TeVPA 2023
Napoli

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Searches for Dark Matter with the ATLAS Experiment at the LHC

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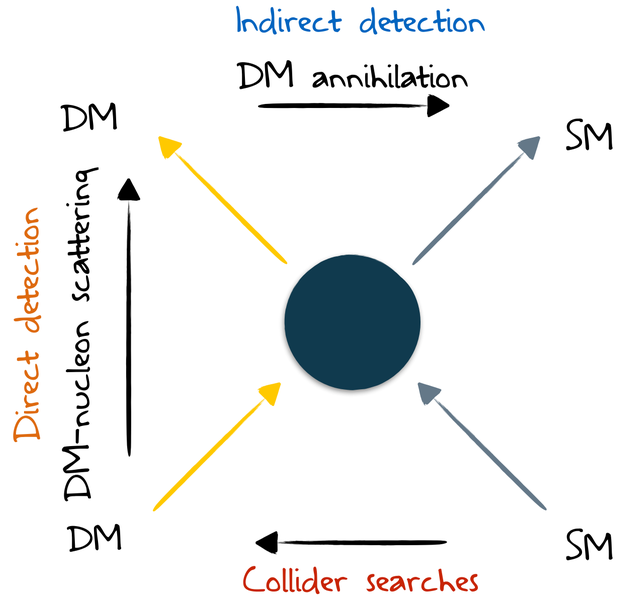
On behalf of ATLAS Collaboration

PROBING DARK MATTER

Dark Matter constitutes the dominant component of the total matter in the Universe

How can we study Dark Matter?

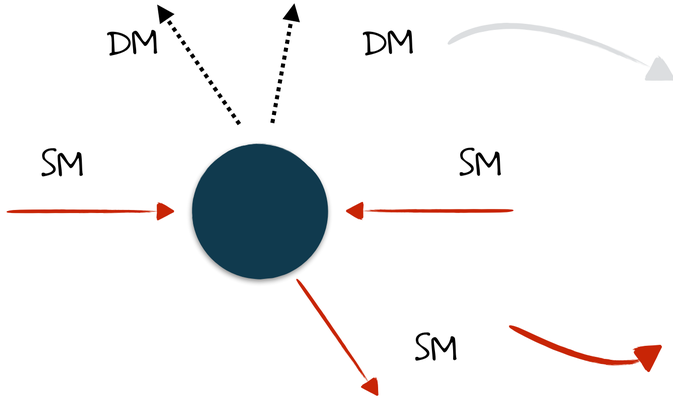
- **Direct detection** experiments looking for scattering processes between DM and ordinary matter
  - ↪Sensitive to spin interaction
- **Indirect detection** experiments that search for the annihilation products originating from WIMP collisions
  - ↪Look for excesses or anomalies
- **Collider searches** with WIMP pair production through SM particle collisions
  - ↪Sensitive to low DM masses, give complementarity with respect to other DM detections
  - ↪Many other DM models tested



How we can detect DM at LHC?

Pair production with **large missing transverse energy (MET)** in the detector

But we need a "visible" object to tag event → Search for DM events in association with a SM particle

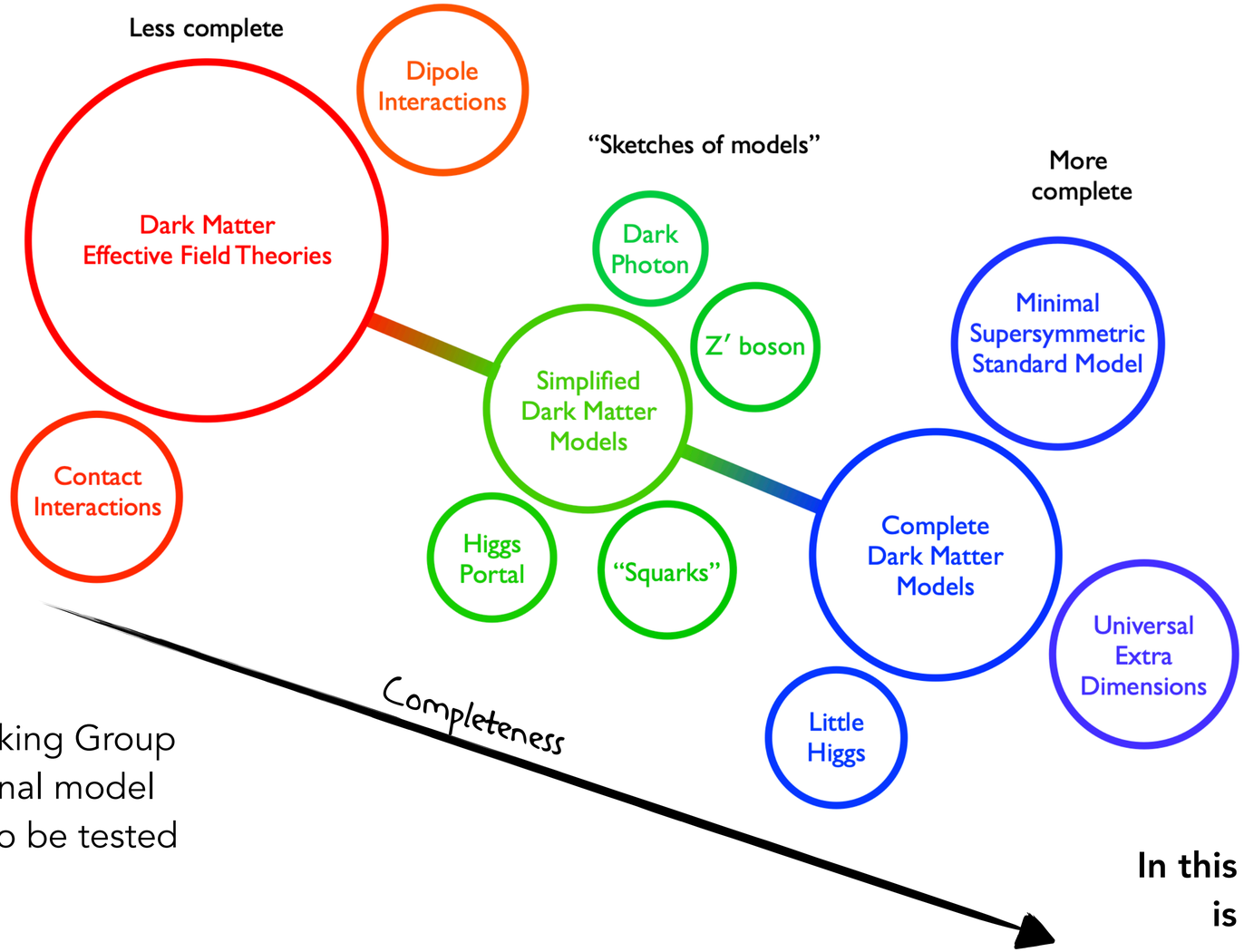


Dark Matter particles have no strong or EW interactions… they are undetectable for collider detectors!

Use SM particles (well-known) to tag the events of interest: jets, Z, W, H, γ

Dark Matter Models at The LHC

A large number of DM models can be built, which populate all the "theory space" of all possible DM candidates



- Different DM models in three distinct classes.
- Hidden sectors consist of DM particles that do not directly couple to SM fields, but via a portal / mediator
- **Could lead to non- E_T^{miss} signatures**
- Have their own pros and cons,
- All well-motivated and interesting

LHC DM Working Group provides signal model benchmarks to be tested

In this talk an overview of most recent results is provided (not covering all models)

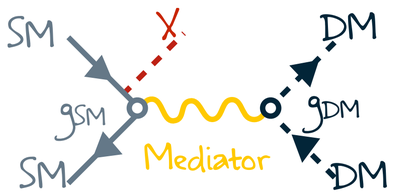
DM Simplified Models

- Introduce **mediators**: scalar, pseudoscalar, vector, axial vector mediators with minimal decay width assumption
- DM is a **Dirac fermion**
- 4 parameters: **DM and mediator masses, DM and SM couplings**
  - ↪ Fix coupling and scan masses
- Two complementary approaches: **direct** and **mediator** searches, probe different regions of high-dimensional phase space

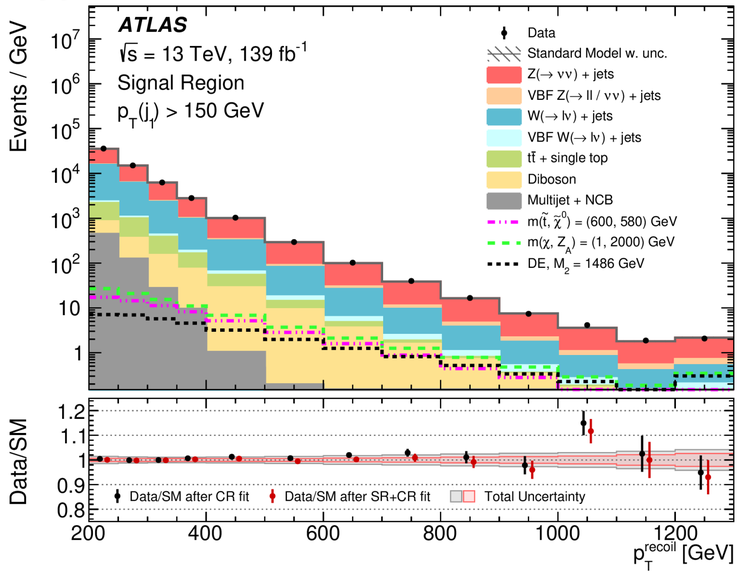
LHC DMWG Paper

Direct searches: $E_T^{miss} + X$

- Using Initial state radiation or associated production
- Selection requires events with high E_T^{miss} and an "X" object (jet, photon, W, Z, Higgs…)



- Look for deviation from SM backgrounds (e.g. in E_T^{miss} distribution)

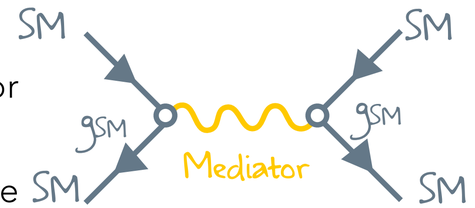


E_T^{miss} + jet best channel if tagging object comes from ISR!

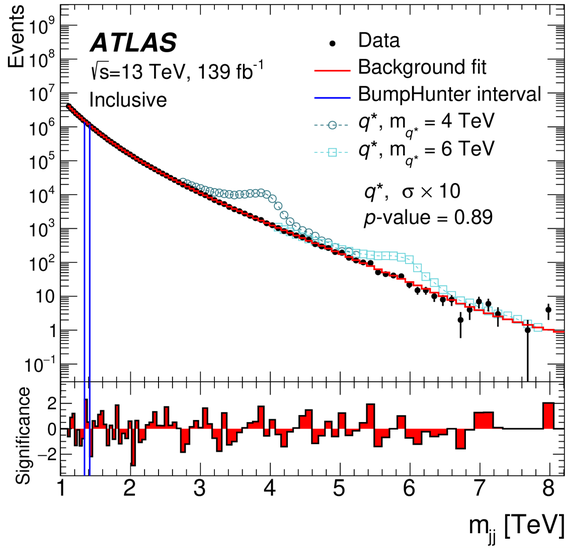
MonoJet

Mediator searches

- Bump hunt for mediator decays to fermions
- Look for mass peak above background continuum



