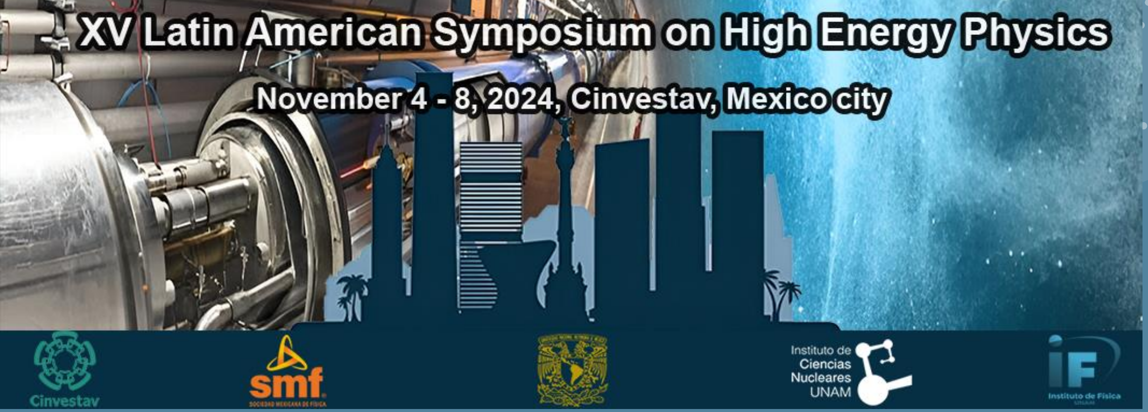


Exotic searches at ATLAS

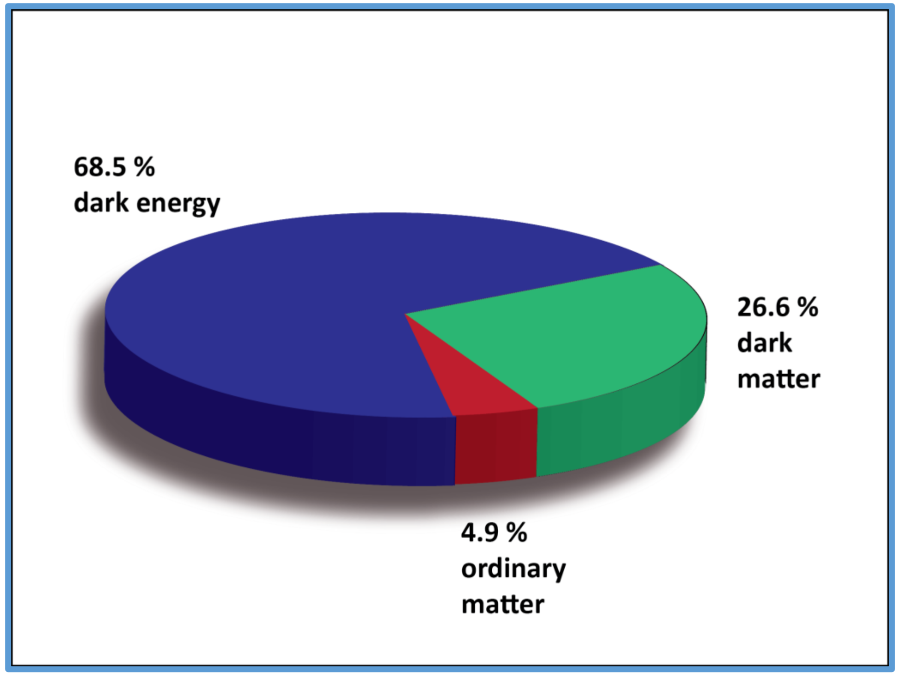
- Christos Vergis (he/his/him)
  on behalf of the ATLAS Collaboration
- 04 November 2024

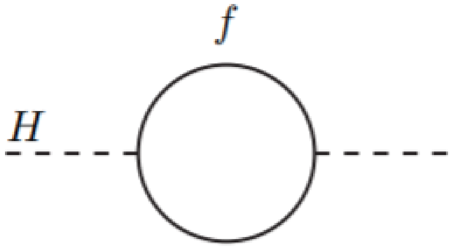
ATLAS EXPERIMENT

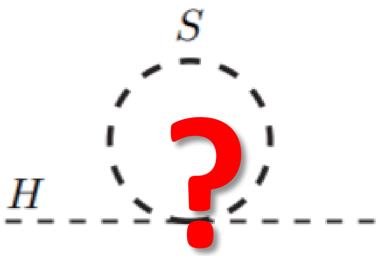
Los Exotics

Introduction

- ATLAS : General purpose Detector
  Extensive ongoing program for
  Beyond Standard Model searches
- Why do we care? SM agrees well with Experiment, but:
  - No particle explanation for observed Dark Matter
  - Naturalness/Hierarchy problem:
    why mass of the Higgs is so small?)
  - No Gravity (Extra dimensions, String Theory)
  - Origin of neutrino masses

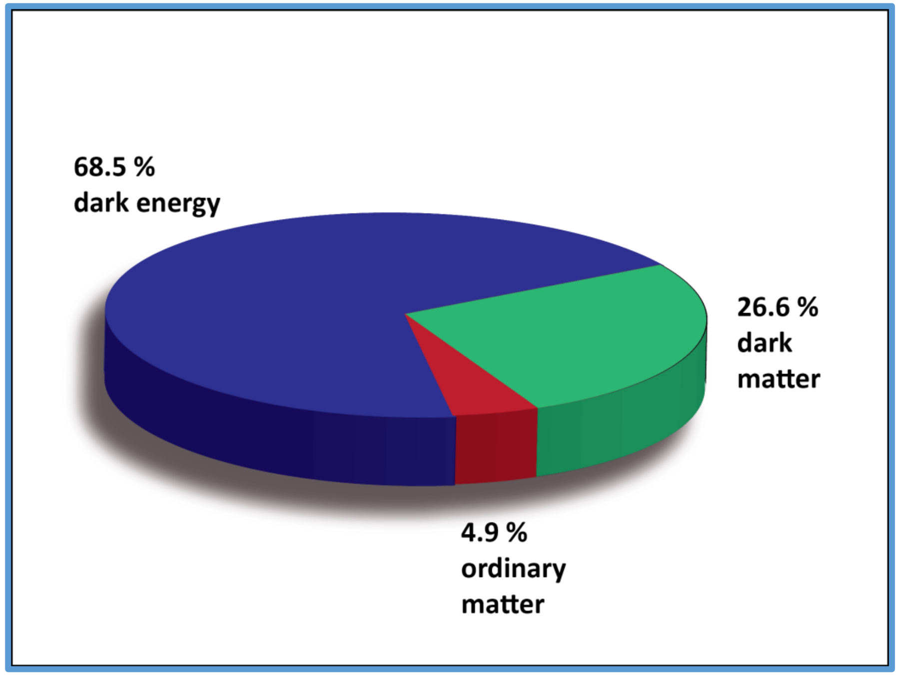


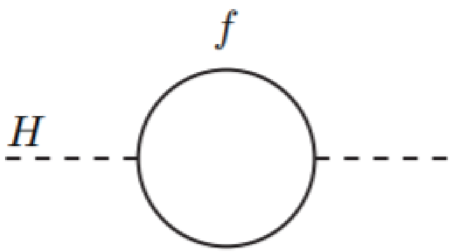


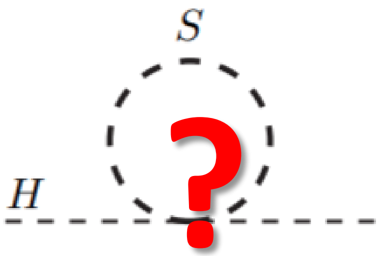


Exoduction

- ATLAS : General purpose Detector
  Extensive ongoing program for
  Beyond Standard Model searches
- Why do we care? SM agrees well with Experiment, but:
  - No particle explanation for observed Dark Matter
  - Naturalness/Hierarchy problem:
    why mass of the Higgs is so small?)
  - No Gravity (Extra dimensions, String Theory)
  - Origin of neutrino masses
- This talk covers five such searches
  (Falling under the umbrella of Exotics)

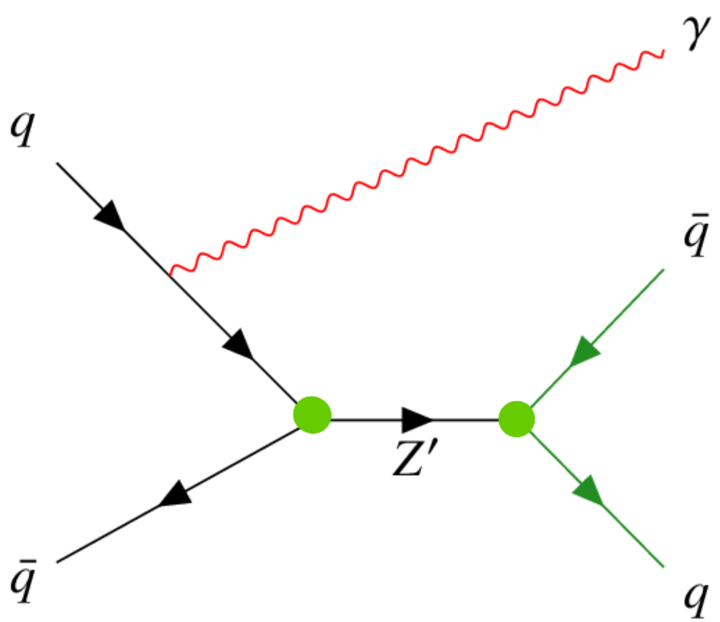






Low-mass resonance search

2408.00049



Dark matter models and other (e.g. low-mass strings):
predict presence of new spin-1 mediators (Z’)

Requirement for Z’ to be produced at LHC: **qqZ’ coupling non vanishing**

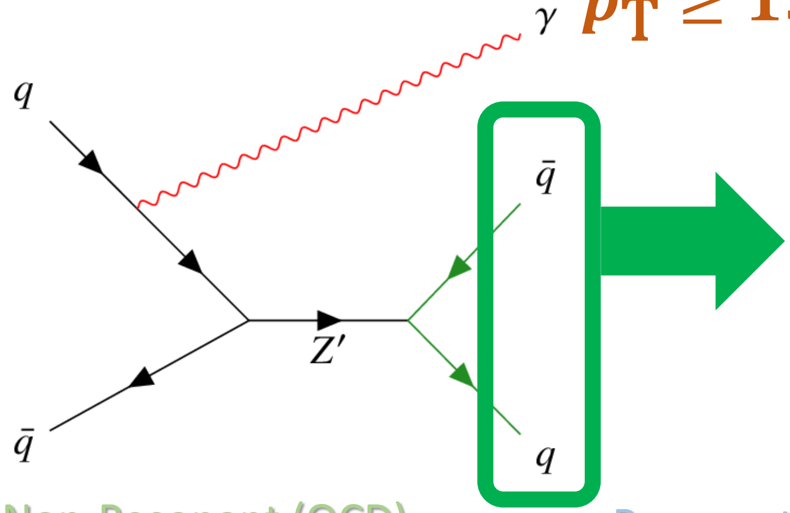
Z’ could then decay into quarks (“leptophobic”)

Challenges:
Large event rate from QCD background
Either use:
a) Trigger-less analysis
b) Initial-State Radiation to trigger the event
(lower momentum γ-triggers)

Low-mass resonance search

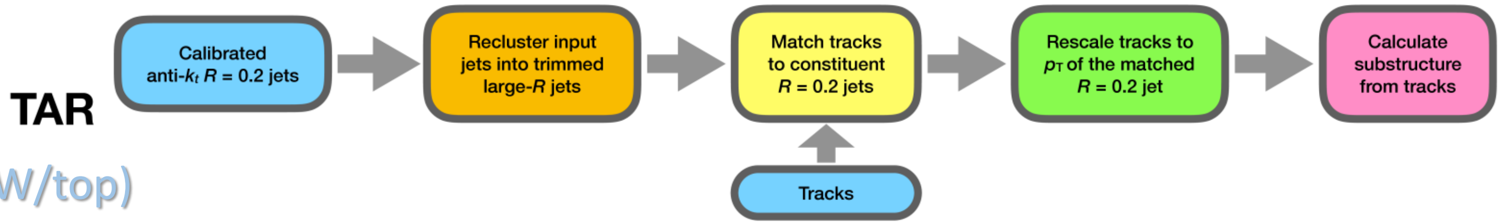
2408.00049

$p_{\mathrm{T}} \geq 150$ GeV



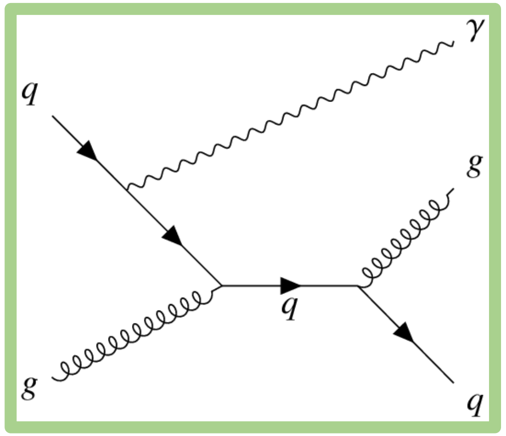
Collimated jet (large R-jet)

Collimated jets from the Z’ decay reconstructed using the “Track-Assisted Reclustered” (TAR) jet technique:
Combines calorimeter & tracker info to improve resolution of jet substructure observables.

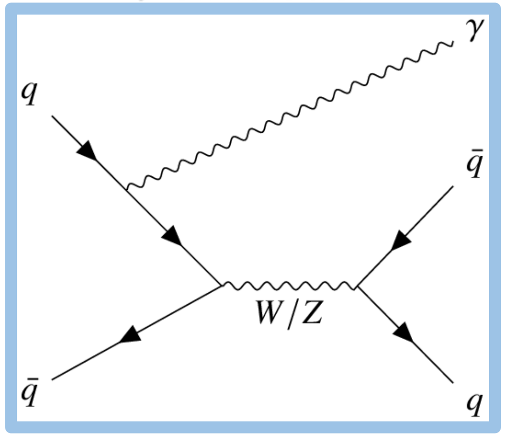


Track assisted techniques for jet substructure

Non-Resonant (QCD)
→ Data-Driven



Resonant (Z/W/top)
→ Simulation



Low-mass resonance search

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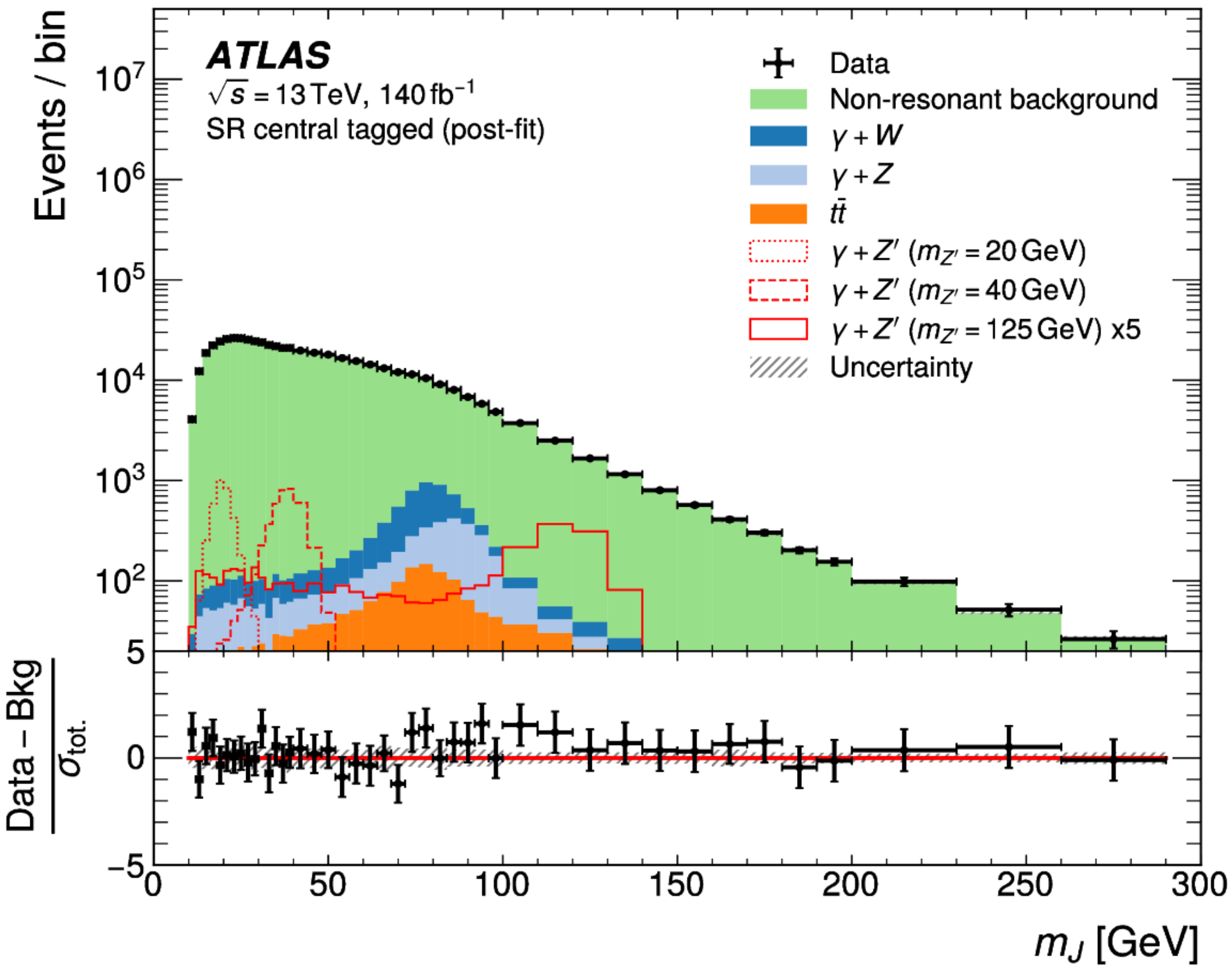


