Perturbative unitarity and the LHC di-photon excess

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Based on <u>arXiv:1604.05746</u> in collaboration with: Jernej F. Kamenik (JSI, Ljubljana), Marco Nardecchia (DAMTP, Cambridge)

Outline

- Phenomenological aspects of the LHC di-photon excess
- Application of <u>partial wave unitarity</u> to the di-photon excess:



The LHC di-photon excess

• Both ATLAS and CMS observe a di-photon excess at ~ 750 GeV

[See F. Malek talk on Saturday]



3.9 σ local (2.1 σ global) - best fit for $\Gamma/M \sim 6\%$

[See M. Quittnat talk on Saturday]



2.9 σ local (1.6 σ global) - narrow width

The LHC di-photon excess

- Both ATLAS and CMS observe a di-photon excess at \sim 750 GeV
- Disclaimer
- I assume this is not a statistical fluctuation (we will know soon!)
- O(400) papers on the arXiv since Dec 15th (apologies for the missing refs.)
- <u>Here</u>: not a specific model, but some general "theoretical constraints"

Stick to the <u>simplest</u> interpretation

• A single 750 GeV resonance

[See A. Carmona talk on Monday]

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- spin 0 (spin 1 not allowed by Landau-Yang theorem, spin 2 too exotic)

Stick to the <u>simplest</u> interpretation

• A single 750 GeV resonance

[See A. Carmona talk on Monday]

- spin 0
- SM singlet without mixing with the H (extra EW and Higgs precision constraints)



Stick to the <u>simplest</u> interpretation

• A single 750 GeV resonance

[See A. Carmona talk on Monday]

- spin 0

- SM singlet without mixing with the H
- CP scalar (pseudo-scalar also ok, if CP violated extra constraints from EDMs, ...)

Stick to the simplest interpretation

- A single 750 GeV resonance
- spin 0
- SM singlet without mixing with the H
- CP scalar
- s-channnel 2-body decay (other kinematical options available)



[See A. Carmona talk on Monday]

EFT of a di-photon resonance

• Assuming a spin-0 SM gauge-singlet scalar resonance S

[see e.g. |5|2.04933, |603.06566]

04/12

$$\mathcal{L}_{\text{eff}} \supset -\frac{g_3^2}{2\Lambda_g} SG_{\mu\nu}^2 - \frac{e^2}{2\Lambda_\gamma} SF_{\mu\nu}^2 - \sum_q y_{qS}S\overline{q}q$$

• Decay widths

$$\Gamma_{gg} \equiv \Gamma(S \to gg) = 8\pi \alpha_s^2 \frac{M_S^3}{\Lambda_g^2}$$
$$\Gamma_{\gamma\gamma} \equiv \Gamma(S \to \gamma\gamma) = \pi \alpha_{\rm EM}^2 \frac{M_S^3}{\Lambda_\gamma^2}$$
$$\Gamma_{q\bar{q}} \equiv \Gamma(S \to q\bar{q}) = \frac{3}{8\pi} y_{qS}^2 M_S$$



or



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04/12

$$\mathcal{L}_{\text{eff}} \supset -\frac{g_3^2}{2\Lambda_g} SG_{\mu\nu}^2 - \frac{e^2}{2\Lambda_\gamma} SF_{\mu\nu}^2 - \sum_q y_{qS}S\overline{q}q$$

• Fit cross-section

$$\sigma(pp \to S \to \gamma\gamma) = \sigma(pp \to S)\mathcal{B}_{\gamma\gamma} \simeq 3 \div 6 \text{ fb}$$

$$\sigma(pp \to S) = \frac{1}{M_S s} \left[\sum_{\mathcal{P}} C_{\mathcal{P}\overline{\mathcal{P}}} \Gamma_{\mathcal{P}\overline{\mathcal{P}}} \right]$$

