Dark sector searches in ATLAS (The past, present and the future...)

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TAU - UoM workshop
27/03/2023

The big picture!

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

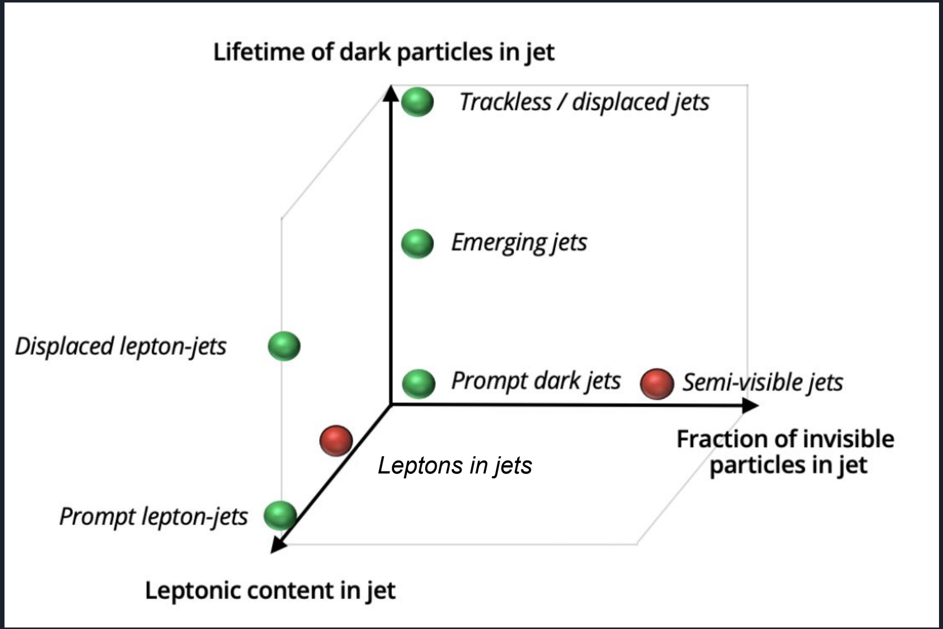
Looking at unusual topologies and hidden corners of the phase space

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

Dark hadrons decaying PROMPTLY in a QCD-like fashion, fully (dark jets)

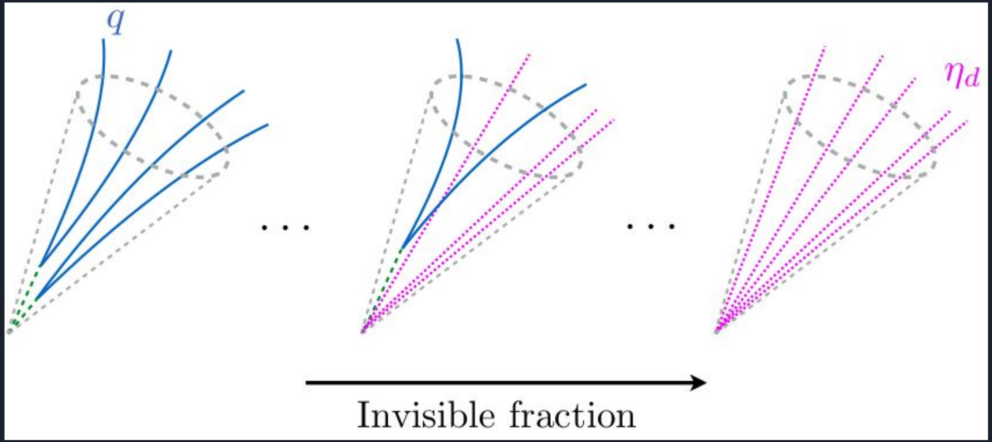
or partially back to visible sector (semi-visible jets)

Dark hadrons undergoing DISPLACED decays in a QCD-like fashion (emerging jets)



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

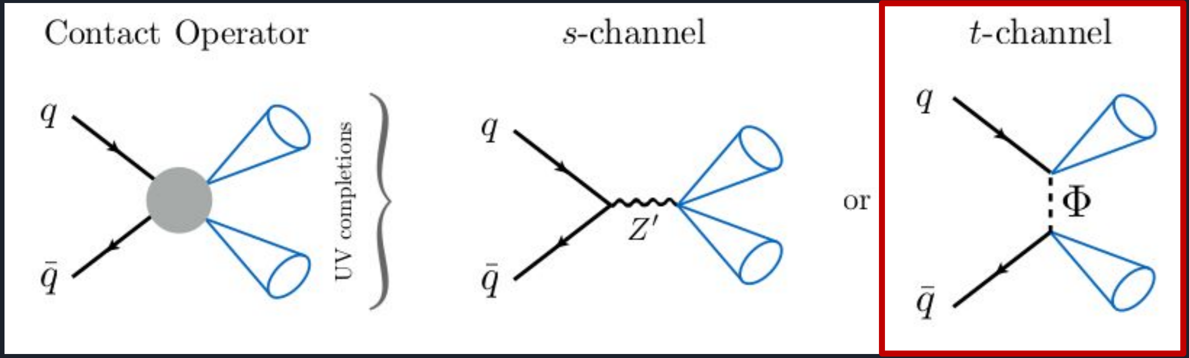
Semi-visible jet production

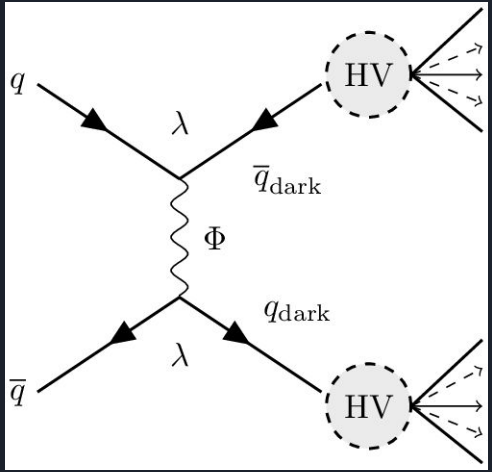


Model Parameters:

1. M_ϕ = Mass of Scalar Bi - fundamental
2. r_{inv} = no. of stable invisible hadrons/ no. of hadrons
3. M_d = Mass of dark hadrons
4. **λ** = q - ϕ - q_d coupling strength

Link to the paper: https://arxiv.org/abs/1707.05326

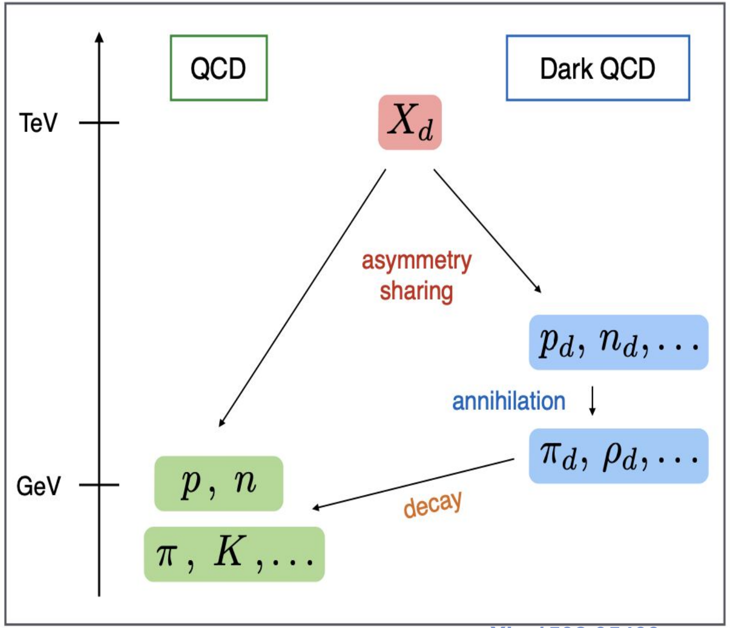




Pythia 8 Hidden Valley Module

Different dark quark flavours

- Combine to form π^+, π^-, π^0, and ρ^+, ρ^-, ρ^0 (assumed to be produced thrice as much as pions)
- Only ρ^0 is 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



arXiv:1502.05409

Signal xs usually very low compared to BG → More of a topology generator rather than full-blown theory model

Decay chains are rather complex and the showering model is still being developed by the theory community

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.

Analysis in a nutshell

TRIGGER

↓

OBJECT & EVENT SELECTION

↓

SELECTION OPTIMISATION

↓

DECIDE CONTROL / VALIDATION / SIGNAL REGIONS

Blinded!

