750 GeV Diphoton Resonance

Experimental Searches and Theoretical Interpretations

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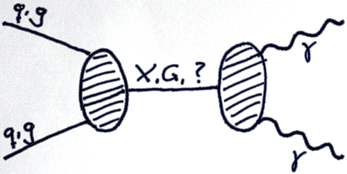
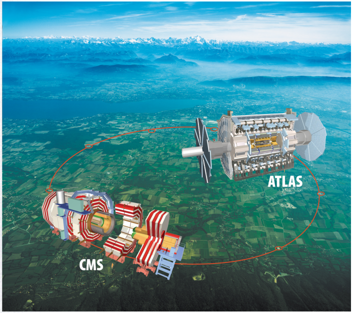
Introduction - Diphoton Resonance Searches at LHC





why $\gamma\gamma$ resonance searches?:

- smooth non-resonant background
  $\rightarrow$ easy to model
- excellent detector resolution for hight-p_T photons
- essential channel for early Higgs discovery

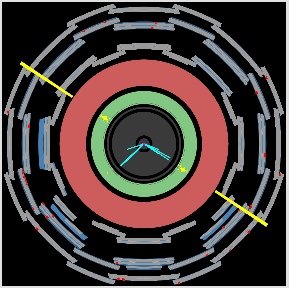
searches were performed at 8TeV already (spin-0/-2):

- new discovery potential at 13TeV
- 13 TeV provides increased production cross sections: 4.7$\times$ for gg and 2.7$\times$ for qq compared to 8TeV

2015 & 2016 13TeV data samples ("ICHEP dataset"):

- **ATLAS:** $3.2 + 12.2$ fb^{-1}
- **CMS:** $3.3 + 12.9$ fb^{-1} (2015 0.6 fb^{-1} w/o magnet)

ATLAS Search - Reconstruction and Event Selection - [ATLAS-CONF-2016-018 & 059]



event trigger:

- 2 photons passing "loose" photon ID criteria
- $E_T > 35(25)$ GeV for leading (subleading) photon

offline photon selection:

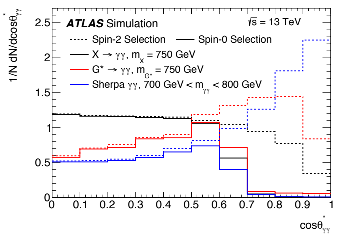
- $|\eta| < 2.37$ excluding barrel-endcap transition regions
- "tight" photon ID: analyse shower shapes
- calo based isolation: $E_T^{iso} < 0.022 \times E_T^{\gamma} + 2.45$ GeV
- track based isolation: $p_T^{iso} < 0.05 \times E_T^{\gamma}$

spin-0 selection: isotropic decay → more central photons

- $E_T^{\gamma}/m_{\gamma\gamma} > 0.4(0.3)$ for leading (subleading) γ
- optimized for max significance → purity > 90%
- subset of spin-2 selection

spin-2 selection: more forward photons

- $E_T > 55$ GeV
- looser selection preserves high-mass signal acceptance

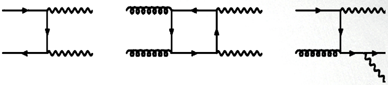


[ICHEP 2016: "Search for a high mass diphoton resonance using the ATLAS detector"]

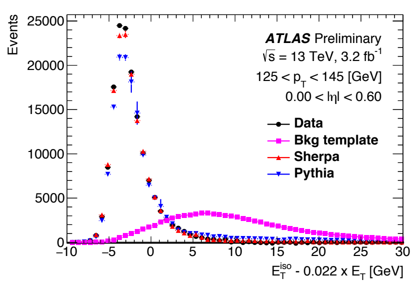
ATLAS Search - Sample Composition and Background Contributions

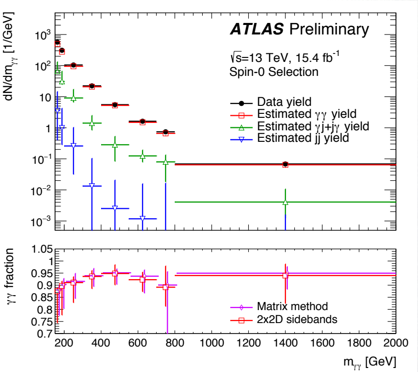
background contributions:

- background is mostly irreducible, non-resoant $\gamma\gamma$
- some reducible γ-jet and dijet contamination
- isolation criteria used to study and reduce background contamination



background composition





diphoton photon purity (increases with mass)

