Dark Showers
Experimental results in ATLAS

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17-05-2024

ROADMAP OF DARK MATTER MODELS FOR RUN 3

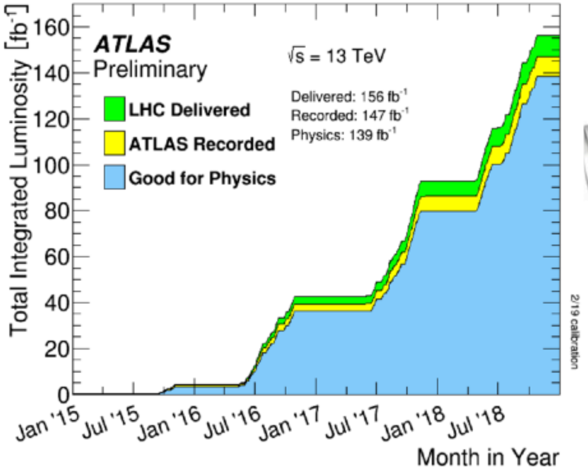
CONTENT

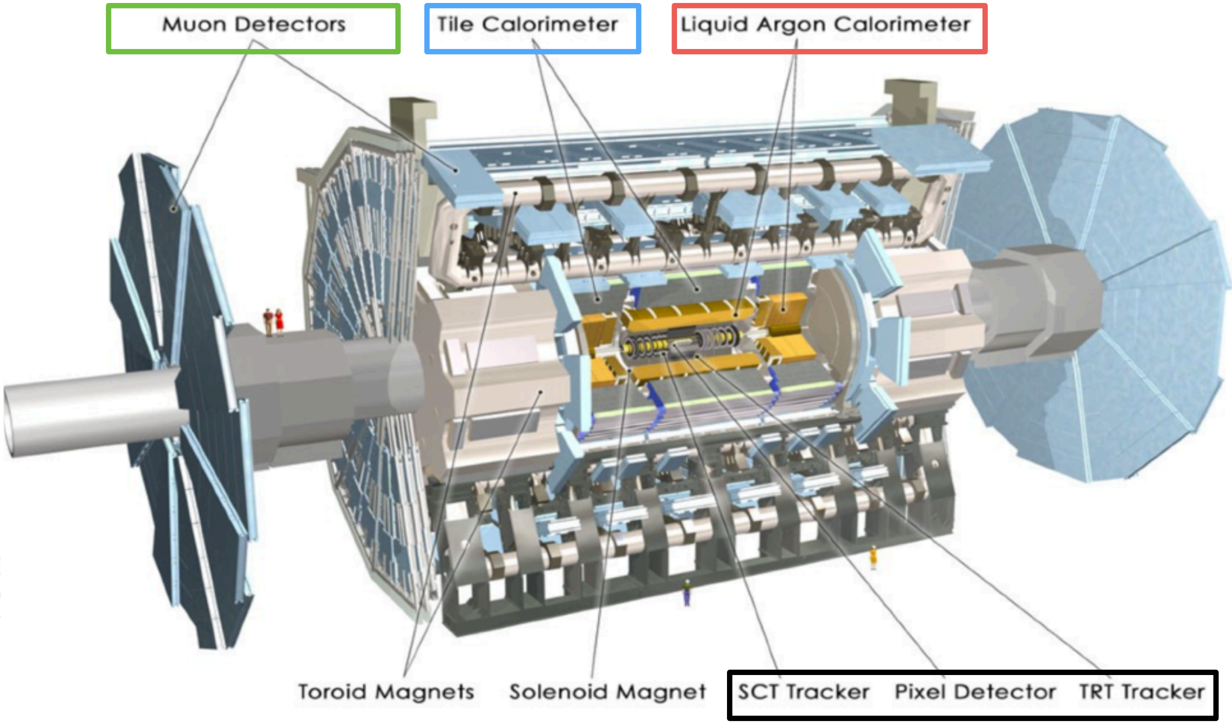
- Dark Shower Searches with ATLAS detector using Run 2 dataset
  - Search for **non-resonant production** of **semi-visible jets** [Phys. Lett. B 848 (2024) 138324]
  - Search for **resonant production** of **dark quarks** in the **dijet** final state [JHEP 02 (2024) 128]
  - Search for **dark mesons decaying to top and bottom** quarks [ATLAS-CONF-2023-021]

Run 2

$\sqrt{s} = 13$ TeV

Total luminosity~ $140\, fb^{-1}$



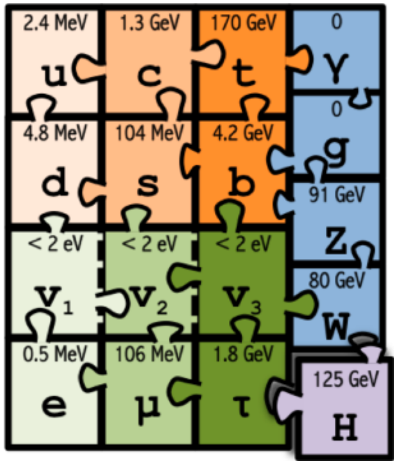


DARK SECTOR

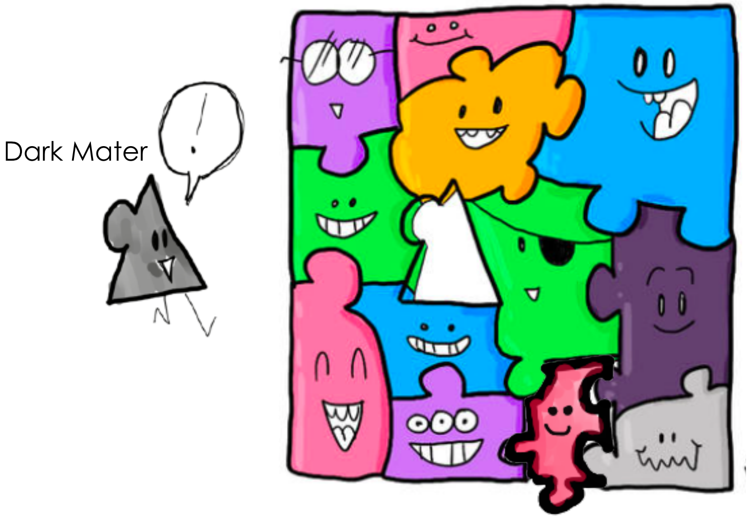
- Models with Dark Matter existing in a hidden sector, composed of particles not charged under Standard Model gauge groups
- Postulate a portal that communicates between SM and dark sectors, i.e. have dark sector state(s) that decay back to SM with small coupling.
- Phenomenologically attractive, as such models can address a lot of current gaps in the SM

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Standard Model



Dark Sector Chris Naish



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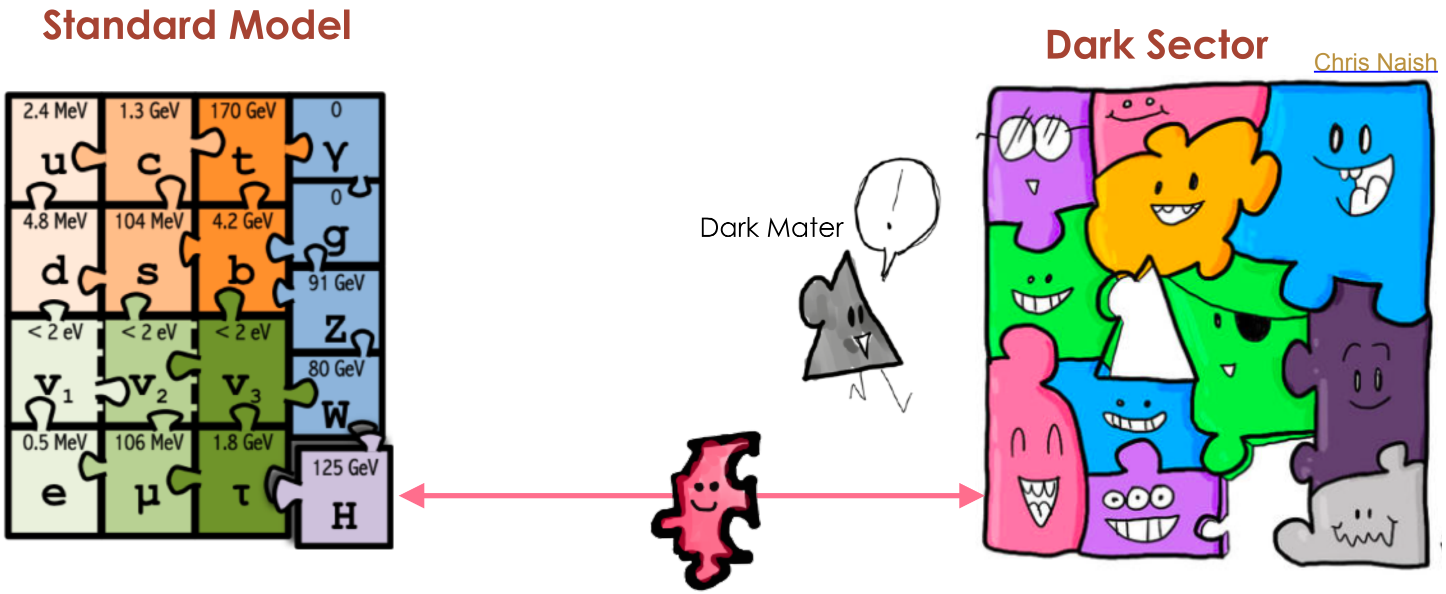
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times SU(N)_{BSM} \times U(1)_D$$



Standard Model

Dark Sector

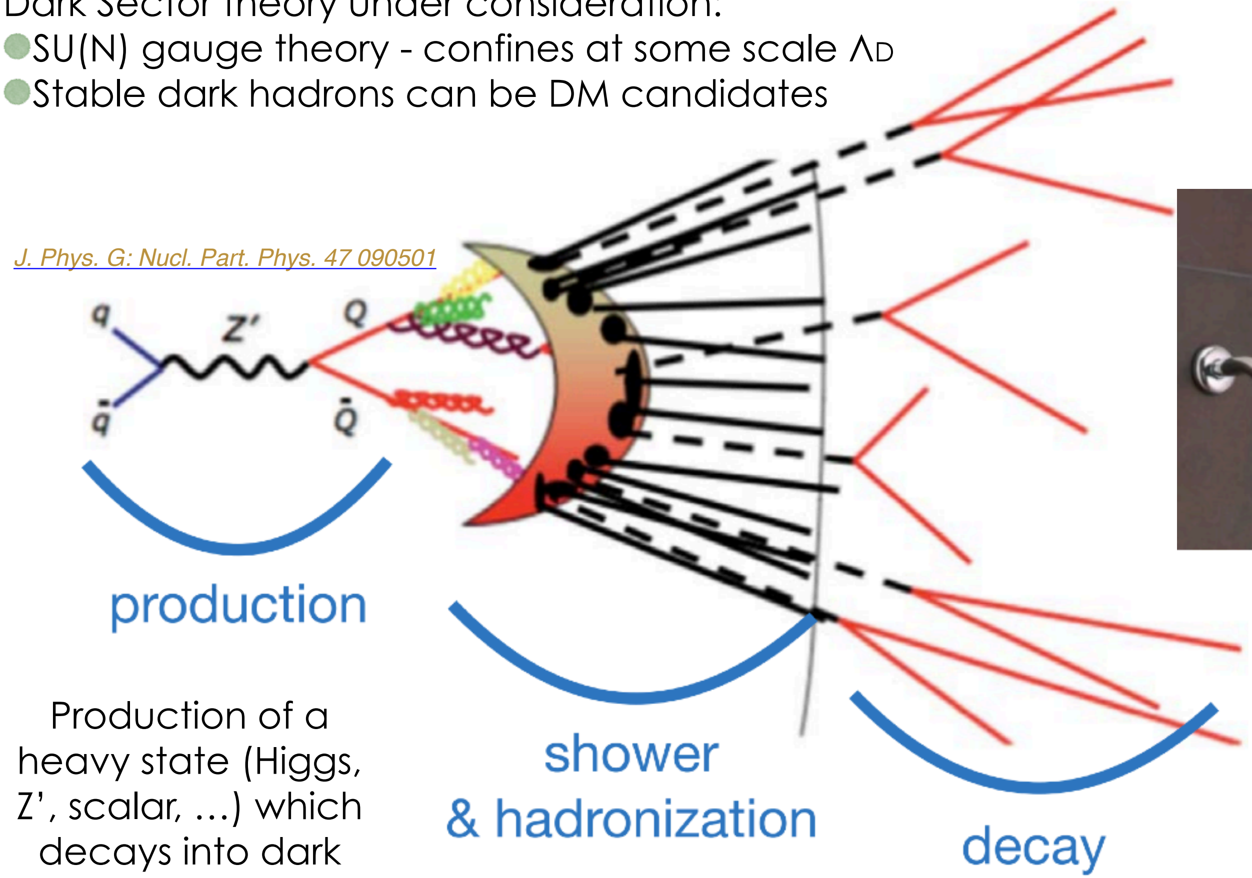
Chris Naish

Dark sectors communicate with the SM through a mediator that is charged under both the SM and hidden sector (Dark photon, Dark Higgs, Axion, Sterile Neutrino)

STRONGLY-INTERACTING DARK SECTORS
DARK QCD/SHOWERS

Dark Sector theory under consideration:

- SU(N) gauge theory - confines at some scale Λ_D
- Stable dark hadrons can be DM candidates


J. Phys. G: Nucl. Part. Phys. 47 090501

Production of a heavy state (Higgs, Z', scalar, ...) which decays into dark sector

Dark states can shower and hadronize leading to some kind of dark jets (or very soft radiation patterns)

Some dark hadrons can decay back to SM particles, other will remain invisible. Some dark hadrons may have a significant lifetime

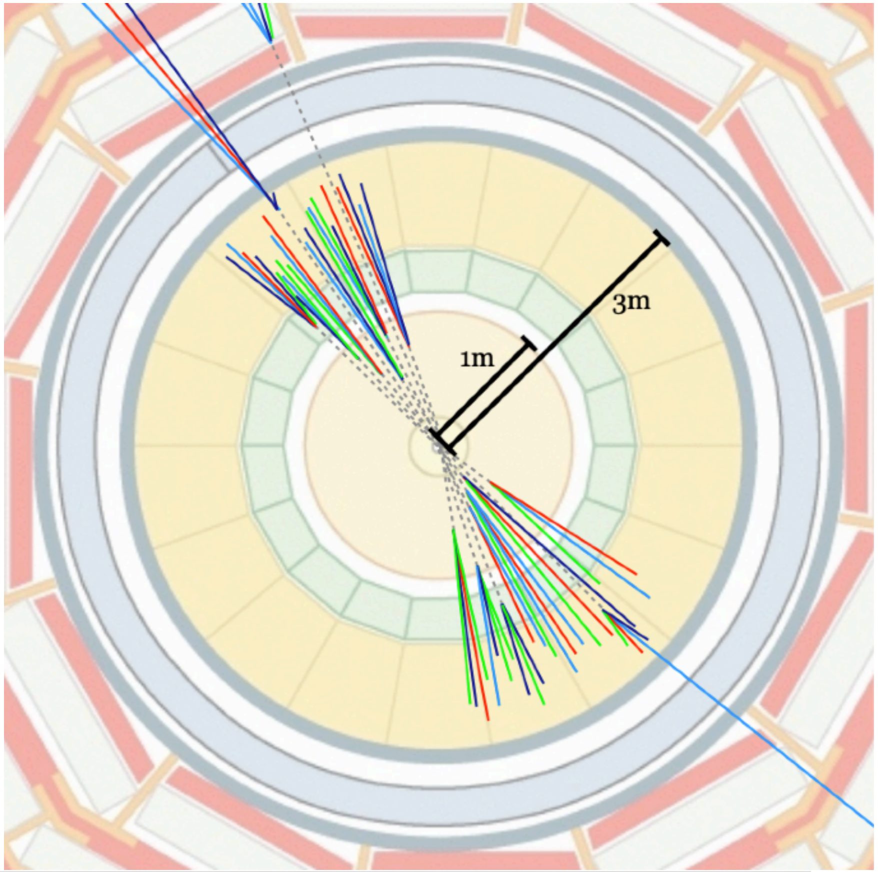
A very wide range of unusual-jet signatures to explore!

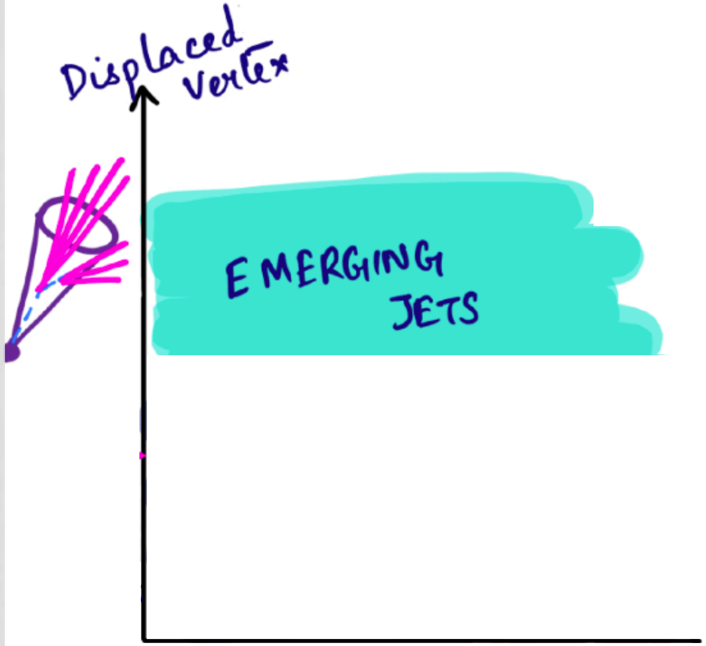
DARK SHOWER SIGNATURES

Emerging Jets

- Some dark hadrons may have a significant lifetime
- There is a notable distance between the interaction point and the decay point: Displaced Vertex!

ArXiv 1502.05409

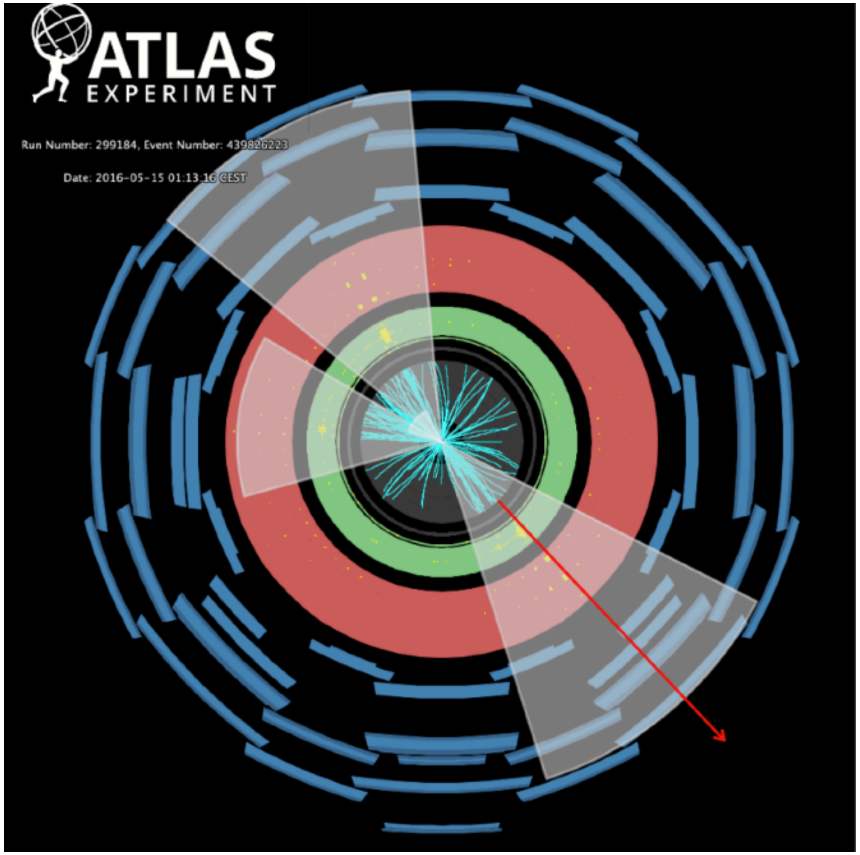




DARK SHOWER SIGNATURES

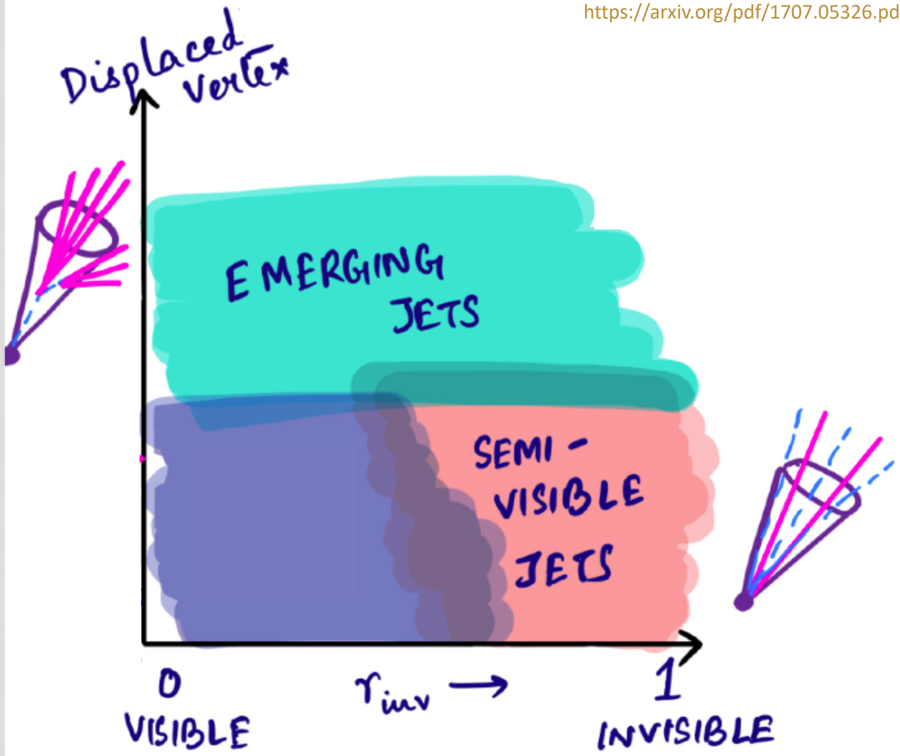
Semi-visible Jets

- Some dark hadrons may decay to SM particles, some others may remain invisible
- $\overrightarrow{E}_{\mathrm{T}}^{\mathrm{miss}}$ aligned with jet

