Searches for BSM Resonances in ATLAS

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University of Massachusetts, Amherst
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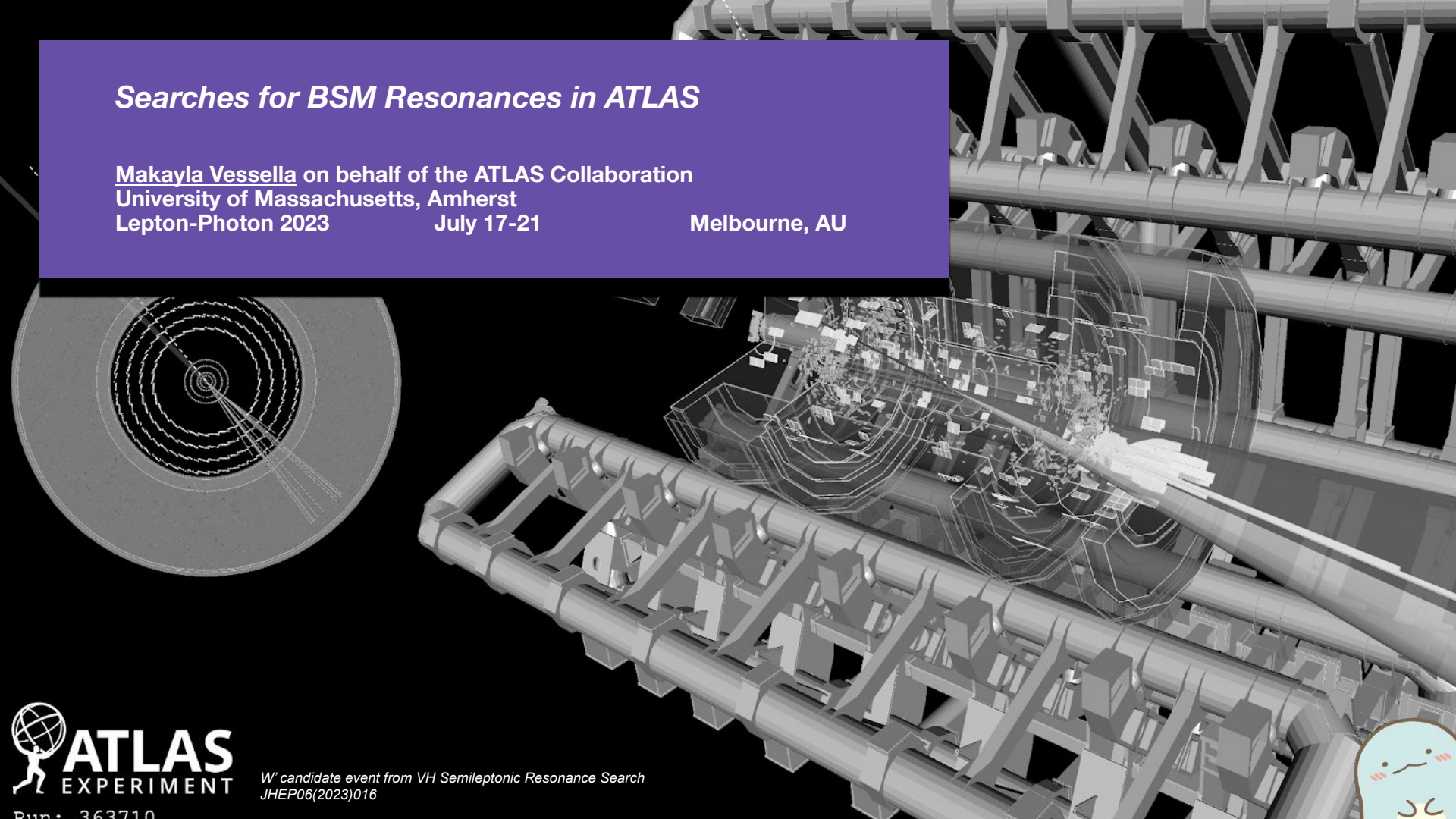
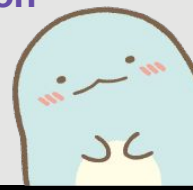


W' candidate event from VH Semileptonic Resonance Search
JHEP06(2023)016

Introduction

- Many **BSM physics models** generically **predict new heavy particles**, aiming to address the hierarchy problem, naturalness questions, lepton flavor universality, g-2 anomalies etc.
- Searches for **heavy resonances** decaying to **pairs of bosons, quarks, or leptons** are an important focus of the ATLAS search program.
    - **Straightforward way to observe new particles** – e.g “bump hunt” in otherwise flat invariant mass spectrum in SM
    - **High center of mass energy** at the LHC allow searches for heavy resonances and new interactions at high energy scales
- Will present a **small selection of recent ATLAS Run-2 results**, paying particular attention to the **novel techniques** used to reconstruct/classify the final states
    - Heavy resonances generally have **boosted topologies** requiring **specialized identification techniques**



Introduction

Searches can fall into **several broad categories**, where I will cover some results including:

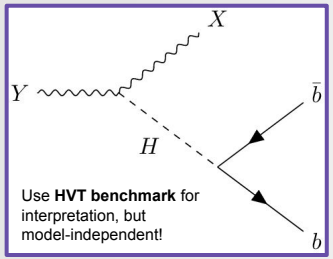
- **General heavy resonances** – HVT W'/Z', 2HDM, etc…
  - **Anomaly detection Y→XH** (*Submitted to PRD: arXiv:2306.03*)
  - **Anomaly detection two-body (j+Y)** (*Submitted to PRL: arXiv:2307.01612*)
- **Leptoquarks**
  - **LQ LQ → tℓtℓ** (*Submitted to EPJC: arXiv:2306.17642*)
- **Vector Like Quarks (VLQs)**
  - **Vector-like top partners → multileptons** (*Submitted to PRD: arXiv: 2307.07584*)
  - **Vector-like top partners →Ht/Zt** (*Submitted to JHEP: arXiv:2305.03401*)

Too many recent results to cover properly in 12 minutes! Many other recent ATLAS results available on the public results page

- See also **Darren's talk** on exotic hadronic resonances and **Yanlin's talk** on BSM Higgs

