Simplified Limits on Resonances at the LHC

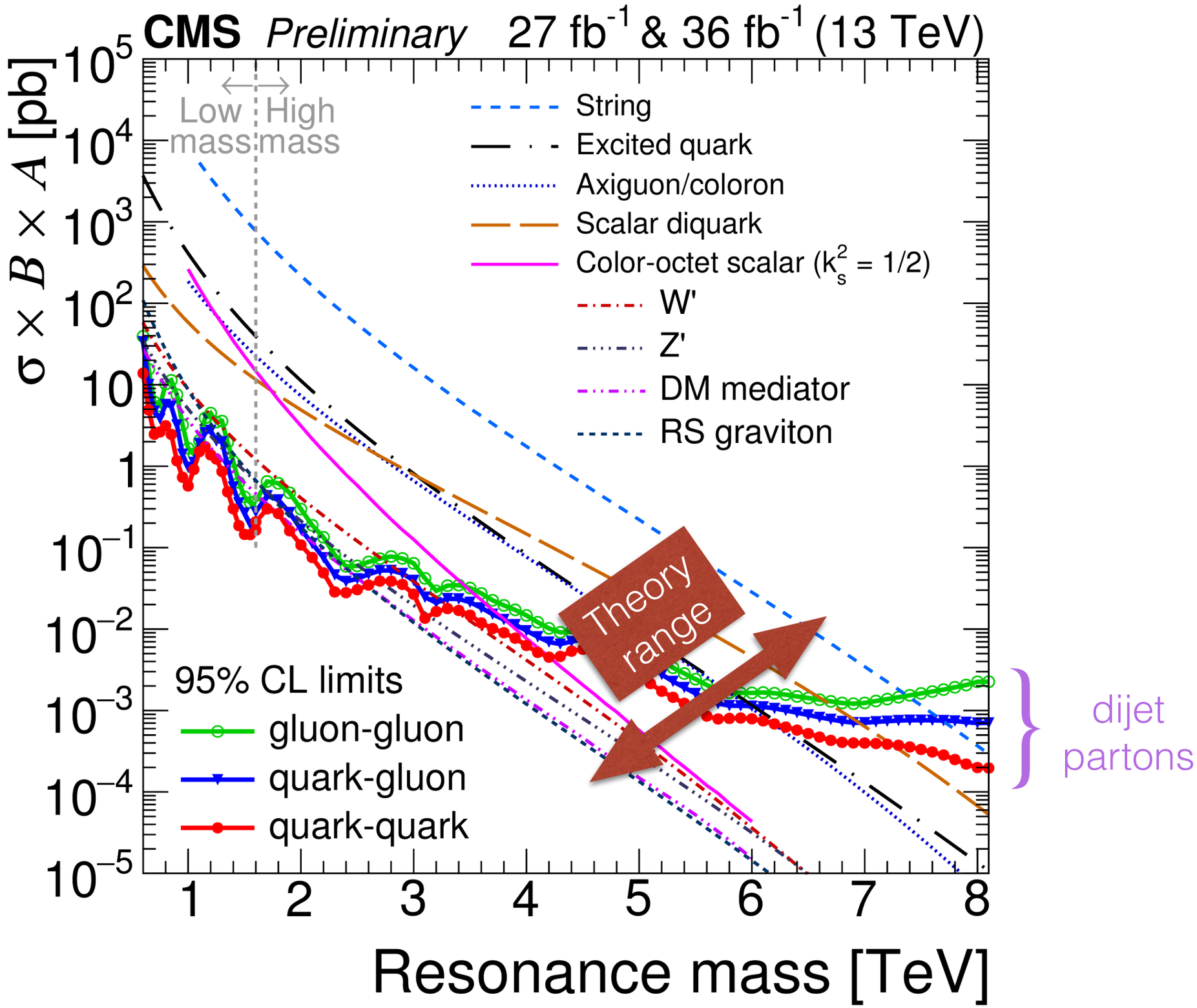
Elizabeth H. Simmons
Michigan State University
May 8, 2017

with R.S. Chivukula, P. Ittisamai, and K.A. Mohan

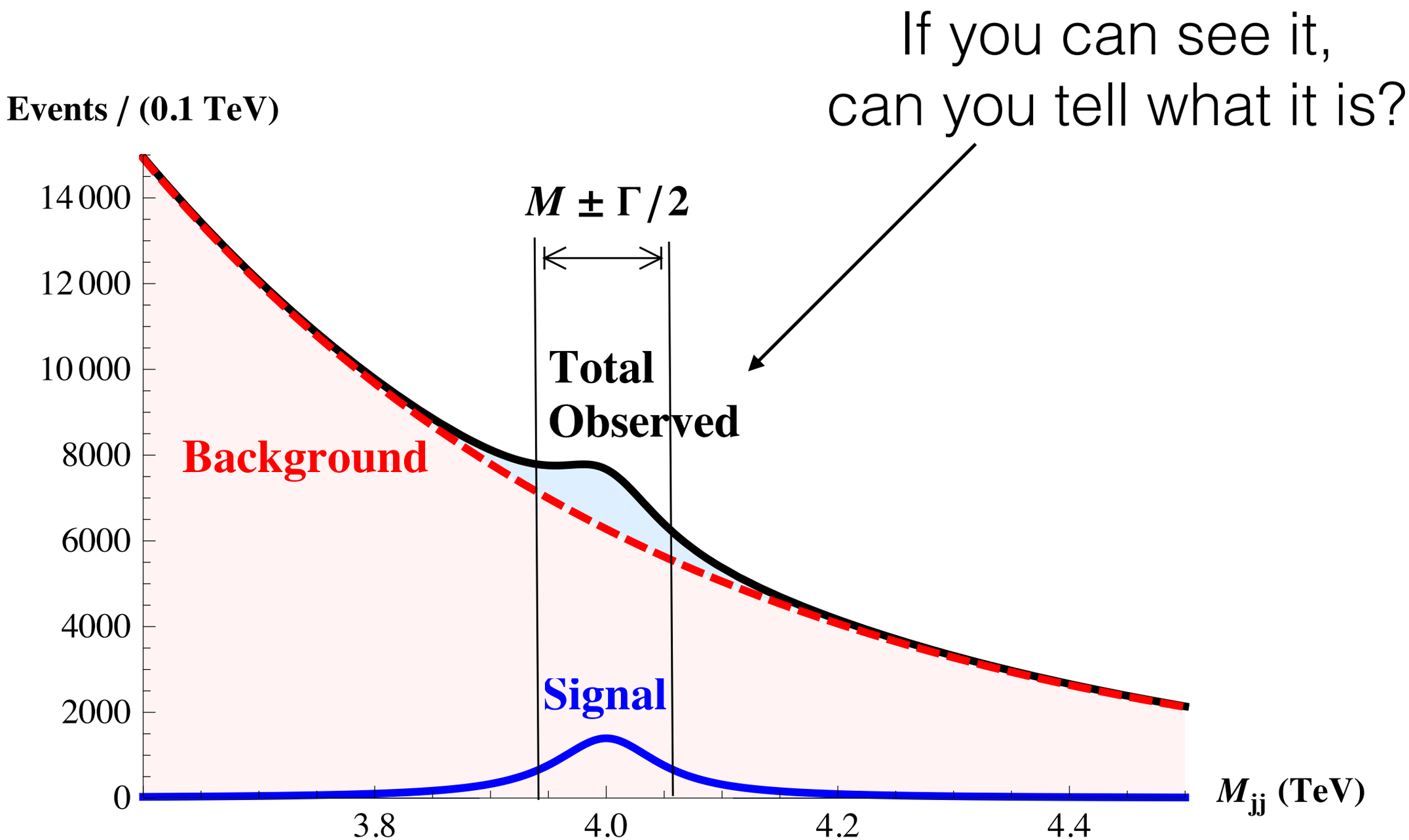
Phys. Rev. 94 (2016) 094029
and work in preparation

