Dark sector showering using semi-visible jets in ATLAS

ATLAS-CONF-2022-038

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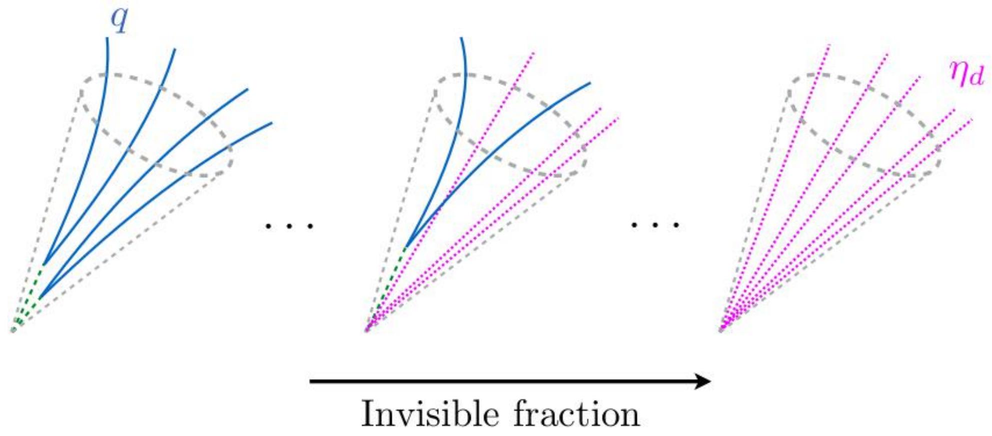
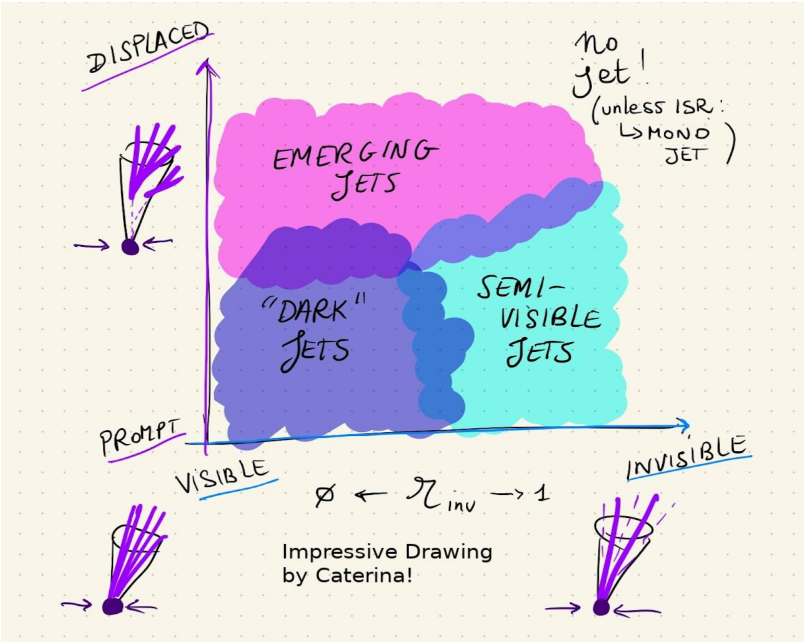
SAIP 2022
4th July 2022

Semi visible jet production

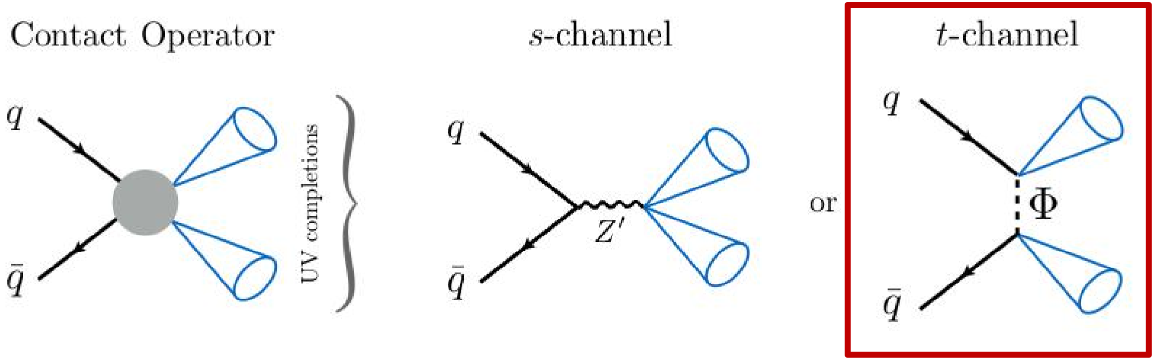




Link to the paper: https://arxiv.org/abs/1707.05326

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. Lambda = 2 vertex coupling strength ~ xs¼



Pythia 8 Hidden Valley Module

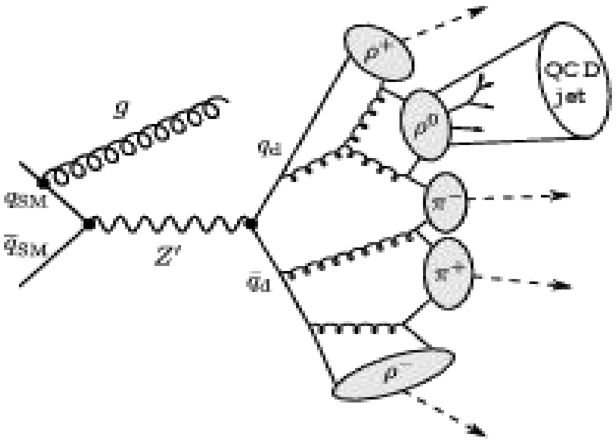
Params in backup

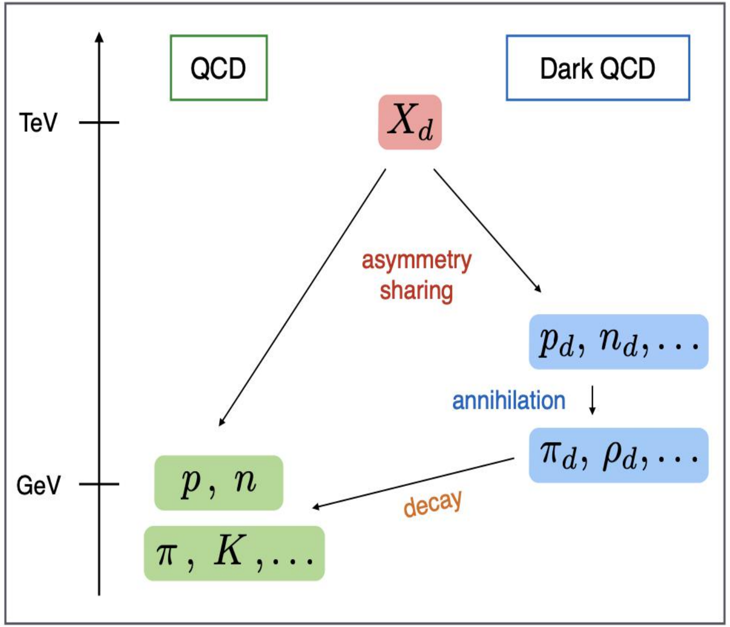
Two different dark quark flavours

- ►Combine to form π⁺, π⁻, π⁰, and ρ⁺, ρ⁻, ρ⁰ (assumed to be produced thrice as much as pions)
- ►Only ρ⁰ 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

