Perturbative unitarity and the LHC di-photon excess

5th International Conference on New Frontiers in Physics

Crete - 13th July 2016

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Based on arXiv:1604.05746 in collaboration with:
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Outline

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

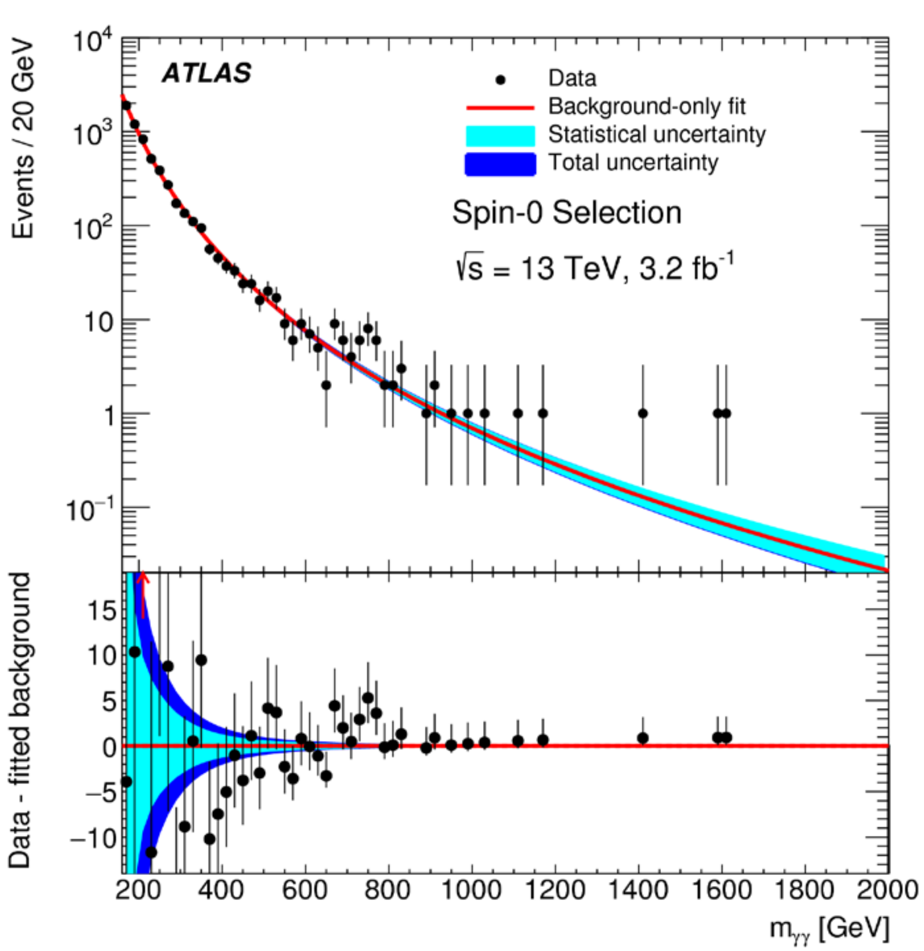
1) range of validity of the EFT ⟶ this talk

2) perturbativity bounds in weakly coupled models ⟶ see backup slides

The LHC di-photon excess

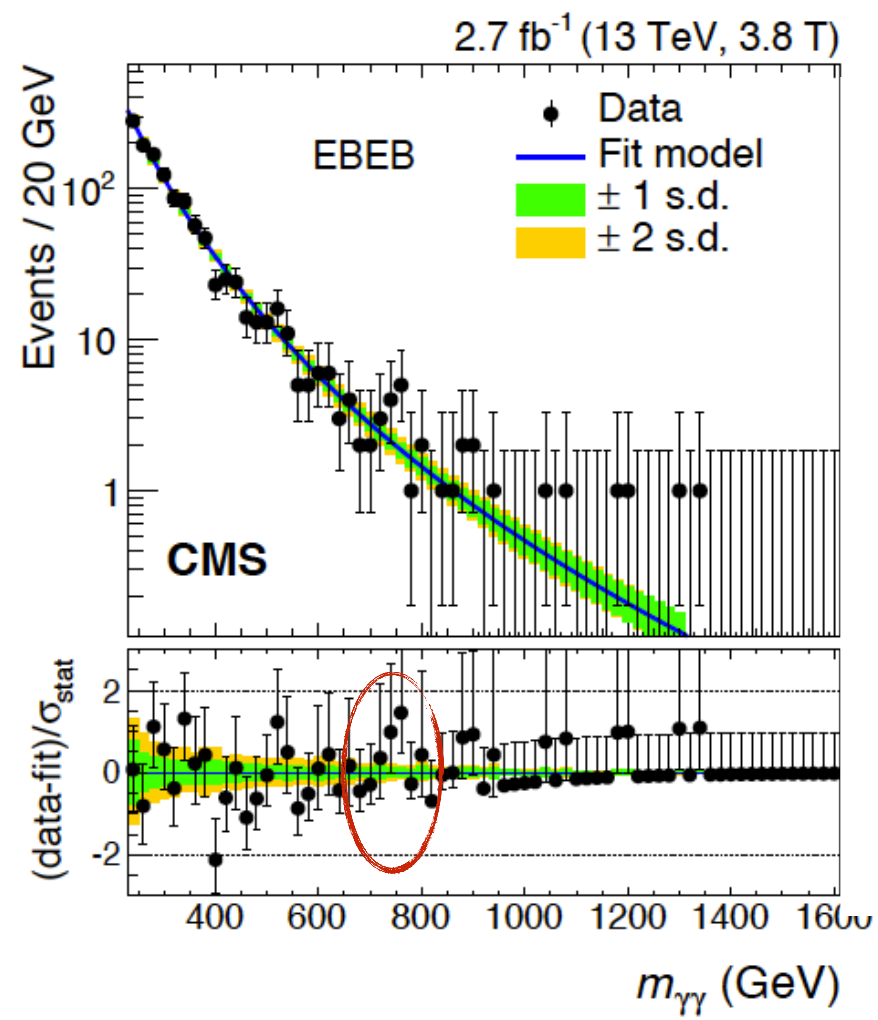
- Both ATLAS and CMS observe a di-photon excess at ~ 750 GeV

[See F. Malek talk on Saturday]



3.9σ local (2.1σ global)
- best fit for Γ/M ~ 6%

[See M. Quittnat talk on Saturday]



2.9σ local (1.6σ global)
- narrow width

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(400) papers on the arXiv since Dec 15th (apologies for the missing refs.)

 - Here: not a specific model, but some general "theoretical constraints"

Stick to the simplest interpretation

- A single 750 GeV resonance [See A. Carmona talk on Monday]

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

Stick to the simplest 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 simplest interpretation

- A single 750 GeV resonance [See A. Carmona talk on Monday]

- spin 0

- SM singlet without mixing with the H

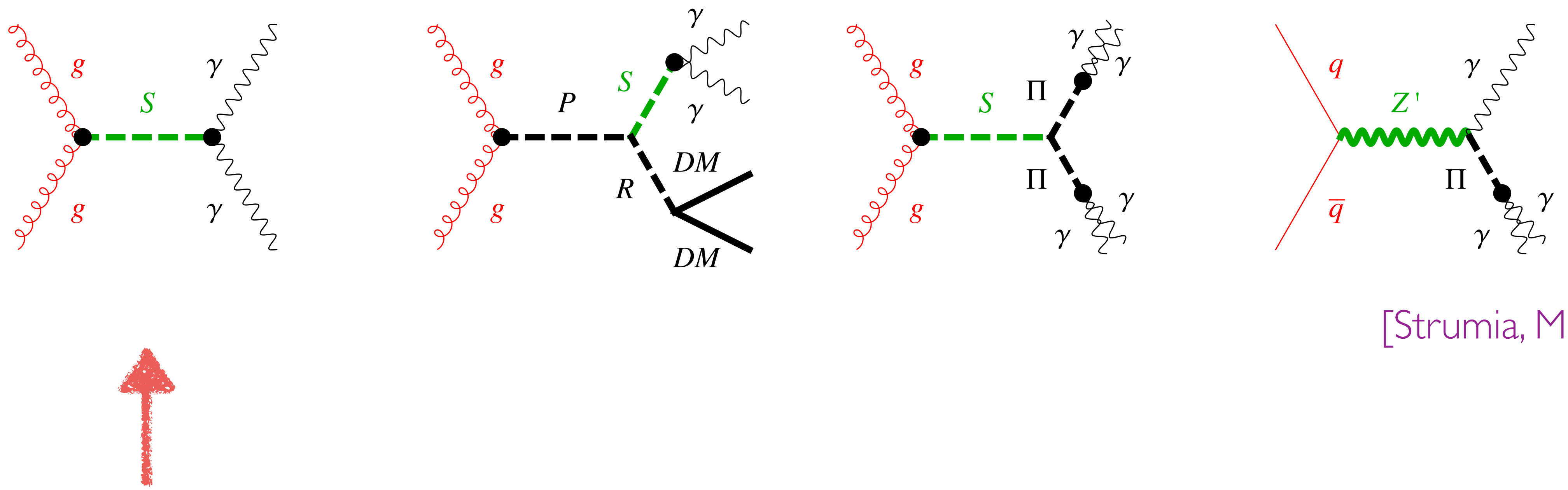
- CP scalar (pseudo-scalar also ok, if CP violated extra constraints from EDMs, ...)

