Not a jet all the way – A search for semi-visible jets in non-resonant production mode in ATLAS

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(on behalf of ATLAS collaboration)

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The big picture!

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

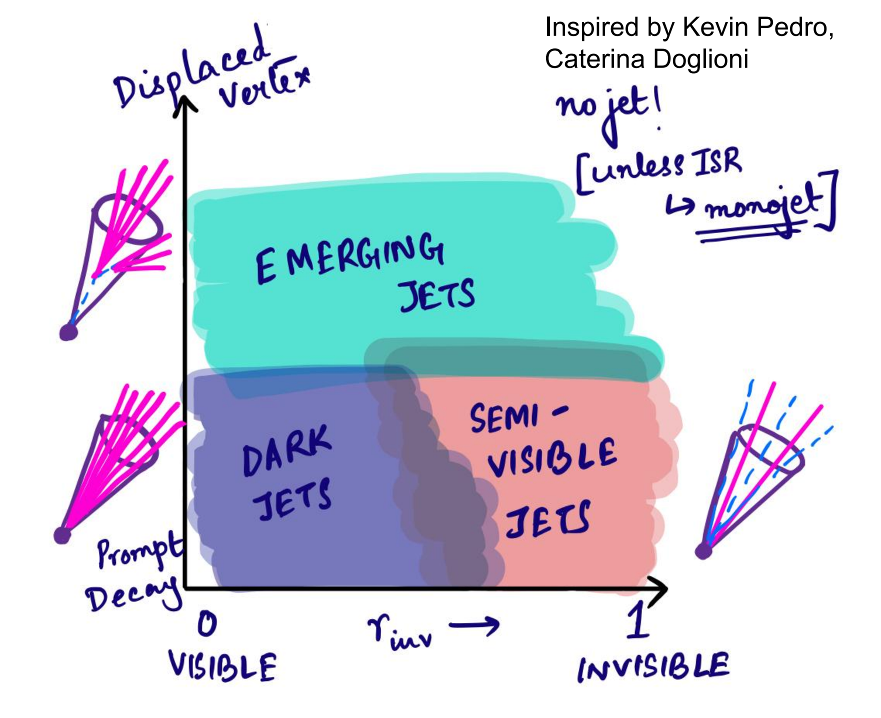
Looking at unusual topologies and hidden corners of the phase space

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

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

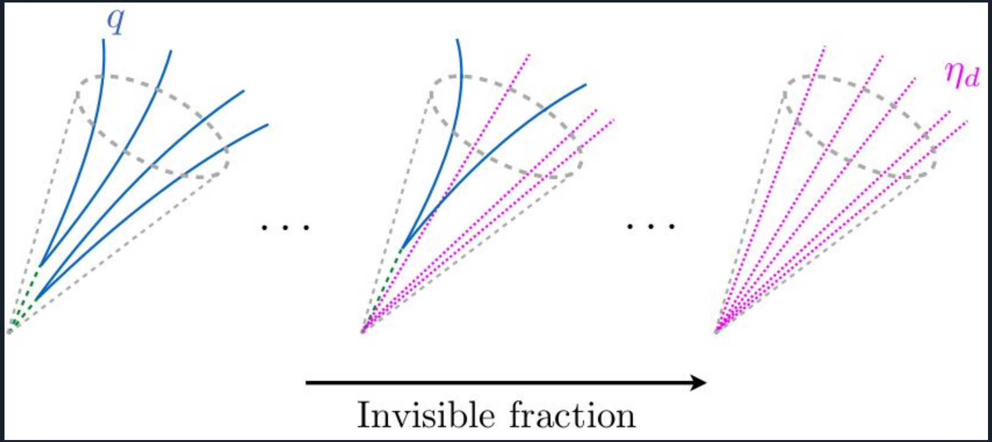
or partially back to visible sector (semi-visible jets)