Dijet searches have the best sensitivity

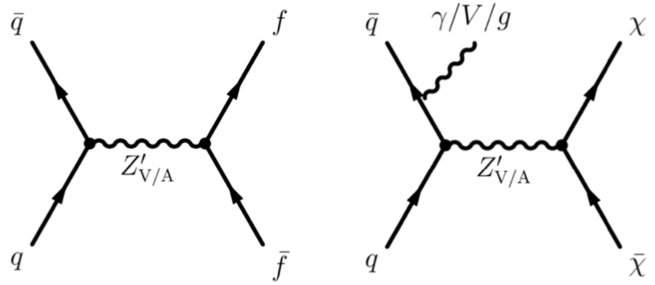


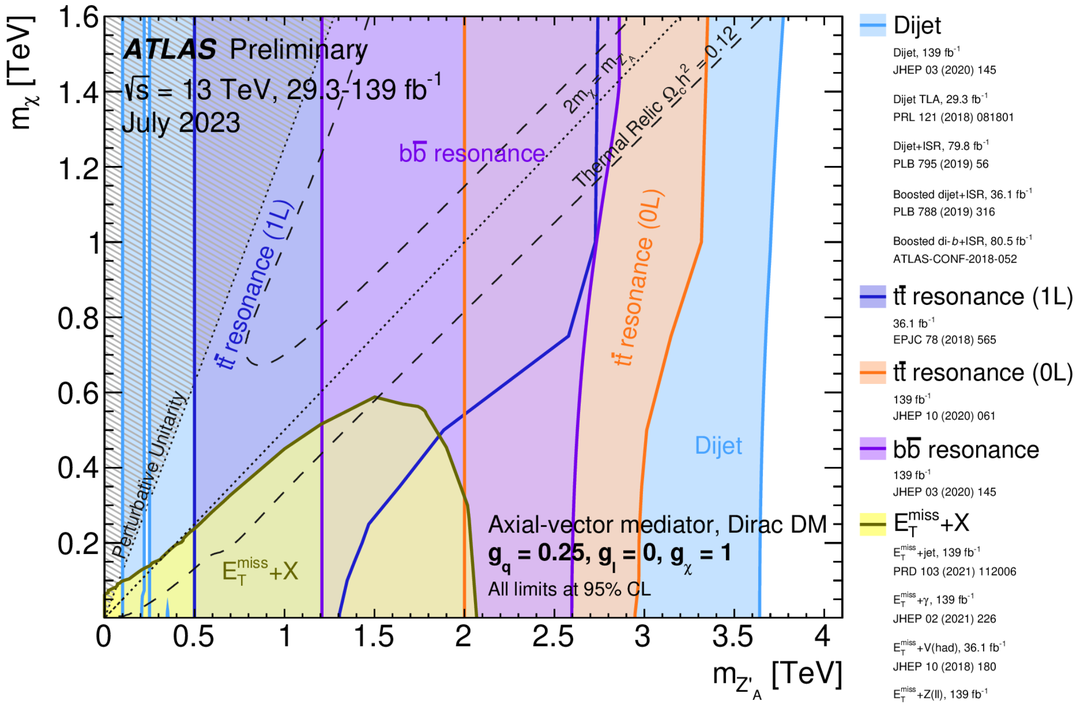
Dijet

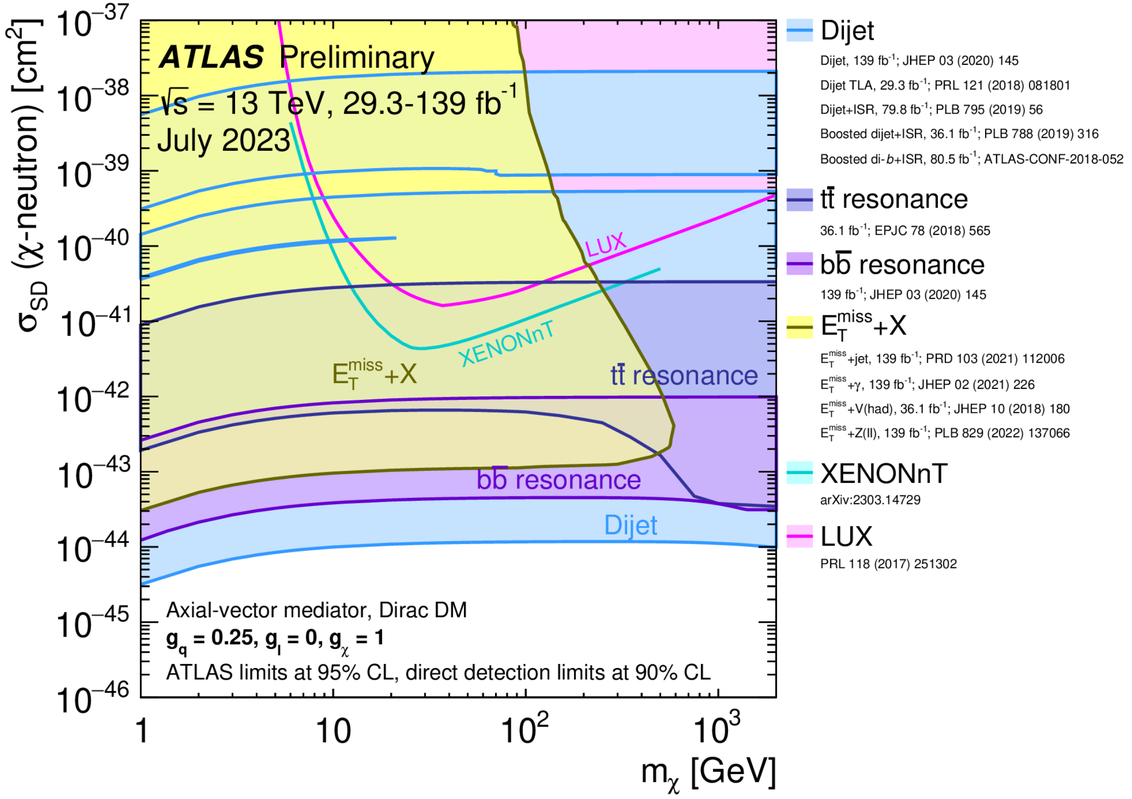
DM Simplified Models

Summary plots: Spin-1 Axial Vector Mediators

- $E_T^{miss} + jet$ is the most sensitive channel among $E_T^{miss} + X$ searches
- Results translated into spin-dependent DM-nucleon elastic scattering cross-section limits
  - ↪ Compared to direct searches
  - ↪ Competitive at low DM masses







Results depend on coupling values

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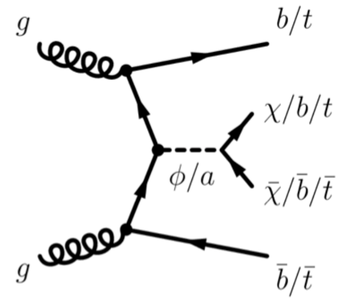
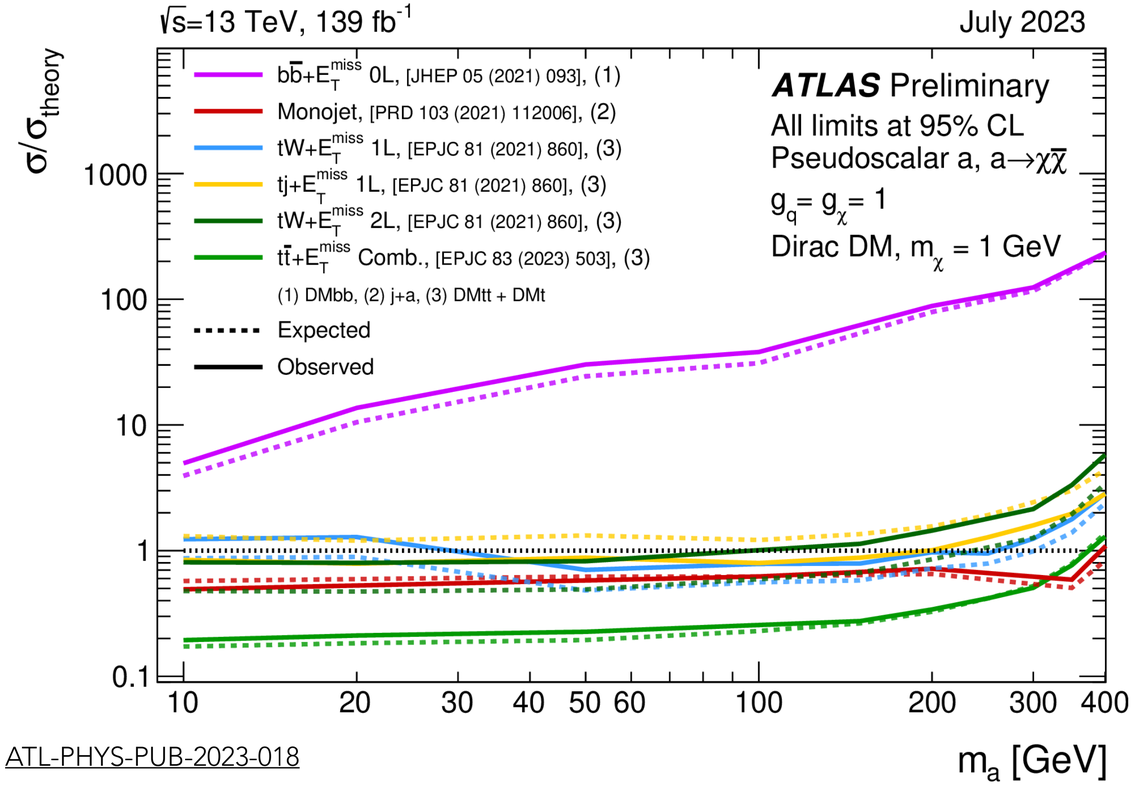
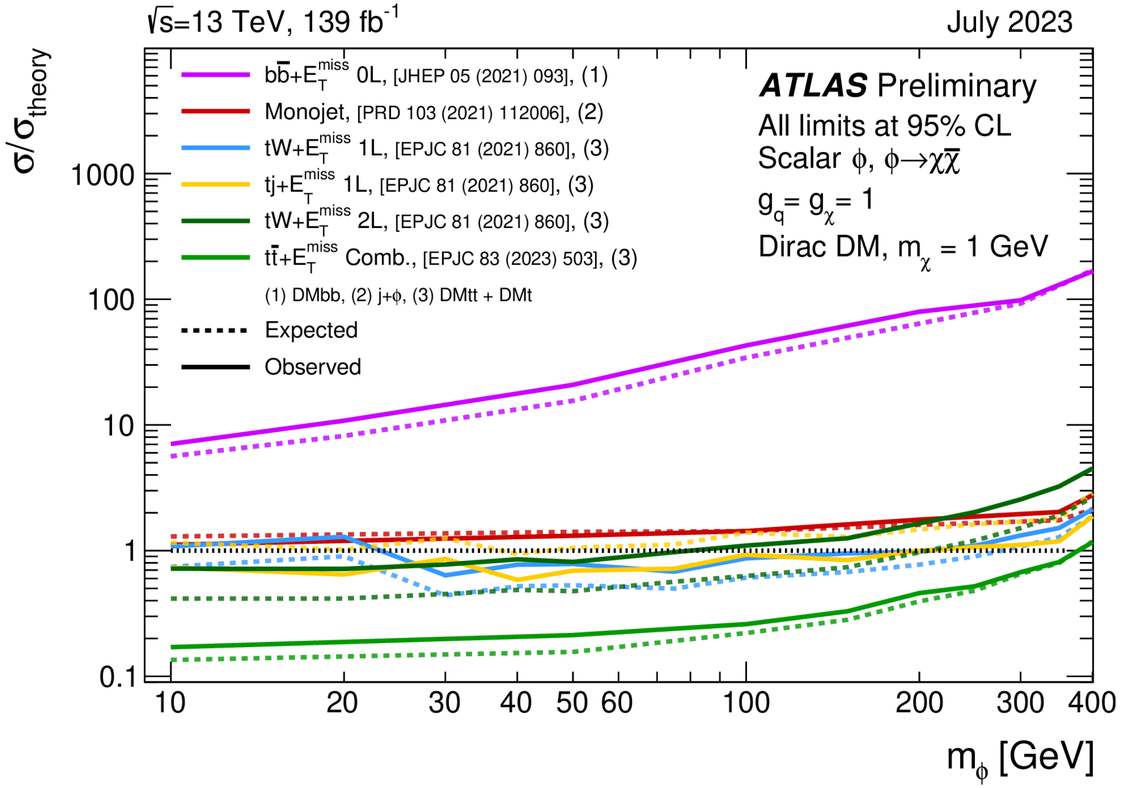
DM Simplified Models

Summary plots: Spin-0 Mediators



- Simplified models with scalar and pseudo scalar mediators
- Yukawa type couplings
  - ↪ Searches with heavy quarks (t, b) dominate
- Strongest limits from $E_T^{miss} + t\bar{t}$ combination for both spin-0 mediator type
  - ↪ Final state is mainly sensitive to the mediator mass range $m_{(\phi/a)} < 2m_t$, where mediator decay into top quarks is kinematically not allowed





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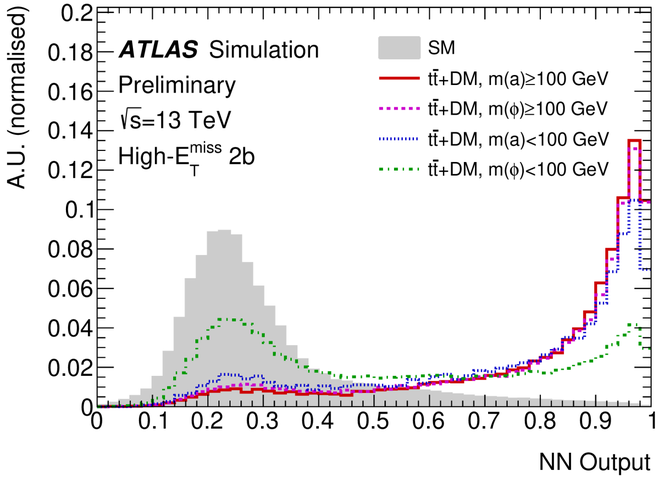
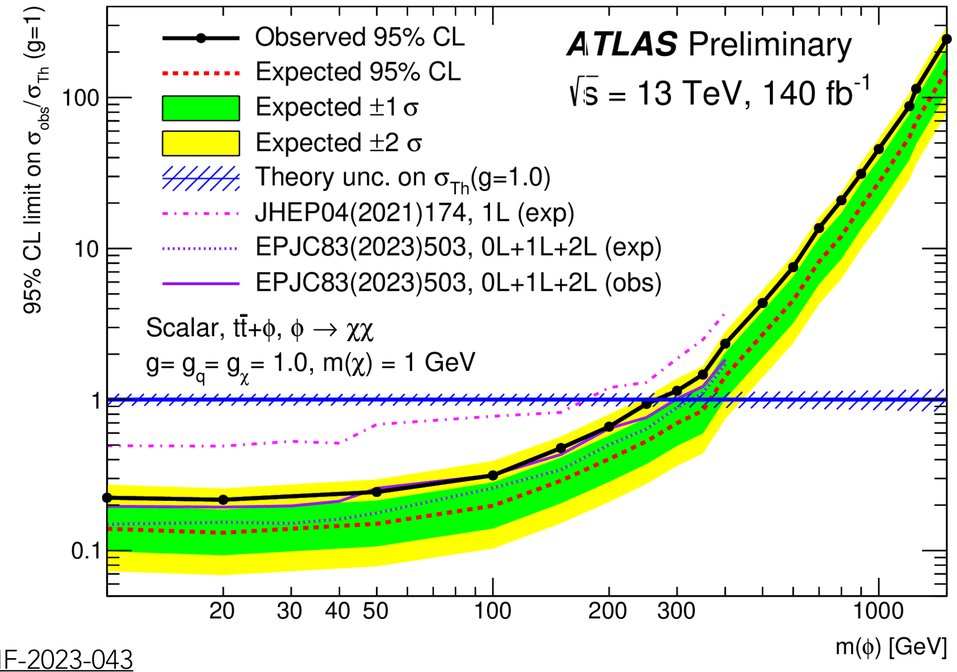
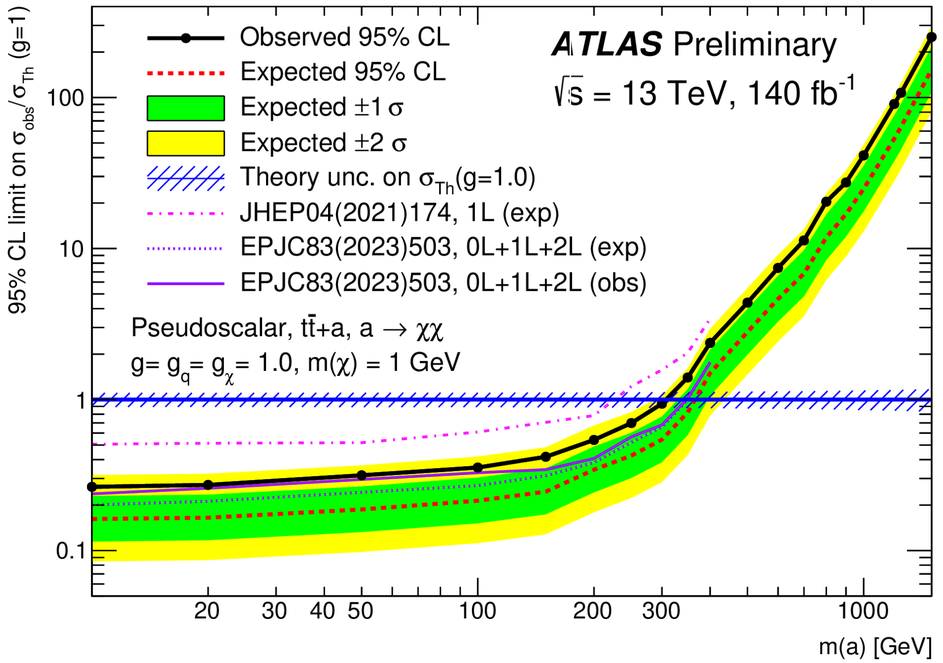
DM Simplified Models

New $E_T^{miss} + t\bar{t}$ analysis

- 1 lepton channel analysis
- New analysis approach developed to achieve higher sensitivity by classifying events with neural networks
- Plan to include in the new $E_T^{miss} + t\bar{t}$ combination