Stick to the simplest interpretation

- A single 750 GeV resonance

[See A. Carmona talk on Monday]

- 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]

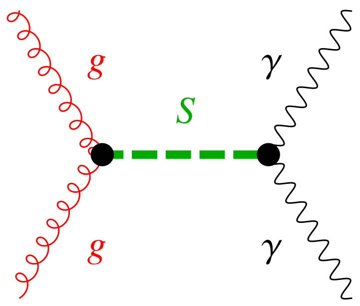
$$\mathcal{L}_{\text{eff}} \supset -\frac{g_3^2}{2\Lambda_g} S G_{\mu\nu}^2 - \frac{e^2}{2\Lambda_\gamma} S F_{\mu\nu}^2 - \sum_q y_{qS} S \overline{q} q$$

- Decay widths

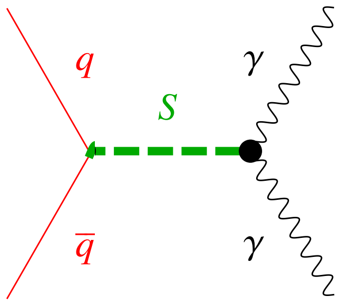
$$\Gamma_{gg} \equiv \Gamma(S \to gg) = 8\pi \alpha_s^2 \frac{M_S^3}{\Lambda_g^2}$$

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

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



or



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- 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

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- 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
✓	✓	✓	✗	✗	✓	✗

- Gain factor $r = \sigma_{13 \text{ TeV}} / \sigma_{8 \text{ TeV}} \gtrsim 5$

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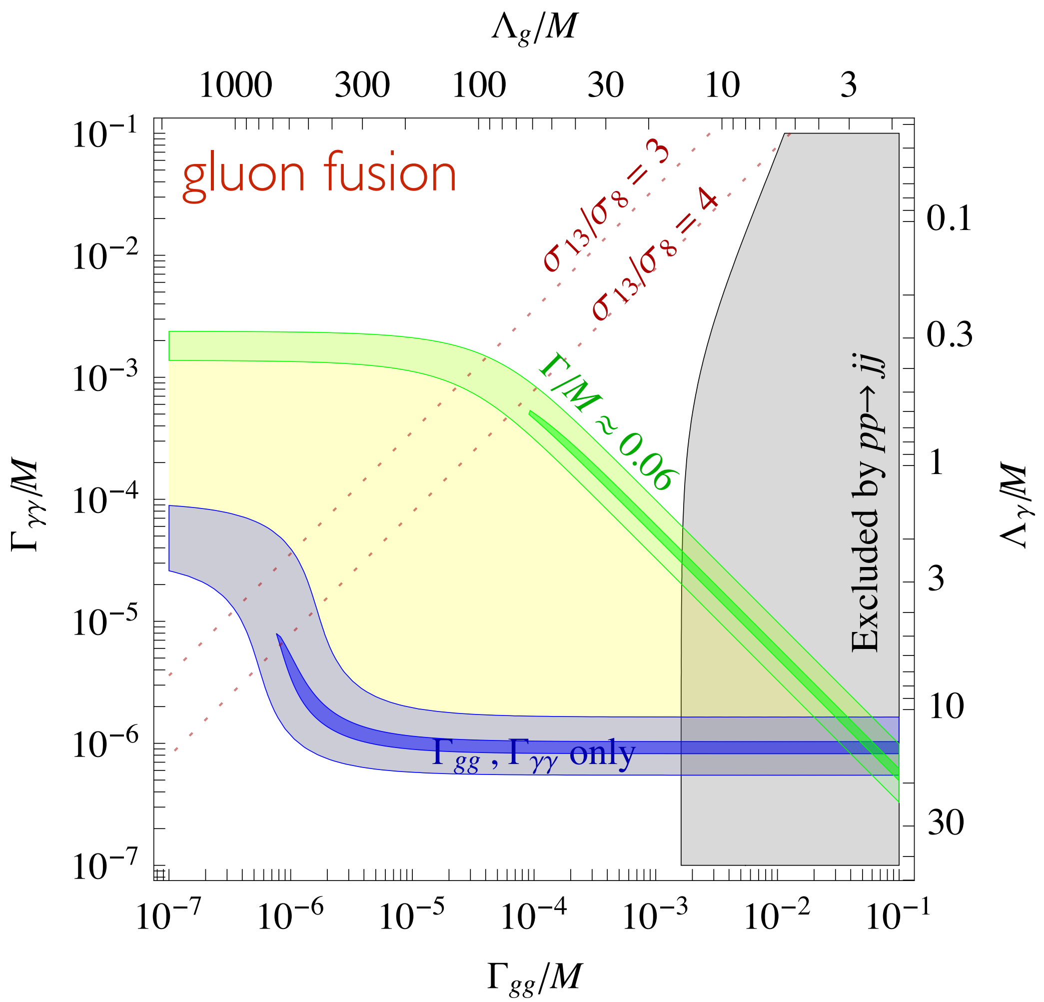
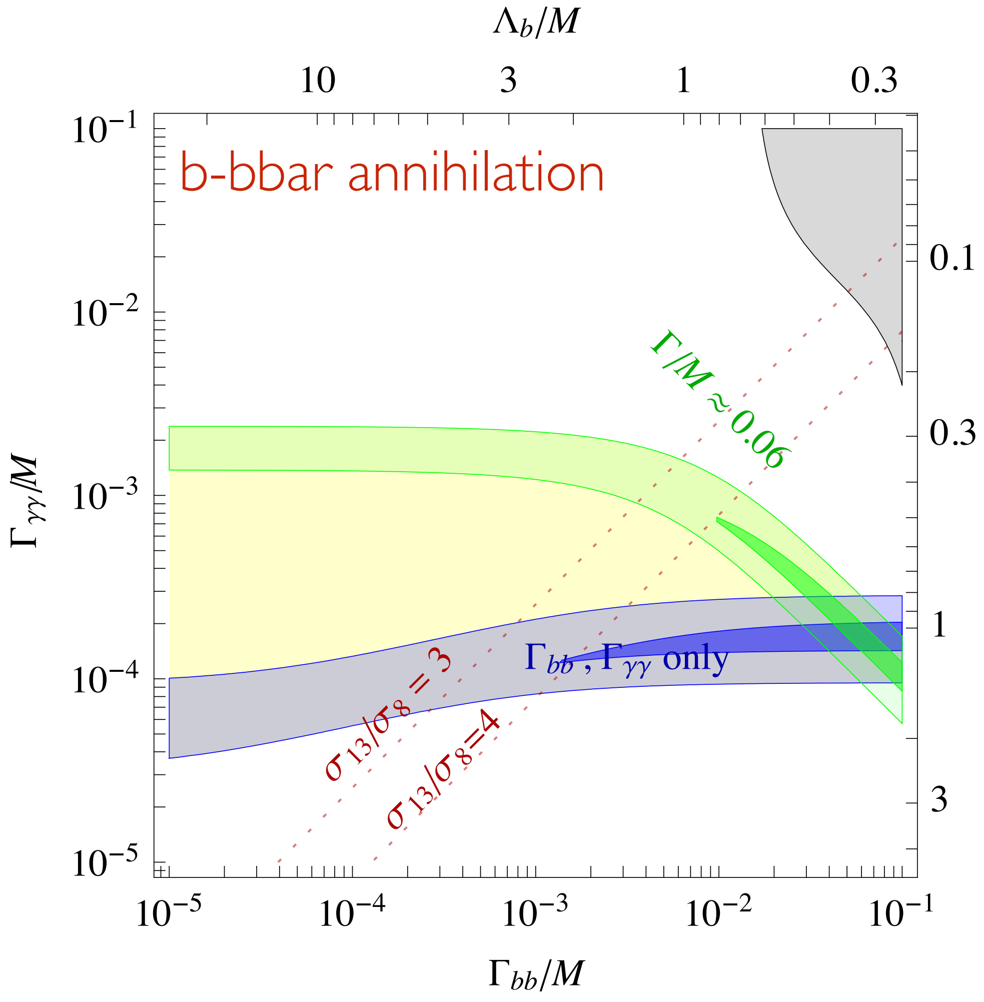
- Production mechanisms





