# Implications of unitarity for the di-photon resonance at 750 GeV

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Based on arXiv:1604.05746 in collaboration with:
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# Outline

- Application of partial wave unitarity to the di-photon excess:

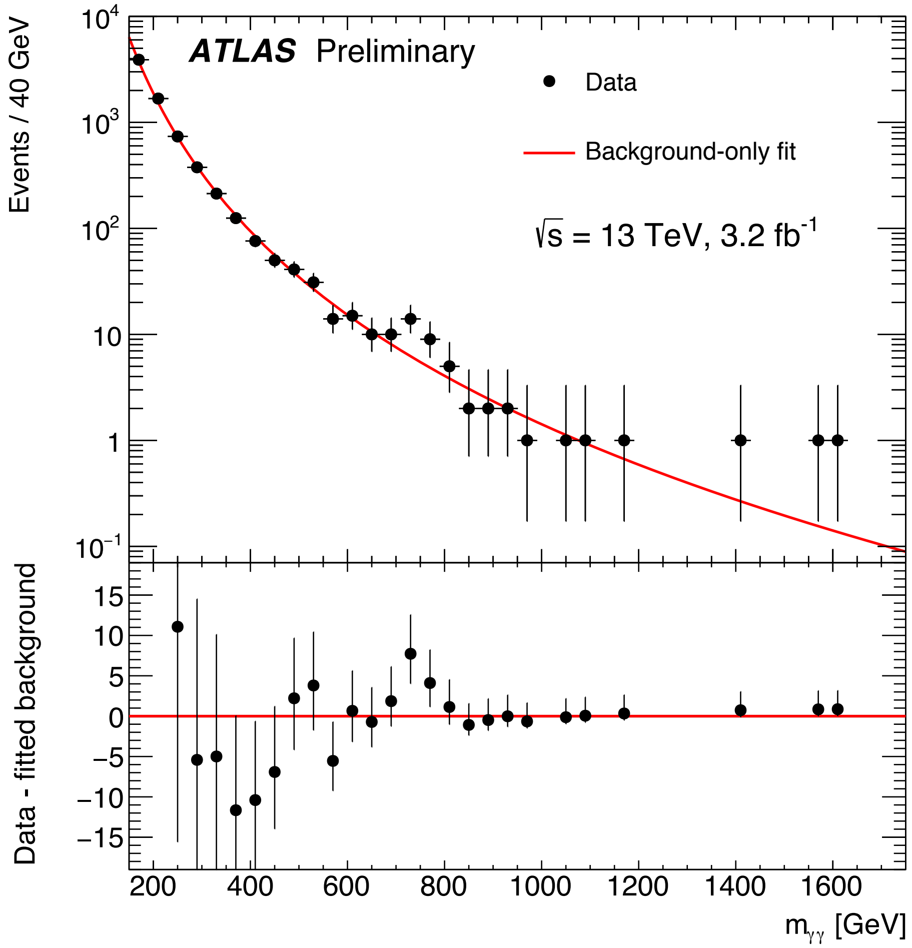
  $\boxed{\text{1) range of validity of the EFT}}$ $\longrightarrow$ this talk

  $\boxed{\text{2) perturbativity bounds in weakly coupled models}}$ $\longrightarrow$ see backup slides

# The LHC di-photon excess

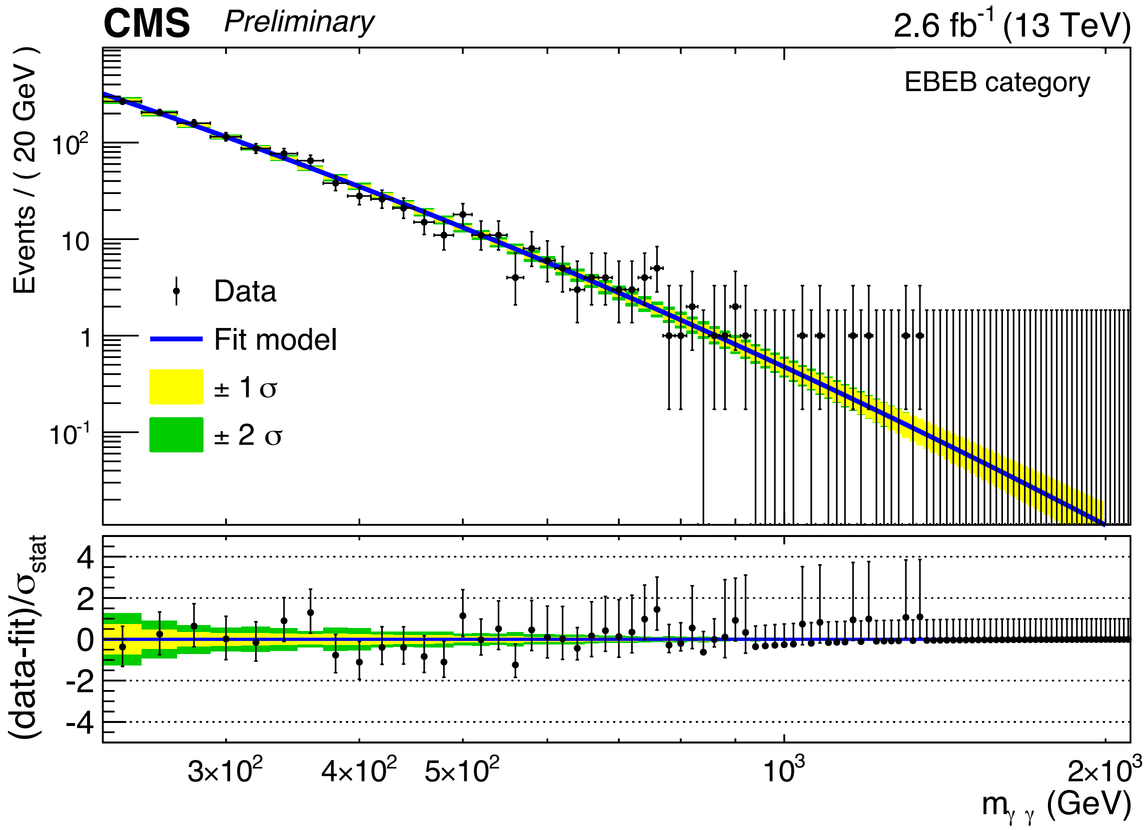
- Hopefully not a statistical fluctuation !

[ATLAS-CONF-2015-081 ]




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

[CMS-EXO-2015-15-004]




$2.6\sigma$ (local) - narrow width

$2.9\sigma$ (local) - after Moriond EW

# EFT of a di-photon resonance

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

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

- Decay widths

$$\Gamma_{\gamma\gamma} \equiv \Gamma(S \to \gamma\gamma) = \pi \alpha_{\text{EM}}^2 \frac{M_S^3}{\Lambda_\gamma^2}$$

$$\Gamma_{gg} \equiv \Gamma(S \to gg) = 8\pi \alpha_s^2 \frac{M_S^3}{\Lambda_g^2}$$

$$\Gamma_{q\bar{q}} \equiv \Gamma(S \to q\bar{q}) = \frac{3}{8\pi} y_{qS}^2 M_S$$

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- Fit cross-section [see e.g. 1512.04933, 1603.06566]

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

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

- Consistency b/w 8 and 13 TeV LHC data singles out gluon fusion or heavy-Q annihilation

