Uncovering Tau-Leptons Enriched Semi-Visible Jets at the LHC

Eur. Phys. J. C 83, 599 (2023)

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19 October 2023

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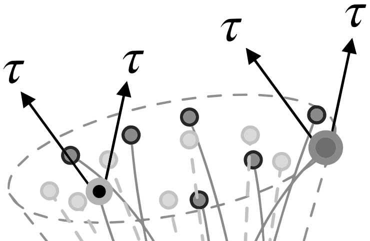
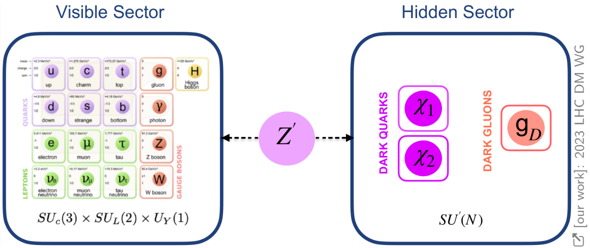


Hidden Dark Sectors

Motivation:

- Previous DM searches: single particle candidates (e.g. WIMPS)
- But a large fraction of visible matter is composite (hadrons)
  - → DM may consist of QCD-like hadrons too!



The hidden valley model:

- New force $SU'(N_c^{\text{dark}})$ carried by "dark gluons" at scale Λ_{dark}
- Z' acts as portal between SM and new dark sector
  - → N_f^{dark} "dark quarks" χ_i charged under $SU'(N_c^{\text{dark}})$
  - → DM candidates: Stable dark hadrons

Hidden Dark Sectors → Semi-Visible Jets

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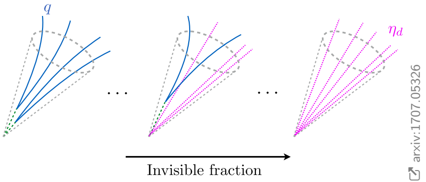
Semi-Visible Jets (SVJ)

- Dark QCD hadronises
- Can convert back into SM quarks via Z'
  - → Shower partly SM (visible), partly DM (invisible)

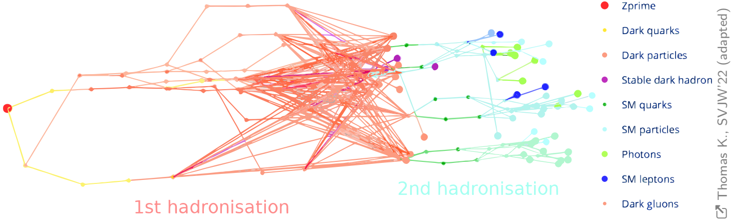
$$r_{\text{inv}} = \left\langle \frac{\text{number of stable hadrons}}{\text{number of hadrons}} \right\rangle$$



Experimental signature:

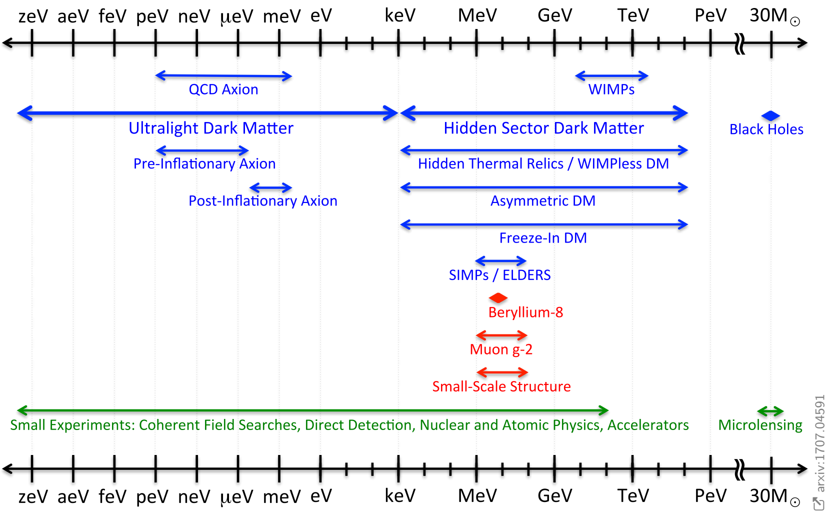
- $\not{E}_{\mathrm{T}}$ ∼ aligned with jets
- Unusual jet substructure due to second hadronisation

SVJ shower with second hadronisation



Hidden Dark Sectors → Dark Matter?