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- SM gauge-invariant EFT

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

- 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 ?*

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A historical detour

- Unitarity arguments often served as a guide in HEP

1) **ππ** scattering in **χ**PT [Weinberg (1966), …]

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

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

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

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)]

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

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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

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

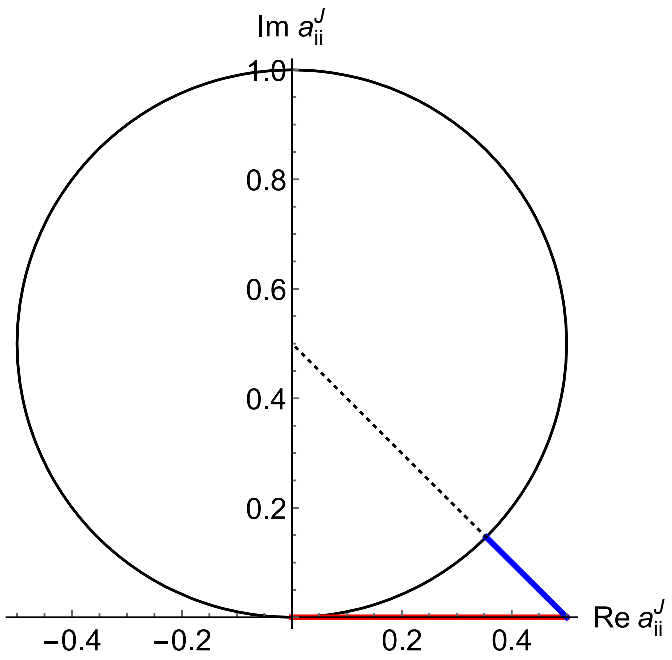
Perturbative unitarity

- 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

 - perturbative expansion breaks down for

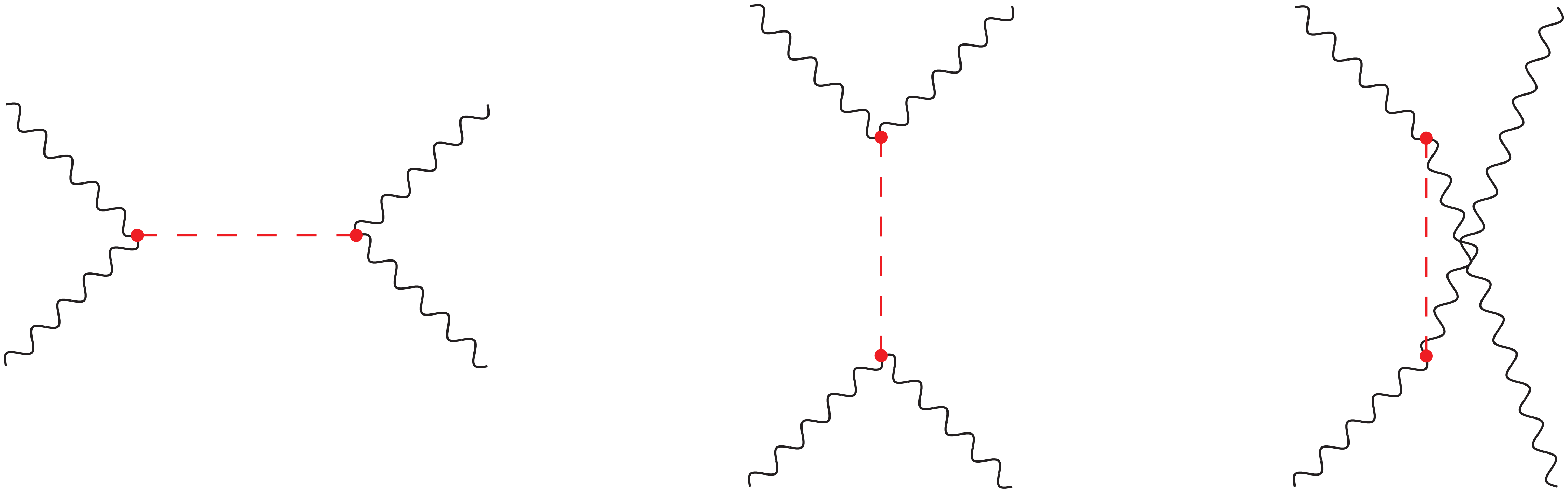
$$\left|\text{Re}\, (a^J_{ii})^{\text{Born}}\right| \leq \frac{1}{2}$$

}

Di-photon scattering

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

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



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

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

$\uparrow$

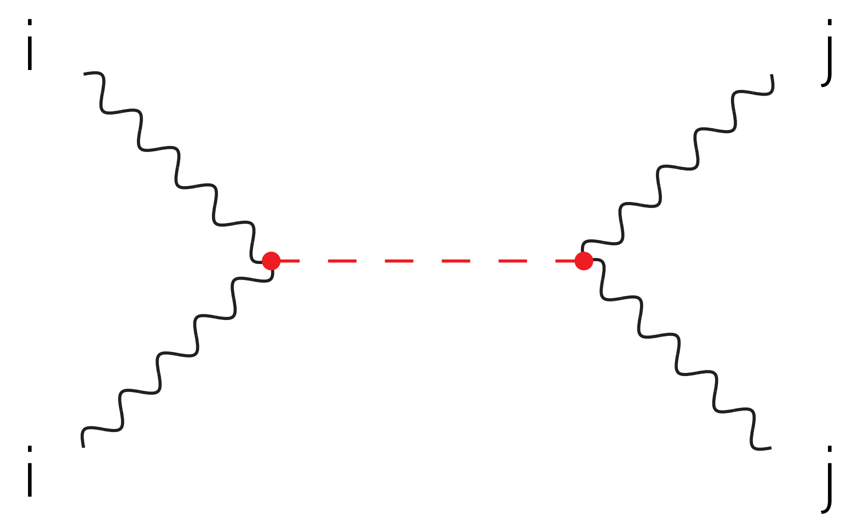
$$\Gamma_{\gamma\gamma} = \pi\alpha_{\rm EM}^2 \frac{M_S^3}{\Lambda_\gamma^2}$$

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

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



$$m_{ij} = \frac{a_i a_j}{s - M_S^2} \quad \longrightarrow \quad \tilde{m}_{\text{eigen.}} \propto \sum_i a_i^2$$

(s-channel dominates at high energies)

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

↓

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

↓

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

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

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

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

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

→

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

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

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

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

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

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

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

SM gauge boson scattering

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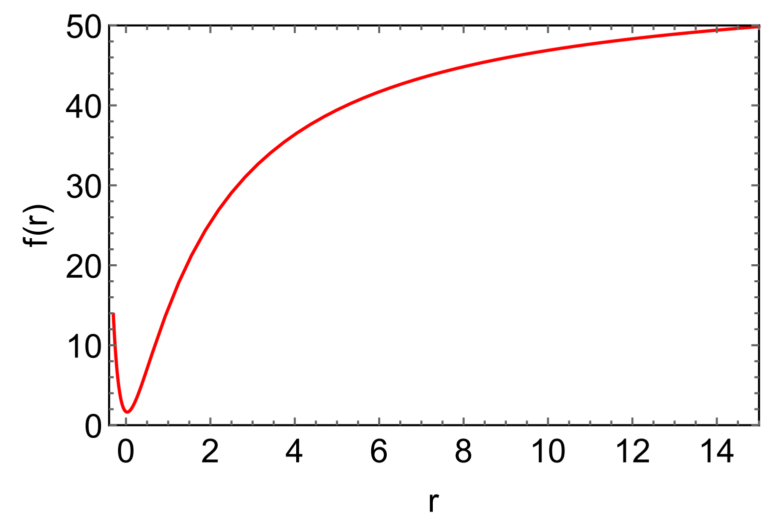
$$f(r) = \frac{3r^2 s_W^{-4} + c_W^{-4}}{(1+r)^2}$$