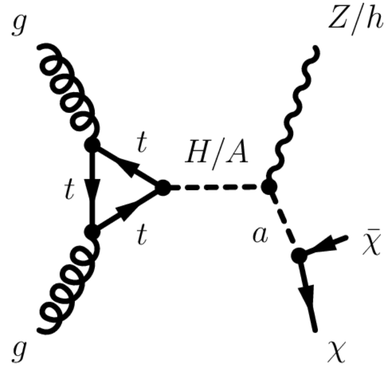


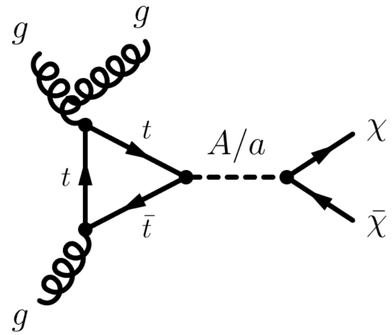


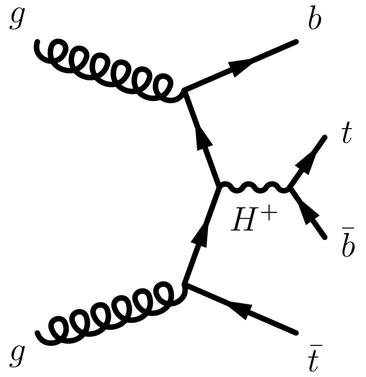
ATLAS-CONF-2023-043

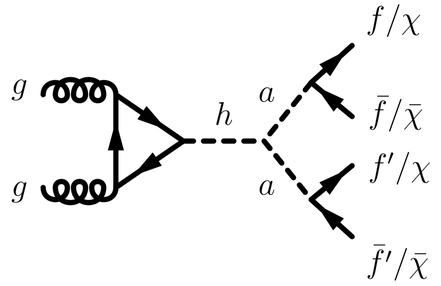
2HDM + PSEUDOSCALAR MEDIATORS

- LHC Dark Matter Working Group recommends as the simplest complete benchmark with a pseudoscalar mediator to evaluate LHC potential on DM searches
- Two Higgs doublet model plus pseudoscalar mediator a (2HDM + *a*)
- Extend scalar SM sector by an additional complex doublet
  - ↪Well motivated by several theories beyond SM
  - ↪**Five Higgs bosons**: a lighter CP-even boson h, a heavier CP-even boson H, a CP-odd boson A, and two charged bosons $H^{\pm}$
  - ↪**15 parameters, reduced to 5 and tested in 6 different scenarios**
- Pseudoscalar mediator *a* couples to fermionic dark matter candidates χ and mixes with the pseudoscalar A
  - ↪Motivated by the reduced constraints from direct detection experiments
- Predicts a wide range of collider signatures with a complex interplay across the model parameter space (A-a mixing)
- Includes signatures not predicted in the commonly used simplified models







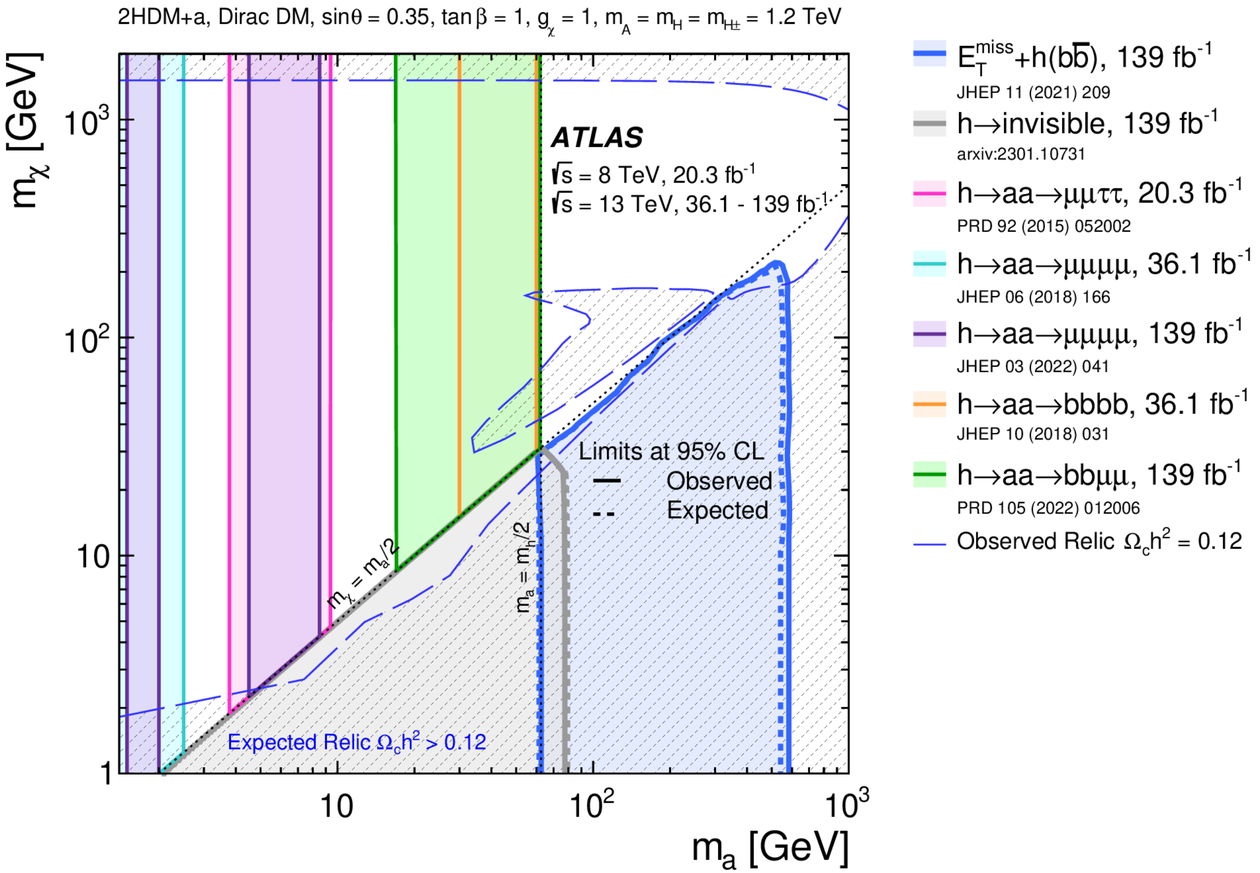


EXOT-2018-64

2HDM + PSEUDOSCALAR MEDIATORS

Benchmark scenario with $m_A = m_H = m_{H^\pm}$

- Complementarity with lower-mass $h \to aa \to ffff$ searches for pseudoscalars
- Light resonant searches powerful when *a* cannot decay to DM.
- Invisible signatures kick in for lower DM masses
- $E_T^{miss} + h(b\bar{b})$ signature dominating ad high m_a masses

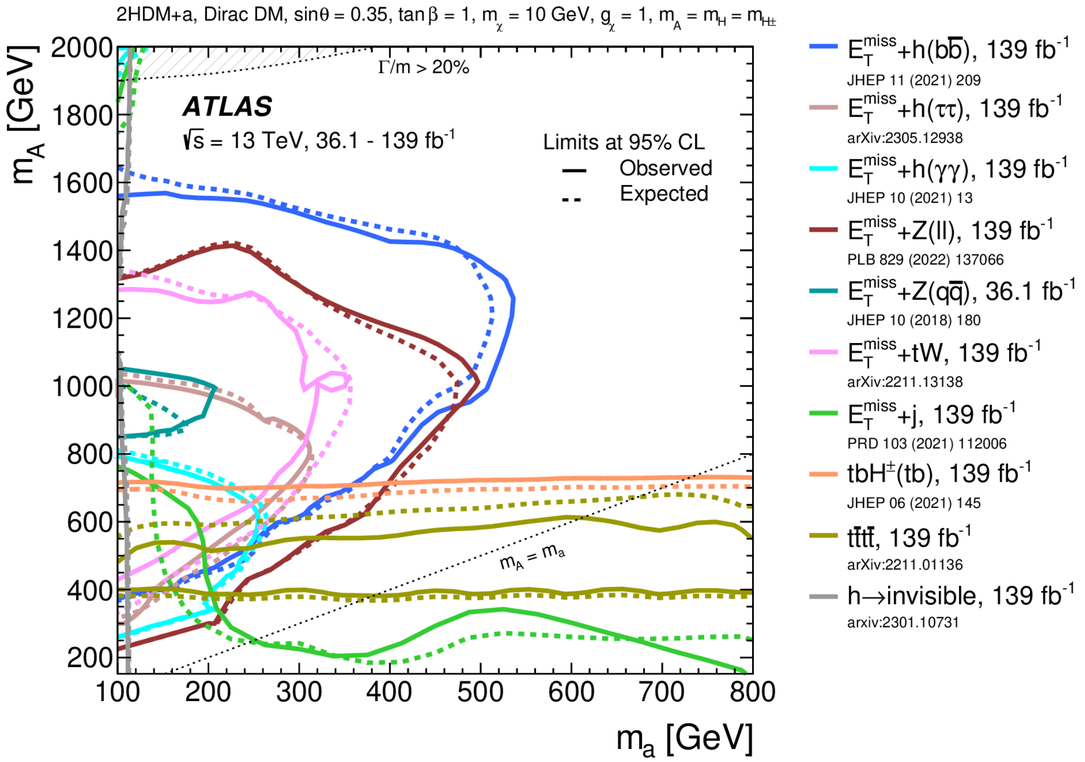


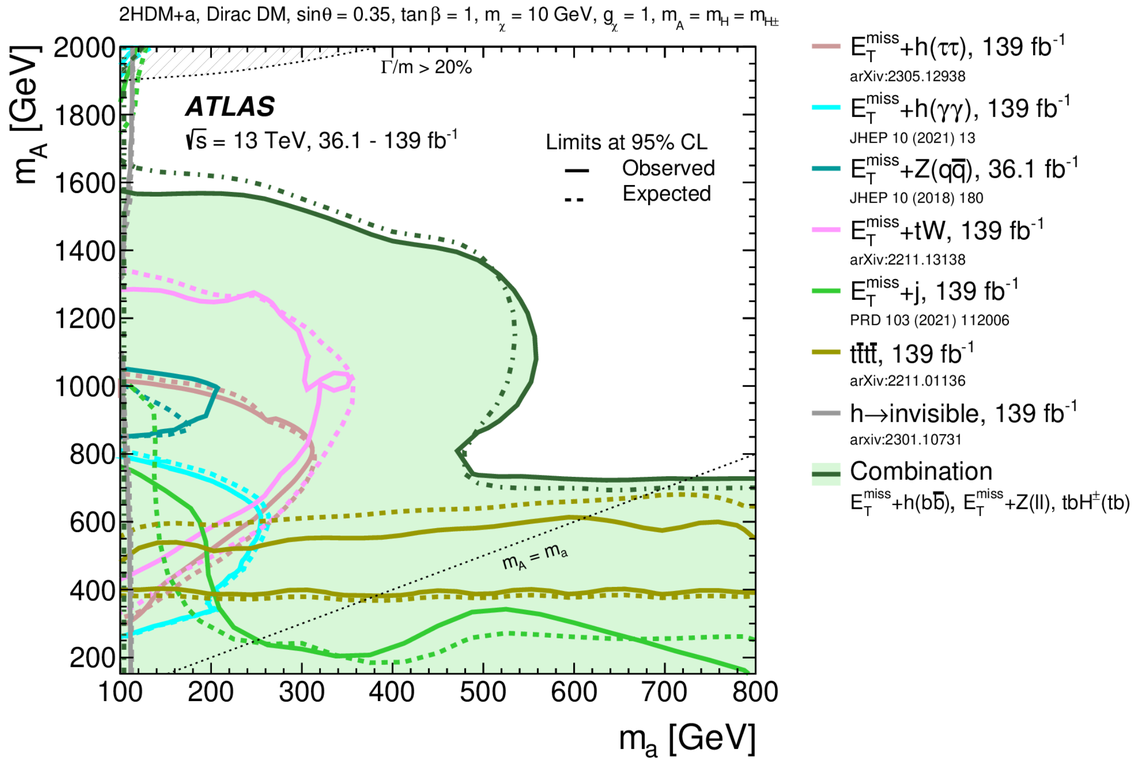
EXOT-2018-64

2HDM + PSEUDOSCALAR MEDIATORS

Benchmark scenario with $m_A = m_H = m_{H^\pm}$

- Most sensitive channels ($E_T^{miss} + h(b\bar{b})$, $E_T^{miss} + Z(\ell\ell)$ and $H^\pm \to tb$) are combined statistically





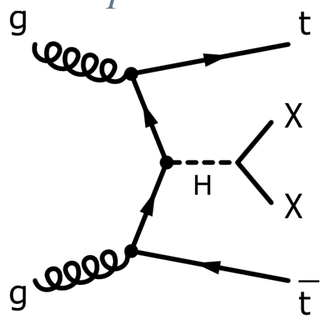
EXOT-2018-64

Dark Matter Searches in Higgs sector

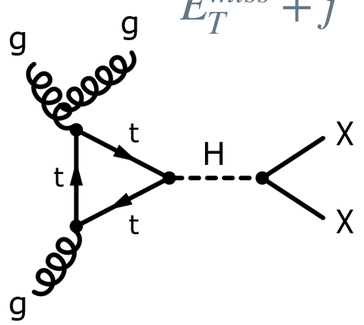
Higgs boson as portal to Dark Matter

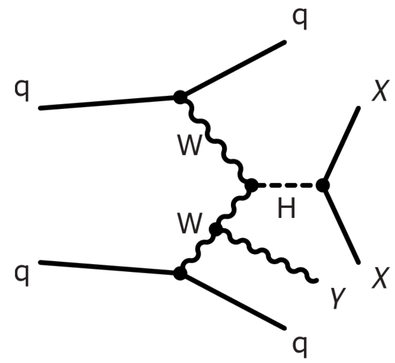
- Higgs boson connects dark sector and the SM sector, either through
  - ↪ Yukawa-type couplings to fermionic DM
- DM can be produced via decay of the Higgs boson
- Look for an anomalous BR (SM is 0.12%)
  - ↪ Look for enhancement of Higgs boson decays to invisible
- Signatures: $E_T^{miss} + X$, each Higgs production mode
- Sensitive led by $VBF + E_T^{miss}$ and $E_T^{miss} + Z(\ell\ell)$ signatures

