Simplified Limits on New States at the LHC

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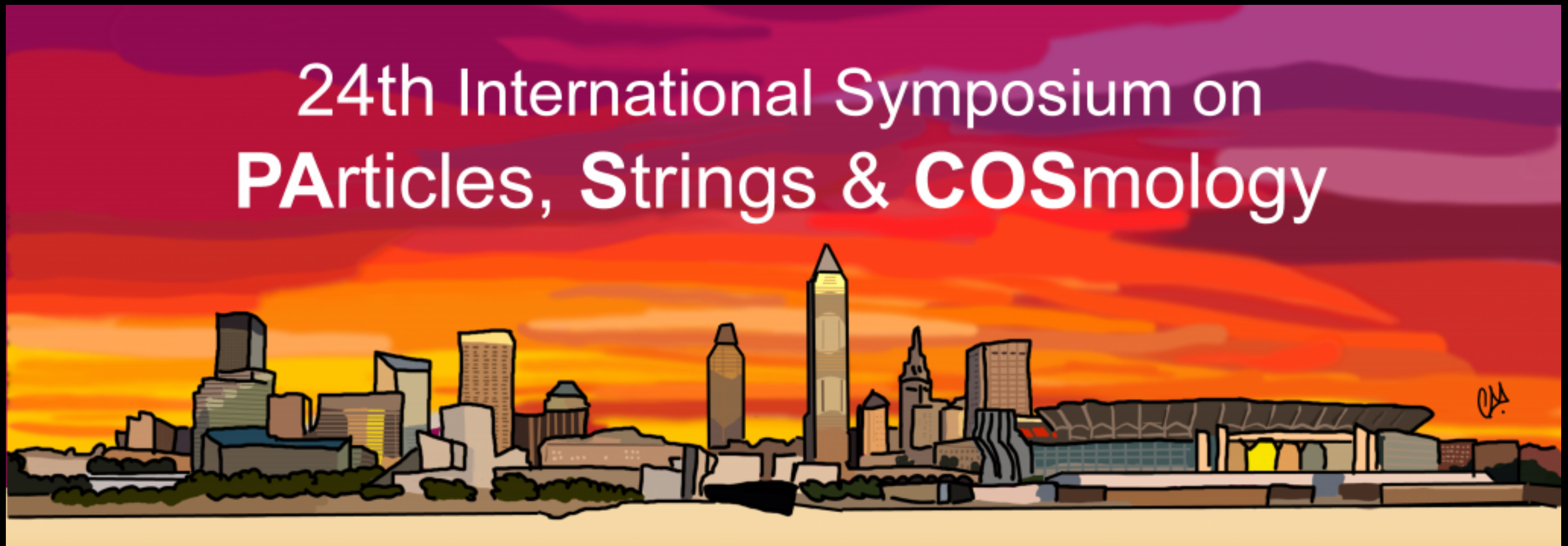
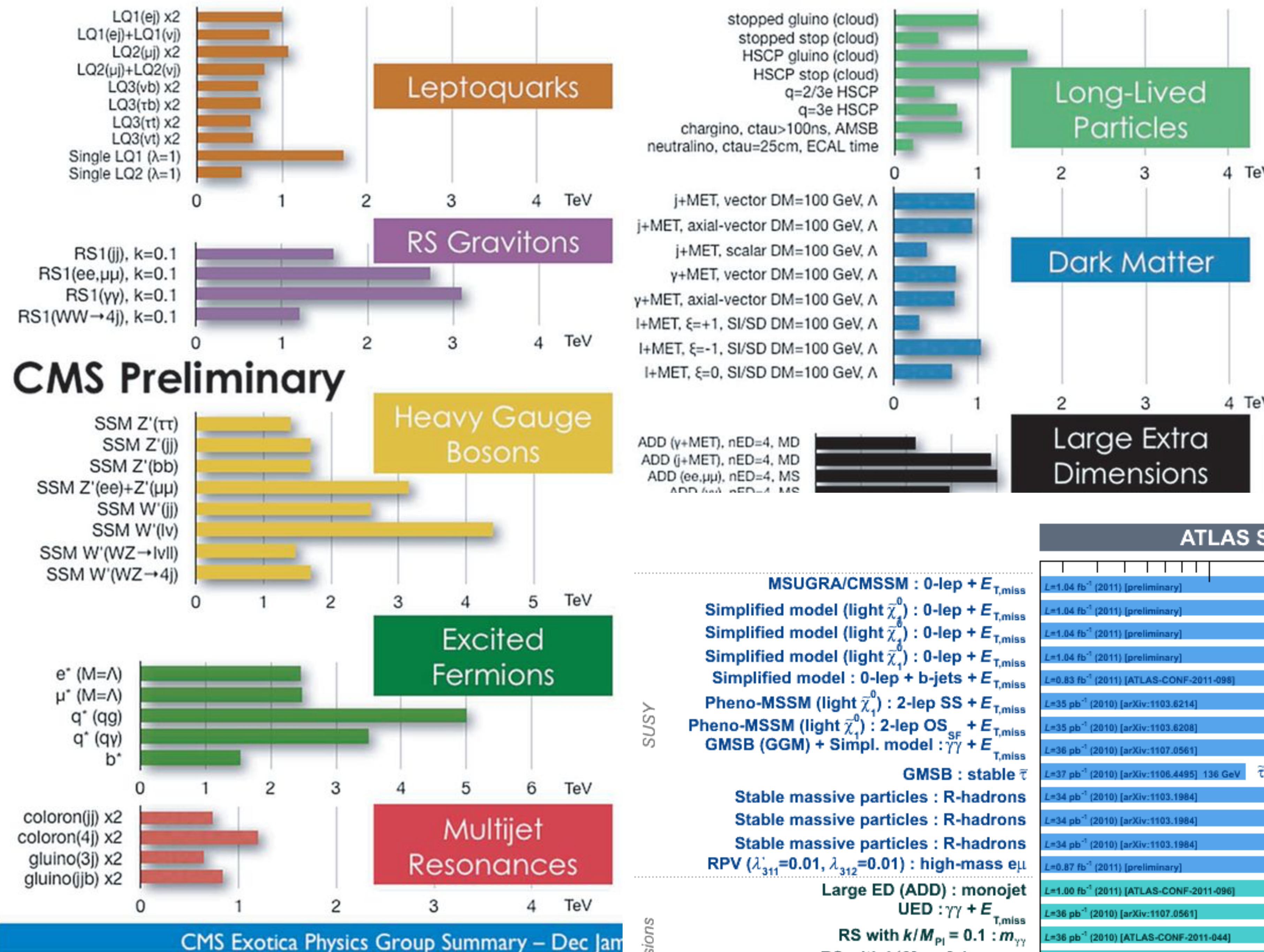
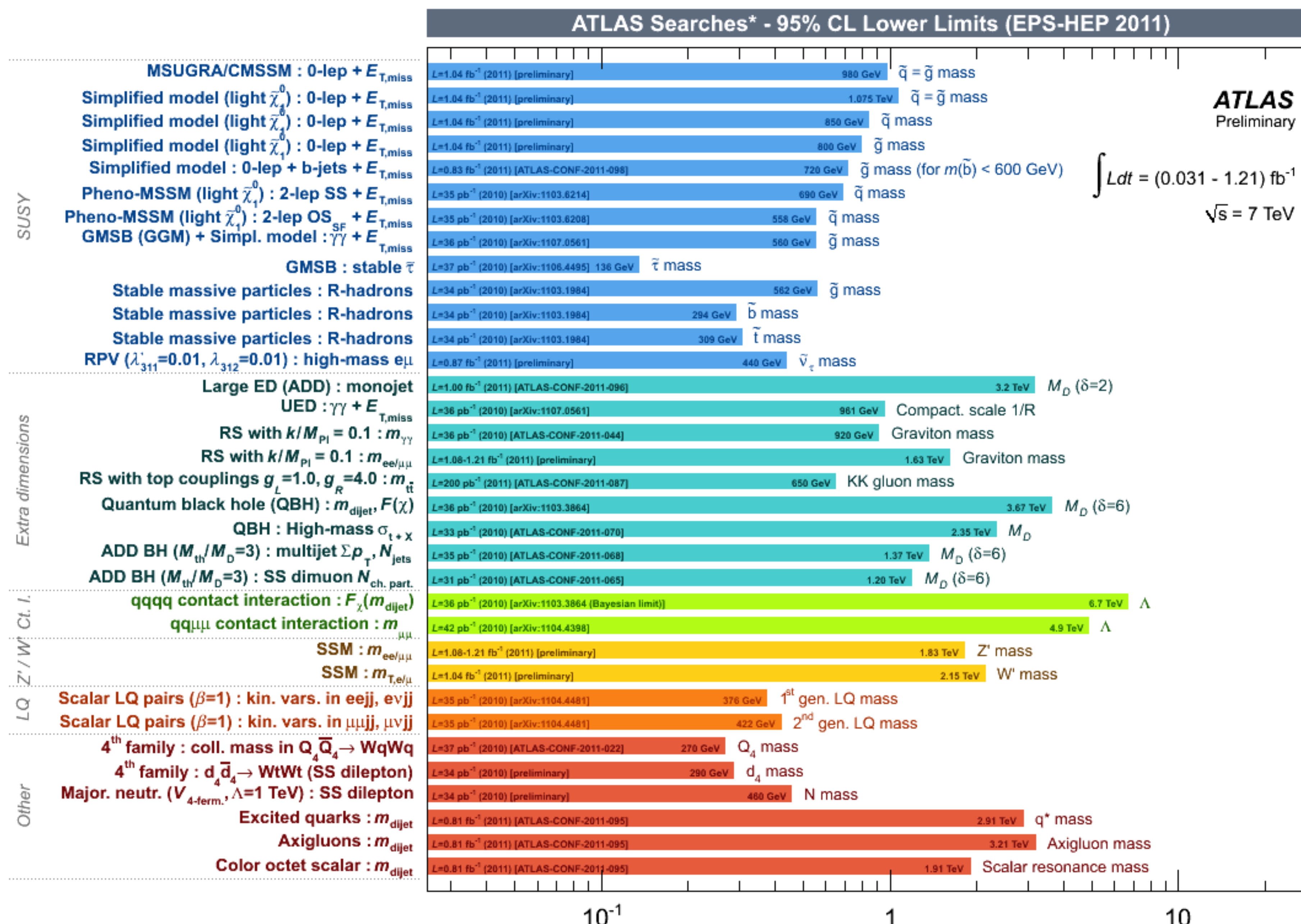


