Search for two-body resonances

(a selection of topics with theoretical bias)

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pp@LHC – Pisa, 16.5.2016

Two body resonances

- Theoretically quite simple:

$$\sigma(pp \to X) = \frac{1}{M_X s} \sum_{ij} \mathcal{P}_{ij} \Gamma(X \to ij)$$

the cross-section is determined from the branching ratios of X.
Observable signals (if narrow width):

$$\mu_{X\to i} = \frac{\Gamma_{X\to i}}{M_X s} \frac{\sum_j \mathcal{P}_j \Gamma_{X\to j}}{\sum_j \Gamma_{X\to j}}$$

- Example: scalar at 13 TeV [Franceschini et al. 1604.06446]

$$\sigma(pp \to \mathcal{F}) = \Big[4900\frac{\Gamma_{gg}}{M_{\mathcal{F}}} + 2400\frac{\Gamma_{u\bar{u}}}{M_{\mathcal{F}}} + 1400\frac{\Gamma_{d\bar{d}}}{M_{\mathcal{F}}} + 190\frac{\Gamma_{s\bar{s}}}{M_{\mathcal{F}}} + 83\frac{\Gamma_{c\bar{c}}}{M_{\mathcal{F}}} + 35\frac{\Gamma_{b\bar{b}}}{M_{\mathcal{F}}} + \\ +150\frac{\Gamma_{\gamma\gamma}}{M_{\mathcal{F}}} + 62\frac{\Gamma_{Z\gamma}}{M_{\mathcal{F}}} + 18\frac{\Gamma_{W_TW_T}}{M_{\mathcal{F}}} + 0.92\frac{\Gamma_{W_LW_L}}{M_{\mathcal{F}}} + 6.5\frac{\Gamma_{Z_TZ_T}}{M_{\mathcal{F}}} + 0.32\frac{\Gamma_{Z_LZ_L}}{M_{\mathcal{F}}}\Big]\,\mathrm{pb}\,.$$

- Peak around the invariant mass of the resonance.
Final state gives informations about spin, parity, … (e.g. vector $\not\to \gamma\gamma$)

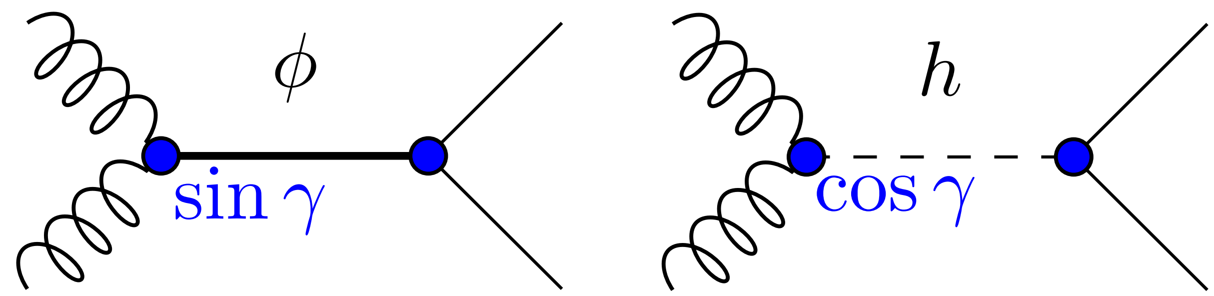
Sketch of the talk

- Scalar singlets: diboson and di-Higgs
- The diphoton “resonance”
- An explicit model: the NMSSM
- Vector resonances: beyond the simplest scenario
- A composite model with scalars and vectors

Scalar singlets

Scalar singlets

- If a CP-even scalar, the mixing with the Higgs boson can be sizeable:
    - can be singly produced
    - decays to SM particles
    - modified Higgs couplings



$$\begin{cases} H = \left(i\pi^+, \dfrac{v + h^0 + i\pi^0}{\sqrt{2}}\right) \\ S = v_S + s^0 \end{cases} \xrightarrow{\text{mass eigenstates}} \begin{cases} h = h^0 \cos\gamma + s^0 \sin\gamma \\ \phi = s^0 \cos\gamma - h^0 \sin\gamma \end{cases}$$

$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 S^2 + \kappa_S S^3 + \lambda_S S^4 + \lambda_{HS} S^2 |H|^2 + \kappa_{HS} S |H|^2$$

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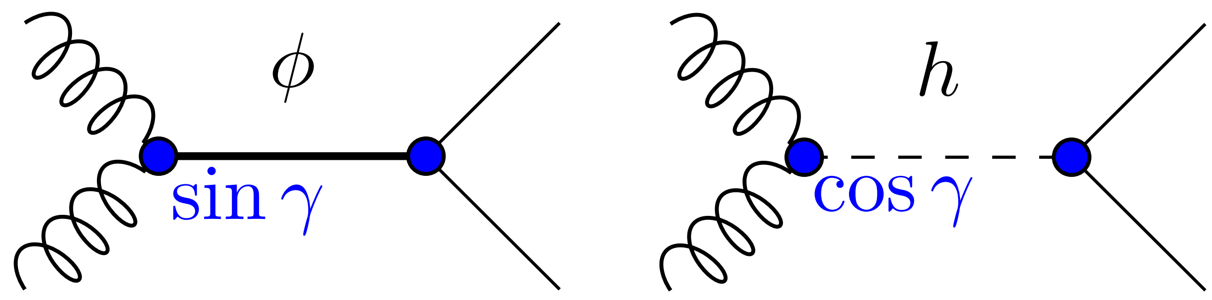

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The phenomenology of ϕ mainly depends on **3 parameters:**
(ignoring effects of higher dimensional operators)

$$\mu_h = c_\gamma^2 \times \mu_{\rm SM},$$
$$\mu_{\phi\to VV,ff} = s_\gamma^2 \times \mu_{\rm SM}(m_\phi) \times (1 - {\rm BR}_{\phi\to hh}),$$
$$\mu_{\phi\to hh} = s_\gamma^2 \times \sigma_{\rm SM}(m_\phi) \times {\rm BR}_{\phi\to hh},$$

ϕ is like a heavy SM Higgs, with narrow width $+\ hh$ channel

Scalar singlet decays

- At high mass the equivalence theorem relates the decay widths

$$\mathrm{BR}_{\phi\to hh} \simeq \mathrm{BR}_{\phi\to ZZ} = \frac{1}{2}\mathrm{BR}_{\phi\to WW} \simeq \frac{1}{4}, \qquad m_\phi \gg m_h$$

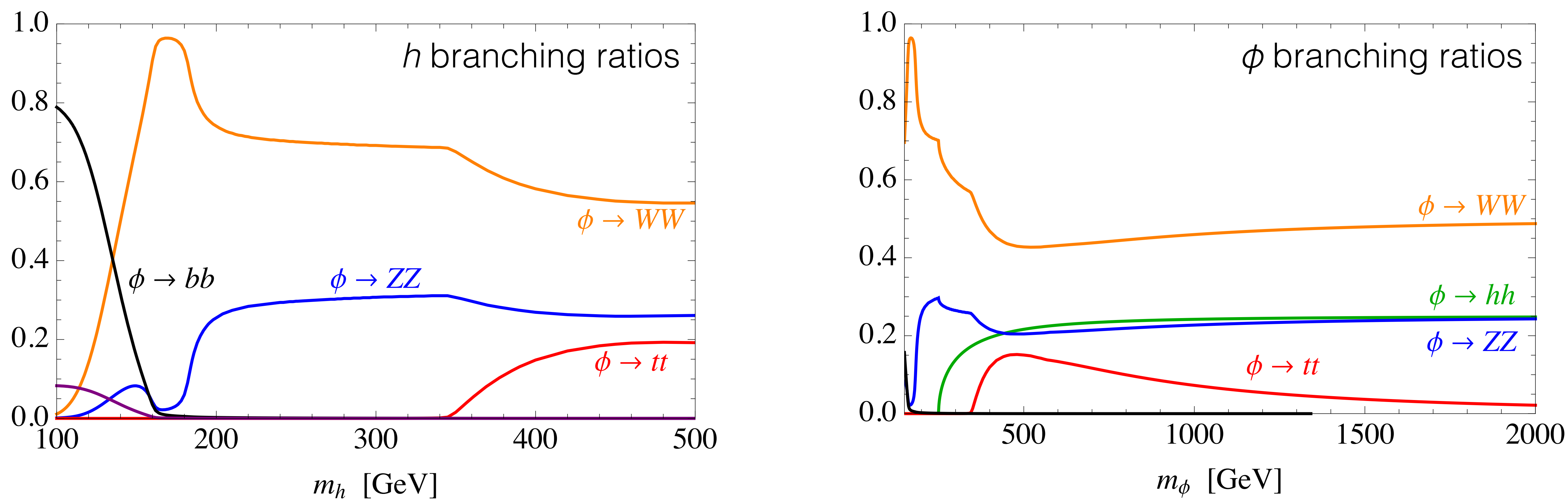
(these are the dominant channels, fermionic modes suppressed)

