Implications of unitarity for the 750 GeV di-photon excess

LNF - Theory Seminar
25 May 2016

Luca Di Luzio
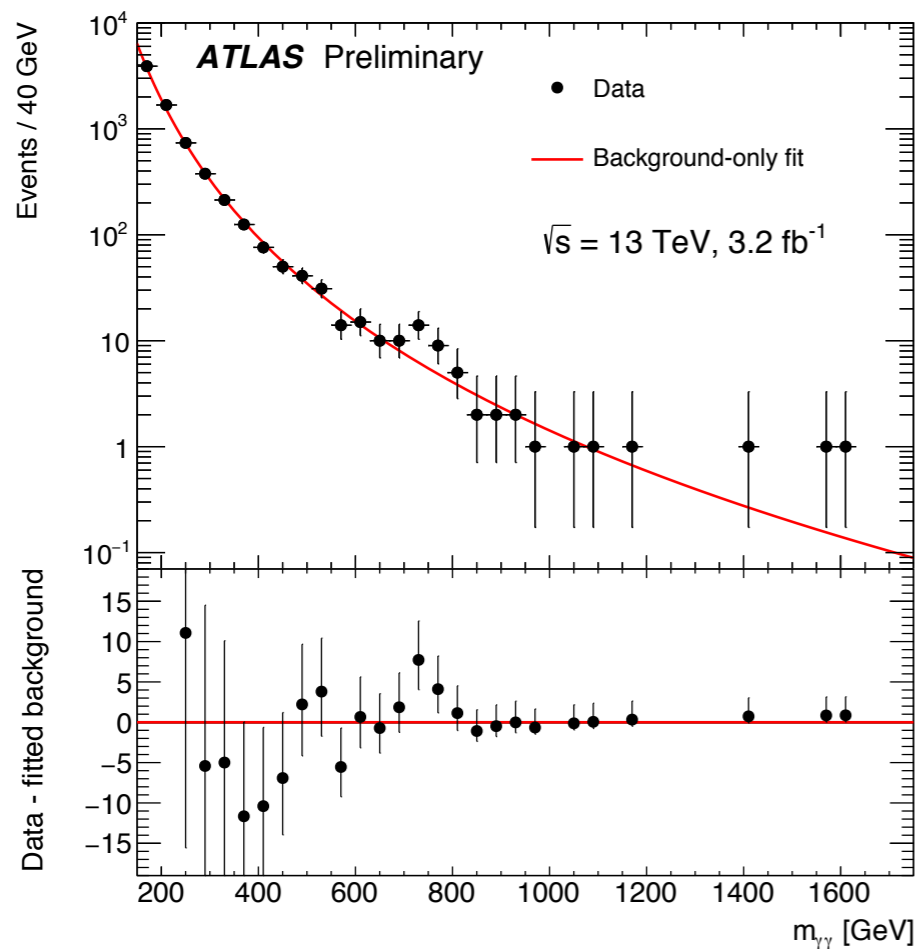
Università di Genova & INFN Genova

Outline

- Phenomenological aspects of the LHC di-photon excess

- Two applications of <u>partial wave unitarity</u>

    1) range of validity of the EFT

    2) perturbativity bounds in weakly coupled models
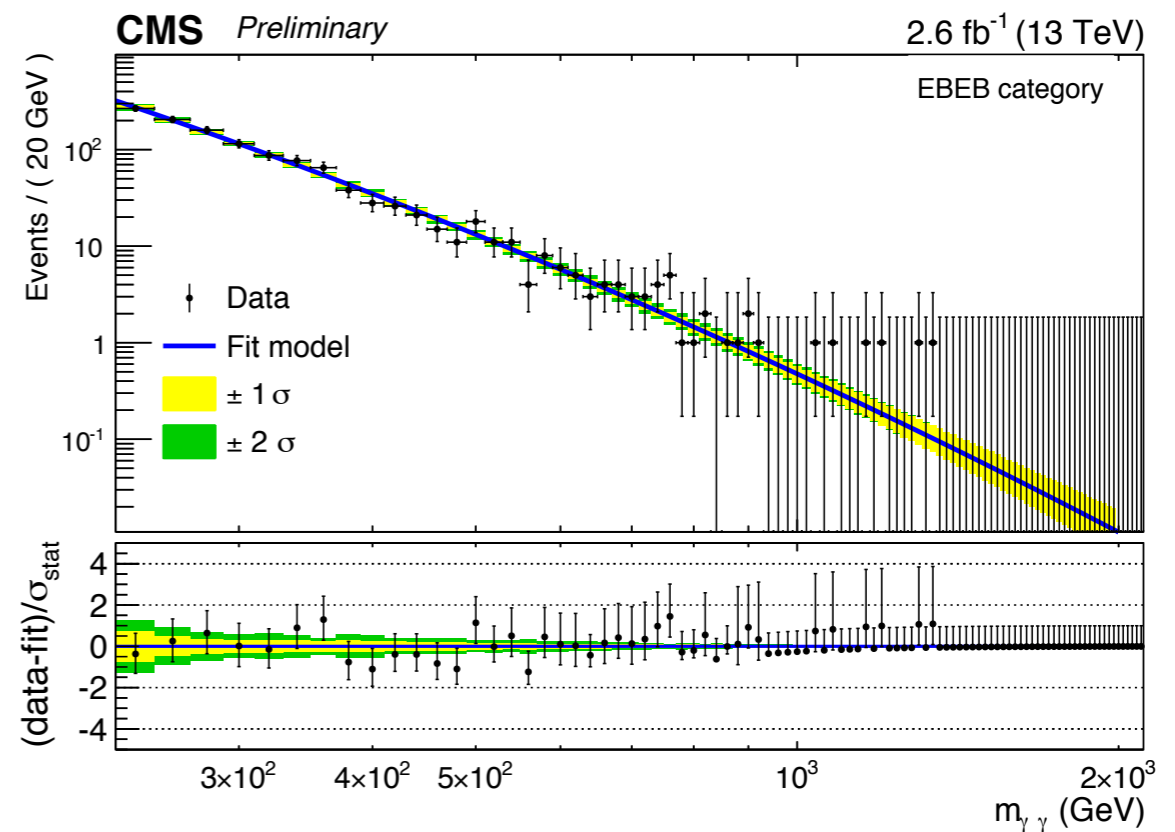
- Conclusions

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

[ATLAS-CONF-2015-081]   [CMS-EXO-2015-15-004]

3.9 σ (local) - best fit for Γ/M ~ 6%

2.6σ (local) - narrow width

2.9σ (local) - after Moriond EW

The LHC di-photon excess

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

- Disclaimer

 - I assume this is not a statistical fluctuation (we will know soon!)

 - O(300) 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

 - 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

  - 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

  - 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 <u>simplest</u> 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)
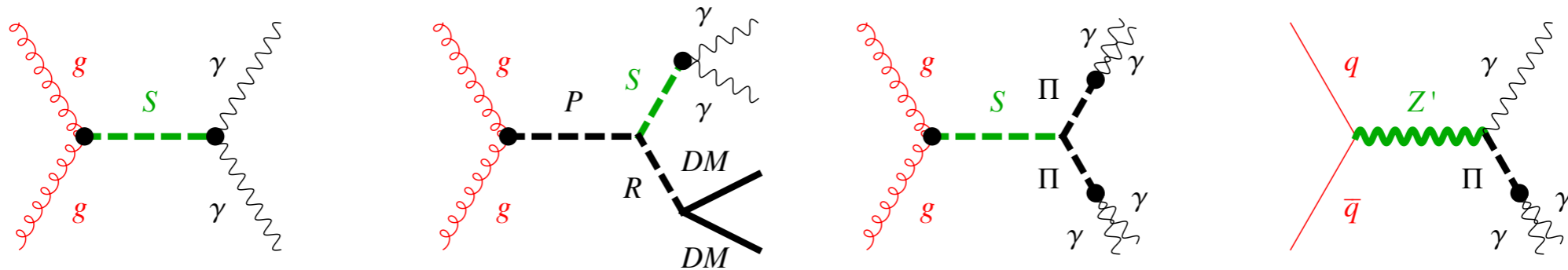
[Strumia, Moriond EW]

EFT of a di-photon resonance

- Assuming a spin-0 SM gauge-singlet scalar resonance S   [see e.g. 1512.04933, 1603.06566]

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

- Decay widths

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

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

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

or

EFT of a di-photon resonance

- Assuming a spin-0 SM gauge-singlet scalar resonance S   [see e.g. 1512.04933, 1603.06566]
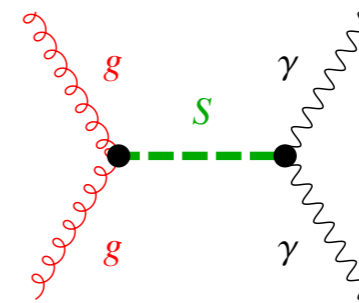
$$\mathcal{L}_{\text{eff}} \supset -\frac{g_3^2}{2\Lambda_g} S G_{\mu\nu}^2 - \frac{e^2}{2\Lambda_\gamma} S F_{\mu\nu}^2 - \sum_q y_{qS} S \bar{q} q$$

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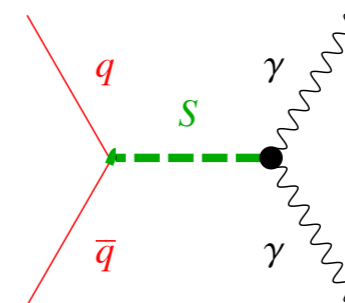
$$\sigma(pp \to S \to \gamma\gamma) = \sigma(pp \to S)\mathcal{B}_{\gamma\gamma} \simeq 3 \div 6 \text{ fb}$$

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

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

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

EFT

Main production issue: consistency with 8 TeV

- Assuming a spin-0 SM gauge-sin...