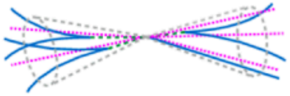


https://atlas.cern/Updates/Briefing/Semi-Visible-Jets

https://arxiv.org/pdf/1707.05326.pdf



$0 < r_{\text{inv}} < 1$ $\quad r_{\text{inv}} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$

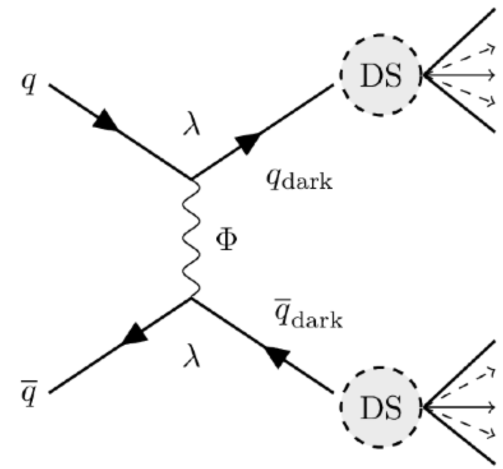


SEMI-VISIBLE JETS

Phys. Lett. B 848 (2024) 138324

Signal Model

- Bi-fundamental scalar portal
  - Focus on t-channel
  - Parameters: m_{q_d}, m_{Φ}, λ, $r_{inv} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$

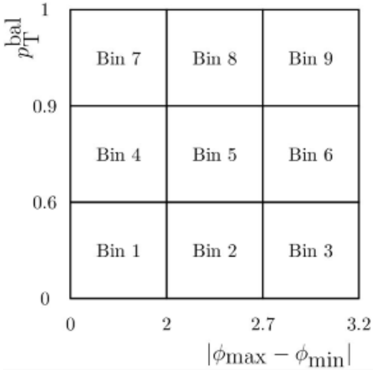


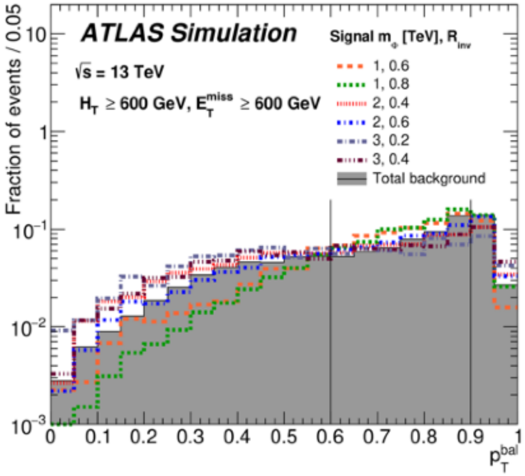
Selection

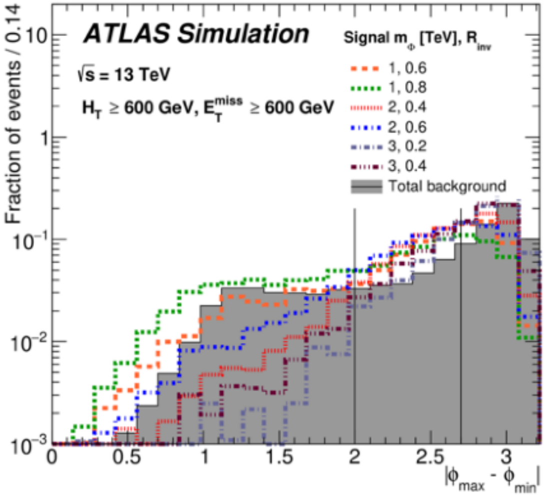
- >=2 jets, $E_{\mathrm{T}}^{\mathrm{miss}}$>200 GeV, $\Delta\phi$(closest jet, $\overrightarrow{E_{\mathrm{T}}^{\mathrm{miss}}}$) < 2
- $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- **Signal Region**: HT>600 GeV, MET>600 GeV, lepton veto

Discriminants

- max-min ϕ: Difference in the azimuthal angle between j_1 and j_2 (farthest-closest from $\overrightarrow{E_{\mathrm{T}}^{\mathrm{miss}}}$)
- p_{T} balance: $p_{\mathrm{T}}^{\mathrm{bal}} = \frac{|\vec{p}_{\mathrm{T}}(j_1) + \vec{p}_{\mathrm{T}}(j_2)|}{|\vec{p}_{\mathrm{T}}(j_1)| + |\vec{p}_{\mathrm{T}}(j_2)|}$







SEMI-VISIBLE JETS

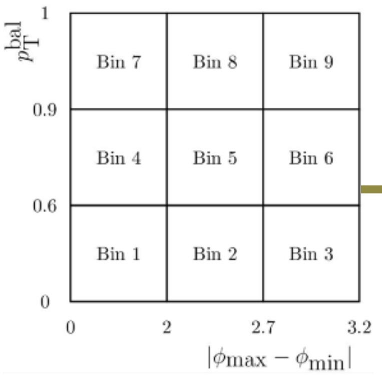
Phys. Lett. B 848 (2024) 138324

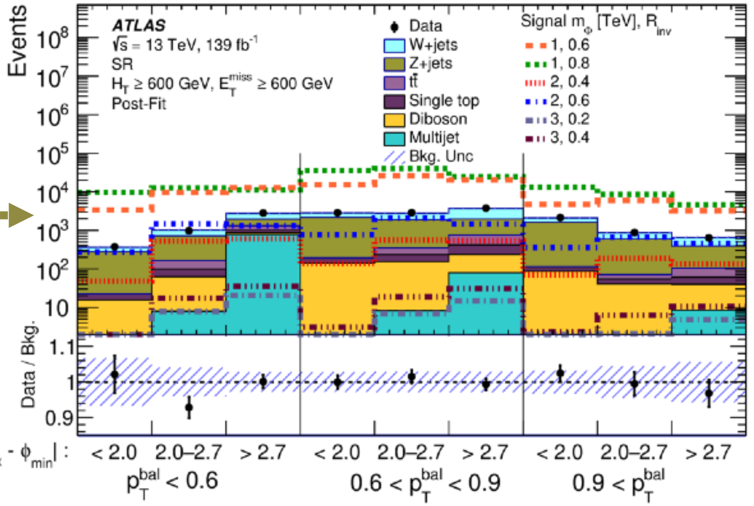
Background

- Dominant: V+jets, Top, multijets
- **Control Regions** for background estimation
  - **1L** : to constrain W+jets & single Top
  - **1L1B**: for Top
  - **2L** : for Z+jets

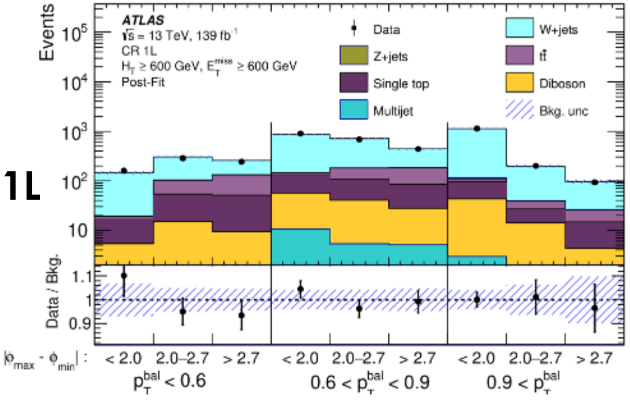
Strategy

- Simultaneous fit of the 9 bins for all regions
- Yield in each bin used as an observable

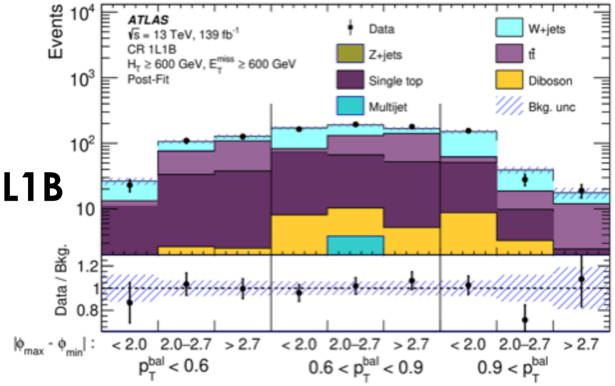




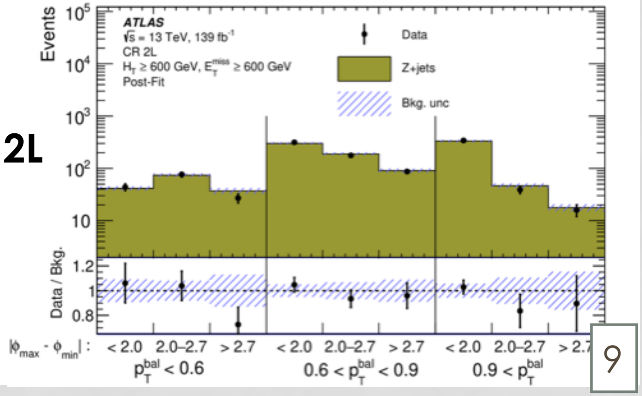
1L



1L1B



2L

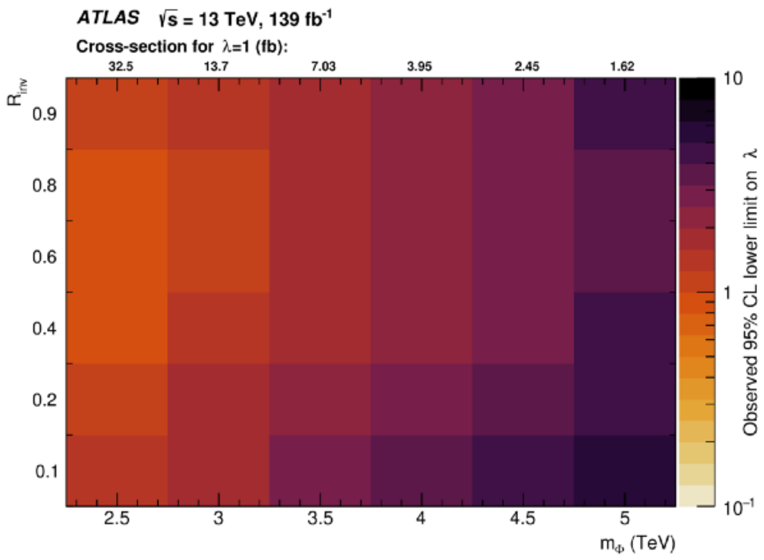


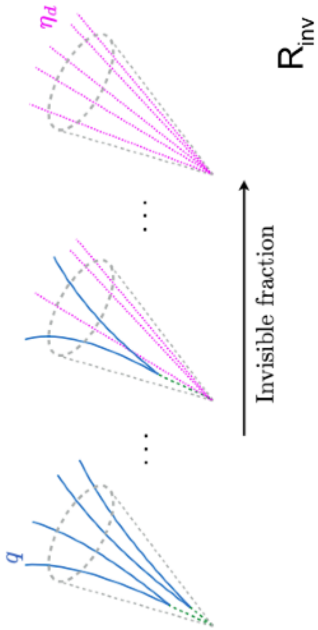
SEMI-VISIBLE JETS

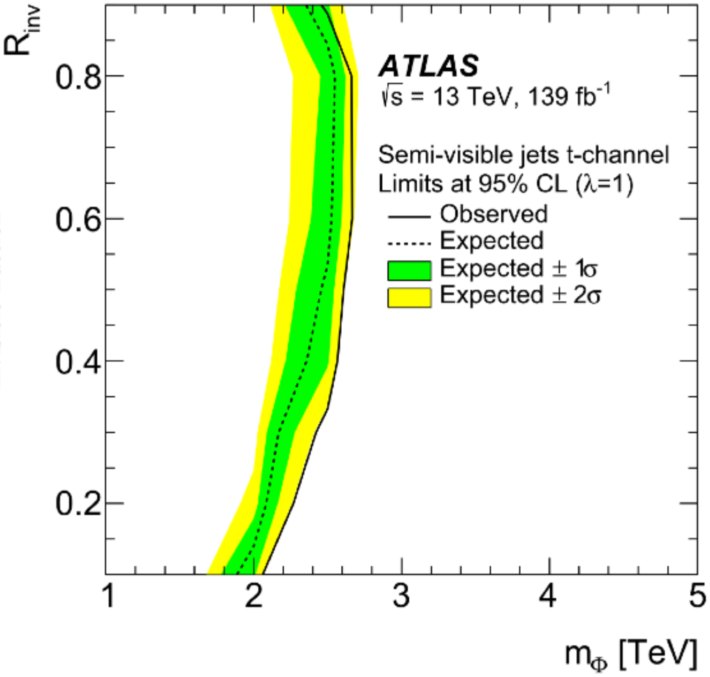
Phys. Lett. B 848 (2024) 138324

Results

- Upper limits extracted on σ as function mediator mass for different r_{inv}





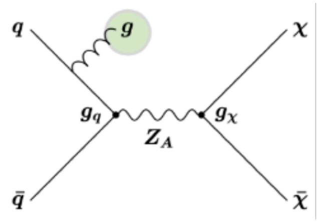


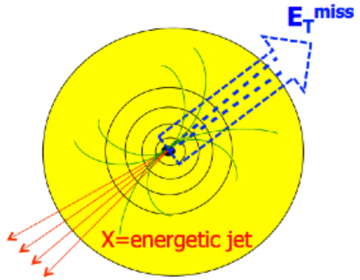
Assuming a coupling strength of unity between the mediator, a SM quark and a dark quark, mediator masses up to 2.7 TeV can be excluded

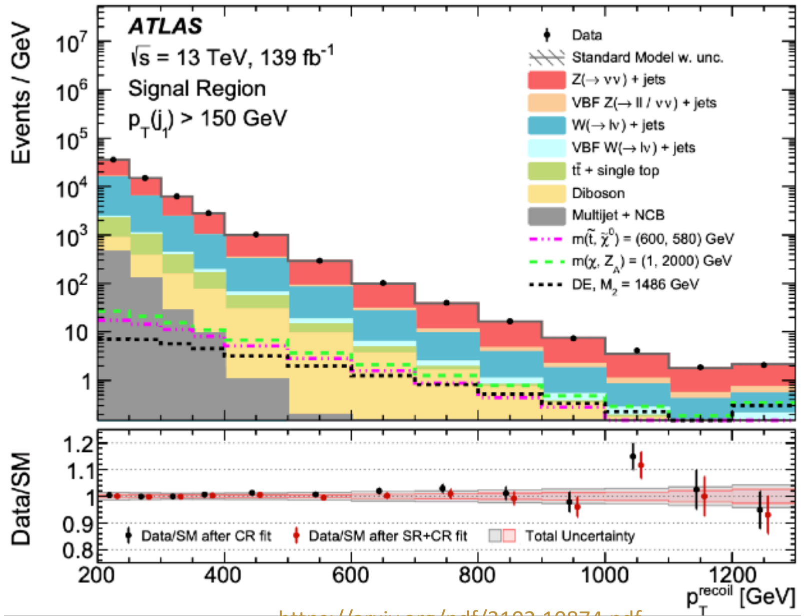
DARK SHOWER SIGNATURES

Mono-Jet

- WIMP-like: Dark hadrons are stable or collider stable. In this case the signal is like WIMP.

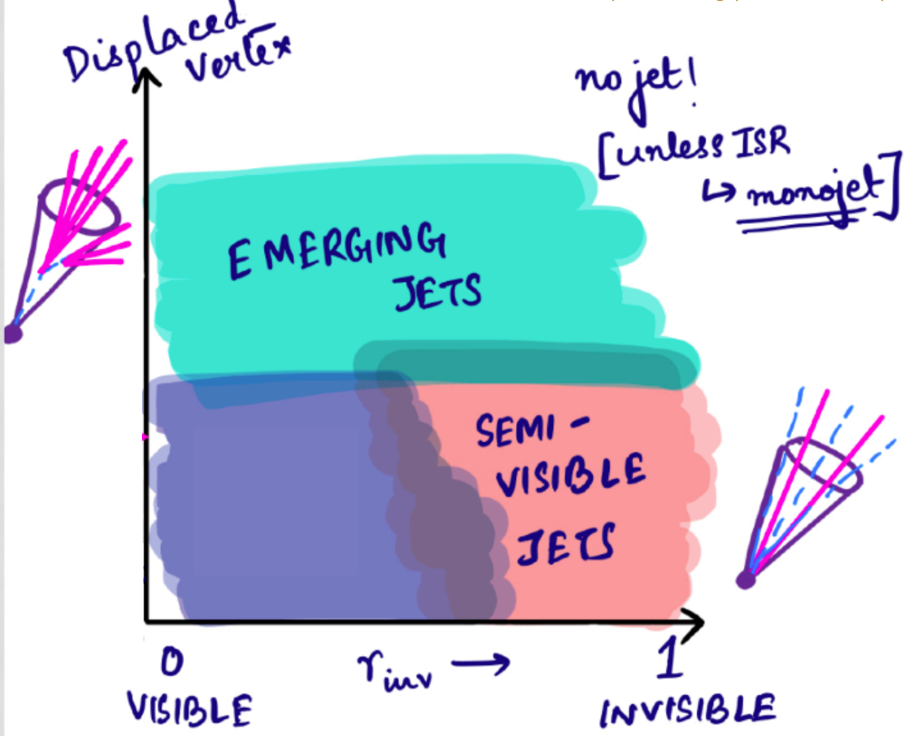


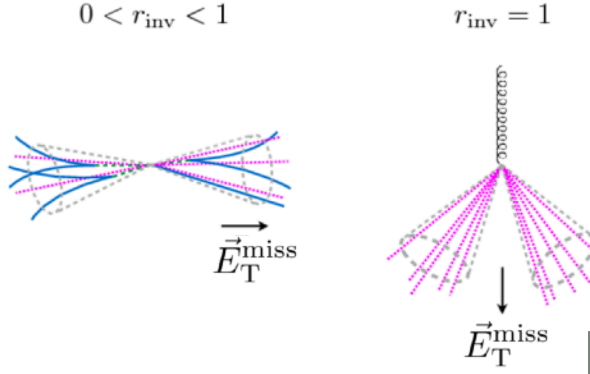




https://arxiv.org/pdf/2102.10874.pdf

https://arxiv.org/pdf/1707.05326.pdf

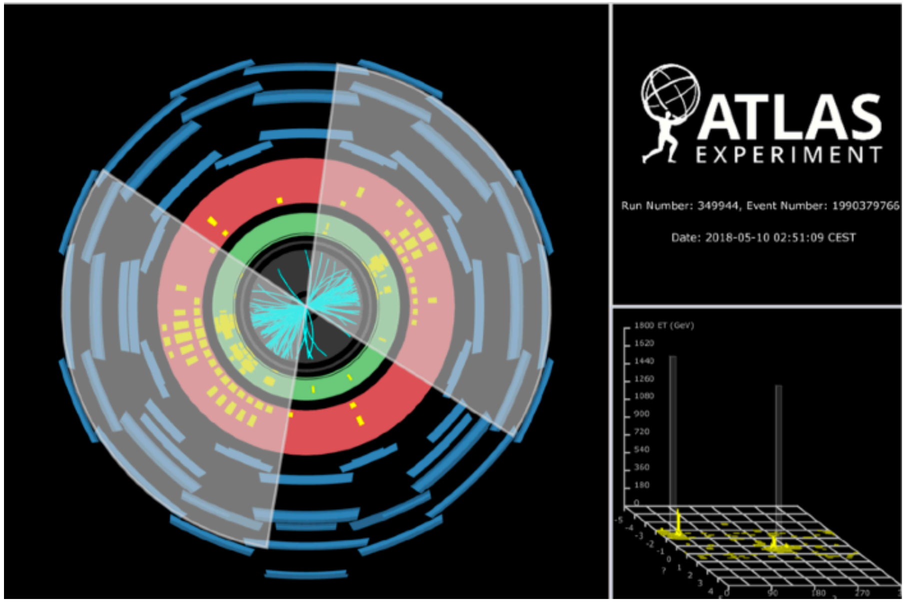




DARK SHOWER SIGNATURES

(Visible) Dark Jets

- Uncovered phase-space: QCD-like (visible) "Dark" jets
- Dark hadrons decay promptly to SM
- Dark QCD jets looks like SM QCD jets.



