Reinterpreting LHC Dark QCD results using MadAnalysis5

Dark showers workshop

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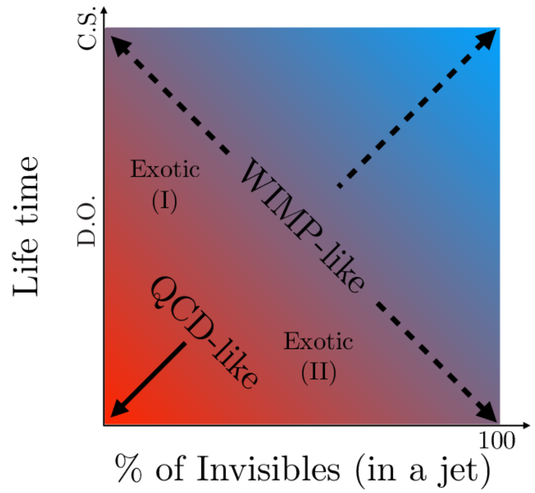
Dark QCD

- Dark QCD models :

  - different possible mediators between q and q_d (Z', Φ ...)

  - 2 main parameters determining the final jet topology :

  fraction of stable dark hadrons and life-time of unstable dark particles



from arXiv:1712.09279

- In MadAnalysis (cf Back-up), different analyses available for reinterpretation of dark QCD models and able to be sensitive to a large phase space :

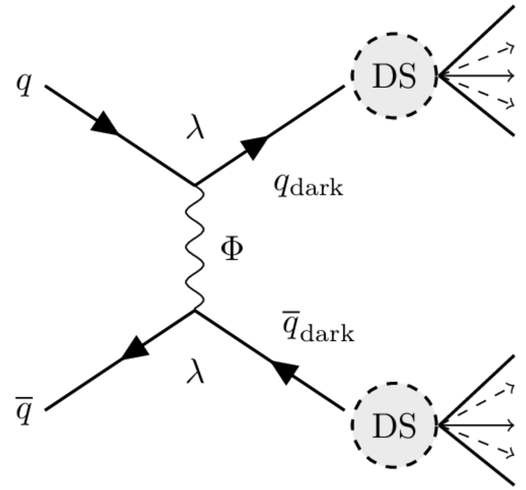
  - ATLAS and CMS semi-visible jets Run-2 analysis (arXiv:2305.18037 and 2112.11125 resp.)
  - ATLAS dark jets Run-2 analysis (arXiv:2311.03944)
  - CMS mono-jet Run-2 analysis (arXiv:2107.13021)
  - ATLAS di-jet Run-2 analysis (arXiv:1910.08447)

ATLAS semi-visible jets (Phys. Lett. B 848 (2024) 138324) (ATLAS-EXOT-2022-37)

- t-channel mediator Φ connecting SM quarks to dark quarks :

  - R_{inv} parametrize fraction of stable and invisible dark hadrons

  - final state with at least 2 jets (R = 0.4) with one of these that is aligned with $\overrightarrow{E_T^{miss}}$



- Signal-plus-background fit to SR and several muon-based CRs simultaneously,

  all divided into 9 bins thanks to $p_T^{bal} = \frac{|\overrightarrow{p_T}(j_1) + \overrightarrow{p_T}(j_2)|}{|\overrightarrow{p_T}(j_1)| + |\overrightarrow{p_T}(j_2)|}$ and $|\phi_{max} - \phi_{min}|$

  Exclusion contours in (m_Φ, R_{inv}) 2D plane

- Analysis accessible at : https://dataverse.uclouvain.be/dataset.xhtml?persistentId=doi:10.14428/DVN/AFYF5Y

$m_\Phi = 1$ TeV, $R_{inv} = 0.6$	**ATLAS**	**MA5**	**Relative difference [%]**	**ATLAS cut efficiency [%]**	**MA5 cut efficiency [%]**
Pre-selection	844520.2	802004.396	5.03		
$\Delta\phi < 2.0$	816341.4	773773.493	5.21	96.66	96.48
$p_{T,\ leading\ jet} > 250$ GeV	791042.5	747516.248	5.50	96.90	96.61
$N_{b-jet} < 2$	707151.0	747516.248	5.71	89.39	100
τ jet veto	701537.9	724219.427	3.23	99.21	96.88
$E_T^{miss} > 600$ GeV	101378.1	108504.199	7.03	14.45	14.98
$H_T > 600$ GeV	101235.2	108504.199	7.18	99.86	100

