Broader Use of Simplified Limits on Resonances at the LHC

Elizabeth H. Simmons
Michigan State University
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with R.S. Chivukula, P. Ittisamai, and K.A. Mohan

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and arXiv:1707.01080
The Usual Suspects: Dijet Resonances

How to represent a broader class of models?
s-channel Resonance

If you can see it, can you tell what it is?
### Simplified s-channel Model

- **Resonance** characteristics:
  - Couplings
  - Mass, width
  - Spin

- **Corresponding observables**:
  - BR, $\sigma \ast BR$
  - $d\sigma/dm_{ab}$
  - $d\sigma/d\cos\theta_{ab}$
  - Flavor tagging; jet substructure
  - Event properties

**NB:** If $x,y$ can be light quarks, t-channel process may be relevant.
Narrow Width Approximation

\[
\sigma_R(pp \rightarrow x + y) = \int_{s_{min}}^{s_{max}} d\hat{s} \hat{\sigma}(\hat{s}) \cdot \left[ \frac{dL^{ij}_{\hat{s}}}{d\hat{s}} \right]
\]

\[
\hat{\sigma}_{ij \rightarrow \hat{R} \rightarrow xy}(\hat{s}) = 16\pi(1 + \delta_{ij}) \cdot \mathcal{N} \cdot \frac{\Gamma(R \rightarrow i + j) \cdot \Gamma(R \rightarrow x + y)}{(\hat{s} - m_R^2)^2 + m_R^2 \Gamma_R^2}.
\]

\[
\frac{1}{(\hat{s} - m_R^2)^2 + m_R^2 \Gamma_R^2} \approx \frac{\pi}{m_R \Gamma_R} \delta(\hat{s} - m_R^2)
\]

\[
\sigma_R(pp \rightarrow x + y) = 16\pi^2 \cdot \mathcal{N} \cdot \frac{\Gamma_R}{m_R} \cdot (1 + \delta_{ij}) BR(R \rightarrow ij) \cdot BR(R \rightarrow xy) \left[ \frac{1}{s} \frac{dL^{ij}}{d\tau} \right]_{\tau = \frac{m_R^2}{s}}
\]

(Note: Can be corrected for K-factor(s) & Acceptance)
Branching Ratios

\[ \sigma_R(\text{pp} \to x + y) = 16\pi^2 \cdot \mathcal{N} \cdot \frac{\Gamma_R}{m_R} \cdot (1 + \delta_{ij}) \cdot \text{BR}(R \to ij) \cdot \text{BR}(R \to xy) \cdot \left[ \frac{1}{s} \frac{dL_{ij}}{d\tau} \right]_{\tau = \frac{m_R^2}{s}} \]

Simplest case: one relevant incoming / outgoing state

\[ \text{BR}(R \to i + j)(1 + \delta_{ij}) \cdot \text{BR}(R \to x + y) = \frac{\sigma_{xy}^R}{16\pi^2 \mathcal{N} \frac{\Gamma_R}{m_R} \left[ \frac{1}{s} \frac{dL_{ij}}{d\tau} \right]_{\tau = \frac{m_R^2}{s}}} \]

\[ \leq 1/4 \quad (ij \to R \to xy) \]
\[ \leq 1 \quad (ij \to R \to ij) \]
\[ \leq 1/2 \quad (ii \to R \to xy) \]
\[ \leq 2 \quad (ii \to R \to ii) \]

Upper bound on product of BR shows which classes of models are viable.
Better Variable: $\zeta$

$$\sigma_R(pp \to x + y) = 16\pi^2 \cdot \mathcal{N} \cdot \frac{\Gamma_R}{m_R} \cdot (1 + \delta_{ij}) BR(R \to ij) \cdot BR(R \to xy) \left[ \frac{1}{s} \frac{dL^{ij}}{d\tau} \right]_{\tau = \frac{m_R^2}{s}}$$

**Simplest case: one relevant incoming / outgoing state**

$$\zeta \equiv (1 + \delta_{ij}) BR(R \to i + j) \cdot BR(R \to x + y) \cdot \frac{\Gamma_R}{m_R}$$

$$= \frac{\sigma^{XY}}{16\pi^2 \cdot \mathcal{N}} \times \left[ \left[ \frac{1}{s} \frac{dL^{ij}}{d\tau} \right]_{\tau = \frac{m_R^2}{s}} \right]$$

- Collapses different widths onto a single curve
- For upper bound, use $\Gamma/M \sim 0.1$
In this paper we have summarized the experimental situation of the alleged diboson excess around 1-100 fb seen by the LHC. We have provided a thorough analysis of the data and interpretations that necessarily imply the existence of new resonance(s) and an extension beyond the standard model.