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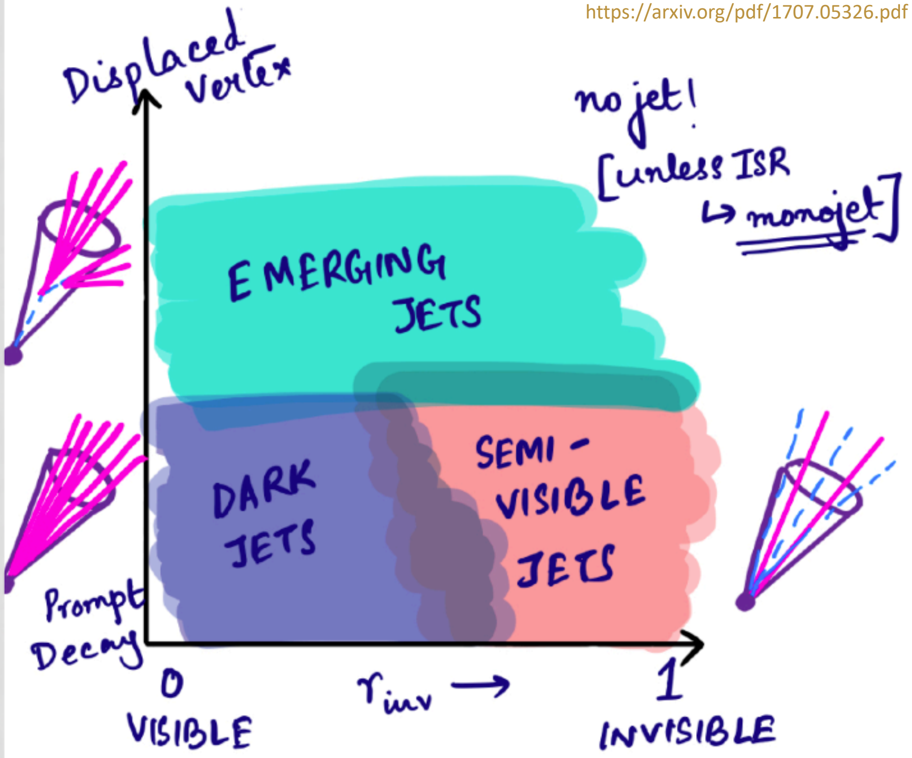
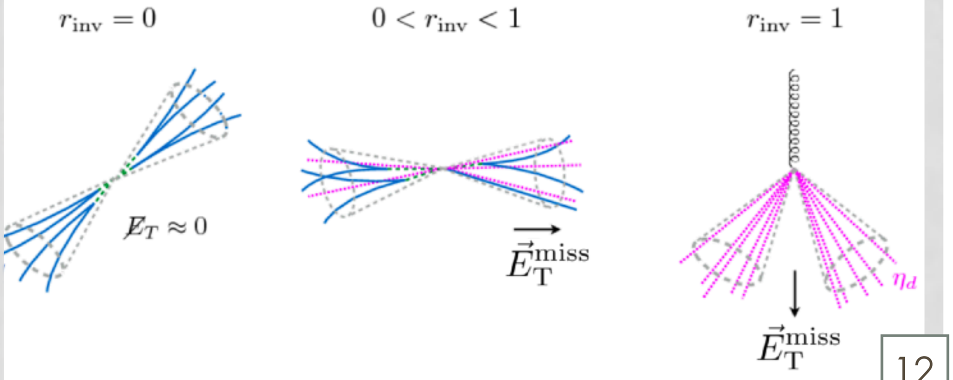


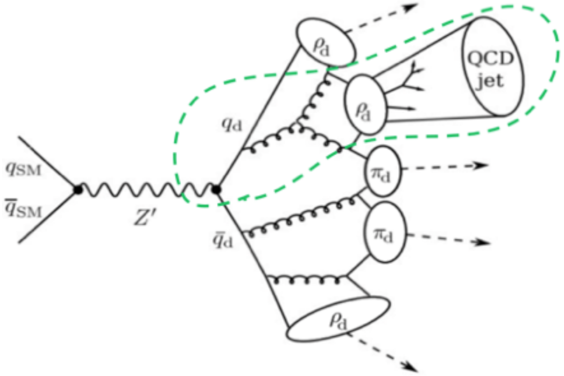


(VISIBLE) DARK JETS

JHEP 02 (2024) 128

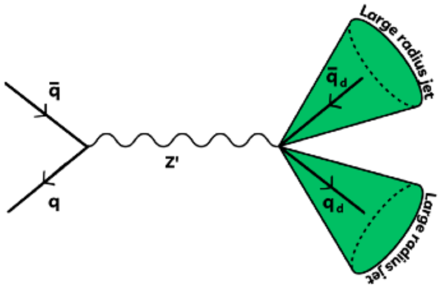
Signal Model

- Heavy Z' mediator arXiv:1712.09279
  - 4 different benchmark models (A, B, C, D)

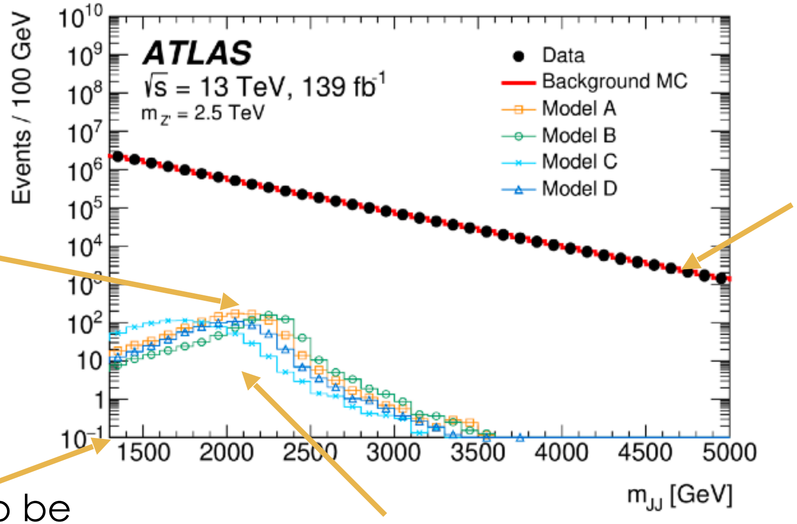


Selection

- **Trigger** on Large-R jets
- **Select** events with 2 central and high p_T Large-R jets



Look for a resonant excess in the di-jet invariant mass distribution above QCD background



Signal xsec is arbitrary (depends on the Z' coupling)

Bin size ~ exp. resolution

Lower mJJ bound to be above trigger turn-on

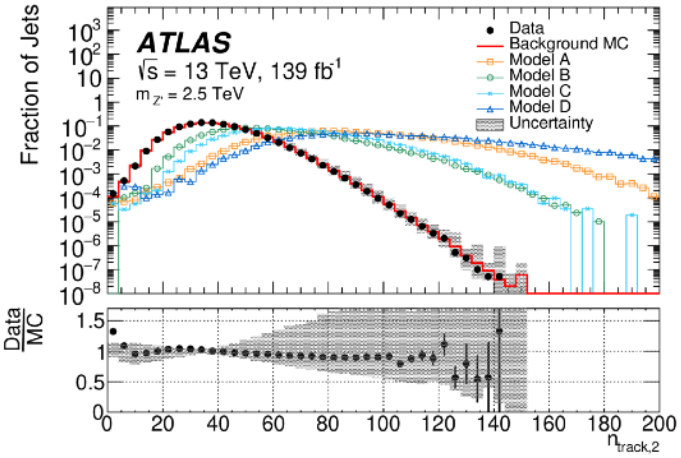
Signal width are quite large (~15%) and shifted

(VISIBLE) DARK JETS

Strategy

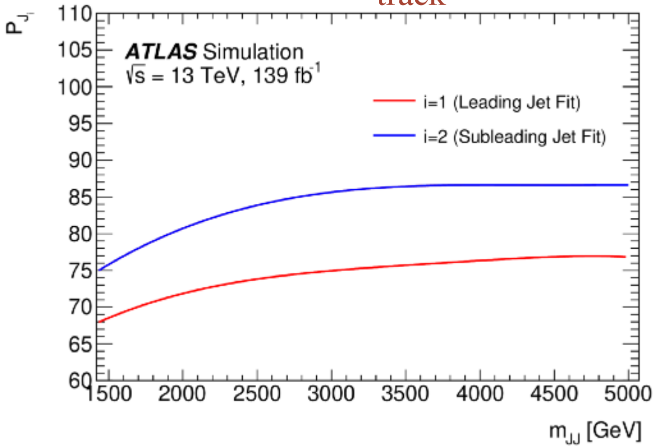
1) Tag Dark Jets!

- Number of tracks inside jet, n_{track}, is a strong discriminating variable.
  - A $\mathbf{n}_{trk}$ cut sculpts the background spectrum



Discriminant

- Decorrelated from m_{JJ}: $n^{\epsilon}_{\text{track}}(m_{JJ}) = n_{\text{track}} - \mathrm{P}(\mathrm{m_{JJ}})$
  - Targets a 1% background efficiency
  - Selecting jets with $n^{\epsilon}_{\text{track}} > 0$

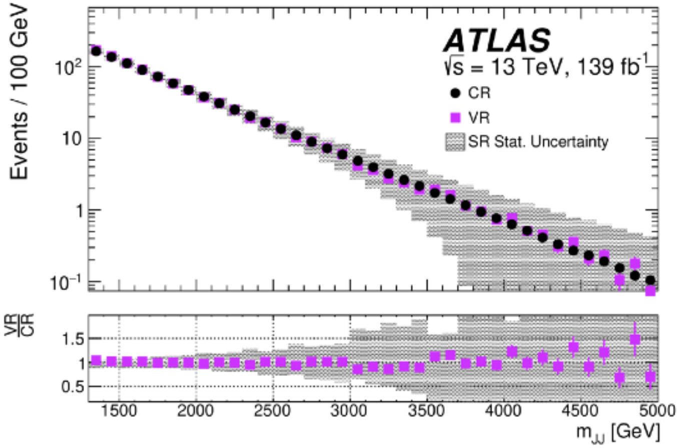


Background

2) Model a smoothly falling QCD multi jet background

- Can not be estimated with a direct fit to data due to large signal width
- Background shape fixed from data

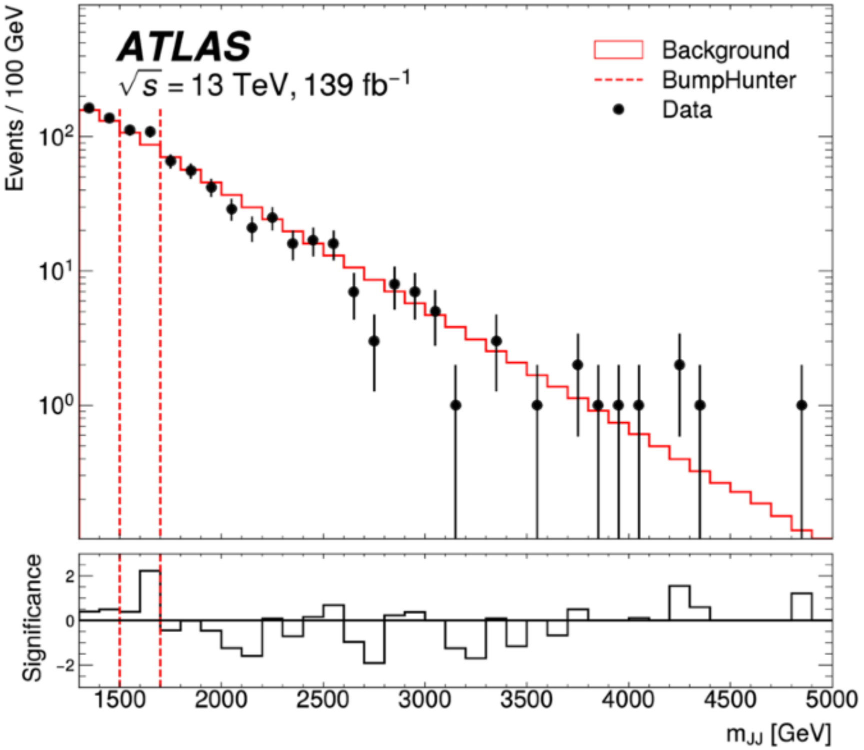
  Control Region with $n^{\epsilon}_{\text{track}} < 0$
- Normalisation is free to float



(VISIBLE) DARK JETS

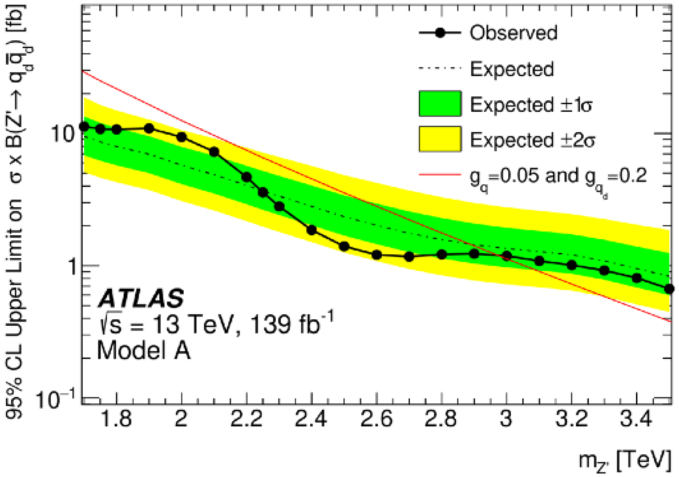
Results

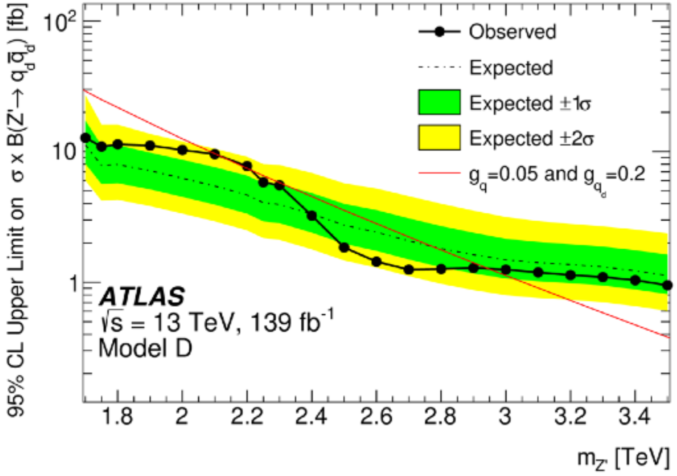
Look for resonance over the data-driven background



- No significant excess was observed
- Exclusion depends on the model, but can reach 3-3.5 TeV for some models for which the usual $Z' \to q\ q$ search cannot say anything

Limits on $\sigma \times Br(Z' \to q_d\ \bar{q}_d)$





First such search at LHC!

DARK QCD SIGNATURES

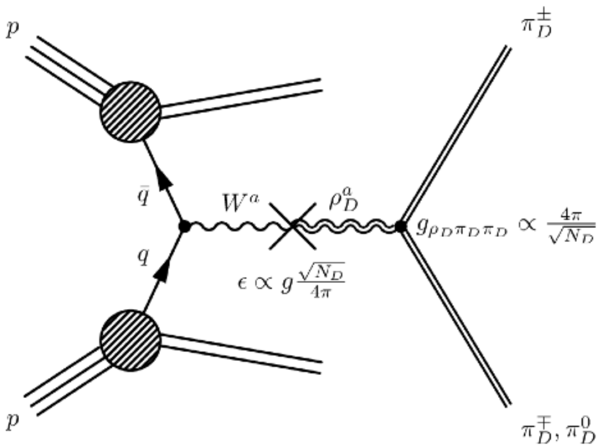
- Portal does not need to be a new exotic mediator
- Dark pions could be produced by SM bosons or dark rho (η = mπ/mρ < 0.5)

Search for Dark Mesons

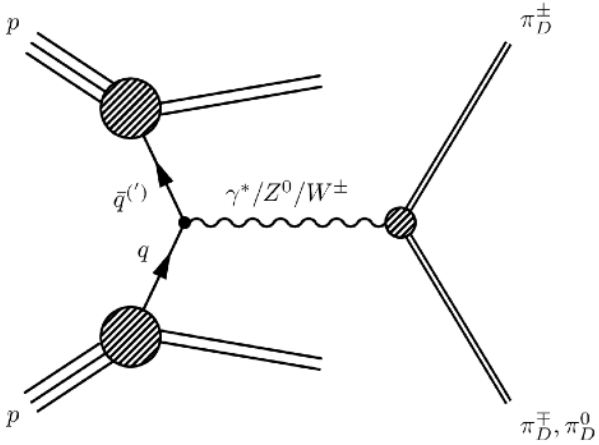
ATLAS-CONF-2023-021

- Two Stealth DM models JHEP08(2019)020 with dark pions decaying promptly back to SM states (top and bottom dominating)
- Not a mediator search!

Resonant production via ρD



Drell-Yan-type production

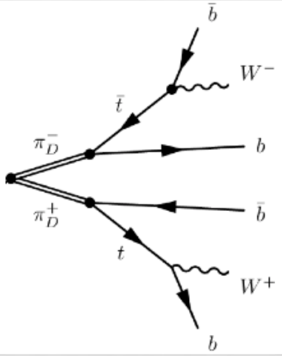


SEARCH FOR DARK MESONS

ATLAS-CONF-2023-021

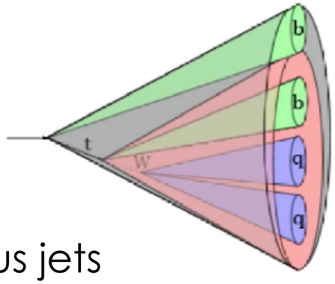
Signal Model

- Strongly coupled dark sector interacting only with the EW part of the SM
- Free parameters of model: m_{π_D} and $\eta = m_{\pi D}/m_{\rho D}$
- Focus on gaugephobic decays of dark pions into SM particles
- tttb and ttbb final states
- Dark pions π_D reconstructed with Reclustered Large-R jets



Selection

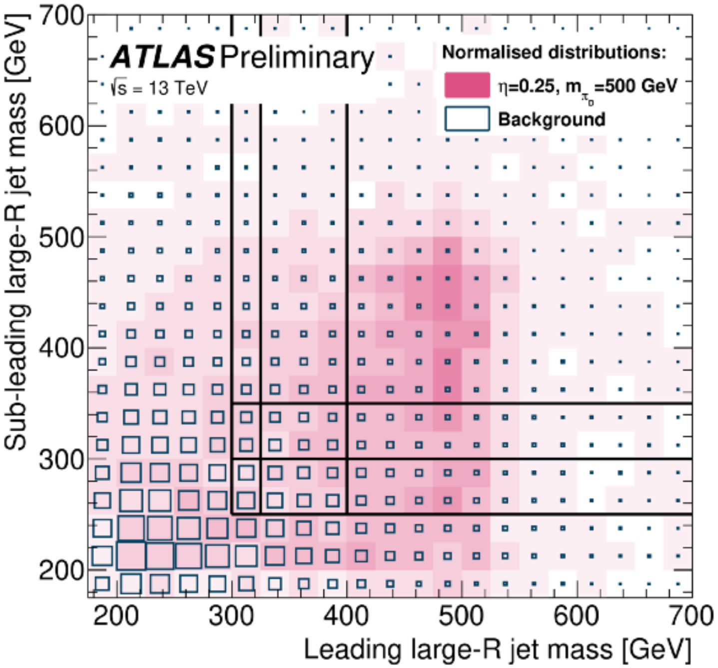
- Signature: 8–10 jets with ≥ 4 b-jets
- Triggers: $H_T = \sum |p_T^{\text{jet}}|$



- **Selection overview:** ≥2 large-radius jets with masses >250 GeV & >300 GeV for π_D, 2 b-jets with $\Delta R < 1$ & $m_{bb}/p_{T,bb} > 0.25$

Strategy

- Reconstruct each dark pion with large-R jet
  - Require each to contain two b-jets
- Categorisation: 9 SRs defined in the plane spanned by the masses of the two large-R jets



SEARCH FOR DARK MESONS

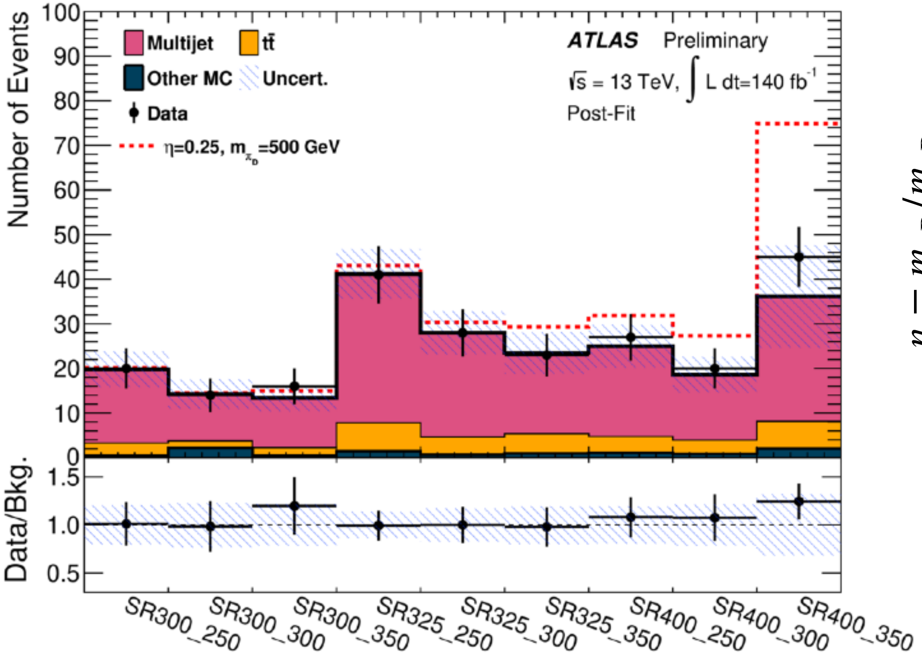
ATLAS-CONF-2023-021

Background

- Main background:
  - Multiple QCD jets
- Model:
  - Data-driven 4D ABCD estimate

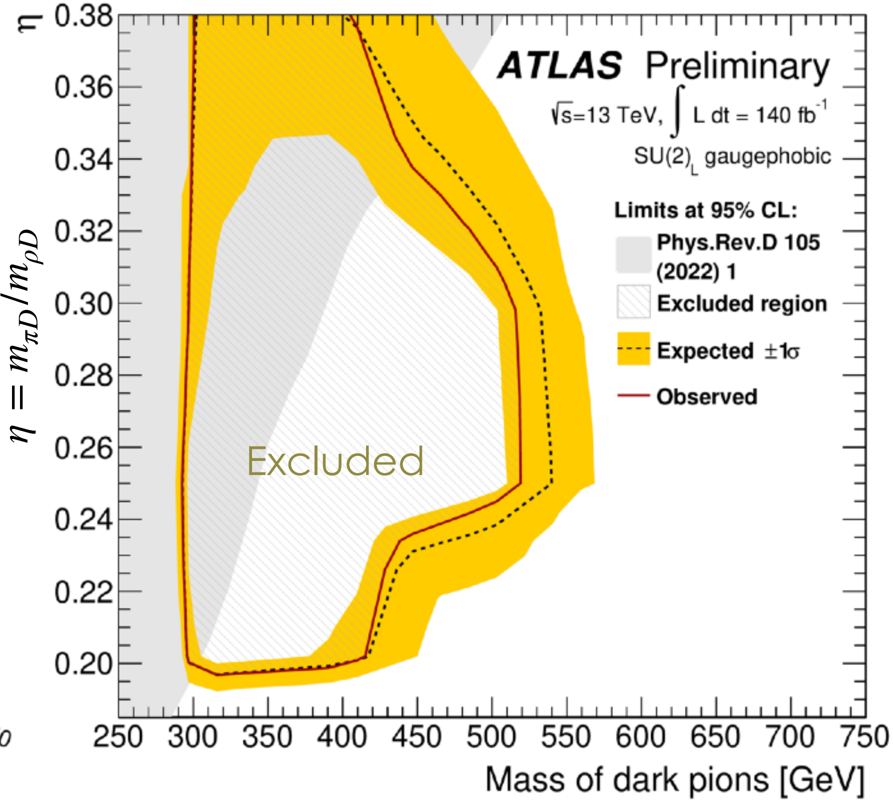
Results

- Simultaneous profile likelihood fit over all regions



- No significant excess of data events over SM expectation

First dedicated LHC search!