- Fit cross-section

$$\sigma(pp \to \gamma\gamma) \approx$$

Indicates large singles out preferred production modes

- Consistency b/w 8 and 13 TeV
- Gain factor depends only on...

heavy flavor annihilation/gluon fusion

pure photon fusion disfavored

$$\checkmark \; S \; \times \; is \; \times \; le \; \checkmark \; t \; \times \; decay \; modes$$

- Gain factor $r = \sigma_{13\,TeV}/\sigma_{8\,TeV} \gtrsim 5$
  - Another option: change topology and kinematics

- Assuming a spin-0 SM gauge-singlet scalar resonance S   [see e.g. 1512.04933, 1603.06566]

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

- Production mechanisms

- Assuming a spin-0 SM gauge-singlet scalar resonance S   [see e.g. 1512.04933, 1603.06566]

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

- Needs large di-photon width → $\Gamma_{\gamma\gamma}/M_S \propto \alpha_{\text{EM}}^2/16\pi^3 \sim 10^{-7}$ (weakly coupled models)
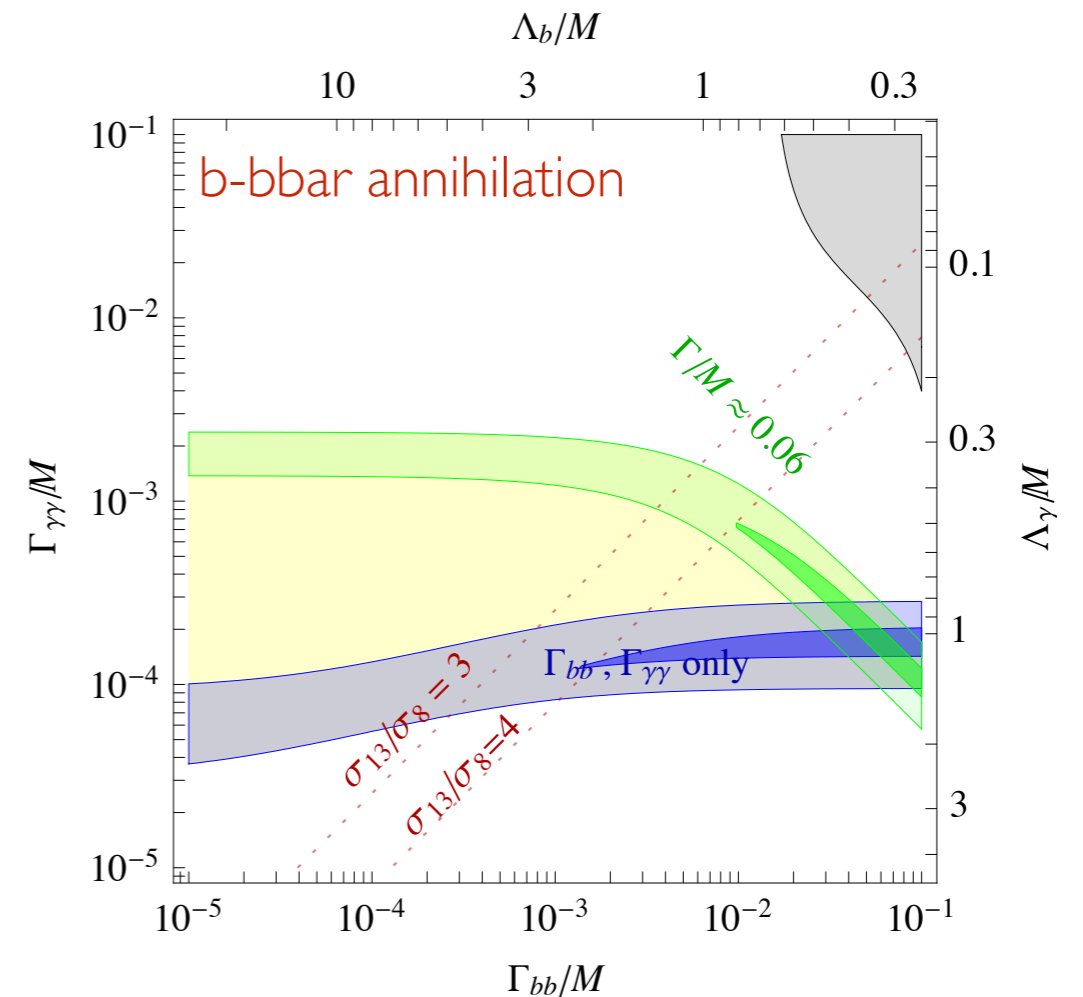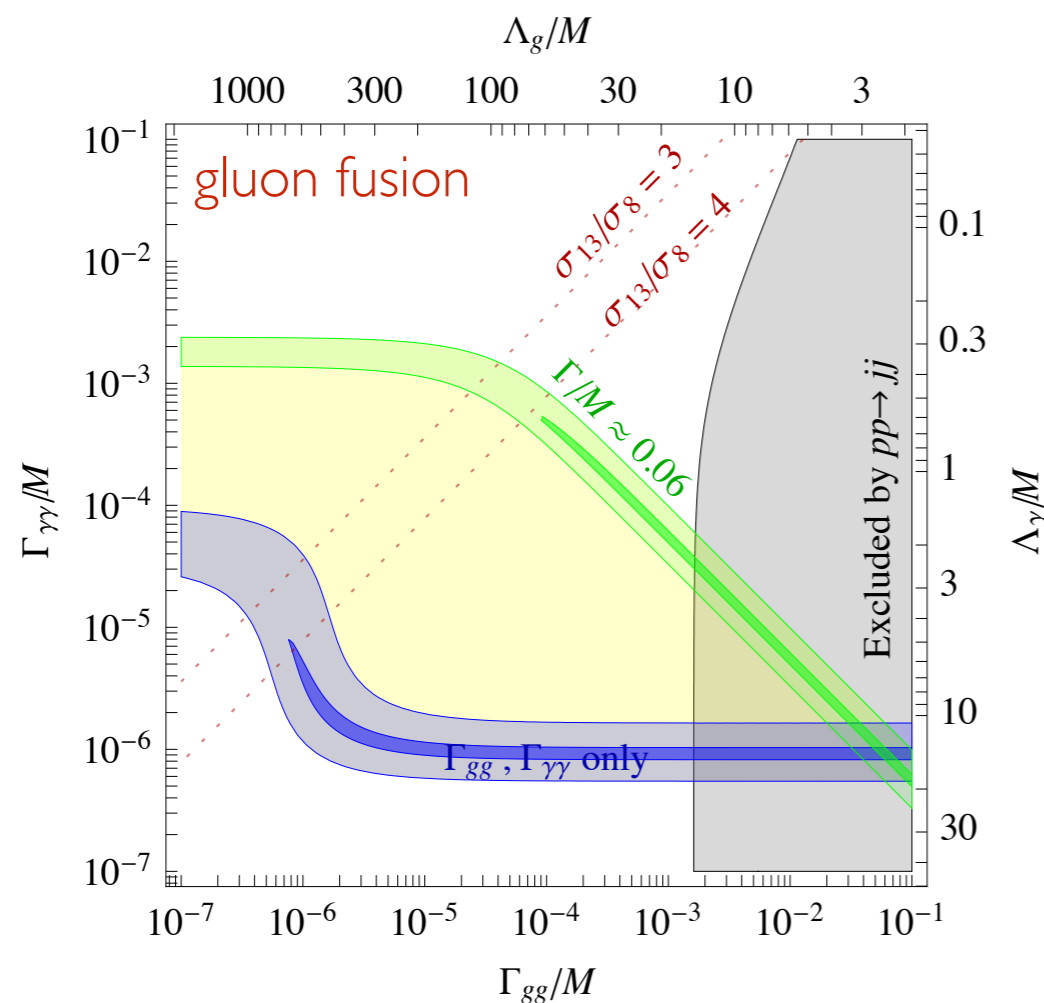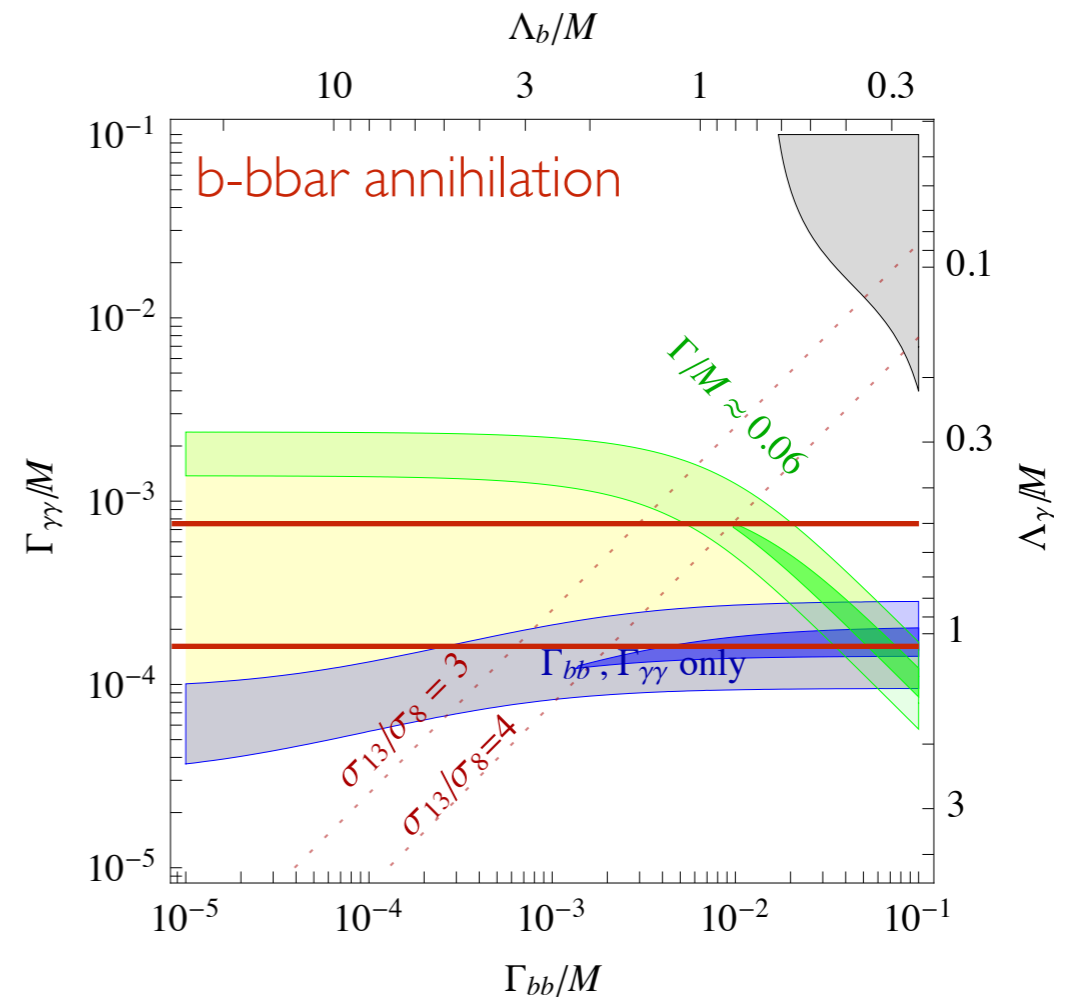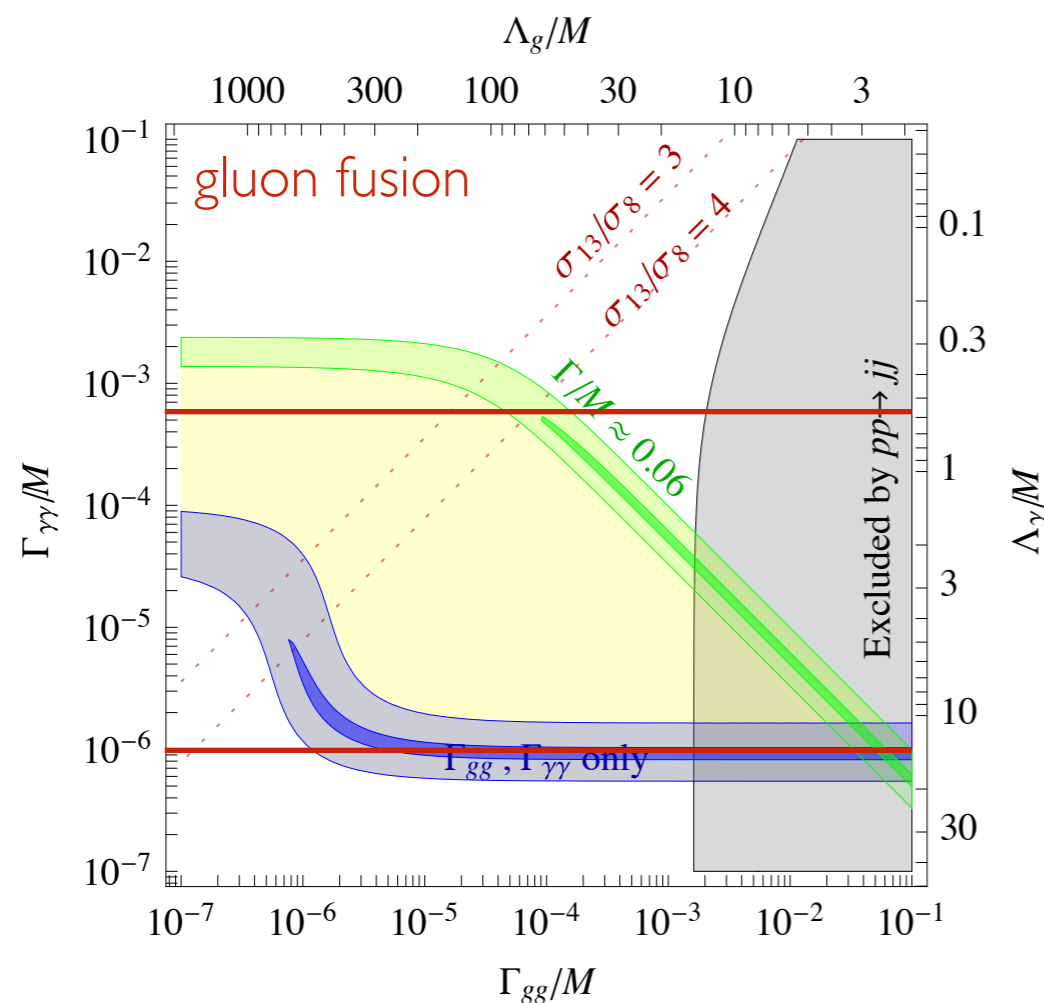
EFT of a di-photon resonance

