SHINING LIGHT ON THE DIPHOTON RESONANCE

유레 쥬팡

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based on Altmannshofer, Galloway, Gori, Kagan, Martin, JZ, 1507.07927
Kamenik, Safdi, Soreq, JZ, 1603.06566

Korea Physics Symposium, Daejeon, Apr 21, 2016

READING THE TEA LEAVES

* thanks to Yevgeny Kats

- could the diphoton resonance be real?
- some numerology*
  - in ancient greek "digamma"=6 $\digamma$ `\digamma`
  - 6 x "the god particle"

$$6 \times 125 \text{ GeV} = 750 \text{ GeV}$$

- warning: discussions about di-photon very preliminary
  - may resemble the above reading of the tea leaves
  - should be settled with more data

COMBINING THE DATA

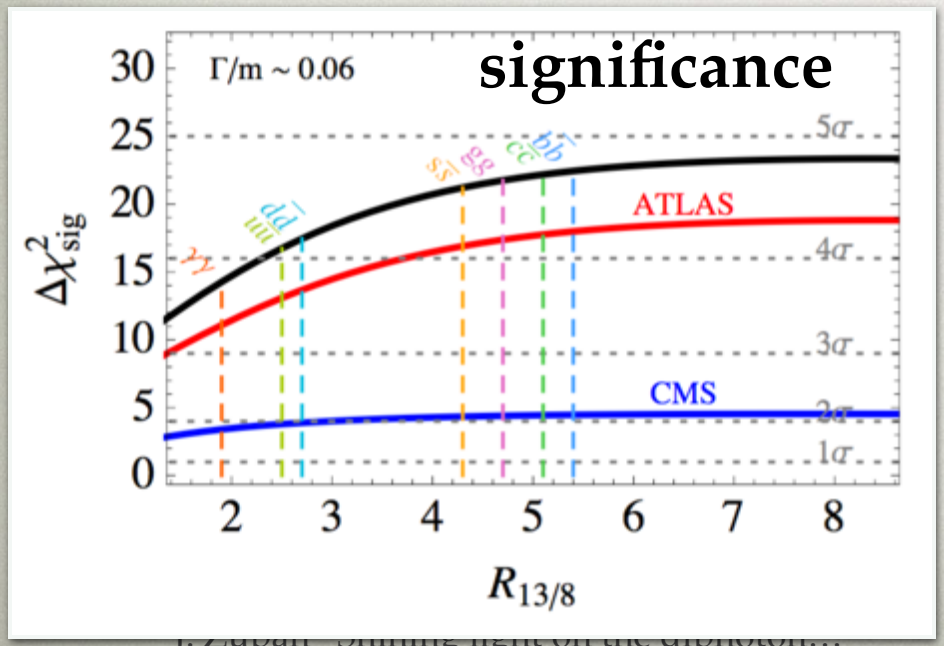
Kamenik, Safdi, Soreq, JZ, 1603.06566

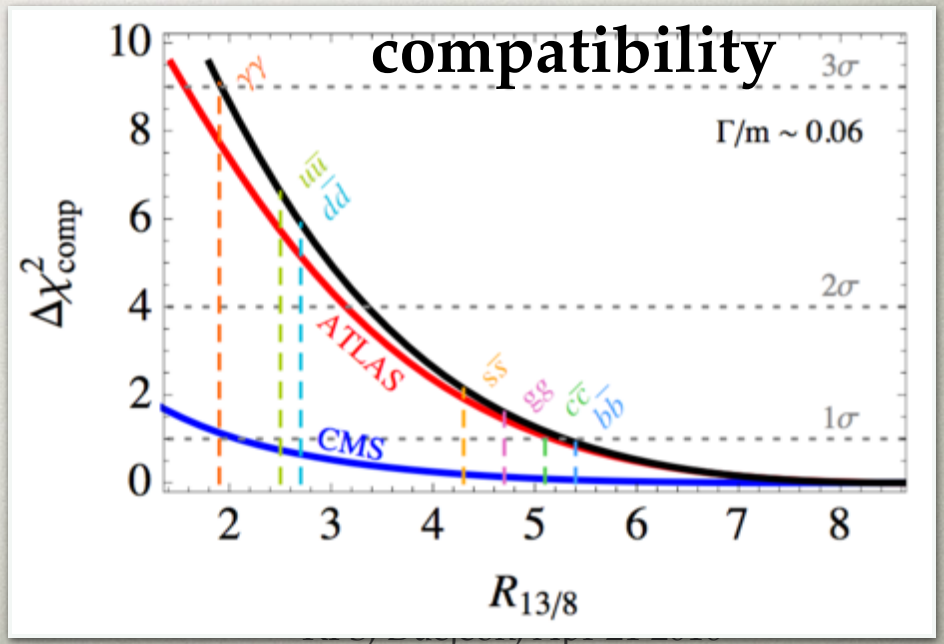
- a global combination of ATLAS+CMS, 8TeV+13TeV
  - relative signal depends on production mechanism

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

$$r = \sigma_{13\,\mathrm{TeV}}/\sigma_{8\,\mathrm{TeV}}$$

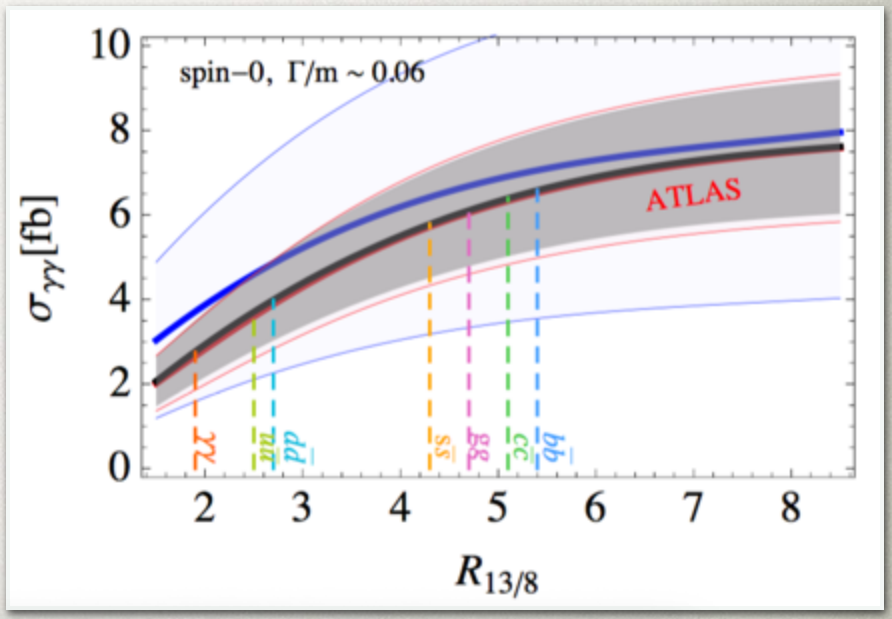
- prefers: heavy quark/gluon initial state
- combined excess significance close to 5 sigma