- (m_{π_D}, η) values in the low-medium -end are excluded

CONCLUSIONS AND OUTLOOK

- ATLAS has a wide ranging and successful collider search programme
- Now including non-WIMP searches, i.e. dark photons (2306.07413, JHEP07(2023)133), ALPS (JHEP07(2023)234), **strongly coupled dark sectors** in this talk
- More LHC Run-2 results still coming

- Run-3 dataset growing fast!
  - 350 fb-1 to be recorded
- Many new ideas, both experimental (new techniques, new signatures) and theoretical (new models, anomalies)

Sandbox Studio, Chicago with Corinne Mucha

- Semi-visible
- Dark Jets
- Dark Mesons

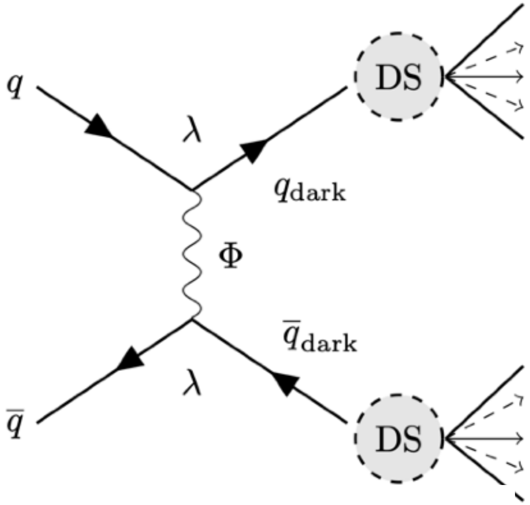
BONUS SLIDES

SEMI-VISIBLE JETS

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

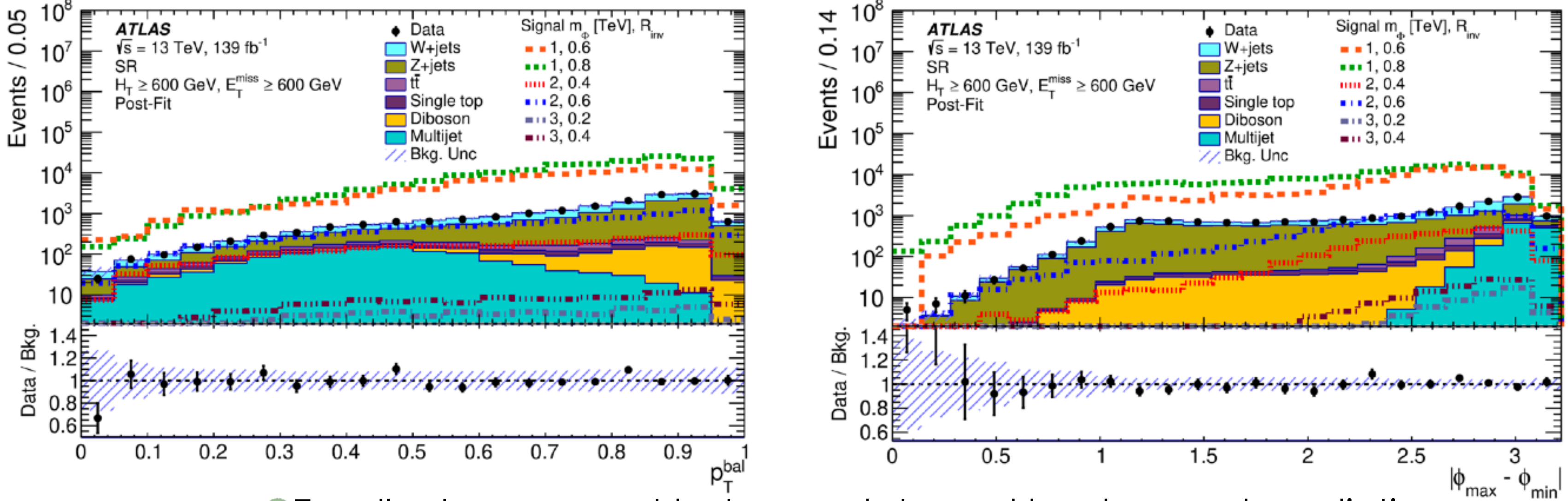
- Signals: bifundamental t-channel scalar
  - $r_{inv} = 0.1, 0.2, 0.4, 0.6, 0.8$, and 0.9
  - $m_{q_d} = 10$ GeV

$$r_{\text{inv}} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$



- >=2 jets, MET>250 GeV, $\Delta\phi$(closest jet,MET) < 2
- **Signal Region**: HT>600 GeV, MET>600 GeV, lepton veto
- **Control Regions** for BG estimation using muons
- Simultaneous fit of max $\Delta\phi$ - min $\Delta\phi$ and pT balance of jets

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



- Excellent agreement between data and background prediction.

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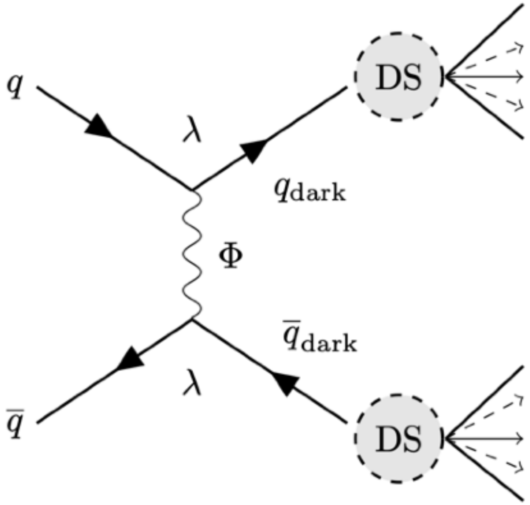
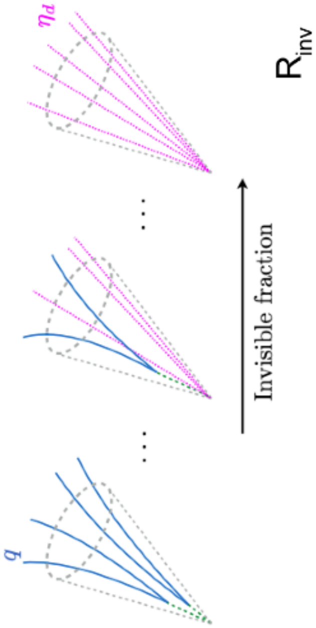
SEMI-VISIBLE JETS

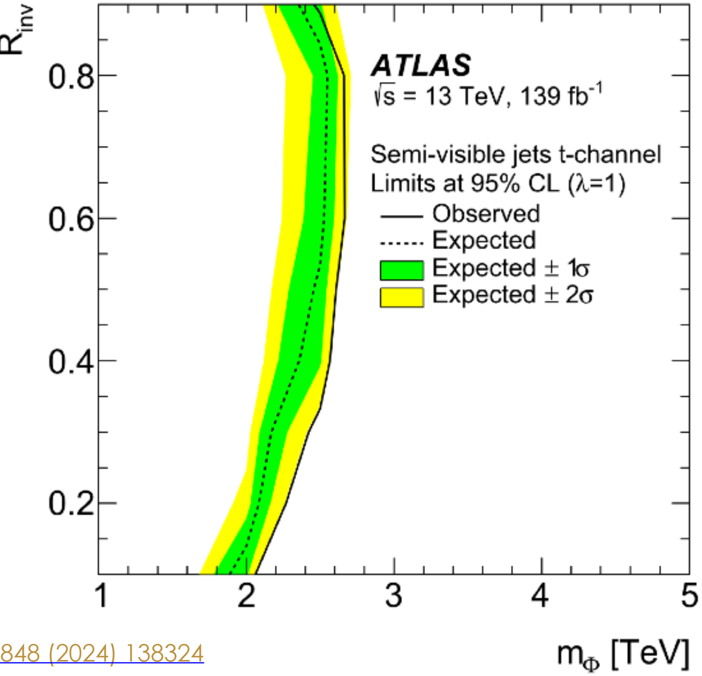
Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS

- Signals: bifundamental t-channel scalar
  - $r_{inv} = 0.1, 0.2, 0.4, 0.6, 0.8$, and 0.9
  - $m_{q_d} = 10$ GeV
- >=2 jets, MET>250 GeV, $\Delta\phi$(closest jet,MET) < 2
- **Signal Region**: HT>600 GeV, MET>600 GeV, lepton veto
- **Control Regions** for BG estimation using muons
- Simultaneous fit of max $\Delta\phi$ - min $\Delta\phi$ and pT balance of jets

$$r_{\text{inv}} \equiv \left\langle \frac{\#\text{ of stable hadrons}}{\#\text{ of hadrons}} \right\rangle$$







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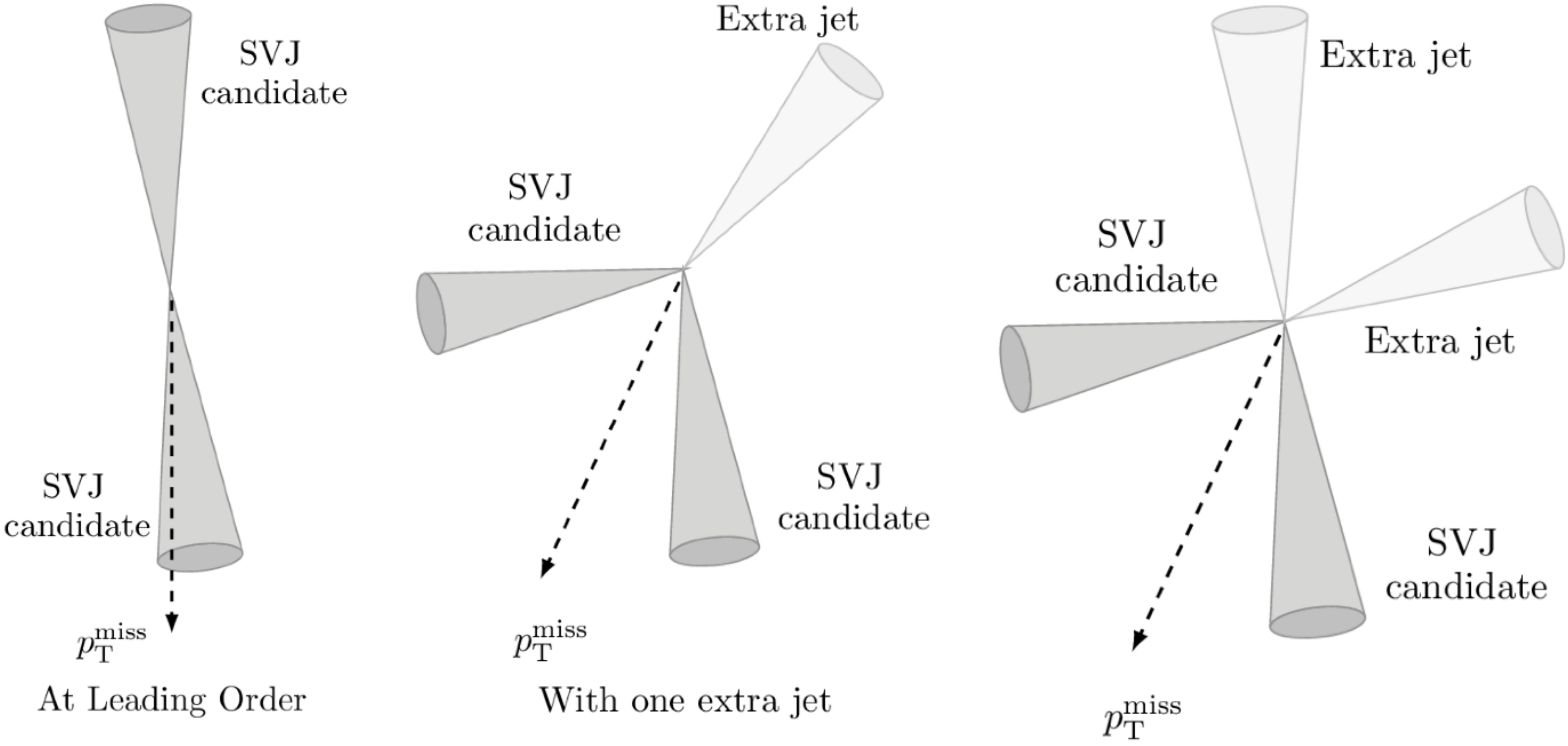
Assuming a coupling strength of unity between the mediator, a SM quark and a dark quark, mediator masses up to 2.7 TeV can be excluded