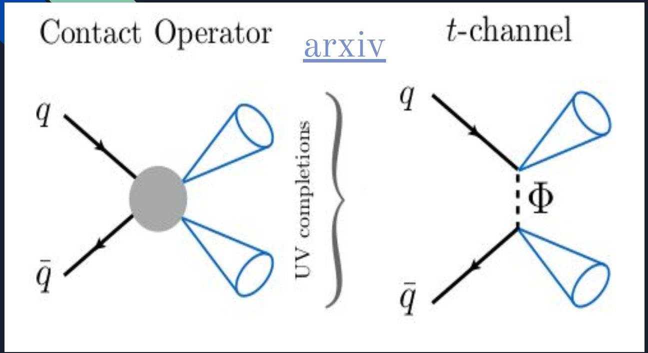
↓

INCLUDE SYSTEMATIC UNCERTAINTIES

↓

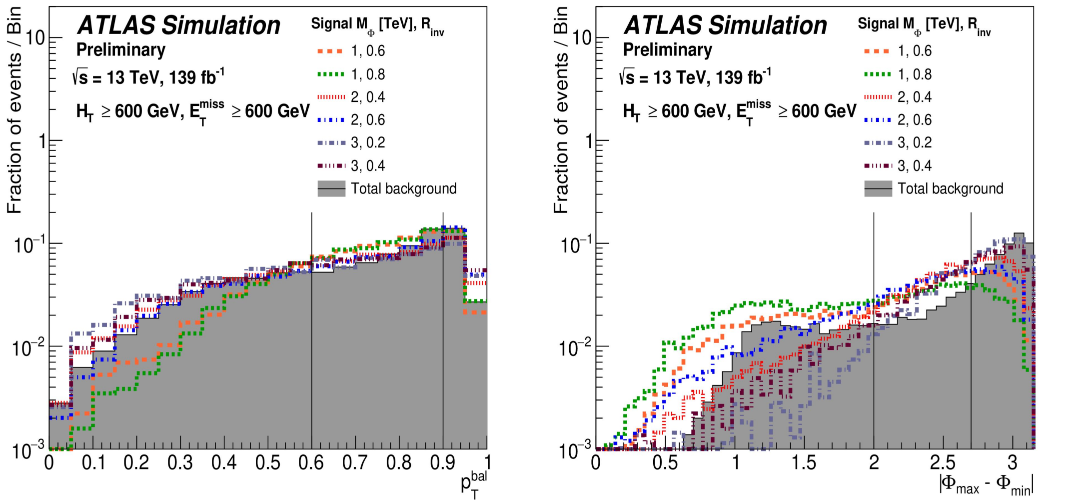
CHECK WHAT THE DATA TELLS US!

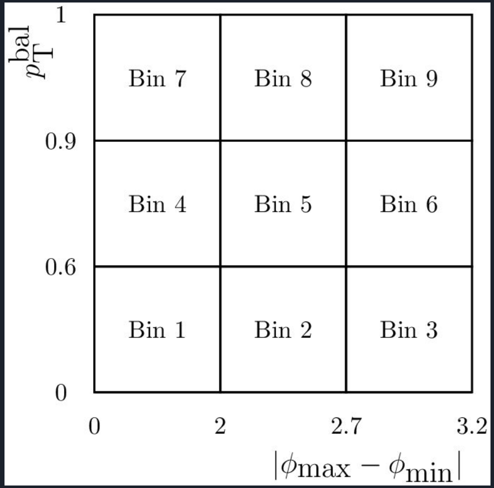
ATLAS Semi-visible jets t - channel



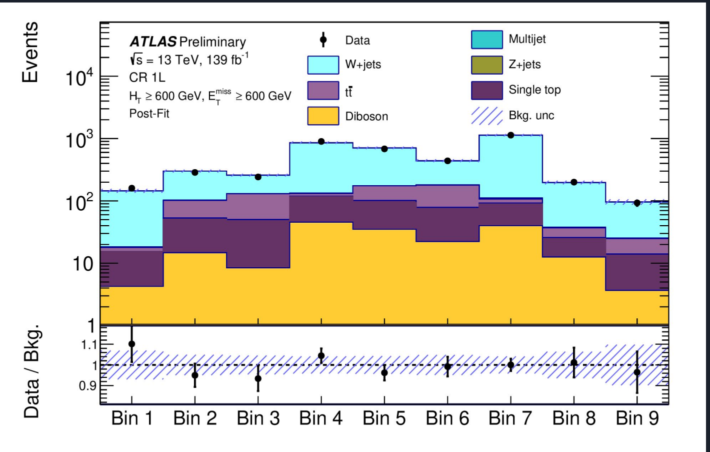
ANALYSIS STRATEGY

1. Minimal requirements, two akT R=0.4 jets, MET > 200 GeV, Δϕ (closest jet, MET) < 2.0, no tau-jets or leptons
2. Two sensitive variables: p_T balance for svj & antisvj, max-min phi
3. Binning in SR (MET > 600 GeV, H_T > 600 GeV) and corresponding CRs based on p_T balance and max-min phi



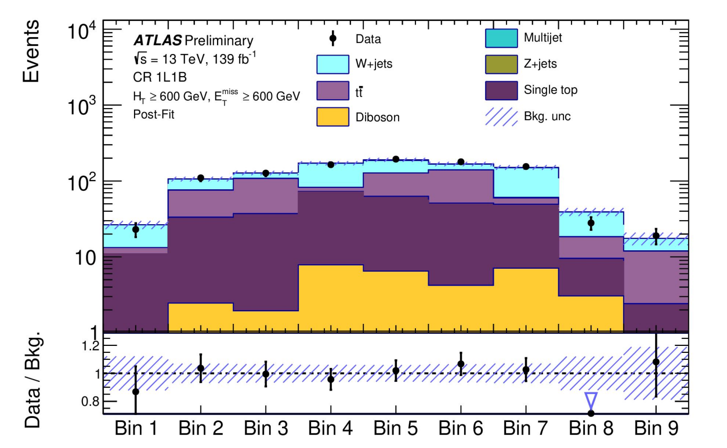


Fit Strategy & 9-bin histograms - CR

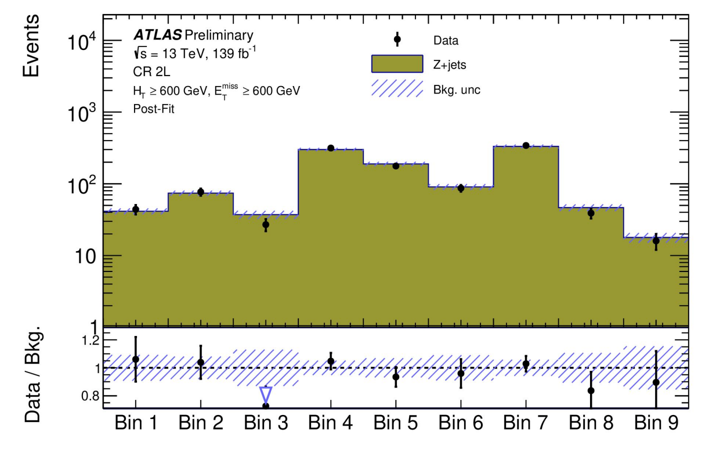


CR 1Lepton: used to control W+jets / single top background contributions

CR 1Lepton 1B-jet: used to control ttbar / single top background contributions



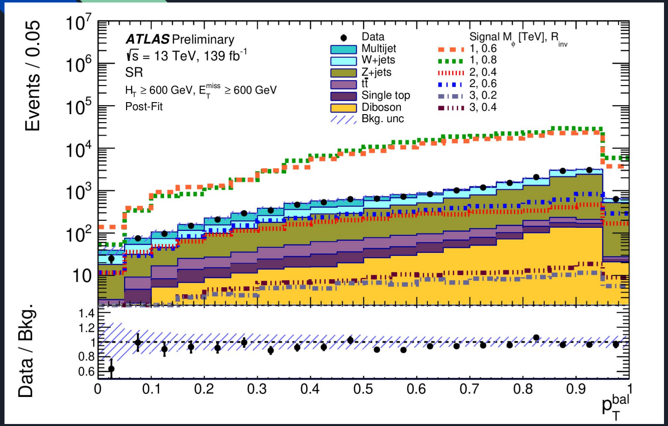
CR 2Leptons:
used to control Z+jets background contributions

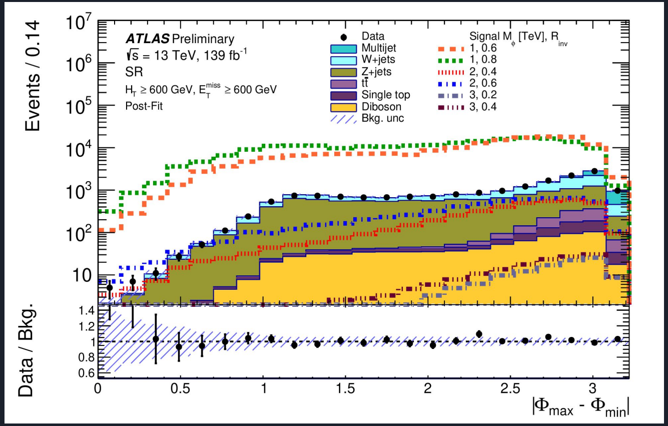


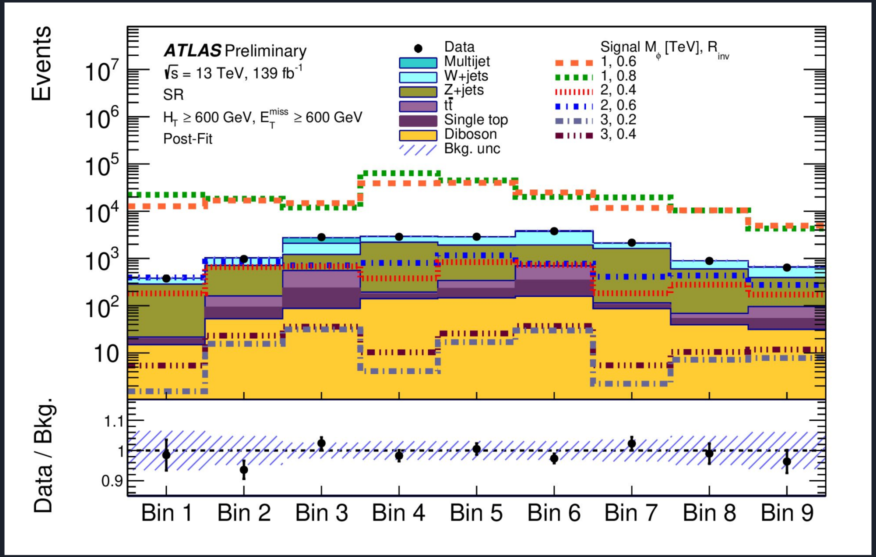
Simultaneous maximum likelihood function fit performed using the product of all relevant Gaussian and Poisson PDFs and 9-bin yields, using MC templates, with dedicated theoretical and experimental systematic uncertainties for 0L SR, 1L CR, 1L1B CR, 2L CR (details in backup)

Results...