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 Samples

Signal: Madgraph + Pythia8 with r_{inv} = 0.2, 0.4, 0.6, 0.8 and M_D = 10 GeV, M_{phi} = 1000 - 5000 GeV (in 500 GeV intervals)

Background samples:

Process	Generator	ME order	PDF	Parton shower	Tune
Multijet	Pythia 8.230	LO	NNPDF23LO	-	A14
W/Z+jets	Sherpa 2.2.11 [17, 18]	NLO (up to 2 jets)	NNPDF3.0NNLO	Sherpa MEPSatNLO	Sherpa
$t\bar{t}$	Powheg-Box 2	NLO	NNPDF3.0NLO	Pythia 8.230 with NNPDF23LO	A14
Single top	Powheg-Box 2	NLO	NNPDF3.0NLO	Pythia 8.230 with NNPDF23LO	A14
Diboson	Sherpa 2.2.1	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}

data15_13TeV/20170619/physics_25ns_21.0.19.xml

data16_13TeV/20180129/physics_25ns_21.0.19.xml

data17_13TeV/20180619/physics_25ns_Triggerno17e33prim.xml

data18_13TeV/20190318/physics_25ns_Triggerno17e33prim.xml

Analysis preselections

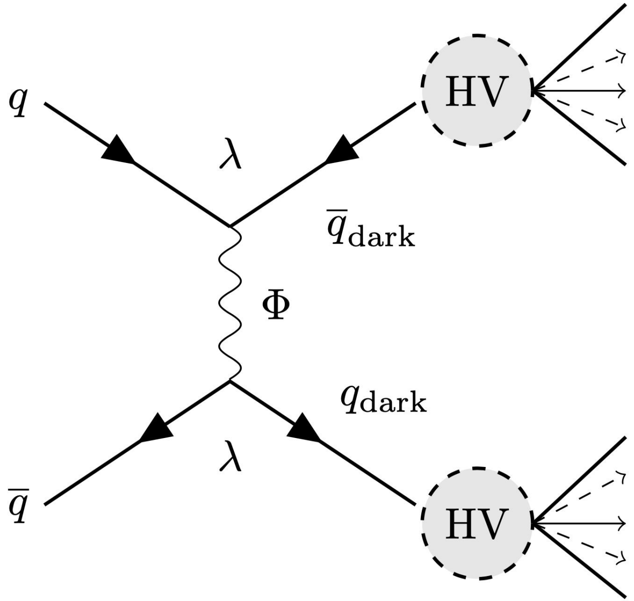
1. No electrons / muons (p_T > 7 GeV)
2. Looking at events with MET trigger (trigger is fully efficient, tests in backup slide), MET > 200 GeV
3. At least 2 jets with leading jet p_T > 250 GeV, other jet p_T > 30 GeV and |eta| < 2.8, jet cleaning LooseBad (also TightBad selection applied on data leading jet, for NCB treatment)
4. Dead-tile correction, LAr, SCT error veto
5. DeltaPhi(closest jet, MET) < 2.0
6. B-tagged jets < 2
7. Tau jets (p_T > 20 GeV) < 1

Key variables for this analysis:

- MET
- Scalar jet pT sum, HT
- DeltaPhi (closest jet, MET)
- p_T balance (between closest and farthest jet from MET)

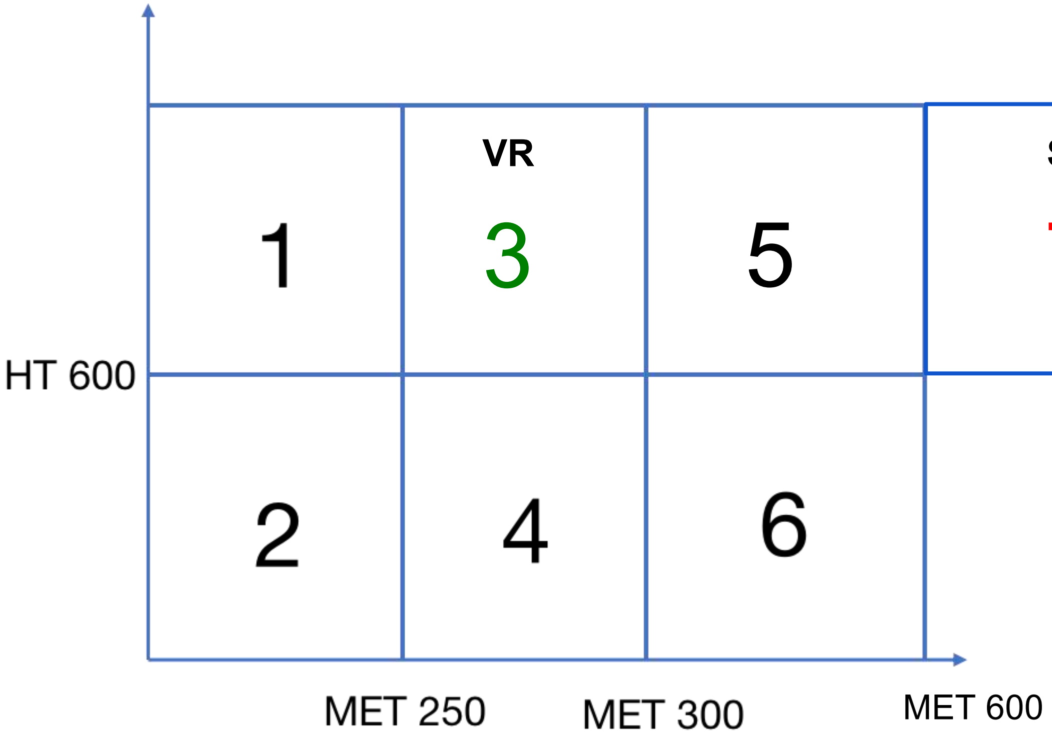
$$\Delta_{\rm rel} p_{\rm T}(j_1, j_2) = \frac{|\vec{p_{\rm T}}(j_1) + \vec{p_{\rm T}}(j_2)|}{|\vec{p_{\rm T}}(j_1)| + |\vec{p_{\rm T}}(j_2)|}$$

- Maxminphi |Δϕ(farthest jet, MET) - Δϕ(closest jet, MET)|



The resultant MET direction is aligned along one of the jets.