Search is performed on TAR-jet invariant mass: m_J

Other observable: D_2^{DDT} a mass-decorrelated D_2

(discriminant for jet prongness : 2 for Z′, 1 for NR QCD)

4 Regions defined using D_2^{DDT} (at 0) and η_γ (at 1.3)

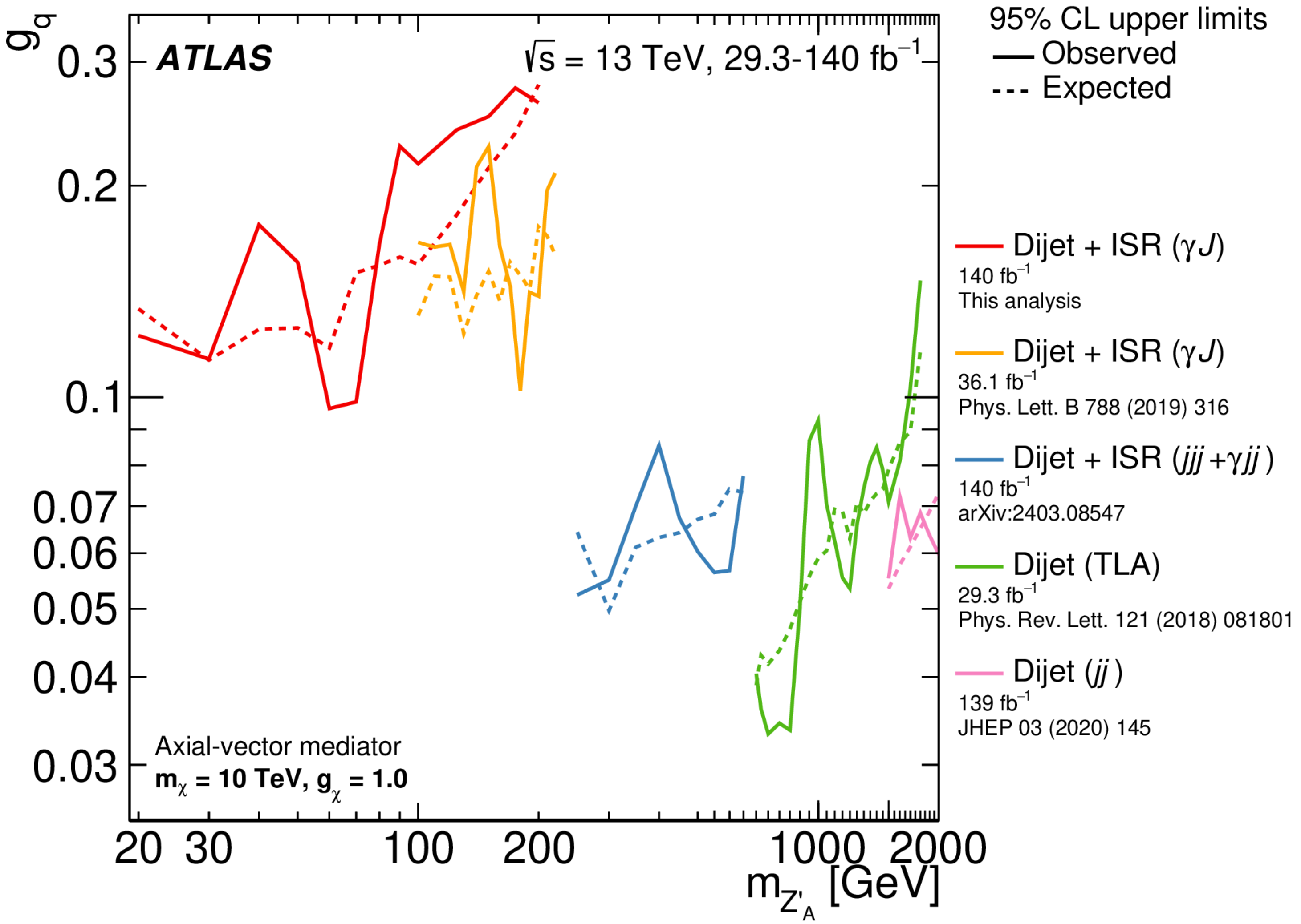
1. Signal Region (Tag + central)
2. CR1 (Tag + forward)
3. CR2 (Antitag + central)
4. CR3 (Antitag + forward)

Simultaneous fit SR together with 3 other CR

Dominant uncertainties:

1. Statistical (size of data)
2. Non-resonant background uncertainties

Low-mass resonance search - Results 2408.00049



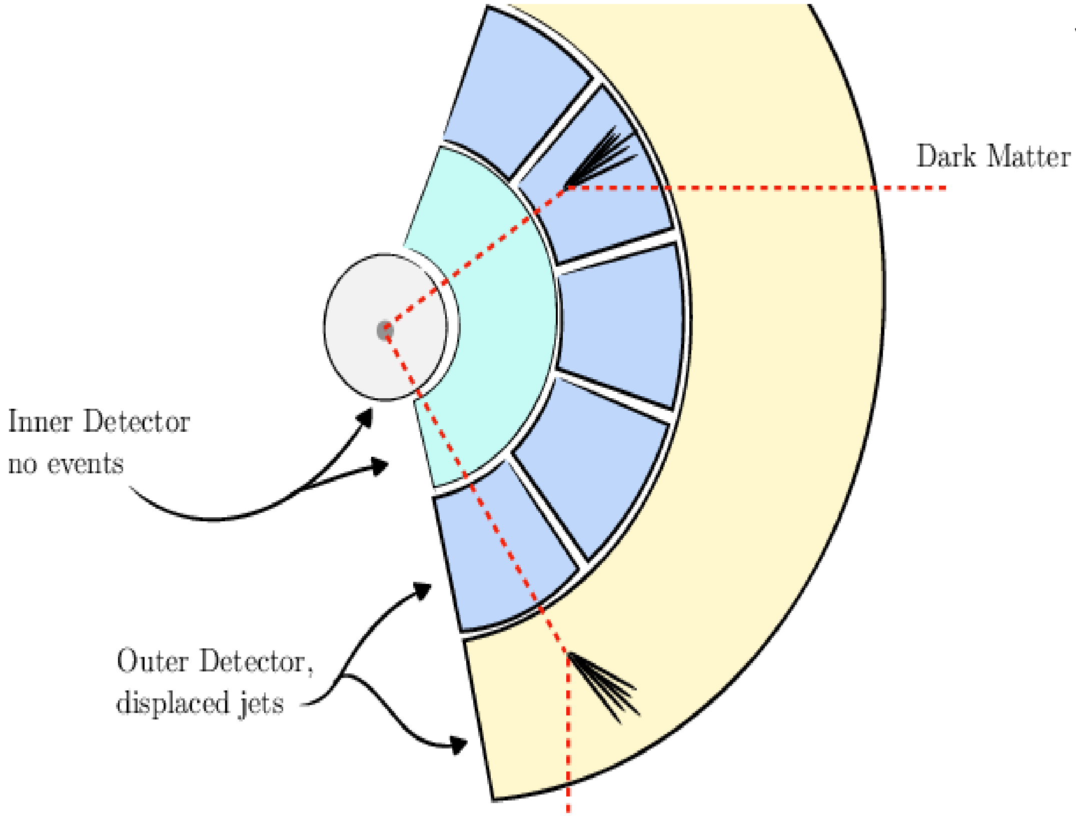
No excess observed in data
→Analysis derives 95% Confidence Level upper limits on the qqZ' coupling constant g_q

Current results shown in **RED**

Sensitivity obtained In Z' masses [20,100] GeV:
Due to ISR γ triggers + use of TAR jets

LLPs Displaced Jets with leptons/jets

2407.09183



Various supersymmetric models, dark-matter candidates, axion-models, hierarchy problem: predict existence of Long-Lived Particles

Benchmark Models: Hidden-Sector Models
Axion-Like Particle Models (photophobic)
Dark Photon Z_d

Neutral LLPs if produced at ATLAS can decay inside the detector producing displaced jets ($c\tau \sim cm - m$)

Interesting quantity is the "CalRatio" for LLPs that decay into the HCAL

$$\text{CalRatio}=\frac{E_{HCAL}}{E_{ECAL}}$$

LLPs Displaced Jets with leptons/jets

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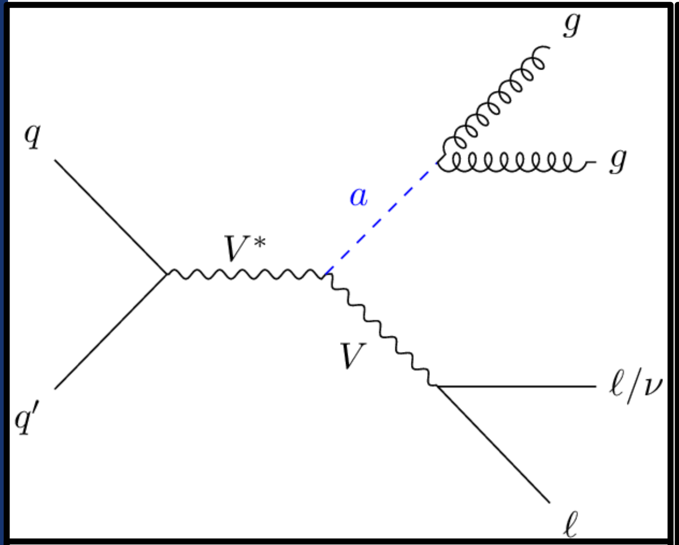

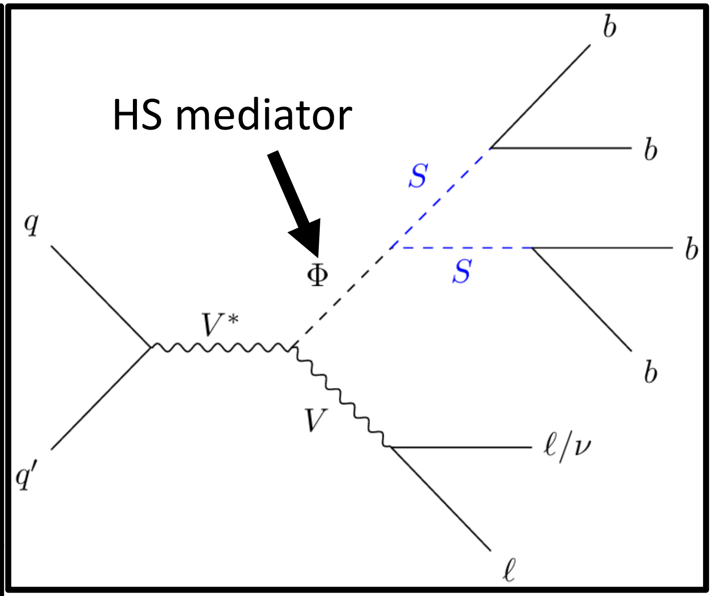

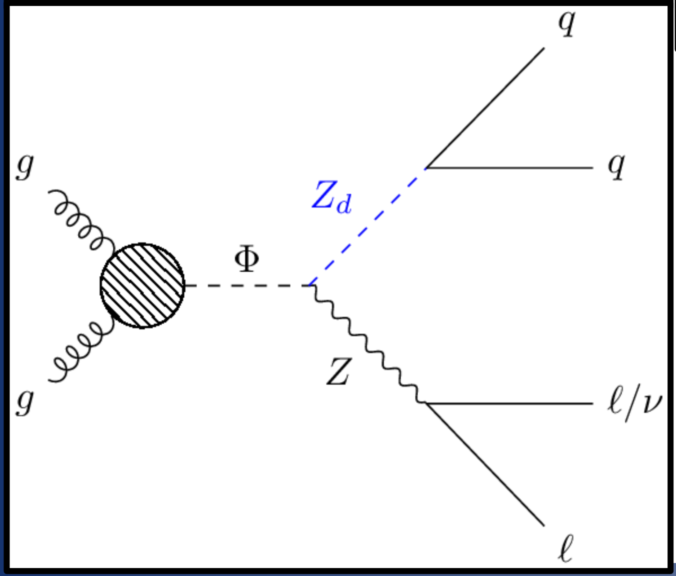

3 Main search **channels** & **Backgrounds**:

- **CalRatio+2Jets**

e.g. gluon-gluon Fusion mediator production of Φ
Production of two LLPs:

i. Boosted and decay into one-merged displaced jet

ii. Not boosted, decays into two jets

Multijet , **Non-collisional background**

- **CalRatio+W** & **CalRatio+Z**

e.g. V-associated production of ALP or Φ
V+jets , **Top**

Different triggers depending on the targeted channel

LLPs Displaced Jets with leptons/jets

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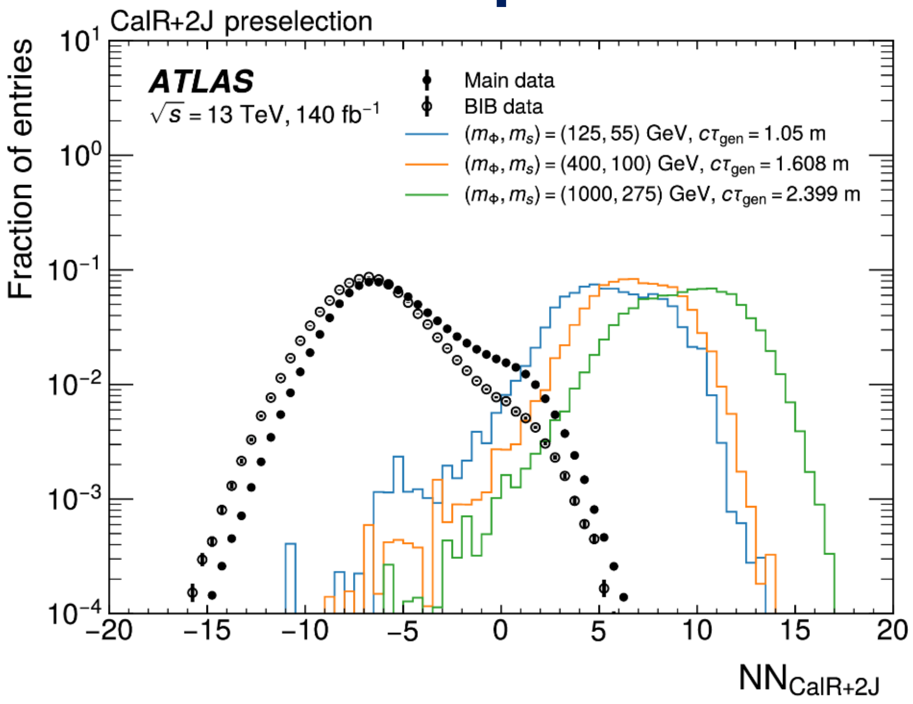

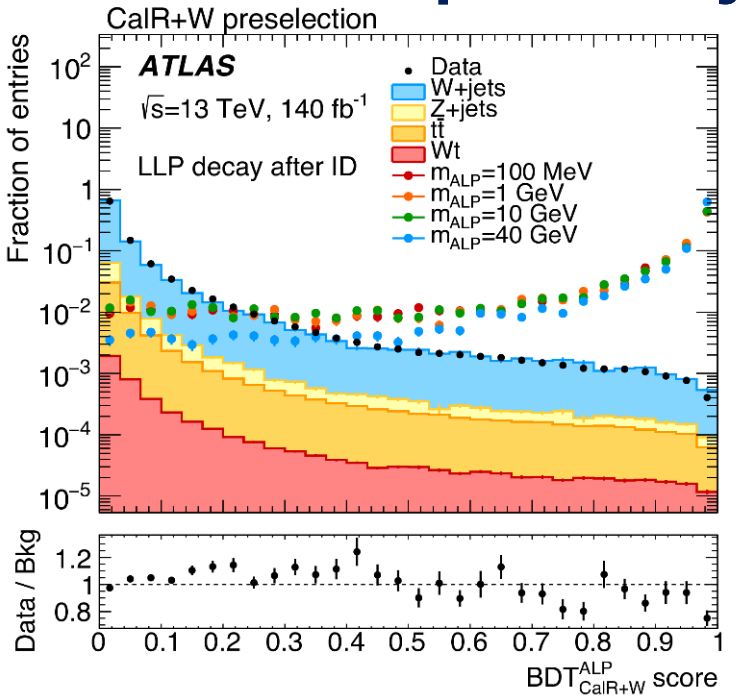

NNs used to determine per-jet if is Displaced or not

Event-based signal-background discrimination:
Mainly Machine-Learning techniques
CalR+2Jet chan: Neural Networks
CalR+W/Z chan: BDT