The Usual Suspects: Dijet Resonances

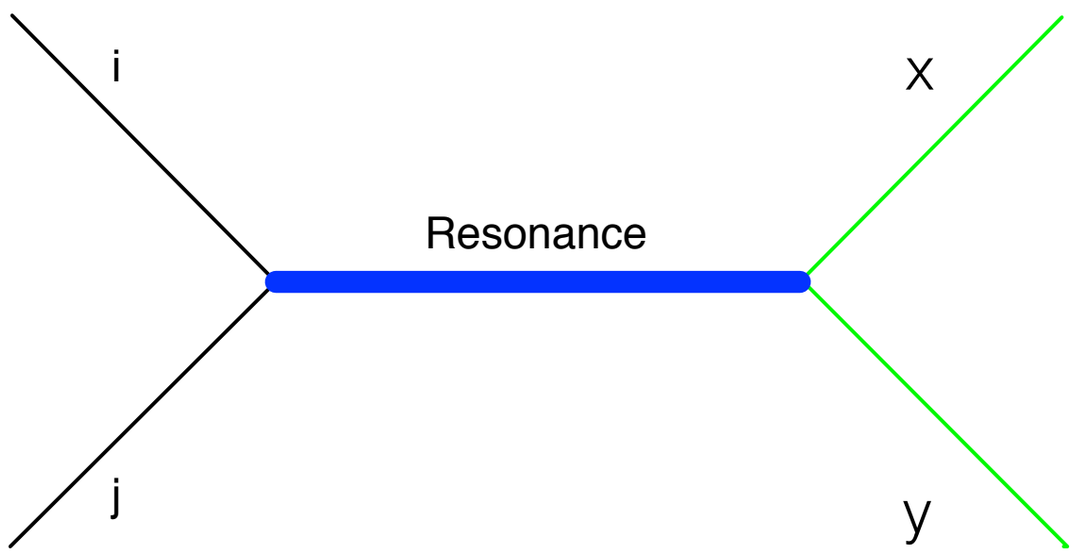
How to represent a broader class of models?



s-channel Resonance



Simplified s-channel Model



i,j = u,d,g,γ,W,Z

x,y = j,t,b,g,γ,W,Z,h

Resonance Characteristics	**Corresponding Observables**
couplings	BR, σ * BR
mass, width	$d\sigma/dm_{ab}$
spin	$d\sigma/d\cos\theta_{ab}$
x,y (each channel)	flavor tagging; jet substructure
i,j	event properties

NB: If x,y can be light quarks,
t-channel process may be relevant

Narrow Width Approximation

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

$$\hat{\sigma}_{ij\to R\to xy}(\hat{s}) = 16\pi(1+\delta_{ij}) \cdot \mathcal{N} \cdot \frac{\Gamma(R \to i+j) \cdot \Gamma(R \to x+y)}{(\hat{s} - m_R^2)^2 + m_R^2 \Gamma_R^2}\,, \quad \boxed{\mathcal{N} = \frac{N_{S_R}}{N_{S_i} N_{S_j}} \cdot \frac{C_R}{C_i C_j}}$$

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

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

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

Branching Ratios

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

Simplest case: one relevant incoming / outgoing state

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

$$\left.\begin{array}{ll} \leq 1/4 & (ij \to R \to xy) \\ \leq 1 & (ij \to R \to ij) \\ \\ \leq 1/2 & (ii \to R \to xy) \\ \leq 2 & (ii \to R \to ii) \end{array}\right\}$$

Upper bound on product of BR shows which classes of models are viable.