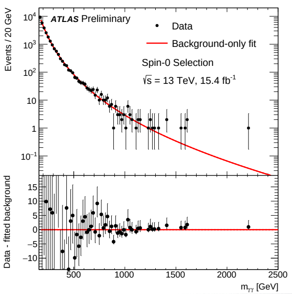
- spin-0 $\sim 93\%$
- spin-2 $\sim 94\%$

ATLAS Search - Background Modelling

spin-0: background parametrized by analytic function:

- test many functions and choose the one with smallest bias on fitted signal
- "spurious signal" modelling systematic: number of signal events fitted to background only MC

$$F(x) = N\left(1 - x^{1/3}\right)^{b} x^{a\log(x)}, \quad x = (m_{\gamma\gamma}/\sqrt{s})$$

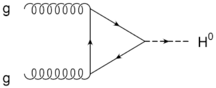


spin-2: background template histogram for high-mass sensitivity:

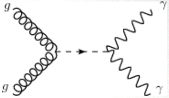
- $\gamma\gamma$ background: from Diphox NLO calculations
- γ-jet and dijet background: from anti-tight γ-ID control regions
- normalization from isolation distribution in at low $m_{\gamma\gamma}$

ATLAS Search - Signal Modelling

spin-0 benchmark model
hight mass SM Higgs



spin-2 benchmark model
RS graviton model (lowest excitation)

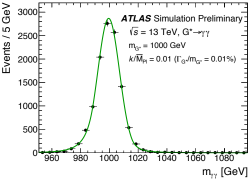


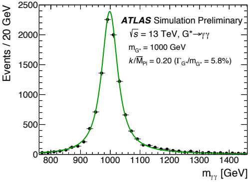
- expected model line-shape parametrized as function of mass and width
- convoluted with double sided Crystal Ball (DSCB) function to model detector resolution

small width

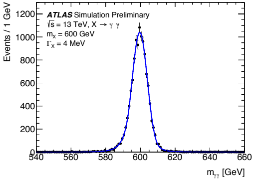
large width

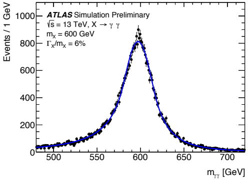
spin-0





spin-2



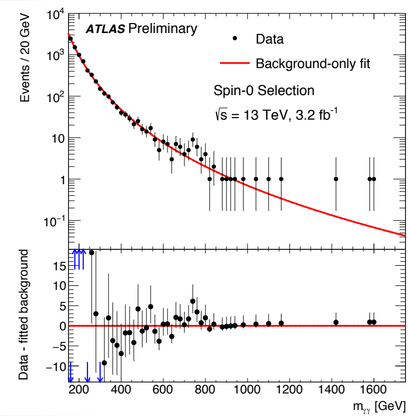


ATLAS Search - Analysis & Results **2015** [ATLAS-CONF-2016-018]

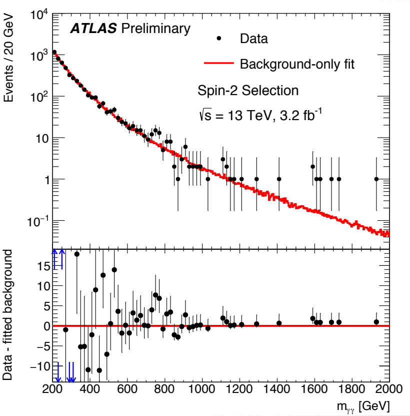
Statistical Methodology

- maximum likelihood fit to mass distribution $N_S(\sigma_S) f_S(m_{\gamma\gamma}) + N_B f_B(m_{\gamma\gamma})$
- calculate local p-values from test statistics $q_0(m_X, \alpha) = -2 \log \dfrac{L(0, m_X, \alpha, \hat{\hat{\nu}})}{L(\hat{\sigma_S}, m_X, \alpha, \hat{\nu})}$

spin-0 selection:

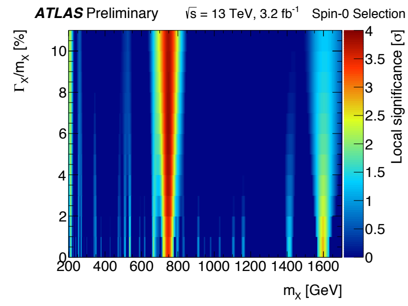


spin-2 selection:

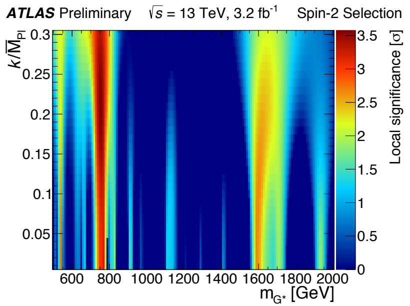


ATLAS Search - Signal Significances in the Mass-Width Plane **2015**

spin-0 selection, Higgs model:



spin-2 selection, graviton model:



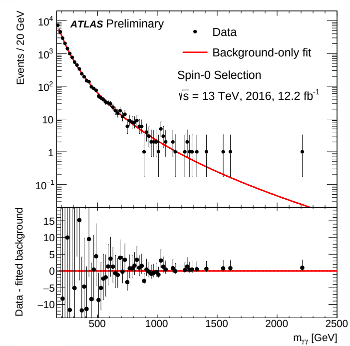
- broad excesses around $m_{\gamma\gamma} = 750 GeV$
- 3.8-3.9σ local significance
- 2.1σ global significance, "look elsewhere effect"

ATLAS Search - Results **2016** [ATLAS-CONF-2016-018]

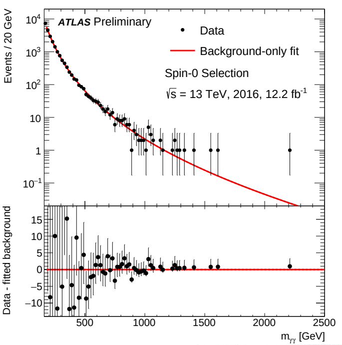
- re-analyse 2015 data w/ improved reconstruction → slightly smaller significance, max at 730 GeV
- spin-0 analysis with 12.2 fb^{-1} 2016 ICHEP dataset published
- spin-2 analysis still ongoing

spin-0 analysis:

2016 only



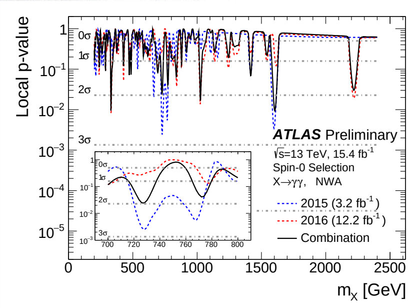
2015 + 2016



- No significant excesses in 2016 data and 2015 + 2016 combination
- compatibility between 2015 and 2016 signal cross-sections at 730 GeV: 2.7σ

ATLAS Search - Significance Narrow Width Signal **2015+2016**

background only compatibility:

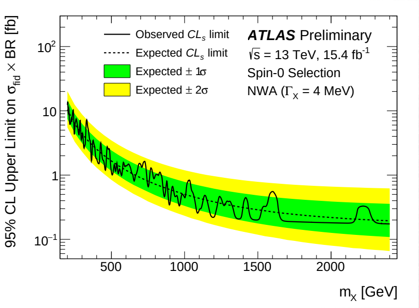


⇒ no excess with a global significance above 1σ

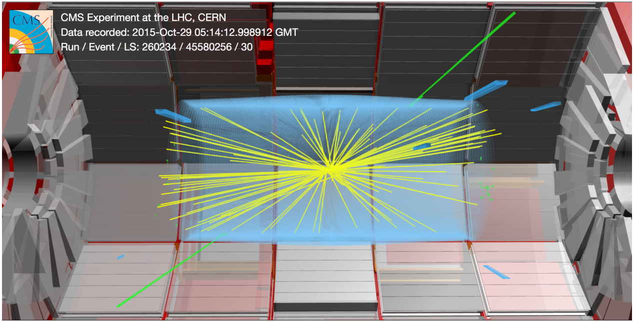
⇒ excess at 750GeV from 2015 vanished in 2016 (spin-0 analysis)

limit setting:

- limit setting on fiducial cross-section (minimize model dependence)



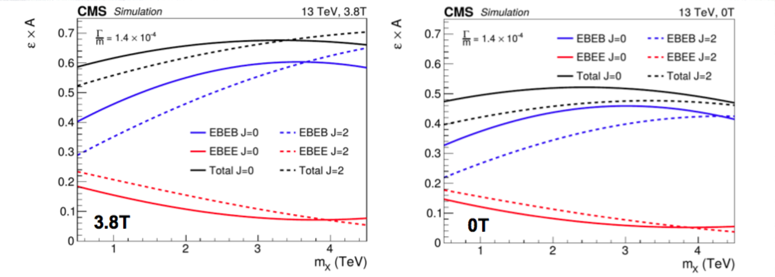
CMS Search - Event Selection



Simple event selection:

- Common spin-0 and spin-2 selection
- Two photons with $p_T > 75$ GeV
- Isolation criteria are imposed
- At least one γ in the barrel $|\eta| < 1.44$

CMS Search - Selection efficiency



- Events split in barrel-barrel(**EBEB**) and barrel-endcaps(**EBEE**) categories
  Per-photon efficiency in the barrel ≈ 90%
  Per-photon efficiency in the endcaps ≈ 85%
- 0.6 fb^{-1} recorded without magnetic field
  No information on track momenta → lower selection efficiency

CMS Search - Likelihood Fit

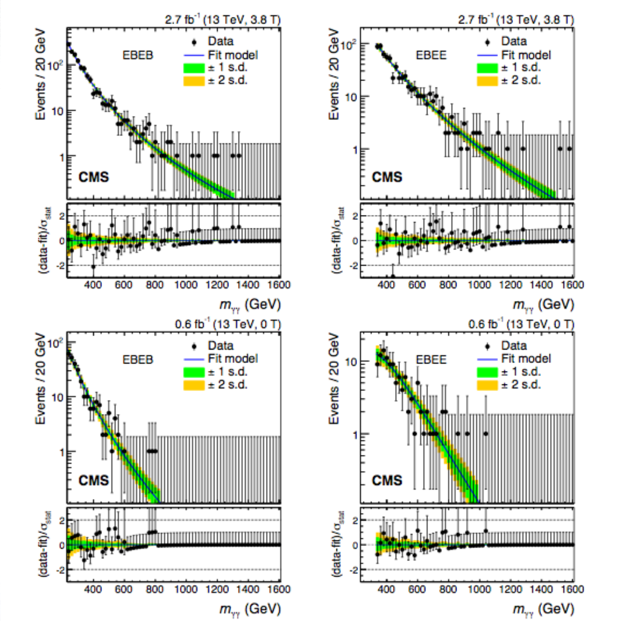
Signal modeling

- Convolution of intrinsic line-shape and detector resolution
- Taken from simulation, corrections are derived from $Z \rightarrow e^+ e^-$ data
- 3 scenarios tested:
  Detector resolution dominates: $\Gamma/m = 1.4 \cdot 10^{-4}$
  Comparable resolution and width: $\Gamma/m = 1.4 \cdot 10^{-2}$
  Resonance width dominates: $\Gamma/m = 5.6 \cdot 10^{-2}$

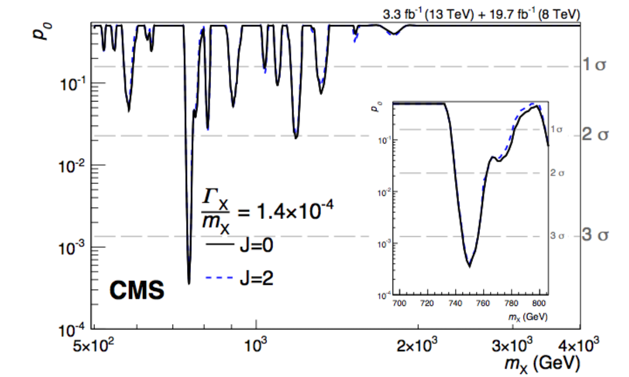
Background modeling

- Dominant contribution: non-resonant $\gamma\gamma$
- $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{a+b\log(m_{\gamma\gamma})}$
- Independent shape for each category
- Possible mis-modeling studied on MC and included as bias term