Data-driven approach for Background estimation using ABCD Method

1) NN/BDT
2) $\Sigma_{jet\,|\,p_T > p_T^{threshold}} \Delta R_{min}(jet\,, track)$ {thresholds: 40/50 GeV after optimization}

For (1) the Distance Correlation ("DisCo") technique is used to decorrelate $\Sigma\Delta R_{min}$ from NN by penalizing NN through the loss-function

LLPs Displaced Jets with leptons/jets

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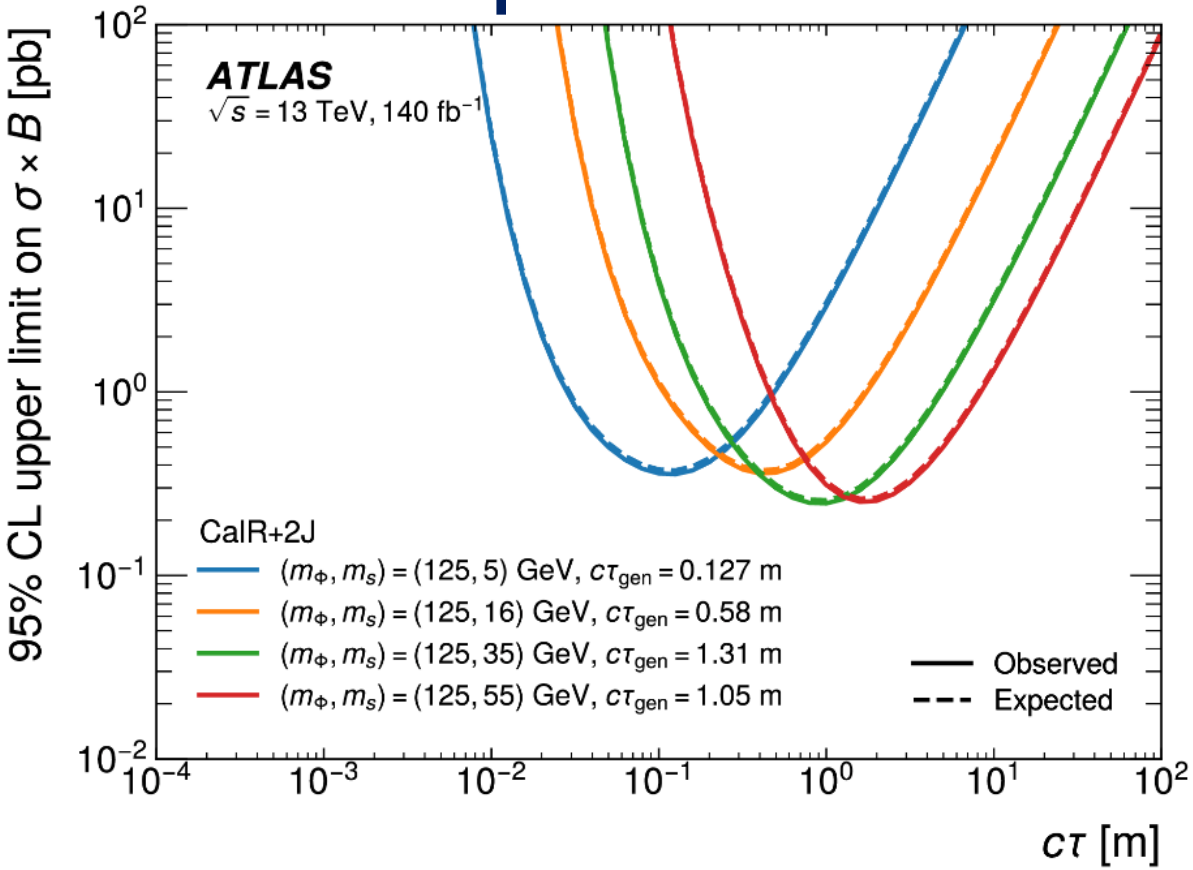
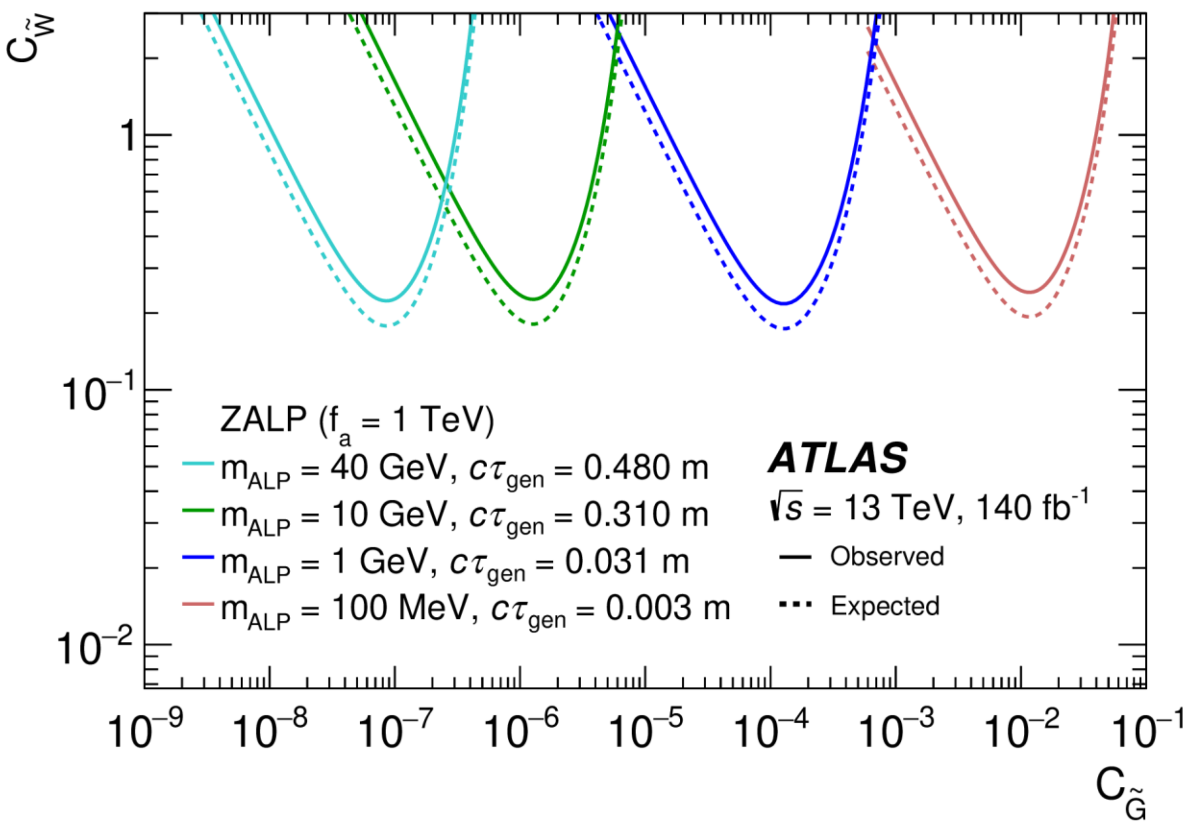


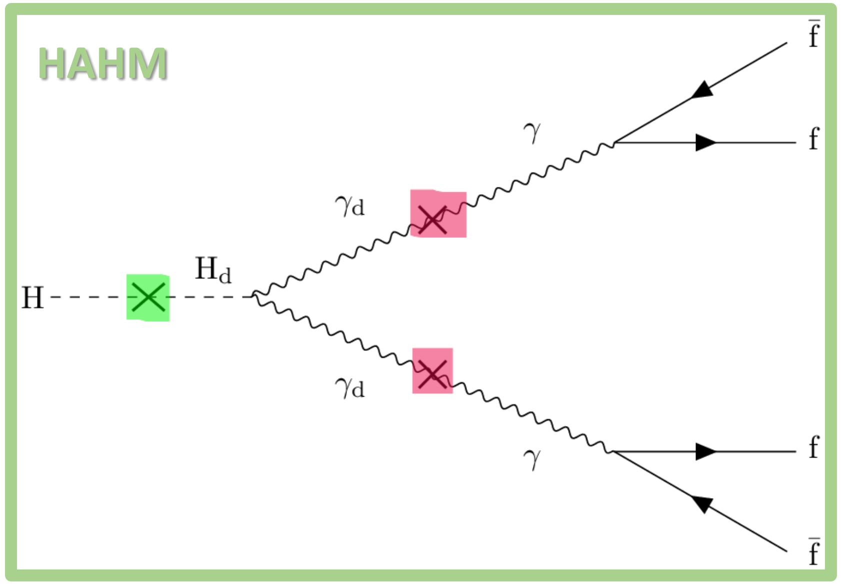


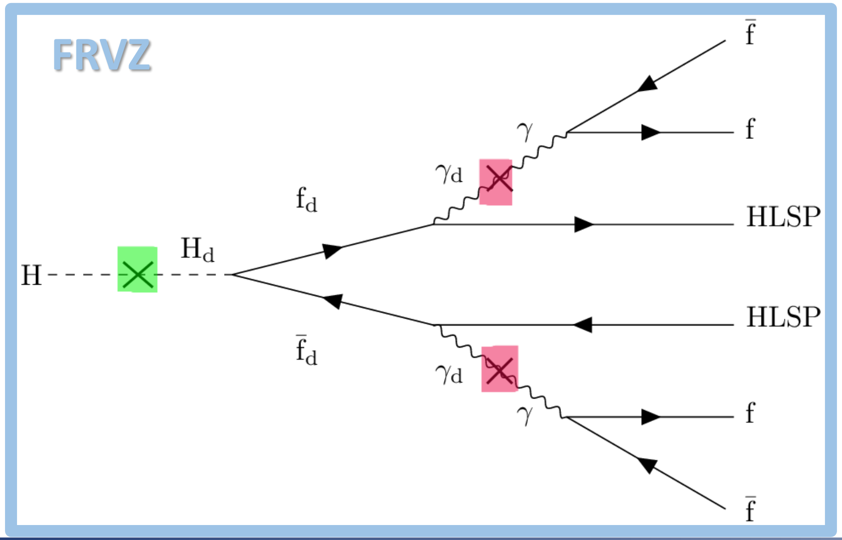
CaloR+2J limits improved CaloR previous search [2203.01009] for lower lifetimes

Z/W limits extended at higher-lifetimes compared to the displaced vertices search in the Inner Detector [2403.15332] ($c\tau \propto C_{\tilde{G}}^{-2}$ and cross-section $\sigma \propto C_{\tilde{W}}^{2}$)

Dark Photon Search ee/μμ

2407.09168





Motivated by Hidden sector theories associated with solutions to naturalness, thermal dark matter

U'(1) dark that is broken giving massive "Dark Photon" γ_d

The Hidden Higgs H_d responsible can be mixed with SM H

The γ_d interacts with γ/Z via coupling **ε**

Two models targeted with pair production of γ_d :

Hidden Abelian Higgs Model

With dark H_d directly coupling to dark photons

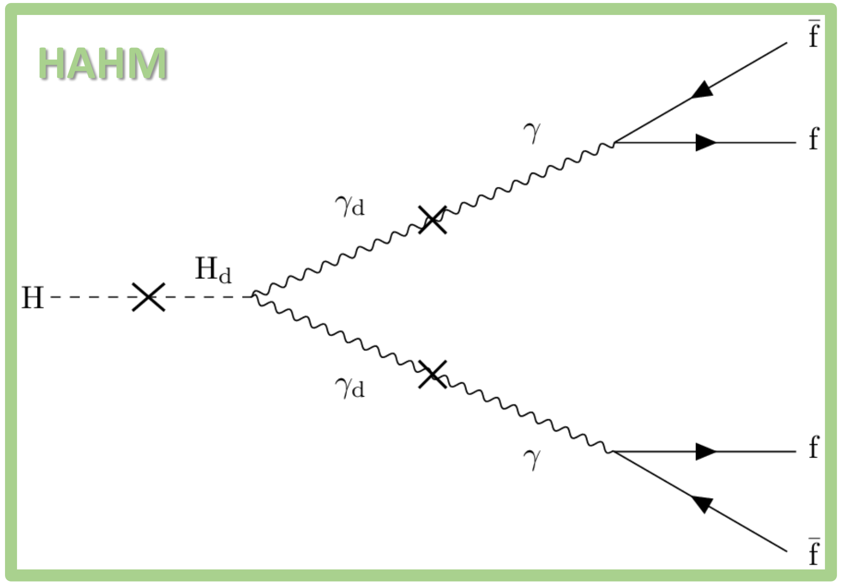
or

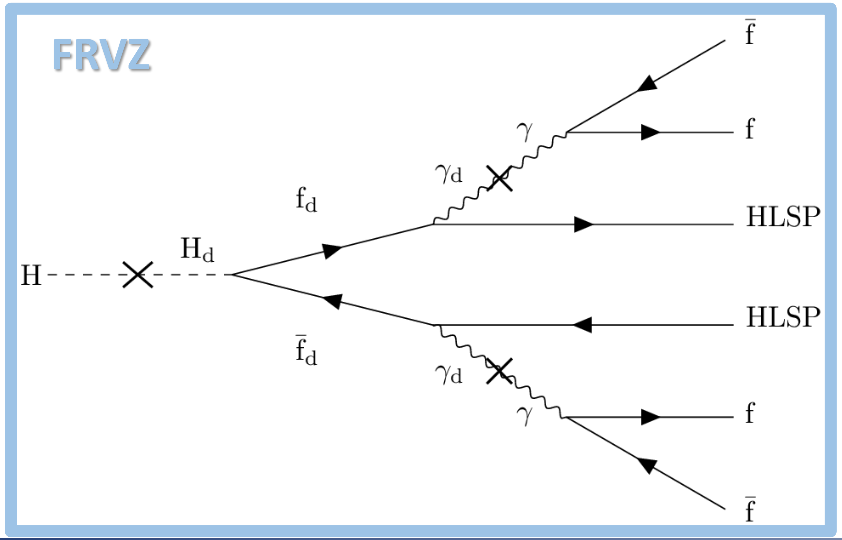
Falkowski-Ruderman-Volansky-Zupan

With dark H_d coupling to dark fermions f_d decaying into γ_d and Hidden Lightest Stable Particles

Dark Photon Search ee/μμ

2407.09168





For low mass γ_d relative to H: Collimated leptons
μ-channel : where at least one muon pair in final state
e-channel : **else** and optimized for $m_{\gamma_d} \leq 2 \cdot m_\mu$

Trigger events with combination of:
Single/Multi-electron
Multi-muon
eμ triggers

Main backgrounds from meson or γ* decays or overlapping ID tracks.

