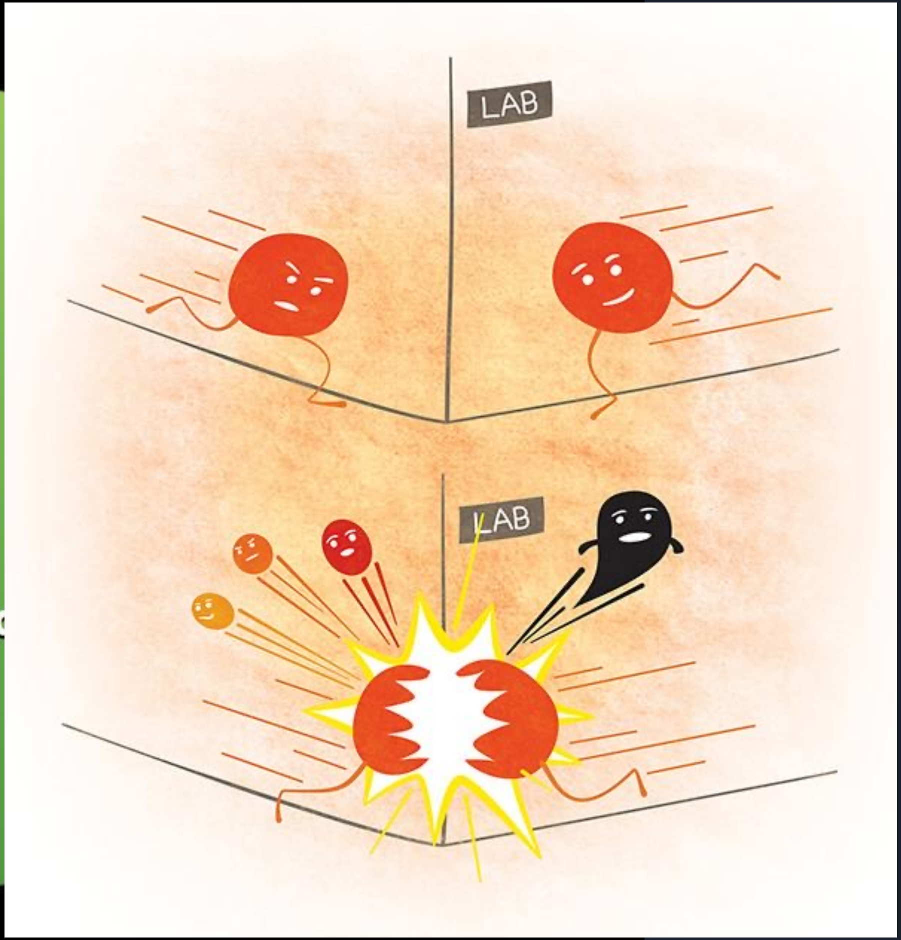
What is its nature?



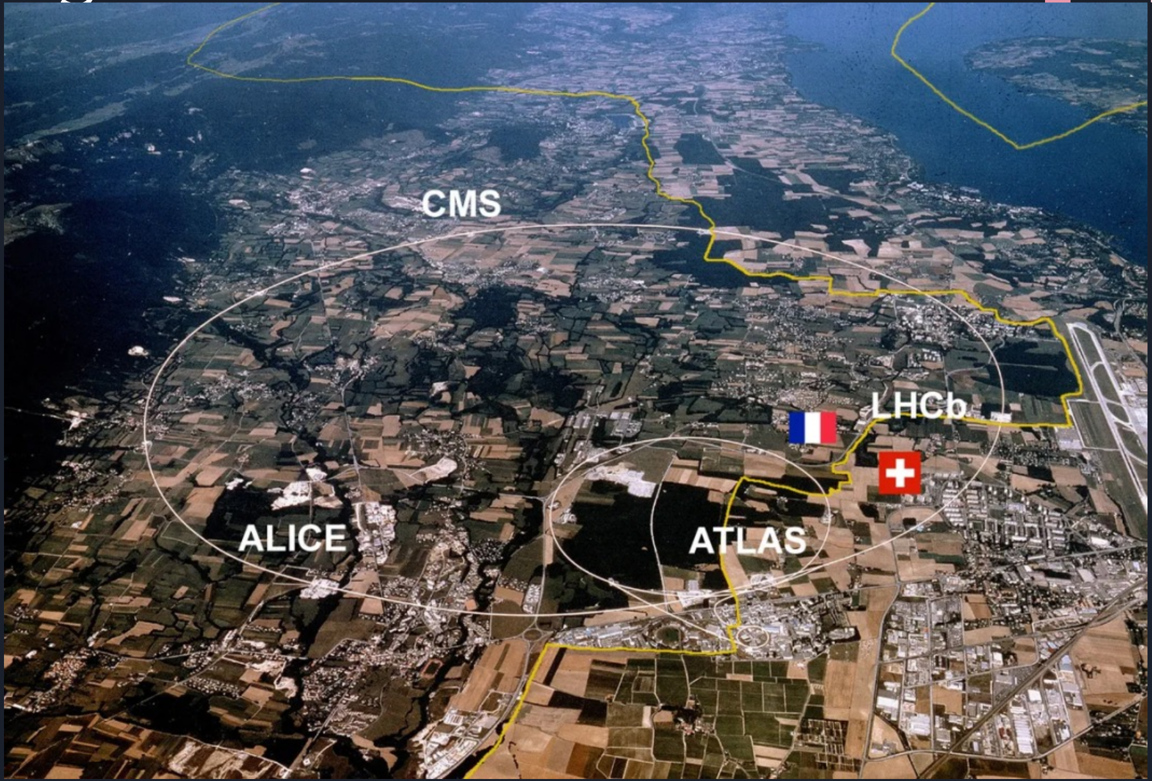


What is its nature?

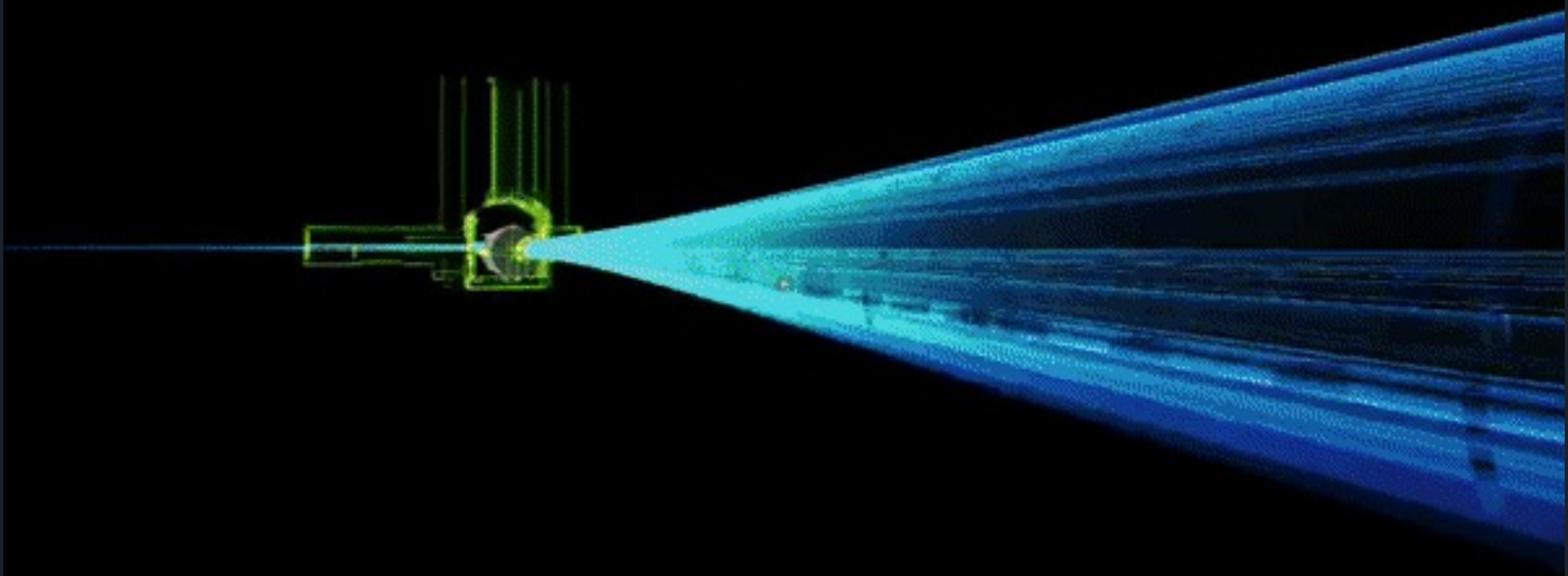


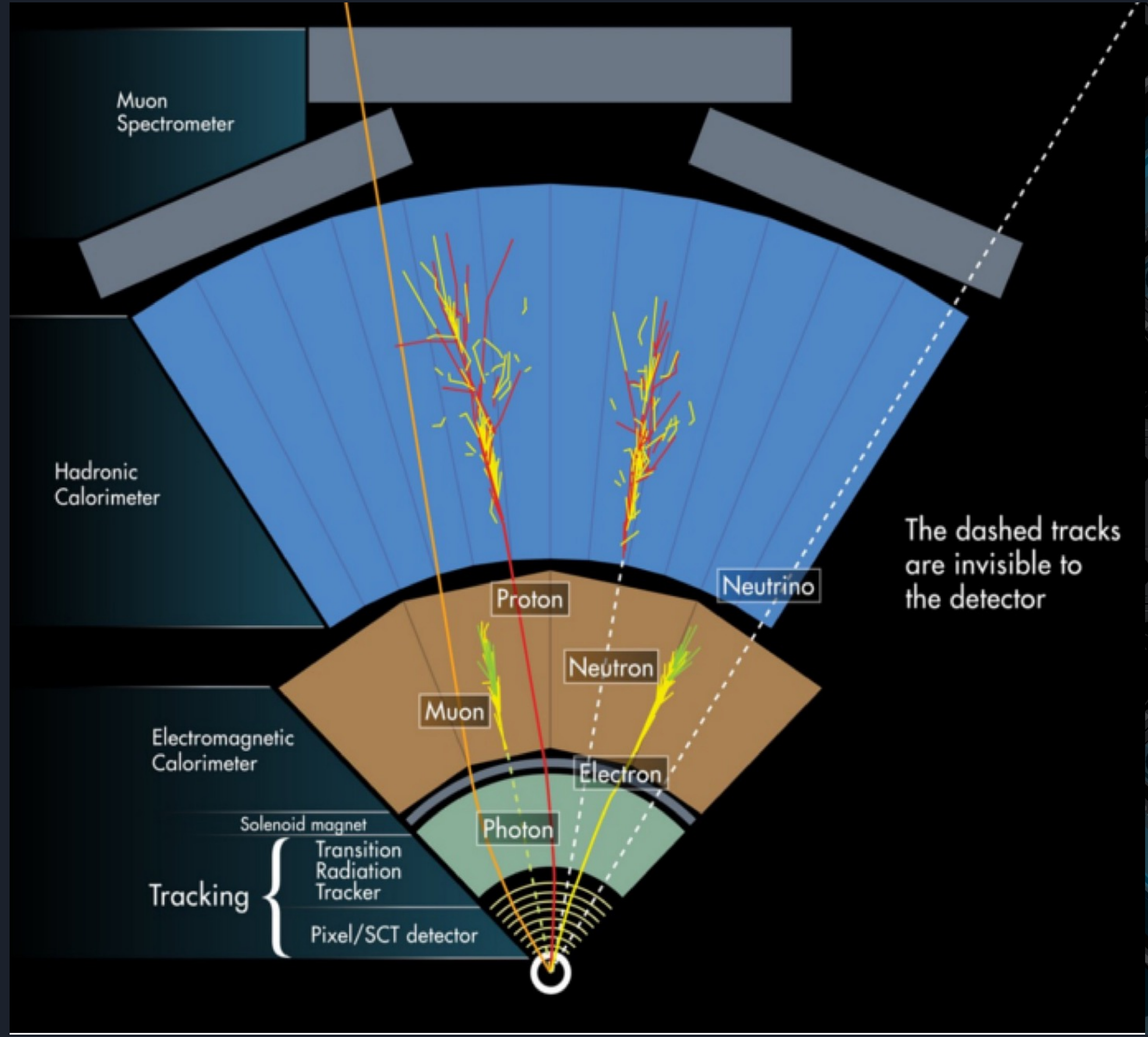


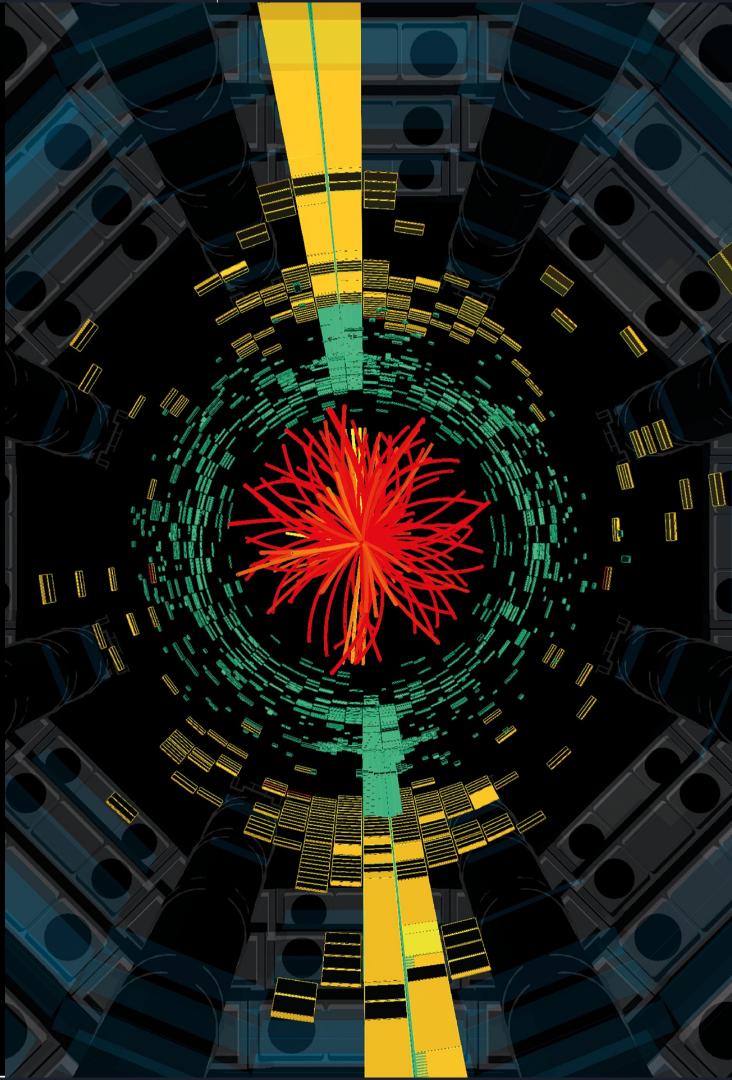
… at the Large Hadron Collider



World's largest and most powerful particle accelerator.
Circumference of 27 km, running underground across the borders of Switzerland and France.




Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

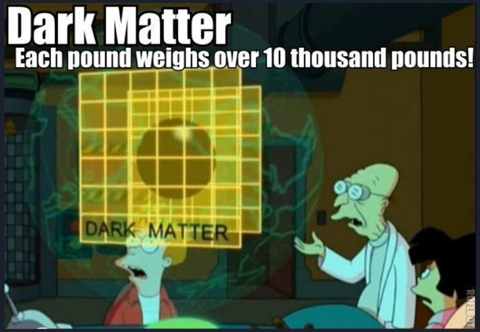


Hidden Sectors

SM Sector — Connectors / Portals — Hidden Sectors

Connectors / Portals: Z′, SUSY particles, Higgs, Extra Dim, Leptoquarks, CP-odd..

Hidden Sectors: can be strongly or weakly coupled i.e., dark Higgs, dark photon, dark SU(N), Asym DM...



When a Hidden Sector particle is (quasi-)stable, a dark matter candidate can potentially exist

We have not found any concrete sign of new physics … yet!

Looking at unusual topologies and hidden corners of the phase space

→ **signature based searches, using benchmark models.**

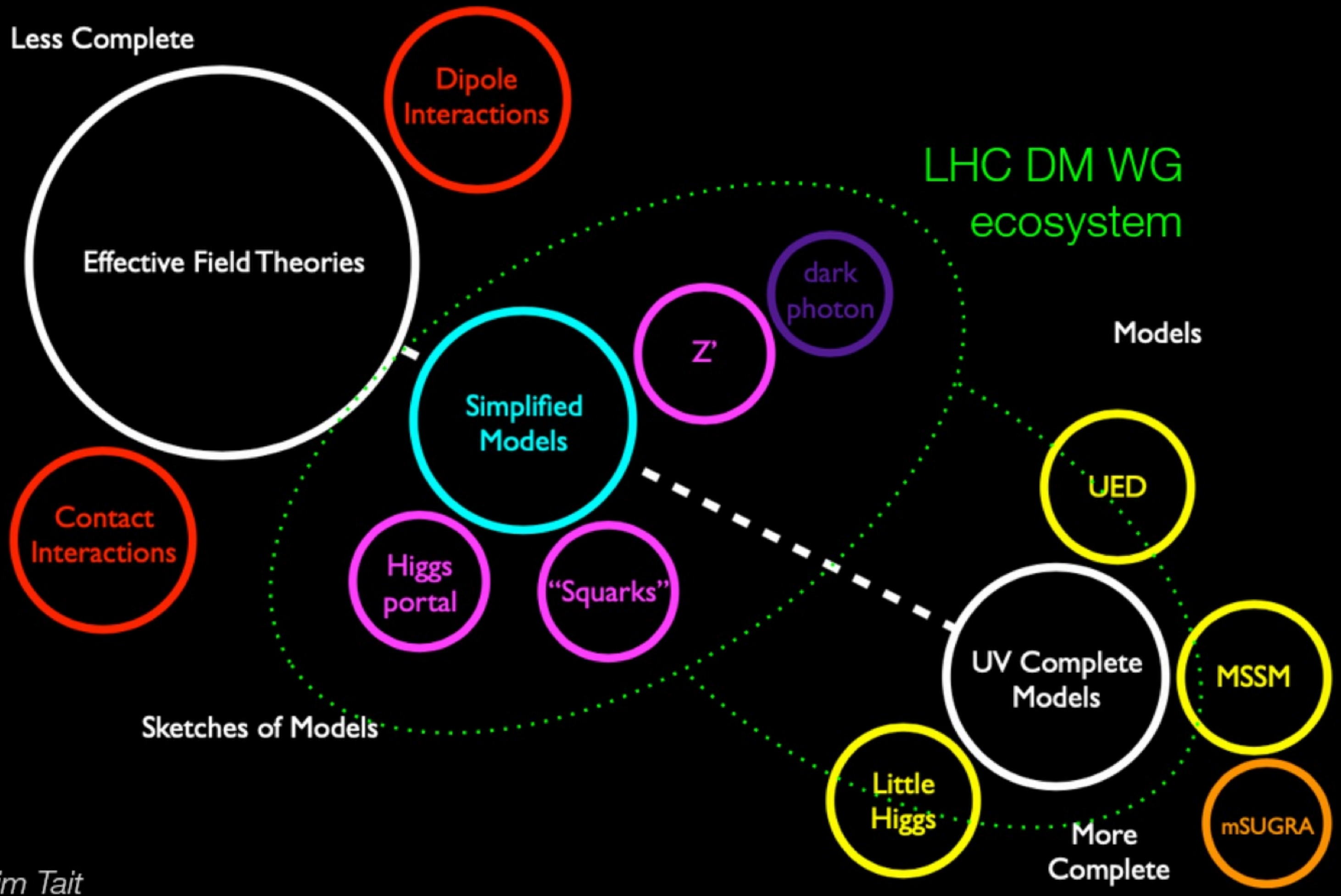
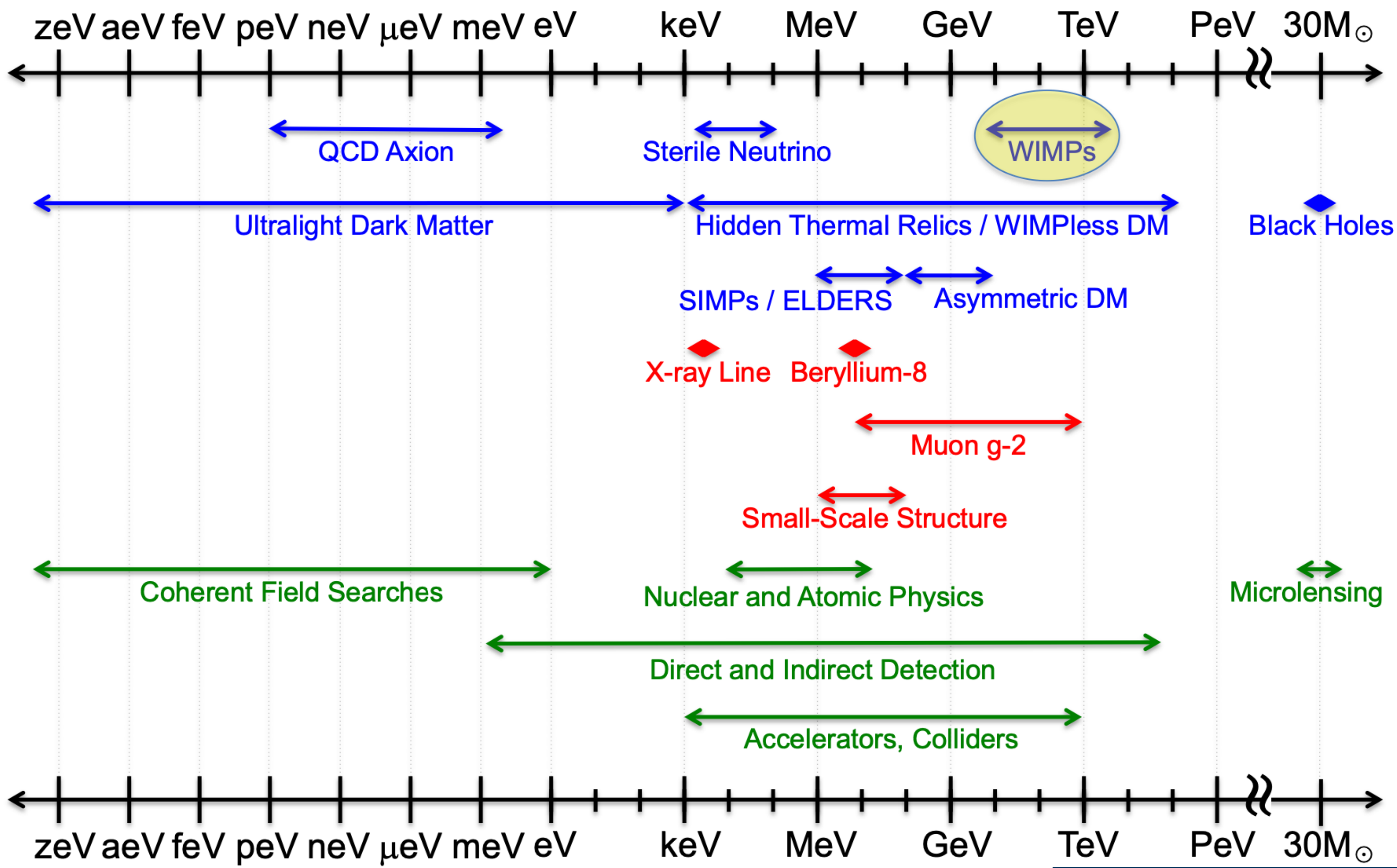