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)

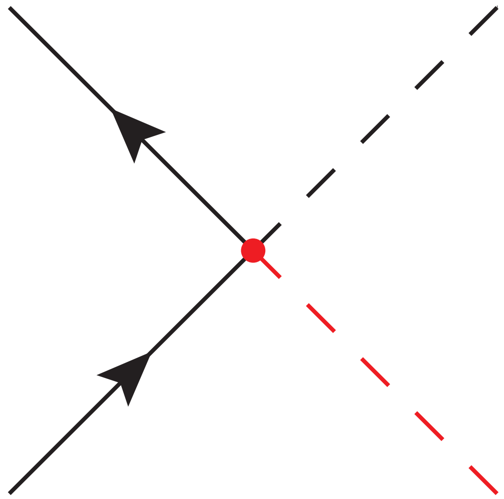


- future determination of $S \to WW, ZZ, Z\gamma$ crucial to strengthen the bound

SM quark annihilation

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

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



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- Tree-level unitarity bound

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

$$\uparrow$$

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

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

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)

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

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

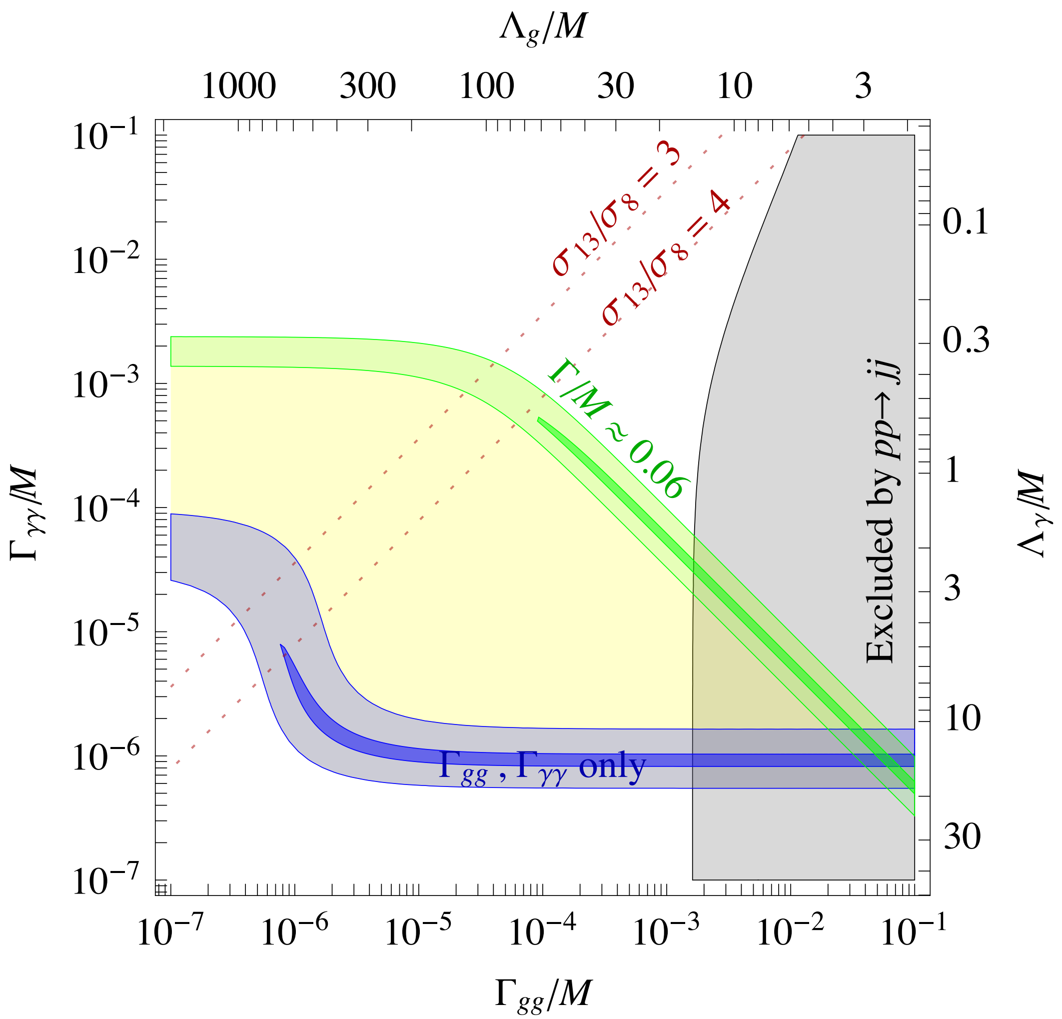
- Endangered calculability in a wide class of di-photon models (large width scenario)

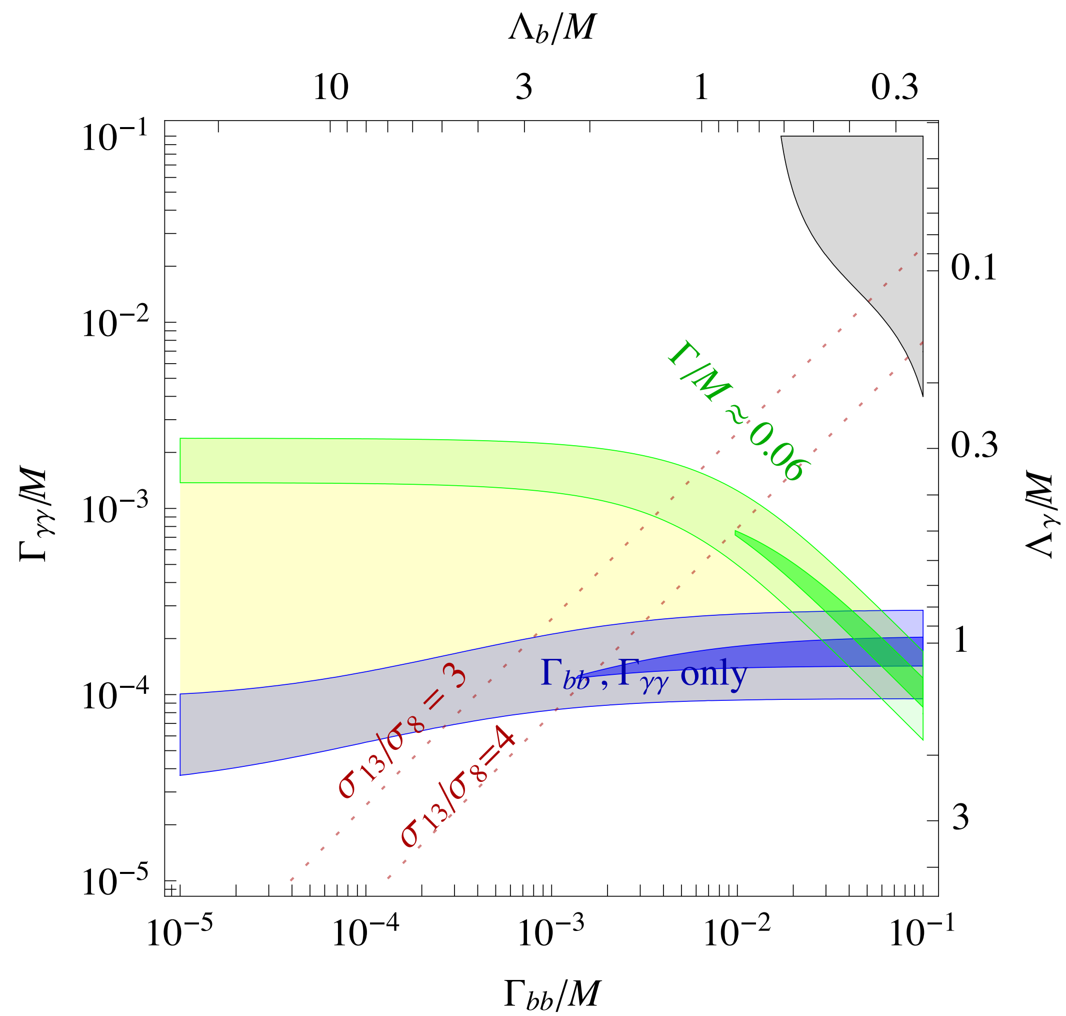
[see backup slides]

Backup slides

Production mechanisms

[from 1512.04933]