Dark Photon Search ee/μμ

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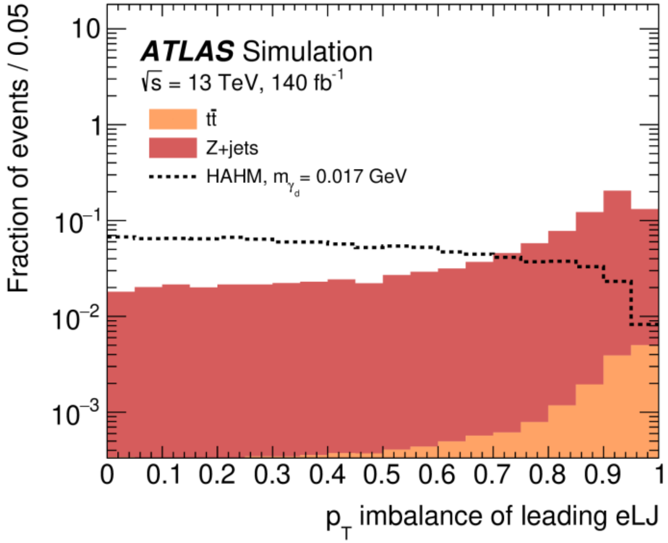

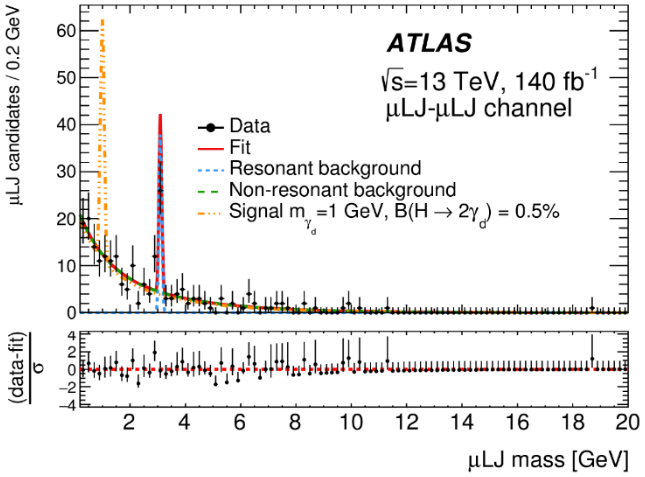

e-channel

ABCD method background estimation

Using the transverse momentum imbalance:

$$p_T^{imbal} = \left|p_T^{track1} - p_T^{track2}\right| / \left|p_T^{track1} + p_T^{track2}\right|$$

And the ratio of the electron cluster energy in cells along the ϕ-axis, R_φ

Binned maximum likelihood fit in the SR and the 3 CRs

μ-channel

Parametric background estimation

Search for bump in mass distribution

Systematic uncertainties 2-4%

(Analysis is statistically limited)

Dark Photon Search ee/μμ

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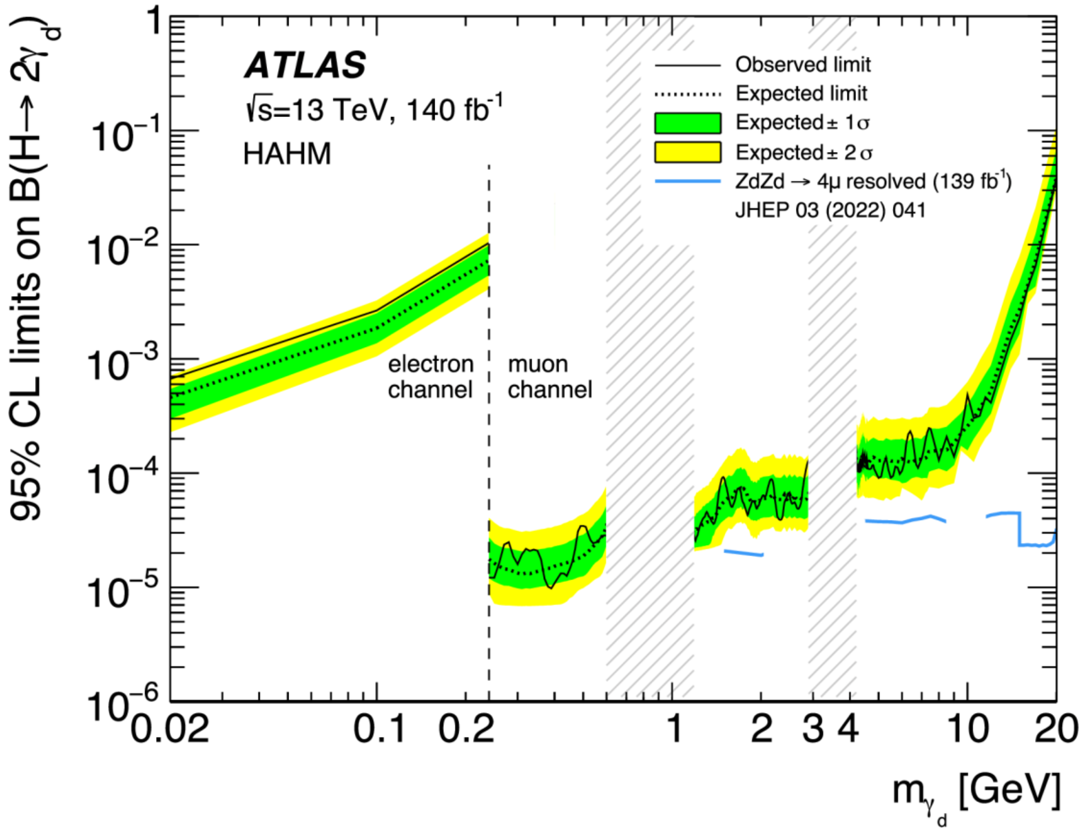
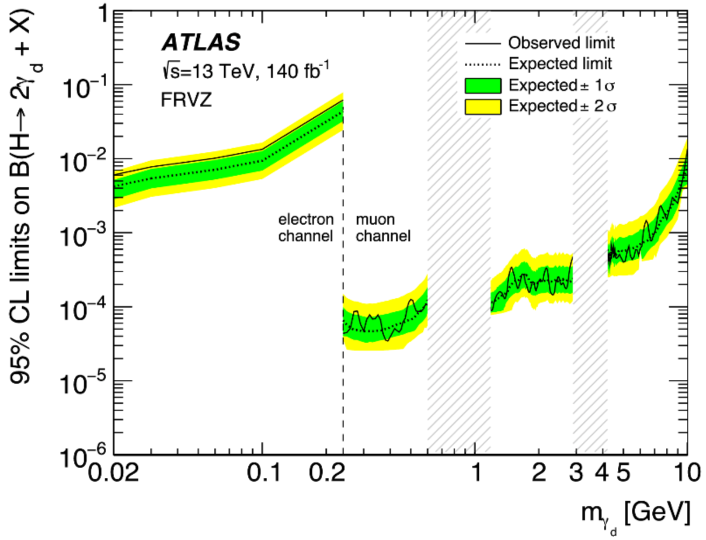


50 times better than Run 1, mainly due to shape-fit approach for background estimate. Complementary to resolved 4-muon dark photon search

Gaps in the muon channel due to the presence of meson resonances

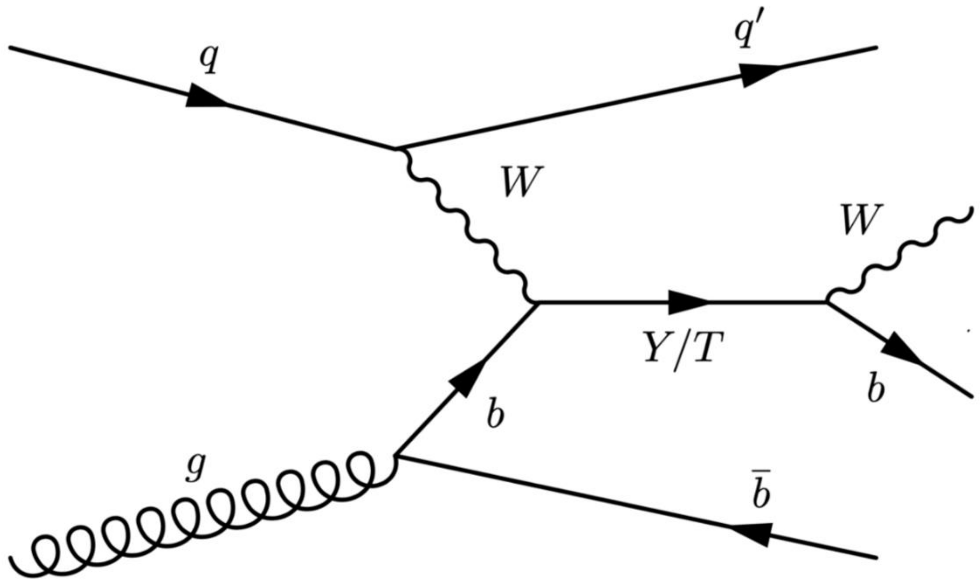
Extends down to 17MeV with the electron channel



Similar picture coming from FRVZ

VLQ Wb(allhad)

2409.20273



Additional Vector-Like Quarks introduced by theories targeting naturalness problem by cancelling Higgs-mass corrections from top-quarks (e.g. composite Higgs models, Little Higgs models etc)

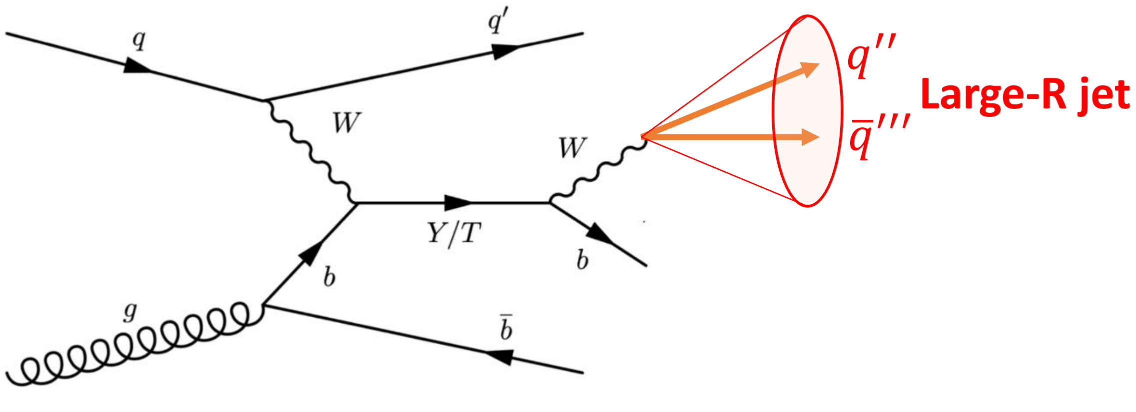
VLQ as SM quarks but Left- and Right-components transform similarly

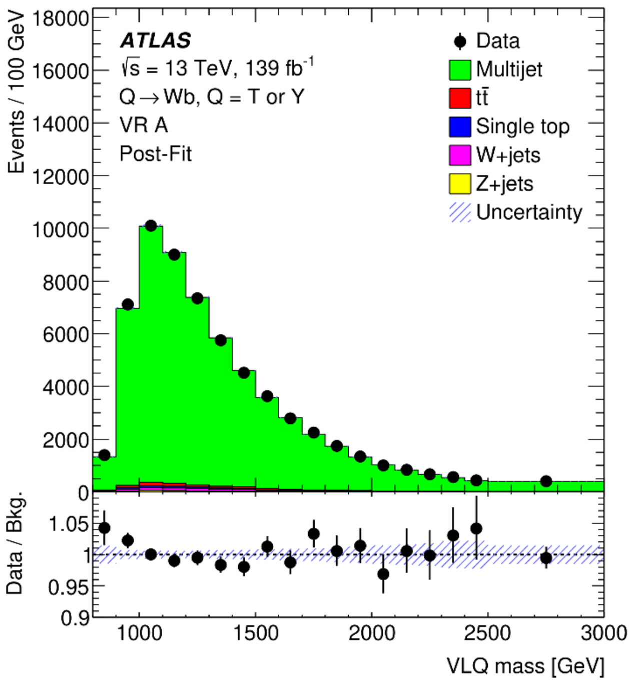
Two types of VLQ:
T VLQ: q=+2/3 and exist in **1**, **2**, **3**
Y VLQ: q=-4/3 and exist in **2**, **3**
(relevant for this analysis)
Presence of b-jets in the final state, alongside with W as couplings to third generation preferred, with coupling κ

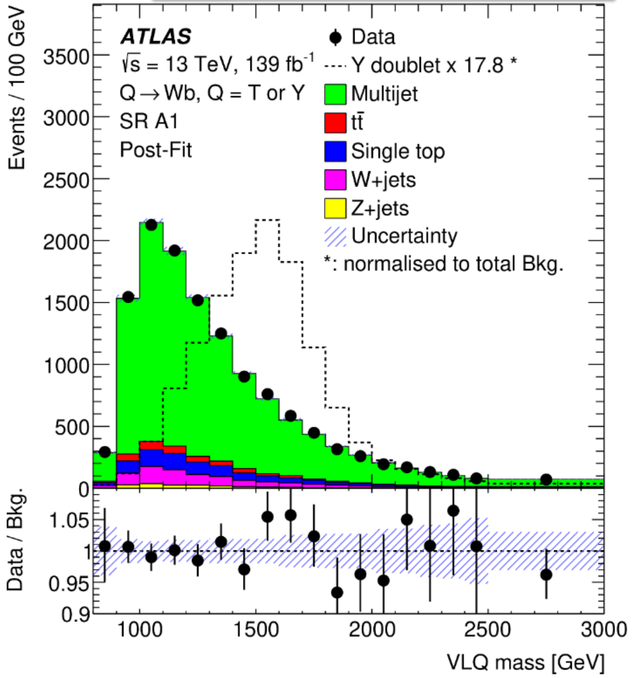
First time searching for VLQ using (boosted) W-hadronic decays

VLQ Wb(allhad)

2409.20273







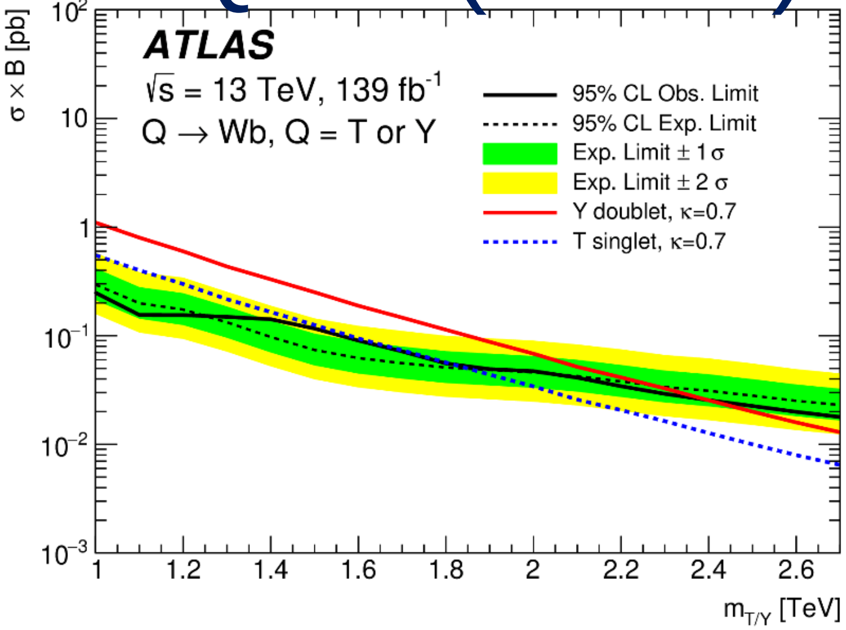
Use of Large-R Jet trigger

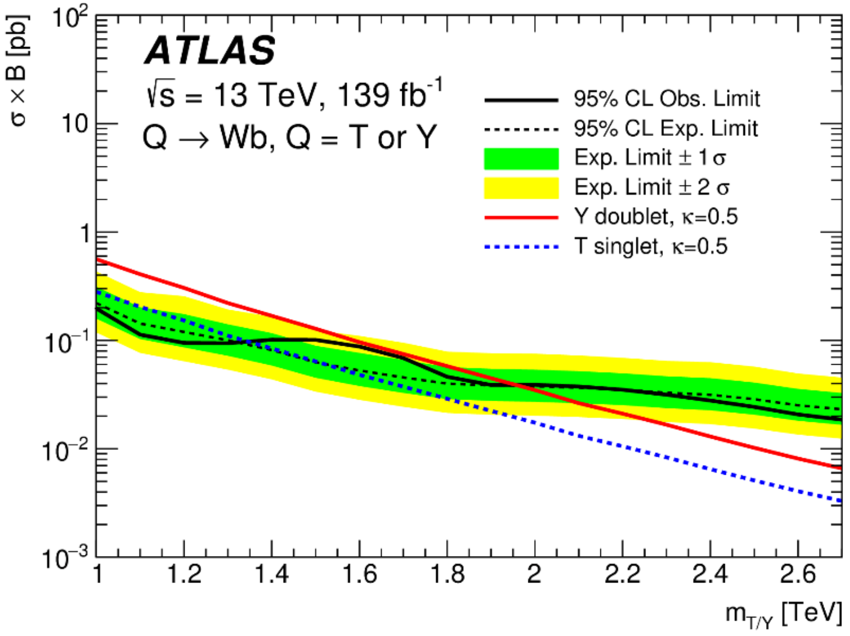
Cut-based W-tagger used with different signal efficiencies requirements (50% Tight and 80% Loose)
→ select events with Large-R jet originates from W boson

Main background multijet (data-driven) using an ABCD-method
"Tight" W-tagging + ≥1 b-jet for defining SR
Looser requirements for W tagging or b-veto used for VR/CRs (VR used for multijet uncertainty)
Analysis is systematically limited (e.g. from non closure test Multijet systematic)

VLQ Wb(allhad)

2409.20273





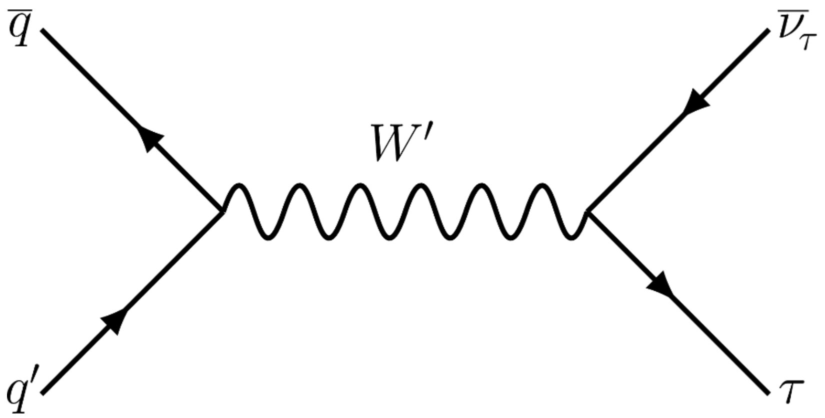
Upper limits on Y VLQ in (B,Y)-doublet rep for different couplings κ

