“Search for new physics in multi-body invariant masses in events with at least one isolated lepton and two jets using $\sqrt{S}$ = 13 TeV pp collision data collected by the ATLAS detector"

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Young Scientist Symposium Series (YSSS)

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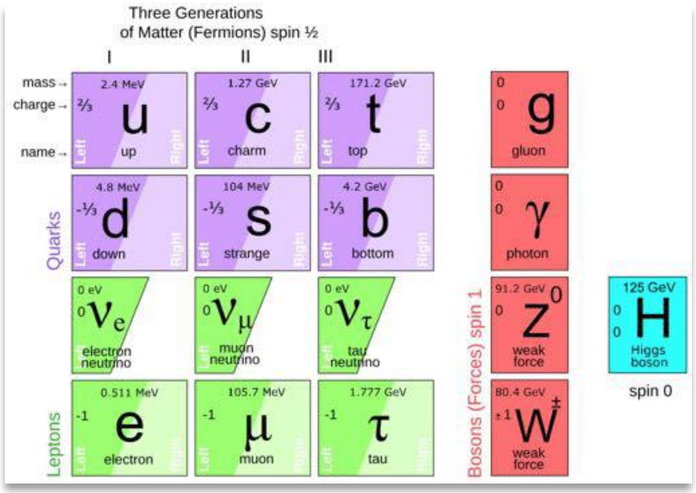
Motivation

Is there anything beyond the Standard Model?

Standard Model is a successful theory with precise predictions, verified by collider experiment like LHC.

- **The problem with Standard Model?**
  - Need high levels of fine tuning to avoid quadratic divergence in Higgs mass correction
  - No explanation for Dark Matter
  - No unification of forces



- **Beyond the Standard Model:**
  - New structure, particles and/or symmetries could stabilize Higgs mass against large radiative corrections.
  - DM particle candidate.
  - Presence of new heavy gauge bosons or new Higgses could give new insights.

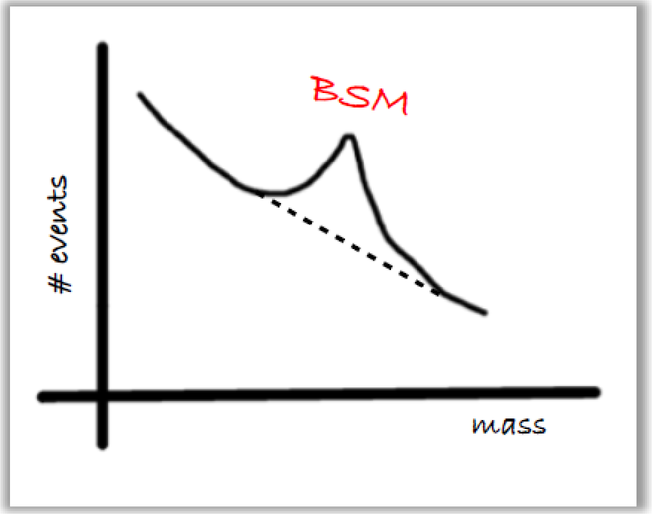
Model independent searches in invariant mass

- No signs of physics beyond the Standard Model (BSM)
- Searching for a resonance: 'bump hunting'
- signal-like deviations in two-body invariant masses of jets, leptons or photons

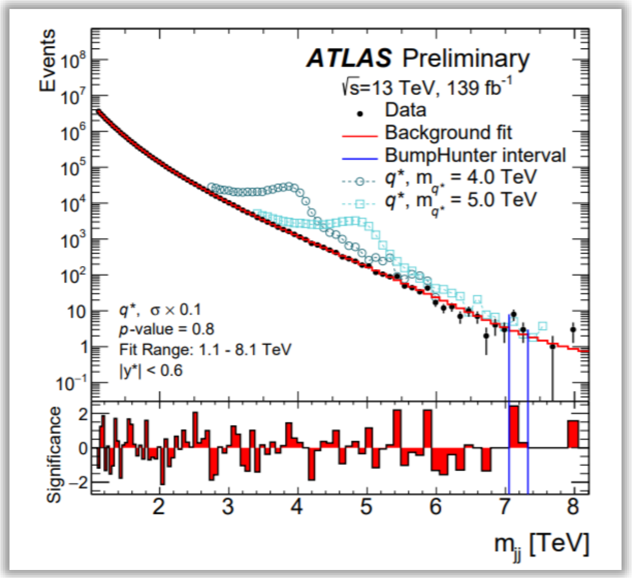
- Dijet invariant-mass distribution searches provide a means of investigating a variety of BSM theories

by UA1, UA2 Collaborations at the CERN SppS; CDF, D0 at the Tevatron & by both CMS and ATLAS experiments at LHC

- Inclusive searches are typically restricted to m_{jj} > 1.0 TeV due to p_T^{jet} trigger thresholds.
- Overcome trigger limitations by exploiting spectator objects, *e.g.* photons, leptons