$E_T^{miss} + t\bar{t}$

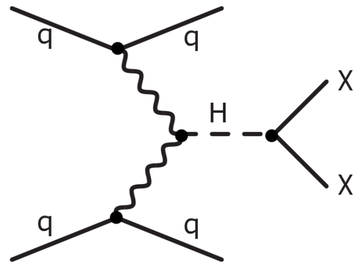


$E_T^{miss} + j$

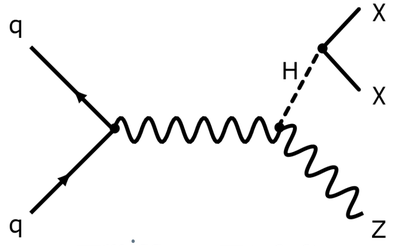




$VBF + E_T^{miss} + \gamma$



$VBF + E_T^{miss}$

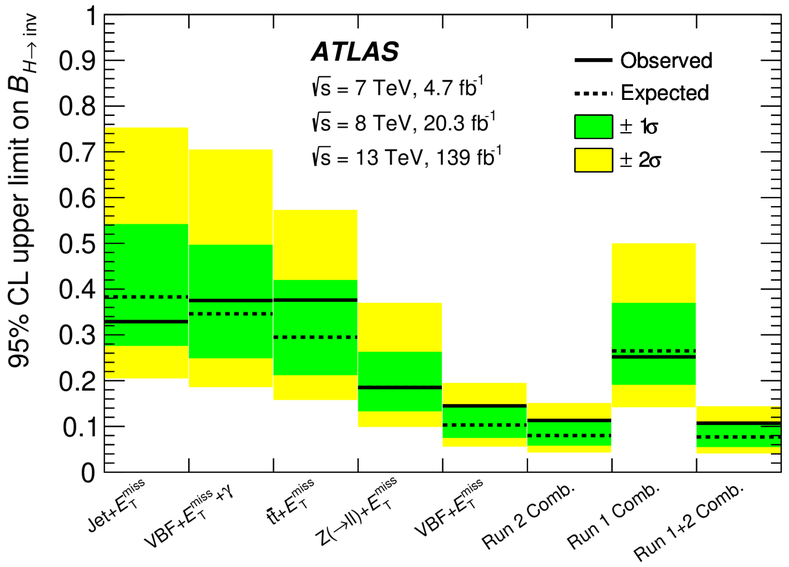


$E_T^{miss} + Z(\ell\ell)$

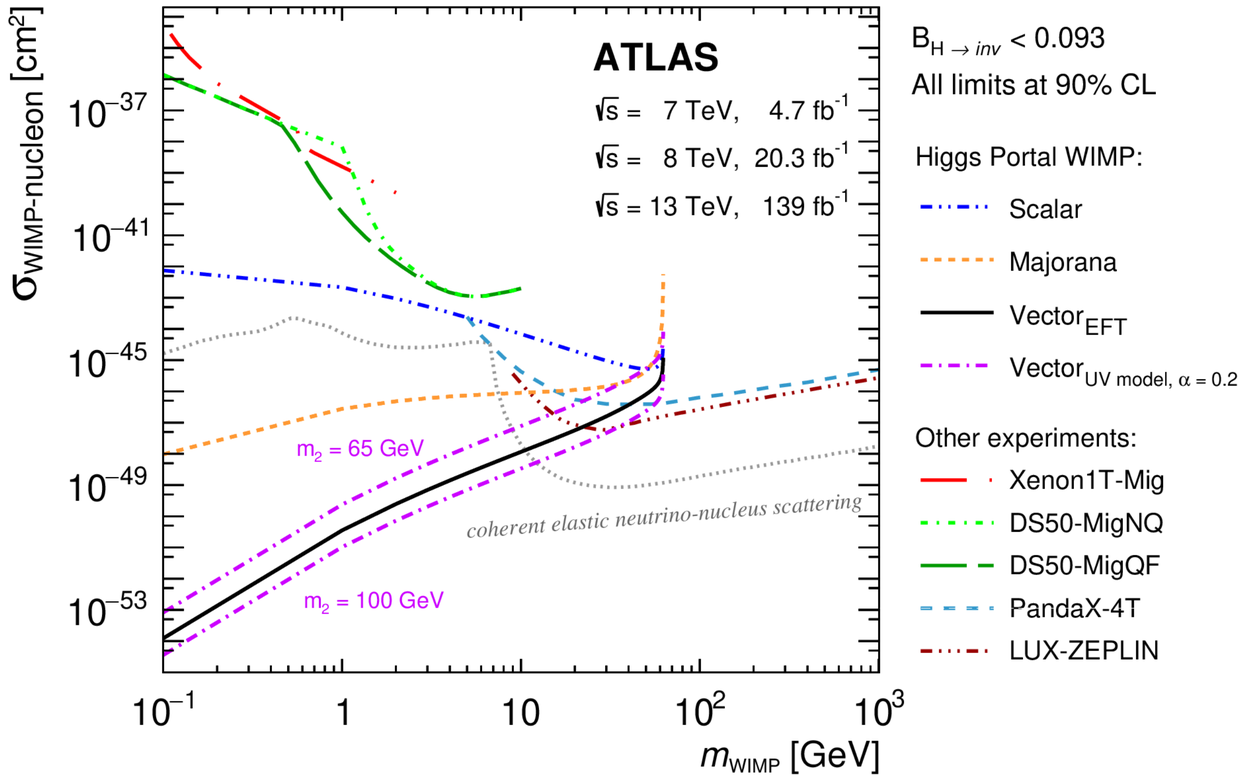
DARK MATTER SEARCHES IN HIGGS SECTOR

Higgs boson as portal to Dark Matter

- Statistical combination with Run-1 and Run 2 results
- Already probing BR(H→ Inv) at the 10% level!



Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$ + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + $E_{\mathrm{T}}^{\mathrm{miss}}$	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

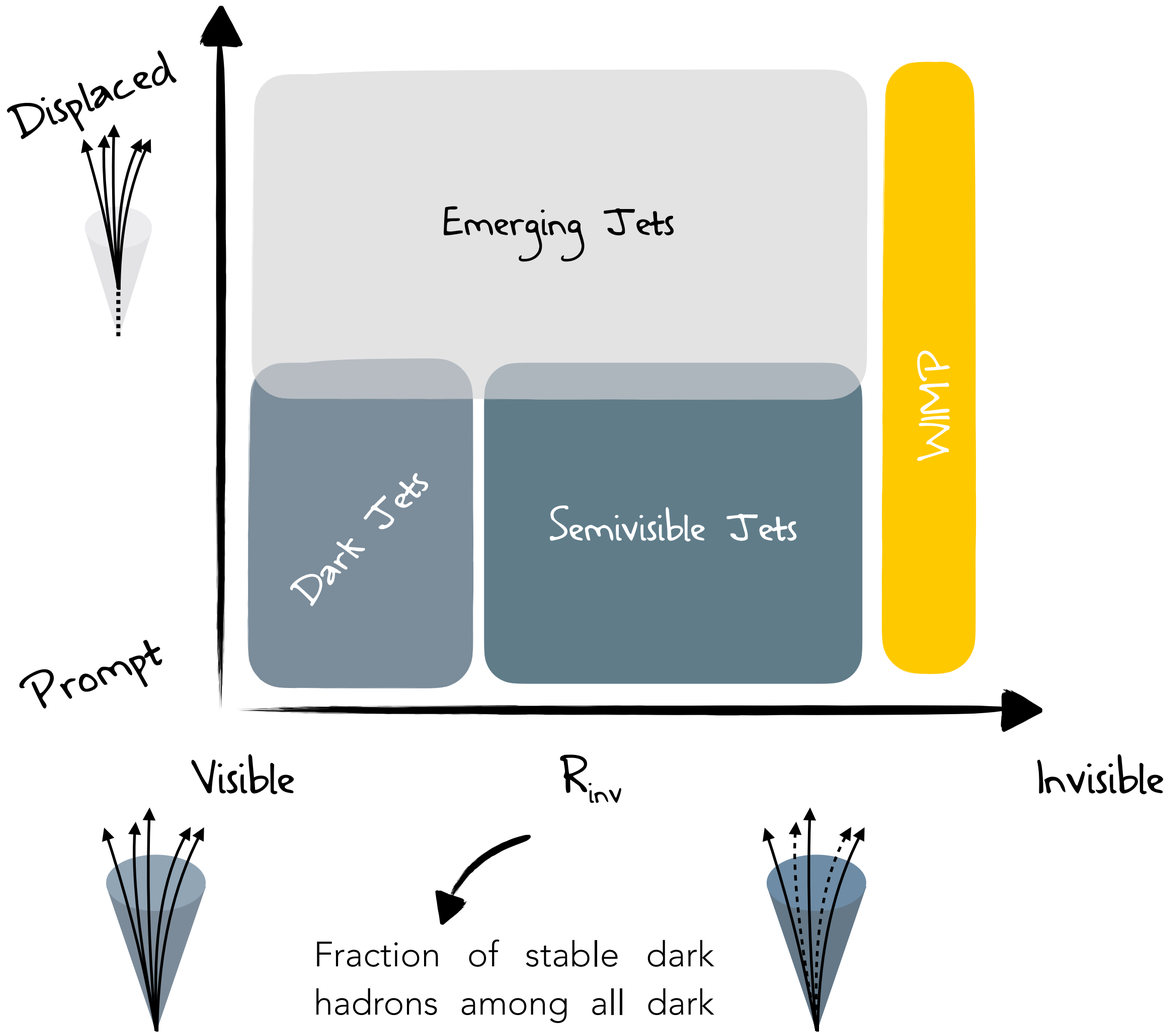


- Comparison to direct detection experiments
- Upper limits at 90% CL on the spin-independent scattering cross-section for several WIMP hypothesis

HIGG-2021-05

Dark Sector

- Models with DM existing in a hidden sector, composed of particles which don't undergo SM gauge interactions
  - ↪ May communicate with the SM via mediators, which could be DM candidates or provide portals to them
- Can also have strongly interacting dark sectors
  - ↪ Could provide dark matter candidates in the form of stable dark hadrons
  - ↪ Dark quarks form bound dark hadron states
  - ↪ Unstable dark hadrons can decay to SM quarks, others leave detector without interaction: dark or semi-visible jet
- Very wide range of signatures to look for



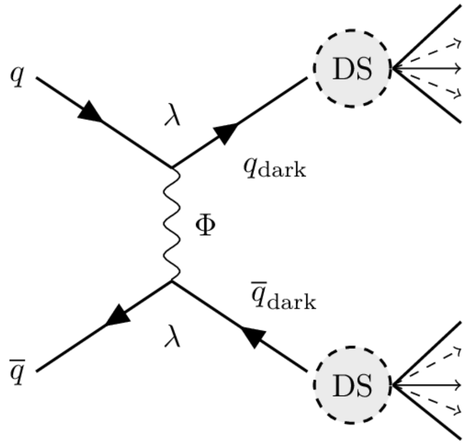
Dark Sector @ colliders

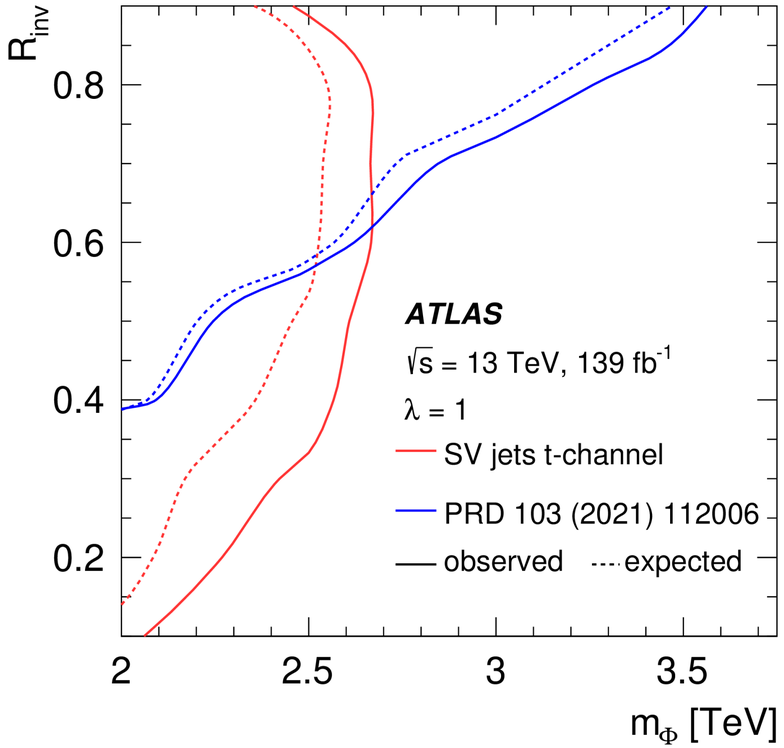
More information in Olivera's talk

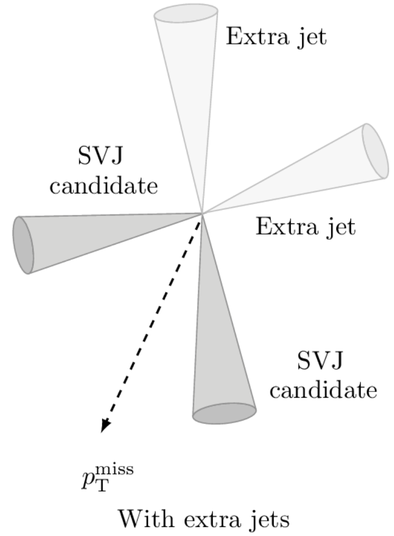
SEMIVISIBLE JETS

What happens if dark-matter particles are produced inside a jet of Standard-Model particles?

- Semi-visible jets (SVJ), with a significant contribution to the event's missing pT, can arise in strongly interacting dark sectors
- This results in an event topology where one of the jets can be aligned with the direction of the missing pT
- Search for semi-visible jets produced via a -channel mediator exchange Φ
  - ↪ Unknown coupling λ
- The search is more sensitive at intermediate values of the invisible fraction Rinv