DIPHOTON RATE

- the combined rate $\sigma_{\gamma\gamma}=\sigma(S)$ $Br(S\to\gamma\gamma)$ depends on whether
  - spin 0, spin 2
  - narrow/large decay width
  - production mode
- anywhere between 1 and 10 fb



	narrow width ($\Gamma/m \to 0$)		wide width ($\Gamma/m = 6\,\%$)	
production mech.	spin-0	spin-2	spin-0	spin-2
$\gamma\gamma$	1.2 ± 0.4	1.8 ± 0.5	2.8 ± 0.7	4.4 ± 1.2
$b\bar{b}$	3.6 ± 0.8	5.3 ± 1.1	6.6 ± 1.4	10.3 ± 2.2

QUESTIONS

- Can S couple only to photons?
- Can all WW, ZZ, $Z\gamma$ channels be zero simultaneously?
- What production mechanism?
- Can S have 45 GeV decay width by only coupling to the SM?
- What models are viable?

PHOTON FUSION

Csaki, Hubisz, Lombardo, Terning, 1601.00638; 1512.05776; Fichet, von Gersdorff, Rayon, 1512.05751, 1601.01712; Harland-Lang, Khoze, Ryskin, 1601.07187

- can S couple only to photons?
  - produced from photon fusion
- have EW symmetry, broken by H
- at dim-9 an operator that couples S to only $\gamma\gamma$ after EWSB

$$\mathcal{L}_9 \supset \frac{1}{m_S^5} S(gB_{\mu\nu}H^\dagger H - g' W^i_{\mu\nu} H^\dagger \sigma^i H)^2$$

  - what symmetry ensures that this is the leading operator?

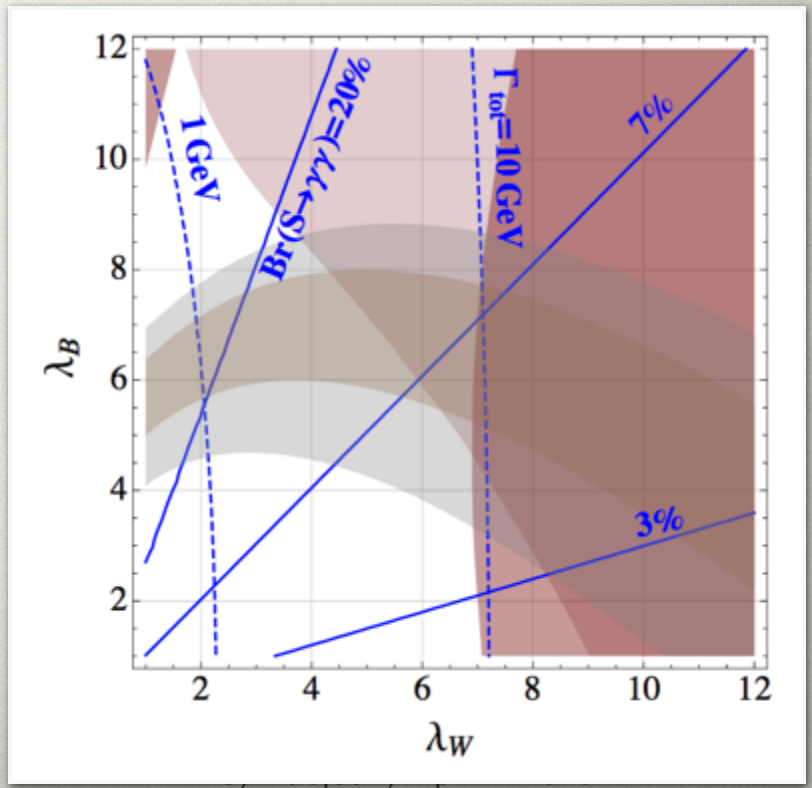
W FUSION

Altmannshofer, Galloway, Gori, Kagan, Martin, JZ, 1507.07927

- for instance at dim-5 two couplings

$$\lambda_B \frac{\alpha}{\pi c_W^2 v_W} S B_{\mu\nu} B^{\mu\nu} \qquad \lambda_W \frac{\alpha}{\pi s_W^2 v_W} S W^a_{\mu\nu} W^{a\mu\nu}$$

- possible to have large enough production if only these two
  - but not Γ=45GeV
- relatively large Wilson coefficients



DECAYS TO OTHER EW BOSONS

- can all *WW*, *ZZ*, $Z\gamma$ channels be zero simultaneously?
- if only these two dimension 5 operators

$$\lambda_B \frac{\alpha}{\pi c_W^2 v_W} S B_{\mu\nu} B^{\mu\nu}$$

$$\lambda_W \frac{\alpha}{\pi s_W^2 v_W} S W^a_{\mu\nu} W^{a\mu\nu}$$

  - the answer is no: 4 branching ratios, 2 params
- how general is this conclusion?
  - note: already at dim-4 other relevant couplings

EFT ANALYSIS

- assume that Effective Field Theory expansion is valid (i.e. a mass gap exists)
  - SM + extra state, *S*
  - *S* can be spin-0, spin-2, EW singlet, doublet, triplet
- here focus on spin-0 singlet
- write all operators up to and including dim-5

EFT ANALYSIS

- 5 params. relevant for coupling S to EW gauge bosons

$$\mathcal{L}^{(4)}_{\rm int} = -\mu_S S H^\dagger H - \frac{\lambda_S}{2} S^2 H^\dagger H .$$

$$\mathcal{L}^{(5)}_{\rm int} = \lambda_g \frac{\alpha_s}{4\pi m_S} S G^a_{\mu\nu} G^{a\mu\nu} + \lambda_B \frac{\alpha}{4\pi c_W^2 m_S} S B_{\mu\nu} B^{\mu\nu} + \lambda_W \frac{\alpha}{4\pi s_W^2 m_S} S W^a_{\mu\nu} W^{a\mu\nu} + \ldots$$
$$- \frac{\lambda_H}{m_S} S (H^\dagger H)^2 + \frac{\lambda'_H}{m_S} S D_\mu H^\dagger D^\mu H$$
$$- \frac{\lambda_d}{m_S} S \bar{Q}_L d_R H - \frac{\lambda_u}{m_S} S \bar{Q}_L u_R H^c - \frac{\lambda_\ell}{m_S} S \bar{L}_L \ell_R H + \text{h.c.} ,$$

note change in λ_W,λ_B normalization!

