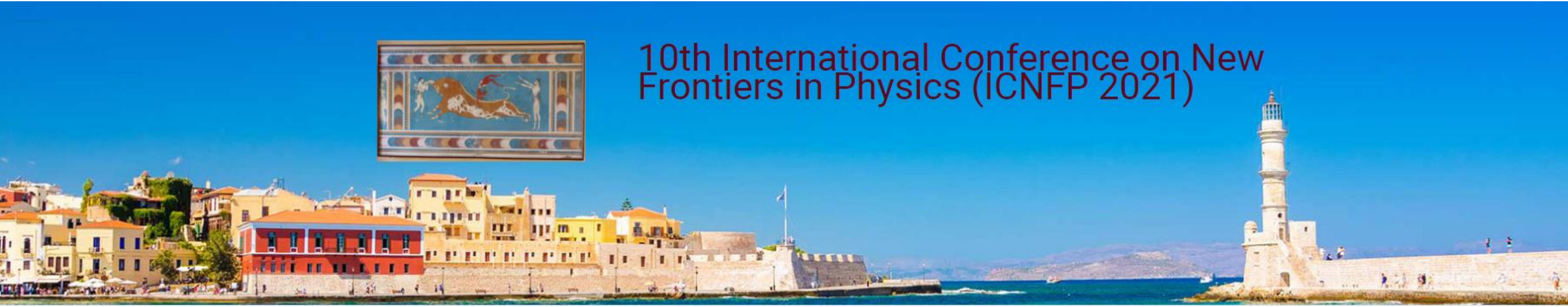

Model-Independent Searches for New Physics in Multi-Body Invariant Masses

Smita Darmora*, Sergei Chekanov*, Carlos C.E. Wagner*†, Wasikul Islam & Jinlong Zhang*

*Argonne National Laboratory, USA , † Univeristy of *of Wisconsin, Madison WI, USA.*

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Motivation

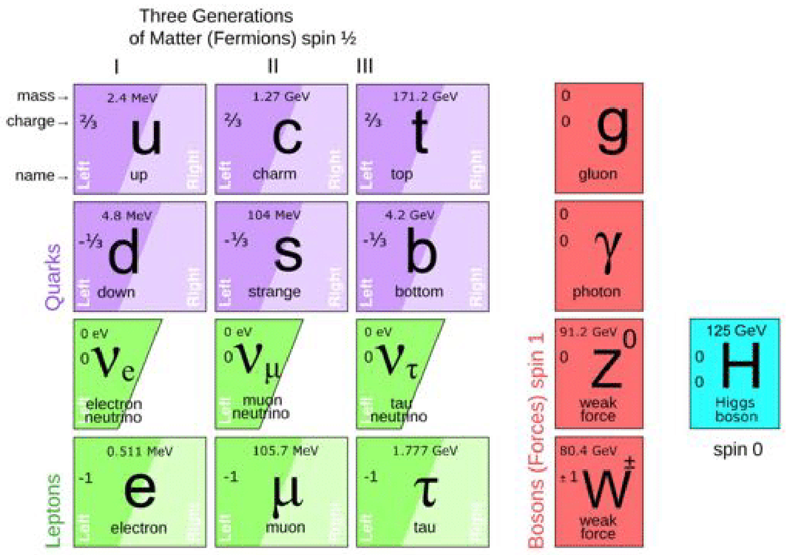
- The standard Model is a successful theory with precise predictions, verified by collider experiment like LHC.

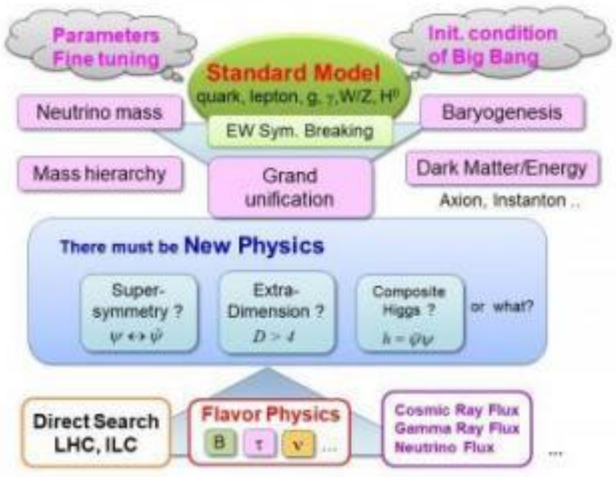
The problem with Standard Model?

- 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
- Two-Higgs-doublet models can introduce Flavor-changing neutral currents, which have not been observed so far.