- Assuming a spin-0 SM gauge-singlet scalar resonance S   [see e.g. 1512.04933, 1603.06566]

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

- SM gauge-invariant EFT

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

- matching: $\dfrac{1}{\Lambda_\gamma} = \dfrac{1}{\Lambda_B} + \dfrac{1}{\Lambda_W}$ $y_{qS} = \dfrac{v}{\sqrt{2}\Lambda_q}$

- 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

1) $\pi\pi$ scattering in χPT   [Weinberg (1966), …]

 - the scale of unitarity violation ~ 500 MeV signals the onset of NP (QCD)

2) LHC "no lose theorem" $\rightarrow$ $\Lambda \lesssim 1\ \mathrm{TeV}$ [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), …]

$$m_{\mathrm{DM}} \lesssim 300\ \mathrm{TeV}$$

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(θ) eliminated by projection onto J-th partial waves   [Jacob, Wick (1959)]

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

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(θ) eliminated by projection onto J-th partial waves   [Jacob, Wick (1959)]

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

- $\beta(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ → kinematics (zero at threshold)

- $\mu_i = \lambda_{i1} - \lambda_{i2}$ and $\mu_f = \lambda_{f1} - \lambda_{f2}$ → helicity formalism

- $d_{\mu_i\mu_f}^J(\theta)$ → Wigner d-functions (e.g. $d_{00}^J = P_J$ Legendre polynomials)

Partial wave projection

- Scattering matrix: $\qquad\qquad S = 1 + iT$

- 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

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

Perturbative unitarity

- Unitarity (an axiom of QFT)

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

- For f = i (optical theorem)

$$\operatorname{Im} a_{ii}^J \geq |a_{ii}^J|^2 \qquad \longrightarrow \qquad \left(\operatorname{Re} a_{ii}^J\right)^2 + \left(\operatorname{Im} a_{ii}^J - \frac{1}{2}\right)^2 \leq \frac{1}{4}$$
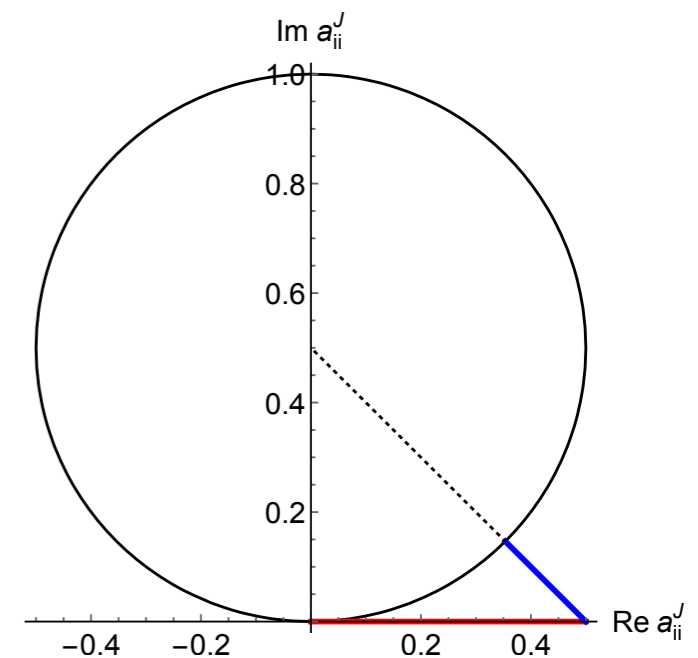
- In practical perturbative calculations S-matrix unitarity is always approximate

- perturbative expansion breaks down for $\boxed{|\operatorname{Re}(a_{ii}^J)^{\text{Born}}| \leq \frac{1}{2}}$

Di-photon scattering

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

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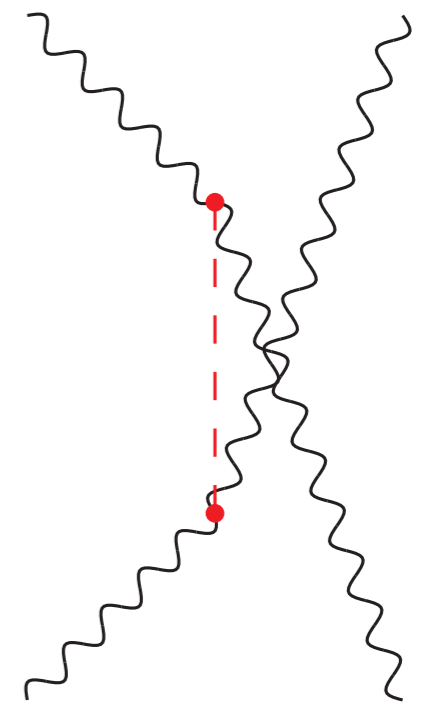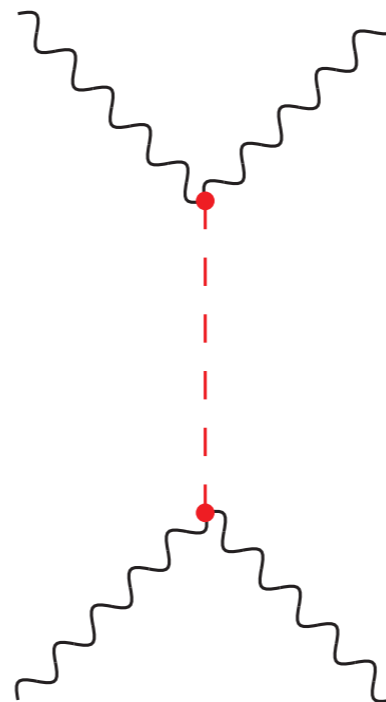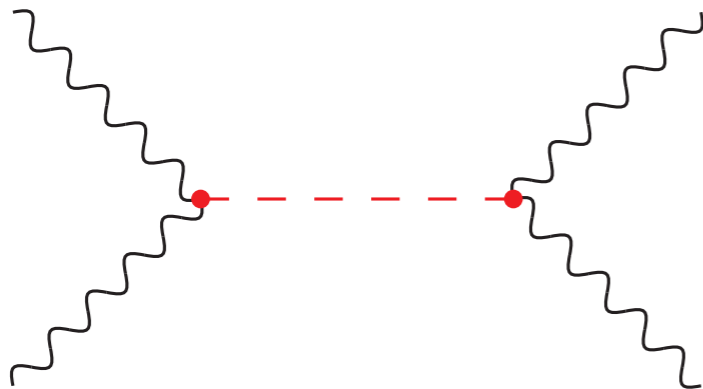
Di-photon scattering