Analysis and fit strategy → dividing the MET and HT distributions into 7 regions

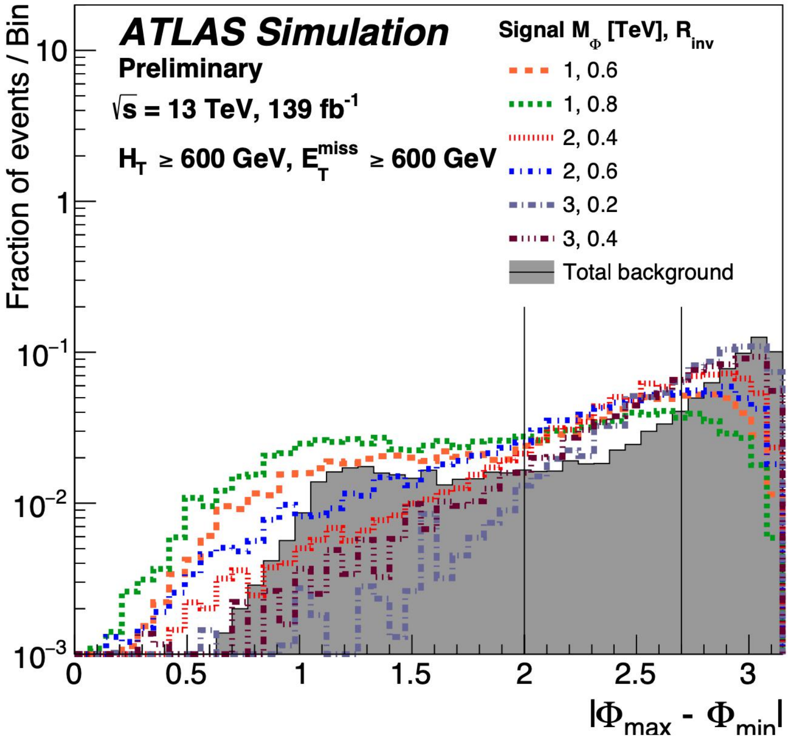


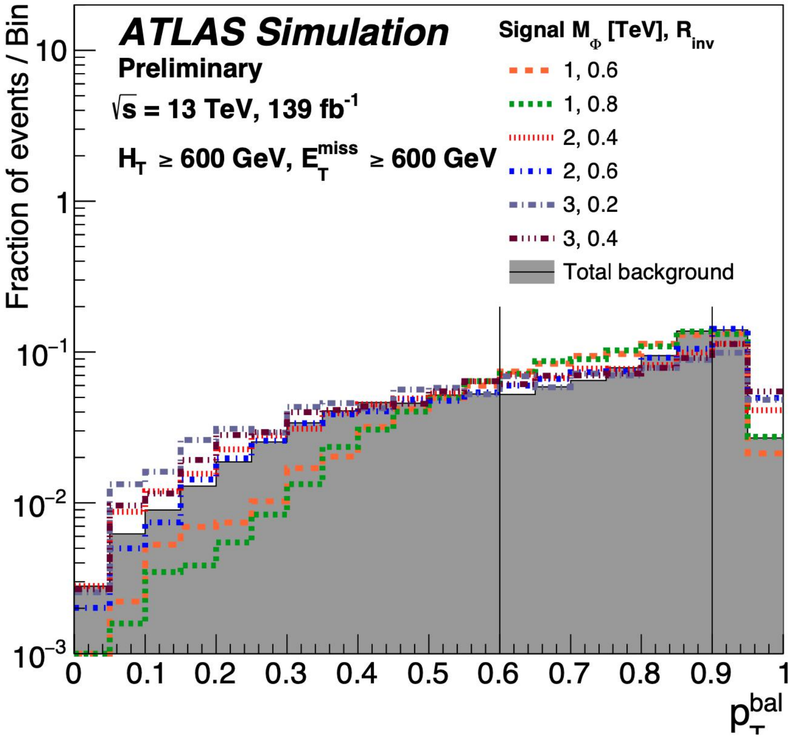
HT >= 600 GeV, MET >= 600 GeV is the signal region.

Only Region 3 is used as the validation region. Rest are not used.

Region 7 (SR) was blinded

Kinematic distributions in SR (HT >= 600 GeV, MET >= 600 GeV)

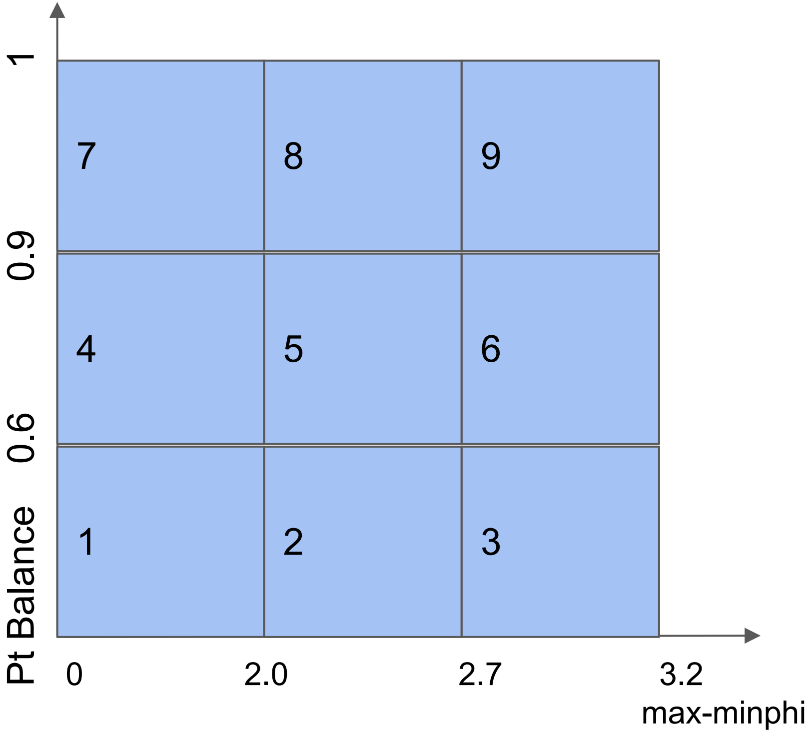




Strategy of the categorization

Yields in these nine bins ((3 max-minphi bins) x (3 p_T balance bins)) are treated as the observables in different regions.

