The land of dark matter: a collider perspective

Sukanya Sinha
DMLAND
28th August 2024

University of Manchester

courtesy: M. Blanke

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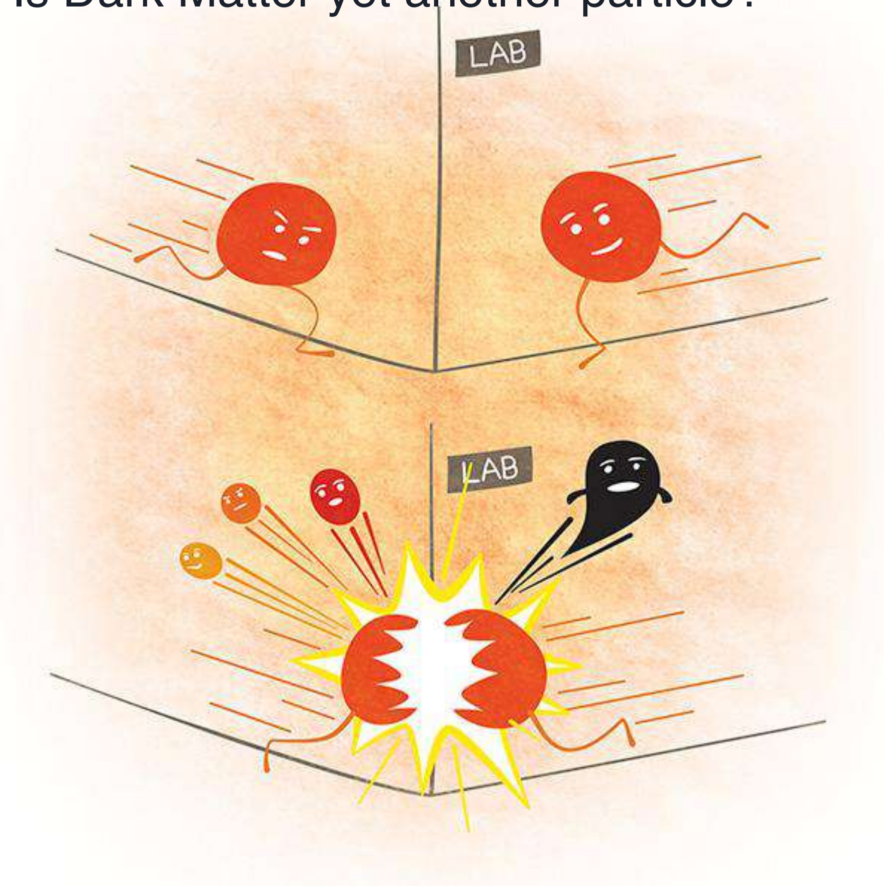
More complete review in recent [Roadmap of DM models workshop]

Non-comprehensive / slightly biased

courtesy: M. Blanke

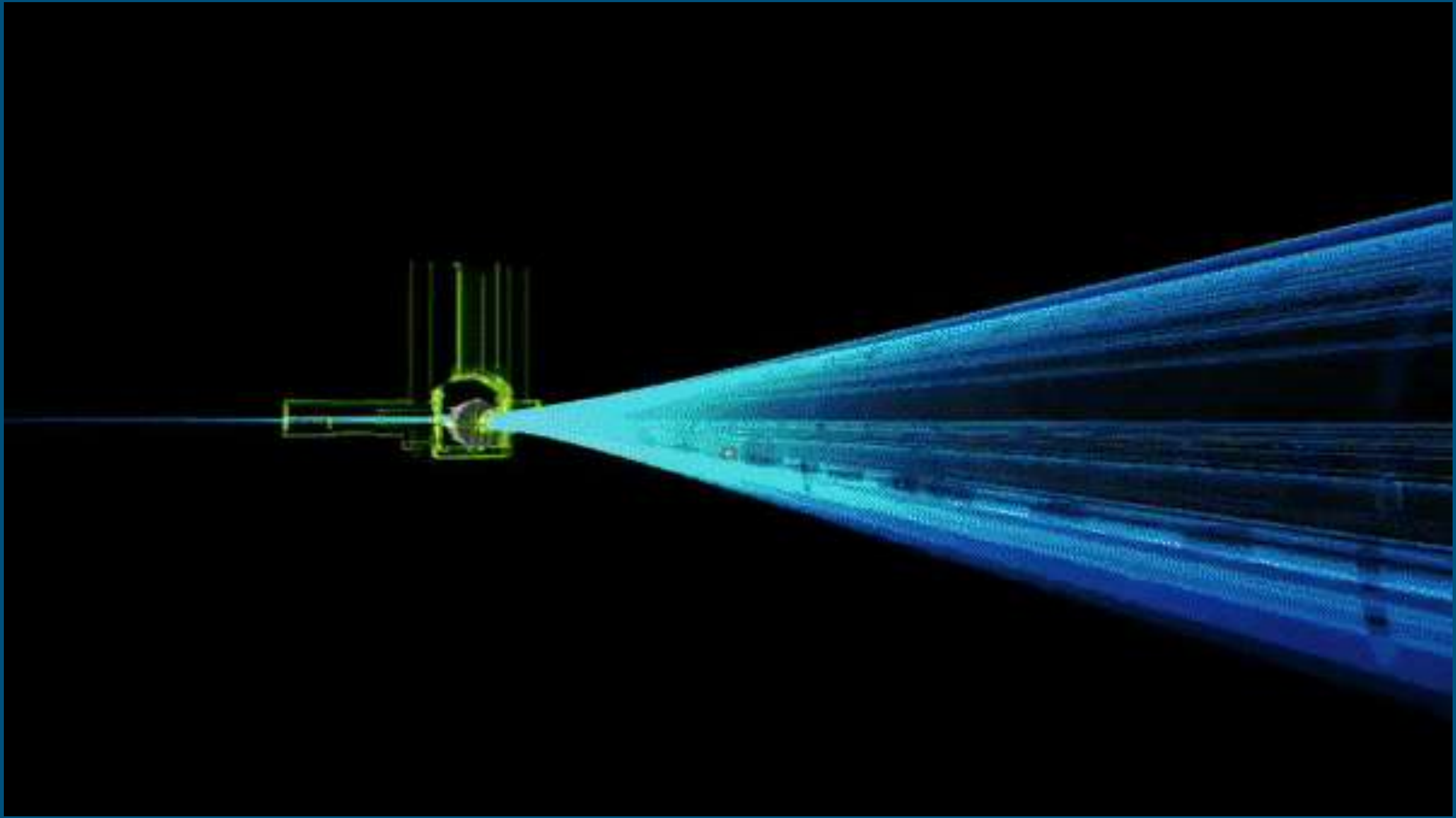
Is Dark Matter yet another particle?

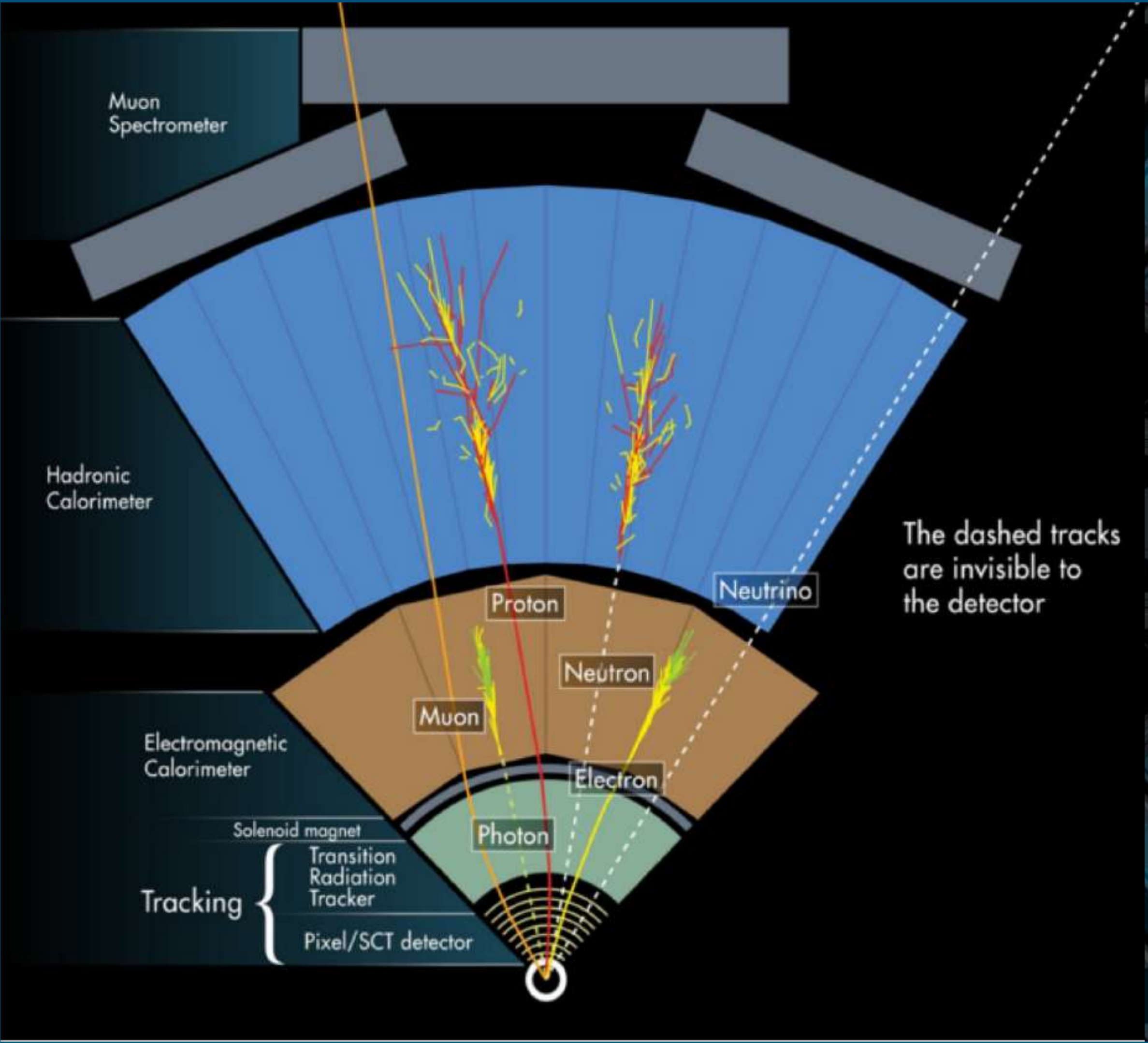


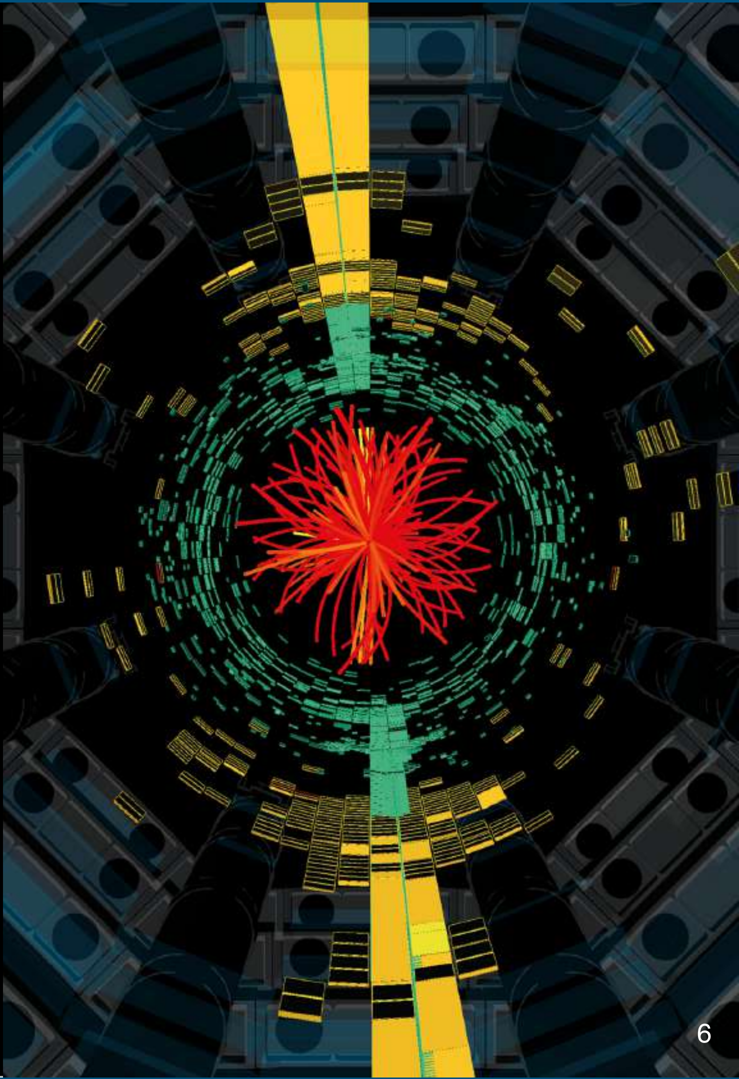
P.S: ★ Marks discussion points for today afternoon

… at the Large Hadron Collider

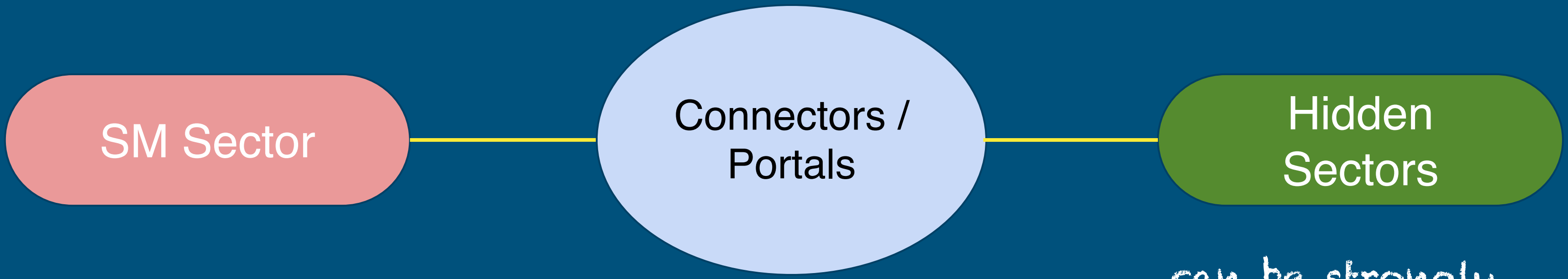
World’s largest and most powerful particle accelerator.
Circumference of 27 km, running underground across the borders of Switzerland and France.