9-bin & Kinematic distributions - SR







We haven't found new physics :-(Excellent agreement between data and estimated background…

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%.

Why care about setting limits?

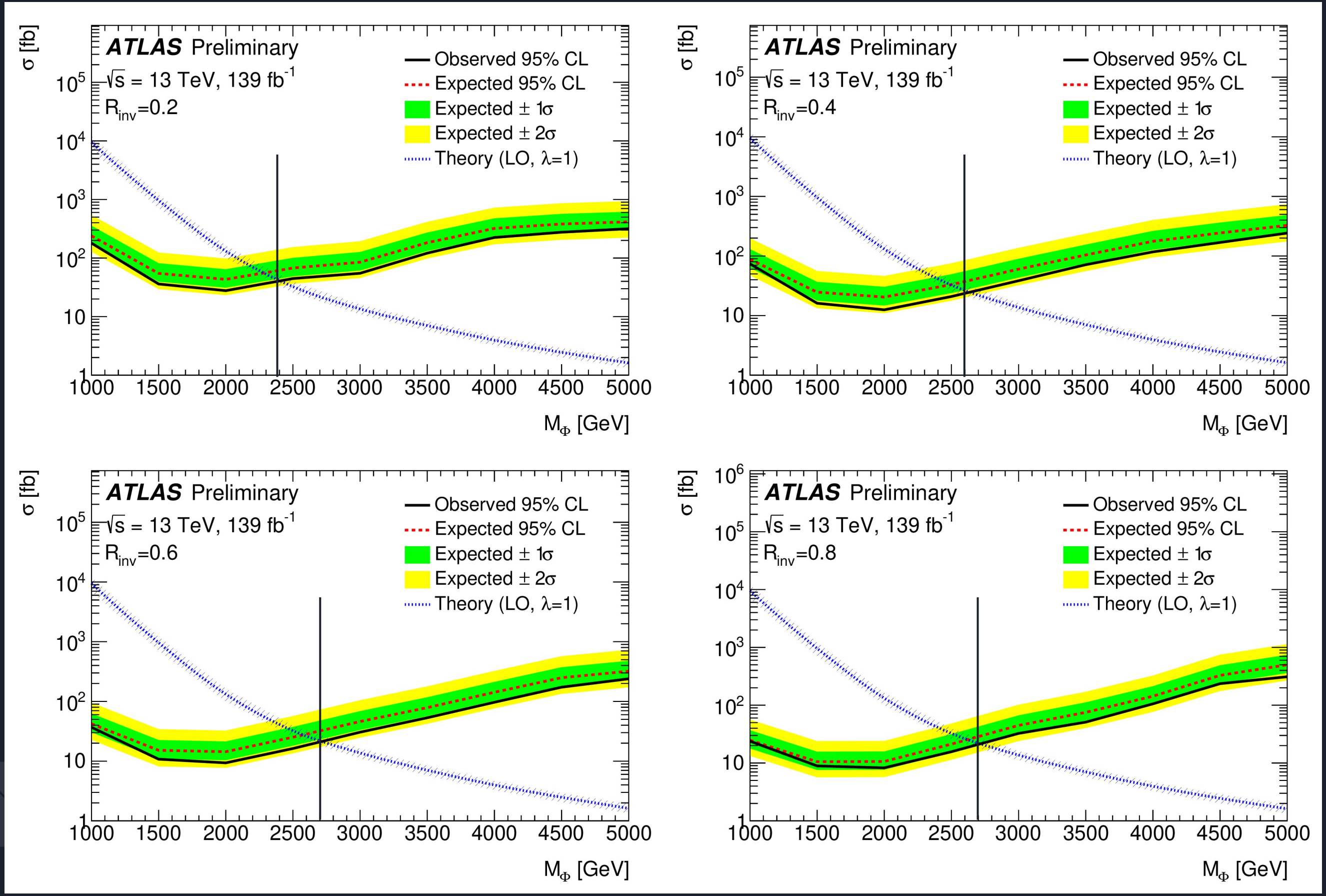
We all want to find new physics.

But out of 100 new physics models, at least 99 are wrong, possibly all 100 are!

So null results → narrows down the phase space where new physics might exist…

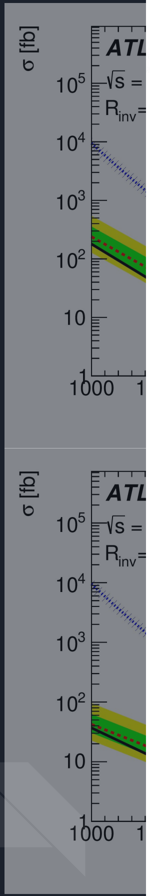
And techniques/methods developed can help in a future discovery!

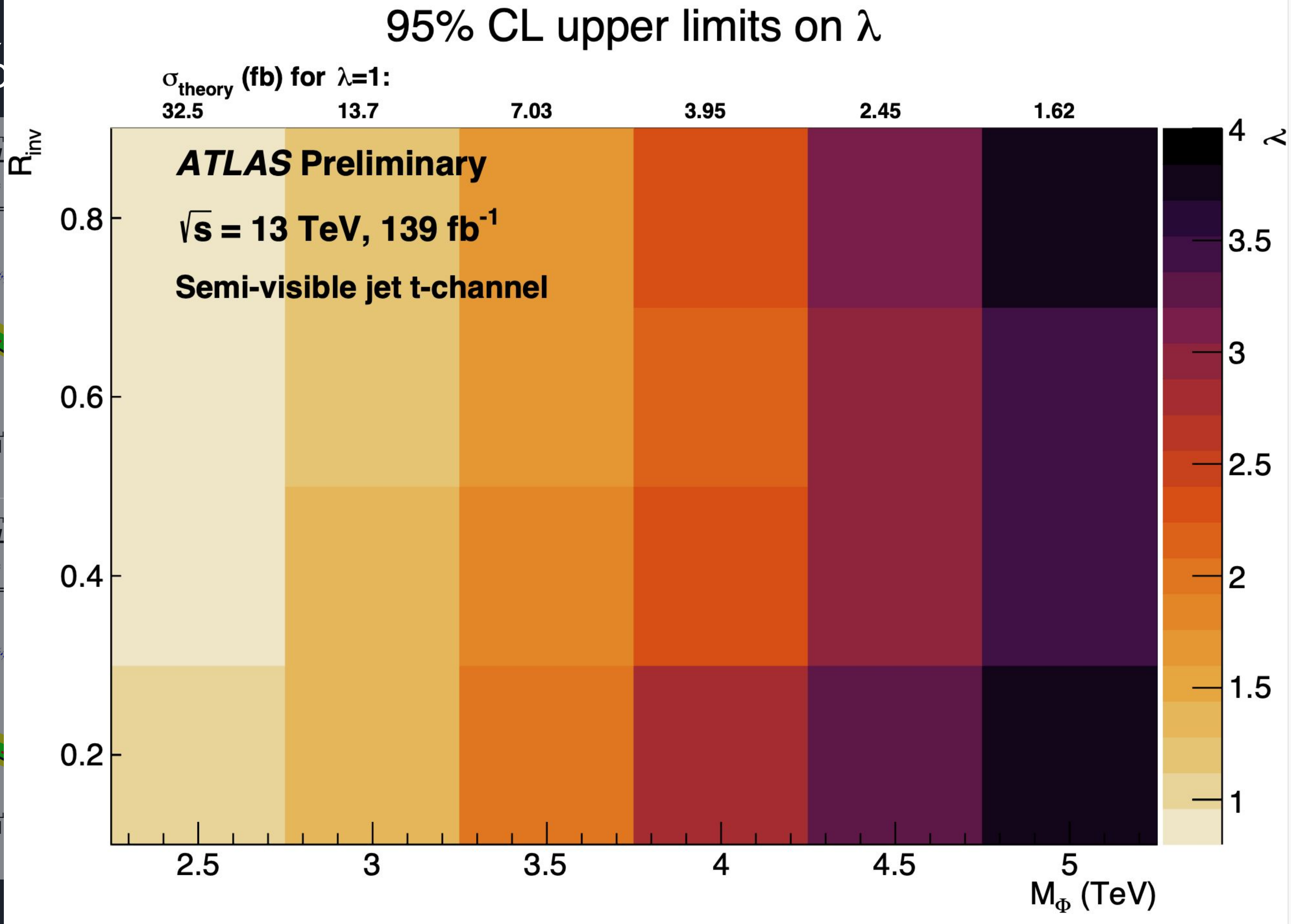
95% CL Limits on mediator mass



Assuming unity coupling between q - ϕ - q_d, can exclude mediator masses upto 2.7 TeV, subject to values of R_{inv}