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

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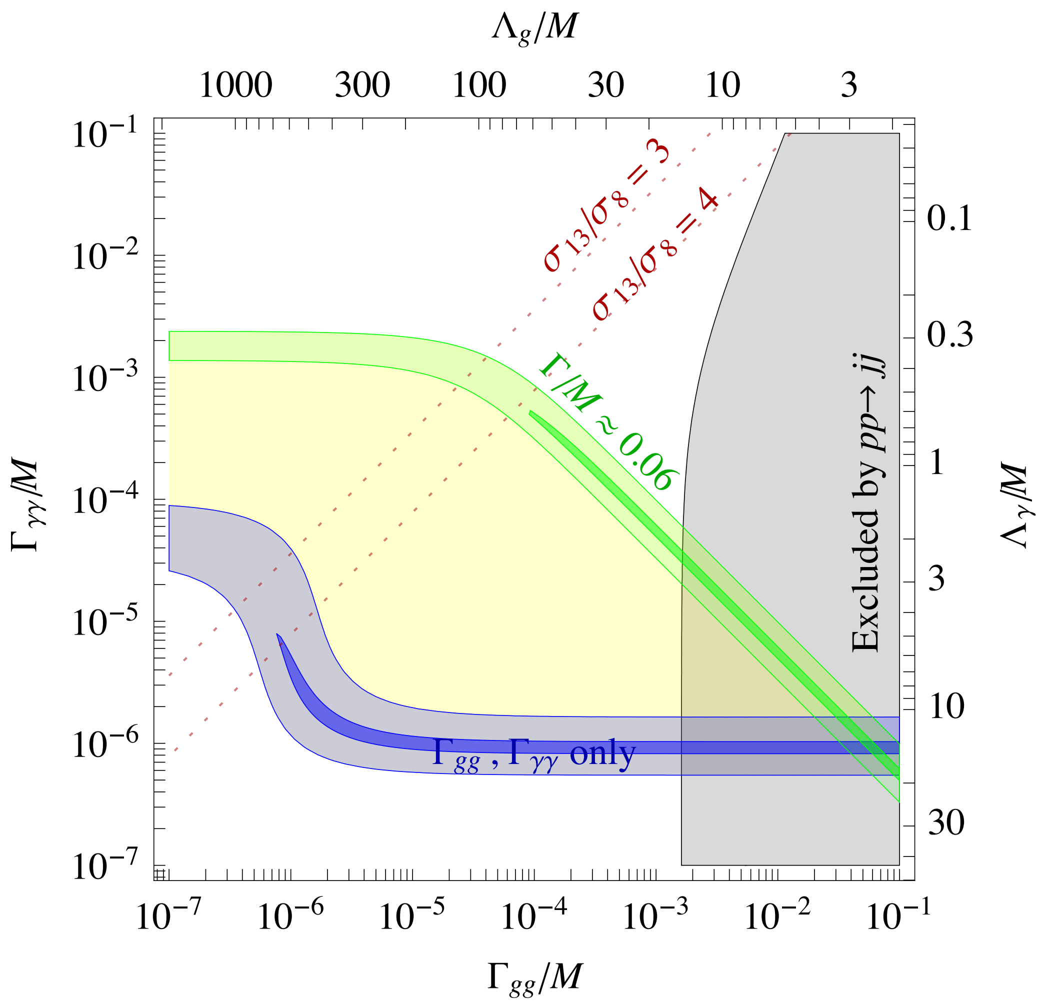
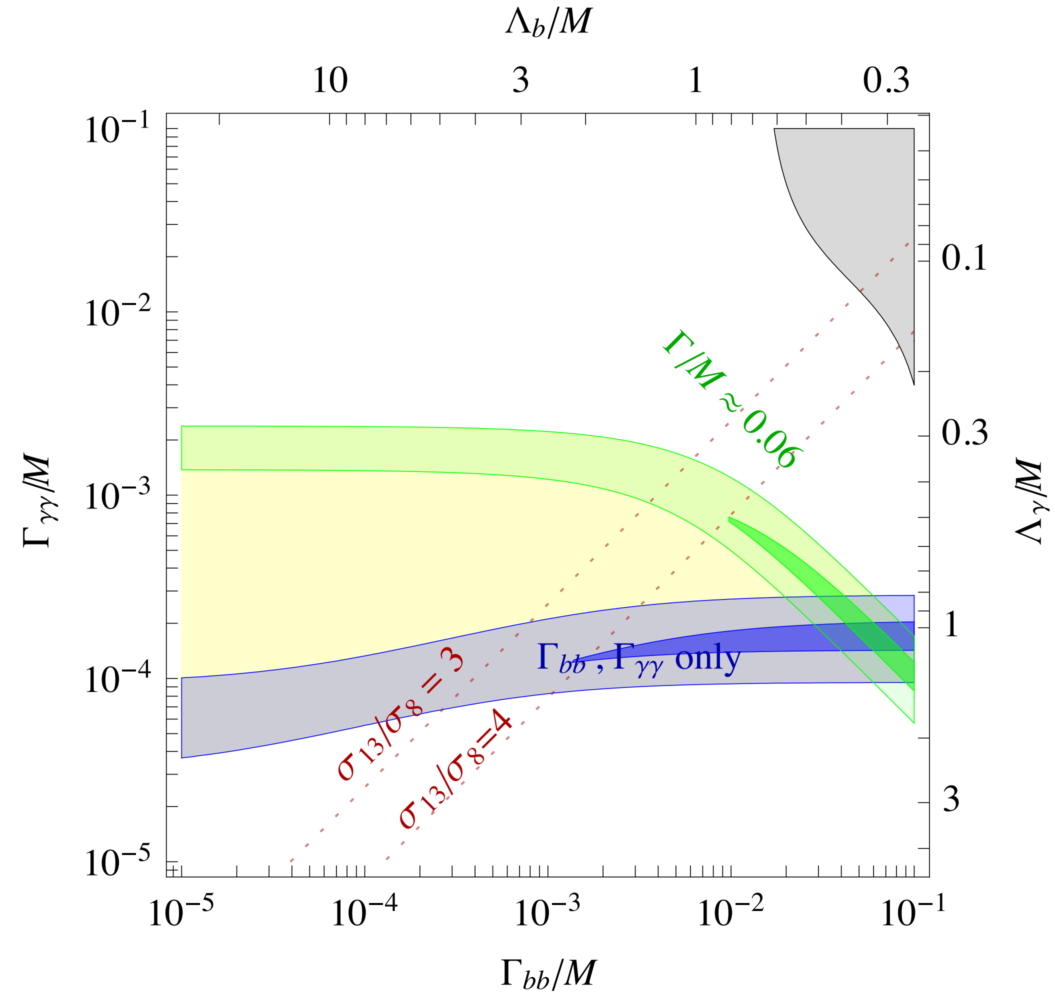
gluon fusion




b-bbar annihilation



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- SM gauge-invariant EFT

$$\mathcal{L}_{\rm eff}^{\rm SM-invariant} \supset -\frac{g_3^2}{2\Lambda_g} S G_{\mu\nu}^2 - \frac{g_2^2}{2\Lambda_W} S W_{\mu\nu}^2 - \frac{g_1^2}{2\Lambda_B} S B_{\mu\nu}^2 - \frac{S}{\Lambda_q} \left( \overline{Q}_L q_R H + \text{h.c.} \right)$$

- 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 ?*

# Partial wave projection

- Scattering matrix: $S = 1 + iT$

- 2 → 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)]

$$a^J_{fi} = \frac{\beta_f^{1/4}(s, m^2_{f1}, m^2_{f2})\beta_i^{1/4}(s, m^2_{i1}, m^2_{i2})}{32\pi s} \int_{-1}^{1} d(\cos\theta)\, d^J_{\mu_i\mu_f}(\theta)\, \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)$$

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

# Partial wave projection

- Scattering matrix: $S = 1 + iT$
- 2 → 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

$$\boxed{a^0_{fi} = \frac{\beta_f^{1/4}(s, m^2_{f1}, m^2_{f2})\beta_i^{1/4}(s, m^2_{i1}, m^2_{i2})}{32\pi s} \int_{-1}^{1} d(\cos\theta)\, \mathcal{T}_{fi}(\sqrt{s}, \cos\theta)}$$

