THE FATE OF THE F(750)

SWHEPPS 2016

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Aegeri - 07 June 2016

Mainly based on arXiv:1512.04933 and arXiv:1604.06446
in collaboration with R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia

Status

SUMMARY

Citation: Particle Data Group, 2016 update

$\boxed{F\ (750_{000})}$

$I(J^P) = ?(0^?)$

J needs confirmation

OMITTED FROM SUMMARY TABLE

Needs confirmation.

F MASS

VALUE (GeV)	EVTS	DOCUMENT ID	TECN	COMMENT
750 ± 30 OUR AVERAGE		ATLAS, CMS		$pp \to F$

• • • We do not use the following data for average, fits, limits, etc. • • •

F WIDTH

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<100	95	ATLAS, CMS		$pp \to F$

• • • We do not use the following data for average, fits, limits, etc. • • •

F DECAY MODES

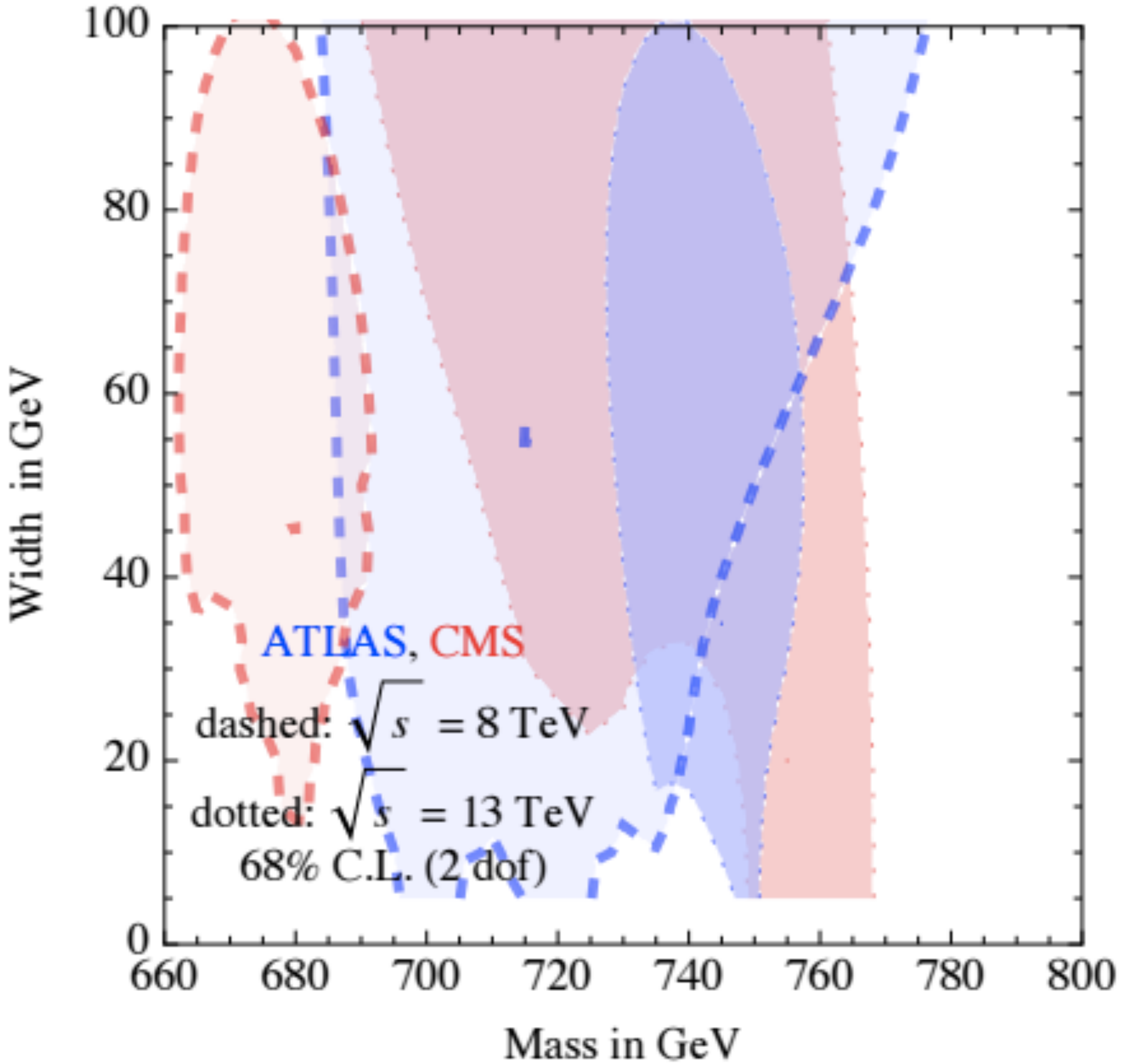
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\gamma\gamma$	seen
Γ_2	$\gamma Z, ZZ, jj$	expected

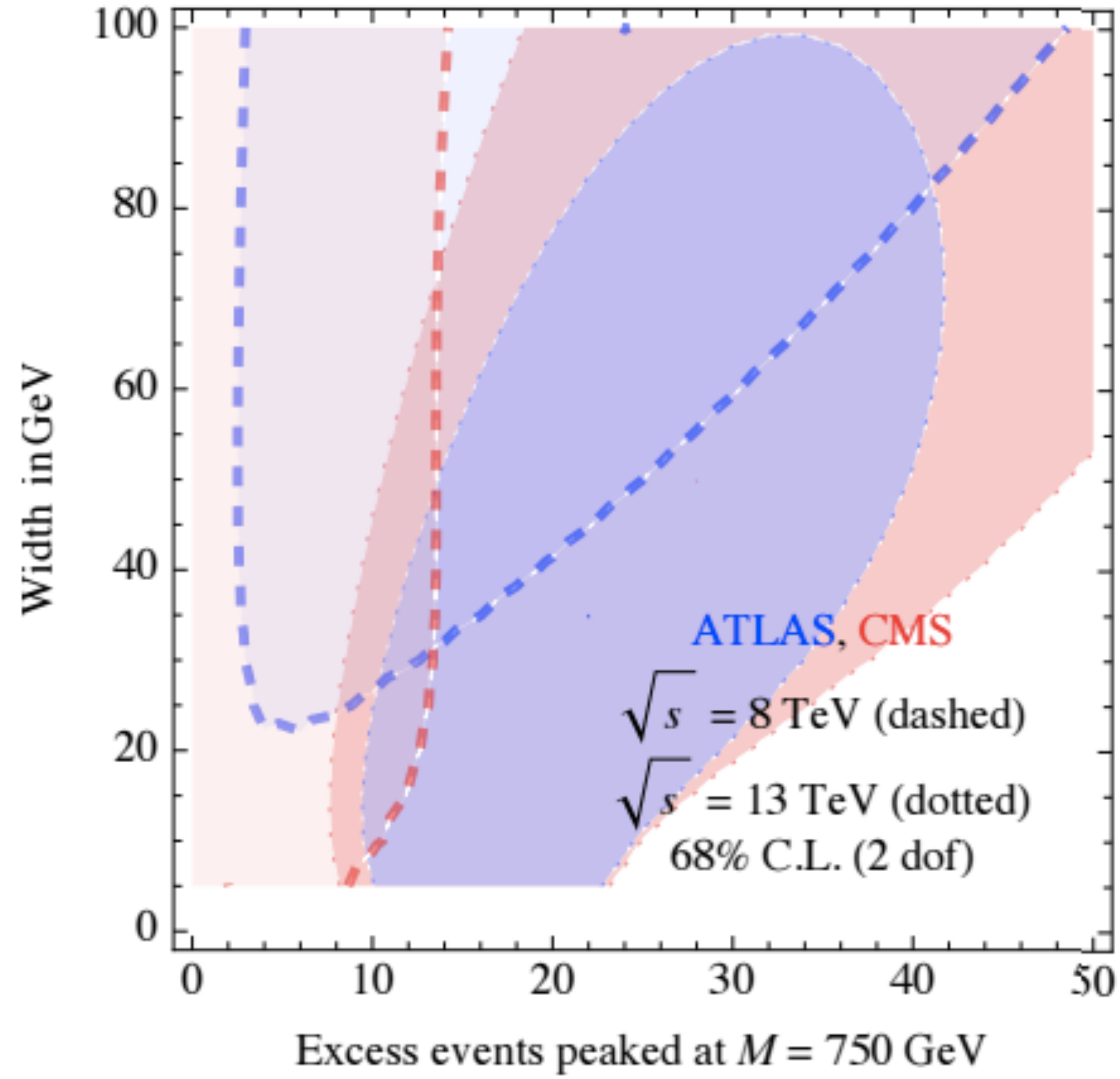
A. Srumia, 1605.09401 [hep-ph]

ATLAS: 3.9σ local

CMS: 3.4σ local

SUMMARY





Fitted signal rate in diphoton in the few fb region depending on the width assumption

Not much information on the width, which however could be large and measurable

Prospects

PRODUCTION

Spin is not known, it can be any integer except 1 (Landau-Yang)

The limited statistics makes the dependence of the observed rate on the spin weak

From model building point of view spin-0 and singlet under the SM gauge group seems favoured

We present our results for a spin-0 singlet for concreteness

It can be extended in a similar way to different spin/quantum numbers

$$\sigma(pp \to F) = \frac{1}{s} \sum_{\wp} C_{\wp} \frac{\Gamma_{\wp}}{M_F}$$

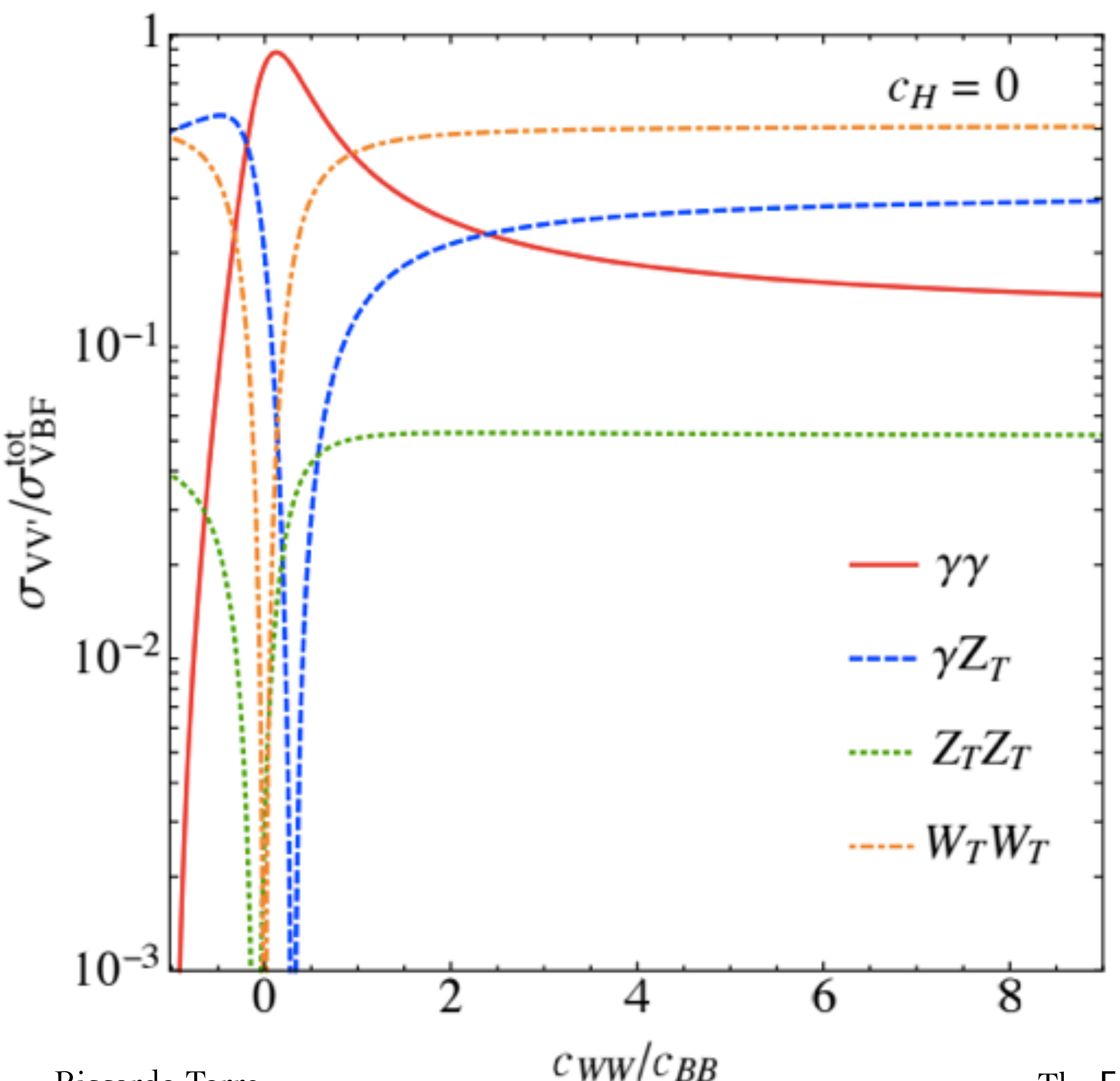
$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}	$C_{\gamma\gamma}$	$C_{Z_LZ_L}$	$C_{Z_TZ_T}$	$C_{Z_T\gamma}$	$C_{W_LW_L}$	$C_{W_TW_T}$
8 TeV	1.07	2.7	7.2	89	158	174	11(8)	0.01	0.3	3.1	0.03	0.8
13 TeV	15.3	36	83	627	1054	2137	54(64)	0.14	2.8	27	0.4	8

$$\begin{aligned}\sigma(pp \to F) \quad = \quad & \Big[4900\frac{\Gamma_{gg}}{M_F} + 2400\frac{\Gamma_{u\bar{u}}}{M_F} + 1400\frac{\Gamma_{d\bar{d}}}{M_F} + 190\frac{\Gamma_{s\bar{s}}}{M_F} + 83\frac{\Gamma_{c\bar{c}}}{M_F} + 35\frac{\Gamma_{b\bar{b}}}{M_F} + \\ & +150\frac{\Gamma_{\gamma\gamma}}{M_F} + 62\frac{\Gamma_{Z\gamma}}{M_F} + 18\frac{\Gamma_{W_TW_T}}{M_F} + 0.92\frac{\Gamma_{W_LW_L}}{M_F} + 6.5\frac{\Gamma_{Z_TZ_T}}{M_F} + 0.32\frac{\Gamma_{Z_LZ_L}}{M_F}\Big]\,\mathrm{pb}\end{aligned}$$

PRODUCTION: VBF

The case in which the new particle is produced in photon fusion has been studied extensively

This only makes sense if its interactions are not SU(2) invariant, otherwise one should consider all VBF channels



$\sqrt{s}$	$C_{\gamma\gamma}$	$C_{Z_L Z_L}$	$C_{Z_T Z_T}$	$C_{Z_T \gamma}$	$C_{W_L W_L}$	$C_{W_T W_T}$
8 TeV	11(8)	0.01	0.3	3.1	0.03	0.8
13 TeV	54(64)	0.14	2.8	27	0.4	8

The relevance of the various channels depend on parton luminosities and partial widths

Photon fusion dominates only when coupling to hypercharge gauge bosons is much larger than coupling to SU(2) ones

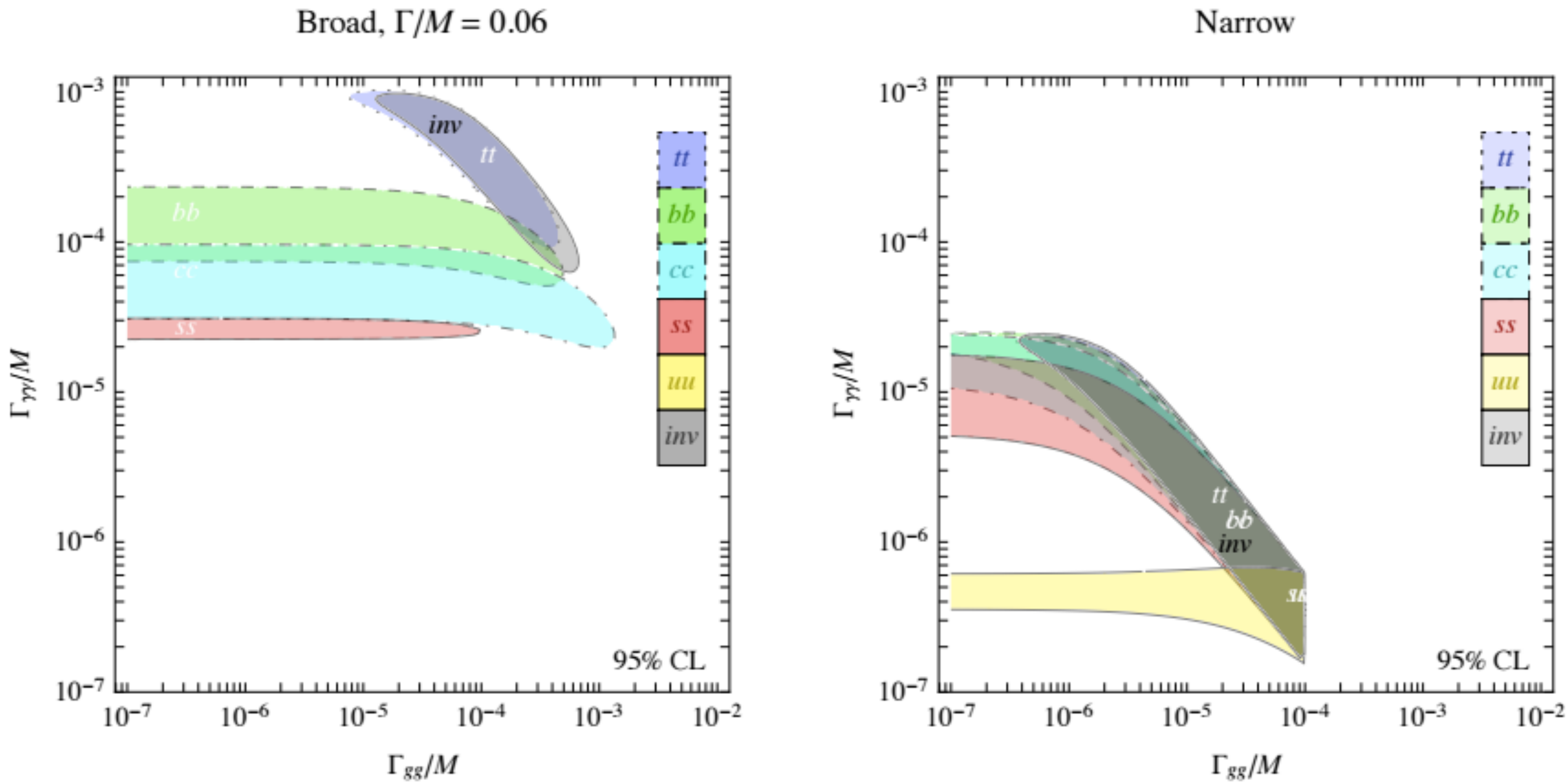
There is a large region where W fusion dominates and photon fusion is suppressed

DECAY: CP-EVEN

Global fit assuming coupling to photons, gluons and a third particle

Large width more difficult to explain since a large width into photons is required (typically generated from loops of fermions/scalars and expected to be small)

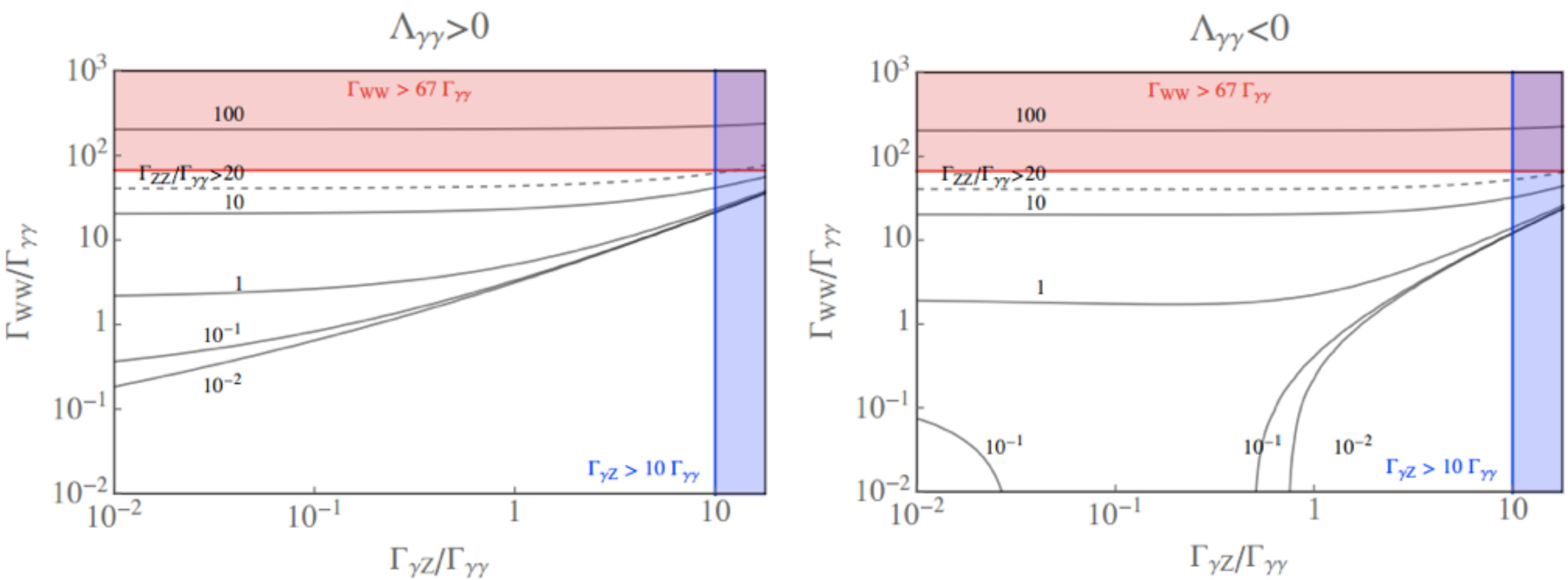
Large width generally points toward large couplings/multiplicities, i.e. strong coupling



DECAY: CP-EVEN

In the case of a CP-even scalar singlet, and considering the most general effective Lagrangian up to dim-6, the four diboson channels $\Gamma_{\gamma\gamma}$, $\Gamma_{\gamma Z}$, Γ_{ZZ}, $\Gamma_{W^+W^-}$ only depend on three parameters

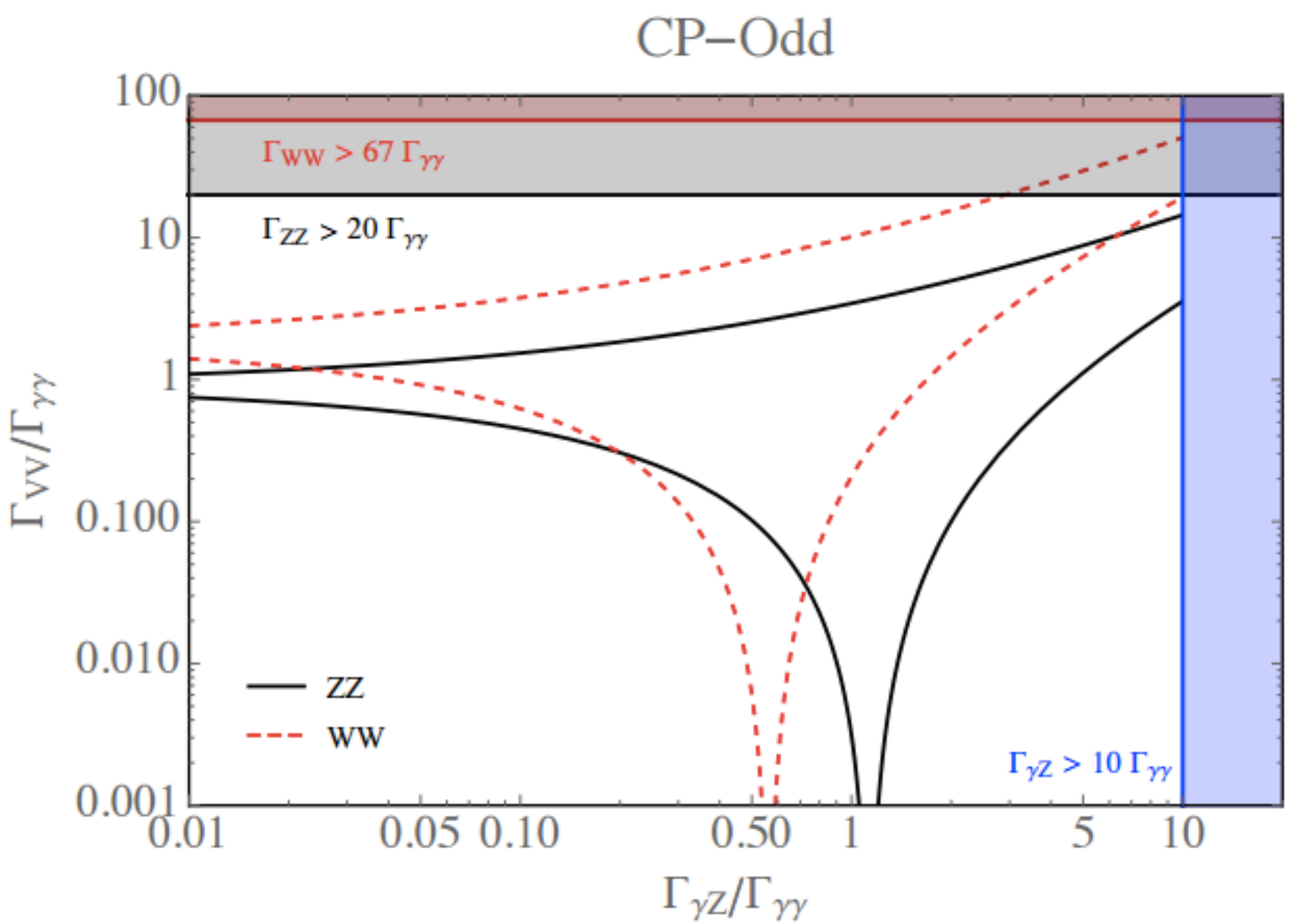
Therefore once two ratios are measures, say $\Gamma_{W^+W^-}/\Gamma_{\gamma\gamma}$ and $\Gamma_{\gamma Z}/\Gamma_{\gamma\gamma}$, the third is predicted, $\Gamma_{ZZ}/\Gamma_{\gamma\gamma}$



DECAY: CP-ODD

In the CP-odd case there are only two parameters

Therefore once one ratio is measured the other two are predicted



3-BODY DECAYS

The operator $1/\Lambda_\Psi F H\psi_L\psi_R$, generally present for a CP-even singlet, allows for an unsuppressed 3-body decay into $V\bar{\psi}\psi$ or $H\bar{\psi}\psi$, which is of order of % compared to the two body decay

Splitting of massless gauge bosons into two fermions(gauge bosons) are enhanced by single(double) infrared logs (exclusive rates)

For gluons one has (using cuts $p_T > 150\ \mathrm{GeV},\ |\eta| < 5,\ \Delta R_{jj} > 0.4$)

$$\frac{\sigma\left(pp \to F \to ggg\right)}{\sigma\left(pp \to F \to gg\right)} \approx 11\%$$

In the case of photons

$$\sum_{\wp} \Gamma(F \to \gamma \wp^- \wp^+) \approx 22\% \times \Gamma(F \to \gamma\gamma)$$

where 5% comes from W, 4% from u-quarks, 4% from e, etc.