Resonances Abound in BSM Theories

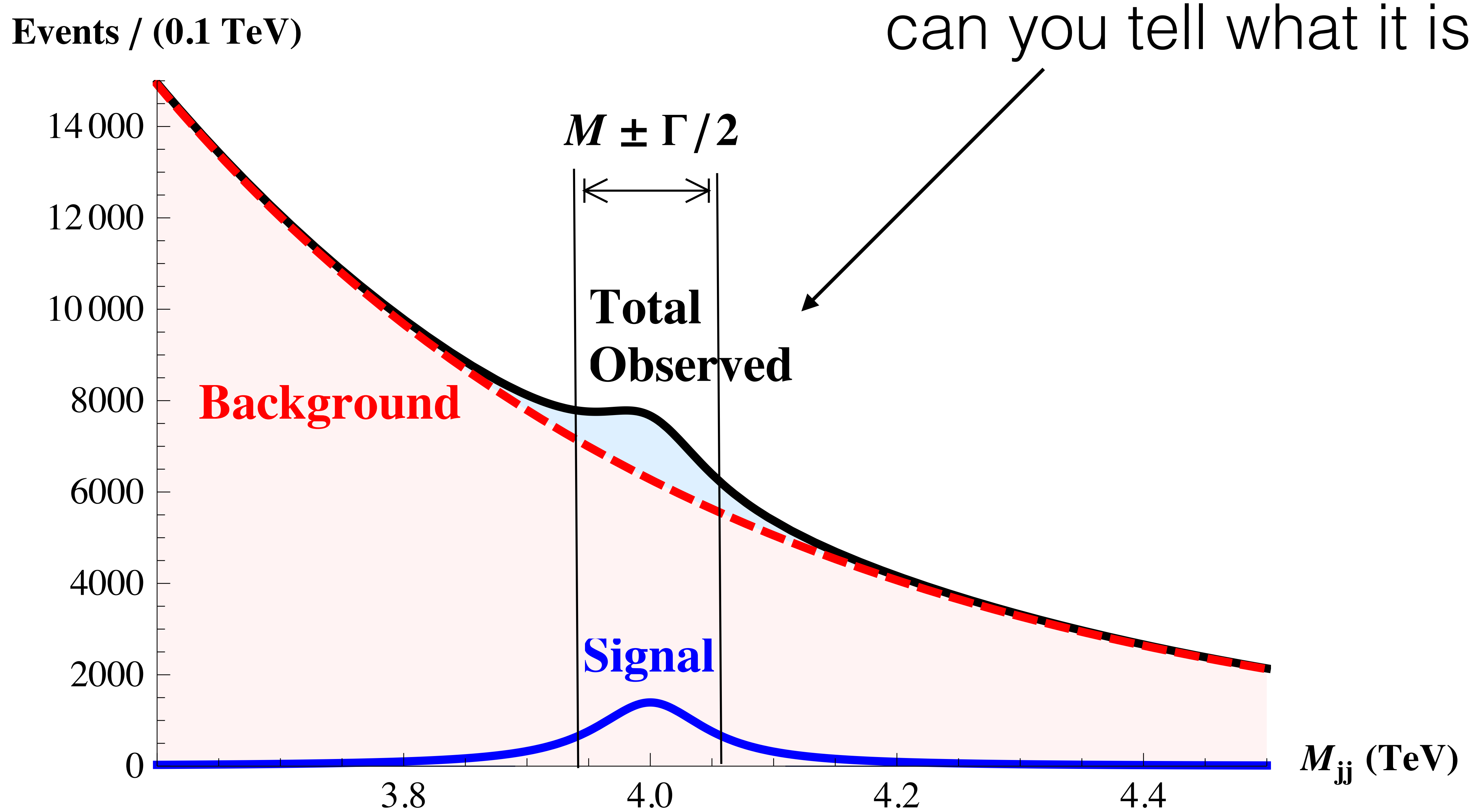




Experiments Resolutely Search for Them

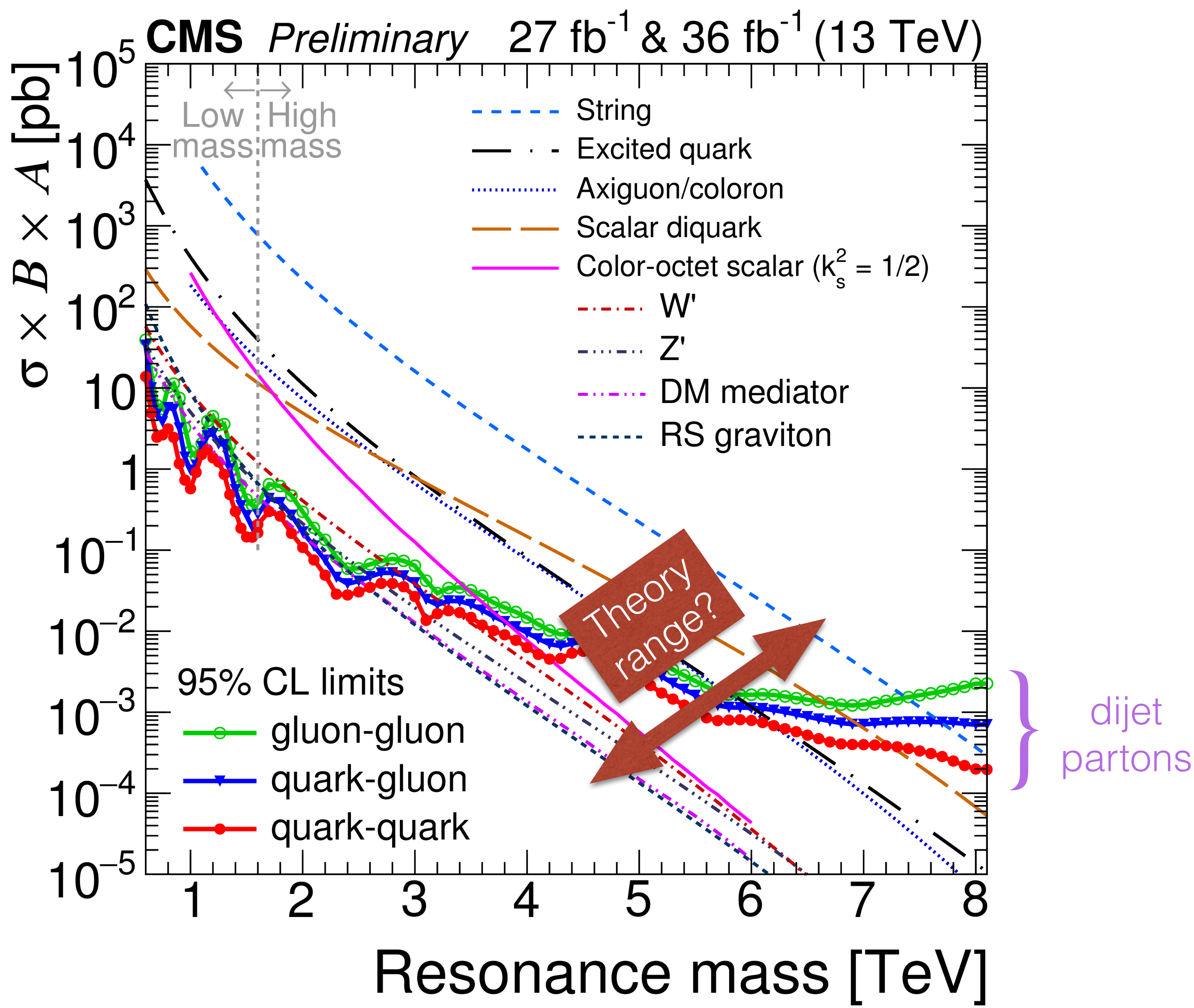
S-Channel Resonance

If you can see it,
can you tell what it is?