Contribution of different backgrounds is different for each of the bins, so the signal-depleted but specific background-enriched bins in the SR itself are used to estimate the background.



Theoretical Systematics

Consider impacts of theoretical uncertainties on both shape and normalization of pre-fit yields

- **PDF:** [mapped to Scale term in pull] [mapped to PDF term in pull]
  - RMS standard deviation of 100 eigen-variations of nominal PDF (for all bkg and signal)
- **μ_R and μ_F (QCD scale):** (for all bkg and signal) [terms in appendix list with MUR, MUF - mapped to Scale term in pull]
  - Vary μR and μF coherently by x2 or x0.5
- **PS** [mapped to Scale term in pull]
  - **Top :** Compare Herwig7 vs. Pythia8 PS generators
- **α_s (ISR) (Top only):** Choose Var3c up/down variants of the Powheg A14 tune [mapped to Var term in pull]
- **ME (Top only):** Compare mc@NLO vs. MadGraph5 ME generators [mapped to MEVar term in pull]

Top processes: ttbar, Single Top (Powheg+Pythia8)

Experimental Systematics

- Considered experimental systematics from calibration of the detector and LHC machine
- Evaluated impact of up/down variations in weights and observables corresponding to each source of experimental uncertainty on yield in each region and bin
- Symmetrized to reduce the impact of stat fluctuations in up/down yield variations.

- Experimental systematics considered:
    - **JES - Strong Reduction (list as in twiki)**
    - **JER - Simple JER (list as in twiki)**
    - **MET_TST (reso para/perp, scale)**
    - **Muon (sf, scale, isol, sagitta, ttva, ms, …)**
    - **Tau (detector, insitu exp/fit, model closure, physics list, …)**
    - **Flavour Tagging (eigenvars b/c/light, extrapolation/fromcharm/ …)**
    - **PRW**
    - **JET_JVT**
    - **Luminosity**

The statistical analysis

- In the absence of a new signal, $$N_{\text{expected}} = \sum_{i \in \text{bg}} N_{\text{i}} \times \text{PDF}_{\text{i}}$$

  where, N_i is the yield of i-th background with a probability distribution function given by PDF_i

- 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

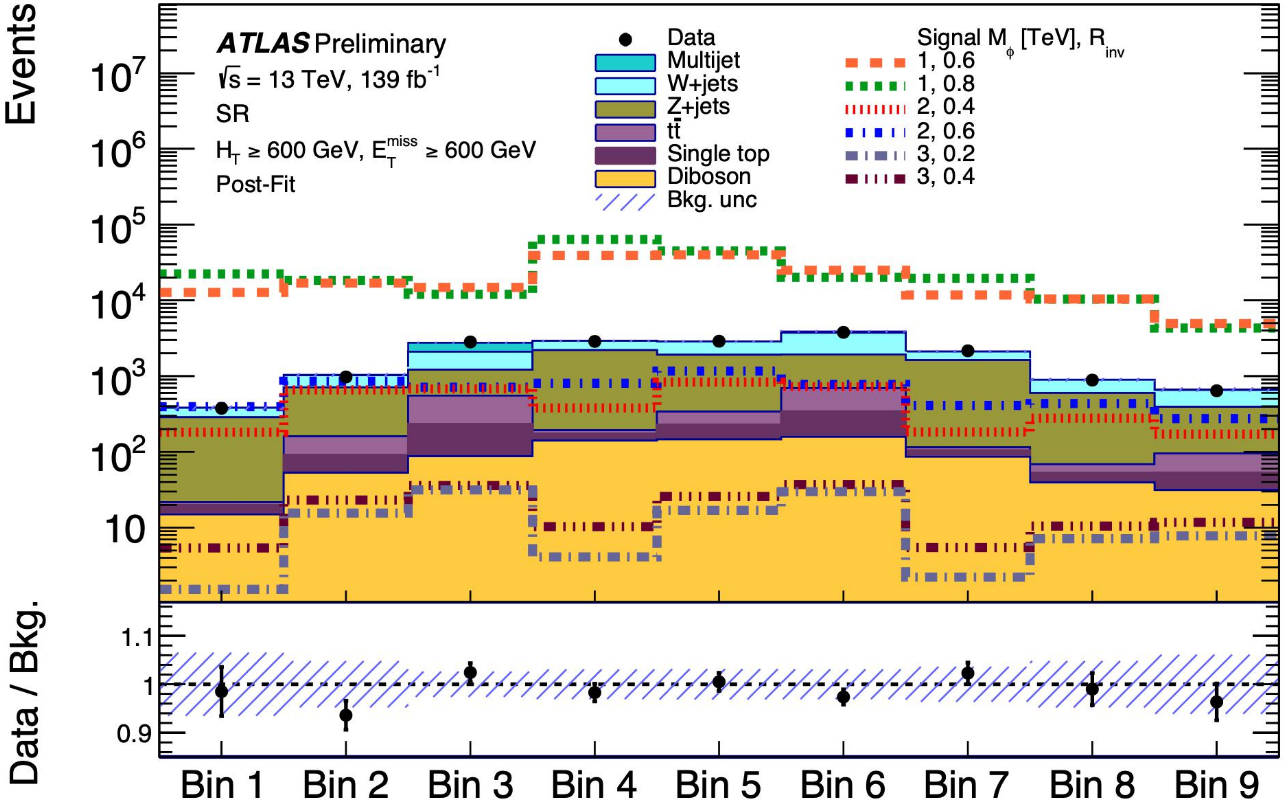
The term f_{constr}(\theta) of represents the product of the gaussian constraints applied to each of the nuisance parameters,

