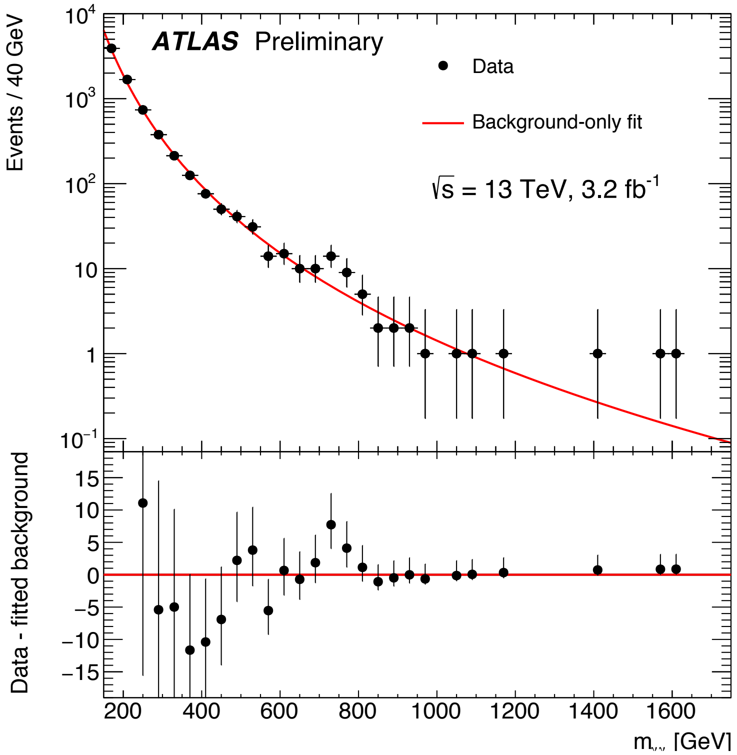
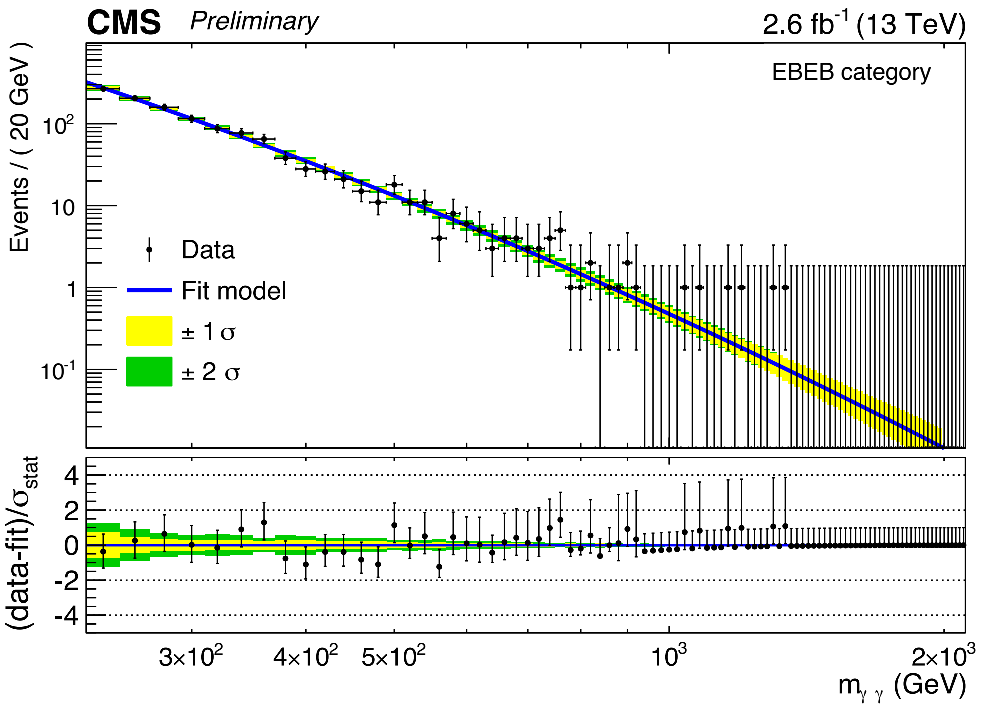
Di-photon at 750 GeV (A first read)

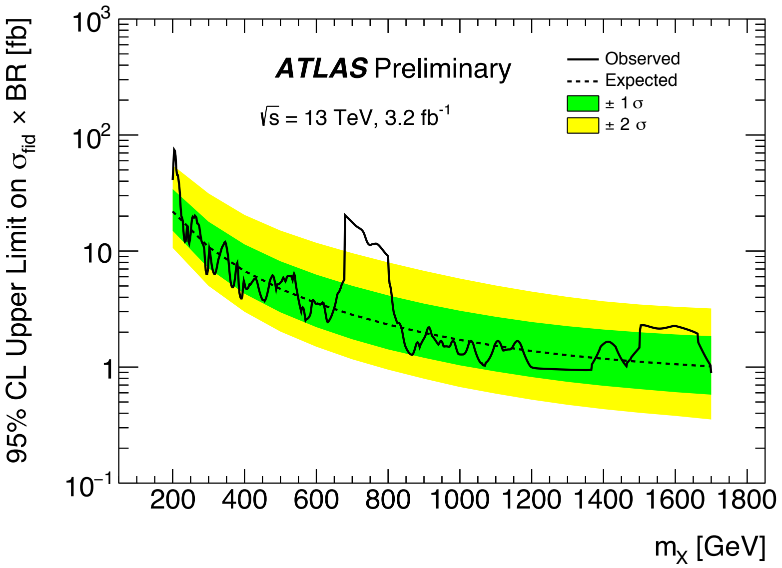
LianTao Wang

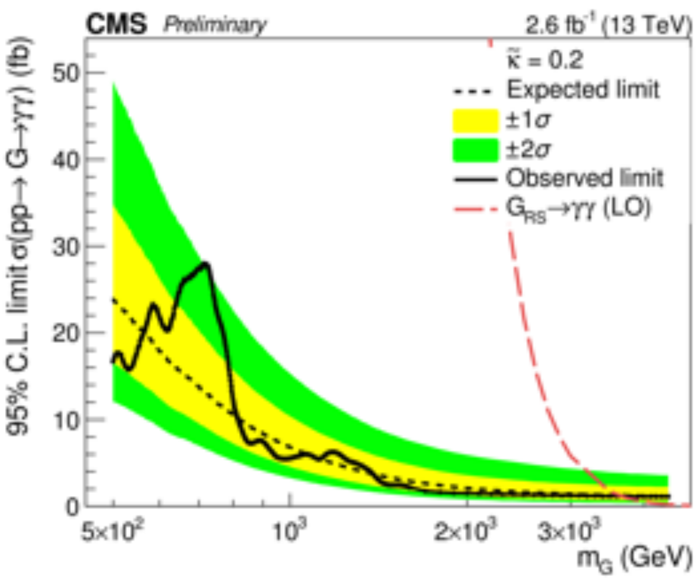
Jan 13. U. Chicago

Excess around 750 GeV?









$3.9\sigma(\text{local})$

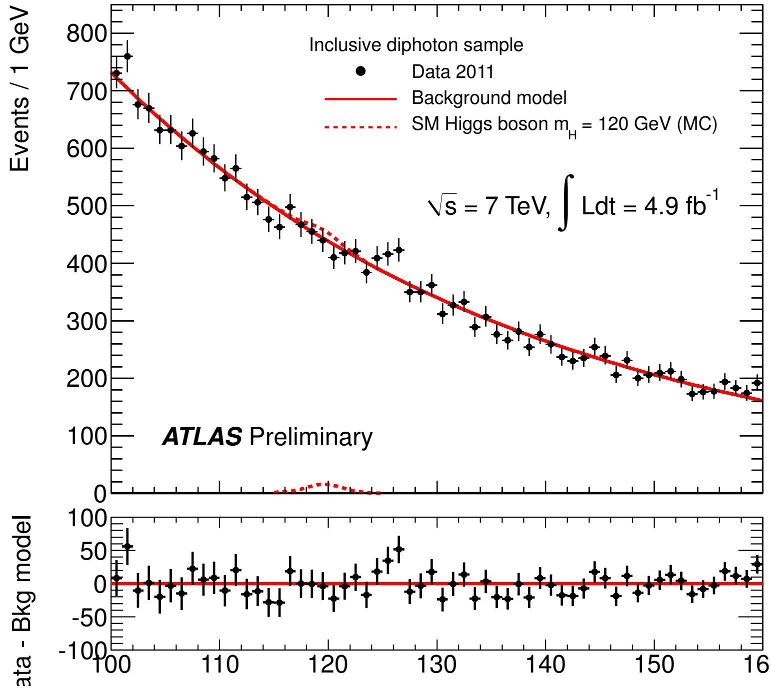
$2.3\sigma(\text{global})$

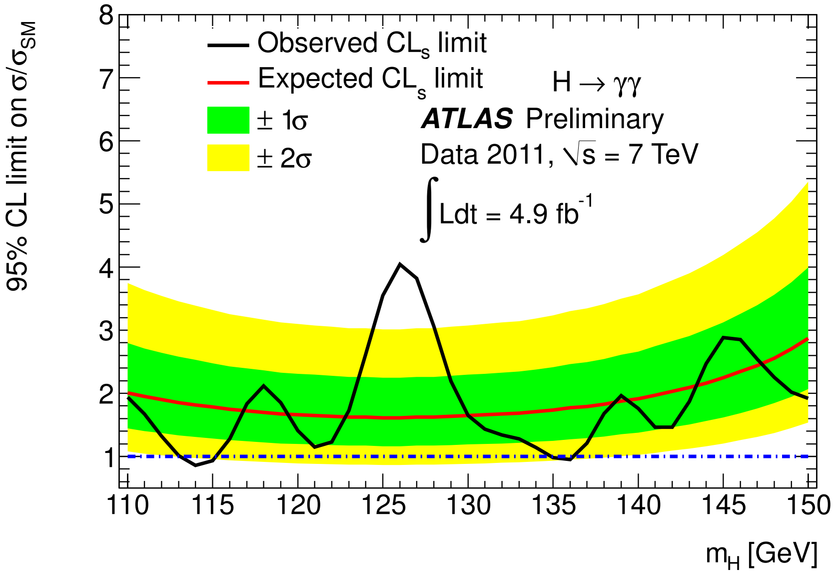
$3\sigma(\text{local})$

$1.7\sigma(\text{global})$

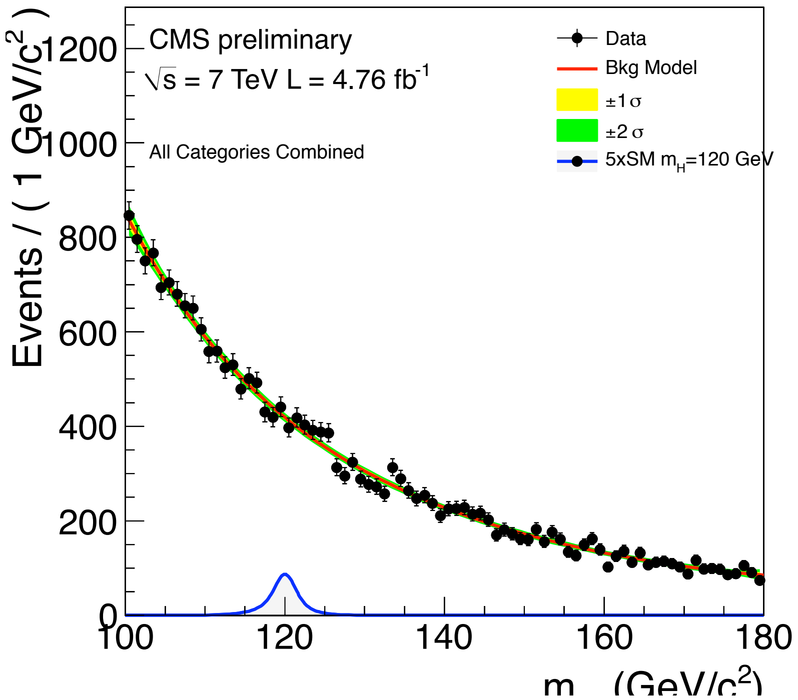
Certainly too early to claim victory. But, tantalizing…

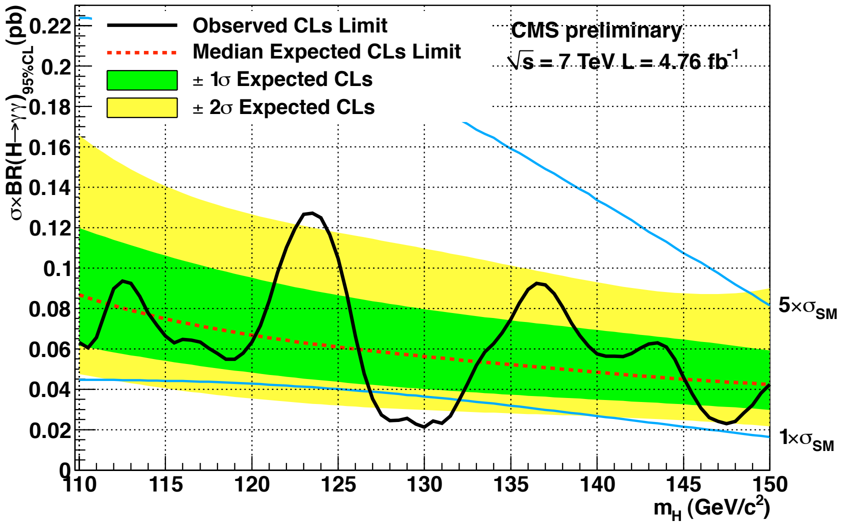
Exactly 4 years ago, $m_{\gamma\gamma} \approx 125$





$$2.8\sigma(\text{local})$$
$$1.5\sigma(\text{global})$$

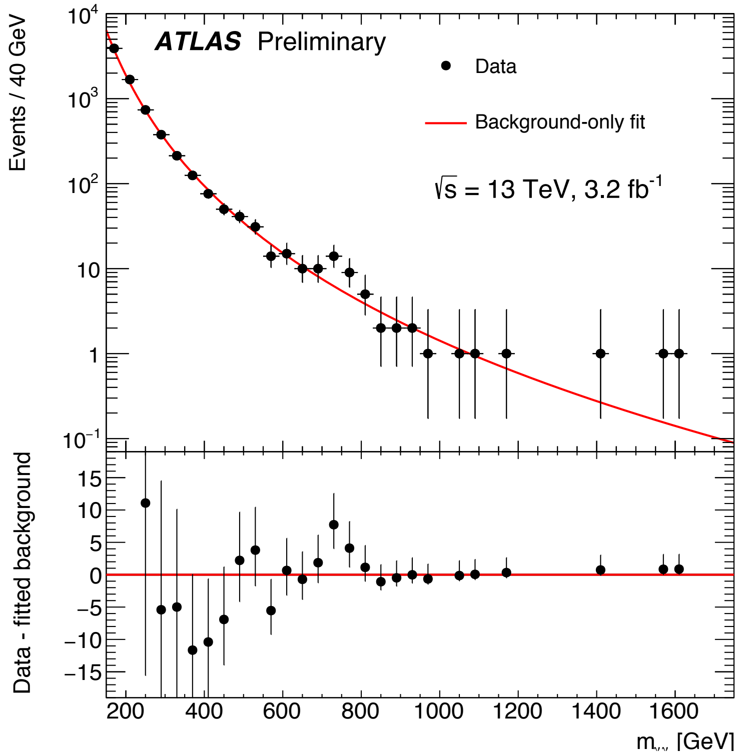


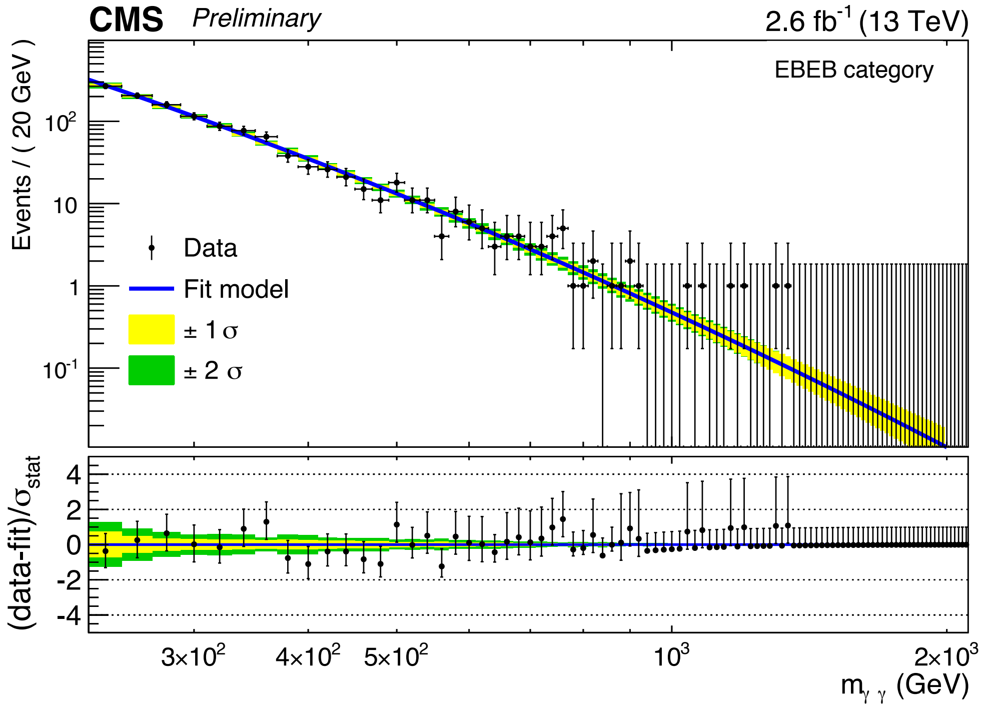


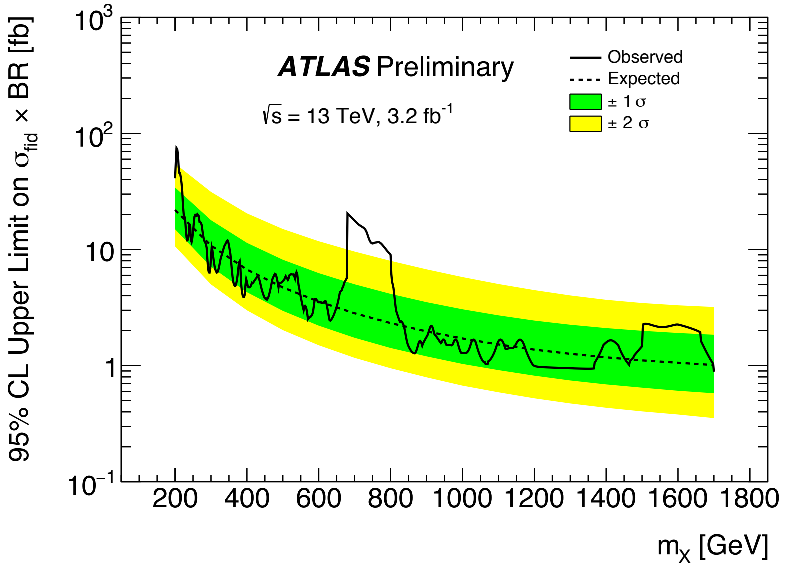
$$2.31\sigma(\text{local})$$
$$0.79\sigma(\text{global})$$

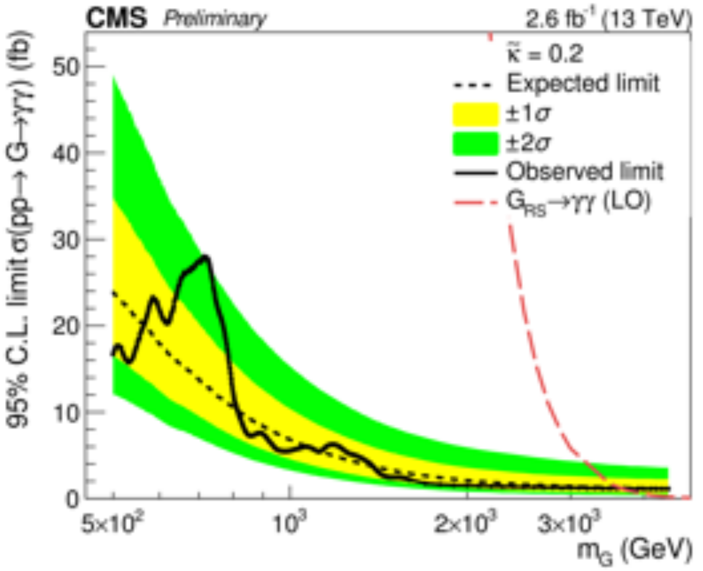
- There is some hope this time too?