Figure: Tim Tait

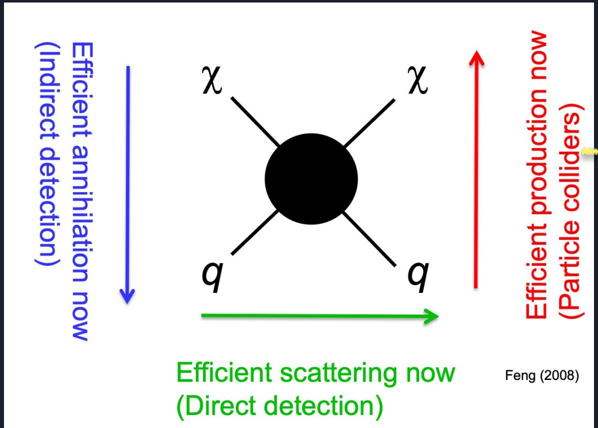


J.Feng Les Houches school notes

WIMPs

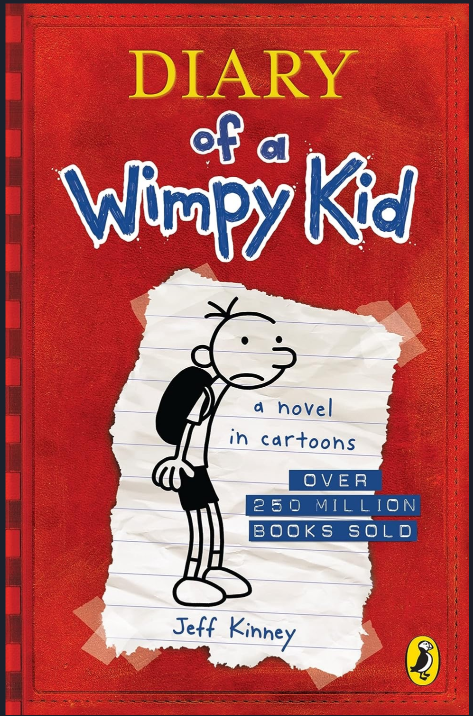
The miracle… WIMPs motivated by

- cosmology (production mechanism of thermal freeze-out, expected to have right relic density)
- particle theory (i.e. present in many BSM models)
- particle experiment (accessible in current and near-future energy scales)



Complementarity of various WIMP dark matter detection methods

Direct WIMP production of $\chi\chi$ pairs is invisible
→ must look for signatures of WIMPs produced in conjunction with other particles.



If SUSY: pair of squarks/gluinos → neutralino WIMP (i.e. MET) (not discussed in detail)

Simplified models: DM + few other particles → few defining parameters

Over the years, hundreds of dark matter models and search strategies have been proposed….

ATLAS Collaboration, G. Aad et al., *Search for dark matter in events with a hadronically decaying W or Z boson and missing transverse momentum in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, *Phys.Rev.Lett.* **112** (2014), no. 4 041802, [arXiv:1309.4017].

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CMS Collaboration, V. Khachatryan et al., *Search for dark matter, extra dimensions, and unparticles in monojet events in proton?proton collisions at* $\sqrt{s} = 8$ *TeV*, *Eur. Phys. J.* **C75** (2015), no. 5 235, [arXiv:1408.3583].

ATLAS Collaboration, G. Aad et al., *Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, *Phys. Rev.* **D91** (2015), no. 1 012008, [arXiv:1411.1559]. [Erratum: Phys. Rev.D92,no.5,059903(2015)].

ATLAS Collaboration, G. Aad et al., *Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at* $\sqrt{s}$=8 *TeV with the ATLAS detector*, *Phys.Rev.* **D90** (2014) 012004, [arXiv:1404.0051].

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C75 (2015), no. 5 235, [arXiv:1408.3583

ATLAS Collaboration, G. A

Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$= 13 TeV with the ATLAS detector

ATLAS uses the Higgs boson as a tool to search for Dark Matter

29th October 2020 I By ATLAS Collaboration

Phys. Rev. **D90** (2014) 012004, [arXiv:

state at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration, G. Aad et al., *Search for energetic*
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Search for direct pair production of supersymmetric partners to the τ lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration • Albert M Sirunyan (Yerevan Phys. Inst.) et al. (Jul 30, 2019)

Published in: *Eur.Phys.J.C* 80 (2020) 3, 189 • e-Print: 1907.13179 [hep-ex]

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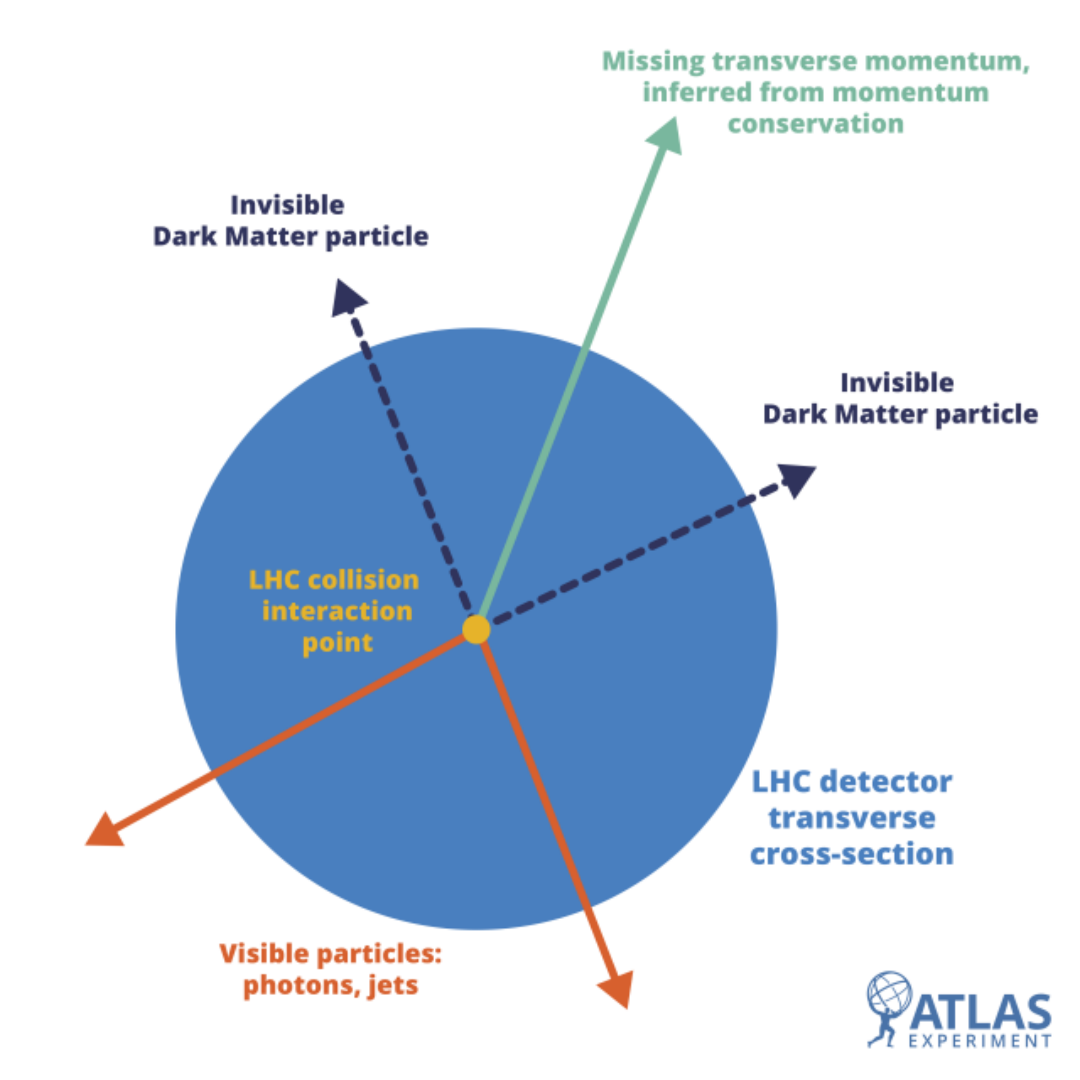

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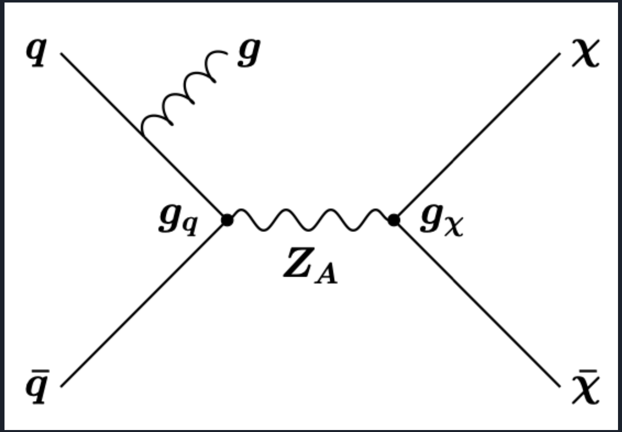
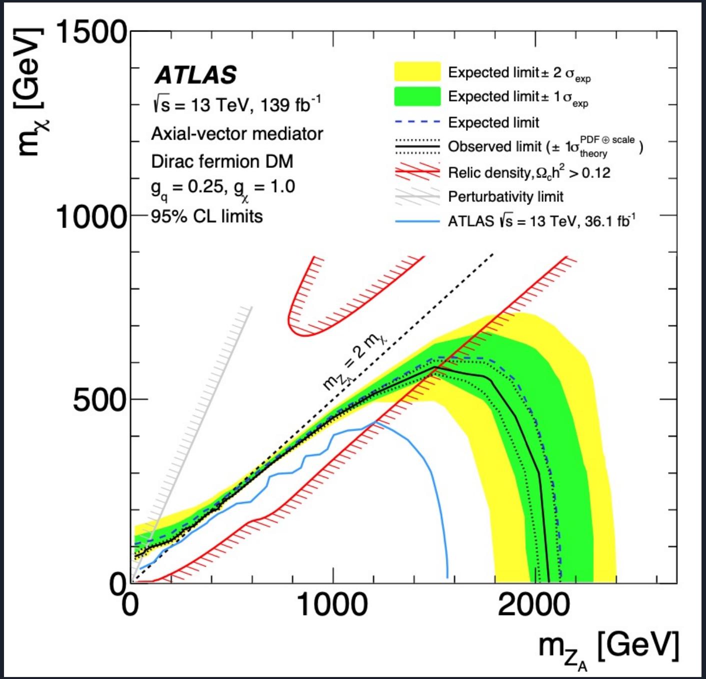
WIMPs



Mono-jet: WIMP pair production with ISR gluon

Exclusive (EM)	EM0	EM1	EM2	EM3	EM4	EM5	EM6
E_T^{miss} [GeV]	200–250	250–300	300–350	350–400	400–500	500–600	600–700
	EM7	EM8	EM9	EM10	EM11	EM12	
	700–800	800–900	900–1000	1000–1100	1100–1200	> 1200	
Inclusive (IM)	IM0	IM1	IM2	IM3	IM4	IM5	IM6
E_T^{miss} [GeV]	> 200	> 250	> 300	> 350	> 400	> 500	> 600
	IM7	IM8	IM9	IM10	IM11	IM12	
	> 700	> 800	> 900	> 1000	> 1100	> 1200	



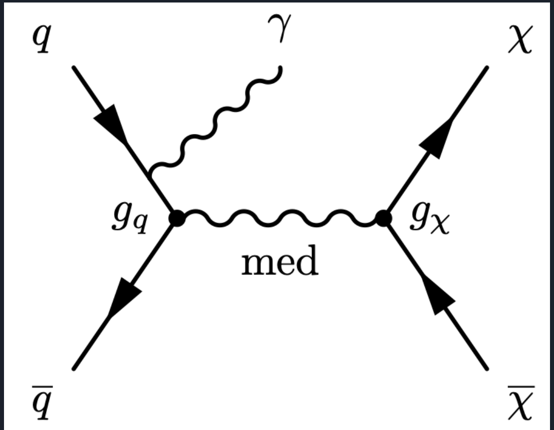
In the region $m_{Z_A} > 2m_\chi$, mediator masses up to about 2.1 TeV are excluded for m_χ= 1 GeV

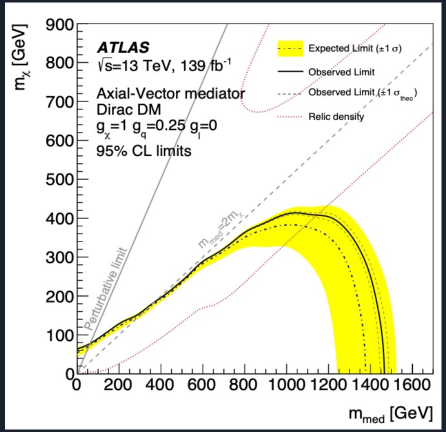
Masses corresponding to relic density determined by the Planck and WMAP satellites
→ line that crosses the excluded region at m_{Z_A}~ 1500 GeV and m_χ ~ 585 GeV

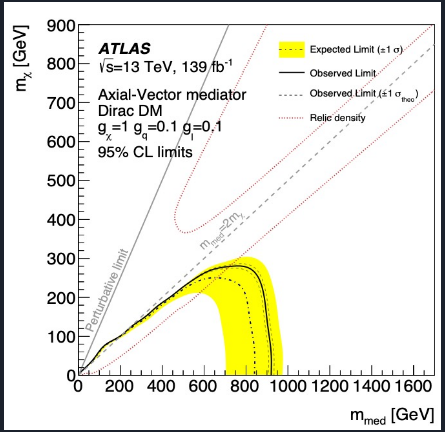
Phys. Rev. D 103, 112006 (2021)

WIMPs

[JHEP 02 (2021) 226]







Mono-photon: WIMP pair production with ISR photon

	SRI1	SRI2	SRI3	SRI4	SRE1	SRE2	SRE3
E_T^{miss} [GeV]	> 200	> 250	> 300	> 375	200–250	250–300	300–375

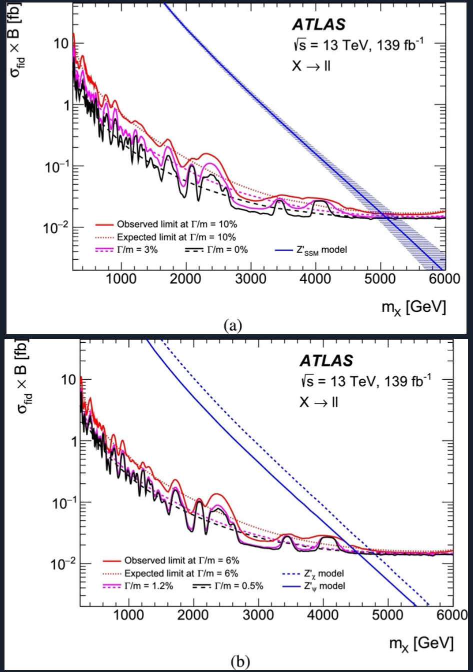
Masses corresponding to relic density determined by the Planck and WMAP satellites

Mediator	g_q	g_χ	g_ℓ	m_{med} [GeV]	m_χ [GeV]
Axial-vector	0.25	1	0	1460	415
Axial-vector	0.1	1	0.1	920	280
Vector	0.25	1	0	1470	580
Vector	0.1	1	0.01	950	400

WIMPs

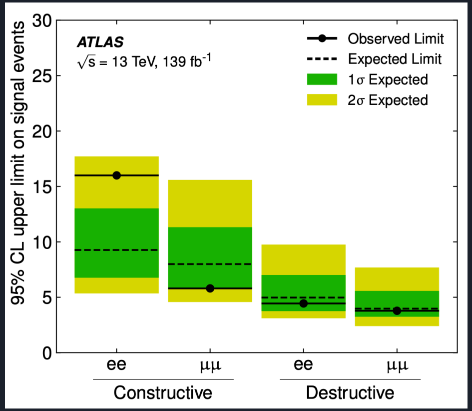
di-jet and dilepton final states

Phys. Lett. B 796 (2019) 68



Observed limit on fiducial $\sigma \times BR$ ranges from 3.6 (13.1) fb at 250 GeV to about 0.014 (0.018) fb at 6 TeV for the zero (10%) relative width signal in the combined dilepton channel.