In general one cannot reconstruct CP from 3-body decays and should consider 4-body processes

4-BODY DECAYS

Decay to four gluons would in principle allow to measure CP looking at angular distributions. However this is practically limited due to the difficulty in reconstructing the kinematics of the four jets in the region sensitive to CP

Decay into four leptons more promising (analog to π^0)

Defining ϕ as the relative angle between the planes of the two e^+e^- pairs in the centre-of-mass frame (such that for $\phi = 0$ the two pairs lie in a common plane with the same-sign leptons adjacent to each other).

$$\frac{2\pi}{\Gamma_{4\ell}} \frac{d\Gamma_{4\ell}}{d\phi} = 1 + \kappa_1 \cos 2\phi + \kappa_2 \sin 2\phi$$

decay	$\Gamma_{4\ell}/\Gamma_{\gamma\gamma}$	κ_1
$eeee$	3.63×10^{-4}	∓ 0.235
$\mu\mu\mu\mu$	1.36×10^{-4}	∓ 0.216
$\tau\tau\tau\tau$	0.49×10^{-4}	∓ 0.195
$ee\mu\mu$	4.12×10^{-4}	∓ 0.224
$ee\tau\tau$	2.56×10^{-4}	∓ 0.194
$\mu\mu\tau\tau$	1.64×10^{-4}	∓ 0.205

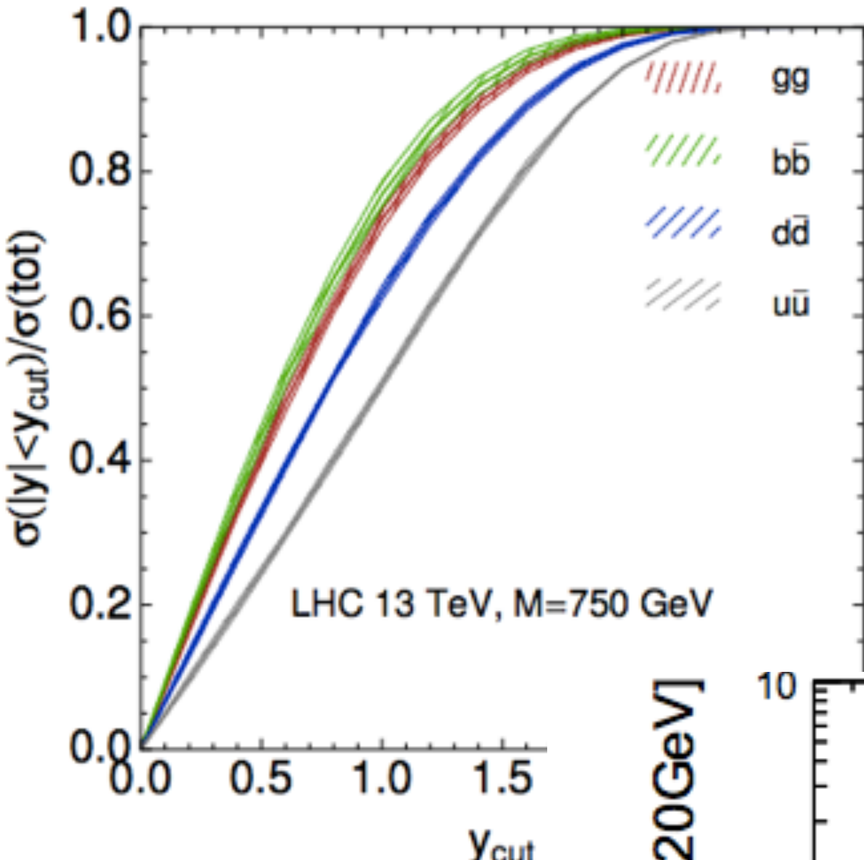
The sign of κ_1 allows to measure the CP properties of F

In the case the decay to ZZ is observed an analysis similar to the Higgs could be done (taking into account that couplings to longitudinal/transverse can be different)

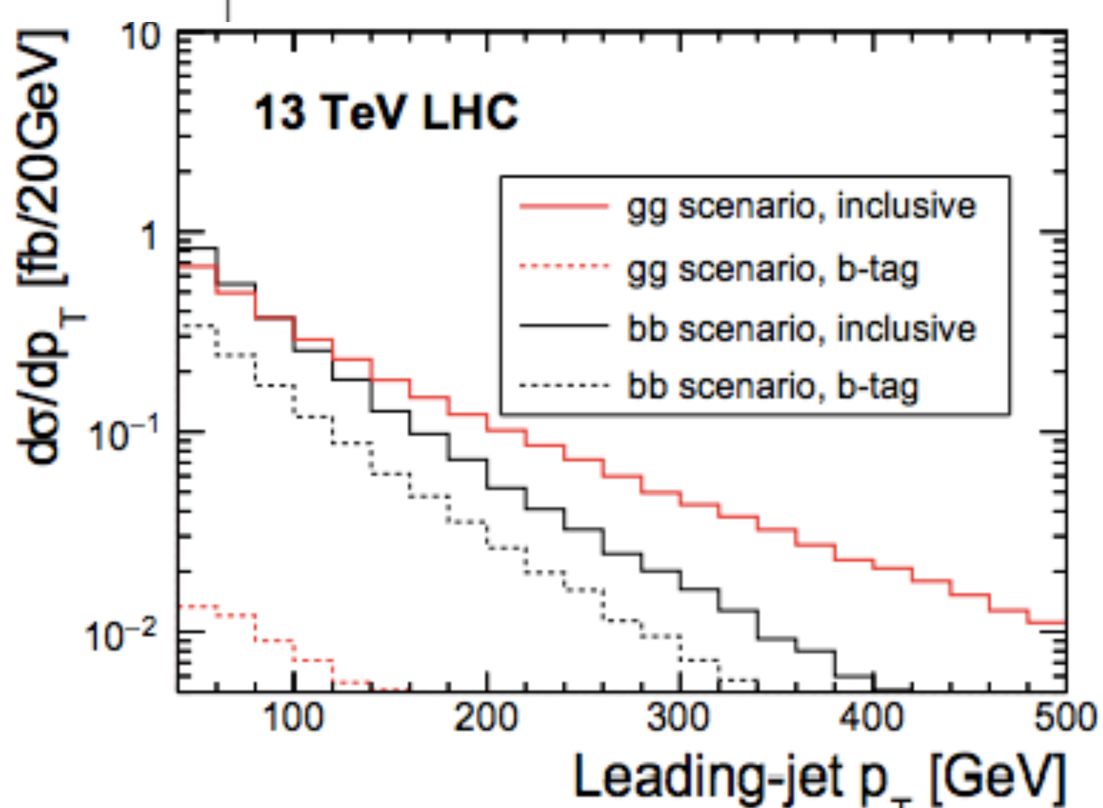
INITIAL STATE FROM FJ

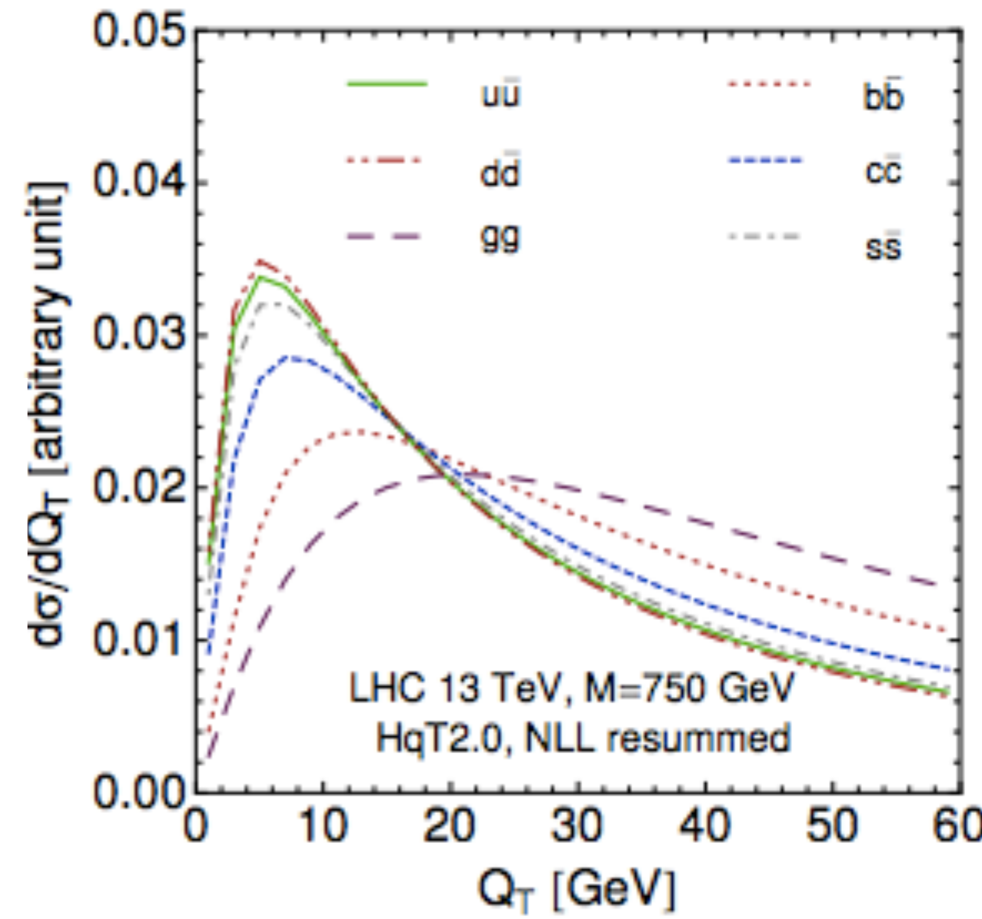
The production of F in association with a jet could be a potential probe of the production mechanism (initial state)

$\sqrt{s} = 13\,\mathrm{TeV}$	eq.	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	GG
		F couples to					
σ_{Fj}/σ_F	(20a)	9.2%	7.6%	6.8%	6.7%	6.2%	27.%
σ_{Fb}/σ_F	(20b)	6.2%	0	0	0	0	0.32%



Gao, Zhang, Zhu, 1512.08478 [hep-ph]





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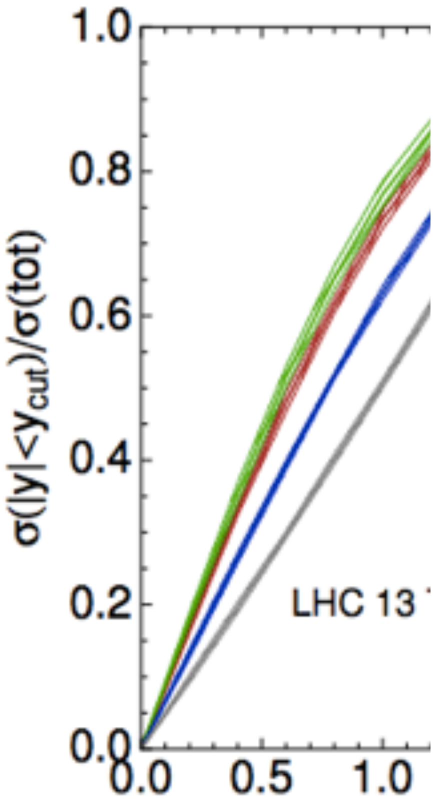
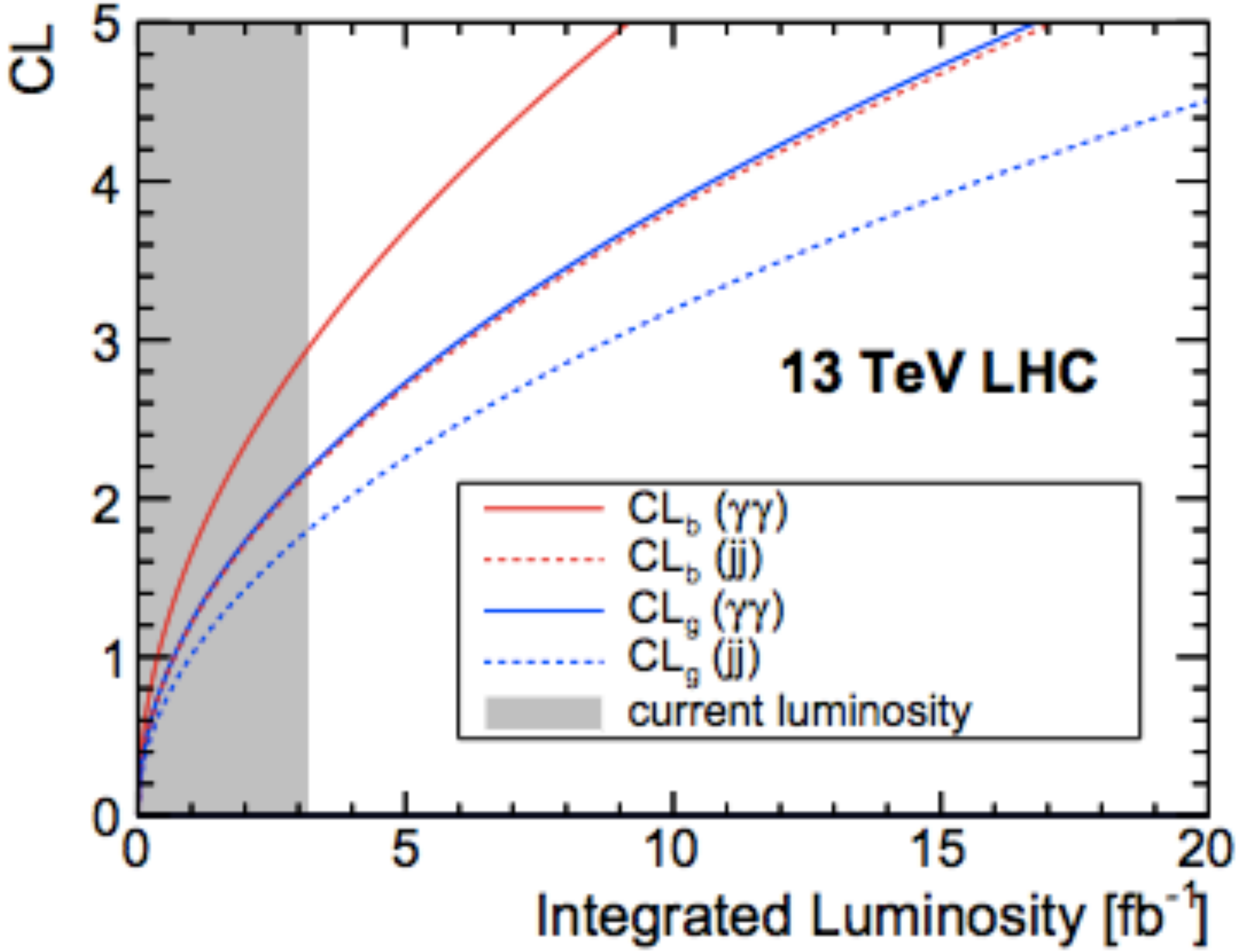
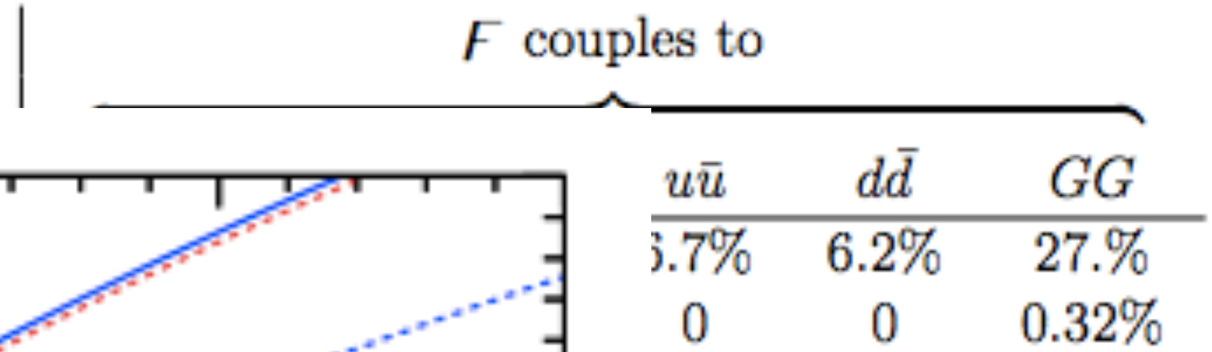
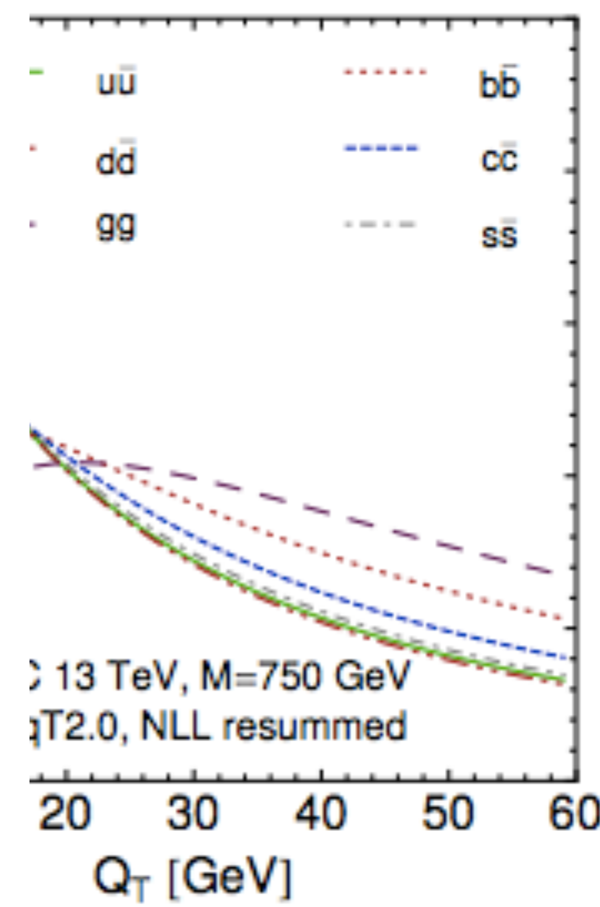
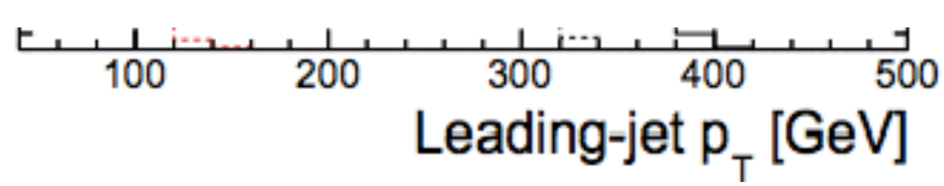








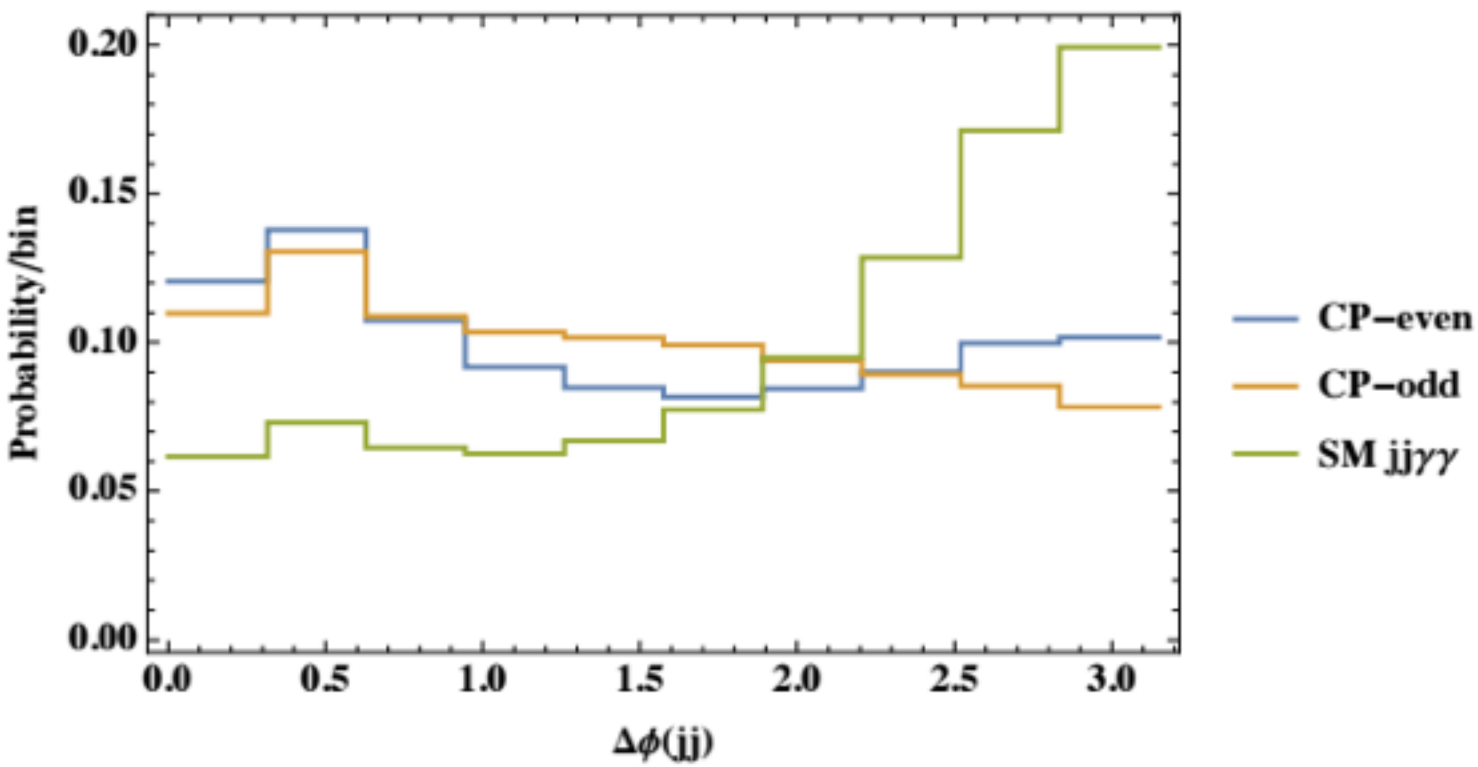


CP FROM F JJ

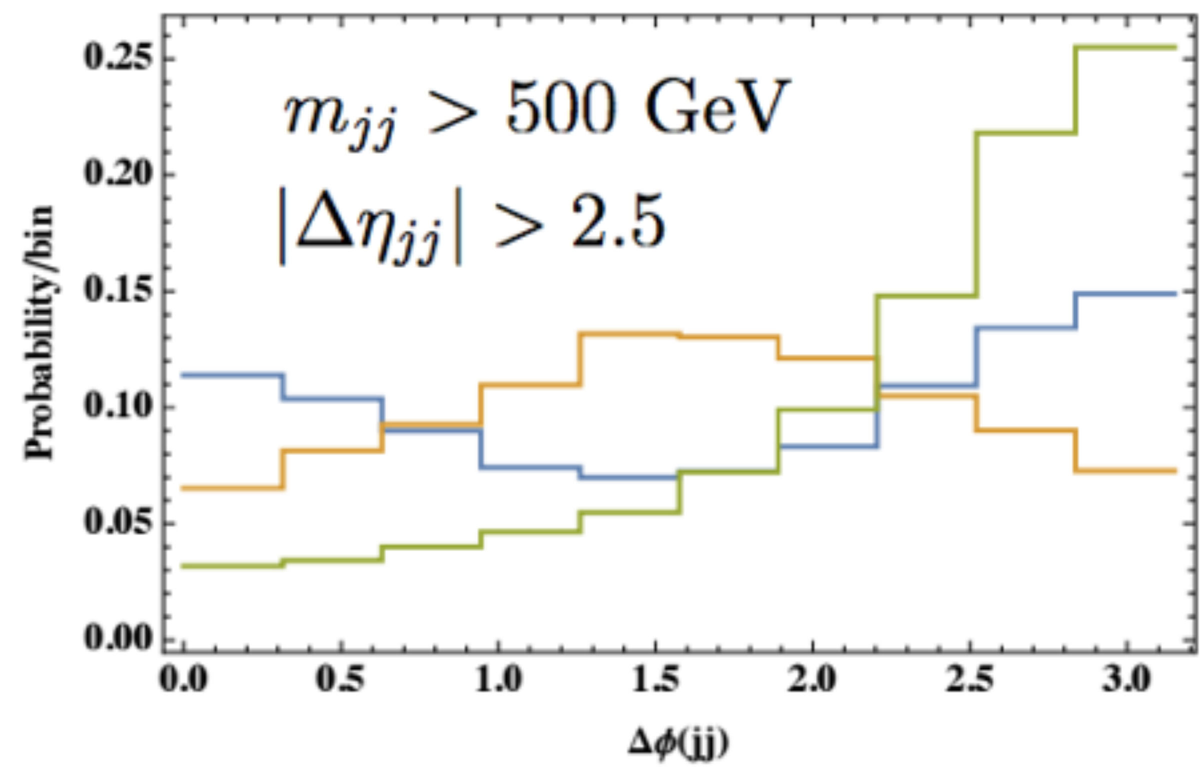
The production of F in association with two jets could allow to measure the CP properties of F. Analogously to the Higgs one can exploit the $\Delta\phi_{jj}$

$$|\eta_j| < 5, \qquad p_T > 75 \text{ GeV}$$

$$p_{T,\gamma_1} > 40 \text{ GeV}, \qquad p_{T,\gamma_2} > 30 \text{ GeV}, \qquad \eta_\gamma < 2.37, \qquad 700 \text{ GeV} < m_{\gamma\gamma} < 800 \text{ GeV}$$