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

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

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

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

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

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

SM gauge boson scattering

- Bounds can be strengthened by looking at the full $V_i V_i \to V_j V_j$ scattering matrix

- i = any of the 8 + 3 + 1 (transversely polarized) SM gauge bosons
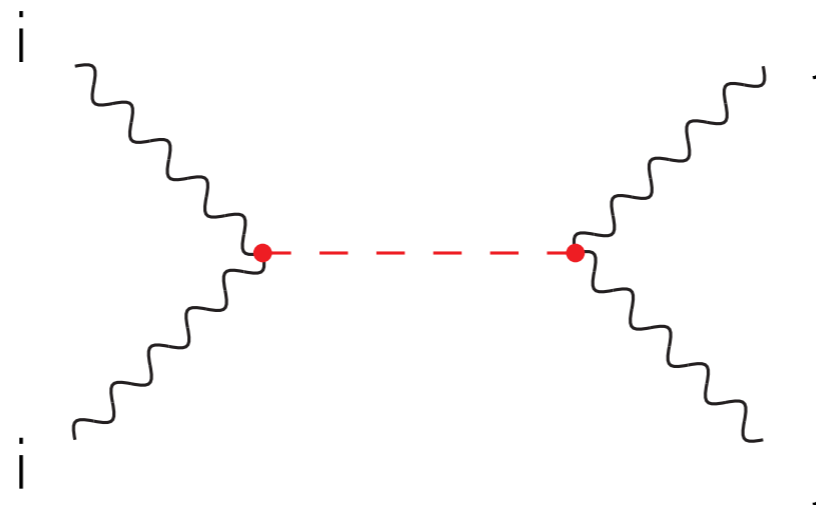
$$m_{ij} = \frac{a_i a_j}{s - M_S^2} \qquad \longrightarrow \qquad \tilde{m}_{\text{eigen.}} \propto \sum_i a_i^2$$

(s-channel dominates at high energies)

SM gauge boson scattering

- Bounds can be strengthened by looking at the full $V_i V_i \to V_j V_j$ scattering matrix

- i = any of the 8 + 3 + 1 (transversely polarized) SM gauge bosons

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

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

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

SM gauge boson scattering

- Bounds can be strengthened by looking at the full $V_i V_i \to V_j V_j$ scattering matrix

 - in terms of "measured" quantities:

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

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

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

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

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

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

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

SM gauge boson scattering

- Bounds can be strengthened by looking at the full $V_i V_i \to V_j V_j$ scattering matrix

- in terms of "measured" quantities:

i) gluon scattering

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

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

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

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

SM gauge boson scattering

- Bounds can be strengthened by looking at the full $V_i V_i \to V_j V_j$ scattering matrix

  - in terms of "measured" quantities:

i) gluon scattering

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

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

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

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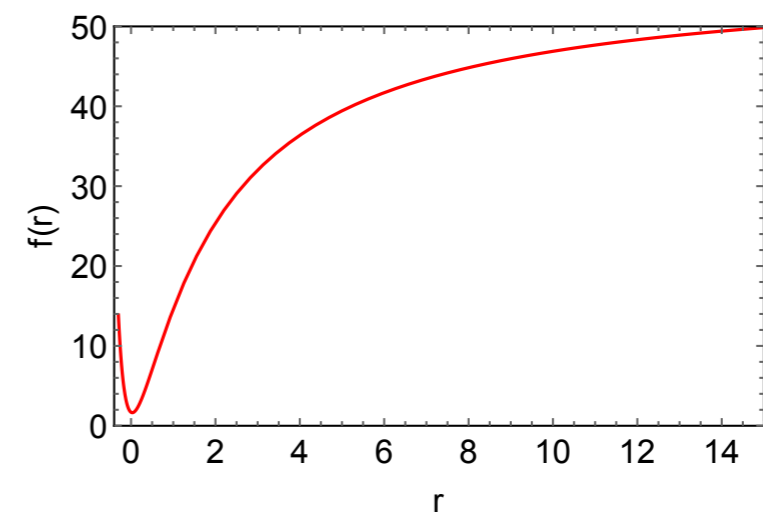
- future determination of $S \to WW, ZZ, Z\gamma$ crucial to strengthen the bound

SM quark annihilation

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

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

SM quark annihilation

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

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

- Tree-level unitarity bound

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

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

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

Di-photon "no lose theorem"

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

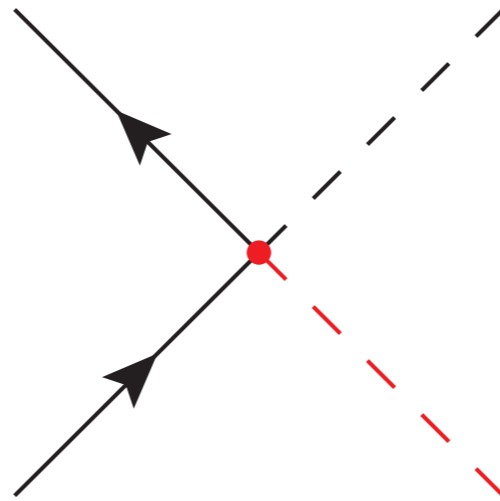$$\sqrt{s} \lesssim 11 \div 59 \text{ TeV} \left(\frac{\Gamma_{\gamma\gamma}/M_S}{10^{-4}} \right)^{-1/2}$$ →   independently of production mechanism

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

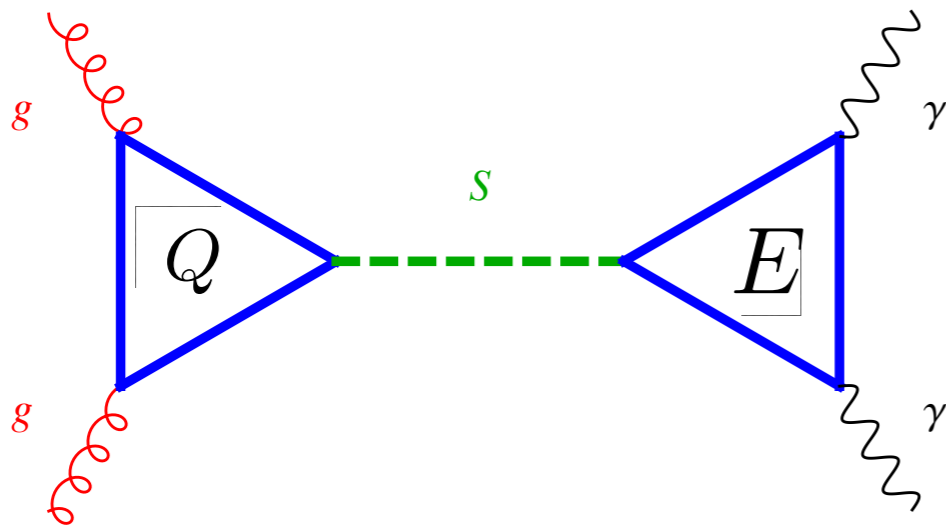$$\sqrt{s} \lesssim 6.2 \text{ TeV} \left(\frac{\Gamma_{q\bar{q}}/M_S}{0.06} \right)^{-1/2}$$ →   q-qbar initiated production

- 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)

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

$$\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left| \mathcal{P}(\tau_Q) \right|^2 ,$$

$$Q \sim (3, 1, 0)$$
$$E \sim (1, 1, 0)$$

$$\Gamma(S \to \gamma\gamma) = M \frac{\alpha^2}{16\pi^3} Y^4 N_E^2 y_e^2 \tau_E \left| \mathcal{P}(\tau_E) \right|^2 ,$$

$$\mathcal{L} \supset i y_q S \, \bar{Q} \gamma^5 Q + i y_e S \, \bar{E} \gamma^5 E$$

where $\tau_Q = 4M_Q^2/M^2$ and $\tau_E = 4M_E^2/M^2$ and the loop function is defined as

$$\mathcal{P}(\tau) = \arctan^2(1/\sqrt{\tau - 1}) .$$

In order to be conservative, we take the values of mediator masses close to their experimental exclusion limit. In particular, we take $M_Q = 1$ TeV and

[see backup slides for scalar mediators or q-qbar initiated models & related unitarity bounds]

• **A large diphoton rate** (colored widths normalized to the mass of the scalar are given by

$$\frac{\Gamma(S \to gg)}{M} = 5.7 \cdot 10^{-6} \, y_q^2 N_Q^2 , \qquad \frac{\Gamma(S \to \gamma\gamma)}{M} = 1.1 \cdot 10^{-7} \, Y^4 y_e^2 N_E^2$$

$$M_E \to 400 \text{ GeV}$$

and we neglected corrections of order $(M/2M_Q)^2$ and $(M/2M_E)^2$, respectively.

• **Narrow Width** $\mathcal{P}(\tau)/M > 10^{-6}$ $\longrightarrow$ $y_q^4 N_Q^2 \gtrsim 10^{?}$ $Y^4 y_e^2 N_E^2 \gtrsim 1.5$ for a top-like state

(3.19)

• **Large Width** $\Gamma_{\gamma\gamma}/M > 10^{-4}$ $\longrightarrow$ $Y^4 N_E^2 y_e^2 \gtrsim 10^3$

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

$$\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left|\mathcal{P}(\tau_Q)\right|^2 ,$$

$$Q \sim (3, 1, 0)$$
$$E \sim (1, 1, 0)$$

$$\mathcal{L} \supset i y_q S\, Q \gamma^5 Q + i y_e S\, E \gamma^5 E$$

- A large di-photon rate is required
  - Narrow width
  - Large width → perturbativity issue !

for a top-like state

Unitarity vs. RGE

- RGE arguments often employed to estimate perturbativity in ren. models

$$\frac{y^2}{16\pi^2} < 1 \qquad \frac{N y^2}{16\pi^2} < 1$$
$$y < 4\pi \qquad y < 4\pi/\sqrt{N}$$

- Landau poles

- Beta function criterium

Other possible issues

1) Landau pole can be very close to the TeV scale [e.g. 1512.08500]

2) Beta function changes very rapidly compared with the coupling itself

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

[1512.07624,
1512.08307,
1512.07889,
1512.08500,
1602.01460,
...., ...,
...., ...,
....]