➡ Phenomenology roughly determined just by m_ϕ and M_{hh} at high mass!

$$\mathrm{BR}_{\phi\to hh} \simeq \frac{1}{4} - \frac{3}{4}\frac{v}{v_s}\sin\gamma + \mathcal{O}\left(\frac{v^2}{m_\phi^2}\right)$$

large deviations possible
at intermediate masses

DB, Sala, Tesi 1505.05488



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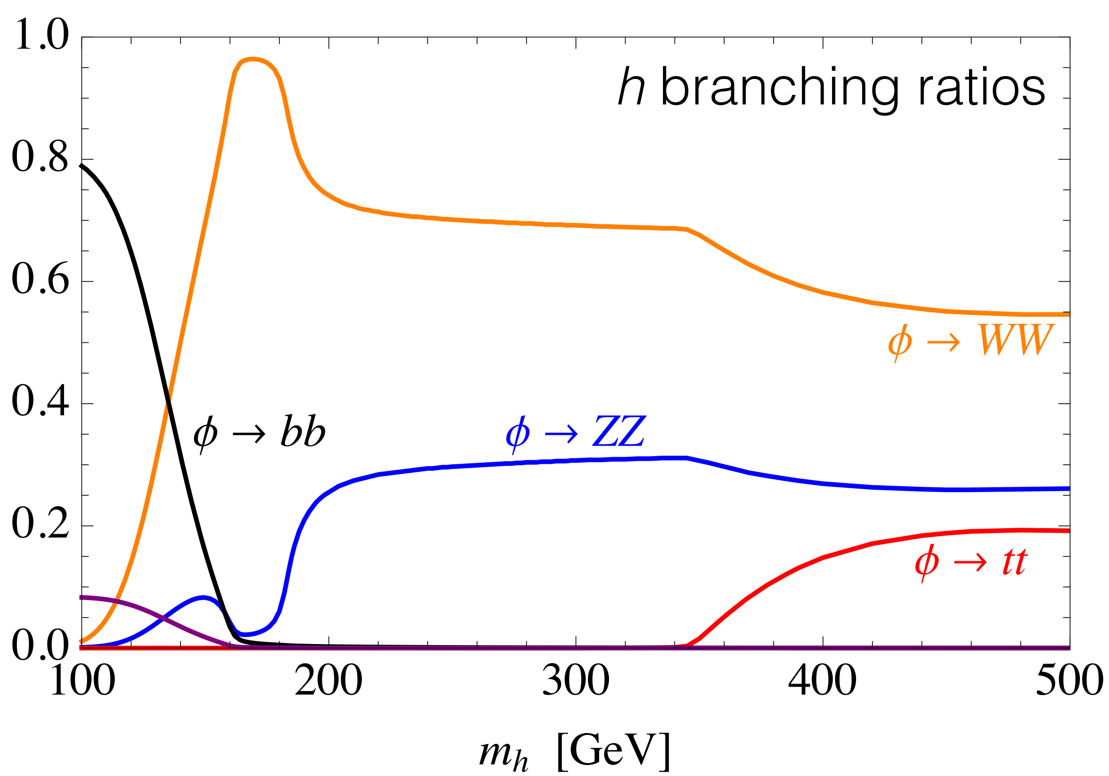
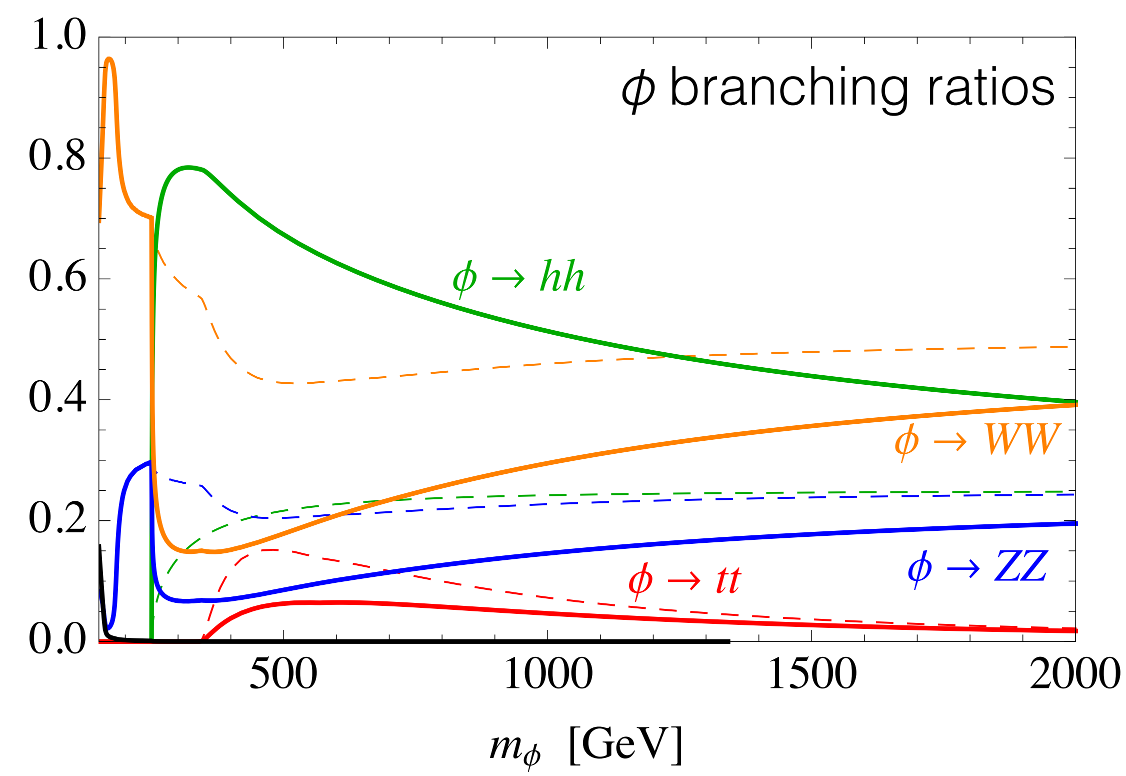
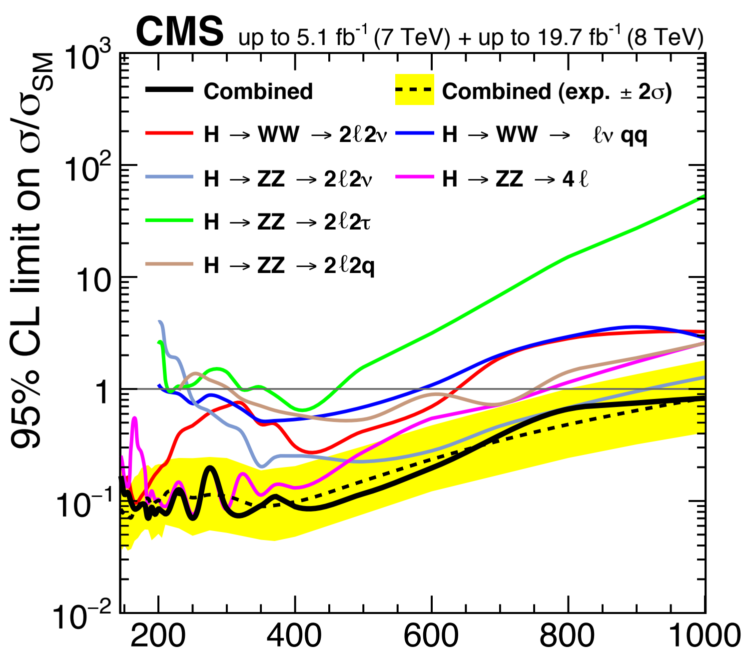
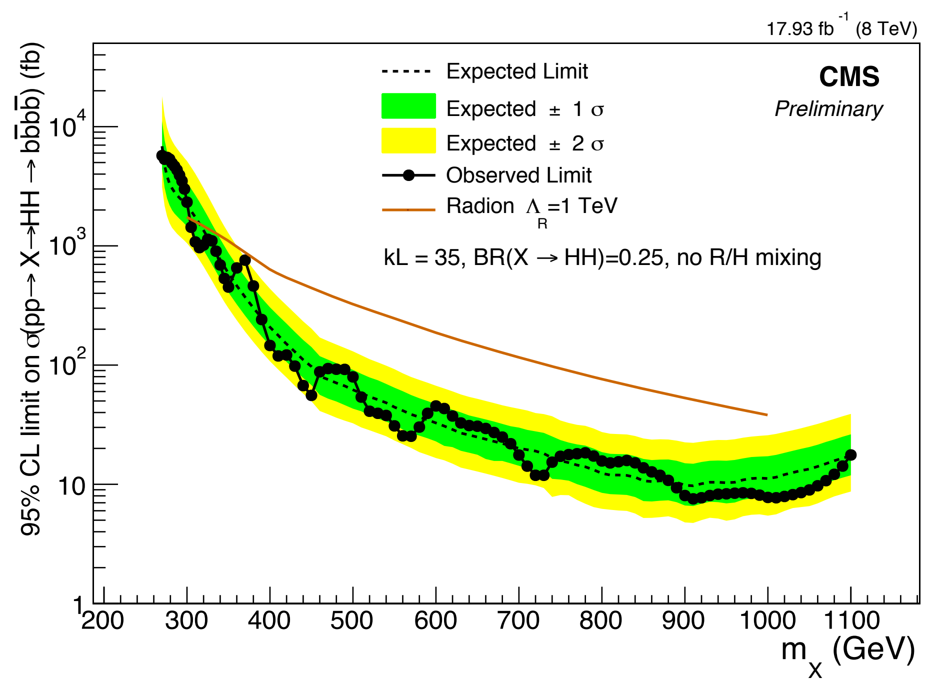