- $C_{\mathcal{P}\overline{\mathcal{P}}} \rightarrow$ parton luminosities

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

best fit has a narrow width and a local statistical significance of 2.90 massuming a large width ence comparable to Γ . In section 4 we interpret the signal $in_{1/2}$ the context of $\Gamma/M \approx 0.06$, the sign $M \approx 0.00$, the significance decr interacting new physics. Modelling the resonance as a composite state allows for a The anomalous events are not $\Gamma/M \approx 0.06$, the significance decreases to 2.0σ , corresponding to a cr explanation of the large width, as well as the partial width in the $\gamma \gamma$ channel. In s jets. No resonances at invariant jets. No resonances at invariant in the anomalous events are that accombanied by significant mix we consider decays in a pair of the property of the part of the property of the part of Sections in the $m_{\gamma\gamma}$ production rate production rate at $f_{c} = 8$ TeV but much more accessible at 13 TeV. This particle into the 750 GeV resonance accompanied either by invisible particles, possibly related matterefor to undetected soft radiation. Conclusions are presented in section $C_{gg/s} \subseteq C_{\gamma}$ $pp \rightarrow \gamma\gamma) \approx \begin{cases} \overline{8 \text{ TeV}} & \overline{1000.42 \pm 0.8} \\ 2 & \overline{13000.42 \pm 0.8} \\ \overline{13000.42 \pm 0.8} \\ \overline{13000.42 \pm 0.8} \\ \overline{1000.42 \pm 0.8} \\ \overline{1000.42 \pm 0.8} \\ \overline{1000.42 \pm 0.8} \\ \overline{10000.42 \pm 0.8$ $\sigma(pp \to \gamma\gamma) \approx$ • Fit cross-section 2 Pnenomenological analysis (10 ± 3) fb ATLAS [1] $\sqrt{s} =$ The data at $\sqrt{s} =$ $(p_B \rightarrow S)$ where $C_{\gamma\gamma}$ has a 100% uncertainty if extracted purely from data will least a factor of 5. uncoloured boson splitting states of provide structure of provide structure of provide structure of provide structure of the pro While the answerged the superturbation at While the answer to the question in the titles could just be "a state to try to interpret the result as a manifestation of new interesting to try to interpret the assume that diverters of a sumesthat the signal is divergences and the the relating them to an effective deseringtion 41B te 217 s of 5004-17e horonalizab John intertexno twas affective Texcu present weakly-coupled renormalizable models that realise the ne we present Grain lay tand a deriver of the same and the s resonance. The total page mars rate ingredients are needed to reproduce 591-1 0 and the second a function of the second and of the apparently large width cou that hyan been at the sections tentrenderpass that signaleing difference comparable to Γ . X s interacting new physics. Modelli exploration for further out of the and welling under tipp Generated in rof-the slare of widtely, as Swelt been side placeting invidual and Marking unaned a add we consider decays onto Dark option to the topology and kinematic strend the topologies \bar{b}' the 04/12 L. Di Luzio (Genova U.) - Perturbative unitarity and the LHC di-photon excess

EFT of a di-photon resonance

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04/2

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Production mechanisms



EFT of a di-photon resonance

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[see e.g. |5|2.04933, |603.06566]

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• SM gauge-invariant EFT

$$\mathcal{L}_{\text{eff}}^{\text{SM-invariant}} \supset -\frac{g_3^2}{2\Lambda_g} SG_{\mu\nu}^2 - \frac{g_2^2}{2\Lambda_W} SW_{\mu\nu}^2 - \frac{g_1^2}{2\Lambda_B} SB_{\mu\nu}^2 - \frac{S}{\Lambda_q} \left(\overline{Q}_L q_R H + \text{h.c.} \right)$$
- matching:
$$\frac{1}{\Lambda_\gamma} = \frac{1}{\Lambda_B} + \frac{1}{\Lambda_W} \qquad y_{qS} = \frac{v}{\sqrt{2}\Lambda_q}$$

- leading interactions of S to SM fields via dim=5 operators

until which scale we do expect the S+SM EFT description to be valid ?



A historical detour

- Unitarity arguments often served as a guide in HEP
 - I) $\pi\pi$ scattering in χ PT

[Weinberg (1966), ...]

- the scale of unitarity violation \sim 500 MeV signals the onset of NP (QCD)
- 2) LHC "no lose theorem" $\rightarrow \Lambda \lesssim 1 \text{ TeV}$

[Lee, Quigg, Thacker (1977), ...]