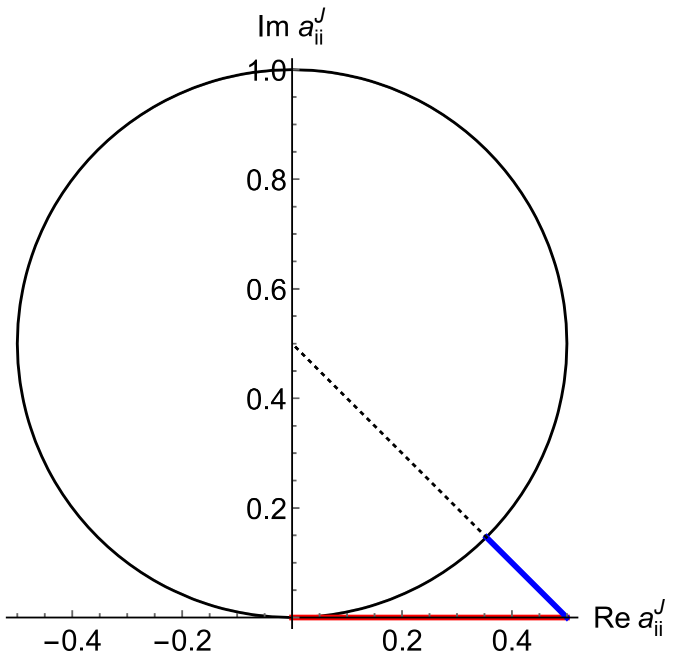
# Partial wave unitarity

- Unitarity (an axiom of QFT)

$$SS^\dagger = 1 \quad \longrightarrow \quad \frac{1}{2i}\left(a^J_{fi} - a^{J*}_{if}\right) \geq \sum_{h \in \text{2-particle}} a^{J*}_{hf} a^J_{hi}$$

- For f = i (optical theorem)

$$\text{Im}\, a^J_{ii} \geq |a^J_{ii}|^2 \quad \longrightarrow \quad \left(\text{Re}\, a^J_{ii}\right)^2 + \left(\text{Im}\, a^J_{ii} - \frac{1}{2}\right)^2 \leq \frac{1}{4}$$




- In practical perturbative calculations S-matrix unitarity is always approximate

 - scattering amplitudes grow with energy in the EFT

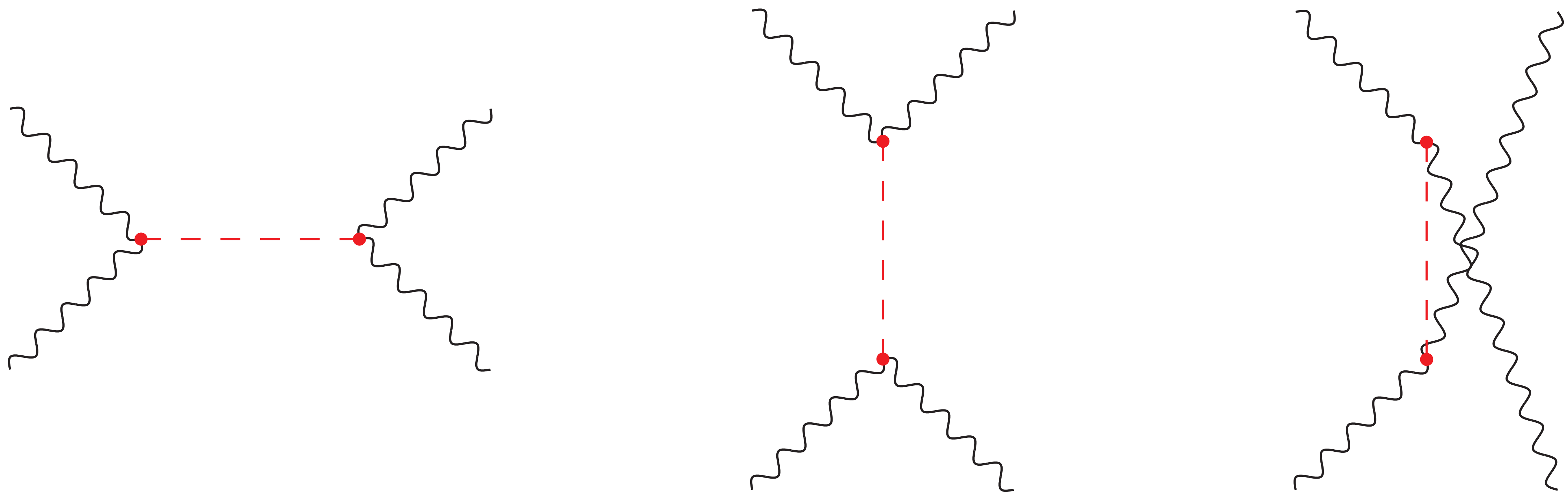
 - perturbative expansion breaks down for

$$\boxed{\left|\text{Re}\,(a^J_{ii})^{\text{Born}}\right| \leq \frac{1}{2}}$$

# Di-photon scattering

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

$$\mathcal{L}_{\text{eff}} \supset -\frac{e^2}{2\Lambda_\gamma} S F_{\mu\nu}^2 \quad \longrightarrow \quad a^0 \simeq -\frac{e^4 s}{32\pi\Lambda_\gamma^2}$$



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

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

$$\uparrow$$

$$\Gamma_{\gamma\gamma} = \pi\alpha_{\text{EM}}^2 \frac{M_S^3}{\Lambda_\gamma^2}$$

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

# SM gauge boson scattering

- Bounds can be strengthened by looking at the full $VV \to V'V'$ scattering matrix

- V (V') any of the 8 + 3 + 1 (transversely polarized) SM gauge bosons

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$$\mathcal{L}_{\rm eff} \supset -\frac{g_3^2}{2\Lambda_g} S G_{\mu\nu}^2 - \frac{g_2^2}{2\Lambda_W} S W_{\mu\nu}^2 - \frac{g_1^2}{2\Lambda_B} S B_{\mu\nu}^2$$

$$\tilde{a}^0 \simeq -\frac{s}{32\pi}\left(\frac{8g_3^4}{\Lambda_g^2} + \frac{3g_2^4}{\Lambda_W^2} + \frac{g_1^4}{\Lambda_B^2}\right)$$ (highest eigenvalue)

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

# SM gauge boson scattering

- Bounds can be strengthened by looking at the full $VV \to V'V'$ scattering matrix

- in terms of "measured" quantities:

$$\frac{1}{\Lambda_g^2} = \frac{\Gamma_{gg}}{8\pi\alpha_s^2 M_S^3}$$

$$\frac{1}{\Lambda_W^2} = \frac{\Gamma_{\gamma\gamma}}{\pi\alpha_{\rm EM}^2 M_S^3}\left(\frac{r}{1+r}\right)^2$$

$$\frac{1}{\Lambda_B^2} = \frac{\Gamma_{\gamma\gamma}}{\pi\alpha_{\rm EM}^2 M_S^3}\left(\frac{1}{1+r}\right)^2$$

$$r \equiv \frac{\Lambda_B}{\Lambda_W}$$

$\longrightarrow$

$$\sqrt{s} \lesssim M_S \left(\frac{\Gamma_{gg}}{M_S} + f(r)\frac{\Gamma_{\gamma\gamma}}{M_S}\right)^{-1/2}$$

$$f(r) = \frac{3r^2 s_W^{-4} + c_W^{-4}}{(1+r)^2}$$

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

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- in terms of "measured" quantities:

i) gluon scattering

$$r \equiv \frac{\Lambda_B}{\Lambda_W}$$

$$\sqrt{s} \lesssim M_S \left( \frac{\Gamma_{gg}}{M_S} + f(r) \frac{\Gamma_{\gamma\gamma}}{M_S} \right)^{-1/2}$$

$$\sqrt{s} \lesssim 24 \text{ TeV} \left( \frac{\Gamma_{gg}/M_S}{10^{-3}} \right)^{-1/2}$$