Back to 750





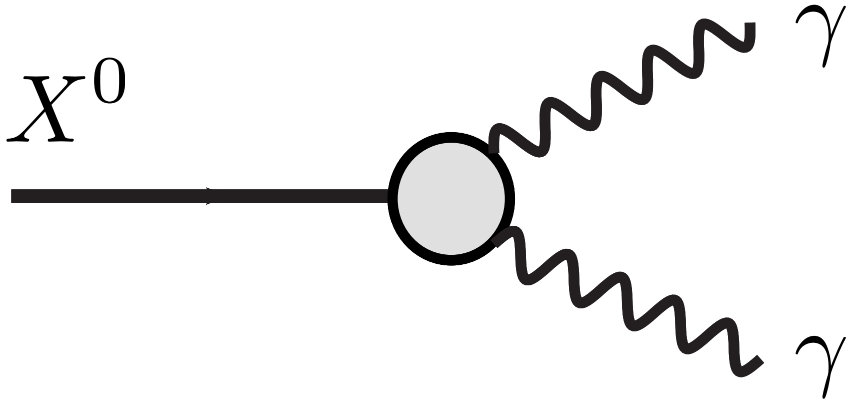




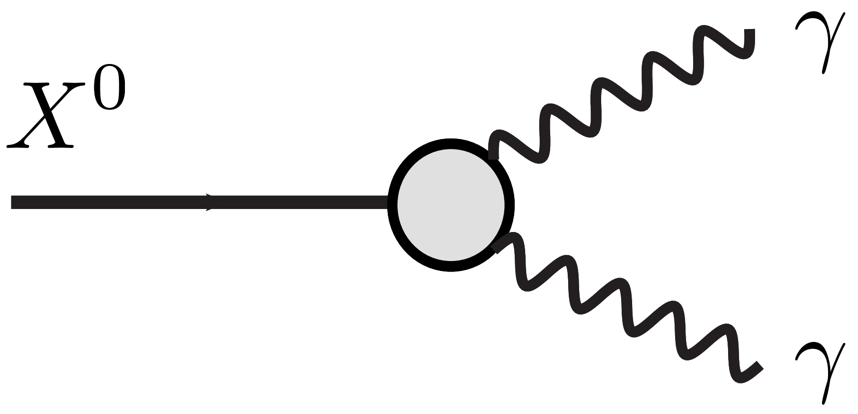
"signal rate": 4 fb?

Large. Same order as the SM Higgs to diphoton rate.

Di-photon resonance

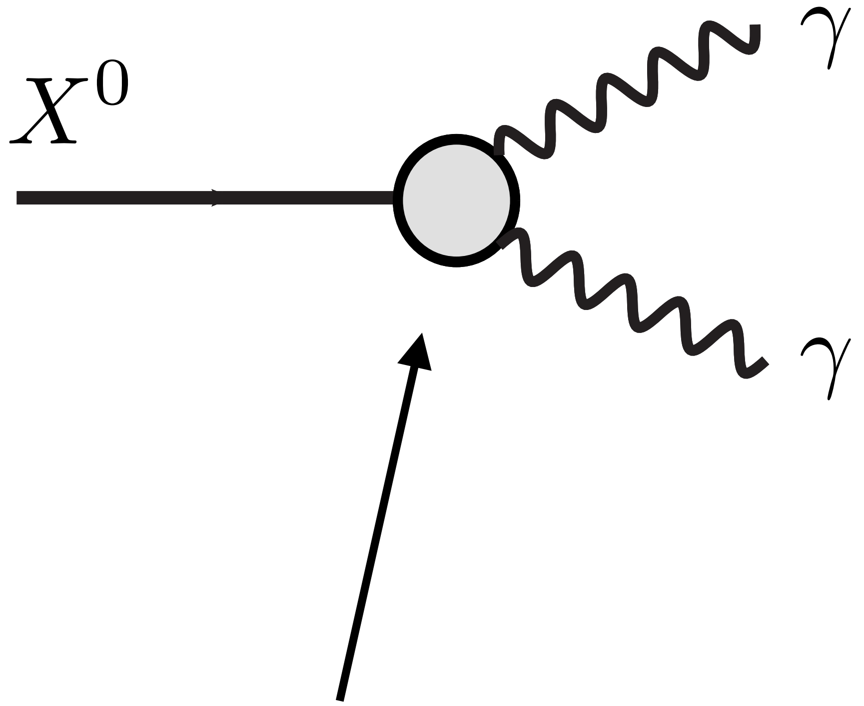


Di-photon resonance



- Can be spin 0 or 2.
  - Not spin-1. Landau-Yang theorem.
  - Completely identical to the argument of the 125 GeV di-photon resonance.
- Spin 0 is much more compelling than spin-2.
  - Very difficult to write down a complete model of spin-2.

How can neutral particle goes to photon, which only couples to charged particles



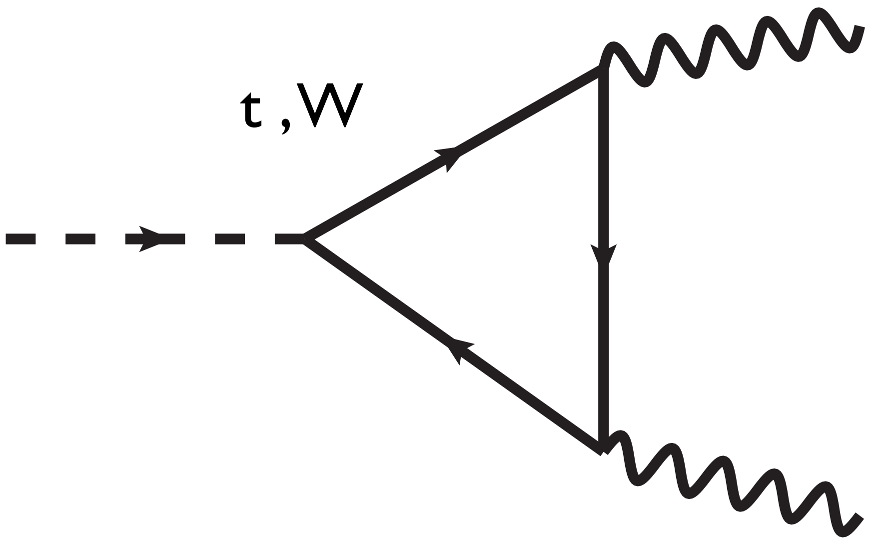
Must be charged particles here.

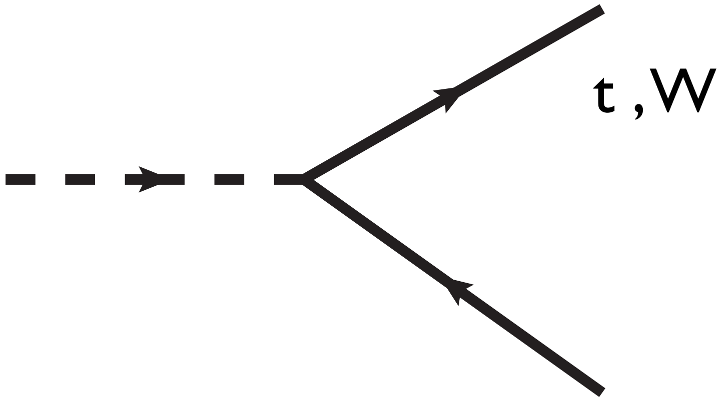
For the SM higgs, they are top quark and W boson

Can top and/or W do it for the X(750)?

No. Can not (just) be top or W.

750 GeV res. can not be alone.
Must have more new physics!!





- Say X couples to top and or W, with arbitrary coupling.
  - BR(di-photon) is less than 10^{-4}.
  - 4 fb to di-photon means 10s -100 pb to ttbar and or WW.
  - A factor of 4 or 5 in the production rates between 8 and 13 TeV.
  - ttbar and/or WW signal of at least pb at 8 TeV.

Possible to have pb(s) level tt or WW resonance at Run 1?

- No.

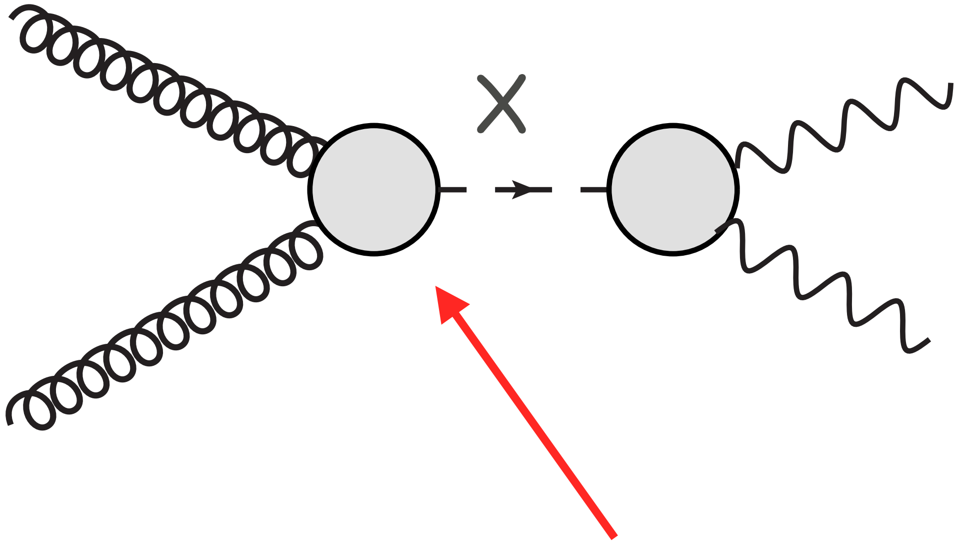
final state	700 GeV	750 GeV	
$t\bar{t}$ (narrow)	540 fb	450 fb	CMS [6]
$t\bar{t}$ (wide)	620 fb	520 fb	CMS [6]
WW $(\ell\nu jj)$	60 fb	70 fb	ATLAS [10]

- Must be more new physics in addition to the 750 GeV resonances!!

Production

- Unlikely from qqbar.
  - Suppressed by small quark masses, otherwise suffer from sever flavor constraints.

- Possibly (like the Higgs)



Need more new physics here as well, colored!

What kind of scalar?

- CP even, real scalar.
    - Typically will mix with the Higgs.
    - More constraining
    - Decays like Higgs with tiny BR to di-photon.
    - Difficult to work.
- CP odd, pseudo-scalar.
    - Much better candidate.

Pseudo-scalar (η) interaction

$$\mathcal{L}_{\rm int} = \frac{y_f}{\Lambda_f}\eta(i\overline{f_L}Hf_R + {\rm h.c.}) + \frac{c_B}{\Lambda_g}\frac{g'^2}{16\pi^2}\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_W}{\Lambda_g}\frac{g^2}{16\pi^2}\eta W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{c_g}{\Lambda_g}\frac{\alpha_s}{4\pi}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Pseudo-scalar (η) interaction

with SM top

$$\mathcal{L}_{\text{int}} = \boxed{\frac{y_f}{\Lambda_f}\eta(i\overline{f_L}Hf_R + \text{h.c.})} + \frac{c_B}{\Lambda_g}\frac{g'^2}{16\pi^2}\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_W}{\Lambda_g}\frac{g^2}{16\pi^2}\eta W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{c_g}{\Lambda_g}\frac{\alpha_s}{4\pi}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Pseudo-scalar (η) interaction

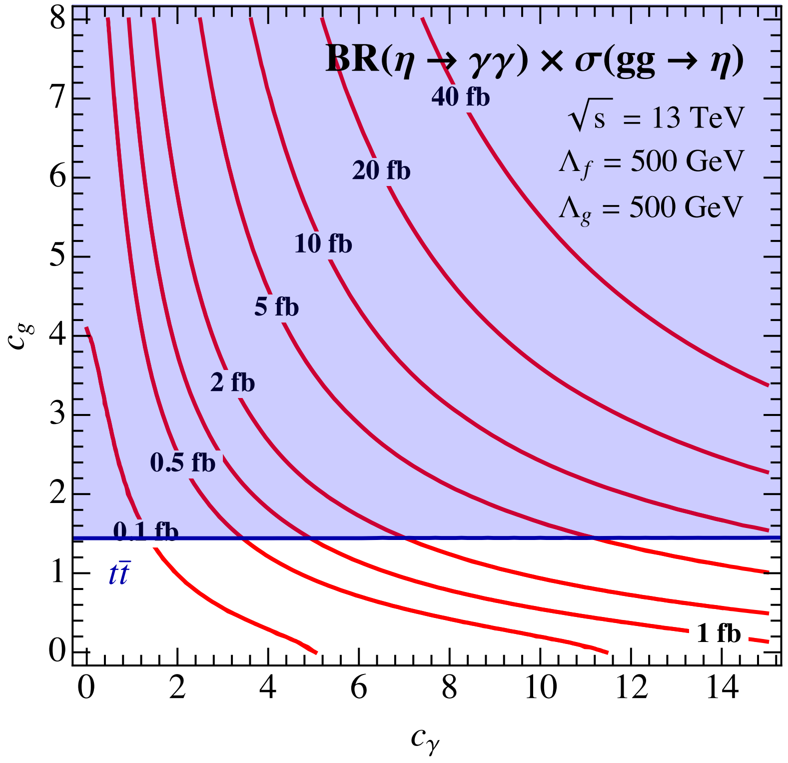
$$\mathcal{L}_{\rm int} = \overbrace{\frac{y_f}{\Lambda_f}\eta(i\overline{f_L}Hf_R + {\rm h.c.})}^{\text{with SM top}} + \overbrace{\frac{c_B}{\Lambda_g}\frac{g'^2}{16\pi^2}\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_W}{\Lambda_g}\frac{g^2}{16\pi^2}\eta W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{c_g}{\Lambda_g}\frac{\alpha_s}{4\pi}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu}}^{\text{anomaly-like}}$$

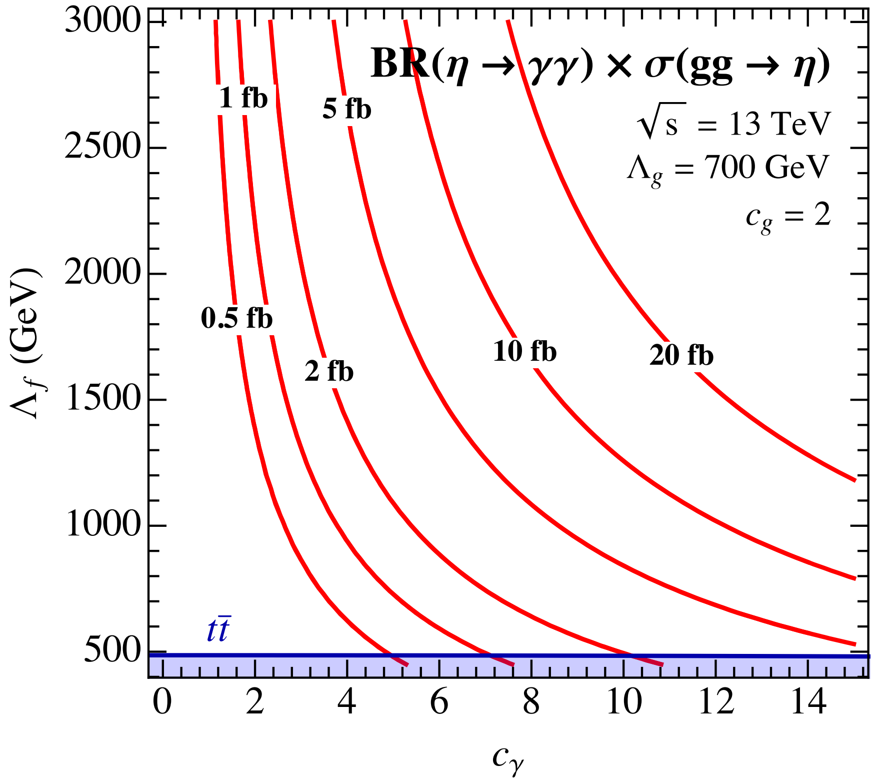
Pseudo-scalar (η) interaction

with SM top

anomaly-like

$$\mathcal{L}_{\rm int} = \frac{y_f}{\Lambda_f}\eta(i\overline{f_L}Hf_R + \text{h.c.}) + \frac{c_B}{\Lambda_g}\frac{g'^2}{16\pi^2}\eta B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{c_W}{\Lambda_g}\frac{g^2}{16\pi^2}\eta W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{c_g}{\Lambda_g}\frac{\alpha_s}{4\pi}\eta G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