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

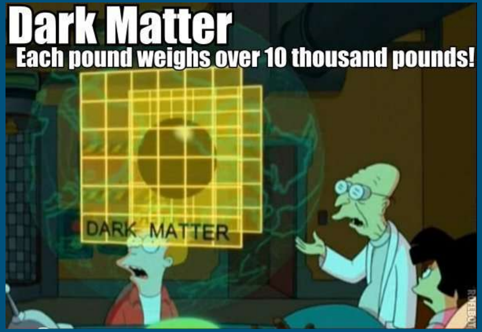


Hidden Sectors



Z′, SUSY particles, Higgs, Extra Dim, Leptoquarks, CP-odd..

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.**

Note: Any hidden sector with more than one particle in it generically contains unstable particles. These are often long-lived due to tiny SM portal couplings being only decay (and collider production) channel [see backup]

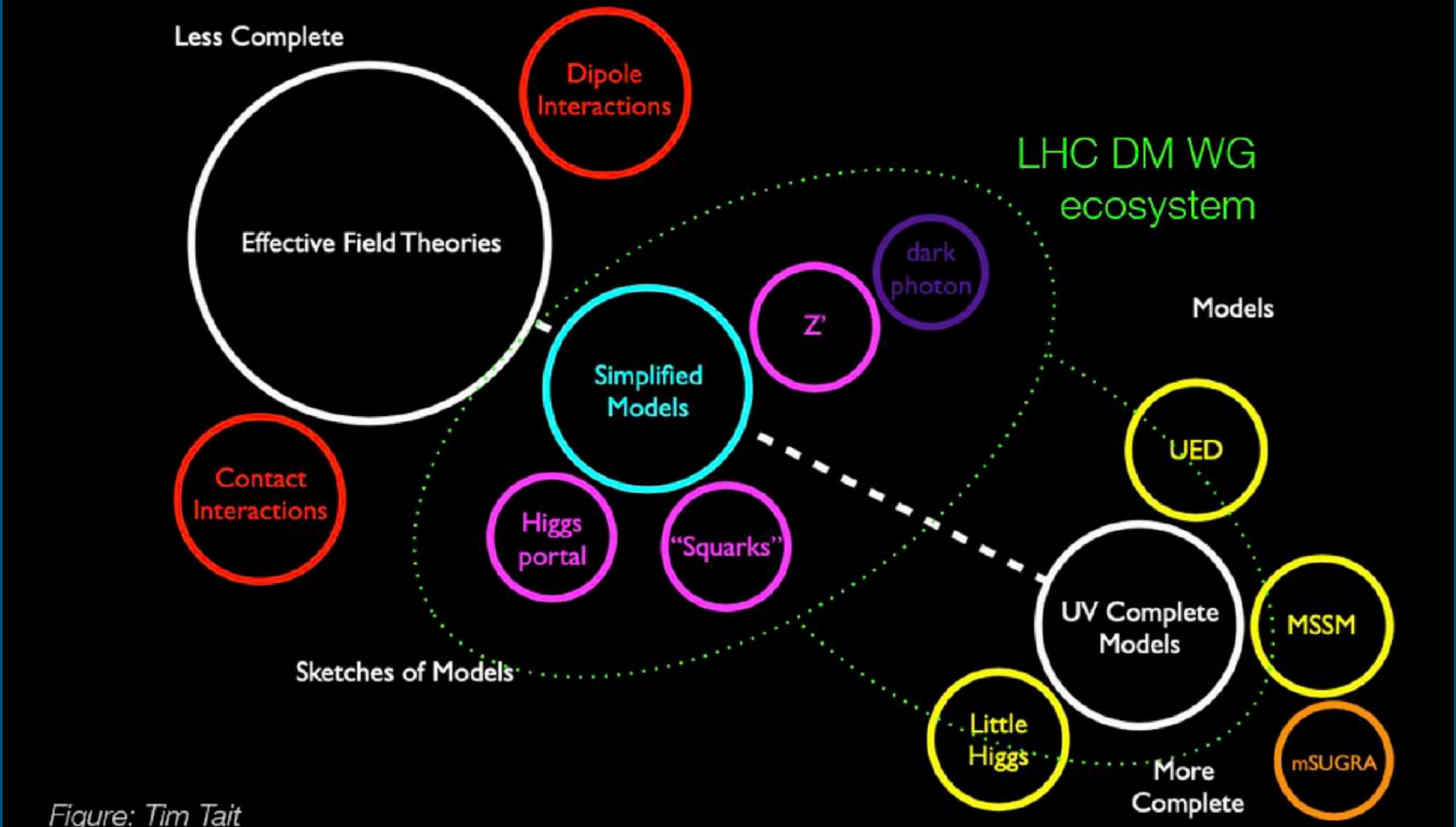
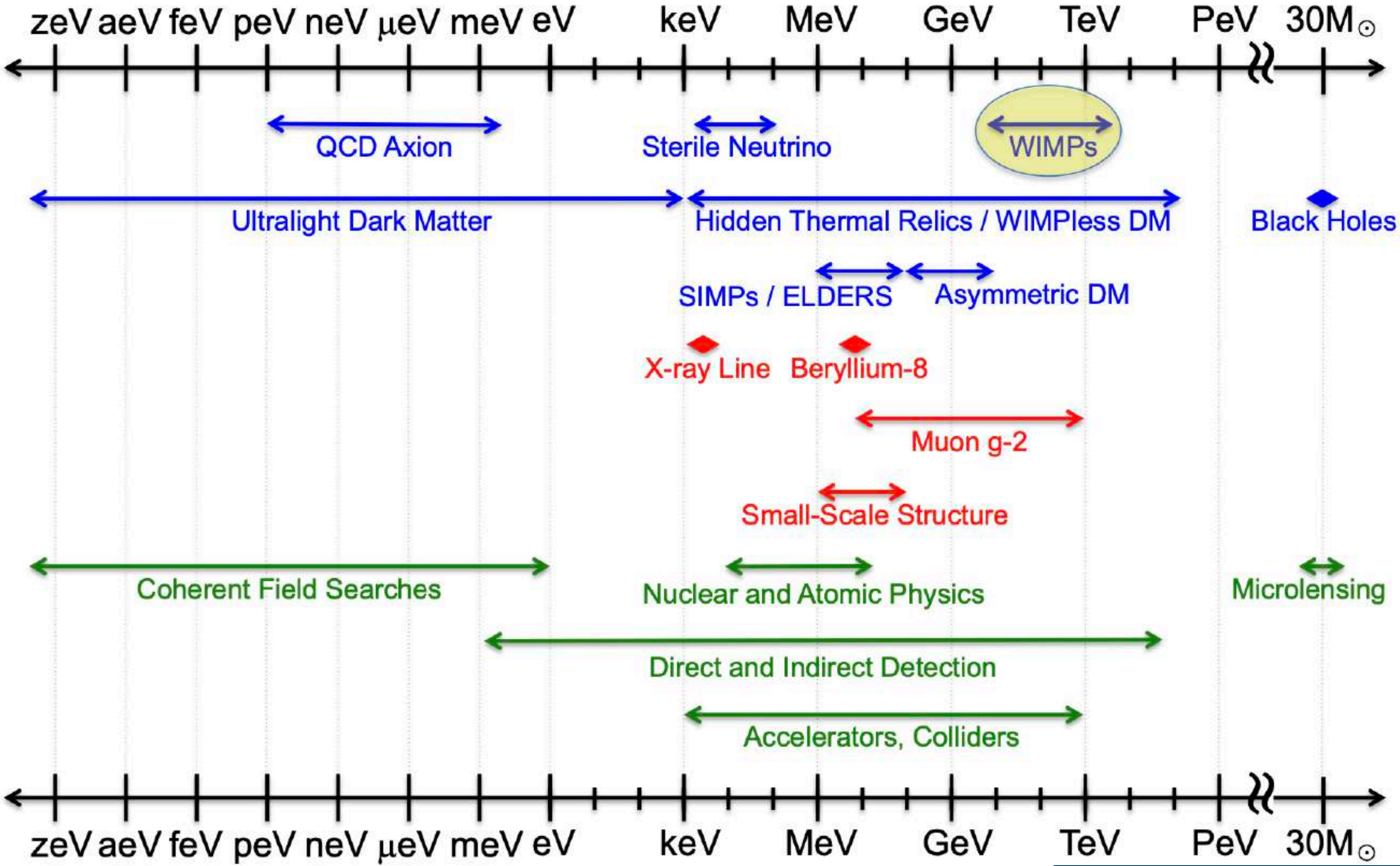


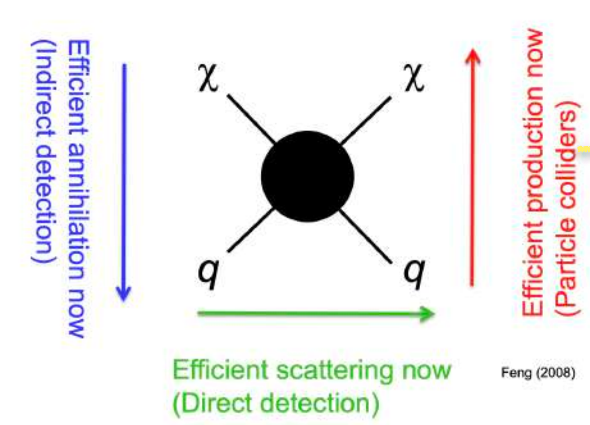
Figure: Tim Tait



J.Feng Les Houches school notes

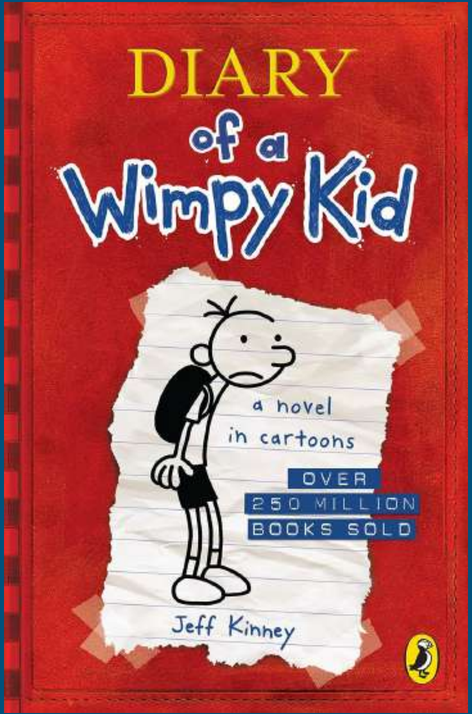
WIMPs

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

WIMPs

Over the years, several 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].

WIMPs

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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].

WIMPs

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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WIMPs

CMS Collaboration, V. Khachatryan et a
unparticles in monojet events in proton?p
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:

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]

WIMPs

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ATLAS uses ... Matter

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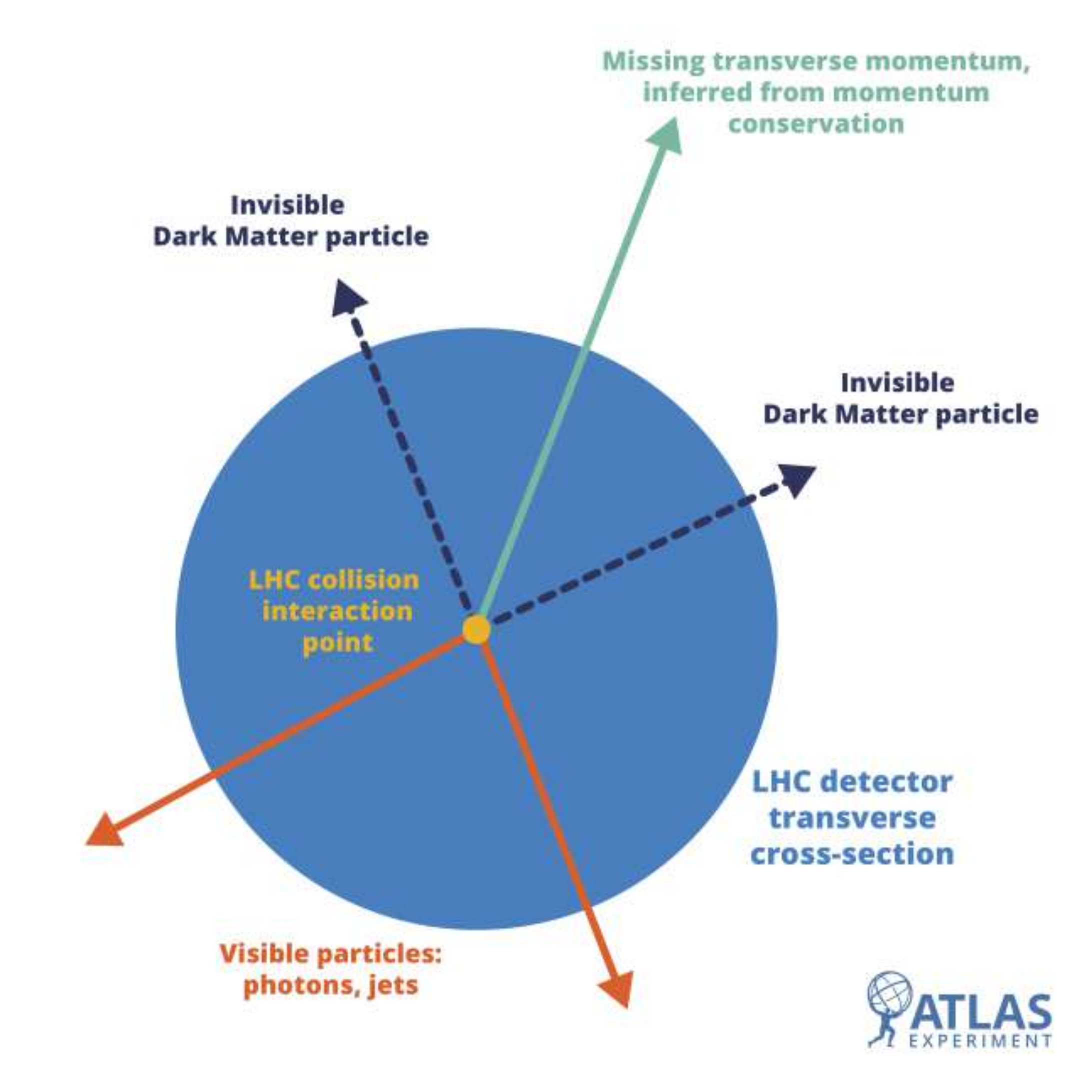