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



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

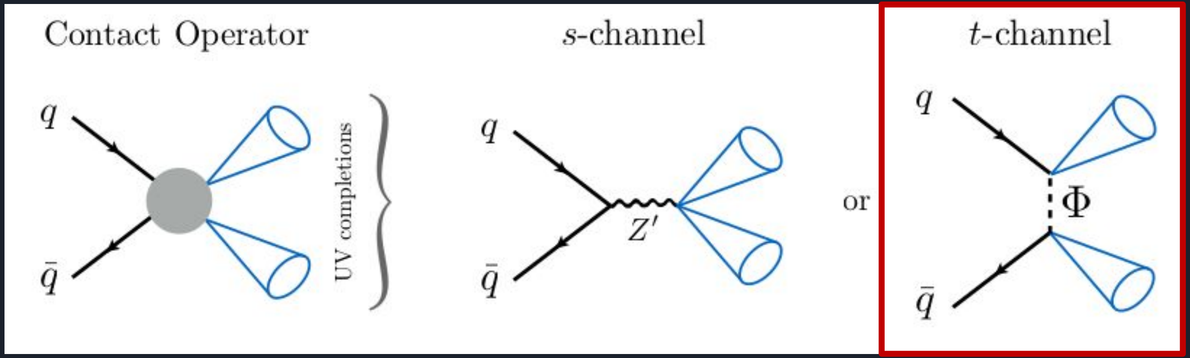
Semi-visible jet production



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

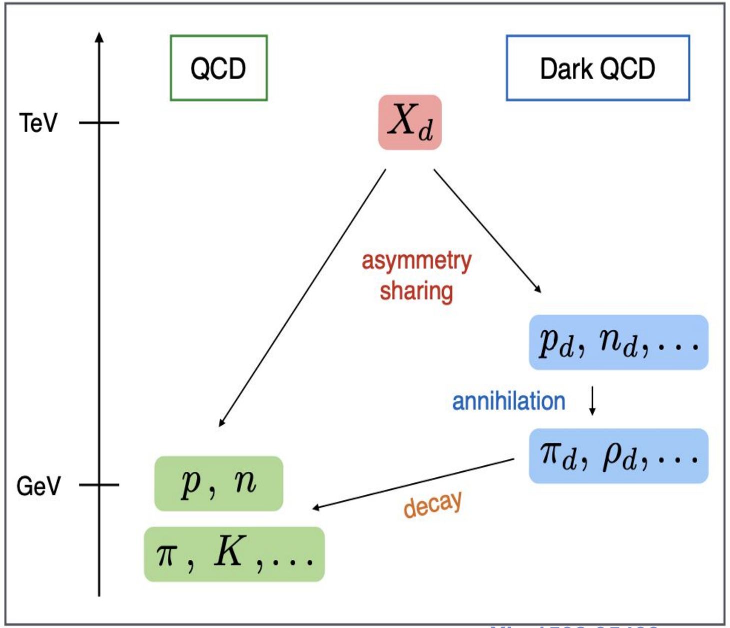
Link to the paper: https://arxiv.org/abs/1707.05326



Pythia 8 Hidden Valley Module

Two 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.

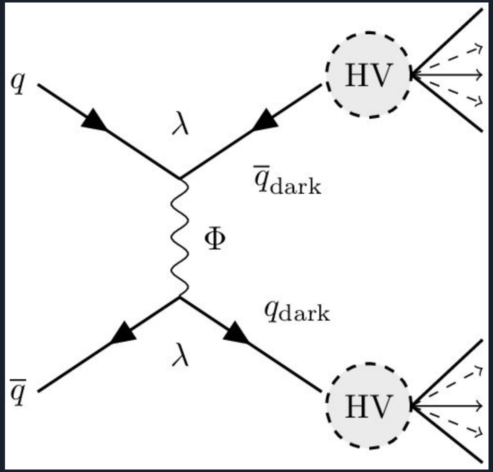
Correct DM relic density obtained when dark baryon masses are in the 10 GeV range.

Analysis 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).

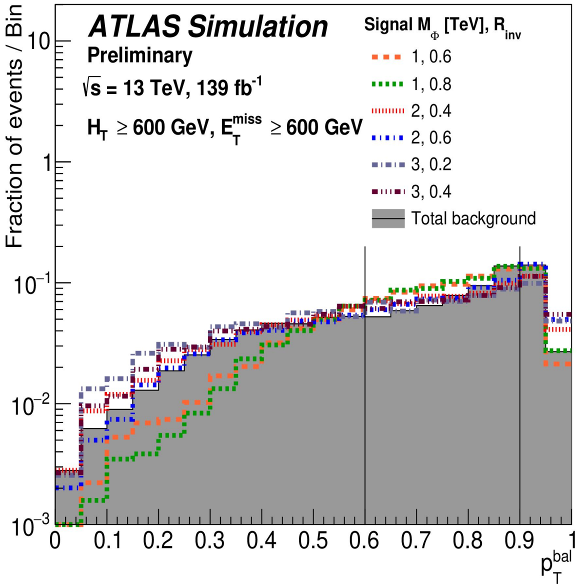
The corresponding 1L, 1L1B and 2L control regions (CR) defined using leptonic selections (and leptons added back to MET) with same MET and H_T requirements as in SR.

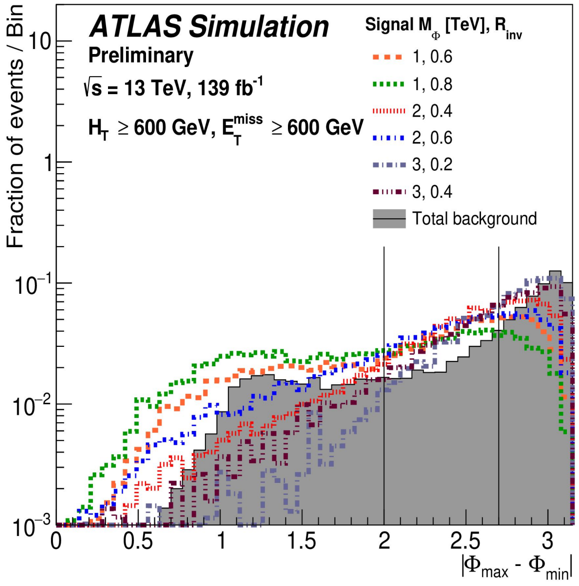
Key Observables

1. the p_{T} balance between the closest jet (j_1) and farthest jet (j_2) from $E_{\mathrm{T}}^{\mathrm{miss}}$ direction, termed as $p_{\mathrm{T}}^{\mathrm{bal}}$:

$$p_{\mathrm{T}}^{\mathrm{bal}} = \frac{|\vec{p_{\mathrm{T}}}(j_1)+\vec{p_{\mathrm{T}}}(j_2)|}{|\vec{p_{\mathrm{T}}}(j_1|+|\vec{p_{\mathrm{T}}}(j_2)|}.$$