CMS semi-visible jets (JHEP 06 (2022) 156) (CMS-EXO-19-020)

- s-channel mediator Z' coupled to SM quarks and dark quarks χ :

  - r_{inv} : fraction of invisible dark hadrons, m_{dark} : dark hadron mass

  - final state with at least 2 jets (R = 0.8) with one of these that is aligned with $\overrightarrow{E_T^{miss}}$

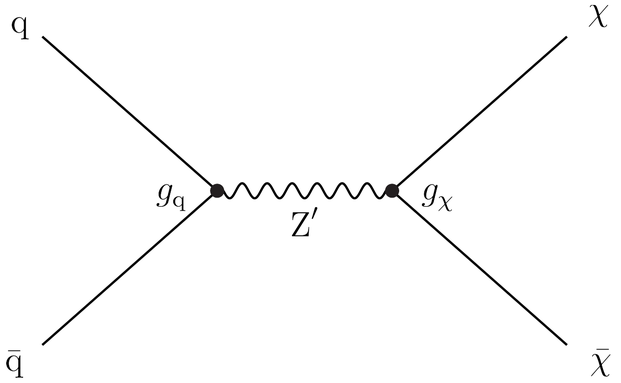
- Background only fit of observed di-jet transverse mass m_T distribution in the SR

  Search for a resonance in the m_T spectrum (m_T distribution : smoothly falling for background events, peak for signal process)

  Limits on $\sigma_{Z'} \times \mathrm{BR}(Z' \to \bar{\chi}\chi)$ in function of $m_{Z'}$ and exclusion contours

  in ($m_{Z'}$, m_{dark}) and in ($m_{Z'}$, r_{inv}) planes

- Implementation of the analysis in validation



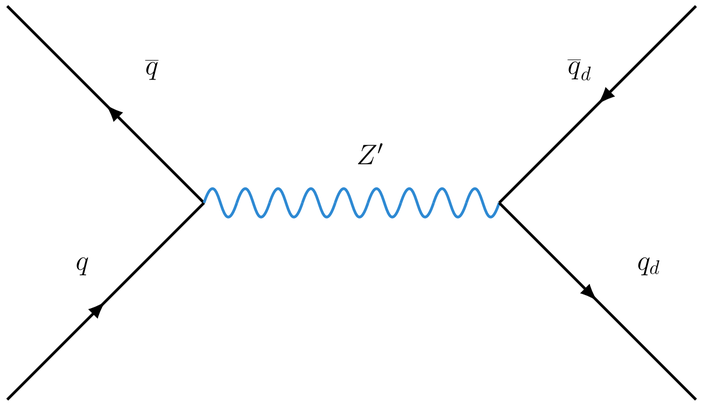
ATLAS dark jets (JHEP 02 (2024) 128)
(ATLAS-HDBS-2018-45)

- Z' mediator coupling to q and q_d :
  - prompt decay of dark hadrons to SM particles, several different decay modes considered (cf back-up)
  - final state : at least 2 jets (R = 1.0) with an important track multiplicity

- Search for a resonance in the m_{jj} spectrum, background shape extracted from a control region

  Limits on $\sigma \times \mathrm{BR}(Z' \to \bar{q}_d q_d)$ in function of $m_{Z'}$

- Implementation in MadAnalysis validated, available soon in the database



Model C, $m_{Z'} = 2.5$ TeV	**ATLAS**	**MadAnalysis**
Trigger, $m_{jj} > 1.3$ TeV	65.8	66.8
$m_{j1,2} > 50$ GeV, $p_{T,j1} > 500$ GeV, $p_{T,j2} > 400$ GeV	81.3	79.8
$\lvert\eta_{j1,2}\rvert < 2$	100.0	98.5
$m_{j1,2} < 600$ GeV, $p_{T,j1,2} < 3000$ GeV	99.9	99.9
$n^{\epsilon}_{track,\ j1,2} > 0$	11.6	11.6
Total	6.2	6.1