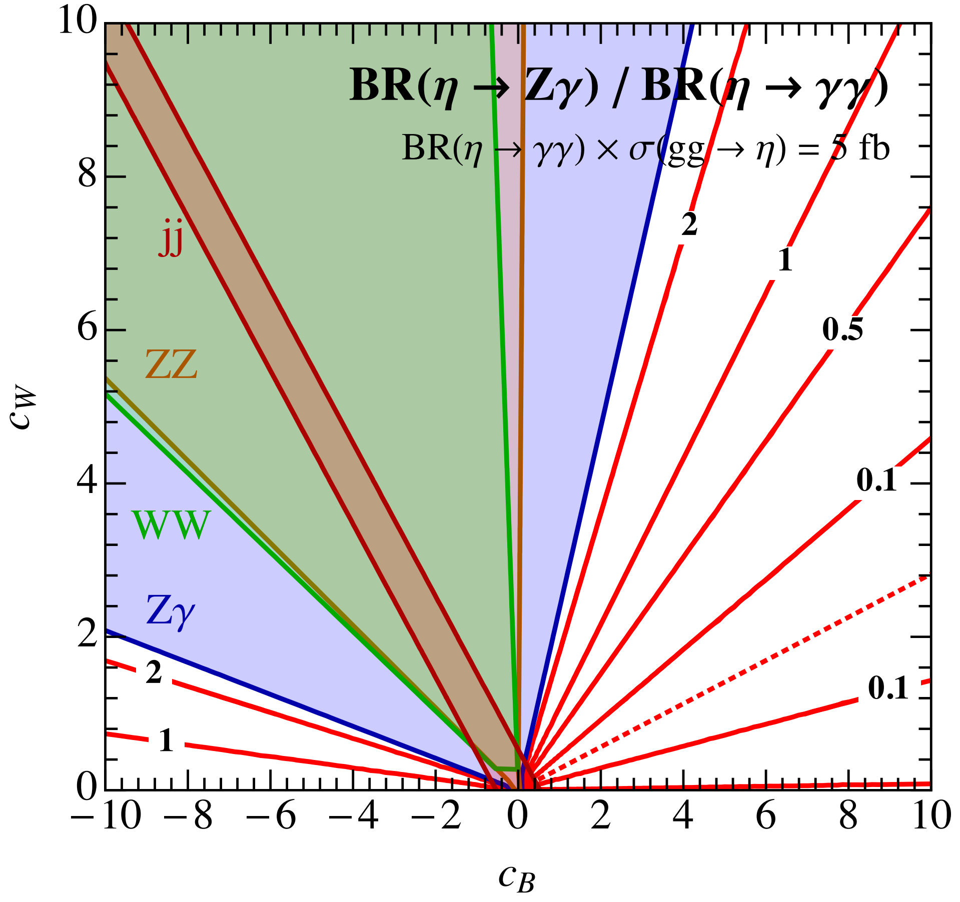


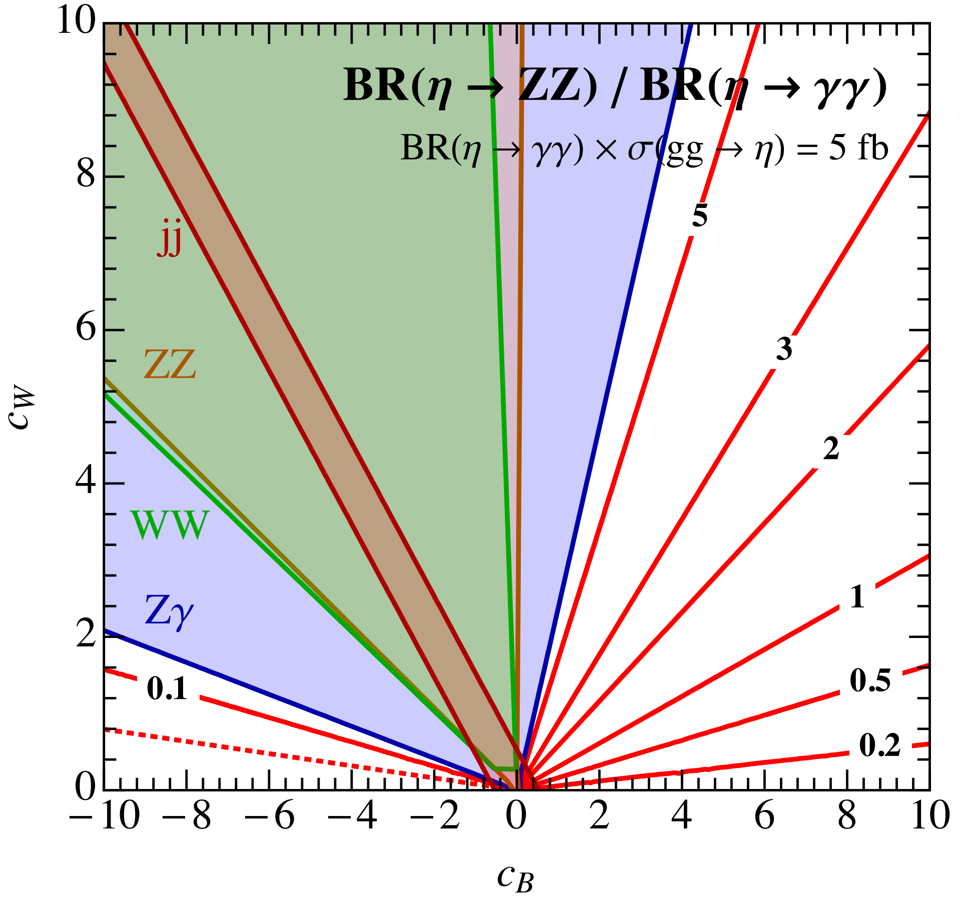


M. Low, A. Tesi, LTW

- Need anomaly contribution for large di-photon BR.
- Will have $Z\gamma$ and ZZ.

Zγ, ZZ the next things to look for



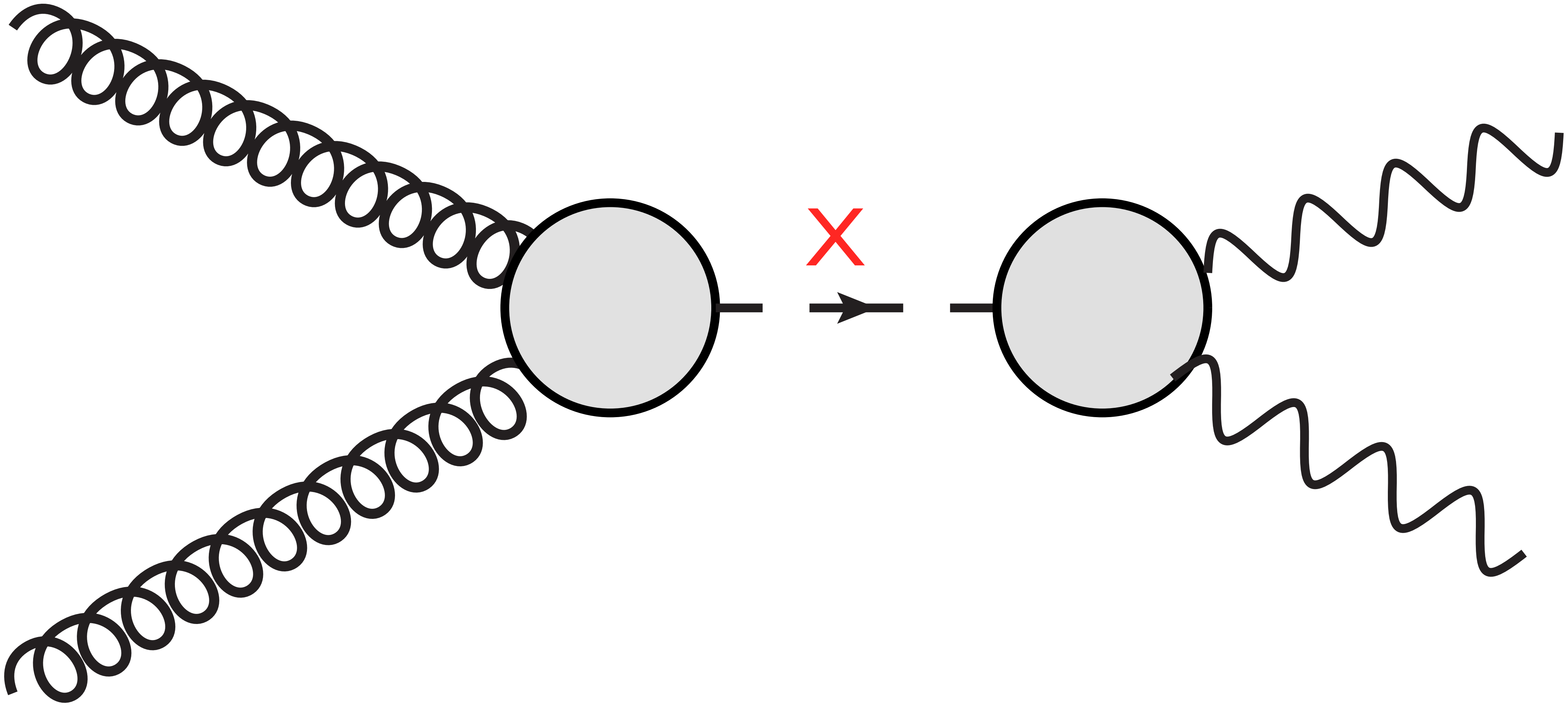


- Also WW, ttbar, hh.