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with a photon
ATLAS
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ed: 13 August 2020
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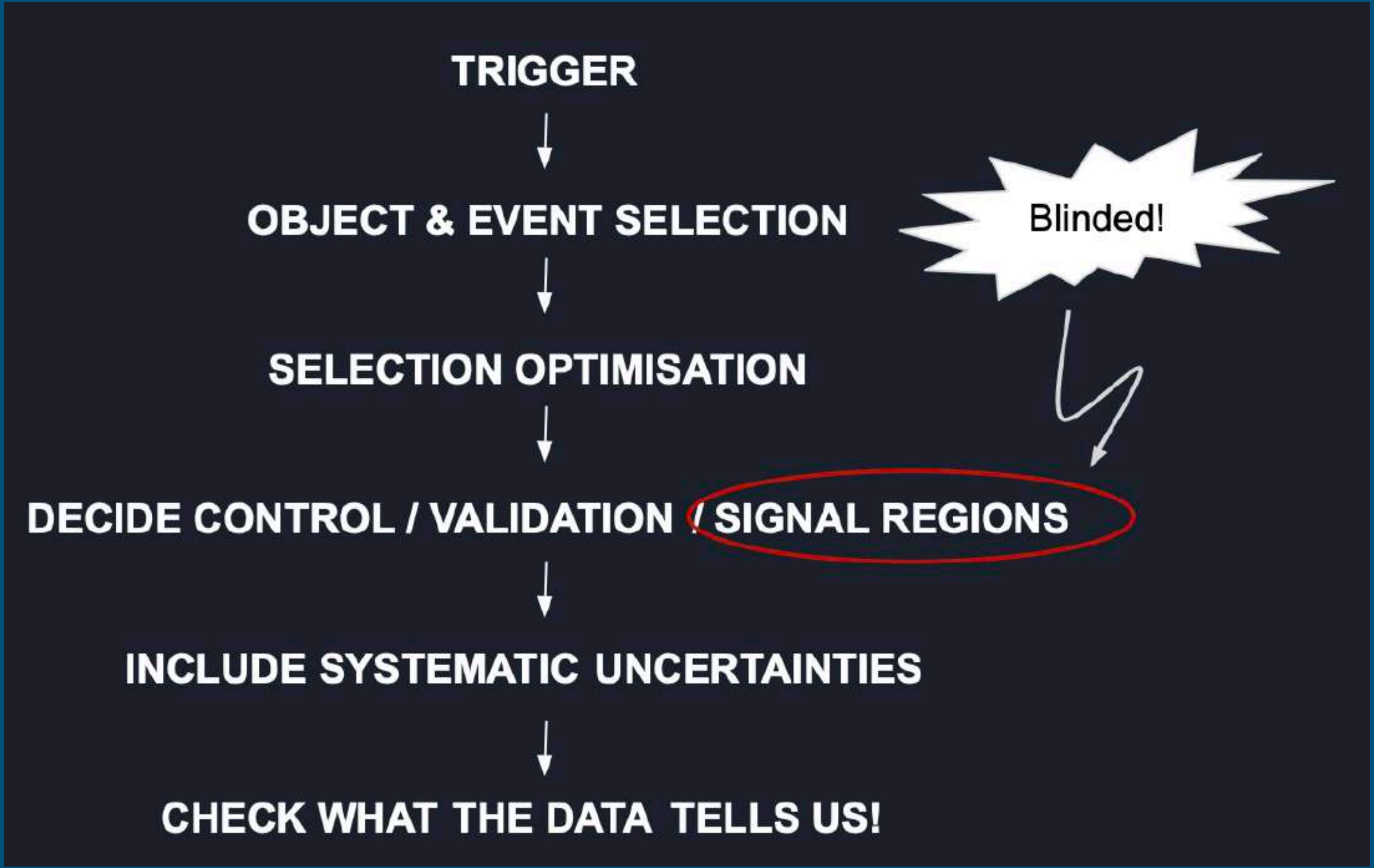
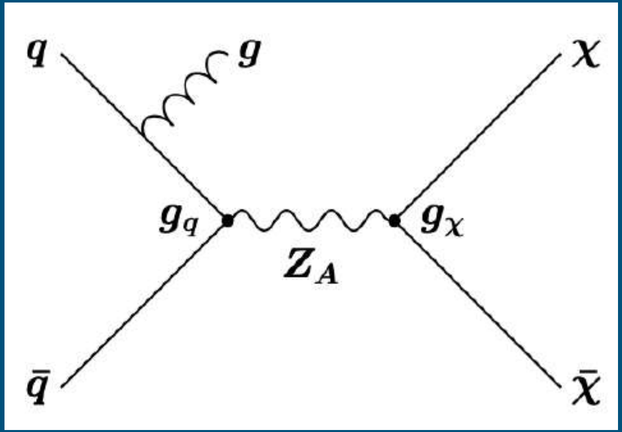
at $\sqrt{s} = 8$ *TeV*
:1309.4017].

Analysis in a nutshell

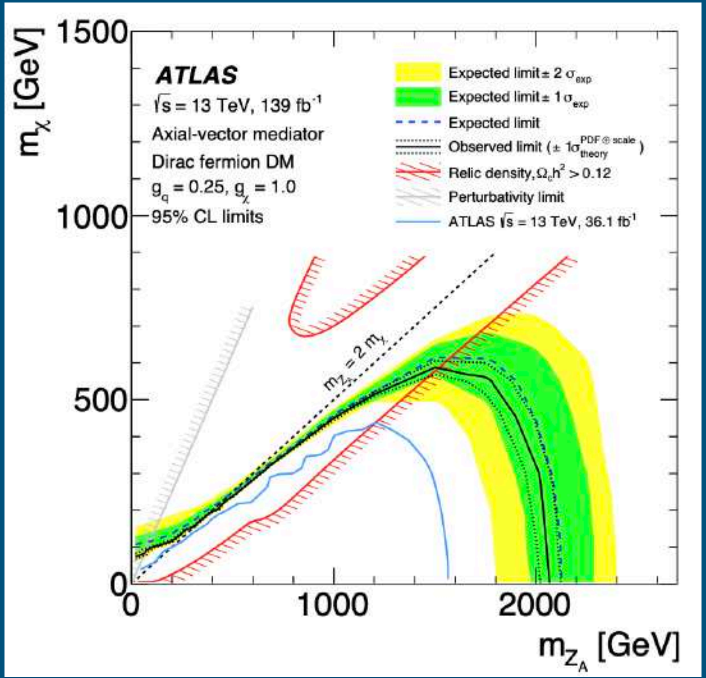


WIMPs



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	



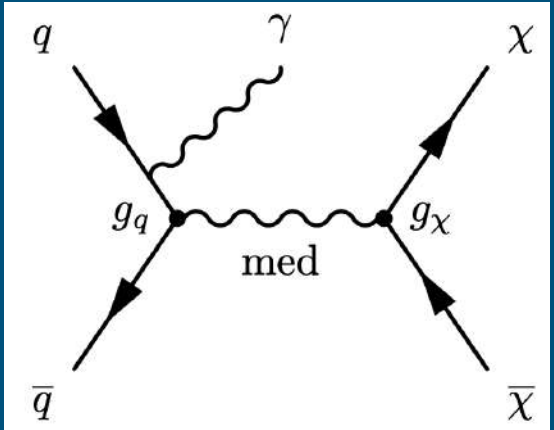
In the region $m_{Z_A} > 2m_\chi$, mediator masses up to about 2.1 TeV are excluded for m_χ= 1 GeV

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)

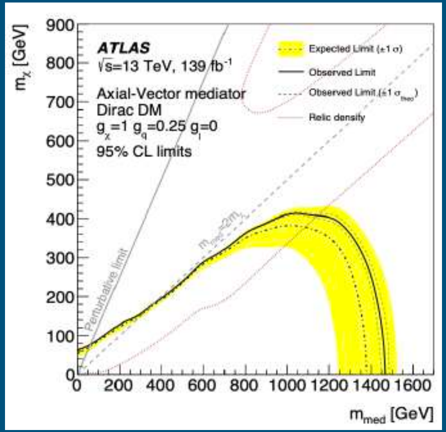
WIMPs

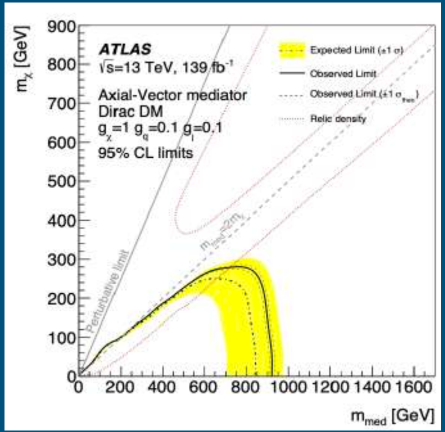
JHEP 02 (2021) 226



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





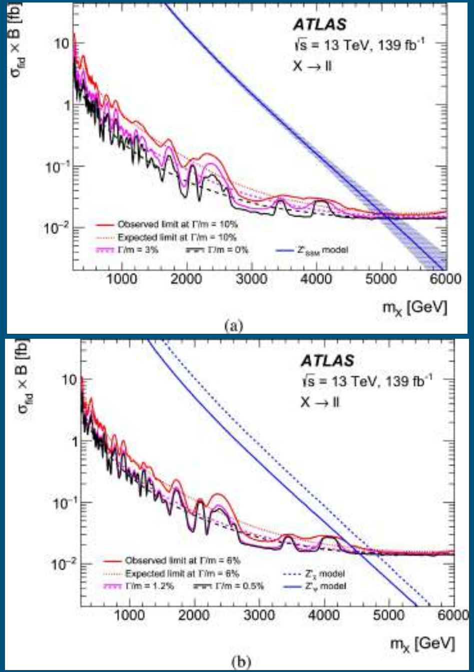
Masses corresponding to relic density determined by the Planck and WMAP satellites

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

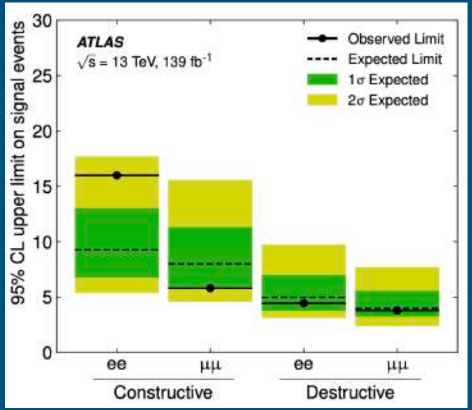
di-jet and dilepton final states

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.

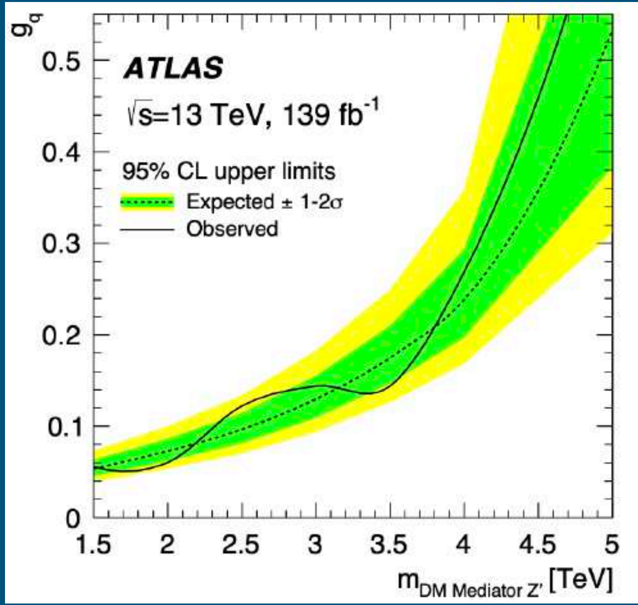
JHEP 11 (2020) 05



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

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

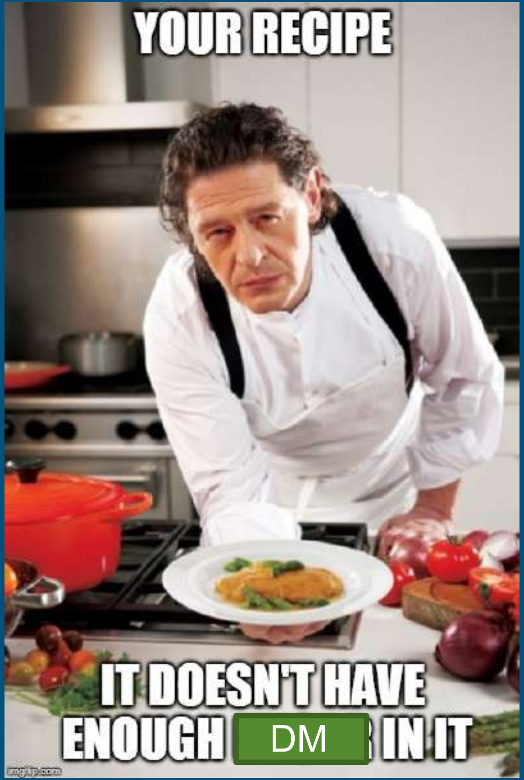


Resonant dijet search: The 95% CL upper limits are set on the universal quark coupling g_q as a function of the Z′ mass