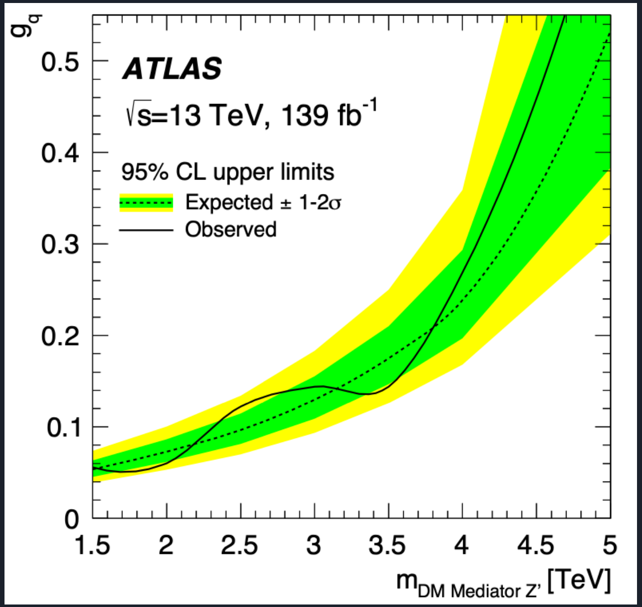
JHEP 11 (2020) 05



$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{ij}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

Non-resonant dilepton: Interference between the DY and CI processes can be constructive or destructive depending on the sign of η_{ij}

JHEP 03 (2020) 145



Resonant dijet search: The 95% CL upper limits are set on the universal quark coupling g_q as a function of the Z′ mass

What are the ingredients for a simplified/collider-friendly DM model?

Basic Ingredients:
- *Generic* signatures
- *Evades constraints*
- *Manageable* no. of parameters
- *Promising* dark matter candidate
  - ability to satisfy relic density

Spices/garnishes:
- Wide range of possible signatures
- Interesting phenomenology
- Potential synergies
  - decays: prompt vs LLP vs invisible
  - resonant vs non-resonant production
  - complementarity with direct/indirect detection

What did I bring to the table?

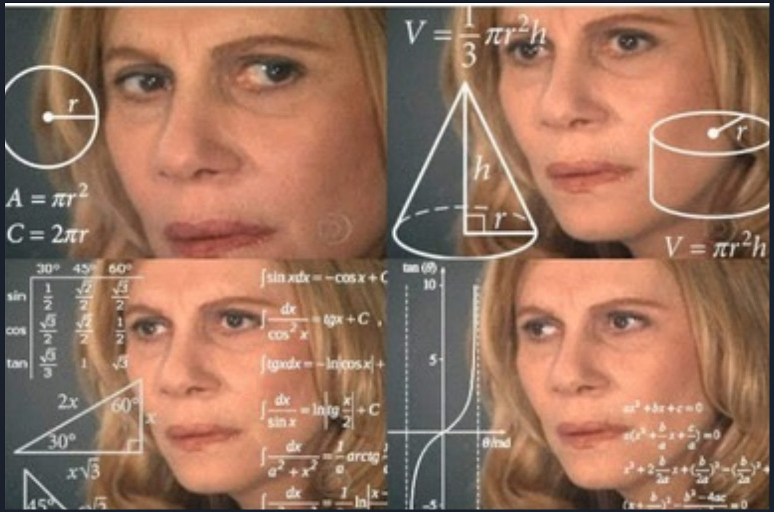
Searches for strongly-interacting dark sectors...

What did I bring to the table?

Searches for strongly-interacting dark sectors...

Confused?

Let’s take a step back....



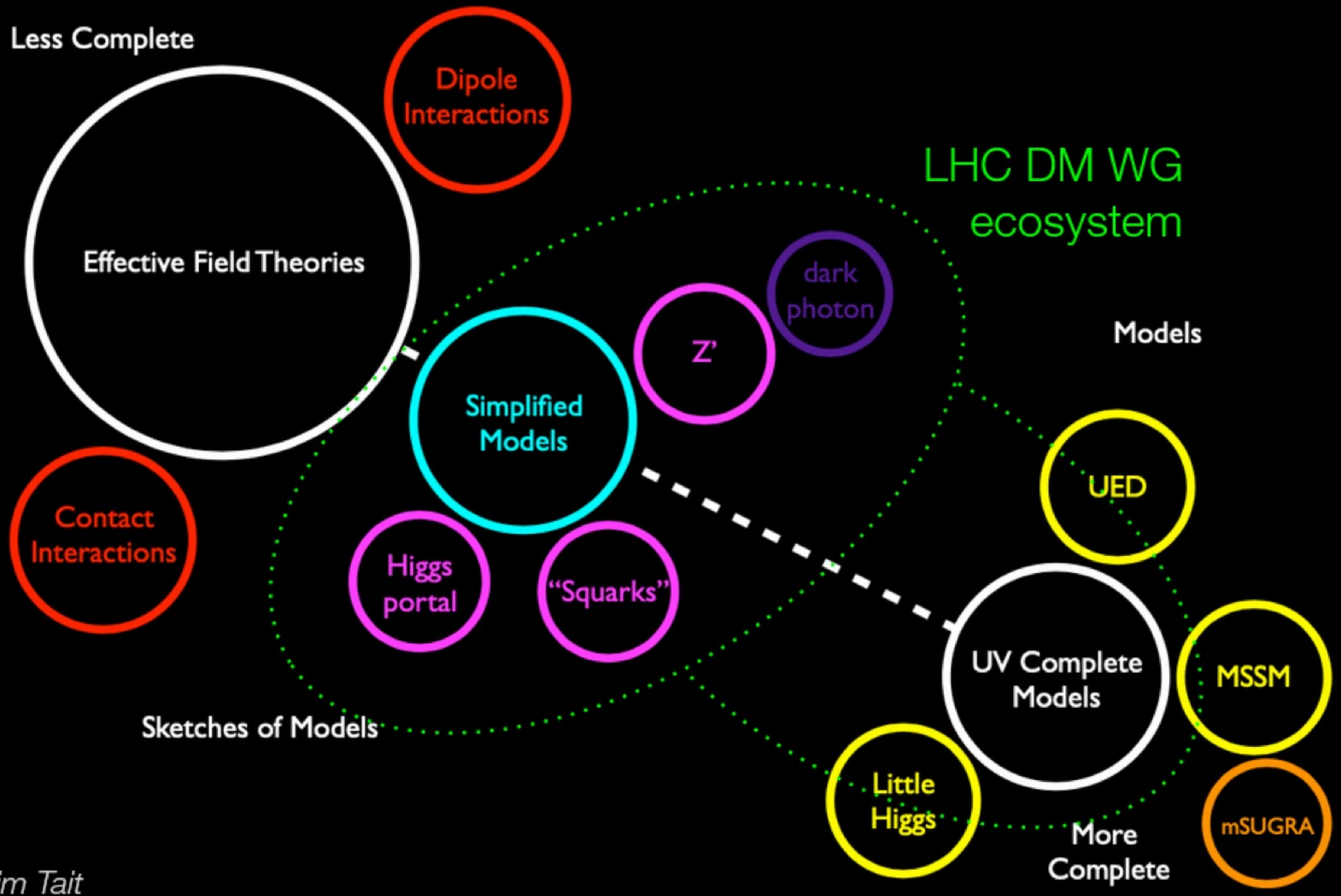


Figure: Tim Tait

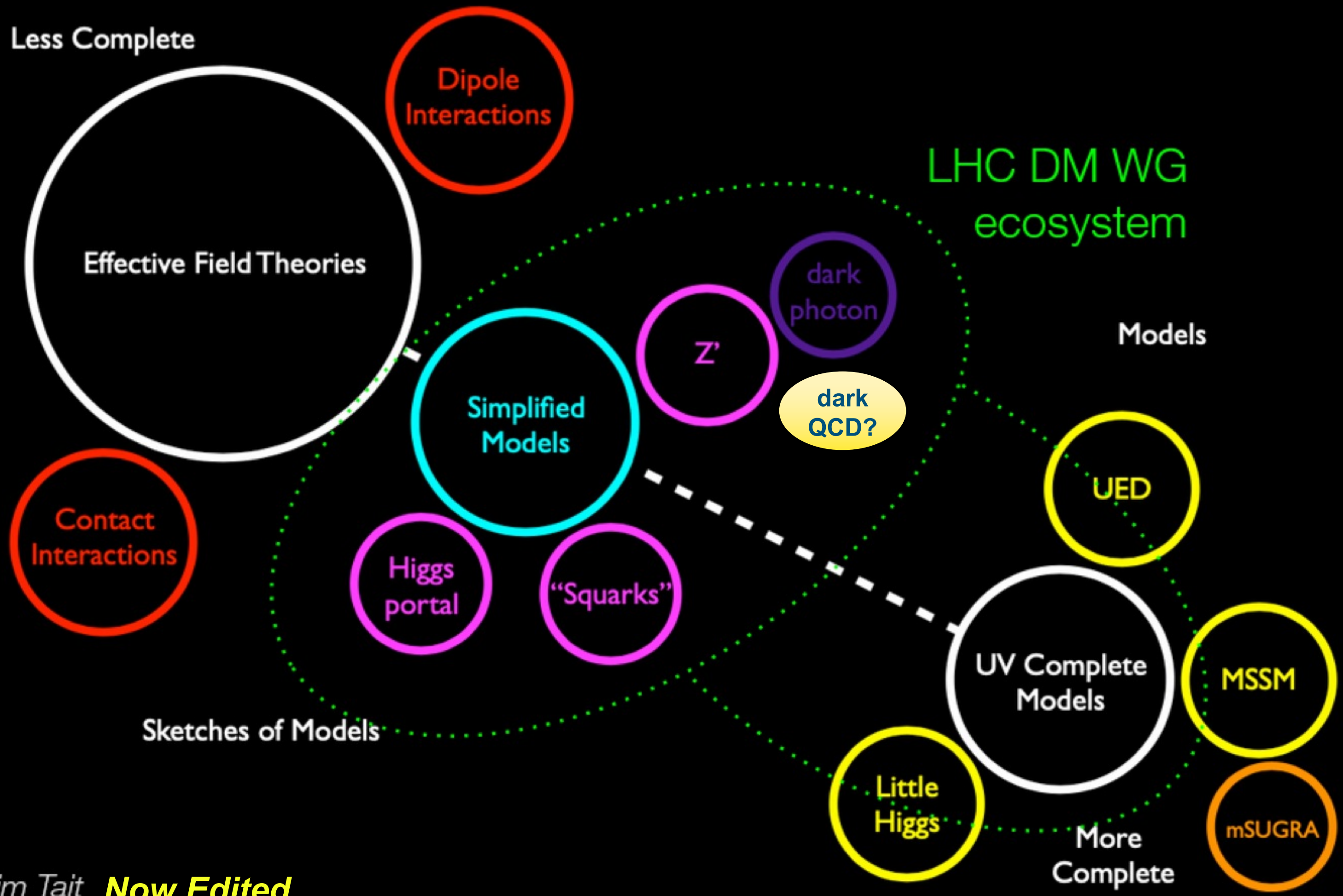


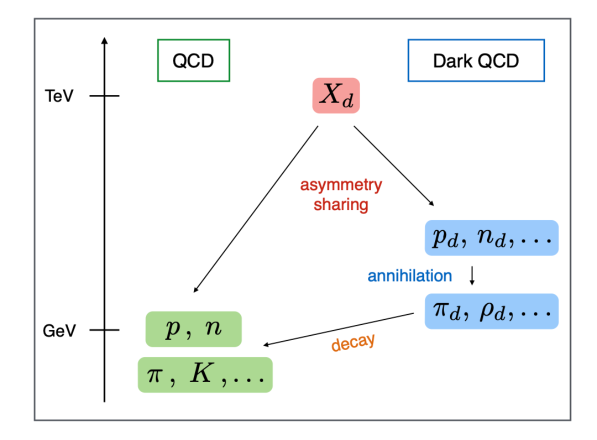
Figure: Tim Tait **Now Edited**

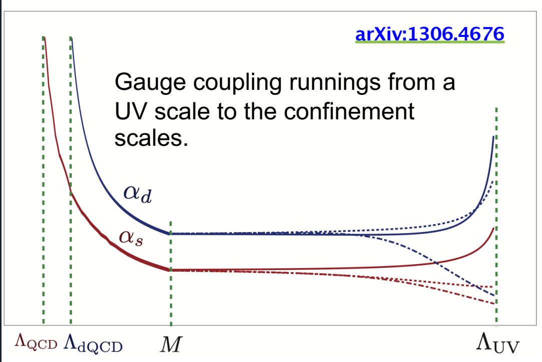
Dark QCD matters!

Hidden Valley may provide cosmologically required DM. No attempt to construct a specific model → set up reasonably generic framework for simulating variety of experimental signatures.

Different dark quark flavours combine to form π_d^+, π_d^-, π_d^0, and ρ_d^+, ρ_d^-, ρ_d^0 (assumed to be produced thrice as much as pions)

- Neutral dark mesons are unstable and (promptly) decays to SM quarks: more likely to decay to b pairs due to need for a mass insertion, to make the angular momentum conservation work out
- Other mesons are (collider-)stable → invisible





Baryon and DM asymmetries shared via a mediator Xd → asymmetry in stable dark baryons.

The symmetric relic density annihilated into dark pions → decay into SM particles.

Correct DM relic density obtained when dark baryon masses are in the 10 GeV range.

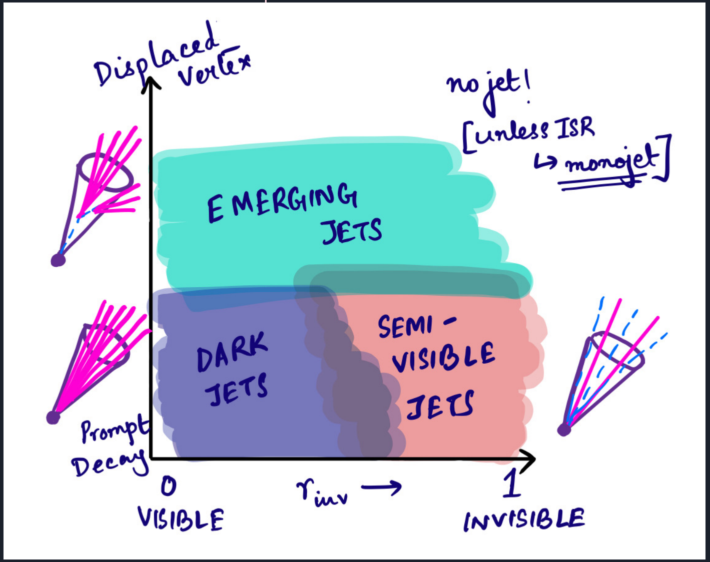
Different UV boundary gauge couplings can lead to the same perturbative IR fixed points.

The final state signatures...

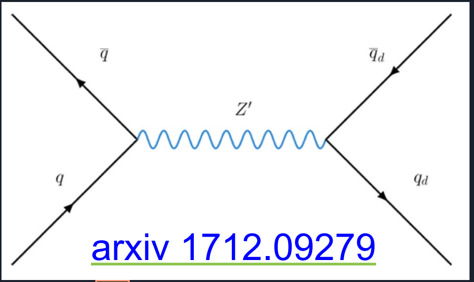
Dark hadrons decaying promptly in a QCD-like fashion,
- fully, or
- partially back to the visible sector

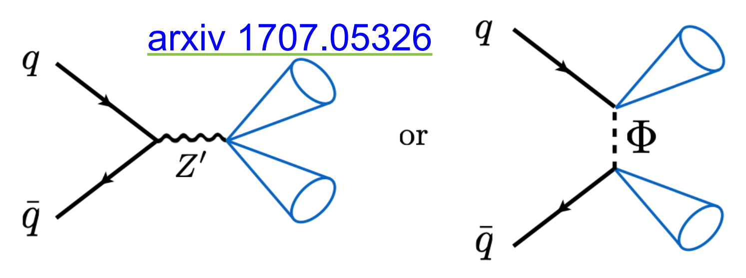
Dark hadrons undergoing displaced decays in a QCD-like fashion

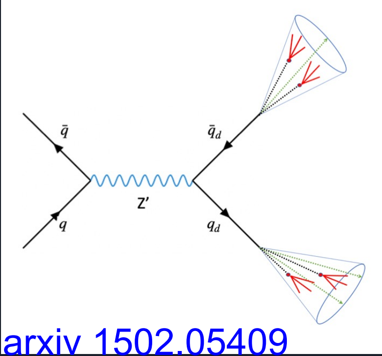
Each signature has a distinctive feature:
-> Dark jets: unique substructure
-> Emerging jets: displaced objects
-> Semi-visible jets: substantial missing energy



Showering using Pythia hidden valley module: at best a guesstimate!