The Usual Suspects: Dijet Resonances

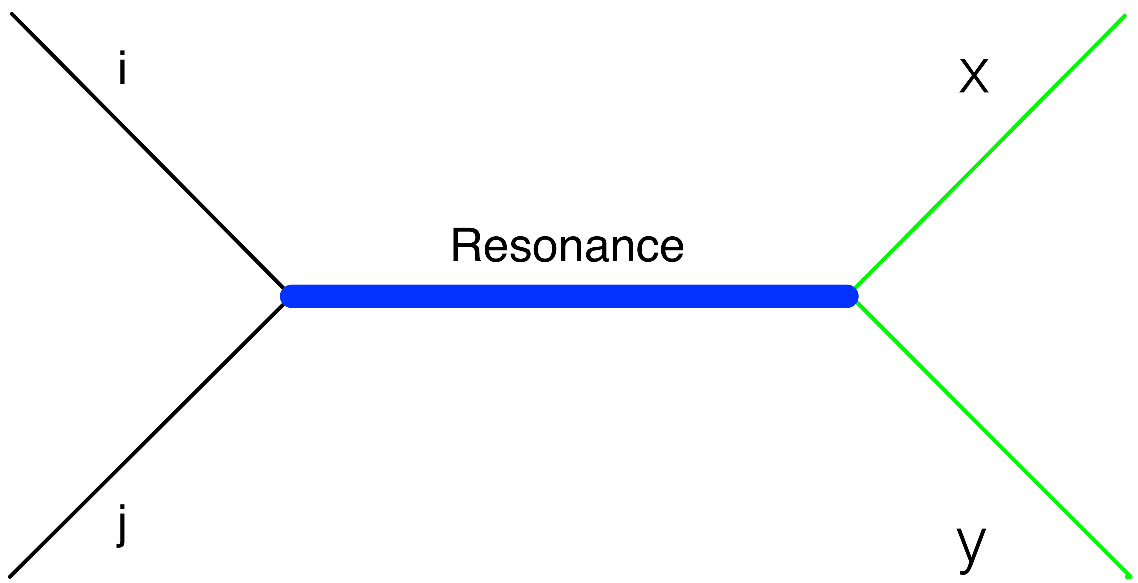
How to represent a broader class of models?



Spanning Space of Possibilities

$$BR(R \to xy) \equiv \frac{\Gamma(R \to xy)}{\Gamma_{TOTAL}(R)} \leq 1$$

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

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

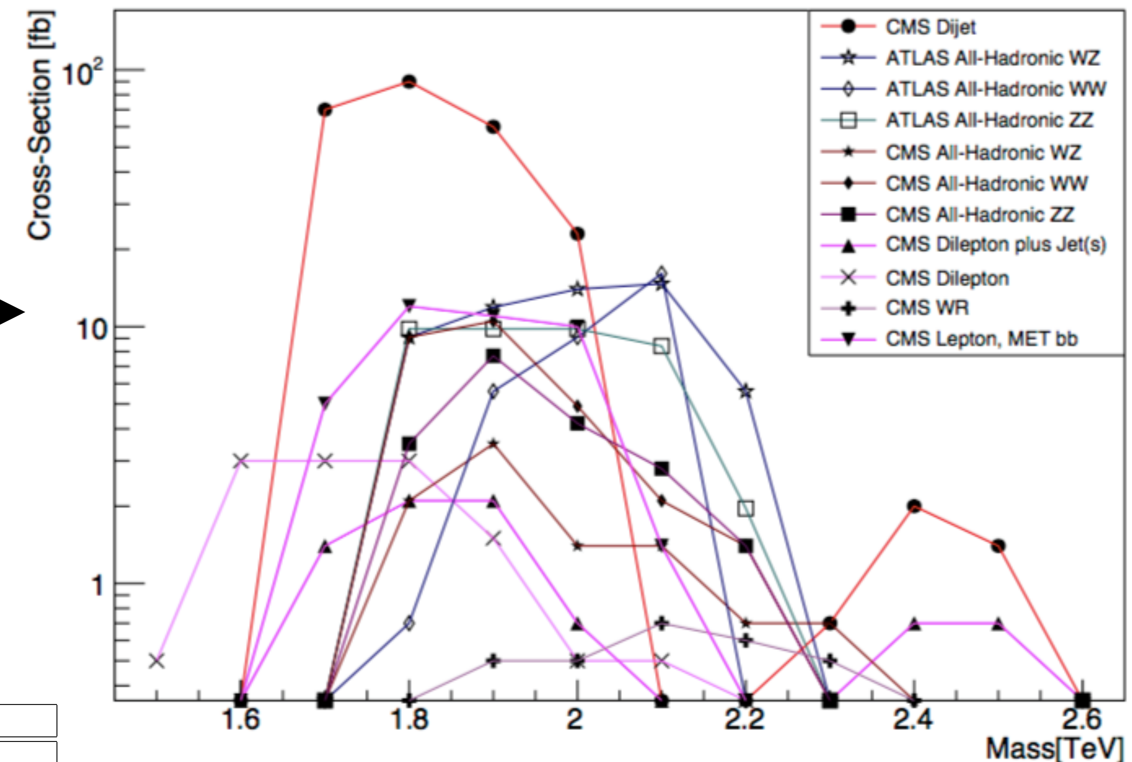
$$= \frac{\sigma_R^{XY}}{16\pi^2 \cdot \mathcal{N} \times \left[\left[\frac{1}{s}\frac{dL^{ij}}{d\tau}\right]_{\tau = \frac{m_R^2}{s}}\right]}$$

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

Memory Lane: Di-Boson Excess

1-100 fb
“WZ” excess ?

data?



models?