95%





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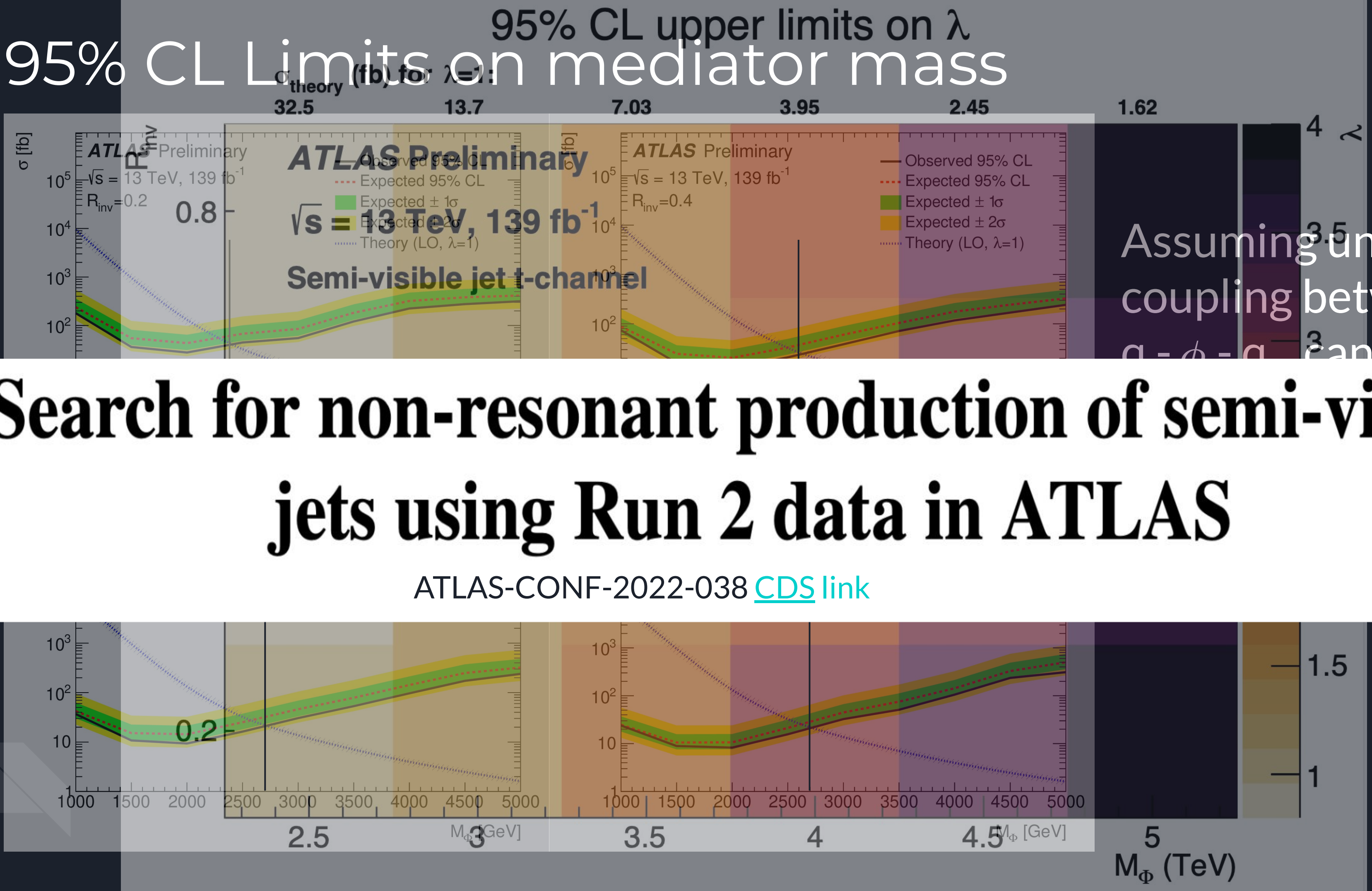
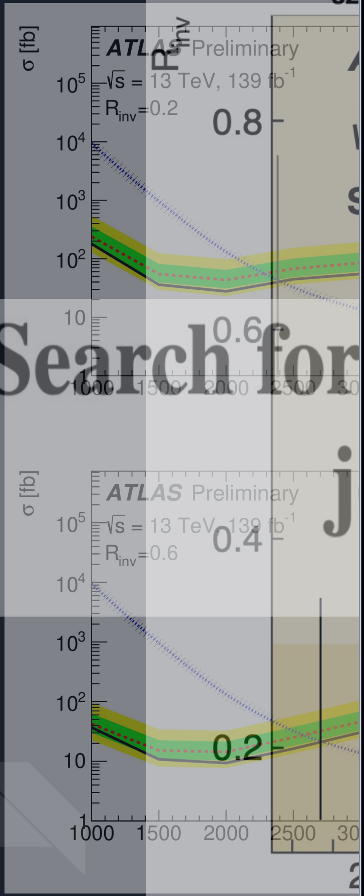


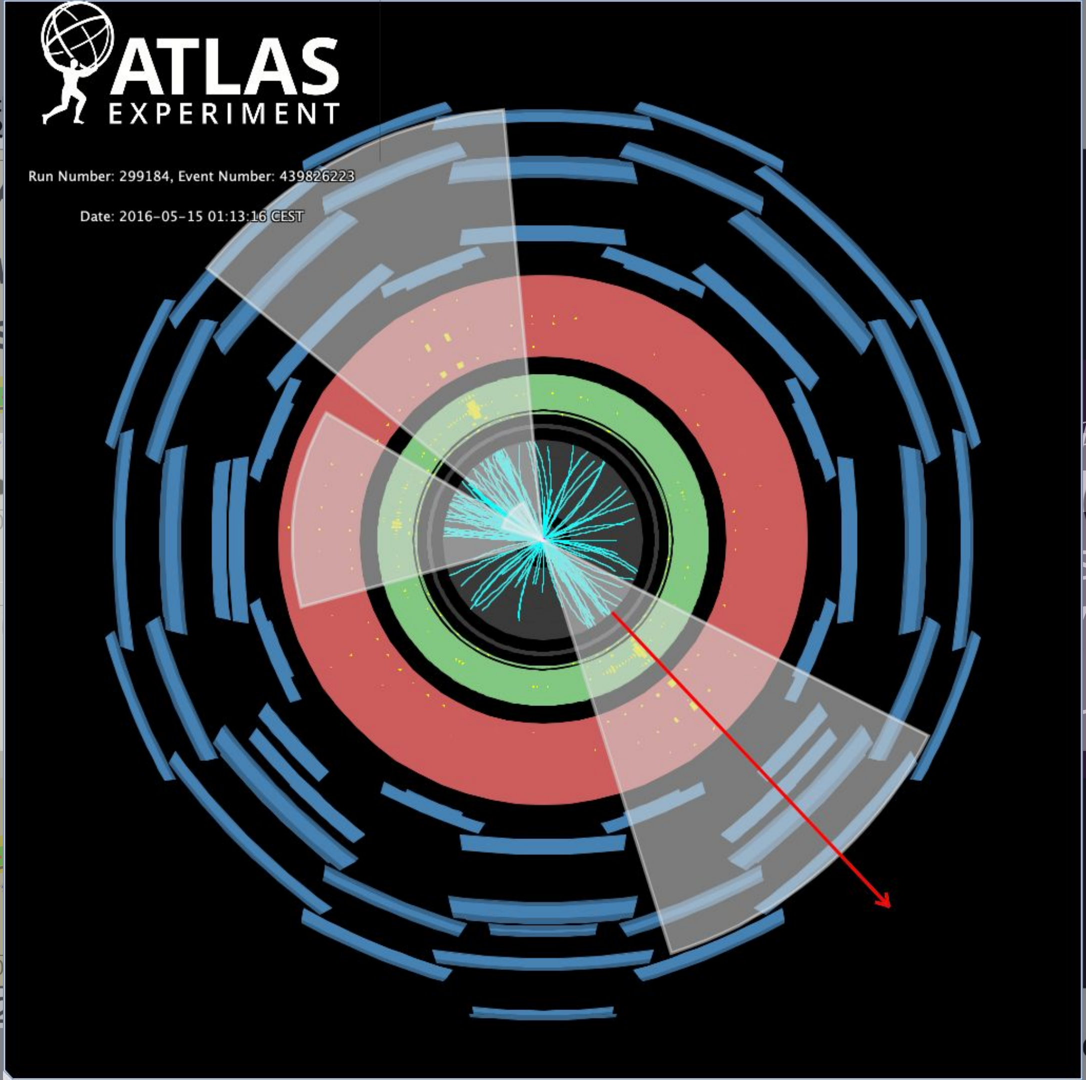
Assuming unity coupling between q - ϕ - q can

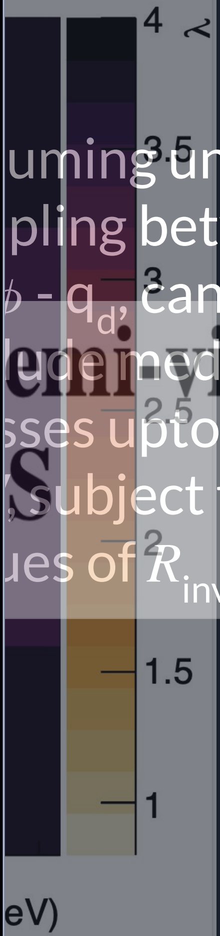
Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS

ATLAS-CONF-2022-038 CDS link

95% CL Li







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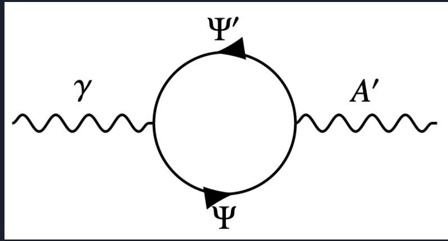
Dark photons in ATLAS (so far)…