SEMI-VISIBLE JETS

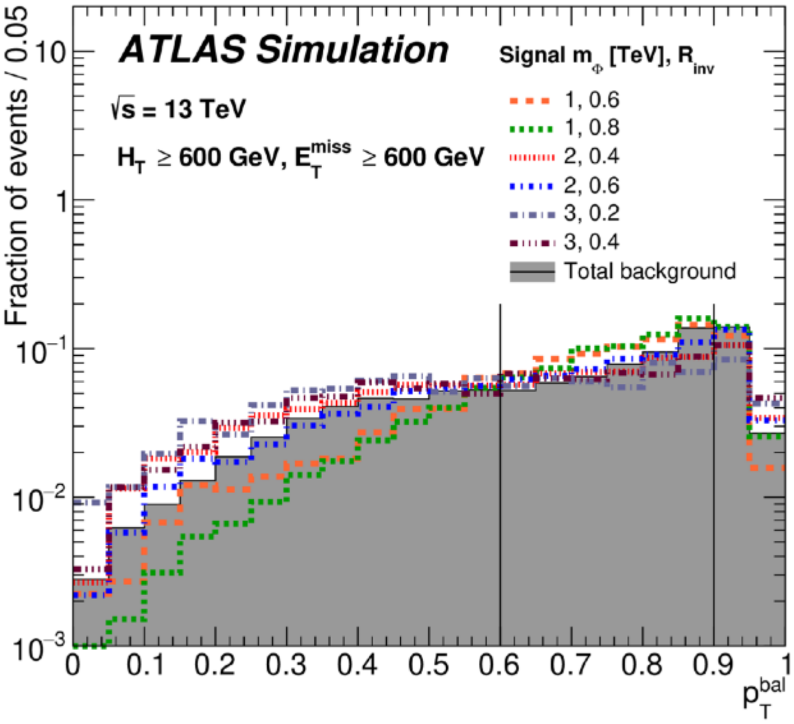


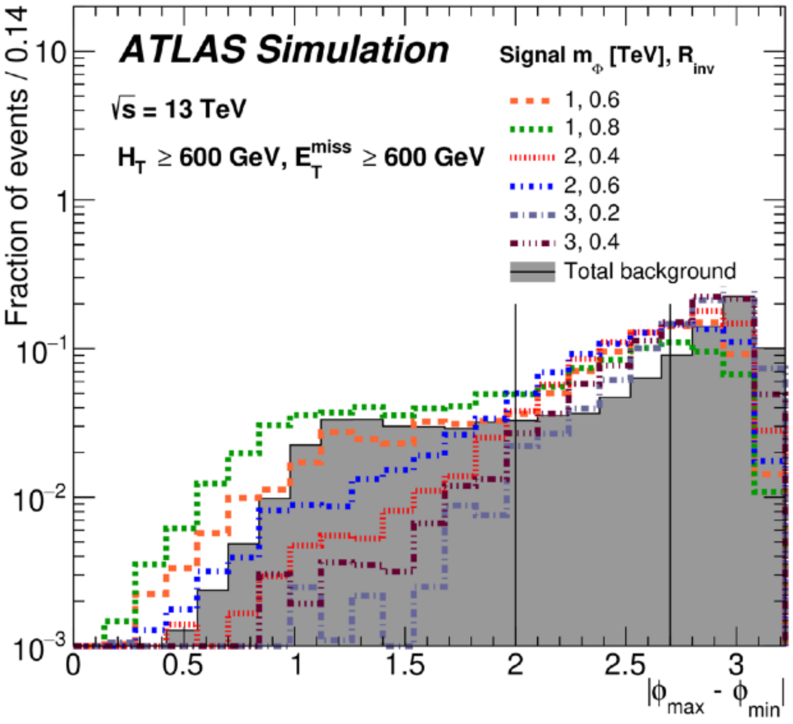
At Leading Order

With one extra jet

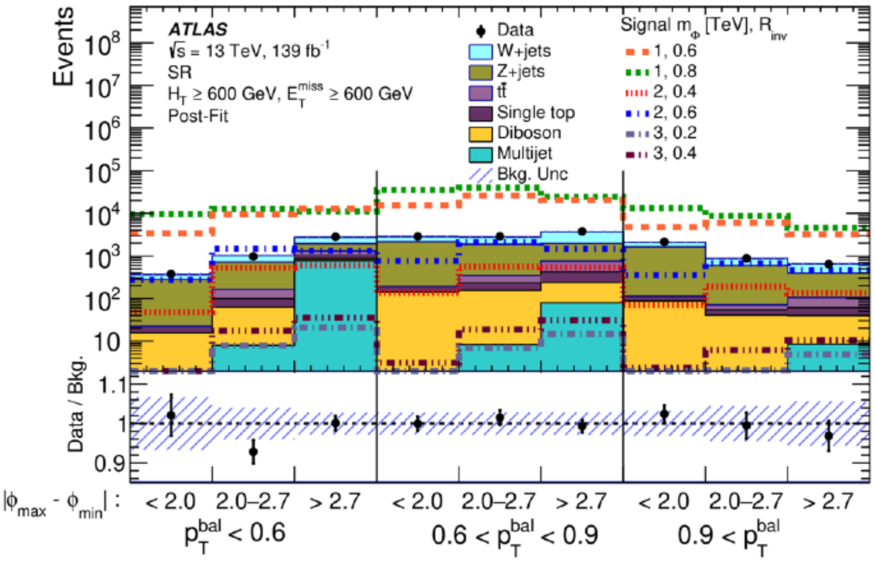
With extra jets

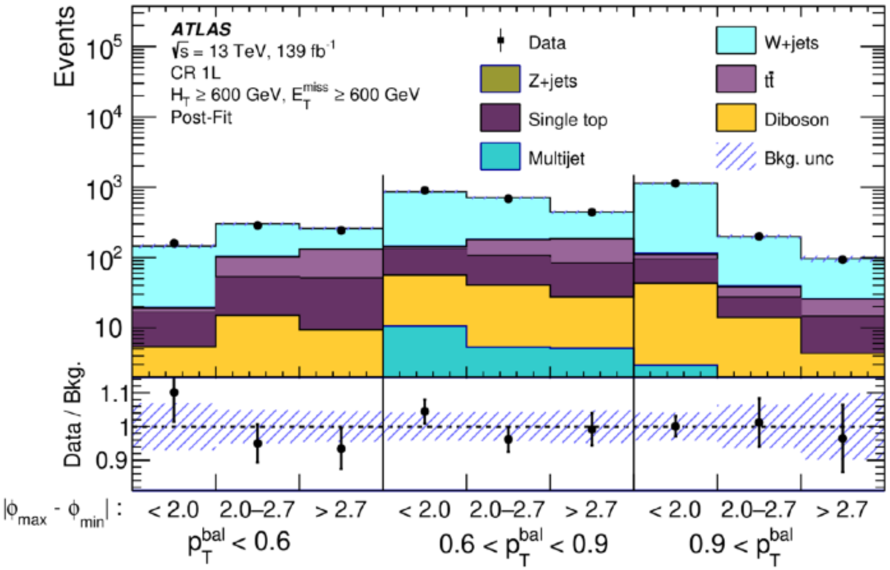
SEMI-VISIBLE JETS

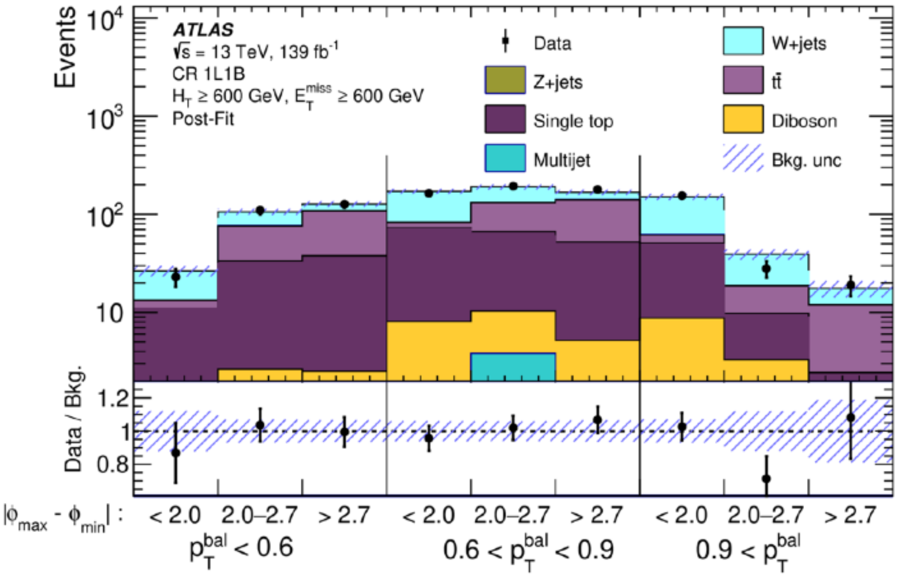


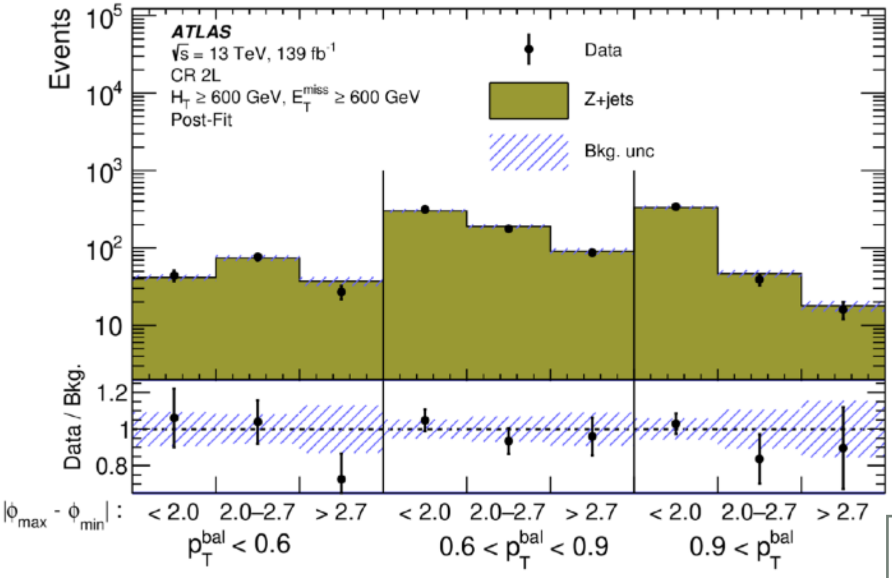


SEMI-VISIBLE JETS









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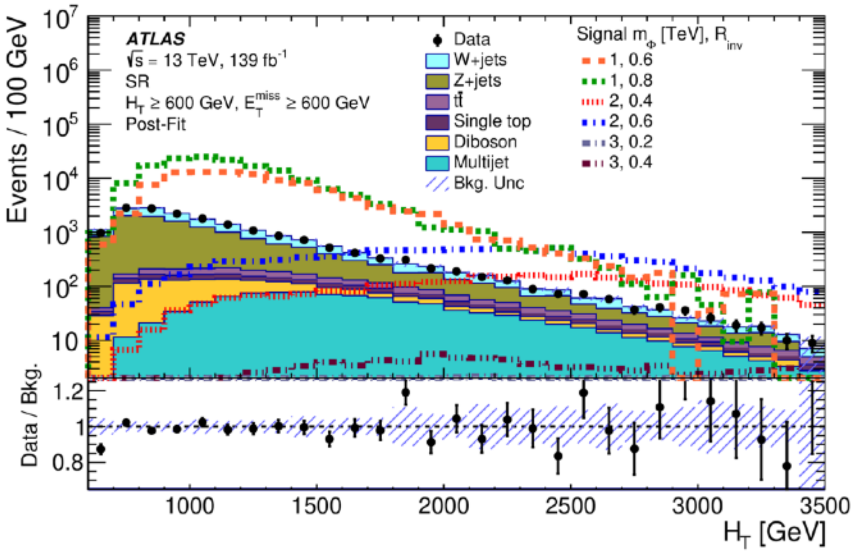
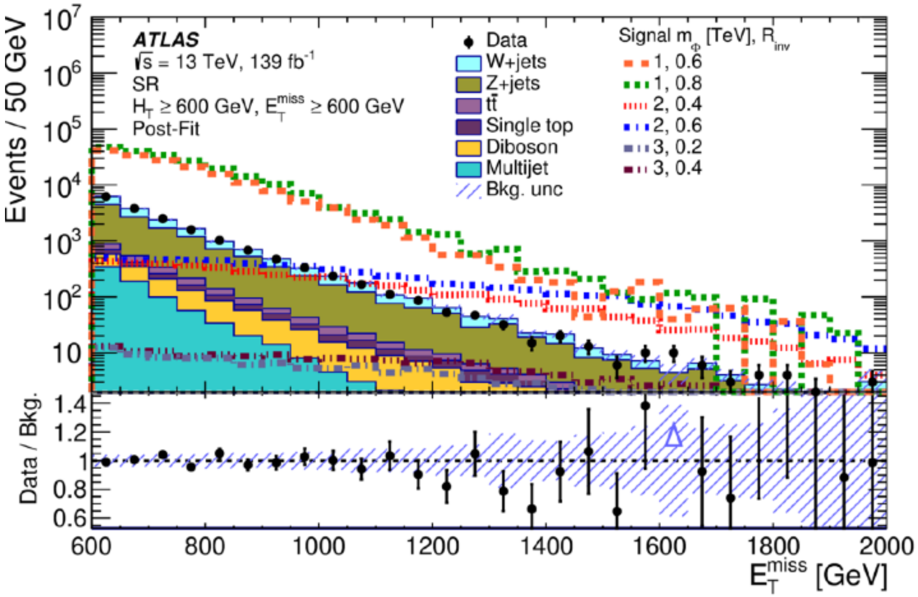
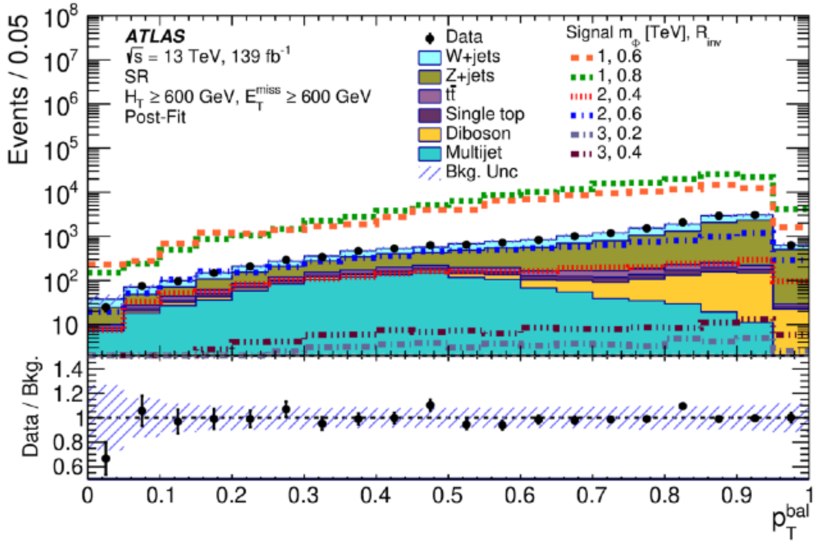
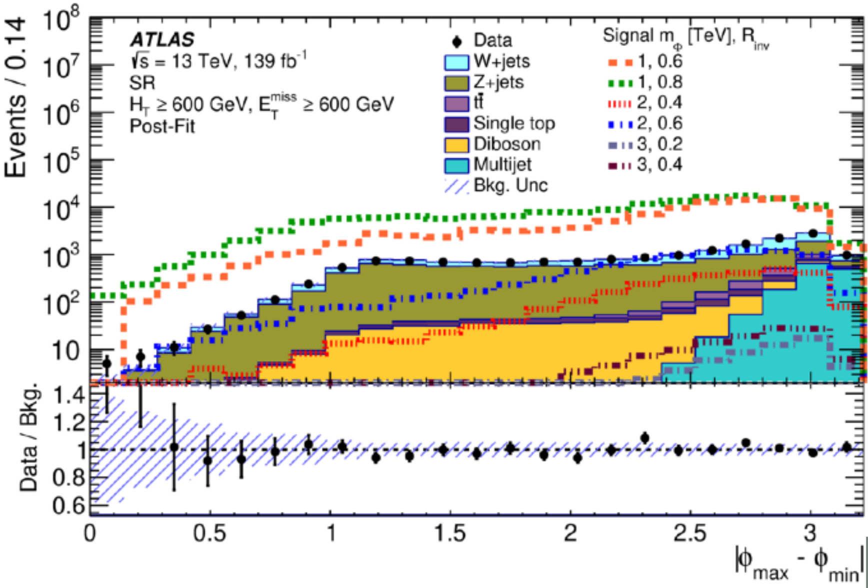
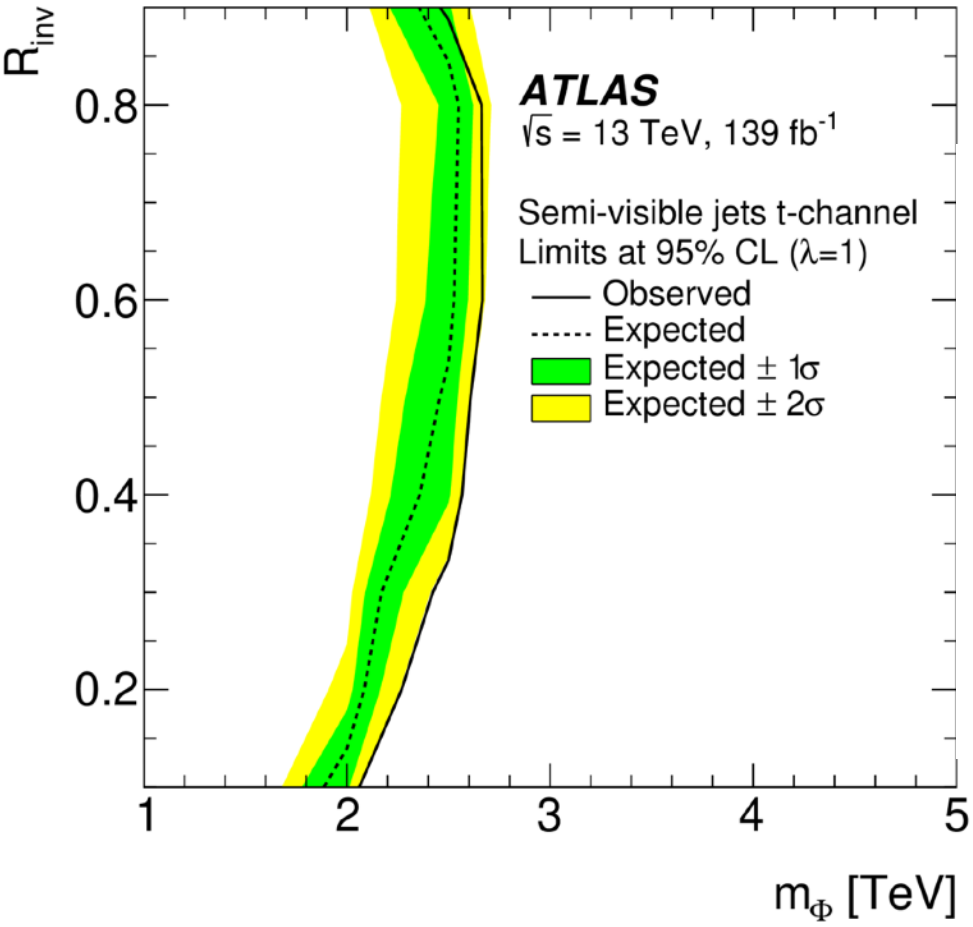


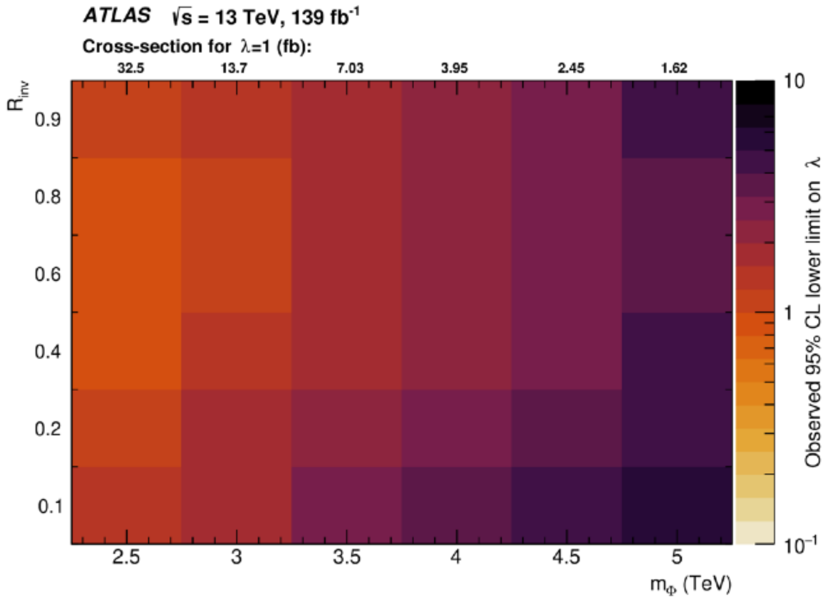






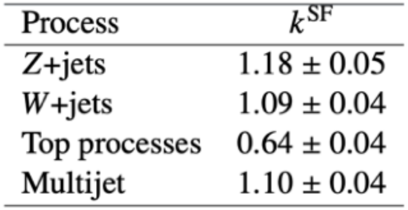
SEMI-VISIBLE JETS





SEMI-VISIBLE JETS RESULTS

Scale Factors



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

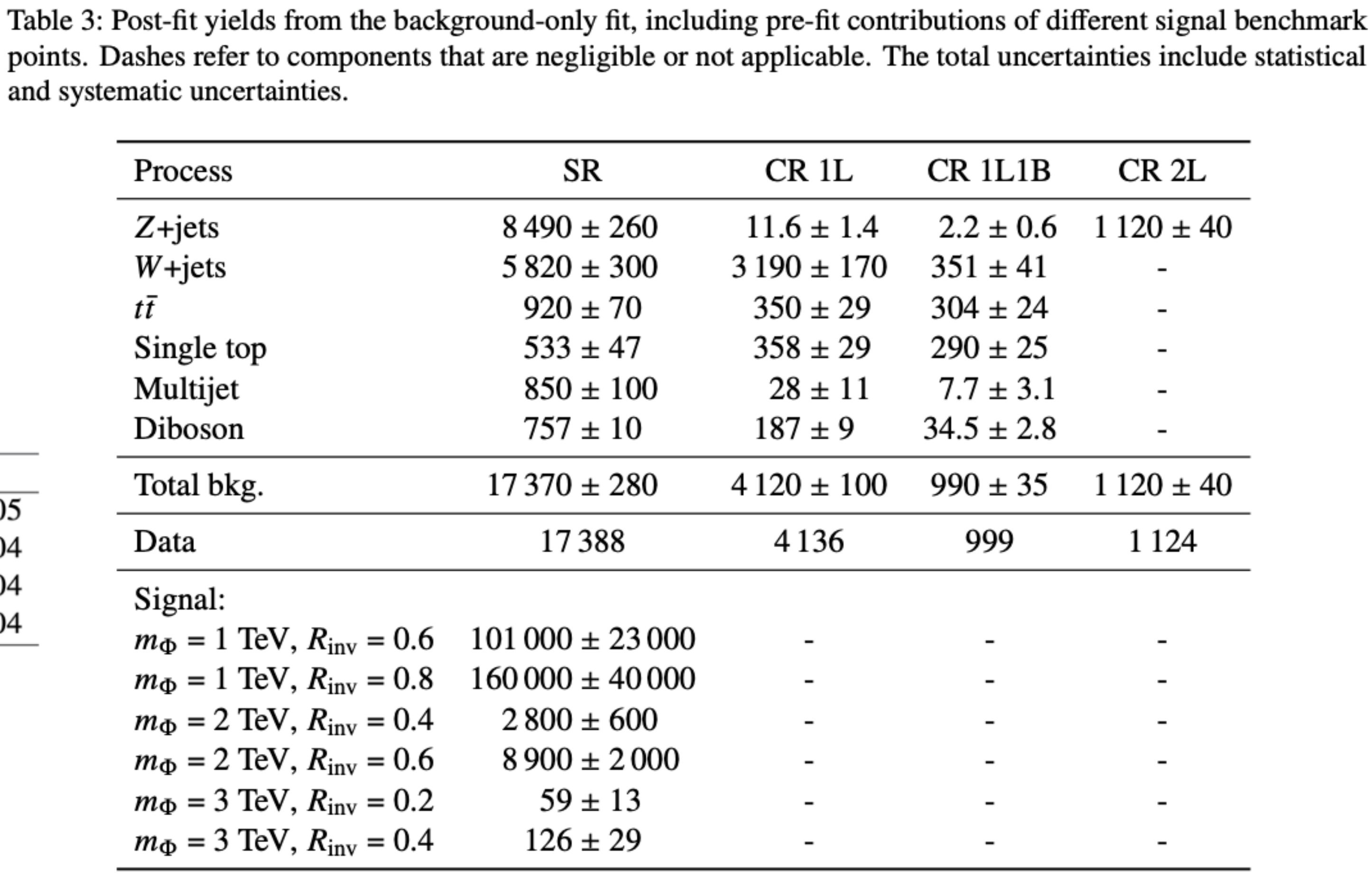


Table 3: Post-fit yields from the background-only fit, including pre-fit contributions of different signal benchmark points. Dashes refer to components that are negligible or not applicable. The total uncertainties include statistical and systematic uncertainties.

Process	SR	CR 1L	CR 1L1B	CR 2L
Z+jets	8 490 ± 260	11.6 ± 1.4	2.2 ± 0.6	1 120 ± 40
W+jets	5 820 ± 300	3 190 ± 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 bkg.	17 370 ± 280	4 120 ± 100	990 ± 35	1 120 ± 40
Data	17 388	4 136	999	1 124
Signal:				
$m_{\Phi} = 1$ TeV, $R_{\mathrm{inv}} = 0.6$	101 000 ± 23 000	-	-	-
$m_{\Phi} = 1$ TeV, $R_{\mathrm{inv}} = 0.8$	160 000 ± 40 000	-	-	-
$m_{\Phi} = 2$ TeV, $R_{\mathrm{inv}} = 0.4$	2 800 ± 600	-	-	-
$m_{\Phi} = 2$ TeV, $R_{\mathrm{inv}} = 0.6$	8 900 ± 2 000	-	-	-
$m_{\Phi} = 3$ TeV, $R_{\mathrm{inv}} = 0.2$	59 ± 13	-	-	-
$m_{\Phi} = 3$ TeV, $R_{\mathrm{inv}} = 0.4$	126 ± 29	-	-	-