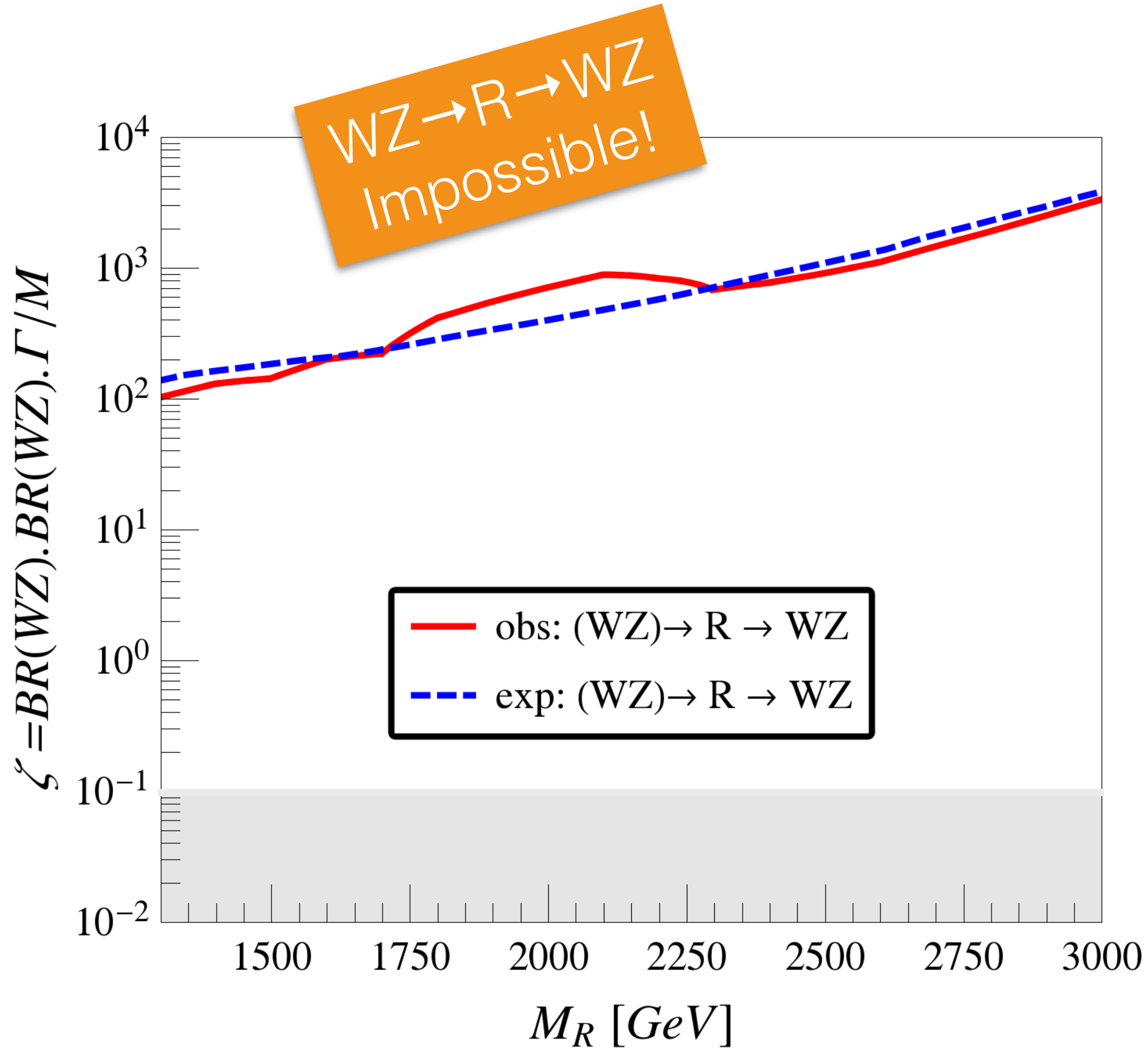
Spin-1 triplets ($V^{\pm}$, V^0)																	
Prod.	WW	ZZ	WZ	Wh	Zh	γh	$W\gamma$	$Z\gamma$	$\gamma\gamma$	gg	hh	$\overline{Q}_3Q_3$	$\bar{q}q$	ll	$\ell^{\pm}\nu$	X	Ref.
DY	✓		✓									(✓)	(✓)	(✓)	(✓)		[39, 140–142]
DY	✓		✓	✓	✓							$\checkmark_{\bar{q}q}$	✓	(✓)	(✓)		[40, 42, 43, 111]
DY	✓		✓	✓	✓							(✓)	(✓)	(✓)	(✓)		[44]
DY	✓		✓	✓	✓							$\checkmark_{\bar{q}q}$	✓	(✓)	(✓)	(✓)	[112]
DY	✓		✓	$\checkmark_{WZ}$	$\checkmark_{WW}$							$\checkmark_{\bar{q}q}$	✓	(✓)	(✓)		[45, 46, 85, 91]
DY	✓		✓	$\checkmark_{WZ}$	$\checkmark_{WW}$							✓	✓	(✓)	(✓)		[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	✓				$\checkmark_{WW}$							$\checkmark_{\bar{q}q}$	✓				[84]
DY	✓				$\checkmark_{WW}$							$\checkmark_{\bar{q}q}$	✓	✓			[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			✓	$\checkmark_{WZ}$								$\checkmark_{\bar{q}q}$	✓			✓	[86, 90, 92–94]
DY			✓	$\checkmark_{WZ}$								$\checkmark_{\bar{q}q}$	✓				[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	✓	✓						(✓)	(✓)	✓	$\checkmark_{WW/2}$	(✓)					[73]
gg	✓	$\checkmark_{WW/2}$				✓			✓	✓	✓	✓				(✓)	[141]
$q\bar{q}$	✓	$\checkmark_{WW/2}$		(✓)	(✓)						✓		✓			✓	[123–125]

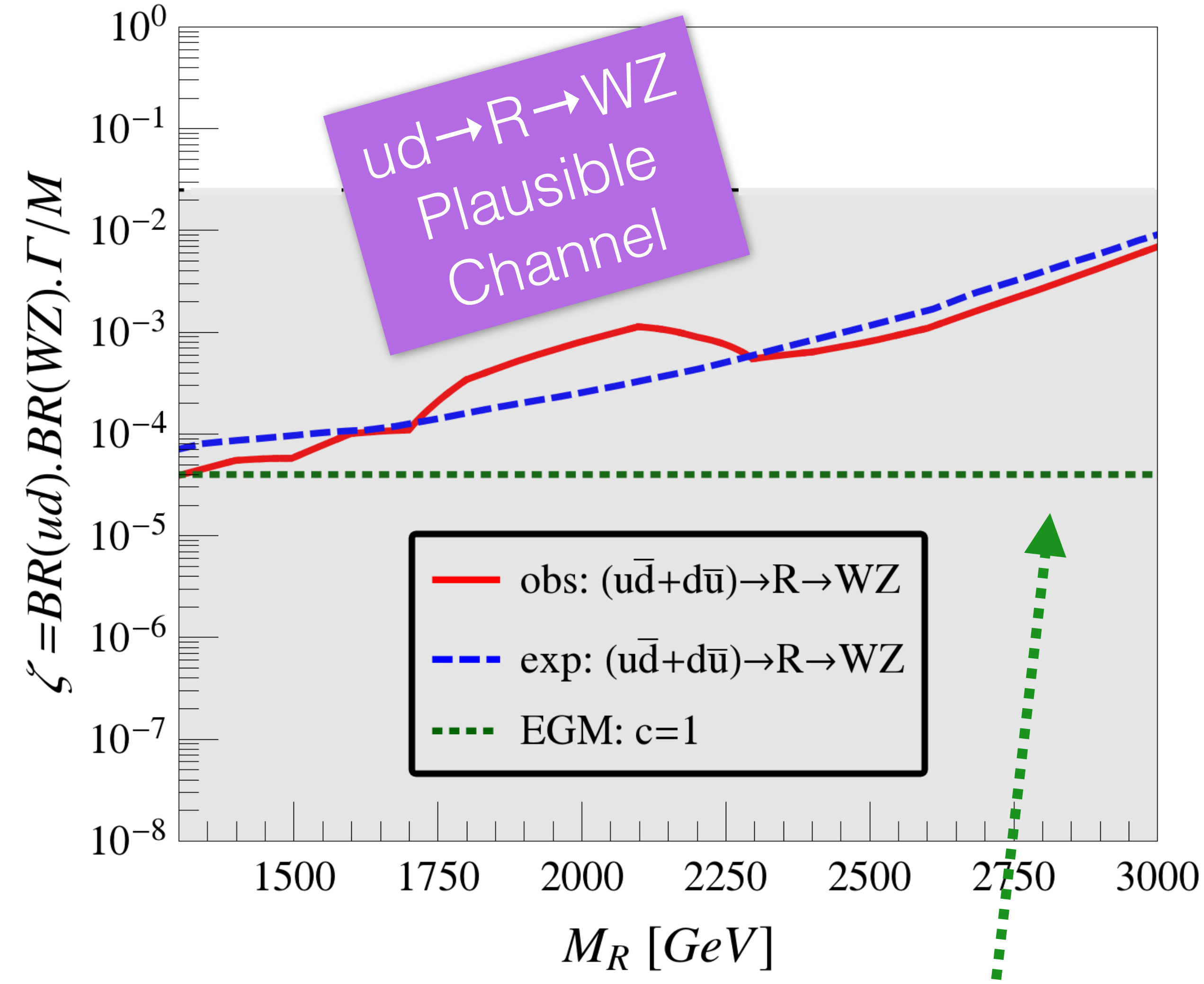
’Unconventional’	
Torsion-free Einstein-Cartan theory	[144]
Tri-boson interpretation: $pp \to R \to VY \to VV'X$	[136]
[Implications in other observables (direct and indirect)]	[95, 97, 142, 145–148]
[Next to leading order predictions]	[148]
[Analysis techniques]	[102, 106, 149, 150]

Les Houches
Pre-Proceeding 2015
The Diboson Excess:
Experimental Situation and
and Classification of Experiments
arXiv:1512.04537