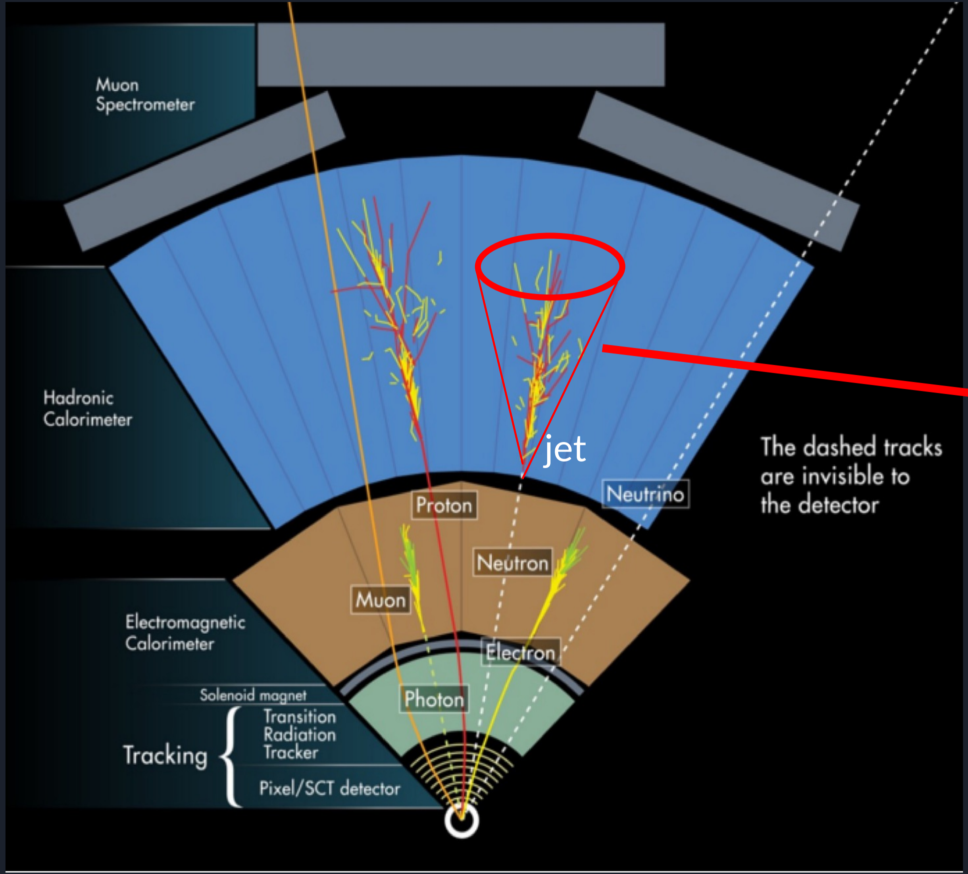


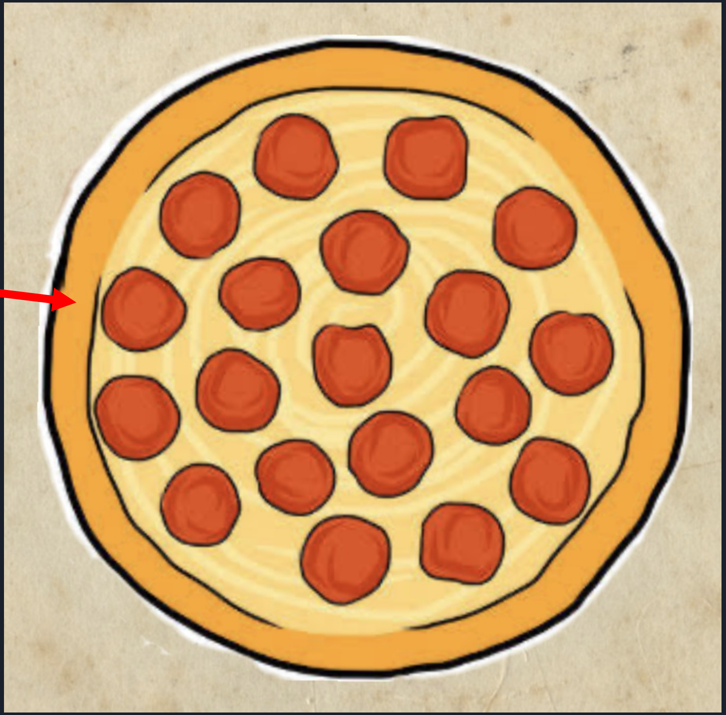




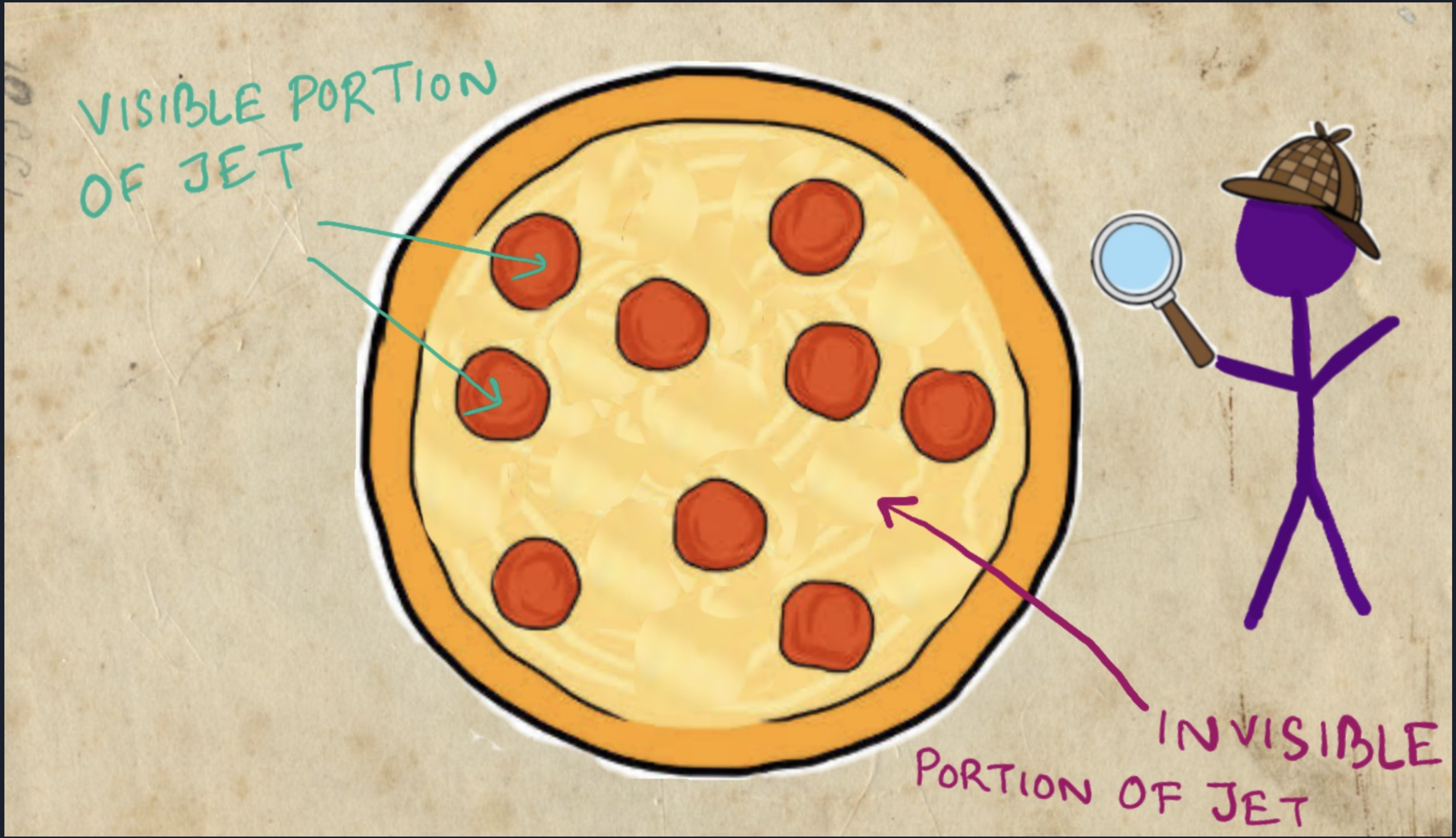
R_{inv} = #stable dark hadrons/#all dark hadrons

The final state signatures...

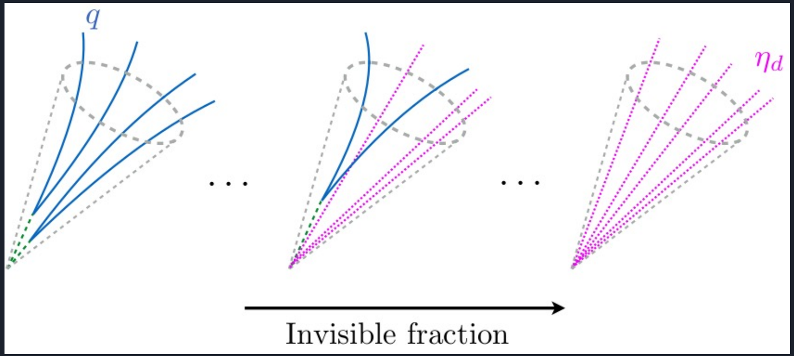




Semi-visible jets



ATLAS semi-visible jets t-channel production



Model Parameters:

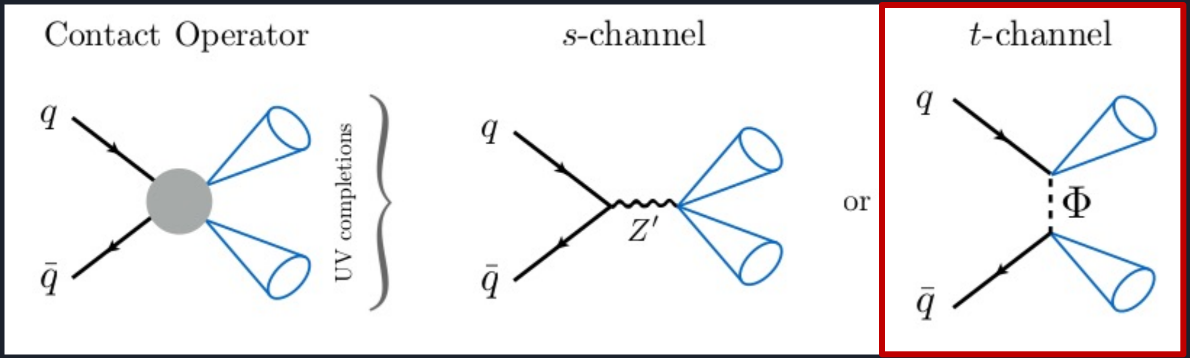
1. M_Φ = Mass of Scalar Bi-fundamental mediator
2. R_{inv} = #stable dark hadrons/ #all dark hadrons
3. M_d = Mass of dark hadrons

Dark sector → SU(2) gauge theory with coupling $\alpha_d = \frac{g_d{}^2}{4\pi}$, containing two fermionic states.
Assuming minimal flavour-violation, light-flavour production channels dominate.

Lagrangian containing the interaction and kinetic terms:

$$\mathcal{L}_{\text{dark}} \supset -\frac{1}{2}\,\text{tr}\, G^{d}_{\mu\nu} G^{d\mu\nu} - \bar{\chi}_a \left(i\not{D} - M_{d,a}\right) \chi_a$$

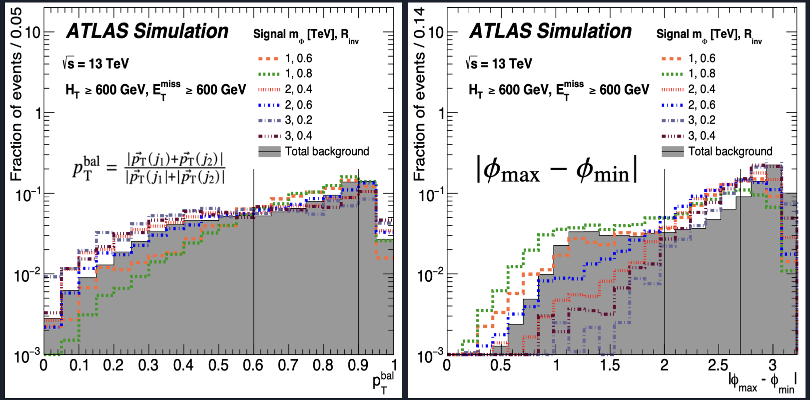
Link to the paper:
1707.05326

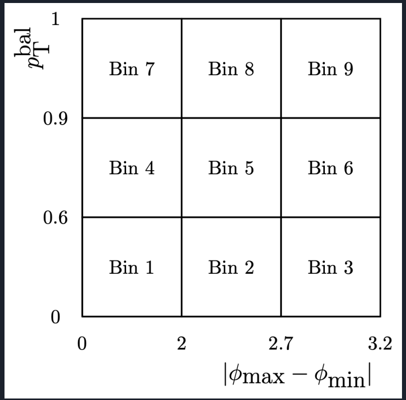


ATLAS semi-visible jets t-channel

Looking at two central R=0.4 jets, MET trigger, Δφ (closest jet, MET) < 2.0, leading jet pT > 250 GeV, HT > 600 GeV, MET > 600 GeV

Two key observables used to design a 9 bin grid: Yield in each bin treated as an observable





The signal events typically have high MET —- better sensitivity for signals with higher mediator masses and *R*inv fraction if search is performed at a high MET range.

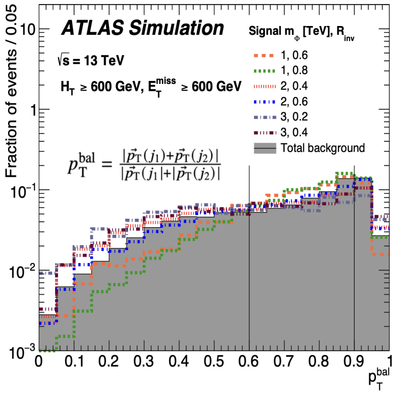
Background samples:

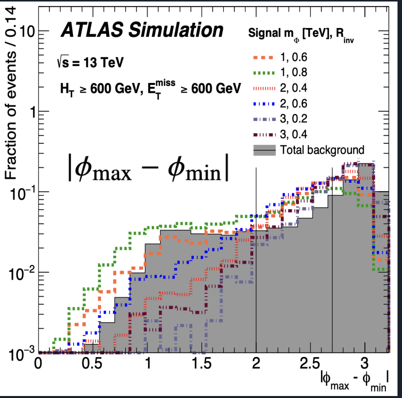
W/Z+jets, ttbar, singletop, multi-jet, diboson

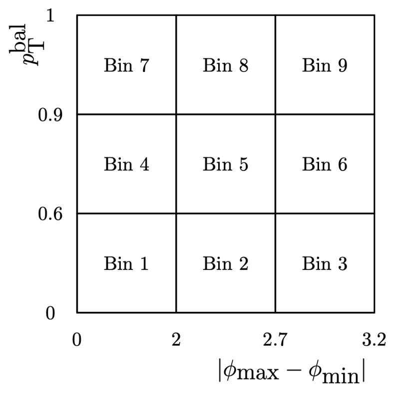
ATLAS semi-visible jets t-channel

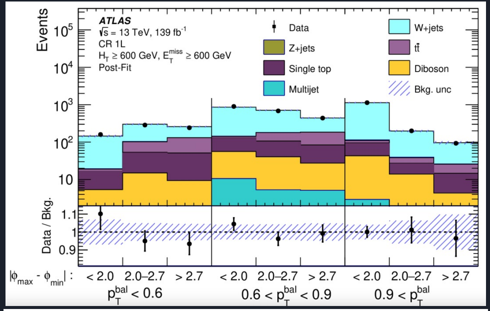
Looking at two central R=0.4 jets, MET trigger, Δφ (closest jet, MET) < 2.0, leading jet pT > 250 GeV, HT > 600 GeV, MET > 600 GeV

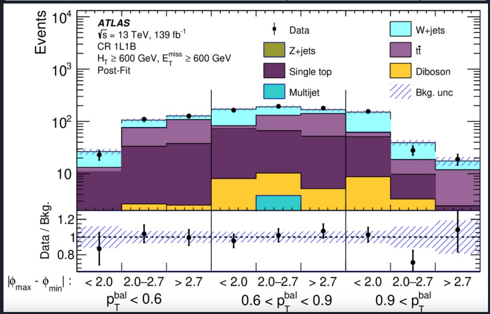
Two key observables used to design a 9 bin grid: Yield in each bin treated as an observable

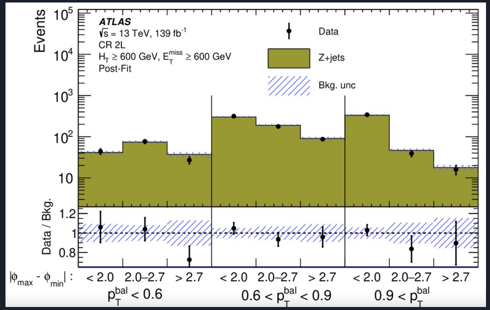












The signal events typically have high MET —- better sensitivity for signals with higher mediator masses and Rinv fraction if search is performed at a high MET range.

MET > 600 GeV and HT > 600 GeV – define SR & CR (1L, 1L1B & 2L)

Partially data-driven method, simultaneously fit SR and three CRs to obtain scale factors for each bg process

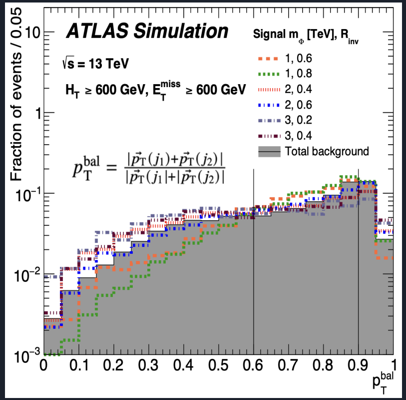
Background samples:

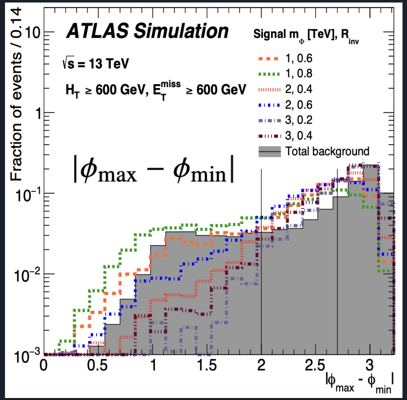
W/Z+jets, ttbar, singletop, multi-jet, diboson

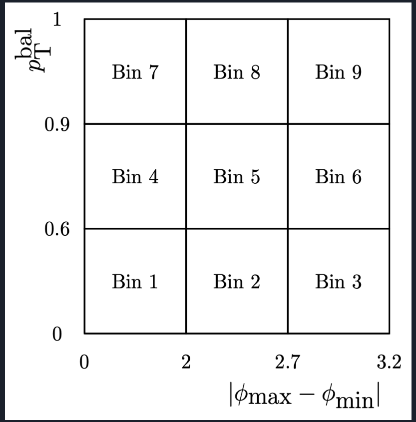
ATLAS semi-visible jets t-channel

ATLAS-EXOT-2022-37

Two key observables used to design a 9 bin grid: Yield in each bin treated as an observable







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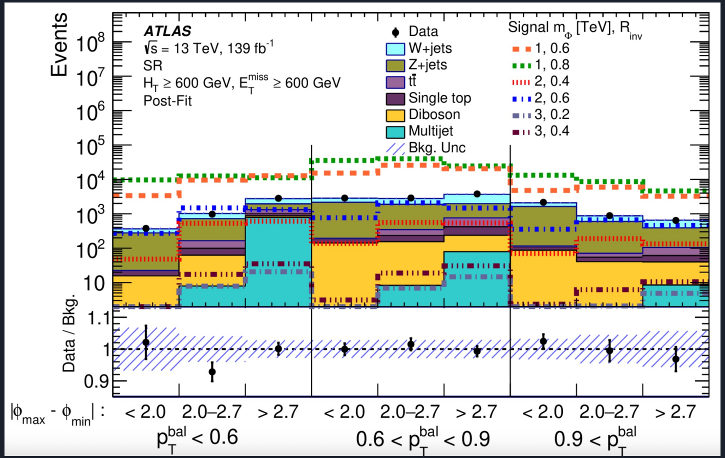


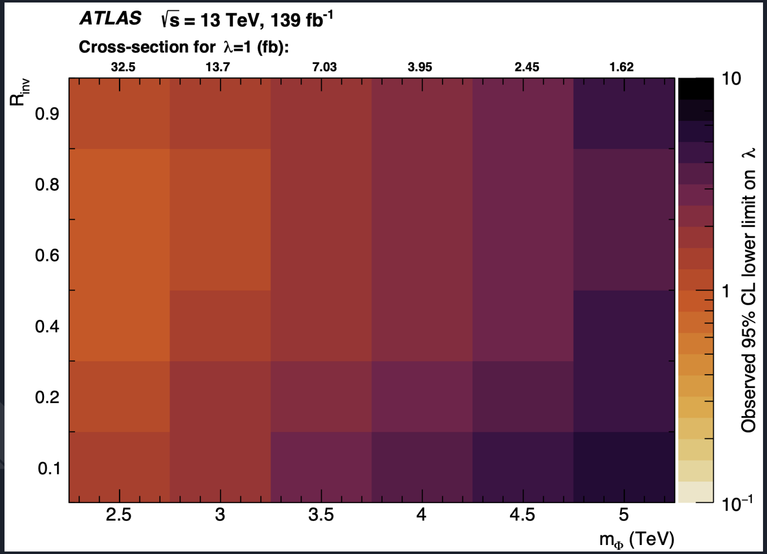
Partially data-driven method, simultaneously fit SR and three CRs to obtain scale factors for each bg process — absence of signal, good postfit agreement!

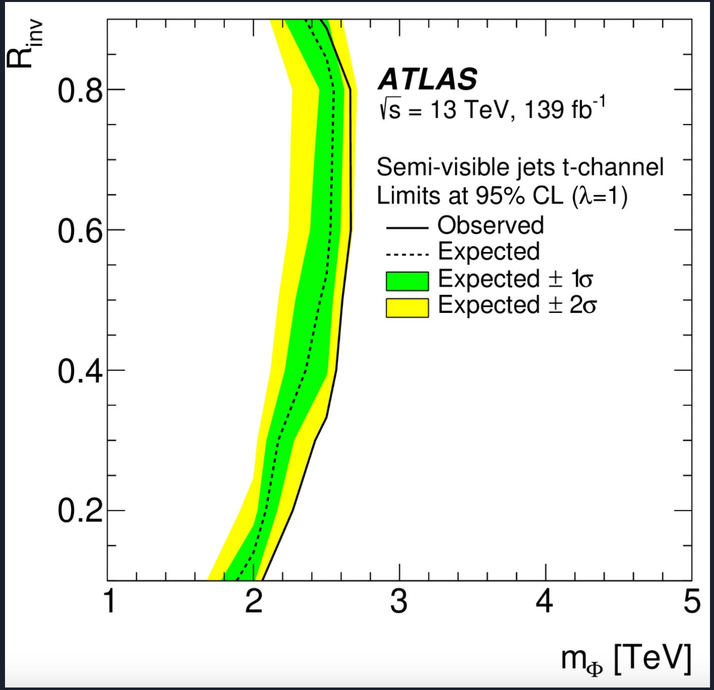
Results

First semi-visible jets result from ATLAS... but not the last!