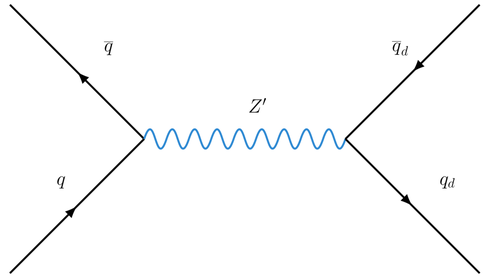


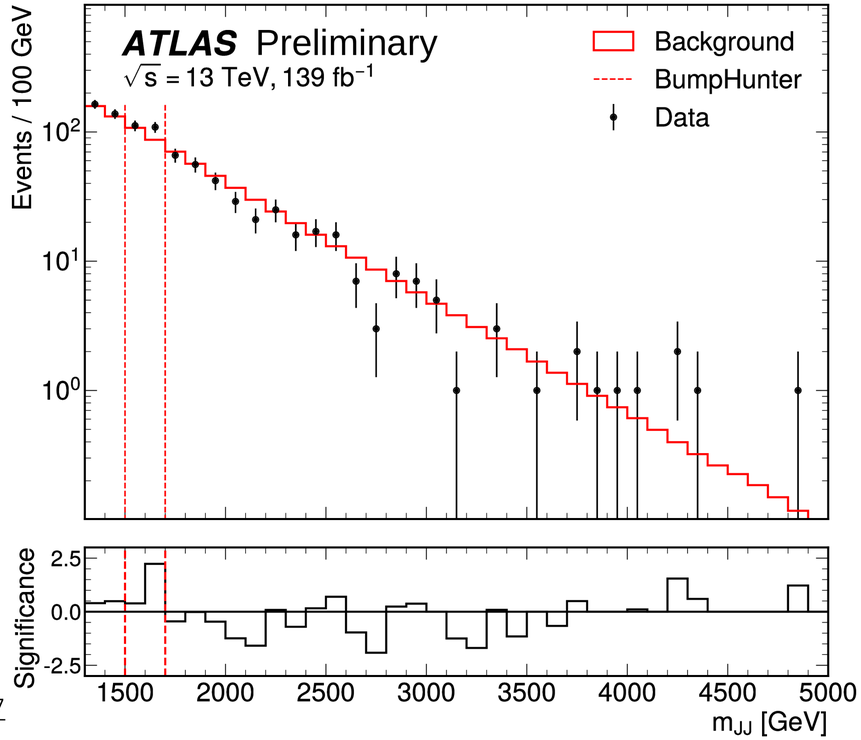
EXOT-2022-37

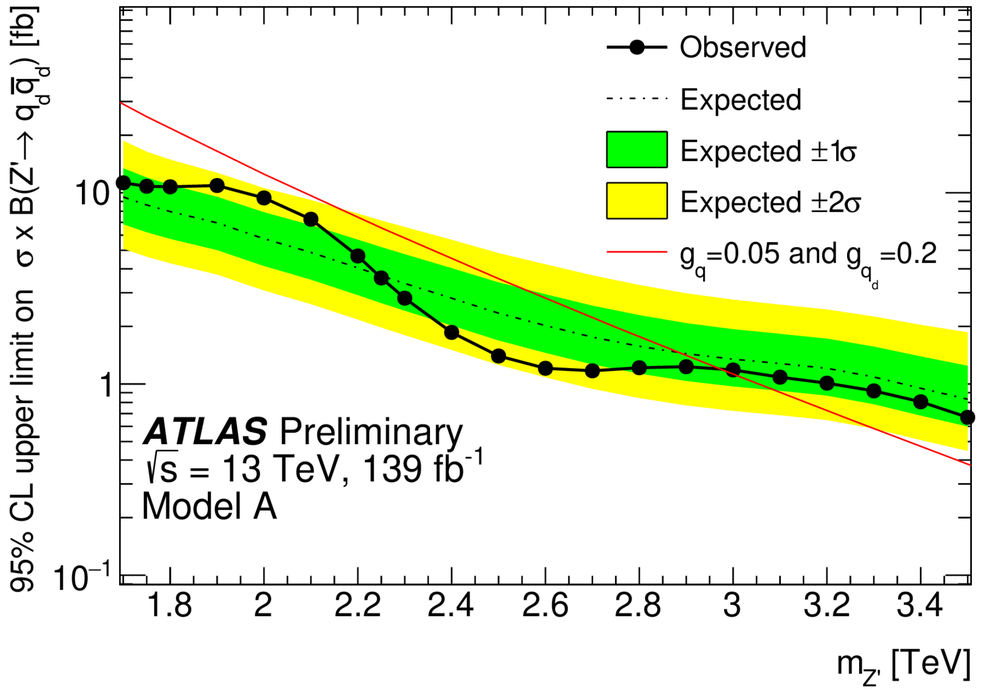
DARK JETS

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

- Dark hadrons are assumed to decay promptly into SM particles
  - ↪ complementary part of the parameter space with respect to semi-visible jet and emerging jet searches
- Dark jets wider than the SM QCD jets
  - ↪ higher charged-particle multiplicity due to the different fragmentation in the dark sector models considered, which is exploited to increase the signal-to-background ratio.
- Looks for a resonant excess above a smooth background in the di-jet invariant mass distribution





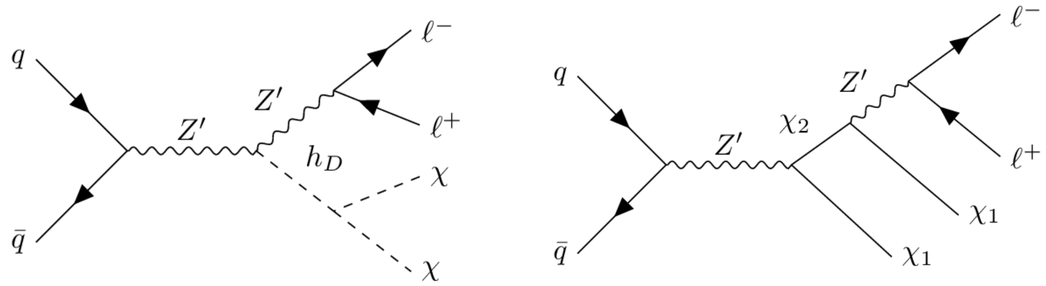


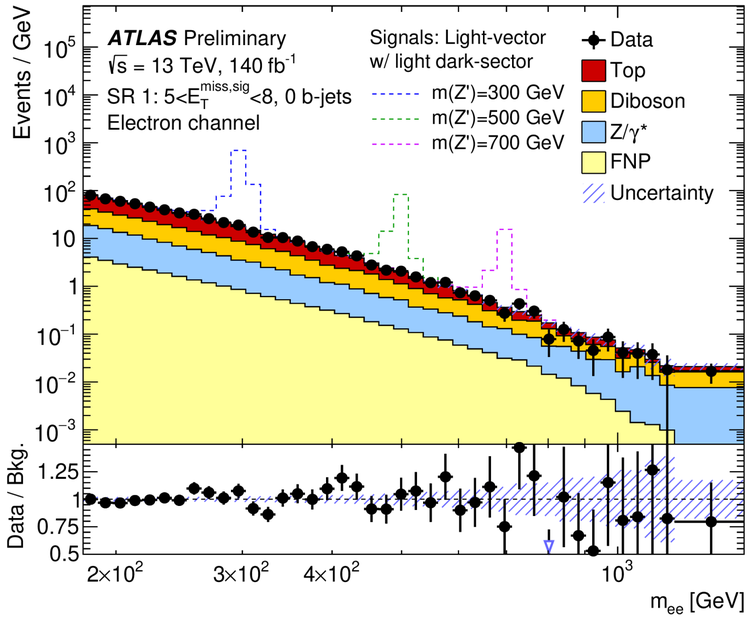
ATLAS-CONF-2023-047

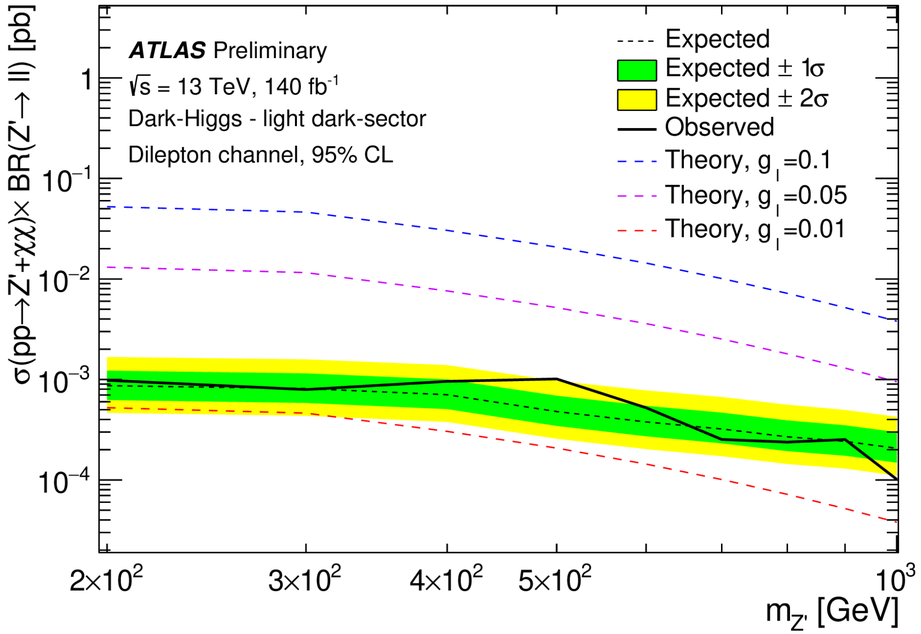
Z′ + Missing Transverse Energy

Search for resonant production of two leptons from a Z′ in association with invisible particles

- Dark Higgs model and light-vector model
  - ↪ Six free parameters in each model: 3 couplings and 3 masses
  - ↪ Test two different scenarios: light and heavy dark-sector
- Signal Regions (SR) requires a dilepton invariant mass $m_{\ell\ell} > 180$ GeV
  - ↪ SRs divided in 3 E_T^{miss} significance bins per flavor (muon/ electron)
- Cross-section and coupling limits as function on Z′ mass





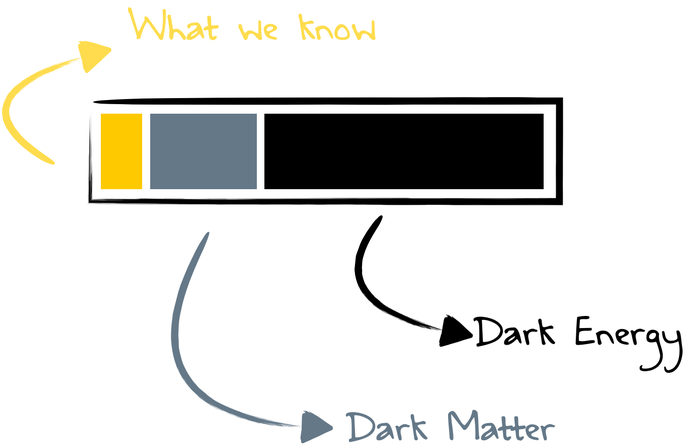


All models do not exclude lepton coupling $g_\ell = 0.01$ (fix $g_q = 0.1$ and $g_{DM} = 1$)

ATLAS-CONF-2023-045

Conclusions

- The nature of the Dark Matter remains one of the main questions in particle physics
  - ↪ Mass? Spin? Interactions?
- A plethora of models is under investigation
  - ↪ Final states with different signatures
  - ↪ Efforts to make combination
  - ↪ No excesses found: results interpreted in terms of exclusion limits
- LHC results can provide complementarity results to non-collider searches
- ATLAS has a board program of searches for Dark Matter candidates
  - ↪ Includes range of WIMP hypotheses - still many options
  - ↪ Now also many results on other options - dark photons, ALPs, dark sectors
  - ↪ Often sophisticated analyses - LHC Run-2 results still coming
  - ↪ Run-3 dataset growing fast! Many new ideas, improved techniques and new theoretical models



Backup

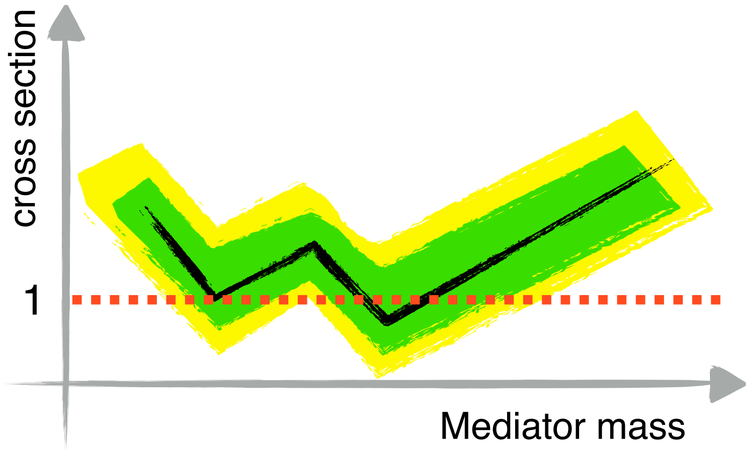
MISSING ENERGY IN ATLAS

- Missing transverse momentum p_T^{miss} represents the total transverse momentum of undetected particles produced
  - ↪ Could indicate the production of invisible particles such as Standard Model neutrinos or BSM particles that escape ATLAS undetected
  - ↪ Detector resolution/acceptance, wrong particle assignement can lead to a different p_T^{miss} reconstructed with respect to its true value
- Traditionally p_T^{miss} is calculated by negative sum of objects:
  - ↪ existing working points to meet analysis requirements but not flexible

$$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} = -\underbrace{\sum_{\text{selected electrons}} \mathbf{p}_{\mathrm{T}}^{e}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},e}} - \underbrace{\sum_{\text{accepted photons}} \mathbf{p}_{\mathrm{T}}^{\gamma}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\gamma}} - \underbrace{\sum_{\text{accepted } \tau\text{-leptons}} \mathbf{p}_{\mathrm{T}}^{\tau_{\mathrm{had}}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\tau_{\mathrm{had}}}} - \underbrace{\sum_{\text{selected muons}} \mathbf{p}_{\mathrm{T}}^{\mu}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss},\mu}} - \underbrace{\sum_{\text{accepted jets}} \mathbf{p}_{\mathrm{T}}^{\mathrm{jet}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,jet}}} - \underbrace{\sum_{\text{unused tracks}} \mathbf{p}_{\mathrm{T}}^{\mathrm{track}}}_{\mathbf{E}_{\mathrm{T}}^{\mathrm{miss,soft}}}$$

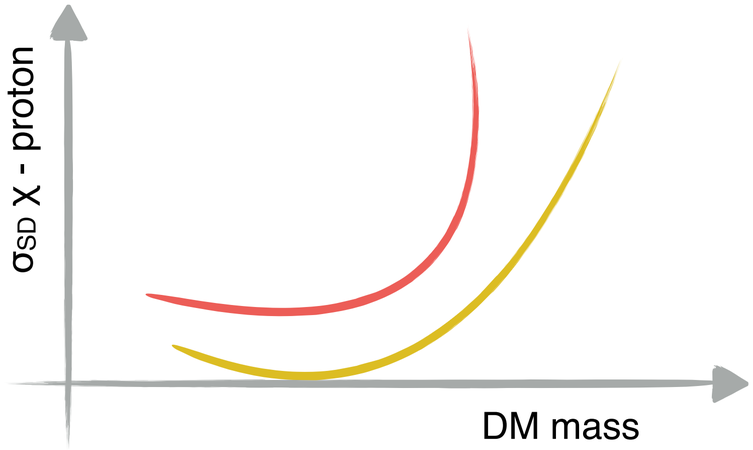
$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{hard term}} \qquad \underbrace{\qquad\qquad\qquad}_{\text{soft term}}$$

How to interpret results?