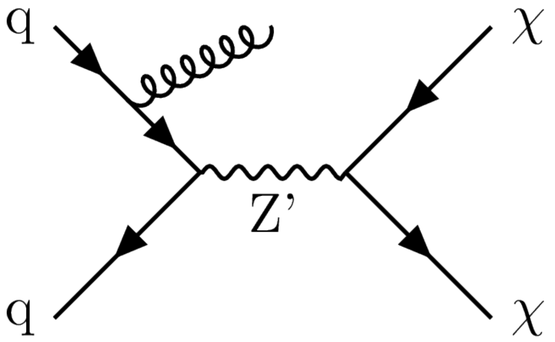
ATLAS and **MadAnalysis** : cut relative efficiency (%)

CMS mono-jet (JHEP 11 (2021) 153) (CMS-PAS-EXO-20-004)

- Final state : at least one energetic jets (R = 0.4) with large E_T^{miss}, no leptons and no photons

- Several models producing such signature :

  - for instance : pair production of WIMPs χ with a spin-1 mediator Z' and considering ISR



- SM process contribution determined thanks to simultaneous fit of p_T^{recoil} (p_T of the system that recoils against the hadronic activity) distributions in multiple CRs and in SR

  Limits on specific models parameters (exclusion contours in (m_{med}, m_{DM}) plane or limits on g_χ/g_q in function of m_{med})

- Analysis accessible at : https://dataverse.uclouvain.be/dataset.xhtml?persistentId=doi:10.14428/DVN/IRF7ZL

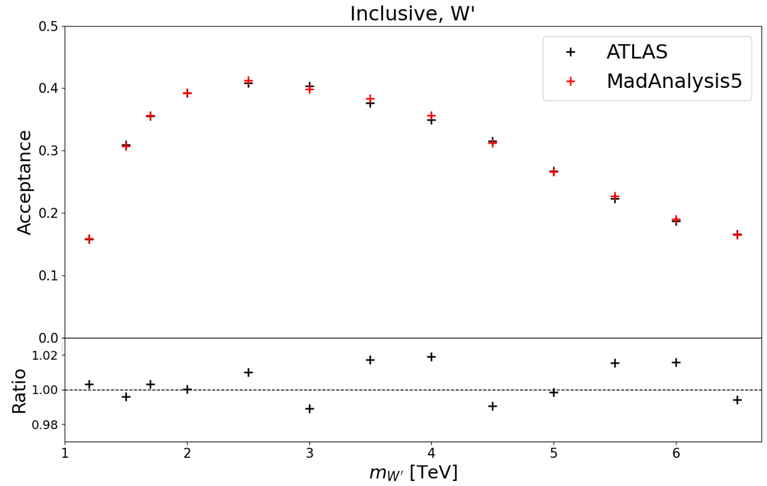
ATLAS di-jet (JHEP 03 (2020) 145) (ATLAS-EXOT-2019-03)

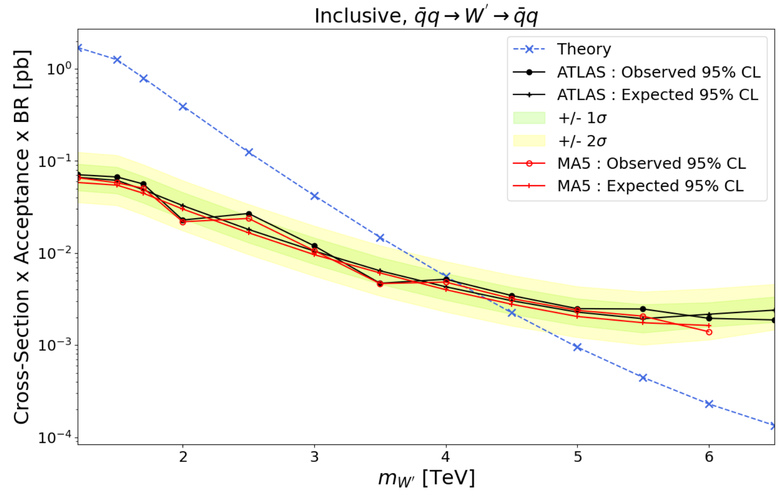
- Can be sensitive to a Z' coupled to q and q_d through $\bar{q}q \rightarrow Z' \rightarrow \bar{q}q$