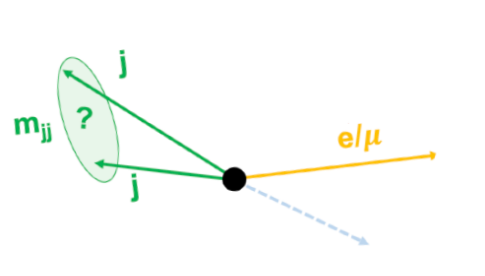


$m_{jjl}, m_{jjll}, m_{jbl}, m_{bbl}$



- JHEP 06 (2020) 151

Motivation: Multi-body searches



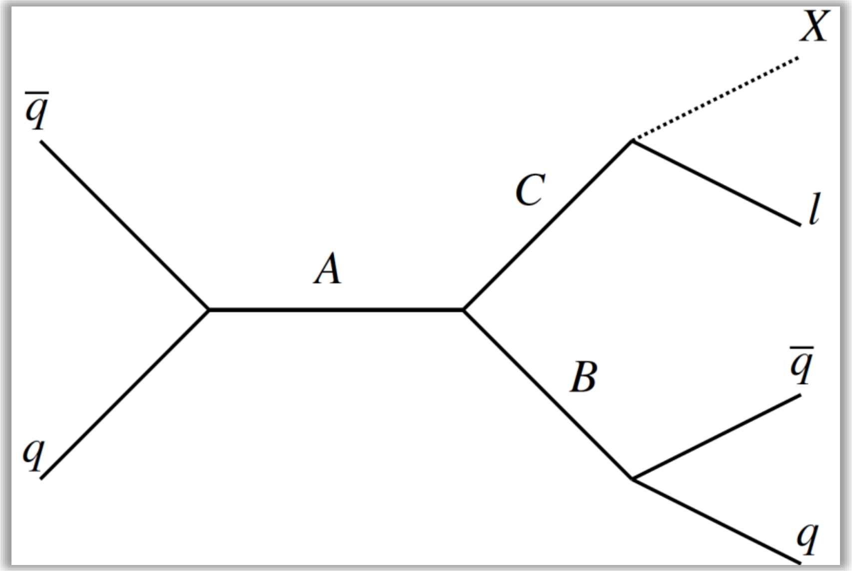
- Dijet resonance search can be extended by having very similar strategies but with the inclusion of lepton in the invariant mass.
- Mass reconstructions of Dijets + a lepton and diets + two lepton are sensitive to various BSM Physics processes.
- Only a handful number of LHC studies went beyond the two-object mass distributions.
- LHC data have not been fully explored in multi-body invariant masses with same precession as 2-body invariant masses.
- We investigate three- and four-body (3- and 4-body) invariant masses for BSM processes.

Cascade decays of BSM particles

Event topologies which have a special property for model independent BSM searches:

- Three body invariant mass
- Four body invariant mass

- Cascade decay of a heavy particle A into two other particles B and C.
- Popular channel: when B & C known bosons (W, Z or H, on/off shell).
- Generally, however, A and B may not be known.
- when B and C are bosons, their 2-body decay modes are ether hadronic ($q\bar{q}$) or leptonic ($l^{\pm}\upsilon_{l}$, $l^{+}l^{-}$).
- B decays to two jets, while C decays to a lepton and X, X : is another lepton, neutrino or some other particle (detectable/undetectable).



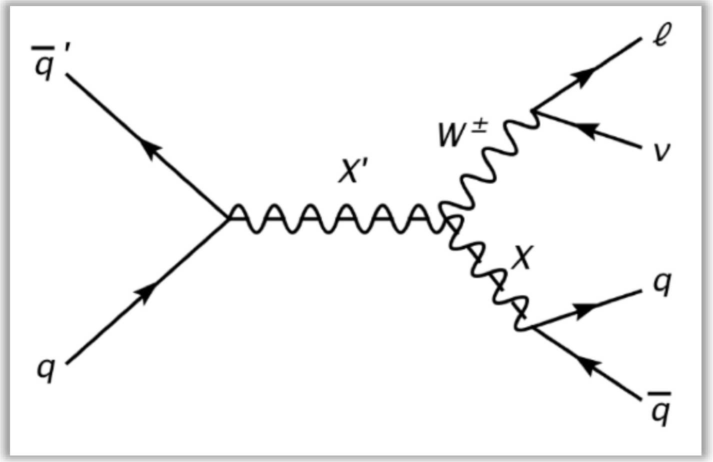
Multi-body searches

Searches *jjl*, *jjll*, *jbl*, and *bbl* channels.

- Resonance search in 3/4-body invariant mass spectrum in events with two jets and one or two leptons.

- New final state signature, sensitive to new particles that are:
  - Produced in association with a *W/Z* boson.
  - Decays to produce a *W/Z* boson or lepton along with another particle that decays to two jets.

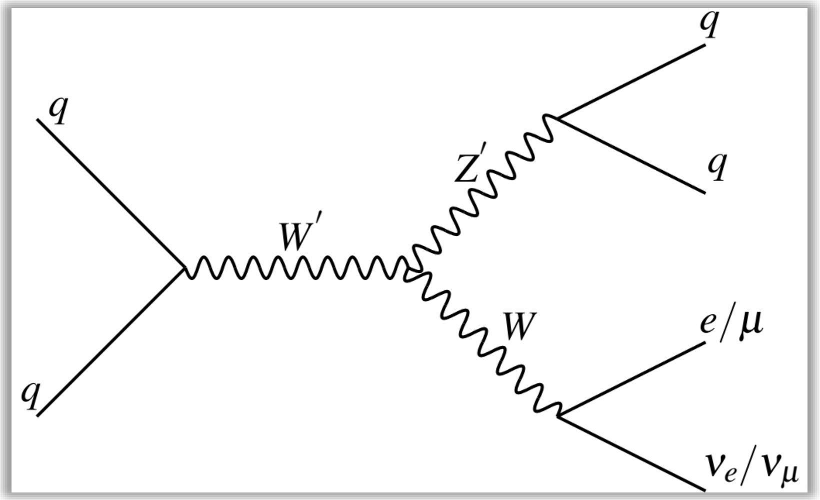
- Using full Run 2 dataset and using lepton triggers allows for sensitivity to lower invariant mass range compared to jet triggers.