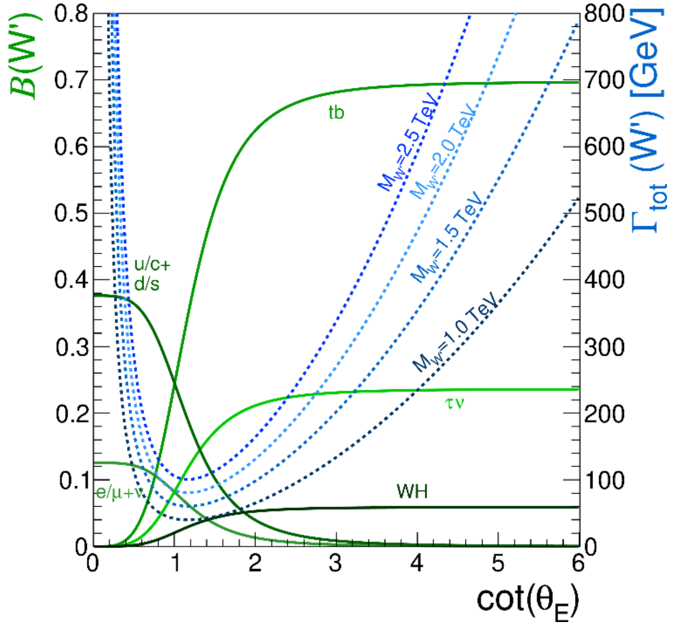
The limits for the T-singlet are obtained by scaling σB by a factor of "2" (to account for $B(T \to Wb) = 0.5$)

About 0.6-0.7TeV improvements for κ=0.5-0.7 from previous search (leptonic W decays)

$W' \to \tau\nu$

2402.16576





New theories beyond SM predict heavy charged gauge bosons (TopFlavor model, Left-Right Symmetric models, Little Higgs models)

Search interpretation:
1. Sequential Standard Model (SSM) : W' same couplings as SM W, with universal couplings to fermions
2. Non-Universal Gauge Interaction Model (NUGIM) : couplings can vary

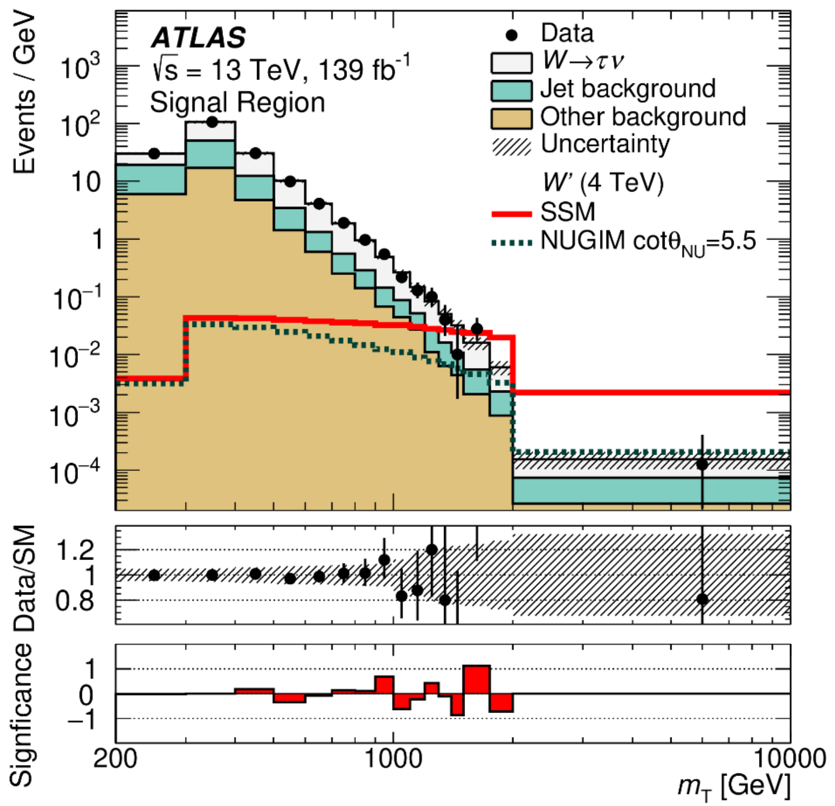
in hadronic tau decays (B≈65%)

Motivated e.g. by R(D)/R(D*) discrepancies between SM and experiment, high top-quark mass, etc

Trigger events with E_T^{miss} triggers (E_T^{miss} >150 GeV)

$W' \rightarrow \tau\nu$

[2402.16576](2402.16576)



Back-to-back and balanced momenta for hadronically decaying τ (1 or 3 prong jets using Recurrent NNs for discrimination from jets) and E_T^{miss}

Background estimation:
Real tau decays: simulation
Jets misidentified as taus: Data-driven
Main background : offshell production of $W \rightarrow \tau\nu$

Imbalanced momenta used for background Validation

Main variable of search transverse mass

$$m_T = \sqrt{2E_T^{miss} \cdot p_T^{\tau} \cdot (1 - \cos\Delta\varphi_{\mathrm{E_T^{miss}},p_T^{\tau}})}$$

Main systematics: Tau Energy Scale
(analysis statistically limited at high-masses)

$W' \to \tau\nu$

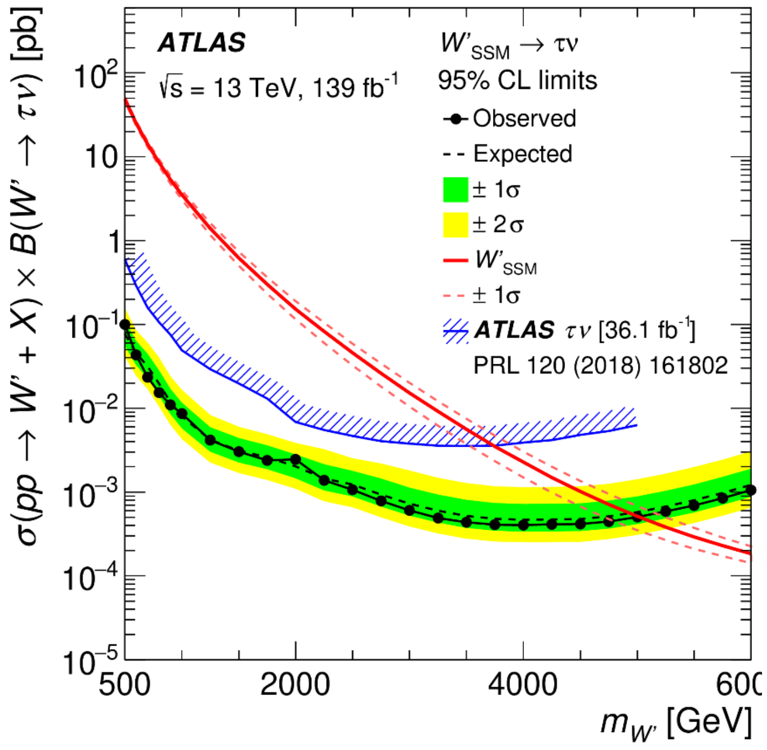
2402.16576

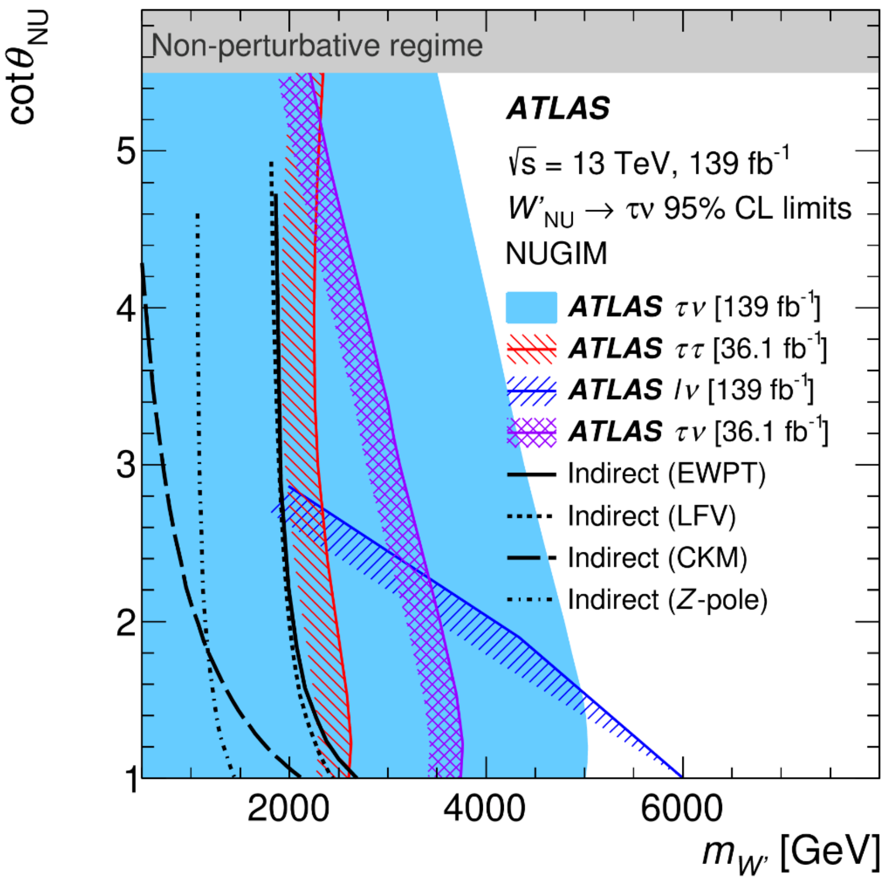
Upper limits on σB for SSM (exclude up to 5TeV)

Exclusion limits for W' masses in NUGIM with enhanced couplings to 3rd generation

Improvements relative to partial Run-2 dataset:

1. increased dataset size
2. improved reconstruction/identification of tau leptons
3. Multi-bin fit approach





Thank You

A summary of 5 recent searches performed in the Exotics category from ATLAS

Unfortunately, I could not come with the news of a discovery, but still impressive results through exclusion limits

Most analyses presented here are still statistically limited and will be benefitted by more data:
The search goes on… (Run 3, HL-LHC)

What final state particles should I look for to claim a groundbreaking discovery in Particle Physics in my next public talk?

Memory updated

For a groundbreaking discovery, targeting final states with unique or unexpected particles is key, especially if they break known conservation laws or point to new interactions. Here are some high-impact final states to consider:

1. **New Resonances**: Look for unexpected peaks in invariant mass distributions that might suggest new particles, like a heavy boson or fermion, similar to the Higgs discovery. Anomalies around known particle masses or unexpected decay widths could indicate new physics.
2. **Lepton Flavor Violation**: Final states with unexpected combinations of leptons (e.g., muons and electrons together) might point to lepton flavor violation, challenging the Standard Model.
3. **Dark Sector Signatures**: Photons or neutrinos accompanied by missing energy can signal dark matter particles or hidden sector particles. Searches involving missing transverse momentum can be especially impactful if the background can be ruled out.
4. **Multilepton Anomalies**: Unusual combinations of multiple leptons, especially with differing charges, might suggest rare processes or the existence of new forces or particles (e.g., multilepton final states in B-meson decays).
5. **High-pT Jets with Missing Energy**: These could hint at supersymmetric particles or other exotic processes, especially if they're accompanied by large missing transverse energy.
6. **Heavy Ion Collisions**: Unexpectedly high-energy or high-multiplicity particles in heavy ion collisions could reveal new states of matter, like quark-gluon plasma at higher temperatures.
7. **New Bosons or Long-lived Particles**: Long-lived particles leaving displaced vertices or decaying far from the interaction point would be a strong signature of new physics.

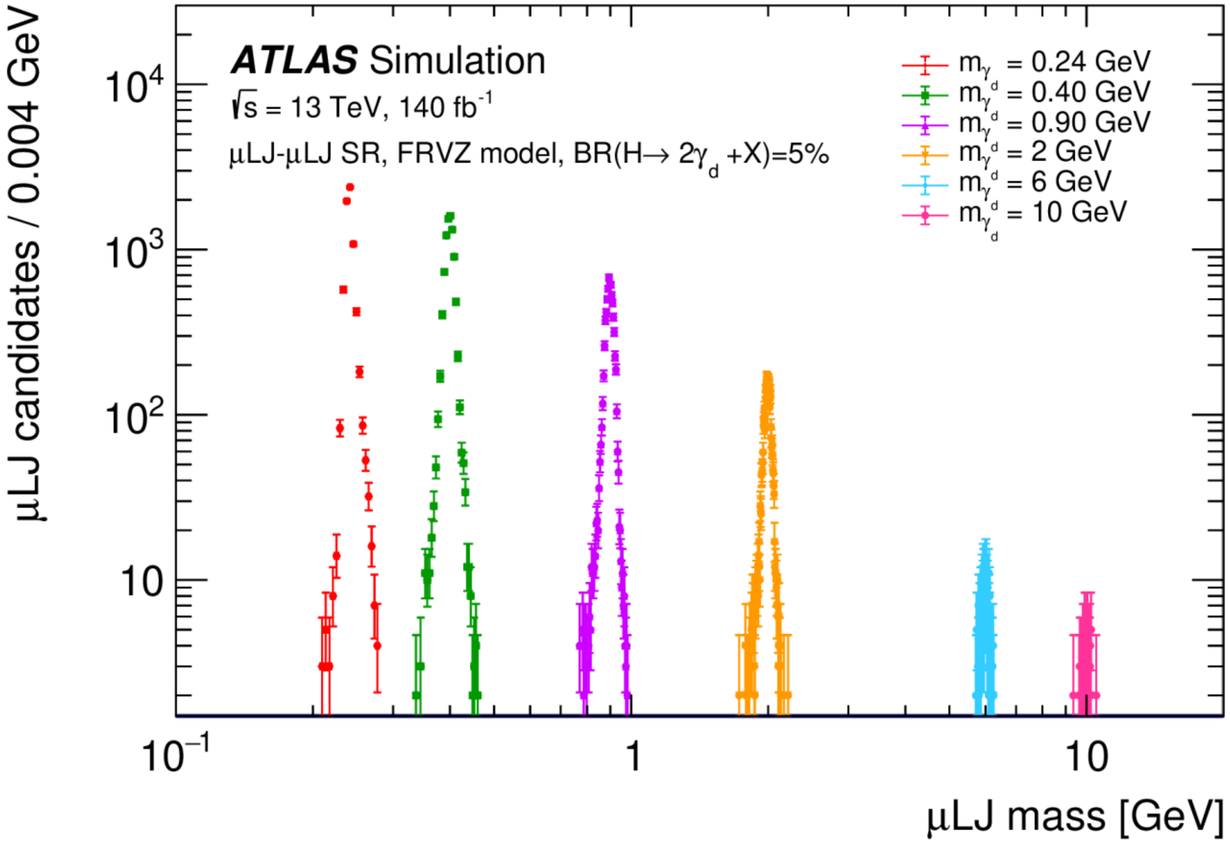
Backup

Long Lived Particle

μJμJ definition

Requirement / Region	μLJ–μLJ	μLJ–eLJ
Number of μLJs	≥ 2	≥ 1
Number of eLJs	0	≥ 1
muon triggers	yes	yes
electron-muon triggers	–	yes
electron triggers	–	yes
eLJ $p_{\mathrm{T}}^{\mathrm{imb}}$	–	< 0.8
$\Delta\phi(\mu\mathrm{LJ}, e\mathrm{LJ})$	–	> 2