- Many models of heavy particles decaying into a pair of SM quark has been considered
  Final state : at least two energetic jets (R = 0.4)

- Inclusive, 1b ($N_{b-jet} \geq 1$) and 2b ($N_{b-jet} = 2$) signal regions
  Search for a local excess in the observed m_{jj} spectrum above a SM contribution
  Upper limits on $\sigma \times A \times \epsilon$ in function of the mass for all the considered heavy particles

- Analysis accessible at : https://dataverse.uclouvain.be/dataset.xhtml?persistentId=doi:10.14428/DVN/KHJ1MW





Reinterpretation

- Process considered : leptophobic Z' decaying into $\bar{q}q$ or $\bar{q}_d q_d$

  $\mathrm{BR}(Z' \to \bar{q}q) = \mathrm{BR}(Z' \to \bar{q}_d q_d) = 50$ % to have a sufficiently high cross-section for performing the subsequent studies

  Other parts of the event generation follow CMS semi-visible jet s-channel production cards

```
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4900023:addChannel = 1 0.25 102 1 -1
4900023:addChannel = 1 0.25 102 2 -2
```

- Scan of $m_{Z'}$ and r_{inv} for now

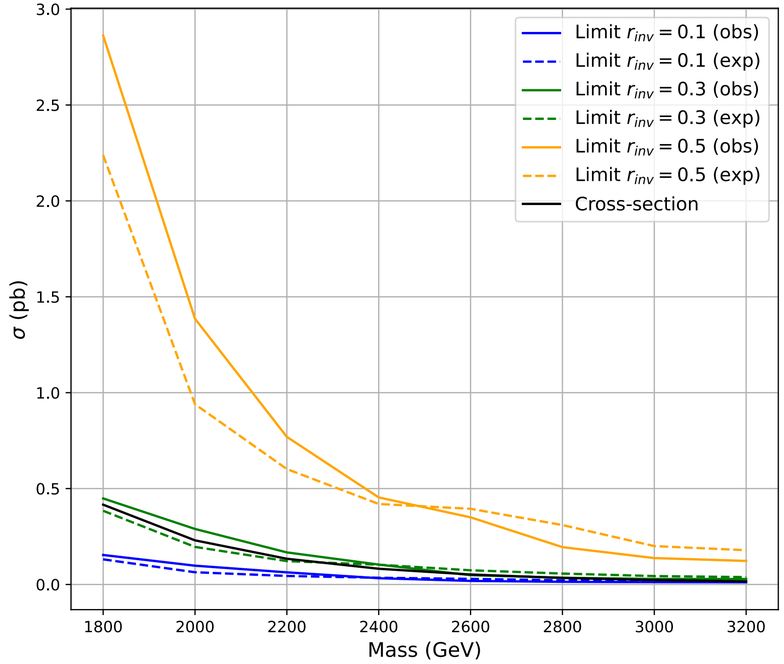
  Parameters that could be scanned : g_q, g_{q_d}, dark hadrons

  masses, dark QCD confinement scale Λ_{QCD} ...