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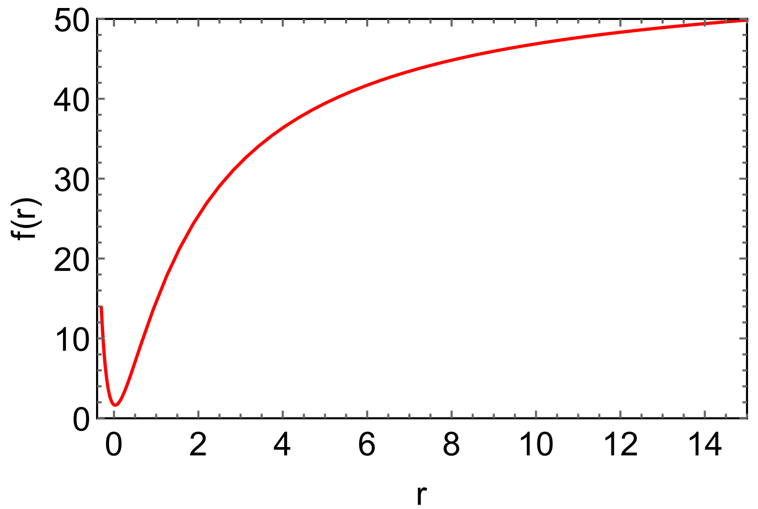
ii) EW gauge boson scattering

$$\sqrt{s} \lesssim 11 \div 59 \text{ TeV} \left( \frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}} \right)^{-1/2}$$

max f(r)      min f(r)

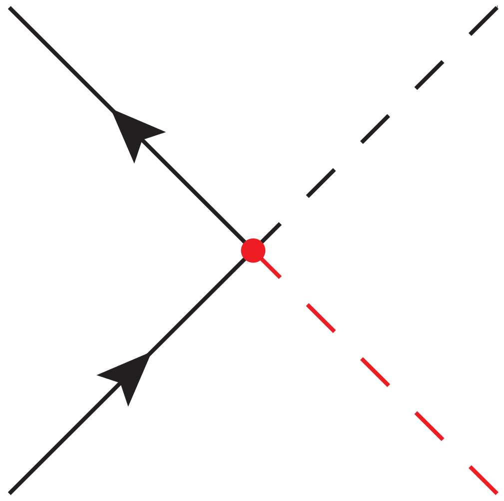



- future determination of $S \to WW, ZZ, Z\gamma$ crucial to strengthen the bound

# SM quark annihilation

- $\overline{Q}q \to SH$ scattering

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{\Lambda_q} S \overline{Q}_L q_R H \quad \longrightarrow \quad a^0 \simeq \frac{1}{16\pi}\frac{\sqrt{s}}{\Lambda_q}$$



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- Tree-level unitarity bound

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

$$y_{qS} = \frac{v}{\sqrt{2}\Lambda_q}$$

$$\Gamma_{q\bar{q}} = \frac{3}{8\pi} y_{qS}^2 M_S$$

# Conclusions

- Perturbative unitarity as a tool to infer:

1) the range of validity of a given EFT

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

$$\sqrt{s} \lesssim 11 \div 59 \text{ TeV} \left( \frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}} \right)^{-1/2} \longrightarrow$$ independently of production mechanism

$$\sqrt{s} \lesssim 24 \text{ TeV} \left( \frac{\Gamma_{gg}/M_S}{10^{-3}} \right)^{-1/2} \longrightarrow$$ gg initiated production

$$\sqrt{s} \lesssim 6.2 \text{ TeV} \left( \frac{\Gamma_{q\bar{q}}/M_S}{0.06} \right)^{-1/2} \longrightarrow$$ q-qbar initiated production

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- new d.o.f. unitarizing the amplitudes' growth are required below this scale

- a physics case for the 50-100 TeV collider *(worse case scenario)*

(in many models addressing the di-photon excess new d.o.f. lie much below 10 TeV)

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2) the range of validity of perturbation theory in renormalizable models

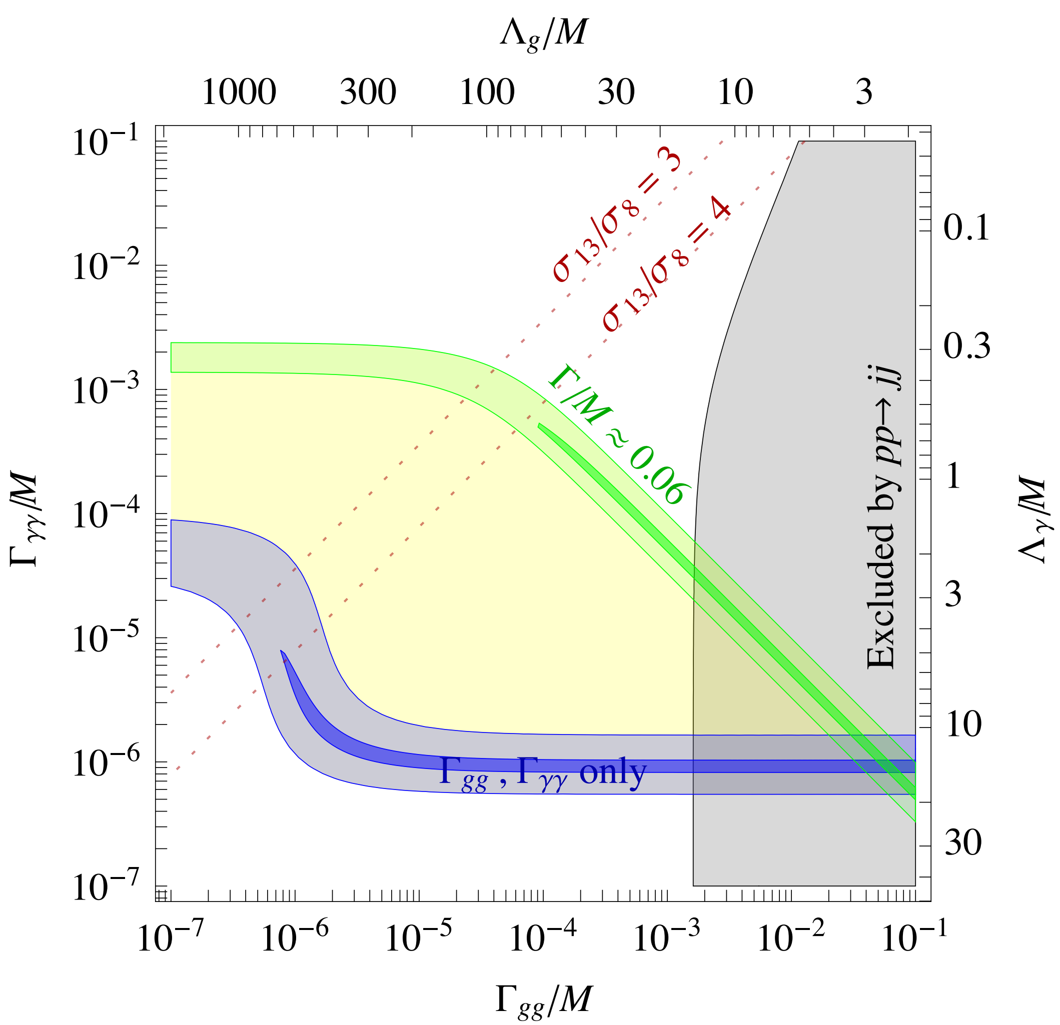
- Endangered calculability in many weakly coupled models (large width scenario)
- Perturbative models require non-trivial model building
- Unitarity bounds conceptually different from RGE criteria (but similar results)