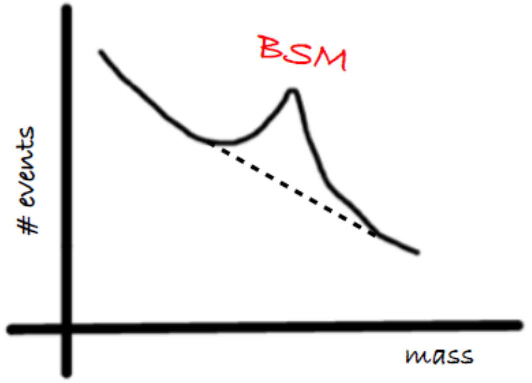


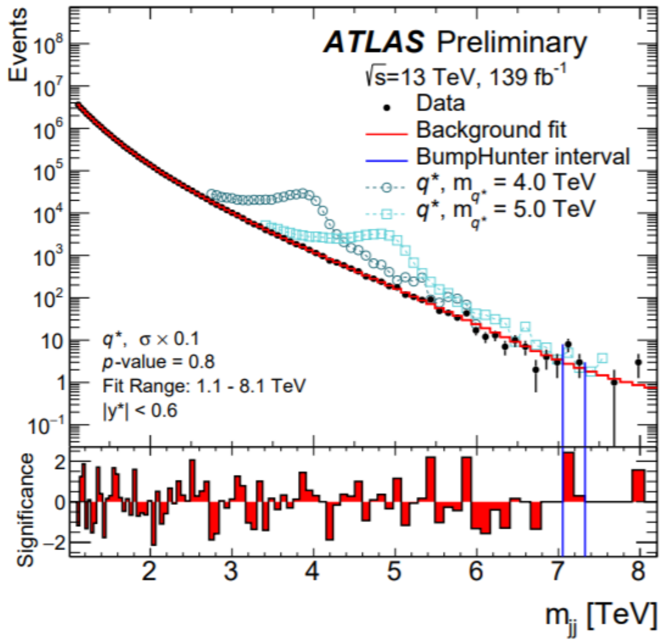
Model independent searches in invariant mass

- No signs of physics beyond the Standard Model (BSM)
- Searching for a resonance: 'bump hunting'
- signal-like deviations in two-body (2-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

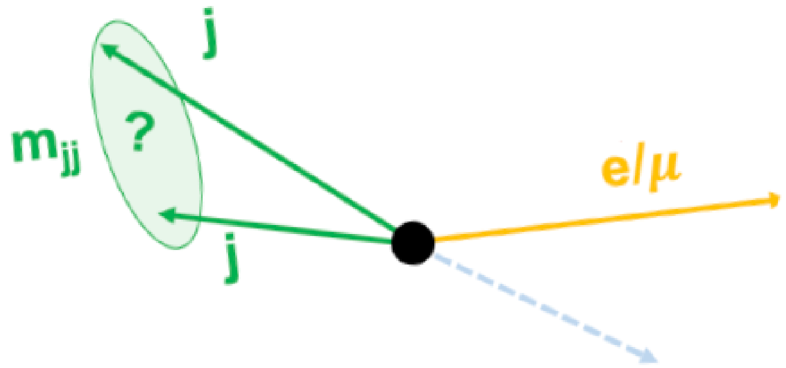
- Inclusive searches are typically restricted to m_{jj} > 1.0 TeV due to p_T^{jet} trigger thresholds.
- Overcome trigger limitations by exploiting spectator objects, *e.g.* photons, leptons
- JHEP 06 (2020) 151





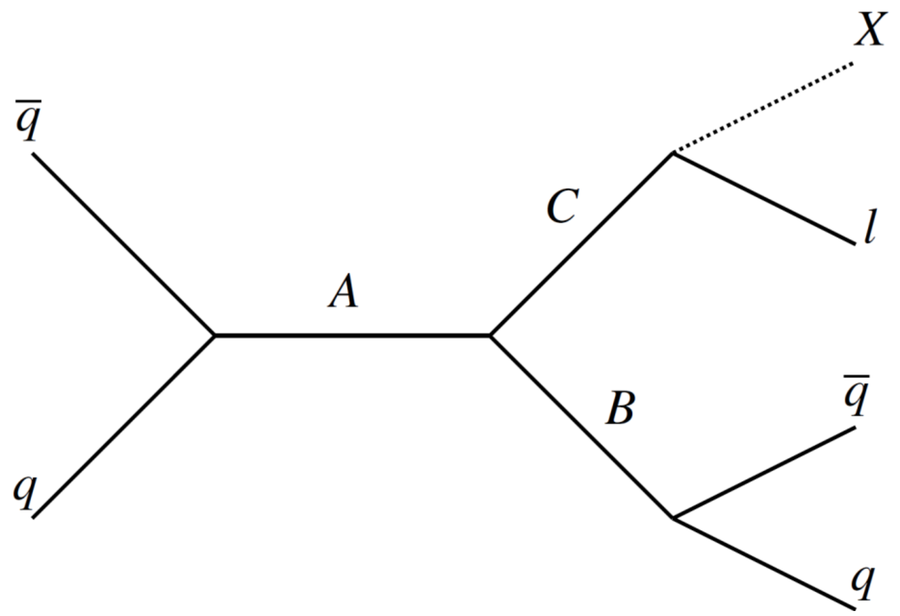
Motivation: Multi-body searches

- 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 + 2 leptons are sensitive to various BSM Physics processes.
- Only a handful number of LHC studies went beyond the two-object mass distributions.
- In such studies, Monte Carlo descriptions are used to establish the backgrounds hypothesis.
- We investigate three- and four-body (3- and 4-body) invariant masses for BSM processes



Cascade decays of BSM particles

- Cascade decay of a heavy particle A into two other particles B and C.
- most popular channel: when B and C are known bosons (W, Z or H, on-shell / 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 ($l^{\pm}\upsilon_l \; l^{+}l^{-}$).