Dark Sector Candidates, Anomalies, and Search Techniques



- Hidden sector dark hadrons good candidate for dark matter
- Span wide mass range compared to WIMPS

SVJ: An Emerging Field of Study

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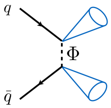
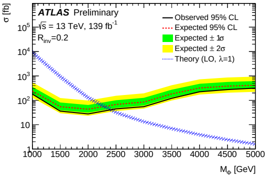
SVJ is an exciting new signature

- Hidden valleys PYTHIA module made modeling of signal possible
- Cohen et. al. (arxiv:1707.05326) proposed LHC search strategy
- First SVJ workshop in July 2022 kicked off many new studies

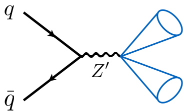
Fully hadronic SVJ, t-channel in ATLAS

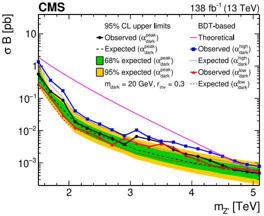




ATLAS-CONF-2022-038

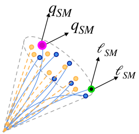
Fully hadronic SVJ, s-channel in CMS

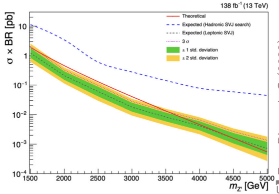




JHEP 06 156 (2022)

Prospects for lepton-enriched SVJ





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see Cesare Cazzaniga's talk

Our Signal Model: Tau-Enriched Semi-Visible Jets

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Z' coupling to SM q and ℓ:

$$\mathcal{L}_{SM} \supset -Z'_\mu \bar{u}_i \gamma^\mu (g^{u_R}_{ij} P_R + g^{u_L}_{ij} P_L) u_j$$
$$-Z'_\mu \bar{d}_i \gamma^\mu (g^{d_R}_{ij} P_R + g^{d_L}_{ij} P_L) d_j$$
$$-Z'_\mu \bar{e}_i \gamma^\mu (g^{e_R}_{ij} P_R + g^{e_L}_{ij} P_L) e_j$$

Z' coupling to dark q_v:

$$\mathcal{L}_{q_v} \supset -Z'_\mu \bar{q}_{vi} \gamma^\mu (g^{q_{vR}}_{ij} P_R + g^{q_{vL}}_{ij} P_L) q_{v}$$

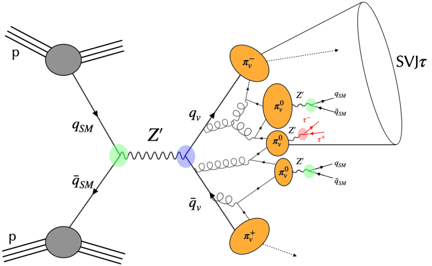
$\Rightarrow$ Dark mesons decaying into SM:

$$\Gamma_{\pi_a \to f_i \bar{f}_i} = \frac{N_c F_\pi^2}{32\pi} (\Delta^f_{ii} \Delta^{q_v}_a)^2 \frac{m_{\pi^a} m^2_{f_i}}{M^4_{Z'}} \sqrt{1 - \frac{4 m^2_{f_i}}{m^2_{\pi_a}}}$$

$Z' \leftrightarrow e, \mu$ coupling suppressed

$\rightarrow$ Avoids existing constraints from di-lepton searches

$\rightarrow$ Leaves possibility of τ in jets



[our work]: Eur. Phys. J. C 83, 599 (adapted)

Model based on:

- "An effective Z'"
  Phys. Rev. D 84, 115006 (2011)
- "Quark flavor transitions in $L_\mu - L_\tau$ models"
  Phys. Rev. D 89, 095033 (2014)

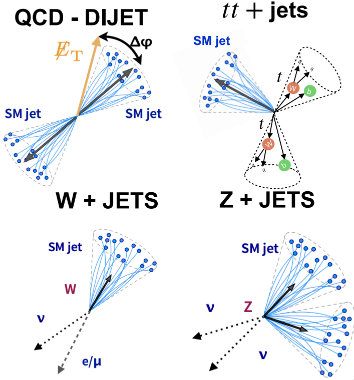
Event generation

- **Madgraph5:** Matrix element + cross-section
- **Pythia8 (Hidden Valley Module):** Parton shower, hadronisation
- **DELPHES3 + FASTJET:** Jet clustering, fast detector simulation