Di-Boson 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 & Decay Modes

Easy to evaluate for any model class or model

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

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

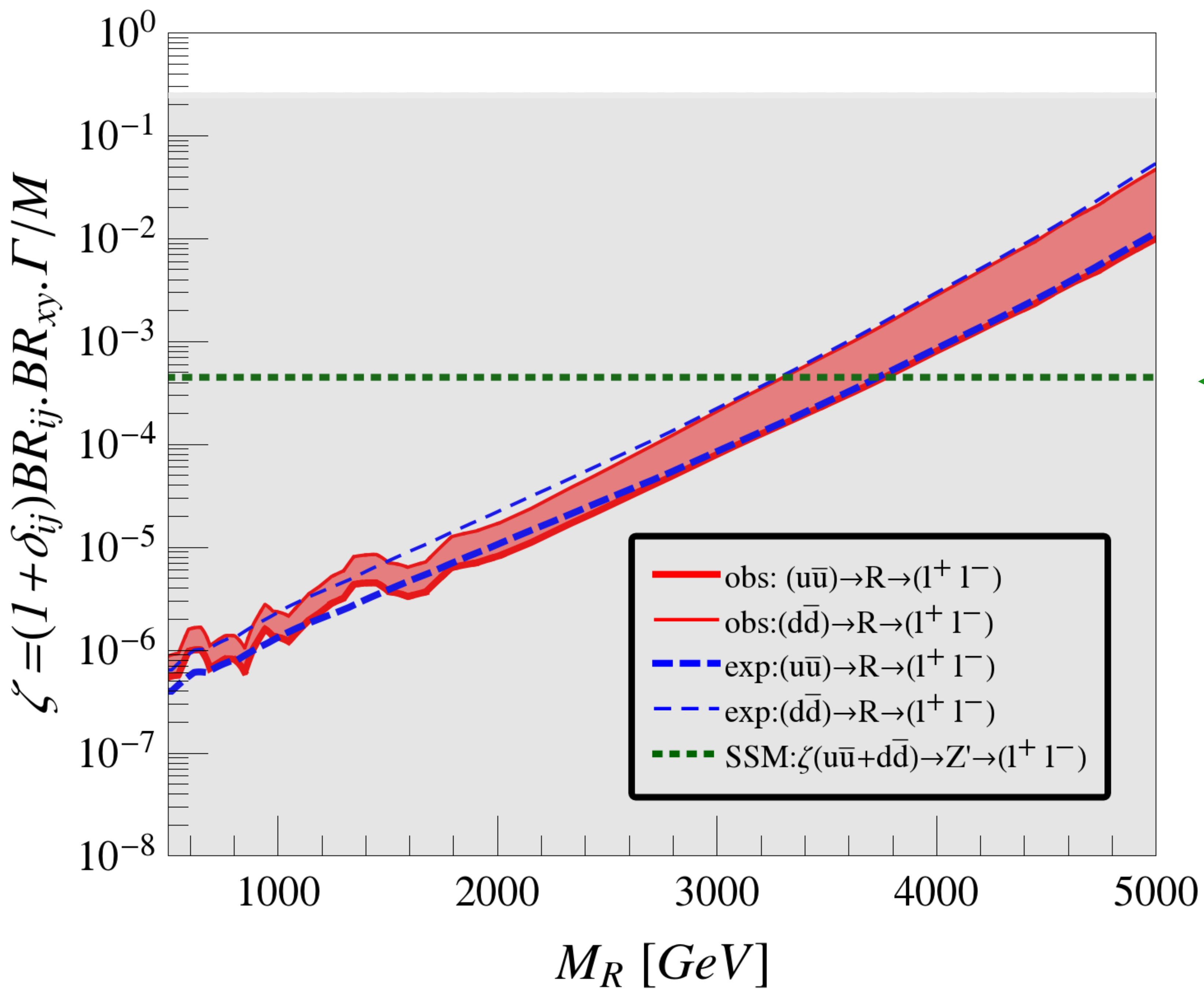
Reporting experimental limits in this format simplifies comparison with theory

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

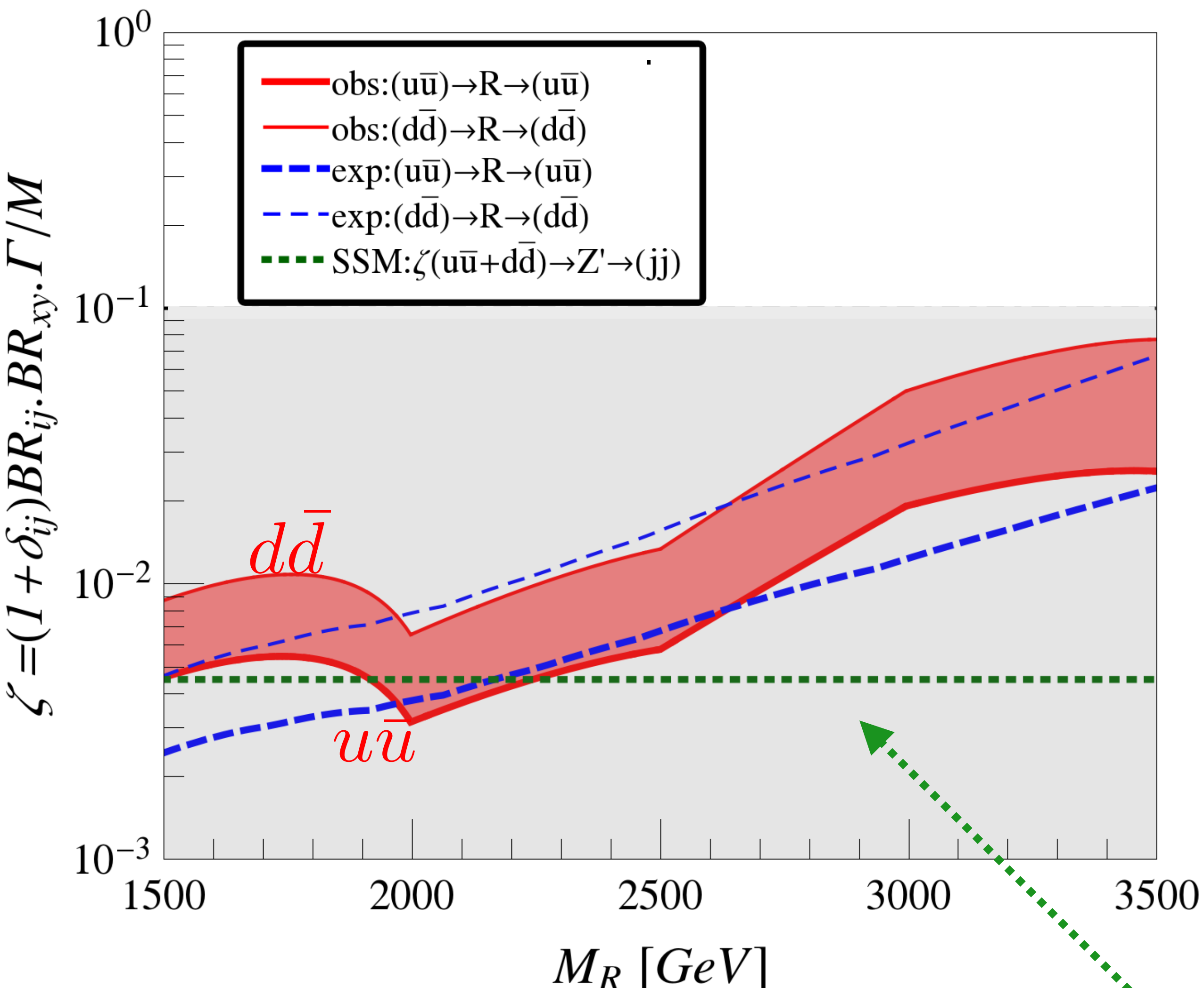


band indicates range between
Resonances (R)
coupling only to up-type quarks
vs. only to down-type quarks

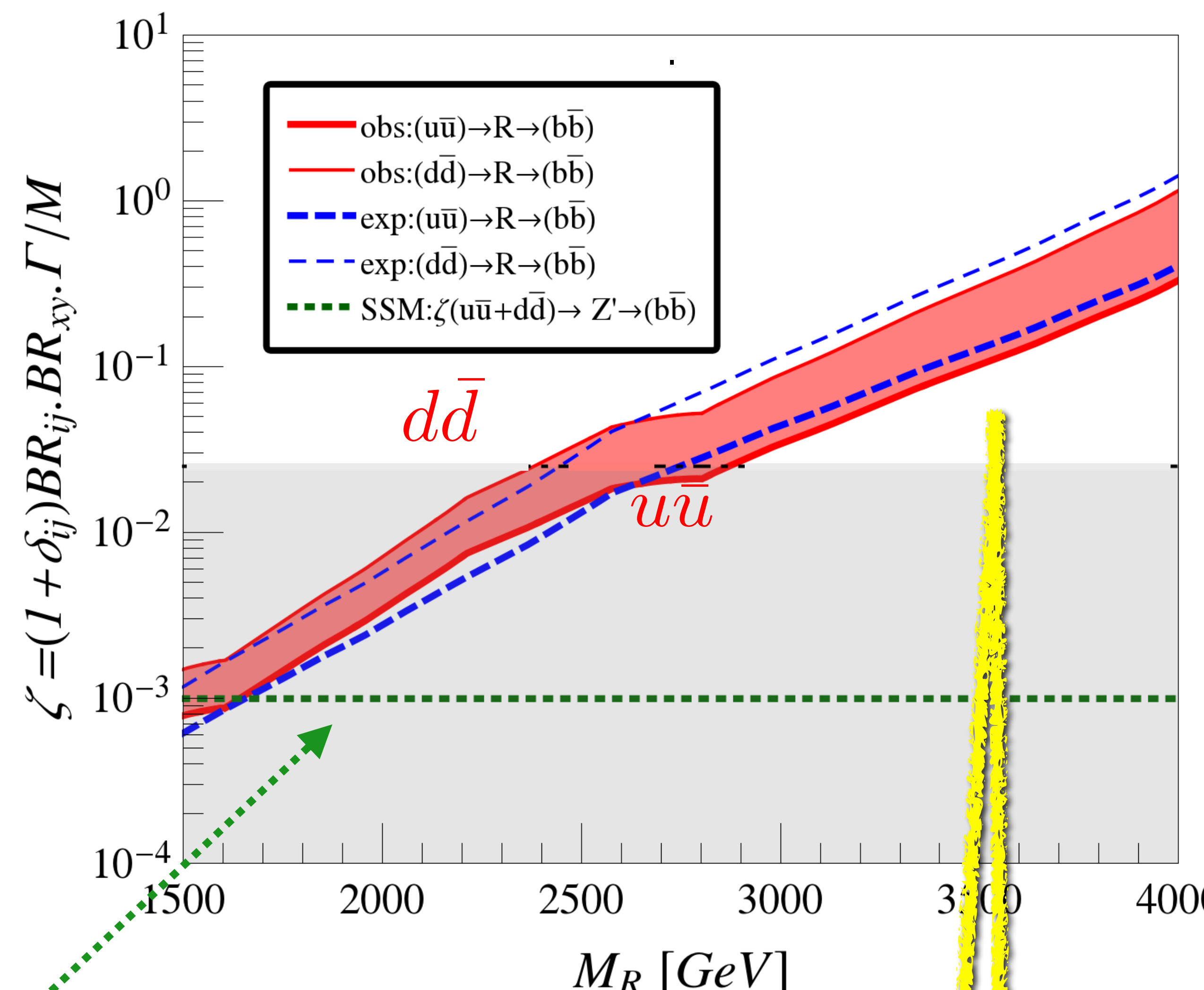
Sequential SM Z' is
excluded below ~3.5 TeV