We assume that B decays to two jets, while C decays to a lepton and X, where X is another lepton, neutrino or some other particle (detectable or undetectable)

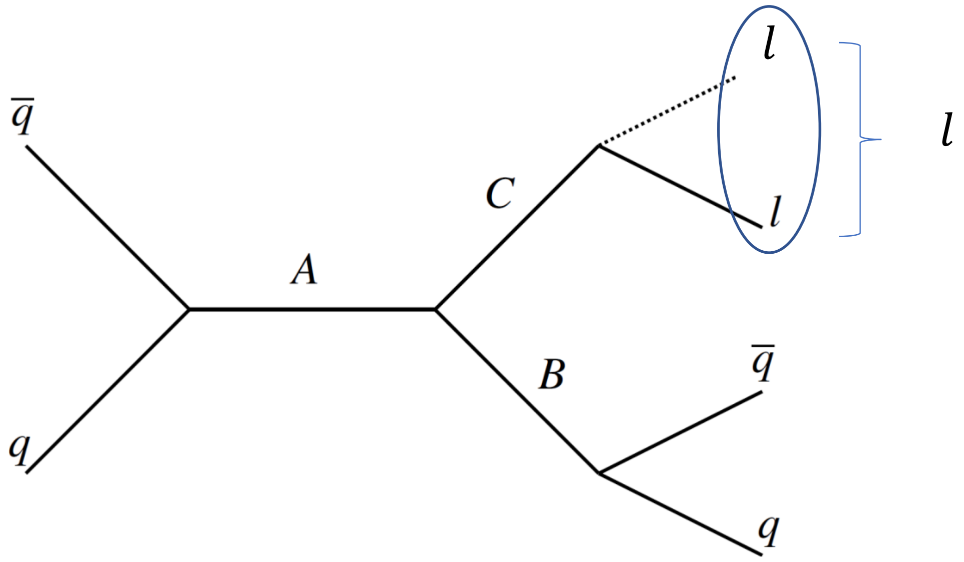
Three body invariant masses

For an unknown resonance A, if A → BC, 3 body reconstruction can be sensitive to the mass of particle A.

Three-body invariant masses m_{jjl} reconstructed from two jets and a lepton can be a more powerful variable in the identification of the process A → B C than 2-body masses under the following conditions:

- Particle B is not boosted and the two jets originating from B is well resolved
- Particle C doesn't have constraints on mass compared to A due to the presence of at least one lepton
- B, C are broad in signal widths and A having small partial width ($\frac{\Gamma}{m} < 0.2$)

Seen by experiment



Specific BSM models

Specific BSM models that can be found using 3 and 4-body invariant masses.

- Three body invariant masses
  - Model with SM boson
    - Sequential Standard Model
  - Radion Model

- Four body invariant masses
  - Composite lepton model

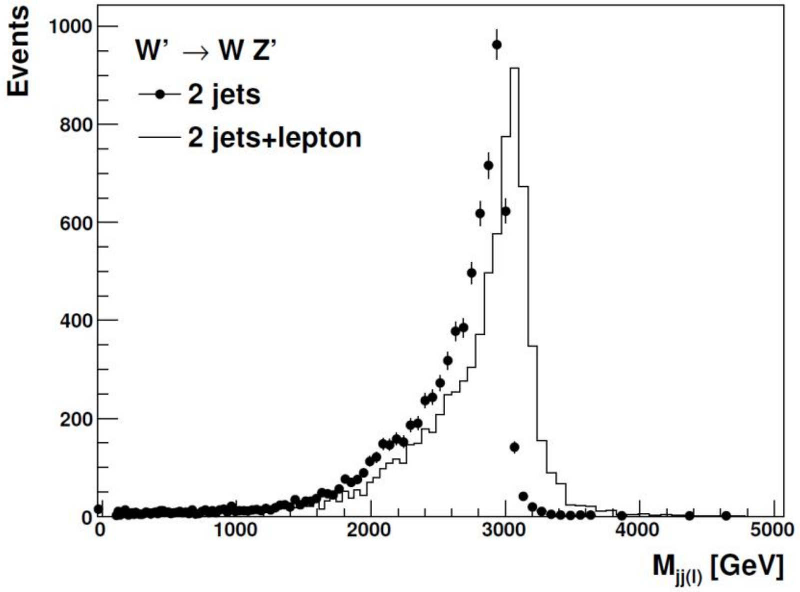
Model with SM boson:

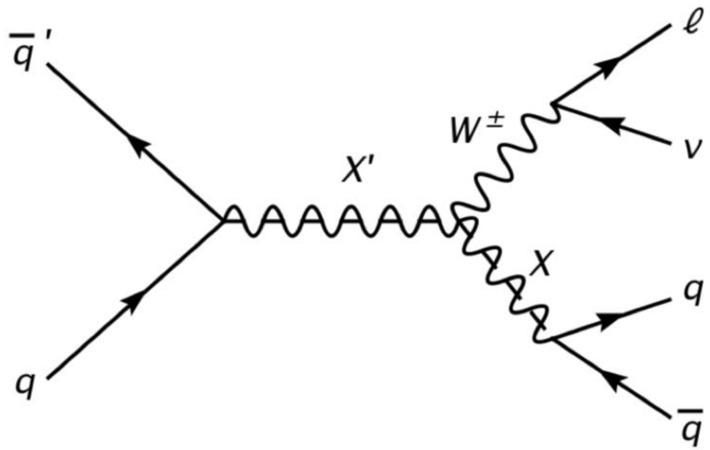
Sequential Standard Model

Following process from **Sequential Standard Model** scenario is considered for three body mass reconstructions :

$$W' \rightarrow WZ' \rightarrow l\nu q\bar{q}$$

- Z' dijet resonance produced in association with a leptonically decaying W
- Mass difference between the W' and Z' was set to 250 GeV.