Event selection

- Based on CMS hadronic SVJ search
  JHEP 06 156 (2022)
- Number of good jets: $N(j^{\mathrm{AK8}}) \geq 2$
  $p_{\mathrm{T}}(j_{1,2}^{\mathrm{AK8}}) > 200$ GeV and $|\eta(j_{1,2}^{\mathrm{AK8}})| < 2.4$
- Jet separation: $\Delta\eta(j_1^{\mathrm{AK8}}, j_2^{\mathrm{AK8}}) < 1.5$
- Jet-$\not{E}_{\mathrm{T}}$ separation: $\Delta\phi_{\min}(\not{E}_{\mathrm{T}},\ j_{1,2}^{\mathrm{AK8}}) < 0.8$
- Veto on mini-isolated leptons: $N_{\mu,e} = 0$

Backgrounds



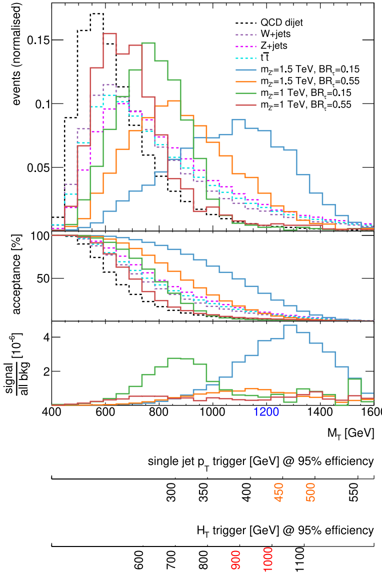
Hadronic triggers

- Based on CMS hadronic SVJ search (JHEP 06 156 (2022))
- H_T or p_T trigger emulated by M_T cut
- Lowest possible (unprescaled) triggers:
  - $H_T \sim$ 900 – 1000 GeV
  - $p_T \sim$ 450 – 500 GeV

    $\to$ $M_T \sim$ 1.2 TeV cut

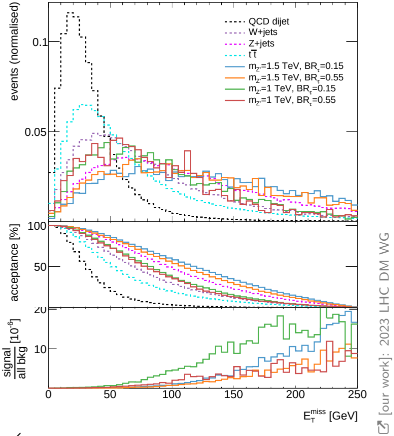
Limitations

- Low acceptance for signals with $m_{Z'} < 1.5$ TeV
- More effective triggers possible?



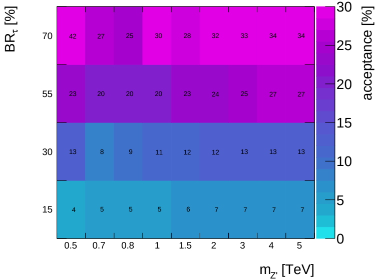
[our work]: Eur. Phys. J. C 83, 599 (adapted)

Tau and $\not{E}_T$ Triggers

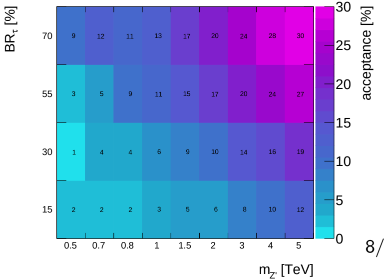


- $\not{E}_T$ triggers require extremely low thresholds
- Single τ triggers limited by isolation
- Di-τ triggers avoid isolation criterion but have overall low acceptance

Single-τ trigger isolation requirement



Di-τ trigger requirement



[our work]: Eur. Phys. J. C 83, 599

Alternative Trigger Strategies

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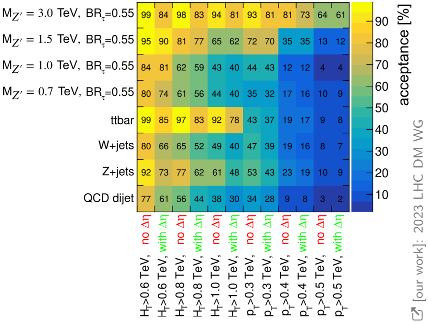
Topological triggers