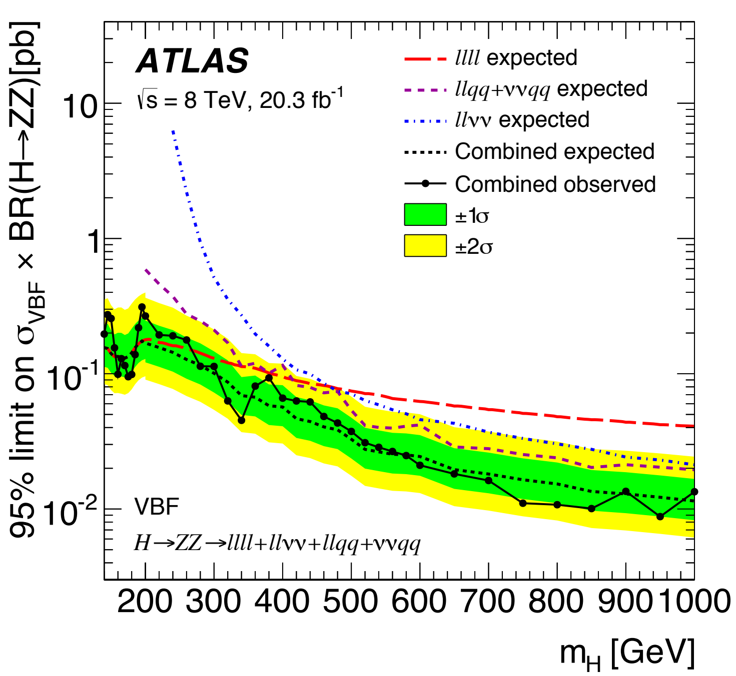


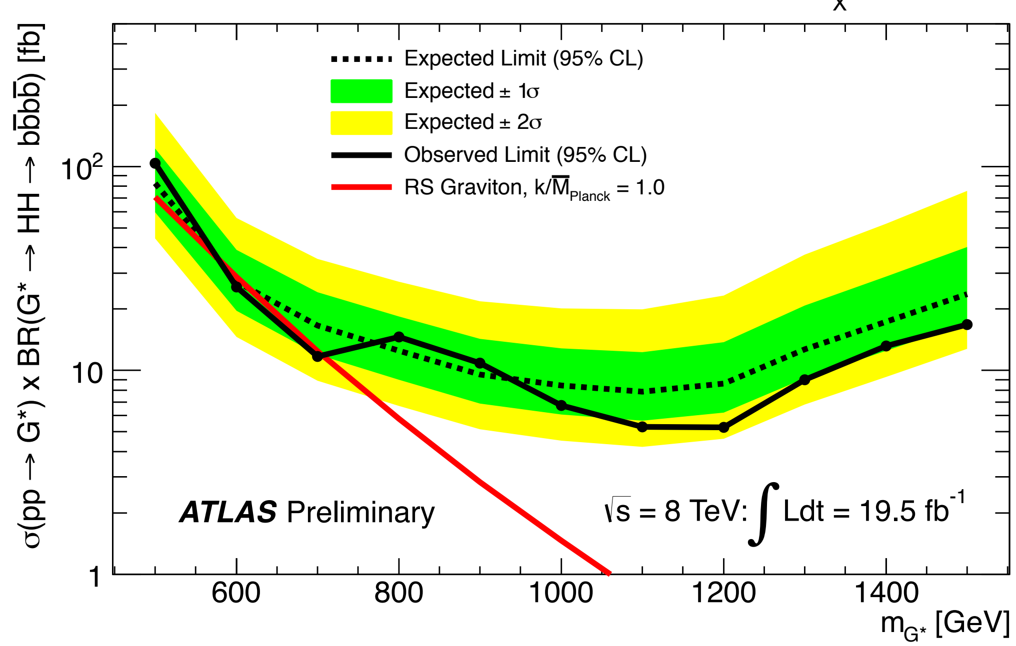
Direct searches: VV & hh

- Several LHC searches for resonances in the WW, ZZ, hh channels
- Run-I limits still stronger below ~ 1 TeV (but Run-II almost comparable)









- Combination of all ZZ, WW channels
- hh mainly 4b (also 2b2γ, 2b2τ, 4τ, 2b2W…)

Projections for the future

How to get fast estimates of the reach of future machines?

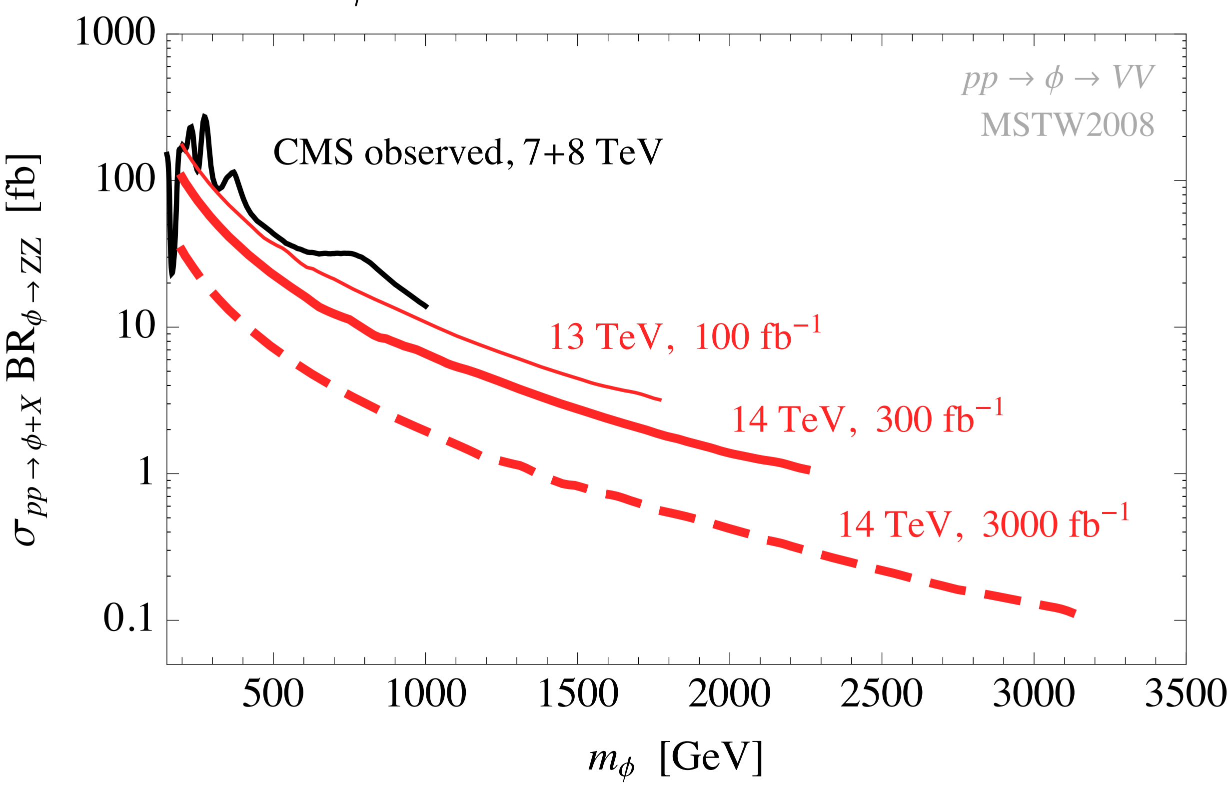
- Rescale 8 TeV LHC data with the parton luminosity of the bkg