In some scenarios, the discovery potential using three-body masses is as strong as when using the two-jet masses

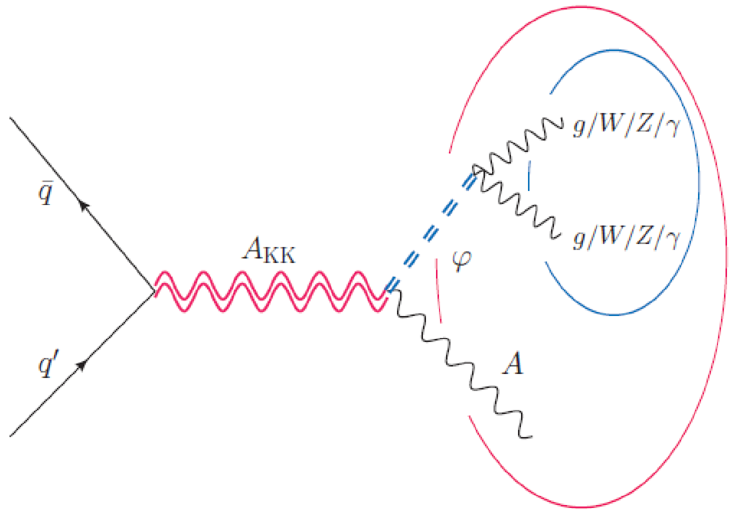
Radion Model

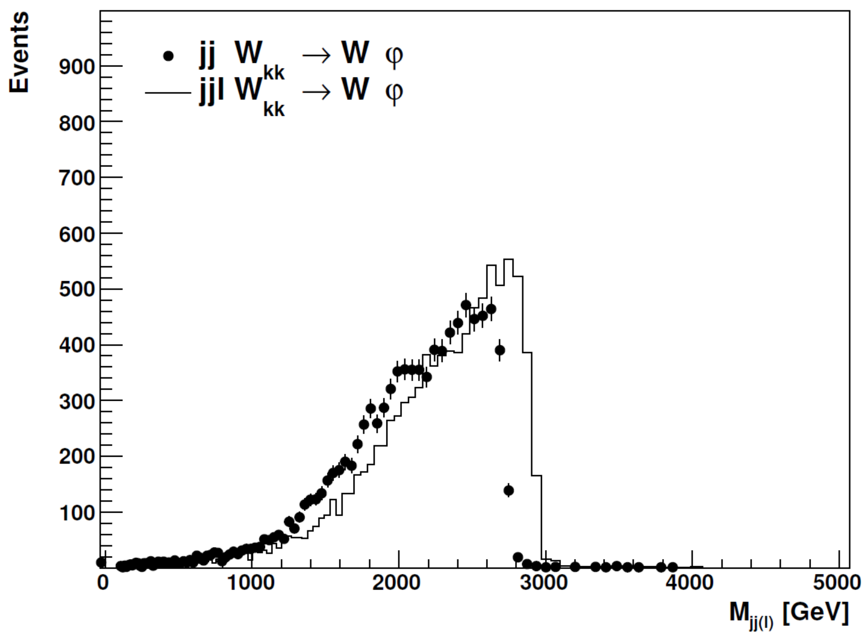
arXiv:1612.00047

Radion model where Kaluza-Klein excitation of W boson, W_{KK} decays in following process :

$$\boldsymbol{W_{KK} \rightarrow W + \Phi \rightarrow l\upsilon + q\bar{q}}$$

- masses of $\boldsymbol{W_{KK}}$ and Radion (Φ) are unknown





- $M_{W_{KK}} - \boldsymbol{M_{\Phi}}$ = 250 GeV: leads to the width of m_{jjl} close to the width of m_{jj}.

Four body invariant masses

For 4-body decay analysis, consider the example, where X could be a lepton or jet

Hence, events with at least two jets and leptons lead to the following combinations: m_{jjll} or m_{jjjl}

Useful for heavy TeV scale particle A, A → BC

- Particle A decaying to two heavy particles when both B and C are heavy and all decay products are well resolved
- Event topologies contributing to m_{jjjl} , when a particle C decays to a lepton and jets