The largest post-fit effects: signal modelling uncertainties ~8%, Z+jets modelling uncertainties ~7%, top process modelling uncertainties ~4%. The rest of the contributions are less than 2%.

- Excellent agreement between data and background prediction
- Assuming a coupling strength of unity between the mediator, a Standard Model quark and a dark quark, mediator masses up to 2.7 TeV can be excluded.
- For mediator mass of 2.5 TeV or higher can also express the limits in terms of the q-q_d-ϕ vertex coupling strength λ, as XS ~ λ^4





Phys. Lett. B 848 (2024) 138324

Results

Firs
last

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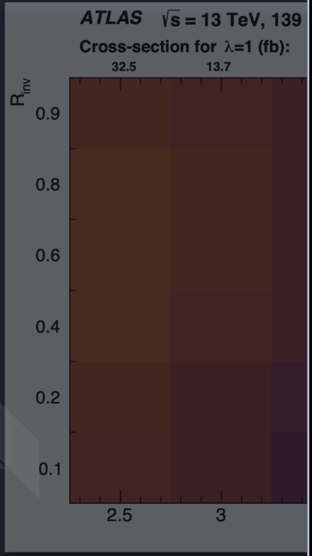
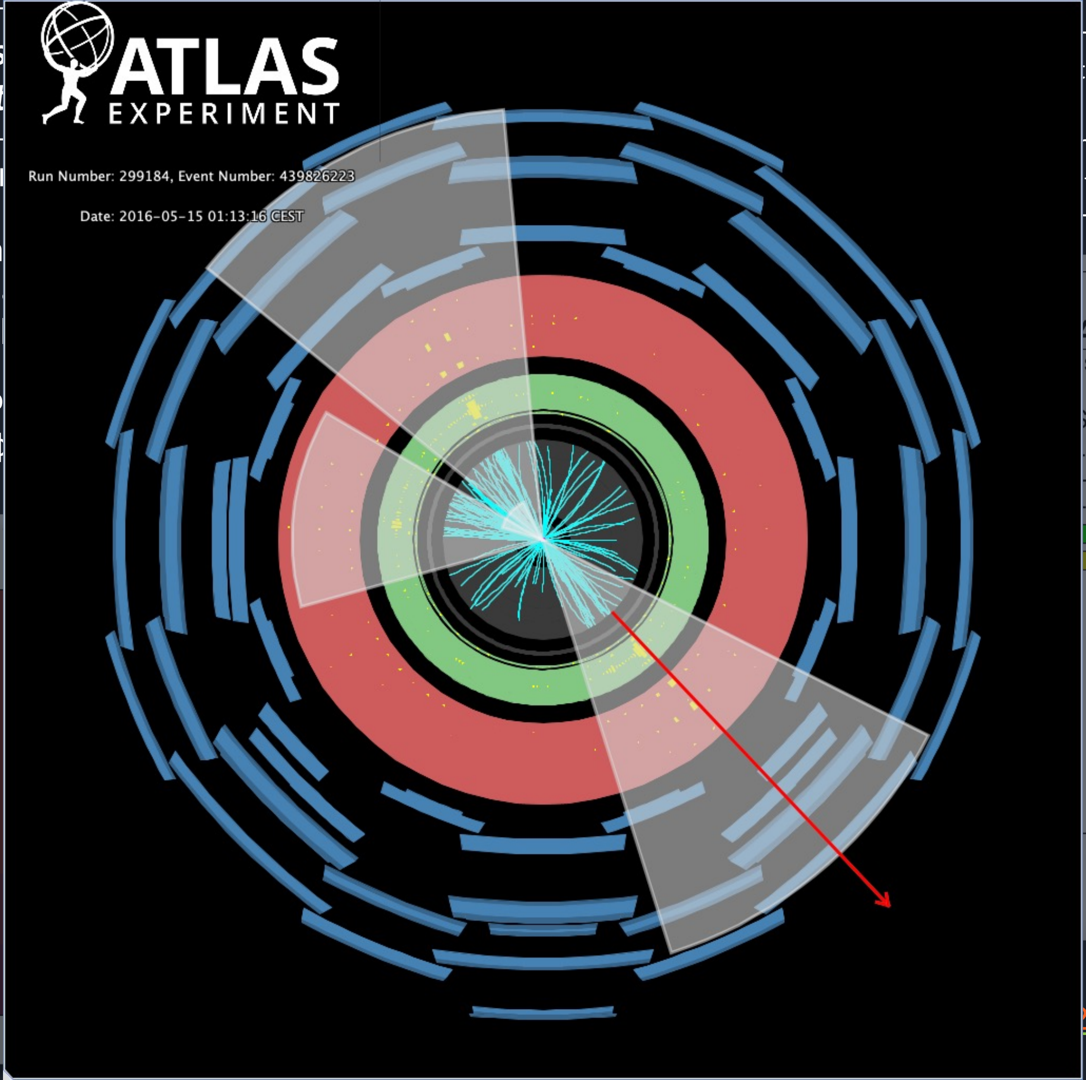
- Assuming a couplin Standard Model qu 2.7 TeV can be exc
- For mediator mass o in terms of the q-qd-ϕ





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Z+jets modelling uncertainties
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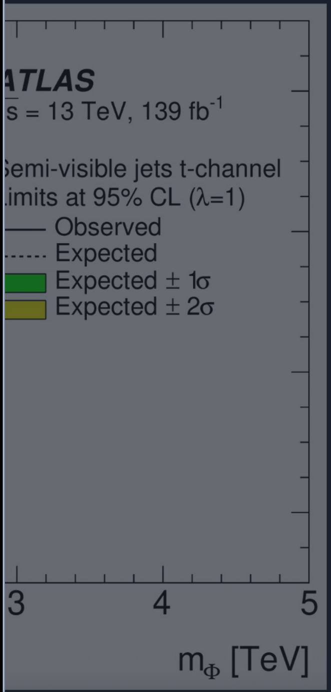


24

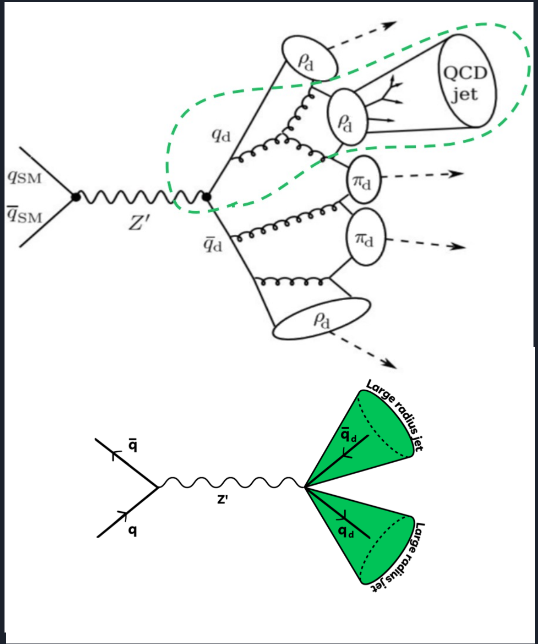
ATLAS dark jet resonances

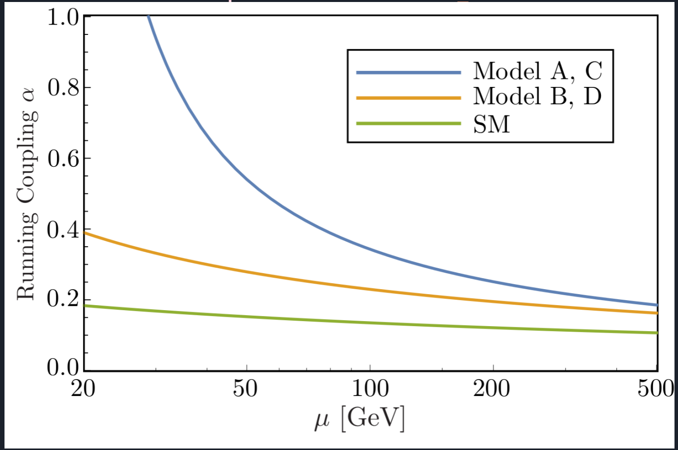
[arXiv:1712.09279]

4 different benchmark models (A, B, C, D)

Higher running coupling for dark sector models.
Main differences with respect to SM jets:

- Higher number of soft particles (and higher number of tracks).
- Larger jets, due to **double hadronization**





Signal masses generated using the Hidden Valley module of Pythia 8.235

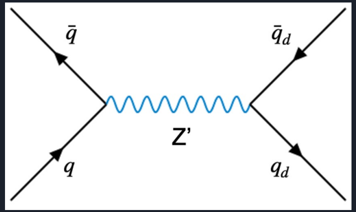
- Signal masses per model from mZ'=1.5 TeV to mZ'=3.5 TeV in bins of 250 GeV for low masses and then 500 GeV
- Signal width not very narrow (~15%)

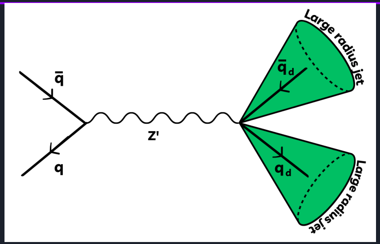
Model	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d decay mode
A	2	15	20	10	50	$\pi_d \to c\bar{c}$
B	6	2	2	2	4.67	$\pi_d \to s\bar{s}$
C	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV
D	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV

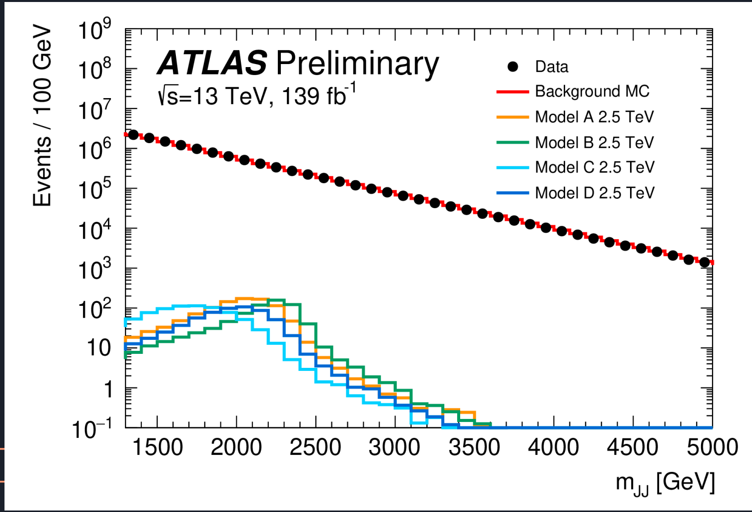
ATLAS dark jet resonances

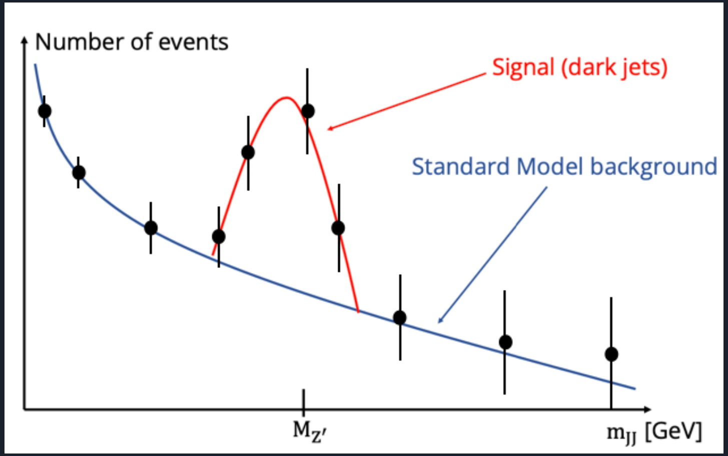
- **Reconstructed Objects:** Two Large radius jets (Trimmed LCTopo jets)
- **Trigger on Large-R jets**
- **Preselection cuts:** $|\eta(j_{1,2})| < 2.0$ $p_{\mathrm{T}}(j_1) > 500$ GeV , $p_{\mathrm{T}}(j_2) > 400$ GeV $m(j_{1,2}) > 50$ GeV

Signal scenario: Two dark jets
- Tag two dark jets using substructure information
- Look for a resonance over dijet background



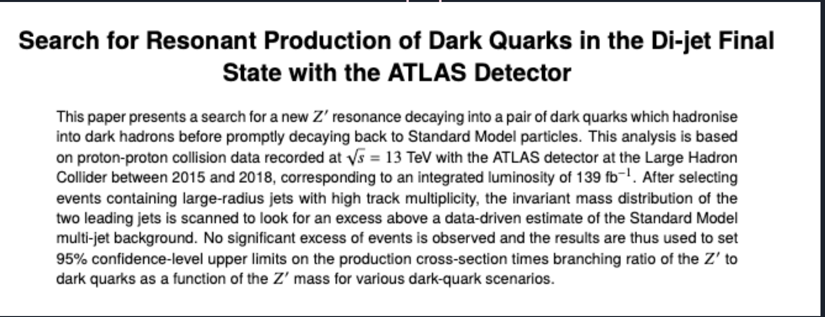






ATLAS dark jet resonances

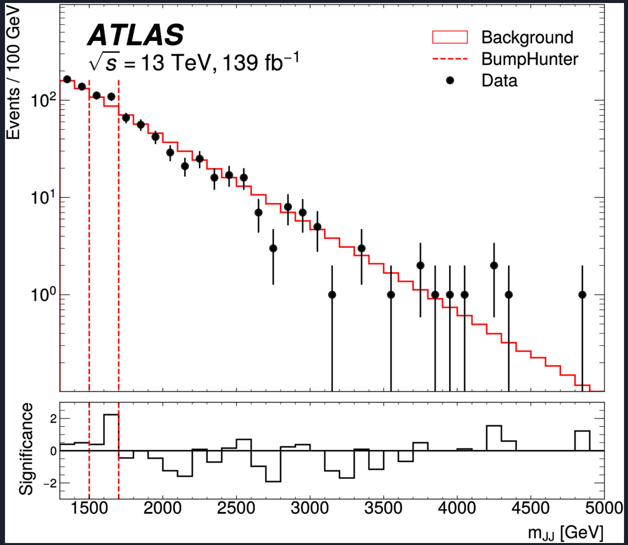
Two largeR jets with a high track multiplicity
-> Tag dark jets using substructure information -> study ungroomed no.of tracks associated to the jets, n_{trk}, which is decorrelated from dijet mass -> obtain bkg. template from dedicated CRs -> look for a m_{JJ} resonance over the dijet background [BumpHunter]

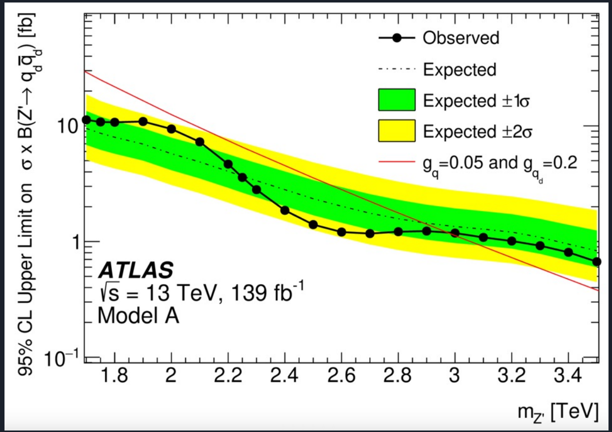

Search for Resonant Production of Dark Quarks in the Di-jet Final State with the ATLAS Detector

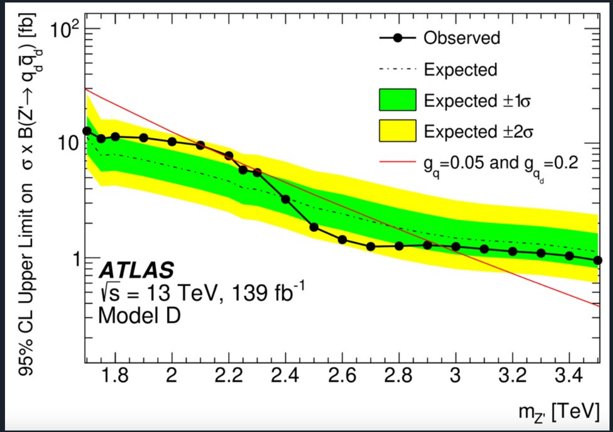
This paper presents a search for a new Z' resonance decaying into a pair of dark quarks which hadronise into dark hadrons before promptly decaying back to Standard Model particles. This analysis is based on proton-proton collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider between 2015 and 2018, corresponding to an integrated luminosity of 139 fb^{-1}. After selecting events containing large-radius jets with high track multiplicity, the invariant mass distribution of the two leading jets is scanned to look for an excess above a data-driven estimate of the Standard Model multi-jet background. No significant excess of events is observed and the results are thus used to set 95% confidence-level upper limits on the production cross-section times branching ratio of the Z' to dark quarks as a function of the Z' mass for various dark-quark scenarios.