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

CR-SR Simultaneous fit strategy

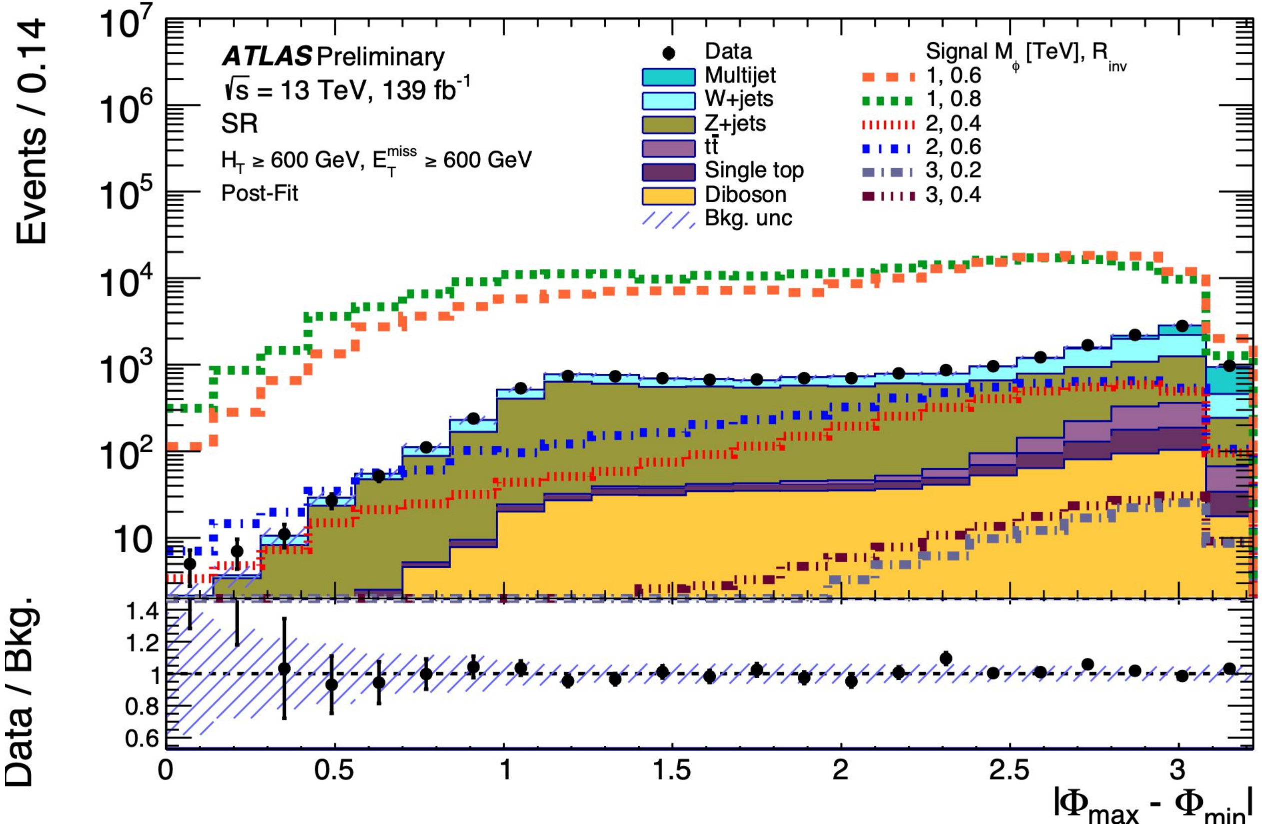
- The signal region (SR) 9-binned histograms are fitted simultaneously with 1LCR, 1L1BCR and 2LCR.
- Dedicated systematic uncertainties are applied to the 0L SR, 1L CR, 1L1BCR & 2L CR 9-binned histogram.
- Limits are reported in terms of mediator masses, assuming a unity coupling between the mediator, the dark quark and the SM quark.
- Limits are also reported in terms of coupling strength \lambda, for each of the different 36 signal (mass,rinv) points
    - XSection = \lambda^4 x Nominal XS
    - Limit on XSection = limit on \mu x Nominal XS
    - Obtain \lambda (for limit on \mu == 1)
    - Set exclusion for each signal Mass-rinv point based on \lambda

Fit Results



We didn't find new physics... :-(

Excellent agreement between data and estimated background...



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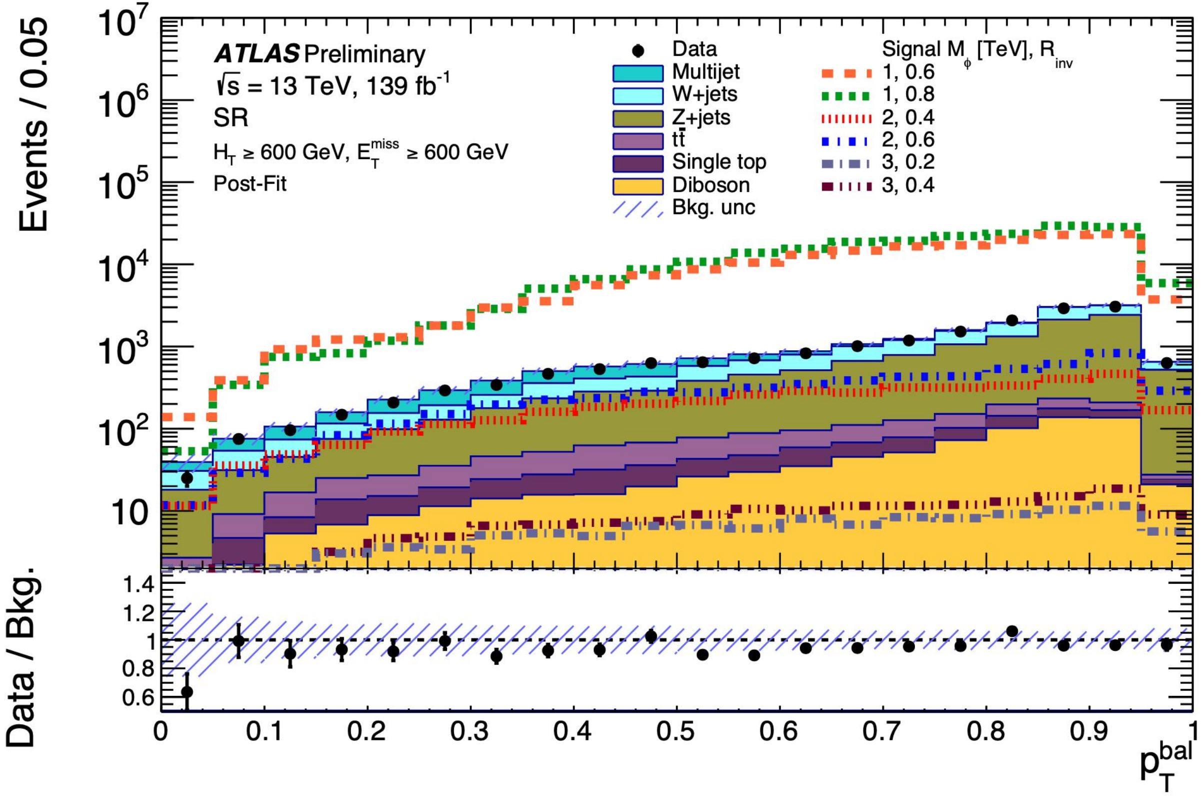