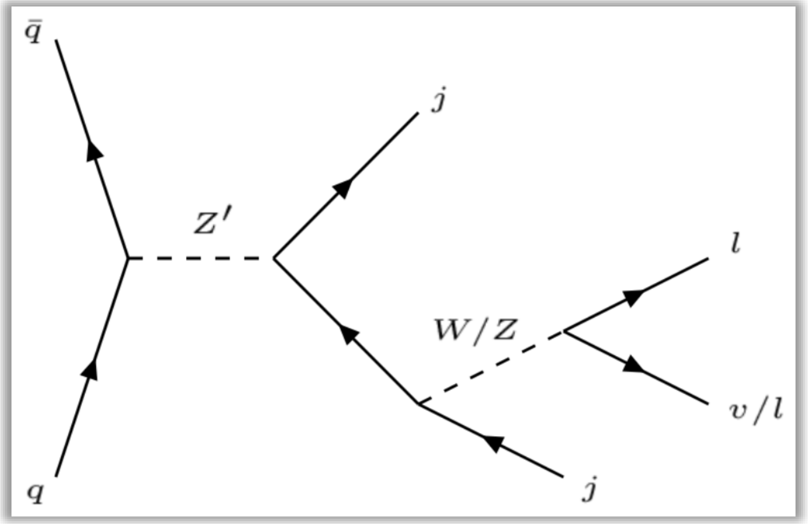
Signal Models

Study reports on model-independent searches for generic BSM resonance in 3/4 –body invariant mass distribution.

- **Sequential Standard Model**, which includes new heavy gauge bosons W’and Z’
  - Was studied in previous analysis to set Z’, now setting limits on W’



SSM signal process



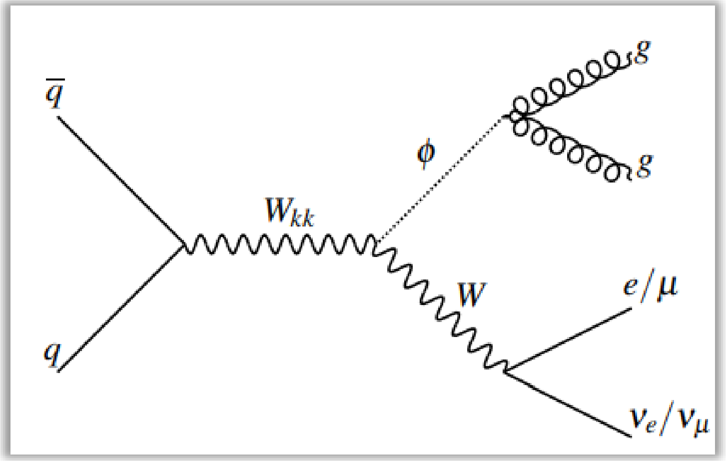
Simplified DM model signal process

- **Simplified dark matter model** with a Z’ mediator
  - Benchmark model for dark matter searches.

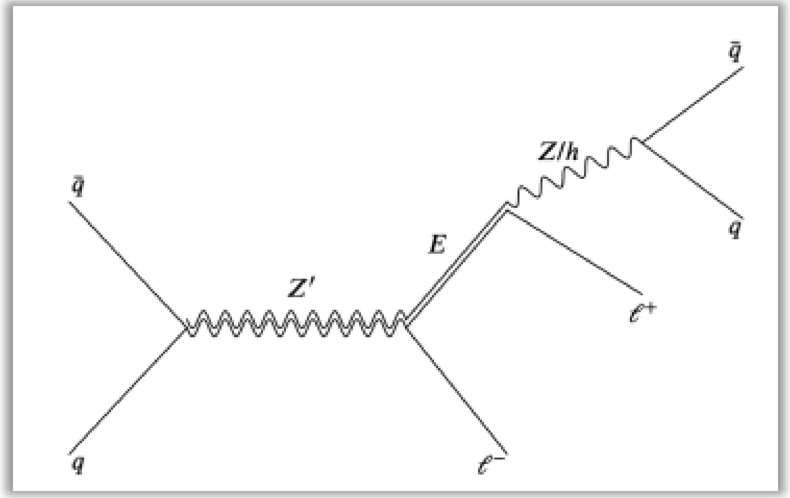
Signal Models

Setting limits on generic gaussian signals as well as four BSM models

- **Radion model** that includes Kaluza-Klein gauge bosons coupling to a radion, decays to gluons.
  - Search for the KK gauge bosons that decay to a radion along with a SM W/Z boson.



Radion model signal process



Composite lepton signal process

- **Composite lepton model** predicts Z’ that decays to a new vector like composite lepton E along with a SM lepton Z’ -> E l.
- E can then decay as Z/h l, with Z/h eventually decays to 2 jets.
- Signal process produces high energy leptons that result in a large acceptance in 2 jet + 2 lepton.