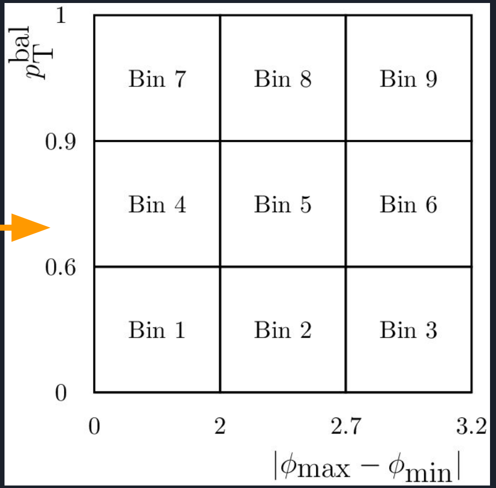
2. the difference in the azimuthal angle between j_1 and j_2 as defined above, termed $|\phi_{\max} - \phi_{\min}|$:



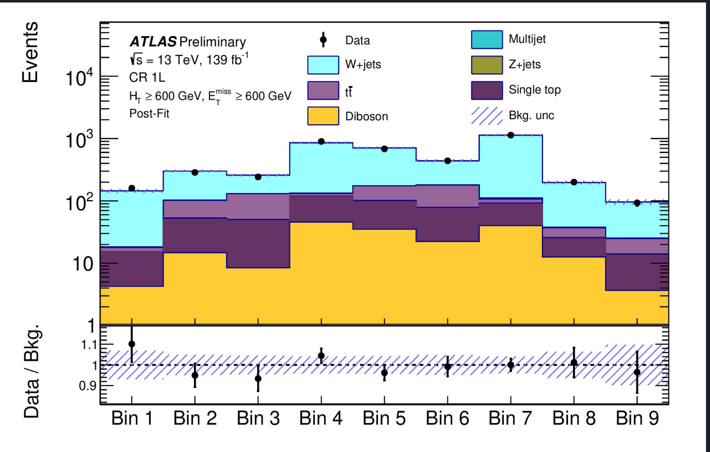


Yields in these nine bins ((3 max-minphi bins)x(3 p_{T} balance bins)) are treated as the observables in different regions.

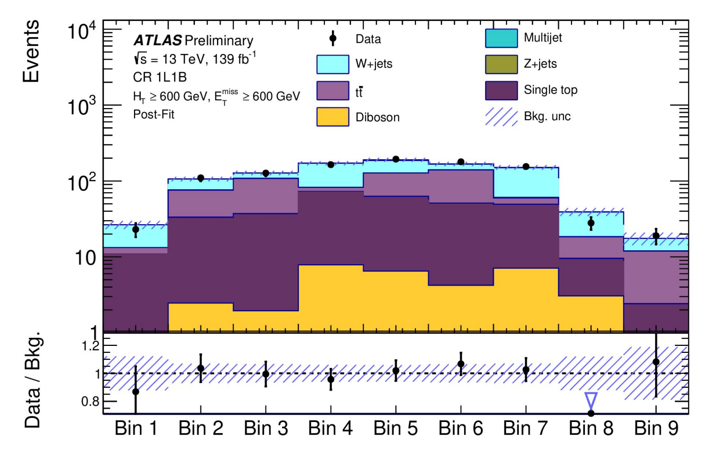
Contribution of different backgrounds is different for each of the bins, so the signal-depleted but specific background-enriched bins in the SR itself are used to estimate the background.



Fit Strategy & 9-bin histograms - CR

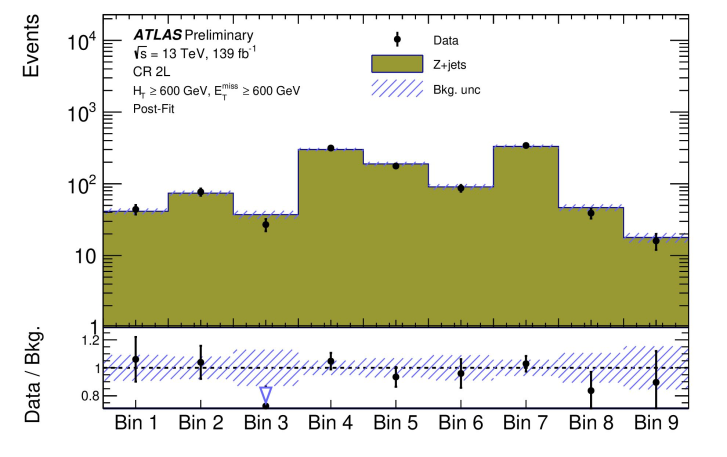


CR 1L1B: used to control ttbar / single top background contributions



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

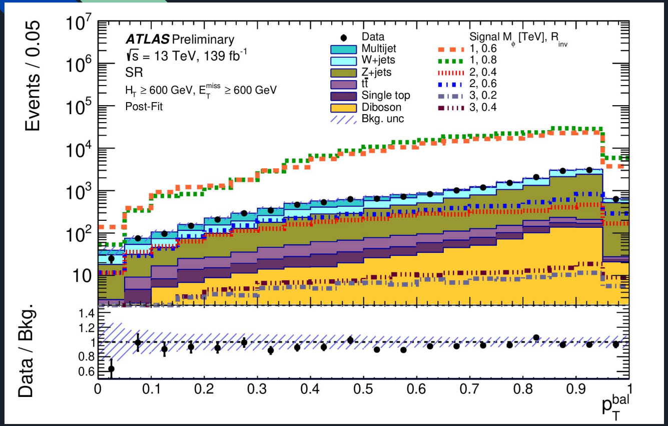
CR 2L: used to control Z+jets background contributions