85% CL



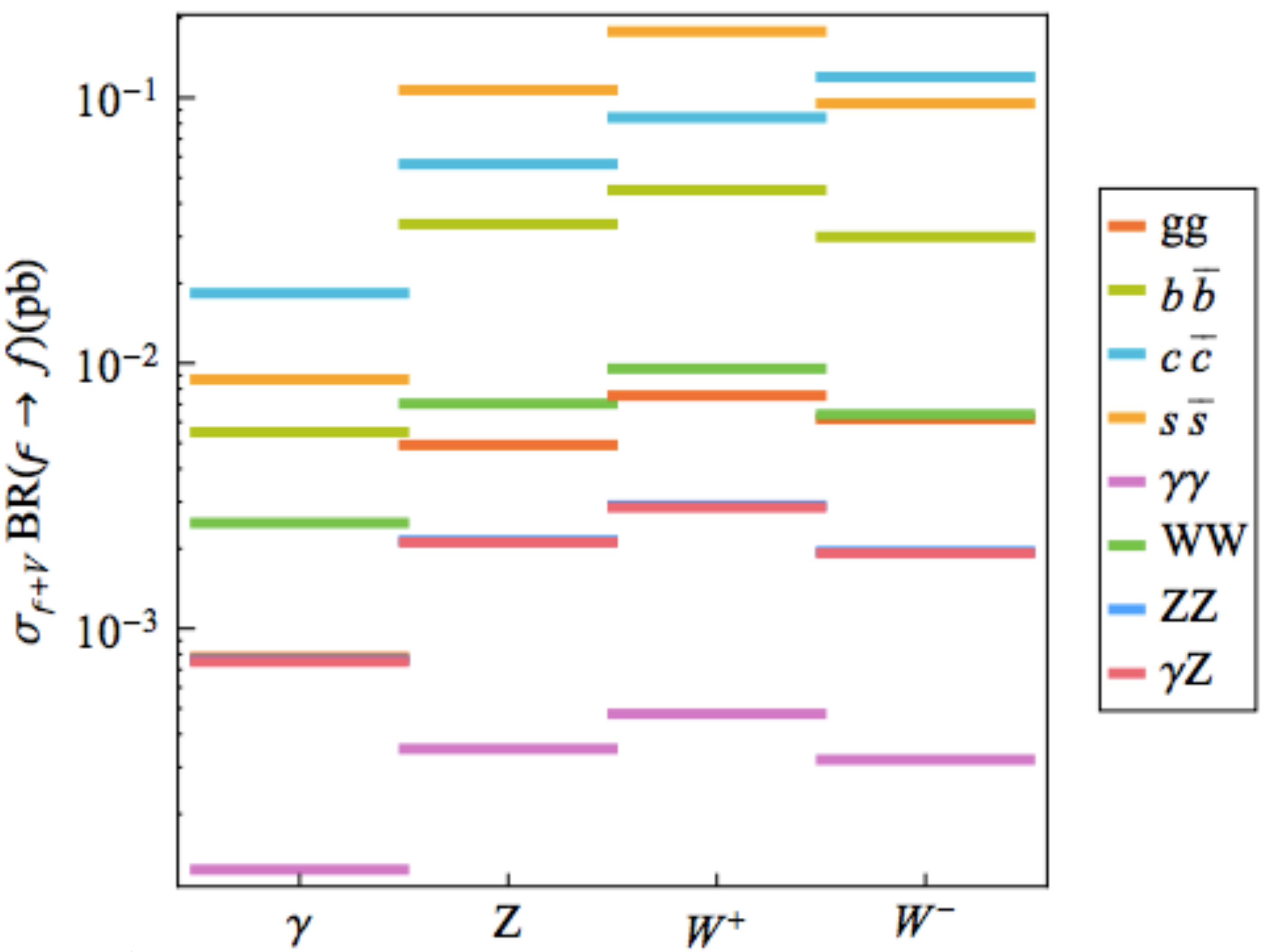
95% CL

CP-even(odd) hypothesis rejection with 100 fb^{-1}

Similar results can be achieved exploiting the thrust event shape

ASSOCIATED PRODUCTIONS

$\sqrt{s} = 13\,\text{TeV}$	eq.	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	GG
		$\mathcal{F}$ couples to					
$\sigma_{\mathcal{F}\gamma}/\sigma_{\mathcal{F}}$	(28b)	0.37%	1.5%	0.38%	1.6%	0.41%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}Z}/\sigma_{\mathcal{F}}$	(28b)	1.1%	1.1%	1.3%	2.0%	1.9%	$3\ 10^{-6}$
$\sigma_{\mathcal{F}W^+}/\sigma_{\mathcal{F}}$	(28c)	$5\ 10^{-5}$	1.7%	2.4%	2.6%	4.1%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}W^-}/\sigma_{\mathcal{F}}$	(28d)	$3\ 10^{-5}$	2.3%	1.2%	1.0%	1.7%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}h}/\sigma_{\mathcal{F}}$	(28e)	1.0%	1.1%	1.2%	1.9%	1.8%	$1\ 10^{-6}$



Measurements of associated productions with EW gauge bosons can allow to distinguish different channels and measure different couplings in the case of production from quark annihilation

PAIR PRODUCTION: LET

Consider a toy renormalizable model $\mathscr{L}_{\mathcal{Q}} = \sum \bar{\mathcal{Q}}_r (i\not{D} - M_r - y_r \mathcal{F}) \mathcal{Q}_r$

LET => $\mathscr{L}_{\text{LET}} = \sum \left(I_r N_r \frac{\alpha_3}{6\pi} G^{a\mu\nu} G^a_{\mu\nu} + q_r^2 N_r' \frac{\alpha}{6\pi} F^{\mu\nu} F_{\mu\nu} \right) \ln \left(1 + \frac{\mathcal{F}}{v_r} \right)$ $\qquad v_r \equiv \frac{M_r}{y_r}$

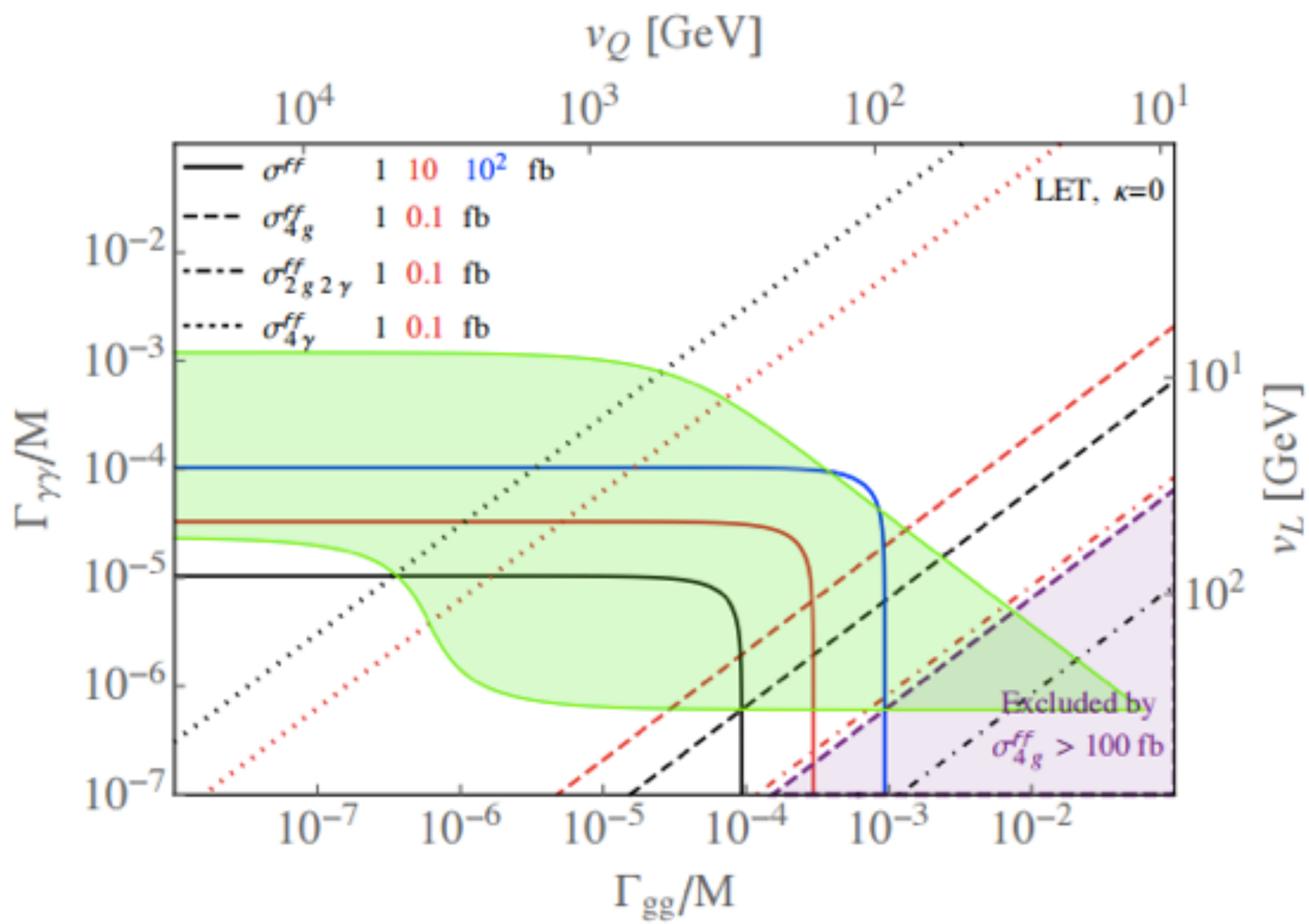


Figure 16: *Within the green region one can reproduce the di-photon excess $\sigma(pp \to \gamma\gamma) \approx 3\,\text{fb}$ at the 13 TeV LHC. Contours of constant $\sigma(pp \to \mathcal{F}\mathcal{F})$ are shown as solid lines, $\sigma(pp \to \mathcal{F}\mathcal{F} \to 4g)$ as dashed, $\sigma(pp \to \mathcal{F}\mathcal{F} \to \gamma\gamma gg)$ as dotdashed, and $\sigma(pp \to \mathcal{F}\mathcal{F} \to 4\gamma)$ as dotted. These cross sections are computed using LET with two triplets of coloured fermions and three leptons with unit charge, and the $\mathcal{F}^3$ coupling is set to zero. The required scales $v_Q = M_Q/y_Q$ and $v_L = M_L/y_L$ are also shown.*

Summary: at LHC

SUMMARY: MEASURING F PROPERTIES

Is this signal due to a resonance or to more complicated kinematics?

- Look at the events to find more structure
- Look at interference with SM (processes with different structure don't interfere)
- More statistics would allow to exclude two/more nearby resonances
- Distribution of MET very important to distinguish associated production involving DM

Spin

- Look at the angular distribution of the two photons

C-P properties

- If ZZ is observed soon look at 4-lepton distributions (like for the Higgs)
  Here differently from the Higgs this could be CP-even but still coupling only to transverse bosons, which can make things harder!
- The angular distribution of jets in Sjj events can be a good discrimination
- Observing the hh channel means is CP-even
- Observing the Zh channel means is CP-odd

SU(2) quantum numbers

- Associated productions with W, Z, h and pair production

Other properties

- Pair production
- Precise measurements of the S properties may require a Future Collider

Future: post-LHC

LEPTON COLLIDERS

	Triple LEP (see FCC)	International Linear Collider	Compact Linear Collider
e^+e^-	circular	linear	
$\sqrt{s}$	350 GeV	500 GeV	3000 GeV
acceleration gradient	20 MV/m	31.5 MV/m	100 MV/m
site length	80 - 100 km	31 km	48.4 km
feasibility	mostly LHC technology	mostly LHC technology	new technology
cost	2.5/4.5 billion CHF (tunnel) 2/3 billion CHF (rest, most RF)	7.8 billion CHF	8.3 billion CHF

LEPTON COLLIDERS

	Triple LEP (see FCC)	International Linear Collider	Compact Linear Collider
e^+e^-	circular	linear	
$\sqrt{s}$	350 GeV	500 GeV	3000 GeV

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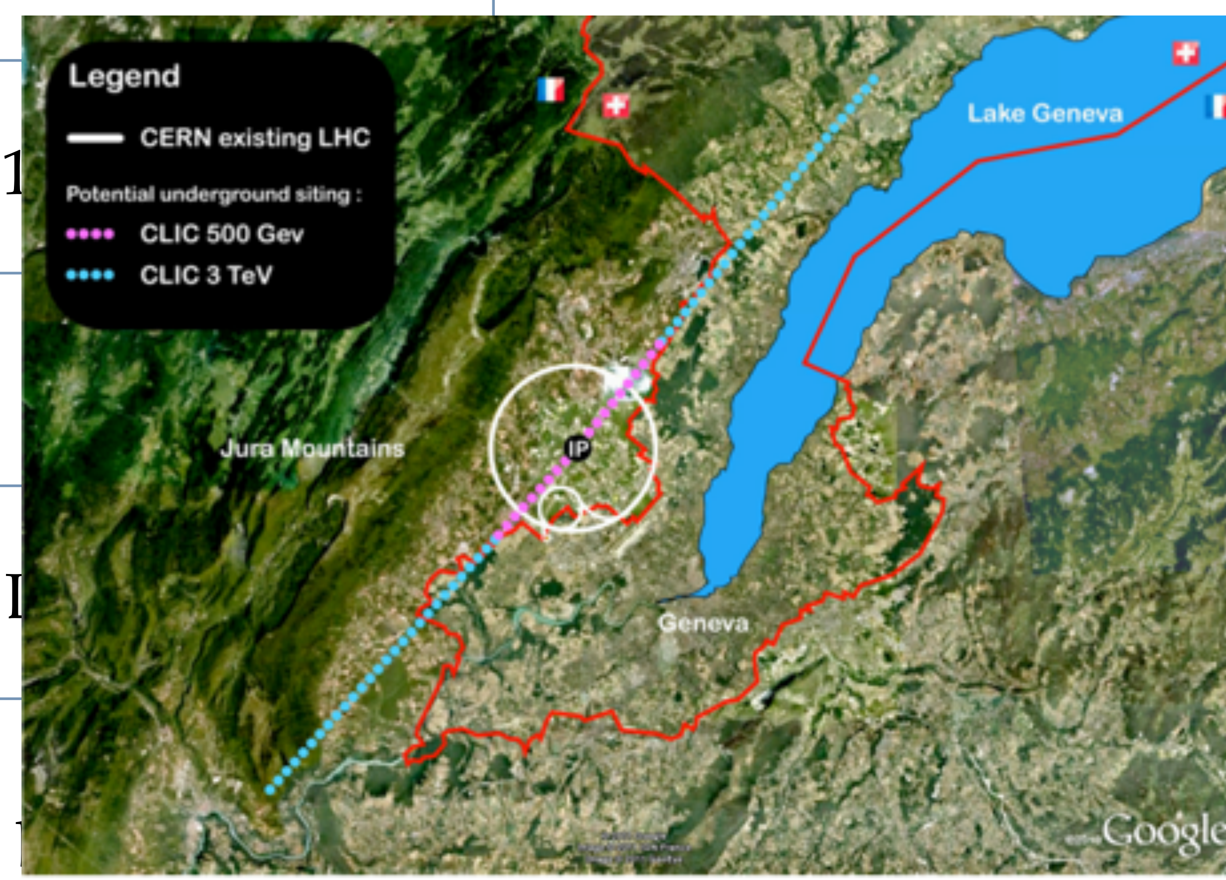
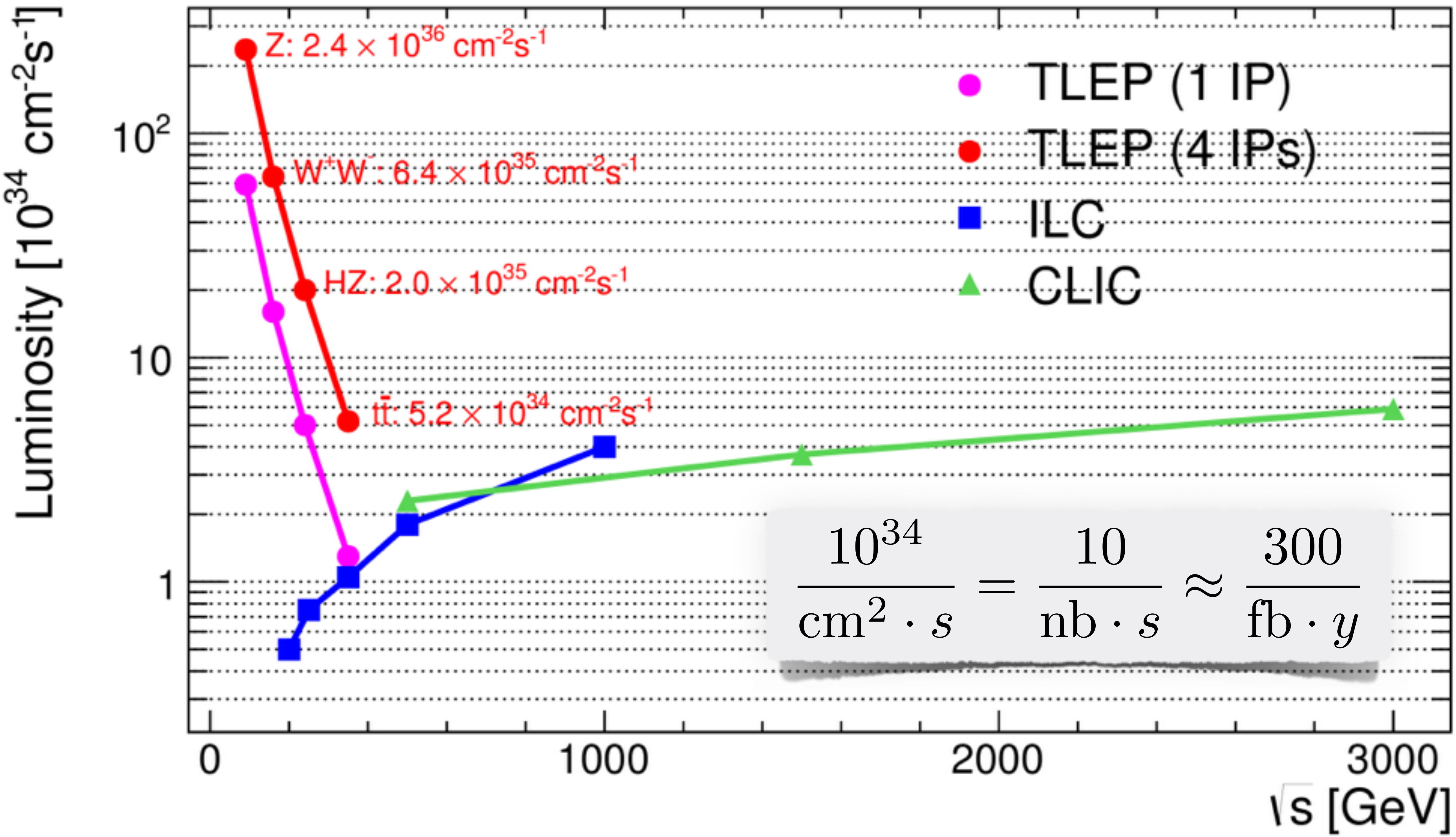


2/3 billion CHF (rest, most RF)

LEPTON COLLIDERS



$$\frac{10^{34}}{\mathrm{cm}^2 \cdot s} = \frac{10}{\mathrm{nb} \cdot s} \approx \frac{300}{\mathrm{fb} \cdot y}$$

2/3 billion CHF (rest,
most RF)

HADRON COLLIDERS

see FCC report (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider)
BSM chapter recently on arXiv: 1606.00947, other channels coming soon

	Future Circular Collider FCC-hh
pp	circular
$\sqrt{s}$	80 - 100 TeV
final luminosity	> 3-10/ab
site length	80 - 100 km
feasibility	new technology
cost	2.5/4.5 billion CHF (tunnel) 2/3 billion CHF (rest, most RF))

HADRON COLLIDERS

	CepC/SppC
pp/e^+e^-	circular
$\sqrt{s}$	240 GeV (ee) - 50/70 TeV (pp)
final luminosity	> 3-10/ab
site length	50 - 70 km
feasibility	new technology
cost	CE → CE much cheaper

WHAT IF F(750) IS TRUE?

Consider two scenarios:

- **LHC Run 2 and HL-LHC do not find new physics**
  - The measurement of the Higgs boson couplings becomes the raison d'être for the HL-LHC
  - After ~1/ab (~2030) still have fairly good detectors, but are facing diminishing return
  - If the high-field magnet technology is ready, stop the HL-LHC and upgrade to run at 33 TeV in ~2035 (less than 20 years from now!)
  - Get ~3/ab @ 25ns with the HL-LHC pileup and ATLAS+CMS Phase II detectors, with the focus on the Higgs boson self-coupling measurement
- **Possibly the only machine we could afford in this scenario**
  - If HE-LHC finds new physics (or CEPC points to a concrete energy scale), go for ~100 TeV machine and reuse the HE-LHC magnets (1/3 of the full number needed for the FCC)

- **LHC Run 2 finds new physics (e.g., X(750))**
  - The scope of the program shifts toward study of its properties
  - Almost all the models predict other partners, which may very well be reachable at 33 TeV
  - Do not want to wait 35 years for the new machine - want to build it as soon as possible
- **Possibly revolutionize the field and break the spell of a flat funding**
  - Consider a 33 TeV machine to be a 30% demonstrator of the FCC at a ~10% cost
  - N.B. cost(33) ~ (cost(100) - CHF 10B)/3 ~ 5B [10B = tunnel + 2 detectors]

From discussion session 33 vs 100 TeV (Landsberg & Incandela), KITP Workshop on Future Colliders, UCSB, last week

Conclusions

CONCLUSION

- The hints for an excess of events in the di-photon spectrum both from ATLAS and CMS with the first data at 13 TeV have generated a lot of excitement
- The excess deserves to be taken seriously due to its presence in both experiments in the same region (though with a modest statistical significance) and to the extremely simple and clean final state, not (directly) involving complicated coloured objects
- If the new particle is discovered, a lot of new measurements should be done to understand its properties: spin, CP, EW quantum numbers, etc.
- Moreover, the presence of the new resonance suggests the existence of other states in the TeV region, which the LHC may be able to see (or at least start seeing)
- A complete measurements of F properties and related states, may however require a higher energy collider
- Proton colliders seem more suitable for this, but, depending on the couplings, also a lepton collider above threshold could be an interesting option
- The possibility of an intermediate step at 33 TeV before going for an FCC at 100 TeV also seem plausible and reasonable

THANK YOU

Backup

PAIR PRODUCTION

One insertion of dim-5 operators (trilinear interaction)

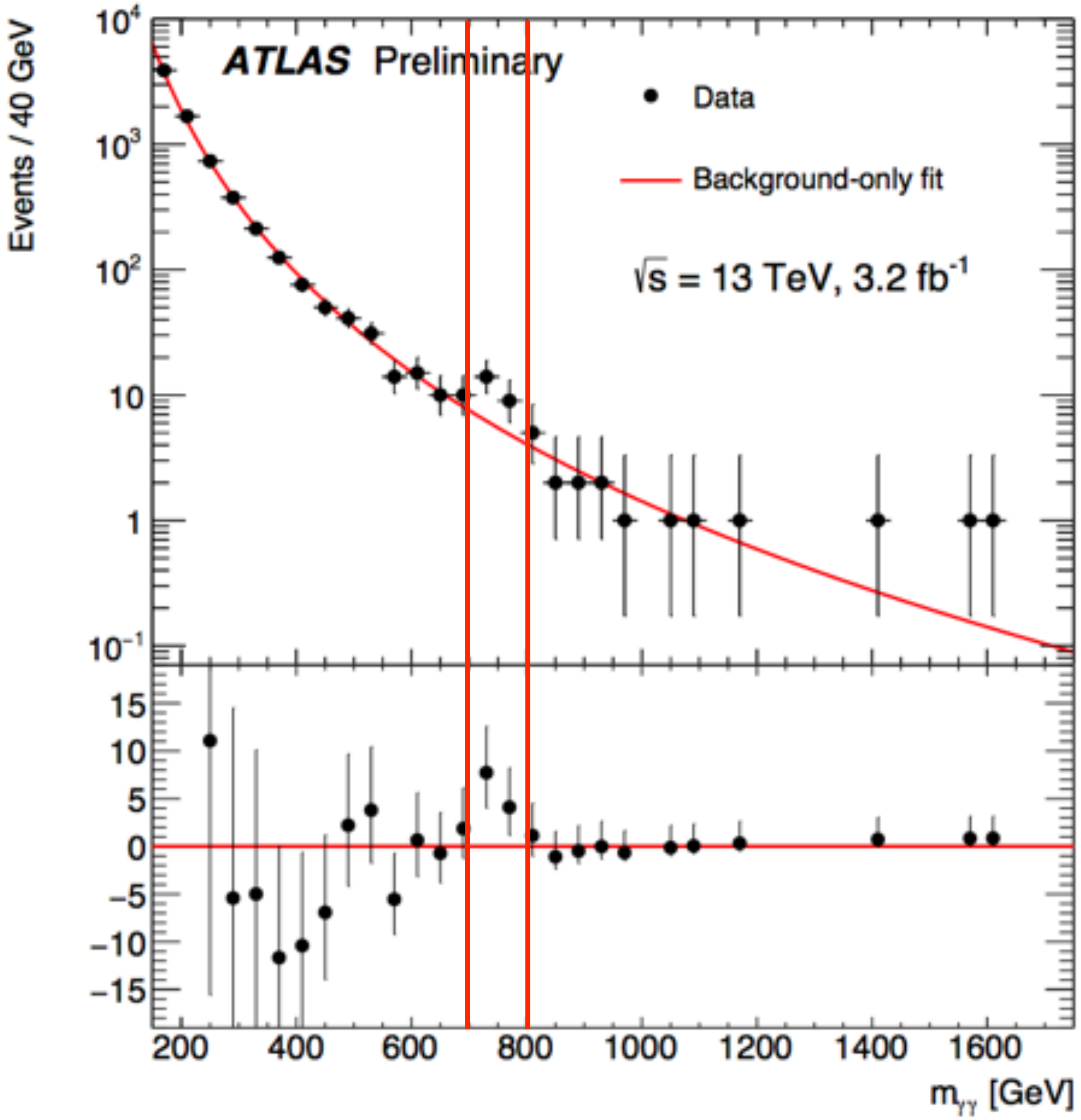
$$\sigma(pp\to FF) \;=\; \kappa_F^2\frac{\mathrm{TeV}^2}{\Lambda^2}(270\,c_{gg}^2+1.9c_u^2+1.4c_d^2+0.07c_s^2+0.04c_c^2+0.017c_b^2)\,\mathrm{fb}.$$