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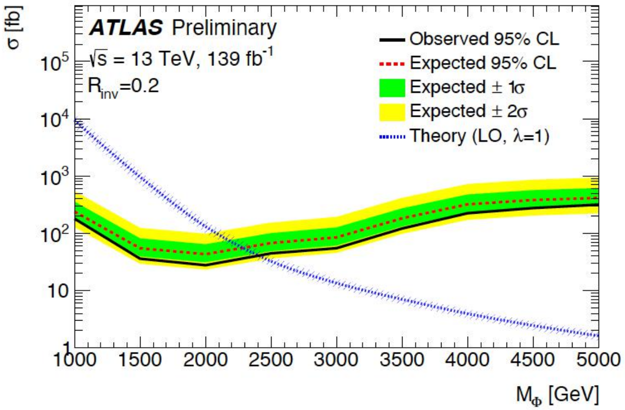
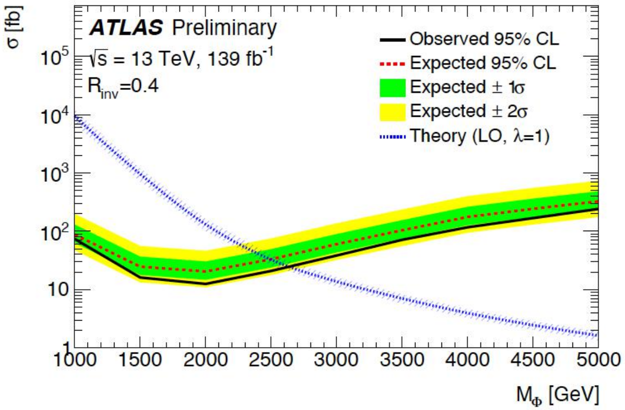
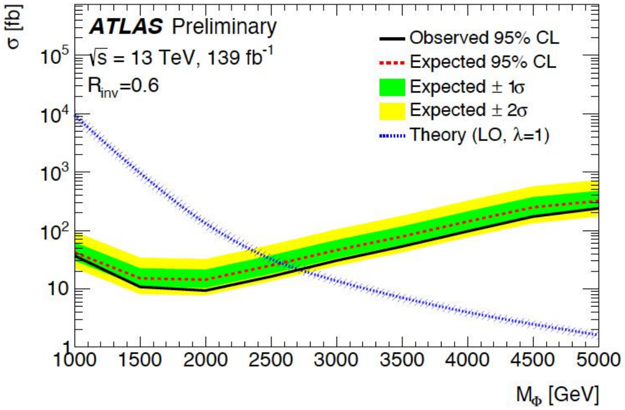
Excellent agreement between data and estimated background...

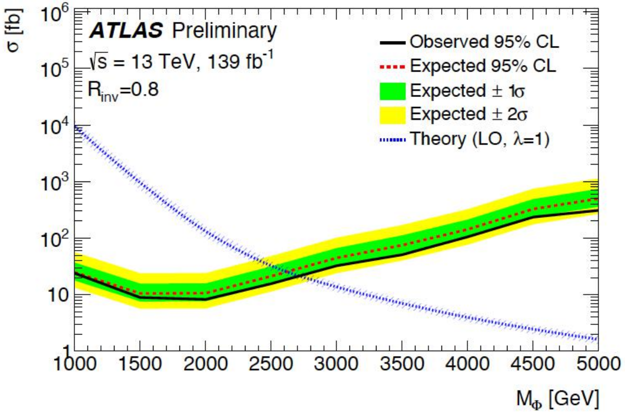
95% CL exclusion limits on mediator mass



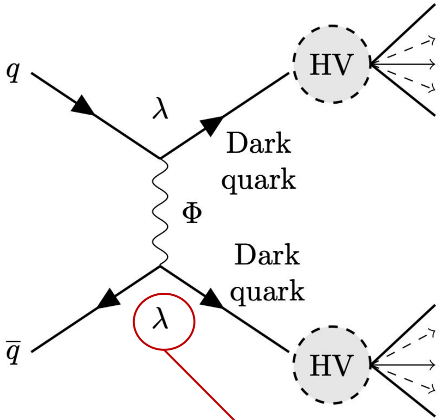


Assuming unity coupling between M_Φ, q and q_d



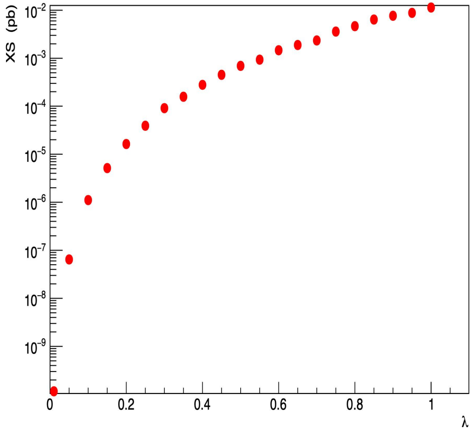


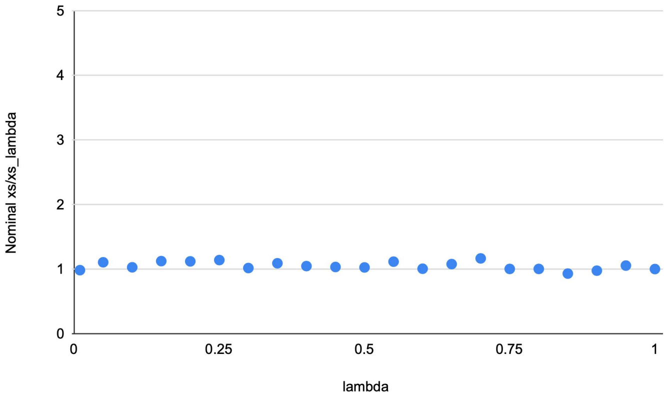
Final presentation of results - Limits on lambda

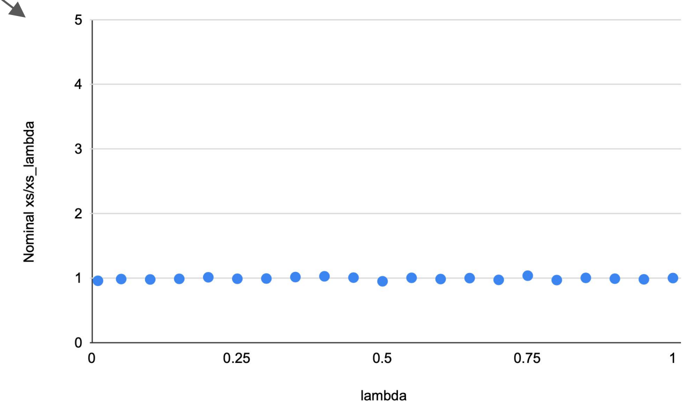


2-vertex coupling strength (λ) can be used for scaling the signal xsection!