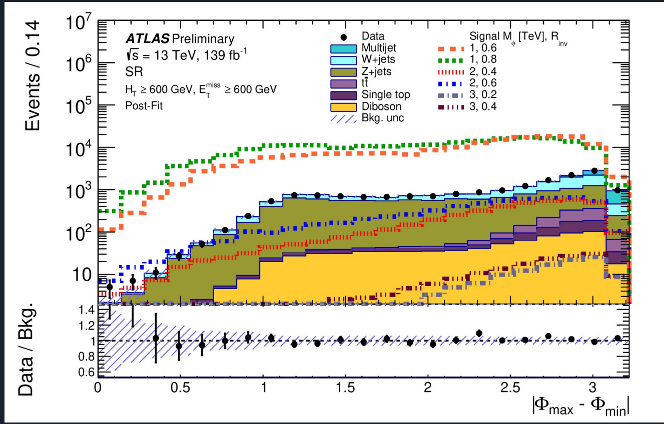


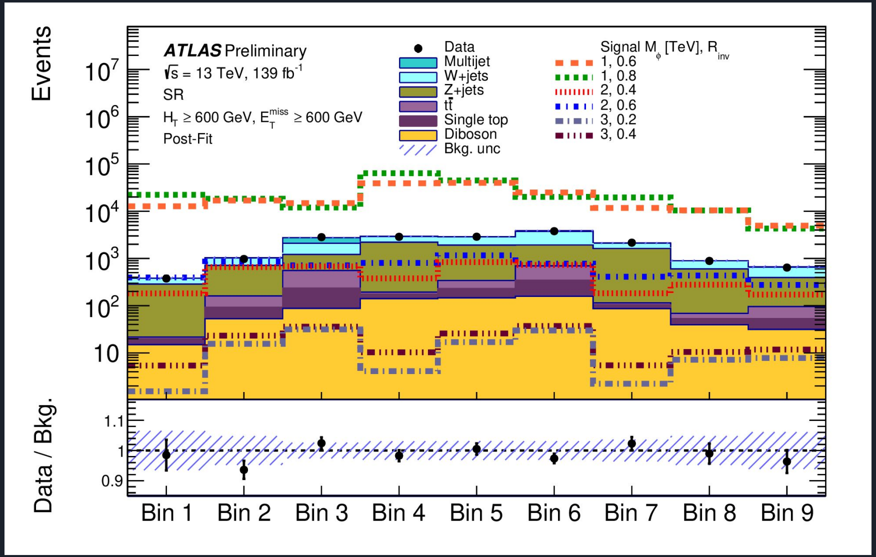
Simultaneous maximum likelihood function fit performed using the product of all relevant Gaussian and Poisson PDFs and 9-bin yields, using MC templates, with dedicated theoretical and experimental systematic uncertainties for 0L SR, 1L CR, 1L1B CR, 2L CR (details in backup)