- upper bound either on the Higgs mass or on the scale of NP unitarizing WW scattering

3) Upper bound on the mass of particle DM (if once in thermal equilibrium)

[Griest, Kamionkowski (1990), ...]

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 $m_{\rm DM} \lesssim 300 {
m ~TeV}$

Partial wave projection

- Scattering matrix: S = 1 + iT
- 2 \rightarrow 2 scattering amplitude in momentum space

$$\langle f|T|i\rangle = (2\pi)^4 \delta^{(4)} (P_i - P_f) \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$$

• Dependence on $cos(\theta)$ eliminated by projection onto J-th partial waves [Jacob, Wick (1959)]

$$a_{fi}^{J} = \frac{\beta_{f}^{1/4}(s, m_{f1}^{2}, m_{f2}^{2})\beta_{i}^{1/4}(s, m_{i1}^{2}, m_{i2}^{2})}{32\pi s} \int_{-1}^{1} d(\cos\theta) \, d_{\mu_{i}\mu_{f}}^{J}(\theta) \, \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$$

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- $\beta(x, y, z) = x^2 + y^2 + z^2 2xy 2yz 2zx \rightarrow \text{kinematics (zero at threshold)}$
- $\mu_i = \lambda_{i1} \lambda_{i2}$ and $\mu_f = \lambda_{f1} \lambda_{f2} \rightarrow$ helicity formalism
- $d_{\mu_i\mu_f}^J(\theta) \rightarrow \text{Wigner d-functions (e.g. } d_{00}^J = P_J \text{ Legendre polynomials)}$

Partial wave projection

- Scattering matrix: S = 1 + iT
- 2 \rightarrow 2 scattering amplitude in momentum space

$$\langle f|T|i\rangle = (2\pi)^4 \delta^{(4)} (P_i - P_f) \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$$

• Focus on J = 0 partial wave

$$a_{fi}^{0} = \frac{\beta_{f}^{1/4}(s, m_{f1}^{2}, m_{f2}^{2})\beta_{i}^{1/4}(s, m_{i1}^{2}, m_{i2}^{2})}{32\pi s} \int_{-1}^{1} d(\cos\theta) \,\mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$$

06/12

Perturbative unitarity

• Unitarity (an axiom of QFT)

- In practical perturbative calculations S-matrix unitarity is always approximate
- perturbative expansion breaks down for

$$|\operatorname{Re}\left(a_{ii}^{J}\right)^{\operatorname{Born}}| \le \frac{1}{2}$$



Di-photon scattering

• $\gamma \gamma \rightarrow \gamma \gamma$ scattering (high-energy limit) [see also 1604.01008]

08/12





Di-photon scattering

• $\gamma \gamma \rightarrow \gamma \gamma$ scattering (high-energy limit) [see also 1604.01008]

08/12



• Tree-level unitarity bound $|\operatorname{Re} a^0| \leq 1/2$

$$\sqrt{s} \lesssim \sqrt{16\pi} \frac{\Lambda_{\gamma}}{e^2} = M_S \left(\frac{\Gamma_{\gamma\gamma}}{M_S}\right)^{-1/2} \simeq 75 \text{ TeV} \left(\frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}}\right)^{-1/2}$$
$$\uparrow$$
$$\Gamma_{\gamma\gamma} = \pi \alpha_{\rm EM}^2 \frac{M_S^3}{\Lambda_{\gamma}^2}$$

- scale of unitarity violation fixed in terms of a "measured" quantity

- Bounds can be strengthened by looking at the full $V_i V_i \rightarrow V_j V_j$ scattering matrix
- -i = any of the 8 + 3 + 1 (transversely polarized) SM gauge bosons



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(s-channel dominates at high energies)

- Bounds can be strengthened by looking at the full $V_i V_i \rightarrow V_j V_j$ scattering matrix
- -i = any of the 8 + 3 + 1 (transversely polarized) SM gauge bosons



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- Bounds can be strengthened by looking at the full $V_i V_i \rightarrow V_j V_j$ scattering matrix
- in terms of "measured" quantities:



$$\frac{s}{32\pi} \left(8\frac{g_s^4}{\Lambda_g^2} + 3\frac{g_2^4}{\Lambda_W^2} + \frac{g_1^4}{\Lambda_B^2} \right) \lesssim \frac{1}{2} \qquad \text{(unitarity bound)}$$