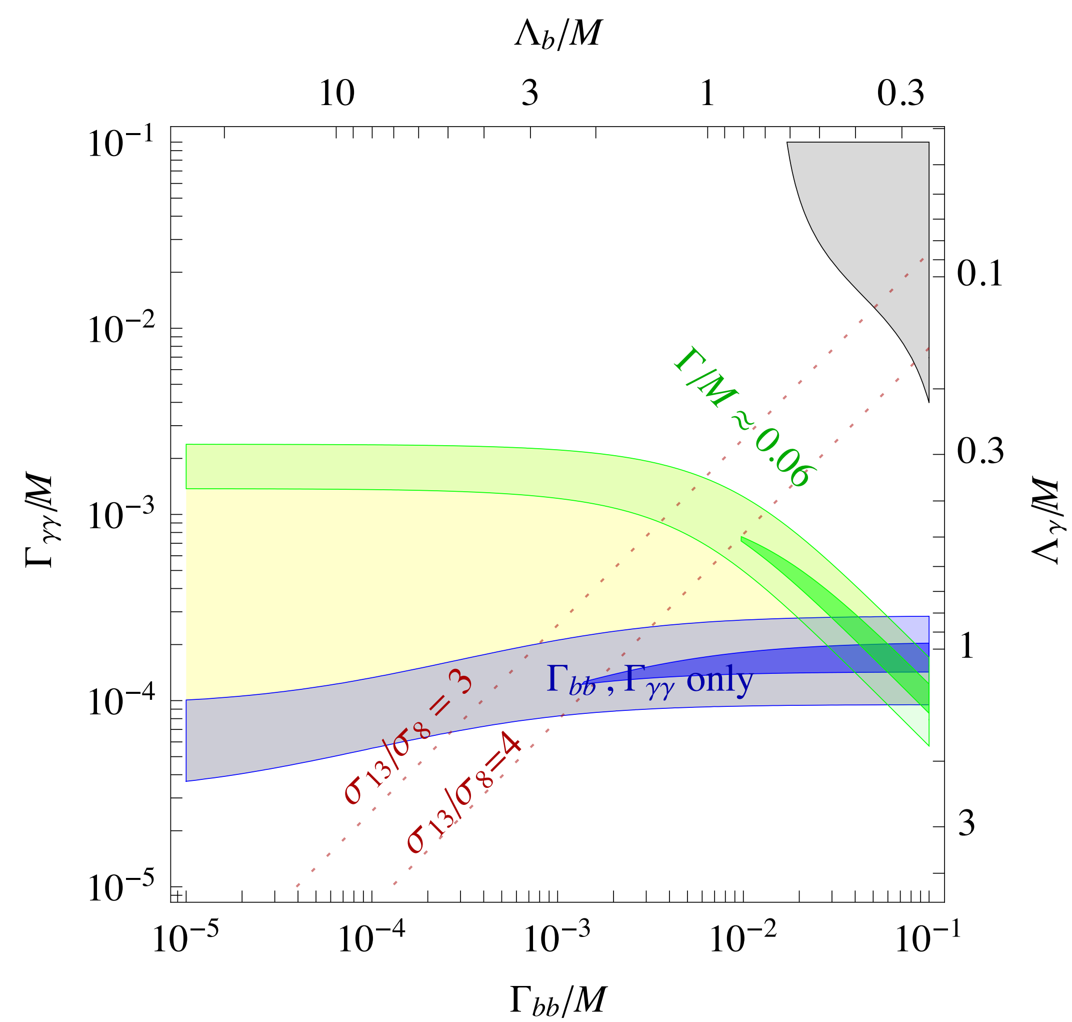
*[see backup slides]*

# Backup slides

# Production mechanisms

[from 1512.04933]



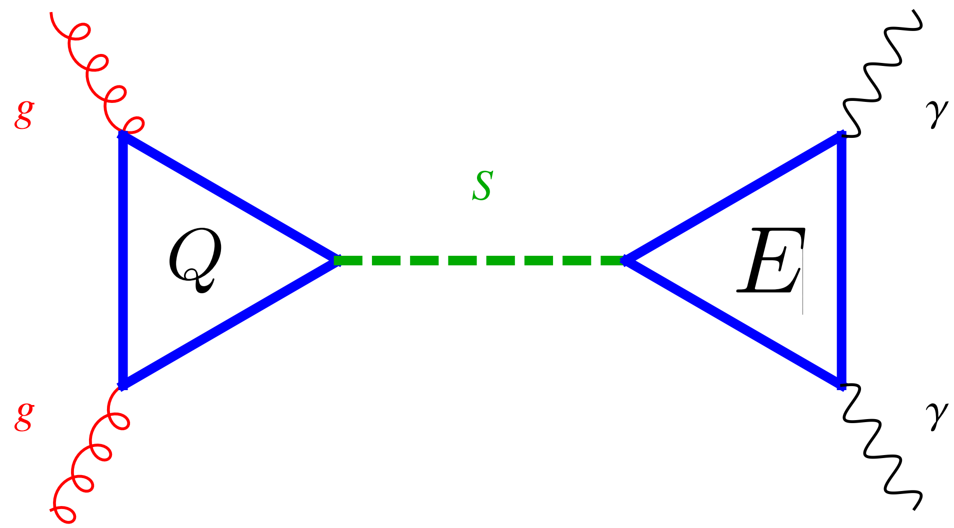




$$\frac{\Gamma_{\gamma\gamma}}{M_S}\frac{\Gamma_{gg}}{M_S} \simeq 4.9 \times 10^{-8}\left(\frac{\Gamma_S/M_S}{0.06}\right)$$

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

# Weakly coupled models

- "Everybody's model" [1512.04933, 1512.08500 + same mechanism in O(100) papers ]




$$Q \sim (3,1,0) \times N_Q \qquad S \sim (1,1,0)$$

$$E \sim (1,1,Y) \times N_E$$

$$\mathcal{L}_I \supset y_Q S \overline{Q} Q + y_E S \overline{E} E$$

*[see below for models with scalar mediators or q-qbar initiated and related unitarity bounds]*

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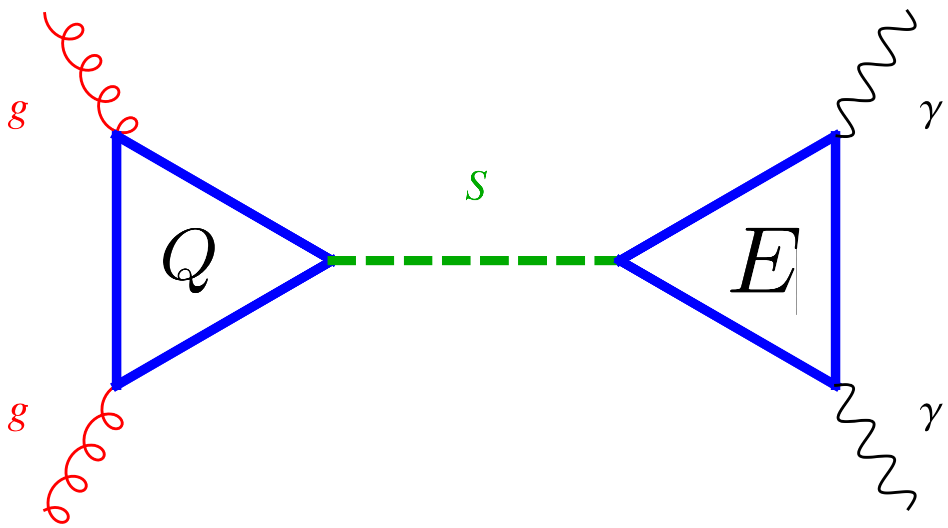



$$Q \sim (3,1,0) \times N_Q \qquad S \sim (1,1,0)$$

$$E \sim (1,1,Y) \times N_E$$

$$\mathcal{L}_I \supset y_Q S \overline{Q} Q + y_E S \overline{E} E$$

- A large di-photon rate is required

$$\frac{\Gamma_{\gamma\gamma}}{M_S} = \frac{\alpha_{\rm EM}^2}{16\pi^3} \left| N_E Q_E^2 y_E \sqrt{\tau_E} \mathcal{S}(\tau_E) \right|^2 \xrightarrow{m_E \simeq 400 \text{ GeV}} \frac{\Gamma_{\gamma\gamma}}{M_S} = 7.8 \times 10^{-8}\ N_E^2 Q_E^4 y_E^2$$