- two give S-H mixing

$$s_\alpha \equiv \sin\alpha \simeq \frac{v^2}{m_S^2}\left(\frac{\mu_S}{v} + \frac{v}{m_S}\lambda_H\right).$$

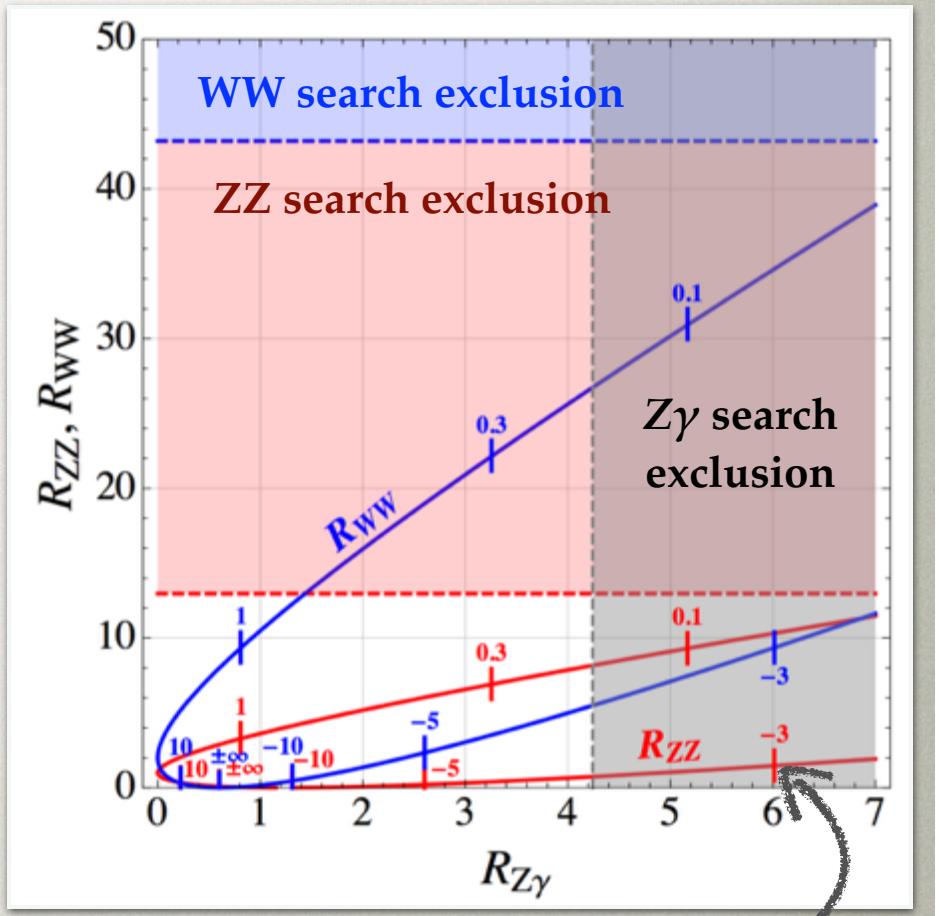
  - enter in one comb. coupling S to longit. W, Z
  - effectively only 3 params, λ_W,λ_B,κ

$$\frac{\kappa}{2}\left(2\frac{m_W^2}{v} S W^{+\mu} W^-_\mu + \frac{m_Z^2}{v} S Z^\mu Z_\mu\right)$$

$$\kappa \equiv 2 s_\alpha + \lambda'_H v/m_S .$$

NO MIXING CASE

- first switch off mixing, i.e., $\kappa=0$
- only decays to transverse W, Z
- two params, λ_W, λ_B,
  - at most one decay Br can be set to zero
- note: ZZ or WW can still be suppressed



$\frac{\lambda_B}{\lambda_W}$

WITH MIXING

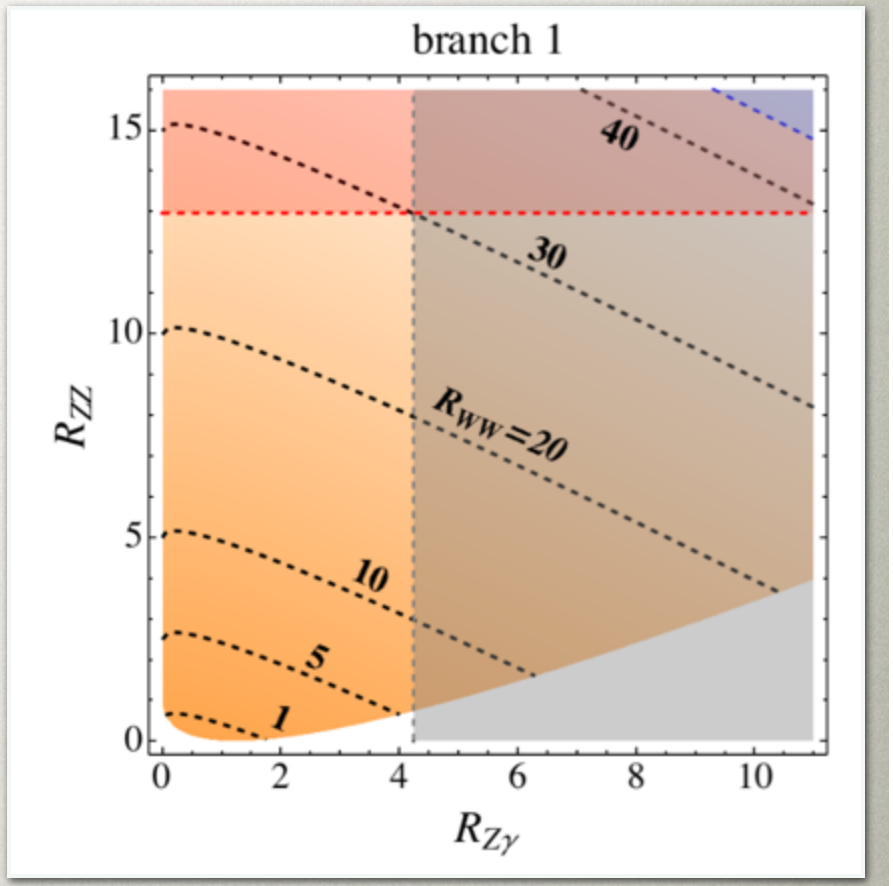
- switch on the mixing, $\kappa \neq 0$
- still at most one Br can be zero
  - due to enhancement of decay to longitudinal *W*, *Z*

$$\lambda_Z \propto \lambda_W + \lambda_B s_W^4$$

$$\Gamma_{Z\gamma} \sim (\lambda_W - s_W^2 \lambda_B)^2$$

$$\Gamma_{ZZ} \sim \alpha^2 \lambda_Z^2 - \alpha \lambda_Z \kappa \mathcal{O}\left(\frac{m_Z}{m_S}\right) + \kappa^2 \mathcal{O}\left(\frac{m_S^2}{m_Z^2}\right)$$

$$\Gamma_{WW} \sim \alpha^2 \lambda_W^2 - \alpha \lambda_W \kappa \mathcal{O}\left(\frac{m_W}{m_S}\right) + \kappa^2 \mathcal{O}\left(\frac{m_S^2}{m_Z^2}\right)$$