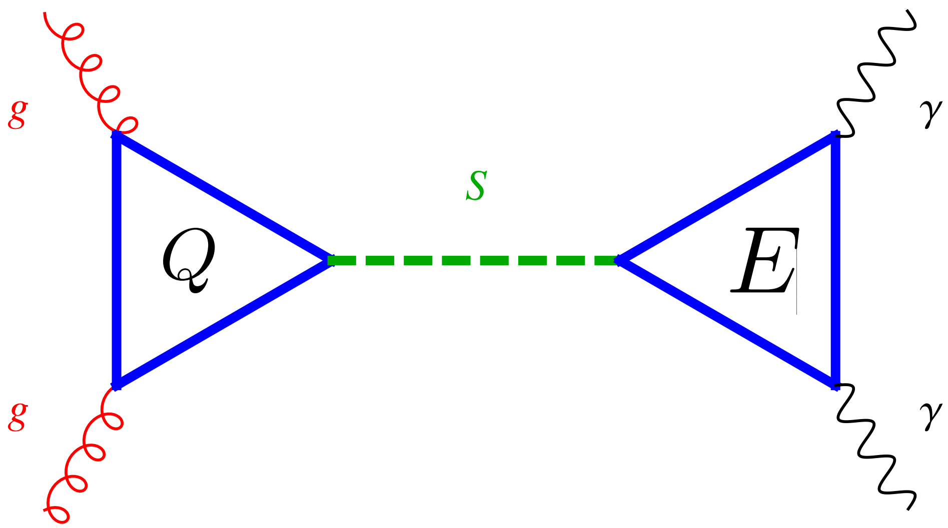


$$\frac{\Gamma_{\gamma\gamma}}{M_S}\frac{\Gamma_{gg}}{M_S} \simeq 4.9 \times 10^{-8} \left(\frac{\Gamma_S/M_S}{0.06}\right)$$

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

Weakly coupled models

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



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

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

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

Weakly coupled models

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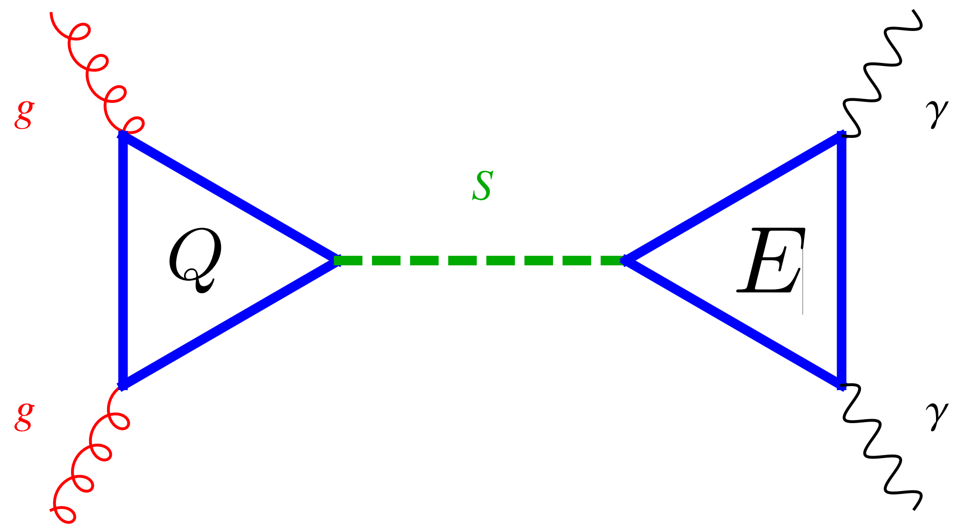


$Q \sim (3,1,0) \times N_Q$ $\quad S \sim (1,1,0)$

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

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

- 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 $\quad \Gamma_{\gamma\gamma}/M_S \gtrsim 10^{-6} \; \rightarrow \; N_E^2 Q_E^4 y_E^2 \gtrsim 10$ $\quad$ (~ 1.5 for a top-like state)

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

Unitarity vs. RGE

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

- Landau poles

- Beta function criterium [e.g. 1512.08500]

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

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

- Unitarity bounds <u>conceptually different</u>

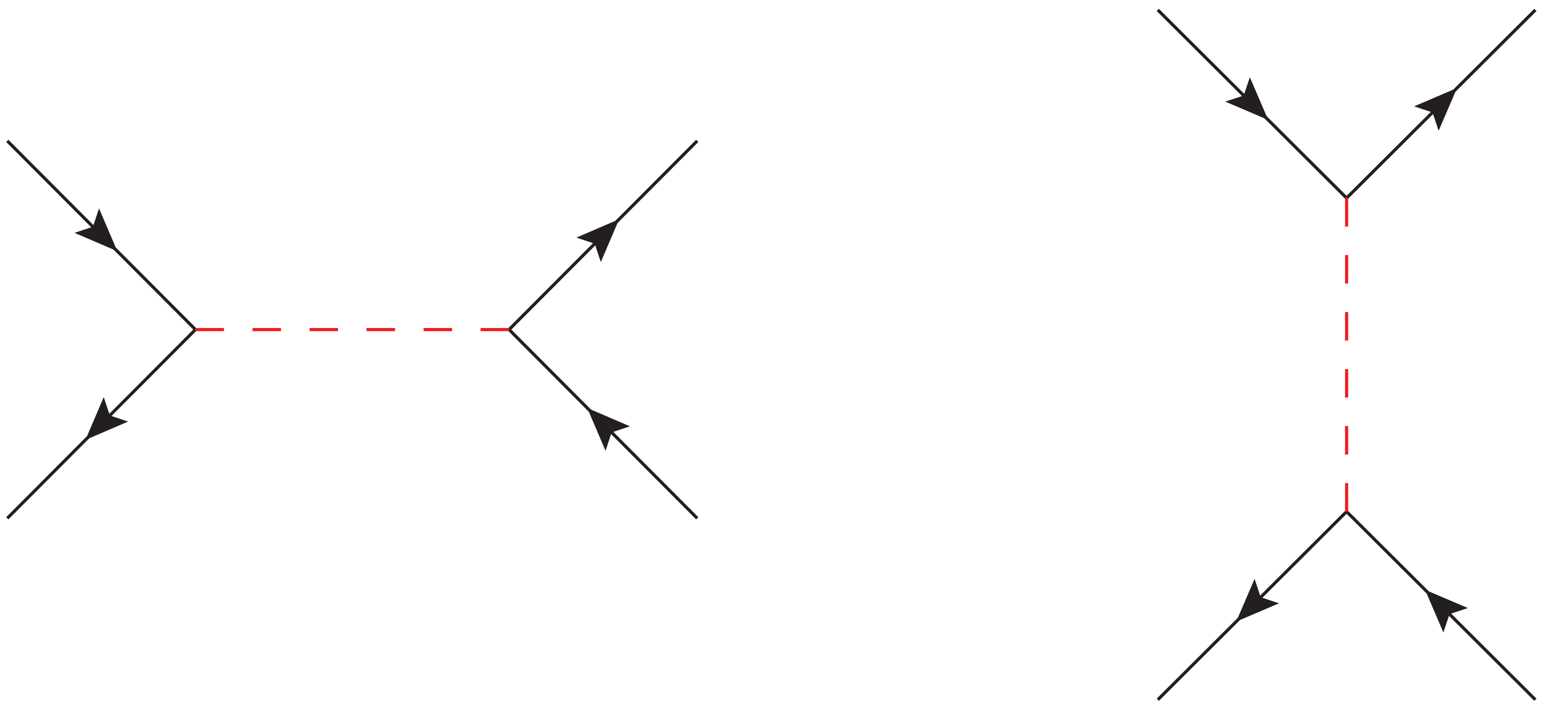
- no calculations beyond tree level required