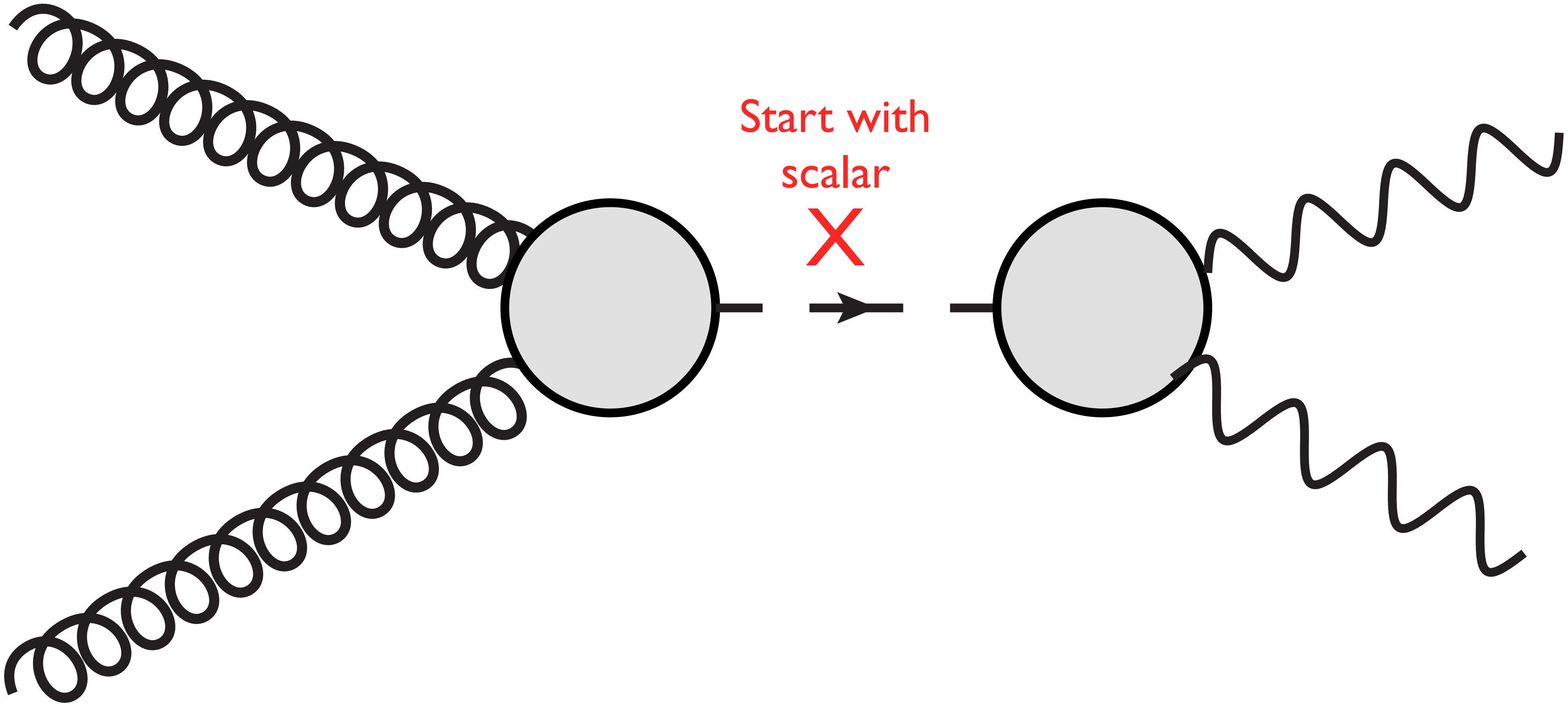
- And everything under 750

NP models

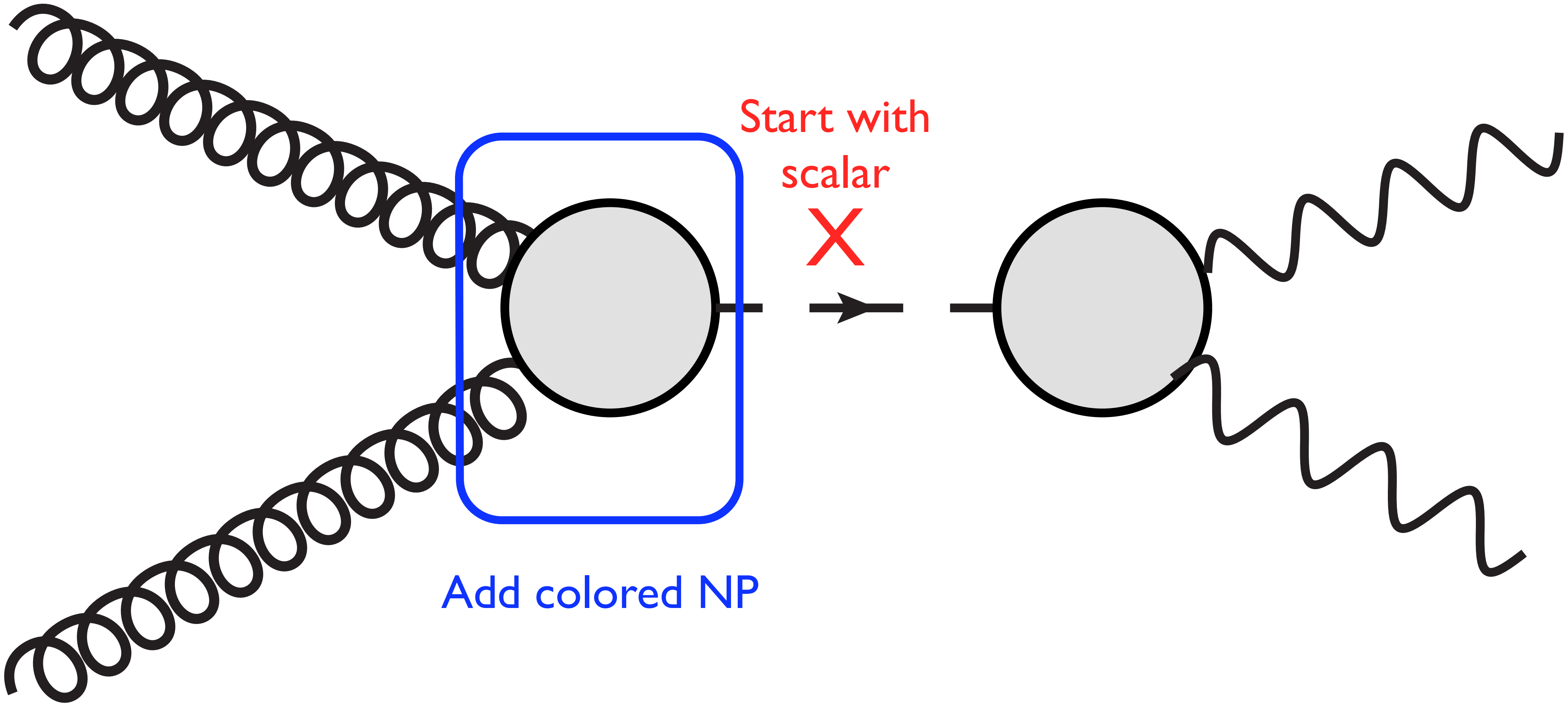
“Simplified” models



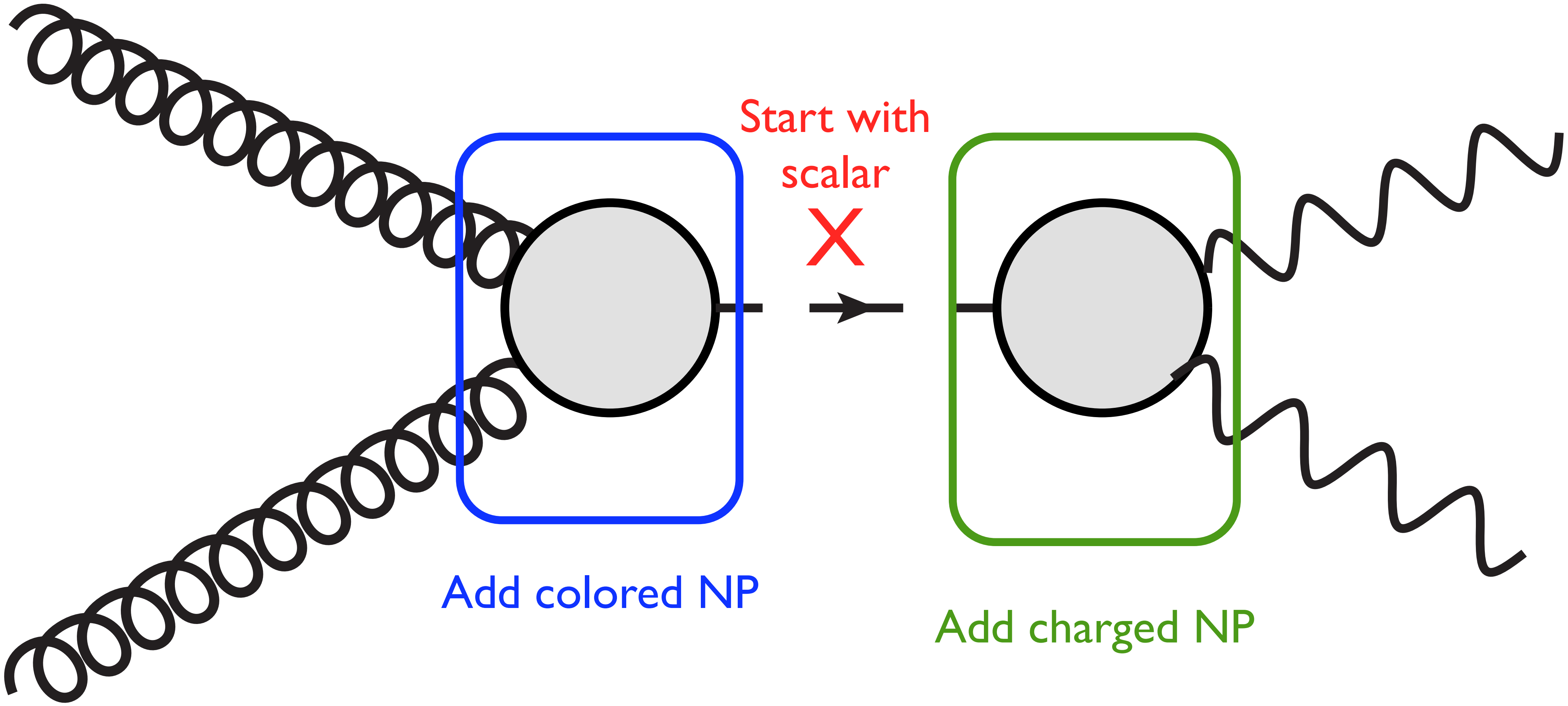
“Simplified” models



“Simplified” models



“Simplified” models



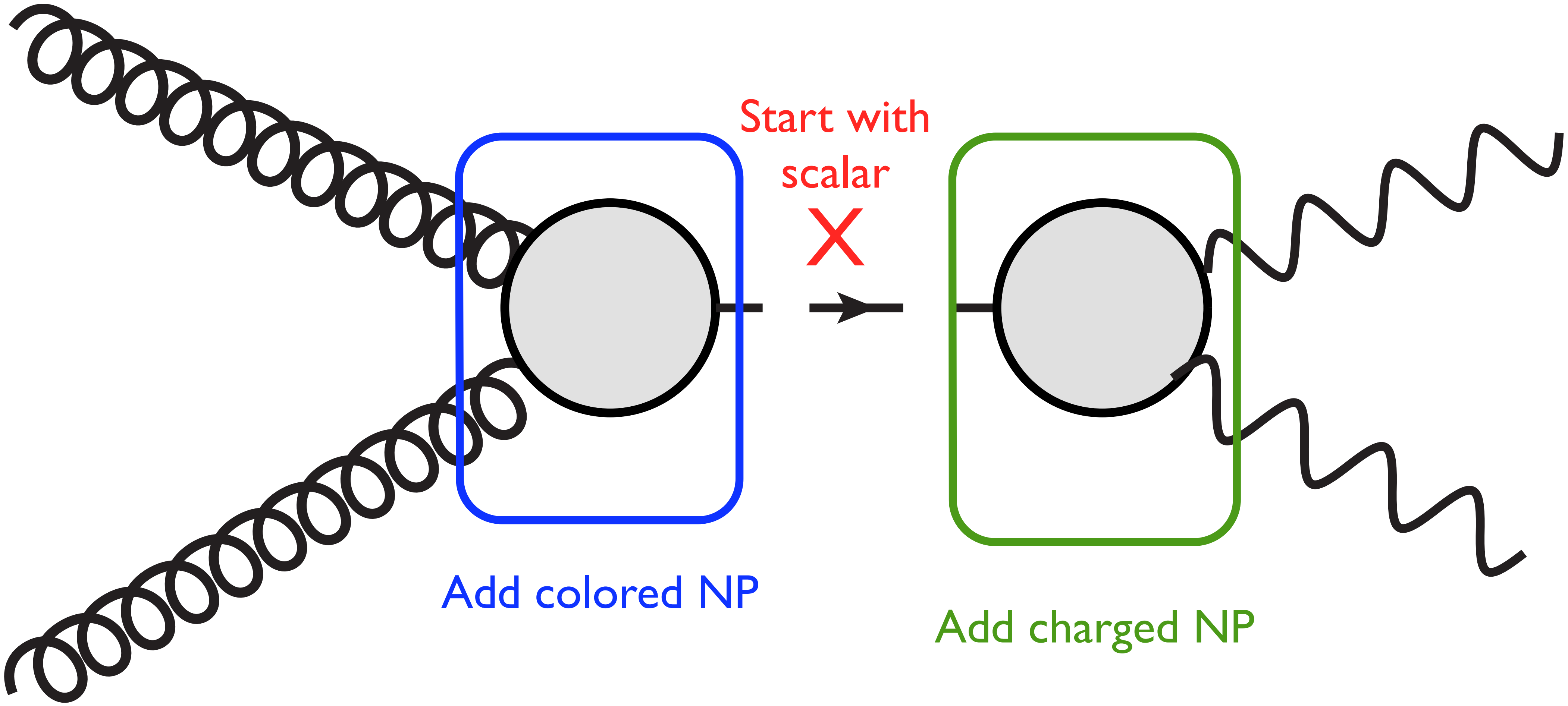
Start with scalar

X

Add colored NP

Add charged NP

“Simplified” models



Start with scalar

X

Add colored NP

Add charged NP

$M_{NP} > 0.5\ M_X.$

Vector like fermions.

Mass, why 750 GeV scalar?

Mass, why 750 GeV scalar?

- We are already puzzled by m_h (125), naturalness problem.

Mass, why 750 GeV scalar?

- We are already puzzled by m_h (125), naturalness problem.

- Now another (pseudo)scalar?
  - Can make things much worse.
  - Not controlling weak scale masses in an obvious way. Even landscape may not help.

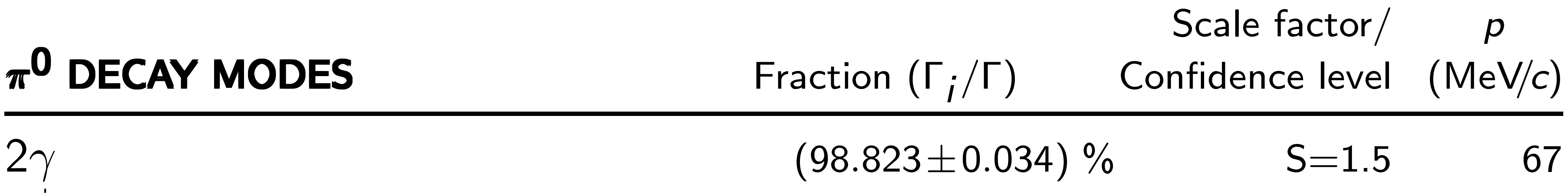
Mass, why 750 GeV scalar?

- We are already puzzled by m_h (125), naturalness problem.

- Now another (pseudo)scalar?
  - Can make things much worse.
  - Not controlling weak scale masses in an obvious way. Even landscape may not help.

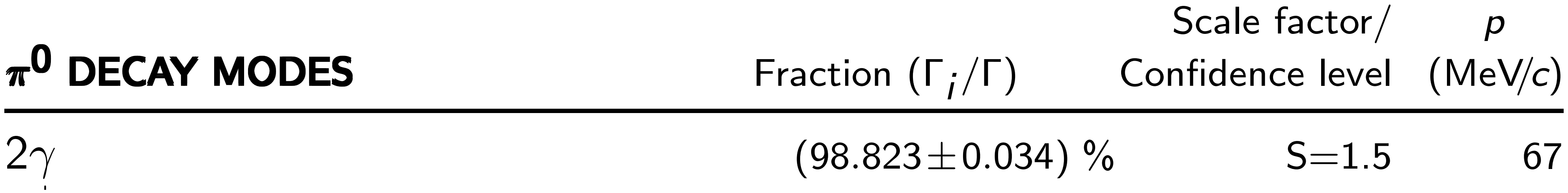
- However, the 750 GeV pseudo-scalar may be the first hint of a natural theory.

Take a page from SM



π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67

Take a page from SM



π^0 **DECAY MODES**	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67

- “π^0” of a new QCD?

- Will have many other “mesons” (typically 10s), will carry SM quantum numbers (colored, etc).

Take a page from SM

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67

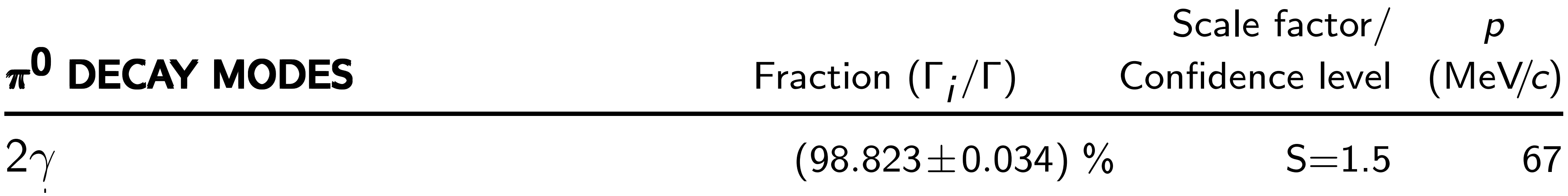
- "π^0" of a new QCD?
- Will have many other "mesons" (typically 10s), will carry SM quantum numbers (colored, etc).

Λ=10 TeV : new gluon and quarks

TeV(s), resonances

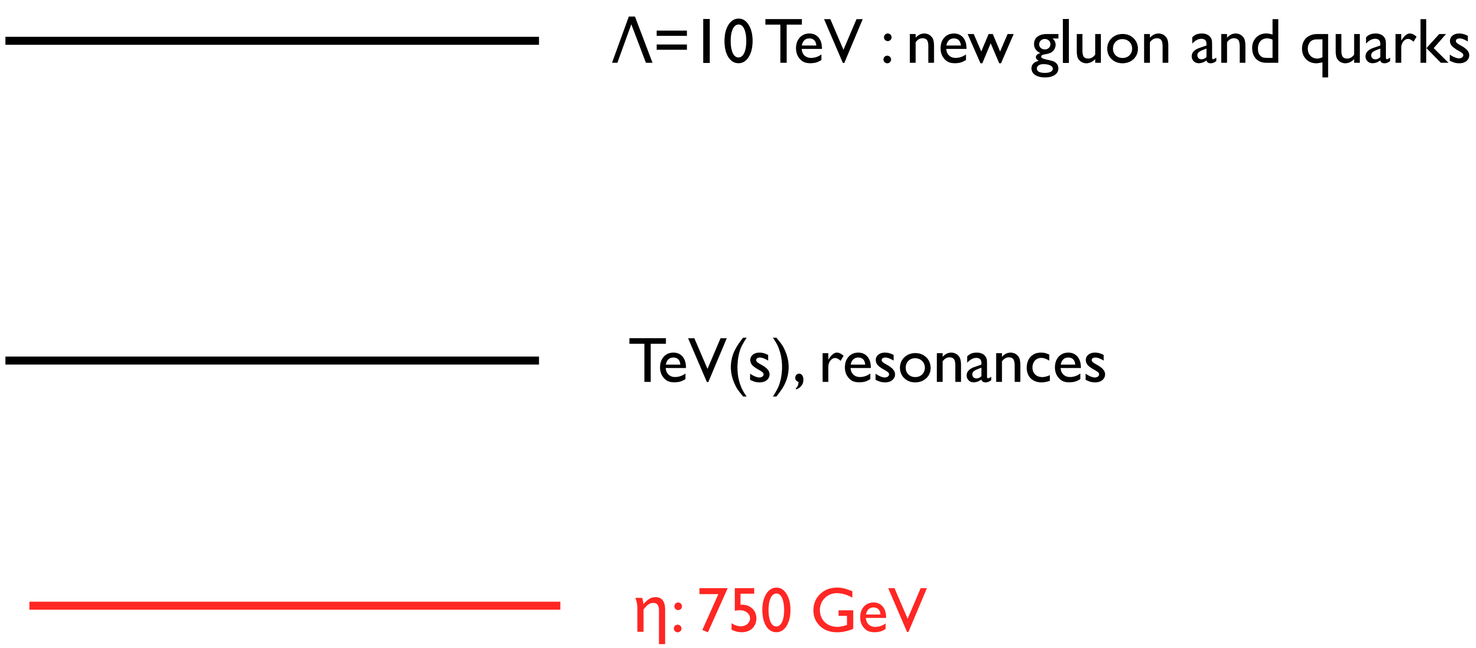
η: 750 GeV

Take a page from SM



π^0 **DECAY MODES**	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67

- "π^0" of a new QCD?
- Will have many other "mesons" (typically 10s), will carry SM quantum numbers (colored, etc).



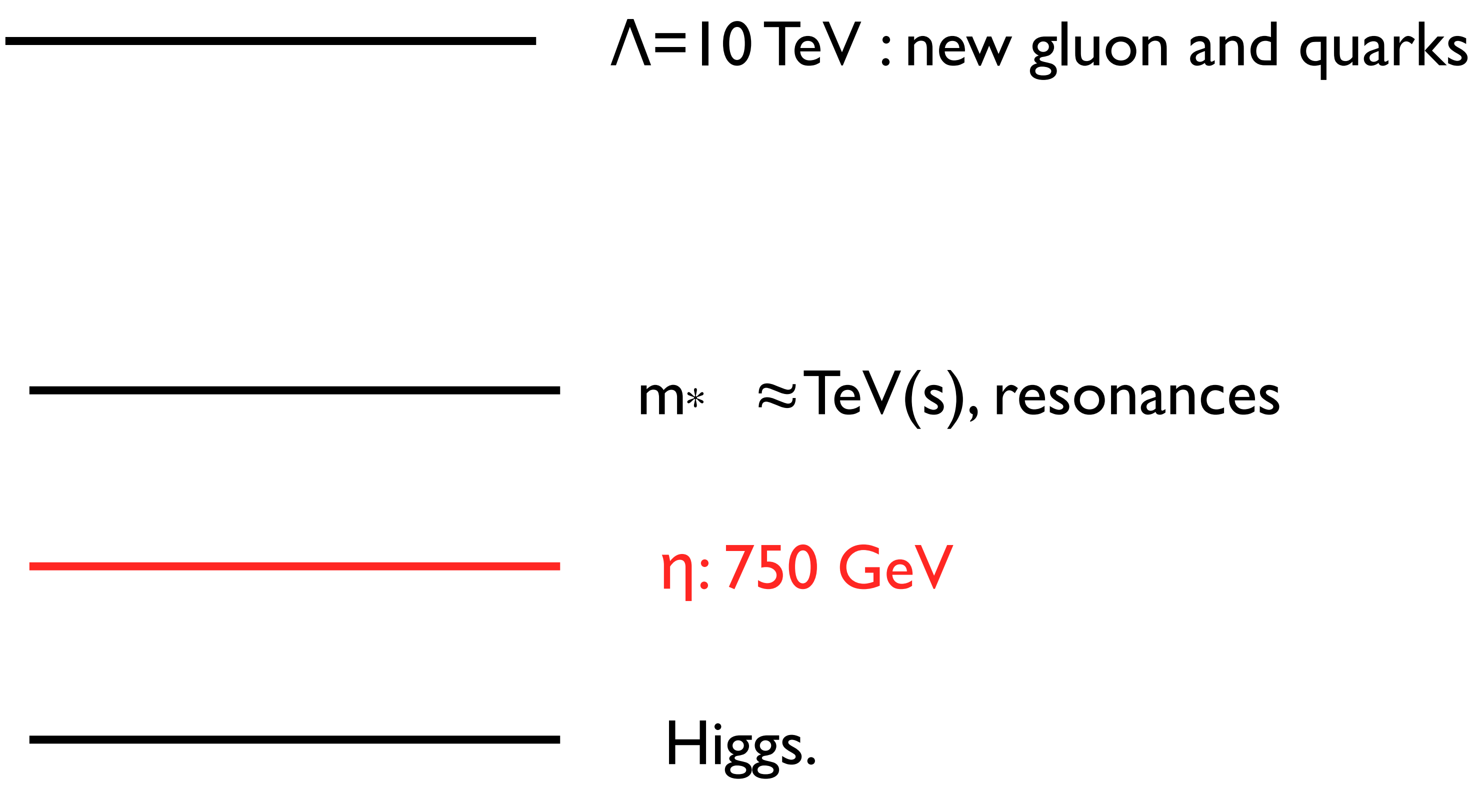
Λ=10 TeV : new gluon and quarks

TeV(s), resonances

η: 750 GeV

Natural. But mass no relation with weak scale.