Possible dark photon models

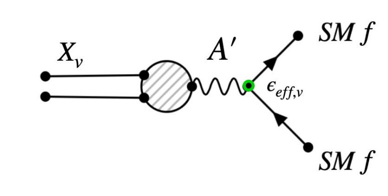


Vector Portal: Add a U(1)' whose massive "dark" gauge boson mixes kinetically with SM photon

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

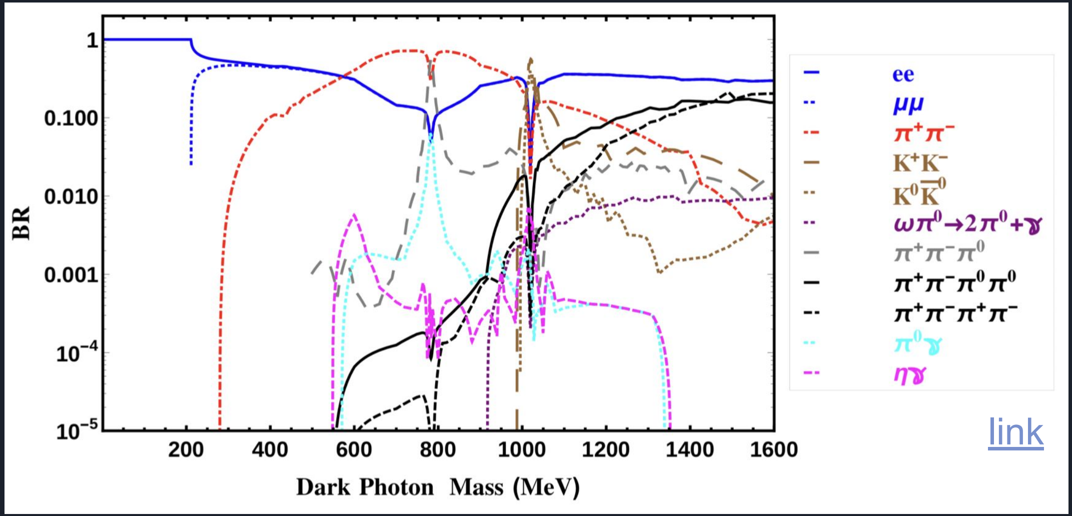
Hidden Valley: sector of dark particles, interacting amongst themselves

- 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'



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−Zγd;
- Annihilation → electron-positron pair annihilates into a photon and a dark photon, i.e., e−e+ → γγ;
- Drell-Yan → qqbar pair annihilates into a dark photon, which consequently decays into a lepton pair or hadrons, i.e., qq¯→ γd → l−l+ or h−h+



link

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

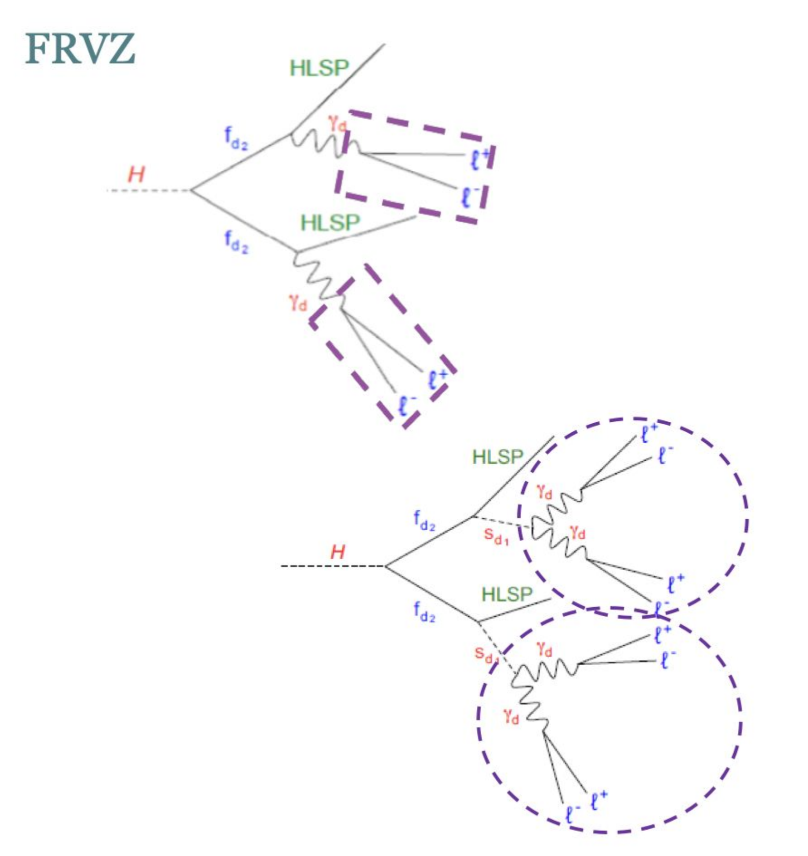
Benchmark models for limit setting

Falkowsky-Ruderman-Volansky-Zupan model

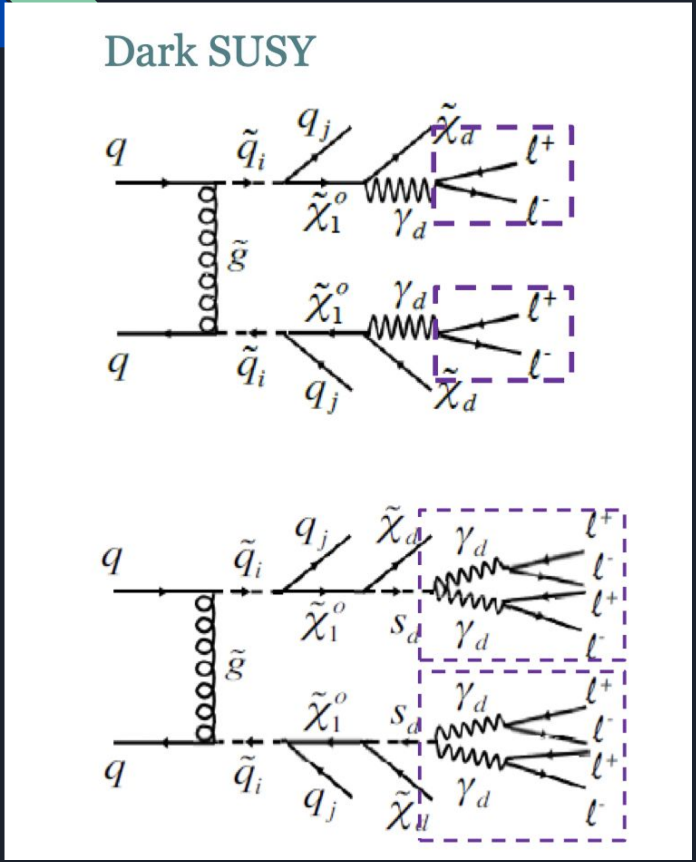
Pair of dark fermions produced in the Higgs boson decay

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.



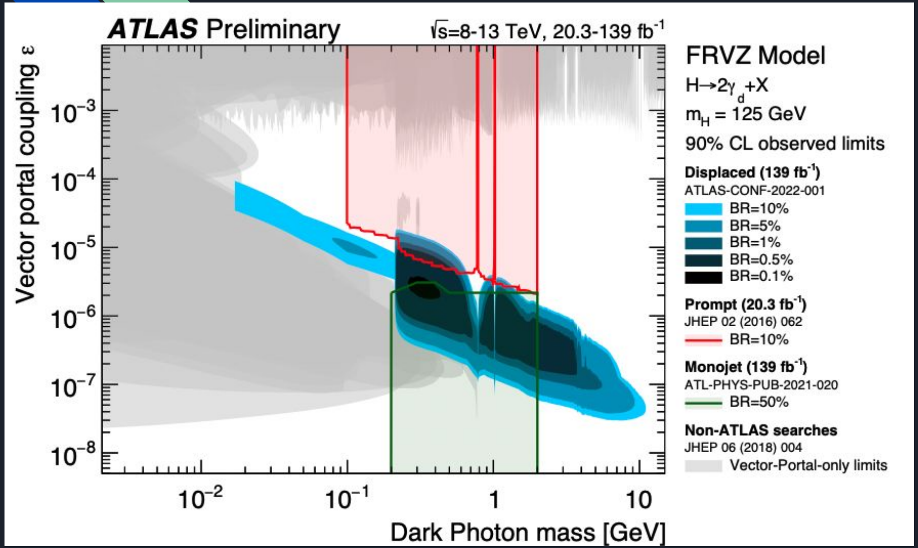
Benchmark models for limit setting



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

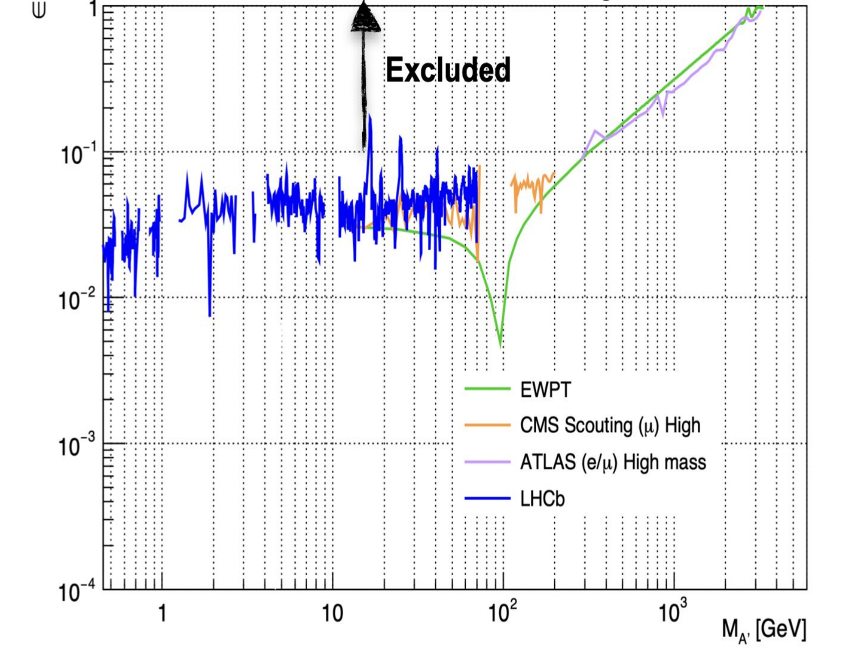
Summary of constraints from colliders



[ATL-PHYS-PUB-2022-007]