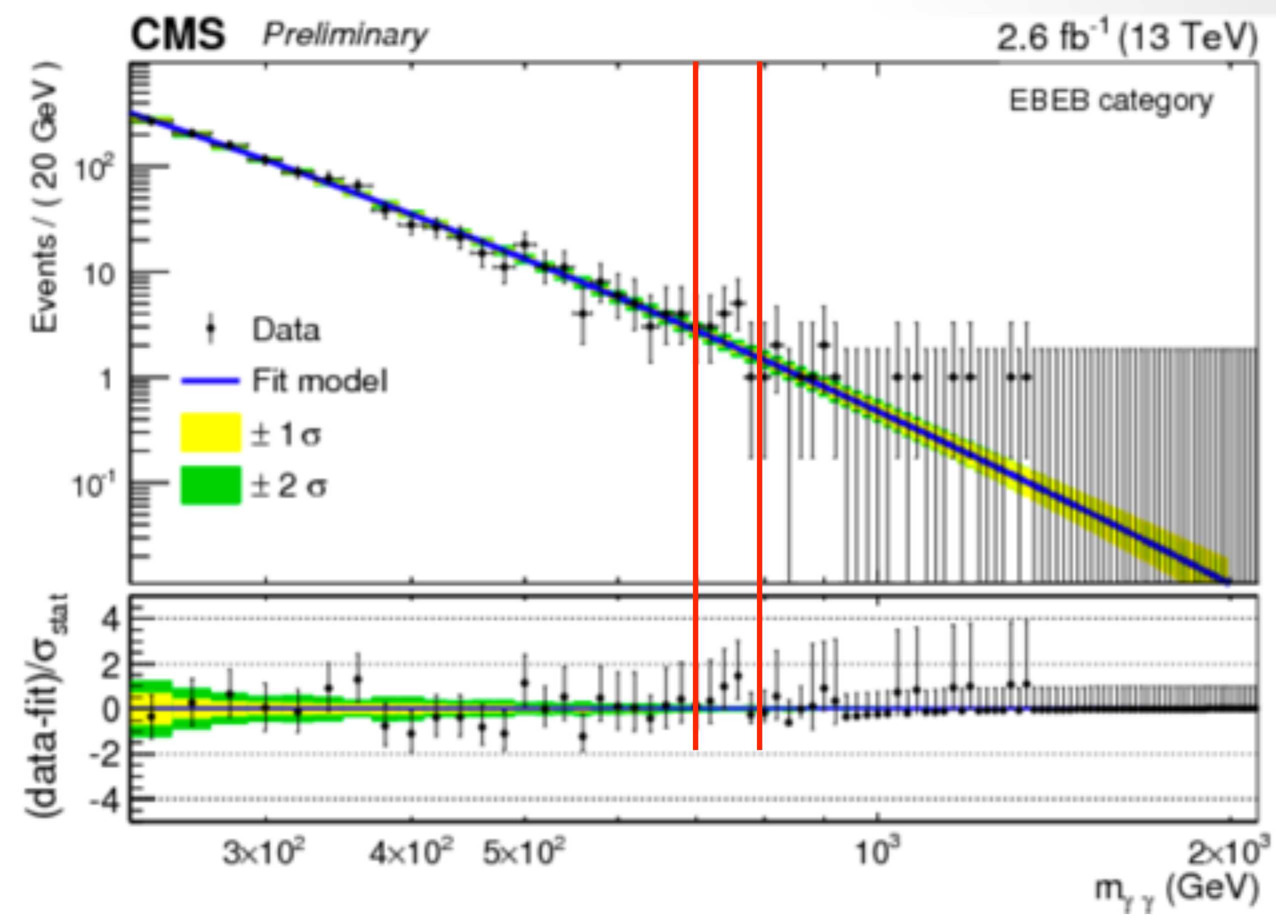
$$\frac{\sigma_{FF}}{\sigma_F}=\begin{cases}(\kappa_F/57)^2 & gg \text{ production}\\ (\kappa_F/63)^2 & u\bar{u} \text{ production}\\ (\kappa_F/88)^2 & b\bar{b} \text{ production}\end{cases}.$$

Two insertions of dim-5 operators and one insertion of dim-6

$$\begin{aligned}\sigma(pp\to FF) \;=\;& \frac{\mathrm{TeV}^4}{\Lambda^4}\Big[1.1c_{gg}^4+2.1c_{gg}^2c_{gg}^{(6)}+0.52c_{gg}^{(6)2}+73c_{F3}^2c_{gg}^2+10^{-3}(0.0074c_{\gamma\gamma}^4+\\ &+0.099c_{\gamma\gamma}^2c_{\gamma\gamma}^{(6)}+0.38c_{\gamma\gamma}^{(6)2})+10^{-6}(11c_u^4+6c_d^4+0.25c_s^4+0.14c_c^4+0.05c_b^4)+\\ &+10^{-3}(4.4c_u^{(6)2}+2.4c_d^{(6)2}+0.1c_s^{(6)2}+0.06c_c^{(6)2}+0.02c_b^{(6)2})\Big]\,\mathrm{pb}\end{aligned} \qquad (35)$$

WHAT HAS BEEN SEEN?





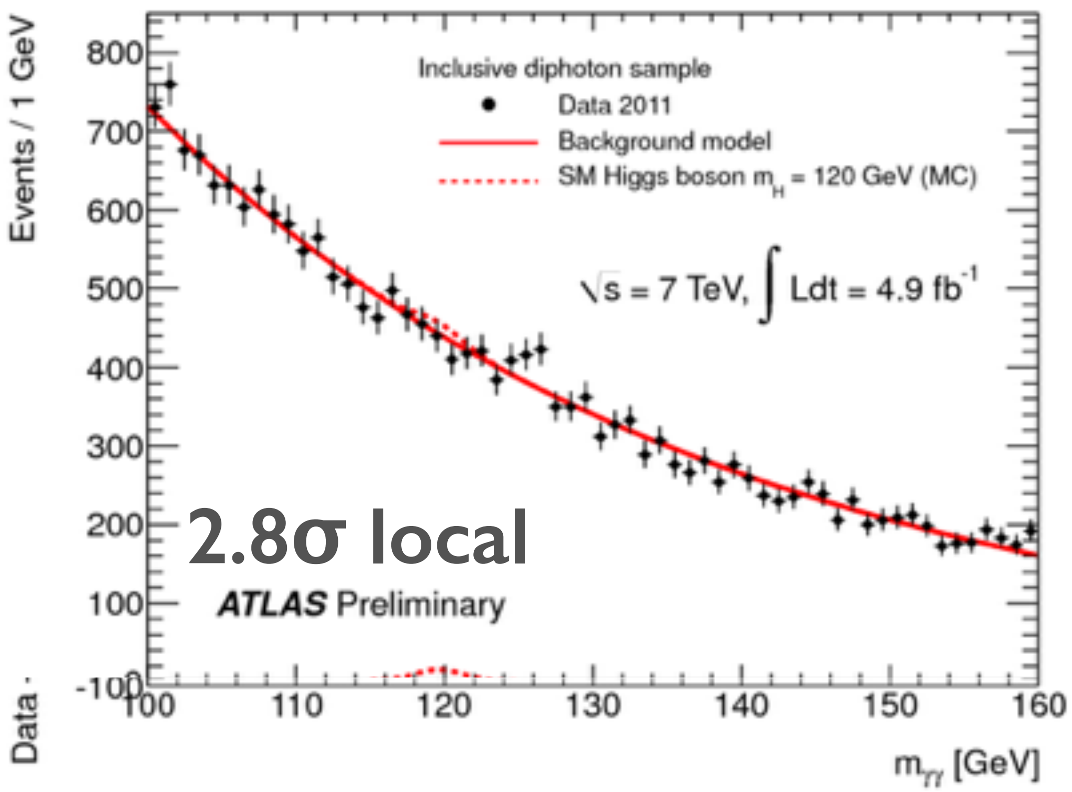
PROS

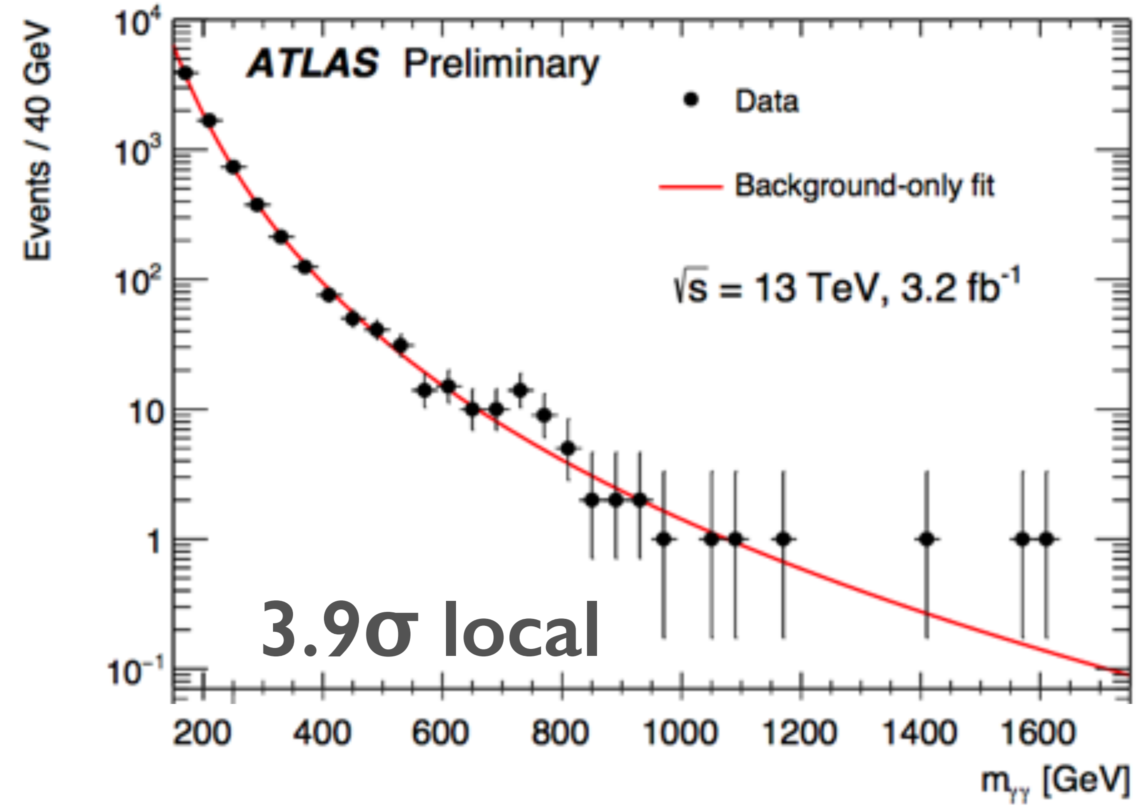
- One of the simplest channels at collider
- Lot of experience from the Higgs

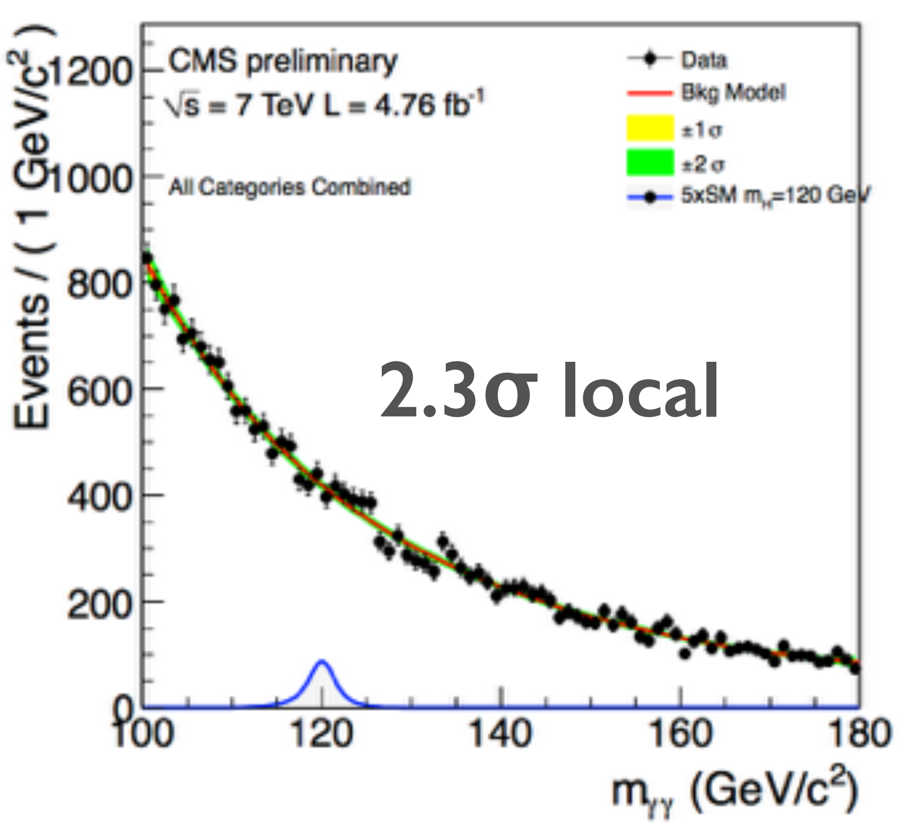
CONS

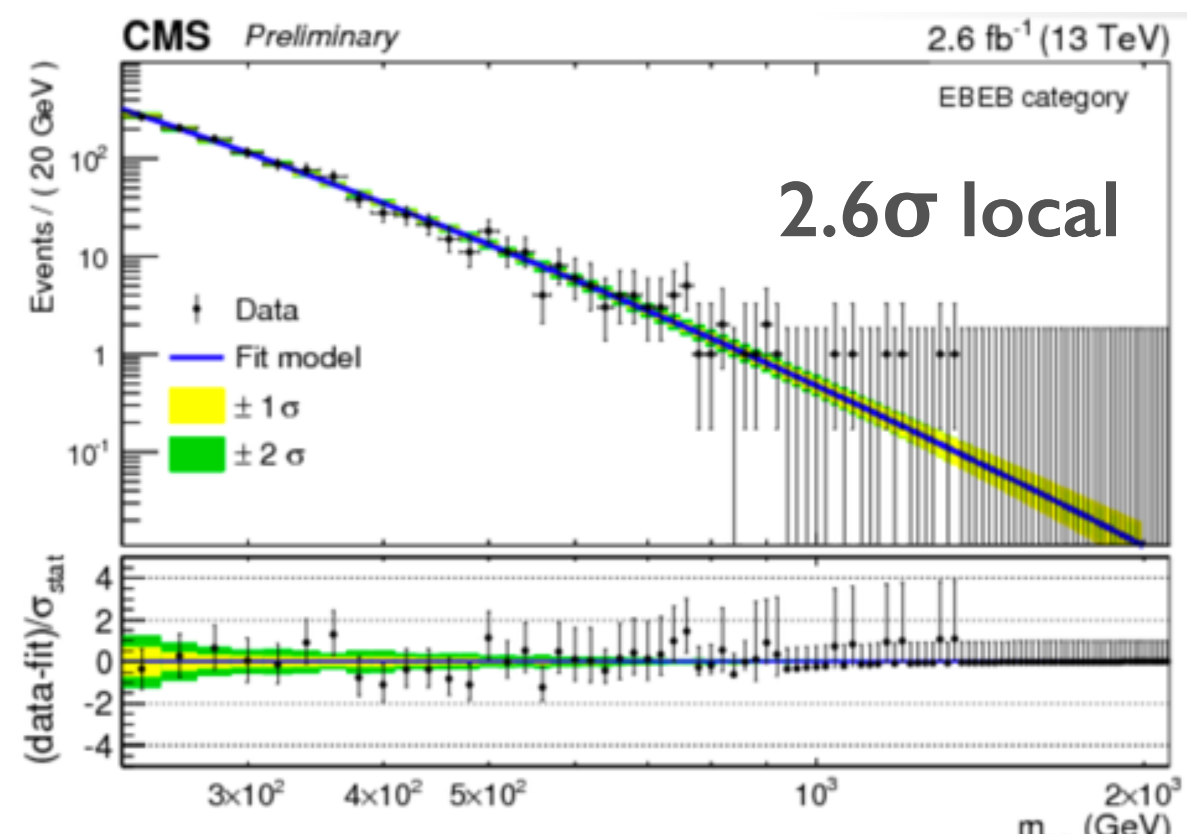
- Limited statistics (could well be a fluctuation)
- Little (public) information about the events (additional jets, met etc.)

A BAYESIAN COMPARISON (DEC 2011 VS DEC 2015)



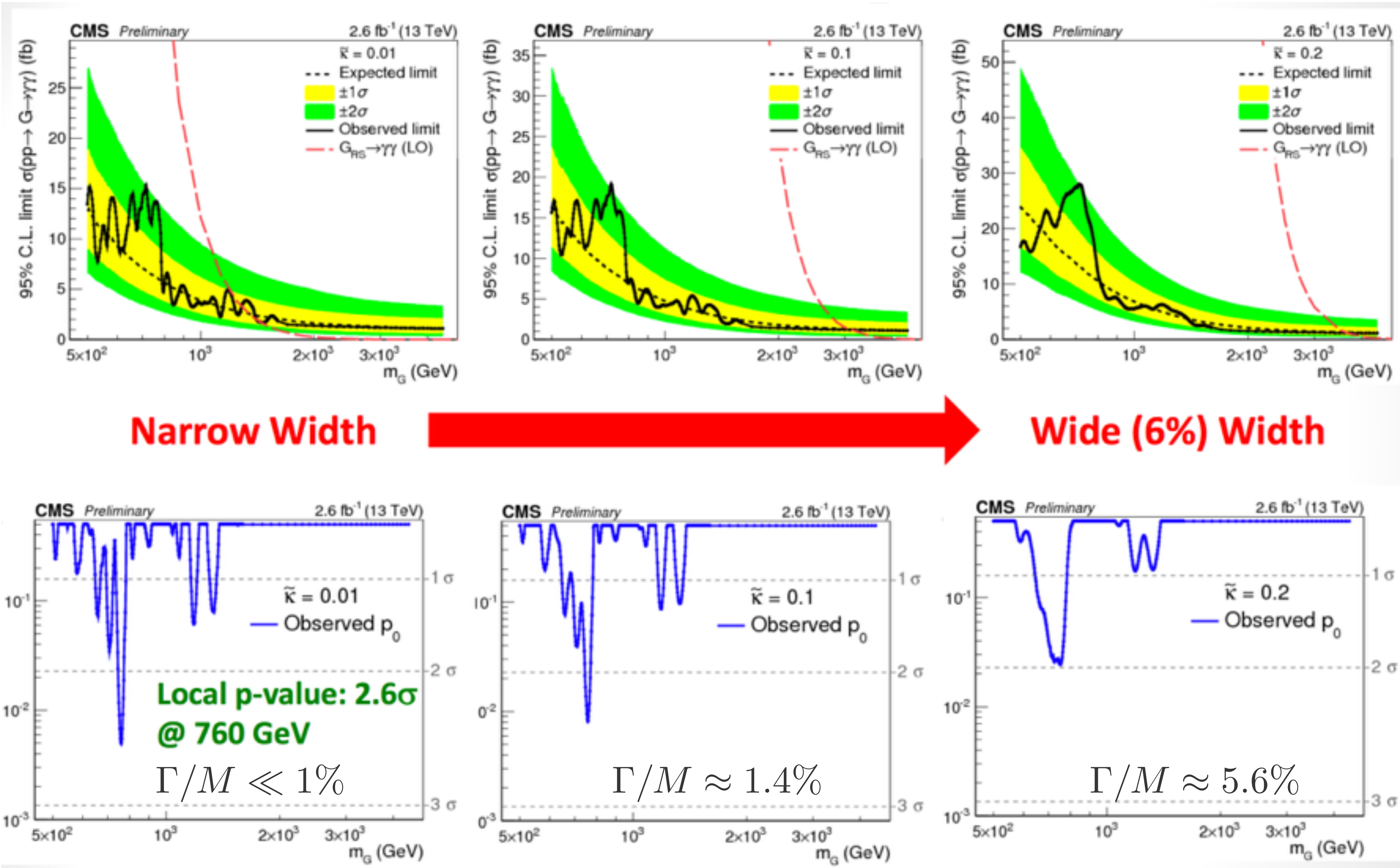






cfr. resolution, width, peak position vs resolution, width, peak position

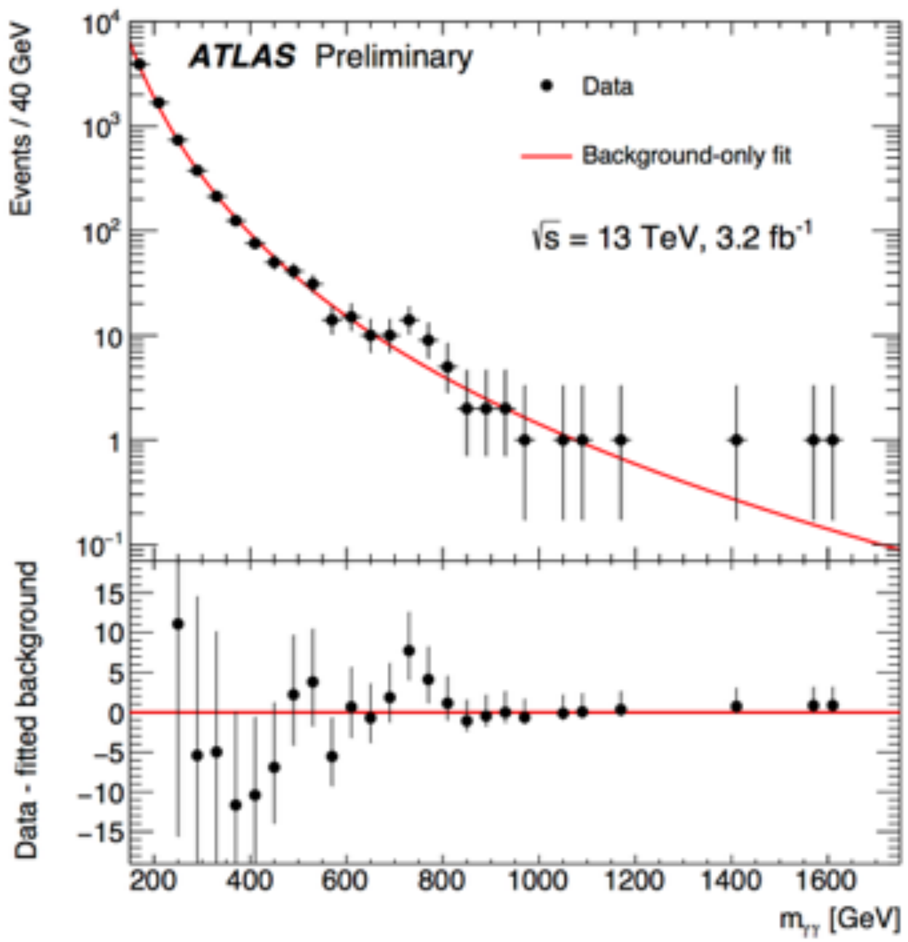
INFORMATION AVAILABLE TO THEORISTS



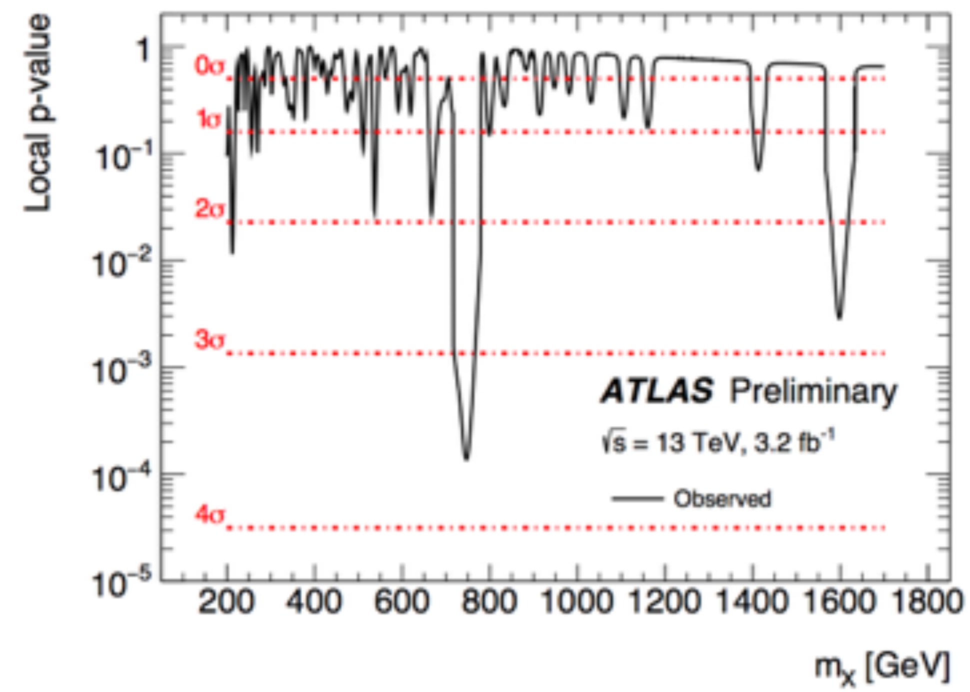
Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ

INFORMATION AVAILABLE TO THEORISTS

Results: Events with mass in excess of 200 GeV are included in **unbinned fit**



- **In the NWA search**, an excess of **3.6σ** (local) is observed at a mass hypothesis of minimal p_0 of 750 GeV
- Taking a LEE in a mass range (fixed before unblinding) **of 200 GeV to 2.0 TeV** the global significance of the excess is **2.0σ**

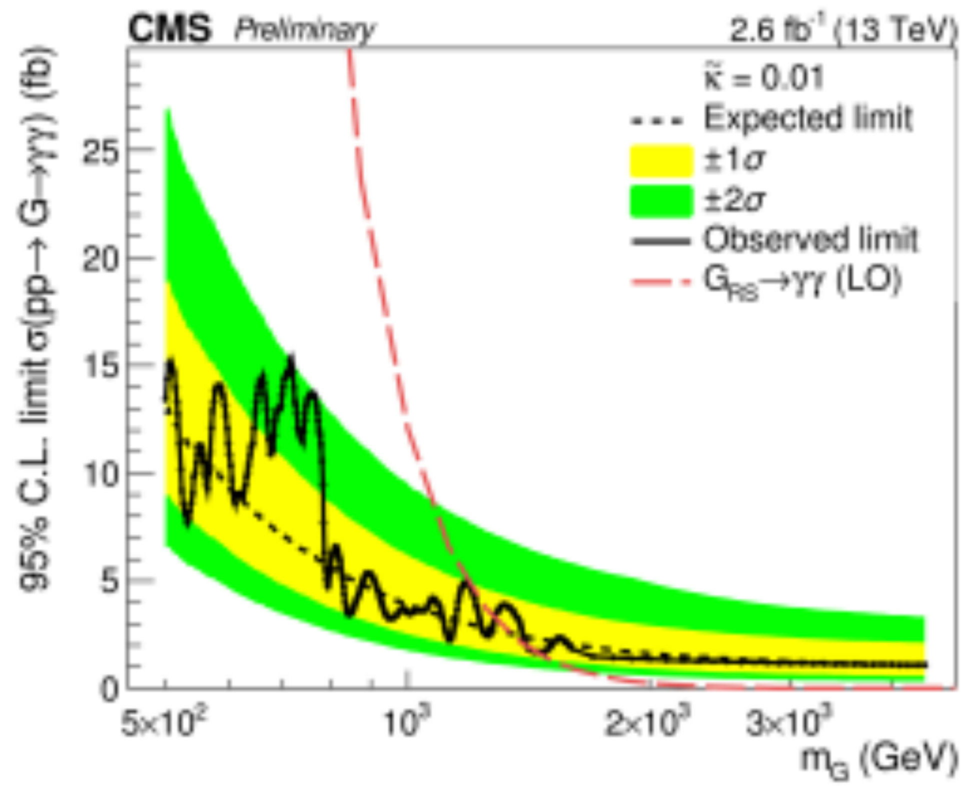


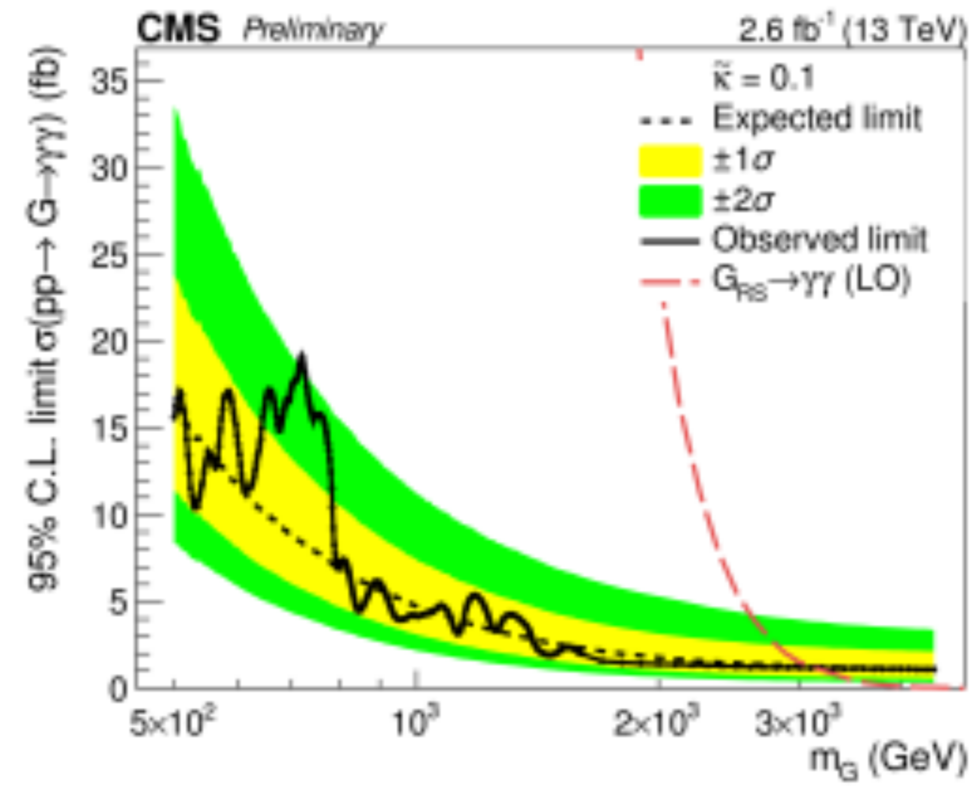
In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

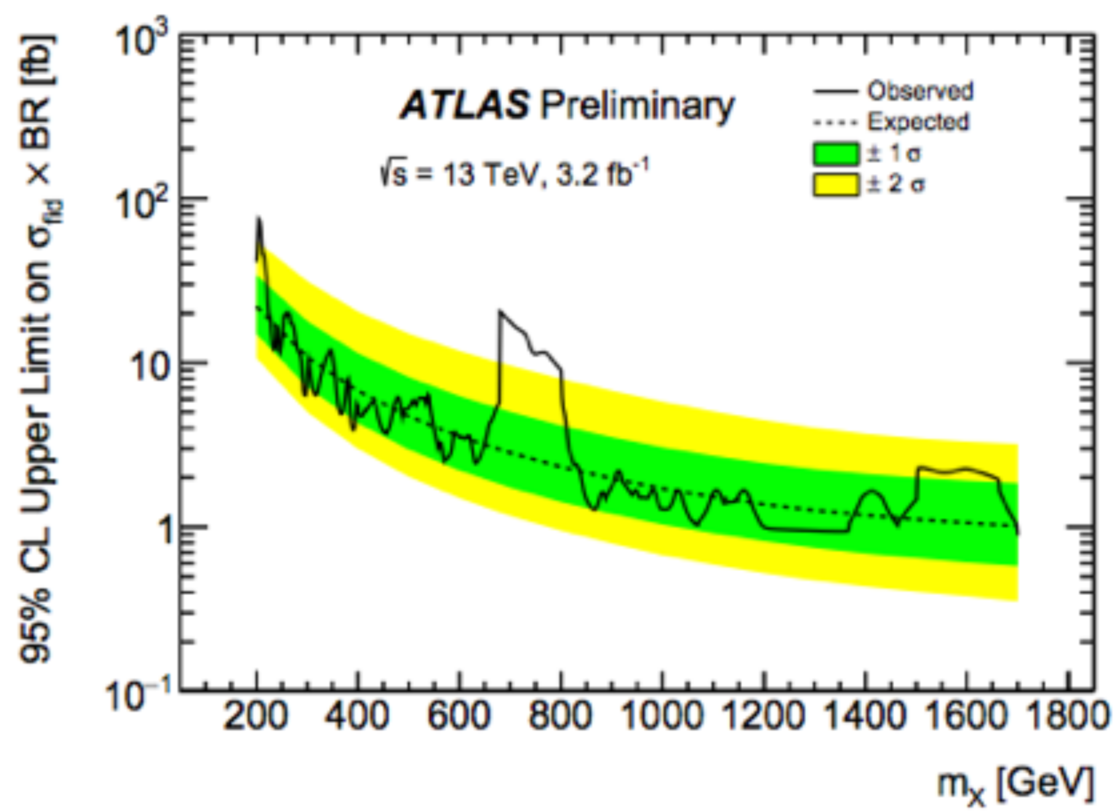
The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV
(Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to **3.9σ**
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

INFORMATION AVAILABLE TO THEORISTS

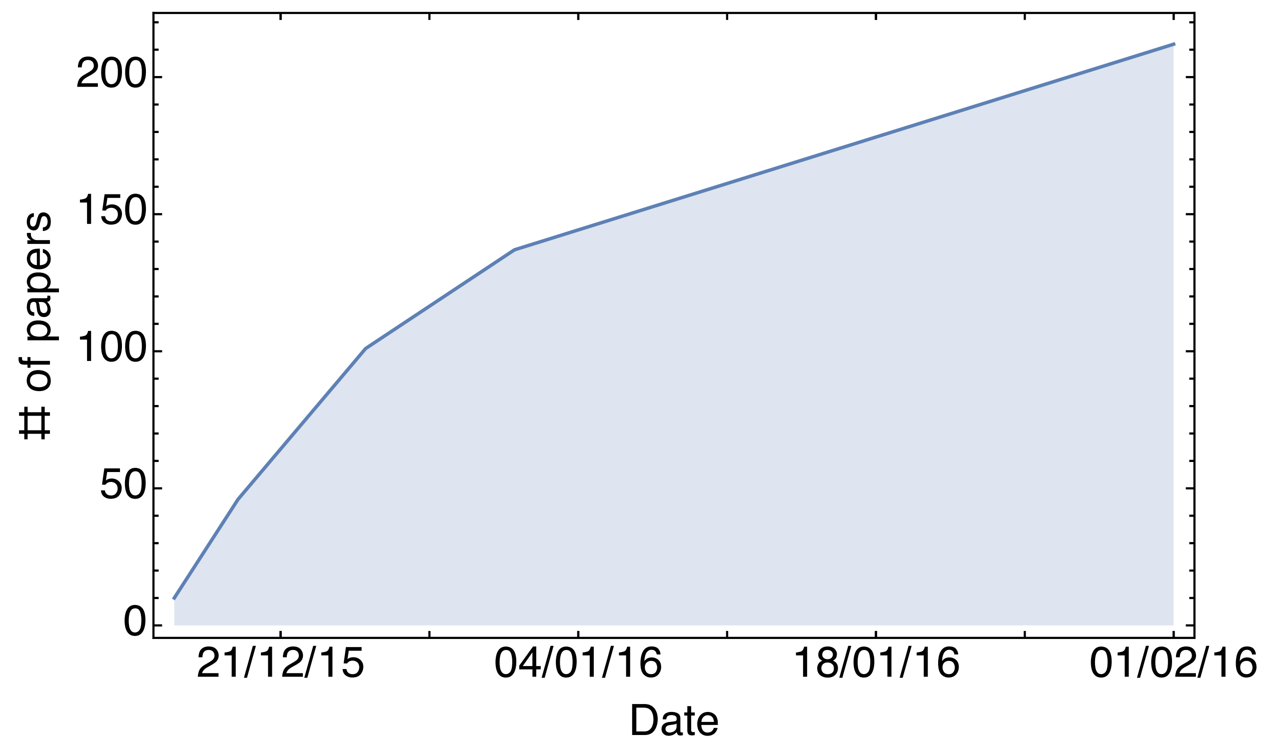




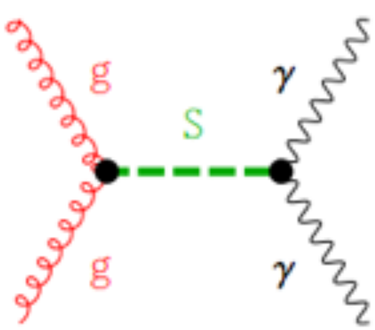


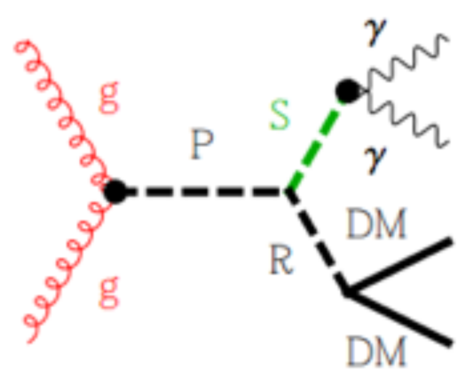
THE THEORISTS REACTION

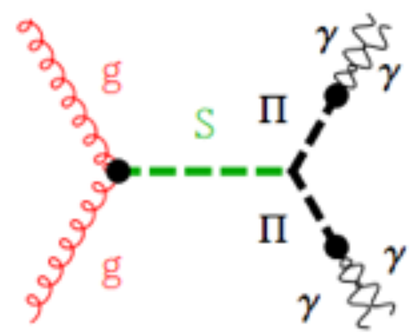
Even with this little information, the theory community could speculate a lot

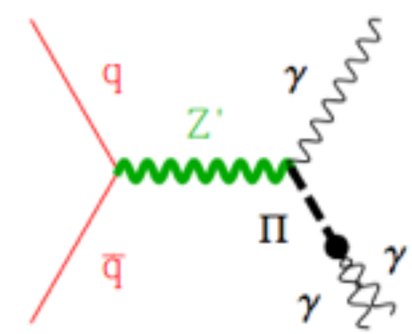


Many different explanations



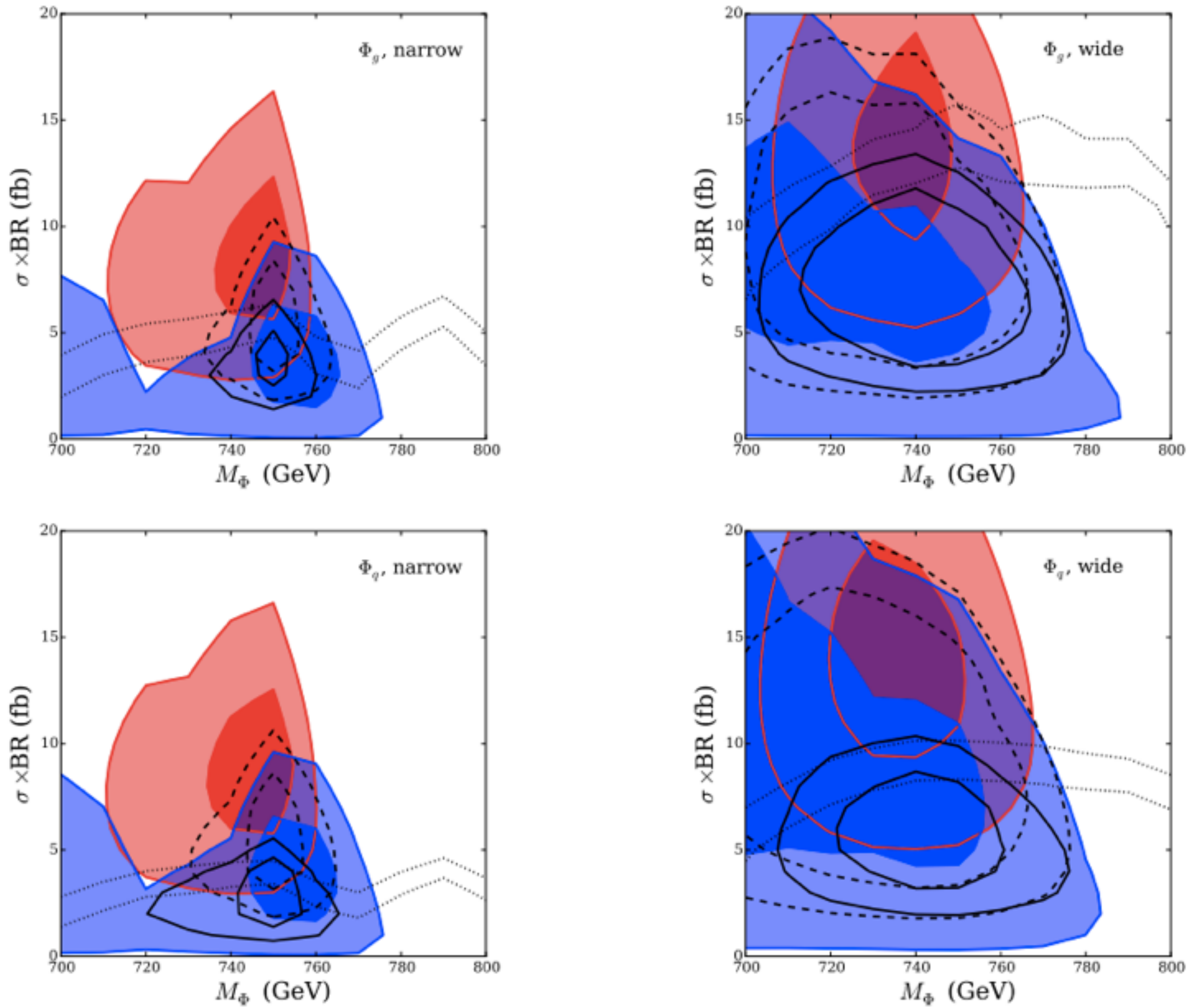






- Spin 0 or 2 due to Landau-Yang
- For narrow resonance very simple (trivial) theory explanations
- For large width harder to explain (non-perturbative couplings, nearby resonances, etc.)

CROSS SECTION BEST FITS



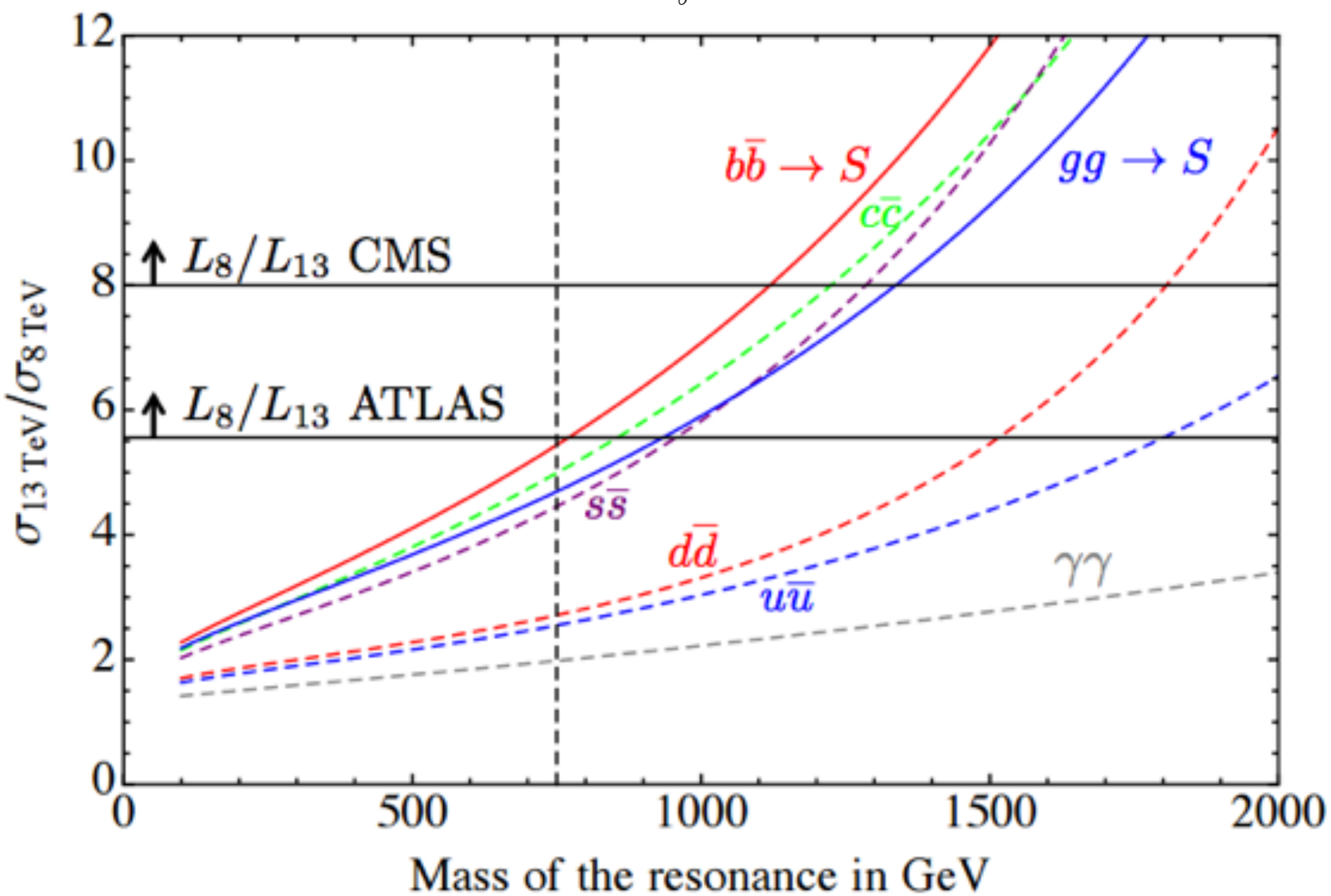
ATLAS
CMS
Dashed: Combo13
Solid: Combo13+8

Buckley, 1601.04751 [hep-ph]

COMPATIBILITY RUN-I/RUN-II

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\text{fb} & \text{CMS [2]} & \sqrt{s} = 8\,\text{TeV}, \\ (0.4 \pm 0.8)\,\text{fb} & \text{ATLAS [3]} & \sqrt{s} = 8\,\text{TeV}, \\ (6 \pm 3)\,\text{fb} & \text{CMS [1]} & \sqrt{s} = 13\,\text{TeV}, \\ (10 \pm 3)\,\text{fb} & \text{ATLAS [1]} & \sqrt{s} = 13\,\text{TeV}, \end{cases}$$

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{M\Gamma s}\left[\sum_{\wp} C_{\wp\bar{\wp}}\Gamma(S \to \wp\bar{\wp})\right]\Gamma(S \to \gamma\gamma) \qquad J = 0, 2$$



$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}	$C_{\gamma\gamma}$
8 TeV	1.07	2.7	7.2	89	158	174	11
13 TeV	15.3	36	83	627	1054	2137	54

$$r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}} = [C_{gg}/s]_{13\,\text{TeV}}/[C_{gg}/s]_{8\,\text{TeV}}$$

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9

GENERAL ANALYSIS (E.G. SPIN 0)

Effective description for a scalar singlet (scalar and pseudoscalar one at a time)

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+g_2^2 S\left(\frac{W_{\mu\nu}^2}{2\Lambda_W}+\frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W}\right)+g_1^2 S\left(\frac{B_{\mu\nu}^2}{2\Lambda_B}+\frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B}\right)$$
$$+S\left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi}+\text{h.c.}\right)+S\frac{|D_\mu H|^2}{\Lambda_H}+\frac{M^2}{2}\left(S+\frac{\Lambda_S}{M^2}(|H|^2-v^2)\right)^2$$

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+e^2 S\left(\frac{F_{\mu\nu}^2}{2\Lambda_\gamma}+\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\tilde{\Lambda}_\gamma}\right)+S\sum_\psi \bar{\psi}(y_{\psi S}+i\gamma_5\tilde{y}_{\psi S})\psi,$$
$$\frac{1}{\Lambda_\gamma}=\frac{1}{\Lambda_B}+\frac{1}{\Lambda_W},\qquad y_{\psi S}=v\frac{\operatorname{Re}\Lambda_\psi}{|\Lambda_\psi|^2},\qquad \tilde{y}_{\psi S}=-v\frac{\operatorname{Im}\Lambda_\psi}{|\Lambda_\psi|^2}$$

Simple model independent prediction (assuming production by gluon-fusion)

$\sigma(pp\to\gamma\gamma)\approx 8\,\text{fb at }\sqrt{s}=13\,\text{TeV}$ ⟶ $\text{BR}(S\to\gamma\gamma)\,\text{BR}(S\to gg)\approx 1.1\times 10^{-6}\,\frac{M}{\Gamma}\approx 1.8\times 10^{-5}$

$\Gamma/M\approx 0.06$ (preferred by ATLAS) ⟶ $\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M}\approx 1.1\times 10^{-6}\,\frac{\Gamma}{M}\approx 6\times 10^{-8}$

If only simplest decay channels are considered, Γ cannot be larger than $\Gamma\lesssim 1500\Gamma_{\gamma\gamma}^{\text{obs}}$

Using the ATLAS preferred value, this bound implies $\Gamma_{\gamma\gamma}/M\gtrsim 4\times 10^{-5}$

GENERAL ANALYSIS (E.G. SPIN 0)

Effective description for a scalar singlet (scalar and pseudoscalar one at a time)

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+g_2^2 S\left(\frac{W_{\mu\nu}^2}{2\Lambda_W}+\frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W}\right)+g_1^2 S\left(\frac{B_{\mu\nu}^2}{2\Lambda_B}+\frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B}\right)$$
$$+S\left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi}+\text{h.c.}\right)+S\frac{|D_\mu H|^2}{\Lambda_H}+\frac{M^2}{2}\left(S+\frac{\Lambda_S}{M^2}(|H|^2-v^2)\right)^2$$

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+e^2 S\left(\frac{F_{\mu\nu}^2}{2\Lambda_\gamma}+\frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\tilde{\Lambda}_\gamma}\right)+S\sum_\psi \bar{\psi}(y_{\psi S}+i\gamma_5\tilde{y}_{\psi S})\psi,$$
$$\frac{1}{\Lambda_\gamma}=\frac{1}{\Lambda_B}+\frac{1}{\Lambda_W},\qquad y_{\psi S}=v\frac{\mathrm{Re}\,\Lambda_\psi}{|\Lambda_\psi|^2},\qquad \tilde{y}_{\psi S}=-v\frac{\mathrm{Im}\,\Lambda_\psi}{|\Lambda_\psi|^2}$$

Production by gamma-fusion

The ratio of inelastic-inelastic/elastic-inelastic/elastic-elastic contributions are about 63:33:4