Better Variable: ζ

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

Simplest case: one relevant incoming / outgoing state

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

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

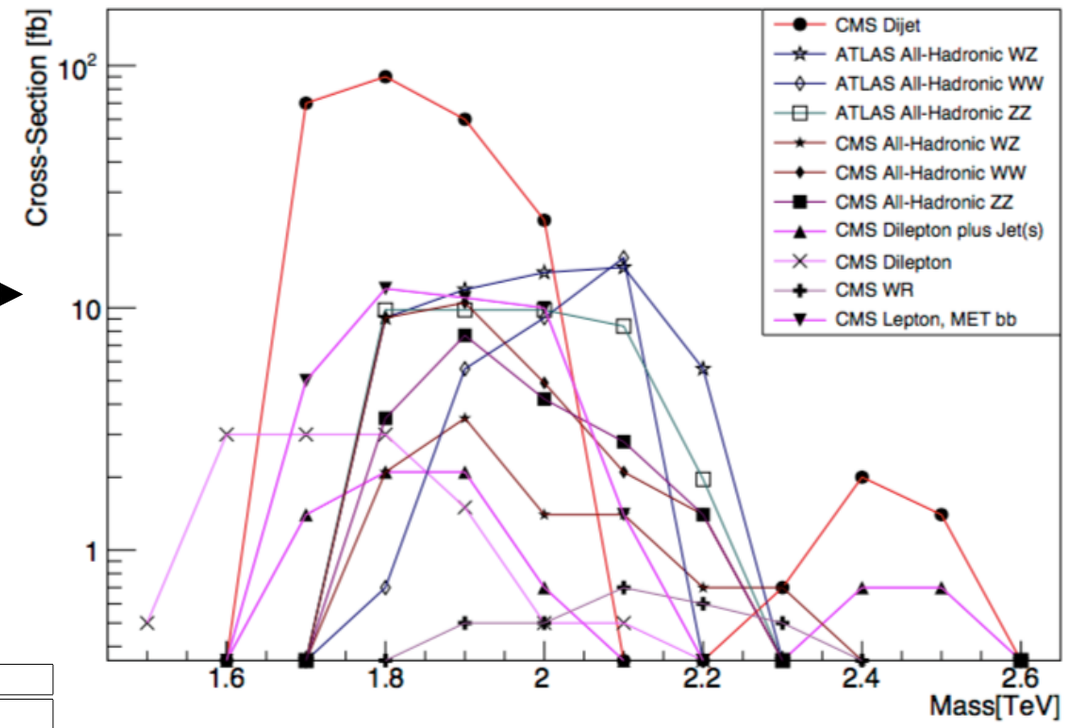
- Collapses different widths onto a single curve
- For upper bound, use $\Gamma/M \sim 0.1$

Memory Lane: DiBoson Excess

1-100 fb
"WZ" excess ?