JHEP 02 (2024) 128

Highest excess: between 1500 < m_{JJ} < 1700 GeV, with a p-value of 0.63







ATLAS dark

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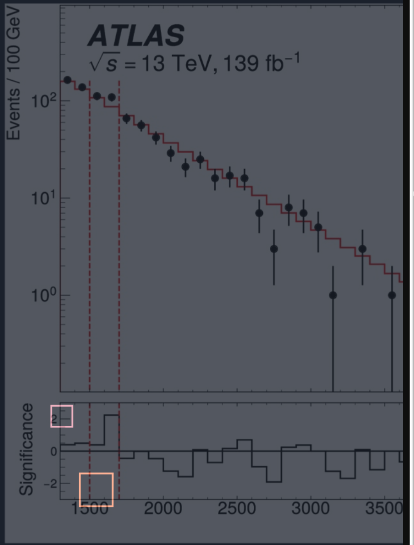
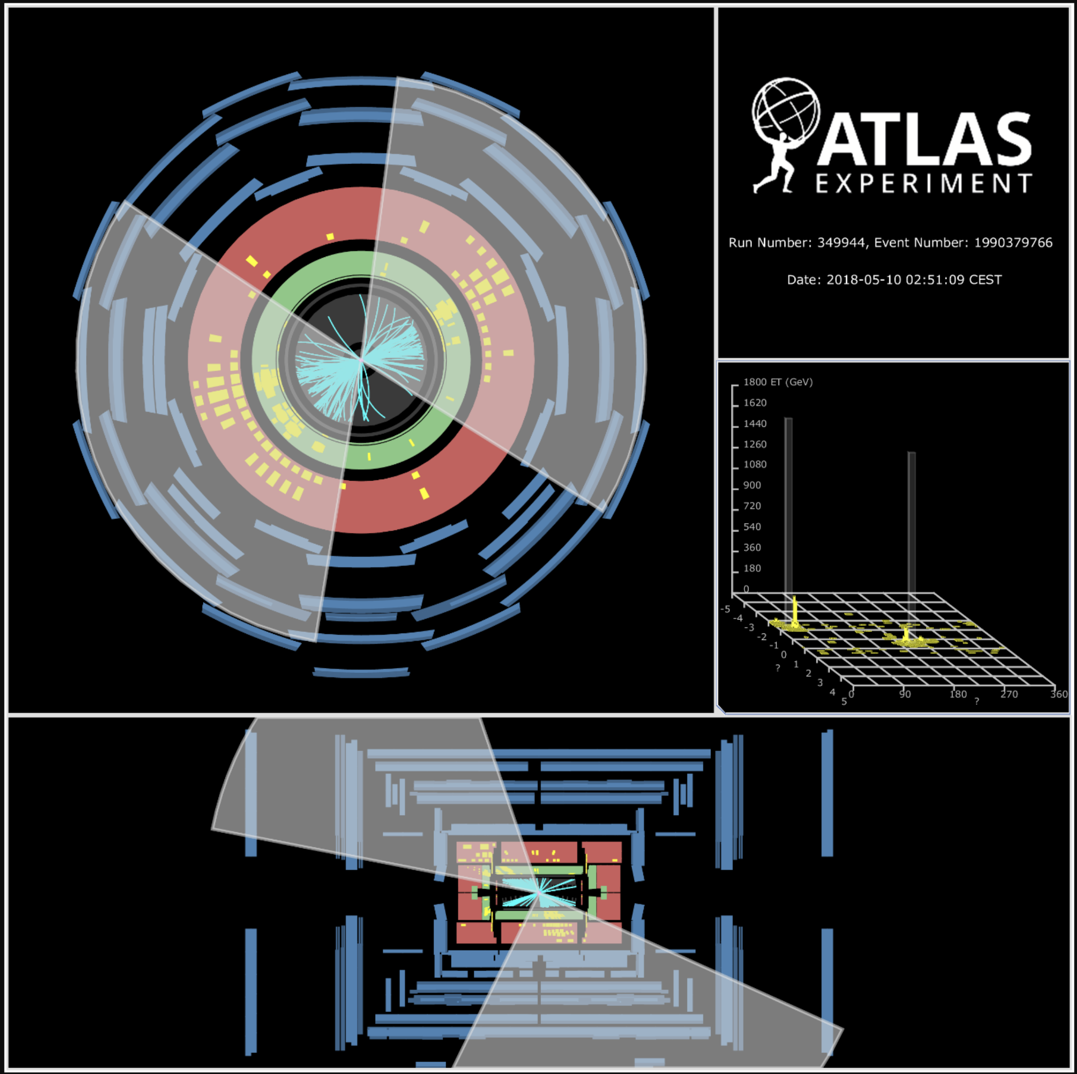
background [BumpHunter]

Highest excess: betwee





f Dark Quarks in the Di-jet Final
TLAS Detector

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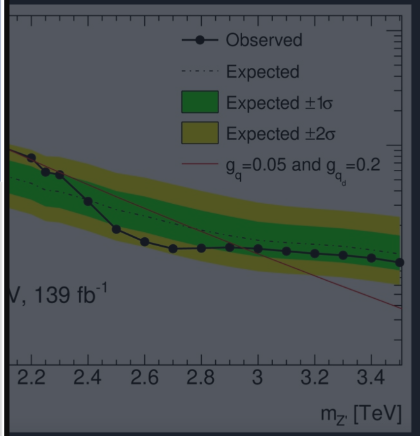
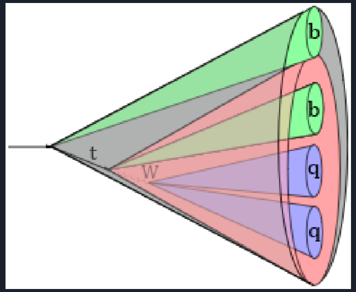


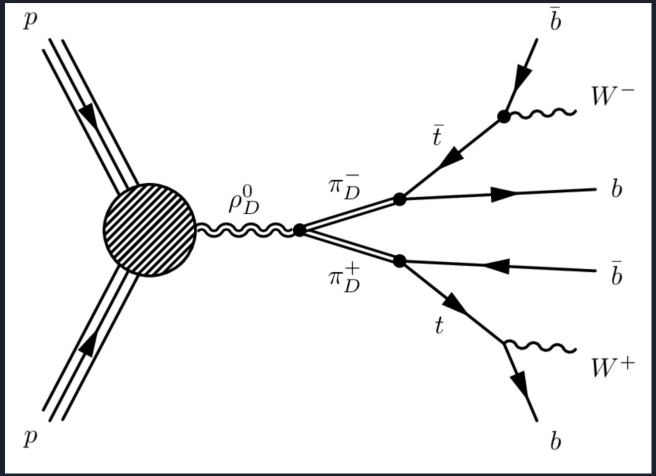
ATLAS dark mesons search

ATLAS-CONF-2023-021

For η (= $\frac{m_{\pi_d}}{m_{\rho_d}}$) < 0.5, ρ_d decay to π_d pairs, resulting in ttbb and tttb signatures (in all hadronic decay mode)



Dark pion identified from jet mass and the flavour tagging of its constituents, reconstruction using reclustering of anti-kt radius 0.4 PFlow jets with radius 1.2



Excellent postfit agreement, limit on dark pion masses, large gain in coverage

ATLAS dark mesons search

ATLAS-CONF-2023-021

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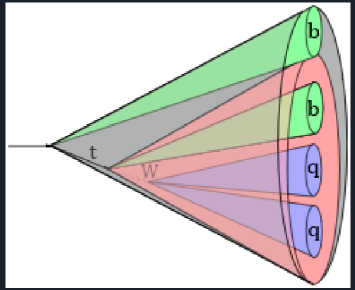
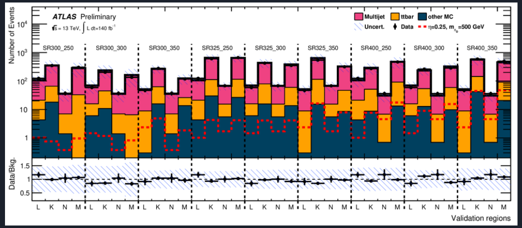


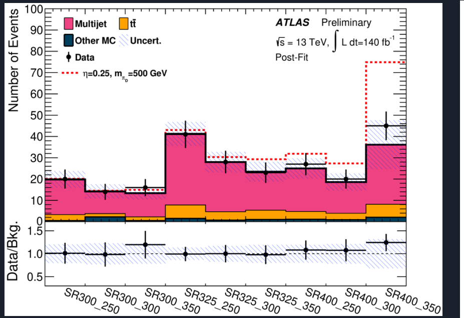
Dark pion identified from jet mass and the flavour tagging of its constituents, reconstruction using reclustering of anti-kt radius 0.4 PFlow jets with radius 1.2

Discriminating variables:

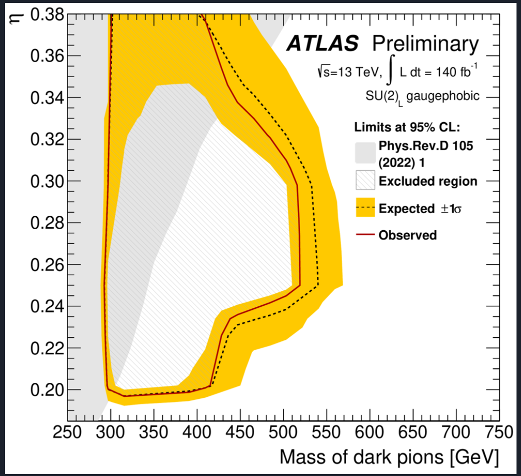
$\Delta R(j, b_2)$: Distance between a RC jet and the second closest b-jet
$m_{bb}/p_{T,bb}$: for the closest b-jet pair to an RC jet to suppress QCD
$m_{\text{jet,R=1.2}}$: Mass of the RC jet, main discriminant

4-variable ABCD method to estimate multijet background based on b-tag and RC jet mass





Agreement in VRs



Excellent postfit agreement, limit on dark pion masses, large gain in coverage

Advertisement break

MITP Youngst@rs dark showers workshop

(Oct 2023): Link

Scope of the workshop: Aim to build collaboration and motivate cross-talk between the experimental and theory community dedicated towards developing and understanding the strongly interacting dark sector.

- **All discussions summarised in report, now on arXiv [arXiv:2311.16330]**

MITP Colours in Darkness workshop summary report

Jon Butterworth[a], Cesare Cazzaniga[b], Aran Garcia-Bellido[c], Deepak Kar[d], Suchita Kulkarni[e], Pedro Schwaller[f], Sukanya Sinha[g], Danielle Wilson-Edwards[g] and Jose Zurita[h]

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[b]ETH Zürich, Institute for Particle Physics and Astrophysics, 8093 Zurich, Switzerland
[c]Department of Physics and Astronomy, University of Rochester, Rochester NY, USA
[d]School of Physics, University of Witwatersrand, Johannesburg, South Africa
[e]Institute of Physics, NAWI Graz, University of Graz, Graz, Austria
[f]PRISMA+ Cluster of Excellence and Mainz Institute for Theoretical Physics, Johannes Gutenberg-Universität Mainz, Mainz, Germany
[g]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
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* **Corresponding author(s): Sukanya Sinha** *

ABSTRACT

This report summarises the talks and discussions that took place over the course of the MITP Youngst@rs Colours in Darkness workshop 2023. All talks can be found at this URL: https://indico.mitp.uni-mainz.de/event/377/.

1 Introduction

In recent years, there has been an increase in the number of search programmes exploring the possiblity of a "dark sector" beyond the Standard Model (BSM) using LHC data. To date, dark matter (DM) searches at the Large Hadron Collide (LHC) have usually focused on WIMPs (Weakly Interacting Massive Particles), but since the standard signatures have found no compelling evidence, several recent phenomenology papers have explored the possibility of accessing the dark sector with unique collider topologies. If dark mesons exist, their evolution and hadronization procedure are currently little constrained. They could

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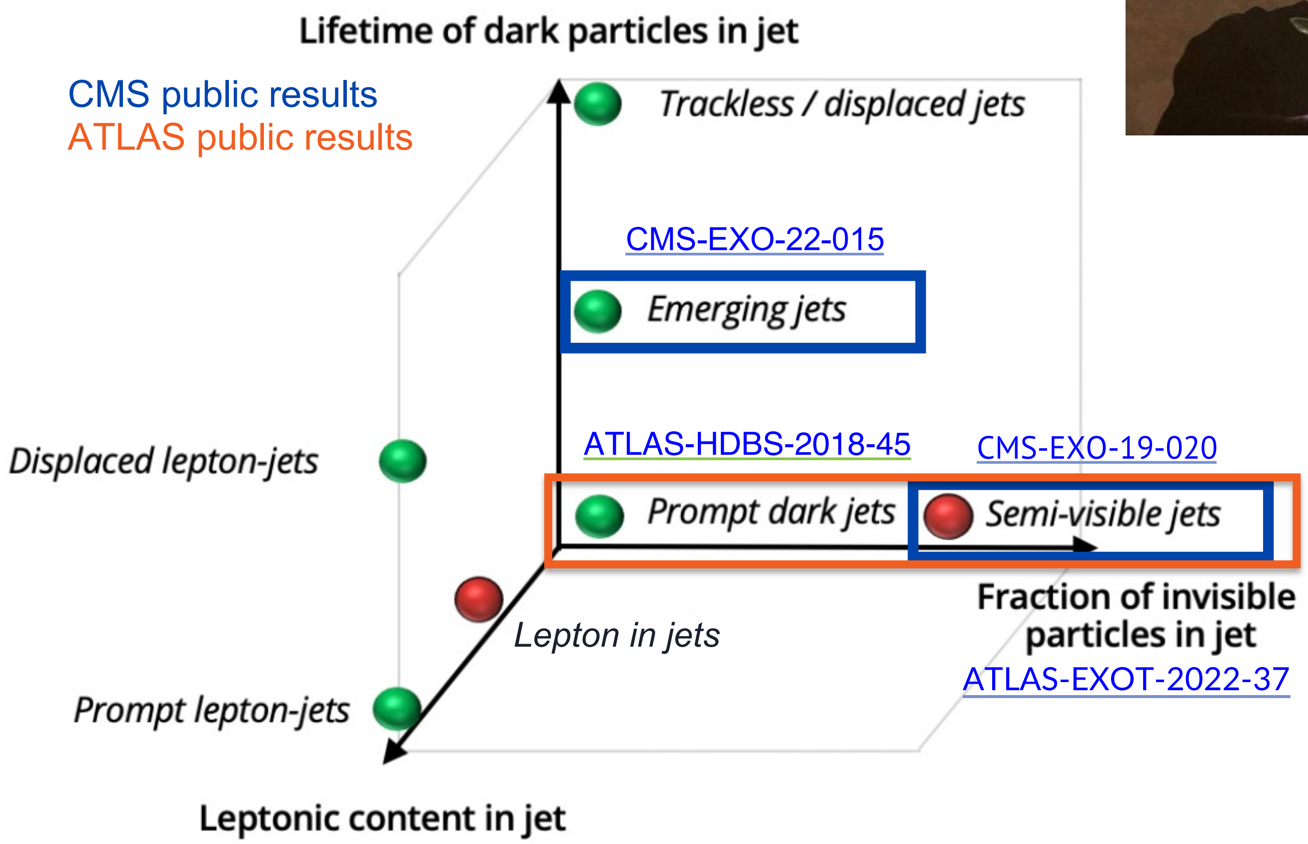
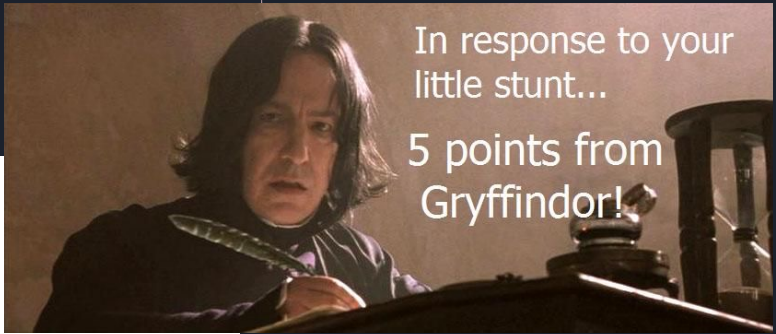
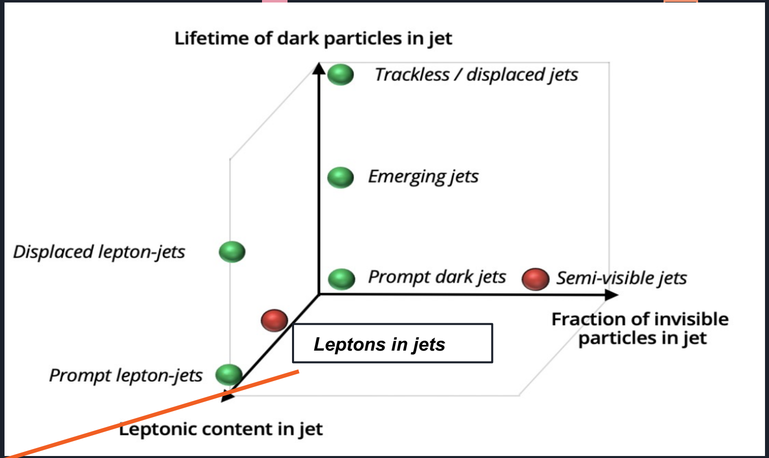
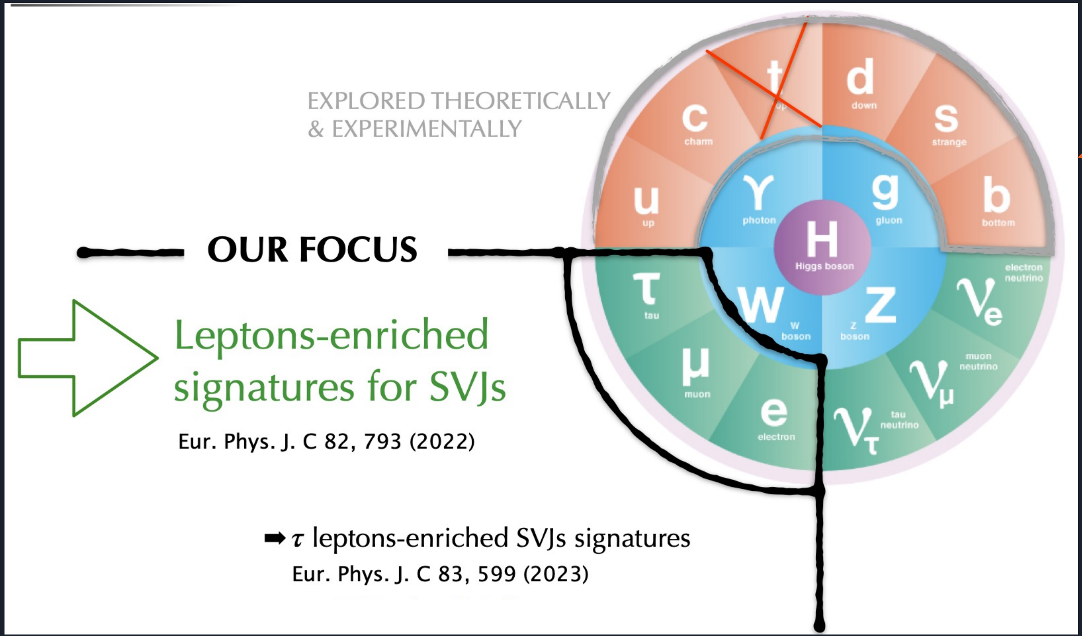
CMS public results
ATLAS public results





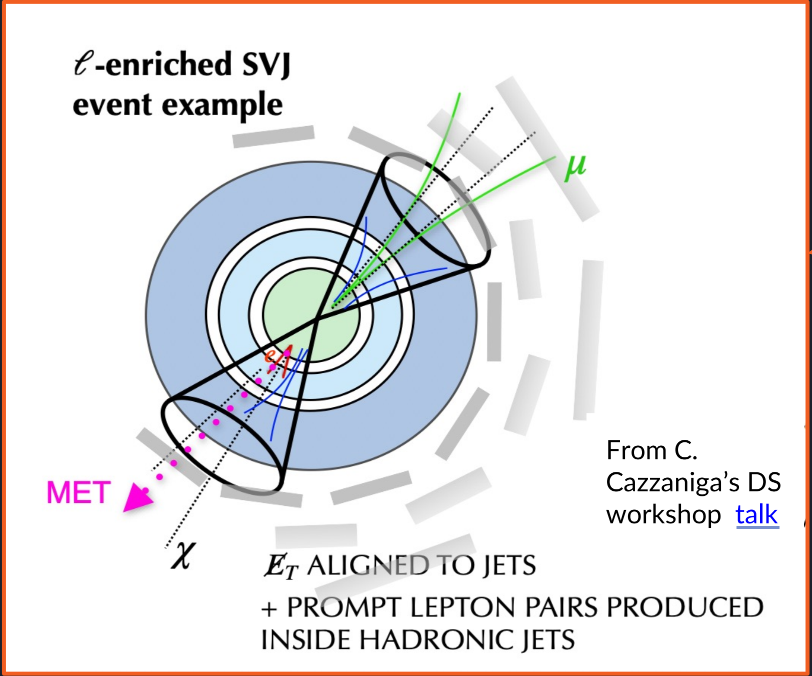
New topologies of interest



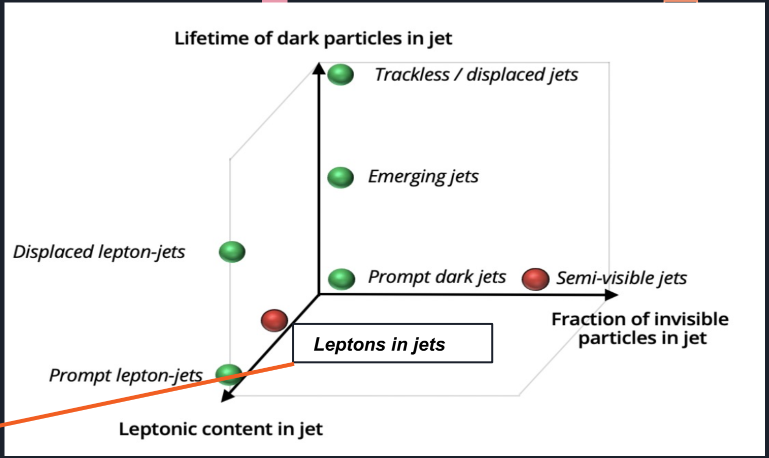


Semi-visible jets with μ/e leptons

arXiv:2206.03909v3



From C. Cazzaniga's DS workshop talk



Leptophobic Z' mediator to evade constraints from high-mass di-lepton searches

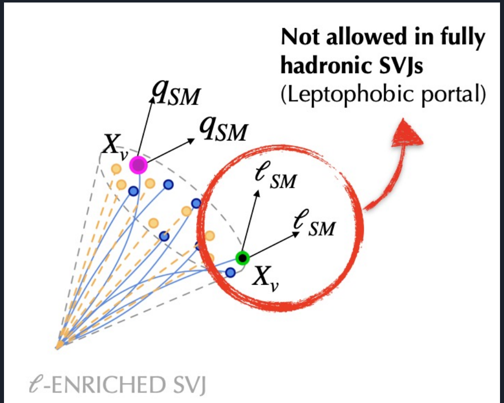
Phenomenological aspects of semi-visible jets with μ/e

Simple modification to vanilla svj signature
→ Favour dark bound state decays to both leptons and quarks

→ Add an additional dark photon as a mediator, satisfying $m_{A'} << m_{Z'}$

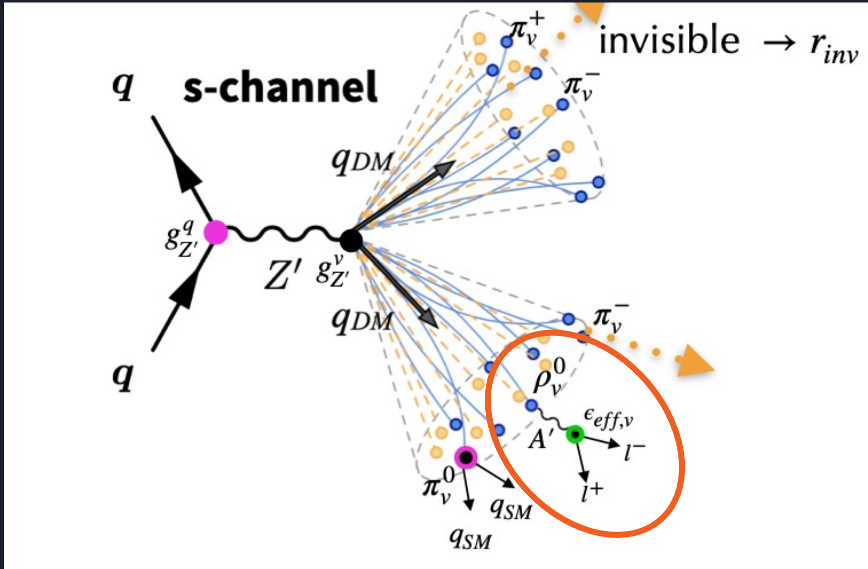
→ prompt decays of A' are allowed.