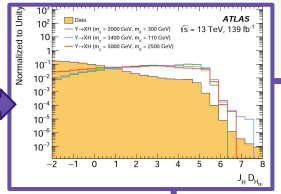
Anomaly detection: Y→XH

- Search for **generic TeV-scale heavy resonance** (**Y**) decaying into a **Higgs boson and a new particle** (**X**) in a **fully hadronic final state** using novel jet-level **anomaly detection**
- **Unsupervised machine learning** approach **broadens sensitivity** to wide range of models



Two large-R jets: J_H (with larger D_{Hbb}) +J_X

$$D_{Hbb} = \ln \frac{P_{\text{Higgs}}}{f_{\text{top}} \cdot P_{\text{top}} + (1 - f_{\text{top}}) \cdot P_{\text{multijet}}}$$



Three signal regions:

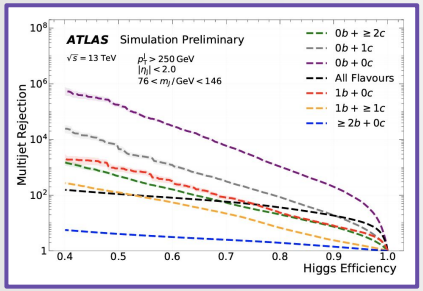
- **Anomaly region:** anomaly score > 0.5, defined using variational recurrent neural network (VRNN)
- **Two-pronged merged**
- **Two-pronged resolved**

Target benchmark X->qq decay, not required to be orthogonal to anomaly region

Merged: m_Y built by two large-R jets
Resolved: m_Y built by large-R Higgs jet and two small-R X jets

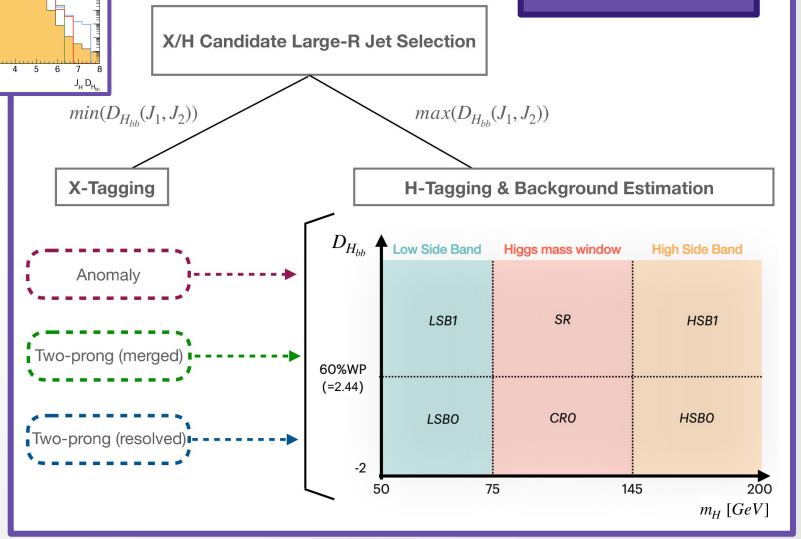
Data driven BG estimate:

- Train DNN to estimate **primarily QCD multijet BG**
- CR0 is mapped into SR with weights derived from **ratio between high-mass sideband regions** and validated with low-mass sidebands

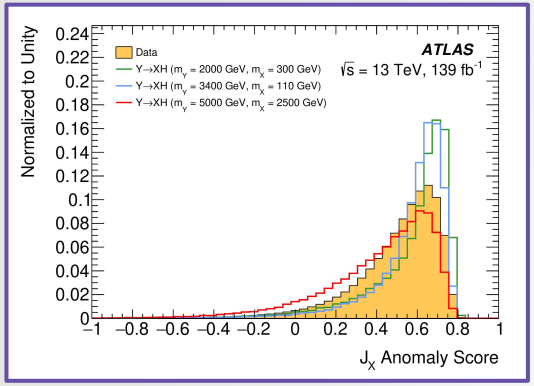


NN based **H->bb tagger** to tag large-R Higgs jet (ATL-PHYS-PUB-2021-035)

Analysis Workflow



Anomaly detection: Y→XH



VRNN trained on TCC jets with p_T>1.2 TeV

- Up to **20 constituent four vectors** per jet, ordered in kt splitting
- Also use **jet substructure observables** D_2 and N-subjettiness ratio for two- and three-prong sensitivity

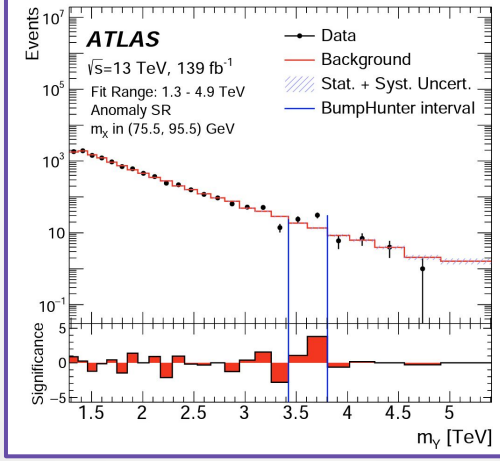
Anomaly score is **data-driven** and **fully model independent!**

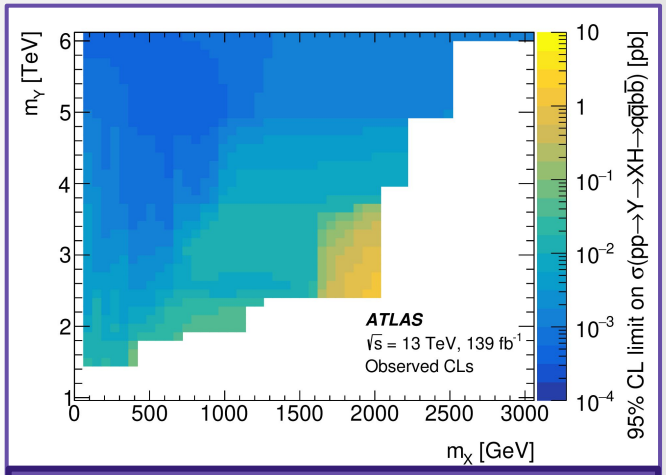
Fit m_Y distribution in overlapping bins of X candidate mass