Monte Carlo simulations

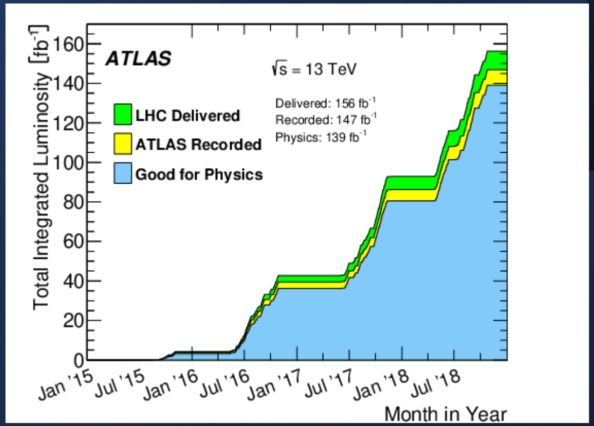
- QCD multijet event sample: Pythia8 generator
- $t\bar{t}$ and W+jet events sample: Powheg-Box v2 generator

- Event simulations are used to estimate contributions to the multi-body mass distribution from various background SM processes.
- To verify some aspects of the analysis procedure, the SM background was modeled using MC simulations.
- Check the shape of various kinematic distributions.
- The dominant sources of background modeled by MC used in this analysis are:
  - multijet (2 jets),
  - $t\bar{t}$
  - W+jets processes.
- All SM background processes were passed through the full ATLAS detector simulation.

Analysis Strategy

1. Performance based object selection
2. Estimate *mx* search range (0.4 to 8 TeV)
3. Define control regions (LE-CR and MC+LE-CR)
4. Determine fit method for background estimation (p5)
5. Bump search using BumpHunter
6. Bayesian Framework for limit calculation

Trigger, Object and baseline event selection



- **ATLAS Data: 2015-2018 (**xAODAnaHelpers + Wjet framework)
- **STDM4 p4238:** derivations
- **Events:** GRL, PVNTrack=2, All HLT single-lepton triggers
- **PFlowJetsantiKT4 (R=0.4):** pT>30 GeV |eta|< 2.8 JVT loose

  JES_MC16Recommendation_Consolidated_Pflow_Apr2019_Rel21.config, Clean=LooseBad
- **B-tagged jets:**DL1, 77% WP; pT>30 GeV |eta|<2.5
- **Muons:**WP:FCTight, Trigger match

  pT>60 GeV (lead) and pT>30 GeV (subleading), |eta|<0.5, d0/sigma<0.5
- **Electrons:**es2018_R21_v0 calibration, WP:FCTight, Trigger match

  pT>60 GeV (lead) and pT>30 GeV (subleading), |eta|<2.5, eta 1.37-1.52 excluded, d0sig_max=5, z0sintheta_max=0.5
- **MET:**Pflow-based, metFinalTrk, JVTcutapplied
- **Overlap removal (OR)**

Analysis procedure

- New resonant state X with a mass m_X can decay into decay into partons and other leptons
- May lead to an excess of events at invariant mass (m_N) at around $m_N = m_X$ in an otherwise smooth and monotonically decreasing invariant mass distribution.

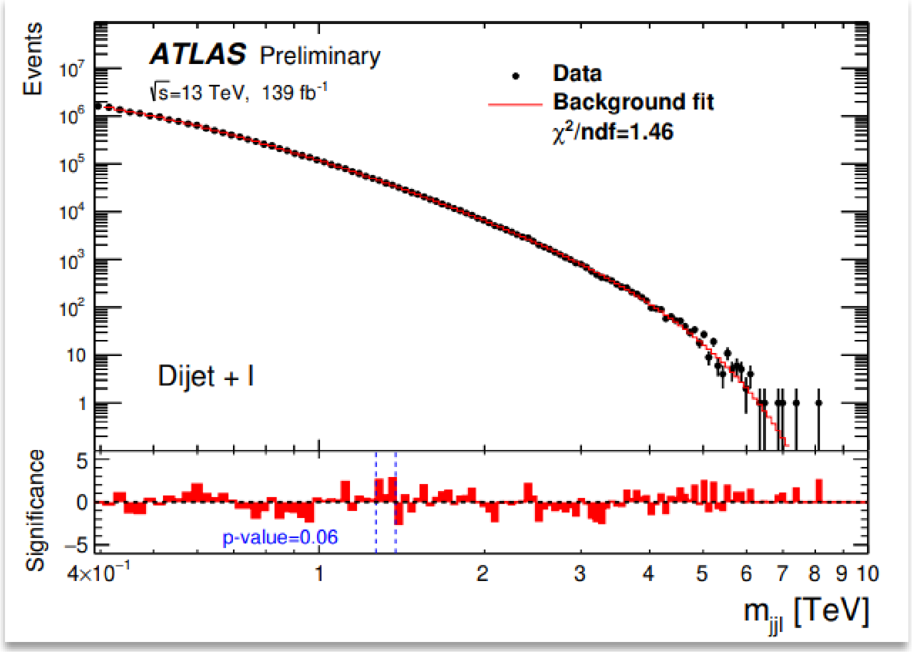
- Search for such an excess in the mass range > 0.4 TeV for m_{jjl} , m_{jjll}, m_{jbl} and m_{bbl} (4 signal region).
- Fit function is used to model the shape of the estimated background

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

- A likelihood fit is performed on a background enhanced sample obtained from a 'loose electron' control region (LE-CR) defined from data.
- To determine if the data deviate significantly from he background-only hypothesis, BumpHunter algorithm used.
- If no statistically significant deviations are observed, the exclusion upper limits are set at the 95% confidence level (CL) on the production cross-section times branching ratio using the Bayesian method

Results (Bump search)

- Data consistent with the background-only hypothesis.
- 5p fits of m_{jjl} show no significant excess.
- Largest deviation in m_{jjl} has local significance of 3.5 σ and global significance of 1.5 σ.
- Deviation from bkg hypothesis is consistent with statistical fluctuation.