### Spin-1 triplets ($V^+, V^0$)

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### Spin-1 $V^0$

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### Spin-1 $V^±$

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**Unconventional**

- Torsion-free Einstein-Cartan theory
- Tri-boson interpretation: $pp \rightarrow RV \rightarrow VV'X$
- Implications in other observables (direct and indirect)

[95, 97, 142, 145-148]

[Next to leading order predictions]

[148]

[Analysis techniques]

[102, 106, 139, 150]

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**Les Houches Pre-Proceeding 2015**

The Diboson Excess: Experimental Situation and Classification of Experiments

arXiv:1512.04537
DiBoson Vector Resonances

**ATLAS** 95% c.l. upper bounds from 20.3 fb$^{-1}$ at 8 TeV

*JHEP* 12, 055 (2015)

In shaded region, $\zeta$ has physically allowed value

Extended Gauge Model would not explain excess
Multiple Production and Decay Modes

\[
\zeta \equiv \sum_{i' j'} (1 + \delta_{i' j'}) \text{BR}(R \to i' + j') \left[ \sum_{x y \in XY} \text{BR}(R \to x + y) \right] \cdot \frac{\Gamma_R}{m_R}
\]

\[
= \frac{\sigma_{XY}^R}{16\pi^2 \cdot N} \times \sum_{i, j} \omega_{i, j} \left[ \frac{1}{s} \frac{dL_{ij}}{d\tau} \right]_{\tau=\frac{m_R^2}{s}}
\]

weighting factor

\[
\omega_{i, j} = \frac{(1 + \delta_{i j}) \text{BR}(R \to i + j)}{\sum_{i' j'} (1 + \delta_{i' j'}) \text{BR}(R \to i' + j')}
\]
Vector Resonance in Dilepton Channel

**ATLAS** 95% c.l. upper bounds from 3.2 fb$^{-1}$ at 13 TeV

**ATLAS-CONF-2015-070**

**Band** indicates range between Resonances (R) coupling only to up-type quarks vs. only to down-type quarks

Sequential SM Z' is excluded below ~3.5 TeV
Leptophobic Vector Resonance in Dijets

**ATLAS** 95% c.l. upper bounds from 3.6 fb\(^{-1}\) at 13 TeV  

**ATLAS** 95% c.l. upper bounds from 3.2 fb\(^{-1}\) at 13 TeV  

band indicates range between Resonances (R) coupling only to up-type vs. only to down-type quarks

data doesn't constrain high-mass region
Simplified Limits
on s-channel resonances, framed as bounds on

\[ \zeta = BR_i \cdot BR_f \cdot \frac{\Gamma}{M} \]

highlight relevant production channels for a newly observed narrow resonance.
Limits on finite-width resonances

ATLAS

\[ \sigma \times A \times \text{BR} \] [pb]

Expected ± 1 σ and ± 2 σ

Obs. 95% CL upper limit for:

- \( \sigma_G/m_G = 0.15 \)
- \( \sigma_G/m_G = 0.10 \)
- \( \sigma_G/m_G = 0.07 \)
- \( \sigma_G/m_G = 0.03 \)
- \( \sigma_G/m_G = 0 \)

\(|y^*| < 0.6\)

\( \sqrt{s} = 13 \) TeV, 37.0 fb\(^{-1} \)
Breit-Wigner Approximation

\[
\sigma_R(pp \rightarrow x + y) = \int_{s_{\text{min}}}^{s_{\text{max}}} d\hat{s} \, \hat{\sigma}(\hat{s}) \cdot \left[ \frac{dL_{ij}}{d\hat{s}} \right]
\]

\[
\hat{\sigma}(\hat{s})_{ij \rightarrow R \rightarrow xy} \equiv \frac{\Gamma_R^2}{m_R^2 \cdot m_R^4} \cdot \frac{\hat{s}}{m_R^4} \cdot 16\pi N (1 + \delta_{ij}) \cdot BR(R \rightarrow i + j) \cdot BR(R \rightarrow x + y) \cdot \left( \frac{\hat{s}}{m_R^2} - 1 \right)^2 + \frac{\Gamma_R^2}{m_R^2}
\]

(includes main impact of s-dependent widths)
Color-octet scalar in dijets

\[ \zeta \equiv (1 + \delta_{ij}) \text{BR}(R \to i + j) \cdot \text{BR}(R \to x + y) \cdot \frac{\Gamma_R}{m_R} \]

\[ = \frac{\sigma_{R}^{XY}}{16\pi^2 \cdot \mathcal{N} \times \left[ \frac{1}{s} \frac{dL_{ij}^{ij}}{d\tau} \right]_{\tau = \frac{m_{sR}^2}{s}}} \]

Breit-Wigner \( \Gamma/M = 0.3 \)

red curves are CMS 95% c.l. upper bounds from 19.7 fb\(^{-1}\) at 8 TeV

Vector resonance in dileptons

Breit-Wigner \( \Gamma / M = 0.03 \)

Breit-Wigner \( \Gamma / M = 0.3 \)

ATLAS 95\% c.l. upper bounds from 13.3 fb\(^{-1}\) at 13 TeV

ATLAS-CONF-2016-045
Simplified Limits readily extend to finite-width resonances.

The corresponding bound from the narrow-width approximation is generally a conservative estimate of the strength of the limit.
Benefits of Simplified Limits approach

• focus on model classes ↔ production mechanisms

• easily identify
  • exclusion limits on BSM resonances
  • whether data constrains a given channel
  • classes of models relevant for a given excess
  • [specific theories consistent with an excess]

• \( \zeta \) derives directly from model parameters
• works for narrow or finite-width resonances

If collaborations report results in terms of \( \zeta \), as well as \( \sigma^*BR \), it will speed and deepen our understanding of new findings.
Low-energy tail of broad peaks