Composite Higgs



Λ=10 TeV : new gluon and quarks

m* ≈TeV(s), resonances

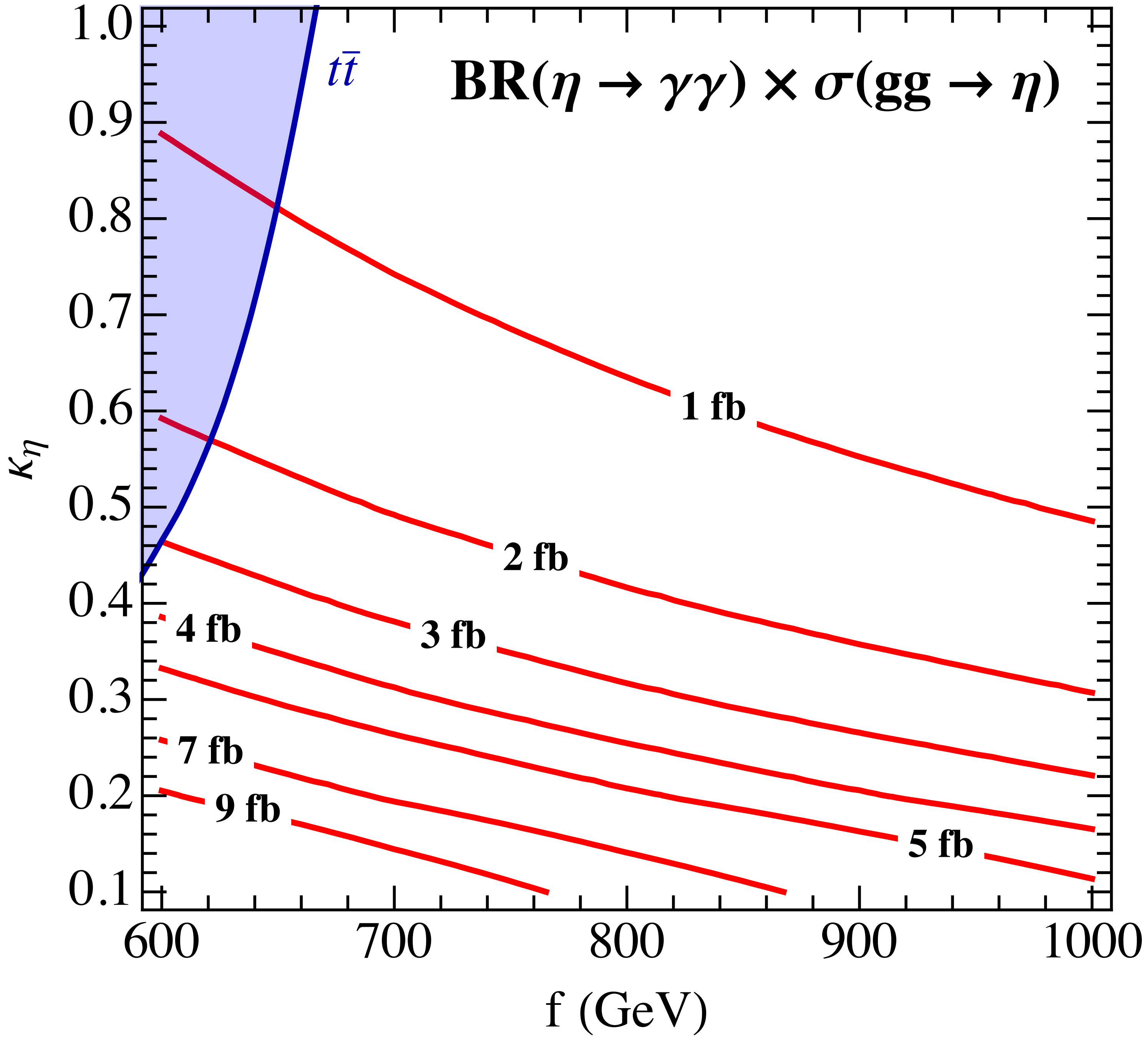
η: 750 GeV

Higgs.

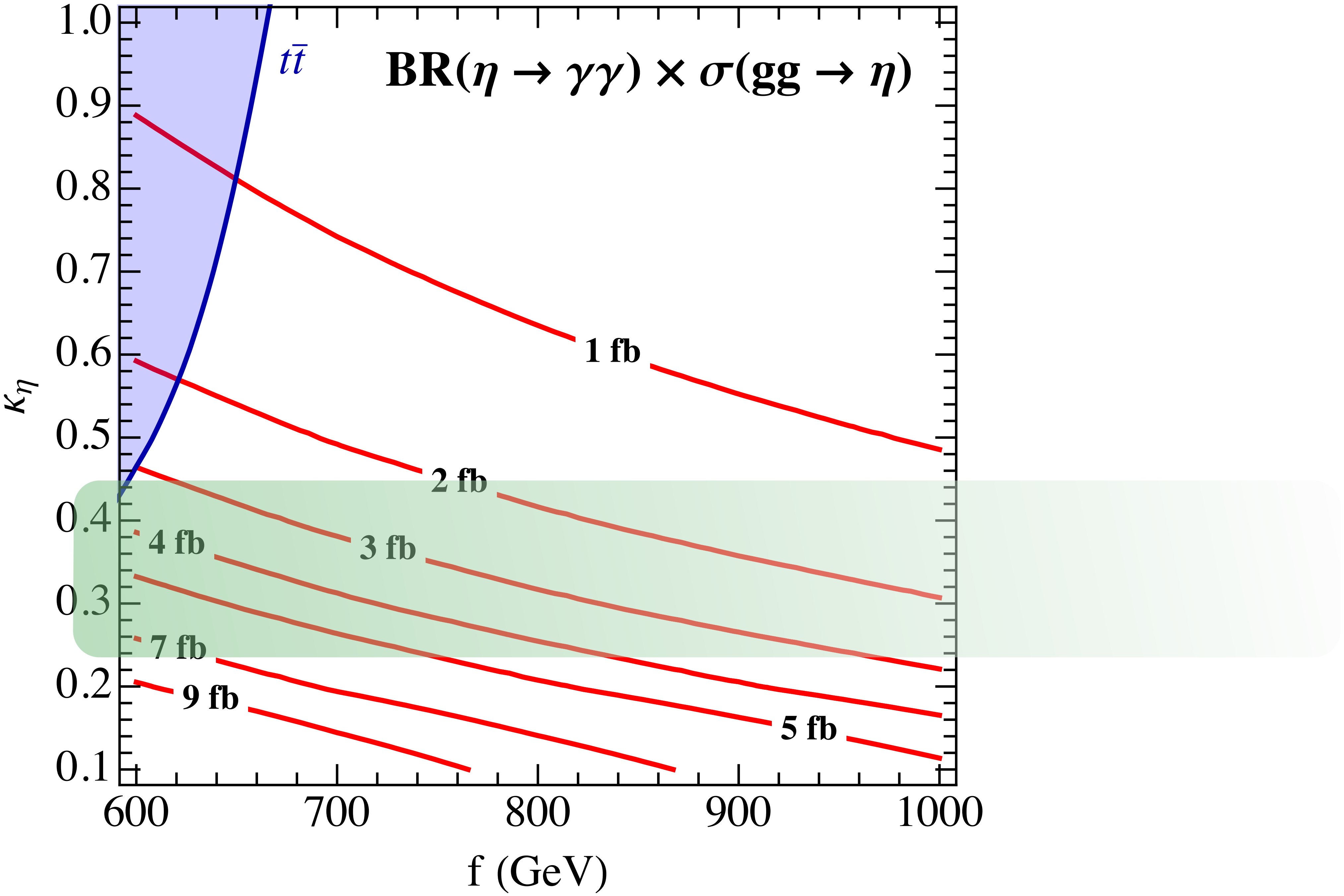
$$m_\eta^2 \simeq \frac{N_c y_t}{2\pi^2}\frac{m_*^3}{f}. \qquad m_\eta \simeq 700\ \mathrm{GeV}\left(\frac{m_*}{1.3\ \mathrm{TeV}}\right)^{3/2}\left(\frac{600\ \mathrm{GeV}}{f}\right)^{1/2}$$

Natural to have 750 with reasonable parameters

Di-photon rate in composite Higgs

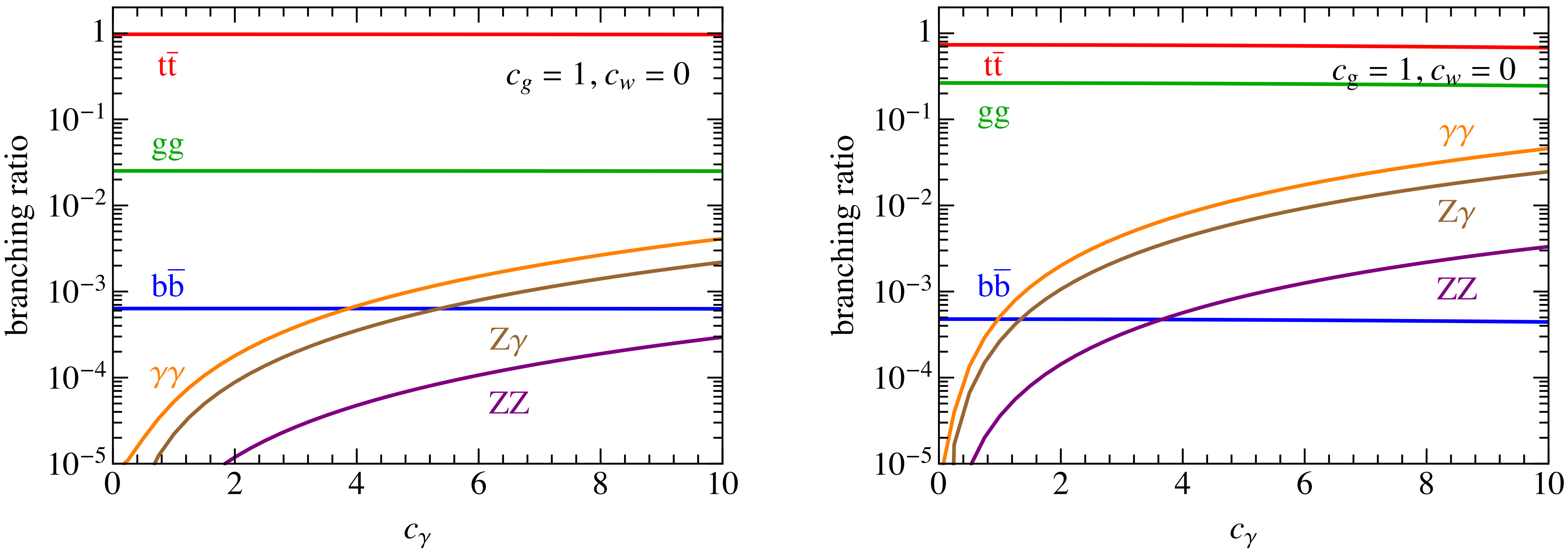


Di-photon rate in composite Higgs



Can explain the excess

New QCD vs composite Higgs

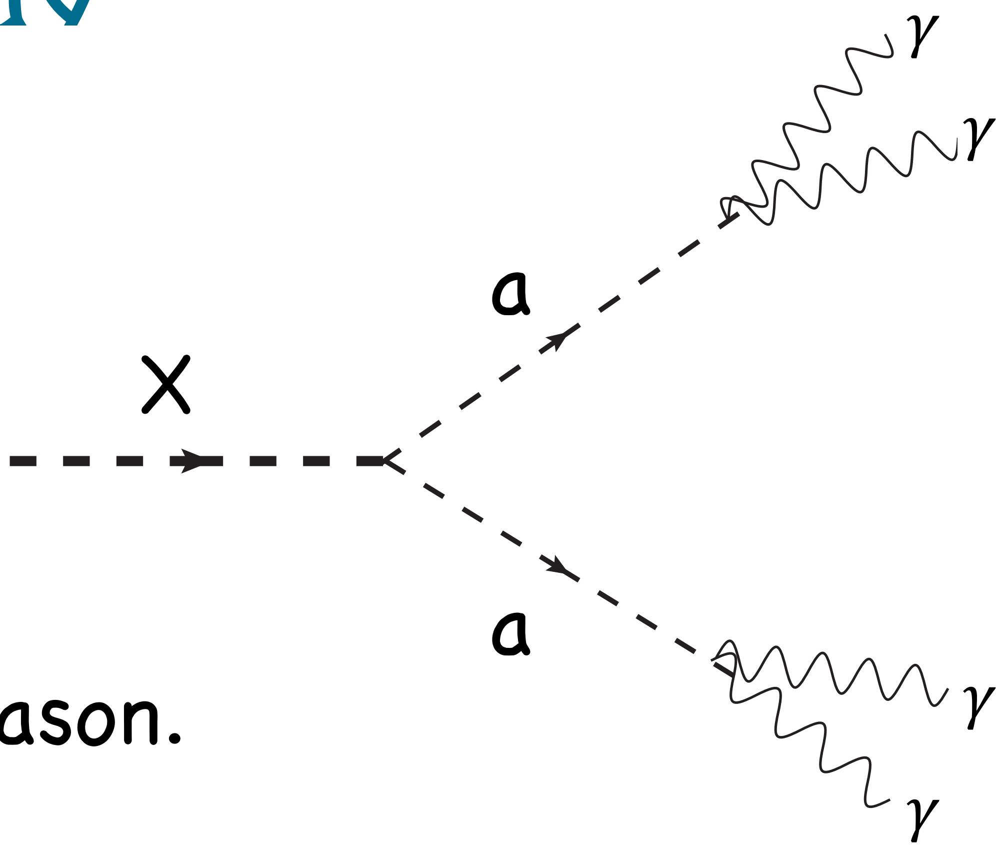


- The presence of ttbar.
- Presence of top-partner.

Alternative: 2-step decay

If $m_a << M_X \approx 750$ GeV,
LHC may not be able to resolve
the two photons.
So it could be a di-photon resonance.

May need $m_a <$ GeV. No compelling reason.
Life time of a challenging

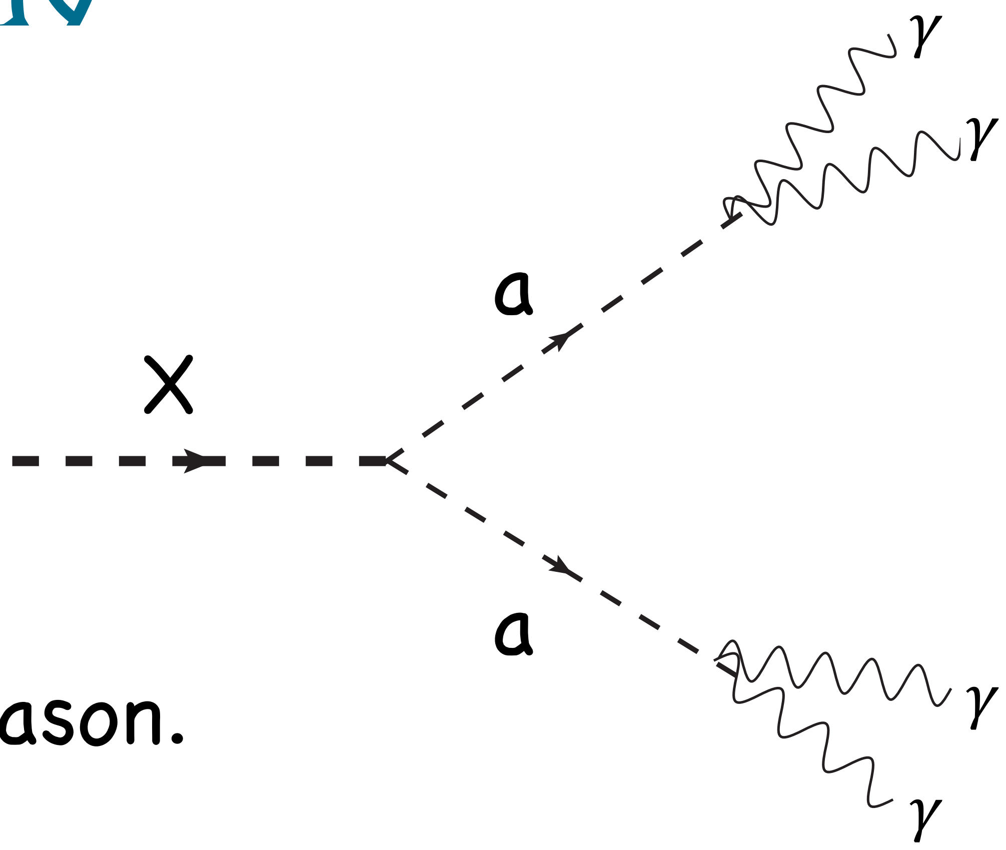


Knapen et al
Strassler et al

Alternative: 2-step decay

If $m_a << M_X \approx 750$ GeV,
LHC may not be able to resolve
the two photons.
So it could be a di-photon resonance.

May need $m_a <$ GeV. No compelling reason.
Life time of a challenging

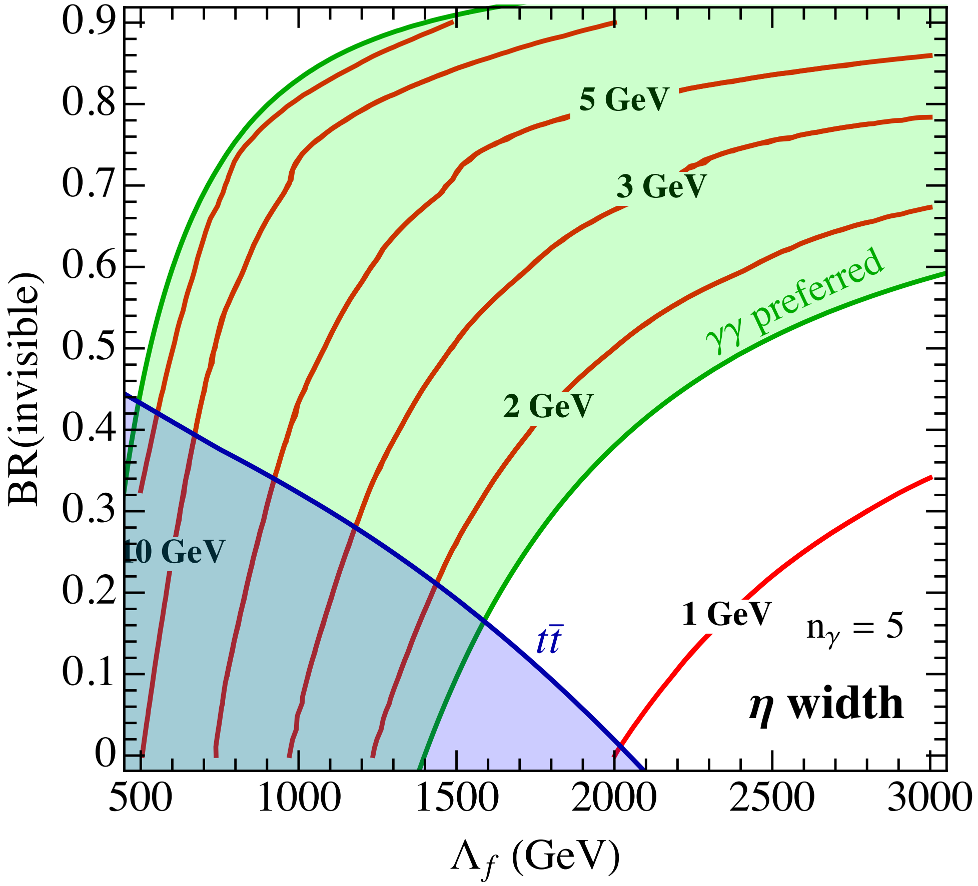


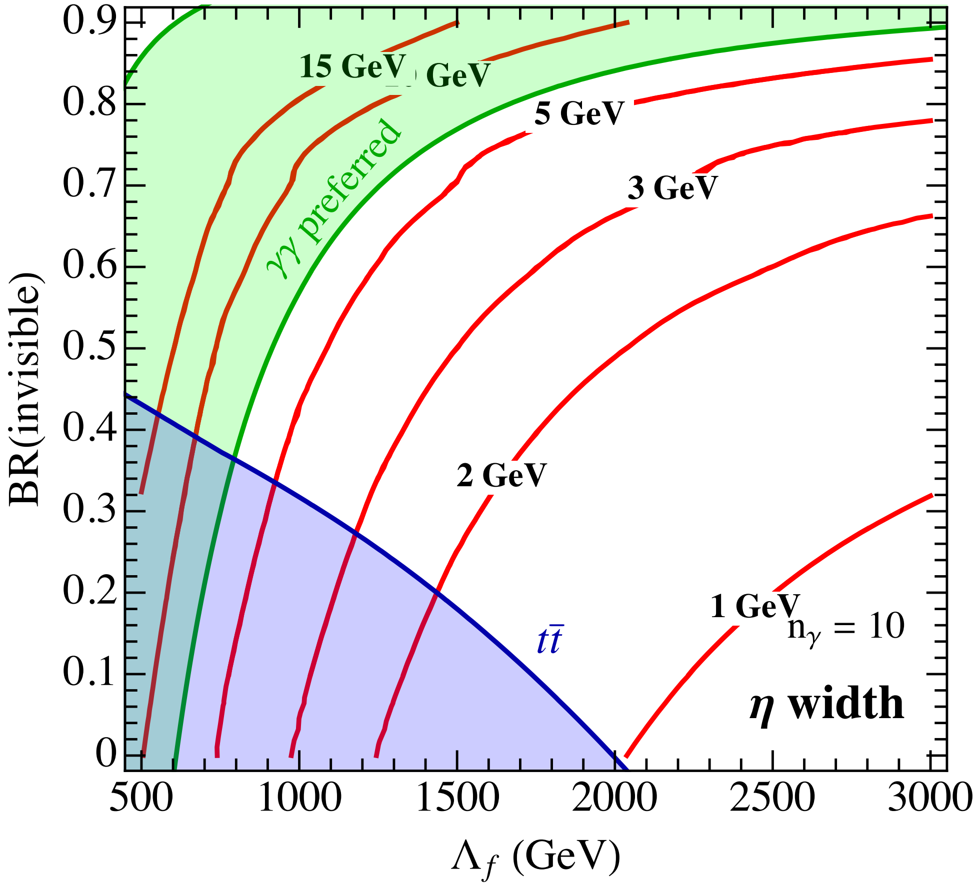
Knapen et al
Strassler et al

- Good "straw man" to test experimentally.
- A "fall back" model if everything else is ruled out.
- Need a lot more new physics to complete the story.