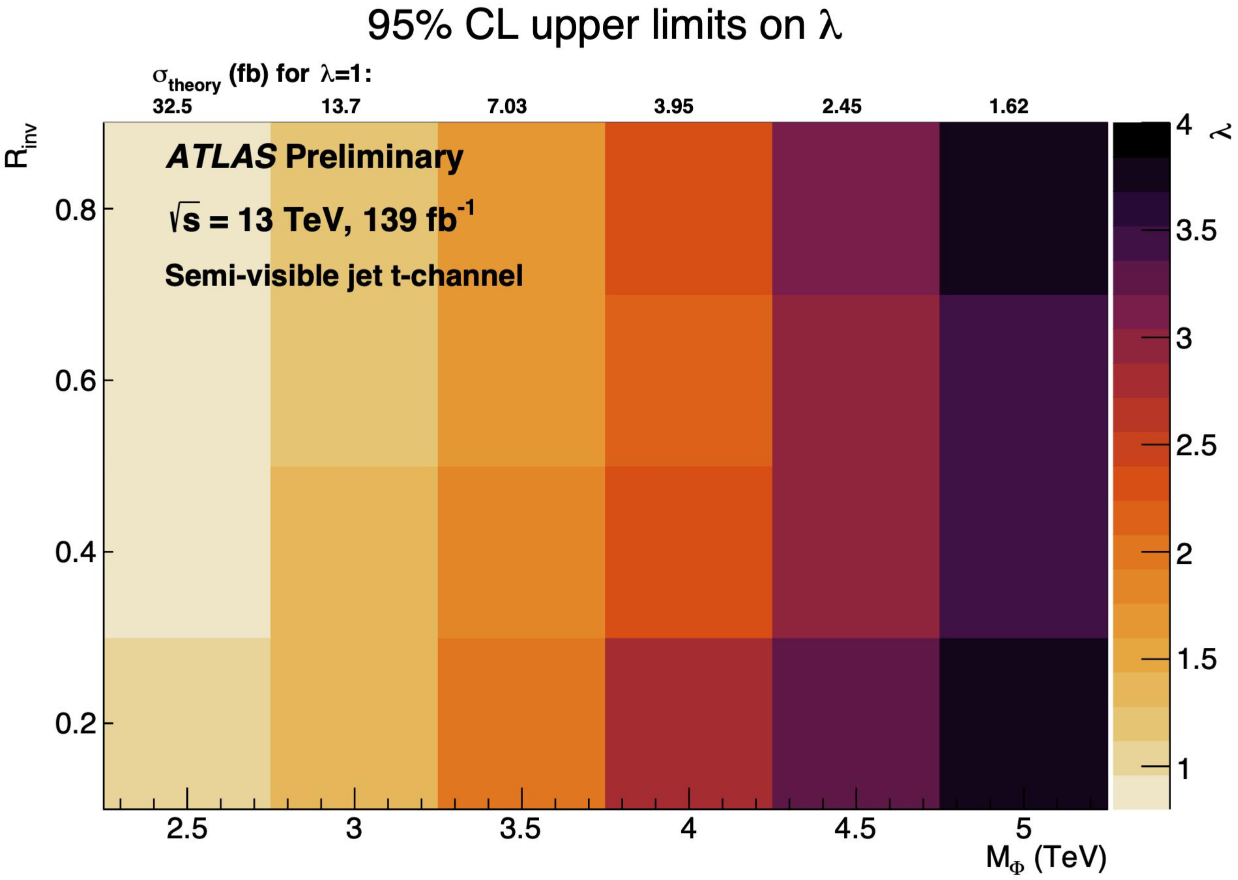
cross section ~ λ^4







Final presentation of results - UNBLINDED SR limits on lambda



Exclusions on **λ** set for each M_{ϕ} - r_{inv} grid point, for MET >= 600 GeV at 95% CL

Conclusions

- Found no excess above SM bkg predictions -- excellent agreement between data and estimated background.
- Setting limits on mediator two-vertex coupling strength, and mediator mass.

This search sets the first bounds on strongly-interacting dark sectors in semi-visible jet t-channel scenarios

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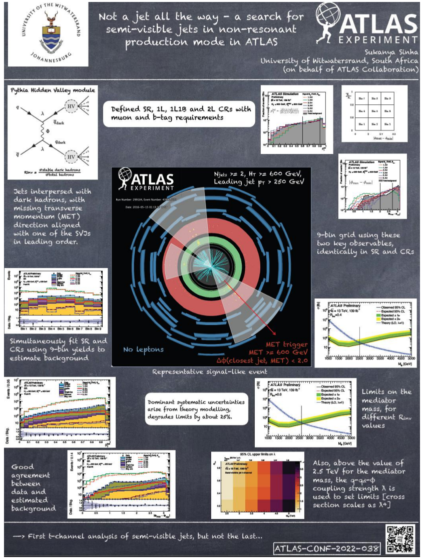
POSTER IN THE BIGGEST PARTICLE PHYSICS CONFERENCE IN THE WORLD -- ICHEP 2022! (THIS WEEK IN BOLOGNA, ITALY)



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.

Tim Cohen <tcohen@uoregon.edu> Tue, Nov 24, 2020, 10:36 PM

to Deepak, Sukanya

Hi Deepak and Sukanya,

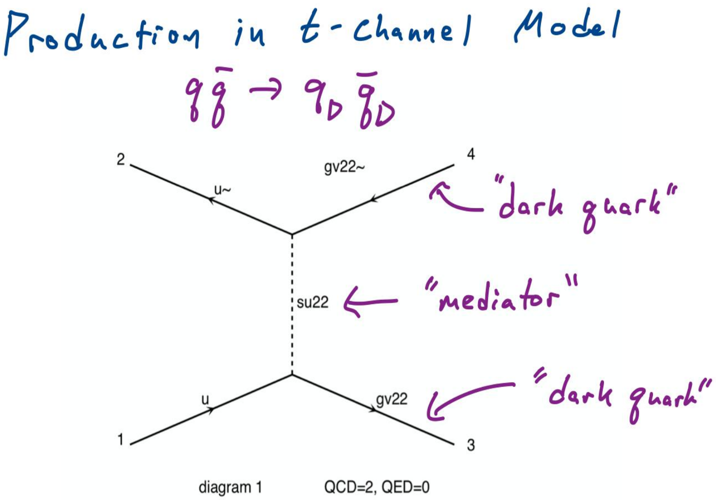
2 vertex coupling strength, lambda free parameter