data? →

models? ↓

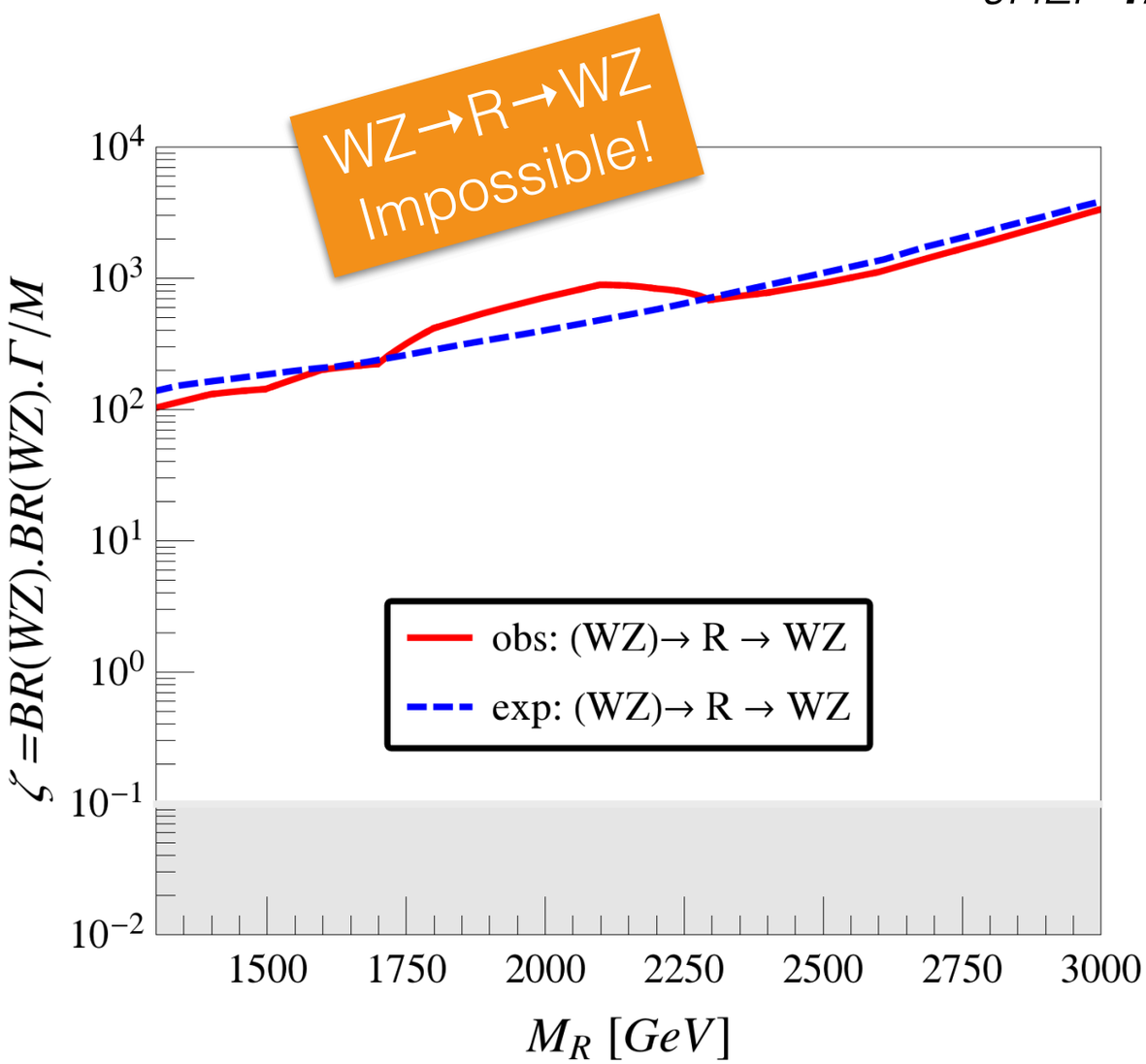


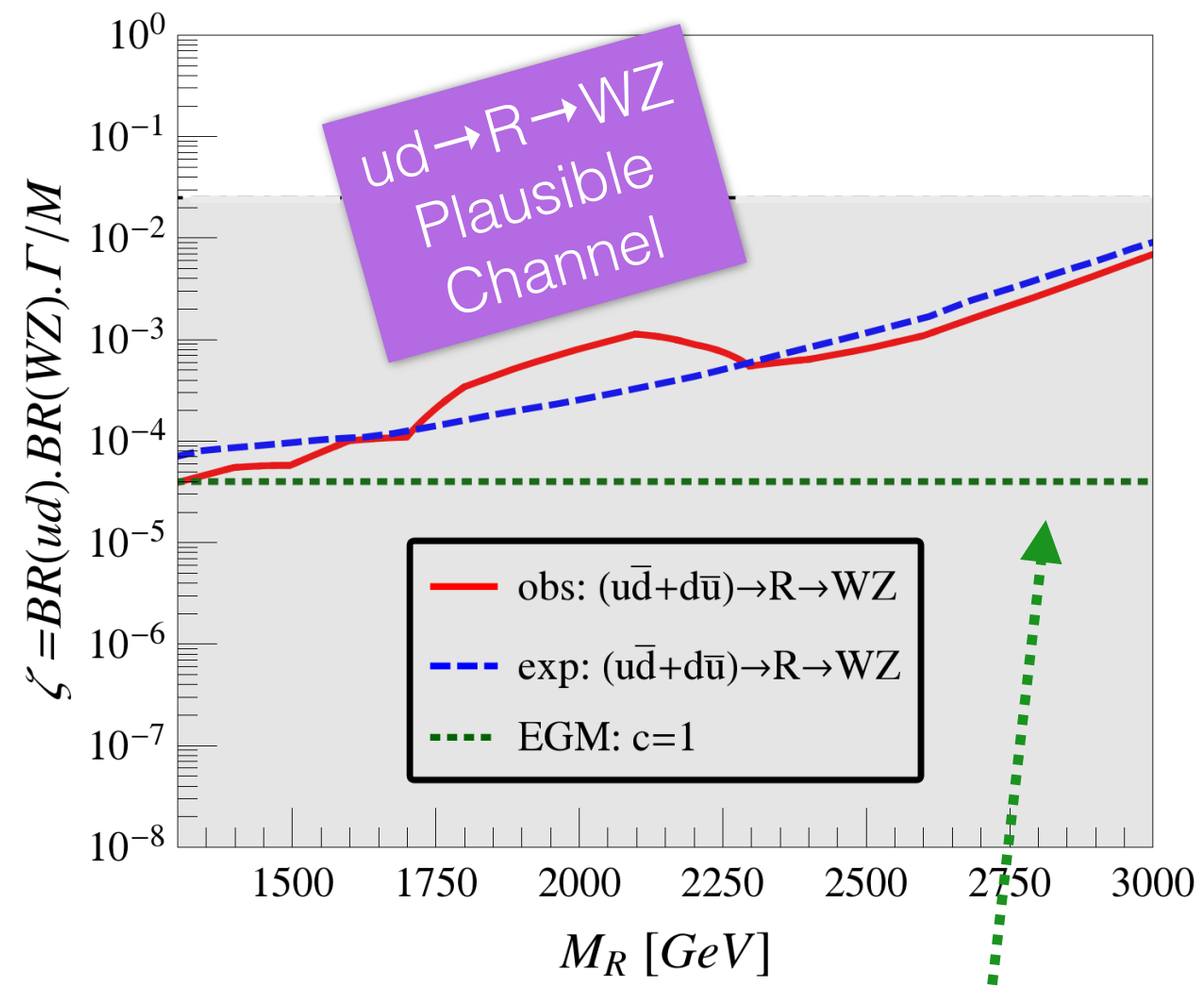
Spin-1 triplets ($V^{\pm}$, V^0)																	
Prod.	WW	ZZ	WZ	Wh	Zh	γh	$W\gamma$	$Z\gamma$	$\gamma\gamma$	gg	hh	$\overline{Q}_3Q_3$	$\bar{q}q$	ll	$\ell^{\pm}\nu$	X	Ref.
DY	✓		✓									(✓)	(✓)	(✓)	(✓)		[39, 140–142]
DY	✓		✓	✓	✓							$✓_{\bar{q}q}$	✓	(✓)	(✓)		[40, 42, 43, 111]
DY	✓		✓	✓	✓							(✓)	(✓)	(✓)	(✓)		[44]
DY	✓		✓	✓	✓							$✓_{\bar{q}q}$	✓	(✓)	(✓)	(✓)	[112]
DY	✓		✓	$✓_{WZ}$	$✓_{WW}$							$✓_{\bar{q}q}$	✓	(✓)	(✓)		[45, 46, 85, 91]
DY	✓		✓	$✓_{WZ}$	$✓_{WW}$							✓	✓	(✓)	(✓)		[41]
Spin-1 V^0																	
Prod.	WW	ZZ	WZ	Wh	Zh	γh	$W\gamma$	$Z\gamma$	$\gamma\gamma$	gg	hh	$\overline{Q}_3Q_3$	$\bar{q}q$	ll	$\ell^{\pm}\nu$	X	Ref.
DY	✓				$✓_{WW}$							$✓_{\bar{q}q}$	✓				[84]
DY	✓				$✓_{WW}$							$✓_{\bar{q}q}$	✓	✓			[117]
DY	✓	✓						✓					✓				[118]
Spin-1 $V^{\pm}$																	
Prod.	WW	ZZ	WZ	Wh	Zh	γh	$W\gamma$	$Z\gamma$	$\gamma\gamma$	gg	hh	$\overline{Q}_3Q_3$	$\bar{q}q$	ll	$\ell^{\pm}\nu$	X	Ref.
DY			✓	$✓_{WZ}$								$✓_{\bar{q}q}$	✓			✓	[86, 90, 92–94]
DY			✓	$✓_{WZ}$								$✓_{\bar{q}q}$	✓				[87, 88]
Scalar																	
Prod.	WW	ZZ	WZ	Wh	Zh	γh	$W\gamma$	$Z\gamma$	$\gamma\gamma$	gg	hh	$\overline{Q}_3Q_3$	$\bar{q}q$	ll	$\ell^{\pm}\nu$	X	Ref.
gg	✓	✓						✓	✓	✓							[75, 131, 143]
gg	✓	✓						(✓)	(✓)	✓	$✓_{WW/2}$	(✓)					[73]
gg	✓	$✓_{WW/2}$				✓			✓	✓	✓	✓				(✓)	[141]
$q\bar{q}$	✓	$✓_{WW/2}$		(✓)	(✓)						✓		✓			✓	[123–125]
'Unconventional'																	
Torsion-free Einstein-Cartan theory																	[144]
Tri-boson interpretation: $pp \to R \to VY \to VV'X$																	[136]
[Implications in other observables (direct and indirect)]																	[95, 97, 142, 145–148]
[Next to leading order predictions]																	[148]
[Analysis techniques]																	[102, 106, 149, 150]

Les Houches
Pre-Proceeding 2015
The Diboson Excess:
Experimental Situation and
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, ζ has physically allowed value