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- Bounds can be strengthened by looking at the full $V_i V_i \rightarrow V_j V_j$ scattering matrix
- in terms of "measured" quantities:

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- Bounds can be strengthened by looking at the full $V_iV_i \rightarrow V_jV_j$ scattering matrix
- in terms of "measured" quantities:



- future determination of $S \rightarrow WW, ZZ, Z\gamma$ crucial to strengthen the bound

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SM quark annihilation

• $\overline{Q}q \rightarrow SH$ scattering





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SM quark annihilation

• $\overline{Q}q \rightarrow SH$ scattering

• Tree-level unitarity bound

$$\sqrt{s} \lesssim 8\pi\Lambda_q = 2\sqrt{3\pi}v \left(\frac{\Gamma_{q\bar{q}}}{M_S}\right)^{-1/2} \simeq 6.2 \text{ TeV} \left(\frac{\Gamma_{q\bar{q}}/M_S}{0.06}\right)^{-1/2}$$
$$y_{qS} = \frac{v}{\sqrt{2}\Lambda_q}$$
$$\Gamma_{q\bar{q}} = \frac{3}{8\pi}y_{qS}^2 M_S$$

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Di-photon "no lose theorem"

• EFT of a di-photon resonance breaks down at scales of few tens of TeV



- new d.o.f. unitarizing the amplitudes' growth are expected below this scale
- a physics case for the 50 TeV collider
 - (a worse case scenario. In typical models new d.o.f. beyond S lie much below 10 TeV)

Conclusions

- <u>Perturbative unitarity</u> as a tool to infer:
- I) the range of validity of a given EFT
- EFT of a di-photon resonance breaks down at scales of few tens of TeV
- 2) the range of validity of perturbation theory in renormalizable models
- Endangered calculability in a wide class of di-photon models (large width scenario)

[see backup slides]



Production mechanisms

[from 1512.04933]



$$\frac{\Lambda_b/M}{10 \quad 3 \quad 1 \quad 0.3}$$

$$\frac{10^{-1}}{10^{-2}} \quad 0.1 \quad 0.3 \quad 0.3$$

$$\frac{\Gamma_{\gamma\gamma}}{M_S} \frac{\Gamma_{gg}}{M_S} \simeq 4.9 \times 10^{-8} \left(\frac{\Gamma_S/M_S}{0.06}\right)$$

 $\frac{\Gamma_{\gamma\gamma}}{M_S} \frac{\Gamma_{b\bar{b}}}{M_S} \simeq 8.4 \times 10^{-6} \left(\frac{\Gamma_S/M_S}{0.06}\right)$

space. We are now ready to compare these bounds with the information O(S) parameters coming from data on S. To this end, we can use the expression of S to the expression of S to the expression of S. adapted to the case of CP-odd interactions. The induced widths free are given by • "Everybody's model" [1512.04933, 1512.08500 + same mechanism in O(100) papers] $\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left| \mathcal{P}(\tau_Q) \right|^2 \,,$ $S \overset{\text{fQS}}{\sim} \overset{(3,1)}{\sim} \overset{(1,0)}{1} \overset{\text{M}}{\overset{\text{M}}{\rightarrow}} \overset{(2,2)}{\overset{(2,2)}{1}} Y^4 N_E^2 \mathscr{G}_e^2 \tau_E (\mathcal{P},(1_E \emptyset))^2 ,$ ς γ S e now ready to compare these of the boot of the second states with the second of the second states of the second mitersfrom idetion Sata on this and his cost we can use the expression of the start $\mathcal{F}_{\tau} = \mathcal{F}_{\tau} = \mathcal{$ given by In order to be conservative we take the values of mediator masses close $y_Q S Q + y_Q S E \gamma E$ experimental exclusion limit. In particular, we take $M_Q = 1$ TeV and • Alarge approtor $X_{3}^{2} + M_{2}^{2} + M_{2}^{2$ $\Gamma(S \to \gamma \gamma)^{S} \stackrel{\rightarrow}{=} M \frac{\gamma \alpha^{2}}{16\pi^{3}} Y^{4} \frac{\alpha^{2}}{16\pi^{2}} Y^{4} \frac{\gamma \alpha^{2}}{16\pi^{2}} \frac{\gamma \alpha^{2}}{16\pi^{2}} Y^{4} \frac{\gamma \alpha^{2}}{16\pi^{2}} Y^{4} \frac{\gamma \alpha^{2}}{16\pi^{2}} \frac{\gamma \alpha^{2}}{$ • Narrow Width $P(\tau) = \operatorname{arctan}^2 (1/\sqrt{\tau - 1})$. for a top-like state der to be conservative, we take the values of mediator masses close $V^4 + V^2 + V^$