Use **BumpHunter for all SRs**, with no subsequent fit to a signal model for anomaly SR

Largest excess is in **anomaly SR** with global significance of **1.43σ**

Anomaly SR with m_X in (75.5,95.5) GeV





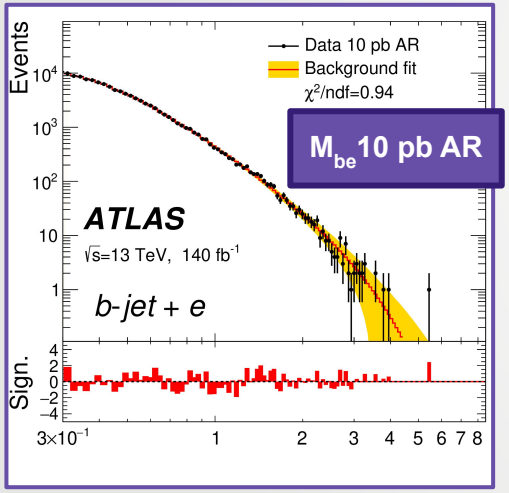
Observed Limits for simultaneous fit of merged+resolved two-prong SRs

Limits on production cross sections set for **wide Y->XH signal grid** in two-prong SRs

From **0.34 fb** for **(m_Y=5000GeV, m_X=600GeV)** to **1.22 pb** for **(m_Y=2500GeV,m_X=2000GeV)**

Anomaly detection: Two body j+Y

- Generic search for heavy resonances in **two-body final states**, where the final states contain a **light or b-jet (j)** and a **lepton (ℓ=e,μ), photon, or additional jet (Y)**
- Use **unsupervised learning** for model-independence like Y->XH, but **uses anomaly detection technique on overall event topology**



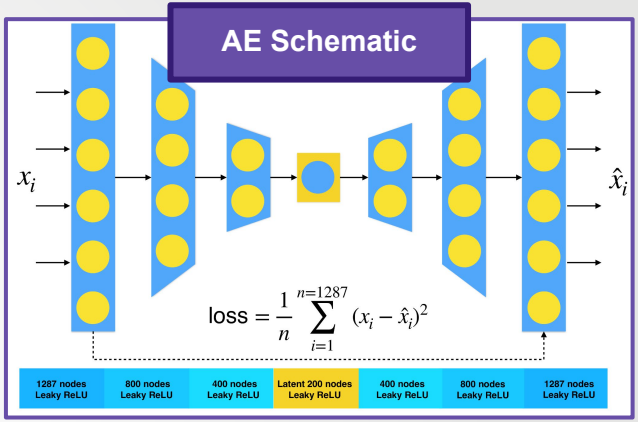
$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x+p_5\ln^2 x}$$

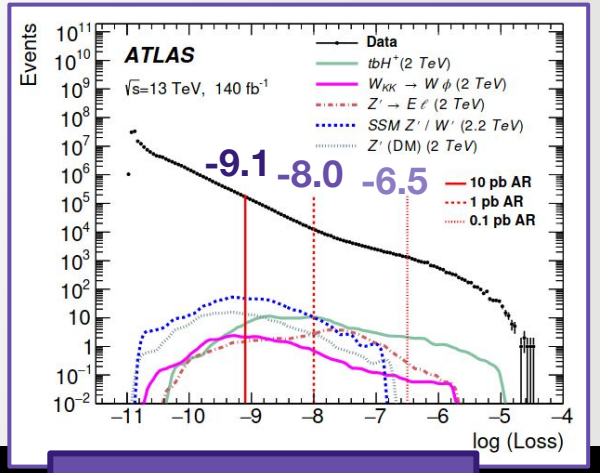
Study **nine invariant mass distributions** using possible combinations of **leading objects of each type** in event

Three anomaly regions (AR) based on log(loss) of **AutoEncoder (AE)** trained on randomly selected **1% of total dataset**

- Structure **kinematic features relevant to BSM searches** (ET_{miss}, transverse energies/masses, rapidity differences etc.) into square **input matrix**
- Three ARs **maintain sensitivity** to different BSM models, where signal events can be **more or less anomalous**

BG estimate: Parameterized as smoothly falling background, based on **fit to SM MC (W+jets, tt, single top)** and loose electron control as proxy for QCD





Data vs Benchmark Models

Anomaly detection: Two body j+Y

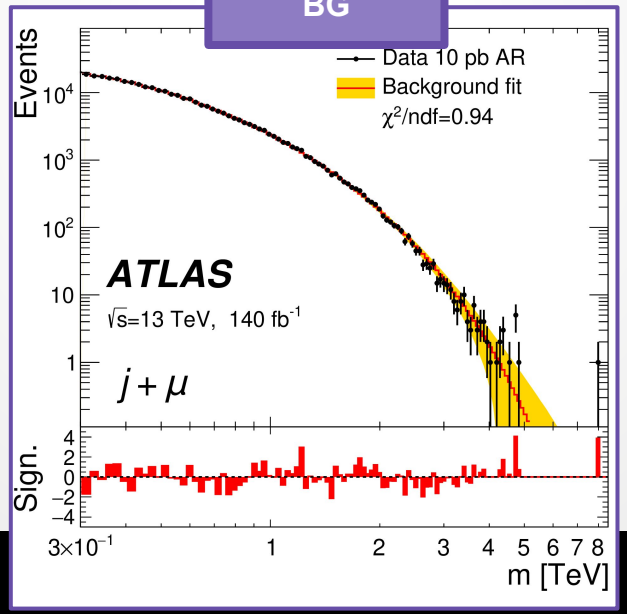
Use **BumpHunter** to search for **localized excesses** in **all invariant mass spectra** in **each AR**

Among the **9 invariant mass distributions**:

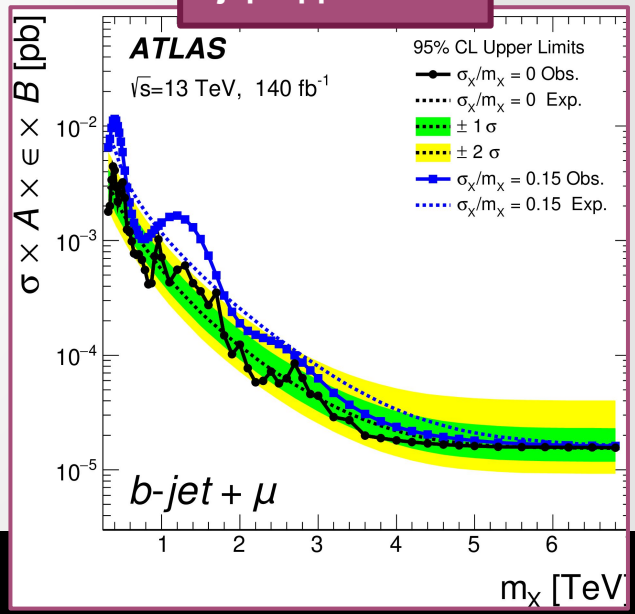
- **Largest excess** in $m_{j\mu}$ **=4.8TeV** with 0% width in **10pb AR, *2.9σ***
- **Second largest excess** in $m_{j\mu}$**=1.2TeV** with 0% width in **10pb AR, *2.8σ***
- **No other significant excesses observed**, including $m_{j\mu}$ in other ARs

Set **95% CL upper limits** on cross section times acceptance for **gaussian signal templates**

j+μ Data vs BG

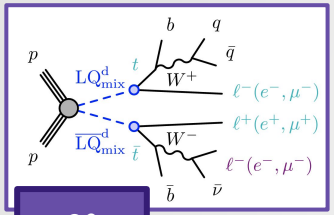


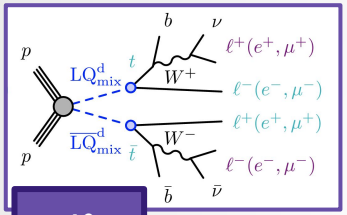
j+μ Upper Limit



Leptoquarks: LQ LQ→tℓtℓ (ℓ=e,μ)

- Search for **LQ pair production** decaying into a **top quark pair** and a **pair of leptons**, in **multi-lepton final states.** ***This is the first ATLAS search for this process!***
- Some explanations for B and g-2 anomalies require **flavor off-diagonal LQ couplings** – can still **preserve flavor symmetries**





$$m_{\text{eff}} = \sum_{\ell,\text{jets}} p_{\text{T}} + p_{\text{T}}^{\text{miss}}$$

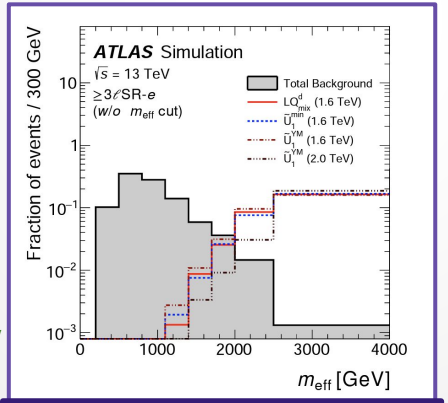
Signal models: scalar LQ^{d}_{mix} **(β=1.0)** and vector U_1

MC Background Estimate:

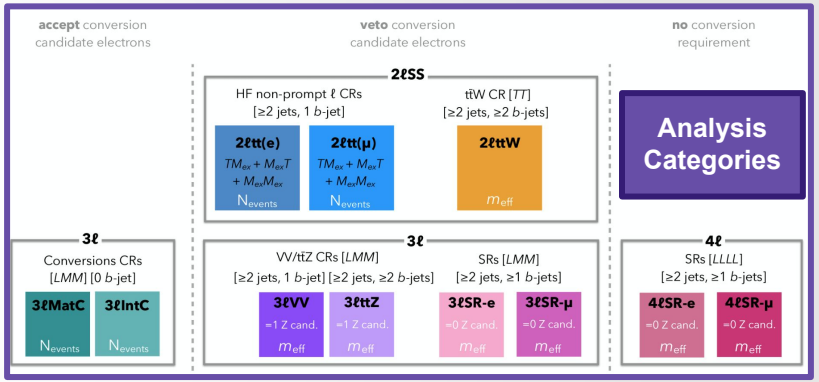
- Major backgrounds include **ttW, ttZ/γ*,VV (V=Z/W), single ℓ**
- Additionally select **3ℓ control regions** enriched in **photon conversions**

Three analysis channels:

- **2ℓSS:** two same-sign light ℓ (CR only!)
- **3ℓ:** three light ℓ
- **4ℓ:** ≥ four ℓ



High-m_{eff} tails are signal enriched



Two separate signal regions (3ℓ,4ℓ) each for **tete/tμtμ** with **min($m_{\ell\ell}$) > 100 GeV**

Control and validation regions for main backgrounds with **min($m_{\ell\ell}$) < 100 GeV**

Require **≥ 2 jets, ≥ 1 b-jets** in **SRs**

Leptoquarks: LQ LQ→tℓtℓ (ℓ=e,μ)

Simultaneous fit to all SRs and CRs

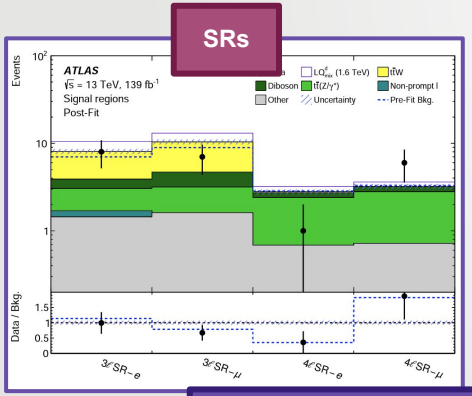
- Main systematic uncertainty from lepton identification but **analysis is statistically limited**

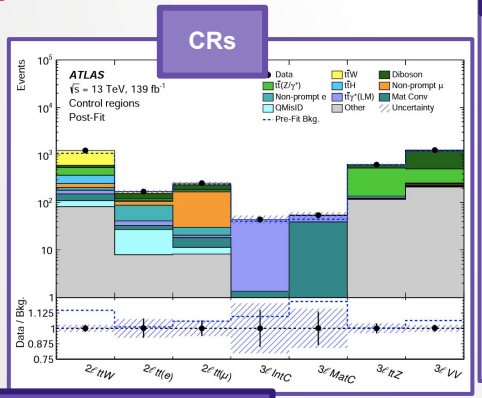
95% C.L. upper limits set on both scalar and vector LQ model