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



2HDM+a

LHC DMWG report: ArXiv 1810.09420

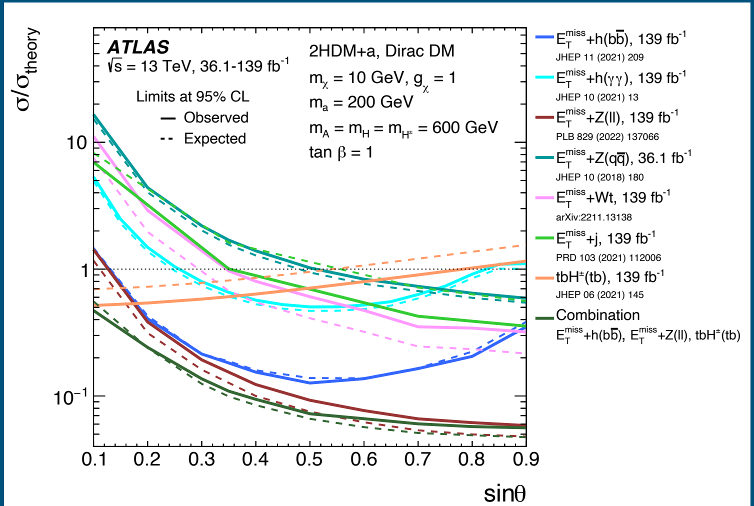
2HDM containing an additional pseudoscalar boson which mediates the interactions between the visible and the dark sector

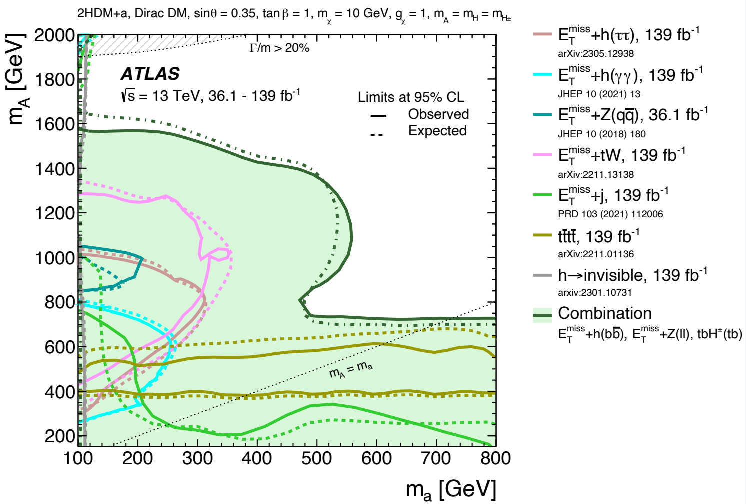
- gauge invariant & renormalisable extension of simplified pseudoscalar model
- DM candidate: singlet under SM gauge group, usually a Dirac fermion
- CP-odd mediator [pseudo scalar to bypass constraints from DD]

FREE PARAMETERS OF THE THEORY:

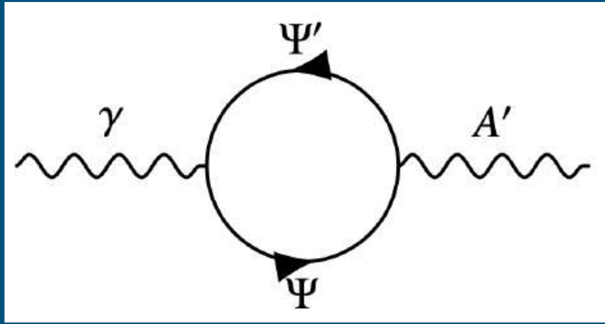
* masses of the heavy Higgs (mA = mH = mH±)
* mass of pseudo-scalar mediator, ma
* mass of DM particle, mχ
* sine of mixing angle b/w CP-odd states a & A, sinθ
* VEV ratio, tanβ

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





Dark-photons

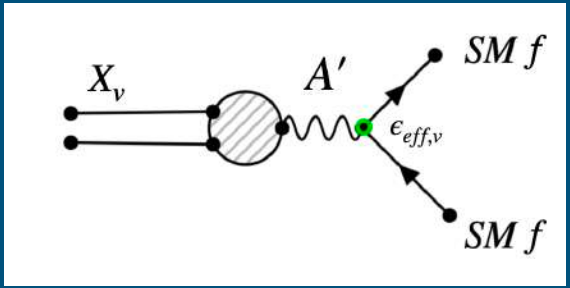


Vector Portal: Add a U(1)′ whose massive "dark" gauge boson mixes kinetically with SM photon

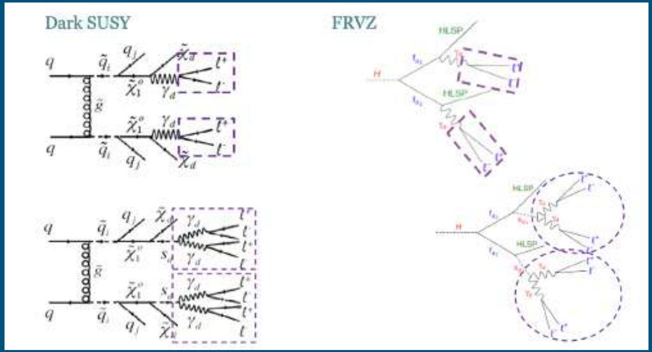
Higgs Portal: Add dark scalar singlet that spontaneously breaks U(1)′ and mixes with SM Higgs

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



Dark SUSY:

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

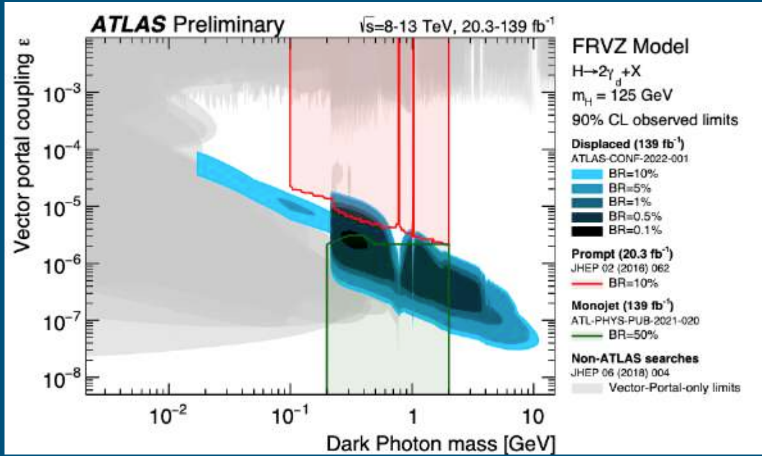
Neutralino → susy DM, and pair of dark photons decaying to pair of leptons

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.



ATL-PHYS-PUB-2022-007

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

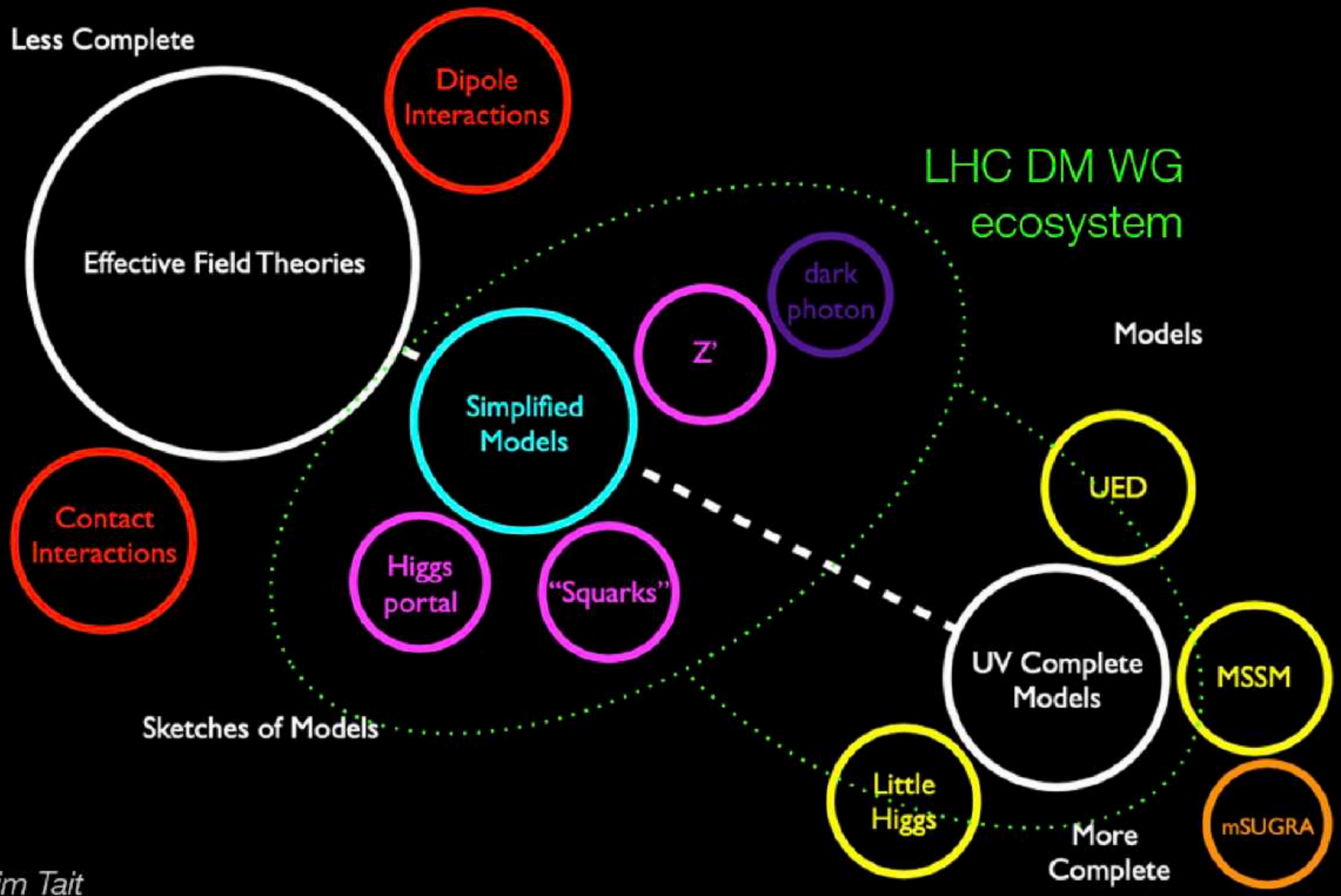


Figure: Tim Tait

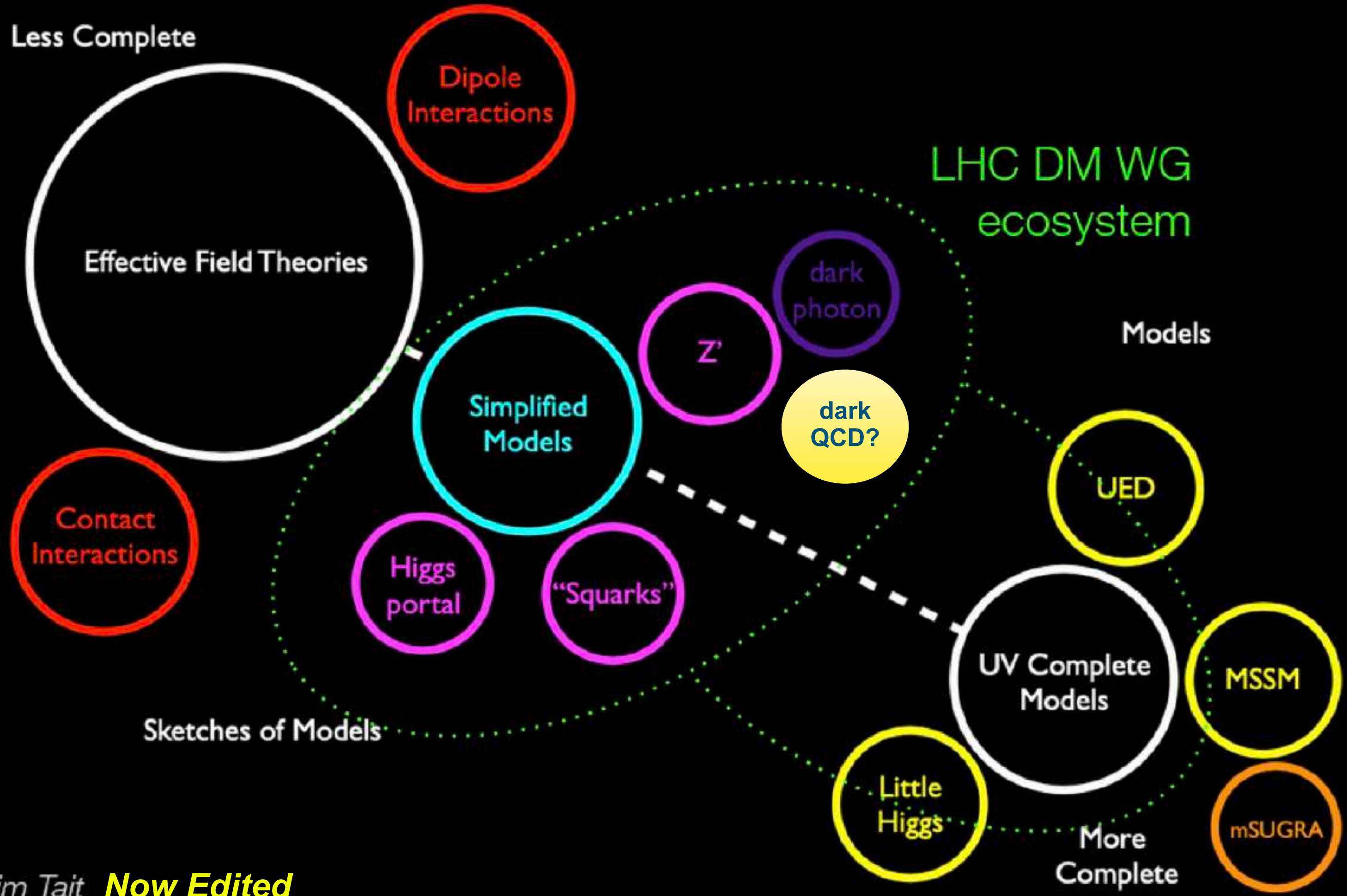


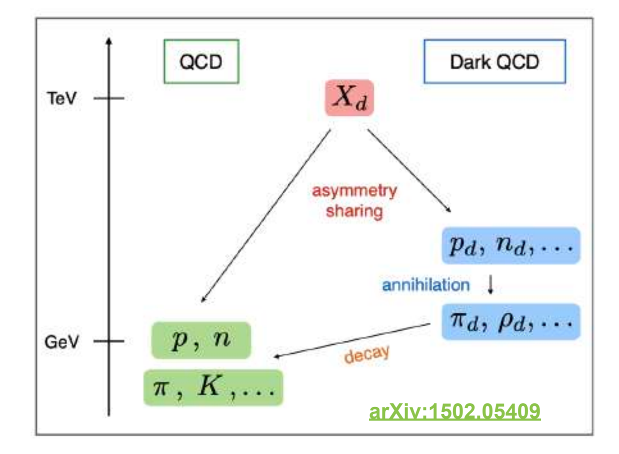
Figure: Tim Tait ***Now Edited***

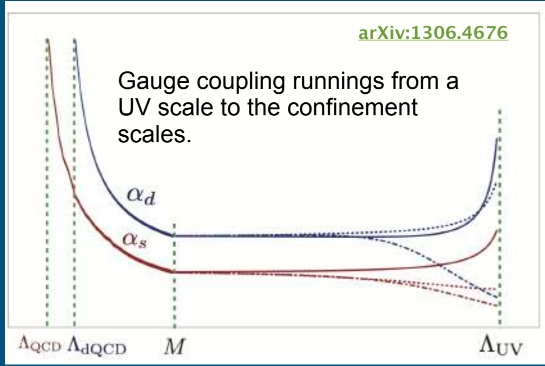
Dark QCD matters!