space. We are now ready to compare these bounds with the information O(S) parameters coming from data on S. To this end, we can use the expression of the space of the expression of the adapted to the case of CP-odd interactions. The induced widths free are given by • "Everybody's model" [1512.04933, 1512.08500 + same mechanism in O(100) papers] $\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left| \mathcal{P}(\tau_Q) \right|^2 \,,$ $S \overset{\text{fQS}}{\sim} \overset{(3,1)}{(1,1,0)} \underset{M}{\overset{\text{M}}{\rightarrow}} \overset{\Lambda^2}{\overset{Q^2}{1,3}} Y^4 N_E^2 \mathscr{G}_e^2 \tau_E (\mathcal{P}, (1_E \mathbb{Q}))^2 ,$ S e now ready to compare these books by the show the second of the second given by ven by In order to be conservative we take the values of mediator masses close A large di-photon rate is required ental exclusion limit. In particular, we take $M_Q = 1$ TeV and A large diphotor $M_{23} = M_{23} =$ $\frac{\Gamma_{\gamma\gamma}}{M_{S}} \Rightarrow \frac{\alpha_{EAS}^{2}}{16\pi^{3}} + M_{EQ}\frac{q^{2}}{E} + M_{EQ}\frac{\alpha^{2}}{2} + M_{E}\frac{\alpha^{2}}{2} + M_{E}\frac{\alpha^{2}$ $\begin{array}{c} M & M_E \rightarrow 400 \text{ GeV} \\ M_E \rightarrow 400 \text{ G$

Unitarity vs. RGE

- RGE arguments often employed $\underbrace{\frac{y^2 y^2}{16\pi P_6\pi^2}}_{y < y 4\pi 4\pi} 1 < 1$
- Landau pokastheorspotsteitiste usesues
- Beta function Longendance bery ensettethet Tevaseale

2) Beta this tis to hard a set of the set of

$$\mu \frac{d}{d\mu} \frac{d}{d\mu} \frac{d}{d\mu} \beta_{y} \beta_{y} \quad \checkmark \quad \mathcal{A} = y + \beta_{y} \log\left(\frac{\mu}{E}\right) \qquad \qquad |\beta_{y}/y| < 1$$

logarithmically sensitive interimentations (and the principle interimentations) is considered by scale (bounds can be in principle interimentations) is considered by scale (bounds can be in principle interimentations). scalarapartpotential

• Unitarity bound by the stight of the second secon

[with [with Luzio and J. Kamenik, tomorrow?]

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- no calculations beyond tree level required
- apply at any \sqrt{s} above threshold

Unitarity bounds

• 2 \rightarrow 2 scatterings of charged mediators $\psi \overline{\psi} \rightarrow \psi \overline{\psi}$



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Generalization in flavor space

• N copies of mediators ψ_i (i = 1, ..., N) interacting via



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• N copies of mediators ψ_i (i = 1, ..., N) interacting via

- e.g. $y_{ij} = y \delta_{ij}$ in the mass basis ("everybody's model")

exploit <u>U(N) global symmetry</u> to label the irreducible sectors of the scattering $N \otimes \overline{N} = \mathbf{1} \oplus \operatorname{Adj}_{N}$