extras

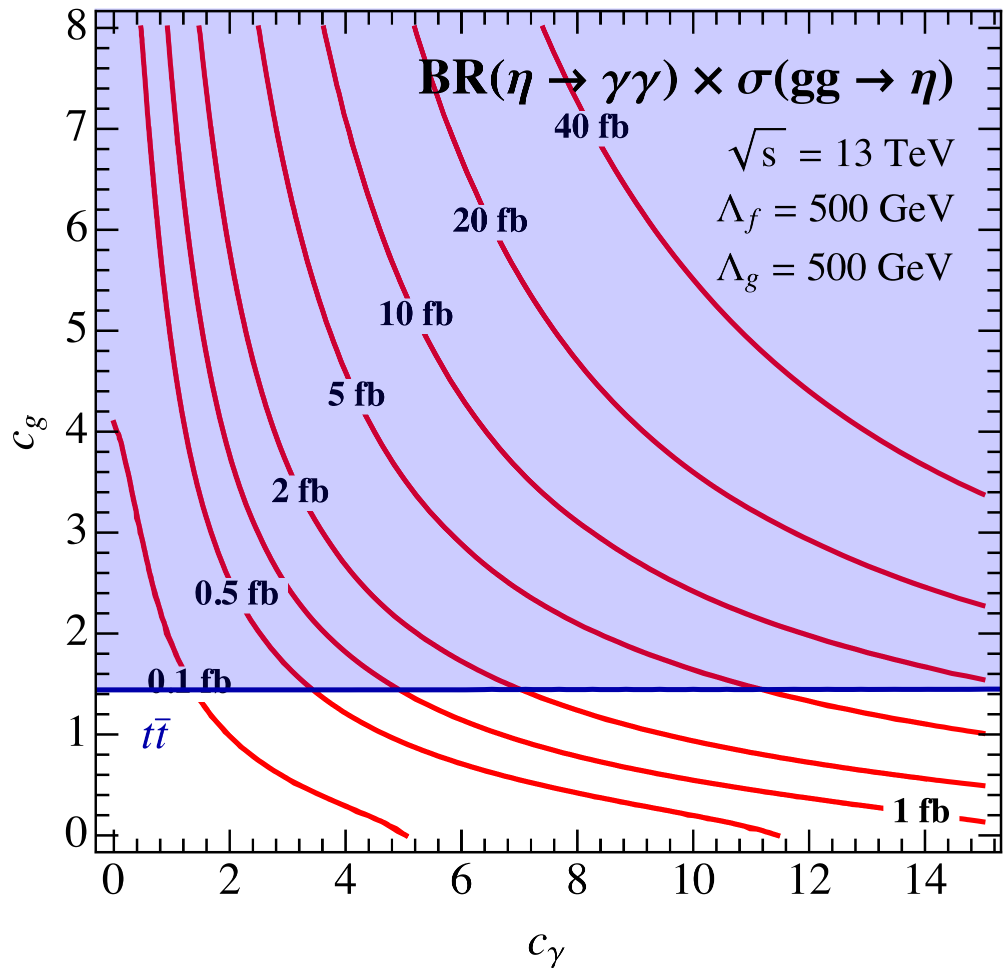
Larger width?

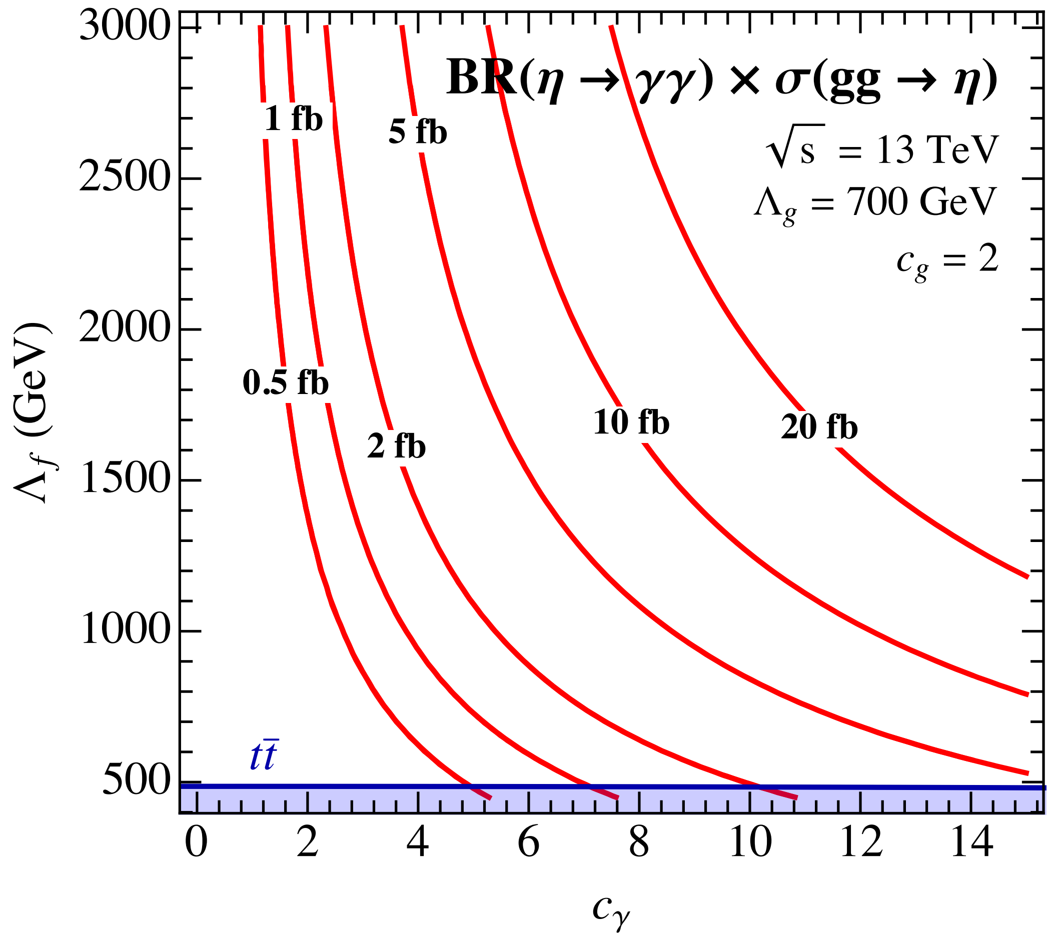




- By adding “invisible” decays.

Di-photon rate, two scenarios



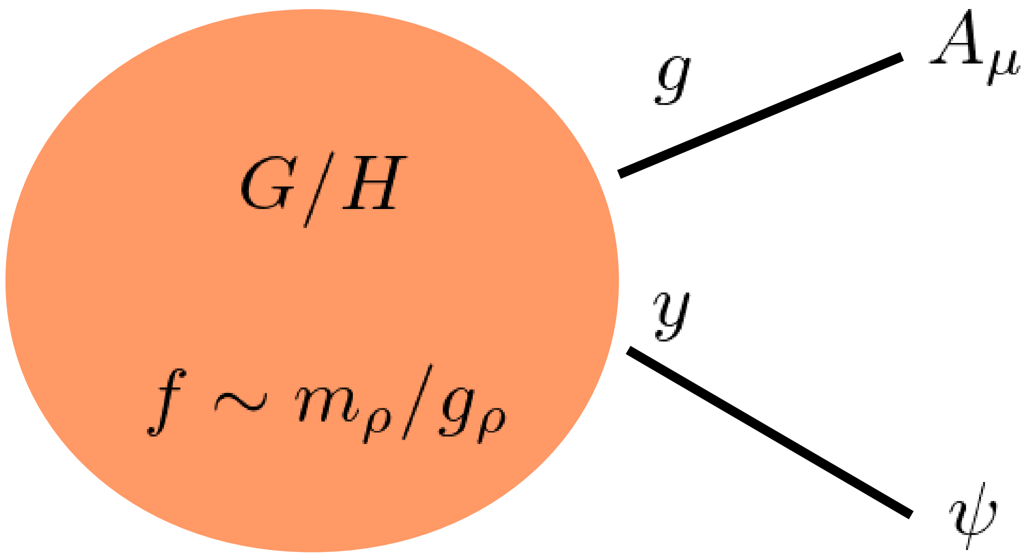


The contribution from top quark dominates production.

The contribution from anomaly dominates production and decay.

All require new physics at 500 GeV to TeV

Composite Higgs



Higgs (and W/Z goldstones) are part of the strong sector

The external fields are the SM quarks and (transverse) gauge bosons

- Higgs boson (and W_L Z_L) and others such as η(750) NGB of symmetry breaking G/H.

- Small explicit symmetry breaking (involving external fields) generates Higgs potential. (NGB ➜ pNGB).

750 GeV and naturalness

750 GeV and naturalness

- Fine-tuning of Higgs
  - compare m_h^2 and $c/16\pi^2 M_{NP}^2$
  - Not finding new physics yet at the LHC, M_{NP} > TeV.
  - Higgs mass is a few percent tuned.
    - ☐ In almost all new physics scenarios: SUSY, composite/Randall-Sundrum, etc.

750 GeV and naturalness

- Fine-tuning of Higgs
  - compare m_h^2 and $c/16\pi^2 M_{NP}^2$
  - Not finding new physics yet at the LHC, M_{NP} > TeV.
  - Higgs mass is a few percent tuned.
    - ☐ In almost all new physics scenarios: SUSY, composite/Randall-Sundrum, etc.

- What would be a natural scalar mass?
  - $m_{scalar}^2 \approx c/16\pi^2 M_{NP}^2$
  - $m_{scalar} > 500$ GeV

750 GeV and naturalness

- Fine-tuning of Higgs
  - compare m_h^2 and $c/16\pi^2 M_{NP}^2$
  - Not finding new physics yet at the LHC, M_{NP} > TeV.
  - Higgs mass is a few percent tuned.
    - ☐ In almost all new physics scenarios: SUSY, composite/Randall-Sundrum, etc.
- What would be a natural scalar mass?
  - $m_{scalar}^2 \approx c/16\pi^2 M_{NP}^2$
  - m_{scalar} > 500 GeV
- So, a plausible scenario is a natural theory (only with Higgs slightly tuned).

Big picture

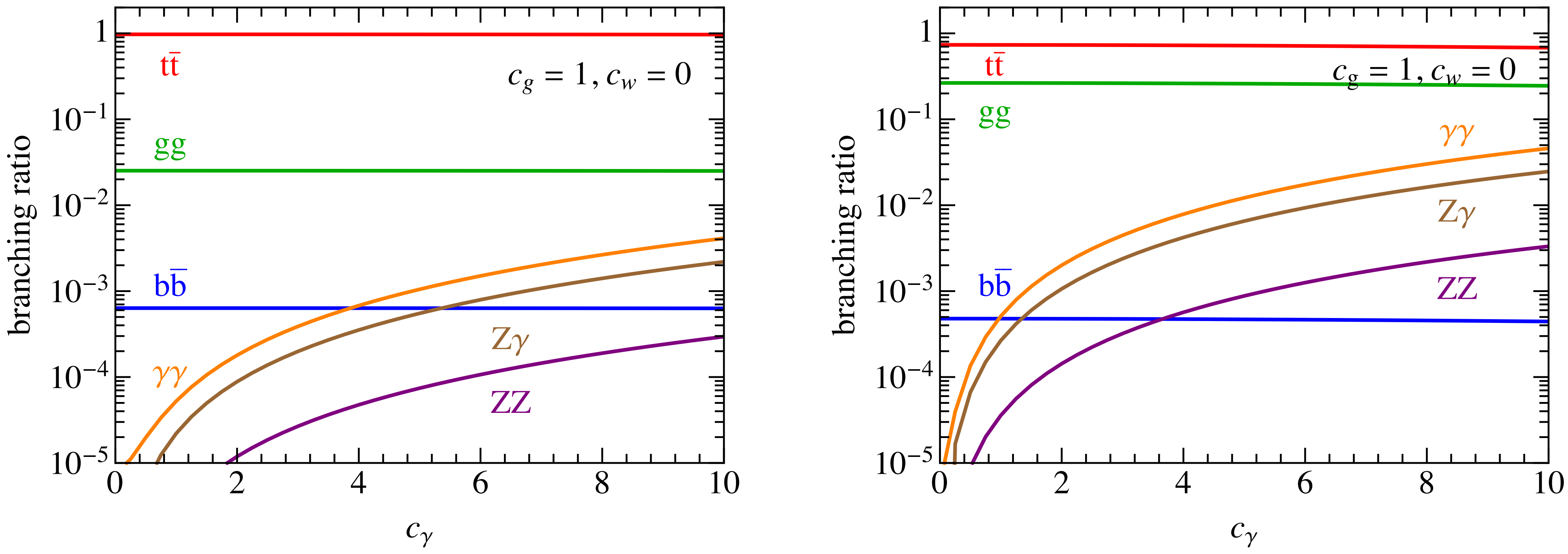
- Likely to be a (pseudo)scalar at 750 GeV.
- Large rate to di-photon. Need additional new physics!
    - Both charged and colored.
    - Perhaps around 500 GeV to TeV-ish, exact range model dependent.
- Looking good for being part of a natural theory.
    - New physics span over a decade of energy beyond TeV.

Going forward

For the LHC

- Will probably know the answer by summer 2016.
- Should look for associated excess in $Z\gamma$, ZZ

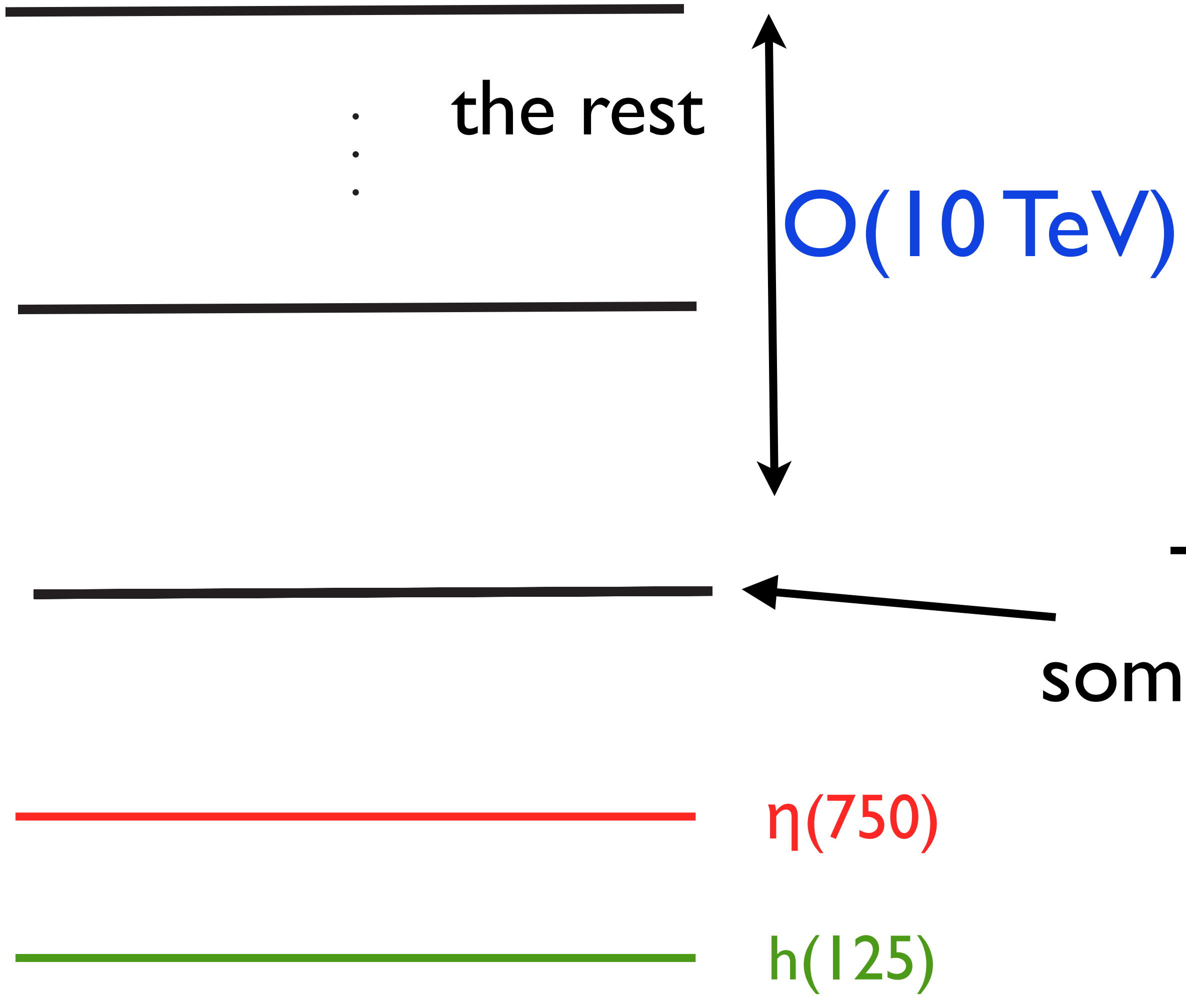
  Perhaps also WW, ttbar, hh



If it is there, beginning of a new era of particle physics.