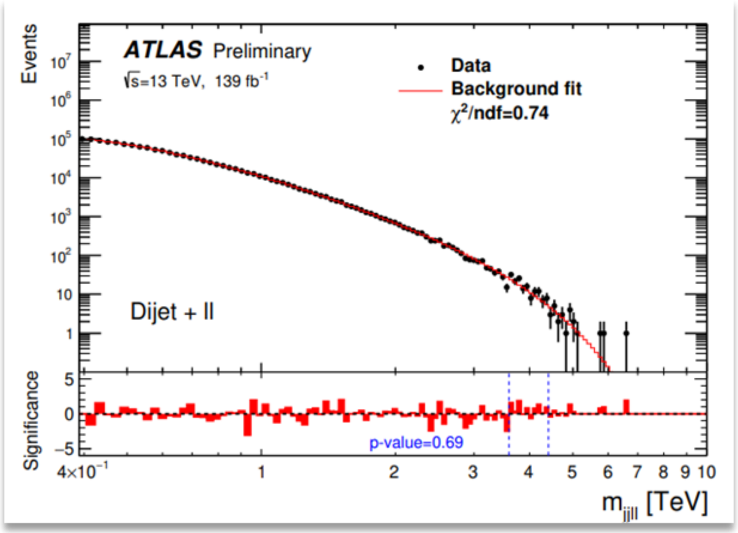


m_{jjl}> 400 GeV

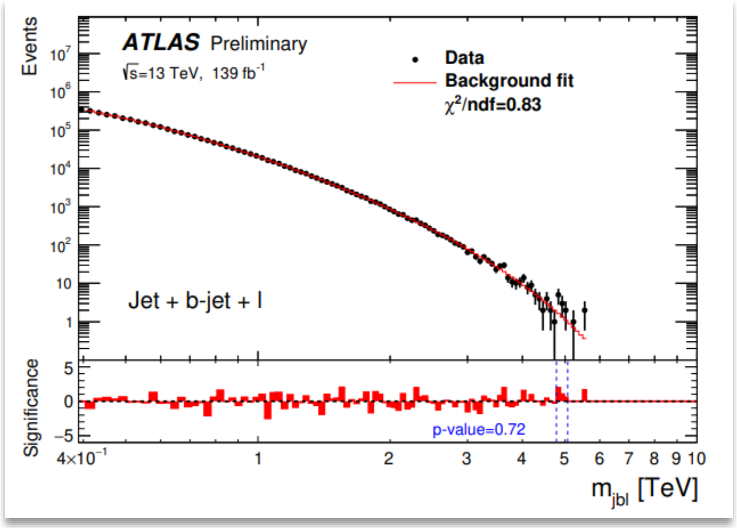
- Invariant masses together with the results of the likelihood fits using the 5p function.
- Quality of fit in terms of χ^2/ndf
- To establish the presence or absence of a signal, BH algorithm is used.
- Bottom panel shows bin-by-bin significance of deviation from bkg hypothesis.
- Distribution of significance is consistent with a normal distribution.

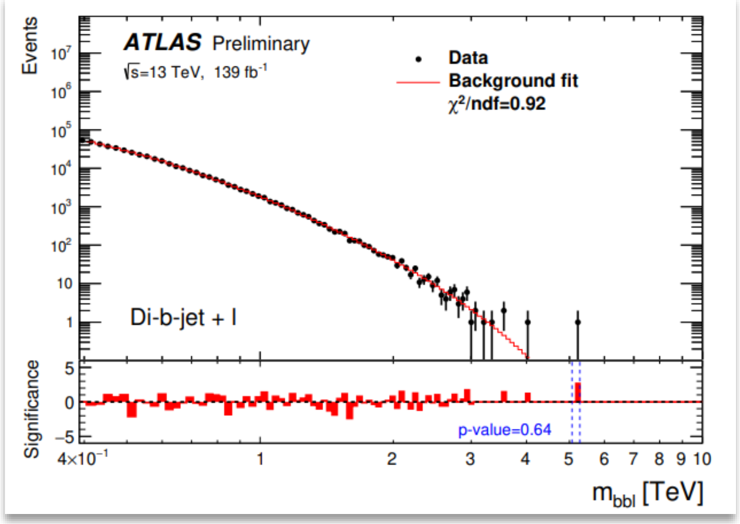
Results (Bump search)

- m_{jjll} distribution with global p-value for the largest deviation near 4TeV is 0.69.
- Bottom plots shows for three body masses with one or two b jets.
- Global p-value for the largest deviation have values > 0.6.
- Distributions do not show significant excess or deviation from background.