OTHER ELECTROWEAK ASSIGNMENTS

- if *S* a pseudoscalar: no mixing with the Higgs, analysis the same as for scalar with $\kappa=0$
- if *S* part of a doublet
  - more operators, possible to set two *Br*'s to zero simultaneously
- is *S* part of a triplet
  - all *Br*'s fixed in terms of $S\to\gamma\gamma$

$$\lambda_\gamma : \lambda_{\gamma Z} : \lambda_Z : \lambda_W = s_W c_W : c_W^2 - s_W^2 : -s_W c_W : 0, \qquad \text{Triplet}, Y_T = 0.$$

- if spin-2 the same analysis as for spin-0

VECTOR BOSON FUSION PRODUCTION

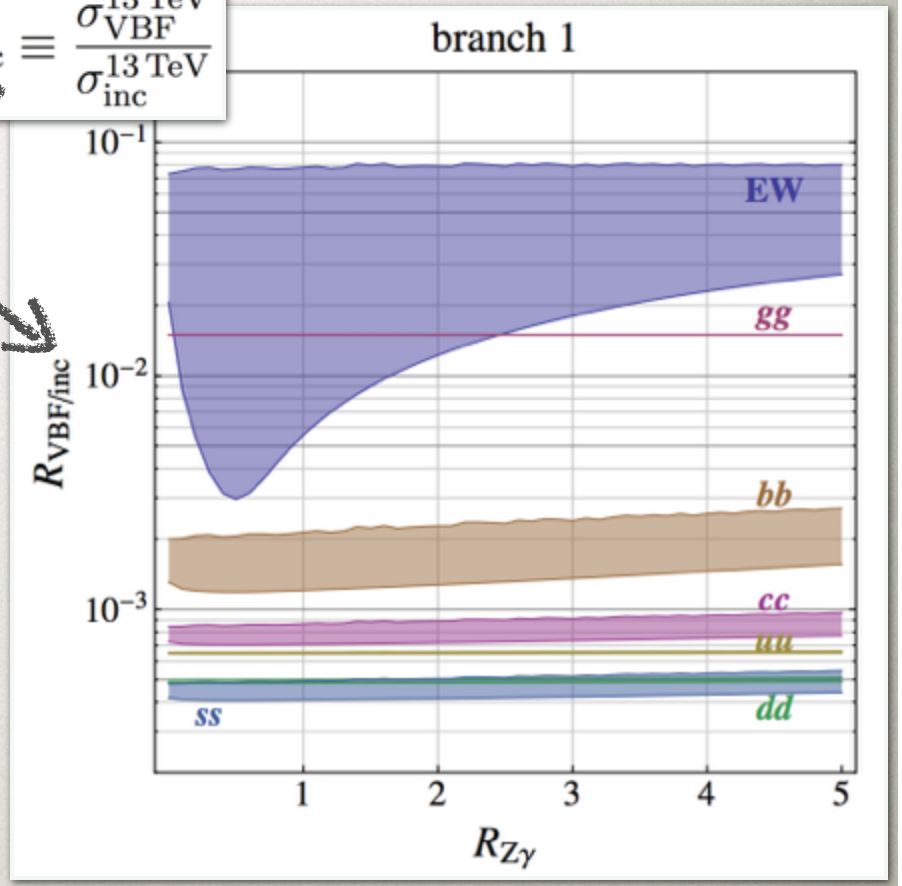
- is it possible to distinguish VBF from gluon fusion?
- require $pp \to Sjj$ with VBF cuts
  - hard cut on m_{jj} essential

$$p_T(j) > 60\,\text{GeV}\,, \quad |\eta_j| < 5\,,$$

$$|\Delta\eta(jj)| > 3.6\,, \quad m_{jj} > 1\,\text{TeV}$$

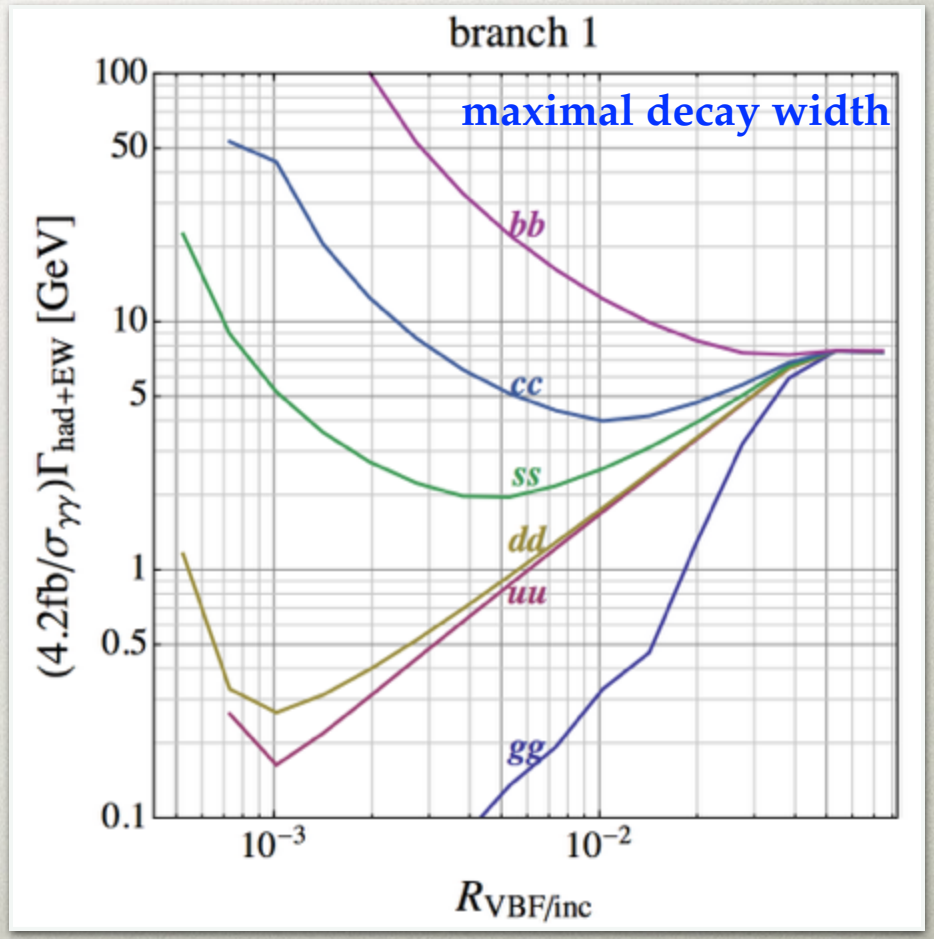
- in most of parameter space VBF distinguish. from other productions
- if VBF measured very useful
  - Γ_{tot} + VBF production fixes absolute sizes of couplings
  - same if any other production mode established