Observed exclusions at $\mathcal{B}(LQ \to te\ (t\mu))=1.0$:

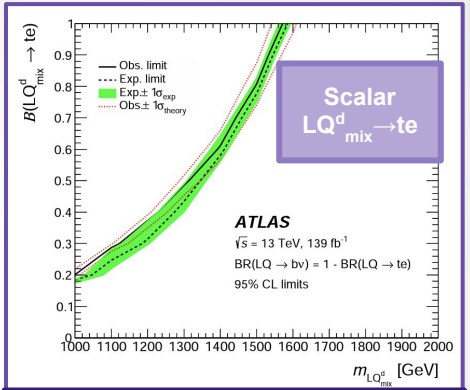
- Scalar $m(LQ^d_{mix})$: **1.58 TeV** ***(1.59 TeV)***
- Yang-Mills vector $m(LQ_U)$: **1.95 TeV** ***(1.95 TeV)***
- Minimal coupling vector $m(LQ_U)$: **1.67 TeV** ***(1.67 TeV)***

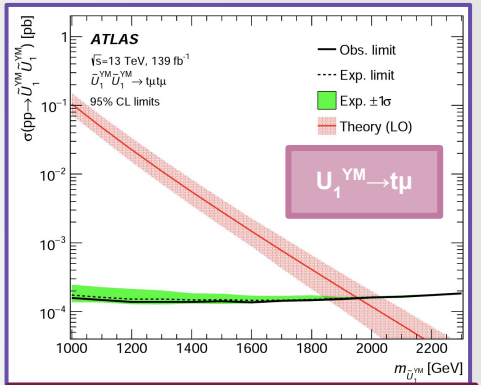
No significant excess from SM expectation observed



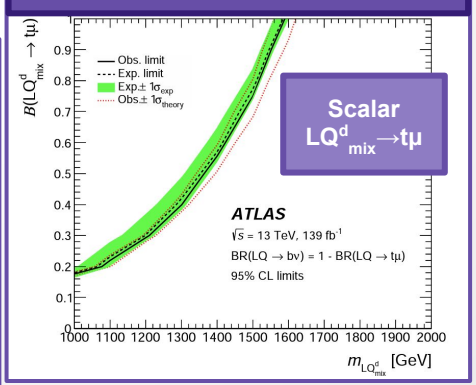


Good post-fit agreement in SRs and CRs

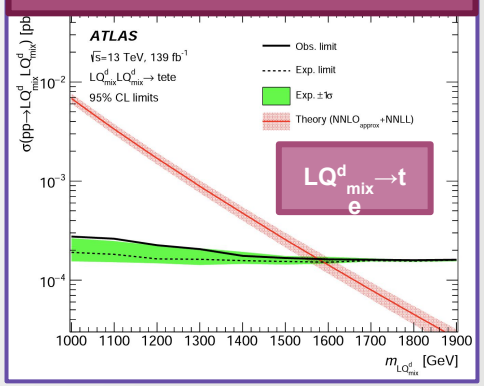




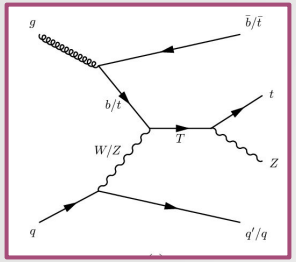
2D exclusion limits in m_{LQ}-$\mathcal{B}$ plane

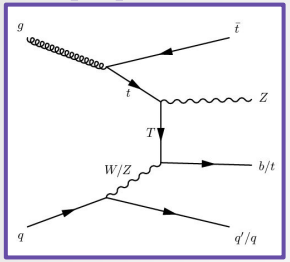


Cross section upper limits



Vector-like top partners to multileptons





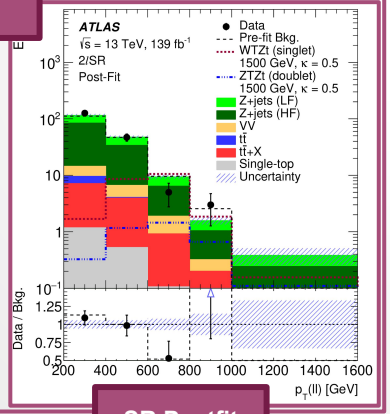
Search for **singly produced vector-like top partners (T)**, with final state containing an opposite-charge pair of electrons or muons (Z candidate) and b-tagged / forward jets. **This is the first ATLAS search for this process!**

VLQs can occur as singlets, doublets or triplets and usually couple to **third-generation SM quarks** via an exchange of charged or neutral bosons. **Single production** of VLQs can have a **larger cross-section at high masses** and is dominated by electroweak processes.

Two analysis channels: Dilepton (2ℓ) and **Trilepton (3ℓ)**
Use ***variable radius reclustered (vRC)*** jets for **stable top-tagging performance** for a wide range of jet p_T, **DLR1 b-tagging** at 77% WP
Require either **two central small-R jets** or at **least one vRC jet**

Dilepton

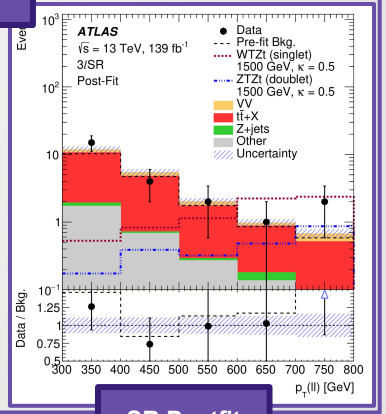
Targets ***hadronically*** decaying top
Two OS same-flavor ℓ
SR additionally requires **one each** of **forward, b-tagged, and top-tagged jets**
Two CRs and three VRs with inverted cuts and top-vetoes
Major Backgrounds (MC): Z+jets, Diboson (VV), tt, tt+X
Use data-driven reweighting factors



SR Postfit

Trilepton

Targets ***leptonically*** decaying top
At least three ℓ
SR additionally requires **one each** of **forward and b-tagged jets**
Three CRs and one VR with inverted cuts and vetoes targeting specific BGs
Major Backgrounds (MC): Diboson (VV), tt+X, Z+jets
Use data-driven reweighting factors