→ logarithmically sensitive to the UV scale (bounds can be in principle circumvented in UV completions featuring an IR fixed point)

Possible criterion $\left|\dfrac{\beta_y}{y}\right| < 1$

3) Vacuum stability: new interactions (and new scalars) can modify the scalar potential

4) Unitary implications from $2 \to 2$ scatterings of mediators

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

- Unitarity bounds **conceptually different**

- no calculations beyond tree level required

- apply at any $\sqrt{s}$ above threshold

Unitarity bounds
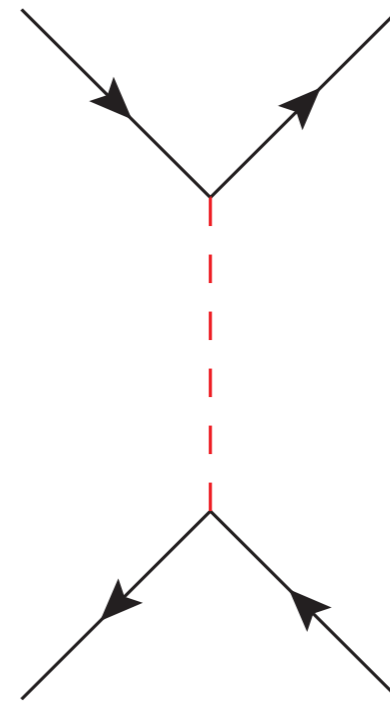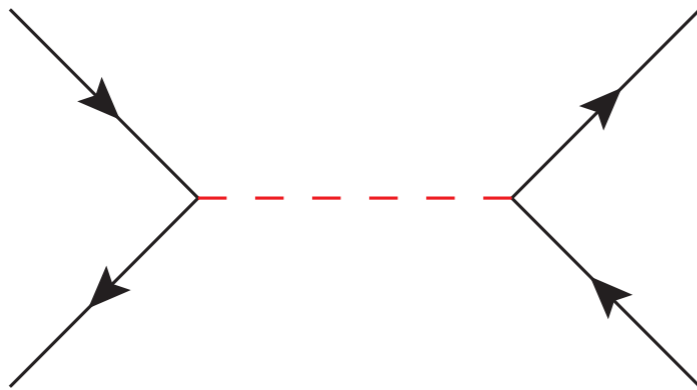
- $2 \to 2$ scatterings of charged mediators $\psi\overline{\psi} \to \psi\overline{\psi}$
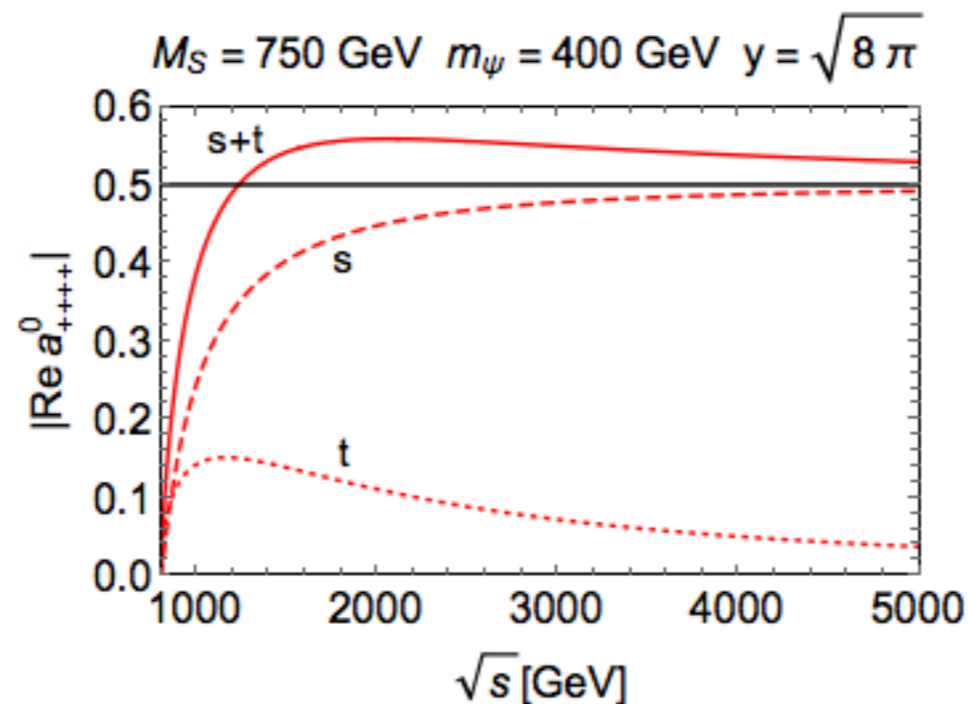
$$\mathcal{L}_I \supset -yS\overline{\psi}\psi \qquad \longrightarrow \qquad a^0 \simeq -\frac{y^2}{16\pi} \qquad \longrightarrow \qquad y \lesssim \sqrt{8\pi}$$

Unitarity bounds

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

$$\mathcal{L}_I \supset -y S \overline{\psi}\psi \qquad \Longrightarrow \qquad a^0 \simeq -\frac{y^2}{16\pi} \qquad \Longrightarrow \qquad y \lesssim \sqrt{8\pi}$$

$M_S = 750$ GeV $\quad m_\psi = 400$ GeV $\quad y = \sqrt{8\pi}$

Unitarity bounds

- $2 \to 2$ scatterings of charged mediators $\psi\overline{\psi} \to \psi\overline{\psi}$
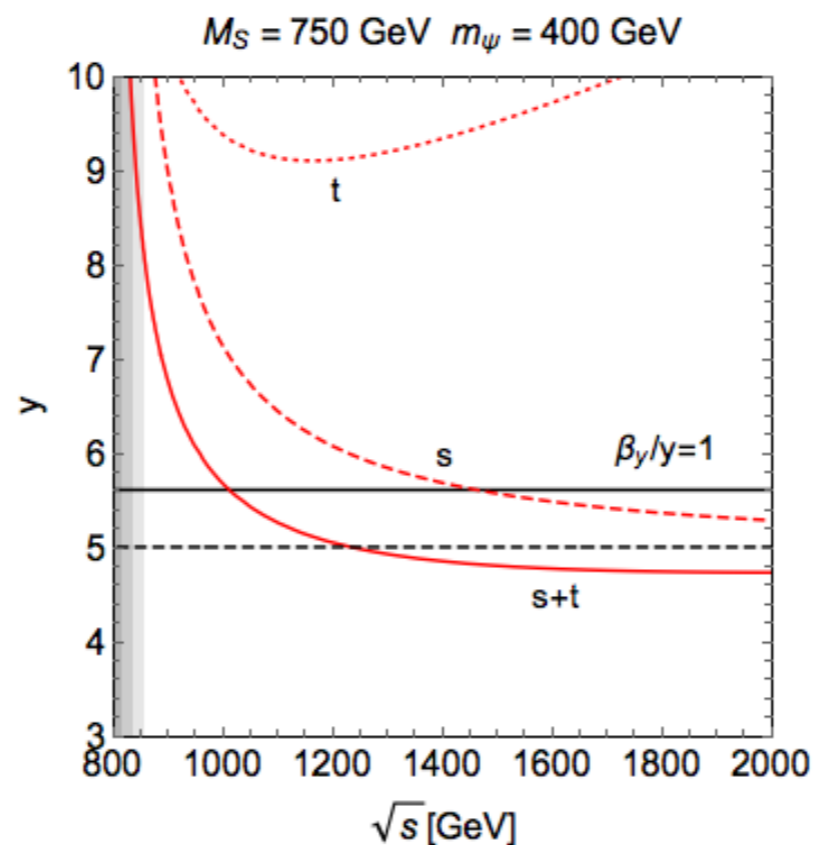
$$\mathcal{L}_I \supset -yS\overline{\psi}\psi \qquad \Longrightarrow \qquad a^0 \simeq -\frac{y^2}{16\pi} \qquad \Longrightarrow \qquad y \lesssim \sqrt{8\pi}$$

$M_S = 750$ GeV $\quad m_\psi = 400$ GeV

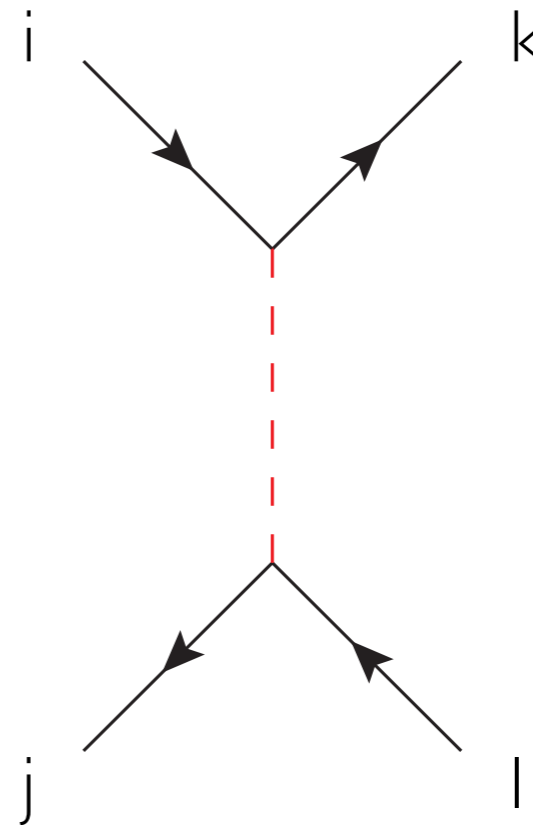- O(1) agreement with beta function criterium $\dfrac{\beta_y}{y} = \dfrac{5y^2}{16\pi^2} < 1$ [1512.08500]