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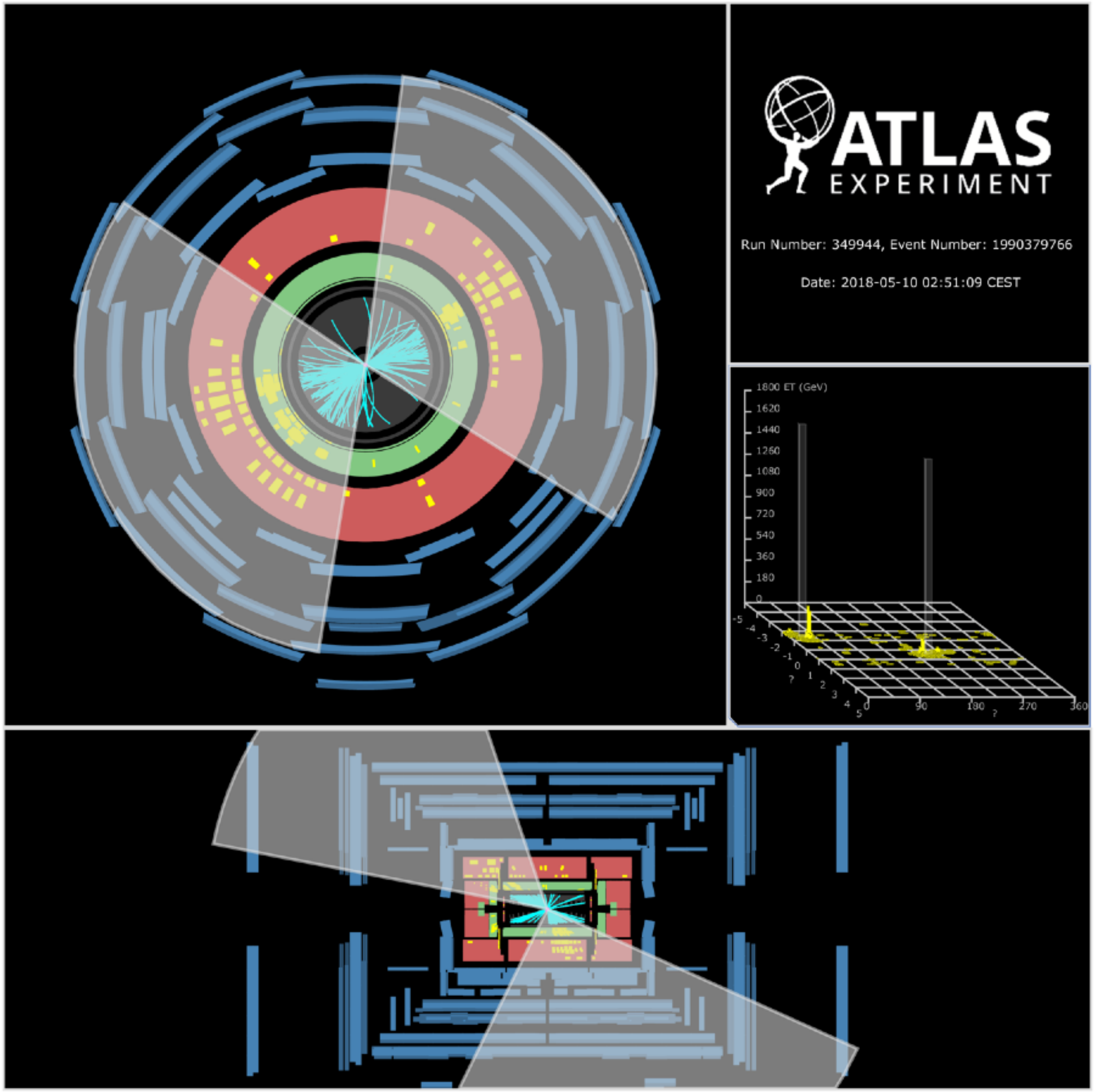
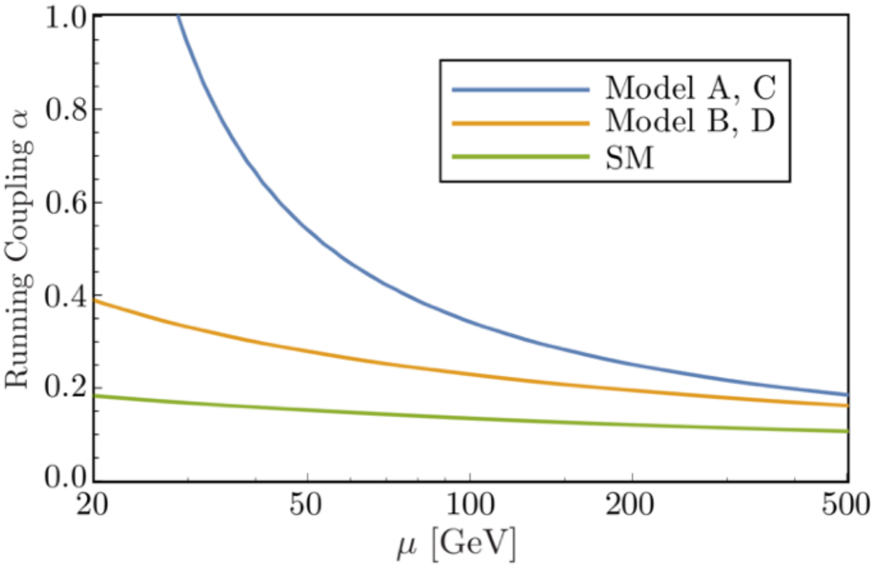
(VISIBLE) DARK JETS



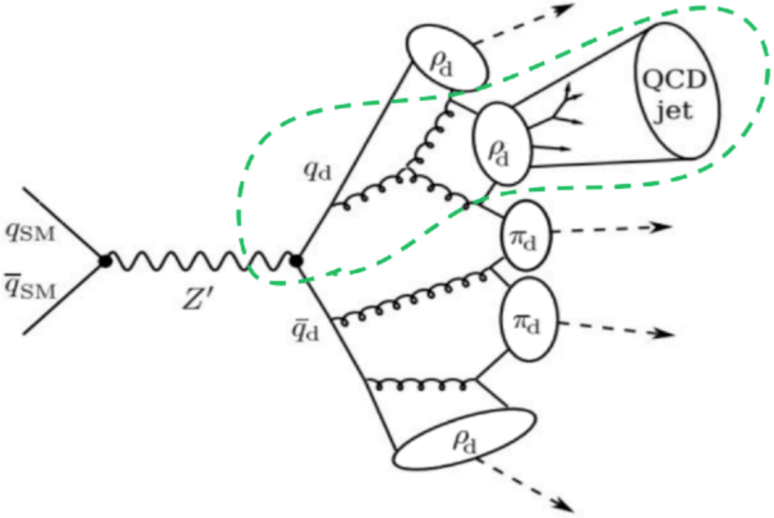
DARK JETS SIGNAL MODELS

- Z' mediator benchmarks arXiv:1712.09279
  - 4 different benchmark models (A, B, C, D)
- Higher running coupling for dark sector models.
- Negligible invisible fraction (stable dark hadrons)



Main differences with respect to SM jets:

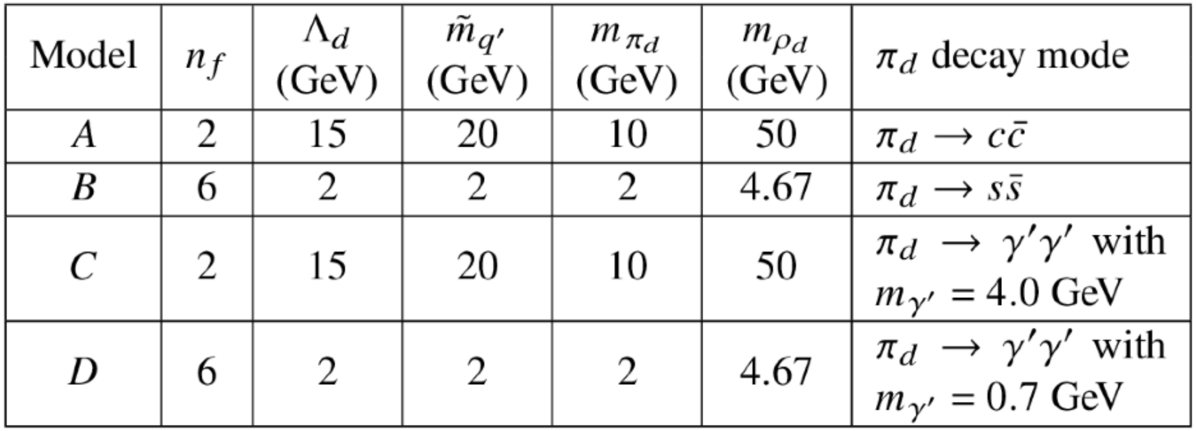
- Higher number of soft particles (and higher number of tracks)
- Wider jets, due to **double hadronization**



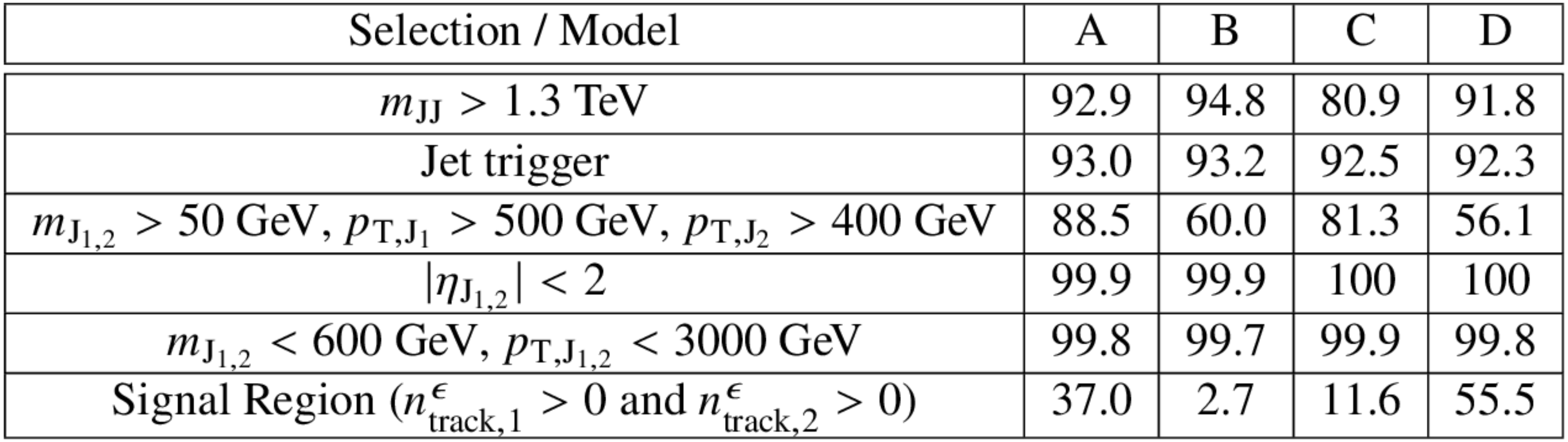
Generated Signals

- Signal masses generated using the Hidden Valley module of Pythia 8.235
- Considering an SU(3) symmetry
- Signal masses per model from mZ'=1.5 TeV to mZ'=3.5 TeV in bins of 250 GeV for low masses and then 500 GeV

(VISIBLE) DARK JETS



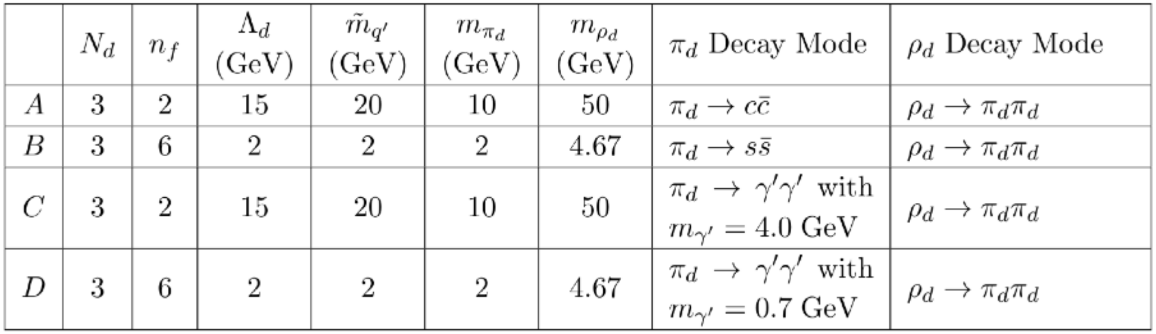
Model	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d decay mode
A	2	15	20	10	50	$\pi_d \to c\bar{c}$
B	6	2	2	2	4.67	$\pi_d \to s\bar{s}$
C	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV
D	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV



Selection / Model	A	B	C	D
$m_{\mathrm{JJ}} > 1.3$ TeV	92.9	94.8	80.9	91.8
Jet trigger	93.0	93.2	92.5	92.3
$m_{\mathrm{J}_{1,2}} > 50$ GeV, $p_{\mathrm{T,J}_1} > 500$ GeV, $p_{\mathrm{T,J}_2} > 400$ GeV	88.5	60.0	81.3	56.1
$\lvert\eta_{\mathrm{J}_{1,2}}\rvert < 2$	99.9	99.9	100	100
$m_{\mathrm{J}_{1,2}} < 600$ GeV, $p_{\mathrm{T,J}_{1,2}} < 3000$ GeV	99.8	99.7	99.9	99.8
Signal Region ($n^{\epsilon}_{\mathrm{track},1} > 0$ and $n^{\epsilon}_{\mathrm{track},2} > 0$)	37.0	2.7	11.6	55.5

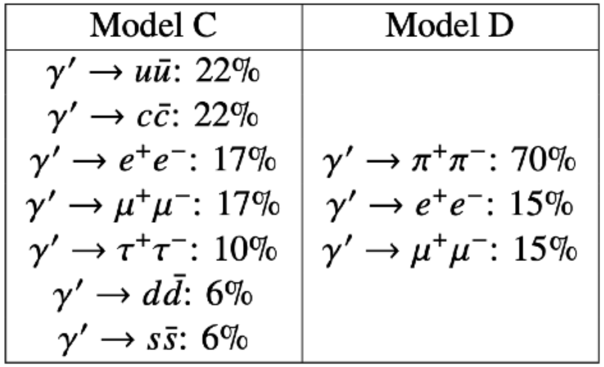
SIGNAL MODELS

- 4 different benchmark models arXiv:1712.09279

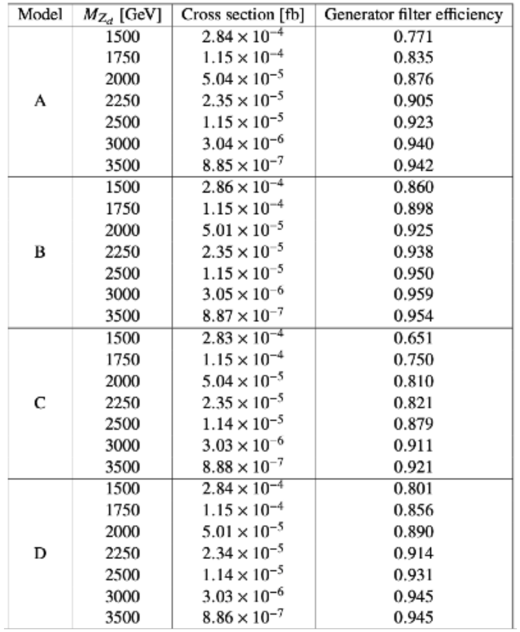


	N_d	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d Decay Mode	ρ_d Decay Mode
A	3	2	15	20	10	50	$\pi_d \to c\bar{c}$	$\rho_d \to \pi_d \pi_d$
B	3	6	2	2	2	4.67	$\pi_d \to s\bar{s}$	$\rho_d \to \pi_d \pi_d$
C	3	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV	$\rho_d \to \pi_d \pi_d$
D	3	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV	$\rho_d \to \pi_d \pi_d$

- ***nf***: Dirac fermions that are fundamentals of **SU(Nd)** and singlets under SM —> ***dark quarks***
- The dark sector **confines at a scale Λd**, which is the approximate mass of the majority of the dark hadrons
- ***πd***: pseudo-Goldstone bosons, analogous to QCD pions—> ***dark pions.***
- ***mπd <= Λd***



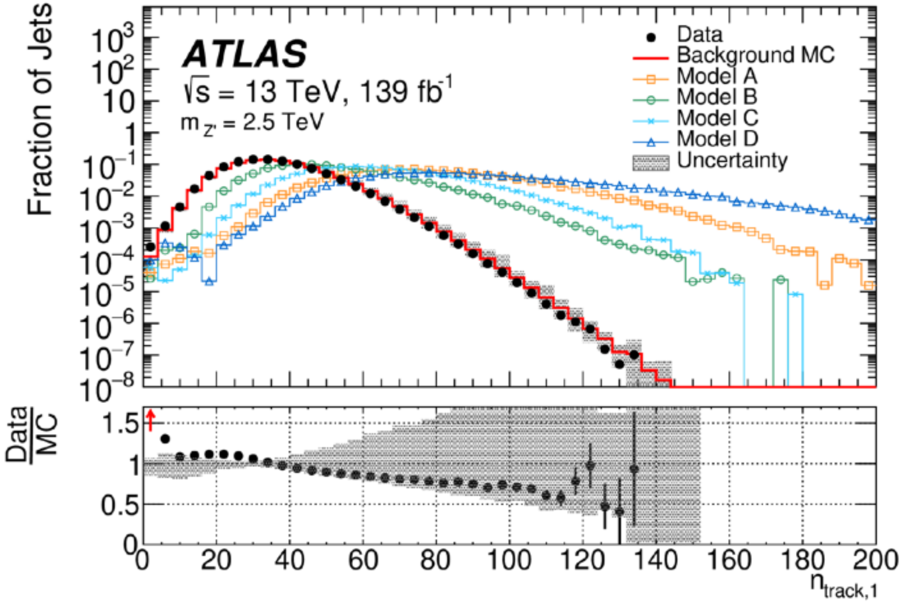
Model C	Model D
$\gamma' \to u\bar{u}$: 22% $\gamma' \to c\bar{c}$: 22% $\gamma' \to e^+e^-$: 17% $\gamma' \to \mu^+\mu^-$: 17% $\gamma' \to \tau^+\tau^-$: 10% $\gamma' \to d\bar{d}$: 6% $\gamma' \to s\bar{s}$: 6%	$\gamma' \to \pi^+\pi^-$: 70% $\gamma' \to e^+e^-$: 15% $\gamma' \to \mu^+\mu^-$: 15%

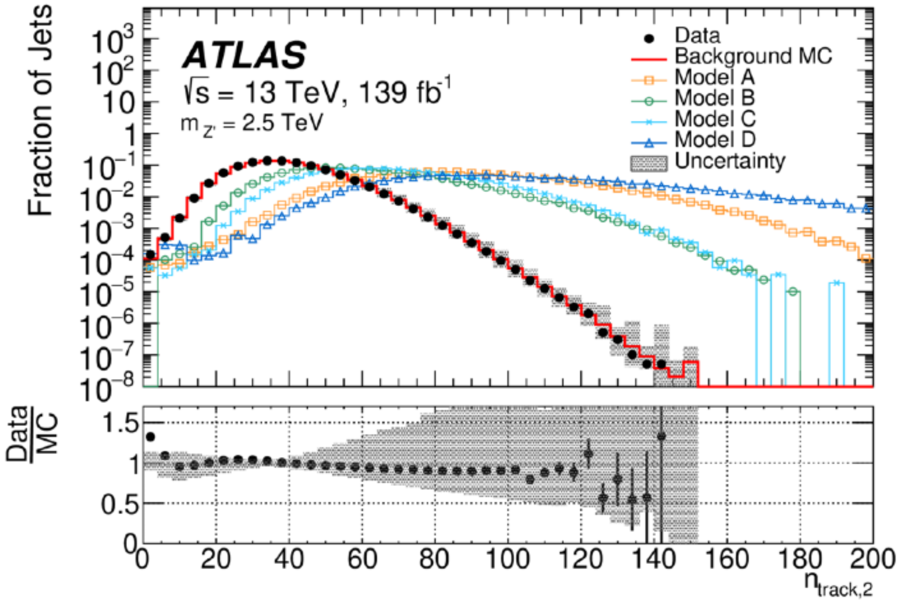


Model	M_{Z_d} [GeV]	Cross section [fb]	Generator filter efficiency
A	1500	2.84×10^{-4}	0.771
	1750	1.15×10^{-4}	0.835
	2000	5.04×10^{-5}	0.876
	2250	2.35×10^{-5}	0.905
	2500	1.15×10^{-5}	0.923
	3000	3.04×10^{-6}	0.940
	3500	8.85×10^{-7}	0.942
B	1500	2.86×10^{-4}	0.860
	1750	1.15×10^{-4}	0.898
	2000	5.01×10^{-5}	0.925
	2250	2.35×10^{-5}	0.938
	2500	1.15×10^{-5}	0.950
	3000	3.05×10^{-6}	0.959
	3500	8.87×10^{-7}	0.954
C	1500	2.83×10^{-4}	0.651
	1750	1.15×10^{-4}	0.750
	2000	5.04×10^{-5}	0.810
	2250	2.35×10^{-5}	0.821
	2500	1.14×10^{-5}	0.879
	3000	3.03×10^{-6}	0.911
	3500	8.88×10^{-7}	0.921
D	1500	2.84×10^{-4}	0.801
	1750	1.15×10^{-4}	0.856
	2000	5.01×10^{-5}	0.890
	2250	2.34×10^{-5}	0.914
	2500	1.14×10^{-5}	0.931
	3000	3.03×10^{-6}	0.945
	3500	8.86×10^{-7}	0.945

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

(VISIBLE) DARK JETS





DECORRELATE m_{JJ} WITH n_{track}: $n^{\epsilon}_{\text{track}}$

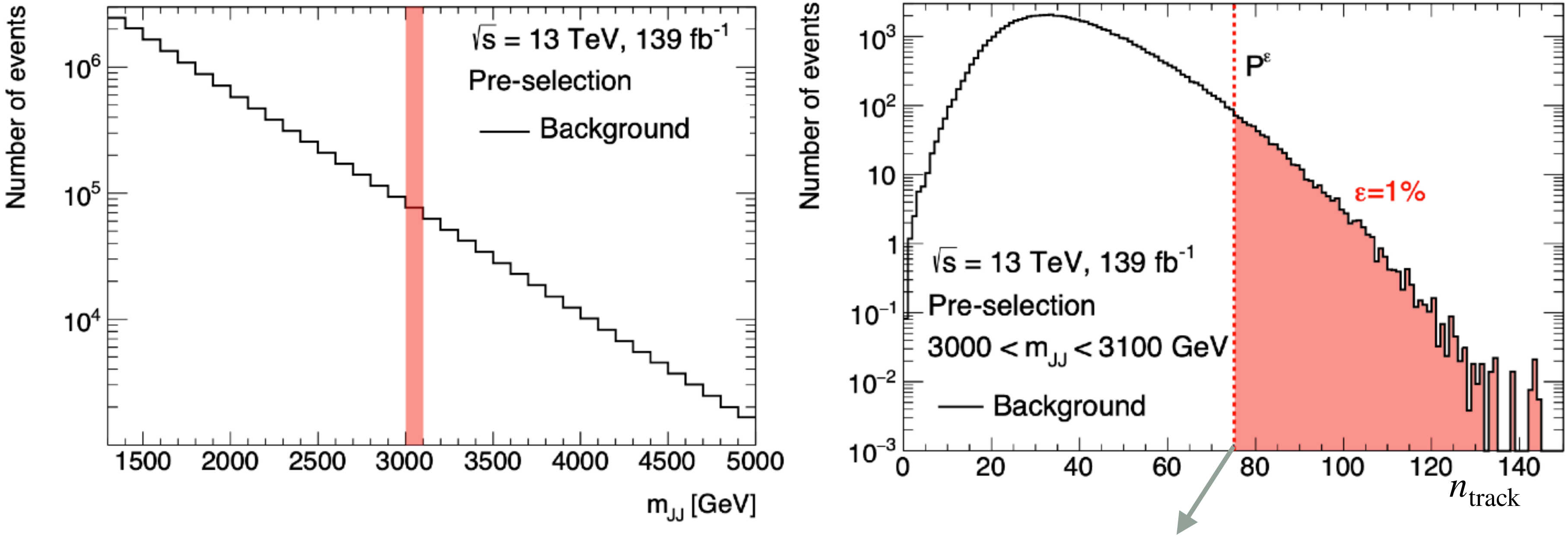
Define a new discriminating variable, $n^{\epsilon}_{\text{track}}$

1. Define a target efficiency, ε, for a background jet to pass the requirement on n_{track}

- **ε** = (Events that pass n_{track} cut) / (total # of events) = **1%**

2. For the leading jet and for each bin in m_{JJ} in the background, the minimal value P_{J_1} for which $n_{\text{track},1} > P_{J_1}$ leads to **ε** is determined

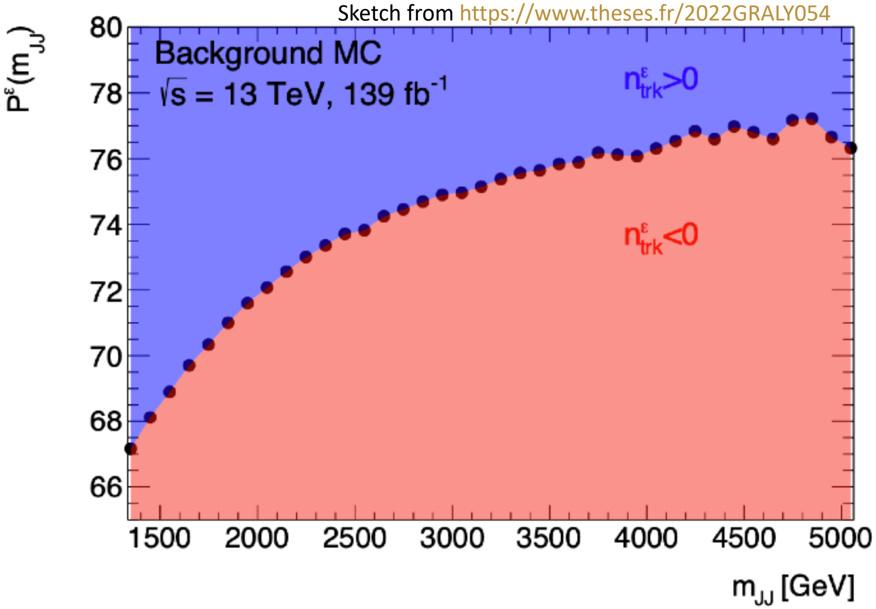
Sketchs from https://www.theses.fr/2022GRALY054



- This value is referred to as the "percentile", denoted by P_{J_1}.