$$R_{\text{VBF/inc}} \equiv \frac{\sigma^{13\,\text{TeV}}_{\text{VBF}}}{\sigma^{13\,\text{TeV}}_{\text{inc}}}$$



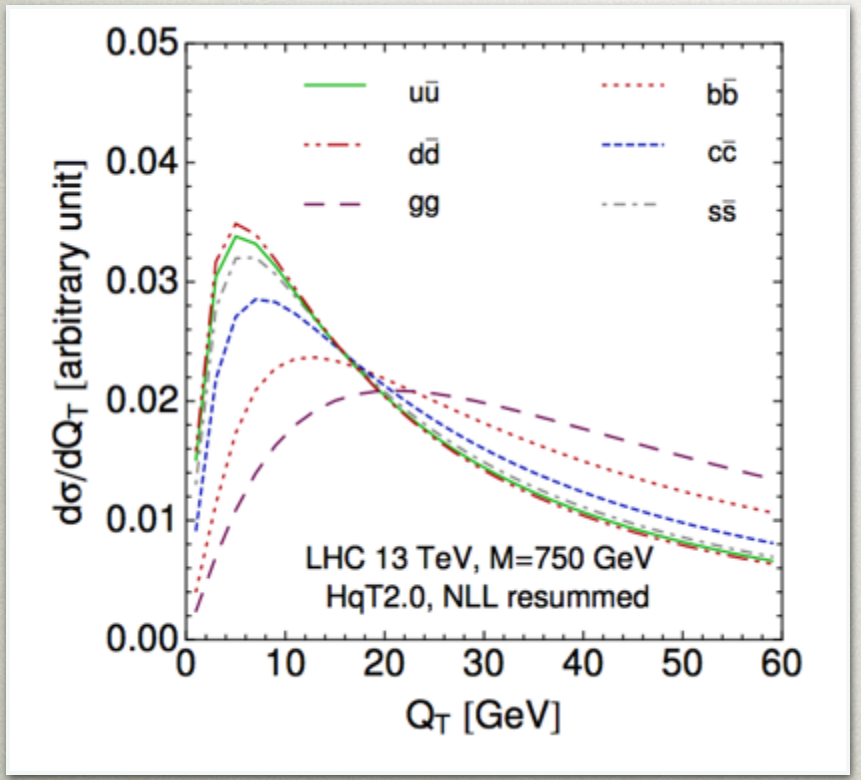
DECAY WIDTH FROM BSM?

- does one need decays to other states beside the SM?
- not at present
  - for *bb* or *cc* production Γ=45GeV possible