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 can be 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 can be (collider-)stable → invisible





Baryon and DM asymmetries shared via a mediator X_d → 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.

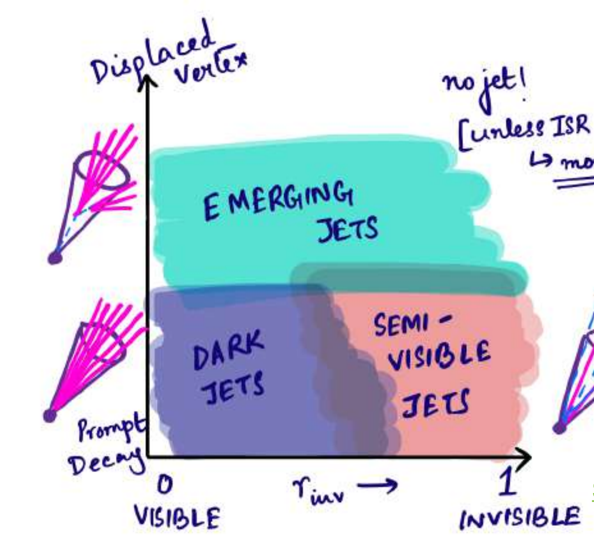
Different UV boundary gauge couplings can lead to the same perturbative IR fixed points.

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



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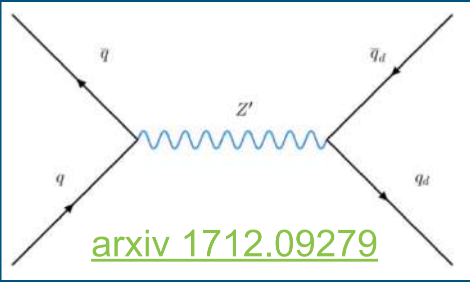
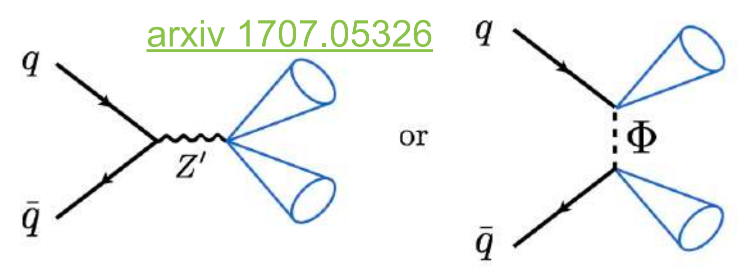
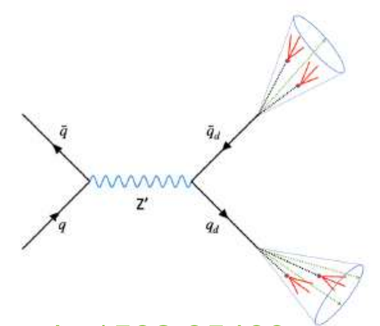
Showering using Pythia hidden valley module: at best a guesstimate!



arxiv 1712.09279



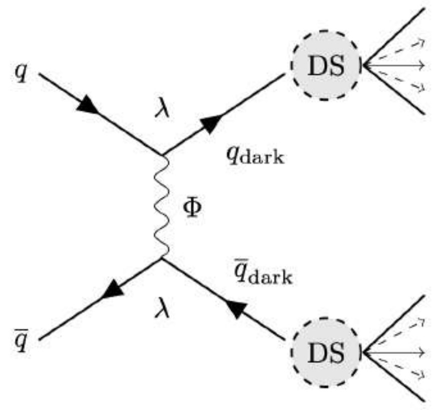
arxiv 1707.05326



arxiv 1502.05409

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

ATLAS semi-visible jet t-channel

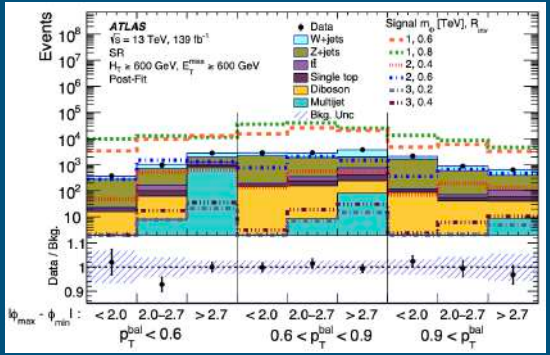


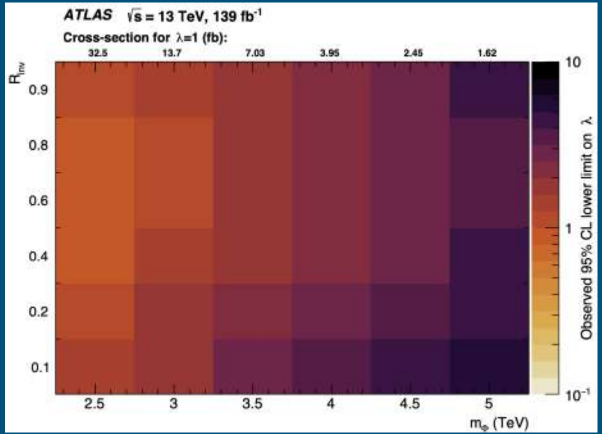
Lagrangian containing the interaction and kinetic terms:

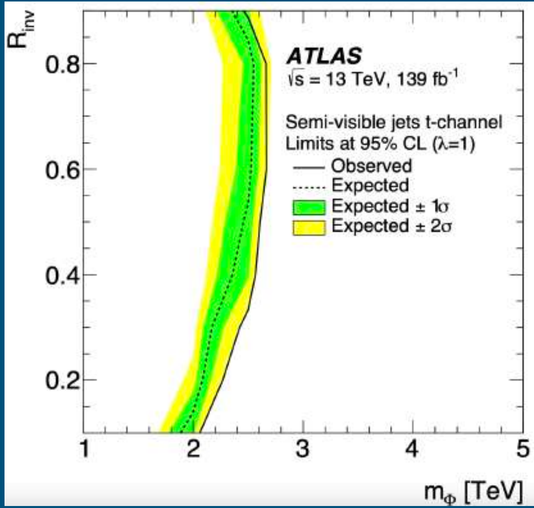
$$\mathcal{L}_{\text{dark}} \supset -\frac{1}{2}\,\mathrm{tr}\, G^{d}_{\mu\nu} G^{d\mu\nu} - \bar{\chi}_a \left(i\not{D} - M_{d,a} \right) \chi_a$$

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.







- 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

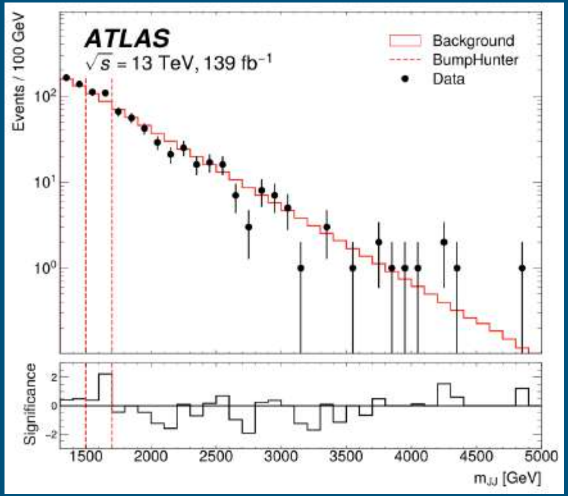
Phys. Lett. B 848 (2024) 138324

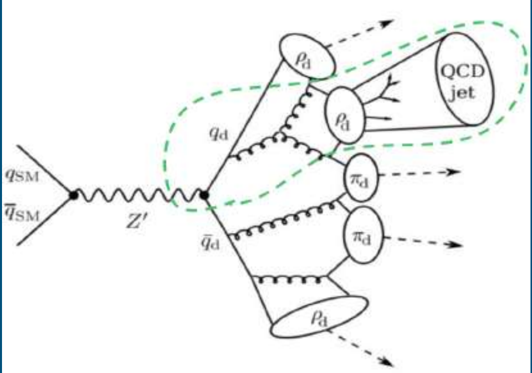
ATLAS dark jet resonances

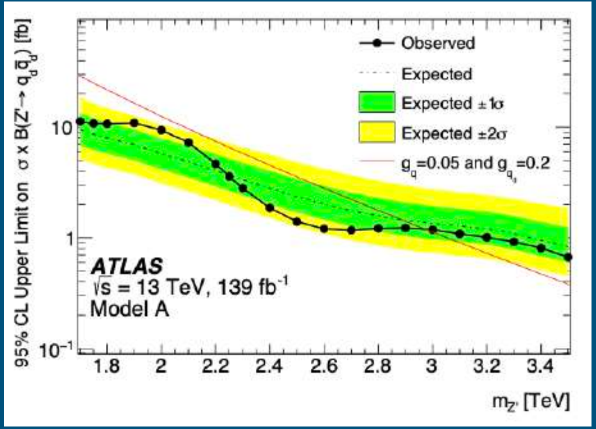
4 different benchmark models (A, B, C, D)

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

JHEP 02 (2024) 128



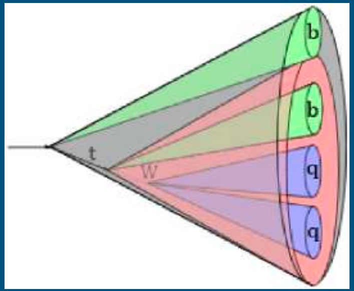




Exclusion depends on the model, can reach 3-3.5 TeV for which usual $Z' \to q\bar{q}$ searches can't say much

Dark mesons search

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)



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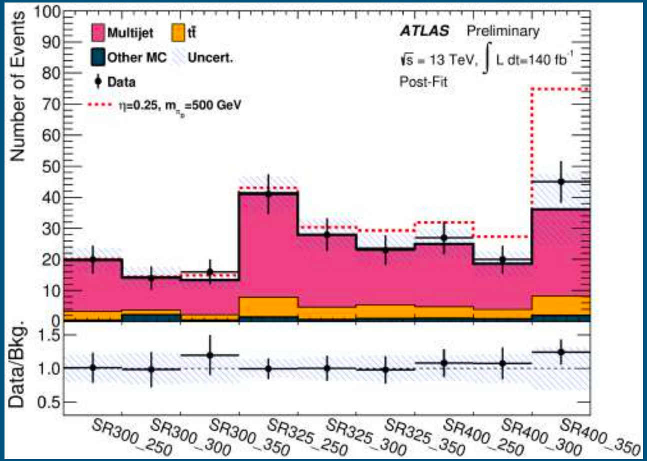
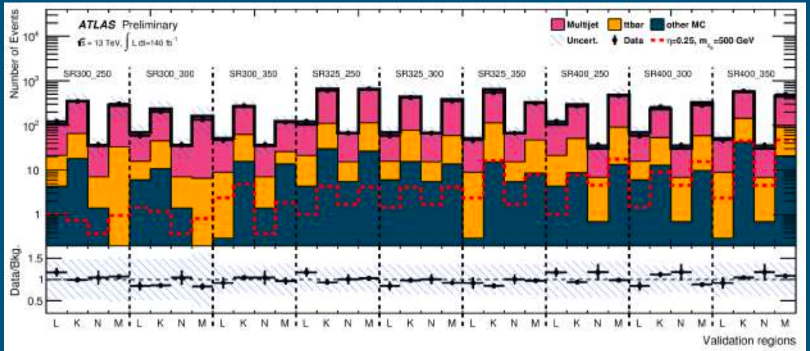
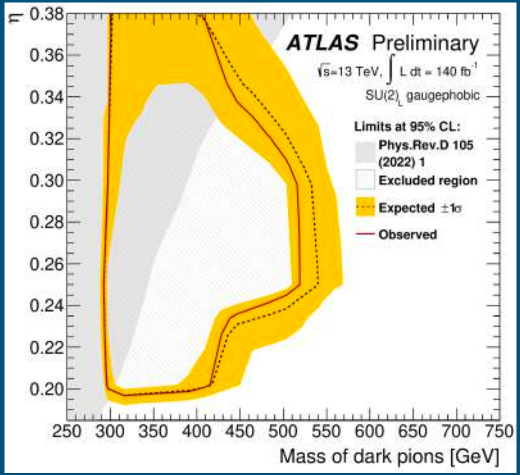




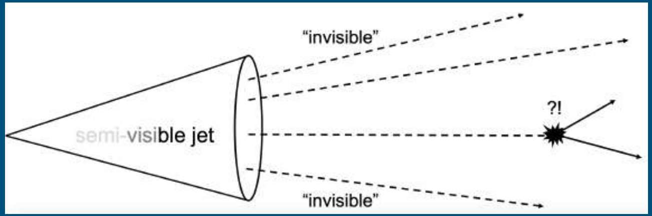


For η = 0.35, m_{π_d} < 434 GeV excluded,

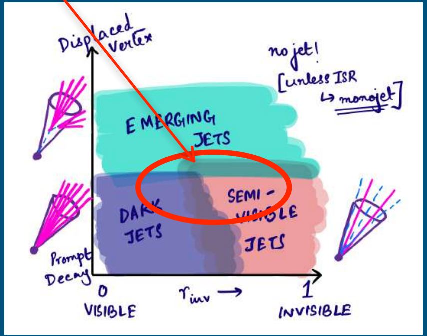
For η =0.25, 280 GeV < m_{π_d} < 522 GeV excluded.