μJμJ signals

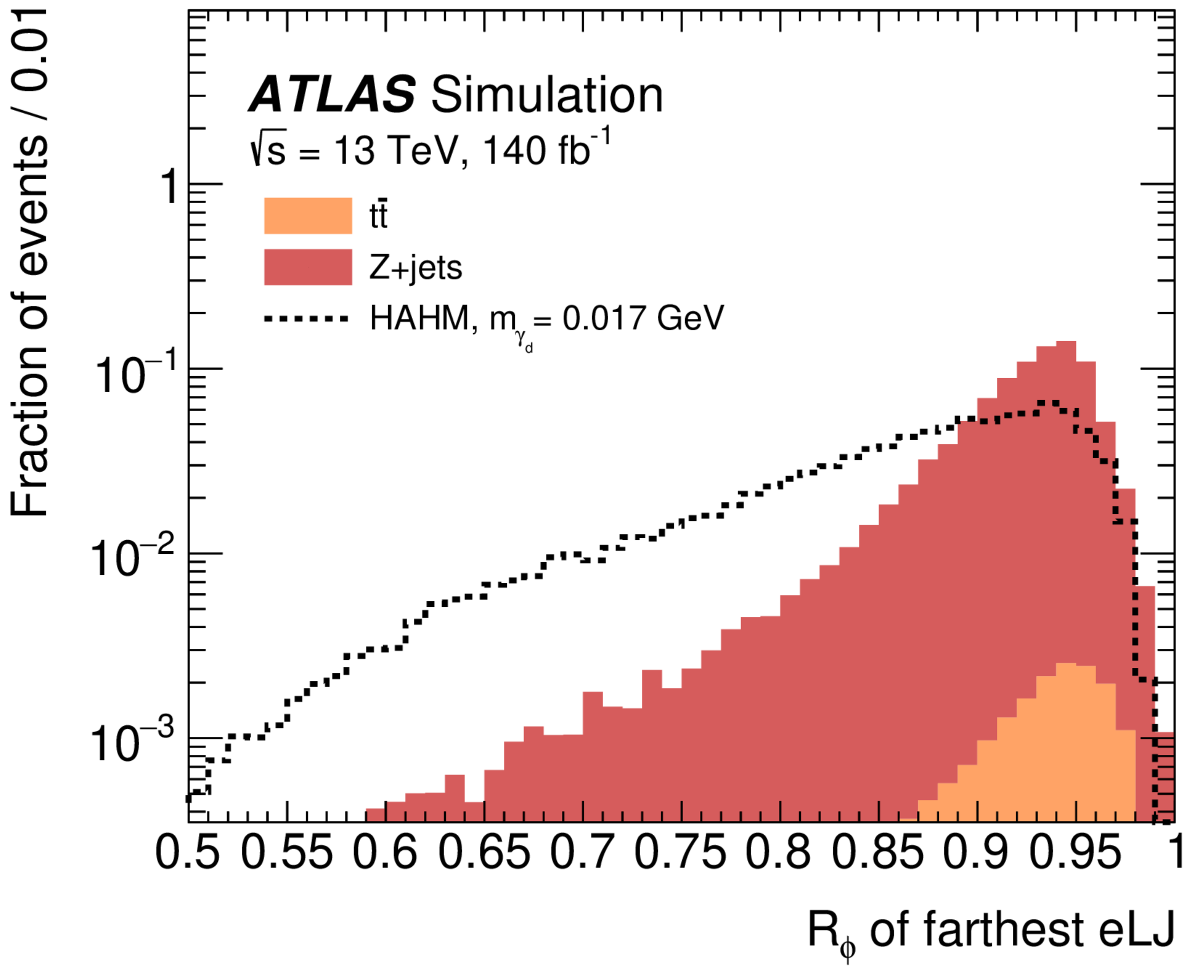


eJeJ definition

Requirement / Region	SR	CR B	CR C	CR D	VR_Z
Applied to both leading and farthest eLJ					
Number of EM clusters in eLJ			1		
eLJ mass imbalance			< 0.8		
Selection on event-level variables					
$\Delta\phi(e\mathrm{LJ}, e\mathrm{LJ})$			> 2.5		
Number of jets ($p_\mathrm{T} > 40$ GeV)			0		
$m(e\mathrm{LJ}, e\mathrm{LJ}) \notin [80, 100]$ GeV	yes	yes	yes	yes	veto
Leading eLJ $p_\mathrm{T}^\mathrm{imb}$	< 0.8	< 0.8	> 0.8	> 0.8	–
Farthest eLJ R_ϕ	< 0.96	> 0.96	< 0.96	> 0.96	–

$$Mass_{imb} = \frac{m_{eLJ1} - m_{eLJ2}}{m_{eLJ1} + m_{eLJ2}}$$

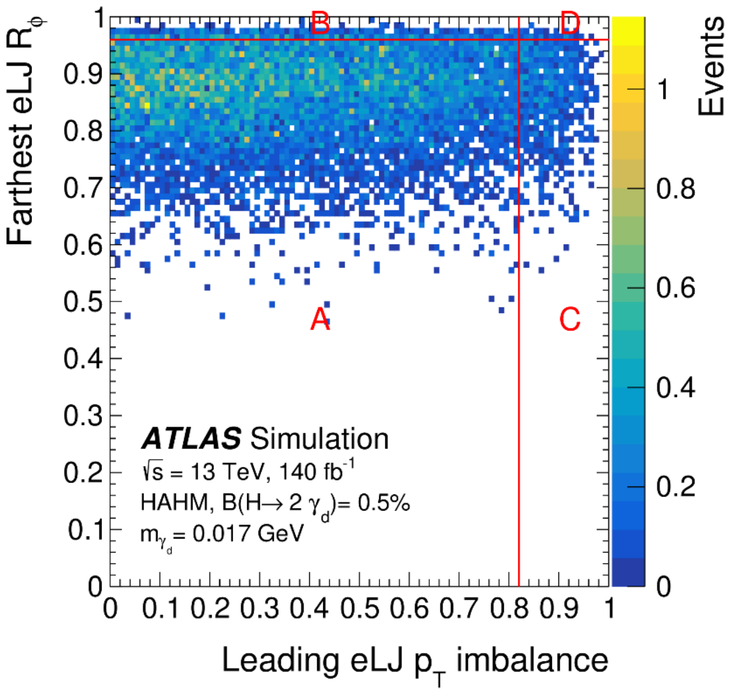
eJeJ Rφ



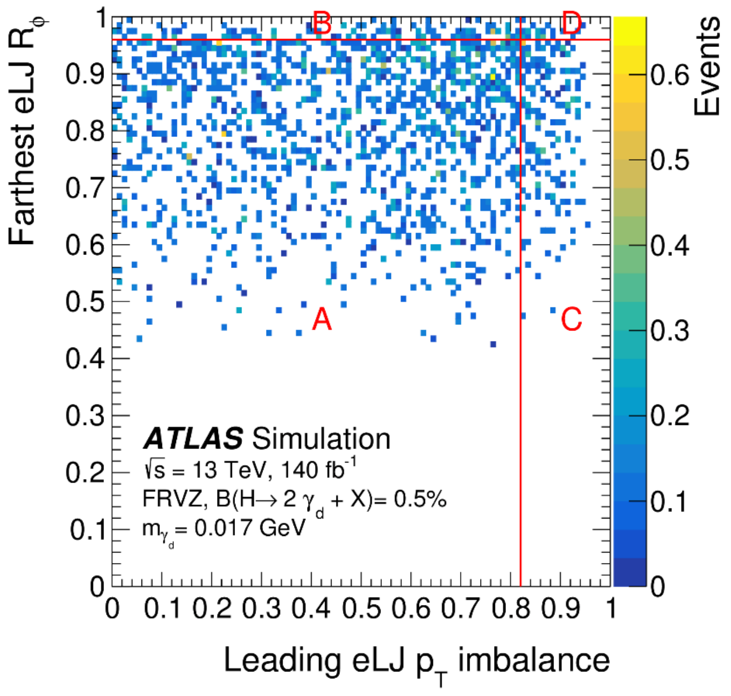
$$R_{\varphi} = \frac{\mathrm{E}_{\varphi\in[1,2,3]cells}}{E_{\varphi\in[1,2,3,4,5,6,7]cells}}$$

eJeJ ABCD method

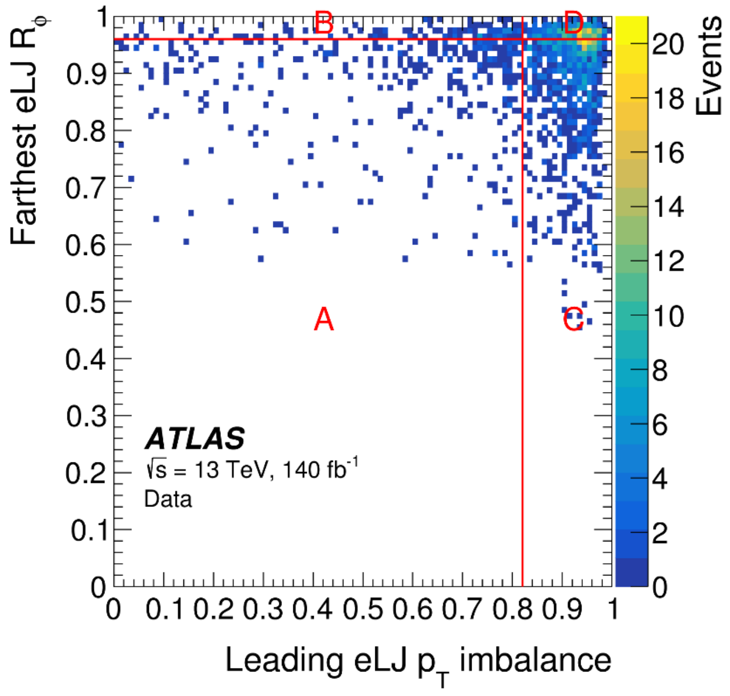
HAHM



FRVZ

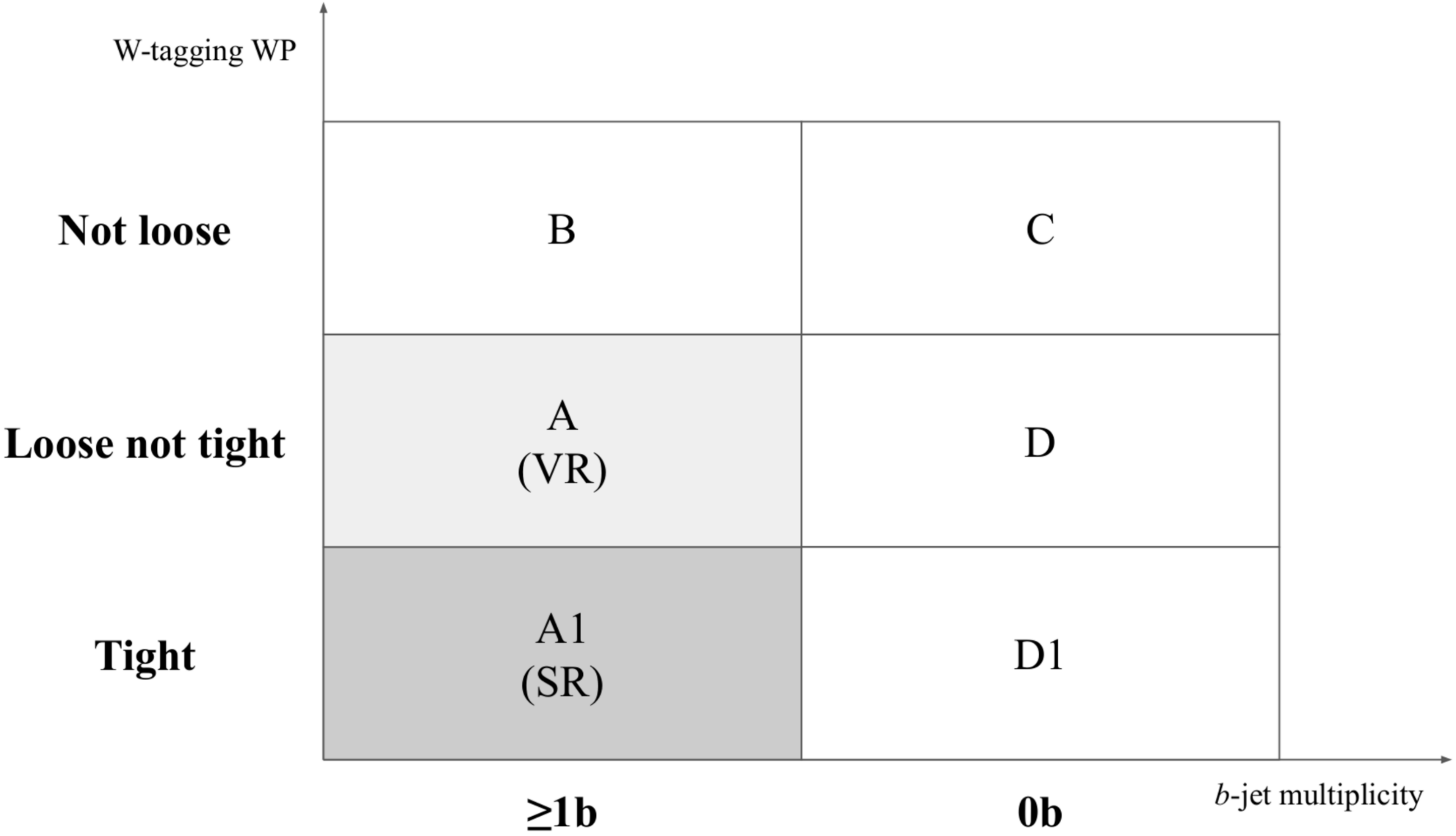


Data



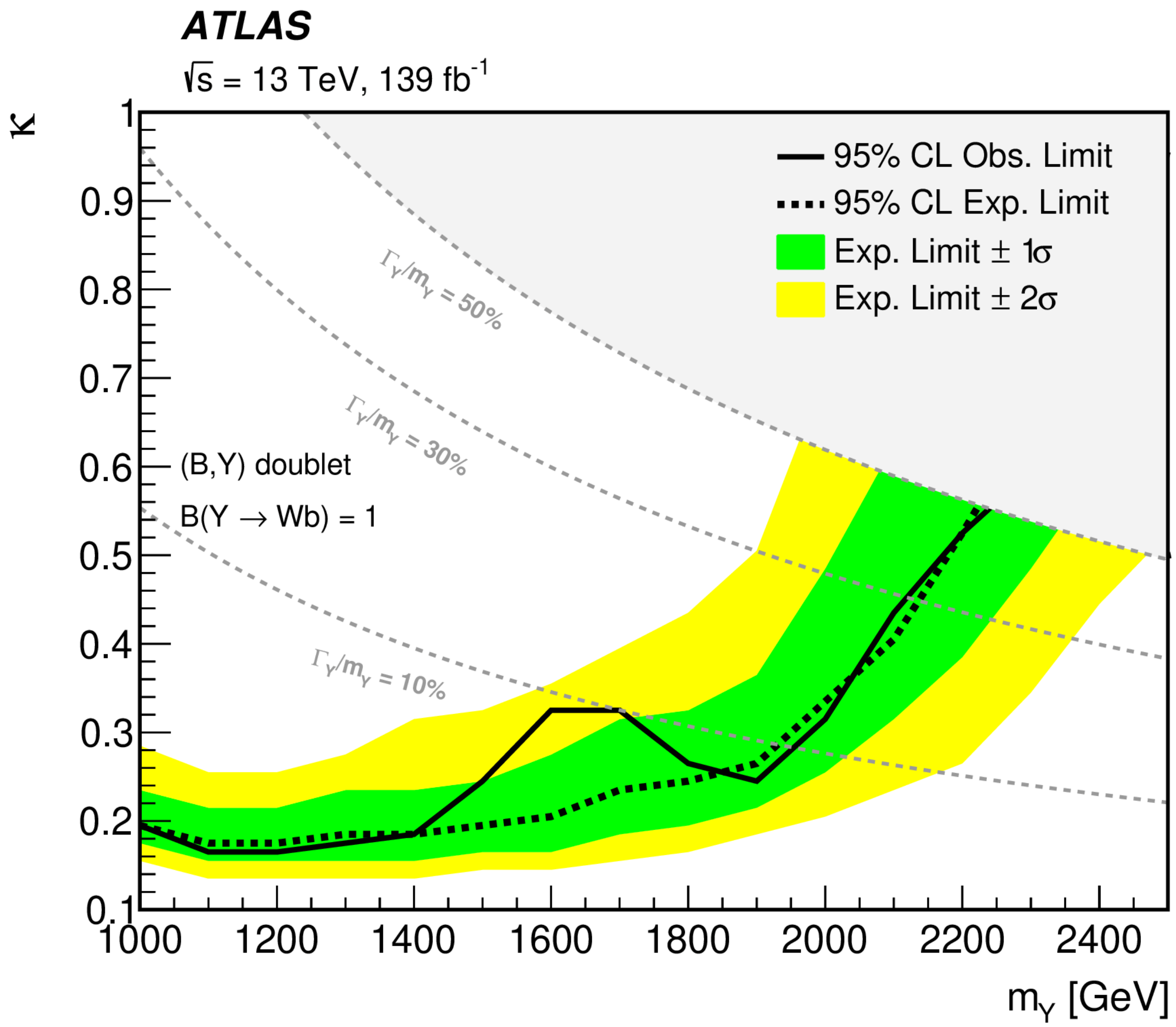
VLQ ABCD Method

$$N_{\mathrm{A/A1}}^{\text{multijet estimate}}[i] = R_{\mathrm{corr}}[i] \times (N_{\mathrm{B}}^{\mathrm{Data}}[i] - N_{\mathrm{B}}^{\text{SM MC backgrounds}}[i]) \times \frac{(N_{\mathrm{D/D1}}^{\mathrm{Data}}[i] - N_{\mathrm{D/D1}}^{\text{SM MC backgrounds}}[i])}{(N_{\mathrm{C}}^{\mathrm{Data}}[i] - N_{\mathrm{C}}^{\text{SM MC backgrounds}}[i])}$$



$$R_{\mathrm{corr}}[i] = \frac{N_{\mathrm{A1}}^{\mathrm{R}}[i]}{N_{\mathrm{B}}^{\mathrm{R}}[i]} \times \frac{N_{\mathrm{C}}^{\mathrm{R}}[i]}{N_{\mathrm{D1}}^{\mathrm{R}}[i]}$$