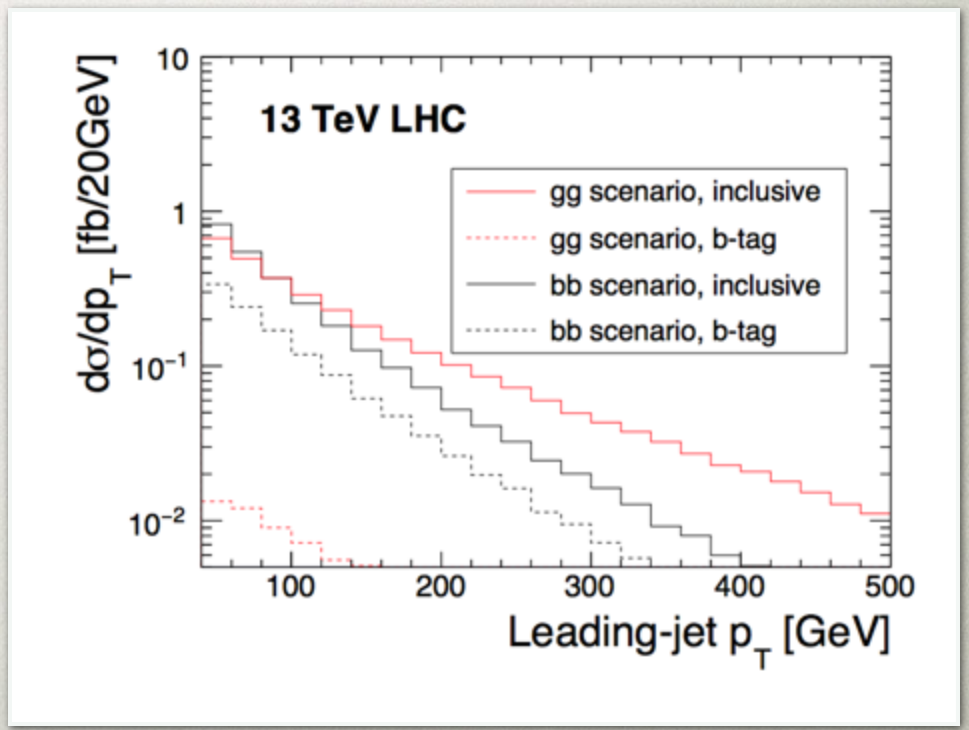


DISTINGUISHING PRODUCTION MODES

- distinguishing from p_T distribution
- for bb production also b-tagging



Gao, Zhang, Zhu, 1512.08478

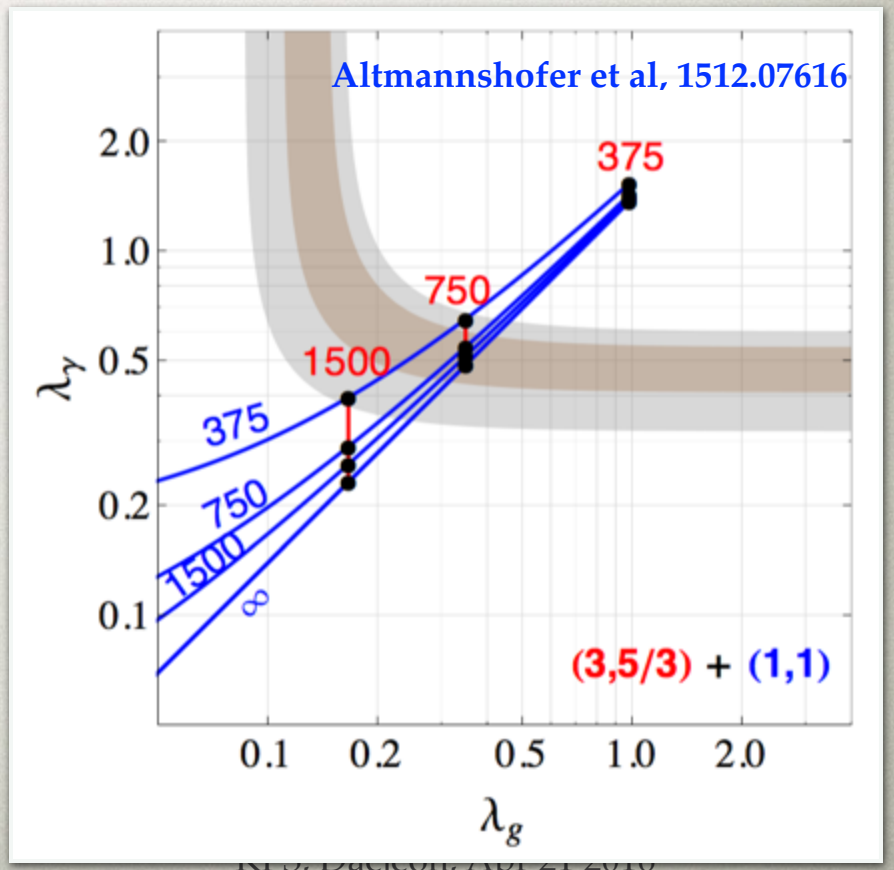


WHAT BSM MODELS?

see talks by Won Sang Cho, Minho Son, Jae Sik Lee, Jeonghyeon, Mihoko Nojiri, Kingman Cheung, Veronica Sanz

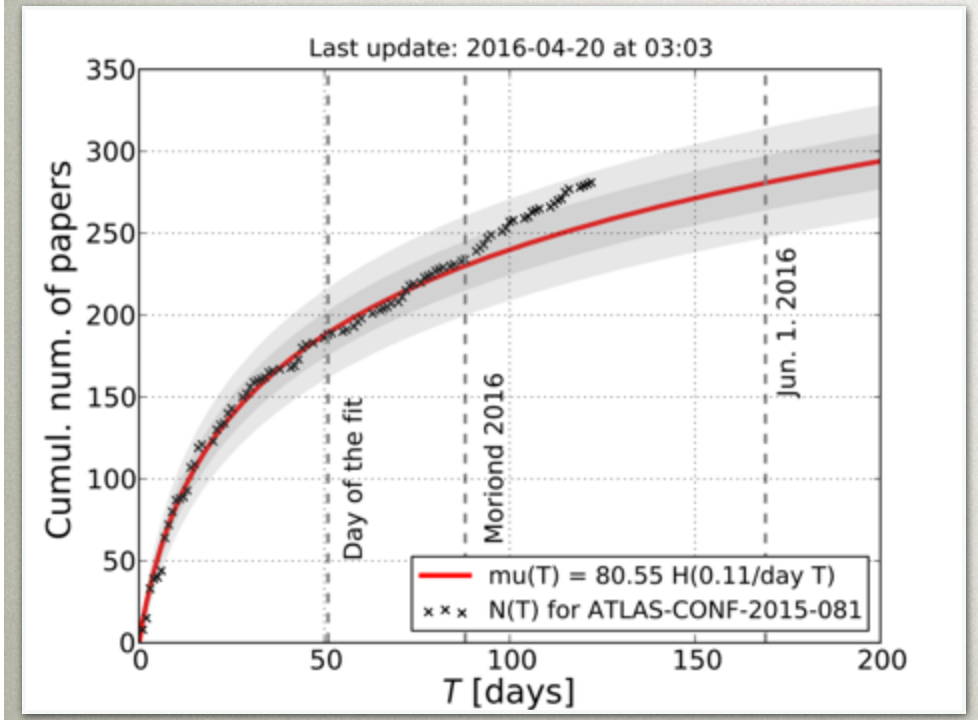
- typically require extra fermions to have large enough gg and $\gamma\gamma$ couplings
  - e.g. vector-like fermions
- an intriguing option

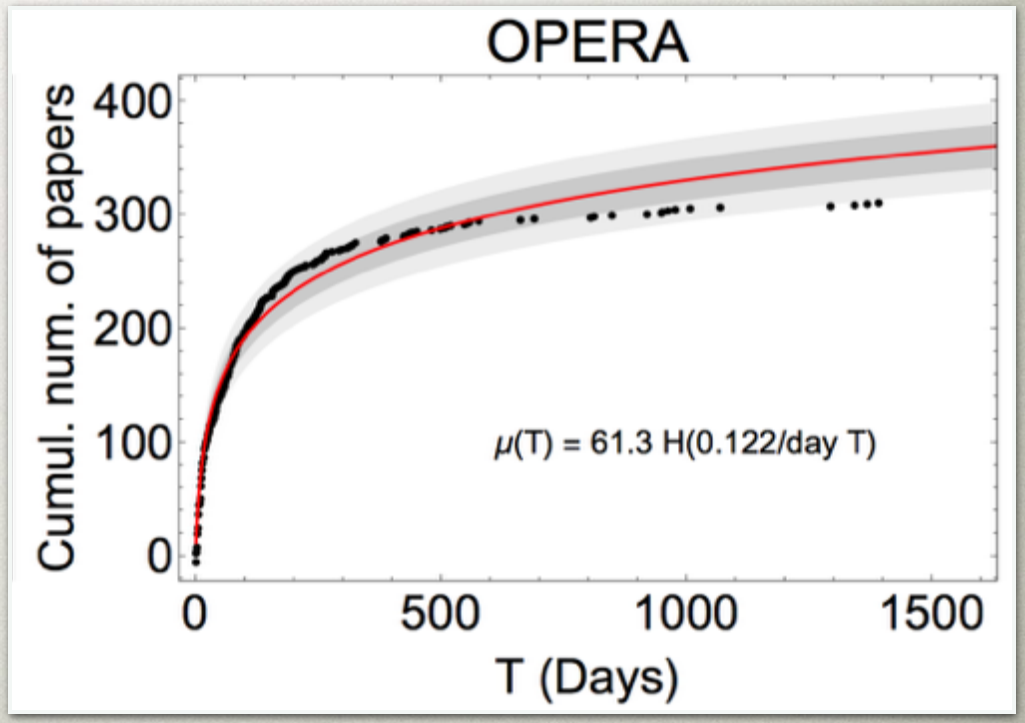
  Kats, Strassler, 1602.08819
  - bound state of single colored scalar
  - end of naturalness?