CMS Search - 2015 Results

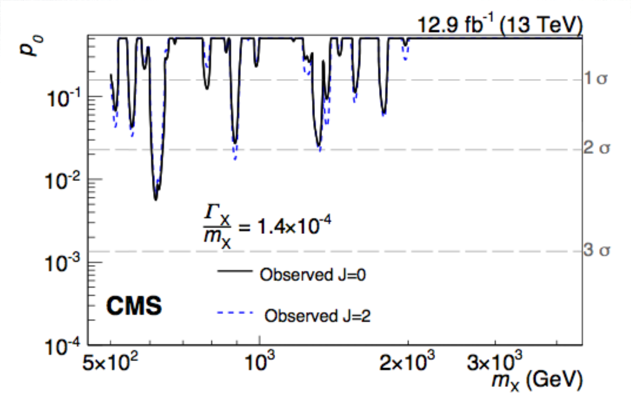


CMS Search - 2015 Results



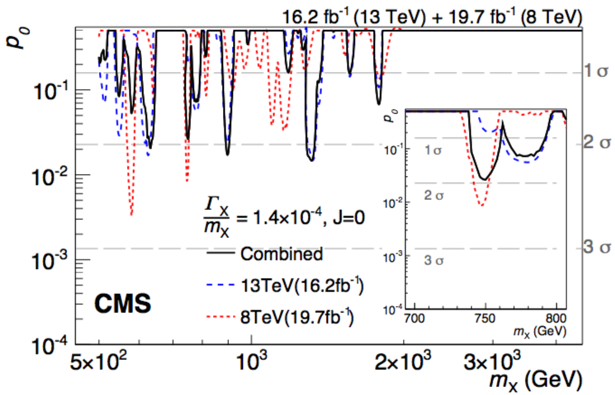
- Largest excess observed for $m \approx 750$ GeV
- Minor differences between spin hypotheses
- Local significance for narrow (large) width: 3.4σ (2.3σ)
- Global significance: 1.6σ

CMS Search - 2016 Results



- No significant excess around $m \approx 750$ GeV
- Largest excess now observed for $m \approx 620$ GeV
- Local significance $\approx 2.4 - 2.7\sigma$

CMS Search - Combined Results



Combination with 2012 and 2015 data:

- Local significance at $m \approx 750$ GeV reduced from 3.4σ to 1.9σ

Summary - Experiment:

- ATLAS and CMS performed searches for diphoton resonances
- Excess around 750 GeV seen in 2015 not confirmed with 2016 data
- Data consistent with background-only hypothesis over the full mass range

The Spin of the Resonance

- spin 1 particle cannot decay into two photons [C.N. Yang, Phys. Rev. 77, 242 (1950)] $\rightarrow$ resonance must have either spin 0 or spin 2
- spin 2 would be very interesting as it might be a graviton candidate
- graviton naturally couples to the energy-momentum tensor and hence universally to all matter and radiation
- makes it theoretically difficult to incorporate the observation of only a single decay channel so far

Modeling the Resonance Theoretically: Preliminaries

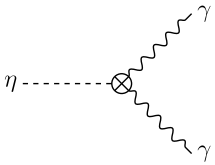
- concentrate on spin 0 case
- let the corresponding scalar field η be real
- two options

$$\eta \text{ is } \begin{cases} \text{scalar} & \Rightarrow \quad \eta \overset{\text{CP}}{\rightarrow} +\eta \\ \text{pseudoscalar} & \Rightarrow \quad \eta \overset{\text{CP}}{\rightarrow} -\eta \end{cases}$$

- more natural choice: pseudoscalar $\rightarrow$ no mixing with Higgs

Effective Field Theory

- η must somehow couple to photons (A^μ), pictorially



- the cross denotes unknown physics, e. g. new particles

Although ignorant of the new physics underlying this interaction we can build an interaction lagrangian describing the phenomenology at low energy $\rightarrow$ effective field theory (EFT)

- we are looking for an interaction term of the form

$$\mathcal{L}_{\text{int}} \sim \eta A^\mu A^\nu$$

- we will impose three symmetries on the interaction lagrangian:
  - Lorentz symmetry
  - U(1) gauge symmetry (QED gauge symmetry)
  - CP symmetry

Lorentz Symmetry

- η is invariant under proper Lorentz transformations
- A^μ transforms as a 4-vector

Hence, possible interaction terms are $\mathcal{L}_{\text{int}} \sim$

- $\eta A^\mu A_\mu$
- $\eta \partial_\mu A_\nu \partial^\mu A^\nu$
- ...

In short: All Lorentz indices must be contracted, which is of course well known!

U(1) Gauge Symmetry

- gauge invariant quantity of QED is the field strength tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- define the dual field strength tensor by $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$

Lorentz + gauge symmetry allows for $\mathcal{L}_{\text{int}} \sim$

- $\eta F^{\mu\nu} F_{\mu\nu}$
- $\eta \tilde{F}^{\mu\nu} F_{\mu\nu}$

CP Symmetry and Final Result

Under CP transformation:

- $F^{\mu\nu}F_{\mu\nu} \to +F^{\mu\nu}F_{\mu\nu}$
- $\tilde{F}^{\mu\nu}F_{\mu\nu} \to -\tilde{F}^{\mu\nu}F_{\mu\nu}$
- recall: $\eta \to -\eta$