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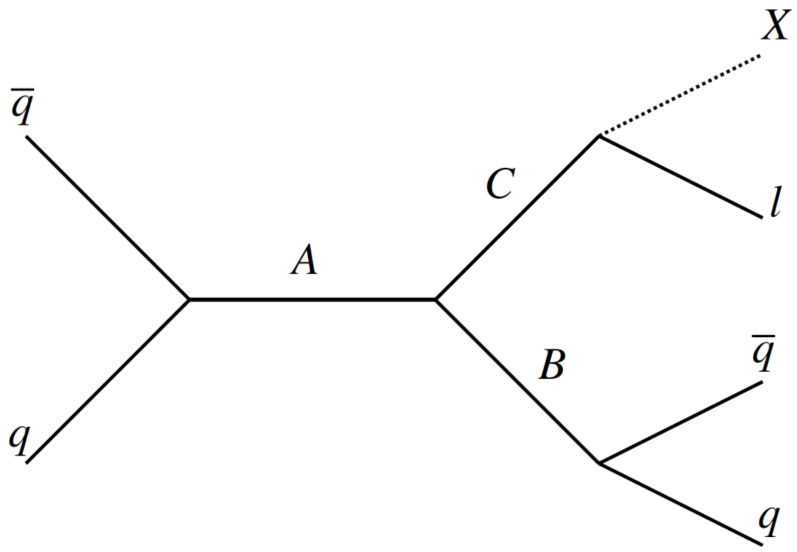
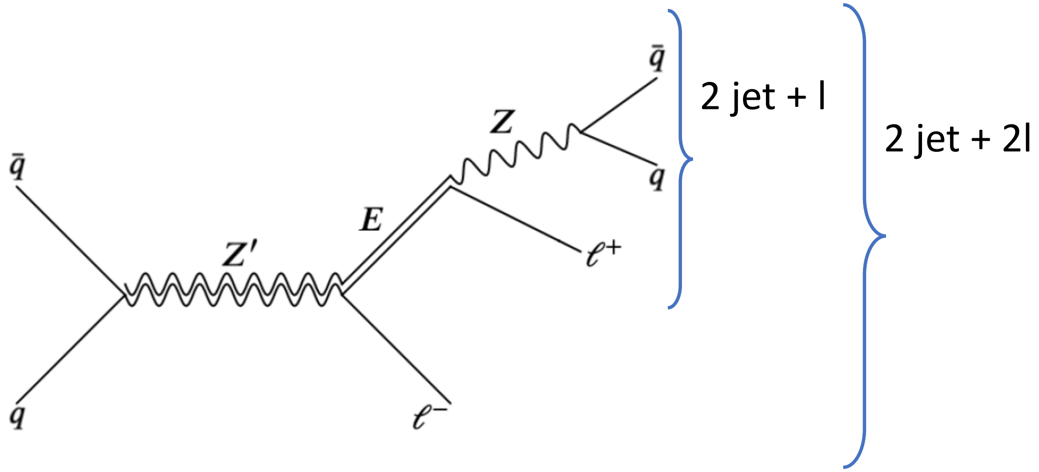


Composite lepton Model

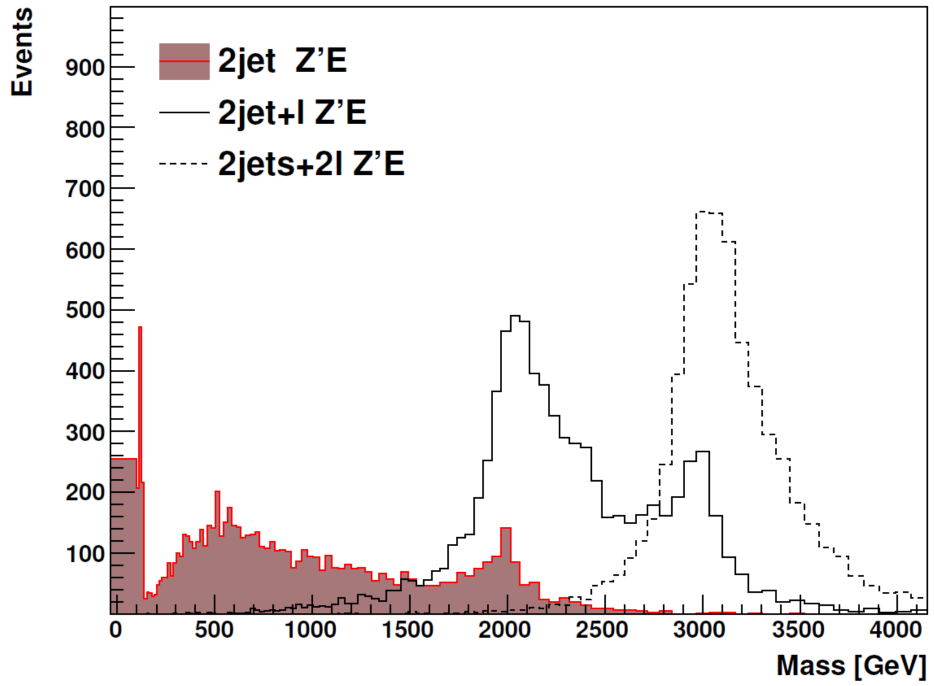
- Composite resonances model that break lepton flavour (LF) universality can be probed using multibody invariant masses.
- The decay channel: $\boldsymbol{pp \rightarrow V \rightarrow E^{\pm}\, l^{\pm}}$ where $\boldsymbol{E}$ is heavy composite lepton $\boldsymbol{E \rightarrow Z/h + l}$



- $\boldsymbol{V}$ is a heavy $\boldsymbol{Z'}$ boson ($M_{Z'} > M_E$)
- When $\boldsymbol{Z/h}$ decays hadronically, m_{jjl} can be used to reconstruct the mass of $\boldsymbol{E}$.
- $\boldsymbol{m_{jjll}}$ is sensitive to the $\boldsymbol{V(Z')}$ mass.
- Even if partial width of $\boldsymbol{E}$ is broad and $\boldsymbol{V}$ is small, $\boldsymbol{m_{jjll}}$ can still be narrow.