Generalization in flavor space

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

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

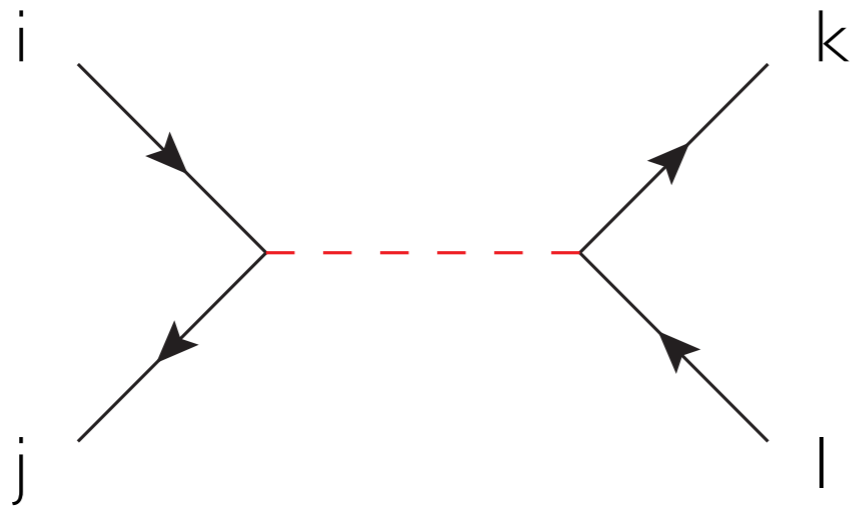# Generalization in flavor space

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

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

- 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 $|\psi\overline{\psi}\rangle_{\mathbf{1}} = \dfrac{1}{\sqrt{N}} \displaystyle\sum_i |\psi_i \overline{\psi}_i\rangle \;\; \rightarrow \;\; {}_{\mathbf{1}}\langle \psi\overline{\psi} | \psi\overline{\psi} \rangle_{\mathbf{1}} = \; i\mathcal{T}_s\, N + i\mathcal{T}_t$

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

Generalization in flavor space

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

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

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

           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 $|\psi\overline{\psi}\rangle_{\mathbf{1}} = \frac{1}{\sqrt{N}} \sum_i |\psi_i\overline{\psi}_i\rangle \quad \rightarrow \quad {}_{\mathbf{1}}\langle\psi\overline{\psi}|\psi\overline{\psi}\rangle_{\mathbf{1}} = i\mathcal{T}_s \, N + i\mathcal{T}_t$
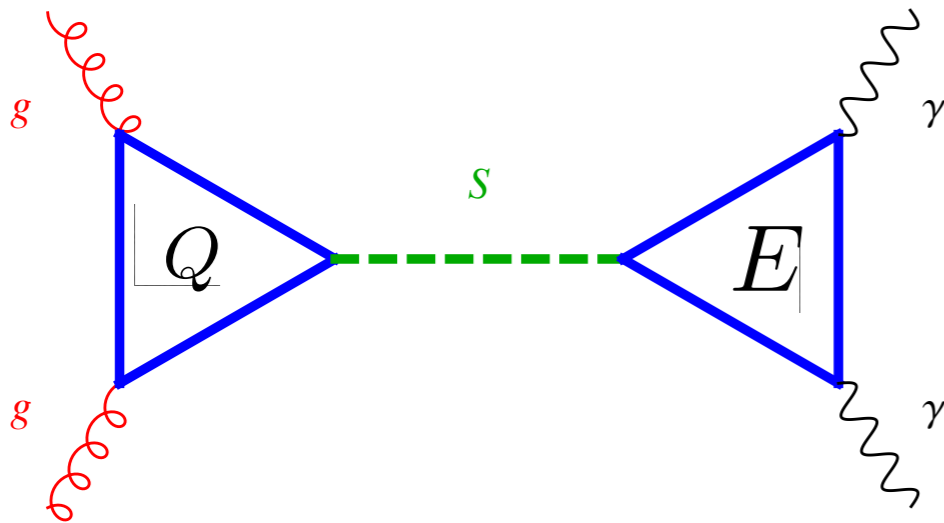
s-channel enhancement $y^2 \rightarrow N\, y^2$ ('t Hooft scaling)

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

$N_E y_E^2 < 8\pi$

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

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

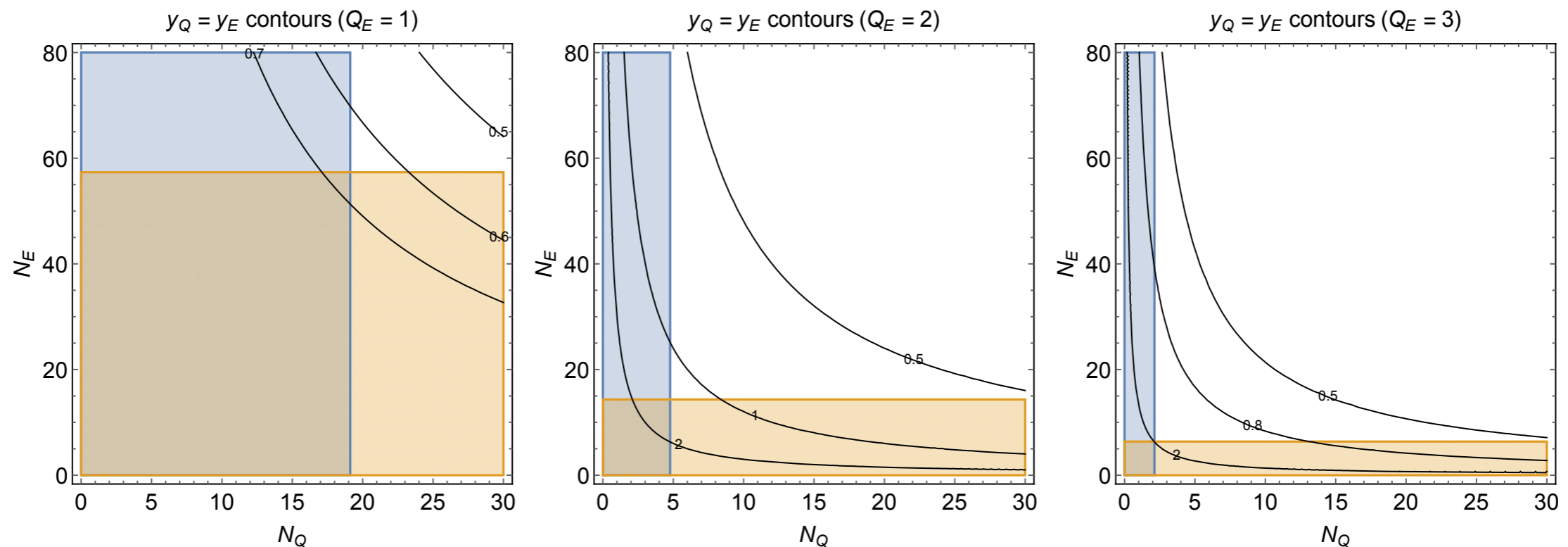$$\Gamma(S \to gg) = M \frac{\alpha_3^2}{8\pi^3} N_Q^2 y_q^2 \tau_Q \left| \mathcal{P}(\tau_Q) \right|^2 ,$$

$$\Gamma(S \to \gamma\gamma) = M \frac{\alpha^2}{16\pi^3} Y^4 N_E^2 y_e^2 \tau_E \left| \mathcal{P}(\tau_E) \right|^2 ,$$

$S \sim (\mathbf{1}, \mathbf{1}, 0)$

$E \sim (\mathbf{3}, \mathbf{1}, Y)$

$\mathcal{P}(\tau) = \arctan^2(1/\sqrt{\tau - 1}) .$

fermion loops

$$\mathcal{L} \supset i y_q S \, \bar{Q} \gamma^5 Q + i y_e S \, \bar{E} \gamma^5 E$$

- A large diphoton rate is required

$$\frac{\Gamma(S \to \gamma\gamma)}{M} = 1.1 \cdot 10^{-7} Y^4 y_e^2 N_E^2$$

$$= 5.7 \cdot 10^{-6} \, y_q^2 N_Q^2$$

$M_E \to 400 \text{ GeV}$

Visualizing the bounds

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

$$N_E y_E^2 < 8\pi$$
$$3 N_Q y_Q^2 < 8\pi$$

$\rightarrow$ unitarity bounds

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

$\rightarrow$ to fit the signal

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

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

- a physics case for the 50 TeV collider

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)