Our final result is therefore

$$\mathcal{L}_{\text{int}} = \frac{c}{\Lambda}\eta\tilde{F}^{\mu\nu}F_{\mu\nu}$$

- c is a coupling constant
- Λ is an energy scale which roughly corresponds to the cutoff scale of this EFT

Reminder: Electroweak Gauge Bosons

- in the SM, the U(1) gauge group of QED is a subgroup of the larger electroweak gauge group $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$
- $U(1)_\mathrm{Y}$: 1 generator $\rightarrow$ 1 vector gauge boson B^μ
- $SU(2)_\mathrm{L}$: 3 generators $\rightarrow$ 3 vector gauge bosons W^1_μ, W^2_μ, W^3_μ
- due to electroweak symmetry-breaking the gauge bosons we observe are linear combinations of these:

$$W^+_\mu = W^1_\mu + \mathrm{i}W^2_\mu$$
$$W^-_\mu = W^1_\mu - \mathrm{i}W^2_\mu$$
$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\,\theta_\mathrm{W} & \sin\,\theta_\mathrm{W} \\ -\sin\,\theta_\mathrm{W} & \cos\,\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

- Weinberg angle $\sin^2\theta_\mathrm{W} \approx 0.23$

Improved Effective Theory

- we will now generalize our old $\mathcal{L}_{\text{int}}$ by demanding invariance under the electroweak gauge symmetry
- the gauge invariant quantities made of electroweak gauge bosons are again the corresponding field strength tensors $B_{\mu\nu}$ and $W^a_{\mu\nu}$
- both $B_{\mu\nu}$ and $W^a_{\mu\nu}$ contain the photon A_μ and hence potentially couple to η:

$$\mathcal{L}_{\text{int}} = \frac{c_{\text{B}}}{\Lambda}\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_{\text{W}}}{\Lambda}\eta W^a_{\mu\nu}\tilde{W}^{a,\mu\nu}$$

- conclusion: electroweak gauge symmetry predicts η to couple also to Z- and maybe to $W^{\pm}$-bosons
- this can help to constrain the possible strength of the couplings and other parameters, see e. g. [1512.05328]

Production of the Resonance

- all partons of the proton are possible production candidates for the resonance
- the probability to find a certain parton in the proton varies with the energy of the process, encoded in parton distribution functions (PDF)
- due to this we have the following gain values in the cross section of the resonance going from 8 TeV in run 1 to 13 TeV in run 2 [1512.04933]:

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

- the cross section corresponding to the excess at 750 GeV is estimated to be [1512.04933]

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

- need high gain value to be consistent with run 1 data $\rightarrow$ gg-fusion is a reasonable production mechanism

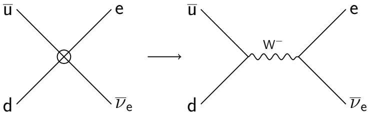
Summary - Theory

- resonance can have spin 0 or 2, most probably spin 0
- electroweak gauge symmetry predicts coupling to Z boson
- possible production mechanism is via gg-fusion

BACKUP

A Familiar EFT: Fermi Theory

- recall β-decay: $\mathrm{d} \to \mathrm{u} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$
- Fermi proposed: $\mathcal{L}_\mathrm{int} \sim G_\mathrm{F} (\overline{\mathrm{u}}\mathrm{d})(\overline{\mathrm{e}}\nu_\mathrm{e}) + \mathrm{h.c.}$
- counting dimensions gives $[G_\mathrm{F}] = -2$

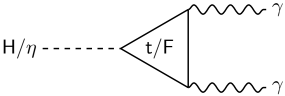


- propagator of W-boson gives a factor $\frac{1}{p^2 - m_\mathrm{W}^2} = \frac{1}{E_\mathrm{CM}^2 - m_\mathrm{W}^2}$
- at low energies $E_\mathrm{CM} \ll m_\mathrm{W} \approx 80$ GeV this gives a roughly constant factor $\frac{1}{m_\mathrm{W}^2}$
- comparing with Fermi's Lagrangian one finds $G_\mathrm{F} \propto \frac{g^2}{m_\mathrm{W}^2}$

  → mass of the new particle hidden in the cross sets the energy scale of the effective theory

Outlook: Possible New Physics

Recall the Higgs detection channel at the LHC (among others):



- might be a good first guess to propose a similar mechanism for the decay of η to two photons
- in order for this to work we have to replace the top quark by new heavy fermions F