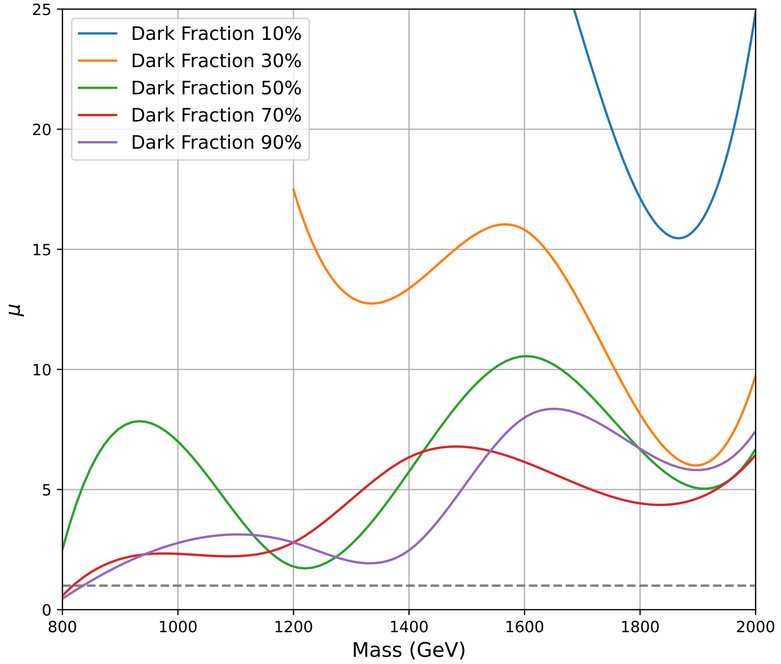
First results

- Left (right) plot : upper limits on signal cross-section σ (signal strength μ) in function of $m_{Z'}$ for different fraction of stable dark mesons r_{inv} obtained with the ATLAS dark jets (semi-visible jets) analysis

- Dark jets analysis has some exclusion power for $r_{inv} \in \{0.1, 0.3\}$ and for higher masses
  SVJ t-channel analysis has some exclusion power for higher r_{inv} and for lower masses



from ATLAS-HDBS-2018-45



from ATLAS-EXOT-2022-37

Back-up

Reinterpretation of LHC results with MadAnalysis5

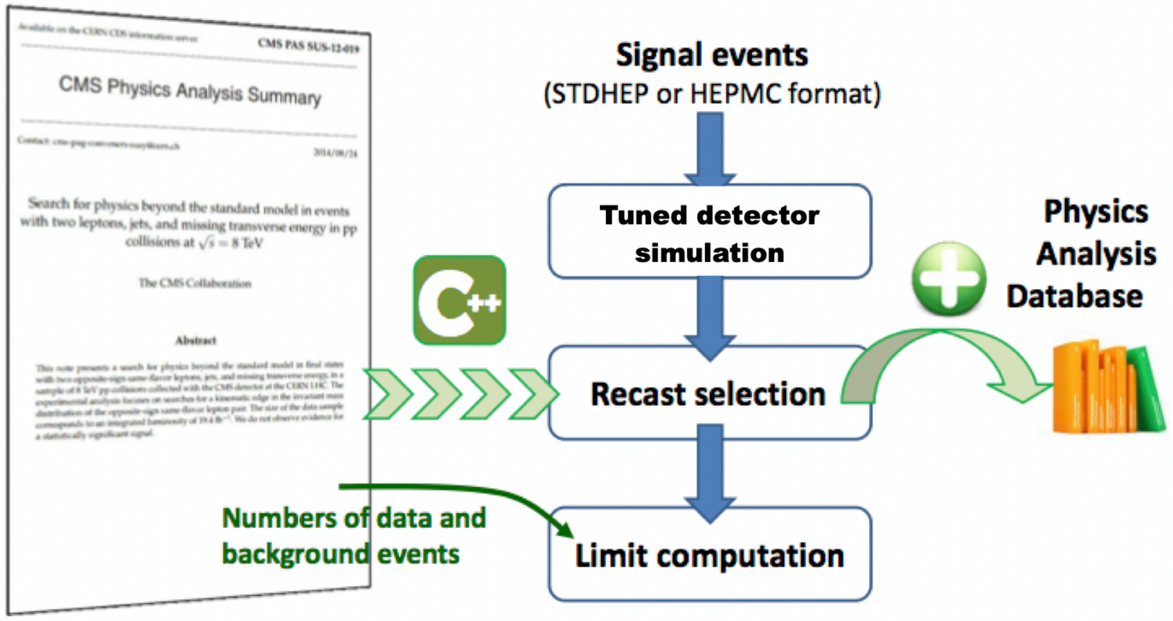
- General functioning of MadAnalysis :

  - analysis of interest implemented in C++ code : reproduction of the analysis strategy

  - detector simulation and analysis code applied to new physics events (at hadron level)

  - prediction of number of signal events in SRs : comparison with data and expected background

  - computation of signal cross-section upper limits



ATLAS dark jets models

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