Results…

9-bin & Kinematic distributions - SR



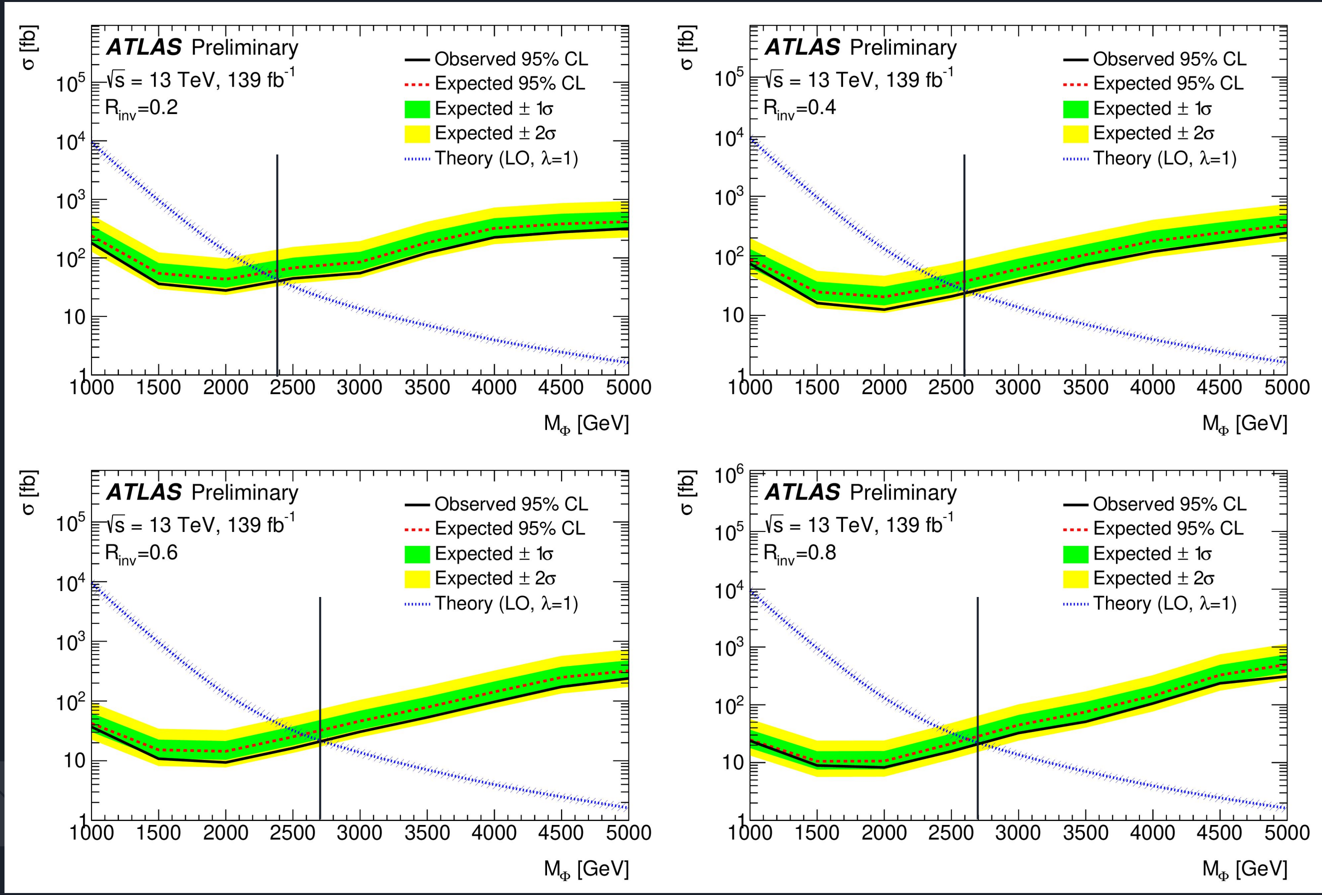




We haven't found new physics :-(Excellent agreement between data and estimated background…

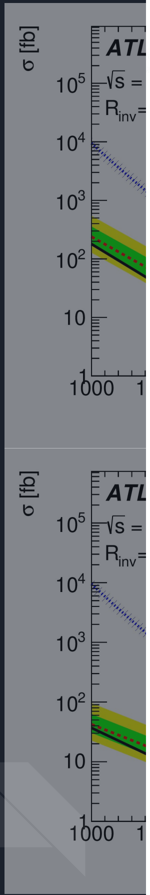
The largest post-fit effects: signal modelling uncertainties ~8%, Z+jets modelling uncertainties ~7%, top process modelling uncertainties ~4%. The rest of the contributions are less than 2%.