Extended Gauge Model would not explain excess

CTEQ6L1

Multiple Production and Decay Modes

Easy to evaluate for any model class or model

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

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

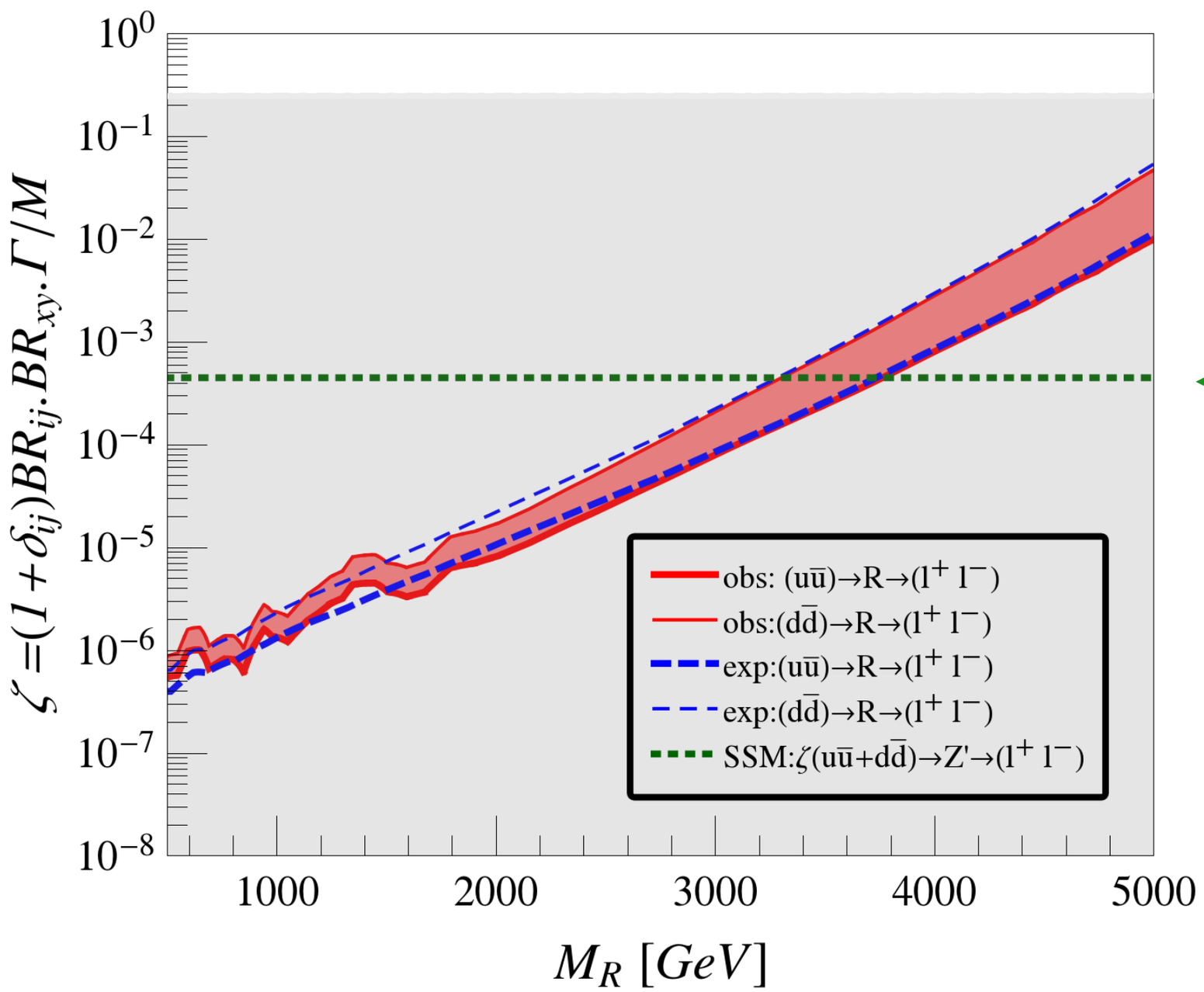
Reporting experimental limits in this format simplifies comparison with theory

weighting factor

$$\omega_{ij}\equiv\frac{(1+\delta_{ij})BR(R\to i+j)}{\sum_{i'j'}(1+\delta_{i'j'})BR(R\to i'+j')}$$