- Make use event geometry
- Jets close to each other ($\Delta\eta$)
- Combined with standard H_T or p_T triggers

  → Much lower bkg acceptance while retaining most signal



Trigger Level Analysis (TLA)

- Save only relevant objects, as reconstructed by HLT
- Much smaller events

  → allows for higher rates
- Successfully used e.g. in general dijet-searches

Partial Event Building (PEB)

- Fully reconstruct only relevant parts (around jets)
- Retains full jet substructure for tagging
- Used e.g. in μ PEB triggers

→ **All of these can be combined!**

BDT used as final discriminant

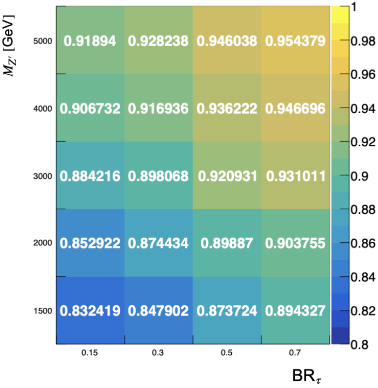
- Variables exploiting e/μ enriched jets from τ decays
- Inter-isolation I_{inter} highest performing input
  - Captures nearby non-isolated leptons in jets

Ranking of inputs

Rank	Variable	Separation
1	$I_{inter}(\mu)$	2.703×10^{-1}
2	$R_{Norm}(\mu)$	2.601×10^{-1}
3	$I_{\gamma\pi}(\mu)$	2.164×10^{-1}
4	$R_{Norm}(e)$	1.786×10^{-1}
5	$I_{inter}(e)$	1.632×10^{-1}
6	$Energyfraction(e)$	7.500×10^{-2}
7	$I_{\gamma\pi}(e)$	7.175×10^{-2}
8	$p_{T,Norm}(\mu)$	6.272×10^{-2}
9	$Energyfraction(\mu)$	6.220×10^{-2}

[our work]: 2023 LHC DM WG

Area under ROC curve



[our work]: Eur. Phys. J. C 83, 599

→ **Best acceptance for high BR_τ and $m_{Z'}$**

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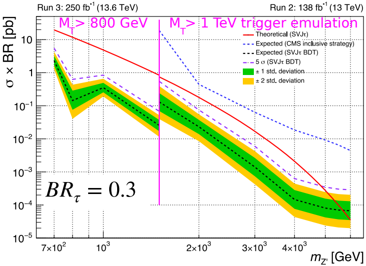
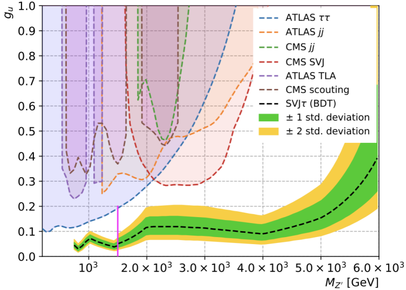
Prospective limits



[our work]: Eur. Phys. J. C 83, 599

Comparison to previous limits



[our work]: Eur. Phys. J. C 83, 599

- Alternative trigger strategies allow to reach lower $M_{Z'}$
- Focus on τ (suppressed $Z' \leftrightarrow e/\mu$ coupling) avoids dilepton limits
- **Proposed BDT achieves limits below any previous constraints over large range of $m_{Z'}$**

Summary and Outlook

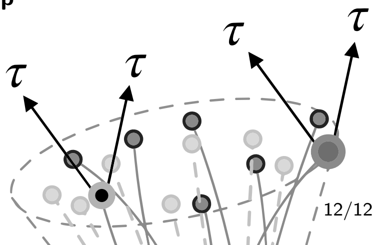
Tau-leptons enriched semi-visible jets (SVJτ)

- Hidden valley: QCD-like dark sector connected to SM via Z' portal
- Dark hadrons candidate for composite dark matter
- Z' decays to SM quarks and τ
  - $\rightarrow$ **Jets with large $\not{E}_\mathrm{T}$ and non-isolated τ**

Prospects for LHC

- Standard hadronic, $\not{E}_\mathrm{T}$, τ triggers suffer from low acceptance
- Efficient trigger strategy combines topo-triggers with TLA & PEB
  - $\rightarrow$ **Hadronic SVJ searches only first step towards a rich SVJ programme**