SR Postfit

Vector-like top partners to multileptons

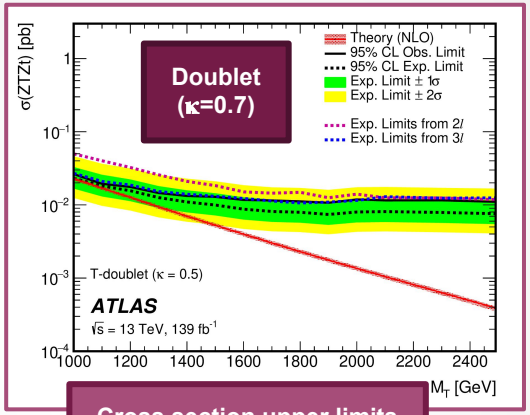
Perform profile likelihood fit of Z candidate **$p_T(\ell\ell)$ distributions** separately for each channel, then combine

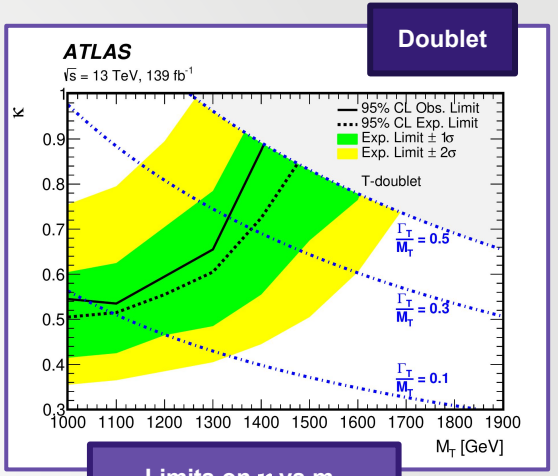
Obtain **95% CL limits** on **excluded masses** and **coupling strengths**:

Singlet: $\kappa < 0.22$ (0.64) for $m_T = 1000$ (1975) GeV

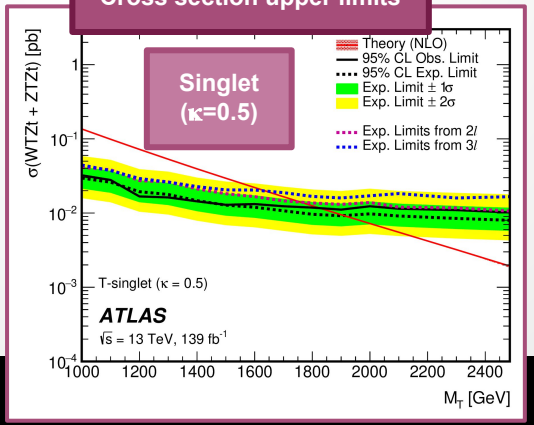
Doublet: $\kappa < 0.54$ (0.88) for $m_T = 1000$ (1425) GeV

No significant excess over the SM expectation is observed.

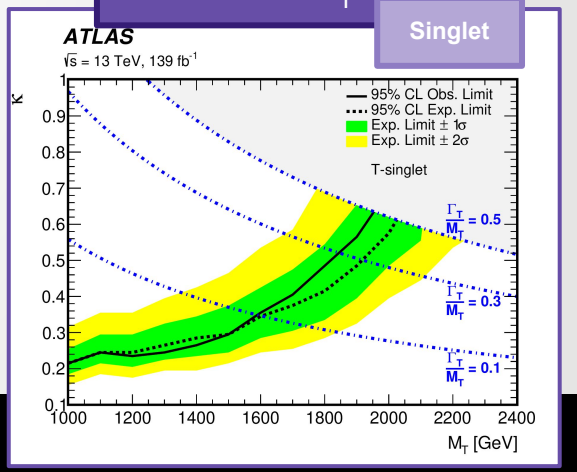




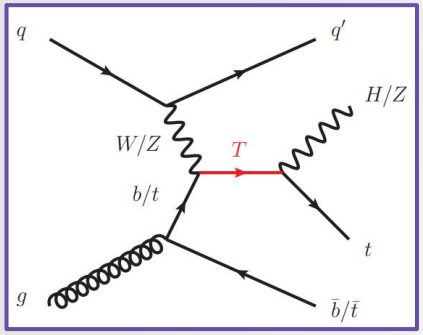
Cross section upper limits



Limits on κ vs m_T



Vector-like top partners → Ht/Zt



Search for **singly produced vector-like top partners (T)** decaying into **Ht or Zt** in final states containing **a single lepton** with **multiple jets and b-jets.**

Target **leptonically decaying top** + **hadronically decaying H/Z**

- **4 production modes:** Ht/Zt, b- or t-associated

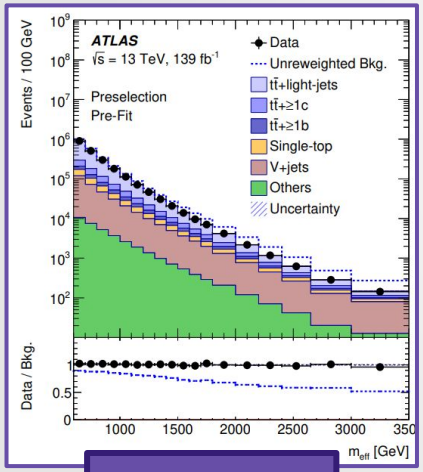
Require **1 lepton, ≥ 3 jets, ≥ 1 b-tagged jet**, other kinematic requirements.