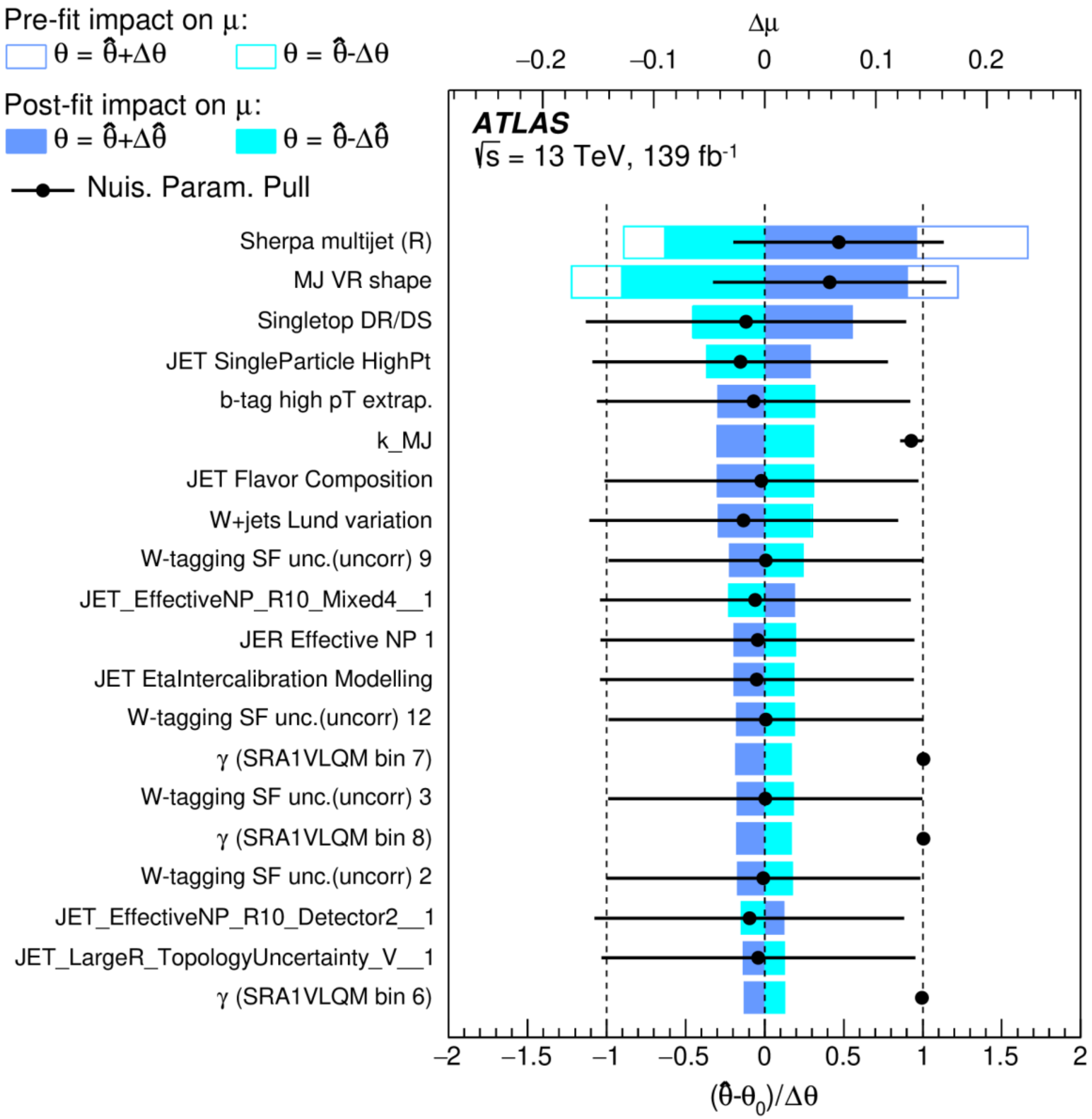
VLQ Limit



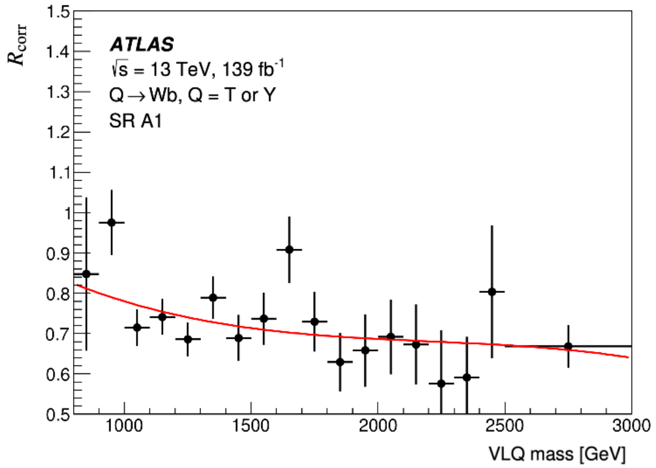
Limits on the (mass,κ) plane for the (B,Y) doublet model
For different widths up to 50%

The regions above the dark lines are excluded at 95%CL by this search

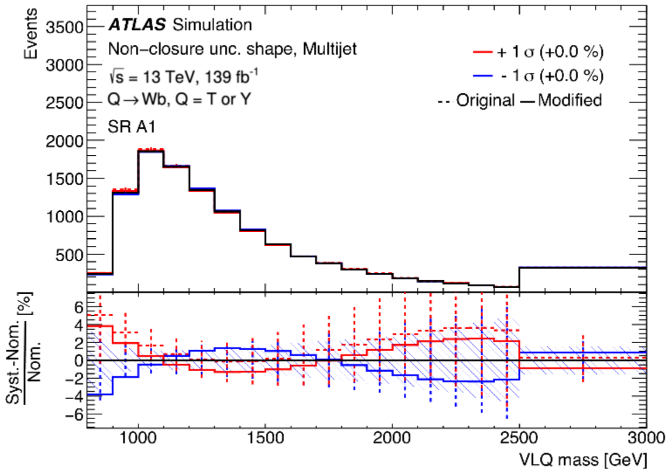
VLQ Systematics



Sherpa Multijet R: related to correction Rcorr when using Sherpa as alternative to Pythia MC

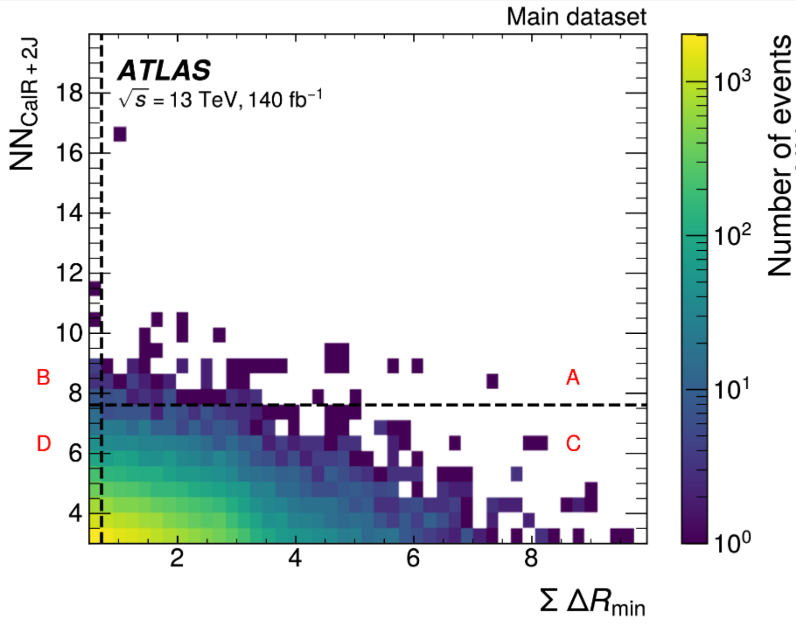


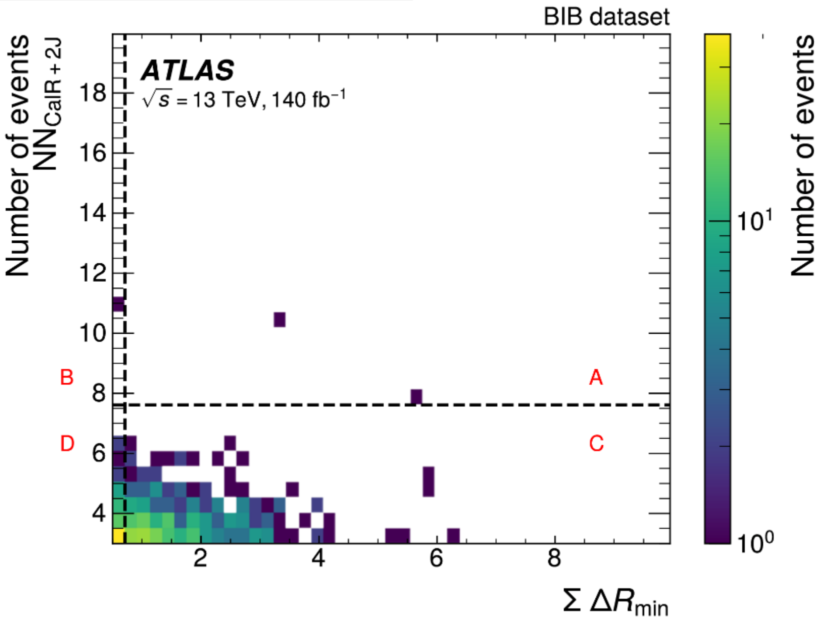
MJ VR shape: from closure test

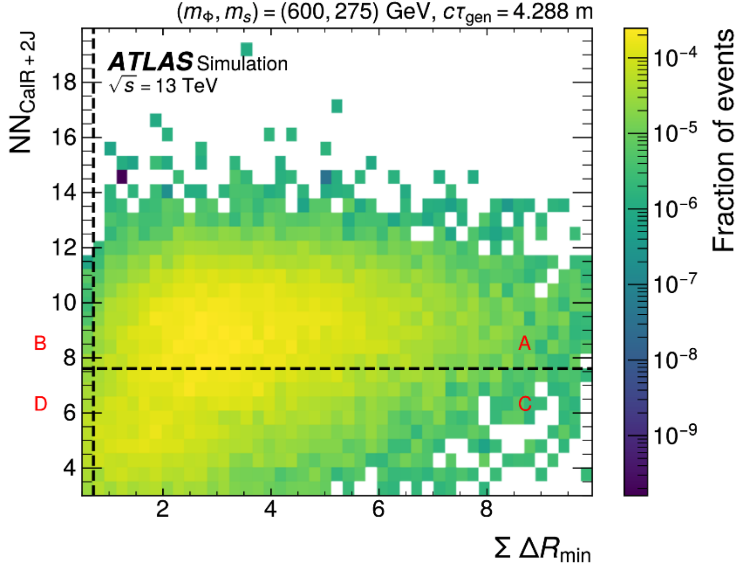


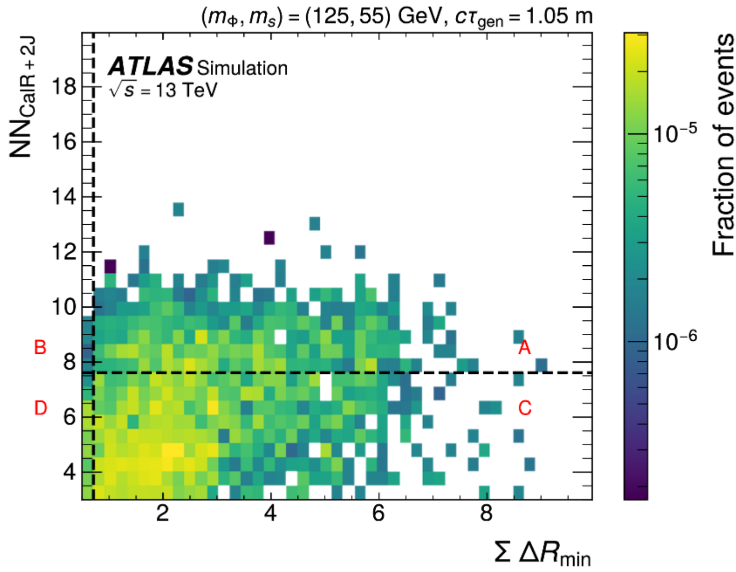
LLP CAL2J

Selection	CalR+2J
Trigger	Satisfy CalRatio trigger
Number of clean jets	≥ 3
$\sum \Delta R_{\mathrm{min}}$	> 0.5
Trigger matching	At least one signal candidate
Signal/BIB jet candidate time	-3 ns $< t <$ 15 ns
Signal/BIB jet candidate $\log_{10}(E_{\mathrm{H}}/E_{\mathrm{EM}})$	> -1.5
Signal jet candidate η	$\notin (1.45, 1.55)$
$\mathrm{NN}_{\mathrm{CalR+2J}}$	≥ 3
Region A	$\sum \Delta R_{\mathrm{min}} \geq 0.71$ $\mathrm{NN}_{\mathrm{CalR+2J}} \geq 7.61$



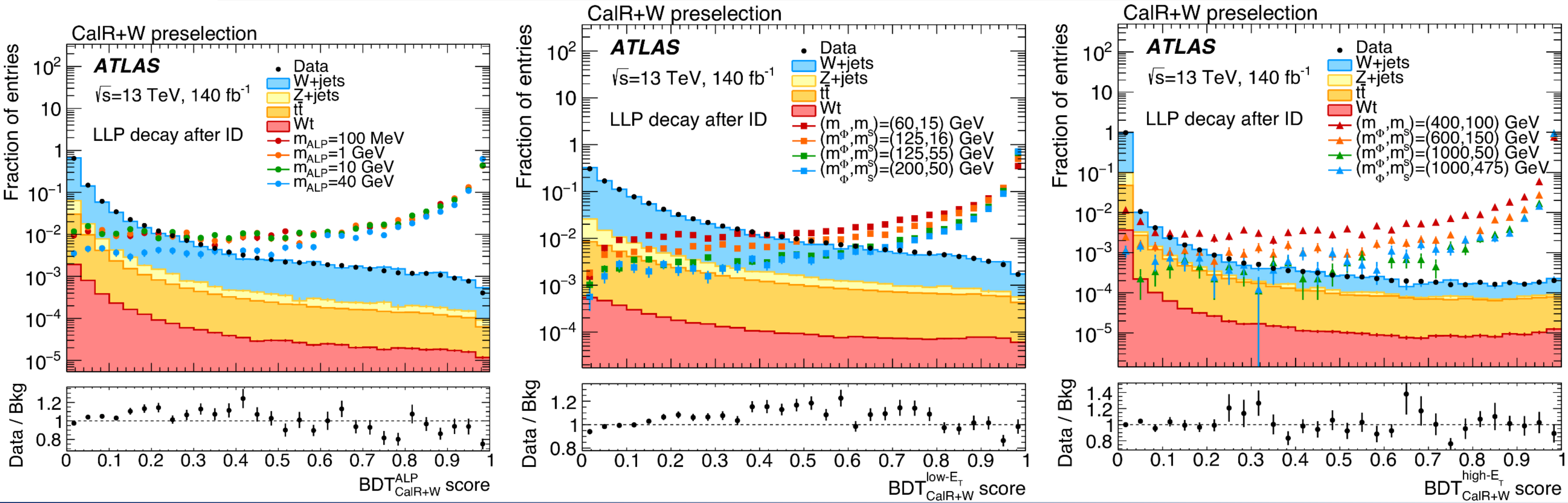






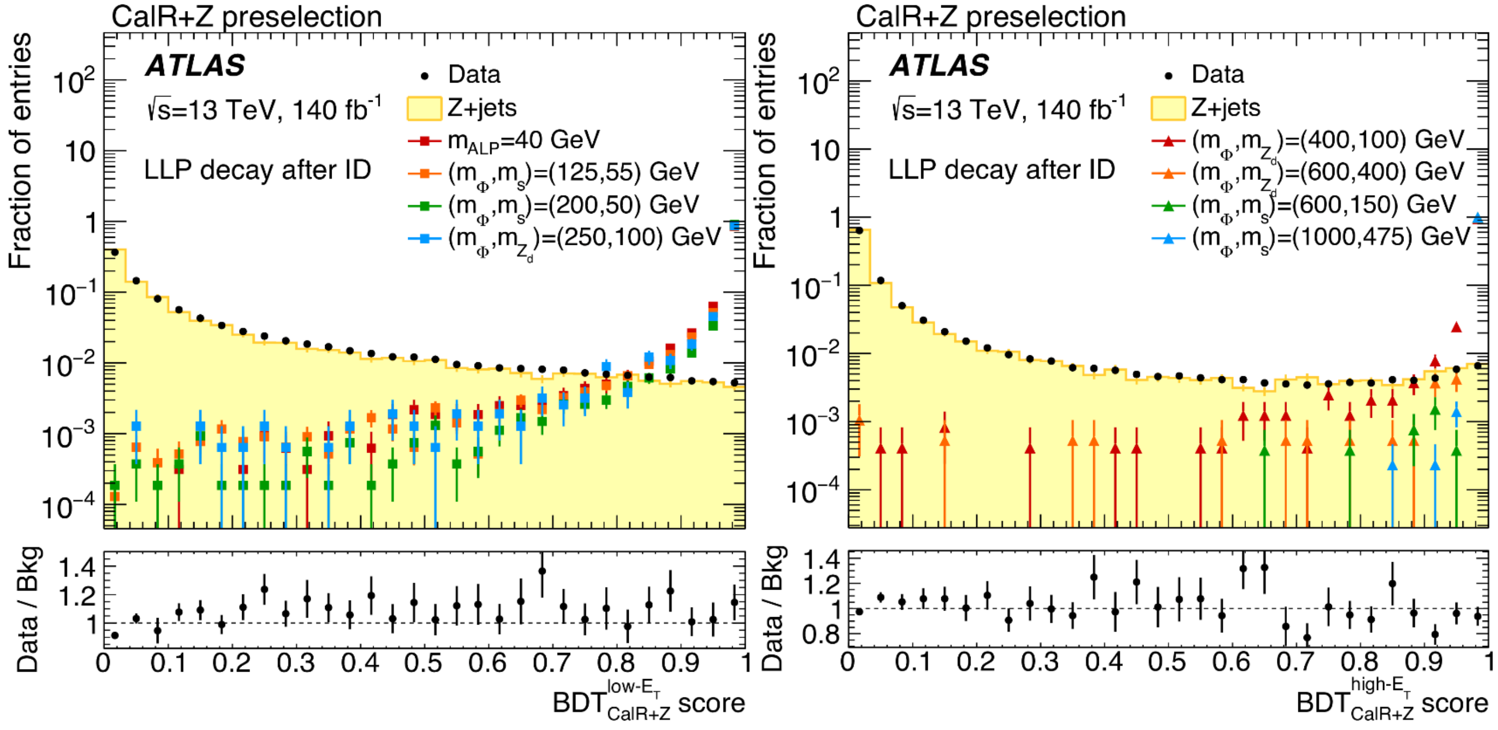
LLP Wcalo BDT

Selection	CalR+W WALP	CalR+W low-E_T	CalR+W high-E_T
Vector boson candidates	$0\ Z$, $1\ W$	$0\ Z$, $1\ W$	$0\ Z$, $1\ W$
BDT score	$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR}+W} > 0.82$	$\mathrm{BDT}^{\text{low-}E_\mathrm{T}}_{\mathrm{CalR}+W} > 0.92$	$\mathrm{BDT}^{\text{high-}E_\mathrm{T}}_{\mathrm{CalR}+W} > 0.89$
$j^{\mathrm{sig}1\ell}$ $\log_{10}(E_\mathrm{H}/E_\mathrm{EM})$	> 1	> 1	–
$j^{\mathrm{sig}1\ell}$ p_T	> 70 GeV	> 60 GeV	> 100 GeV
Lepton p_T	–	> 40 GeV	> 60 GeV
$\Delta\phi(\text{lepton}, E_T^{\mathrm{miss}})$	< 1.5	–	–
Region A	$\mathrm{BDT}^{\mathrm{ALP}}_{\mathrm{CalR}+W} \geq 0.975$ $\sum \Delta R_{\min} \geq 1.1$	$\mathrm{BDT}^{\text{low-}E_\mathrm{T}}_{\mathrm{CalR}+W} \geq 0.985$ $\sum \Delta R_{\min} \geq 1.4$	$\mathrm{BDT}^{\text{high-}E_\mathrm{T}}_{\mathrm{CalR}+W} \geq 0.99$ $\sum \Delta R_{\min} \geq 1.1$