Vector Resonance in Dilepton Channel

ATLAS 95% c.l. upper bounds from 3.2 fb^{-1} at 13 TeV
ATLAS-CONF-2015-070

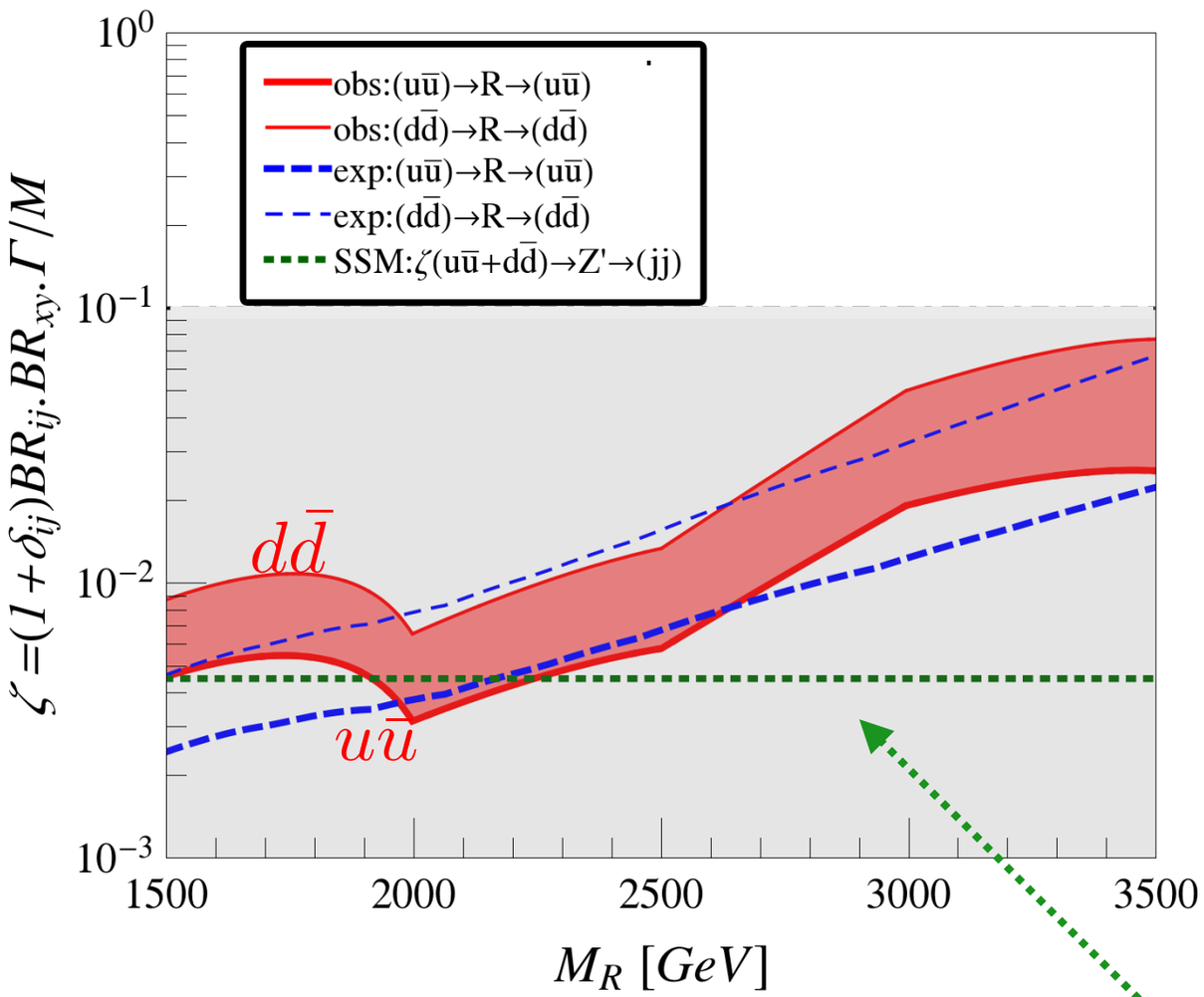


band indicates range between Resonances (R) coupling only to up-type quarks vs. only to down-type quarks

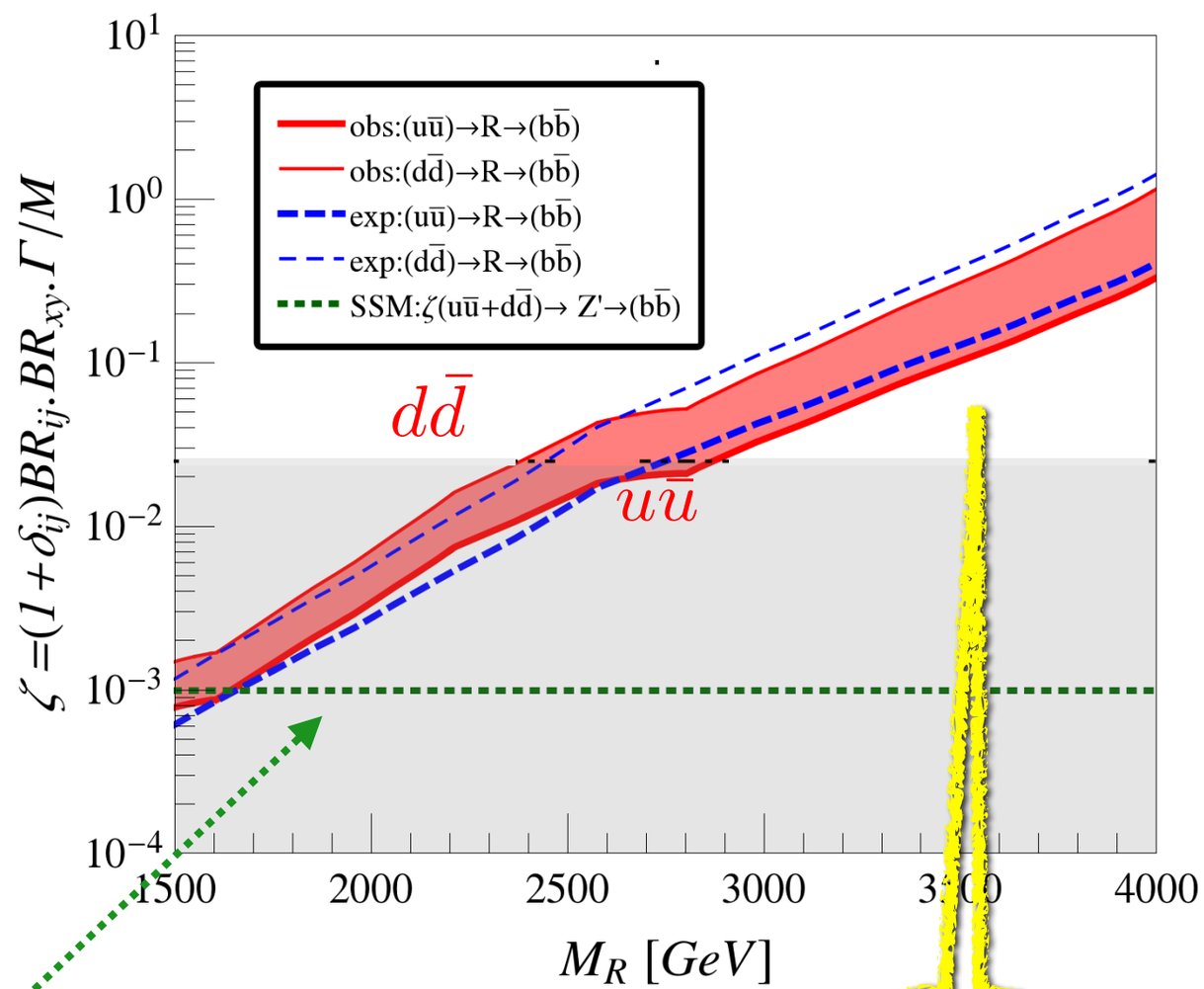
Sequential SM Z' is excluded below ~3.5 TeV

Leptophobic Vector Resonance in Dijets

ATLAS 95% c.l. upper bounds from 3.6 fb^{-1} at 13 TeV *Phys. Lett. B754, 302 (2016)*



ATLAS 95% c.l. upper bounds from 3.2 fb^{-1} at 13 TeV *Phys. Lett. B759, 229 (2016)*



Sequential SM Z'