Mediator mass

- Fix couplings
- Fix DM mass
- #% C.L. on production cross section ratio of mediators

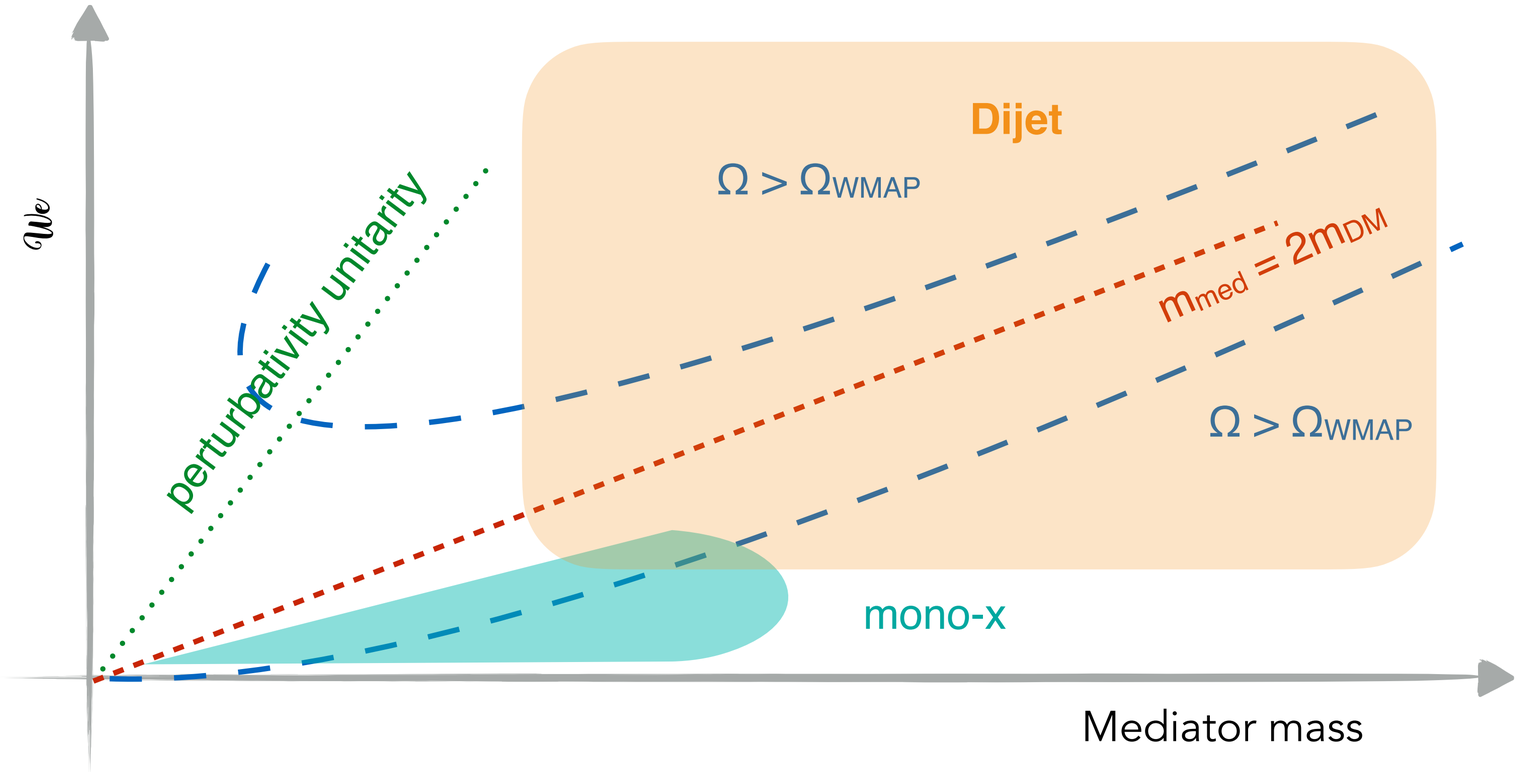


DM mass

- Fix couplings
- Limits on spin χ-nucleon cross sections at # % C.L.
- Allow to compare collider searches with other experiments

Discovery potential depends on assumed interaction and couplings

How to interpret results?



2D plane

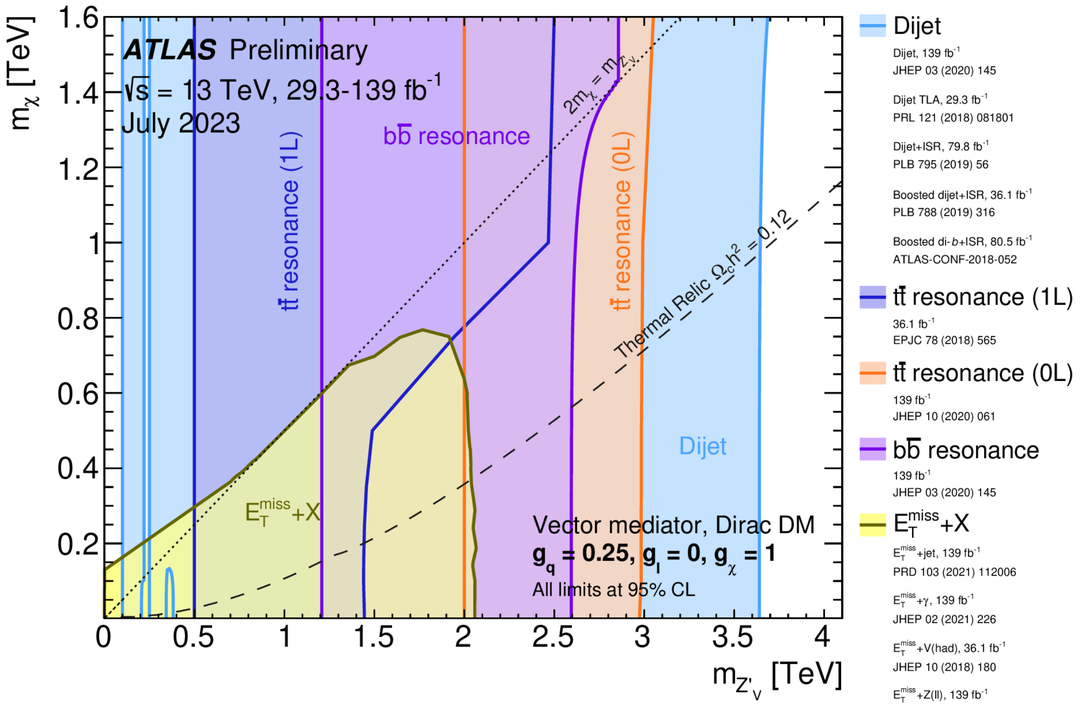
- Fix couplings
- Exclude regions in DM mass - mediator mass plane at #% C.L.

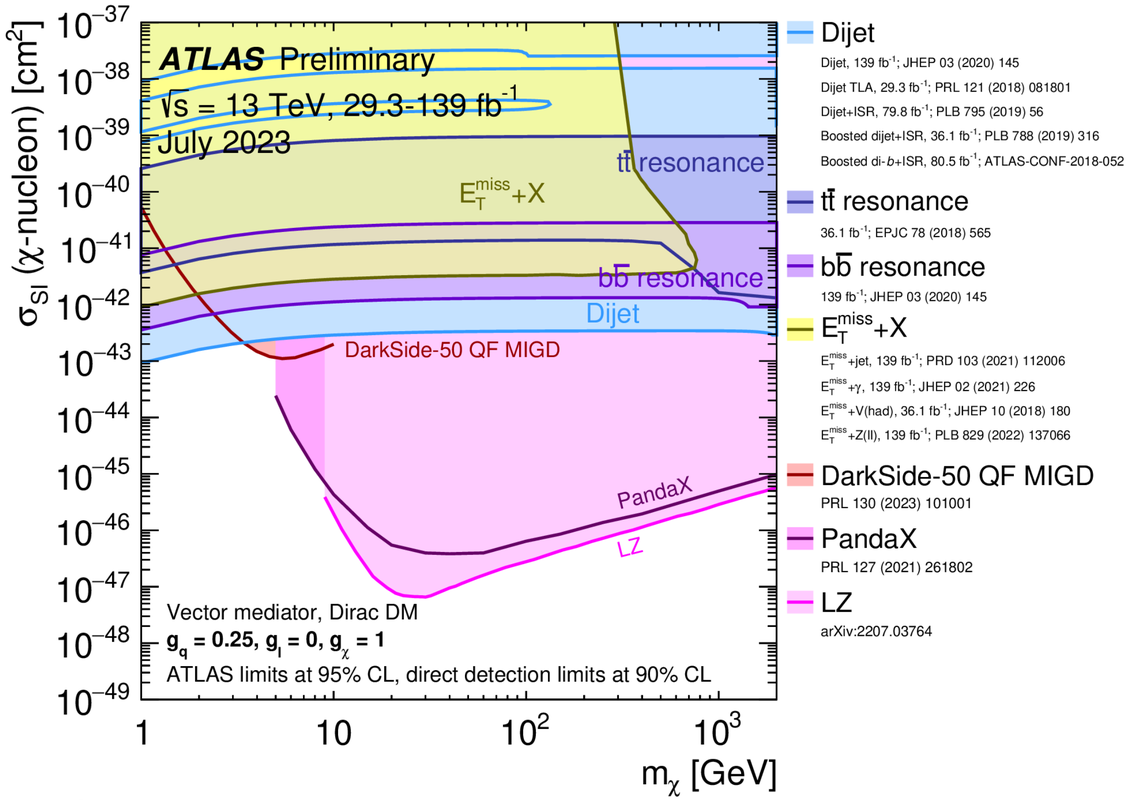
Discovery potential depends on assumed interaction and couplings

DM Simplified Models

Summary plots: Spin-1 Vector Mediators

- $E_T^{miss} + jet$ is the most sensitive channel among $E_T^{miss} + X$ searches
- Results translated into spin-independent DM-nucleon elastic scattering cross-section limits
  - ↪ Compared to direct searches
  - ↪ Competitive at low DM masses

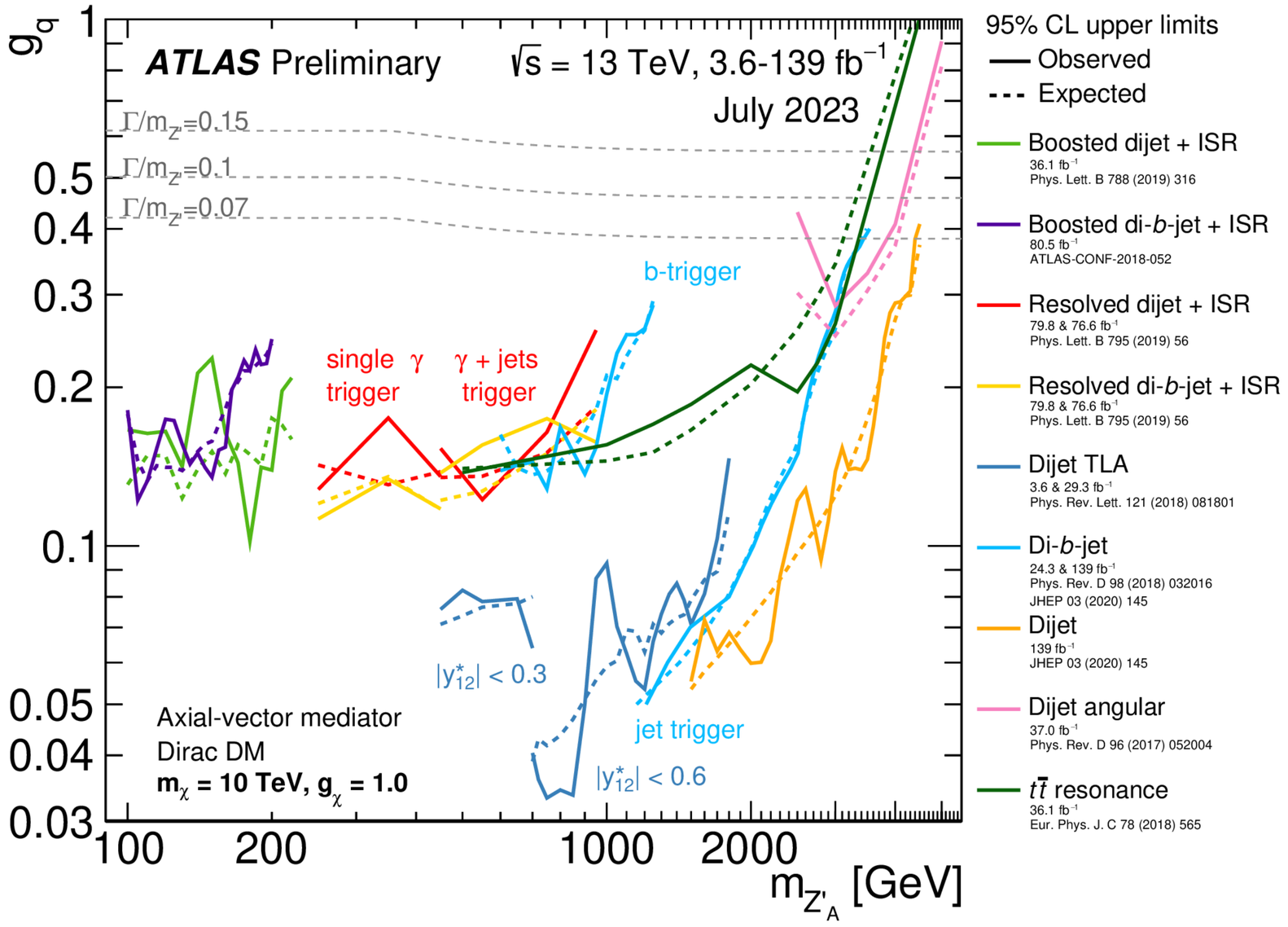




Results depend on coupling values

DM Simplified Models

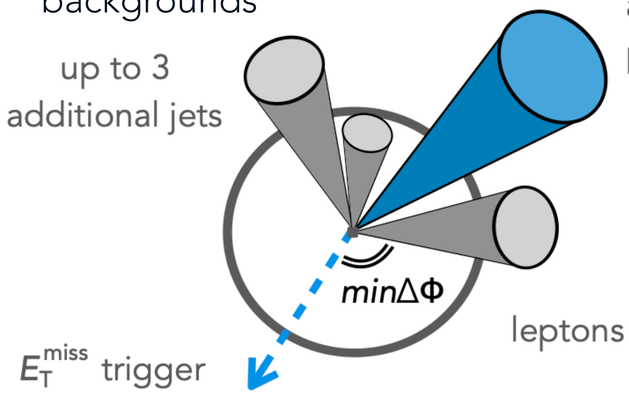
Summary plots: Spin-1 Axial-Vector Mediators