Composite lepton Model

- m_{jj}, m_{jjl} and m_{jjll} invariant masses reconstructed at the truth level of a MC simulation.
- Masses are $M_{Z'}$ = 3 TeV and M_E = 2 TeV
- The observed peak near 3 TeV (shown with dotted line) is due to the decay of Z' .



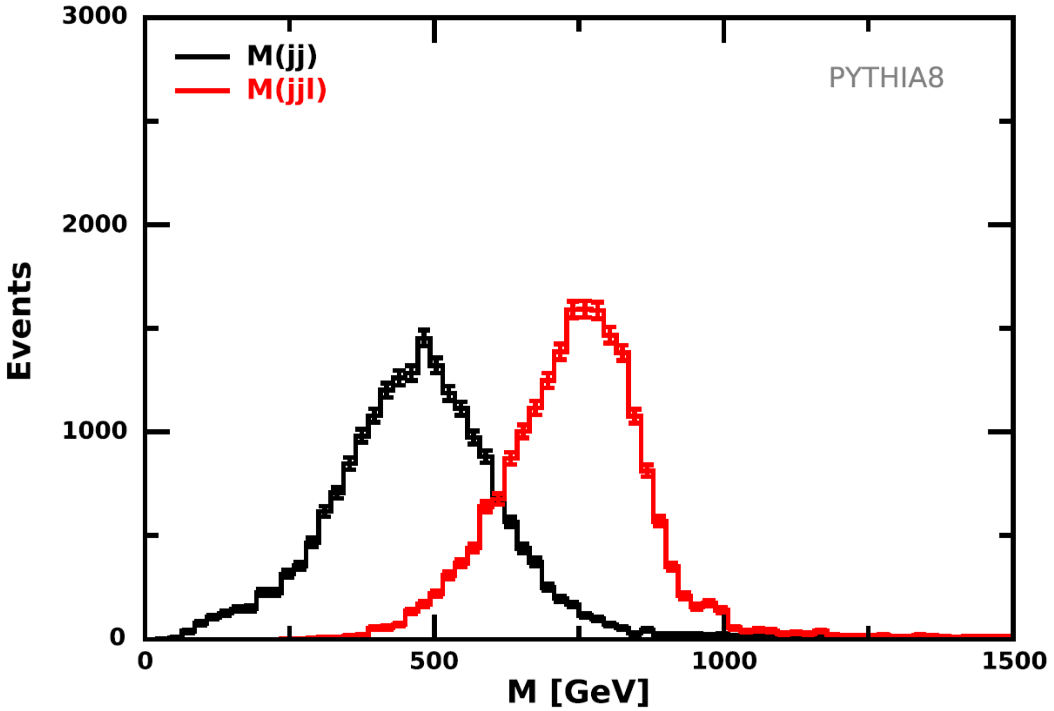
3 and 4-body mass reconstruction presents similar detec3on signatures as strong as reconstructed 2-body mass.

A hypothetical scenario

- Hypothetical examples where 2-body invariant masses are at a disadvantage for searches since the 2-body signal width is larger than 3 or 4-body masses.
- The goal is to illustrate a possible parameter space when 2-body masses are less powerful for searching enhancements on a smoothly falling background than for multi-body masses.
    - Three body invariant mass
    - Four body invariant mass

Three body invariant masses

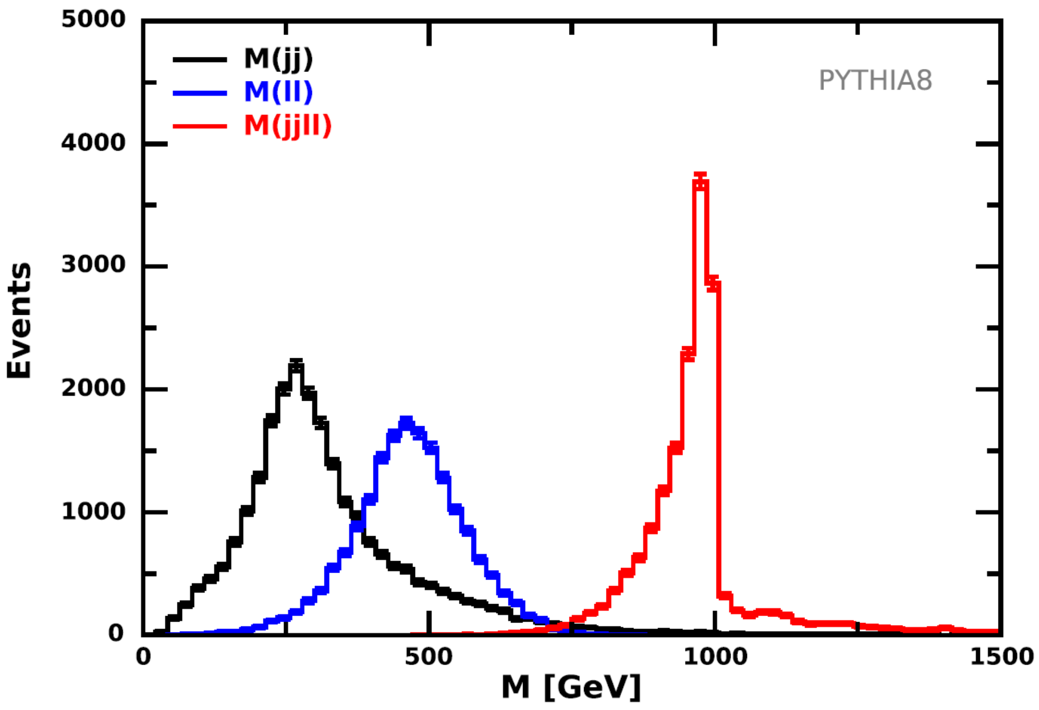
- Process $W' \rightarrow Z' + W^*$, where W', Z' and W^* hypothetical boson.
- Z' decays to two jets, while W^* decays to $l + \upsilon$
- Masses are set:
  - $M_{W'}$ = 1 TeV (Γ = 10 GeV)
  - $M_{Z'}$ = 500 GeV (Γ = 250 GeV)
  - M_{W^*} = 300 GeV (Γ = 250 GeV)
- Width of Z' and W^* in this setup are large ($\frac{\Gamma}{m} \geq 0.5$)