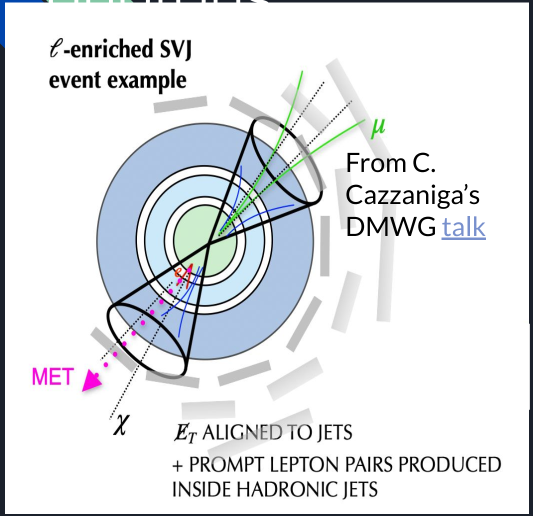
Exclusions available for lepton jets in high mass regions from ATLAS ([prompt electron jets Run-1], [partial Run-2 BHN], [Displaced jets CalRatio]...), CMS (also targeting low mass regions using data scouting techniques), and LHCb dedicated searches.

From C. Cazzaniga's DMWG [talk]

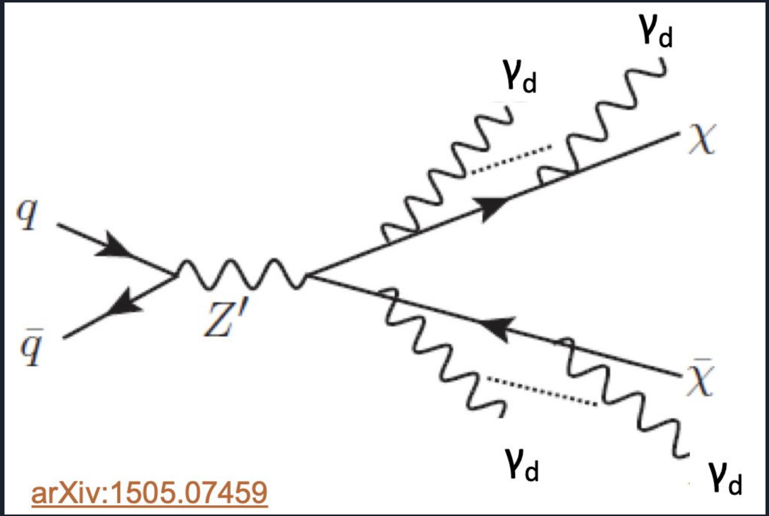


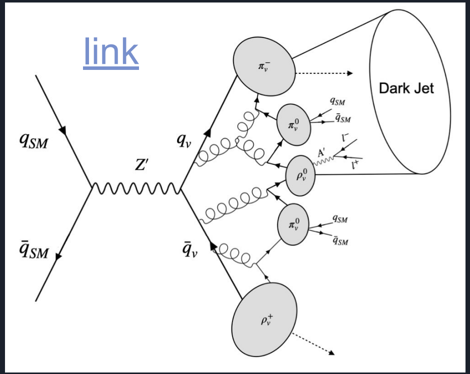
constraints $A' \to \ell^+\ell^-$

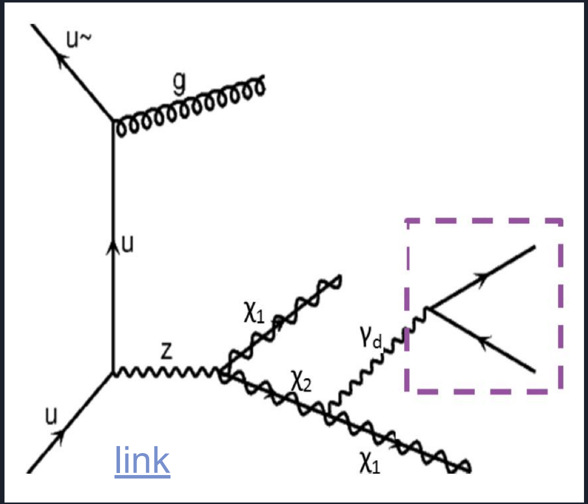
Some unusual/alternative final state signatures of dark photons



Radiating DM: WIMP radiates copious γ_d's due to high α_D







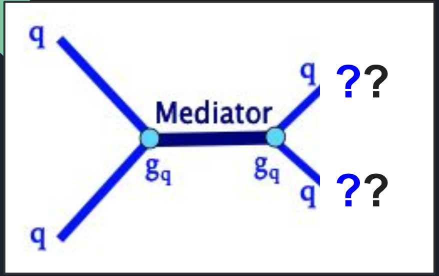
iDM (Inelastic dark matter): Dirac fermion DM, mass eigenstates χ_1 and χ_2 with dominantly off-diagonal interactions

How to select more of the "interesting" data, without cutting a hole in the storage pocket?

Why: Partial Event Building (PEB)

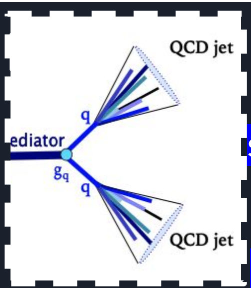
D. Wilson's slides

Dark Z' decays in (dark) quarks



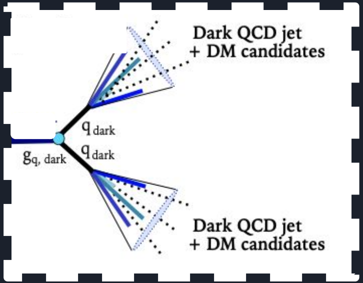
Trigger level analysis(TLA) + **Partial event building (PEB)**

store **only HLT objects** (jets, photons, etc) for analysis



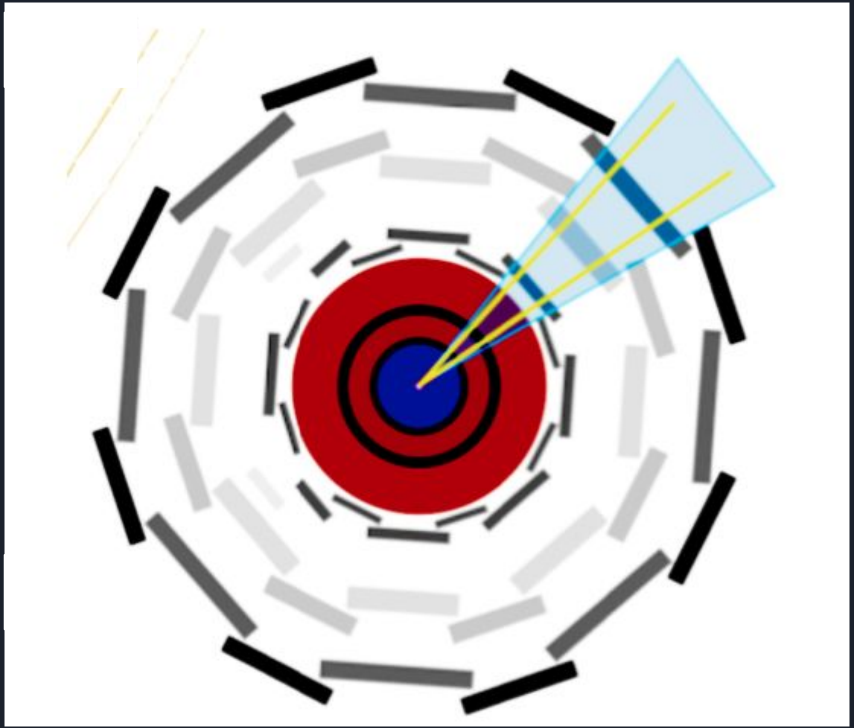
0.5% the size of the full event!

store raw detector information in regions of interest



approx. ⅕ of the size of the full event

write out RAW subdetector information in certain ROIs



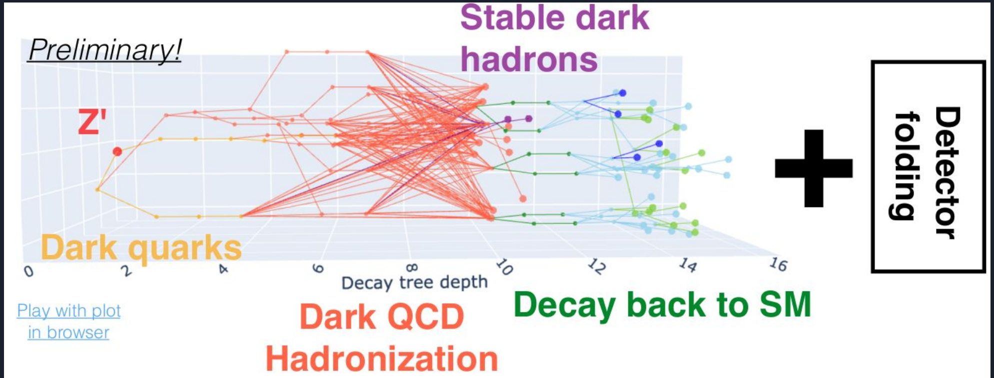
Adapted from H. Russell's poster

Implemented in current release

Partial Event Building (PEB), continued

- ❖ Save only subset of detector raw information
- ❖ Along with HLT objects (TLA)
- ❖ Considerably smaller event size (~1/5th of phys main)
  - ➢ Larger data set
- ❖ Does not need to be reconstructed immediately