Explaining the signal with photon fusion production requires $\Gamma_{\gamma\gamma}/M \sim \text{few}\times 10^{-3}$

Hart to explain theoretically such a width into photons

The elastic cross section is about a tenth of the inelastic one, so a rate around or below 1 fb is expected: very difficult even with forward proton tagging

DECAY WIDTHS

$$\Gamma(S \to \gamma\gamma) = \pi\alpha^2 M \left(\frac{M^2}{\Lambda_\gamma^2} + \frac{M^2}{\tilde{\Lambda}_\gamma^2}\right)$$

$$\Gamma(S \to gg) = 8\pi\alpha_3^2 M \left(\frac{M^2}{\Lambda_g^2} + \frac{M^2}{\tilde{\Lambda}_g^2}\right)$$

$$\Gamma(S \to \psi\bar{\psi}) = \frac{N_\psi M}{8\pi}(y_{\psi S}^2 + \tilde{y}_{\psi S}^2)$$

$$\Gamma(S \to Z\gamma) \approx 2\pi\alpha^2 M^3 \left[\left(\frac{\tan\theta_{\mathrm{W}}}{\Lambda_B} - \frac{\cot\theta_{\mathrm{W}}}{\Lambda_W}\right)^2 + \left(\frac{\tan\theta_{\mathrm{W}}}{\tilde{\Lambda}_B} - \frac{\cot\theta_{\mathrm{W}}}{\tilde{\Lambda}_W}\right)^2\right]$$

$$\Gamma(S \to ZZ) \approx \pi\alpha^2 M^3 \left[\left(\frac{\tan^2\theta_{\mathrm{W}}}{\Lambda_B} + \frac{\cot^2\theta_{\mathrm{W}}}{\Lambda_W}\right)^2 + \left(\frac{\tan^2\theta_{\mathrm{W}}}{\tilde{\Lambda}_B} + \frac{\cot^2\theta_{\mathrm{W}}}{\tilde{\Lambda}_W}\right)^2\right] + \frac{M}{128\pi}\left(\frac{M}{\Lambda_H} + \frac{2\Lambda_S}{M}\right)^2$$

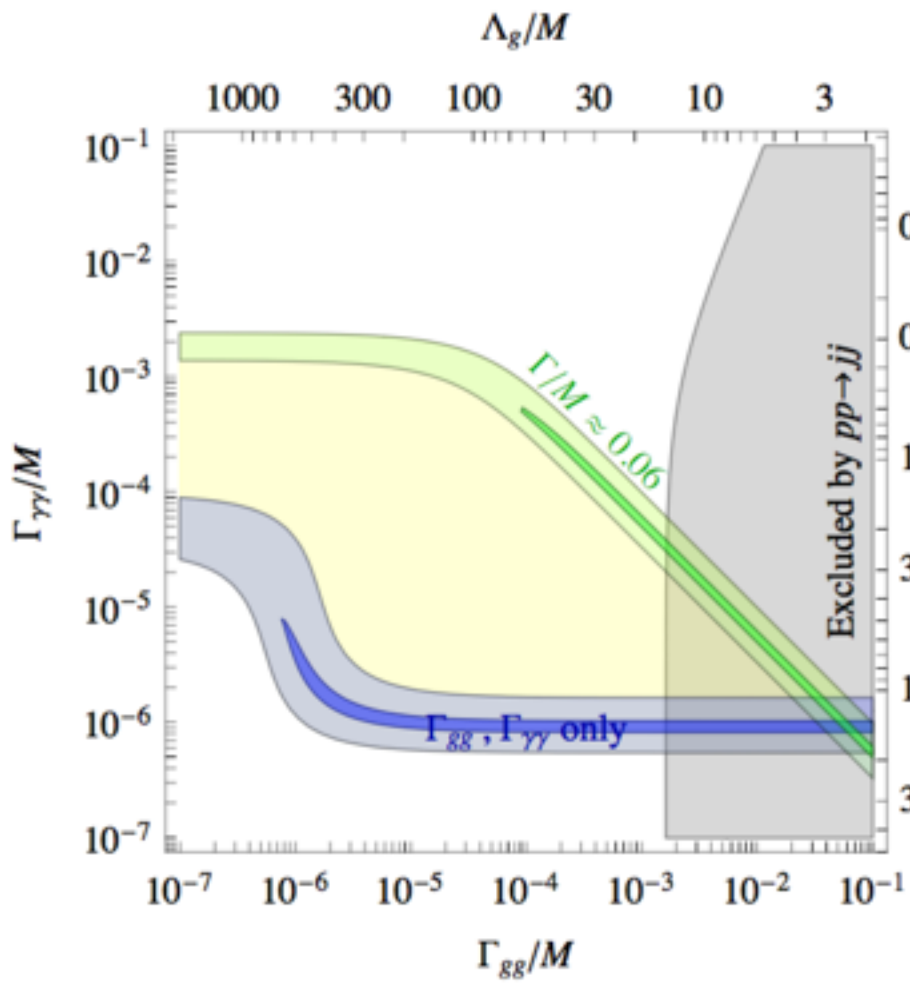
$$\Gamma(S \to W^+W^-) \approx \frac{2\pi\alpha^2 M}{\sin^4\theta_{\mathrm{W}}}\left(\frac{M^2}{\Lambda_W^2} + \frac{M^2}{\tilde{\Lambda}_W^2}\right) + \frac{M}{64\pi}\left(\frac{M}{\Lambda_H} + \frac{2\Lambda_S}{M}\right)^2$$

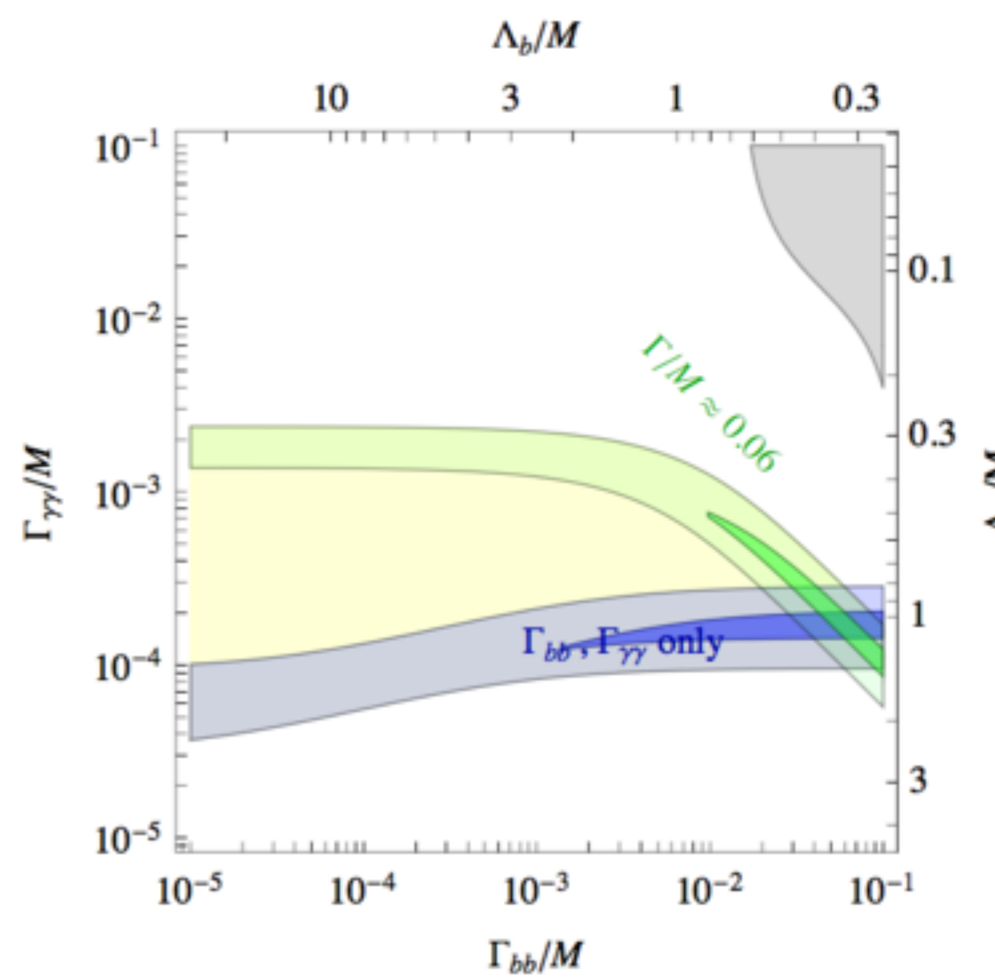
$$\Gamma(S \to hh) \approx \frac{M}{128\pi}\left(\frac{M}{\Lambda_H} + \frac{2\Lambda_S}{M}\right)^2$$

operator	$\frac{\Gamma(S\to Z\gamma)}{\Gamma(S\to\gamma\gamma)}$	$\frac{\Gamma(S\to ZZ)}{\Gamma(S\to\gamma\gamma)}$	$\frac{\Gamma(S\to WW)}{\Gamma(S\to\gamma\gamma)}$
WW only	$2/\tan^2\theta_{\mathrm{W}} \approx 7$	$1/\tan^4\theta_{\mathrm{W}} \approx 12$	$2/\sin^4\theta_{\mathrm{W}} \approx 40$
BB only	$2\tan^2\theta_{\mathrm{W}} \approx 0.6$	$\tan^4\theta_{\mathrm{W}} \approx 0.08$	0

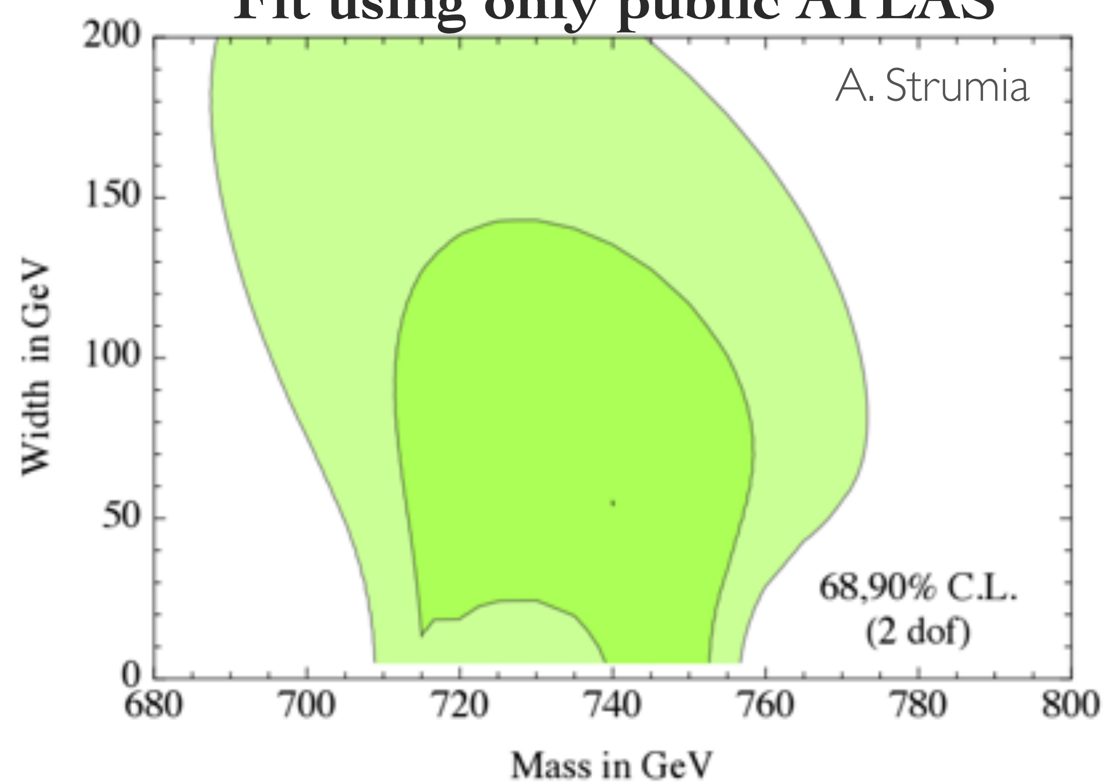
Scalar doublet would have couplings to photons and gluons suppressed by $v/M \sim 0.2$ so it is generally harder to explain the excess

GENERAL ANALYSIS (E.G. SPIN 0)





Fit using only public ATLAS



SUMMARY OF CONSTRAINTS

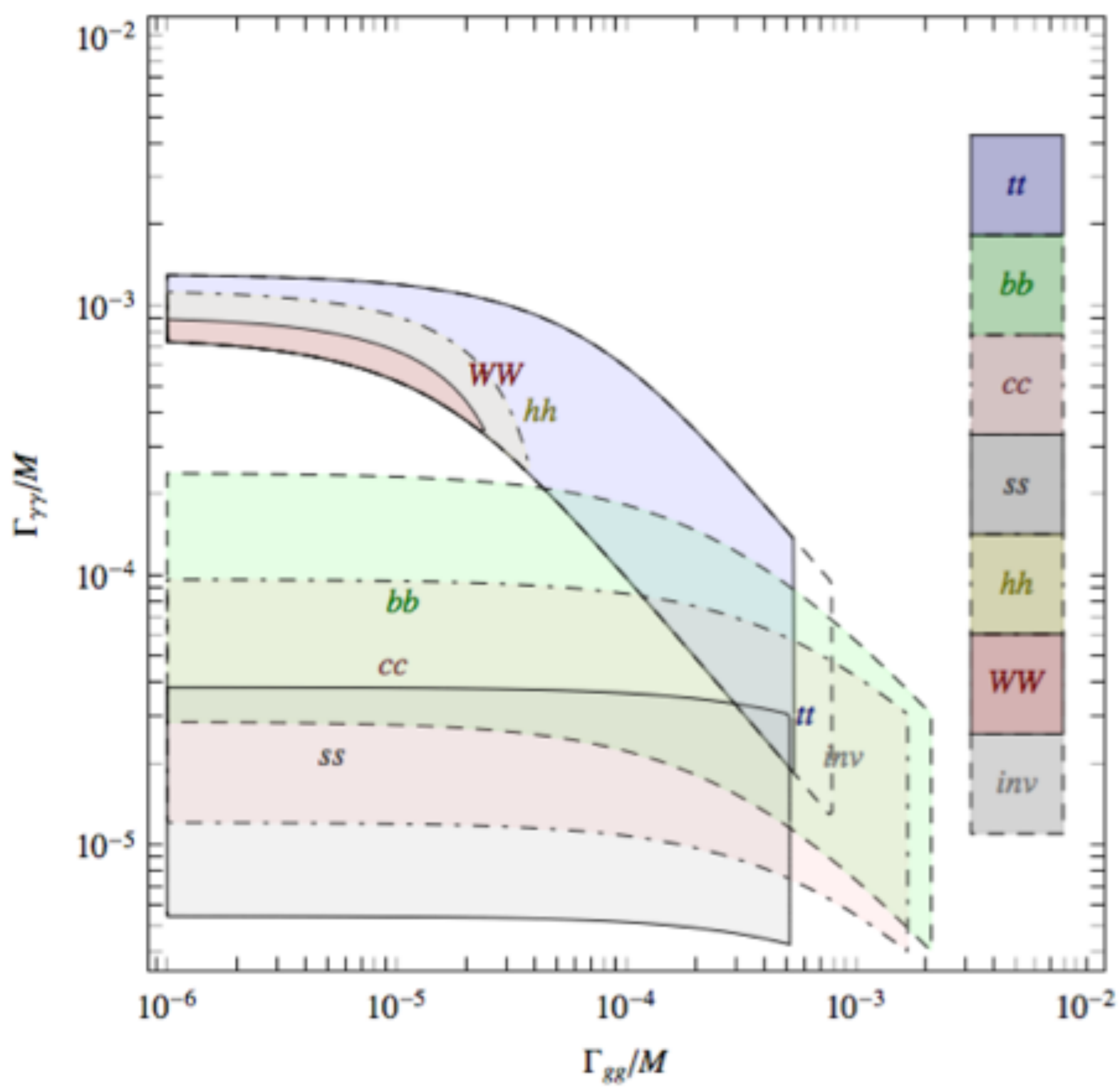
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[7, 8]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[9]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[10]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[11]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[12]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[13]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[14]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[15, 16]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[17]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[18]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[19]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[6]	$< 1300\ (r/5)$

- Constraints in red very strong, these channels cannot account for sizeable width
- Constraints in green less strong, they can possibly account for a sizeable width

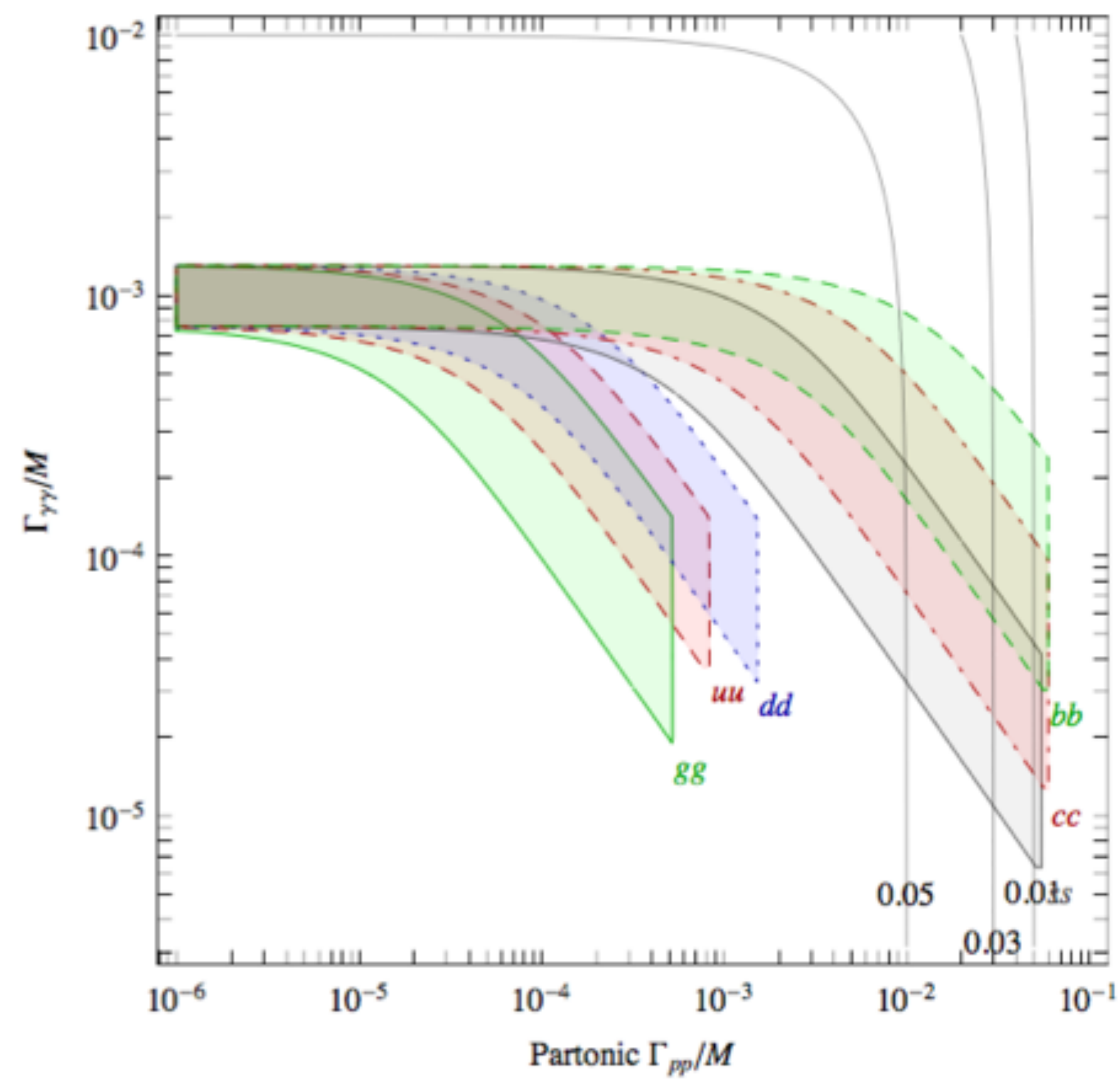
CONSTRAINTS VS WIDTH (E.G. SPIN 0)

Requiring to satisfy the rate, the total width $\Gamma/M \sim 0.06$ and all constraints

Assuming
$S \to gg, \gamma\gamma, X$



Assuming
$S \to p_i p_i, \gamma\gamma, \mathrm{inv}$



Generally requires $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-5}$, which, as we will see, is a large value

SPIN-2

$$S^{\mu\nu}\sum_p \frac{T^{(p)}_{\mu\nu}}{\Lambda_p}$$

$$\Gamma(S\to\gamma\gamma)=\frac{M^3}{80\pi\Lambda_\gamma^2},\qquad \Gamma(S\to gg)=\frac{M^3}{10\pi\Lambda_g^2},\qquad \Gamma(S\to b\bar{b})=\frac{3M^3}{160\pi\Lambda_b^2}.$$

Crucial differences from scalar:

- Angular distributions of the two photons are different
- Width can be sizeable

Example: RS graviton

For the RS graviton all Λ are equal, so we expect a signal in dileptons as big as the one into diphotons, but bounds in dileptons already stronger

ATLAS	CMS
$\sigma\left(pp\to l^+l^-\right)\lesssim 5$ fb	$\sigma\left(pp\to l^+l^-\right)\lesssim 3$ fb

These bounds are milder if rescaled for a spin-2, though even for small cross section there is already tension with the di-photoh excess, suggesting the need for more complicated models

SPIN-2

$$S^{\mu\nu}\sum_p \frac{T^{(p)}_{\mu\nu}}{\Lambda_p}$$

$$\Gamma(S\to\gamma\gamma)=\frac{M^3}{80\pi\Lambda_\gamma^2},\qquad \Gamma(S\to gg)=\frac{M^3}{10\pi\Lambda_g^2},\qquad \Gamma(S\to b\bar{b})=\frac{3M^3}{160\pi\Lambda_b^2}.$$

Crucial differences from scalar:

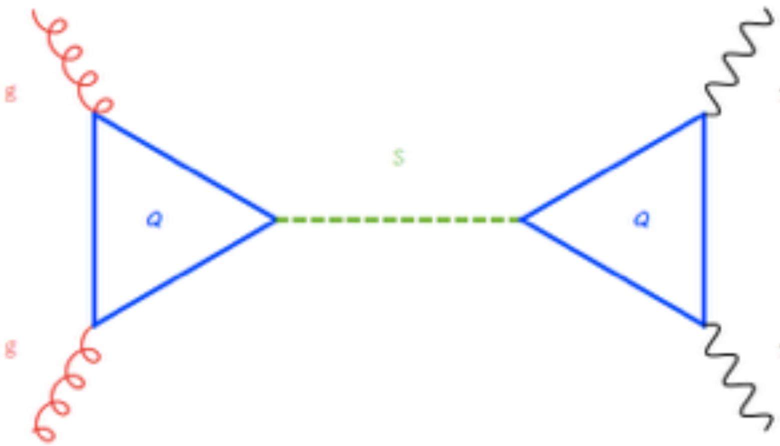
- Angular distributions of the two photons are different

Important to do a model independent analysis of spin-2 not relying just on specific RS-like models

ATLAS	CMS
$\sigma\left(pp\to l^+l^-\right)\lesssim 5\text{ fb}$	$\sigma\left(pp\to l^+l^-\right)\lesssim 3\text{ fb}$

These bounds are milder if rescaled for a spin-2, though even for small cross section there is already tension with the di-photoh excess, suggesting the need for more complicated models

WEAKLY COUPLED MODELS (SMALL WIDTH)

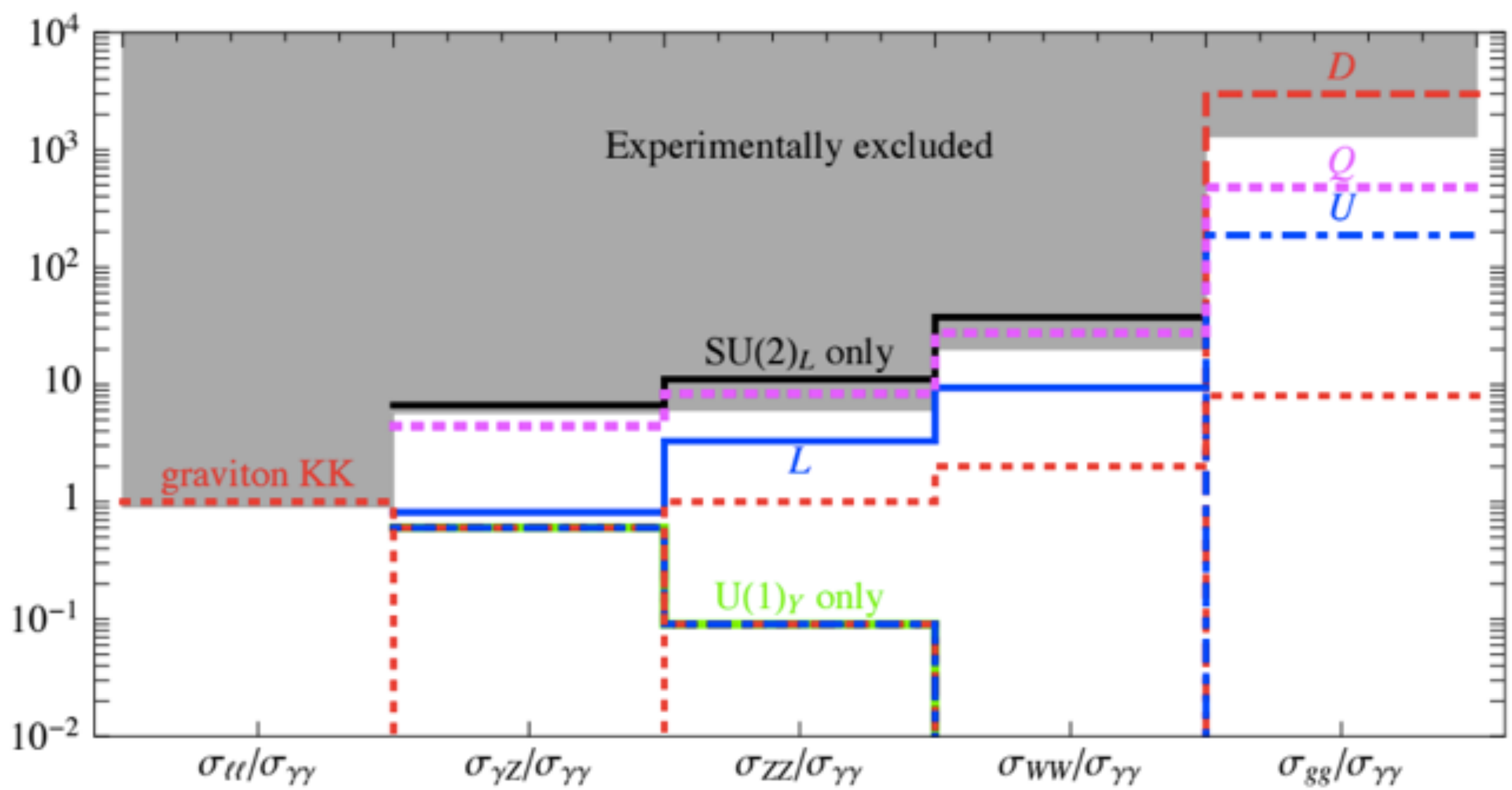


$$S\bar{\mathcal{Q}}_f(y_f + i\,y_{5f}\gamma_5)\mathcal{Q}_f + SA_s\tilde{\mathcal{Q}}_s^*\tilde{\mathcal{Q}}_s.$$

$$\frac{\Gamma(S\to gg)}{M} \approx 7.2\times 10^{-5}\left|\sum_f I_{r_f} y_f \frac{M}{2M_f} + \sum_s I_{r_s}\frac{A_s M}{16M_s^2}\right|^2 ,$$

$$\frac{\Gamma(S\to \gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2\frac{A_s M}{16M_s^2}\right|^2$$