→ Experimental confirmation of a sizeable S-width highly suggestive of a strongly coupled nature of the NP behind the di-photon excess
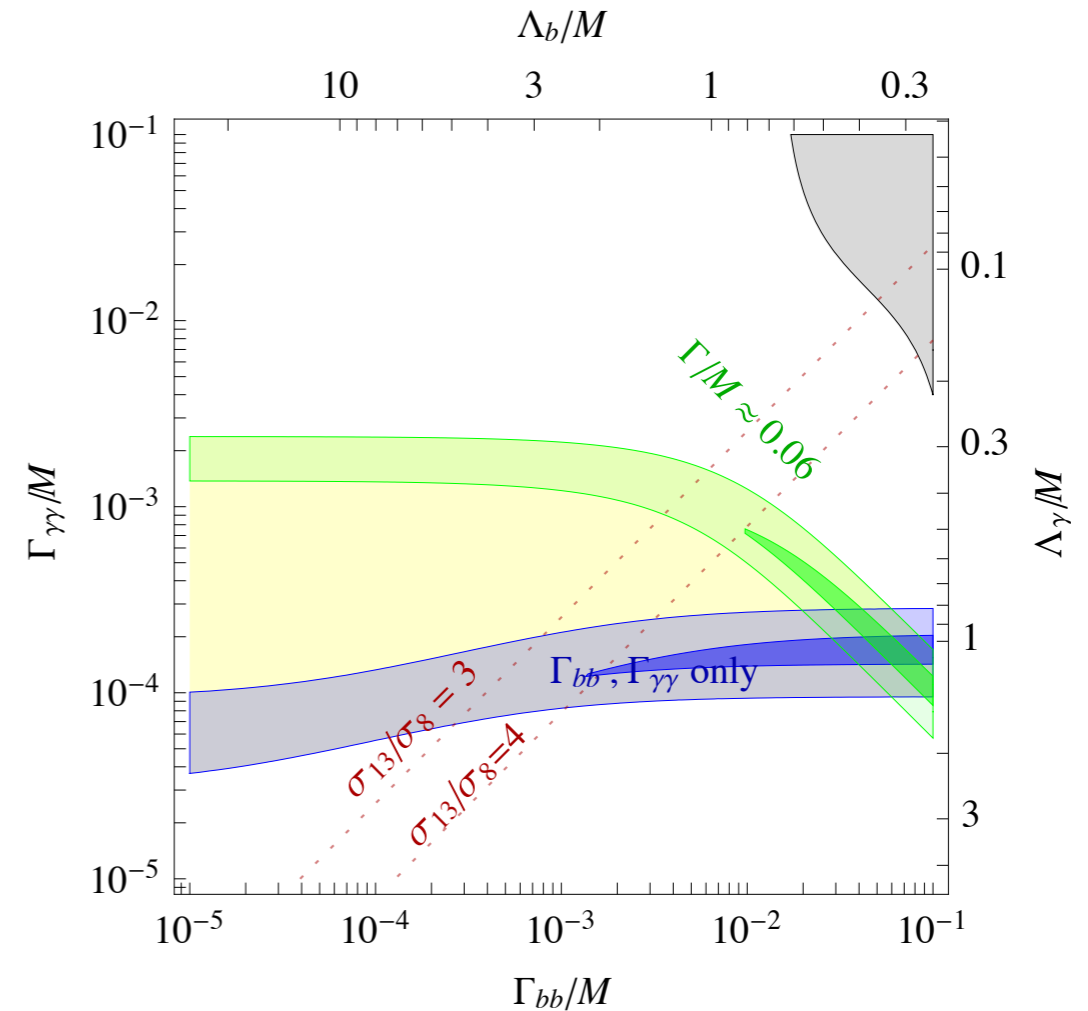
Backup slides

Production mechanisms
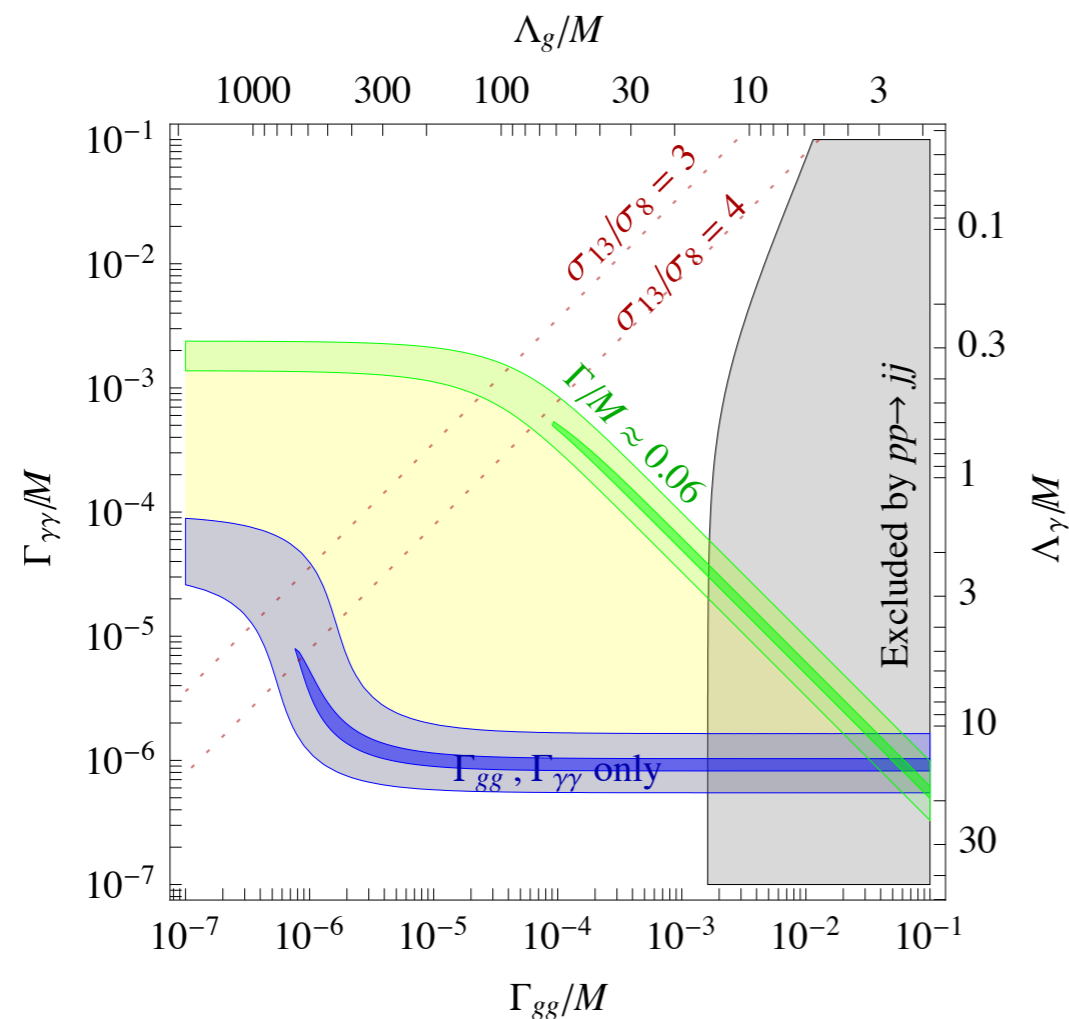
$$\frac{\Gamma_{\gamma\gamma}}{M_S}\frac{\Gamma_{gg}}{M_S} \simeq 4.9\times10^{-8}\left(\frac{\Gamma_S/M_S}{0.06}\right)$$
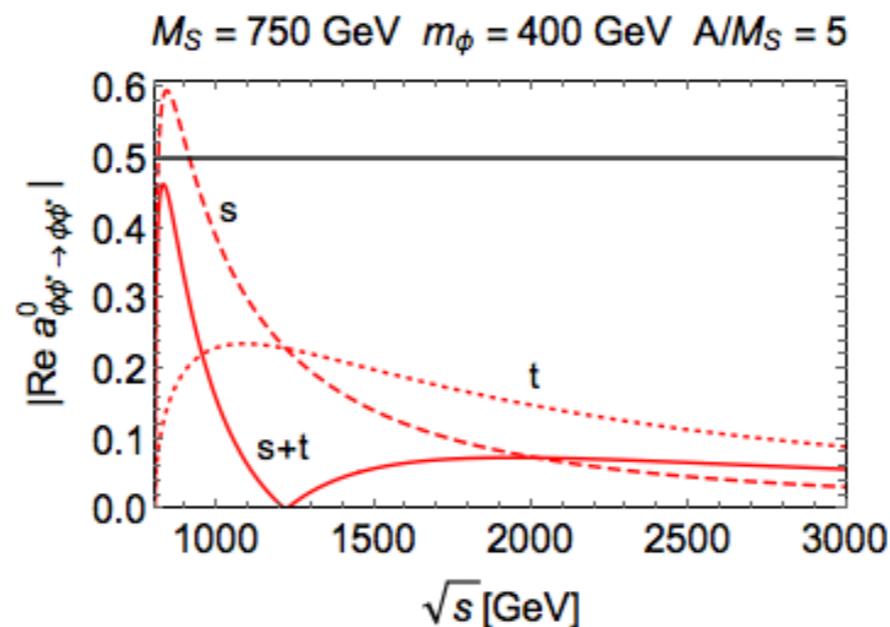
$$\frac{\Gamma_{\gamma\gamma}}{M_S}\frac{\Gamma_{b\bar{b}}}{M_S} \simeq 8.4\times10^{-6}\left(\frac{\Gamma_S/M_S}{0.06}\right)$$

Scalar mediators (gg initiated)

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

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

$M_S = 750$ GeV $\quad m_\phi = 400$ GeV $\quad A/M_S = 5$

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

Scalar mediators (gg initiated)