see also Salam, Weiler '14; Thamm, Torre, Wulzer '15

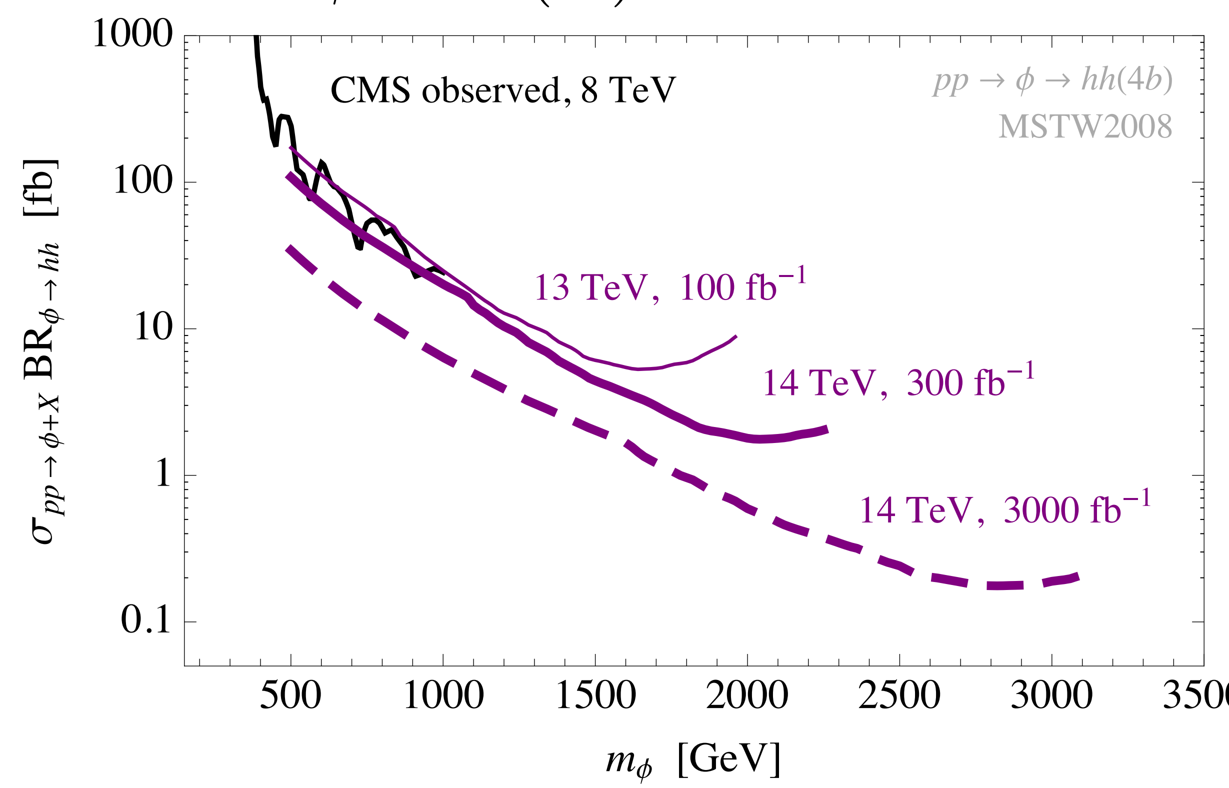
The limit on the cross-section is mainly determined by the number of background events around the resonance peak

DB, Sala, Tesi 1505.05488

$\phi \to VV$ channel



$\phi \to hh(4b)$ channel

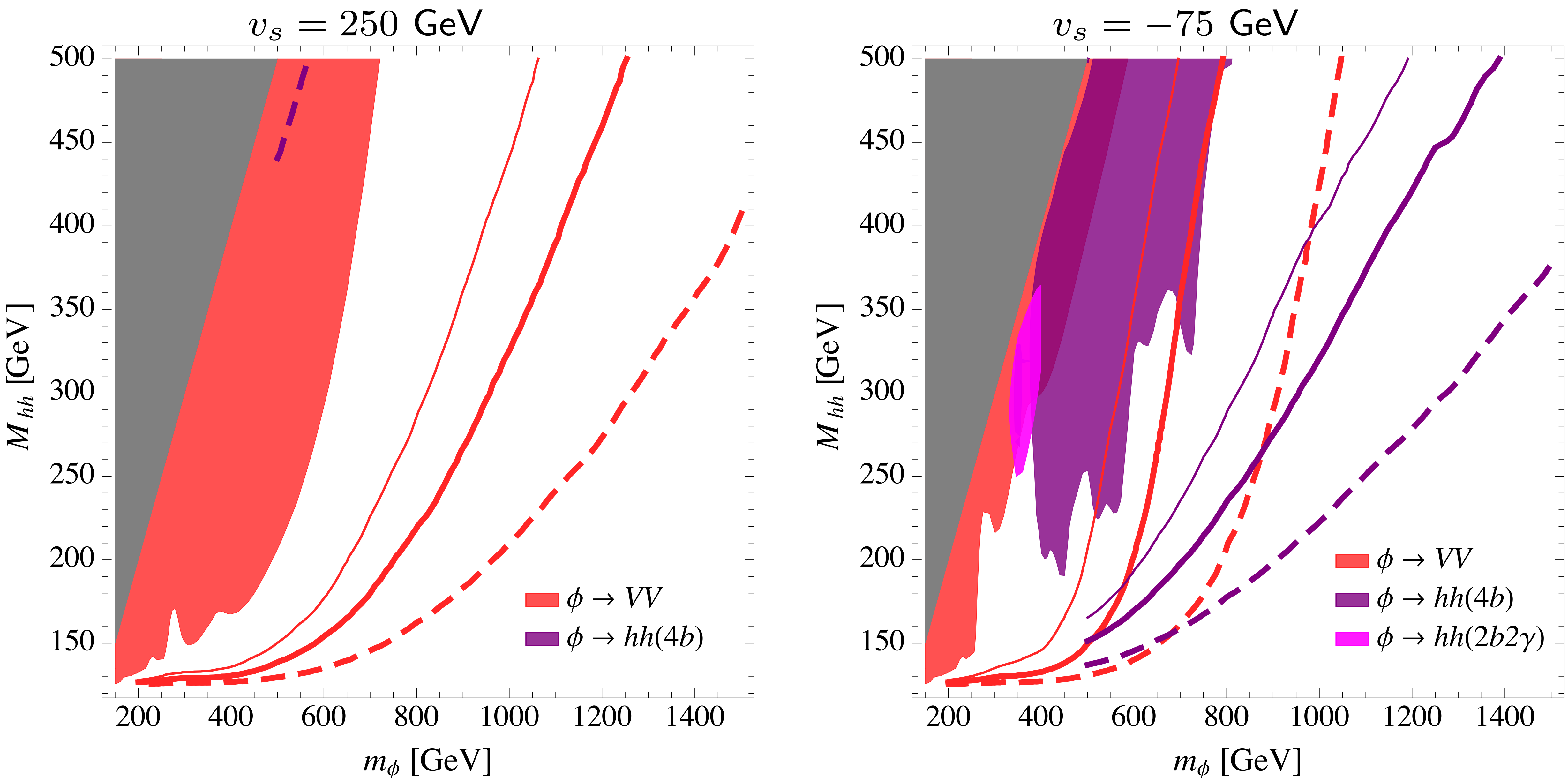


These results are valid for any scalar resonance decaying to VV, hh

Singlets: direct searches at the LHC

$$\sin\gamma^2 = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

$M_{hh} \propto v^2$ depends only on EW physics



Considering both $\phi \to VV$ and $\phi \to hh$ the combined reach does not strongly depend on $\mathrm{BR}_{\phi \to hh}$

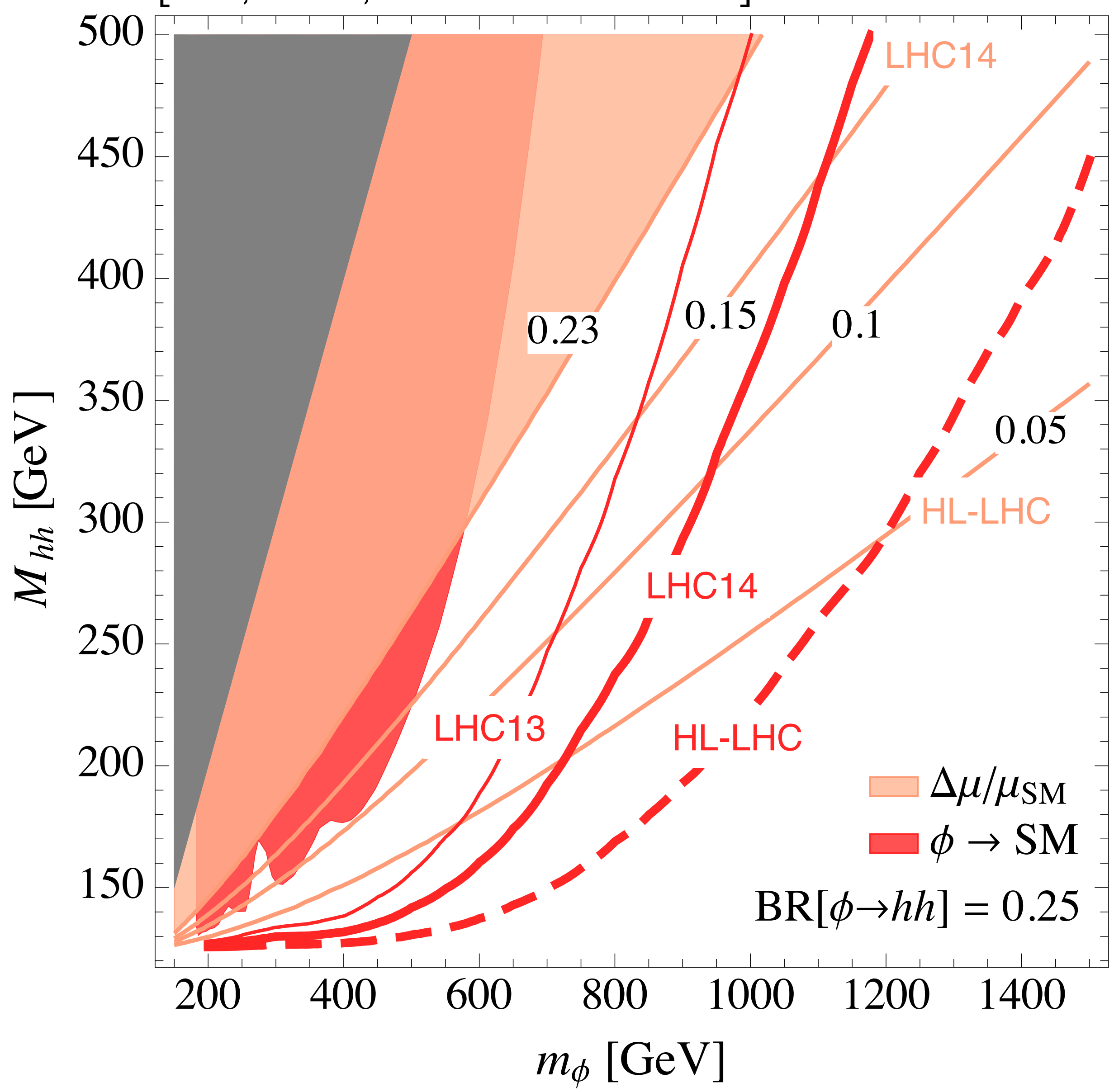
[DB, Sala, Tesi 1505.05488]