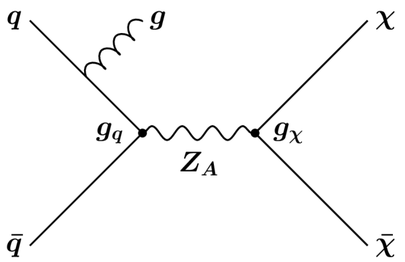


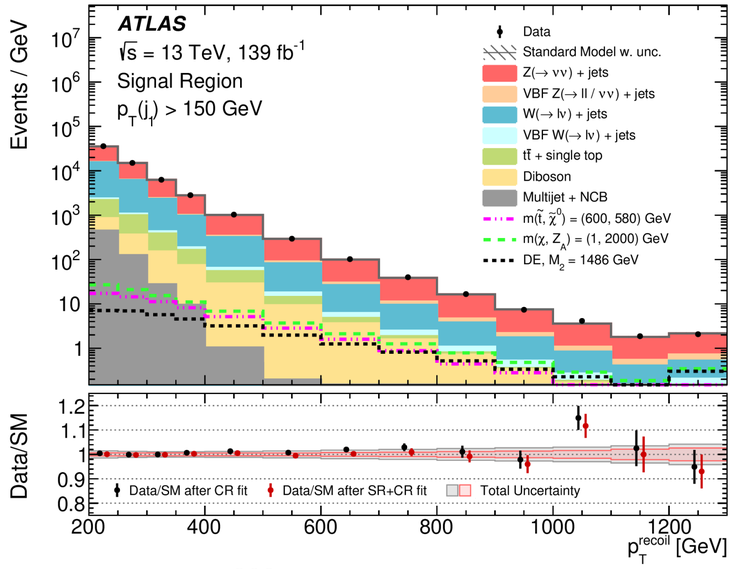
MONOJET

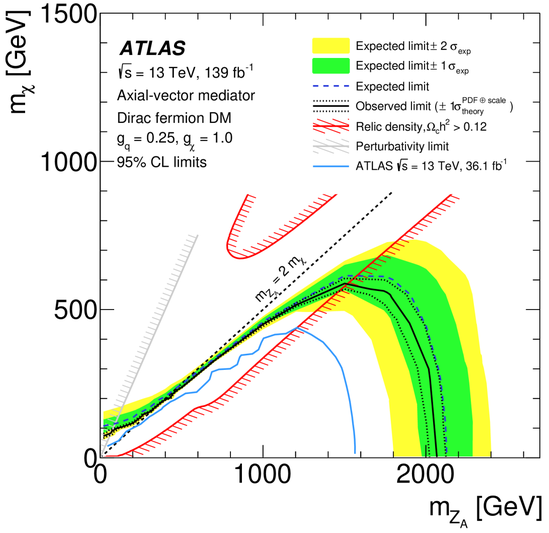
Jets and Dark Matter

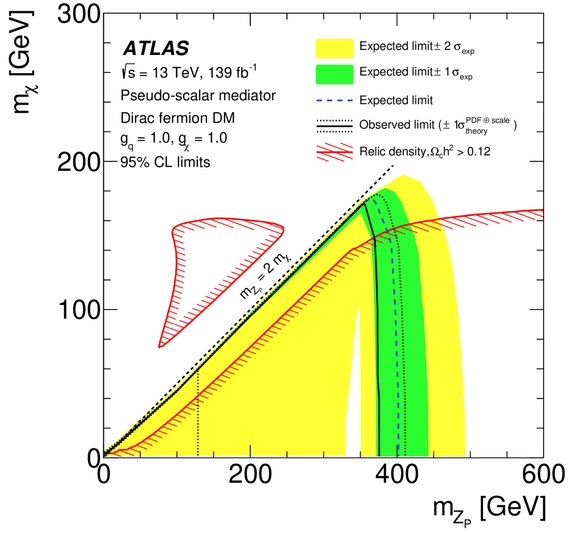
- Inclusive signature sensitive to a wide range of New Physics theories
  - ↪Dark Matter, Dark Energy, SUSY, ALPs, Large Extra Dimensions
  - ↪First time interpretation to pseudo-scalar mediators
- Most sensitive mono-X channel for ISR processes ($\alpha_s >> \alpha_{ew}$)
- Search for a MET excess
- A precision search
  - ↪total background uncertainty:1.2 and 4%
  - ↪Rely on state-of-the-art Monte Carlo generators & theoretical calculations
  - ↪data-driven estimates of QCD multijet & non-collision backgrounds









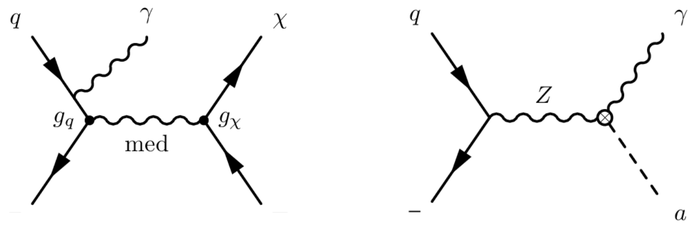


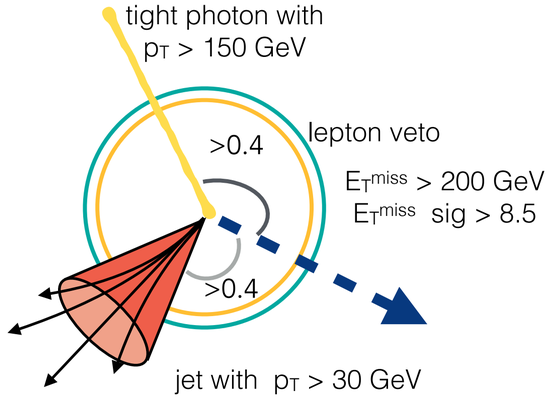
EXOT-2018-06

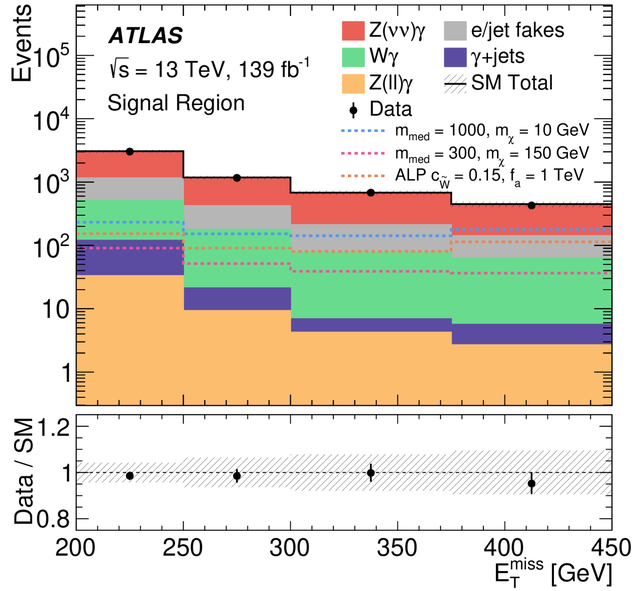
MONOPHOTON

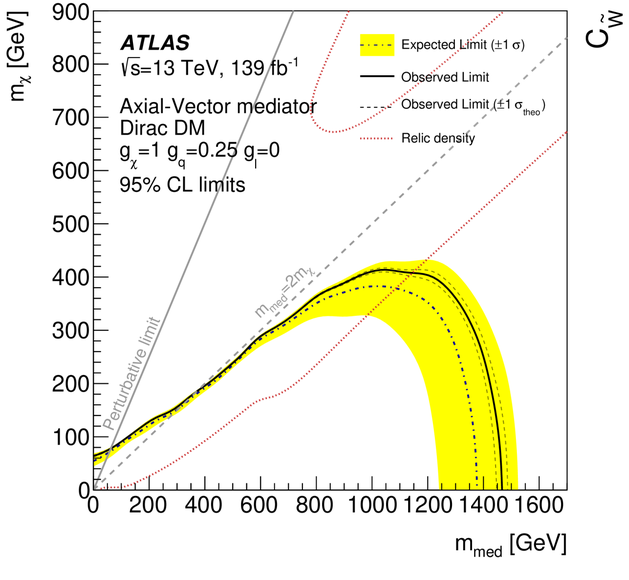
Photons and Dark Matter

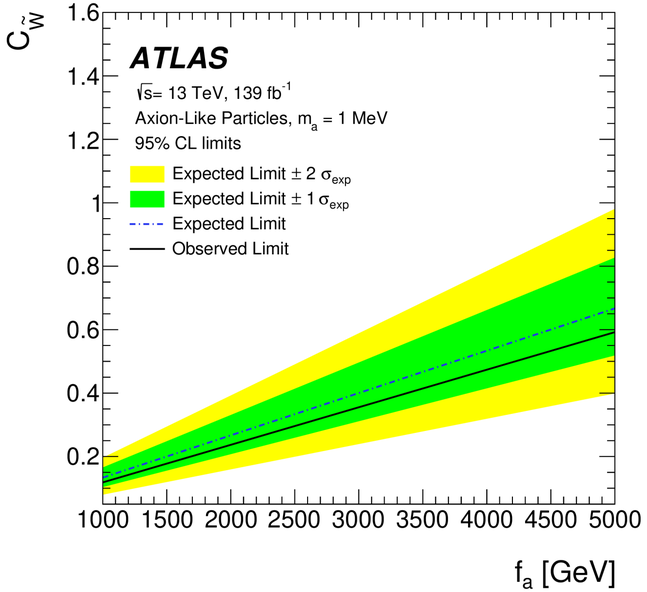
- Final state: high energy photon + MET
  - ↪Clear signature: cross check with monojet
  - ↪Test Spin-1 DM mediators
- First interpretation of model with Axion-Like Particle produced in association with a photon











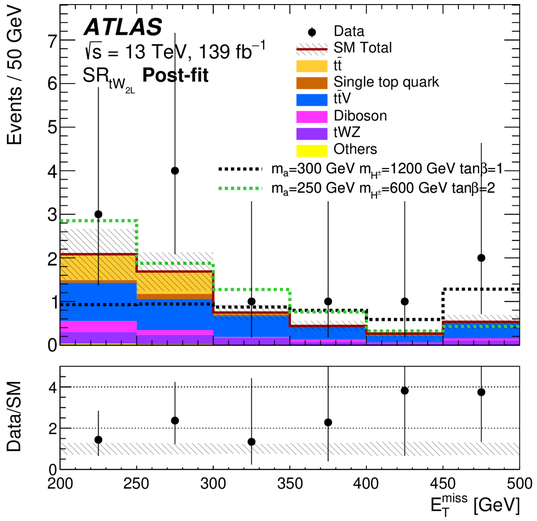
- Recasting analysis for interpretation in high mass Higgs-like resonances
  - ↪Understanding to the $H \to \gamma\gamma_d$ process in ggF production mode (still uncovered)
  - ↪More inclusive search of $H \to \gamma\gamma_d$ but also explore photon+MET resonances
  - ↪Prepare for Run 3

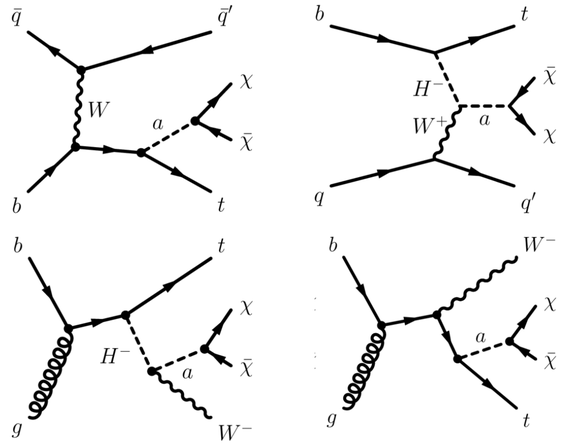
EXOT-2018-63

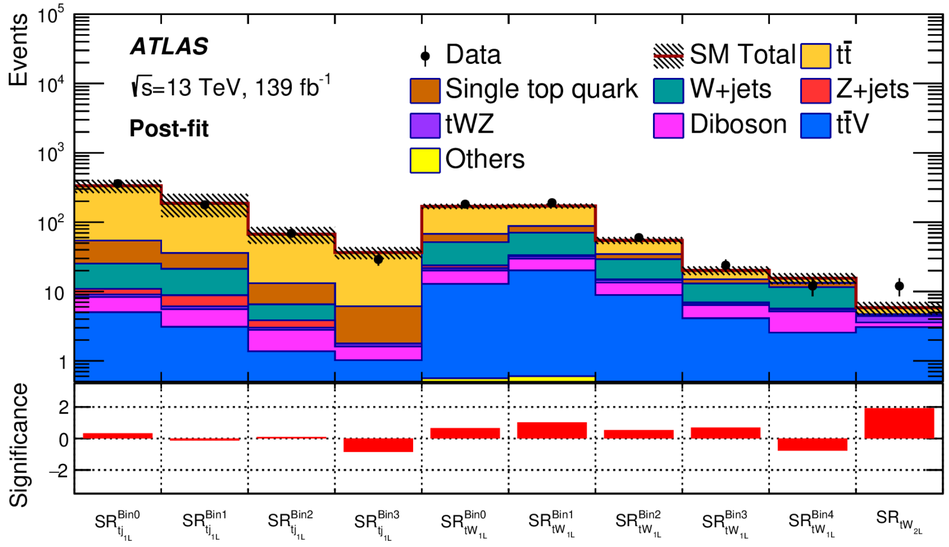
WT+MET

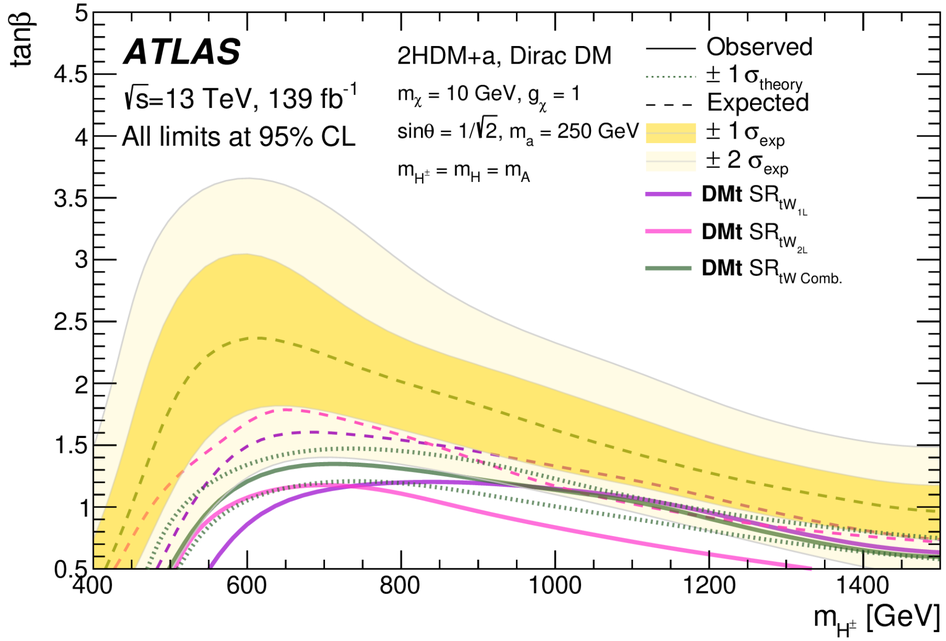
Heavy Quarks and Tops

- Test 2HDM + a model
- Two signatures:
  - ↪Important, previously uncovered signature!
  - ↪ tW+MET: cut based SRs 1L (MET fitted) & 2L (single bin)
  - ↪ tj+MET: 1L, BDT classifier (fitted variable)
- Results reinterpreted in the context of s-channel DM analysis (in the next slides)