- apply at any √s above threshold

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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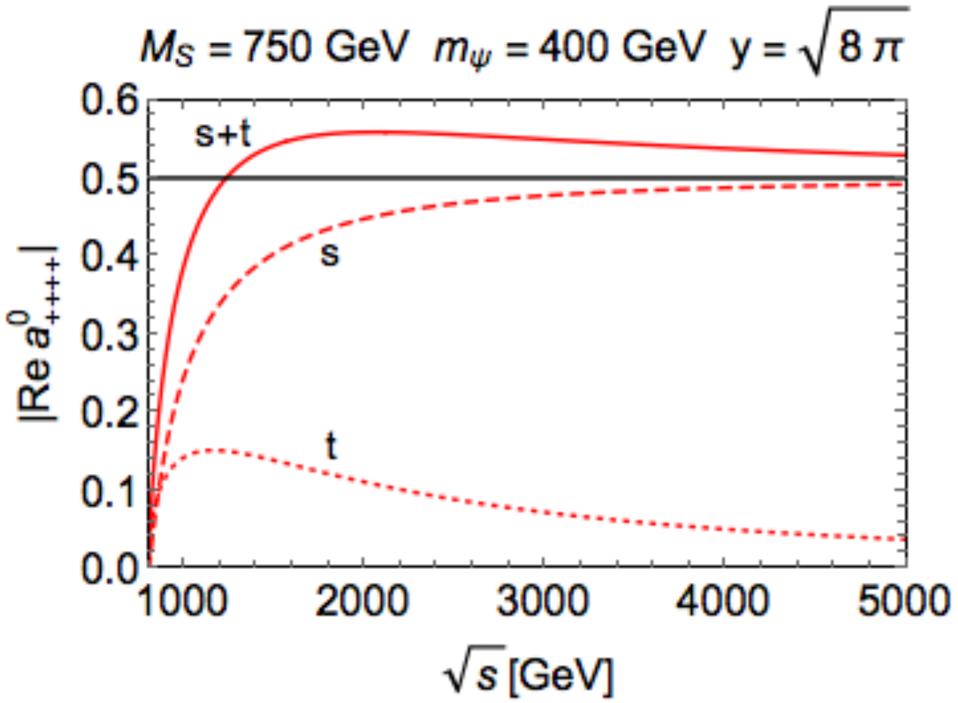

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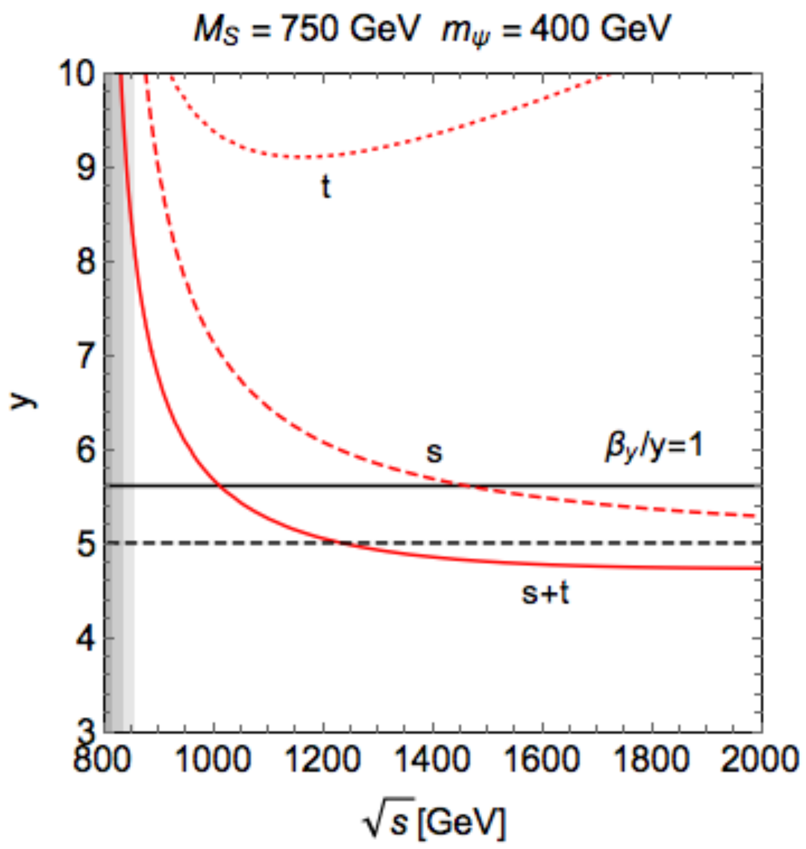
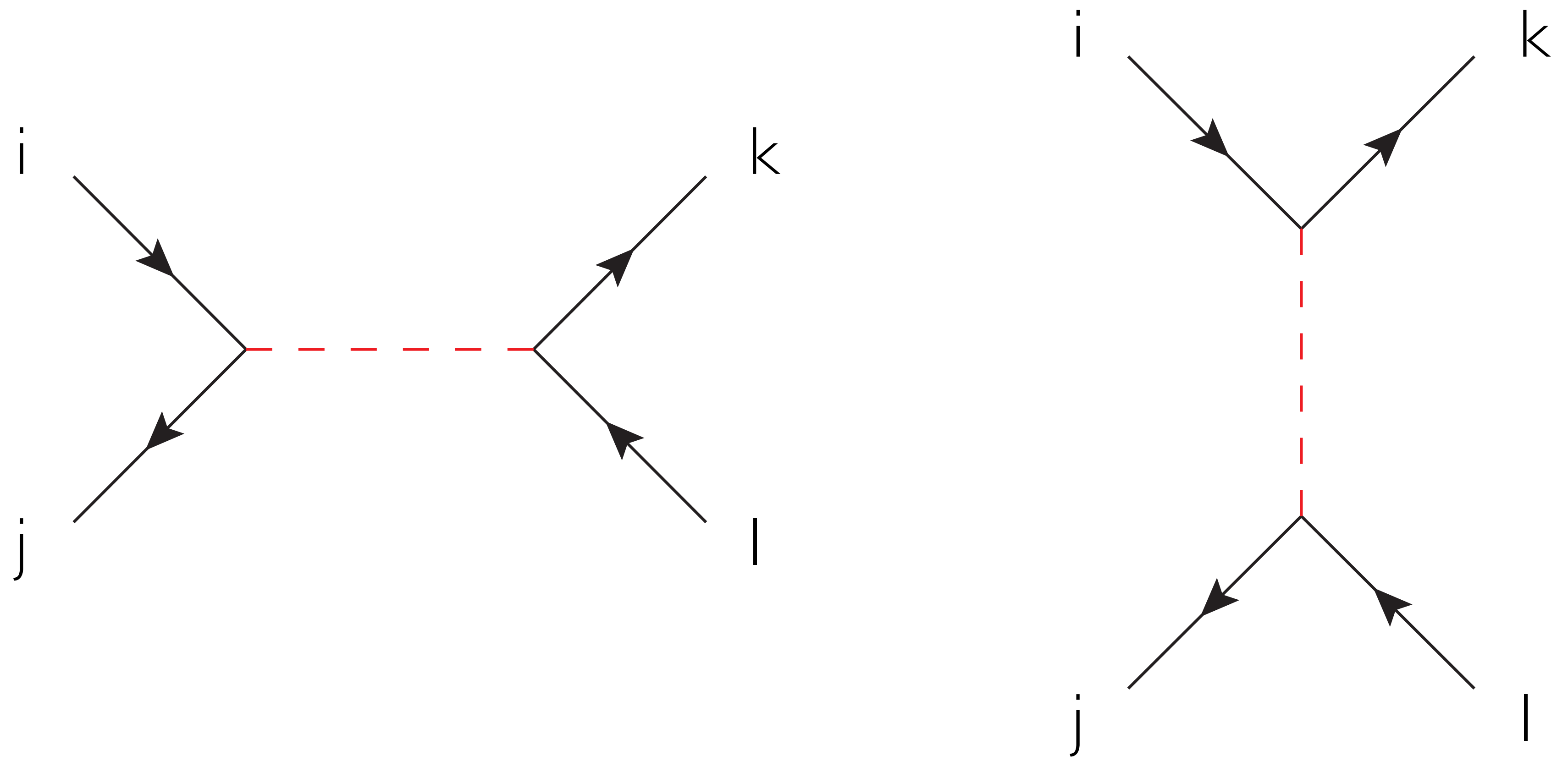


- O(1) agreement with beta function criterium $\frac{\beta_y}{y} = \frac{5y^2}{16\pi^2} < 1$ [1512.08500]

Generalization in flavor space

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

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



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

→ exploit U(N) global symmetry to label the irreducible sectors 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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↓