Singlets: direct vs. indirect

The mixing with ϕ induces modifications in the 125 GeV Higgs couplings

$$\frac{\Delta\mu}{\mu} \propto \sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

[DB, Sala, Tesi 1505.05488]



- Direct searches dominate over Higgs couplings for low masses
- LHC is starting to explore a new territory, still not probed by Higgs couplings.

more details in Filippo's talk

Diphotons

Facts about the diphoton excess

- 8 TeV: small fluctuations at 1-2 σ, but no significant excess
- 13 TeV: excess of events at the level of 3.5-4 σ
- Both ATLAS and CMS
- No other hard activity in the events

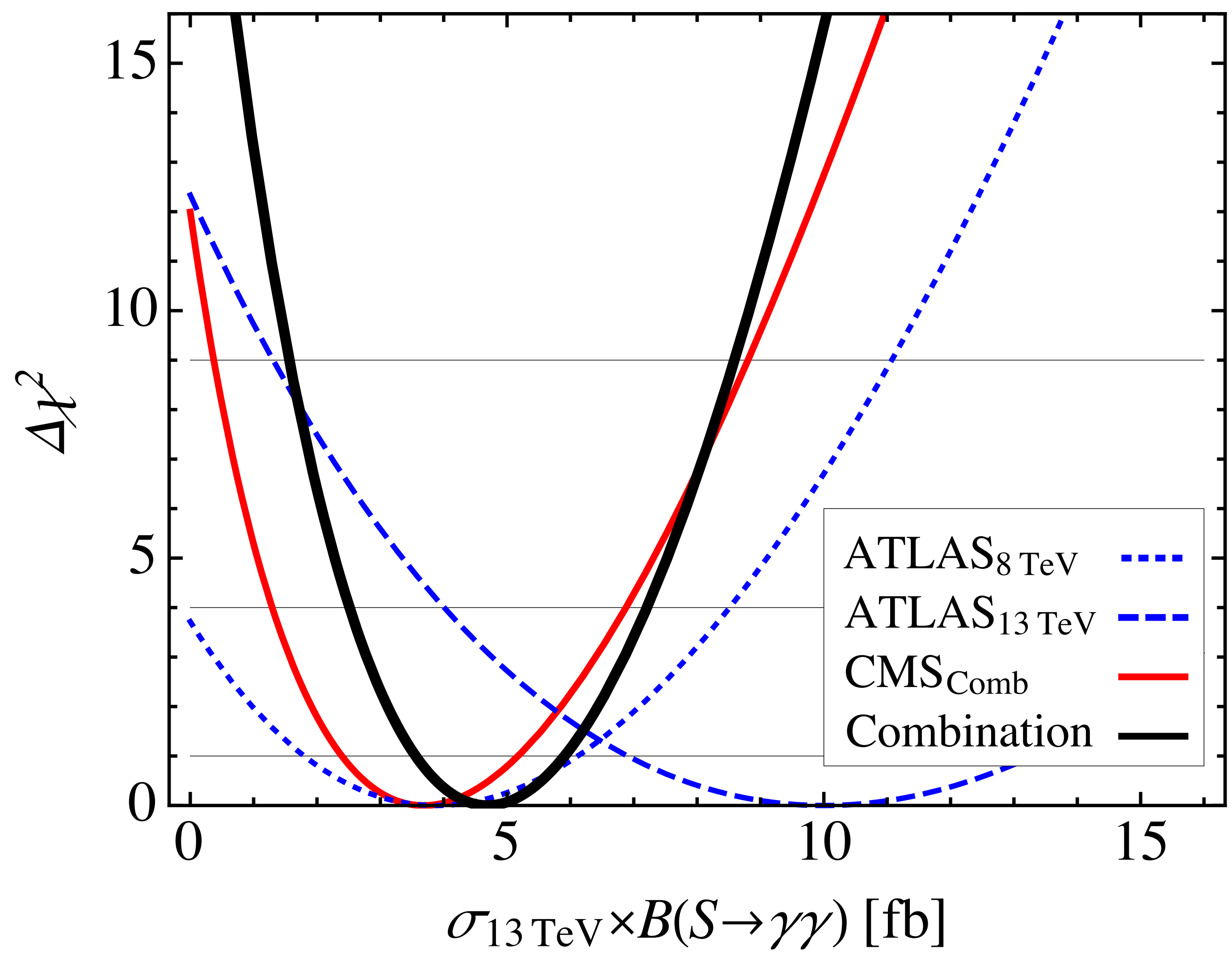
Production mode	gg	uu	dd	ss	cc	bb	$\gamma\gamma$
σ_{13}/σ_8	4.6	2.7	2.5	4.4	5	5.4	1.9

- A naïve combination, assuming gluon-fusion production:

$$\mu_{\gamma\gamma}(13\,\text{TeV}) = 4.7^{+1.2}_{-1.1}\,\text{fb}$$

[DB, Greljo, Marzocca 2016]