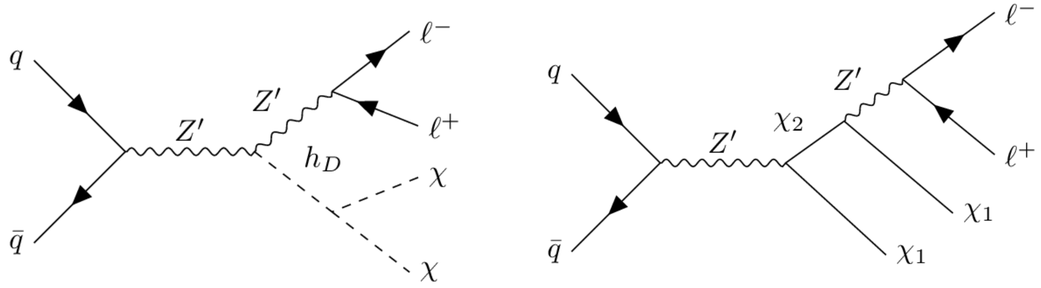


EXOT-2018-43

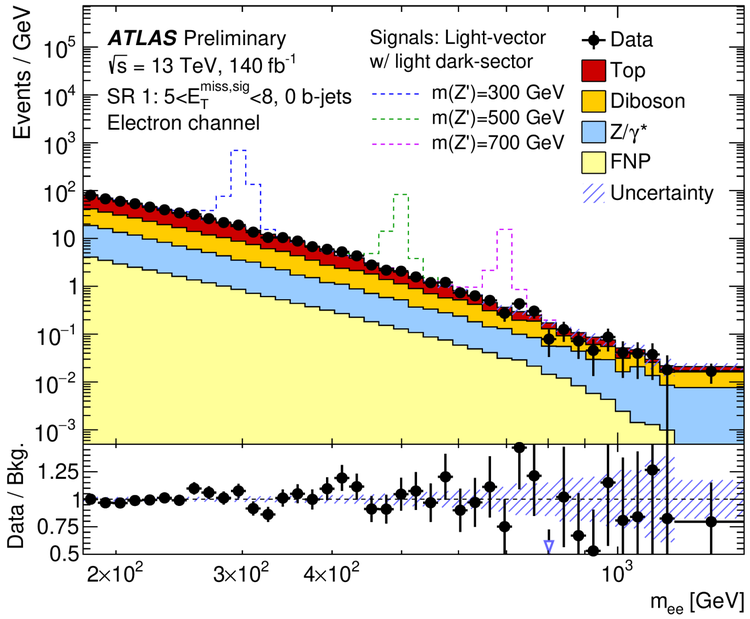
Z′ + Missing Transverse Energy

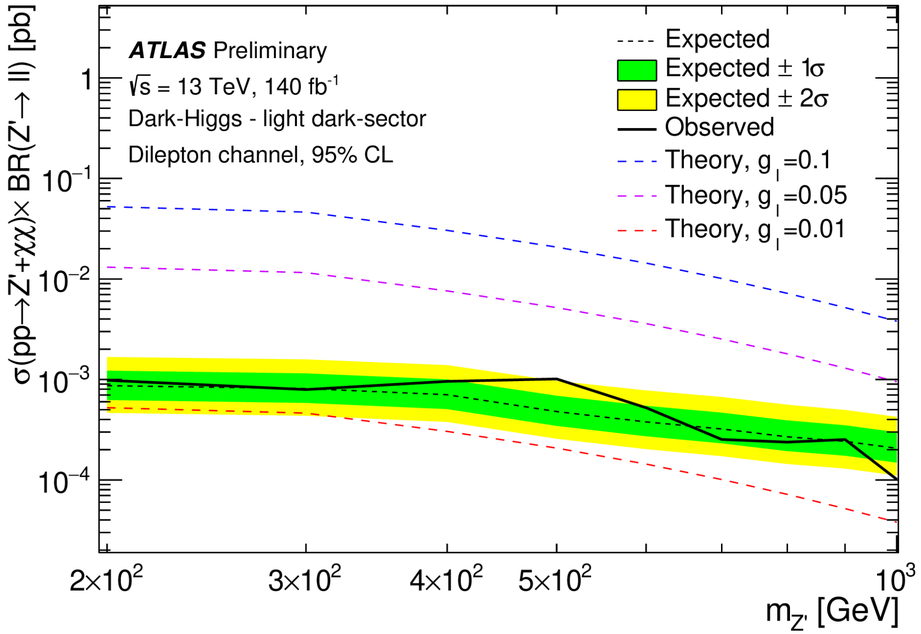
Search for resonant production of two leptons from a Z′ in association with invisible particles

- Dark Higgs model and light-vector model
  - ↪ Six free parameters in each model: 3 couplings and 3 masses
  - ↪ Test two different scenarios: light and heavy dark-sector
- Signal Regions (SR) requires a dilepton invariant mass $m_{\ell\ell} > 180$ GeV
  - ↪ SRs divided in 3 E_T^{miss} significance bins per flavor (muon/ electron)
- Cross-section and coupling limits as function on Z′ mass



	Dark Higgs	Light Vector
Light dark-sector	$m_\chi = 5$ GeV	$m_{\chi_1} = 5$ GeV
	$m_{h_D} = 125$ GeV	$m_{\chi_2} = m_{\chi_1} + m_{Z'} + 25$ GeV
Heavy dark-sector	$m_\chi = 5$ GeV	$m_{\chi_1} = m_{Z'}/2$
	$m_{h_D} = m_{Z'}$	$m_{\chi_2} = 2m_{Z'}$





All models do not exclude lepton coupling $g_\ell = 0.01$ (fix $g_q = 0.1$ and $g_{DM} = 1$)

ATLAS-CONF-2023-045

MONO-X ANALYSIS STRATEGY

①Definition of a set of **signal region**(s) **(SR)**

↪Find the best cuts to optimize signal over background

②Definition of a set of **control regions (CR)** to estimate backgrounds

↪Define a region with a high purity of a specific background

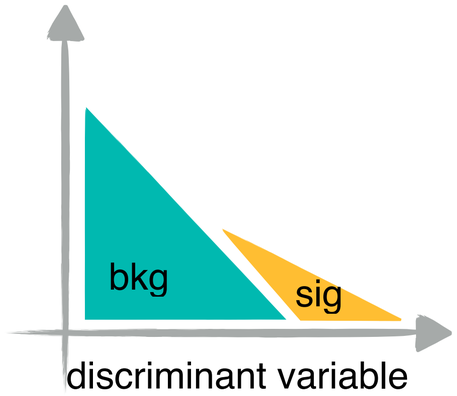
↪Control background from data

↪Extrapolation of **transfer factors (TF)** using a fit technique

↪Rescale Monte Carlo predictions in SR

③Validation of the TF in **validation regions (VR)**

↪Control and test the background estimation technique



④Unblinding ➜ Is there an excess?

⑤If no excess is found the results are interpreted in terms of **limits** on models under study

↪Generate a wide grid of simplified models to exclude a large phase space

DM Simplified Models

New $E_T^{miss} + t\bar{t}$ analysis

- 1 lepton channel analysis
- New analysis approach developed to achieve higher sensitivity by classifying events with neural networks
  - Jet 4-momenta as inputs
- Plan to include in the new $E_T^{miss} + t\bar{t}$ combination

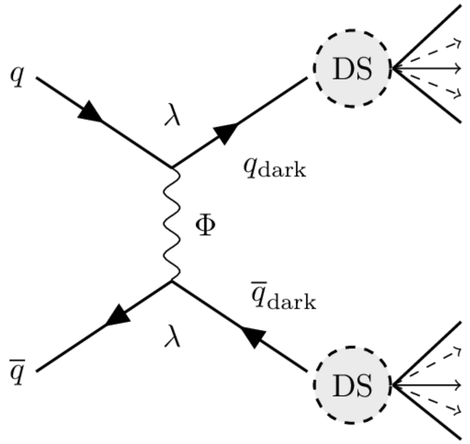
Analysis Category	High-E_T^{miss}		Boosted					
	1b	2b	1b-lep-0t	1b-had-0t	2b-0t	1b-lep-1t	1b-had-1t	2b-1t
N(LR jet)	0		≥ 1					
N(top-tagged LR jet)	-		0			≥ 1		
$N_{b-\text{jet}}$ with $\Delta R(b, \text{LR jet}) < 1.1$	-		0	≥ 1	≥ 1	0	≥ 1	≥ 1
$N_{b-\text{jet}}$ with $\Delta R(b, \text{LR jet}) > 1.1$	-		≥ 1	0	≥ 1	≥ 1	0	≥ 1
top-NN-tagged multiplet	✓		-					
$N_{b-\text{jet}}$	1	≥ 2	-					
$N_{\text{light-jet}}$	≥ 2	≥ 1	-					
top_{had} candidate	top-NN multiplet		LR jet					
top_{lep} candidate	$\ell + \text{j}$	$\ell + b$	$\ell + b$	$\ell(+\text{j})$	$\ell + b$	$\ell + b$	$\ell(+\text{j})$	$\ell + b$
Event NN selection	See Table 3							

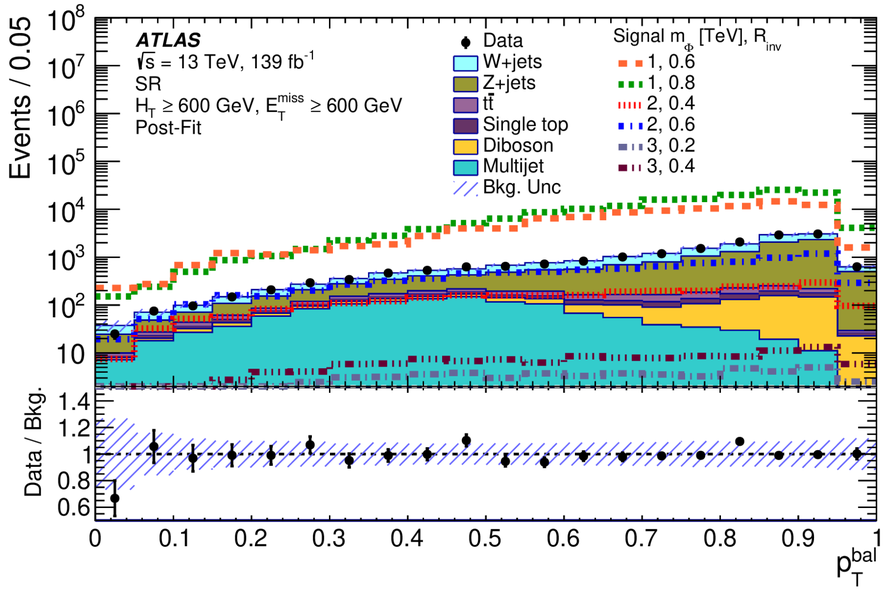
ATLAS-CONF-2023-043

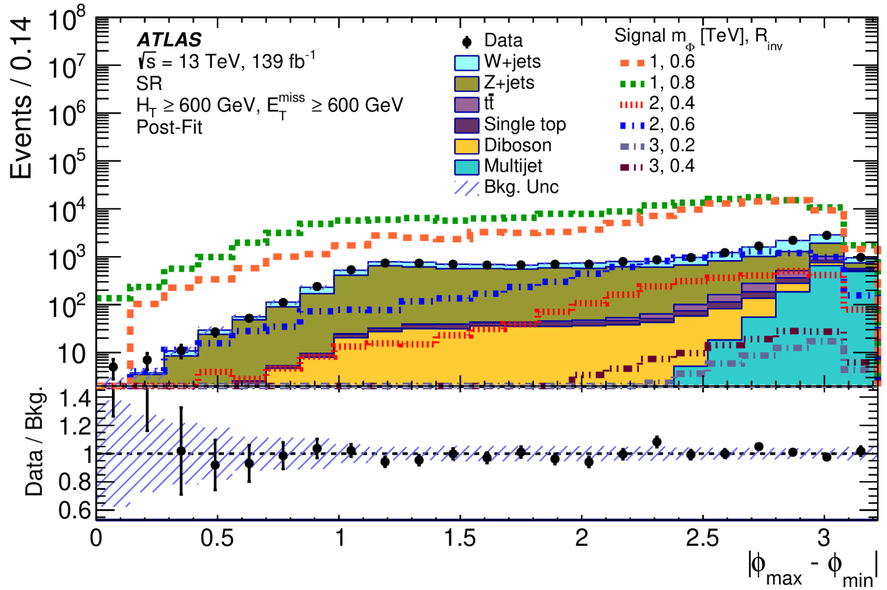
SEMIVISIBLE JETS

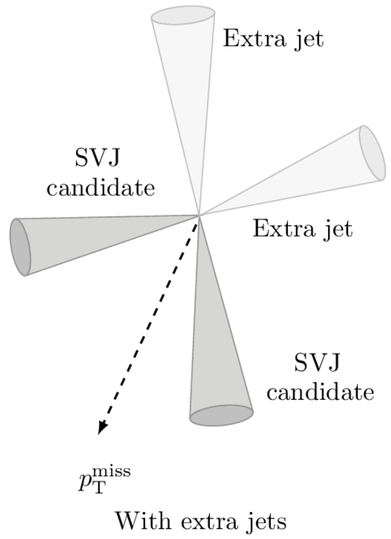
What happens if dark-matter particles are produced inside a jet of Standard-Model particles?

- 2 central jets, leading jet pT > 250 GeV, ETmiss > 600 GeV, jet closest to ETmiss with $\Delta\phi < 2$, HT > 600 GeV
- Backgrounds estimated in dedicated control regions defined with a muon(s): W+jets (1 muon and 0 b-jet), top (1 muon and 1 b-jet), and Z+jets (2 muons and 0 b-jet)
- Signal region binned using two sensitive variables: pt imbalance and azimuthal separation between selected jets







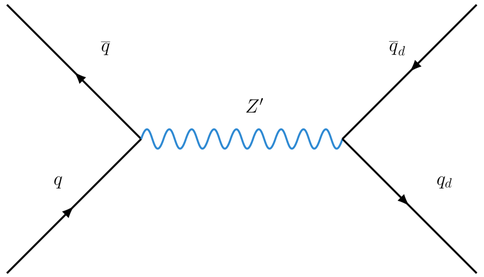


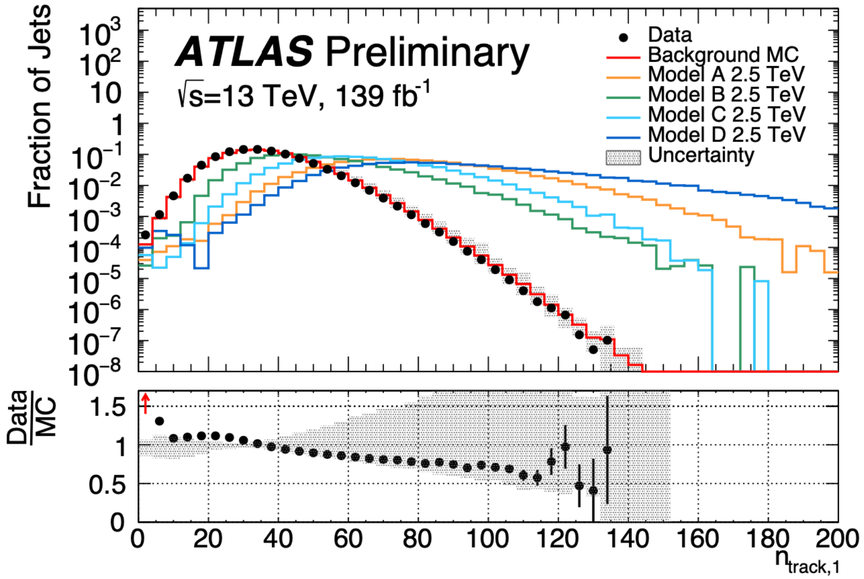
EXOT-2022-37

DARK JETS

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

- Dark hadrons are assumed to decay promptly into SM particles
  - ↪ complementary part of the parameter space with respect to semi-visible jet and emerging jet searches
- Dark jets wider than the SM QCD jets
  - ↪ higher charged-particle multiplicity due to the different fragmentation in the dark sector models considered, which is exploited to increase the signal-to-background ratio.
- Looks for a resonant excess above a smooth background in the di-jet invariant mass distribution





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