Width of m_{jjl} is smaller than the width of m_{jj} despite the presence of the neutrino

Four body invariant masses

- Process $W' \rightarrow Z' + W^*$, where W', Z' and W^* hypothetical boson.
- Z' decays to two leptons, while W^* to two jets
- Masses are set:
  - $M_{W'}$ = 1 TeV (Γ = 10 GeV)
  - $M_{Z'}$ = 500 GeV (Γ = 250 GeV)
  - M_{W^*} = 300 GeV (Γ = 150 GeV)
- Width of Z' and W^* are broad, and a detection of such particles in 2-body decays is difficult



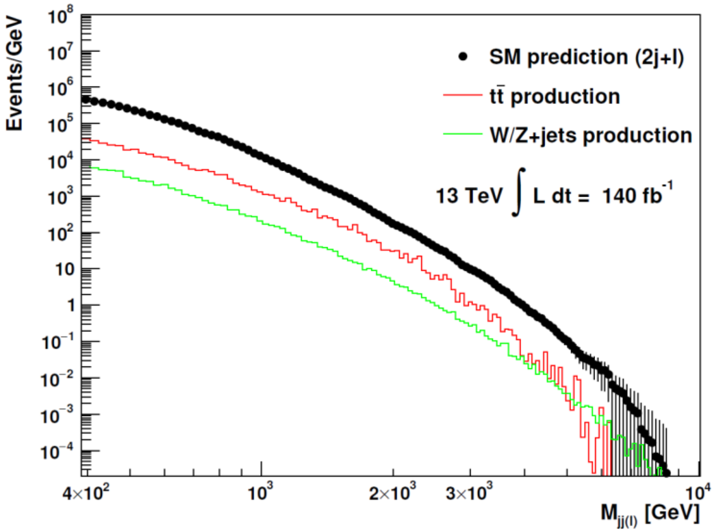
Relative width of m_{jjll} is smaller than the widths of 2-body decays of Z' and W^*.