m_{jjll}> 400 GeV



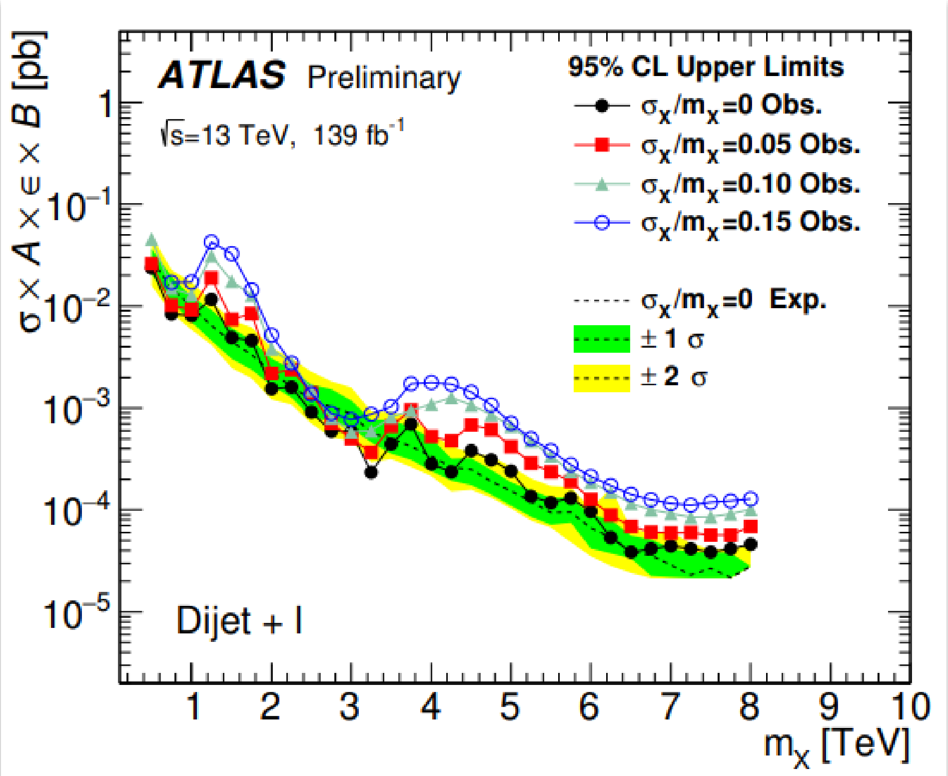


m_{jbl}> 400 GeV

m_{bbl}> 400 GeV

Model independent limits

- Absence of any statistically deviation from 5p bkg function.
- Bayesian method is used to set 95% CL upper limits on the new process cross section.
- 95% CL expected and observed limits of a BSM particle decaying to jjl,
- Calculated using Gaussian shapes with different widths.

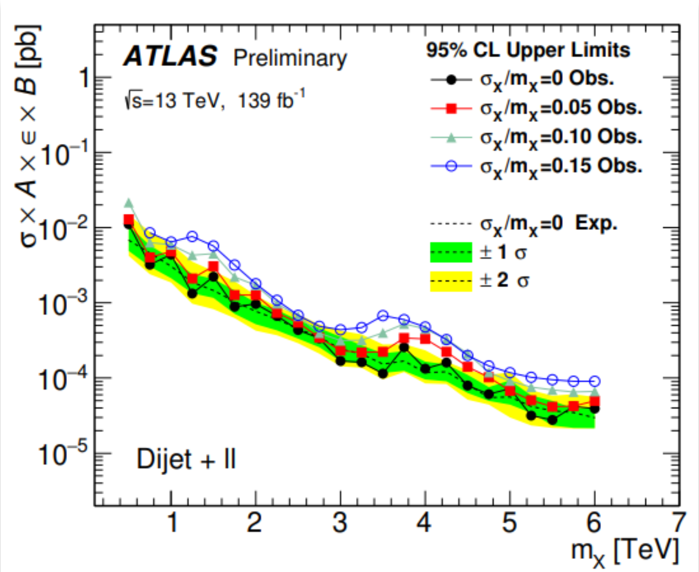


m_{jjl}

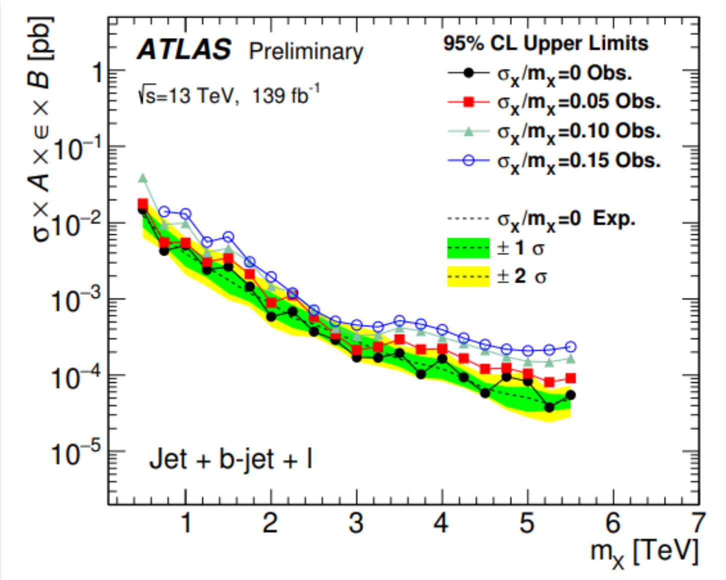
- Observed limits are for different widths, from a narrow width – comparable with the experimental resolution of about 3% – up to 15% of the mean mass.
- Expected limit and the corresponding $\pm 1\sigma$ and $\pm 2\sigma$ bands are shown for the narrow width
- Resulting exclusion limits range from 50 fb to 0.1 fb in the mass range 0.5 – 8 TeV.