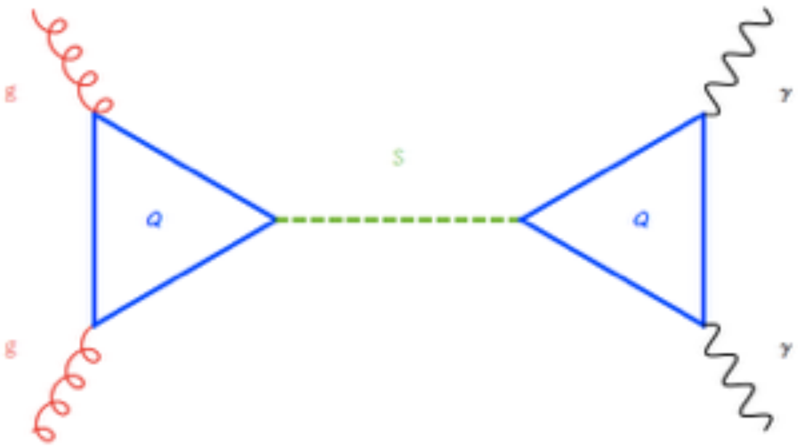
For a small width prefer $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-6}$ which seems feasible with not too large multiplicities, charges, couplings and not too light masses



L, E, U
good candidates

Note:
Cannot work with SM particles in the loop since $\Gamma_{t\bar{t}}/\Gamma_{\gamma\gamma} \approx 10^5$ which is excluded

WEAKLY COUPLED MODELS (SMALL WIDTH)

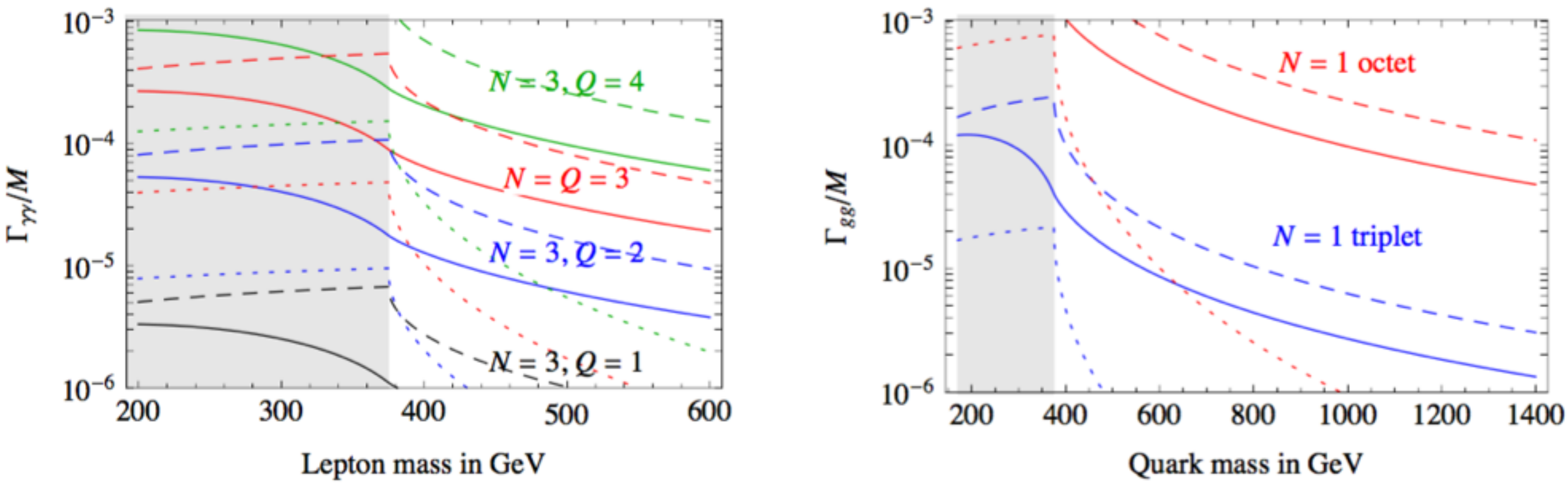


$$S\bar{Q}_f(y_f + i\, y_{5f}\gamma_5)Q_f + S A_s \tilde{Q}_s^* \tilde{Q}_s .$$

$$\frac{\Gamma(S\to gg)}{M} \approx 7.2\times 10^{-5}\left|\sum_f I_{r_f} y_f \frac{M}{2M_f} + \sum_s I_{r_s}\frac{A_s M}{16 M_s^2}\right|^2 ,$$

$$\frac{\Gamma(S\to \gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2\frac{A_s M}{16 M_s^2}\right|^2$$

Scalar (continuous), pseudo−scalar (dashed) and cubic coupling $y, y_5 = 1$, $A = M$



SUSY MODELS

- The simplest SUSY explanation of this excess could be given by the second Higgs doublet
- Due to many constraints from Higgs and EWPT we consider inert limit
- Generically hard to explain the production through loop induced couplings

$$\Gamma_{t\bar{t}}/\Gamma_{\gamma\gamma} \approx 10^5$$

- Loops of SM particles only cannot explain the excess and loops of SUSY particles (enhanced by $(\mu, A_t)/m_{\tilde{t}_1}$) very constrained by
  - Color/charge breaking vacua (relaxed if metastable)
  - Higgs measurements (relaxed e.g. in NMSSM)
- Two options for non minimal SUSY with a neutral scalar
  - RPV sneutrino
  - sgoldstino

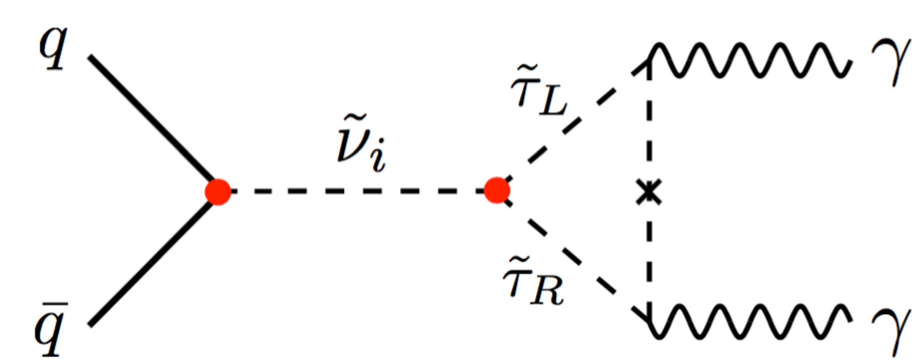
RPV SNEUTRINO

- Production/decay through RPV couplings

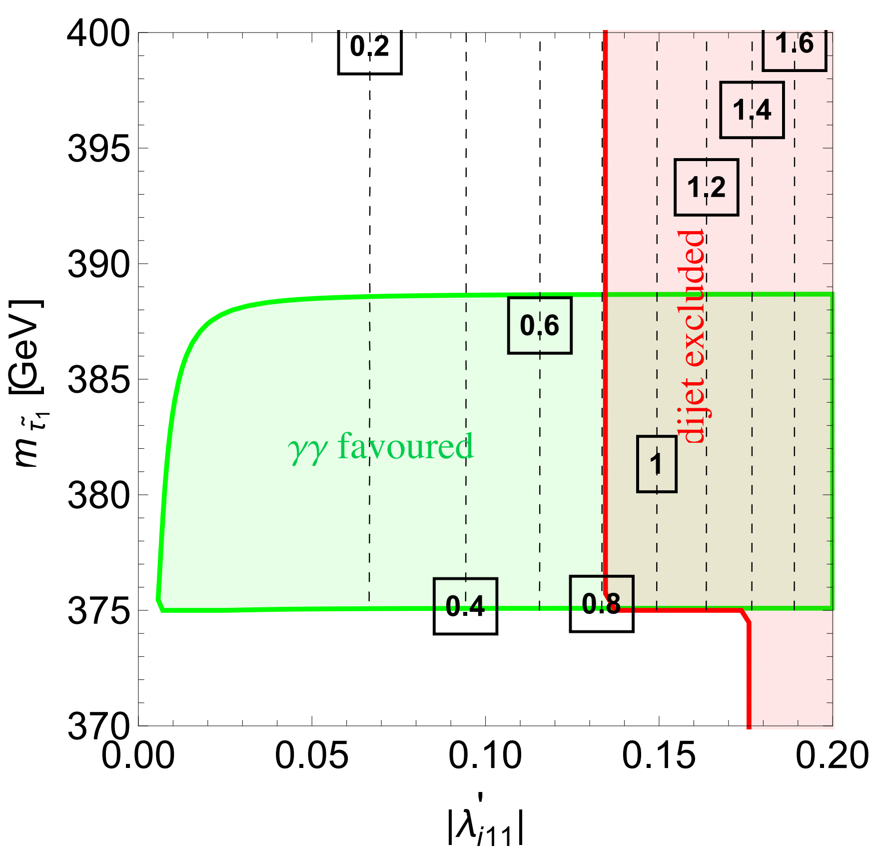
$$W_{\rm LV} = \lambda'_{i11} L_i Q_1 \bar{D}_1$$

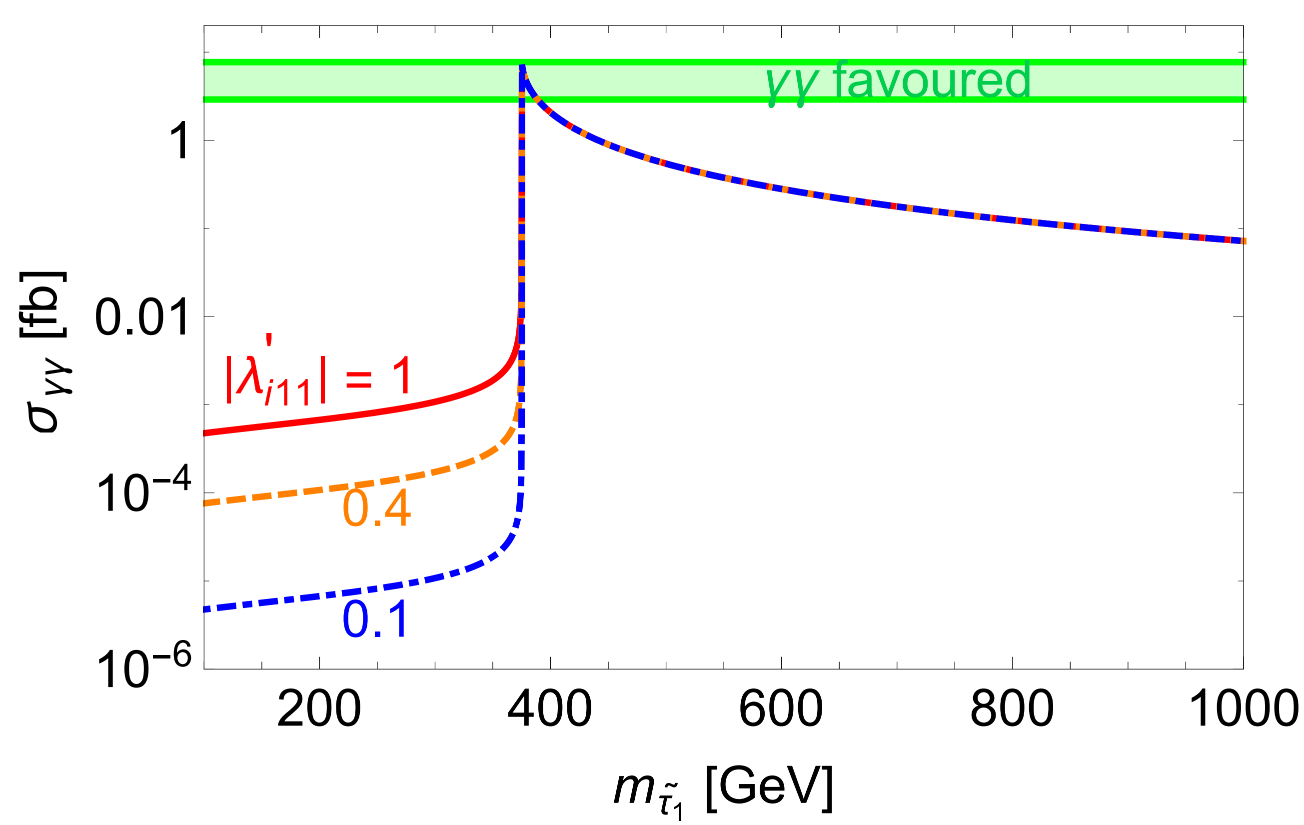
$$\mathcal{L}^{\rm soft}_{\rm LV} = A_{i33} \tilde{l}_i \tilde{l}_3 \tilde{\tau}^+_R + {\rm h.c.}$$

Allanach et al., 1512.07645 [hep-ph]



- Only coupling to light quarks $\Rightarrow$ poor 8TeV compatibility
- Requires (fine-tuned) resonant loop enhancement at $2m_{\tilde{\tau}_1} \approx M$
- A large S width cannot be easily accommodated
- Large trilinear $A_{i33} = 14 m_{\tilde{\tau}_1}$ potentially problematic for vacuum stability





SGOLDSTINO

- Superpartner of the Goldstone fermion responsible for SUSY breaking (goldstino)
- Needs a low SUSY breaking scale, of the order of few TeV

$$\Gamma(\phi \to gg) = \frac{m_3^2 m_\phi^3}{4\pi f^2},$$

$$\Gamma(\phi \to WW) = \frac{m_2^2 m_\phi^3}{16\pi f^2} k\left(\frac{m_W}{m_\phi}\right),$$

$$\Gamma(\phi \to ZZ) = \frac{(m_1 s_{\theta_W}^2 + m_2 c_{\theta_W}^2)^2 m_\phi^3}{32\pi f^2} k\left(\frac{m_Z}{m_\phi}\right),$$

$$\Gamma(\phi \to \gamma\gamma) = \frac{(m_1 c_{\theta_W}^2 + m_2 s_{\theta_W}^2)^2 m_\phi^3}{32\pi f^2},$$

$$\Gamma(\phi \to Z\gamma) = \frac{(m_2 - m_1)^2 s_{\theta_W}^2 c_{\theta_W}^2 m_\phi^3}{16\pi f^2}\left(1 - \frac{m_Z^2}{m_\phi^2}\right)^3,$$

$$\Gamma(\phi \to GG) = \frac{m_\phi^5}{32\pi f^2},$$

PROS

- Possible to split the CP-even/CP-odd sgoldstinos to fake a large width
- Additional tree level contributions to the Higgs mass at small $\tan\beta$ and μ and large B_μ

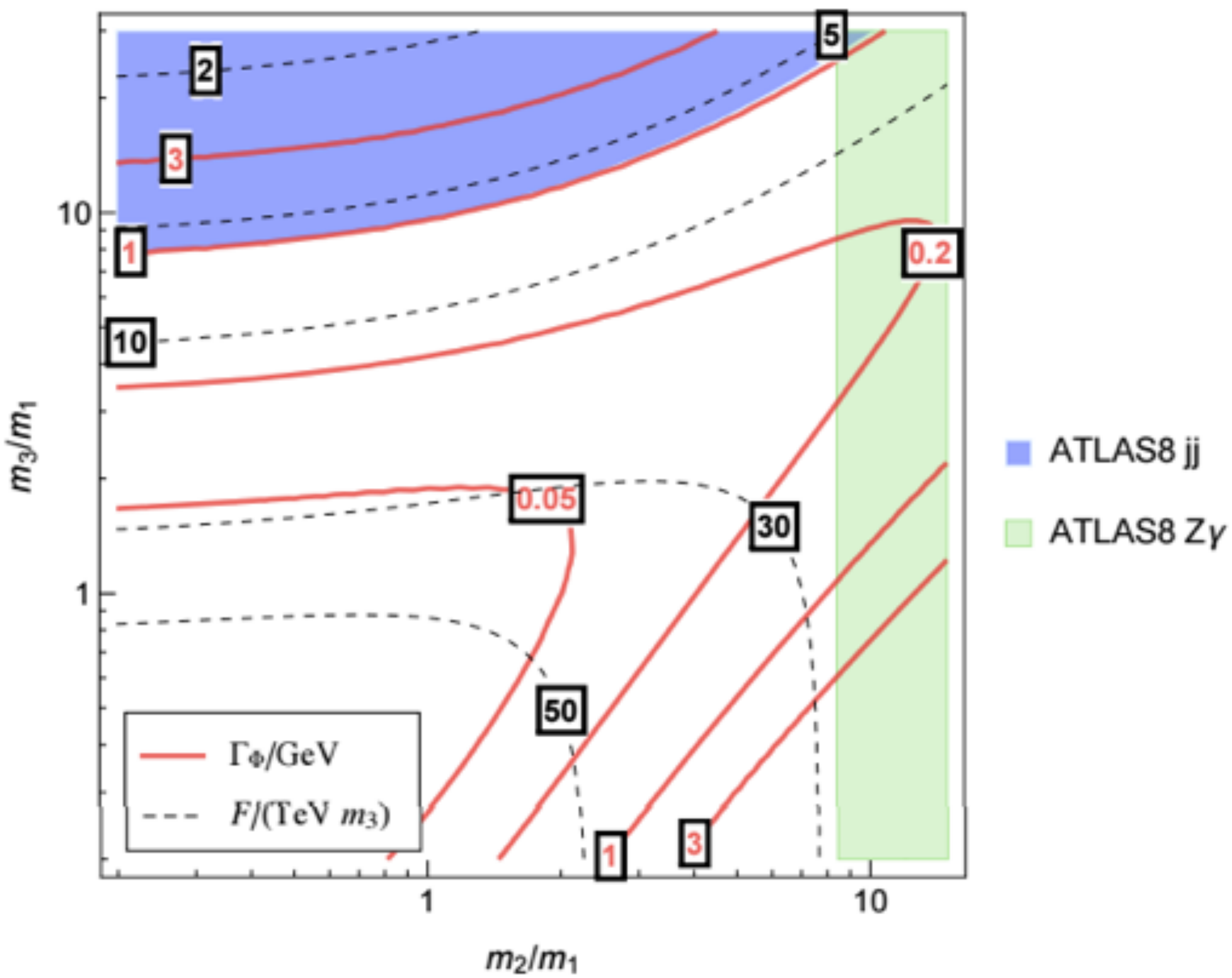
CONS

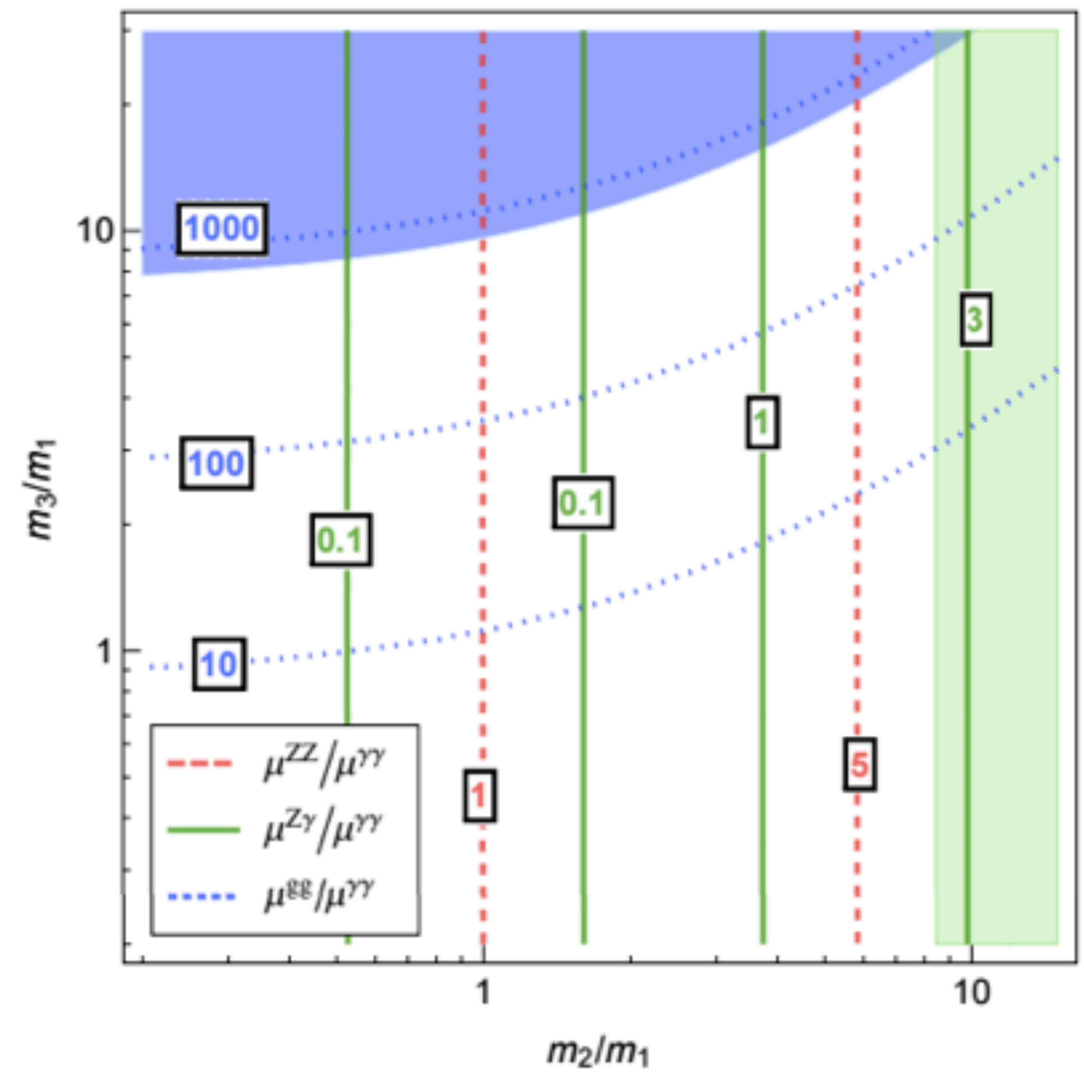
- Only an effective description
- The actual mechanism for SUSY breaking at such low scale and for the generation of light sgoldstino mass not known

Bellazzini et al., 1512.05330 [hep-ph]
Petersson, RT, 1512.05333 [hep-ph]
Demidov, Gorbunov, 1512.05723 [hep-ph]

SGOLDSTINO

- Superpartner of the Goldstone fermion responsible for SUSY breaking (goldstino)
- Needs a low SUSY breaking scale, of the order of few TeV





the generation of light sgoldstino
mass not known

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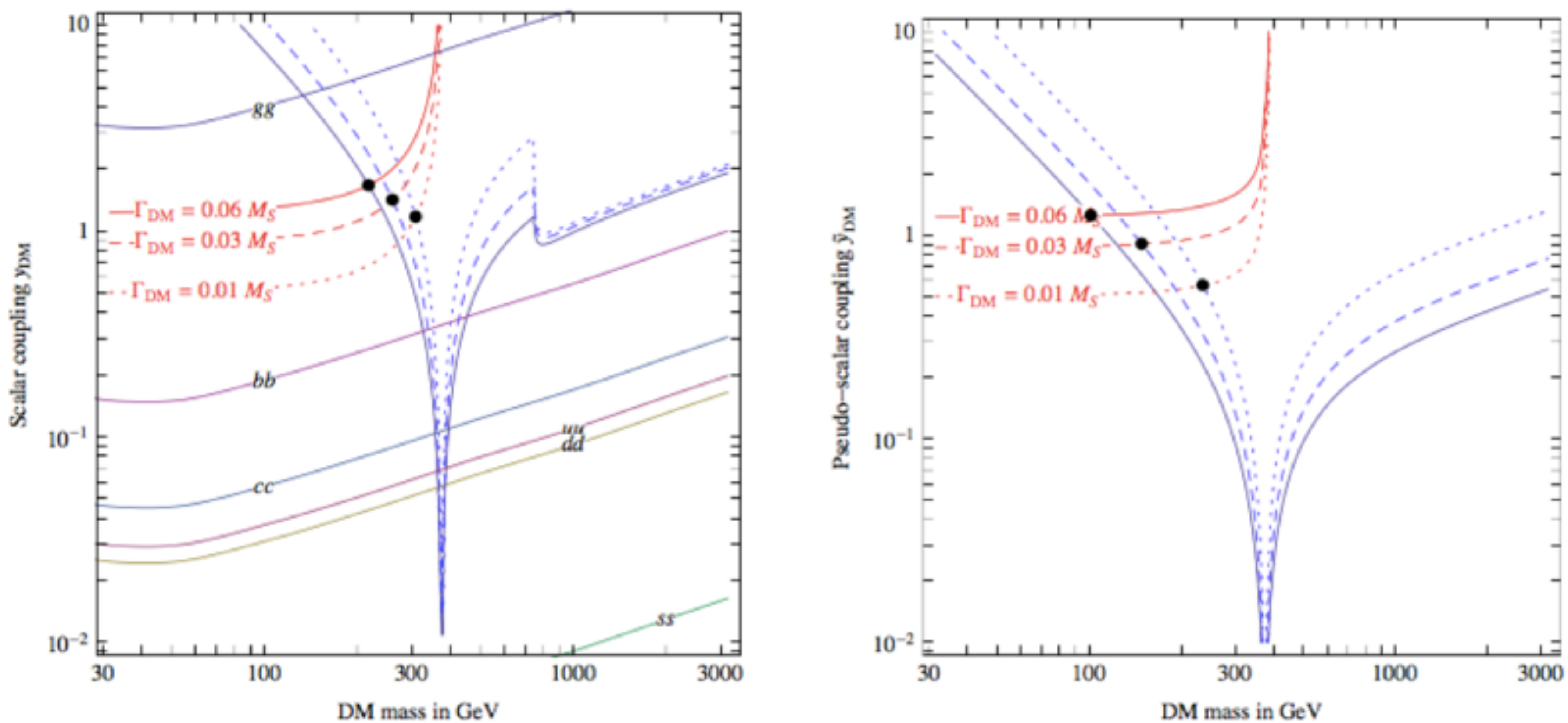
A RELATION WITH DM?