READING THE TEA LEAVES

- is it real? Backovic, 1603.01204
  - "The theory of ambulance chasing" shows a 2 sigma deviation





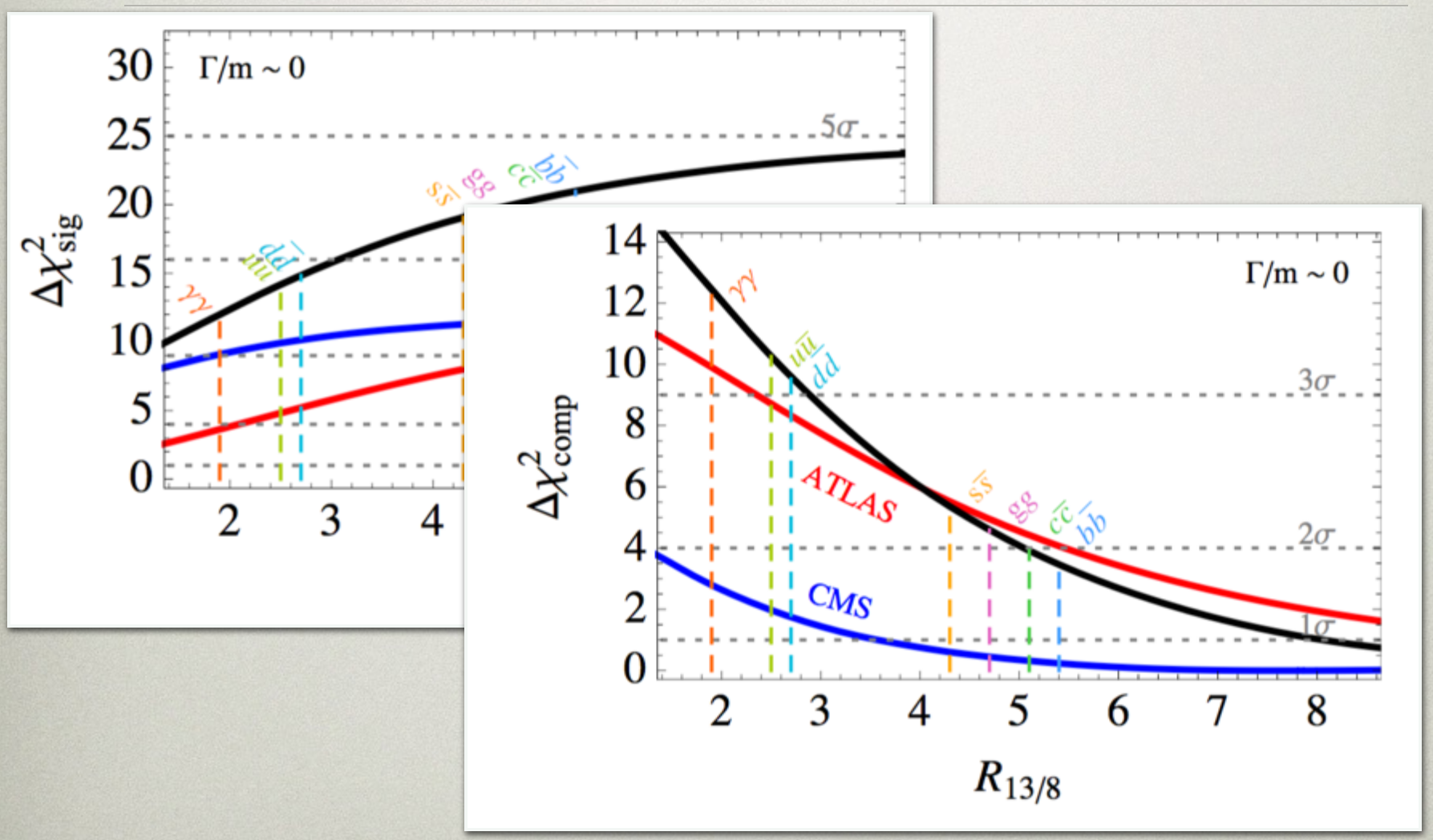
http://cp3.irmp.ucl.ac.be/~mbackovic/

CONCLUSIONS

- diphoton signal + EFT implies signals in ZZ, WW, $Z\gamma$
- after discovery established: determining production mode essential