see also Franceschini et al. 2015
Falkowski et al. 2015
… many others…

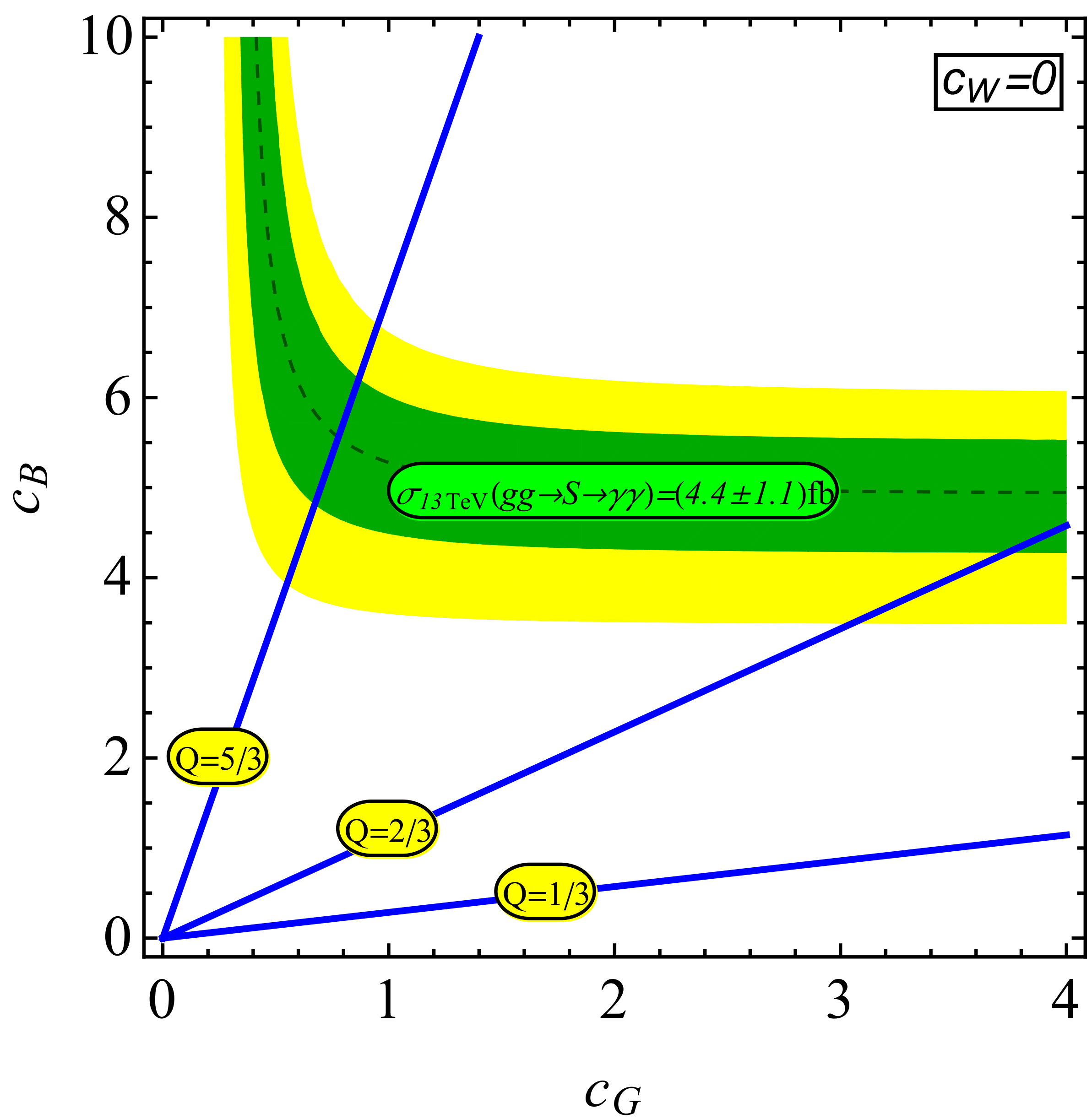


The minimal framework: only loops

$$\mathcal{L} = c_G \frac{\alpha_s}{12\pi m_\phi} \phi\, G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha}{4\pi m_\phi} \phi \left(c_W W^i_{\mu\nu} W^{i,\mu\nu} + c_B B_{\mu\nu} B^{\mu\nu} \right)$$

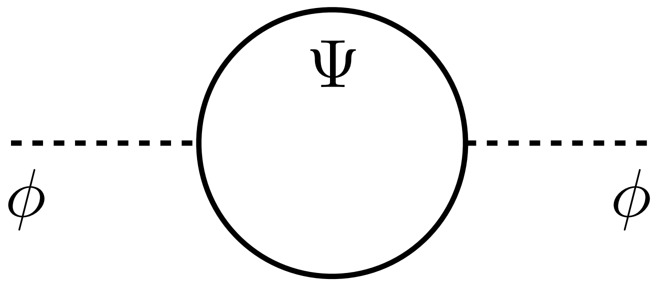
$$c_{\gamma\gamma} = c_B \cos\theta_w + c_W \sin\theta_w$$

$$\Gamma_S \simeq (4.1 c_G^2 + 0.022 c_B^2 + 0.064 c_W^2) \times 10^{-3}\,\text{GeV}$$



A simple realisation:

"everybody's model"



$$c_G = \sum_i g_i \frac{m_\phi}{m_{\Psi_i}} \qquad c_{\gamma\gamma} = \sum_i g_i \frac{m_\phi}{m_{\Psi_i}} N Q_i^2$$

Dijet bound:

$$\sigma(jj) < 1.8\,\text{pb} \quad \Rightarrow \quad c_G < 12$$

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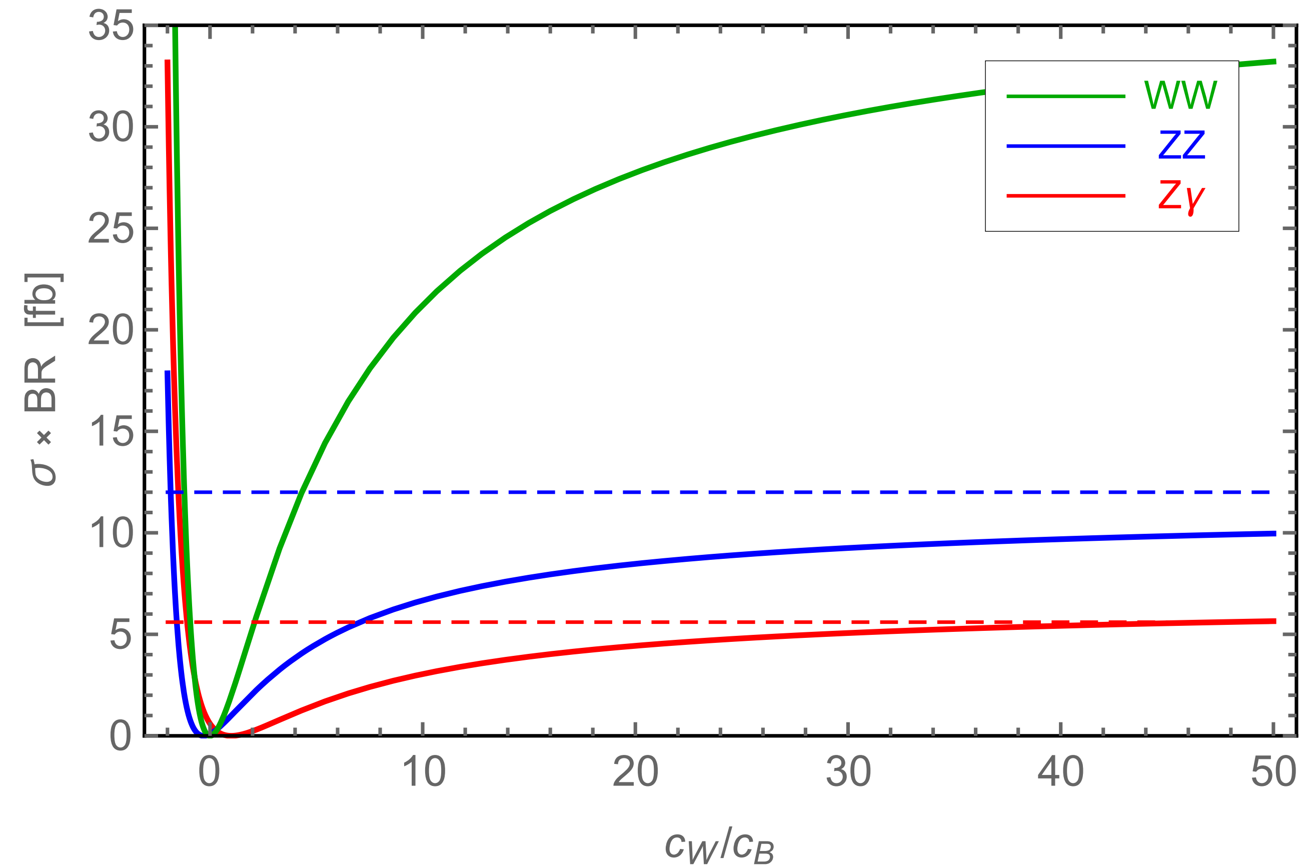
Other decay channels:

$$\frac{\mu_{Z\gamma}}{\mu_{\gamma\gamma}} = \frac{2(1-R_{WB})^2 \tan^2\theta_W}{(1+R_{WB}\tan^2\theta_W)^2}$$

$$\frac{\mu_{ZZ}}{\mu_{\gamma\gamma}} = \frac{(\tan^2\theta_W + R_{WB})^2}{(1+R_{WB}\tan^2\theta_W)^2}$$

$$\frac{\mu_{WW}}{\mu_{\gamma\gamma}} = \frac{2R^2_{WB}}{(\cos^2\theta_W + R_{WB}\sin^2\theta_W)^2}$$



($R_{WB} = c_W/c_B$)

Zγ searches @ 8 TeV: $\sigma(Z\gamma) < 5.6\,\mathrm{fb} \quad \Rightarrow \quad R_{WB} \gtrsim -1.1$