- LHC May also see a few more new physics particles.
- Very unlikely to see all of them.

For example: composite Higgs



the rest

O(10 TeV)

Hard to see the full spectrum with the increase of reach from 8 to 14 TeV

TeV composite resonances, some maybe reachable at the LHC

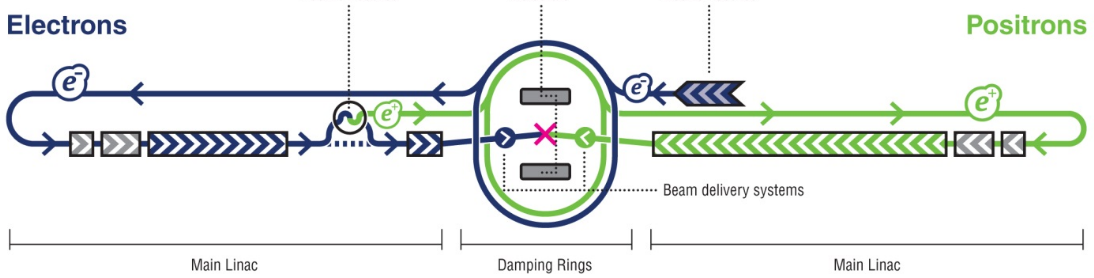
η(750)

h(125)

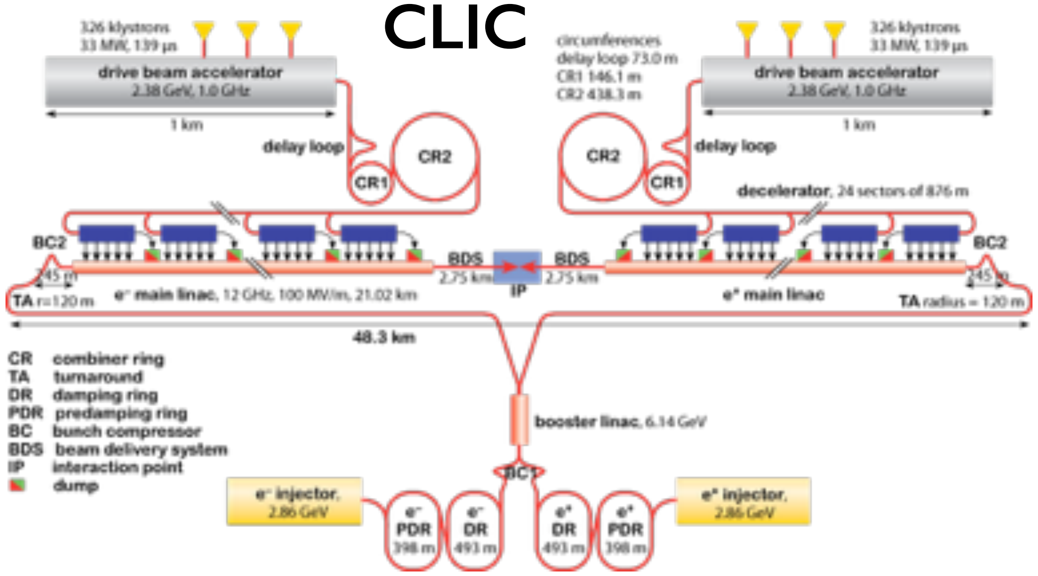
Certainly need to go beyond the LHC!

Beyond the LHC, future facilities

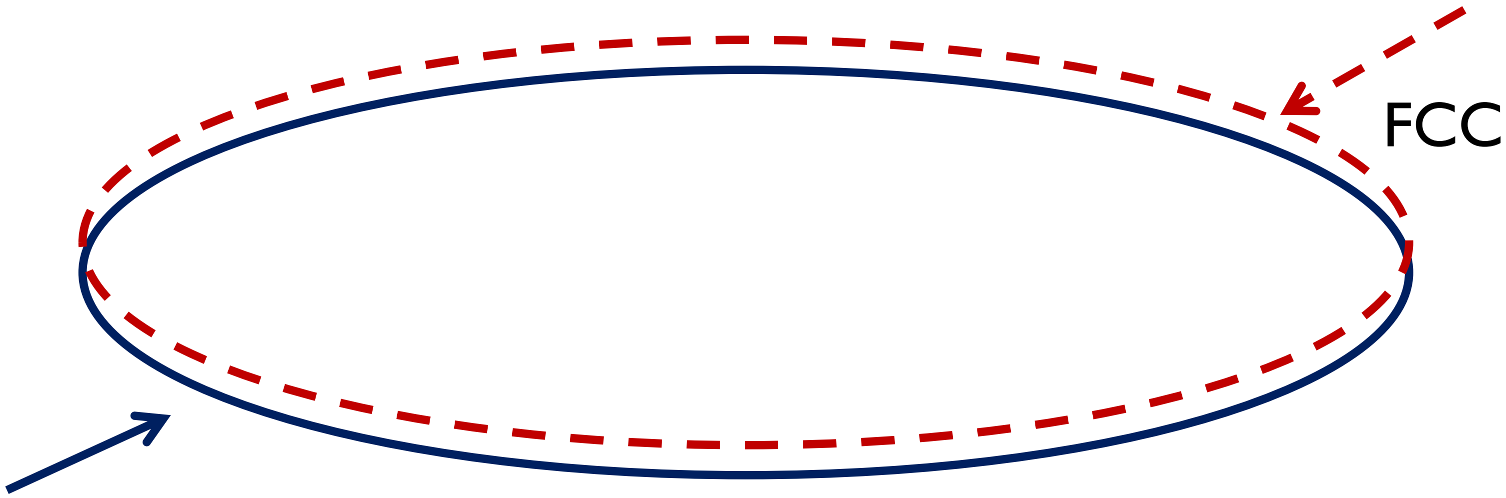
ILC in Japan



CLIC



Circular. “Scale up” LEP+LHC



~100 TeV

pp collider

FCC-hh (CERN), SppC(China)

250 GeV **e⁻e⁺ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Best strategy will take a while to sort out.

Here are a few first impressions.

Recall the big picture:

- Likely to be a (pseudo)scalar at 750 GeV. Large coupling to proton.
- Large rate to di-photon. Need additional new physics!
    - Both charged and colored.
    - Perhaps around 500 GeV to TeV-ish, exact range model dependent.
- Looking good for being part of a natural theory.
    - New physics span over a decade of energy beyond TeV.

Big ring ++

- The motivation for having a very large ring, with the goal of a super proton collider with higher energy (10s to 100 TeV), would be super strong.

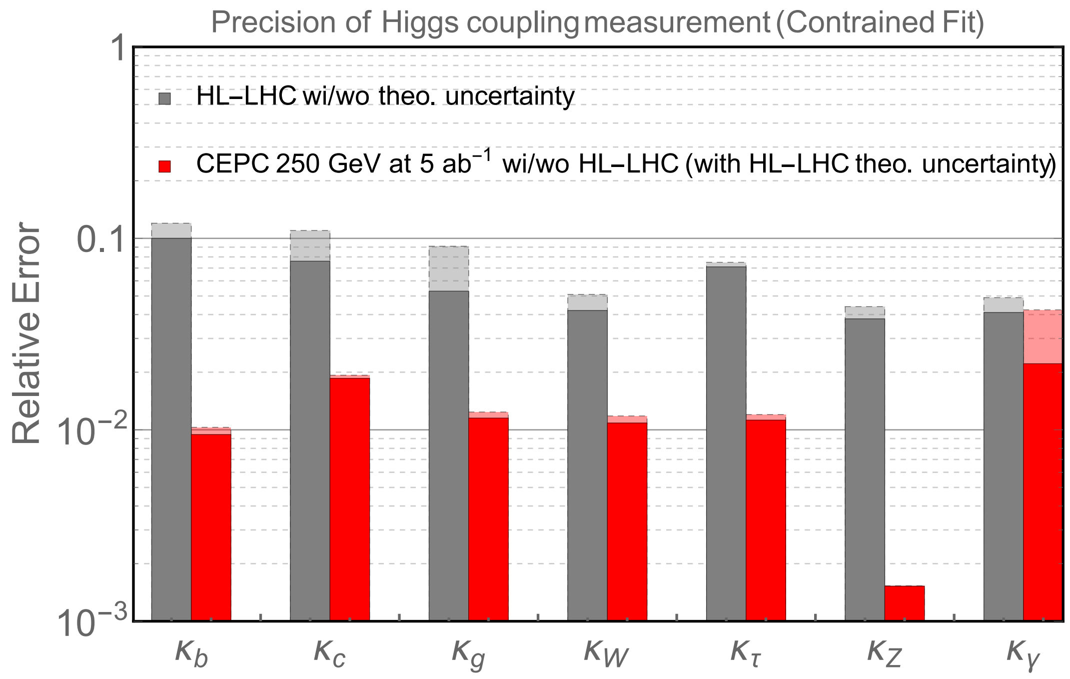
  Completely unravel a new layer of new physics.

  Another 50+ years exciting discoveries.

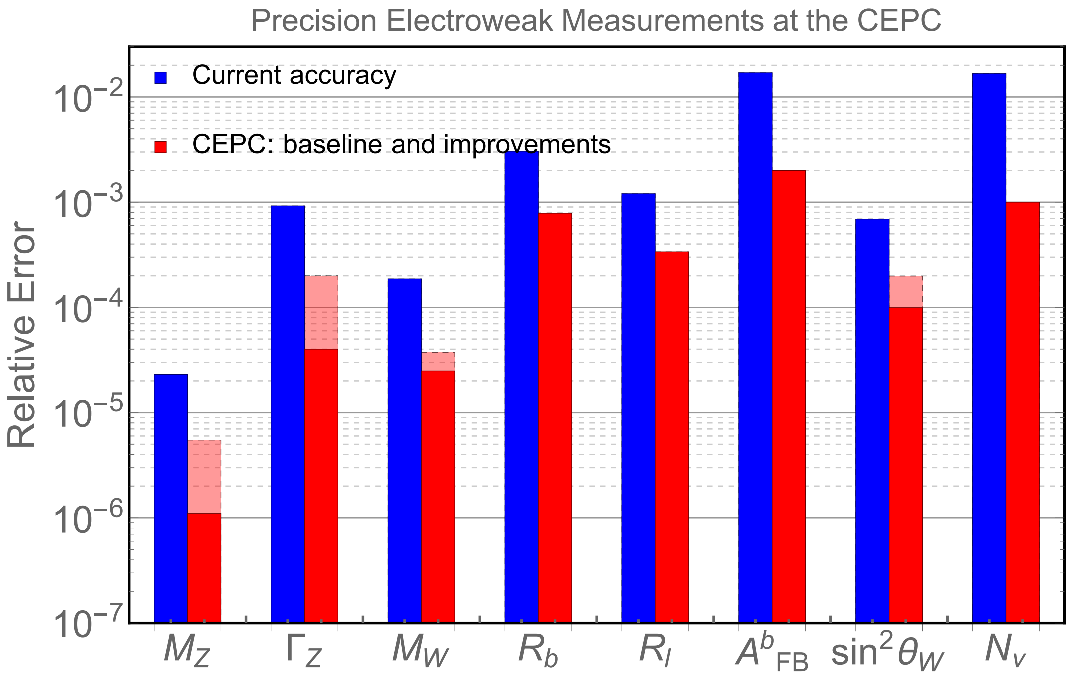
- Lepton colliders, such as CLIC(to lesser extent the ILC), can cover some ground, especially the new charge particles. But unlikely the full story.

On the road to the super proton-proton collider.

- Completely sensible to have a Higgs factory stage.
  - The suite of precision measurement give highly valuable and complementary information.



Precision of Higgs coupling measurement (Contrained Fit)



Precision Electroweak Measurements at the CEPC

A bit of history

- 30+ years ago. SM was incomplete. We need to find the missing particles. Not sure about gauge symmetry.

- That journey is completed by the LHC with the discovery of the Higgs boson.

- Along the way, LEP-I and LEP-II provided a huge amount of information that have determined the direction of the field.
    - Nailed the Higgs boson to be light.
    - Guided the search strategies at the LHC.
    - Much of this are still highly relevant today.

A likely story for CEPC+SPPC

- CEPC will tell us
  - Is the η(750) part of a natural theory, part of the solution to the naturalness problem?
  - What classes of models should be the focus of the SPPC program.
- SPPC
  - Completely discover all the new physics particles, and lead us into a new Standard Model.

Naturalness.

- η(750) sharpens the naturalness problem dramatically.
- If it is part of the natural model: will see large deviations at the Higgs factory and point to particular class of models. SppC will discover full set of new particles.
- If it is not part of the natural model, together with Higgs, it points to new paradigm changes in naturalness.

Need new colliders to guide us.

For example: composite Higgs

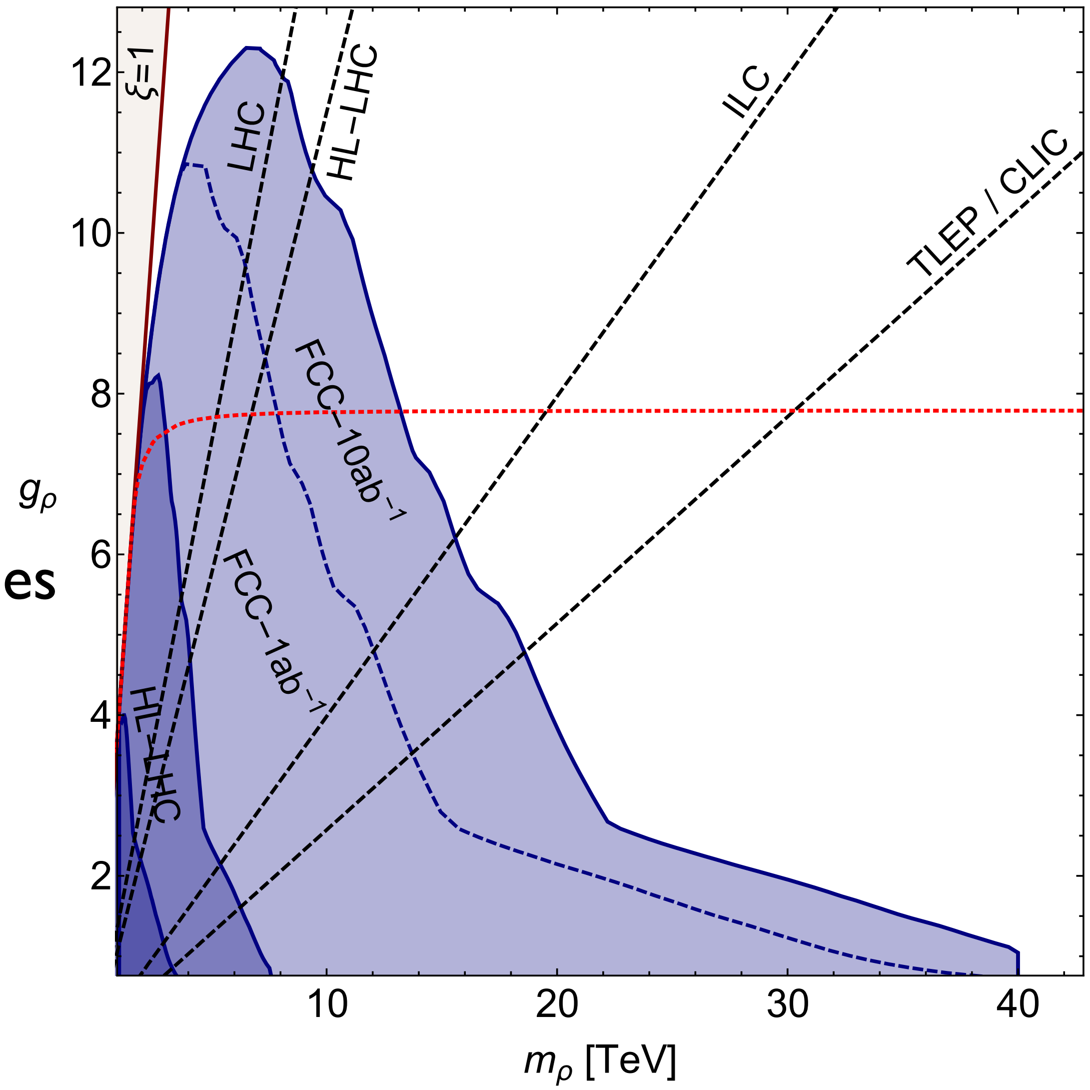
the rest

O(10 TeV)