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,

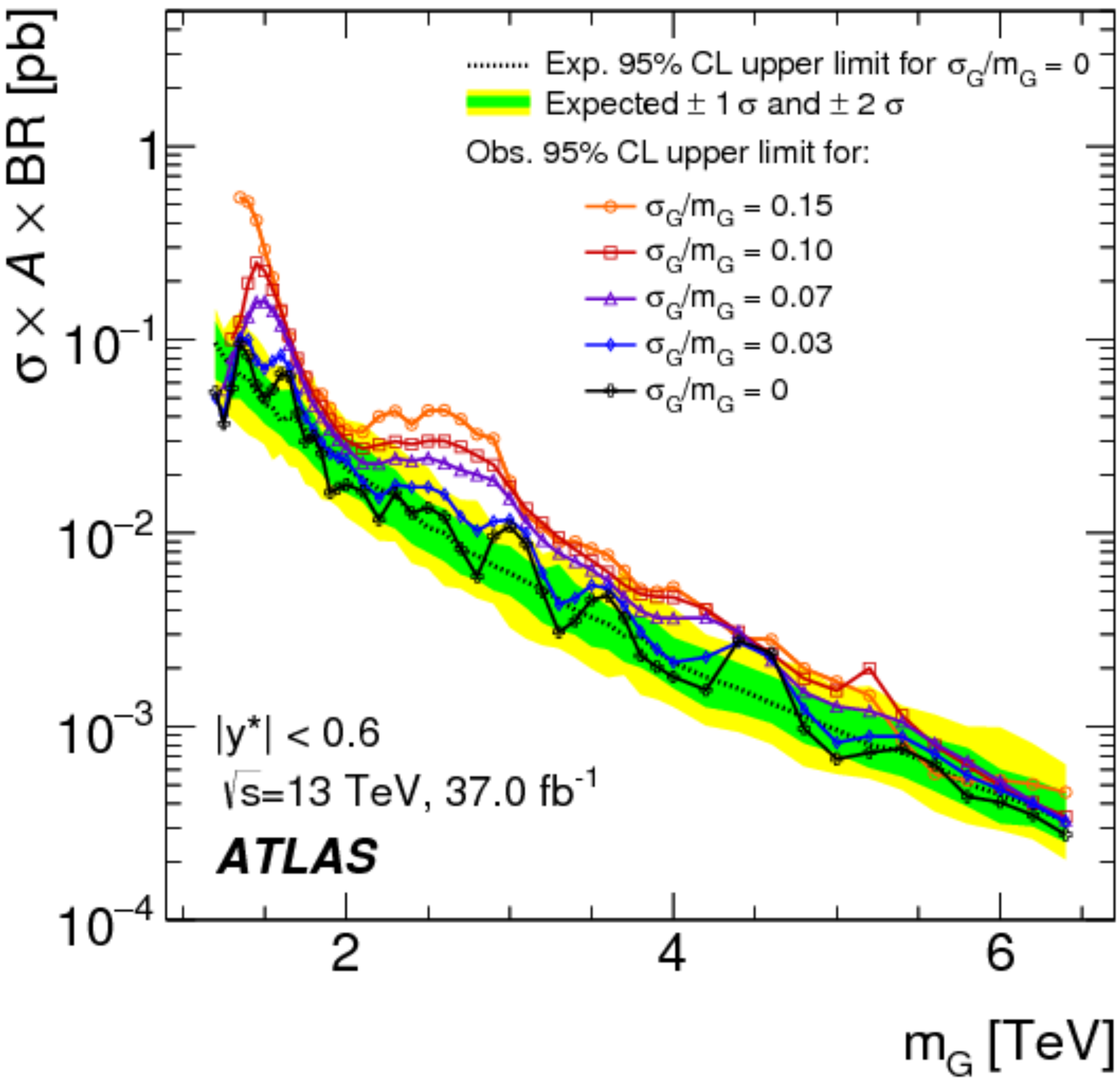
framed as bounds on

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

highlight relevant production channels for a newly observed narrow resonance.

R.S. Chivukula, P. Ittisamai, K.A. Mohan, and E.H. Simmons
Phys. Rev. D94 (2016) 094029

Limits on finite-width resonances



Breit-Wigner Approximation

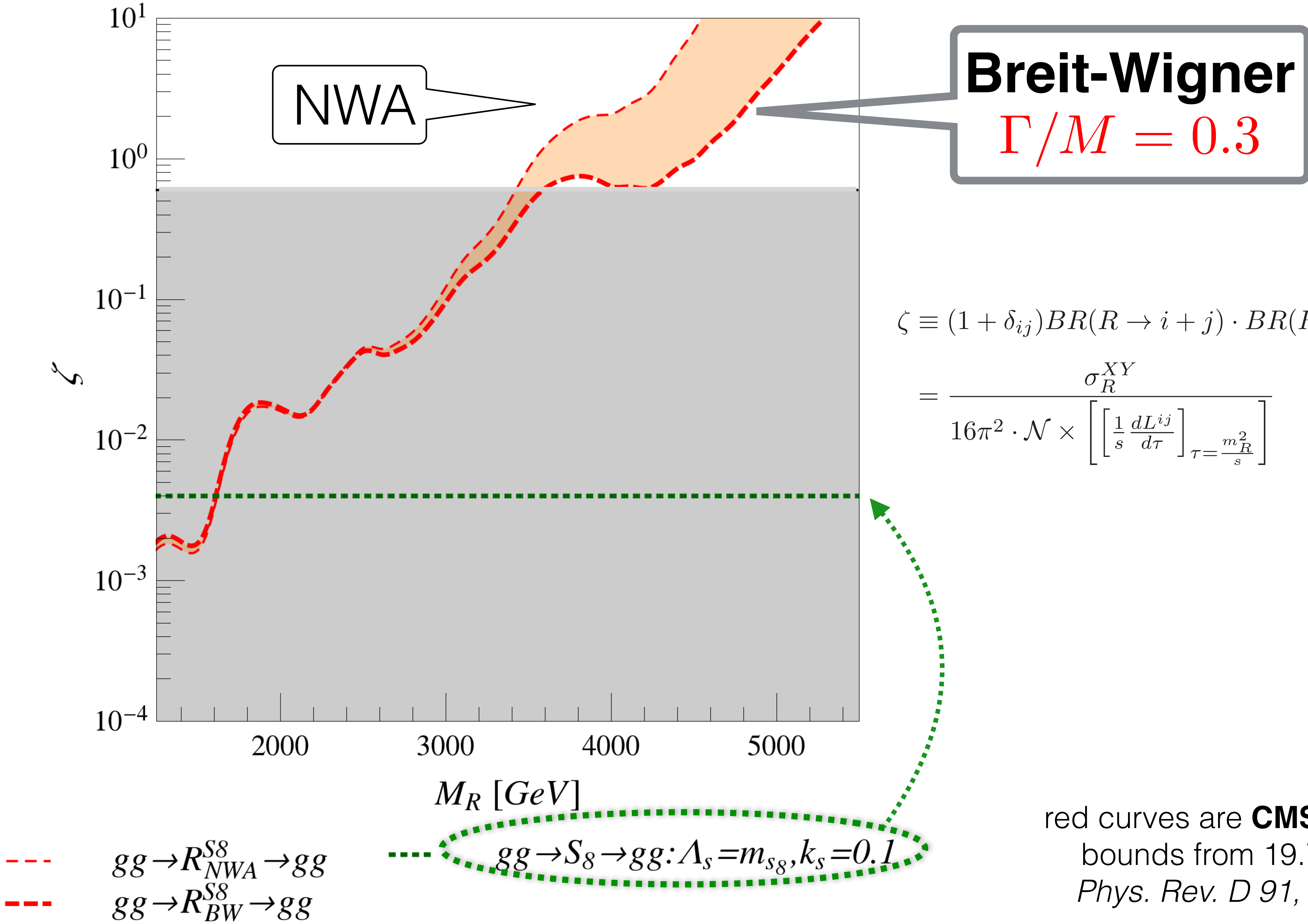
$$\sigma_R(pp \to x+y) = \int_{s_{min}}^{s_{max}} d\hat{s}\,\hat{\sigma}(\hat{s}) \cdot \left[\frac{dL^{ij}}{d\hat{s}}\right]$$