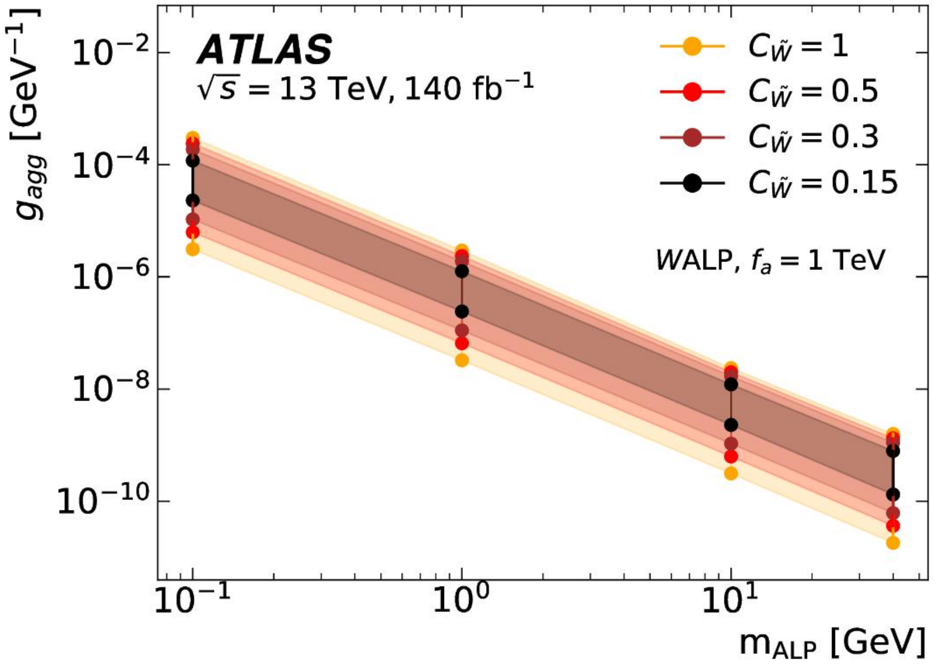


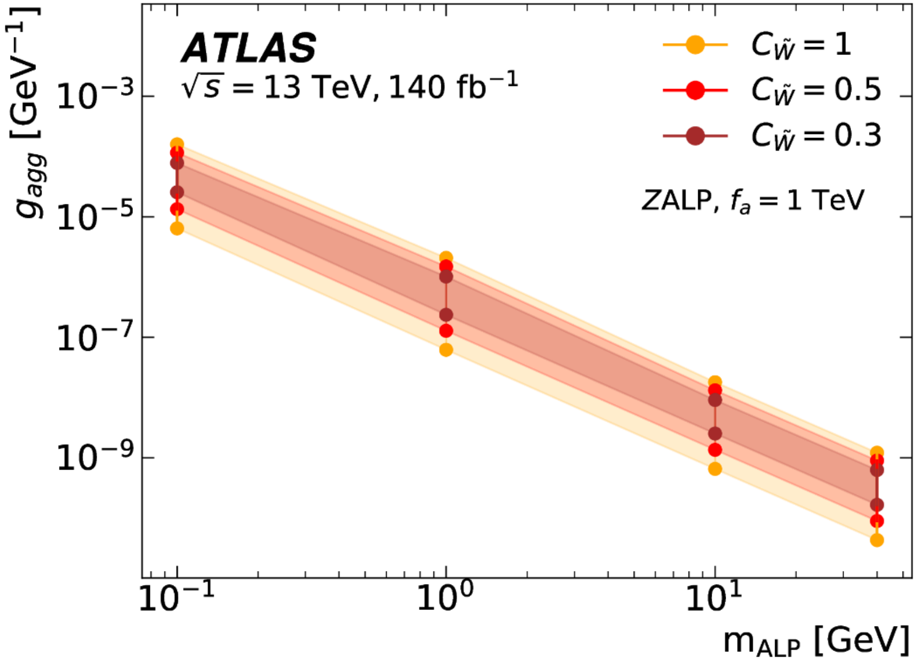
LLP Zcalo BDT

Selection	CalR+Z low-E_T	CalR+Z high-E_T
Vector boson candidates	1 Z, 0 W	1 Z, 0 W
BDT score	$\mathrm{BDT}^{\text{low-}E_T}_{\text{CalR+}Z}$ score > 0.6	$\mathrm{BDT}^{\text{high-}E_T}_{\text{CalR+}Z}$ score > 0.7
$j^{\mathrm{sig}1\ell}$ $\log_{10}(E_H/E_{EM})$	> 0.8	> 0.8
$j^{\mathrm{sig}1\ell}$ p_T	> 80 GeV	> 70 GeV
Lepton p_T	> 70 GeV	> 60 GeV
Region A	$\mathrm{BDT}^{\text{low-}E_T}_{\text{CalR+}Z}$ score > 0.99 $\sum \Delta R_{\min} \geq 0.9$	$\mathrm{BDT}^{\text{high-}E_T}_{\text{CalR+}Z}$ score > 0.985 $\sum \Delta R_{\min} \geq 1$

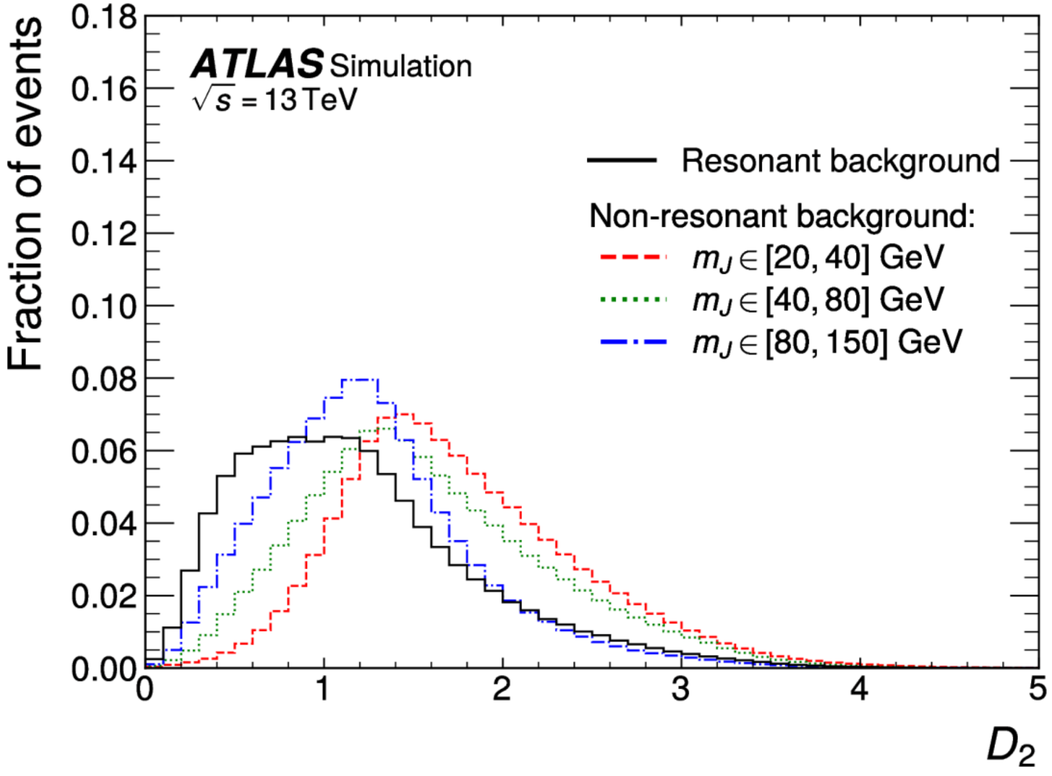


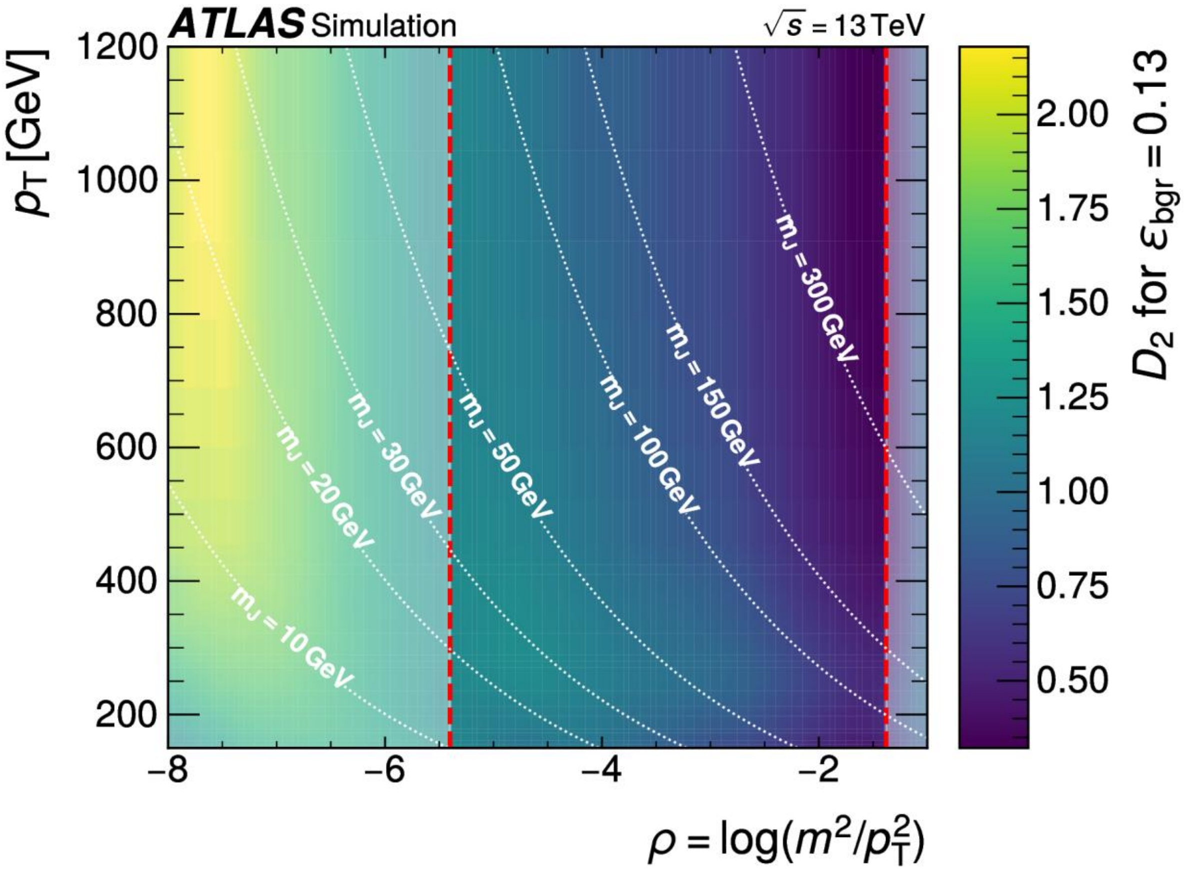
LLP ALP Exclusion





Low Mass Resonance





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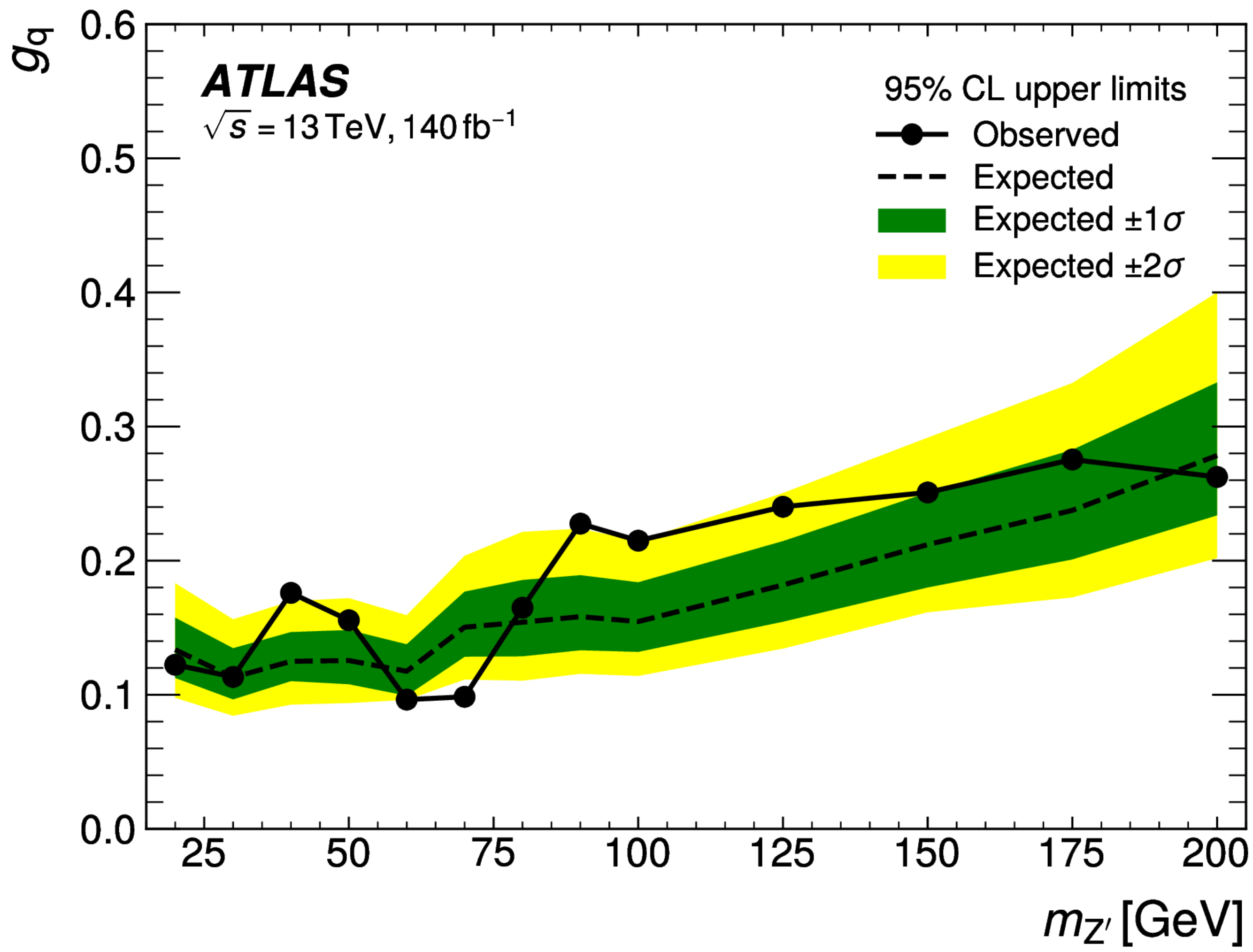
Low Mass Resonance



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