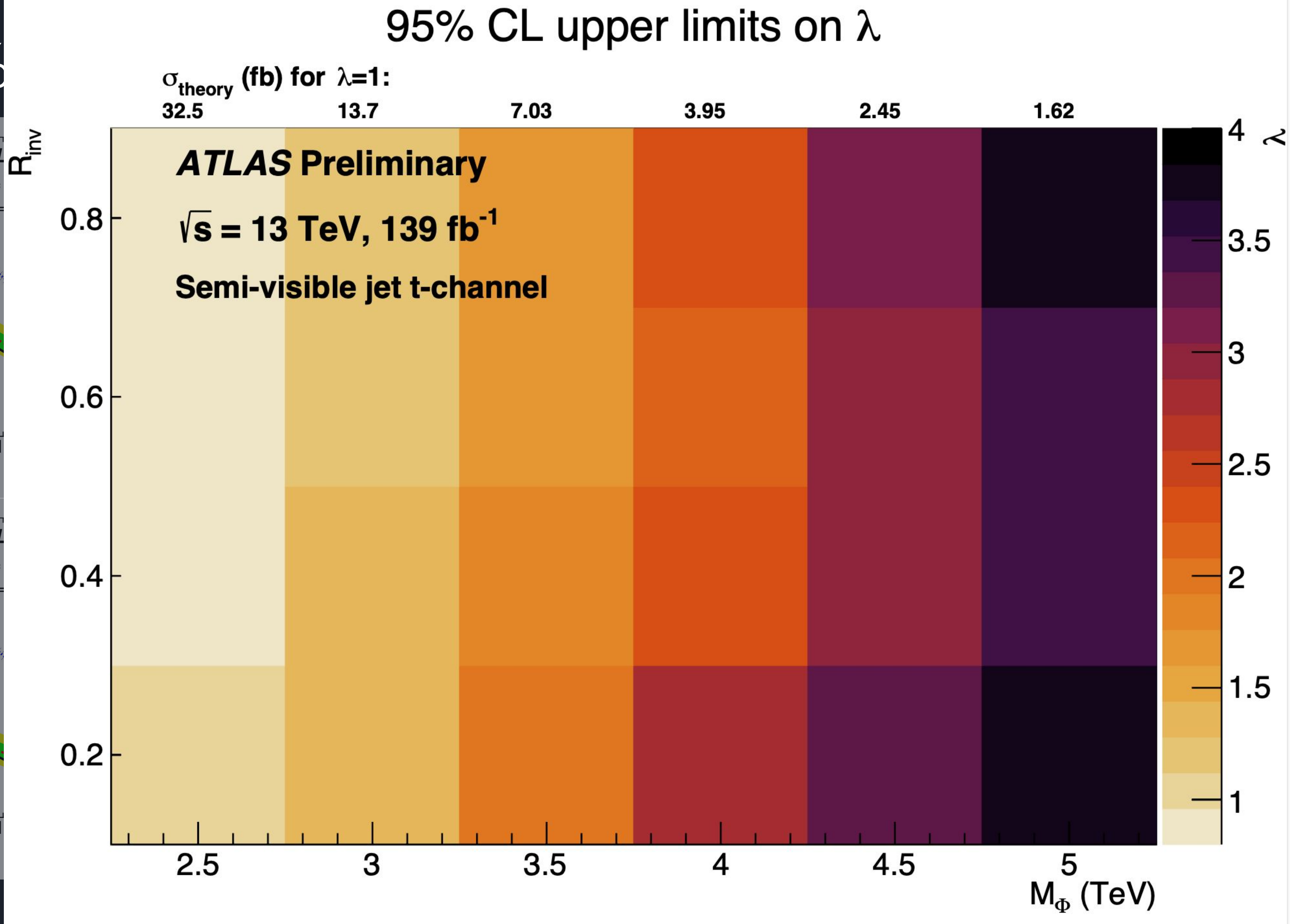
95% CL Limits on mediator mass



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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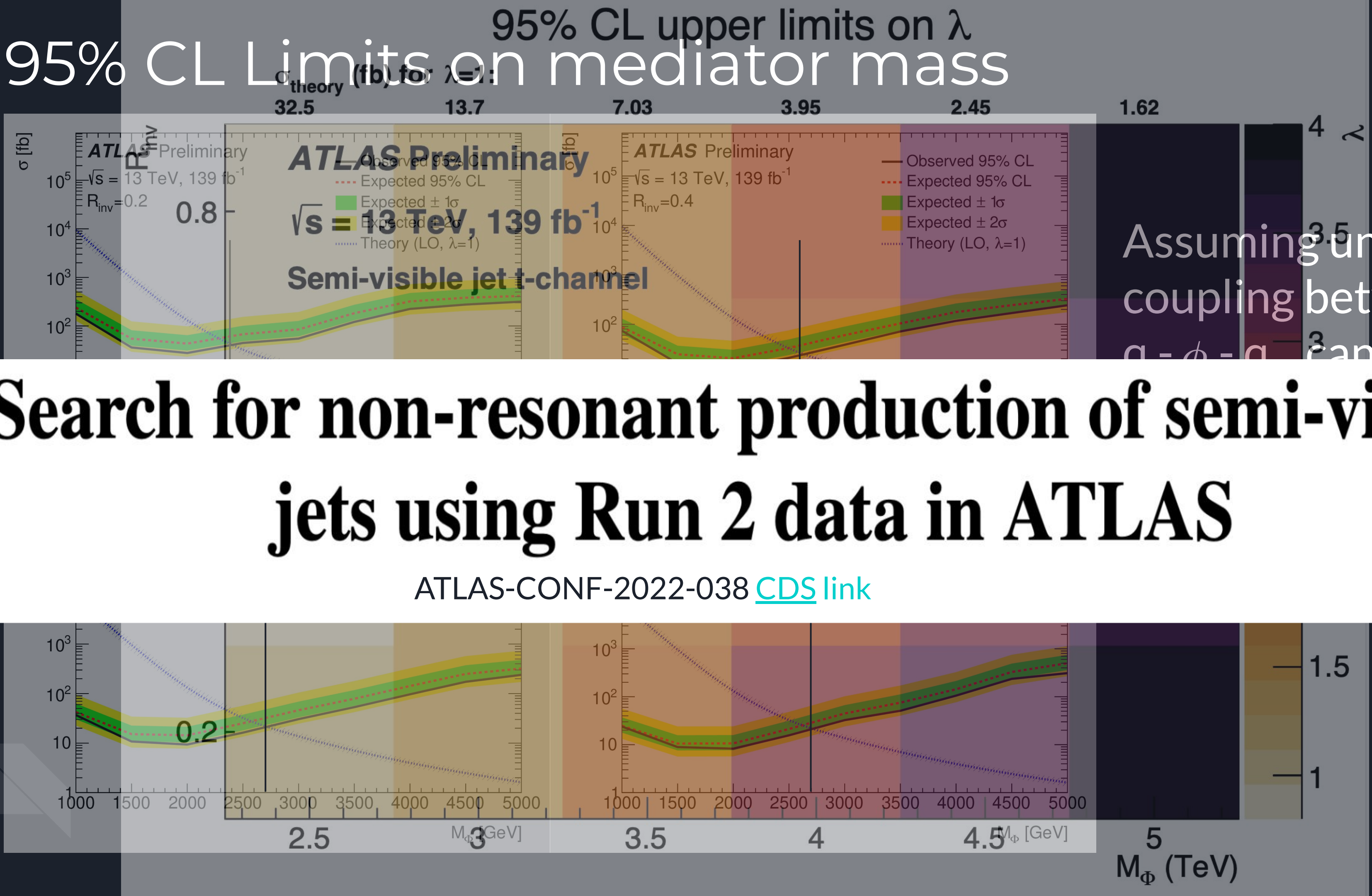