Model independent limits

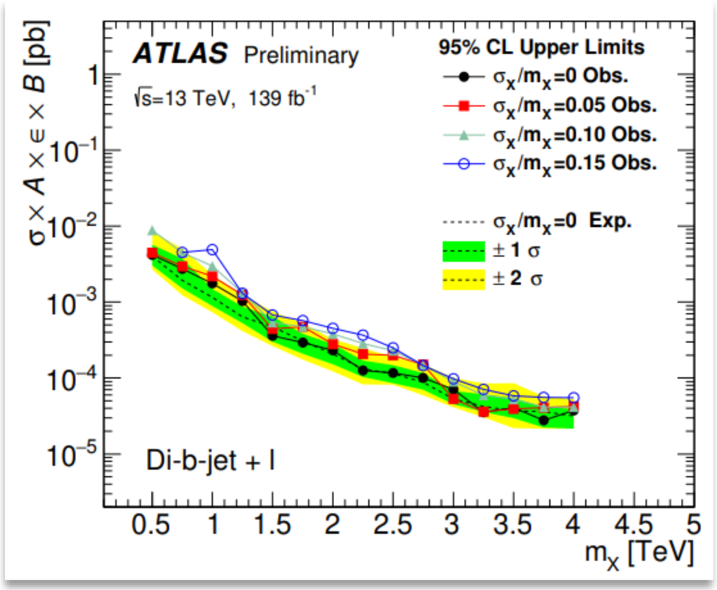
- Contributions from a Gaussian-shaped signal with effective σ_x ranging from approx.
  - exclude from 10 fb to 0.01 fb for resonance masses between 0.4 TeV and 4 – 5 TeV (for m_{jbl} , m_{bbl})



m_{jjll}



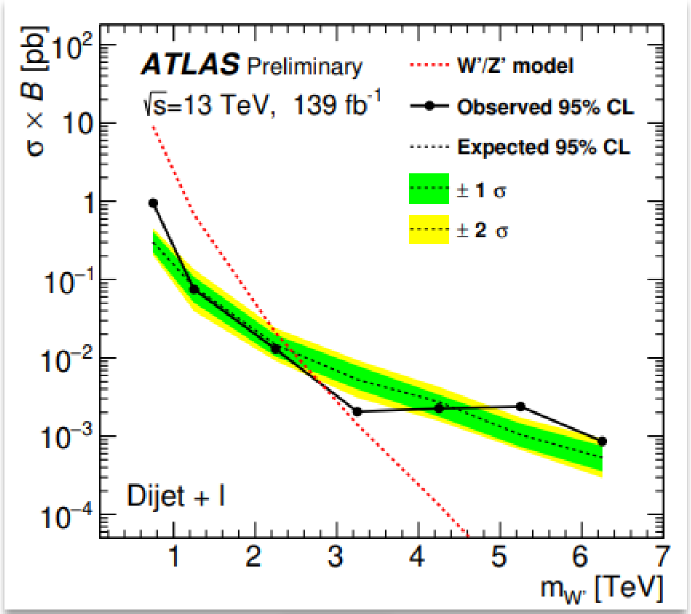
m_{jbl}



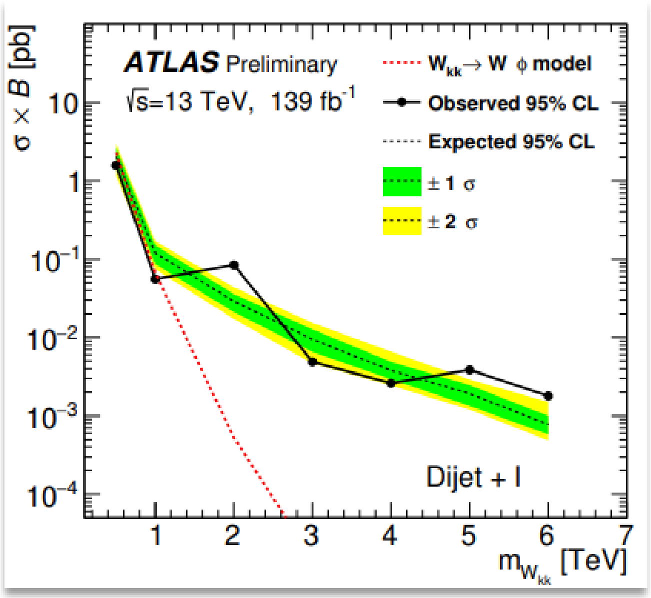
m_{bbl}

Limits on BSM models

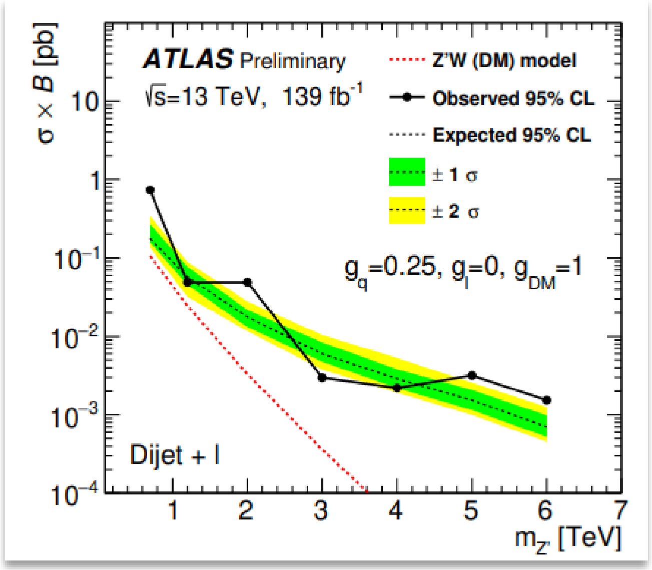
- **SSM** ($W' \rightarrow W Z'$ model) : Excluded for W' masses up to 2.5 TeV, mass difference between W' and Z' is 250 GeV.
- W_{KK} **Radion Model** : *Mass of Radion* m_{ϕ} excluded for masses below 1.0 TeV
- **Simplified Dark Matter Model** We couldn't exclude anything in this model.