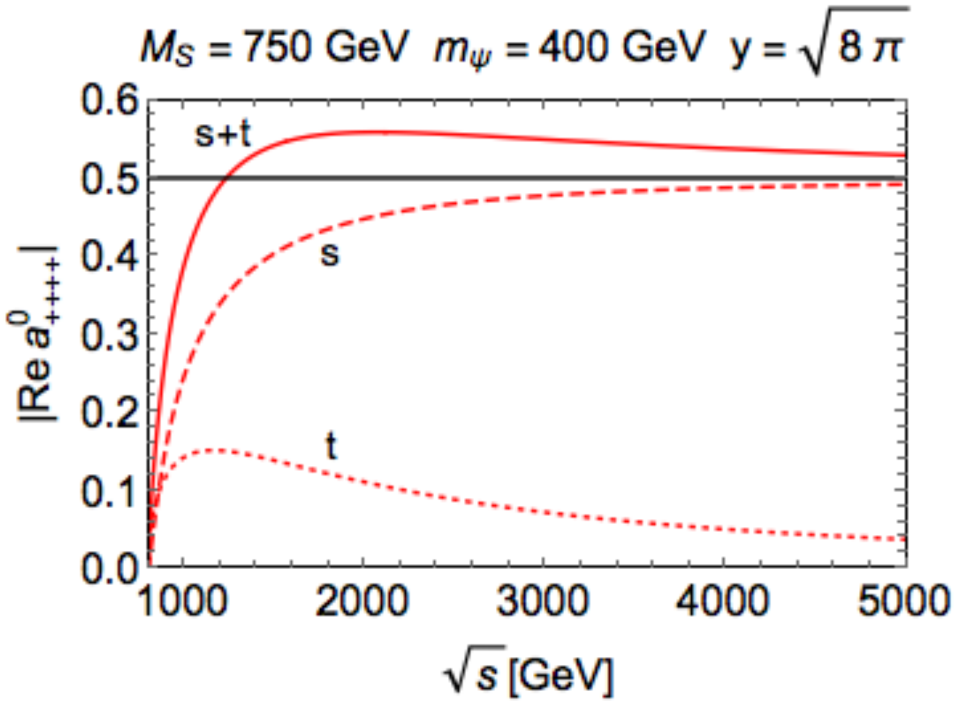
- Narrow width $\Gamma_{\gamma\gamma}/M_S \gtrsim 10^{-6}$ → $N_E^2 Q_E^4 y_E^2 \gtrsim 10$

- Large width $\Gamma_{\gamma\gamma}/M_S \gtrsim 10^{-4}$ → $N_E^2 Q_E^4 y_E^2 \gtrsim 10^3$ → perturbativity issue !

# Perturbative unitarity bounds

- 2 → 2 scatterings of charged mediators $\psi\overline{\psi} \to \psi\overline{\psi}$

$$\mathcal{L}_I \supset -yS\overline{\psi}\psi \quad \rightarrow \quad a^0 \simeq -\frac{y^2}{16\pi} \quad \rightarrow \quad y \lesssim \sqrt{8\pi}$$



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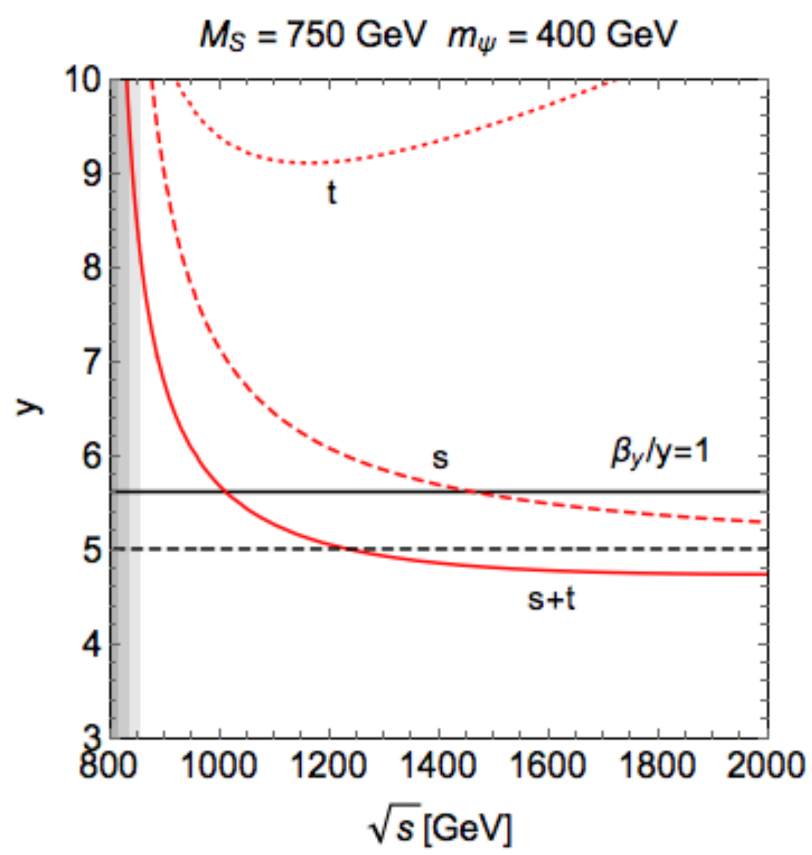


- O(1) agreement with beta function criterium $\dfrac{\beta_y}{y} = \dfrac{5y^2}{16\pi^2} < 1$ [1512.08500]

# Generalization in flavor space

- N copies of mediators $\psi_i \ (i = 1, \ldots, N)$ interacting via

$$\mathcal{L}_I \supset -y_{ij} S \overline{\psi}_i \psi_j \longrightarrow \langle \psi_k \overline{\psi}_l | \psi_i \overline{\psi}_j \rangle = i\mathcal{T}_s \, \delta_{ij}\delta_{kl} + i\mathcal{T}_t \, \delta_{ik}\delta_{jl}$$

- e.g. $y_{ij} = y\delta_{ij}$ in the mass basis

$\longrightarrow$ exploit U(N) global symmetry to label the irreducible sector of the scattering

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

- 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 $|\psi\overline{\psi}\rangle^A_{\mathrm{Adj}} = T^A_{ij} |\psi_i \overline{\psi}_i\rangle \ \rightarrow \ {}^{B}_{\mathrm{Adj}}\langle \psi\overline{\psi} | \psi\overline{\psi}\rangle^A_{\mathrm{Adj}} = \ i\mathcal{T}_t \, \delta^{AB}$