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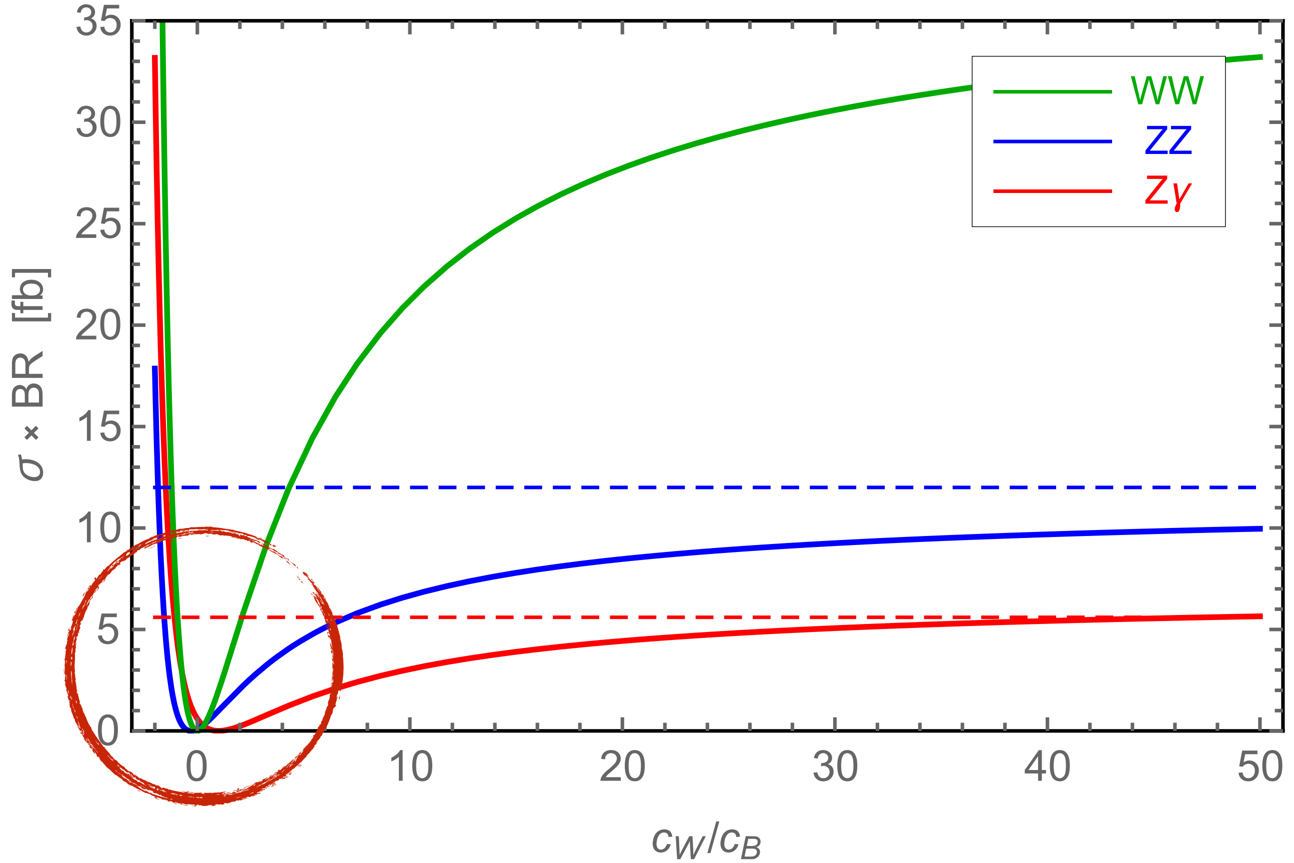


Zγ searches @ 8 TeV: $\sigma(Z\gamma) < 5.6\,\text{fb} \quad \Rightarrow \quad R_{WB} \gtrsim -1.1$

A generic scalar: other (tree-level) SM couplings

$$\mathcal{L} = c_V \frac{\phi}{m_\phi} \left(m_Z^2 Z_\mu Z^\mu + 2 m_W^2 W_\mu^+ W^{-\mu} \right) + c_f \frac{\phi}{m_\phi} m_f \bar{f} f$$
$$+ \frac{\phi}{m_\phi} \left(d_h \partial_\mu h \partial^\mu h - c_h \frac{m_h^2}{2} h^2 \right)$$

- Main decay widths:

$$\Gamma_{\phi \to ZZ} \simeq c_V^2 \times 6.8\,\text{GeV}\,,$$
$$\Gamma_{\phi \to WW} \simeq c_V^2 \times 13.9\,\text{GeV}\,,$$
$$\Gamma_{\phi \to hh} \simeq (d_h + 0.029 c_h)^2 \times 6.3\,\text{GeV}\,,$$
$$\Gamma_{\phi \to t\bar{t}} \simeq c_t^2 \times 3.3\,\text{GeV}$$

- Singlet: $c_V \sim c_f$
- Pseudo-scalar: $c_V = 0$
- Other SU(2) representation: charged states at ~ 750 GeV

- Contribution to γγ and gg also from SM loops:

$$\Gamma_{\phi \to \gamma\gamma} \simeq |c_{\gamma\gamma} + (-0.74 + 0.94i) c_V + (0.40 - 0.99i) c_t|^2 \times 2.3 \times 10^{-5}\,\text{GeV}$$
$$\Gamma_{\phi \to gg} \simeq \left| c_{gg} + \frac{3}{4}(0.59 + 1.5i) c_t \right|^2 \times 4.1 \times 10^{-3}\,\text{GeV}$$

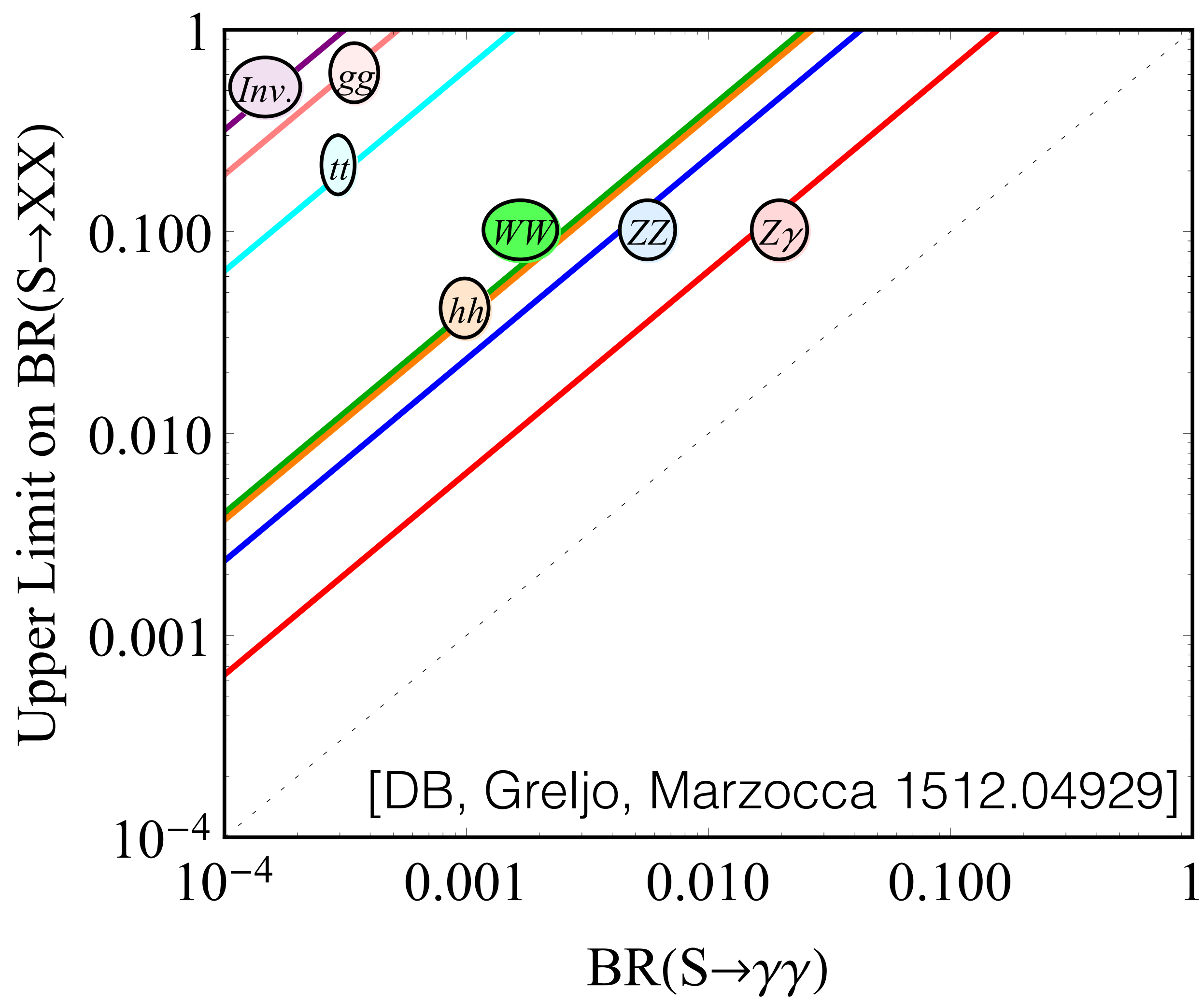
It is not possible to get the γγ signal only with SM particles: $\Gamma_{tt} \gtrsim 10\, m_\phi$

Experimental bounds

- Run-I limits still stronger at 750 GeV (but Run-II almost comparable)

Observed limits on σ x BR from various resonance searches:

Channel	ATLAS [fb]	CMS [fb]
γγ	1.3	2.2
jj	1800	–
ZZ	27	12
Zγ	–	6
WW	220	38
hh	52	35
tt	600	700
Invisible	–	3000