- Connection with DM very appealing
- If the resonance is a portal to DM there are correlated effect on width, relic abundance, (in)direct detection
- A large invisible width can help in saturating the value preferred by ATLAS
- e.g. S is a (pseudo)scalar portal to fermionic DM

$$S\bar{Q}_f(y_f + i\, y_{5f}\gamma_5)Q_f$$



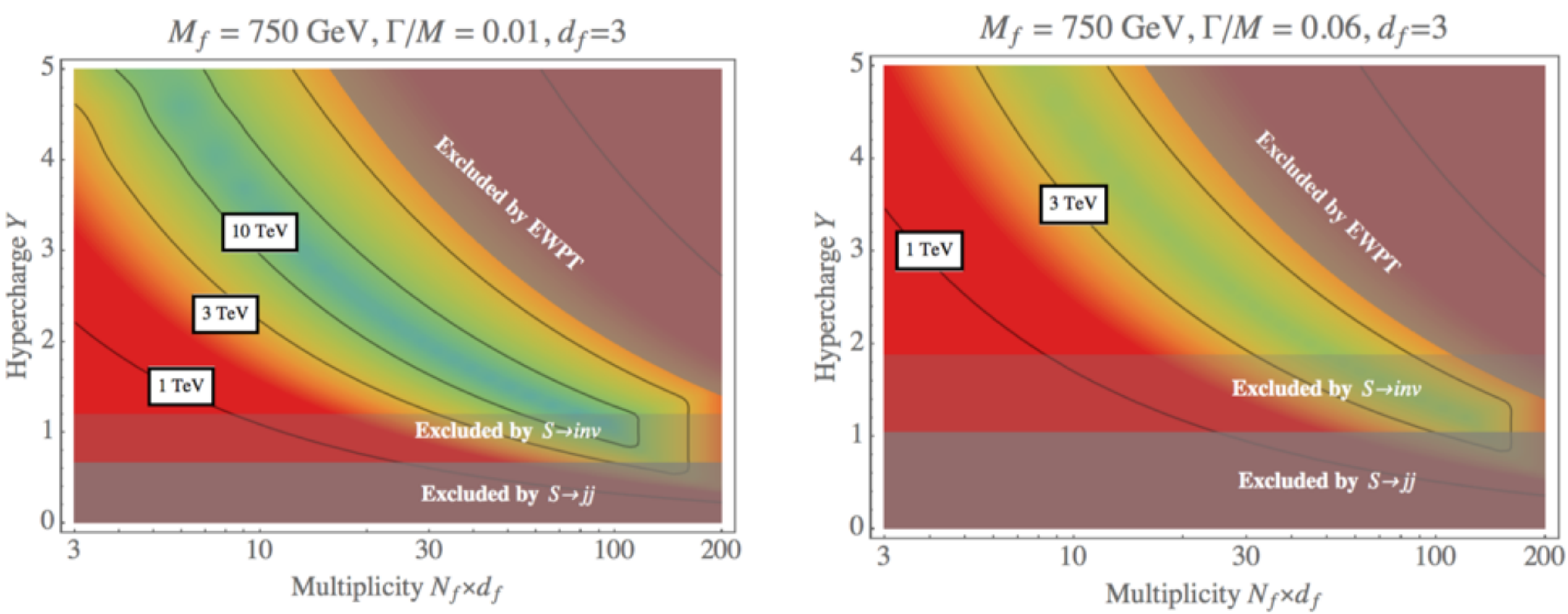
Bounds from direct detection are (weak) irrelevant for S (scalar) pseudoscalar

LARGE WIDTH → STRONG COUPLING

Explaining a large width typically requires large couplings and large number of new particles just above the TeV scale, which points towards strongly coupled models

$$\frac{\Gamma(S\to gg)}{M} \approx 7.2\times 10^{-5}\left|\sum_f I_{r_f} y_f \frac{M}{2M_f} + \sum_s I_{r_s}\frac{A_s M}{16 M_s^2}\right|^2 ,$$

$$\frac{\Gamma(S\to \gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2\frac{A_s M}{16 M_s^2}\right|^2$$



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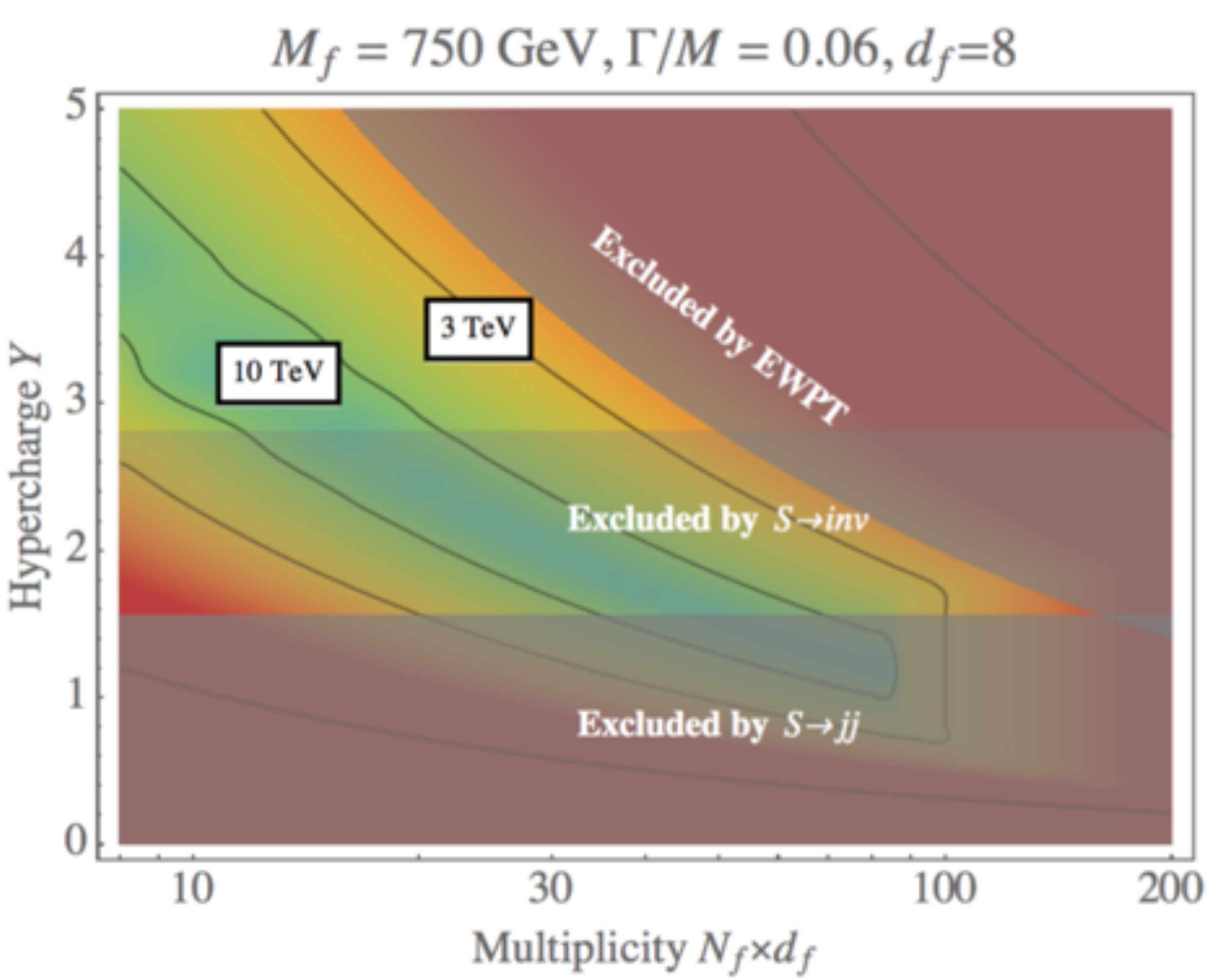

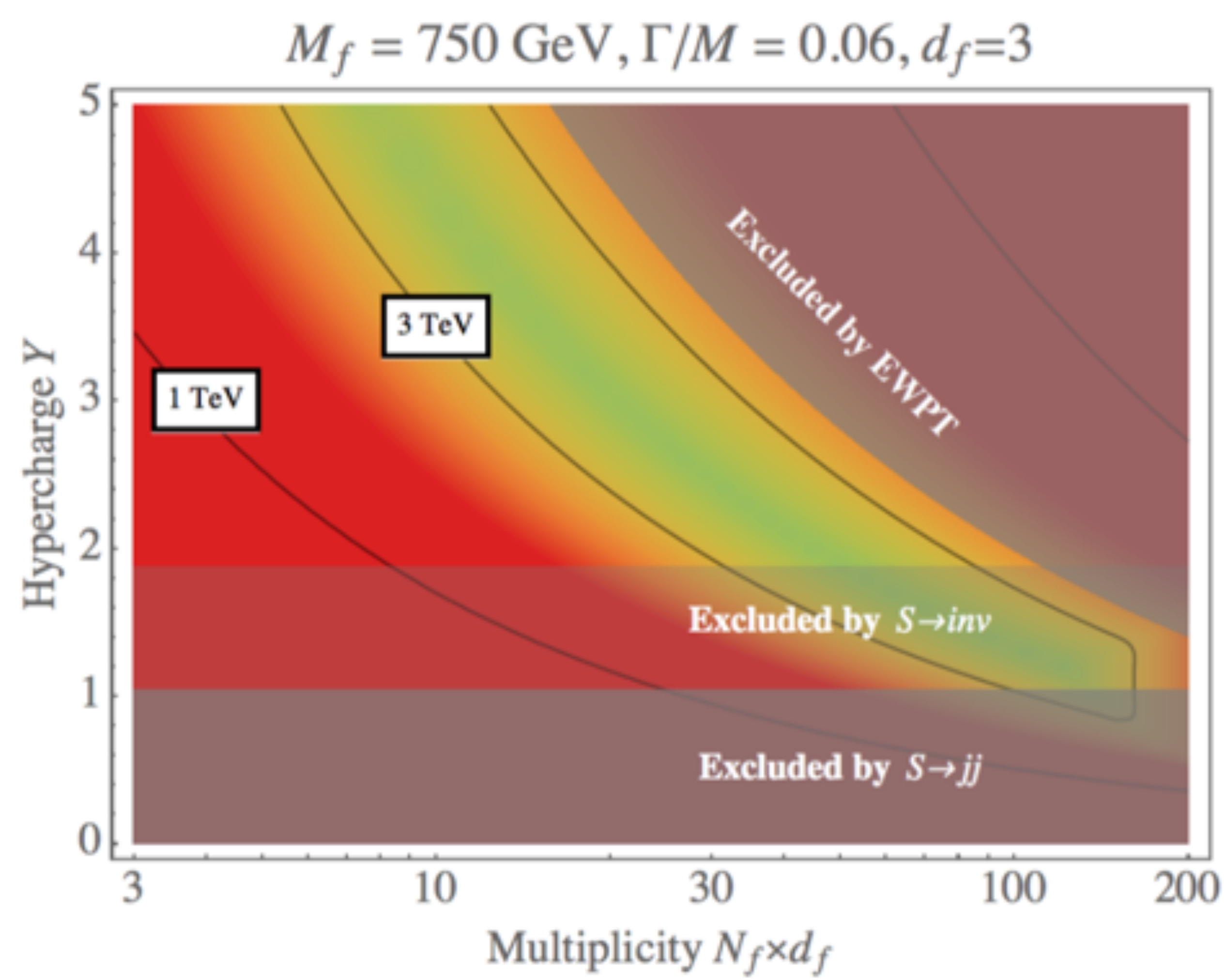

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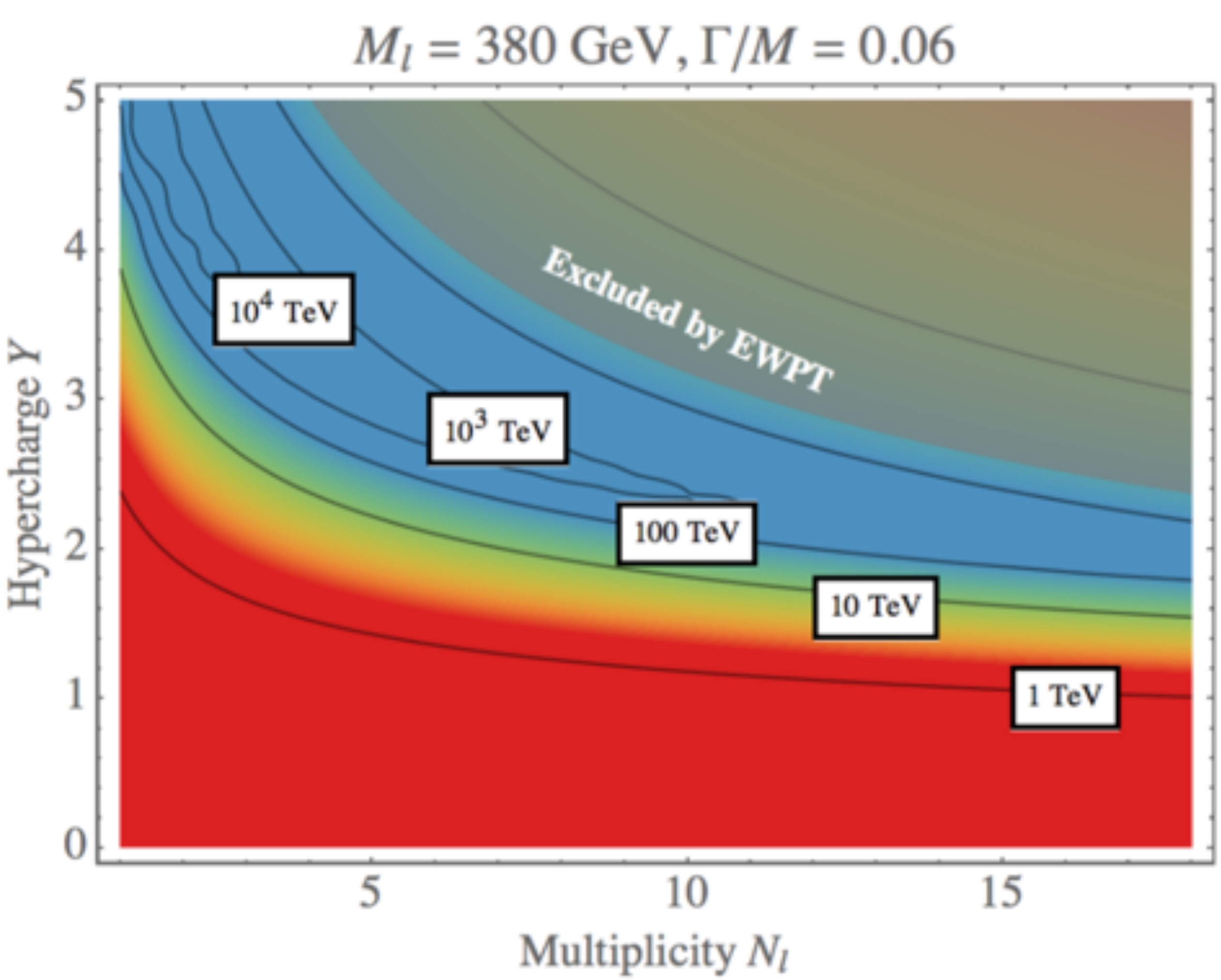
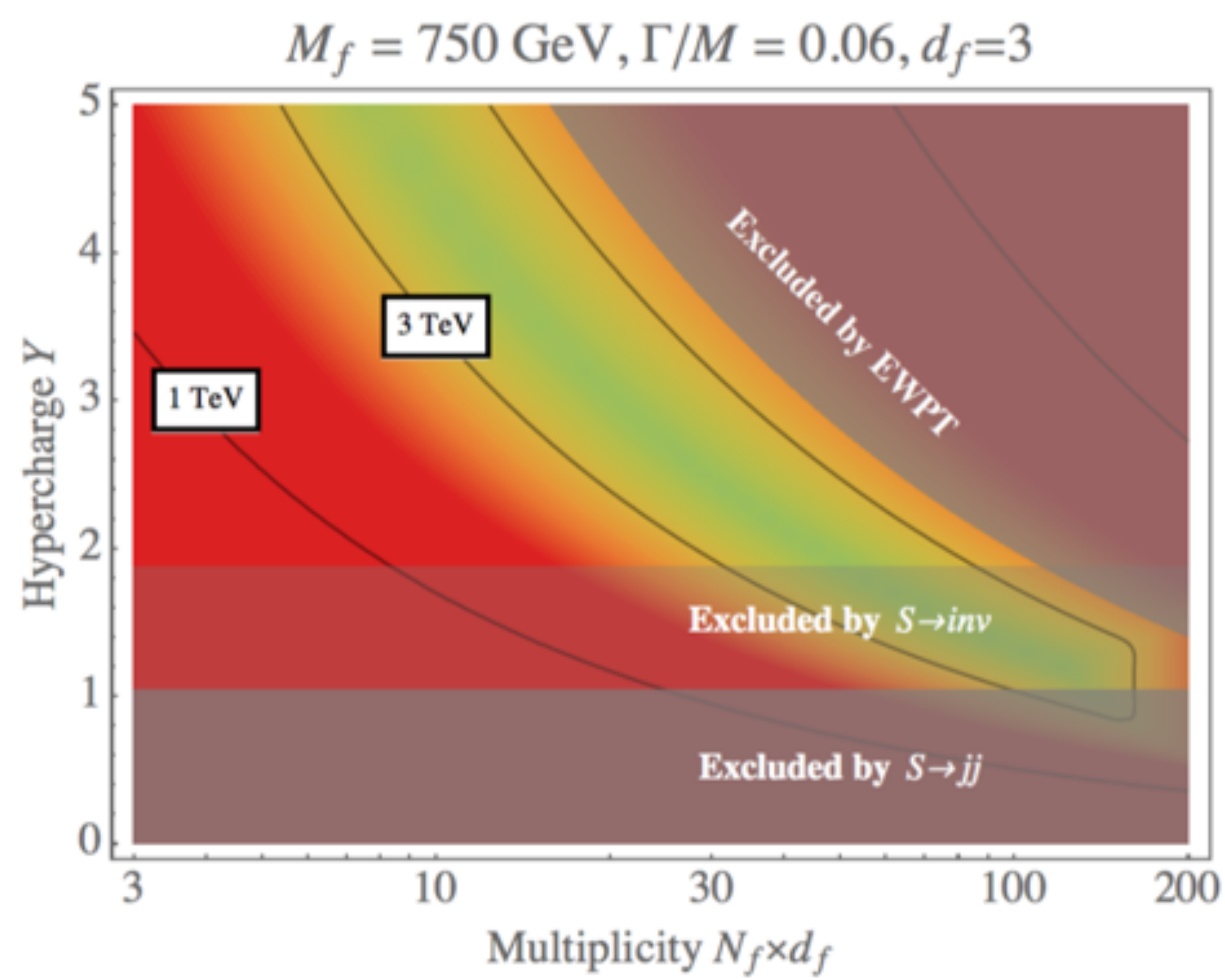
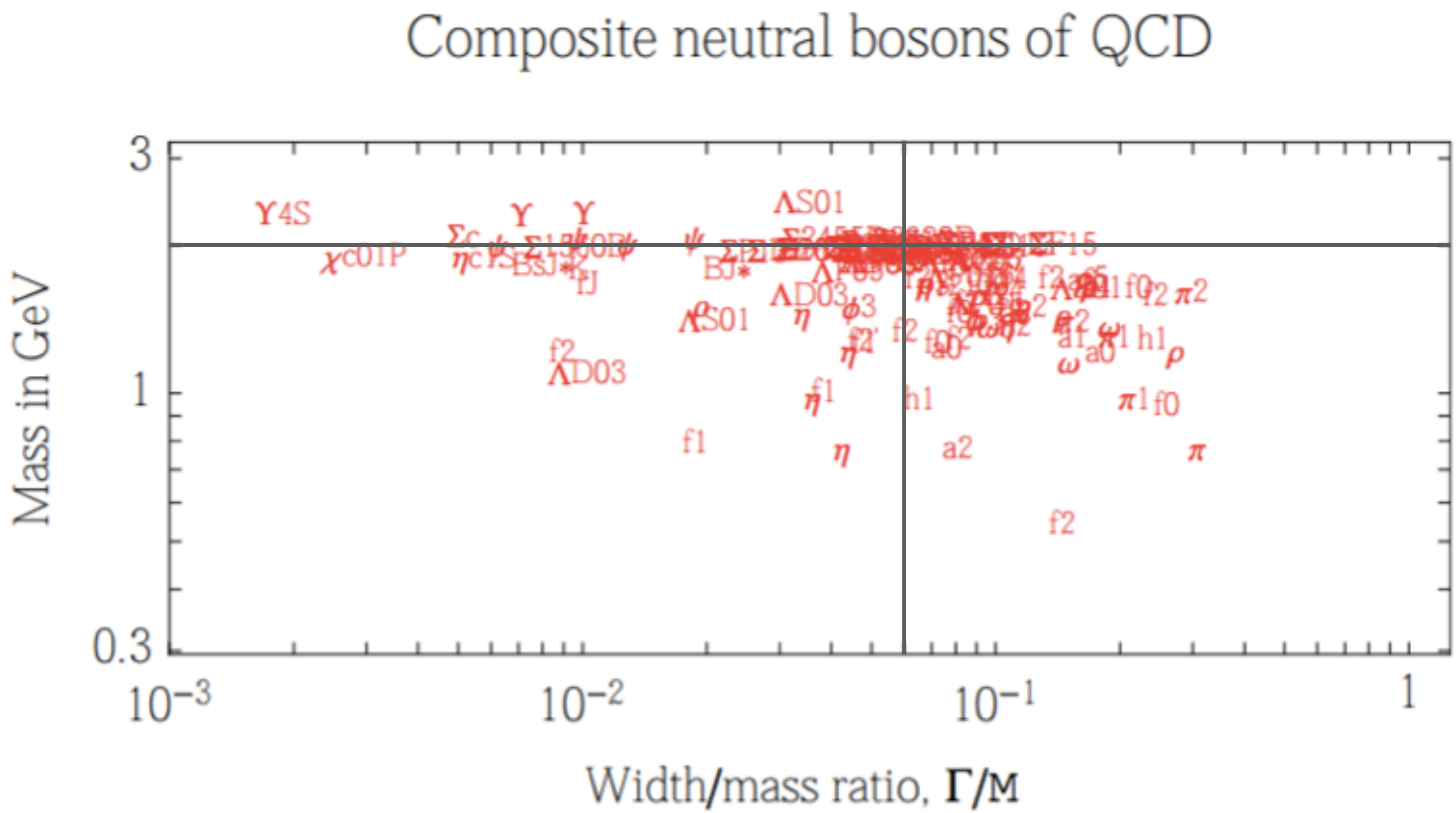




STRONGLY COUPLED MODELS



$\Gamma/M \sim 0.06$ is typical for QCD resonances

However, their mass is typically above the confinement scale Λ, while now bounds on compositeness require the resonance lighter than Λ

In the case of strongly coupled models (like QCD) one needs additional mechanisms to ensure that the resonance can be lighter than Λ

STRONGLY COUPLED MODELS

Explaining a large width typically requires large couplings and large number of new particles just above the TeV scale, which points towards strongly coupled models

- A new scalar that is a PNGB of an extended scalar sector also producing a composite Higgs and is therefore related to electroweak symmetry breaking
  - Pseudo-scalar PNGB coupled through anomalies (Wess-Zumino-Witten terms) or Chern-Simons terms in extra dimensions (e.g. η' in QCD)
  - Scalar PNGB (no WZW term) but coupling typically smaller
  - Dilaton: coupling to Higgs kinetic term (or to tops) can provide the width, but hard to push couplings to photons and gluons
- A new scalar not directly related to the EWSB sector, e.g. in extended confining gauge theories with fermions that are vector-like under the SM
  - QCD-like strong dynamics similar to technicolor: techni-η, techni-pions, techni-quarkonia etc.

The weak feature of strongly coupled models seems to be the difficult in generating a consistent picture of flavour without relying on additional flavour symmetries

MEASURING S PROPERTIES

Is this signal due to a resonance or to more complicated kinematics?

- Look at the events to find more structure
- Look at interference with SM (processes with different structure don't interfere)
- More statistics would allow to exclude two/more nearby resonances
- Distribution of MET very important to distinguish associated production involving DM
- Certainly needs more statistics

Spin

- Look at the angular distribution of the two photons
- Certainly needs more statistics

C-P properties

- If ZZ is observed soon look at 4-lepton distributions (like for the Higgs)
  Here differently from the Higgs this could be CP-even but still coupling only to transverse bosons, which can make things harder!
- The angular distribution of jets in Sjj events can be a good discrimination
- Search in the hh channel, this is a discriminant

Other properties

- Associated productions with W, Z, h and pair production
- Precise measurements of the S properties may require a Future Collider