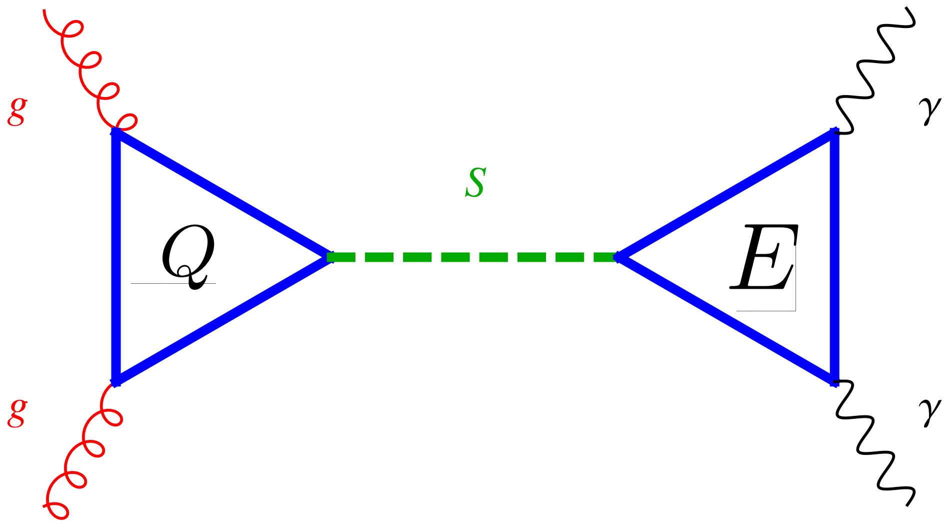
s-channel enhancement $y^2 \rightarrow N \, y^2$ ('t Hooft scaling)

Visualizing the bounds

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

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

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



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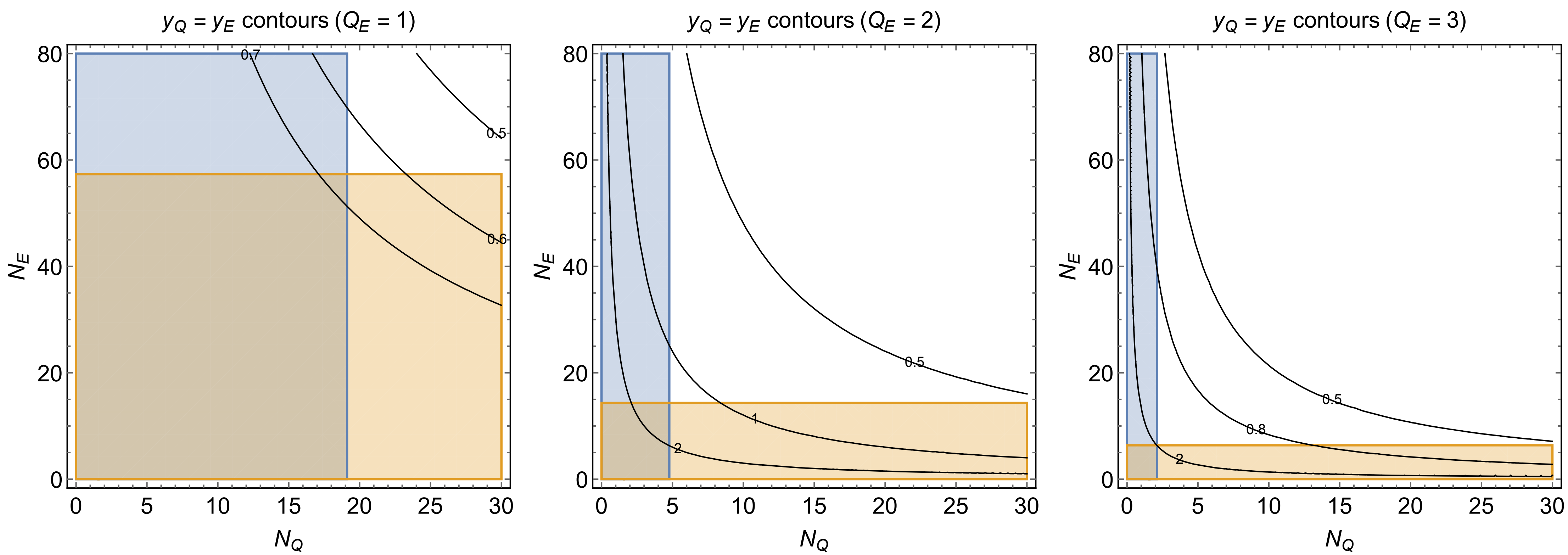
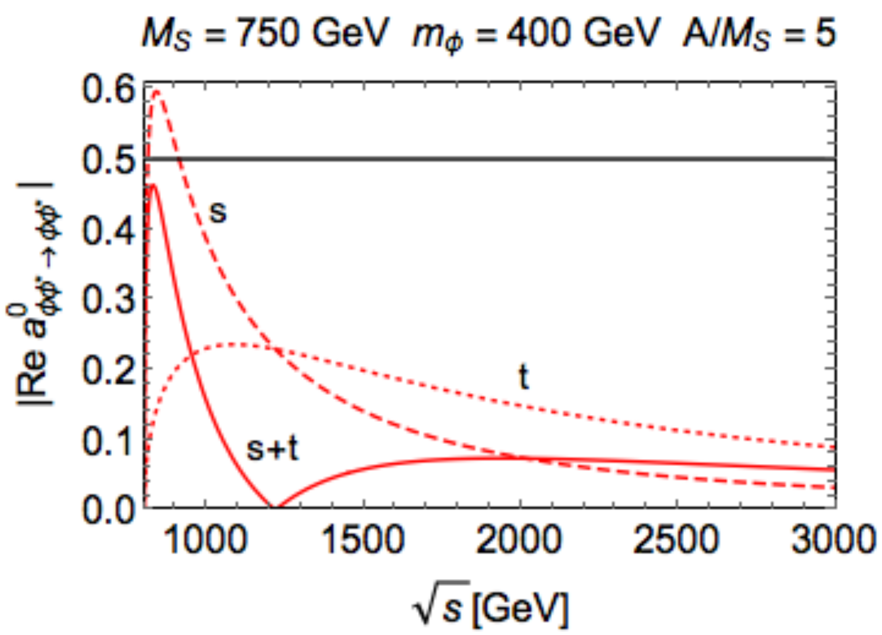


- Large width scenario → requires either exotic EM charges or very large N

Scalar mediators (gg initiated)

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

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



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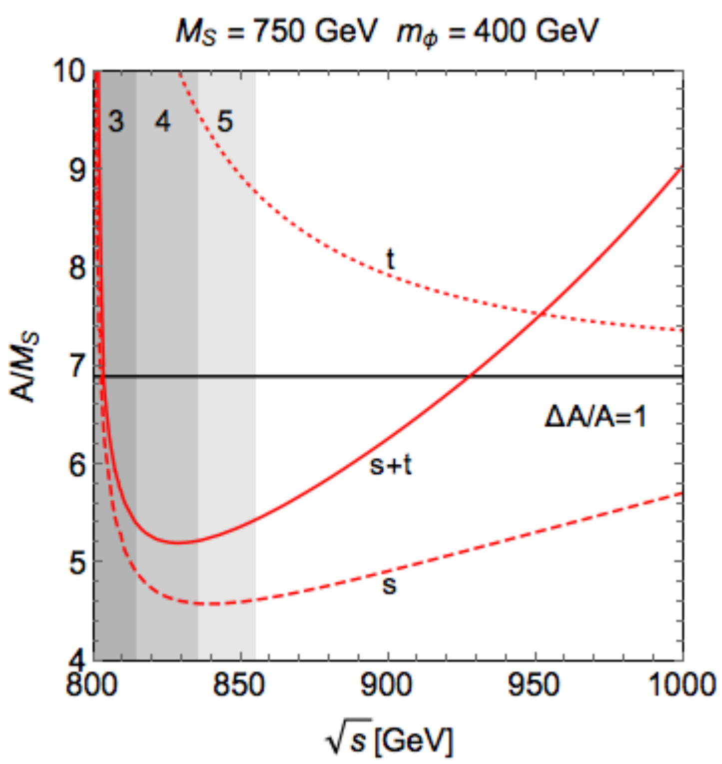