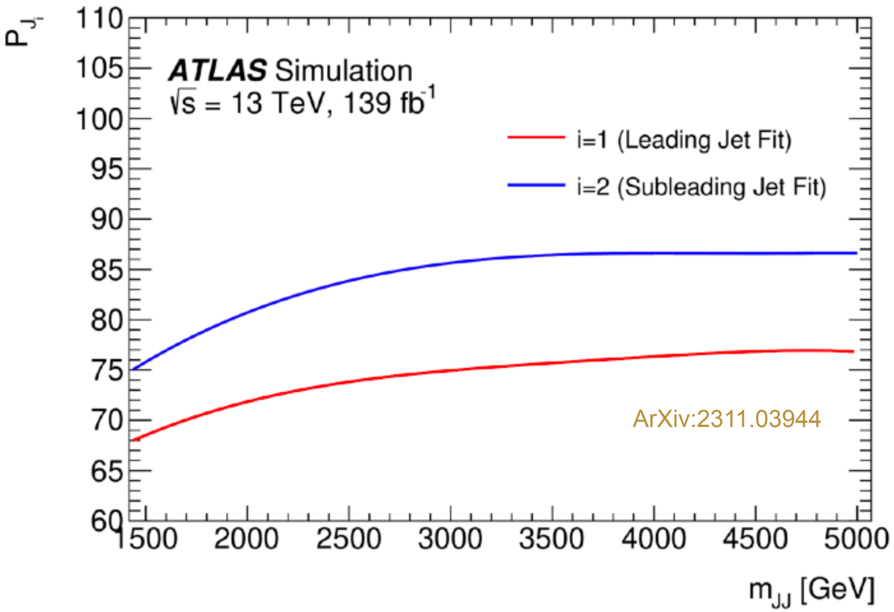
DECORRELATE m_{JJ} WITH n_{track}: $n^{\epsilon}_{\text{track}}$

3. Rinse and repeat for each bin.
Draw P_{J_1} as a function of m_{JJ}:



4. Procedure is repeated with the subleading jet, to find P_{J_2}

5. Fit the P_{J_i} values obtained as a function of m_{JJ}



6. Define new variable $n^{\epsilon}_{\text{track}}$

$$n^{\epsilon}_{\text{track}}(m_{JJ}) = n_{\text{track}} - P(m_{JJ})$$

THE SIGNAL REGION

Signal Region: $n^{\epsilon}_{\text{track}} > 0$ for both jets

$$n^{\epsilon}_{\text{track}}(m_{JJ}) = n_{\text{track}} - \mathrm{P}^{\epsilon}(\mathrm{m_{JJ}})$$

- $n^{\epsilon}_{\text{track}} > 0$ ($\Leftrightarrow n_{\text{track}} > \mathrm{P}^{\epsilon}(\mathrm{m_{JJ}})$) means “apply the cut”
  - Provides the same background efficiency in each m_{JJ} bin

Keeps m_{JJ}shape mostly unbiased!

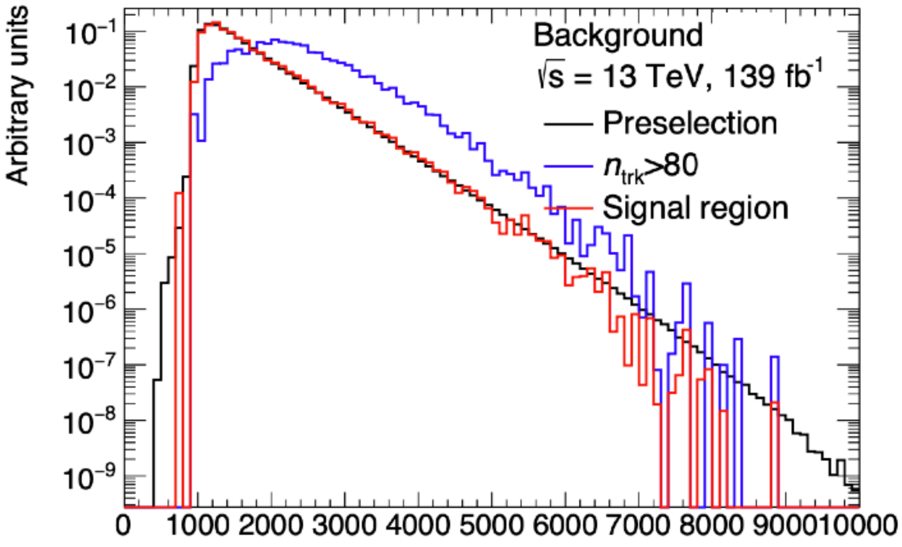
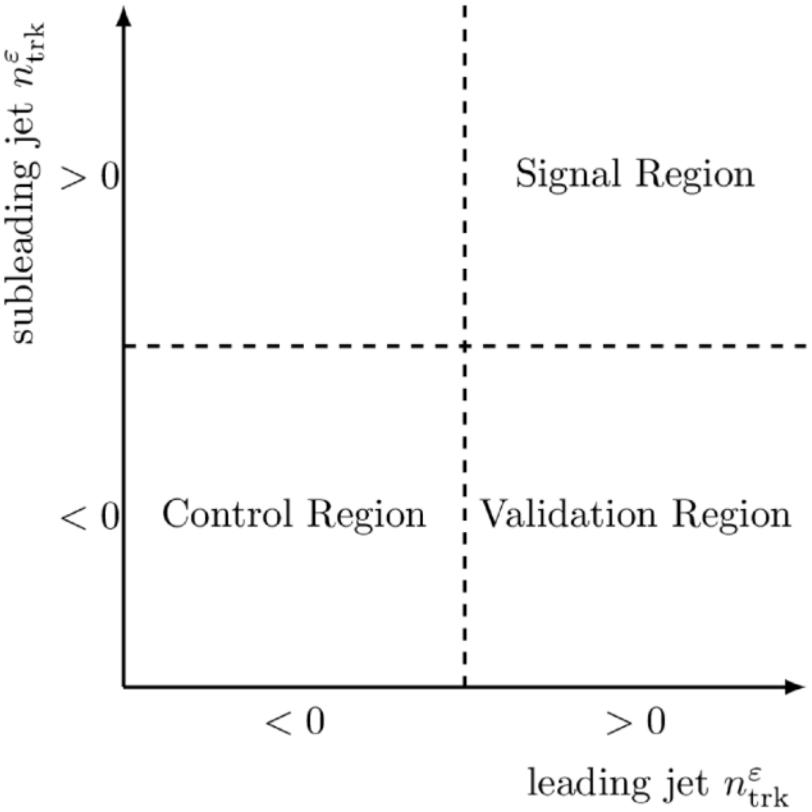


Illustration from https://www.theses.fr/2022GRALY054

Analysis Regions

- By the decorrelation method, different regions can be defined that should all have the same shape in m_{JJ}



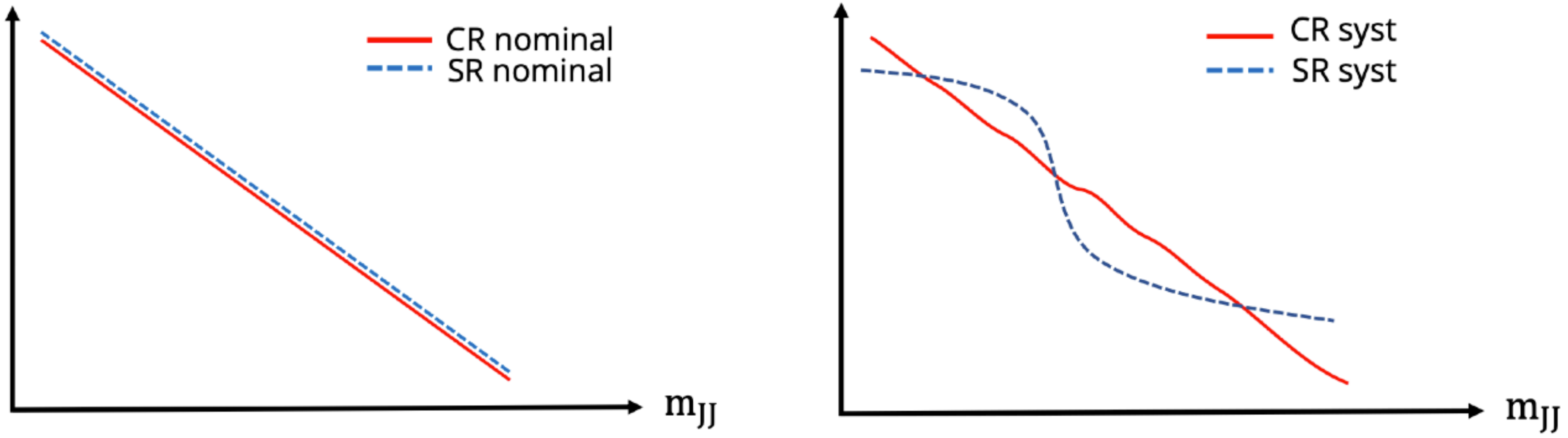
2) SYSTEMATIC UNCERTAINTIES

Background shape uncertainties

- Uncertainty on the data CR/SR shape agreement:
- Percentiles are derived from MC -> the decorrelation may not be perfect in data
- Evaluate this effect in MC:
  - Apply the percentiles to each systematic variation
  - In order to assess the shape agreement between the CR and the SR for each systematic, compute the double ratio:

$$\frac{\left(\frac{\mathrm{SR(nominal)}}{\mathrm{CR(nominal)}}\right)}{\left(\frac{\mathrm{SR(systematic)}}{\mathrm{CR(systematic)}}\right)}$$

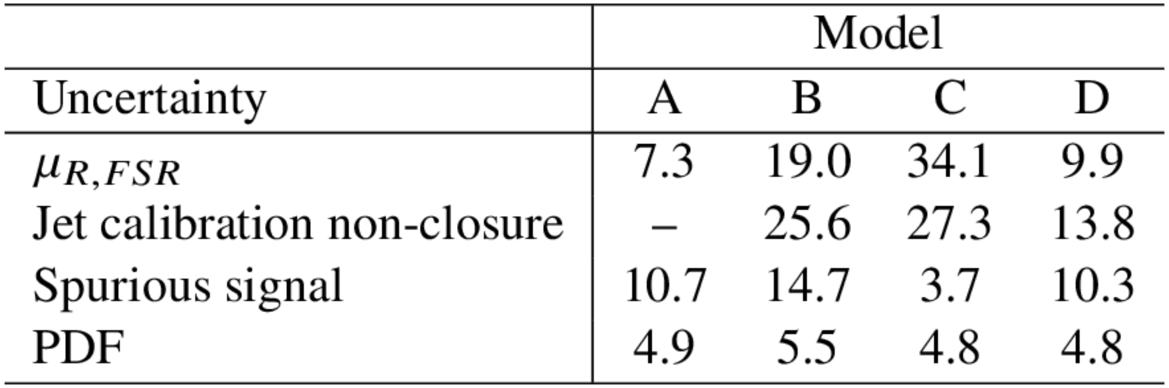
The background template is divided by the estimation of the double ratios



2) SYSTEMATIC UNCERTAINTIES

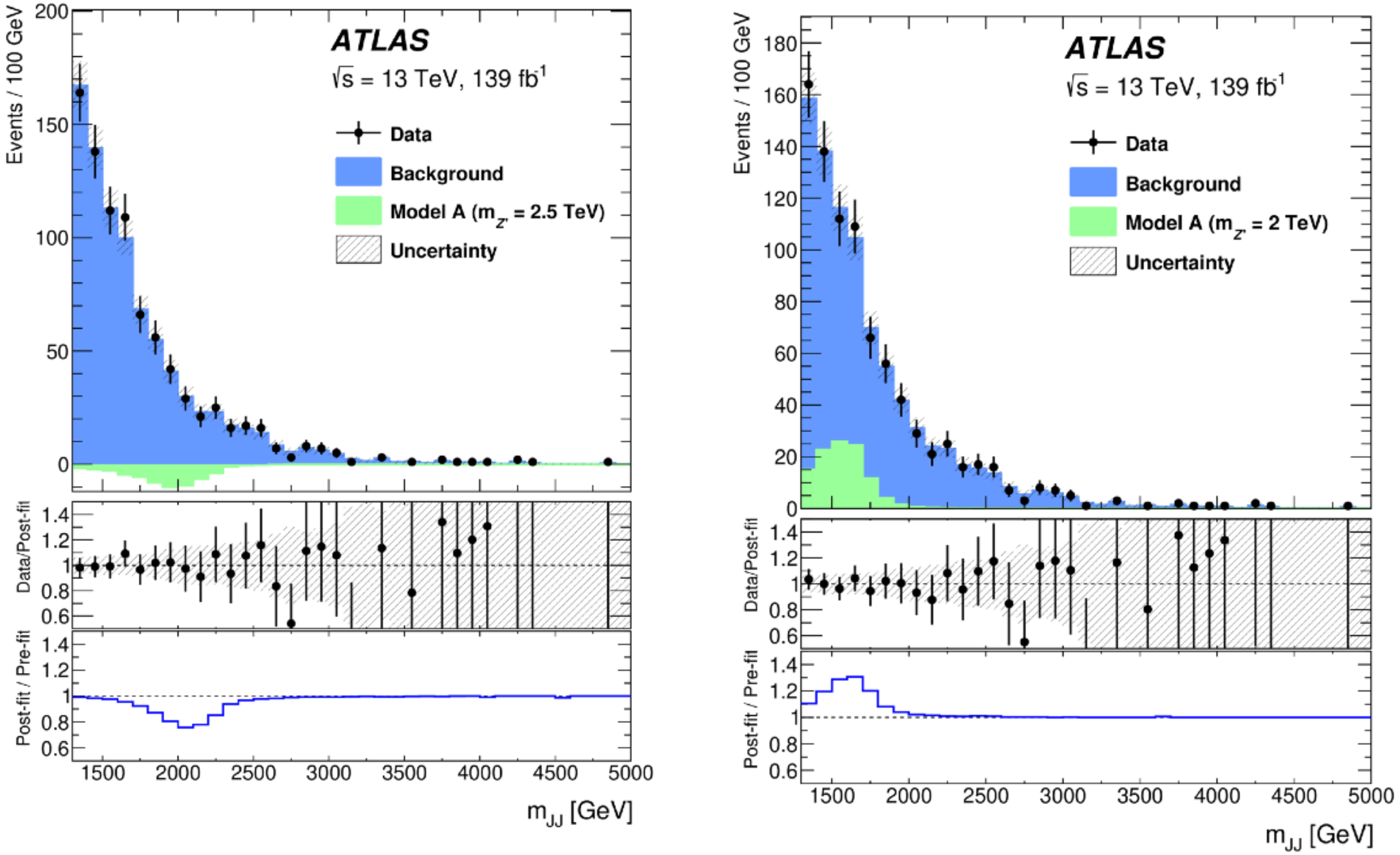
- The shape of the background is taken from the CR + fit for the free normalisation in the SR
  - Only the uncertainties affecting the SR/CR shape agreement are considered for the background

- Exp. uncertainties related to
  - jets (including an additional 5% JES non-closure for our signal jets for some models)
  - tracking (negligible)
  - luminosity (signal only)
  - modelling uncertainties (PDF, scales, parton shower)
  - spurious signal estimated in the VR

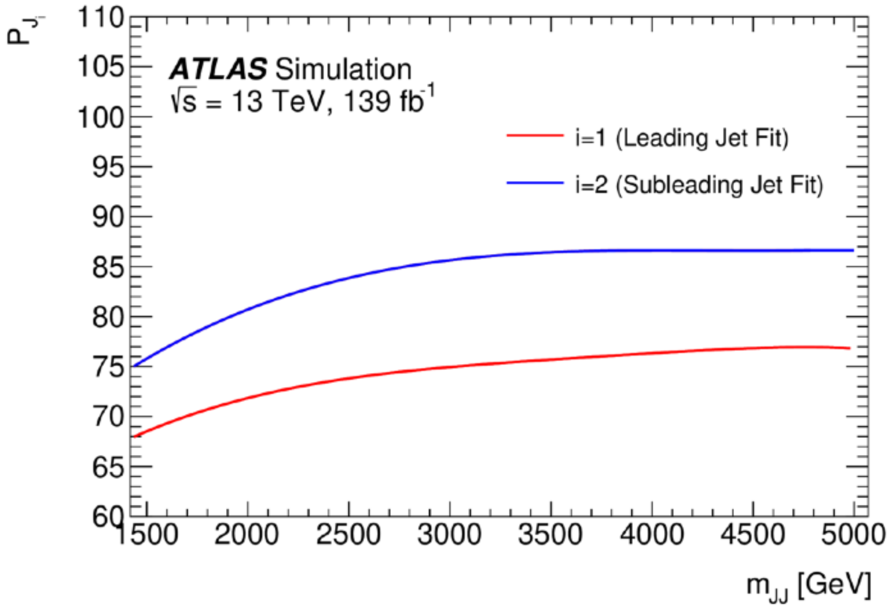


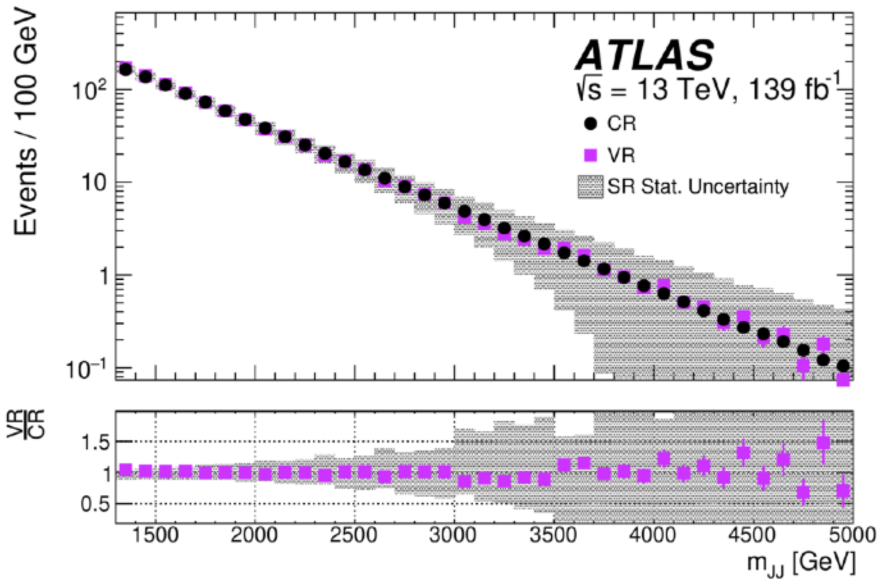
	Model			
Uncertainty	A	B	C	D
$\mu_{R,FSR}$	7.3	19.0	34.1	9.9
Jet calibration non-closure	–	25.6	27.3	13.8
Spurious signal	10.7	14.7	3.7	10.3
PDF	4.9	5.5	4.8	4.8

(VISIBLE) DARK JETS



(VISIBLE) DARK JETS

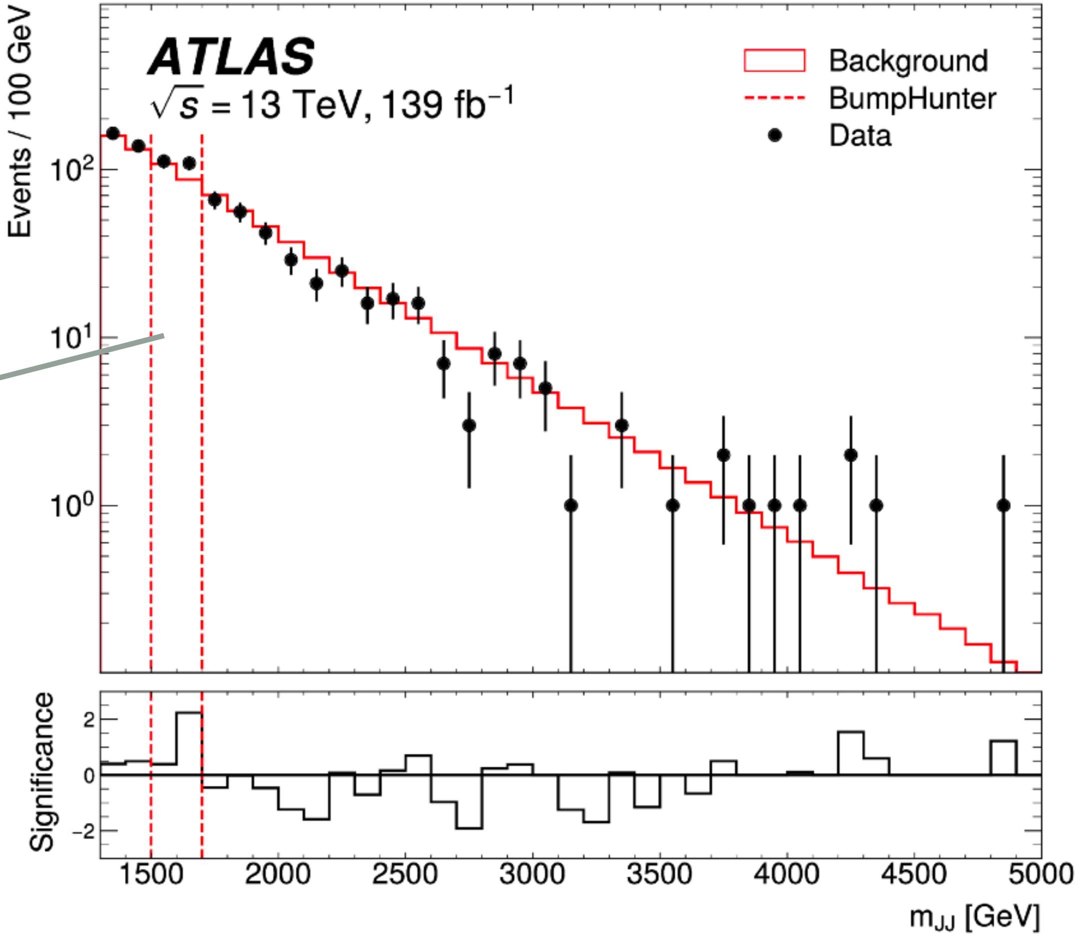




DATA IN THE SIGNAL REGION

- Observed data in the signal region is compared with data in the control region (normalized).