Decay width of DM bound states scales as ~ $1/M^4$ → suppressing the off-shell Z ′ mediated decays



Eur. Phys. J. C 82, 793 (2022)

New decay chain:
$\rho^0_v \rightarrow A' A'$; $A' \rightarrow \ell^+ \ell^-$



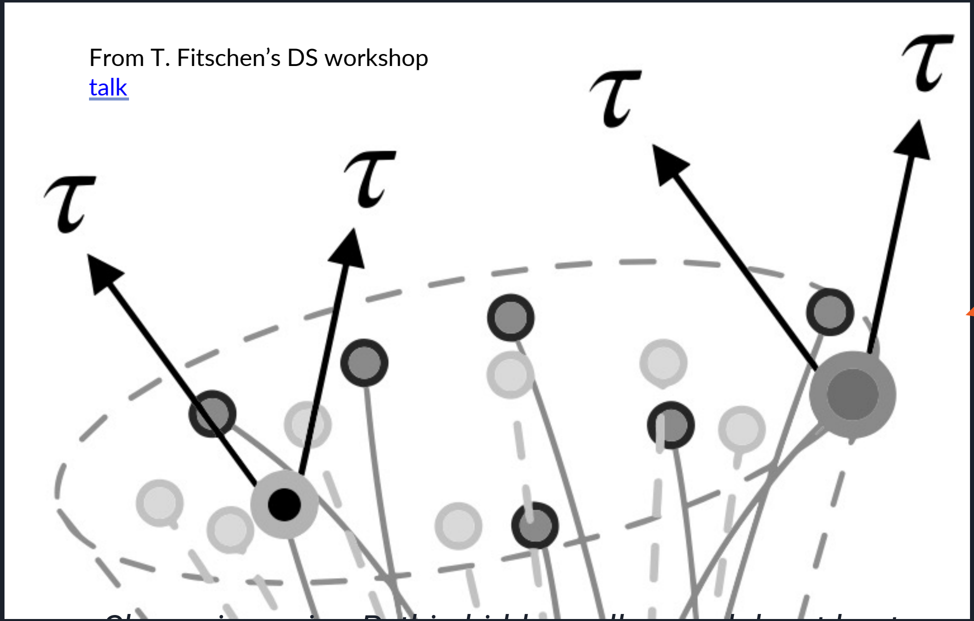
~ **15% democratic decay** of unstable ρ to all lepton flavours

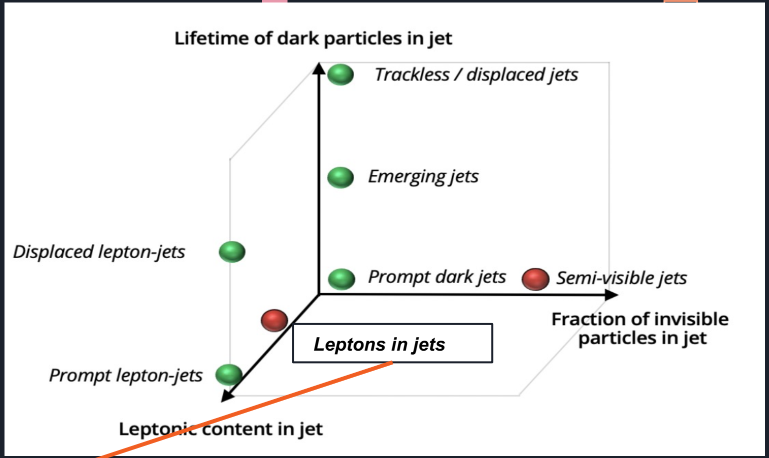
Lagrangian $\mathcal{L}''$ for the A' messenger sector is:

$$\mathcal{L}'' \supset -\frac{1}{4}F_{\mu\nu}[A']F^{\mu\nu}[A'] + \frac{1}{2}M^2_{A'}A'_\mu A'^\mu - \epsilon e Q A'_\mu J^\mu_{q,SM} - \epsilon e Q A'_\mu J^\mu_{l,SM} - g^v_{A'}A'_\mu J^\mu_v. \quad (1)$$

Semi-visible jets with tau leptons

arXiv:2212.11523v2



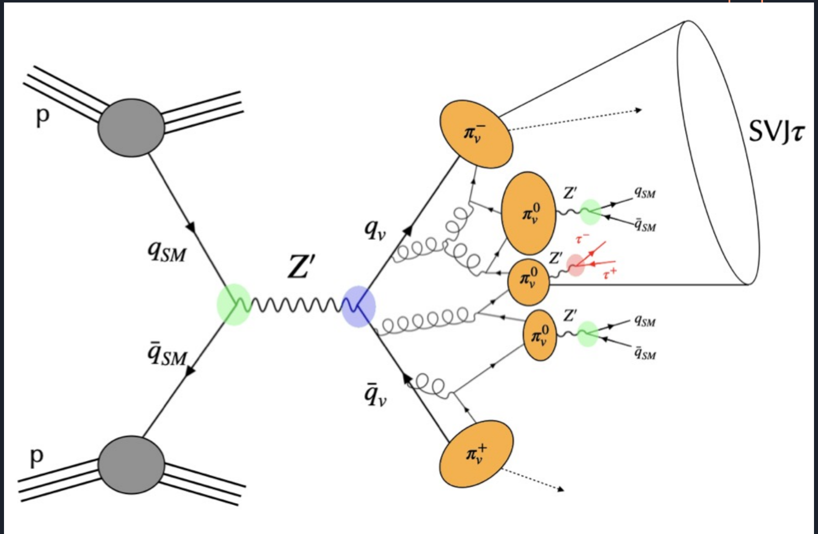


Leptophobic Z' mediator to evade constraints from high-mass di-lepton searches

Phenomenological aspects of semi-visible jets with tau leptons

Simple modification to vanilla svj signature
→ Standard Z’ coupling to dark quarks
→ Add an additional Z’ coupling to SM quarks and leptons

- Z’ coupling to e/mu suppressed



Z' coupling to SM q and ℓ:

$$\begin{aligned}\mathcal{L}_{\mathrm{SM}} \supset & -Z'_\mu \bar{u}_i \gamma^\mu (g_{ij}^{u_R} P_R + g_{ij}^{u_L} P_L) u_j \\ & -Z'_\mu \bar{d}_i \gamma^\mu (g_{ij}^{d_R} P_R + g_{ij}^{d_L} P_L) d_j \\ & -Z'_\mu \bar{e}_i \gamma^\mu (g_{ij}^{e_R} P_R + g_{ij}^{e_L} P_L) e_j\end{aligned}$$

Z' coupling to dark q_v:

$$\mathcal{L}_{q_v} \supset -Z'_\mu \bar{q}_{vi} \gamma^\mu (g_{ij}^{q_{vR}} P_R + g_{ij}^{q_{vL}} P_L) q_{v}$$

⇒ Dark mesons decaying into SM:

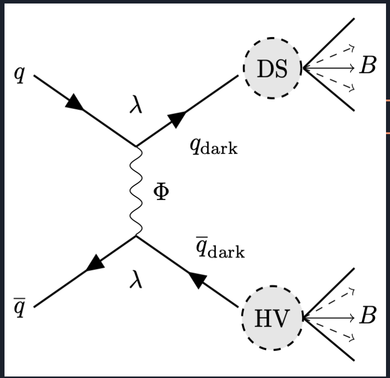
$$\Gamma_{\pi_a \to f_i \bar{f}_i} = \frac{N_c F_\pi^2}{32\pi} (\Delta_{ii}^{f} \Delta_a^{q_v})^2 \frac{m_{\pi^a} m_{f_i}^2}{M_{Z'}^4} \sqrt{1 - \frac{4 m_{f_i}^2}{m_{\pi_a}^2}}$$

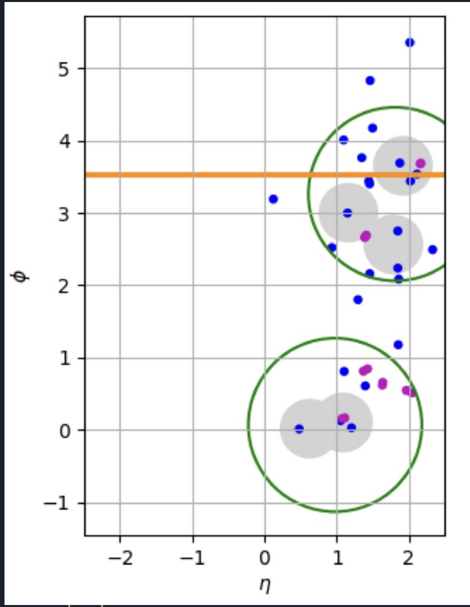
B-phillic SVJ

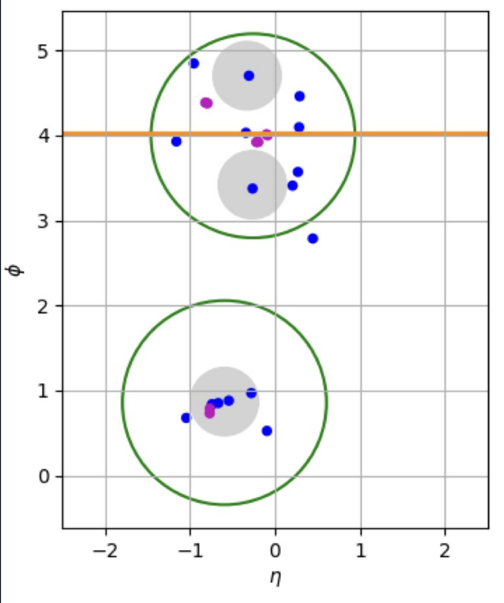
[DK, WN, SS: arXiv:2207.01885](arXiv:2207.01885)

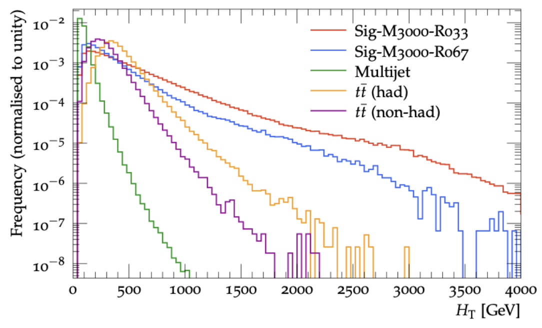
Extra handle on SVJs in collider search, no significant collider constraints

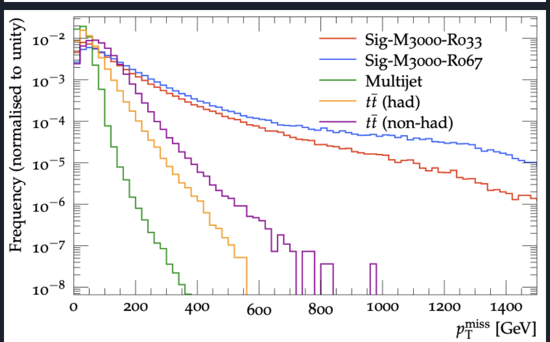
If mass of π_d^0 is lighter than other hadrons:
Helicity flipping suppression forces $\pi_d \rightarrow$ b bbar (if $2m_b < m\, \pi_d^0 < 2m_t$)
i.e., b-philic mode of hidden valley pion decay will be preferred unless there is a hierarchical κ matrix that opposes mass enhancement.







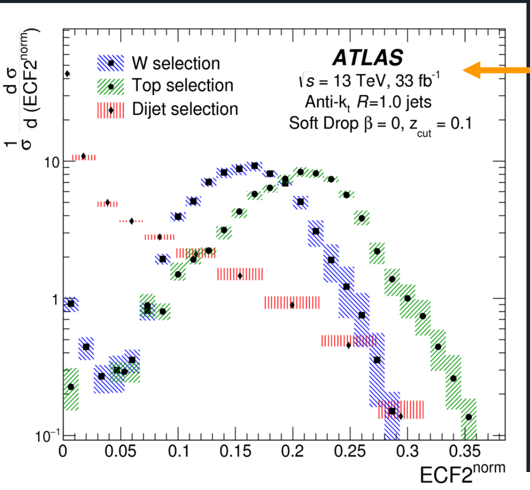




Requiring high H_T and p^T_{miss} can result in having a good S/sqrt(B) significance.

signal reconstruction improved by using variable-radius jets

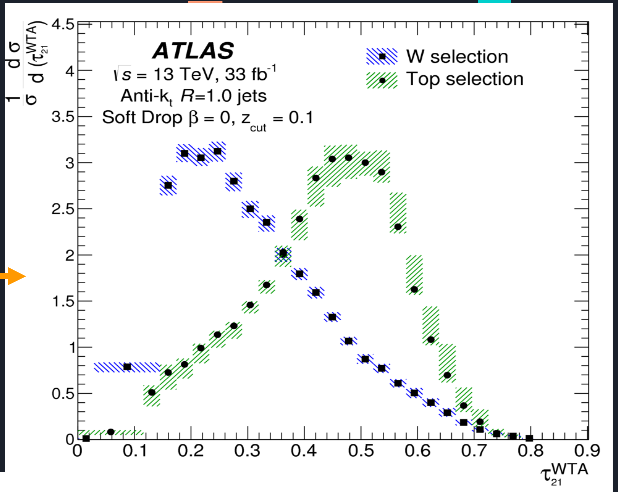
Using jet substructure observables: Example plots from ATLAS



Energy correlation functions:
ECF2:
multi-prong has higher values

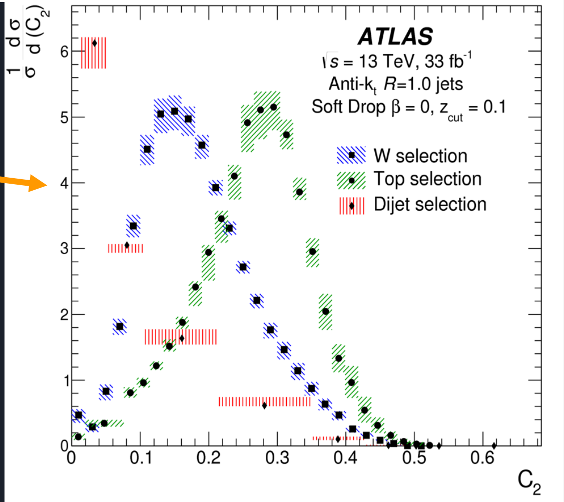
N-Subjettiness:

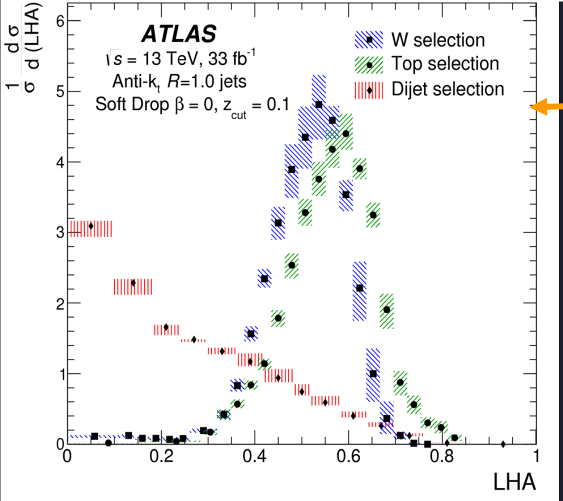
τ_{21}: Lower values indicate more 2 subjet like behaviour



Energy correlation double ratios:

C2:higher value has more subjets



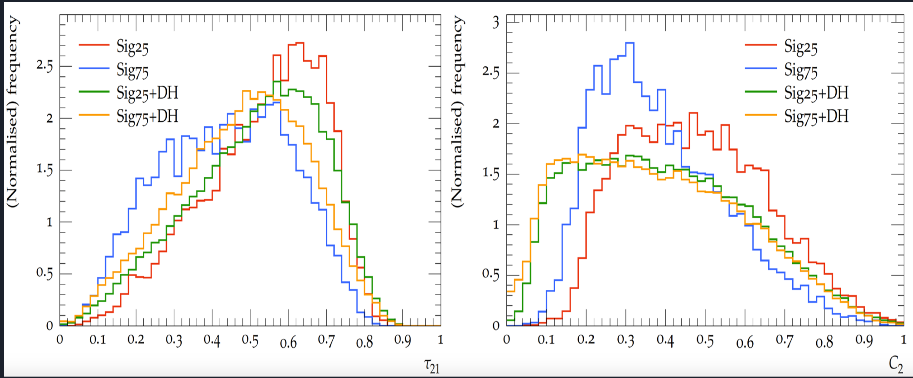


Les Houches Angularity:
higher value means
hard radiations are more
separated

Link to paper

Semi-visible jets Phenomenology

D.Kar & SS: SciPostPhys.10.4.084



Comparing jet substructure variables to see if SVJ substructure is different from light quark/gluon jets (BG). Do they behave more multi-pronged as opposed to mostly single prong?

Comparison can be done in p_T bins or in m/p_T bins, picked the former, as there is no resonance in t-channel.

Conclusions:

1. The substructure becomes less two-pronged with visible and dark hadrons in them, and the absence of the dark hadrons create the two-pronged structure → The substructure is created by the interspersing of visible hadrons with dark hadrons.
2. Specific hidden valley parameter configurations can reduce the dark shower model dependent features of the signal jets.