- singlet channel $|\psi\overline{\psi}\rangle_{\mathbf{1}} = \frac{1}{\sqrt{N}} \sum_{i} |\psi_{i}\overline{\psi}_{i}\rangle \rightarrow {}_{\mathbf{1}}\langle\psi\overline{\psi}|\psi\overline{\psi}\rangle_{\mathbf{1}} = i\mathcal{T}_{s}N + i\mathcal{T}_{t}$

- adjoint channel $|\psi\overline{\psi}\rangle^{A}_{Adj} = T^{A}_{ij}|\psi_{i}\overline{\psi}_{i}\rangle \rightarrow {}^{B}_{Adj}\langle\psi\overline{\psi}|\psi\overline{\psi}\rangle^{A}_{Adj} = i\mathcal{T}_{t}\,\delta^{AB}$

Generalization in flavor space

• N copies of mediators ψ_i (i = 1, ..., N) interacting via

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exploit <u>U(N) global symmetry</u> to label the irreducible sectors of the scattering

 $N \otimes \overline{N} = \mathbf{1} \oplus \mathrm{Adj}_N$

- singlet channel
$$|\psi\overline{\psi}\rangle_{1} = \frac{1}{\sqrt{N}} \sum_{i} |\psi_{i}\overline{\psi}_{i}\rangle \rightarrow _{1}\langle\psi\overline{\psi}|\psi\overline{\psi}\rangle_{1} = \underbrace{i\mathcal{T}_{s}N}_{i} + i\mathcal{T}_{t}$$

s-channel enhancement $y^2 \rightarrow N y^2$ ('t Hooft scaling)

Visualizing the bounds

• <u>5 parameters</u>: y_E , y_Q , N_E , N_Q , Q_E ($m_E = 400 \text{ GeV}$ and $m_Q = 1 \text{ TeV}$)

space. We also space we are addy to compare these bounds with the information parameters \mathcal{B} by \mathcal{B} and \mathcal{B} and \mathcal{B} . To this end, we can use the expression of the space of the end of \mathcal{B} . [77] adapted to the case of CP-odd interactions. The induced widths from are $N_{E}^{2}N_{E}^{2}y_{Q}^{2}Q_{E}^{4} = 2.3 \times 10^{5} \left(\frac{1}{0.06}\right) \rightarrow \text{to fit the signal}$ $\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left| \mathcal{P}(\tau_Q) \right|^2 \,,$ ςς γ $S \overset{\Gamma(S \to \gamma \gamma)}{\sim} = M \underbrace{\frac{\alpha^2}{1.1}}_{0} \underbrace{\gamma^2}_{0} Y^4 N_E^2 y_e^2 \tau_E \left| \mathcal{P}(\tau_E) \right|^2,$ g S We acadyo to ready pare these bounds by the state of the second of the s n by In order to be conservative we take the values of mediator masses close to $U_{Q} S O + U_{Q} S E \gamma E$ experimental exclusion limit. In particular, we take $M_Q = 1$ TeV and M_I • A large approved to the mass of the scalar are given by

$$\Gamma(S \to \gamma \gamma) \stackrel{\Gamma}{=} M \stackrel{\gamma \alpha^2}{\xrightarrow{1}_{1}} M^4 \stackrel{\alpha^2}{\xrightarrow{1}_{1}} \stackrel{\gamma^4}{\xrightarrow{1}_{2}} \stackrel{\gamma^2}{\xrightarrow{1}_{2}} \stackrel{\gamma^4}{\xrightarrow{1}_{2}} \stackrel{\gamma^2}{\xrightarrow{1}_{2}} \stackrel{\gamma^2}{\xrightarrow{1}$$

Visualizing the bounds

• <u>5 parameters</u>: y_E , y_Q , N_E , N_Q , Q_E

$$N_E y_E^2 < 8\pi$$

$$3N_Q y_Q^2 < 8\pi$$
 \rightarrow unitarity bounds

$$N_E^2 N_Q^2 y_E^2 y_Q^2 Q_E^4 = 2.3 \times 10^5 \left(\frac{\Gamma_S / M_S}{0.06}\right) \rightarrow \text{to fit the signal}$$



- Large width scenario \rightarrow requires either <u>exotic EM charges</u> or <u>very large N</u>

Scalar mediators (gg initiated)