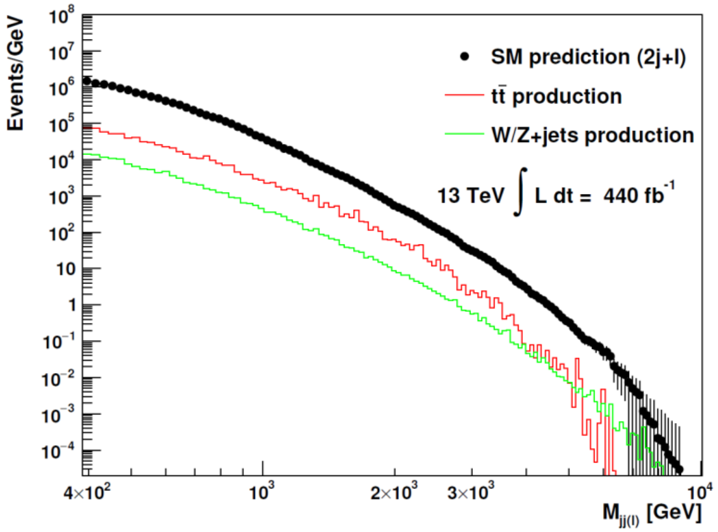
Limit setting

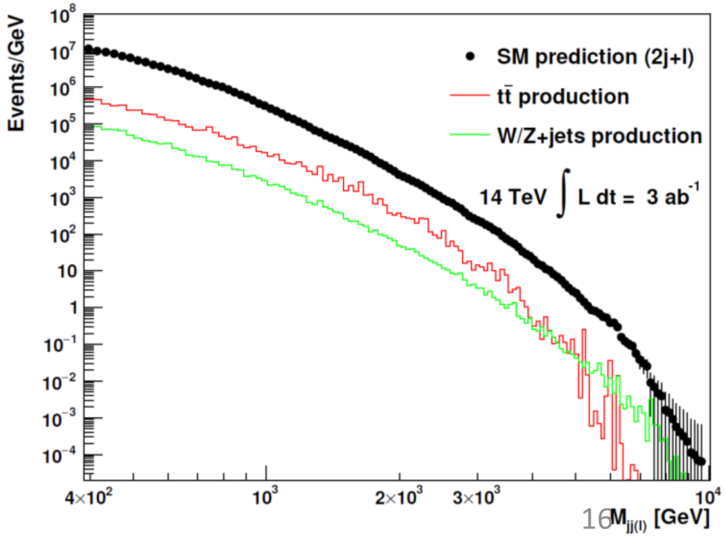
- **For background :** Processes of QCD dijets, W and Z boson process and tt events were simulated with $p_T^l > 60$ GeV, $p_T^{jet} > 30$ GeV conditions.
- m_{jjl} distributions were reconstructed for:
- 140 fb^{-1} of LHC Run 2,
- 440 fb^{-1} for LHC Run 2 and Run 3
- 3 ab^{-1} for HL-LHC.

The distributions show a smoothly falling shapes.

The simulations are performed using Madgraph5 with the PYTHIA 8 shower

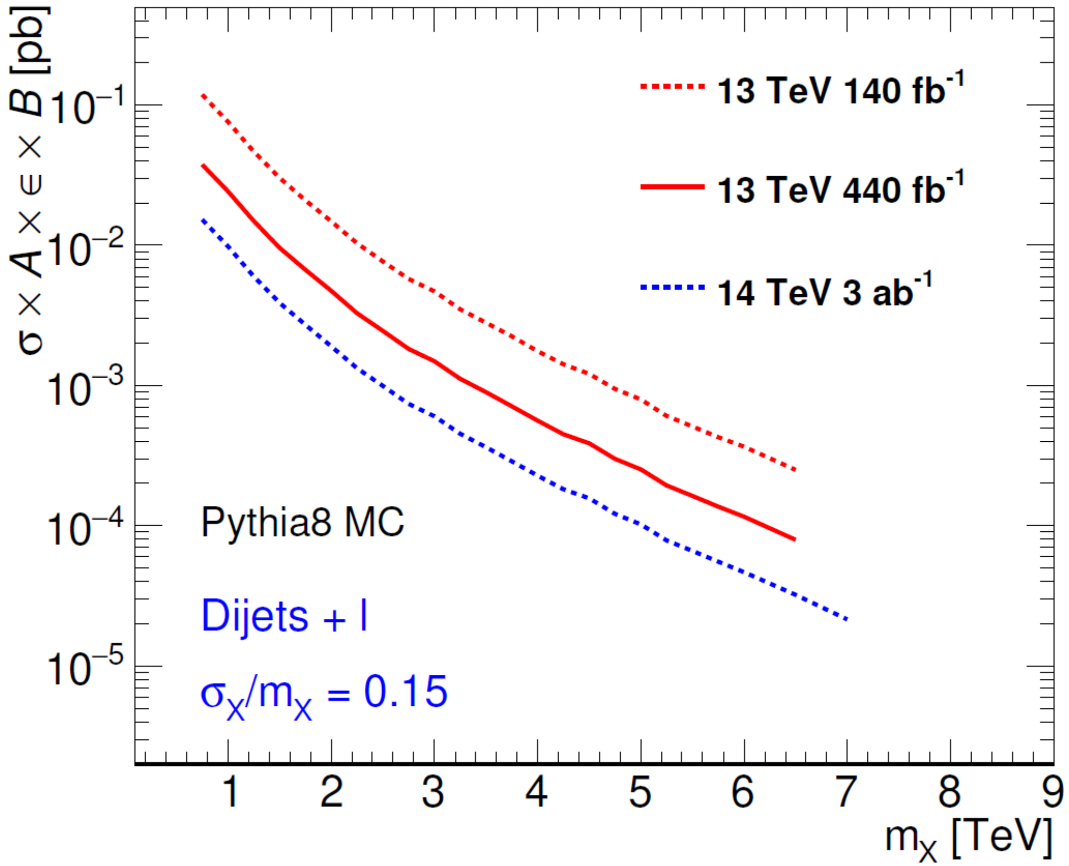






Exclusion limits

- ➢ Expected 95% confidence-level (C.L.) upper limit for a generic Gaussian signal with the width being 15% of the Gaussian peak position, while decaying to two jets and a lepton.
- ➢ Limits are calculated using the frequentist approach with the asymptotic approximation.



Limits can be used to estimate the sensitivity of the LHC data to any phenomenological models predicting Gaussian signals in the m_{jjl} distributions arXiv:2103.10217

Summary

- Model-independent searches for BSM physics in multi-body final states have been performed with some specific cases.
- Cascade decays of the type A → BC → jjl(l), where A is a heavy BSM particle, while either B or C is another heavy particle decaying to jets with a mass smaller than A.
- $\boldsymbol{m_{jjl}}$ may lead to favourable conditions for experimental observations of signal-like structures on a smoothly falling invariant masses.
- The set 95% credibility-level upper limits for new processes that can produce a Gaussian contribution to distribution can be helpful for further studies.

Multi-body invariant masses that include lepton have the potential to bring unexpected discoveries

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Thank you