The land of strong dark sector... and LLPs

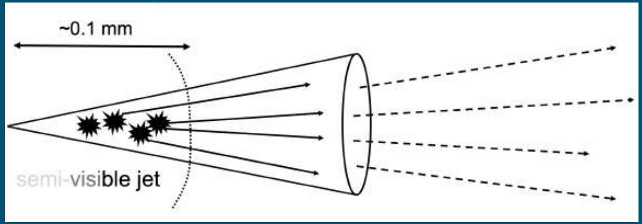
Invisible component in semi-visible jets are also LLPs but just with very long lifetimes:
1. Assign a very long (but not infinite) lifetime to the original "missing" components.



SVJ WS talk

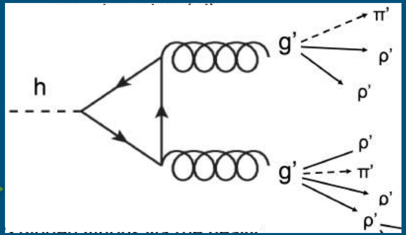


2. Assign a very short but finite lifetime to the original "prompt" components.



3. Add a third component (r_{LLP}) with an arbitrary lifetime

Higgs exotic decays + "prompt" components become LLPs



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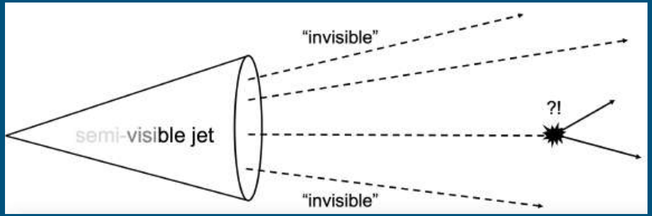

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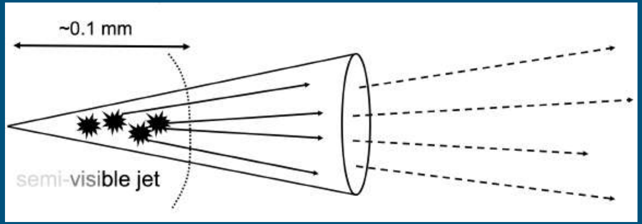

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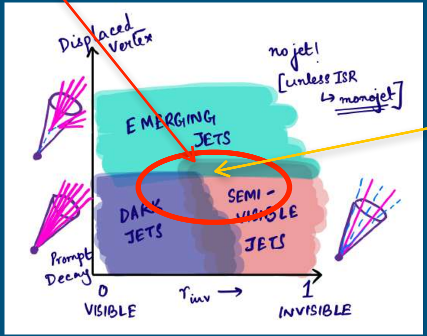
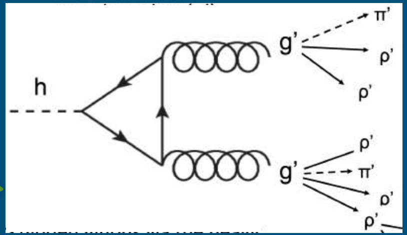
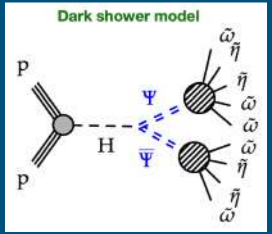
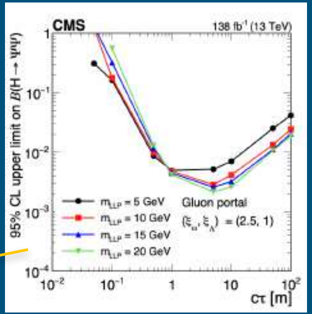
SVJ WS talk





Search for dark showers using Muon Detector Showers: CMS





First LHC sensitivity to Higgs portal dark shower models at BR(H →ss) = 10^{-3} level

Shower is semi-visible, scalar dark mesons couple to SM, vector dark mesons create MET

Decay portal	LLP masses [GeV]	LLP lifetimes [m]	$(x_{i\omega}, x_{i\Lambda})$	Features
Gluon	3, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	hadron-rich shower
Photon	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	photon shower
Vector	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0)	semi-visible jet
Higgs	4, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	heavy flavor-rich shower
Dark photon	2, 5, 10, 15, 20	0.5, 1, 5, 10	(1.0,1.0), (2.5,1.0), (2.5,2.5)	lepton-rich shower

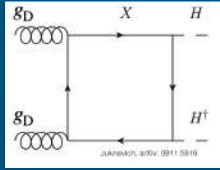
$x_{i\omega}$: mass ratio between dark vector and scalar meson
$x_{i\Lambda}$: ratio of dark sector QCD scale to dark scalar meson mass

Dark sector glueballs

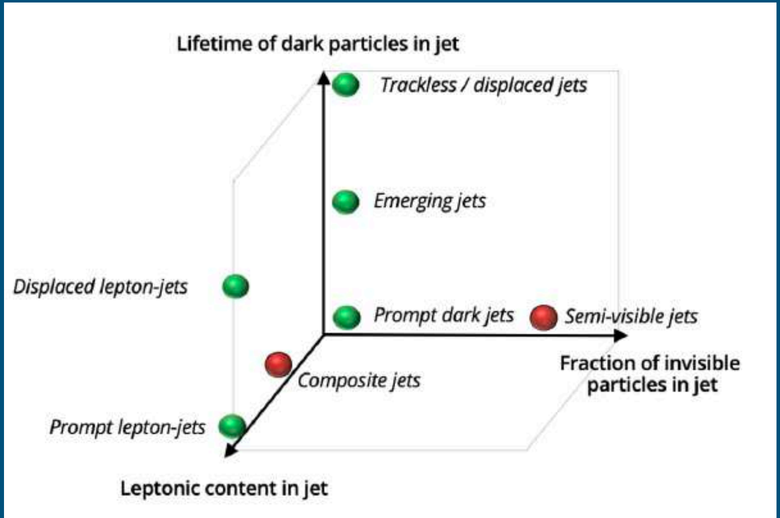
→ in $N_f > 0$ limit, only possible hadronic states. New quantative study now available.

→ can produce LLPs (larger lifetimes of heavier glueball states)

→ can produce SVJs and EJs

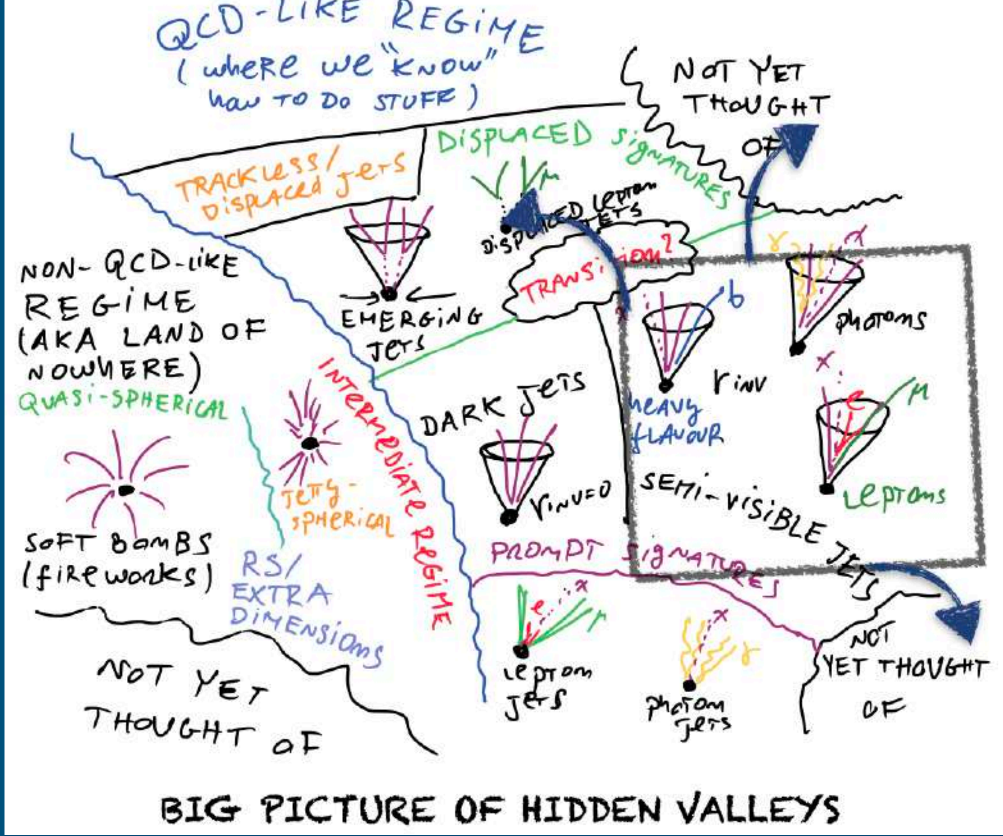


The land of strong dark sector…



GROWING FIELD & UNCHARTED TERRITORIES STILL TO BE EXPLORED !

Courtesy: C. Cazzaniga



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
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[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
[h]Instituto de Física Corpuscular, CSIC-Universitat de Valéncia, Paterna, Spain
* **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

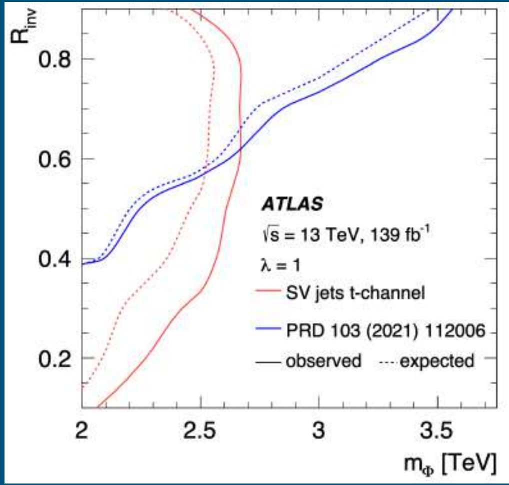
*sukanya.sinha@cern.ch

Potential for reinterpretation

All searches listed above have fairly inclusive selections
→ ALLOWS TO PROBE OTHER MODELS WITH SIMILAR FINAL STATES

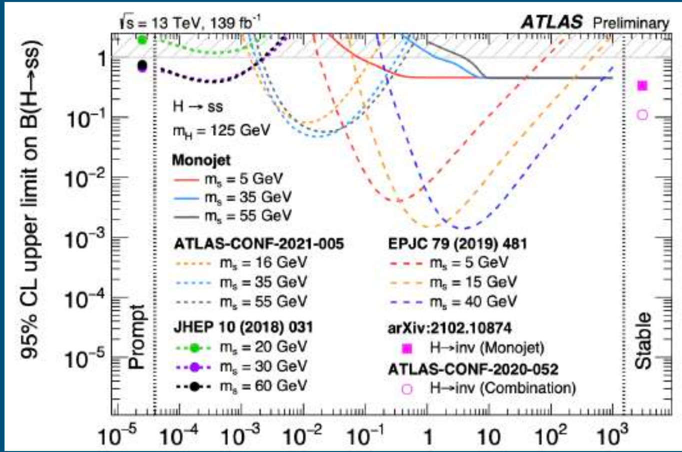
Constraining the dark sector with the mono-jet signature

Phys. Lett. B 848 (2024) 138324

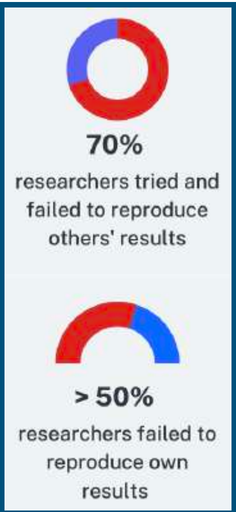


Expected and observed exclusion contours at 95% CL for semi-visible jets signal, using the mono-jet analysis selection.