SSM



Radion model

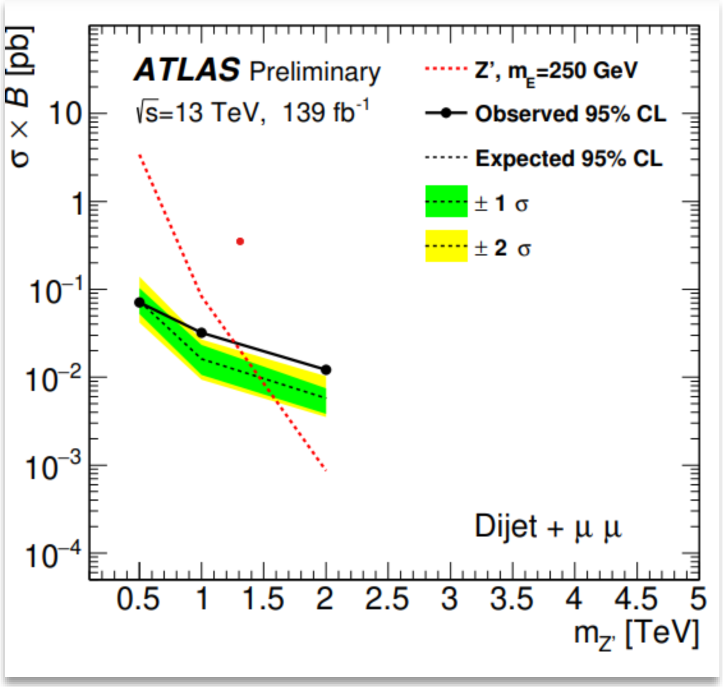


Simplified DM model

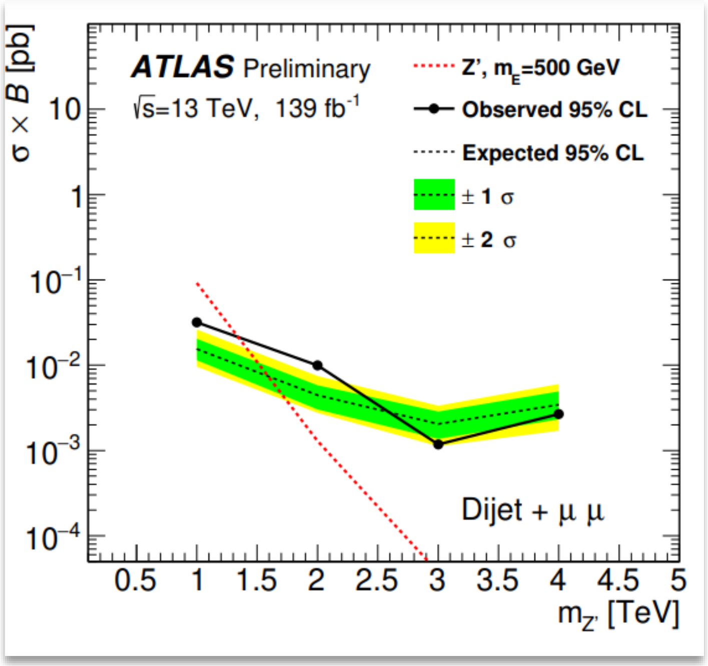
Limits on Composite lepton model

Set limits on composite lepton model in m_{jjll}

- Able to exclude Z' at ~1.3 TeV for M_E = 250 and 500 GeV
- Unable to exclude Z' for higher E masses



Composite lepton model with M_E = 250 GeV



Composite lepton model with M_E = 500 GeV

Summary

ATLAS Paper Draft
EXOT-2020-15
Version 2.0
Target journal: JHEP

Comments are due by: July XX, 2022

Supporting internal notes

ATL-COM-PHYS-2020-632: https://cds.cern.ch/record/2729738

Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton and two jets using $\sqrt{s} = 13$ TeV proton–proton collision data collected by the ATLAS detector

A search for resonances in events with at least one isolated lepton (e or μ) and two jets is performed using 139 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton collision data recorded by the ATLAS detector at the LHC. Deviations from a smoothly falling background hypothesis are tested in three- and four-body invariant mass distributions constructed from leptons and jets, including jets identified as originating from bottom quarks. Model-independent limits on generic resonances characterised by cascade decays of particles leading to multiple jets and leptons in the final state are presented. The limits are calculated using Gaussian shapes with different widths for the invariant masses. The multibody invariant masses are then used to set 95% confidence level upper limits on the cross-section times branching ratios for the production and subsequent decay of resonances as predicted by several new physics scenarios.

Searched for excess in 3/4 body invariant mass distributions in events with two jets and 1/2 leptons

- First search in these channels
- No significant excess was found an in channel, largest deviation found in mjjl with global significance < 3σ
- Set limits on SSM, simplified DM, Radion, and composite lepton models as well as generic gaussian signals
- Preparing for paper publication
- showed public results in ICHEP 22

(international conferences organized by International Union of Pure and Applied Physics (IUPAP))

Analysis Team

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Thank you

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