Cards utilised by Snowmass White paper… link

Summary

- Several avenues of strongly interacting dark sector open for exploration
- General idea evolving around the need of more signature based searches
- Can probe unusual collider phase-space corners by exploiting existing wealth of jet substructure observables
- **First bounds set on these kind of signatures in the t-channel production mode from ATLAS & CMS (many more to come)**

BACKUP

SVJ t-channel systematic uncertainties

- Largest contribution from theoretical components (~25% on signal cross-sections mostly from scale variations).
  - Apart from usual scale and PDF variations, also included ttbar and single top I/FSR variation, ME and PS variation by using alternate generators, DR/DS subtraction scheme difference for tW.
  - W+jets split into heavy and light flavour, and an extra 30% normalisation uncertainty was used for heavy flavour, since Sherpa 2.2 has been found to underestimate V+heavy-flavour by about a factor of 1.3
  - There is known mismodelling in multijet processes, so a data-otherMC vs multijet reweighting is done in 250 < MET < 300 GeV in 9bin distribution → the reweighting factors are obtained in bin 3,6,9, and applied to 1-3, 4-6, 7-9 respectively.
- Standard experimental uncertainties: JES/JER, MET soft term, luminosity, PU reweighting, flavour tagging, reconstruction/identification/isolation/trigger efficiencies on muon and tau leptons.

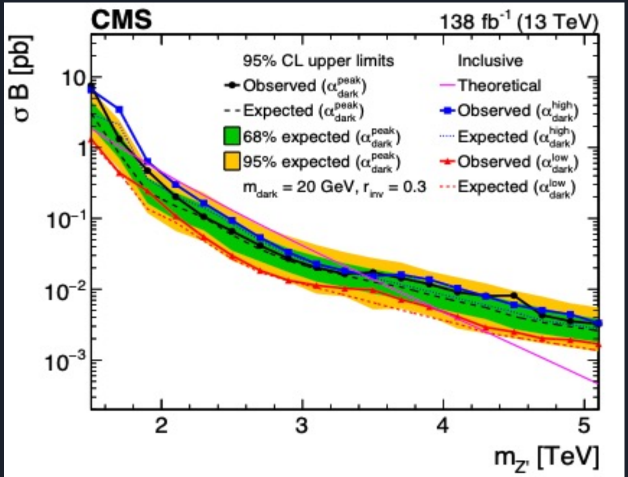
SVJ t-channel fit Strategy

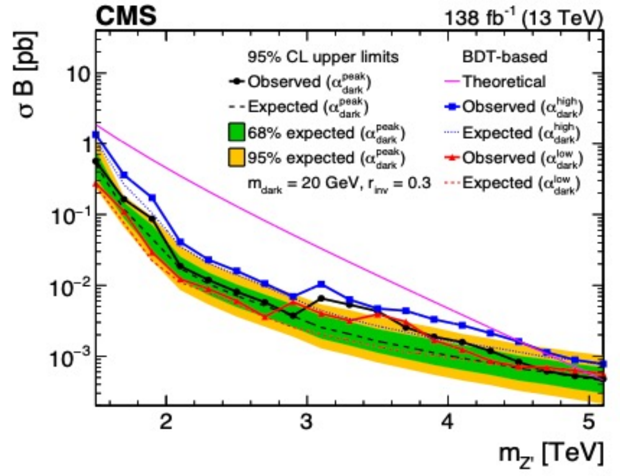
- Maximum likelihood function fit performed using the product of all relevant Gaussian and Poisson PDFs and 9-bin yields, using MC templates.
- The signal region (0L SR) 9-binned histograms are fitted simultaneously with 1LCR, 1L1BCR and 2LCR.
- Dedicated systematic uncertainties are applied to the 0L SR, 1L CR, 1L1BCR & 2L CR 9-binned histogram.

The largest post-fit effects on the shape are signal modelling uncertainties up to 8%, Z+jets modelling uncertainties up to 7%, and top process modelling uncertainties up to 4%. The rest of the contributions are less than 2%.

CMS RESULTS

JHEP 06 (2022) 156, CDS





Inclusive signal regions

Excludes models with

1.5 < $M_{Z'}$ < 4.0 TeV and

0.07 < R_{inv} < 0.53

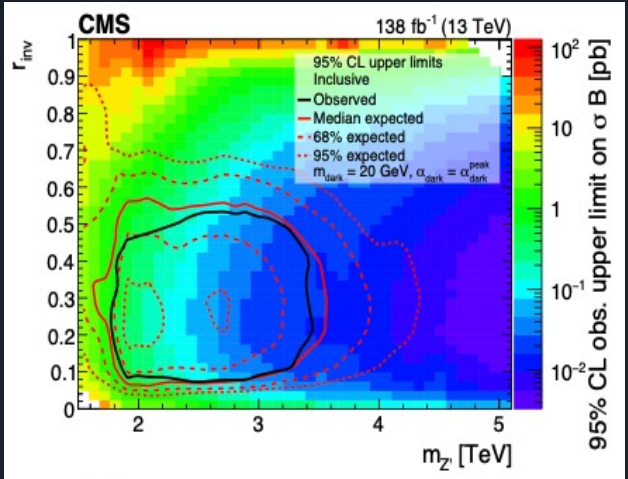
BDT - based regions

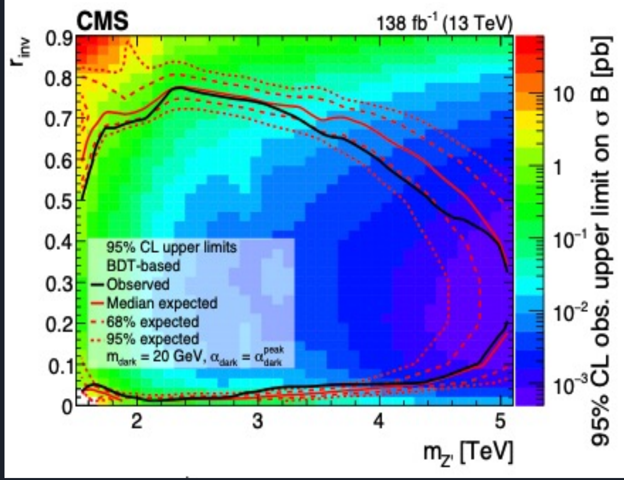
Excludes models with

1.5 < $M_{Z'}$ < 5.1TeV and

0.01 < R_{inv} < 0.77

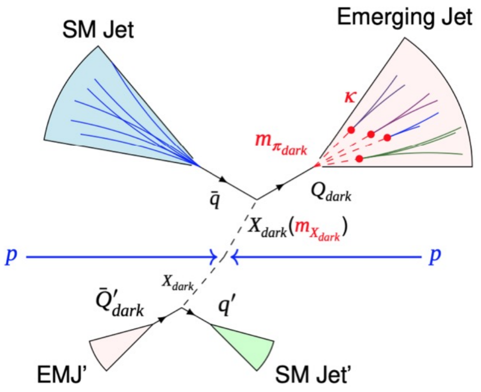
For M_{dark} = 20 geV



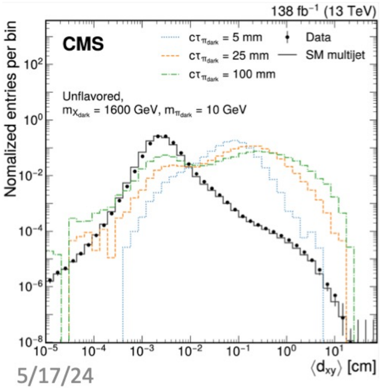


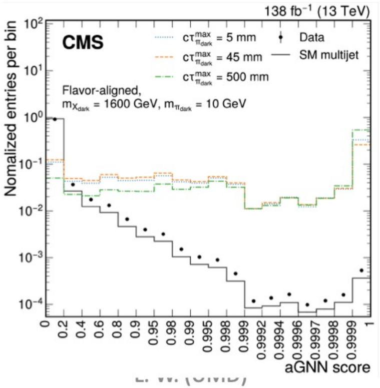
CMS EJ SEARCH METHODOLOGY

From L. Wang's talk



- Signal signatures on detector:
  - Semi-long-lived dark mesons decay back to SM particles, forming **SM showers emerging from vertices** finite distances away from collision points;
  - Tree level two SM jets + 2 emerging jets;
- Cut & Count analysis
- Background estimated using control samples in data based on jet misidentification probabilities.



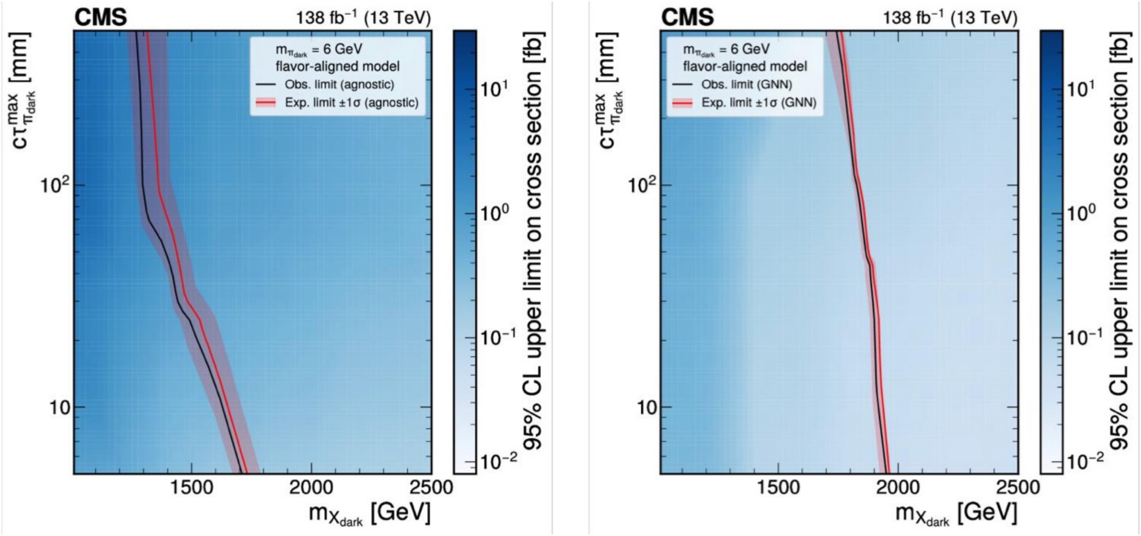


Two approaches:

- **Model-agnostic approach** for reinterpretability;
- **ML-based approach** to maximize sensitivity for the chosen models under search.

CMS EJ SEARCH RESULTS

From L. Wang's talk



- Left: model-agnostic search; Right: ML-based search;
- Only **relevant for flavor-aligned model** scenario as the decay of dark pions starts to behave differently **due to kinematics accessibility**;
- Wider exclusion in ML-based approach comparing to model-agnostic approach.

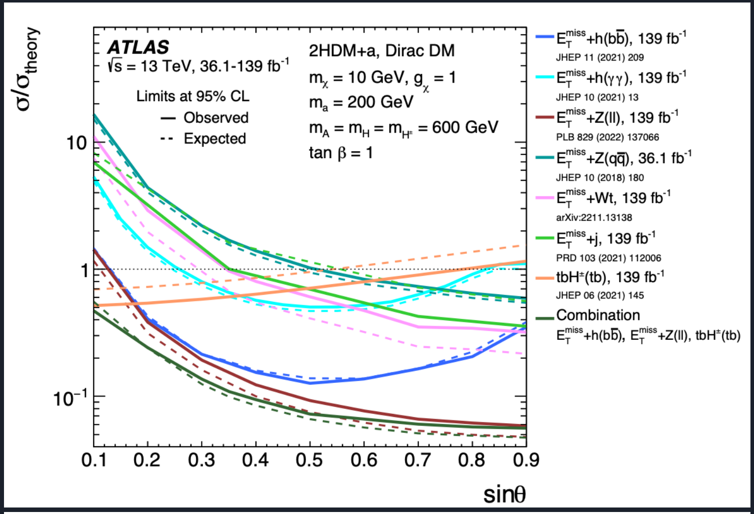
2HDM+a LHC DMWG report: ArXiv 1810.09420

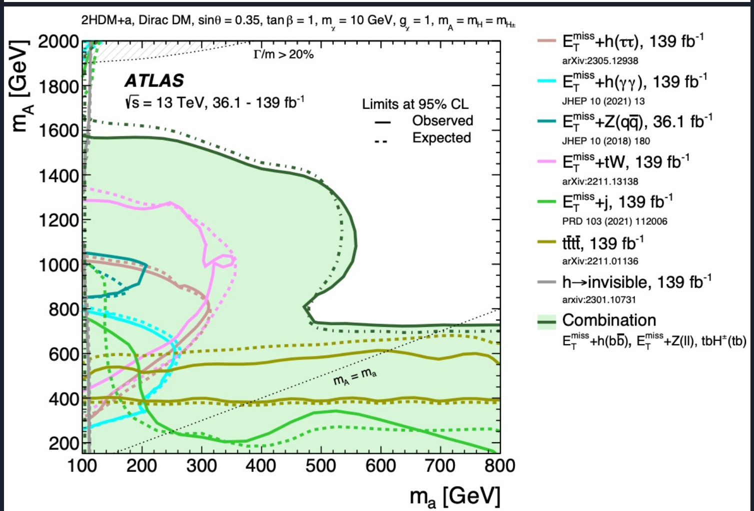
2HDM containing an additional pseudoscalar boson which mediates the interactions between the visible and the dark sector

- gauge invariant & renormalisable extension of simplified pseudoscalar model
- DM candidate: singlet under SM gauge group, usually a Dirac fermion
- CP-odd mediator [pseudo scalar to bypass constraints from DD]

FREE PARAMETERS OF THE THEORY:

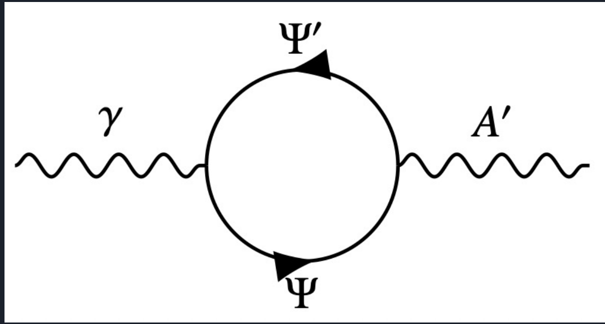
* masses of the heavy Higgs ($m_A = m_H = m_{H\pm}$)
* mass of pseudo-scalar mediator, m_a
* mass of DM particle, m_χ
* sine of mixing angle b/w CP-odd states a & A, $\sin\theta$
* VEV ratio, $\tan\beta$





ATLAS 2HDM+a summary paper
https://arxiv.org/abs/2306.00641

Dark-photons

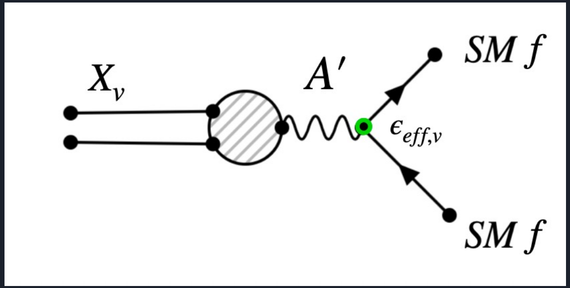


Vector Portal: Add a U(1)′ whose massive "dark" gauge boson mixes kinetically with SM photon

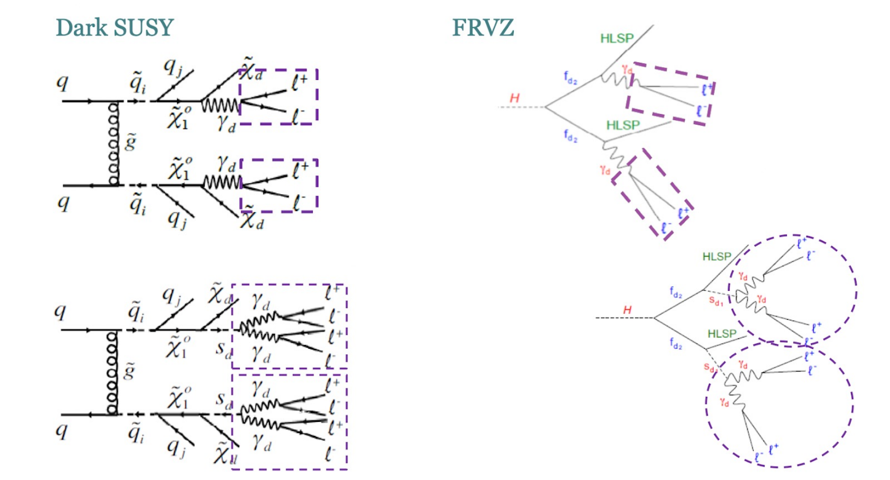
Higgs Portal: Add dark scalar singlet that spontaneously breaks U(1)′ and mixes with SM Higgs

Hidden Valley: sector of dark particles, interacting amongst themselves

- Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
- "Portal" coupling both to SM and HV operators, can be A′



Benchmark models for limit setting



Falkowsky-Ruderman-Volansky-Zupan model:
Pair of dark fermions produced in the Higgs boson decay

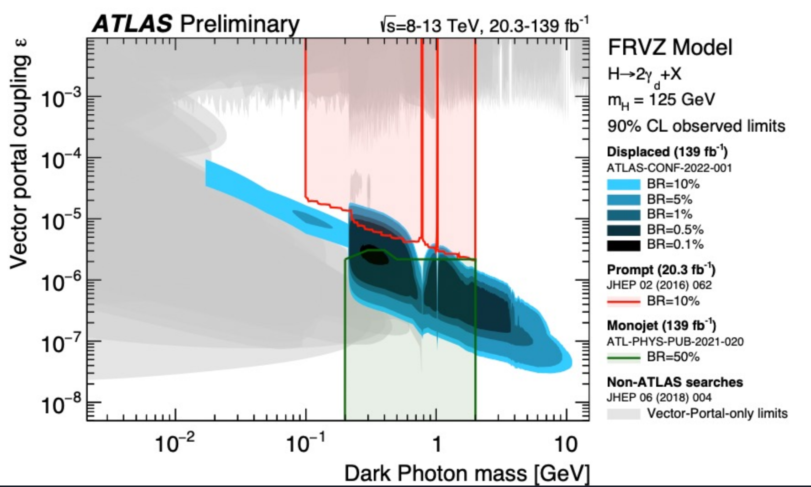
dark fermion decays in turn to a dark photon + a lighter dark fermion assumed to be the Hidden Lightest Stable Particle (HLSP).

dark photon (vector mediator) mixes kinetically with the SM photon and decays to leptons or light hadrons.

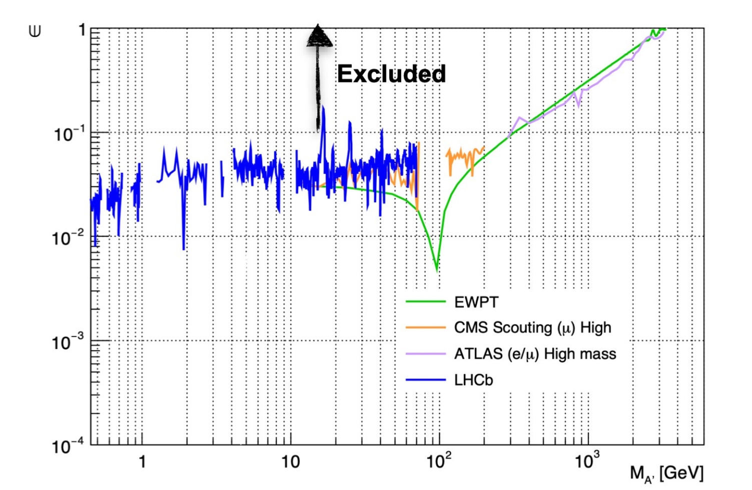
Dark SUSY:

Neutralino → dark photon and susy DM, and dark photon decaying to pair of leptons
Neutralino → susy DM, and pair of dark photons decaying to pair of leptons

Summary of constraints from colliders



ATL-PHYS-PUB-2022-007



constraints $A' \to \ell^+\ell^-$

Exclusions also available for lepton+jets in high mass regions from ATLAS, CMS and LHCb dedicated searches.