ATL-PHYS-PUB-2021-020



Exclusion contours on BR(H → ss) at 95% CL obtained in the mono-jet analysis reinterpretation shown as a function of the s particle proper decay length, compared to dedicated searches



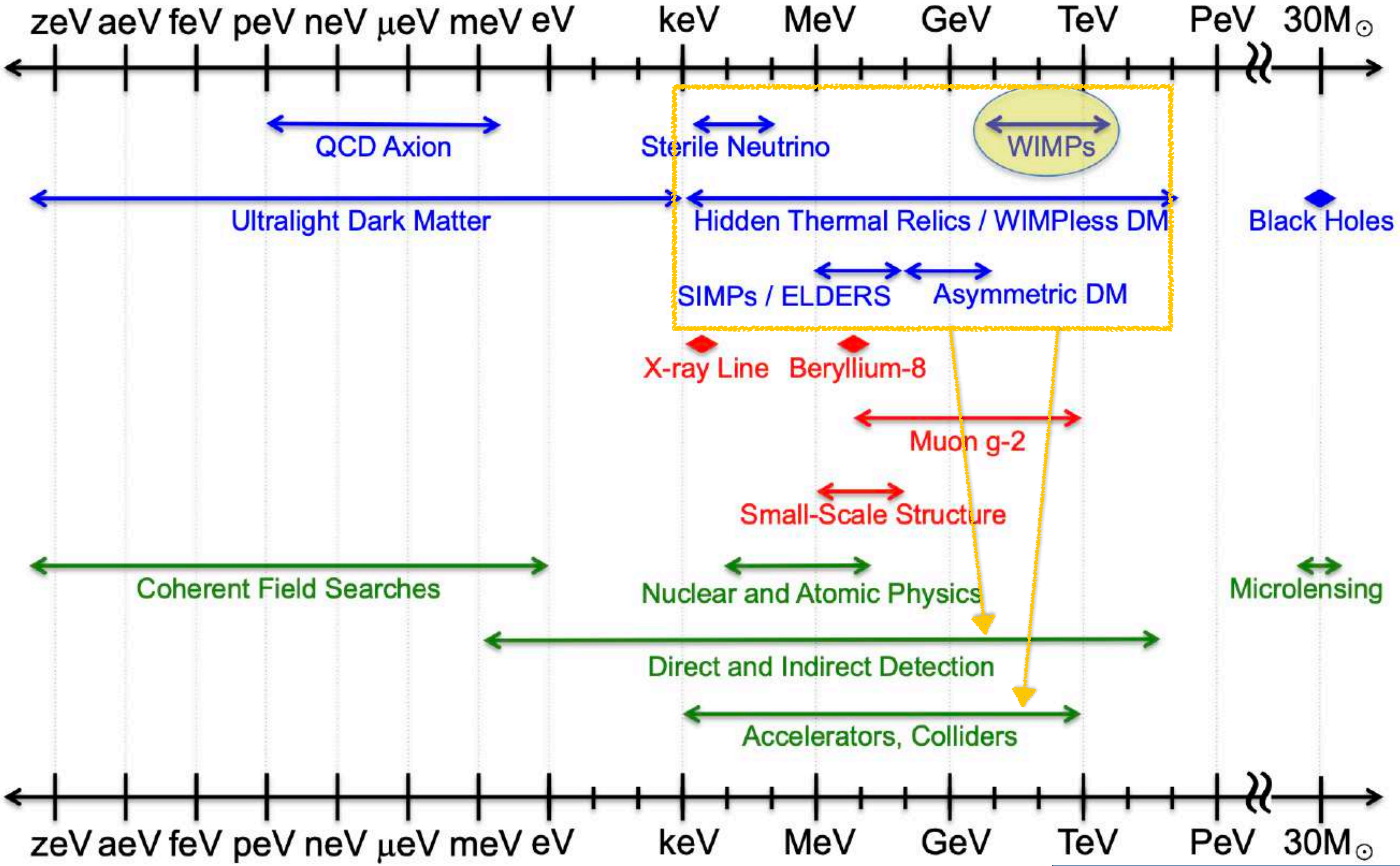
[source]

DM Complementarity going forward?

[Inspired by Snowmass Community slides link]

Multiple observations, experiments and coherent theories are needed for DM discovery

- Observations motivating DM arise from astrophysics & cosmic probes
- Theoretical frameworks are crucial to put different observations into context
- Direct Detection → can discover DM with cosmological origin
- Indirect Detection → can probe decays of cosmological DM into SM particles
- Colliders / accelerators → can produce DM and probe its dark interactions



J.Feng Les Houches school notes

Dark matter mediated by BSM particles★

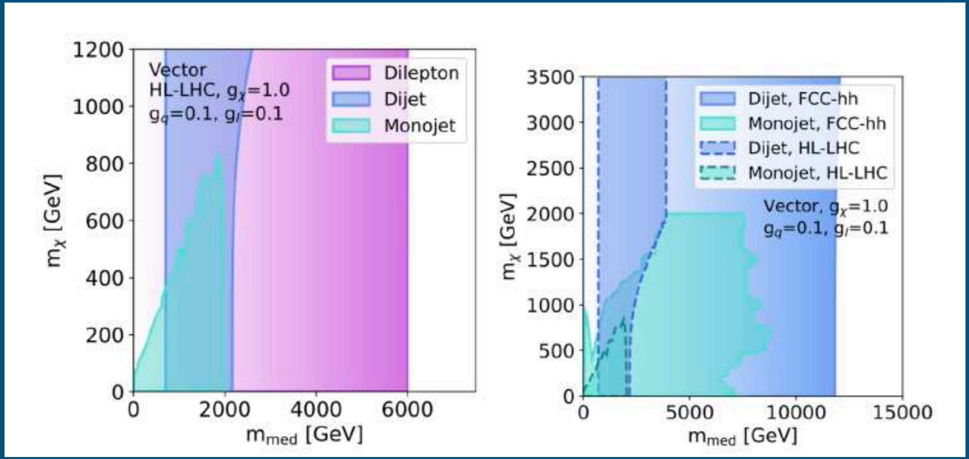
At collider energy scales, we can access the BSM particles that can mediate the SM-DM interactions

- Mediator can decay into DM → points to an excess in missing energy
- Mediator can also decay into SM particles → accessible using resonance searches

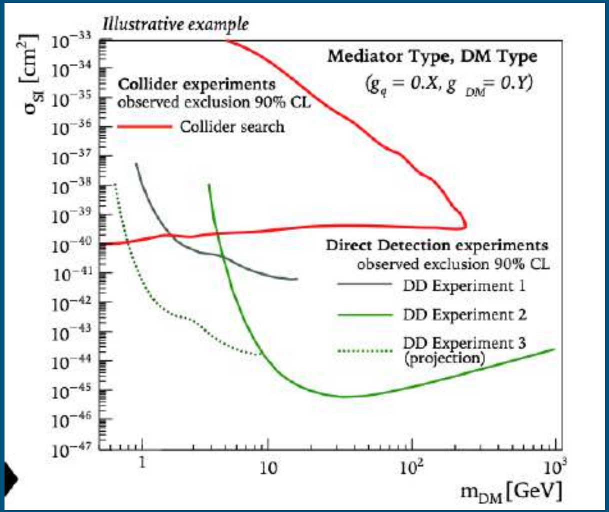
Overlaying results from collider simplified models searches to DD results in DM-nucleon plane:

Perfect region to discover DM would be where both colliders and direct detection have coverage

→ helps to determine both cosmological origin of discoveries as well as nature of interaction



Example scenarios for reach of future colliders for vector mediator resonances



Potential common sketch
(lines should be made more realistic)

Extended dark sectors and dark showers

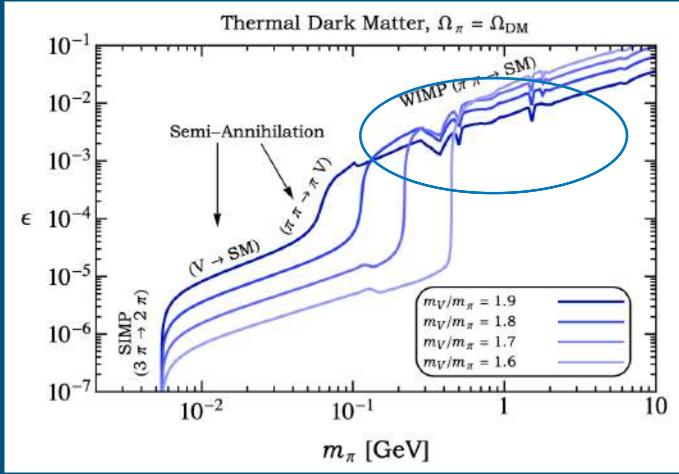
Dark QCD scenarios predict dark matter as a bound state originating due to confinement

- Early collider results exist
- First steps towards consistent collider analysis taken during Snowmass (Dark showers project and meetings)
- Overlap between colliders and direct detection needs more studies
- Excellent opportunity to exploit synergy with accelerator searches
- Some understanding via lattice QCD calculations for properties of SU(N) theories exists

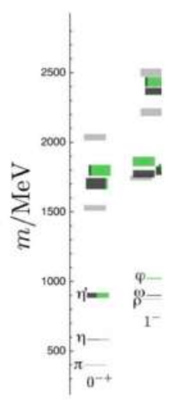
HV sector π abundance in m-ϵ plane arXiv:1801.05805

Contours are regions where π abundance matches DM relic density

Squeeze-out: 2103.09827



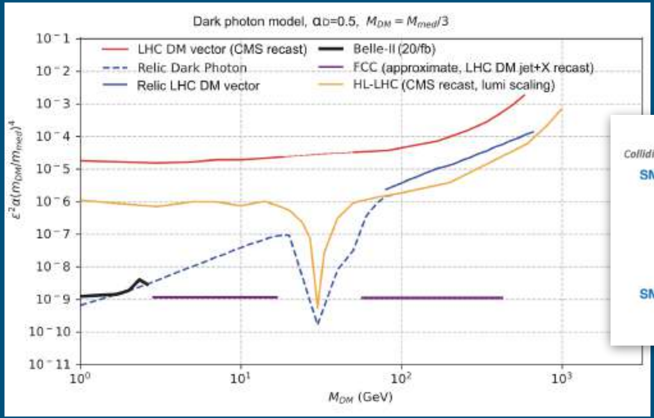
More details in F. Kahlhoefer's talk

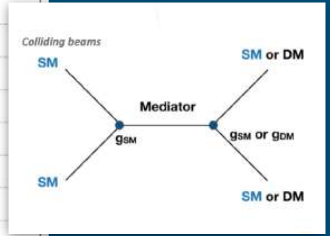


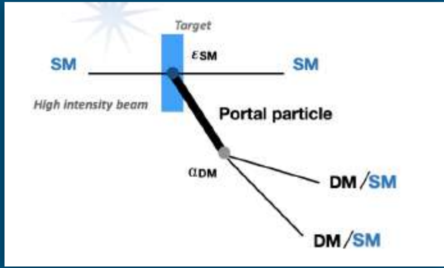
Light-ish dark matter at colliders

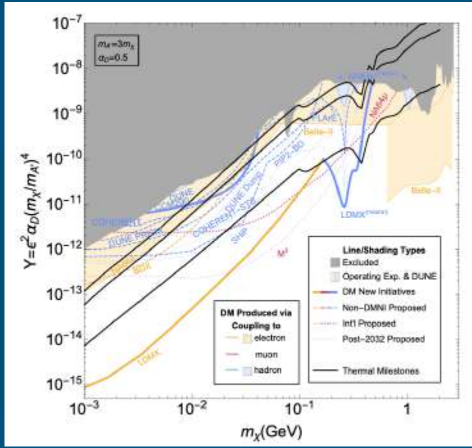
Some models of light dark matter (dark photon/dark Higgs) require new high-mass particles to be theoretically self-consistent

By using the same benchmarks between colliders and accelerator experiments, colliders can discover directly the high-mass particles, complementing light DM discoveries at accelerator experiments



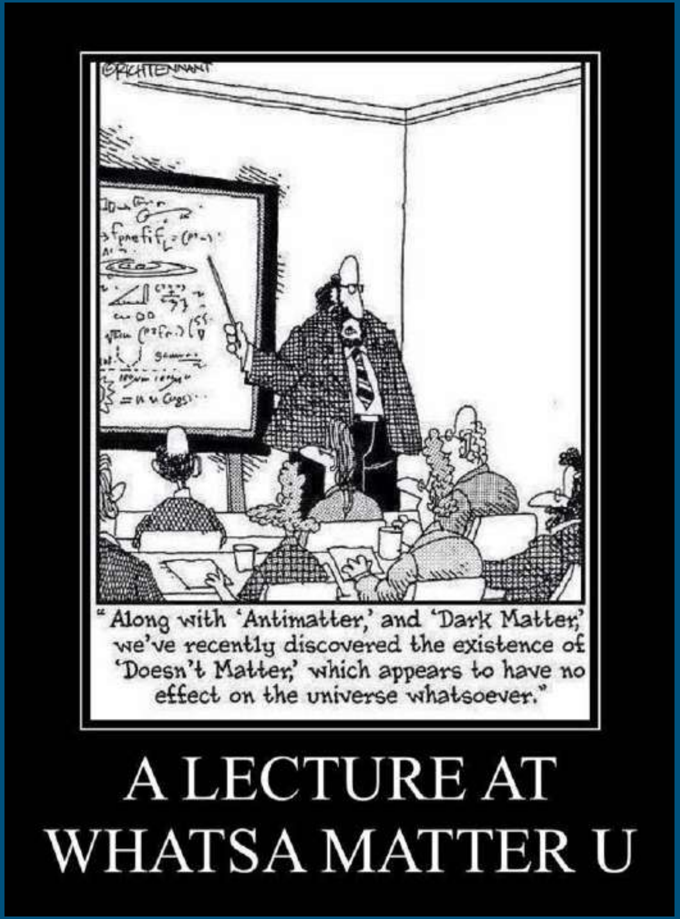






Conclusions

Sector



- Several avenues of dark sector open for exploration
- General idea evolving around the need of more signature based searches
- Confining dark sectors provide a very rich & interesting phenomenology, despite being based on models with only a few ingredients and parameters (quoting: 1905.08810)
- Discussions ongoing between experimentalists and theorists in different platforms (Snowmass Dark Showers working group, LHC DMWG)
- Steps to enhance complementarity
    - By developing a search program spanning across energy scales, as unbiased as possible
    - By extending searches for DM particles with the highest possible lab-accessible masses
    - By constraining properties of SM - DM mediators and/or portal interactions

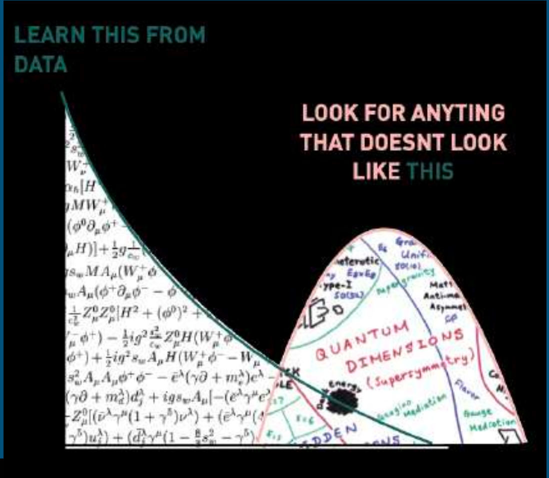
General direction of DM collider searches in 20s and 30s

If we want to capture Dark sector in a simplified model approach,
- We need to be careful not to destroy the beauty of the SM !