See Cesare Cazzaniga's talk for SVJℓ signature



Appendix

Multivariate Analysis: BDT

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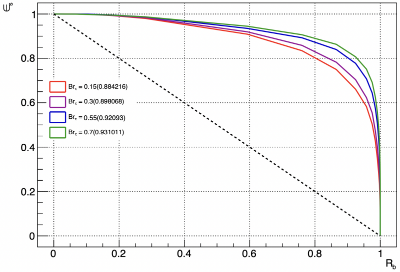
S/B separation



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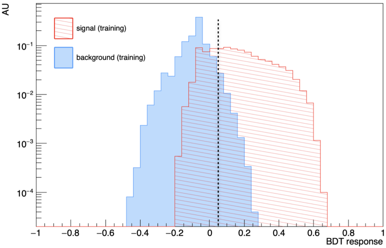
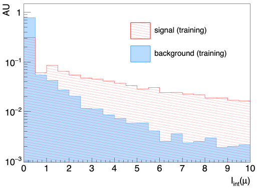
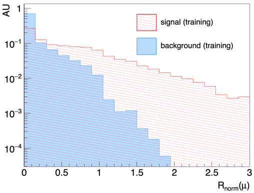
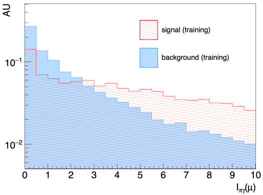


[our work]: Eur. Phys. J. C 83, 599

Highest performing variables



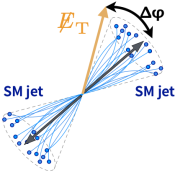




[our work]: Eur. Phys. J. C 83, 599

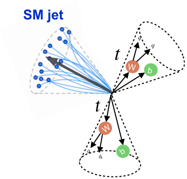
Backgrounds

QCD - DIJET



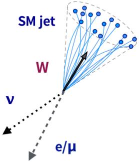
- ✦ Jet mis-measurement induces $\not{E}_T$ aligned with jet
- ✦ Large cross-section

$t\bar{t}$ + jets



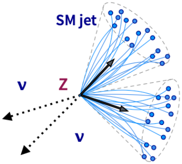
- ✦ Wide, high-pT jets: boosted tops
- ✦ Overlapping lepton from W boson decay
- ✦ Neutrino aligned with jet

W + JETS



- ✦ Lost lepton or hadronic τ
- ✦ Real $\not{E}_T$ from neutrino (less likely to be aligned with jet)

Z + JETS



- ✦ Real $\not{E}_T$ from neutrino but less likely to be aligned with jet

Cesare C.: 2023 LHC DM WG

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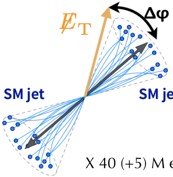
Backgrounds

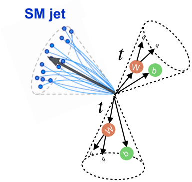
QCD - DIJET



- 2 HARD PARTONS IN ME
- GEN PT CUT: 500 GeV (200 GeV - trigger study)

X 40 (+5) M events

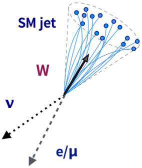
$t\bar{t}$ + jets



- MAXIMUM 2 ADDITIONAL PARTONS IN ME

X 50 M events

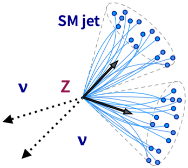
W + JETS



- MAXIMUM 3 ADDITIONAL PARTONS IN ME
- GEN HT CUT: 100 GEV

X 25 M events

Z + JETS

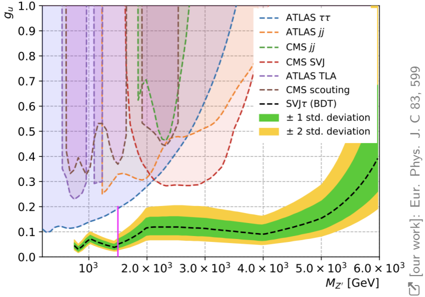


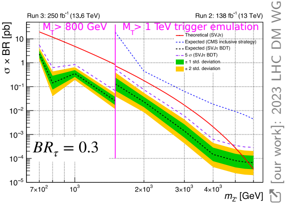
- MAXIMUM 3 ADDITIONAL PARTONS IN ME
- GEN HT CUT: 100 GEV