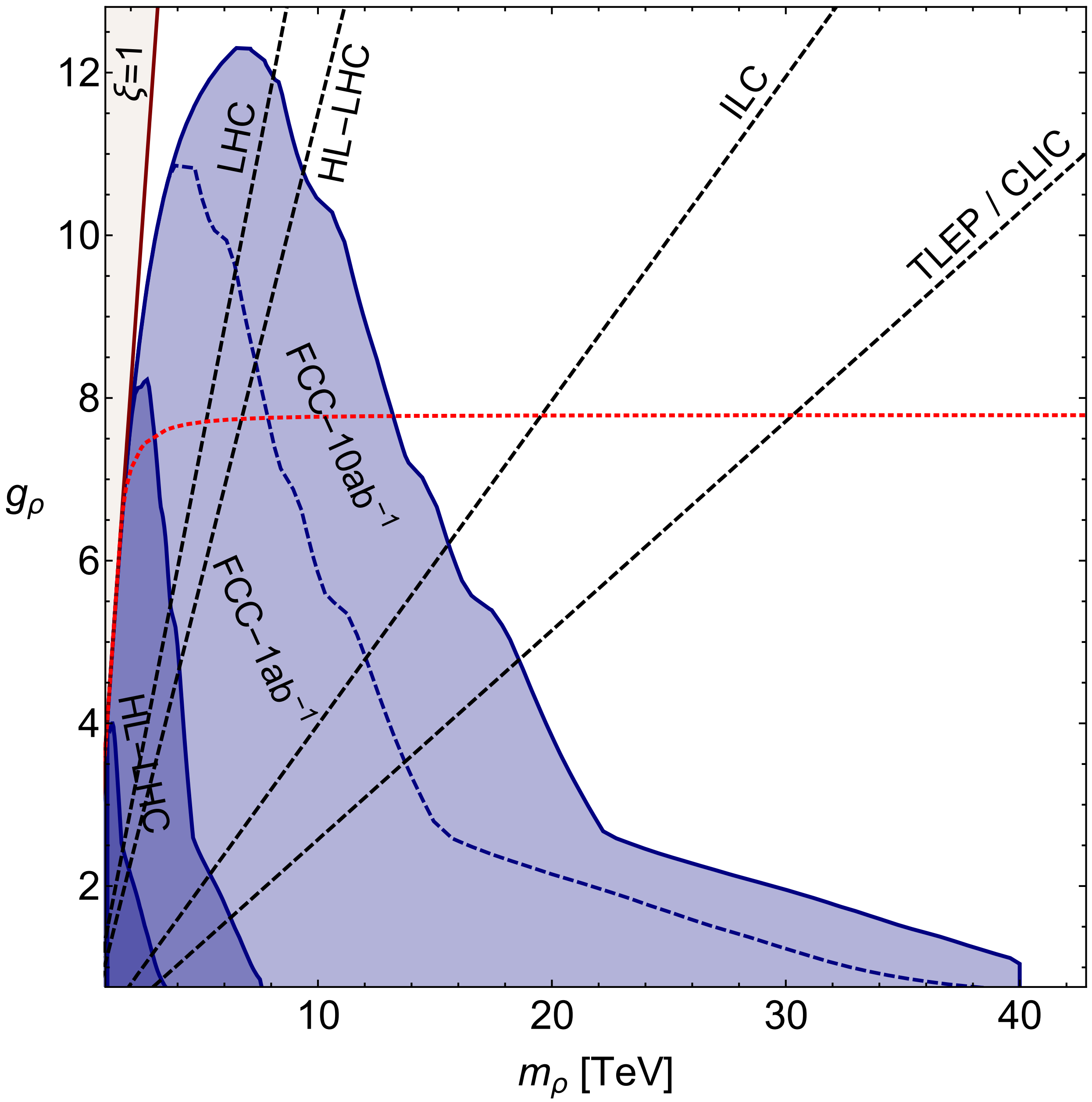
TeVs comp. resonances

η(750)

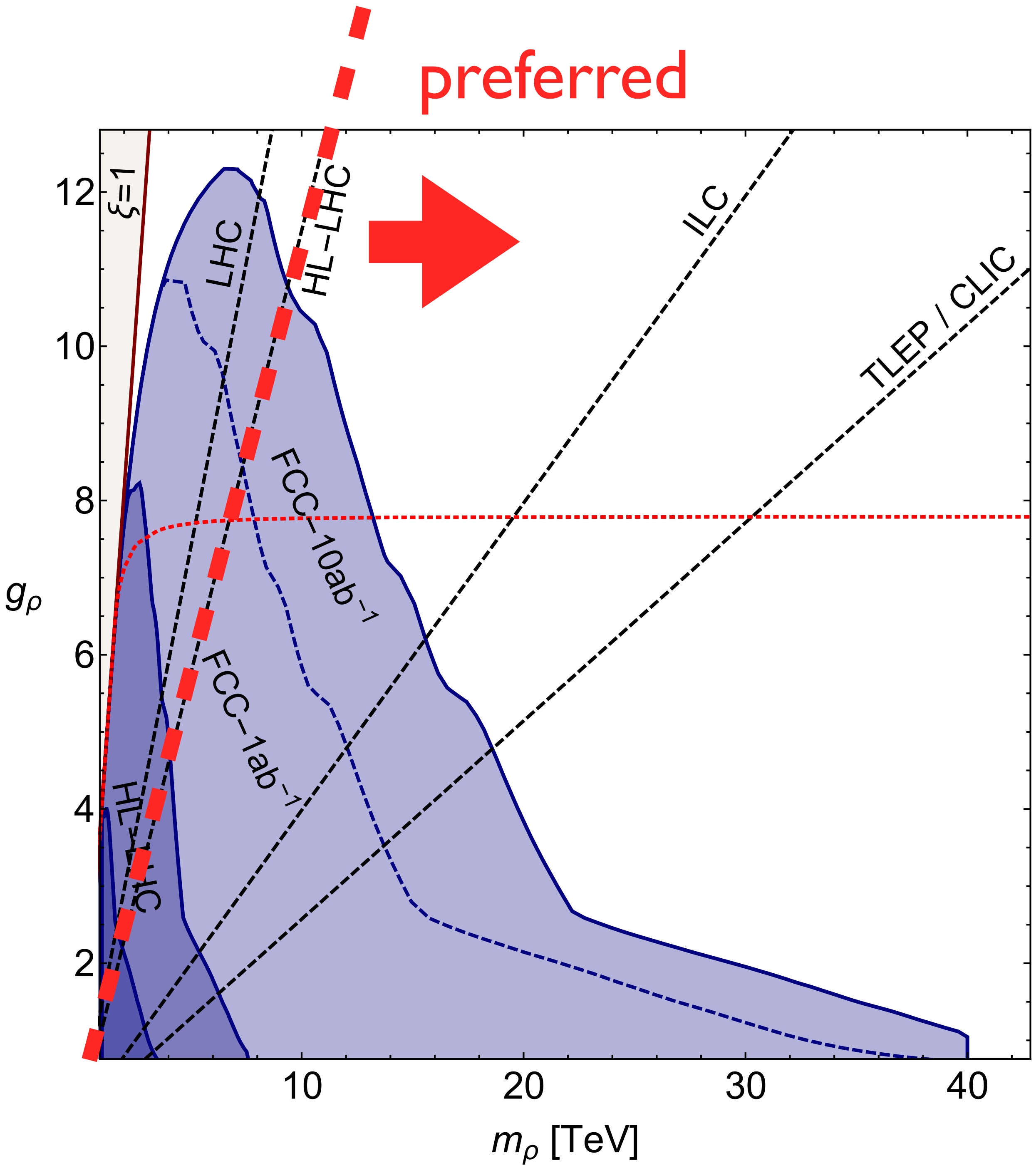
h(125)



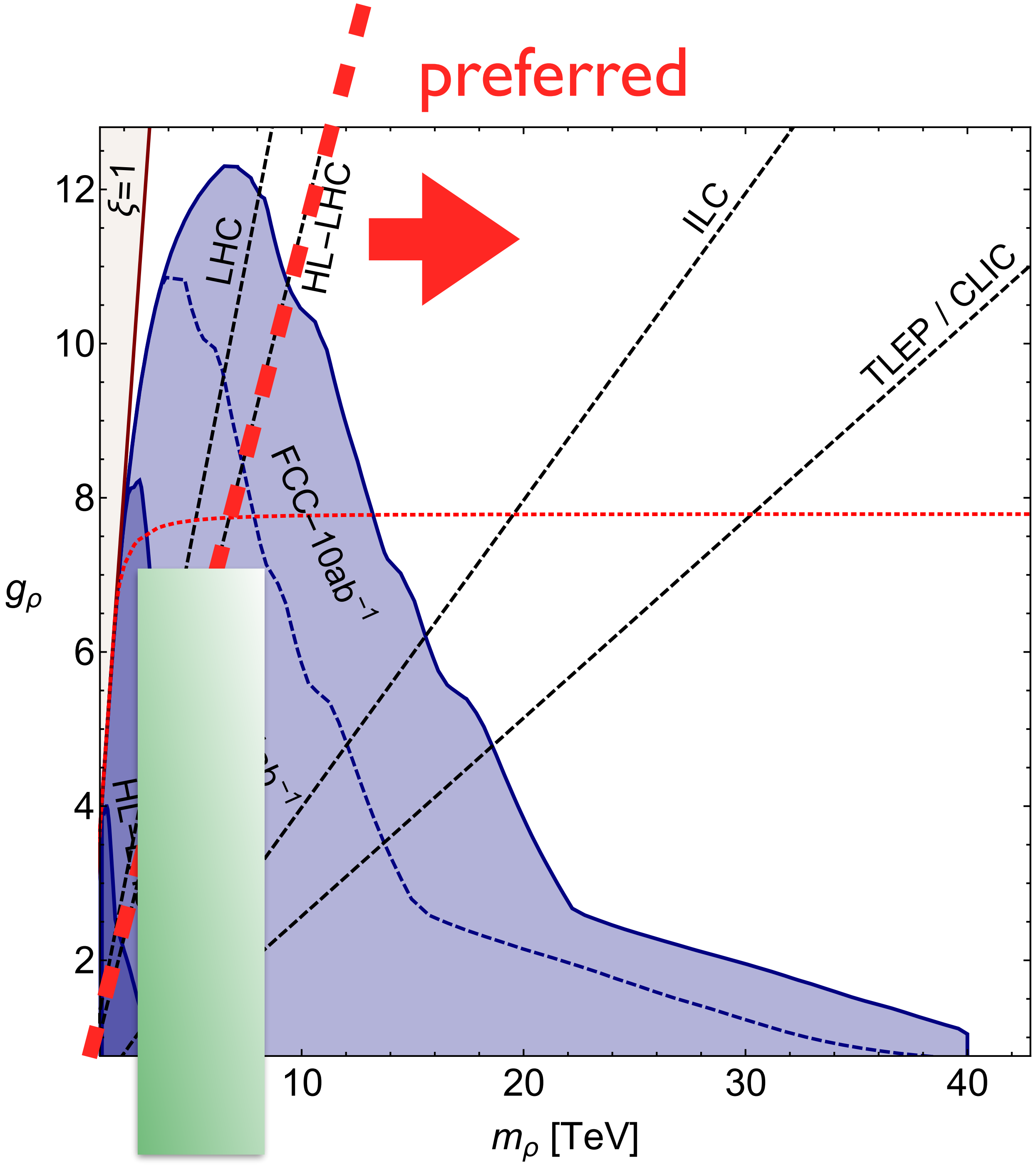
For example: composite Higgs



For example: composite Higgs



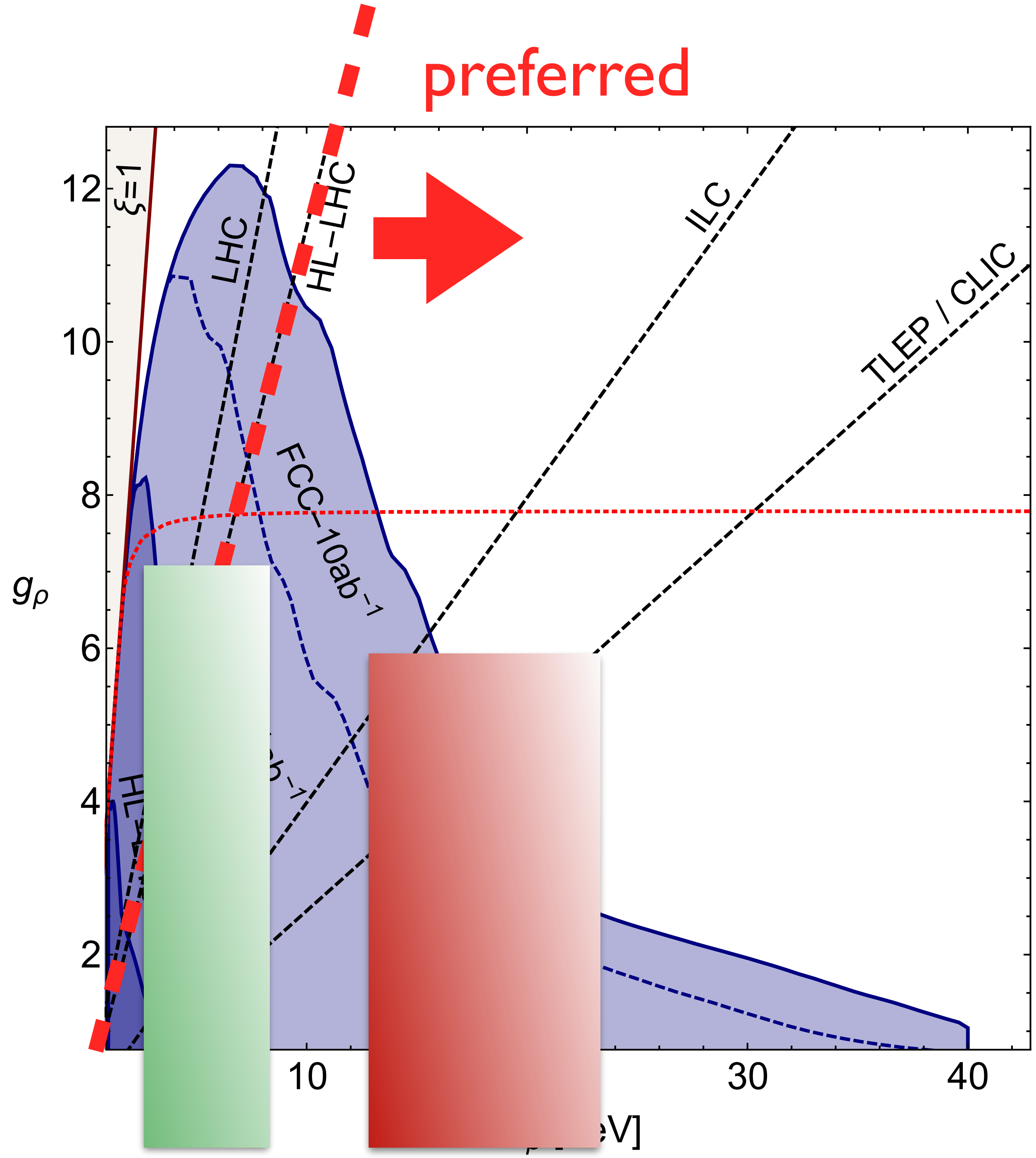
For example: composite Higgs



preferred

new resonances

For example: composite Higgs



new
resonances

new strong integration
new gluon and quarks

Conclusions

- The di-photon excess at 750 GeV intriguing.
  - Certainly can only be part of a much bigger story.
- LHC can start to go further.
- Yet, new and big colliders definitely needed to tell most of the story.

Minimal composite

Agashe, Contino, Pomarol

$$SO(5)/SO(4) \to 4\,\mathrm{GBs}$$

$$U = \exp\left(i\sqrt{2}\frac{\pi^a}{f}T^a\right) \quad T^a = \begin{pmatrix} 0 & X_a \\ -X_a & 0 \end{pmatrix} \quad \Sigma_i = U_{i5}$$

$$\frac{1}{2}(D_\mu\Sigma)^2 \supset \frac{1}{2}(\partial h)^2 + \frac{1}{2}m_V^2 V_\mu^2\left(1 + 2\sqrt{1-\frac{v^2}{f^2}}\frac{h}{v} + \cdots\right)$$

First prediction: deviation in Higgs coupling

→ important constraints

$$\Gamma(\eta \to t\bar{t}) = \frac{N_c}{8\pi}\frac{m_t^2}{\Lambda_f^2} m_\eta \sqrt{1 - \frac{4m_t^2}{m_\eta^2}},$$

$$\Gamma(\eta \to b\bar{b}) = \frac{N_c}{8\pi}\frac{m_b^2}{\Lambda_f^2} m_\eta \sqrt{1 - \frac{4m_b^2}{m_\eta^2}},$$

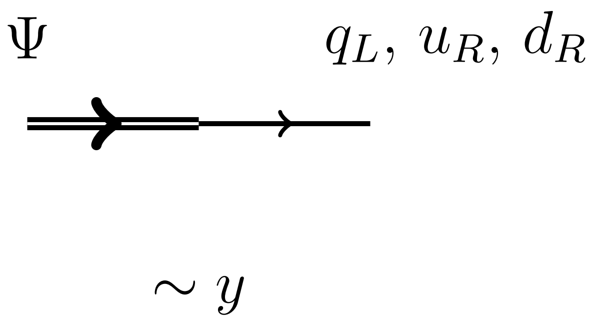
$$\Gamma(\eta \to gg) = \frac{1}{2\pi}\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{m_\eta^3}{\Lambda_f^2}\left|A_-(\tau) + 2c_g\frac{\Lambda_f}{\Lambda_g}\right|^2,$$

$$\Gamma(\eta \to \gamma\gamma) = \frac{1}{4\pi}\left(\frac{\alpha}{4\pi}\right)^2 \frac{m_\eta^3}{\Lambda_f^2}\left|N_c Q_t^2 A_-(\tau) + 2c_\gamma\frac{\Lambda_f}{\Lambda_g}\right|^2,$$

Partial compositeness

composite fermion with the same gauge quantum numbers as SM fermion.

$$\mathcal{L}_{\rm pc} = -m_\Psi \boxed{\bar{\Psi}\Psi} - y_L f(\bar{q}_L \Psi + h.c.) - y_R f(\bar{u}_R \Psi + h.c.)$$



$$y_f = \frac{m_\Psi}{f} \sin\phi_L^f \sin\phi_R^f$$

$$\sin\phi_{L,R} \equiv \frac{y_{L,R}}{\sqrt{(m_\Psi/f)^2 + y_{L,R}^2}}.$$

- Mixing angles not completely fixed.
- For top quark, the mixing should be large, O(1).
  - Top quark heavy because it is composite.
- Less so for light quark and lepton.

$$U(\Pi) = \exp\left(\frac{i}{f}(\widehat{H} + \eta T_\eta + \ldots)\right),$$

$$y_t \overline{t_L} h t_R \left(1 + i\kappa_\eta \frac{\eta}{f} + \mathcal{O}\left(\frac{1}{f^2}\right)\right) + h.c.$$

$$c_\eta \frac{N_c y_R^2}{4\pi^2} m_*^2 \eta^2 + \cdots$$

$$y_t \simeq \frac{f}{m_*} y_L y_R$$

$$m_\eta^2 \simeq \frac{N_c y_t}{2\pi^2} \frac{m_*^3}{f}$$

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

A clear big step above the LHC.

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

A clear big step above the LHC.