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

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

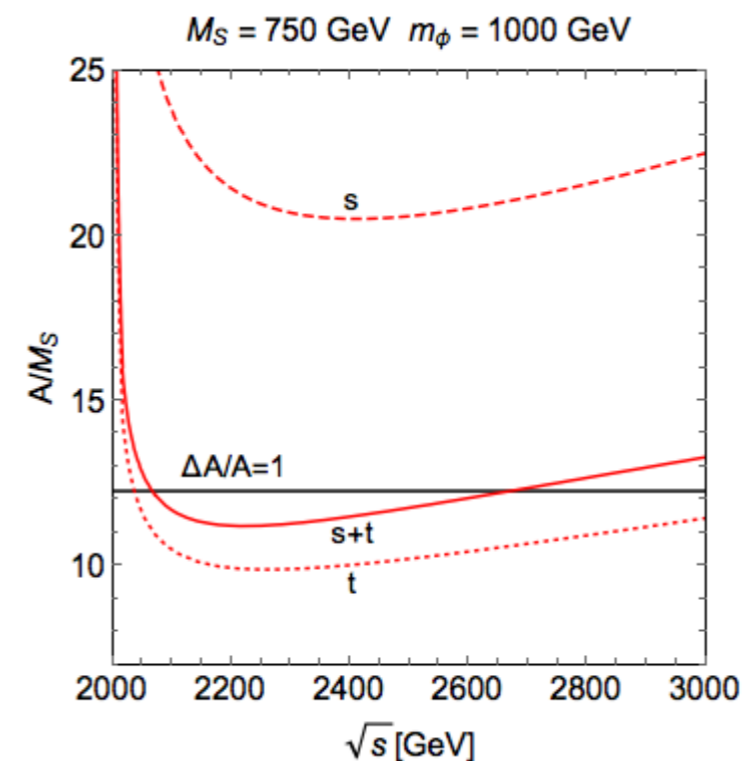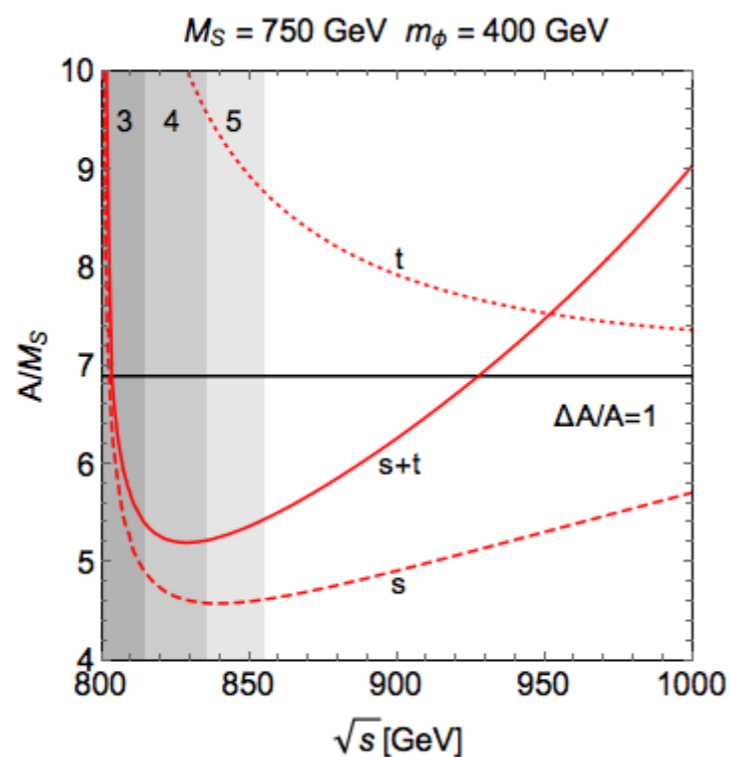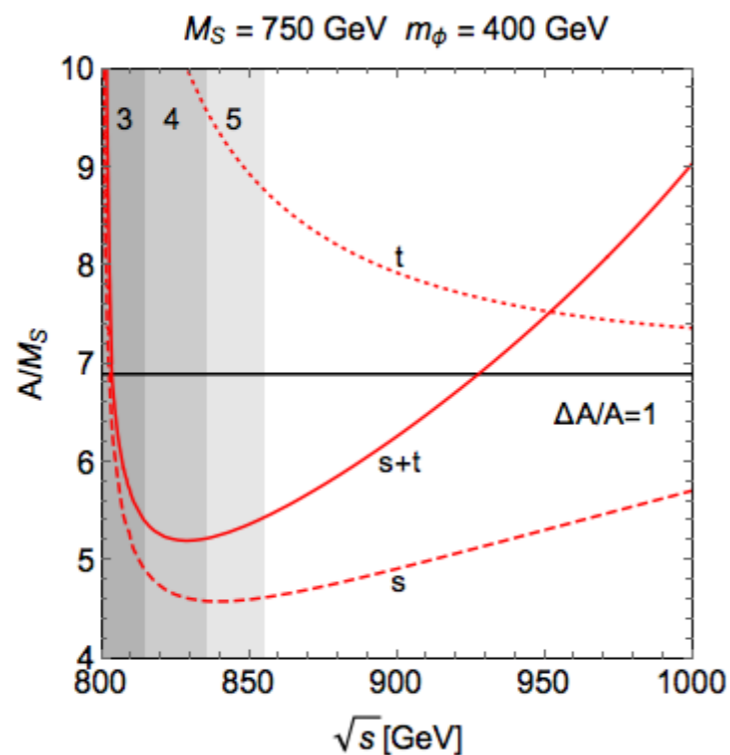$M_S = 750$ GeV $m_\phi = 400$ GeV

$M_S = 750$ GeV $m_\phi = 1000$ GeV

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

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

$$\mathcal{L}_I \supset -AS\phi^*\phi$$

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

$M_S = 750$ GeV $m_\phi = 400$ GeV

$$\frac{\left| \frac{i}{s-M_S^2} \right|^2 - \left| \frac{i}{s-M_S^2+iM_S\Gamma_S} \right|^2}{\left| \frac{i}{s-M_S^2} \right|^2} < \Delta$$

$$\alpha = \sqrt{1/\Delta - 1} \quad (\alpha = 3 \to \Delta = 10\%)$$

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

- Width effects important near s-pole singularities $\alpha = \frac{|s-M_S^2|}{\Gamma_S M_S}$ $(\Gamma_S/M_S = 0.06)$
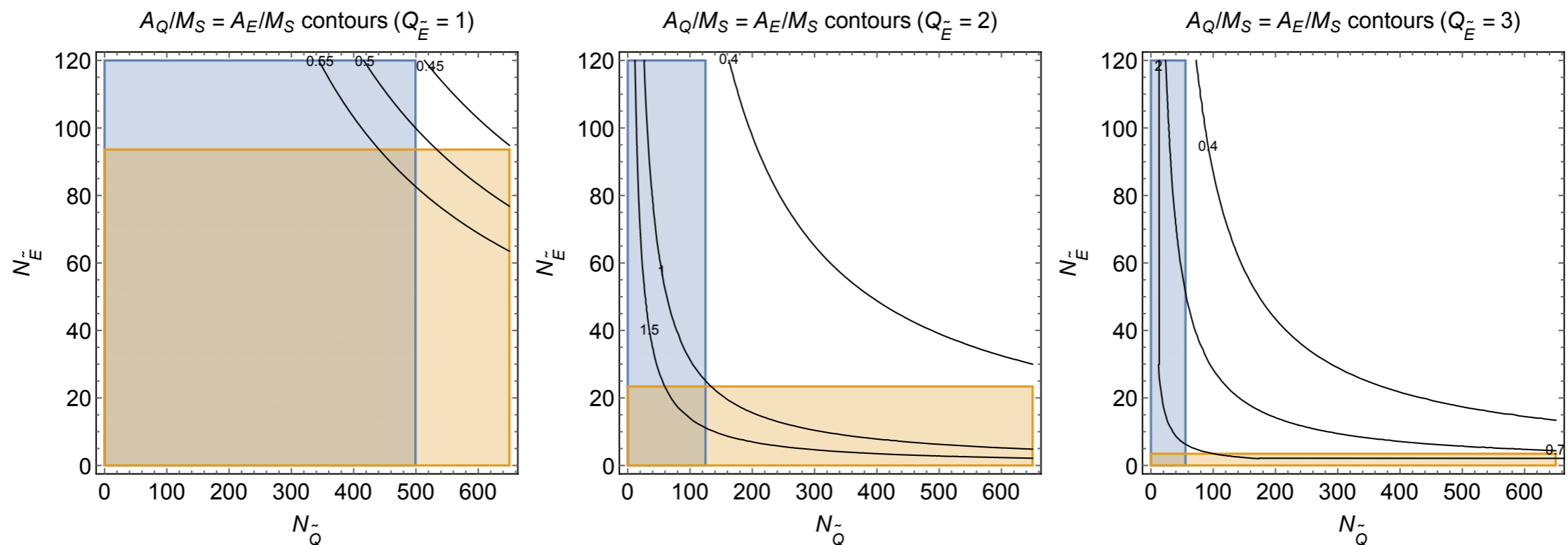
- Flavor enhancement from s-channel

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

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

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

q-qbar initiated

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

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

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

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

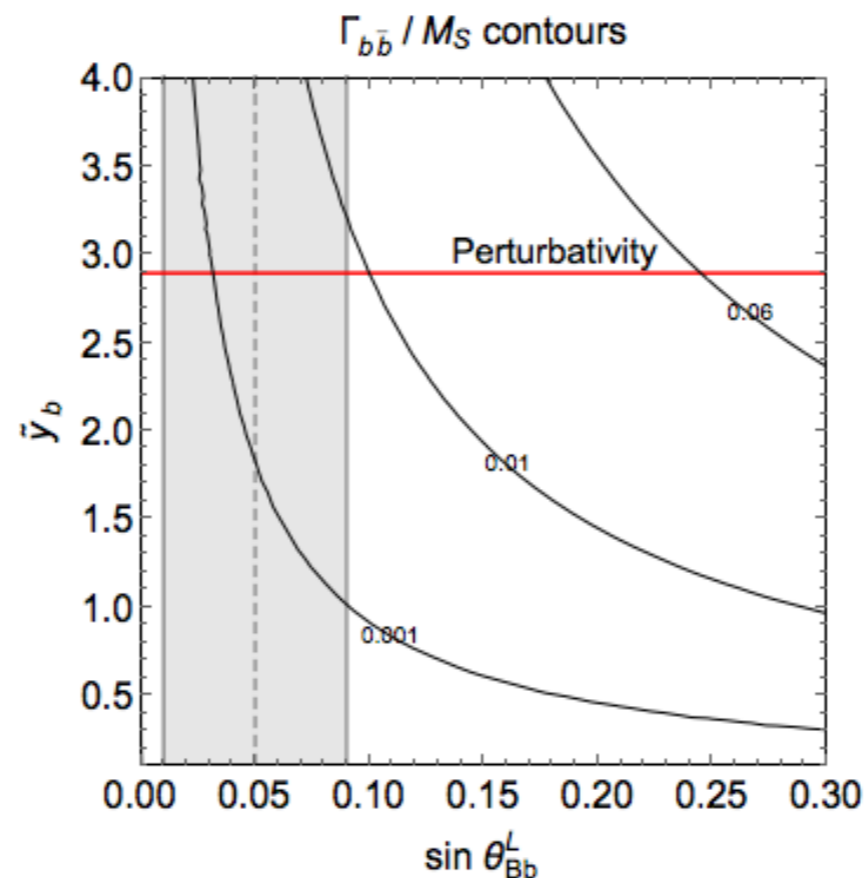$$\theta^R_{\mathcal{B}b} \sim (m_b/m_{\mathcal{B}}) \theta^L_{\mathcal{B}b}$$

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

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

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

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

$\Gamma_{b\bar{b}} / M_S$ contours

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