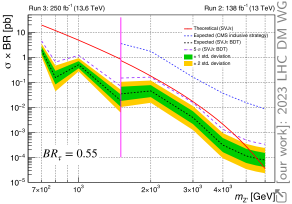
X 25 M events

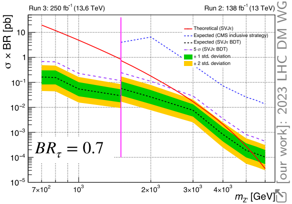
Cesare C.: 2023 LHC DM WG

Results: Prospective Limits









Trigger Level Analysis (TLA)

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Example:
One Run 3 fill in August 2022
at $\langle \mu \rangle = 48$

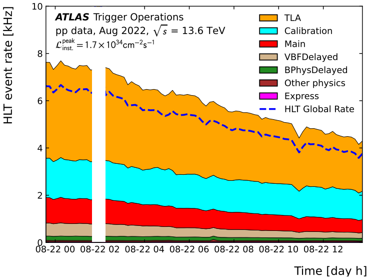
Rate $\times$ event size $\rightarrow$ bandwidth

Physics main
~ 1 kHz $\times$ 1.5 MB $\rightarrow$ 1.5 GB/s

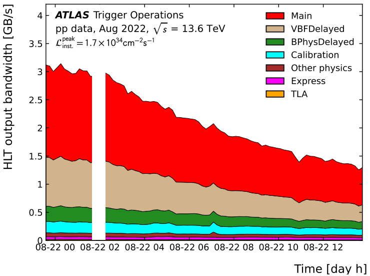
TLA
~ 4 kHz $\times$ 5 kB $\rightarrow$ 20 MB/s

$\rightarrow$ **TLA bandwidth so small, it's not even visible on this plot!**

TLA stream has **highest rate**...



...but **lowest bandwidth**

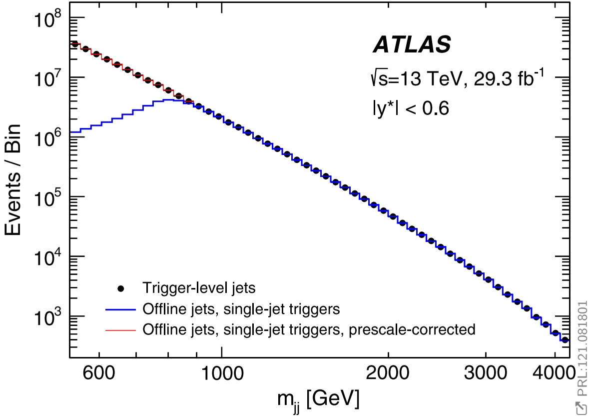


Gap: Emittance scan, no physics data recorded

twiki.cern.ch/.../TriggerOperationPublicResults

TLA vs Prescaling

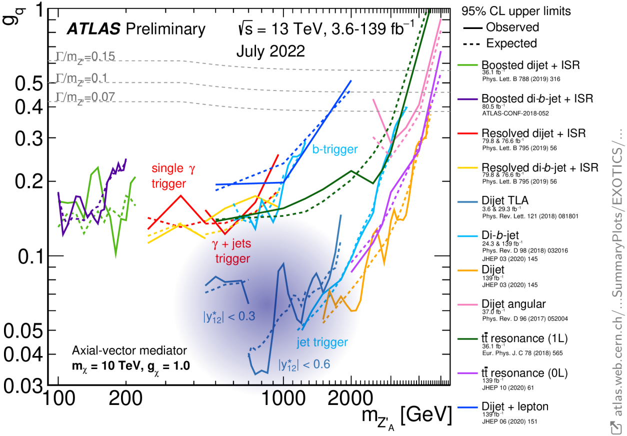
Early Run 2 dijet TLA analysis



- **Offline jets** have to rely on heavily prescaled triggers at low p_T
- **Un-prescaling** recovers spectrum's shape but not statistics
- **TLA** circumvents HLT limitations

TLA in Action

Example: Leptophobic axial mediator in simple DM models



- Variety of techniques needed to span full $m_{Z'} \to$ dijet mass space
- **Early Run 2 TLA** (PRL:121.081801) leading in 400 – 1200 GeV range