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

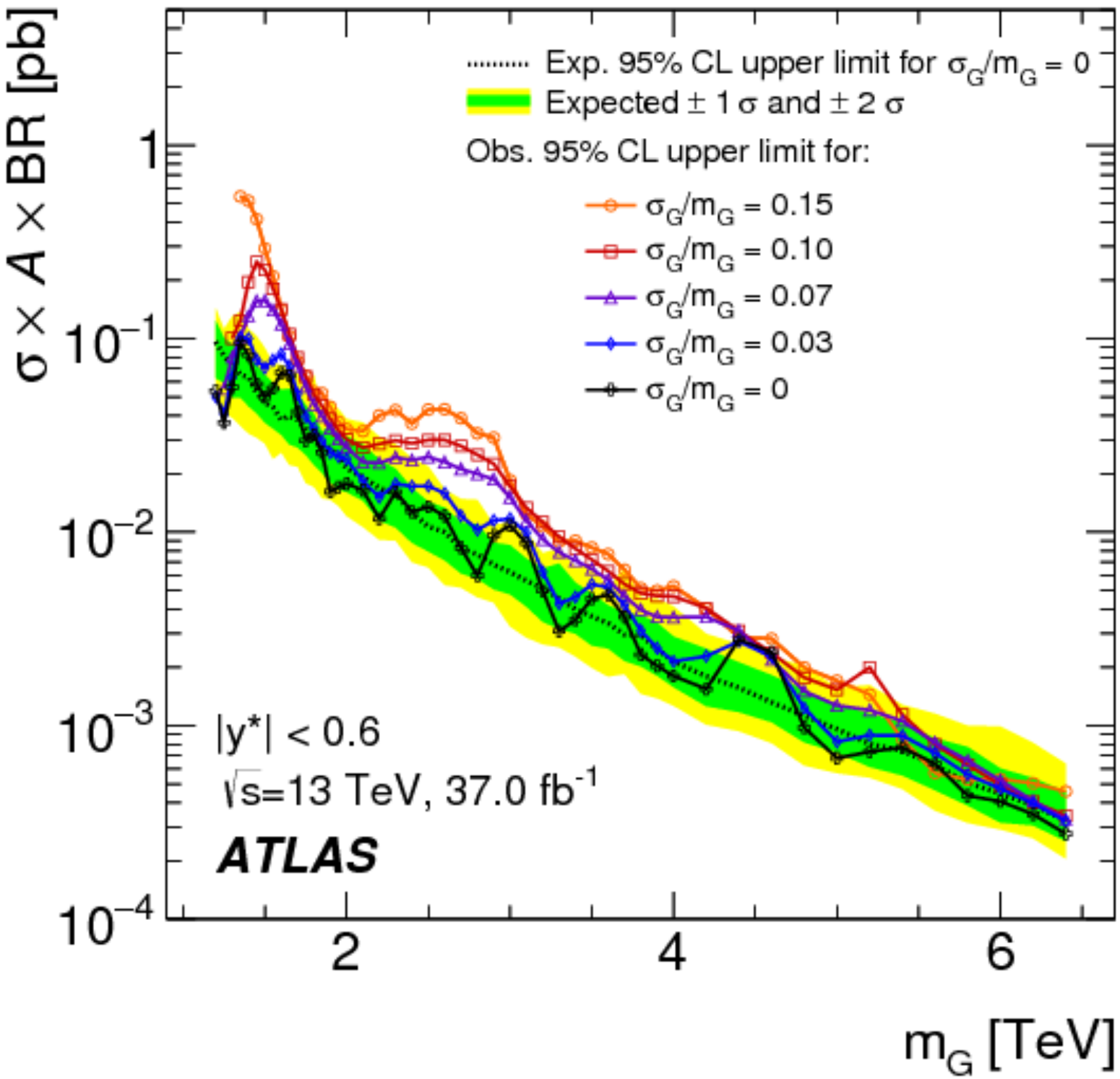
data doesn't constrain high-mass region

Simplified Limits
on s-channel resonances,
framed as bounds on

$$\zeta = BR_i \, BR_f \, \Gamma/M$$

highlight relevant production channels
for a newly observed narrow resonance.

Limits on finite-width resonances



Breit-Wigner Approximation

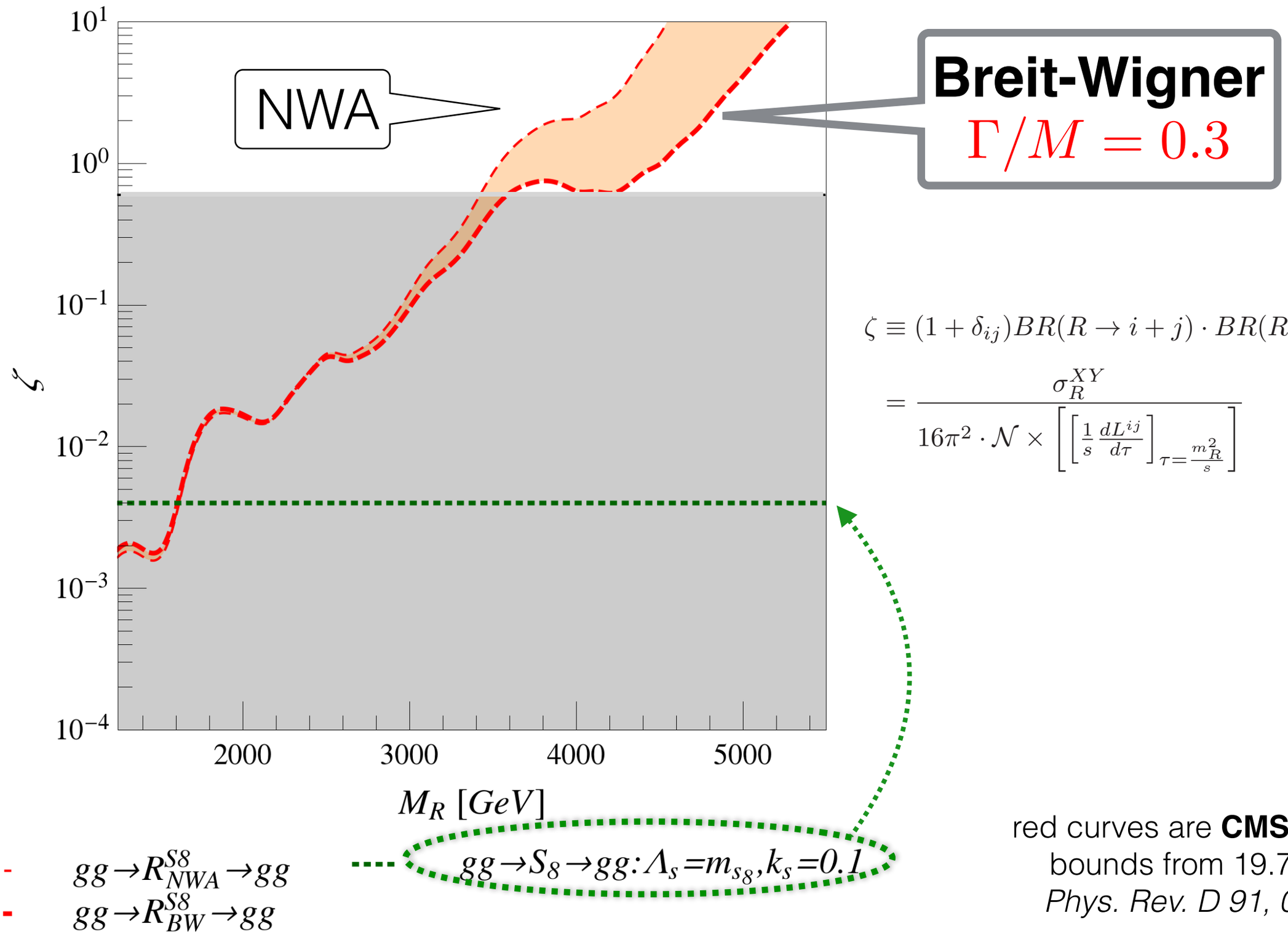
$$\sigma_R(pp \to x + y) = \int_{s_{min}}^{s_{max}} d\hat{s}\, \hat{\sigma}(\hat{s}) \cdot \left[\frac{dL^{ij}}{d\hat{s}}\right]$$