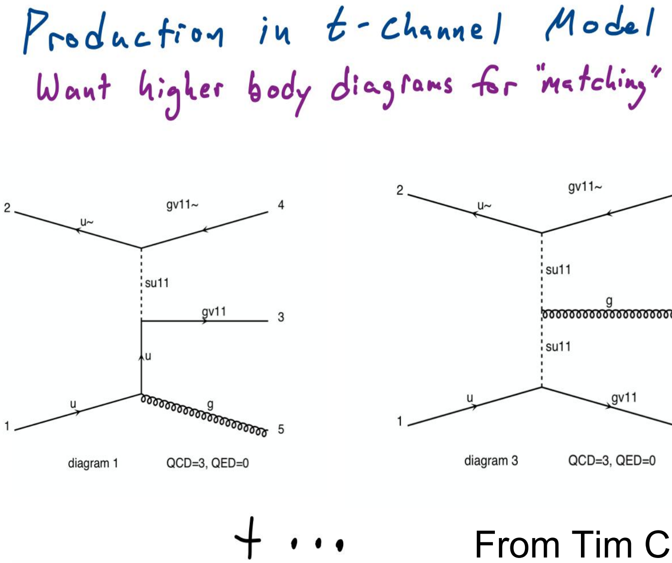
I'm excited to hear that your search is getting so far along!

Regarding the question below (I'm assuming you are still using the "t-channel" model), then the coupling \lambda is simply a free parameter. The only constraint is that it not be too large (if it were bigger than ~ 4\pi it would not longer be perturbative). Otherwise, you should treat this as a free parameter, and I expect that the main result will be to set a constant on this parameter for a given choice of dark sector parameters.

Higher body diagrams

Matched production of pp → $\chi^-\chi^+$ 0, 1, 2 jets

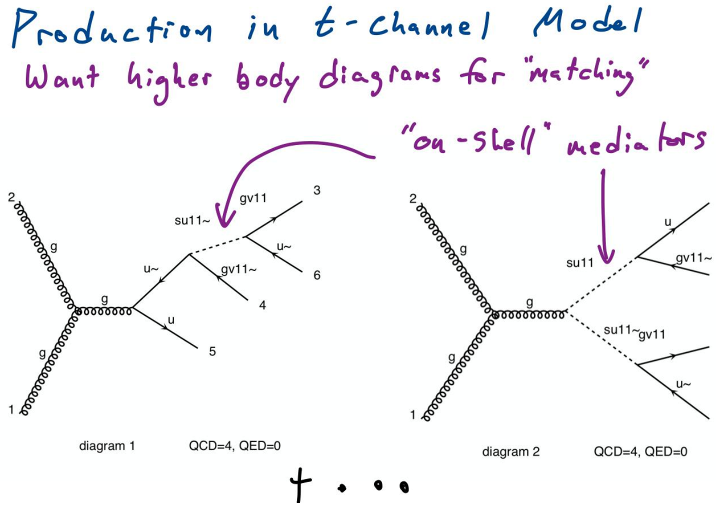




Diagrams with intermediate state mediator particles → produced essentially on-shell (they include the full propagator structure so they in principle can go off-shell, but this is suppressed).

Does not matter for a signature based search

From Tim Cohen's theory talk in JDM - LINK



Mgv (GeV)	XS for gv gv (nb)	XS for g gv and gv gv j (nb)	**XS for gv gv and gv gv j and gv gv j j (nb)**
1500	2.4E-04	2.7E-04	9.6E-04
3000	3.3E-05	2.4E-05	1.4E-05
4500	5.4E-06	3.7E-06	2.4E-06

Dependence on DM mass

The conclusion is, M_D value has no noticeable effect. So subsequently, we will use M_D= 10 GeV, the lowest recommended in PYTHIA8 HV module.

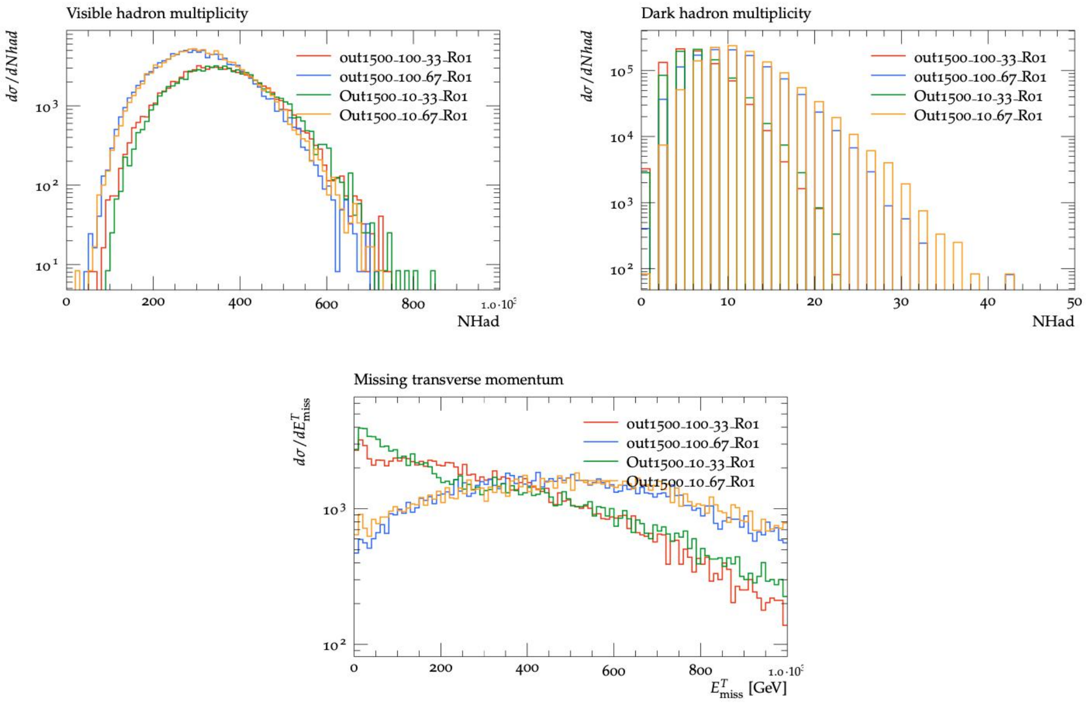


Figure 92: Particle level distributions of visible and dark hadron multiplicities, and E_T^{miss} for varying M_D and r_{inv} while keeping fixed M_ϕ= 1500 GeV.