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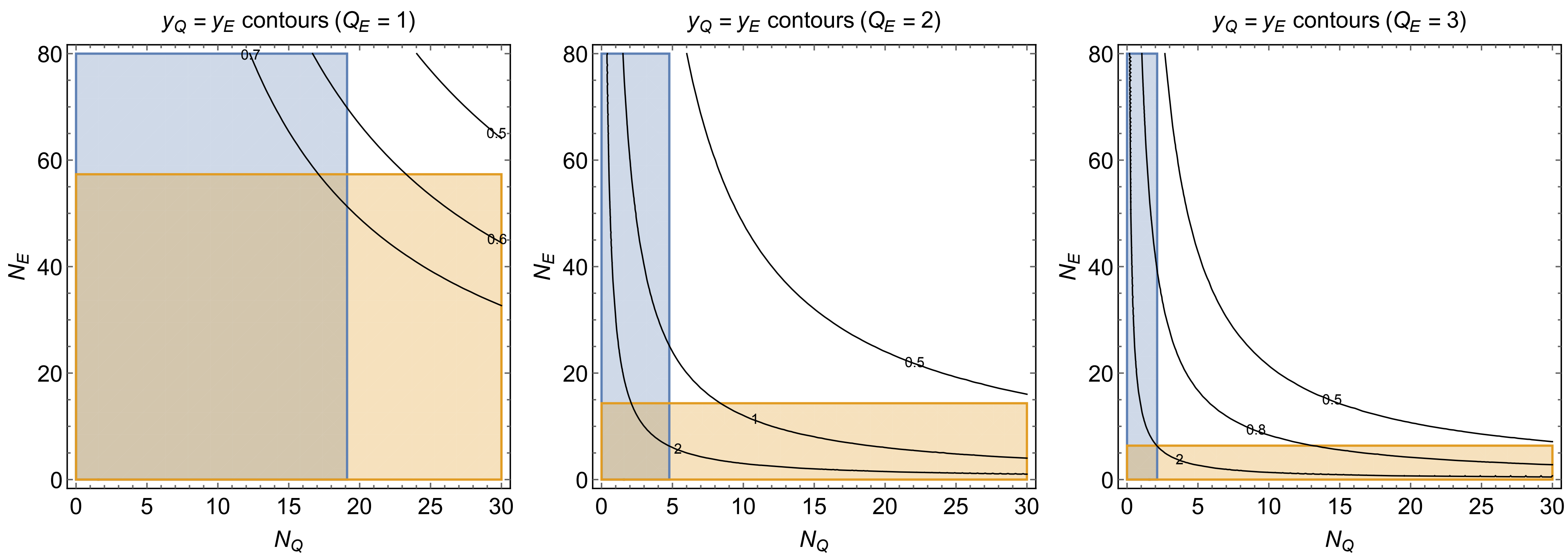
$\downarrow$

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

# Visualizing the bounds

- 5 parameters ( $y_E,\, y_Q,\, N_E,\, N_Q,\, Q_E$ )

$$N_E y_E^2 < 8\pi$$
$$3 N_Q y_Q^2 < 8\pi$$
$$N_E^2 N_Q^2 y_E^2 y_Q^2 Q_E^4 = 2.3 \times 10^5 \left( \frac{\Gamma_S / M_S}{0.06} \right)$$

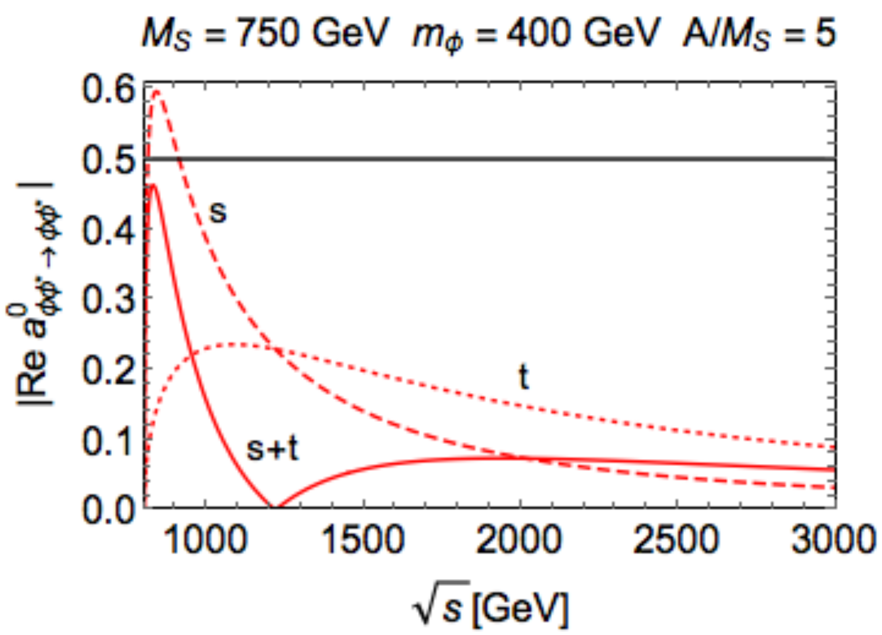



- Large width scenario → requires either exotic EM charges or very large N

# Scalar mediators (gg initiated)

- 2 ➞ 2 scatterings of charged (scalar) mediators $\phi\phi^* \to \phi\phi^*$

$$\mathcal{L}_I \supset -AS\phi^*\phi \quad \longrightarrow \quad a^0_{\phi\phi^*\to\phi\phi^*} = -A^2 \frac{\sqrt{s(s-4m_\phi^2)}}{16\pi s}\left(\frac{1}{s-M_S^2} - \frac{\log\frac{s-4m_\phi^2+M_S^2}{M_S^2}}{s-4m_\phi^2}\right)$$