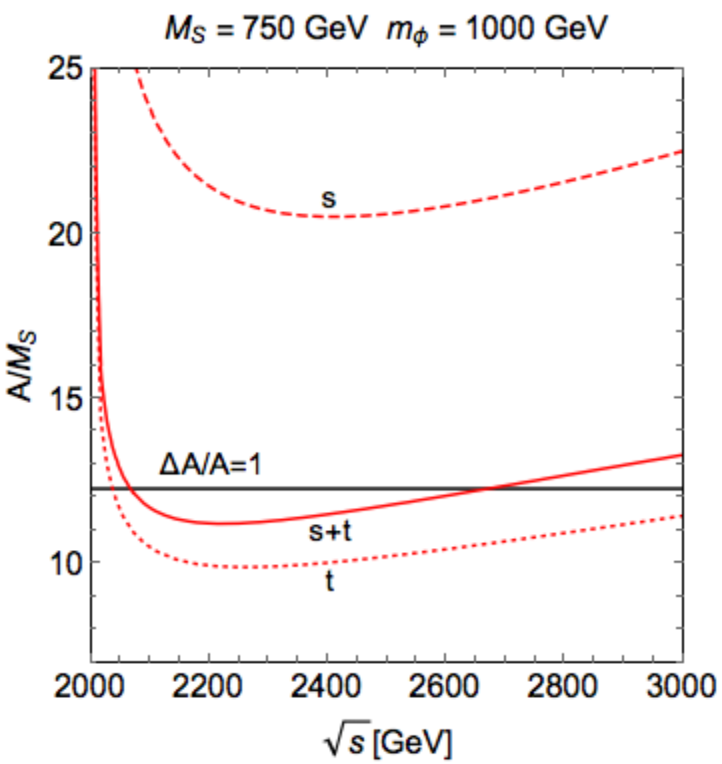

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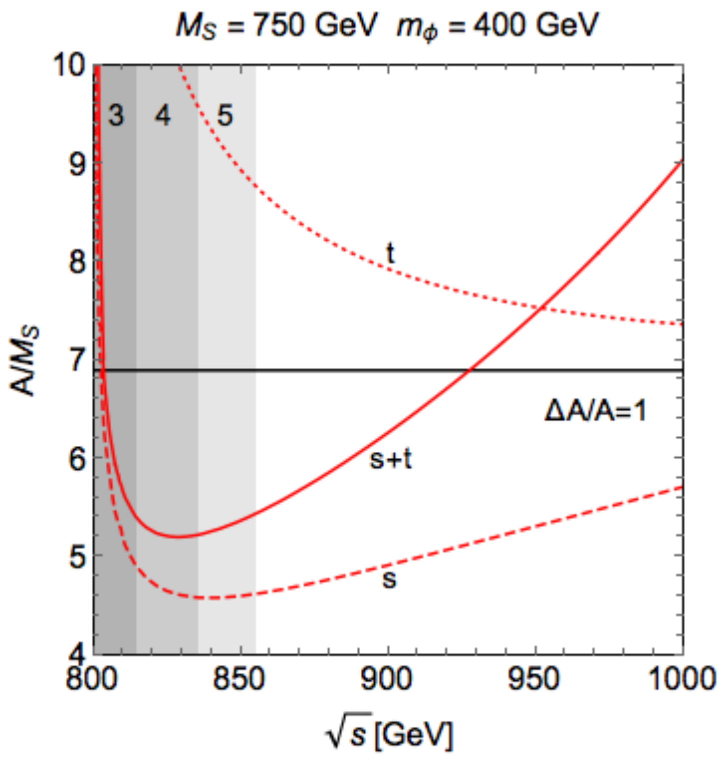


$$\frac{\left|\frac{i}{s-M_S^2}\right|^2 - \left|\frac{i}{s-M_S^2+iM_S\Gamma_S}\right|^2}{\left|\frac{i}{s-M_S^2}\right|^2} < \Delta$$

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

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

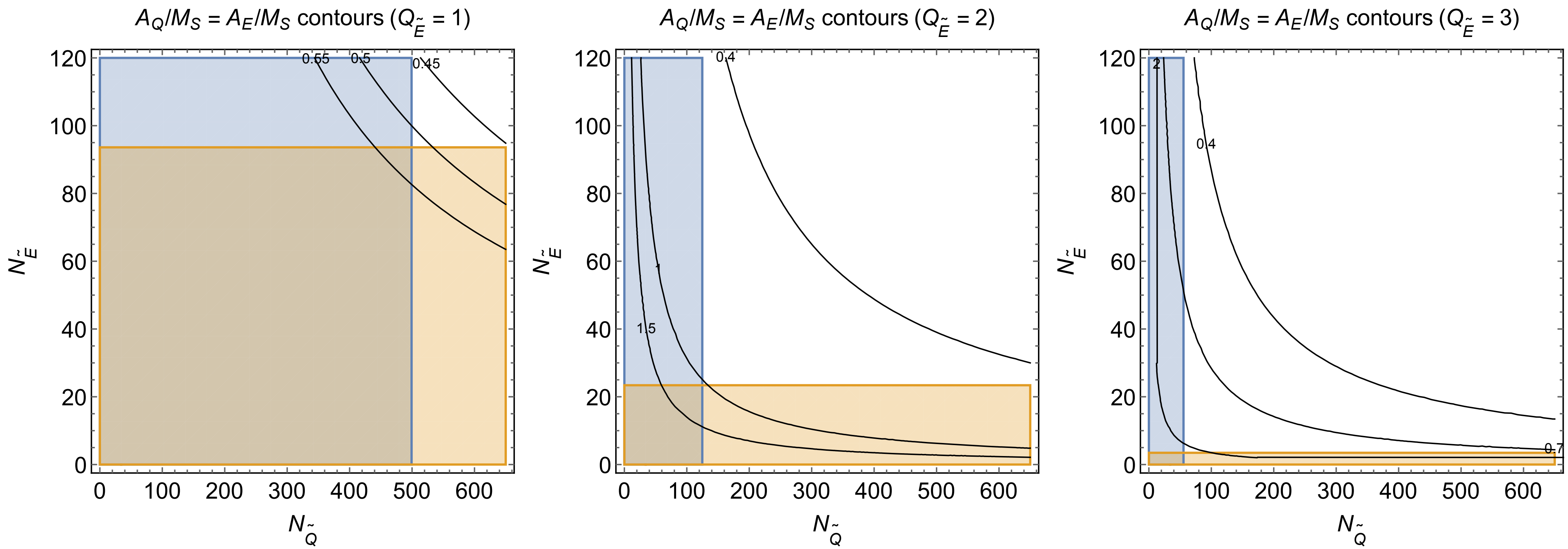
Visualizing the bounds (scalars)

- 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. $\mathcal{B} \sim (3, 1, -1/3)$

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

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

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

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

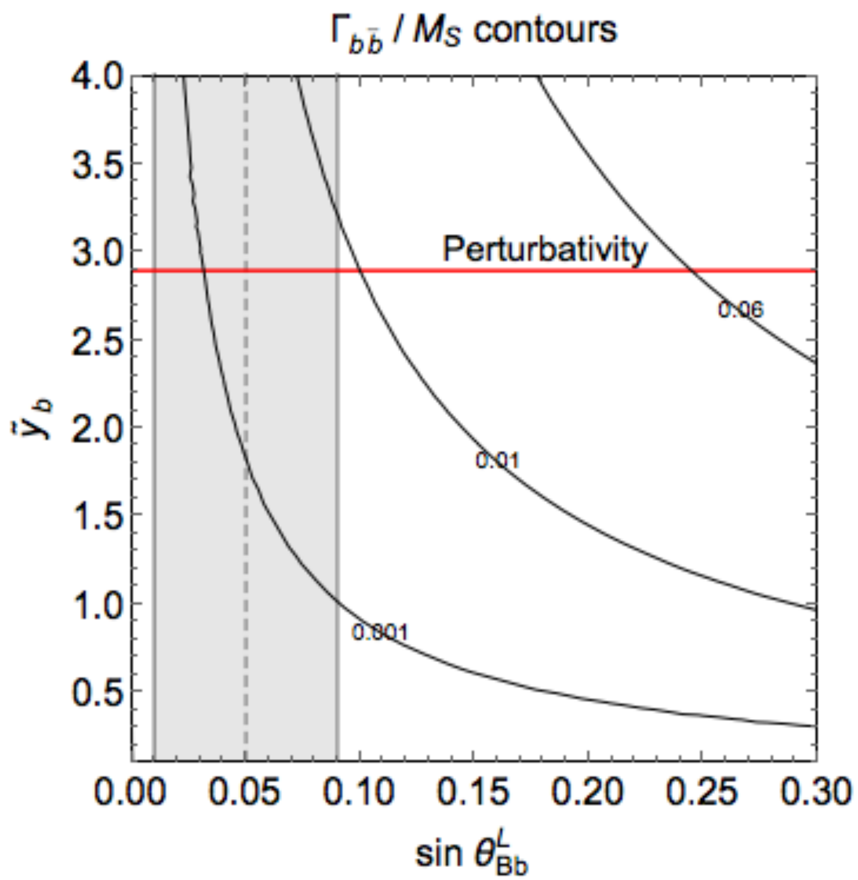
$$\sin\theta^L_{\mathcal{B}b} = 0.05(4)$$

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

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