TLA+PEB: Could be more sensitive to a large no. of unusual jetty models…e.g. unique fragmentation due to second hadronization (not accessible with TLA alone)



- PEB already implemented for calibration and b-physics [ATLAS-TRIG-2018-01-002]
- Can provide offline tracking & substructure information in addition to TLA information (for jetty final states)
  - a. Improves HLT objects wrt TLA, i.e better e/gamma discrimination for HLT
- New in Run-3: high rate, offline-like precision where it matters

Alternative to PEB, with larger event size: **delayed stream**

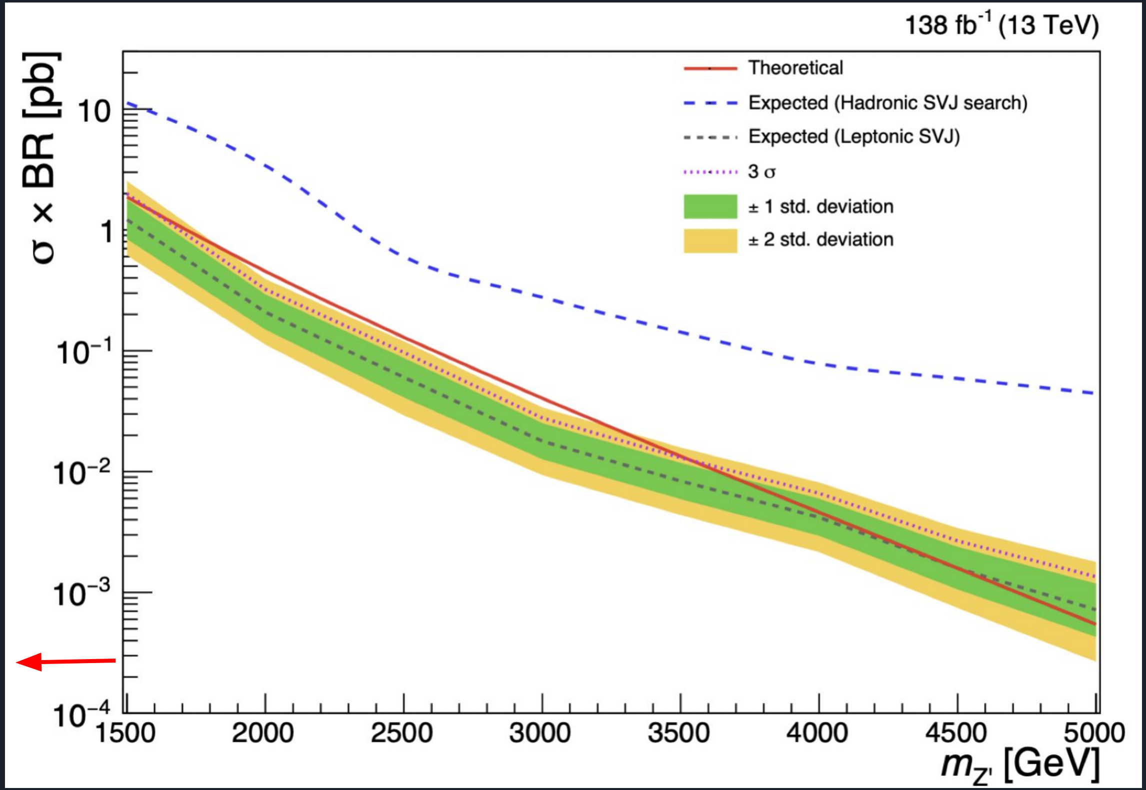
Lepton-in-jet Case Study

Pheno study on SVJ+non isolated leptons [link]

$M_{Z'}$ = mass of the mediator

σ x BR = cross-section x Branching ratio
→ smaller value == rarer process

Exclusions available for lepton jets in high mass regions from ATLAS ([prompt electron jets Run-1], [partial Run-2 BHN], [Displaced jets CalRatio]...), CMS dedicated searches.

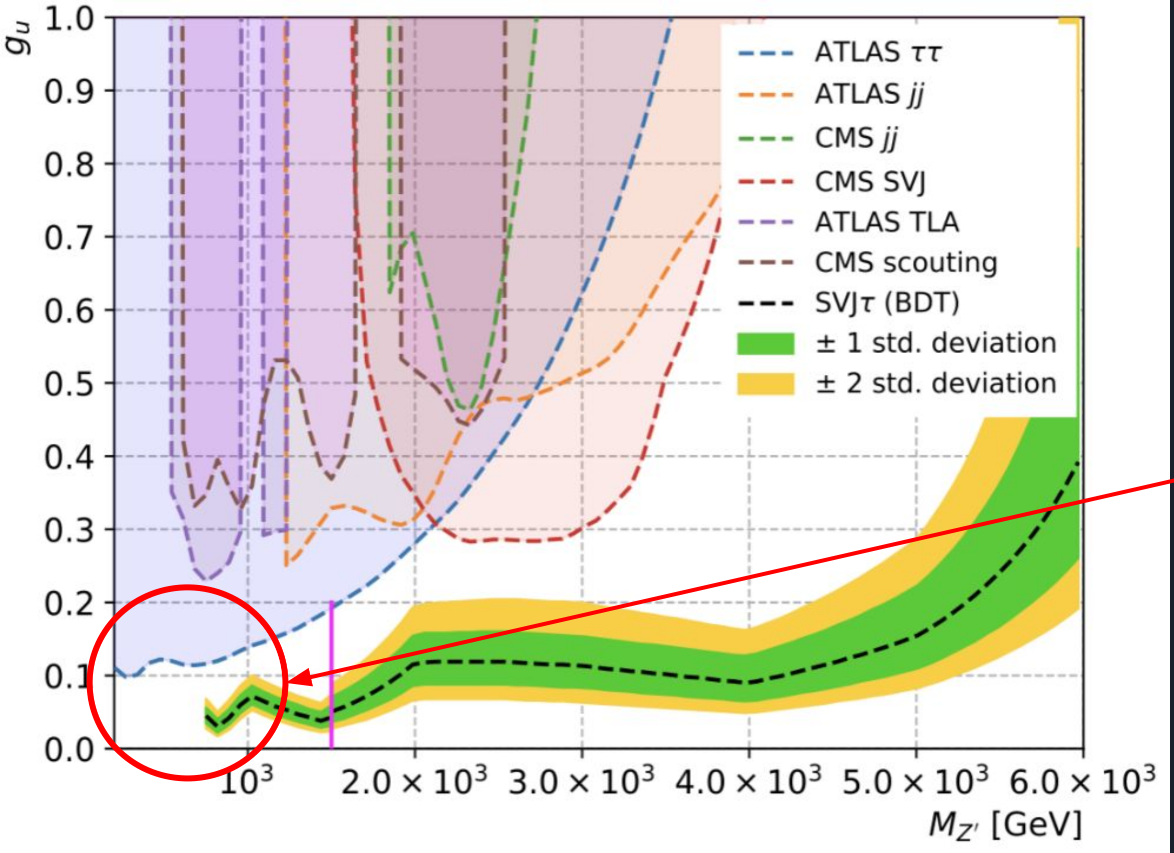


TLA+PEB/delayed stream needed to access lower mass range, for potential discovery

[Delphes study, so pinch of salt needed]

A tau-flavored Case Study

Pheno study on SVJ+tau link



$M_{Z'}$ = mass of the mediator

g_u = coupling of mediator to right-handed up quarks → smaller value == rarer process

TLA+PEB/delayed stream needed to access this range

Trigger strategy that makes low-mass region accessible: HT> ~700-800 GeV

[Delphes study, so pinch of salt needed]

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
    - Potential strategies: Partial Event Building + TLA and/or Delayed Stream
- **First bounds set on these kind of signatures in the t-channel production mode from ATLAS (many more to come)**

BACKUP

HV Parameters (why and what)

Parameter	value
HiddenValley:Ngauge	2
HiddenValley:FSR	on
HiddenValley:spinFv	0
HiddenValley:fragment	on
HiddenValley:pTminFSR	1.1
HiddenValley:probVector	0.75
HiddenValley:alphaOrder	1
HiddenValley:Lambda	0.1
HiddenValley:alphaFSR	1.0

All parameters set as per theory paper

Running HV alpha selected, after discussions with theorists in different platforms (Snowmass, LHC DMWG). Advised to be the safest choice for first analysis.