$$\mathcal{N} = \frac{N_{S_R}}{N_{S_i} N_{S_j}} \cdot \frac{C_R}{C_i C_j}$$

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

(includes main impact of s-dependent widths)

Color-octet scalar in dijets

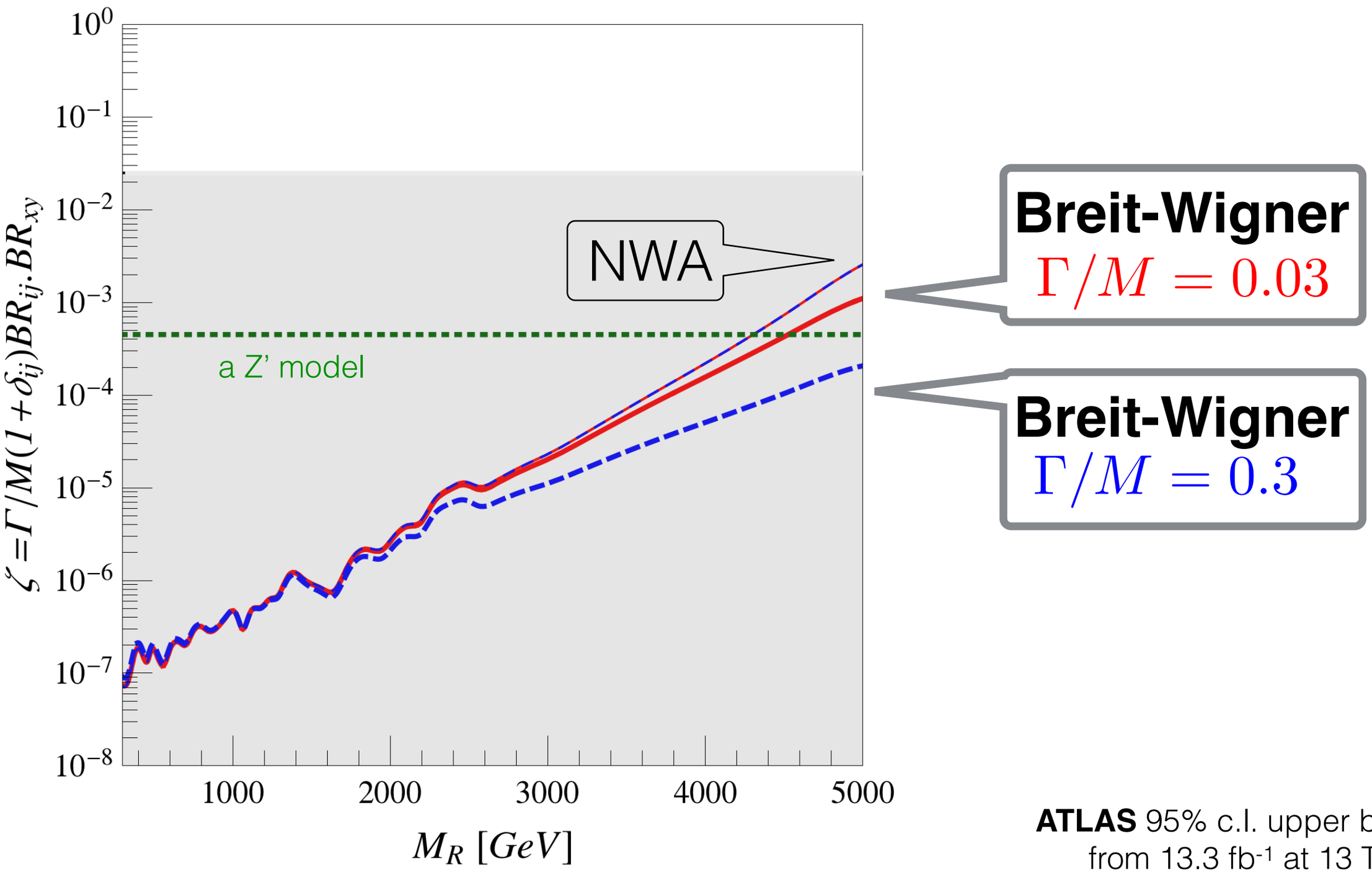


$$\zeta \equiv (1+\delta_{ij}) BR(R \to i+j) \cdot BR(R \to x+y) \cdot \frac{\Gamma_R}{m_R}$$

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

red curves are **CMS** 95% c.l. upper bounds from 19.7 fb^{-1} at 8 TeV *Phys. Rev. D 91, 052009 (2015)*

Vector resonance in dileptons



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]

- ζ derives directly from model parameters
- works for narrow or finite-width resonances

If collaborations report results in terms of ζ, as well as σ*BR, **it will speed and deepen our understanding of new findings.**

Low-energy tail of broad peaks