ATLAS-CONF-2023-047

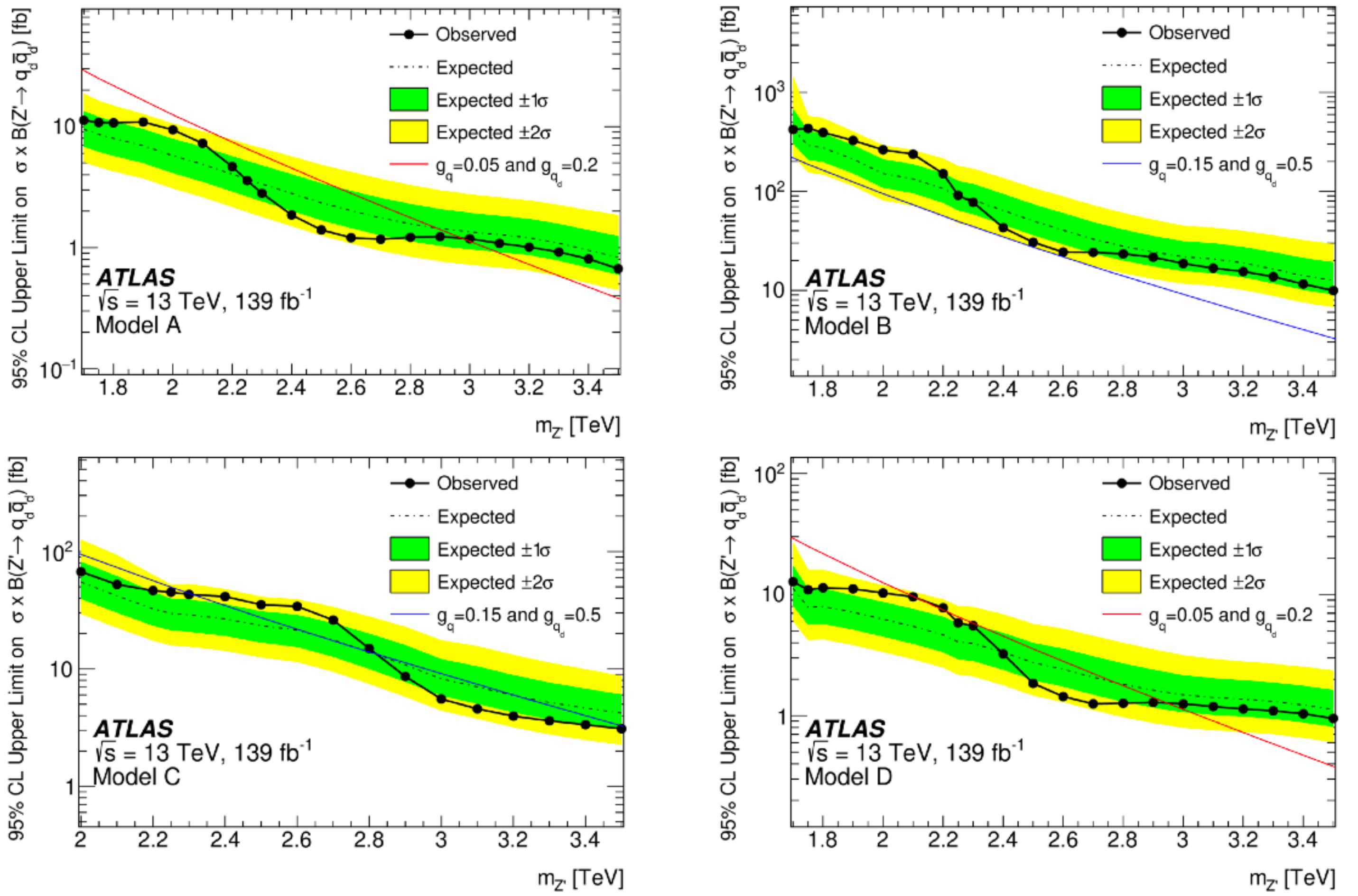


p-value = 0.63

- The BumpHunter algorithm looks for a deviation in the distributions.
  - No significant excess was observed with respect to the background prediction.

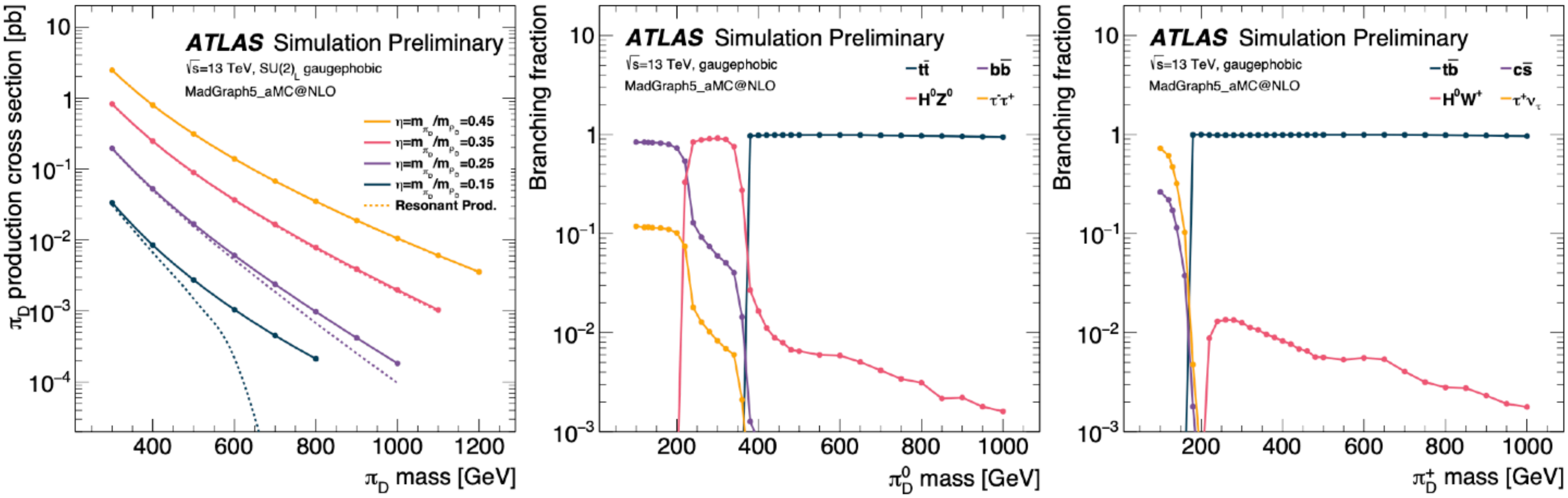
EXCLUSION LIMITS

- Compared to a MG implementation of xsec for $qq \rightarrow Z' \rightarrow q_d\, q_d$ (with $g_q = 0.05$ evading the 'usual' di-jet constraints)



- Exclusion depends on the model, but can reach 3-3.5 TeV for some models for which the usual $Z' \rightarrow q\ q$ search cannot say anything

SEARCH FOR DARK MESONS



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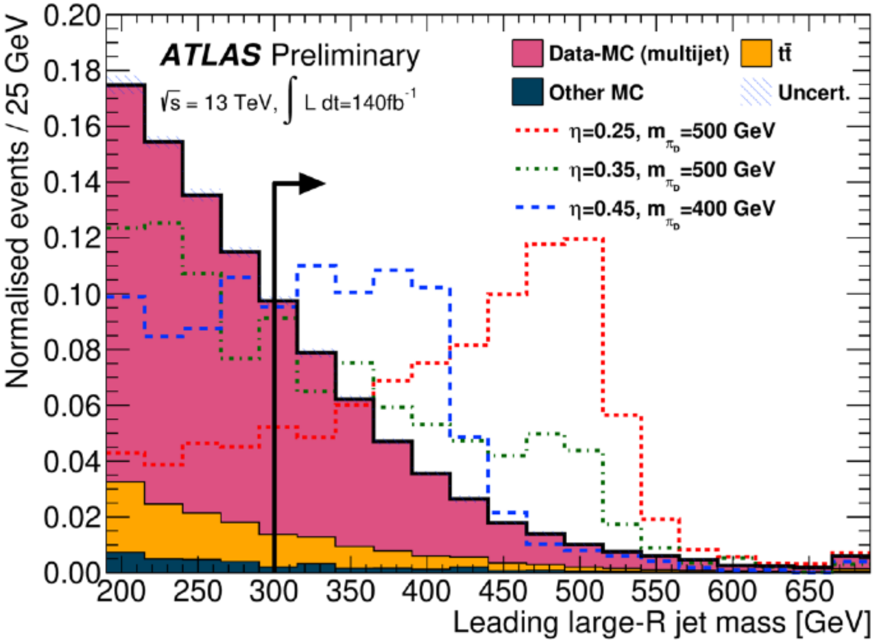

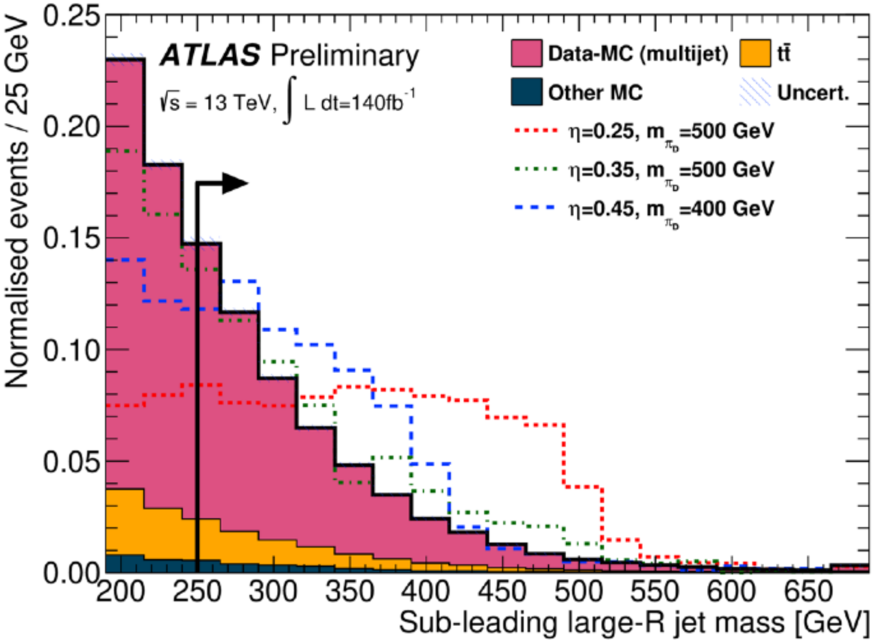

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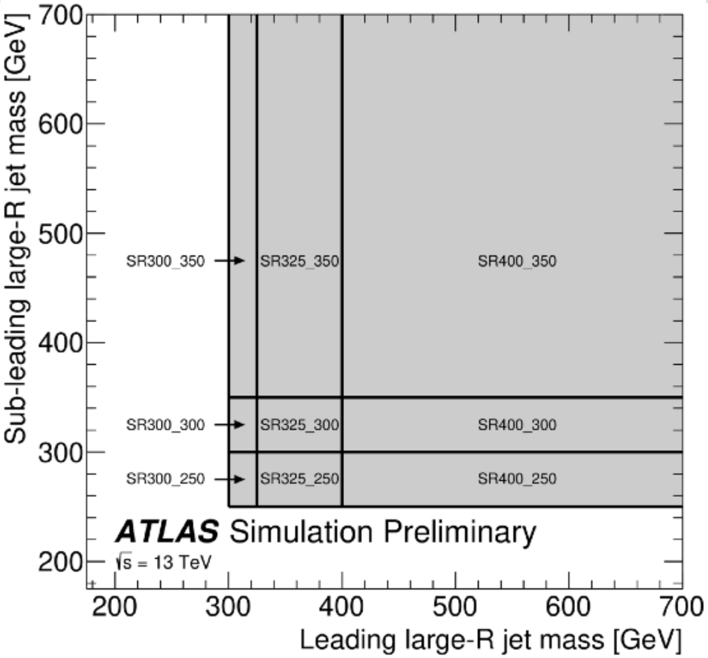
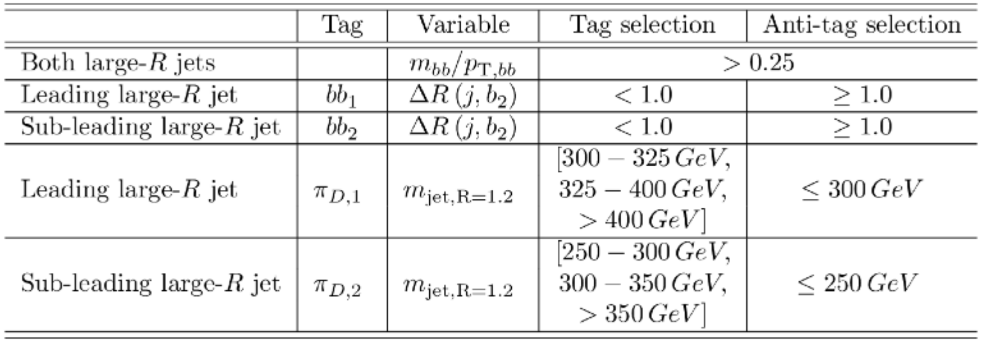


- Selection criteria for the SR ("Tag selection")



	Tag	Variable	Tag selection	Anti-tag selection
Both large-R jets		$m_{bb}/p_{\mathrm{T},bb}$	> 0.25	
Leading large-R jet	bb_1	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Sub-leading large-R jet	bb_2	$\Delta R\,(j, b_2)$	< 1.0	≥ 1.0
Leading large-R jet	$\pi_{D,1}$	$m_{\mathrm{jet,R=1.2}}$	$[300 - 325\,GeV,$ $325 - 400\,GeV,$ $> 400\,GeV]$	$\leq 300\,GeV$
Sub-leading large-R jet	$\pi_{D,2}$	$m_{\mathrm{jet,R=1.2}}$	$[250 - 300\,GeV,$ $300 - 350\,GeV,$ $> 350\,GeV]$	$\leq 250\,GeV$

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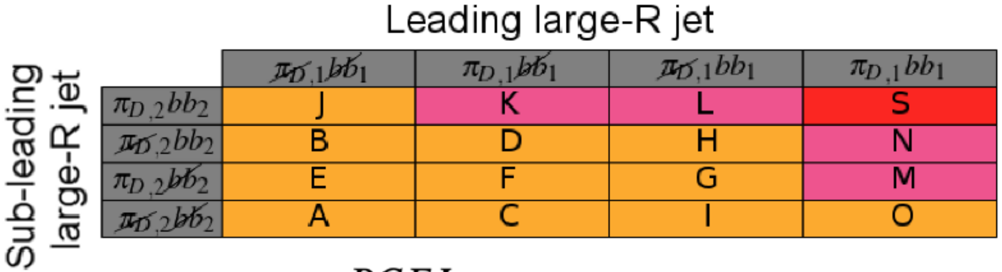
Multijet estimation

- Extrapolate from regions with small m and large ΔR
- Extrapolate from regions with one tag
- 2-tag regions are used to determine correlation correction factors
- 3-tag regions are used for validation

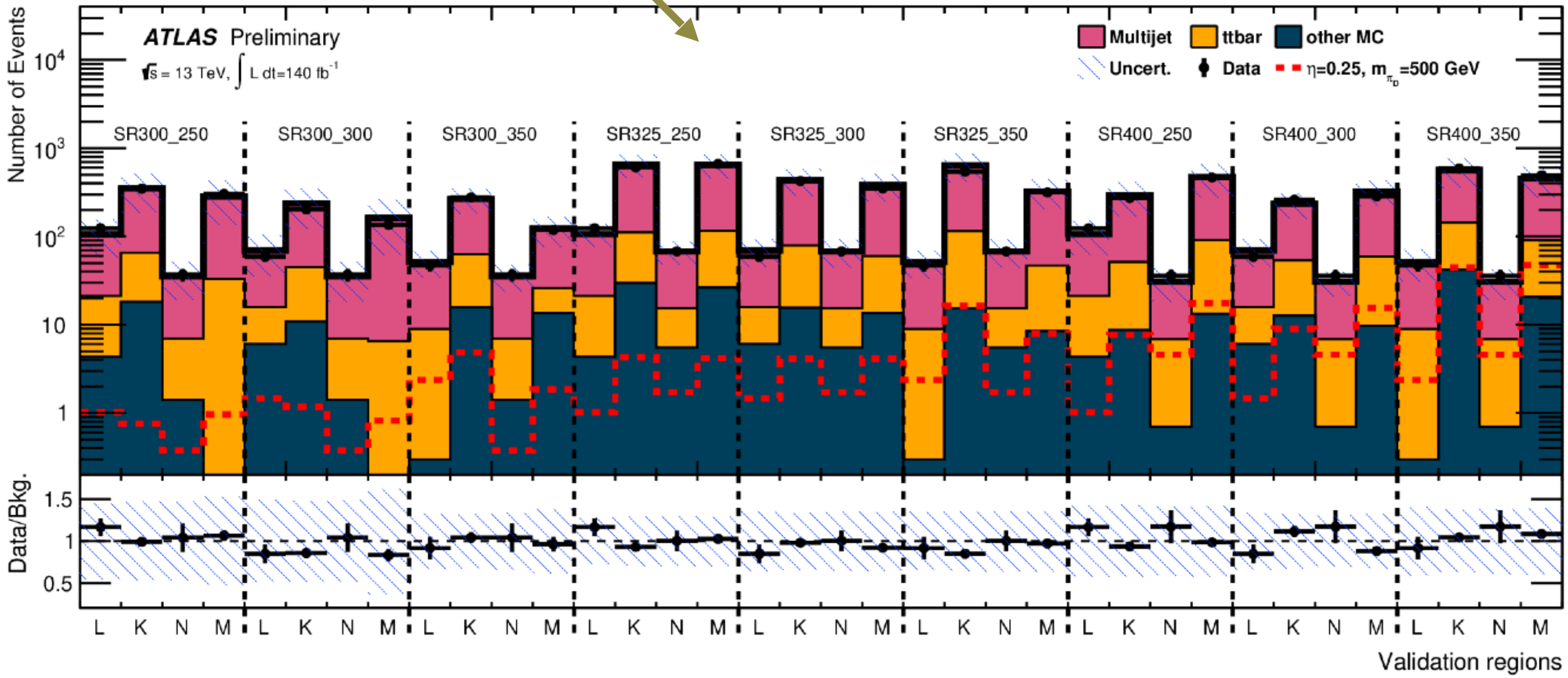


Leading large-R jet

Sub-leading large-R jet

	$\not\pi_{D,1}b\not b_1$	$\pi_{D,1}b\not b_1$	$\not\pi_{D,1}bb_1$	$\pi_{D,1}bb_1$
$\pi_{D,2}bb_2$	J	K	L	S
$\not\pi_{D,2}bb_2$	B	D	H	N
$\pi_{D,2}b\not b_2$	E	F	G	M
$\not\pi_{D,2}b\not b_2$	A	C	I	O

$$\hat{S}' = \frac{BCEI}{A^3}$$ X 6 k-factos



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