Use **vRC jets** to **reconstruct and tag t,H, and W/Z**, use **DL1 b-tagging** for small-R jets

Profile likelihood fit on m_{eff} distributions

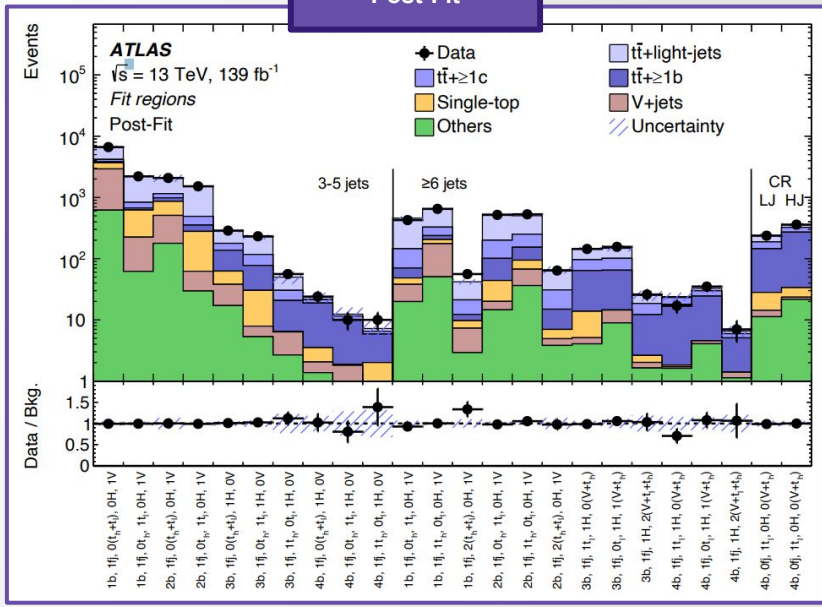
- **24 fit regions** of varying **object+tag multiplicities** to target different **signal+bg processes**

MC BG estimate: tt, Wt, W+jets, with simulations corrected by **data-driven kinematic reweighting**



MC Reweighting prefit comparison

Fit regions Post-Fit



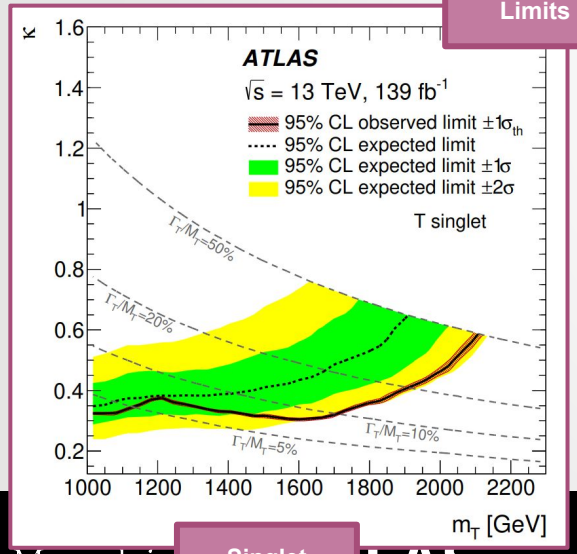
Vector-like top partners → Ht/Zt

Obtain **95% CL limits** on **masses** and **coupling strengths**:

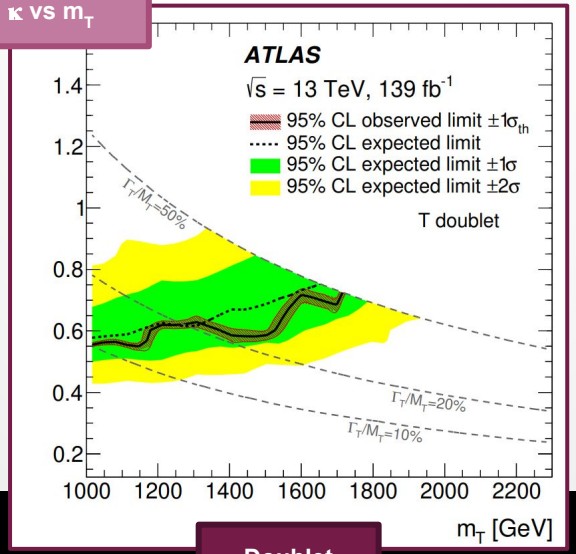
- **Singlet: m_T < 2.1 TeV** for $\kappa \geq 0.6$, $\kappa > 0.3$ for **m_T= 1.6 TeV**
- **Doublet: m_T < 1.68 TeV** for $\kappa \geq 0.75$, $\kappa > 0.55$ for **m_T = 1.0 TeV**

No significant excess over the SM expectation is observed.

Limits on κ vs m_T

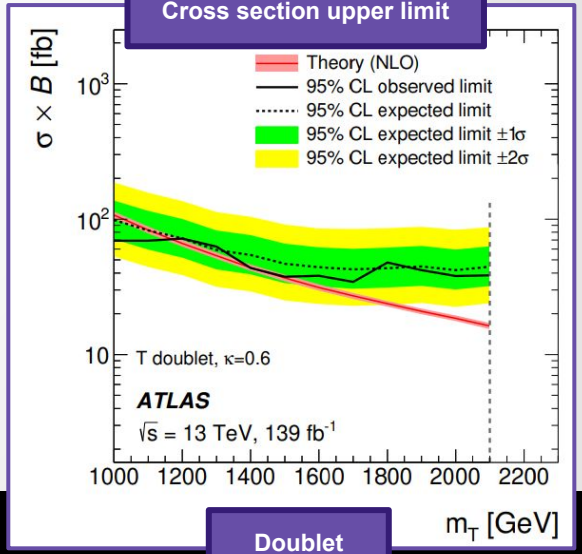


Singlet



Doublet

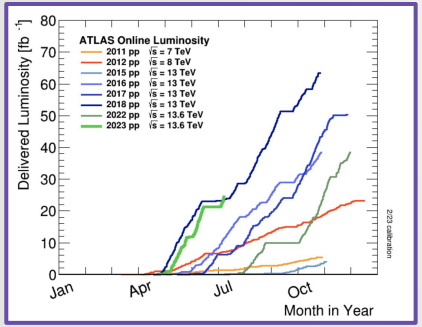
Cross section upper limit

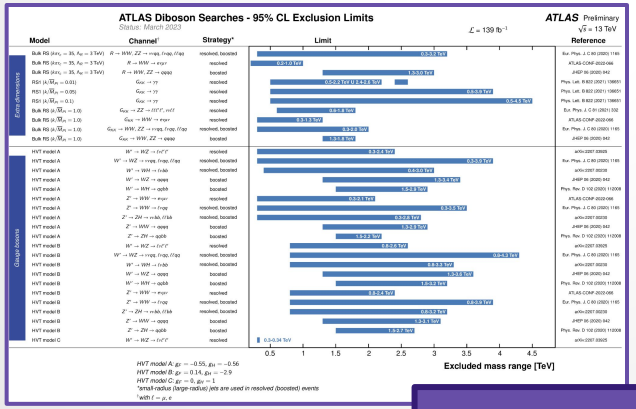


Doublet (κ=0.6)