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

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

(includes main impact of s-dependent widths)

Color-Octet Scalar in Dijets

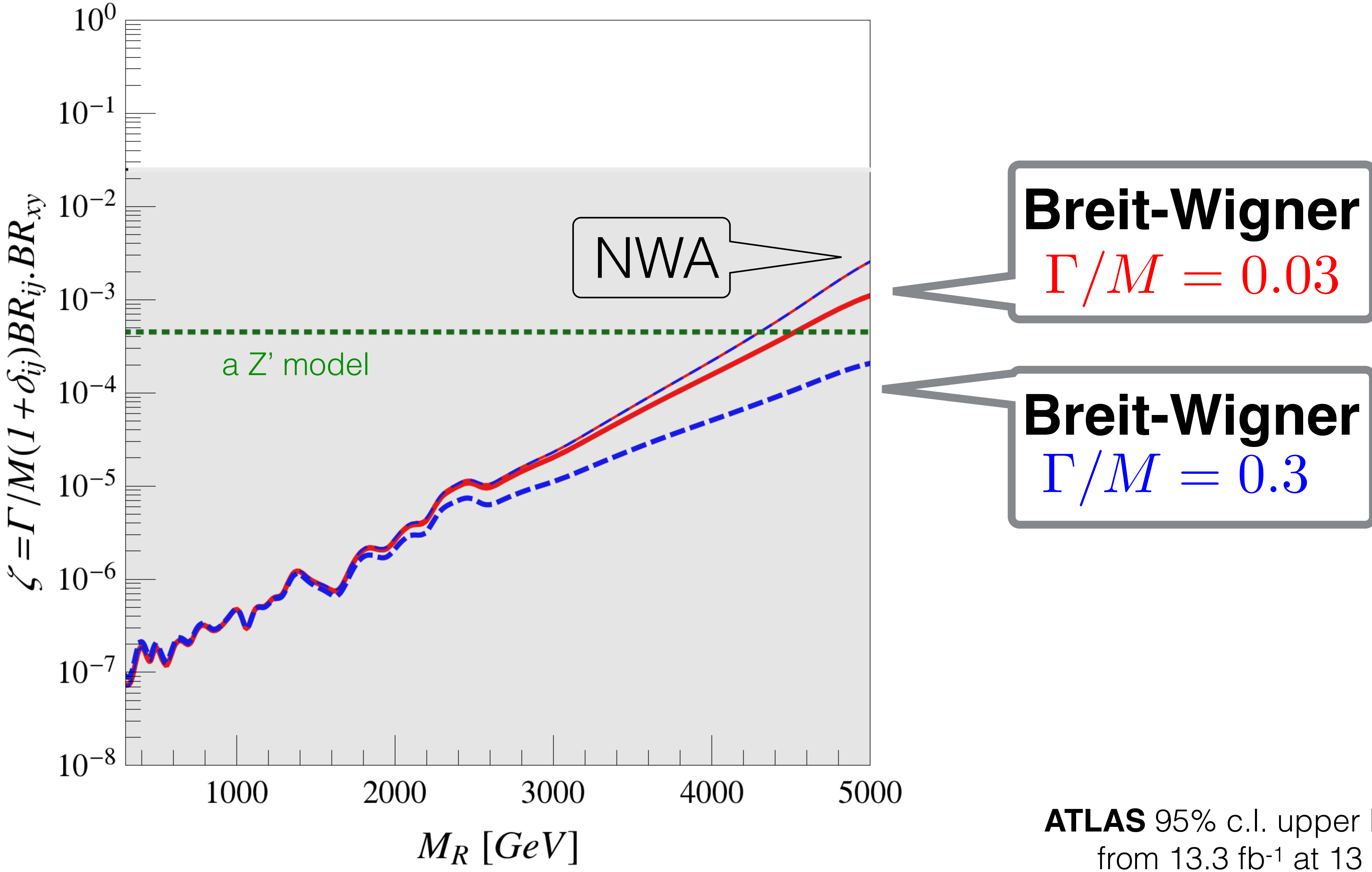


$$\zeta \equiv (1+\delta_{ij}) BR(R \to i+j) \cdot BR(R \to x+y) \cdot \frac{\Gamma_R}{m_R}$$

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

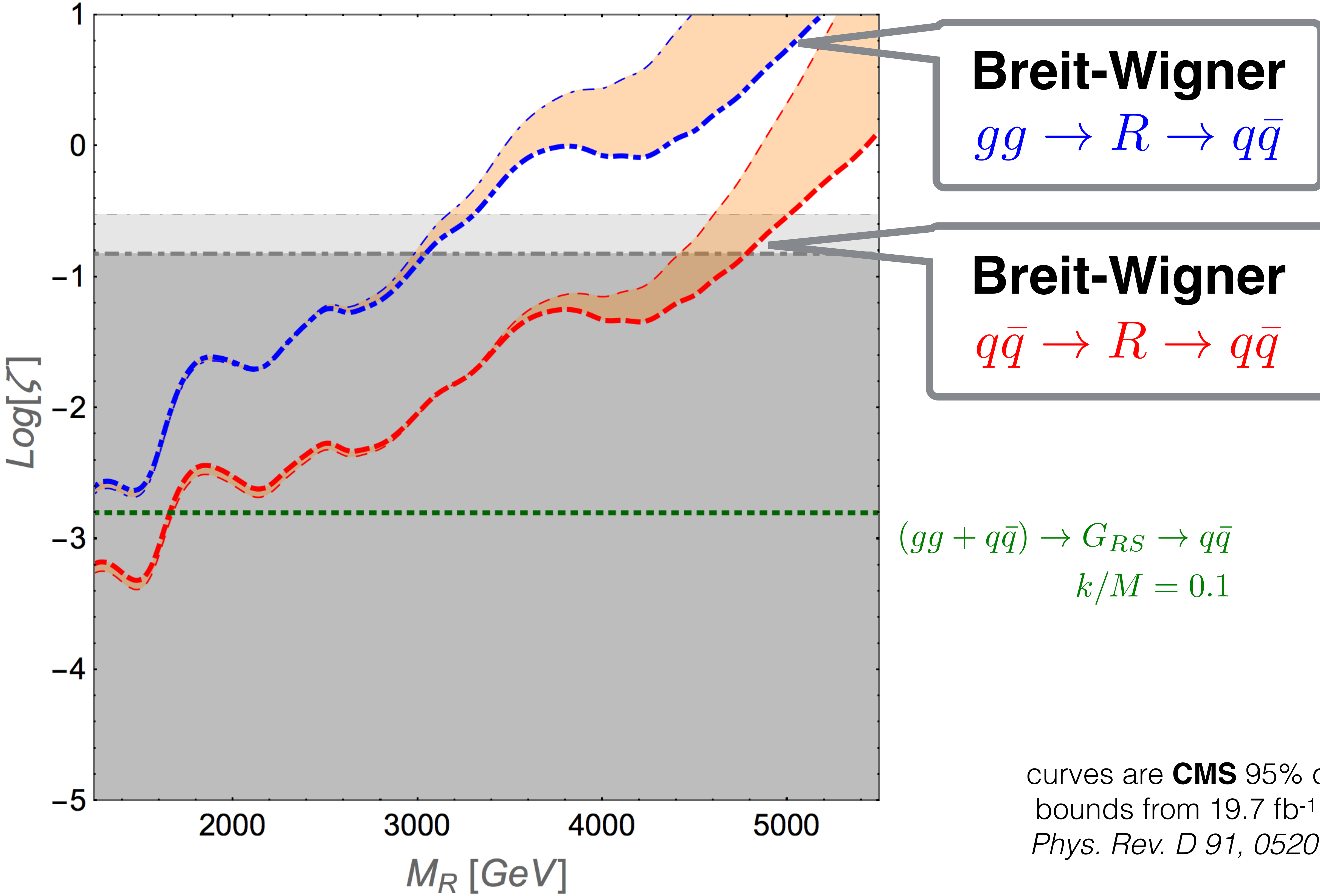
red curves are **CMS** 95% c.l. upper bounds from 19.7 fb^{-1} at 8 TeV
Phys. Rev. D 91, 052009 (2015)

Vector Resonance in DiLeptons



ATLAS 95% c.l. upper bounds
from 13.3 fb^{-1} at 13 TeV
ATLAS-CONF-2016-045

Spin-2 Resonance in Dijets



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

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.