Higgs portal dark matter scenario provides very interesting interference effects on the LHC analysis and it will be more interesting as LHC go to the HL region.

- Hints of $\gamma\gamma$ at $95GeV, 152GeV, 680GeV$
- $\gamma\gamma$ at $95GeV$ supported by $\tau\tau$ and $b\bar{b}$ (LEP) → Many papers!
- $\gamma\gamma, ZZ$ hints at $680GeV$
- $b\bar{b}\gamma\gamma$ hint at $680GeV$, with $\gamma\gamma$ compatible with $95GeV$

All pointing towards extended scalar sector! 2hdm+S/a



- Run-2 simplified models constrained → update
- Improved tools for coupling variation aid presentation.
- Complementarity with detection exp., light DM.
- Codify $h \to$ invisible completions.
- General interest in looking beyond the assumptions/simplifications of the Run-2 WP benchmarks

Why MSSM DM?

Has been in limelight for a long time
⇓
Has been under test at multiple experiments

↙ No hints yet ↘ A relatively smaller allowed parameter space

How does this conventional dark matter candidate stand against the recent experimental results?

Are there any gaps which can be focal points for Run-3 of LHC?

The current experiments, especially the recent results from the electroweakino searches at the LHC and the LZ dark matter DD experiment have squeezed the allowed parameter space to regions which can either be
- regions of heavy higgsinos very close to being probed by few days of LZ data
- contain very low mass higgsinos which can be targeted at the Run-3 of LHC with dedicated analyses to be sensitive in this narrow gap.

Light dark photons are theoretically well-motivated particles, and they arise in many BSM theories.

They can be copiously produced at accelerator experiments.

Plethora of signatures can be searches for. Interesting complementarity between visible, invisible, and semi-visible signatures.

Complementarity between LHC searches (Higgs exotic decays!) and searches at high-intensity experiments.

- Foundation models getting more and more attention in HEP
- Promising concept to uncover the dark sector:
  - Unsupervised pre-training task: this could be done on data directly
  - Small dataset can be sufficient to get good performance

2HDM+a of TypeI is not yet explored → Leads to promising **new signatures**

Goal: New benchmarks of uncovered final states → New analyses with Run3 data

New decay channels: A → a H(bb), A → Z H(aZ)
H → a A(tt), H → H⁺ W

$b\bar{b}+E_T^{miss}$ and $llb\bar{b}$ expand exclusion to masses **below the SM Higgs mass**

Novel collider signatures in the type-I 2HDM+a model

arxiv.2404.05704

Spyros Argyropoulos, Ulrich Haisch and Ilia Kalaitzidou

Snippets from different presentations throughout the Roadmap workshop :)

BACKUP

2HDM+a: a thriving playground for LLPs?

[Hunting LLP@LHC](#)
[arxiv 2302.02735](#)

LLP signatures are possible in 2HDM+a if:

- $\sin\theta \approx 0$
- DM candidate is kinematically inaccessible or decoupled

“a” –> LLP candidate:

* pair produced by SM/BSM CP-even Higgs, depending on it’s mass
* if strong suppression of g_a in $\sin\theta$ –> 0 limit, only spin0 Φ can decay to pair of “a”

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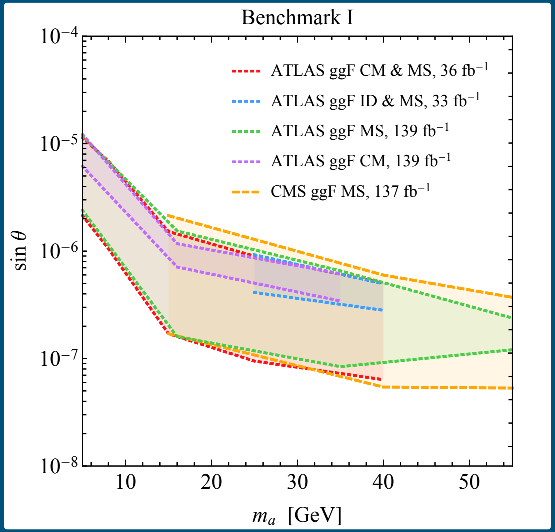

Example benchmarks [λ_{P1} and λ_{P2} are quartic couplings for 2 pseudo scalars]

I: $\{\lambda_{P1}, \lambda_{P2}, m_\chi\} = \{2*10^{-3}, 2*10^{-3}, 170 \text{ GeV}\}$

$\sin\theta$ and ma are free parameters:
ma < mh/2 —> LLP can be pair produced in the decay of 125 GeV Higgs

Excluded proper decay length, $c\tau$ ranges from 0.08 - 59 m

2HDM+a: a thriving playground for LLPs?

Hunting LLP@LHC
arxiv 2302.02735

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- $\sin\theta \approx 0$
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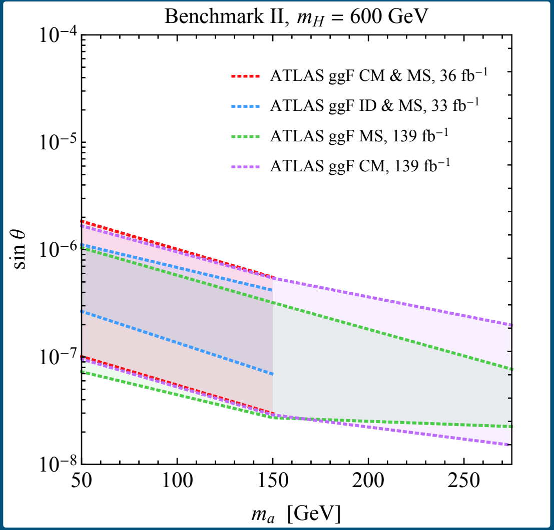
* pair produced by SM/BSM CP-even Higgs, depending on it's mass
* if strong suppression of g_a in $\sin\theta \to 0$ limit, only spin0 Φ can decay to pair of "a"

Example benchmarks [λ_{P1} and λ_{P2} are quartic couplings for 2 pseudo scalars]

II: $\{\lambda_{P1}, \lambda_{P2}, m_\chi\} = \{3, 0, 770 \text{ GeV}\}$

$\sin\theta$, mH and ma are free parameters:
ma > mh/2 & ma < mH/2 –> LLP can be pair produced in the decay of heavy Higgs, followed by displaced decays of "a" to pair of SM fermions or gluons

Excluded $c\tau$ ranges from 0.04 - 53 m

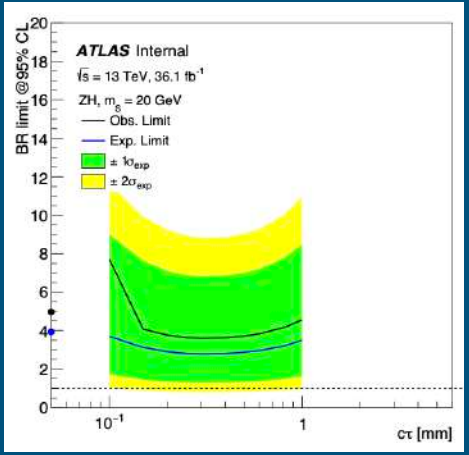


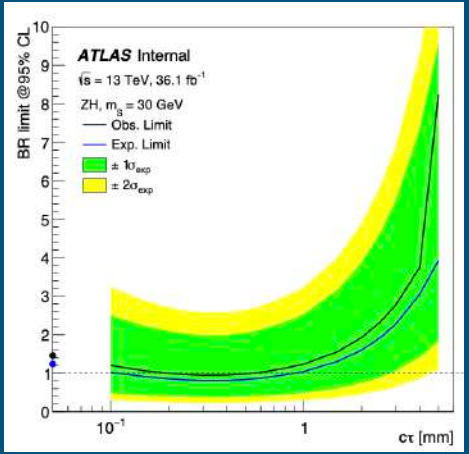
LLP reinterpretation of existing ATLAS searches

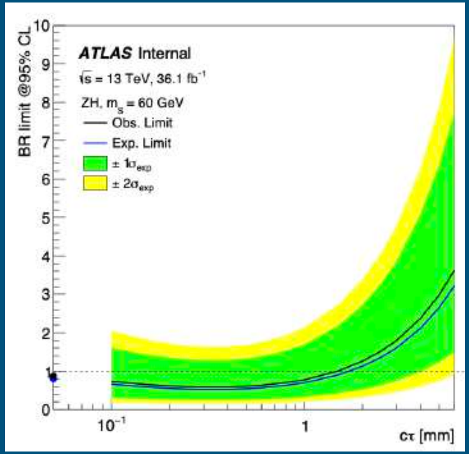
HTop H->2a->4b 2015+2016 (HIGG-2017-05) has a long-lived particle reinterpretation!

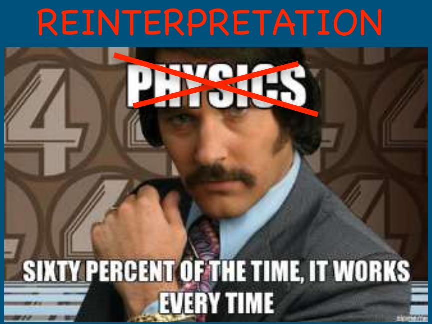
ATL-COM-PHYS-2018-099

Search for H –> SS –> 4b in VH topology associated Higgs boson production:
Signal model: Mg5 SM + dark vector + dark Higgs, recommended by LHC HiggsXS WG
* Samples produced with 0.1, 1 and 10mm mean lifetimes





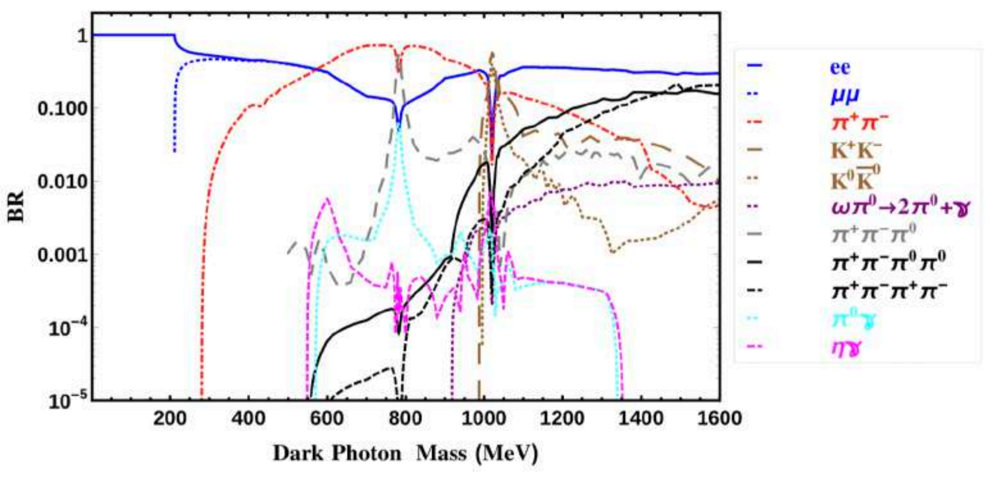




95% CL ZH channels, based on the cut-based analysis strategy

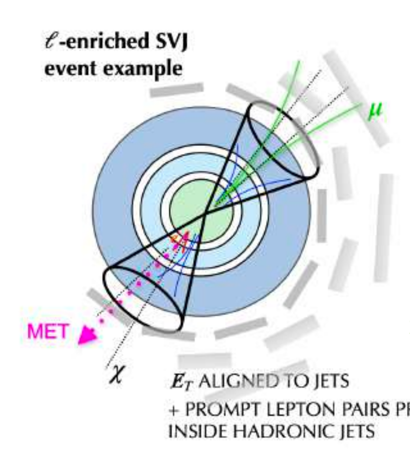
Possible dark photon production and decay modes

- Bremsstrahlung → incoming electron scatters off a nuclei target (Z) and emits dark photon, i.e., e-Z → e-Zγ_d
- Annihilation → electron-positron pair annihilates into a photon and a dark photon, i.e., e-e+ → $\gamma\gamma_d$
- Drell-Yan → $q\bar{q}$ pair annihilates into a dark photon, which consequently decays into a lepton pair or hadrons, i.e., qq̄ → γ_d → l^+l^- or h^+h^-



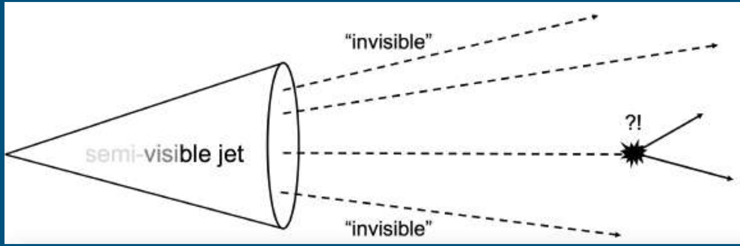
Dark photon decay branching fractions for the visible dark photon scenario for m_γ < 2 GeV.

Other signatures of dark QCD with potential LLP



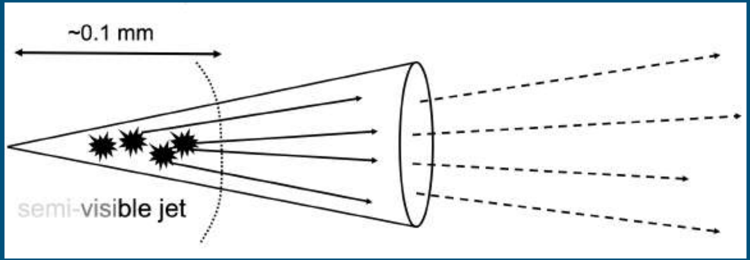
From C. Cazzaniga's DMWG talk

Invisible component in semi-visible jets are also LLPs but just with very long lifetimes:
1. Assign a very long (but not infinite) lifetime to the original "missing" components.



SVJ WS talk

2. Assign a very short but finite lifetime to the original "prompt" components.



3. Add a third component (r_{LLP}) with an arbitrary lifetime

Higgs exotic decays + "prompt" components become LLPs