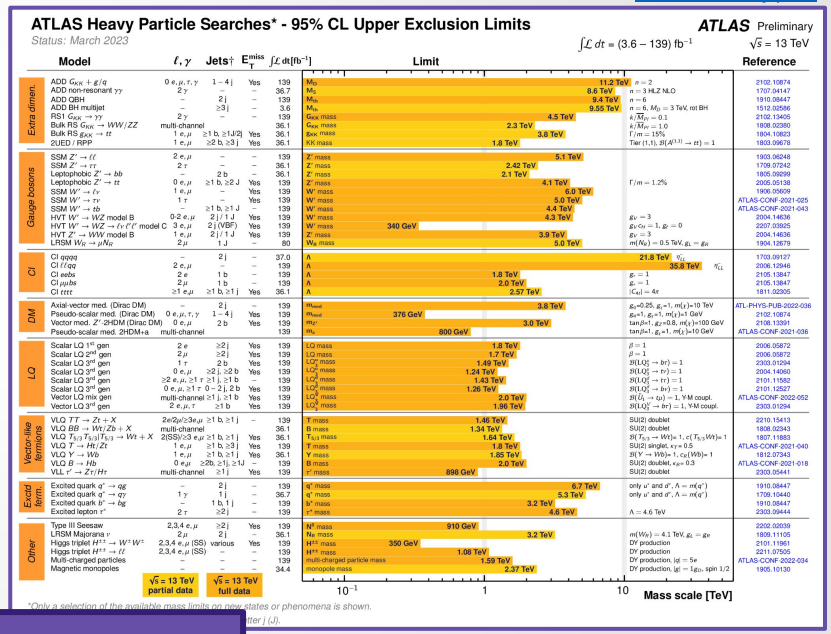
Conclusions

- **ATLAS analyses** cover a **very wide range** of **BSM heavy resonance** searches, yet there is **no evidence yet for new physics**
- **Limits are improving** as more data is analyzed and **new techniques**, many involving **machine learning**, are developed and implemented
- **Stay tuned for results from Run-3!** 😉

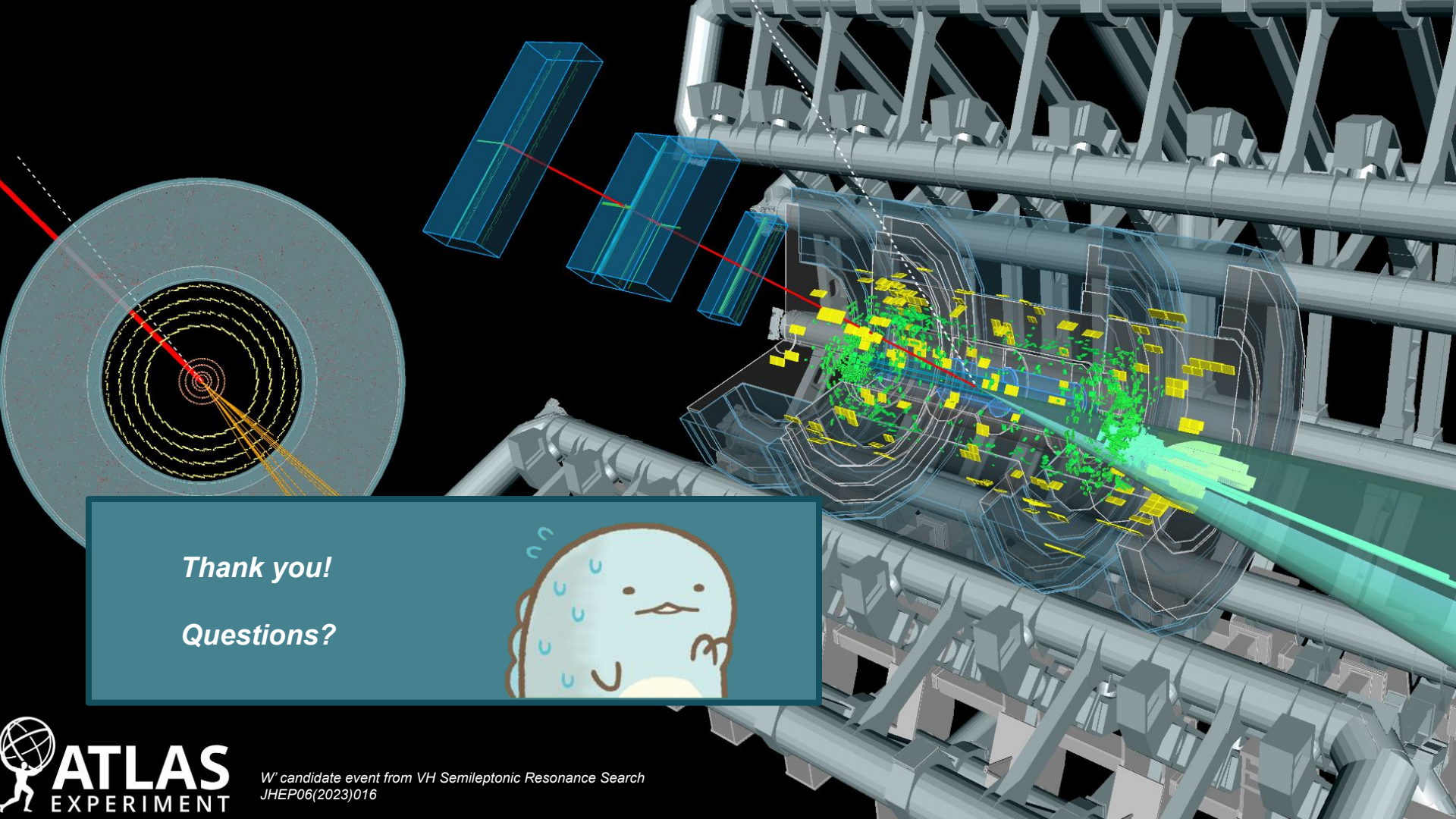




[Link to summary plots](#)



Much more than can be shown here!



Thank you!

Questions?

ATLAS EXPERIMENT

W' candidate event from VH Semileptonic Resonance Search
JHEP06(2023)016