BACKUP SLIDES

NARROW WIDTH



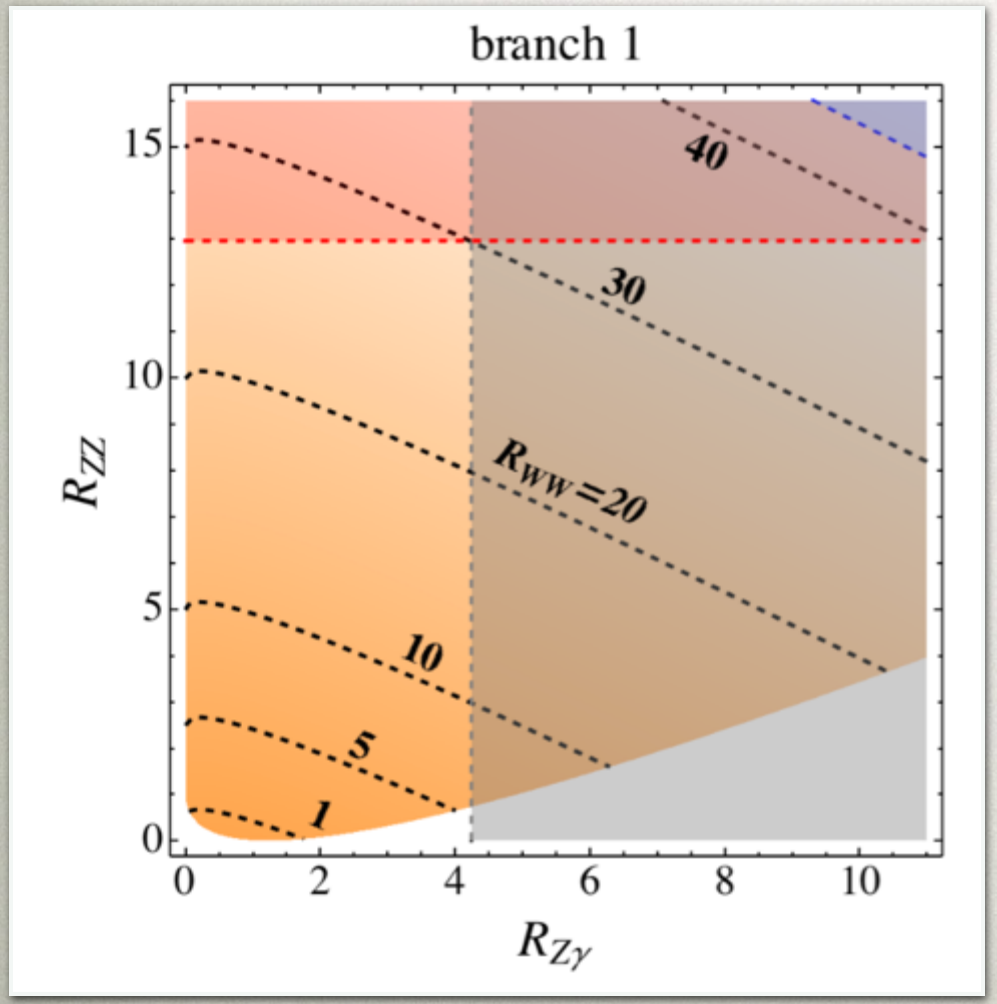
SIGNAL RATE

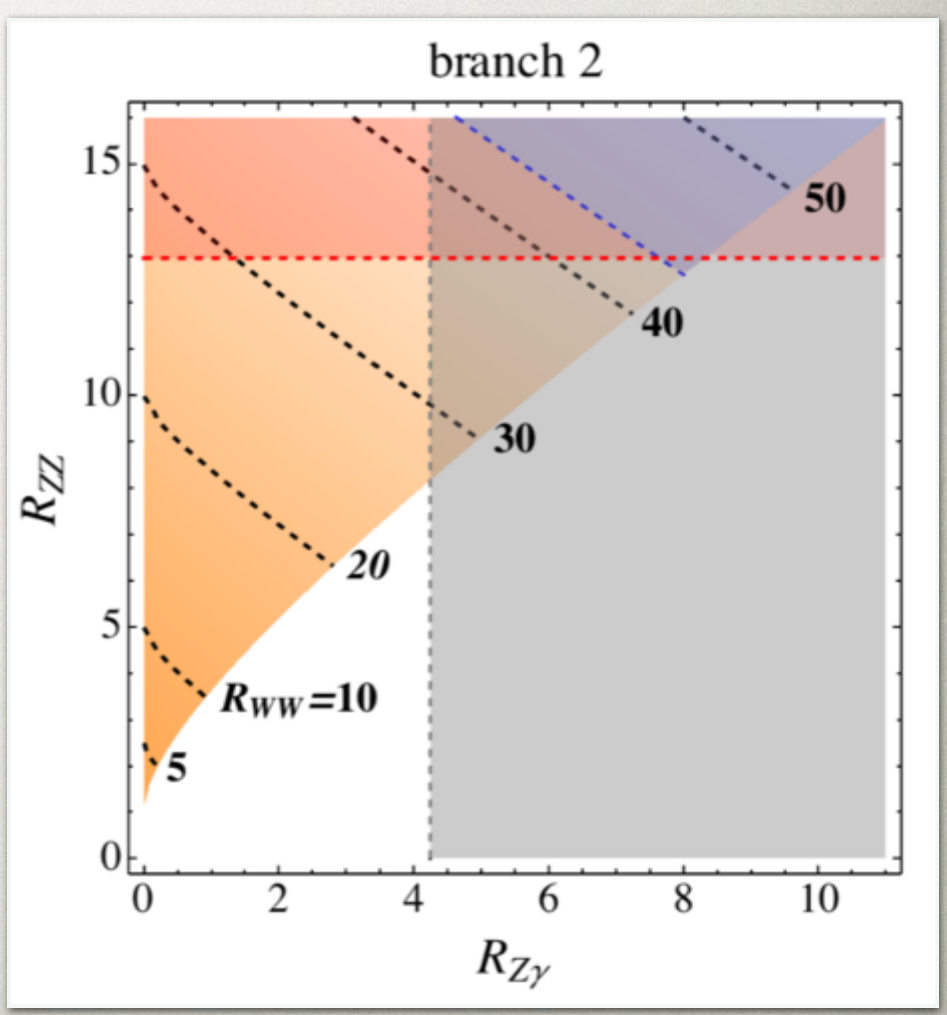
	narrow width ($\Gamma/m \to 0$)		wide width ($\Gamma/m = 6\,\%$)	
production mech.	spin-0	spin-2	spin-0	spin-2
$\gamma\gamma$	1.2 ± 0.4	1.8 ± 0.5	2.8 ± 0.7	4.4 ± 1.2
gg	3.2 ± 0.7	4.7 ± 1.0	6.1 ± 1.3	9.6 ± 2.1
$u\bar{u}$	1.7 ± 0.4	2.5 ± 0.7	3.7 ± 0.9	5.9 ± 1.4
$d\bar{d}$	1.9 ± 0.5	2.7 ± 0.7	4.0 ± 1.0	6.3 ± 1.5
$s\bar{s}$	2.9 ± 0.7	4.4 ± 1.0	5.8 ± 1.3	9.1 ± 2.0
$c\bar{c}$	3.4 ± 0.8	5.0 ± 1.1	6.4 ± 1.3	10.1 ± 2.1
$b\bar{b}$	3.6 ± 0.8	5.3 ± 1.1	6.6 ± 1.4	10.3 ± 2.2

- also bounds

$$\mathcal{R}_{WW} \lesssim 20 \left(\frac{R_{13/8}8\text{fb}}{5\sigma_{\gamma\gamma}}\right) \approx \frac{170\,\text{fb}}{\sigma_{\gamma\gamma}},$$
$$\mathcal{R}_{ZZ} \lesssim 6 \left(\frac{R_{13/8}8\text{fb}}{5\sigma_{\gamma\gamma}}\right) \approx \frac{52\,\text{fb}}{\sigma_{\gamma\gamma}},$$
$$\mathcal{R}_{Zh} \lesssim 10 \left(\frac{R_{13/8}8\text{fb}}{5\sigma_{\gamma\gamma}}\right) \approx \frac{90\,\text{fb}}{\sigma_{\gamma\gamma}},$$
$$\mathcal{R}_{hh} \lesssim 20 \left(\frac{R_{13/8}8\text{fb}}{5\sigma_{\gamma\gamma}}\right) \approx \frac{170\,\text{fb}}{\sigma_{\gamma\gamma}},$$

MIXING CASE, BOTH BRANCHES





VBF PRODUCTION, BOTH BRANCHES