• 2 \rightarrow 2 scatterings of charged (scalar) mediators $\phi\phi^* \rightarrow \phi\phi^*$



1500

2000

√s [GeV]

2500

3000

- A is a relevant coupling \rightarrow unitarity bounds saturated at low-energy

1000

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Scalar mediators (gg initiated)

• 2 \rightarrow 2 scatterings of charged (scalar) mediators $\phi\phi^* \rightarrow \phi\phi^*$



- A is a relevant coupling \rightarrow unitarity bounds saturated at low-energy
- Width effects important near s-pole singularities $\alpha = \frac{|s M_S^2|}{\Gamma_S M_S} \quad (\Gamma_S / M_S = 0.06)$

Visualizing the bounds (scalars)

• Flavor enhancement from s-channel

$$\begin{split} N_{\tilde{E}} \left(\frac{A_E}{750 \text{ GeV}} \right)^2 &< 25\\ 3N_{\tilde{Q}} \left(\frac{A_Q}{750 \text{ GeV}} \right)^2 &< 400\\ N_{\tilde{E}}^2 N_{\tilde{Q}}^2 \left(\frac{A_E}{750 \text{ GeV}} \right)^2 \left(\frac{A_Q}{750 \text{ GeV}} \right)^2 Q_{\tilde{E}}^4 = 1.6 \times 10^8 \left(\frac{\Gamma_S/M_S}{0.06} \right) \end{split}$$



q-qbar initiated

• A vector-like quark mixing with SM quarks, e.g. $\mathcal{B} \sim (3, 1, -1/3)$

 $\mathcal{L}^{\mathcal{B}-b} = \overline{Q}_3 i \not\!\!\!D Q_3 + \overline{b}_R i \not\!\!\!D b_R + \overline{\mathcal{B}} i \not\!\!\!D \mathcal{B} - (M_{\mathcal{B}} + \widetilde{y}_{\mathcal{B}}S) \overline{\mathcal{B}} \mathcal{B} - y_b \overline{Q}_3 H b_R - y_{\mathcal{B}} \overline{Q}_3 H \mathcal{B}_R - \widetilde{y}_b \overline{\mathcal{B}}_L S b_R + \text{h.c.}$

$$\begin{pmatrix} b'_{L,R} \\ \mathcal{B}'_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^{L,R}_{\mathcal{B}b} & \sin\theta^{L,R}_{\mathcal{B}b} \\ -\sin\theta^{L,R}_{\mathcal{B}b} & \cos\theta^{L,R}_{\mathcal{B}b} \end{pmatrix} \begin{pmatrix} b_{L,R} \\ \mathcal{B}_{L,R} \end{pmatrix}$$

 $\mathcal{L}^{\mathcal{B}-b} \ni S\bar{b}'b'\sin\theta^L_{\mathcal{B}b}(\sin\theta^R_{\mathcal{B}b}\tilde{y}_{\mathcal{B}} + \cos\theta^R_{\mathcal{B}b}\tilde{y}_b)$

 $\theta_{\mathcal{B}b}^R \sim (m_b/m_{\mathcal{B}}) \theta_{\mathcal{B}b}^L$

 $\sin\theta_{\mathcal{B}b}^L = 0.05(4)$

$$\frac{\Gamma_{b\bar{b}}}{M_S} = \frac{3}{8\pi} \sin^2 \theta_{\mathcal{B}b}^L \tilde{y}_b^2 = 3 \times 10^{-4} \left(\frac{\sin \theta_{\mathcal{B}b}^L}{0.05}\right)^2 \tilde{y}_b^2$$

q-qbar initiated (bounds)

• A vector-like quark mixing with SM quarks, e.g. $\mathcal{B} \sim (3, 1, -1/3)$

$$\left(\frac{\sin\theta_{\mathcal{B}b}^L}{0.05}\right)^2 \tilde{y}_b^2 = 280 \left(\frac{\Gamma_S/M_S}{0.06}\right) \left(\frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}}\right)^{-1} \qquad \tilde{y}_b^2 < \frac{8\pi}{3}$$



- $S \rightarrow b\overline{b}$ cannot saturate the large width in the perturbative setup