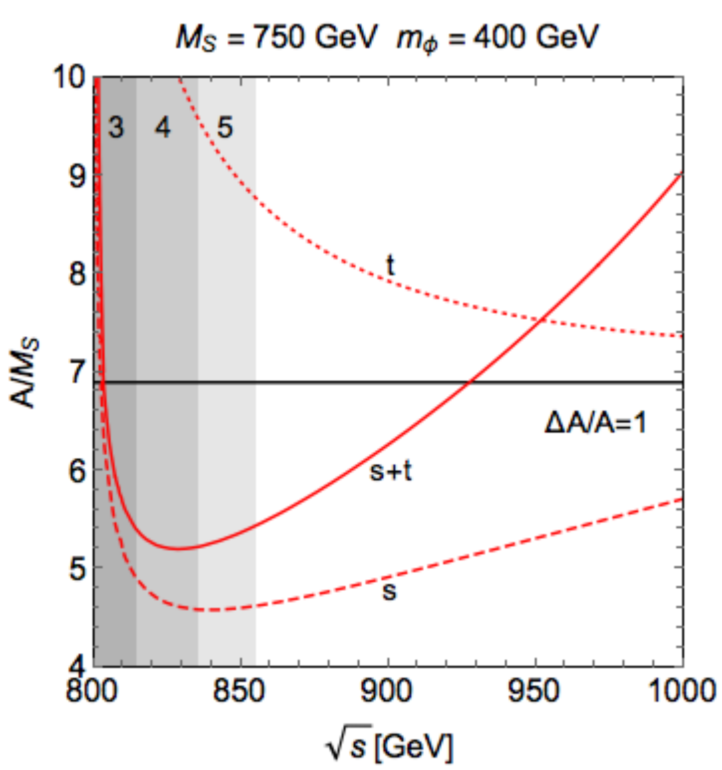


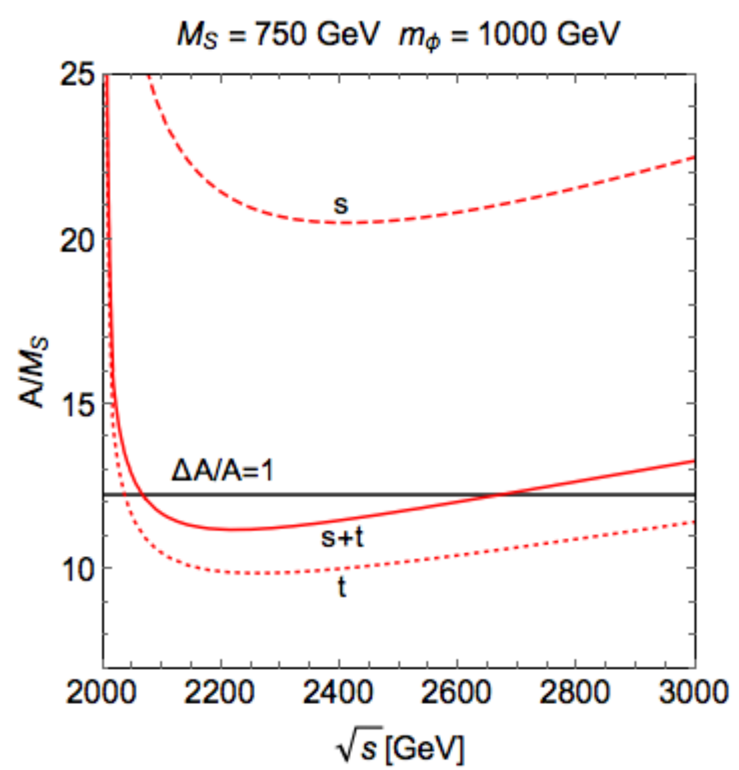

- A is a relevant coupling ➞ unitarity bounds saturated at low-energy

# Scalar mediators (gg initiated)

- 2 ➞ 2 scatterings of charged (scalar) mediators $\phi\phi^* \to \phi\phi^*$

$$\mathcal{L}_I \supset -AS\phi^*\phi \quad \longrightarrow \quad a^0_{\phi\phi^*\to\phi\phi^*} = -A^2\frac{\sqrt{s(s-4m_\phi^2)}}{16\pi s}\left(\frac{1}{s-M_S^2} - \frac{\log\frac{s-4m_\phi^2+M_S^2}{M_S^2}}{s-4m_\phi^2}\right)$$




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

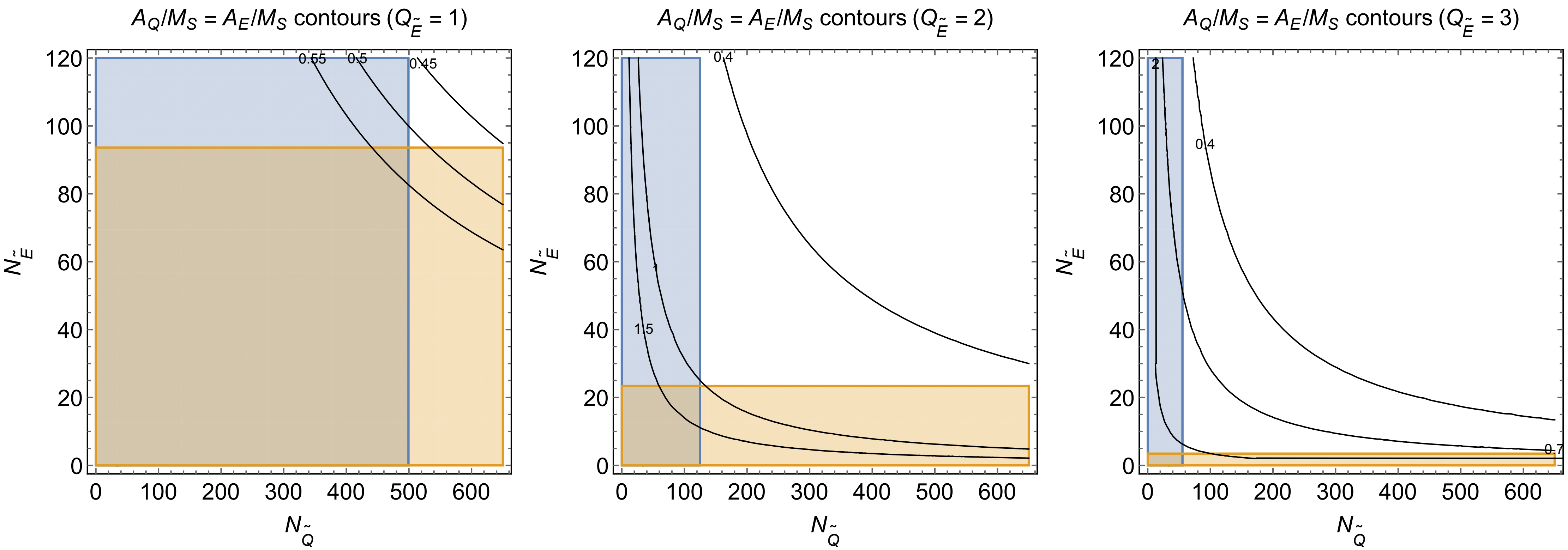
# Visualizing the bounds (scalars)

- Flavor enhancement from s-channel

$$N_{\tilde{E}} \left( \frac{A_E}{750 \text{ GeV}} \right)^2 < 25$$

$$3N_{\tilde{Q}} \left( \frac{A_Q}{750 \text{ GeV}} \right)^2 < 400$$

$$N_{\tilde{E}}^2 N_{\tilde{Q}}^2 \left( \frac{A_E}{750 \text{ GeV}} \right)^2 \left( \frac{A_Q}{750 \text{ GeV}} \right)^2 Q_{\tilde{E}}^4 = 1.6 \times 10^8 \left( \frac{\Gamma_S/M_S}{0.06} \right)$$



# q-qbar initiated

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

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

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

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

$$\theta^R_{\mathcal{B}b} \sim (m_b / m_{\mathcal{B}}) \theta^L_{\mathcal{B}b}$$

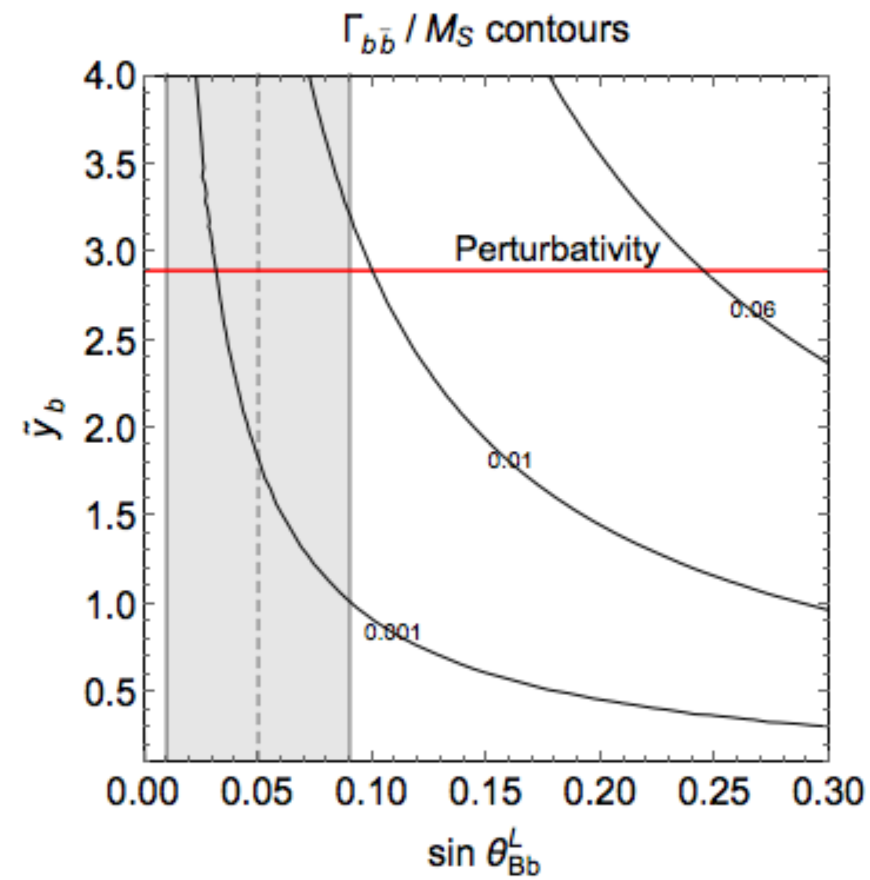
$$\sin\theta^L_{\mathcal{B}b} = 0.05(4)$$

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

# q-qbar initiated (bounds)

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

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




- $S \to b\bar{b}$ cannot saturate the large width in the perturbative setup