Semi-visible jets in ATLAS - Analysis Samples

Signal: Madgraph + Pythia8 with R_{inv} = 0.2, 0.4, 0.6, 0.8 and M_d = 10 GeV, M_ϕ = 1 - 5 TeV (in 500 GeV intervals)

Background samples:

Process	Generator	ME order	PDF	Parton shower	Tune
W/Z+jets	Sherpa2.2.11 [17, 18]	NLO (up to 2 jets)	NNPDF3.0nnlo [9]	Sherpa MEPSatNLO	Sherpa
$t\bar{t}$	Powheg Box2 [19–21]	NLO	NNPDF3.0nlo	Pythia8.230 with NNPDF2.3lo	A14 [14]
Single top	Powheg Box2	NLO	NNPDF3.0nnlo	Pythia8.230 with NNPDF2.3lo	A14
Multijet	Pythia8.230 [13]	LO	NNPDF2.3lo	Pythia8.230	A14
Diboson	Sherpa2.2.1	NLO (up to 2 jets)	NNPDF3.0nnlo	Sherpa MEPSatNLO	Sherpa

Data samples:

2015: 3.20 \pm 0.07 fb^{-1}
2016: 32.9 \pm 0.72 fb^{-1}
2017: 44.3 \pm 1.06 fb^{-1}
2018: 59.9 \pm 1.19 fb^{-1}

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.

Some tables to stare at....

Process	k_i^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

	SR	CR 1L	CR 1L1B	CR2L
Z+jets	8490 ± 260	11.6 ± 1.4	2.2 ± 0.6	1120 ± 40
W+jets	5820 ± 300	3190 ± 170	351 ± 41	-
$t\bar{t}$	920 ± 70	350 ± 29	304 ± 24	-
Single top	533 ± 47	358 ± 29	290 ± 25	-
Multijet	850 ± 100	28 ± 11	7.7 ± 3.1	-
Diboson	757 ± 10	187 ± 9	34.5 ± 2.8	-
Total background	17 370 ± 280	4120 ± 100	990 ± 35	1120 ± 40
Data	17 388	4136	999	1124
Signal:				
M_ϕ=1 TeV, R_{inv}=0.6	180 000 ± 40 000	-	-	-
M_ϕ=1 TeV, R_{inv}=0.8	220 000 ± 50 000	-	-	-
M_ϕ=2 TeV, R_{inv}=0.4	4100 ± 900	-	-	-
M_ϕ=2 TeV, R_{inv}=0.6	5800 ± 1300	-	-	-
M_ϕ=3 TeV, R_{inv}=0.2	117 ± 26	-	-	-
M_ϕ=3 TeV, R_{inv}=0.4	170 ± 40	-	-	-

Statistical analysis

- To determine individual N_i → simultaneous binned maximum likelihood function fit is performed using product of all PDF_i and nine bin yields, using the MC templates
- The fit maximises the likelihood function constructed from the product of all relevant Poisson and Gaussian pdfs. The scale factors for the individual backgrounds, k^{SF} are determined from the fit:

$$\mathcal{L}(\mu, \theta) = \prod_{j \in \text{ 36 bins}} \text{Poisson}(N_j^{\text{obs}} | \mu N_j^{\text{sig}}(\theta) + \sum_{i \in \text{bg}} k_i^{\text{SF}} \times N_{i,j}^{\text{bg}}(\theta)) \times f^{\text{constr}}(\theta)$$

Here, $N_j^{expected}$ is the observed total yield in the bin j, signal strength is \mu, systematic uncertainties in the fit are denoted by nuisance parameters \theta, N_j^{bg}(\theta) is the combined background yield in bin j

The term f_{constr}(\theta) of represents the product of the gaussian constraints applied to each of the nuisance parameters,

$$f_{constr}(\theta) = \prod_{k=1}^{M} G(\theta_k^0 - \theta_k)$$

Analysis preselections

Signal samples: Madgraph + Pythia8 with R_{inv} = 0.2, 0.4, 0.6, 0.8 and M_d = 10 GeV, M_ϕ = 1 - 5 TeV

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

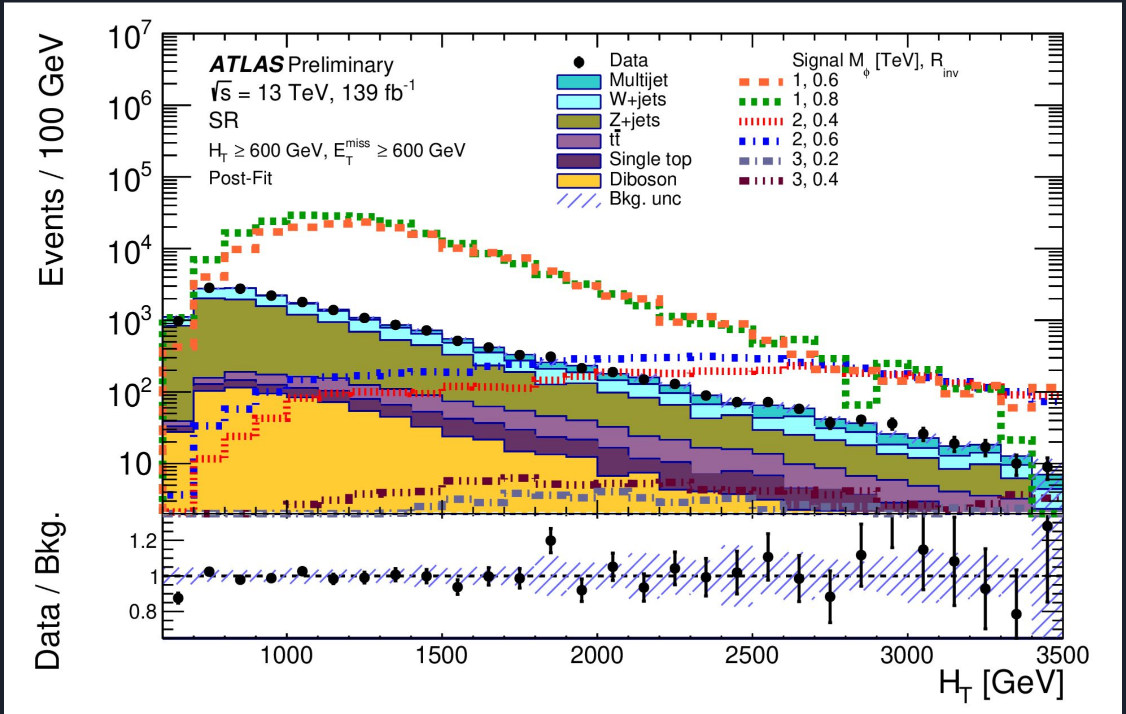
Full Run-2 dataset

1. Looking at events with MET trigger, MET > 200 GeV
2. At least 2 jets (R=0.4) with leading jet p_T > 250 GeV, other jet p_T > 30 GeV and |eta| < 2.8
3. No electrons / muons (p_T > 7 GeV)
4. Dead-tile correction, LAr, SCT error veto, NCB treatment for data
5. DeltaPhi(closest jet, MET) < 2.0
6. B-tagged jets < 2
7. Tau jets (p_T > 20 GeV) < 1

MET > 600 GeV and H_T > 600 GeV after the nominal selection defined as signal region (SR).

The corresponding 1L, 1L1B and 2L control regions (CR) defined using leptonic selections (and leptons added back to MET) with same MET and H_T requirements as in SR.

Kinematic distributions - SR



We haven't found new physics :-(

Excellent agreement between data and estimated background…

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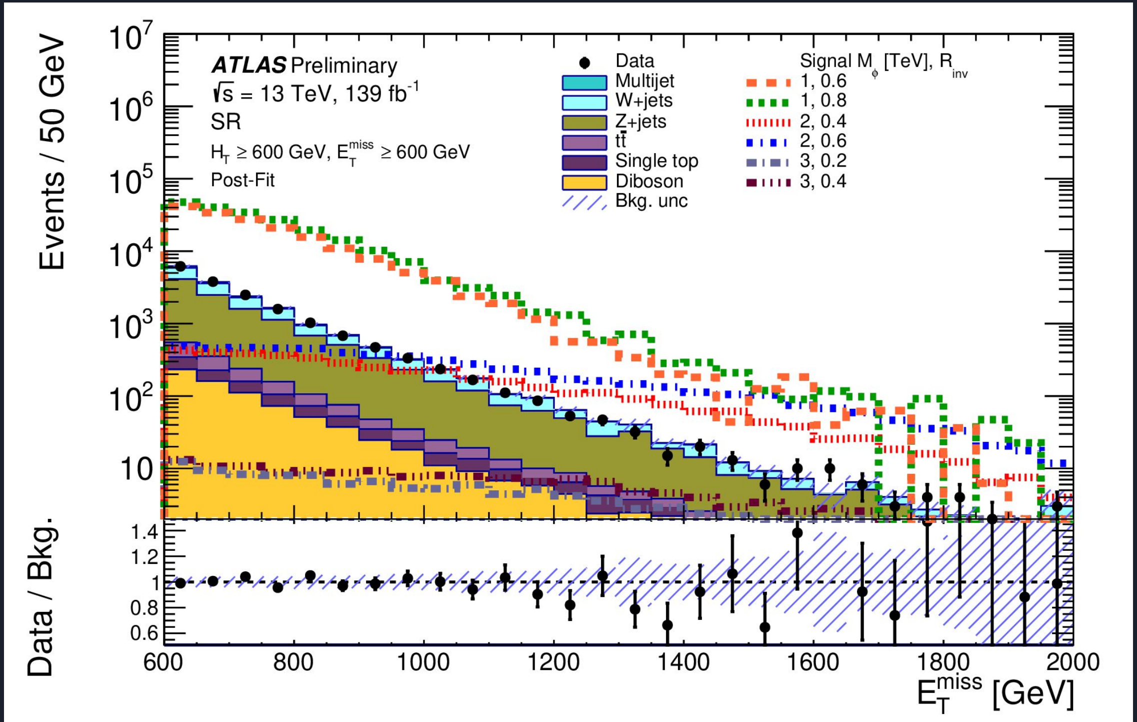

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