R.S. Chivukula, P. Ittisamai, K.A. Mohan, and E.H. Simmons
Phys.Rev. D96 (2017) no.5, 055043

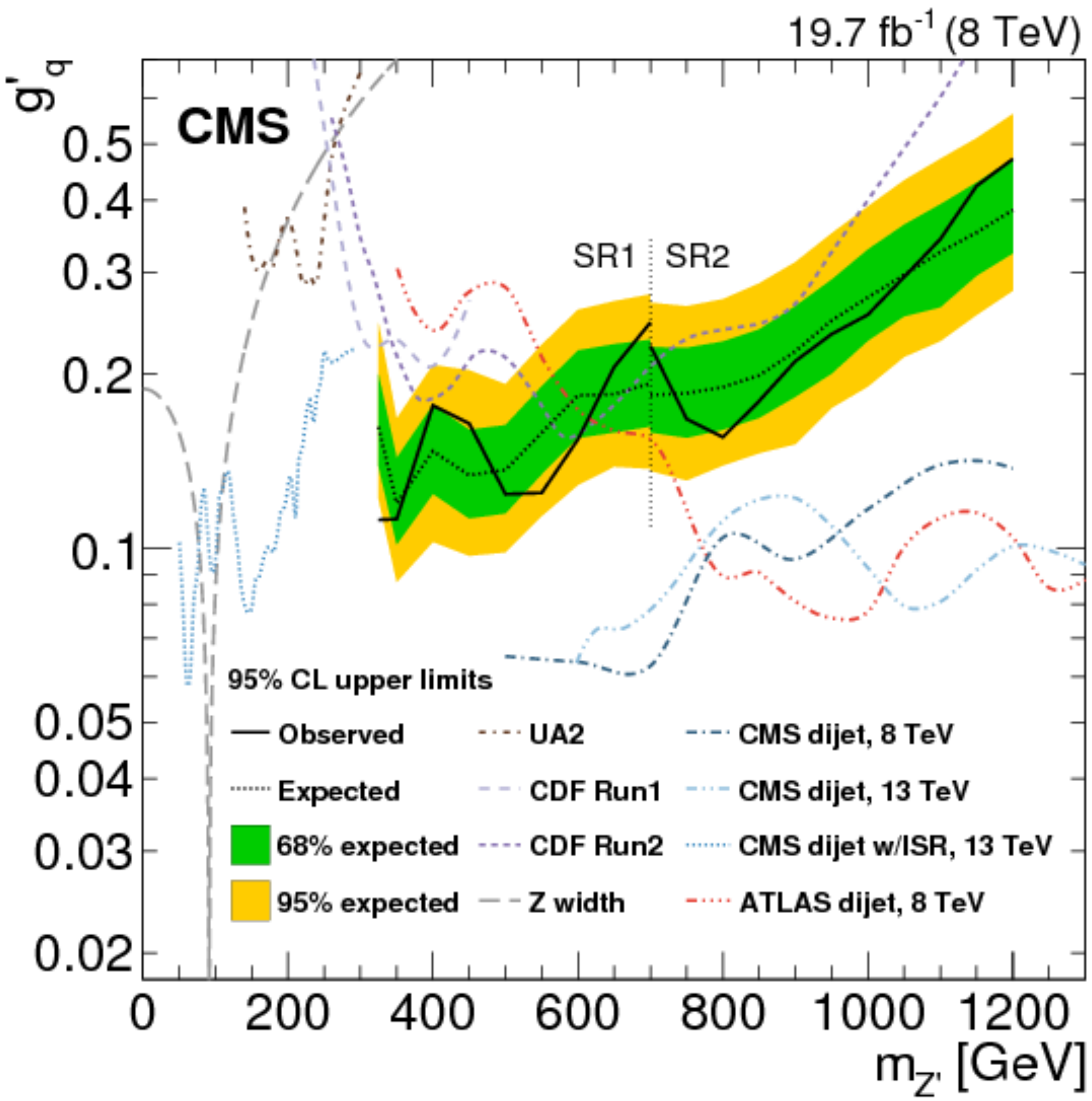
Benefits of Simplified Limits approach

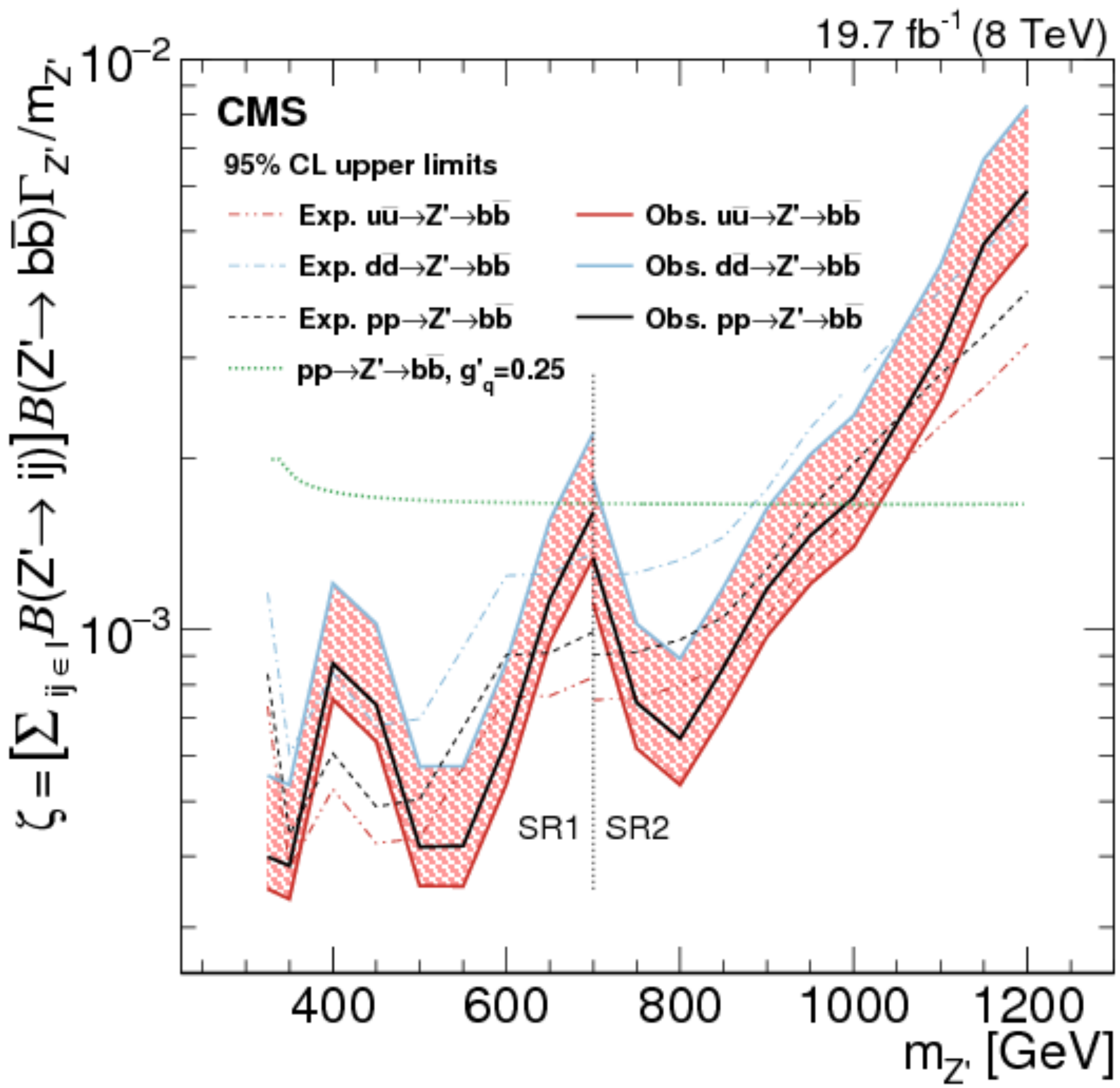
- focus on model classes ⇔ production mechanisms
- easily identify
  - exclusion limits on BSM resonances
  - whether data constrains a given channel
  - classes of models relevant for a given excess
  - [specific theories consistent with an excess]
- ζ derives directly from model parameters
- works 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.**

First Use by CMS

[CMS Collaboration (Sirunyan, Albert M *et al.*)
Phys.Rev.Lett. 120 (2018) no.20, 201801 arXiv:1802.06149 [hep-ex]]





Low-Energy Tail of Broad Peaks