Assuming unity coupling between q - φ - q can

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

ATLAS-CONF-2022-038 CDS link

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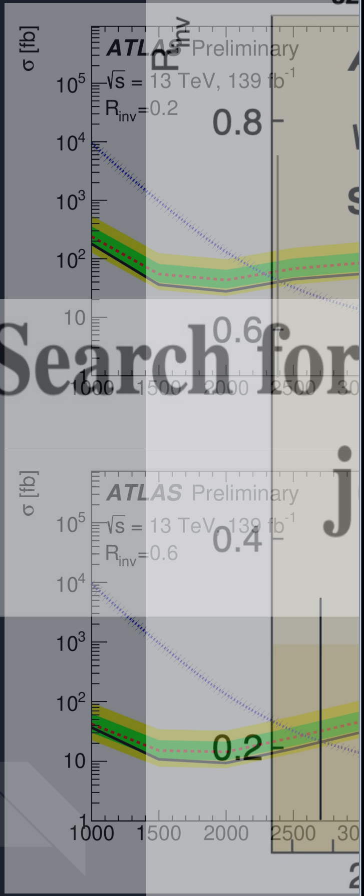

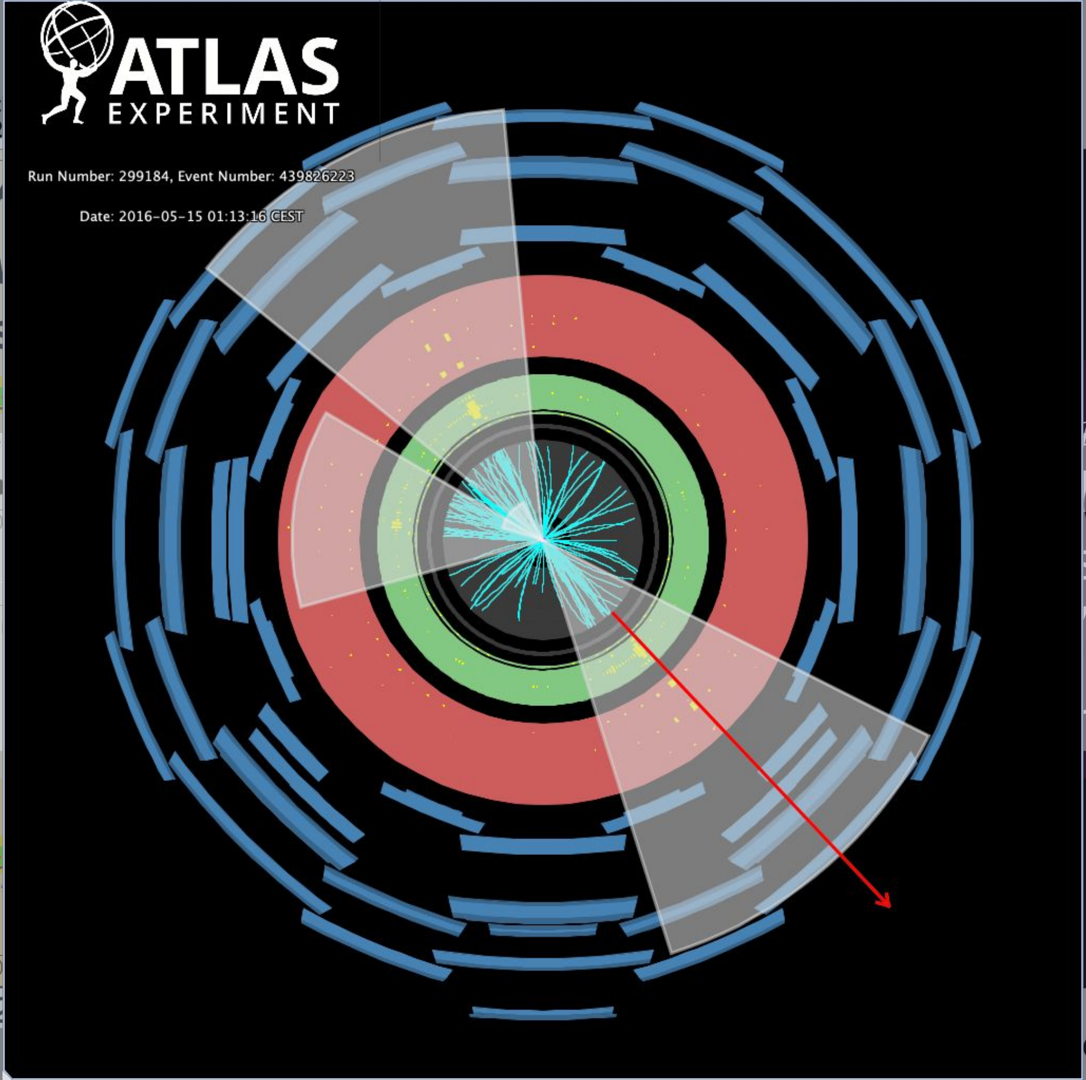

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Summary

- 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 (and new, EFP motivated) wealth of jet substructure observables *[Deepak's talk on Friday]*
- **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:

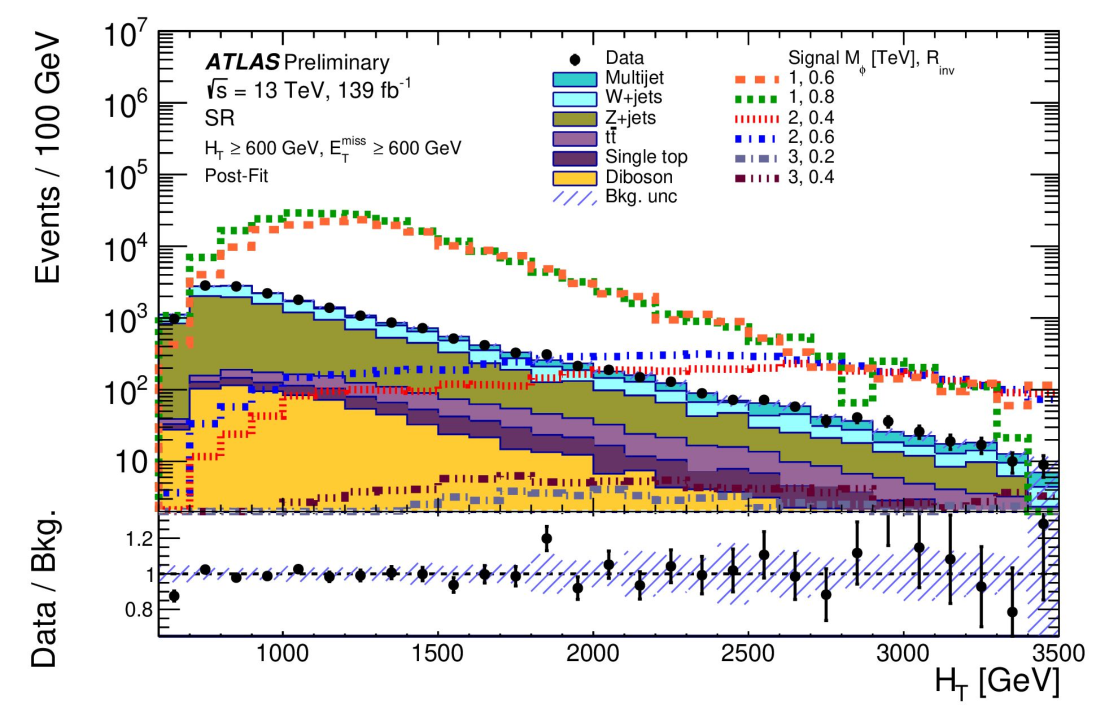
$$\mathcal{L}(\mu, \theta) = \prod_{j \in \text{ 36 bins}} \text{Poisson}(N_j^{\text{obs}} | \mu N_j^{\text{sig}}(\theta) + \sum_{i \in \text{bg}} k_i^{\text{SF}} \times N_{i,j}^{\text{bg}}(\theta)) \times f^{\text{constr}}(\theta)$$

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,

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

Kinematic distributions - SR



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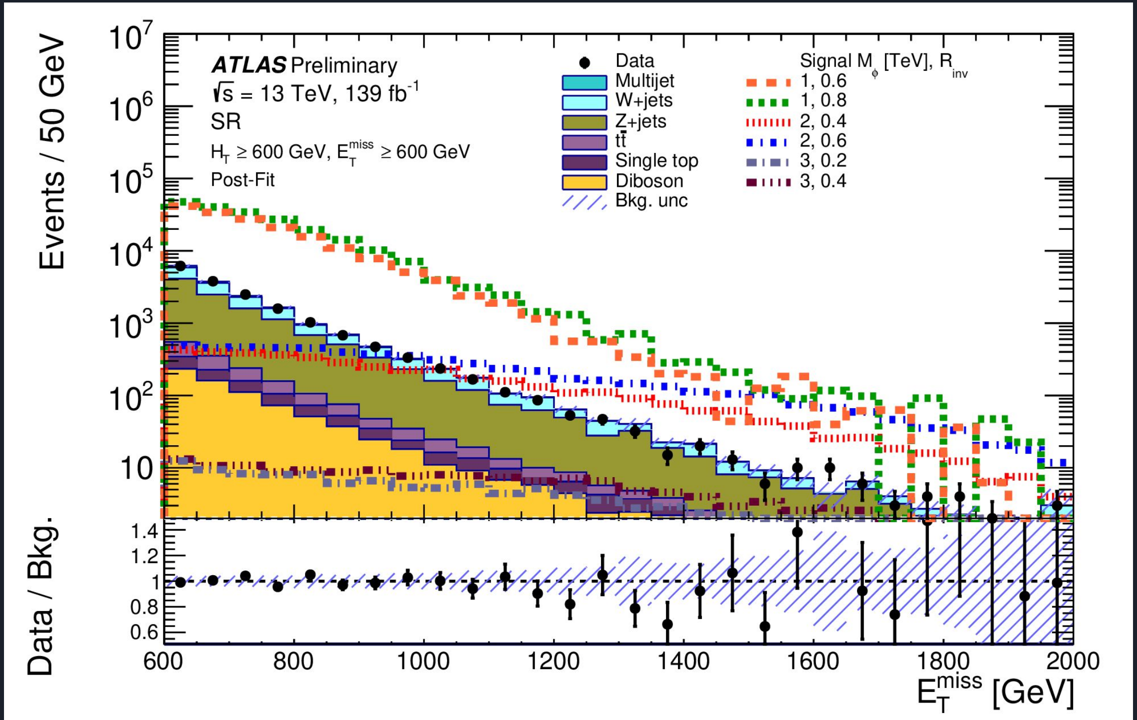

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