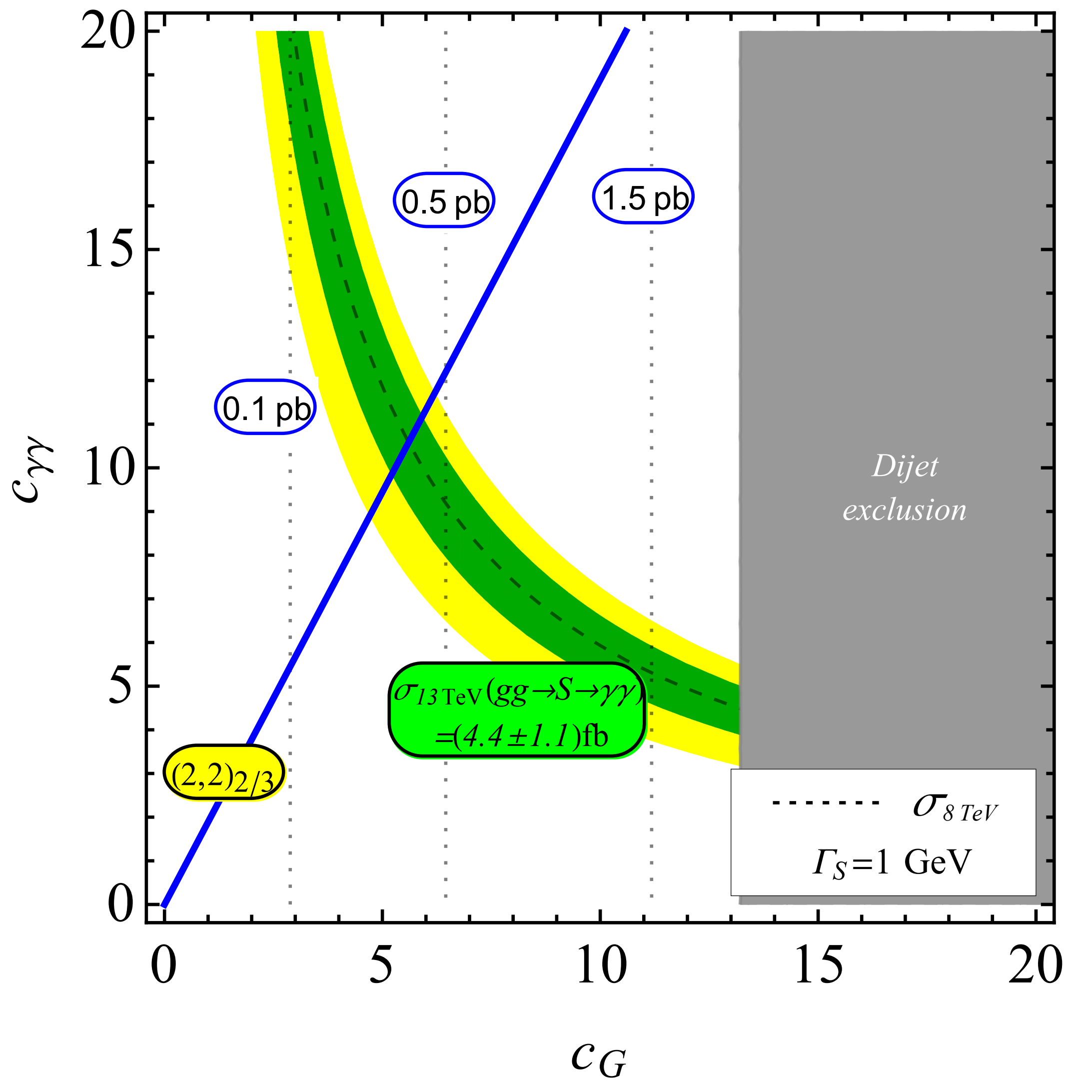


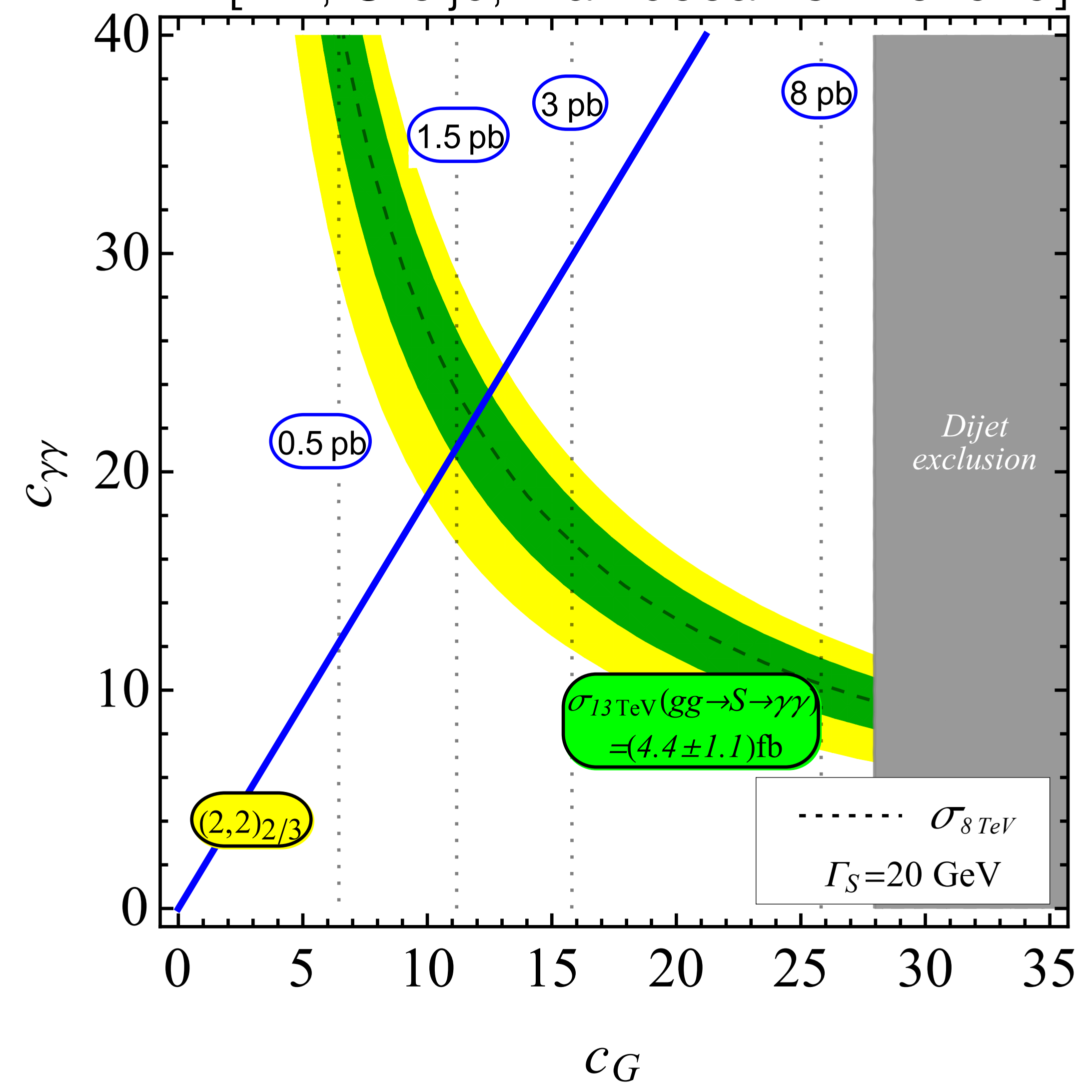
Assuming a diphoton signal that fits the excess: limits on BR's

Large width

$$\mu_{13\,\text{TeV}} = \sigma_{pp\to\phi} \times \mathcal{B}_{\phi\to\gamma\gamma} \simeq 6.3\times10^{-5}\left(\frac{20\,\text{GeV}}{\Gamma_\phi}\right) c_G^2 c_{\gamma\gamma}^2\ \text{fb}$$

[DB, Greljo, Marzocca 1512.04929]





- Dijet bound: $\sigma_{8\,\text{TeV}} \times \mathcal{B}_{\phi\to gg} \simeq 2.4\times10^{-3}\left(\frac{20\,\text{GeV}}{\Gamma_\phi}\right) c_G^4\ \text{fb} \lesssim 1.8\times10^{3}\ \text{fb}$
- A large width (~ 45 GeV) can be only into tt or invisible!

Supersymmetry

SUSY: the NMSSM

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \lambda S H_u H_d + f(S)$$

- MSSM + a scalar singlet: 3 CP-even states (*h*,*H*,*S*), 2 CP-odd (*A*, *P*)
  - ➡ interesting limit when one doublet is heavy: h – S mixing

    A simple case analogous to the one already discussed

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- Extra tree-level contribution to the Higgs mass

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

- Alleviates fine-tuning of the electroweak scale for λ ~ 1 and small tan β

$$\delta v^2\Big|_{\rm NMSSM} \sim \frac{\cot 2\beta}{\lambda^3} \times \tilde{m}^2 \qquad\qquad \delta v^2\Big|_{\rm MSSM} \sim \frac{4}{g^2} \times \tilde{m}^2$$

- Non-perturbative regime at high scales (100 – 1000 TeV) if λ > 0.7

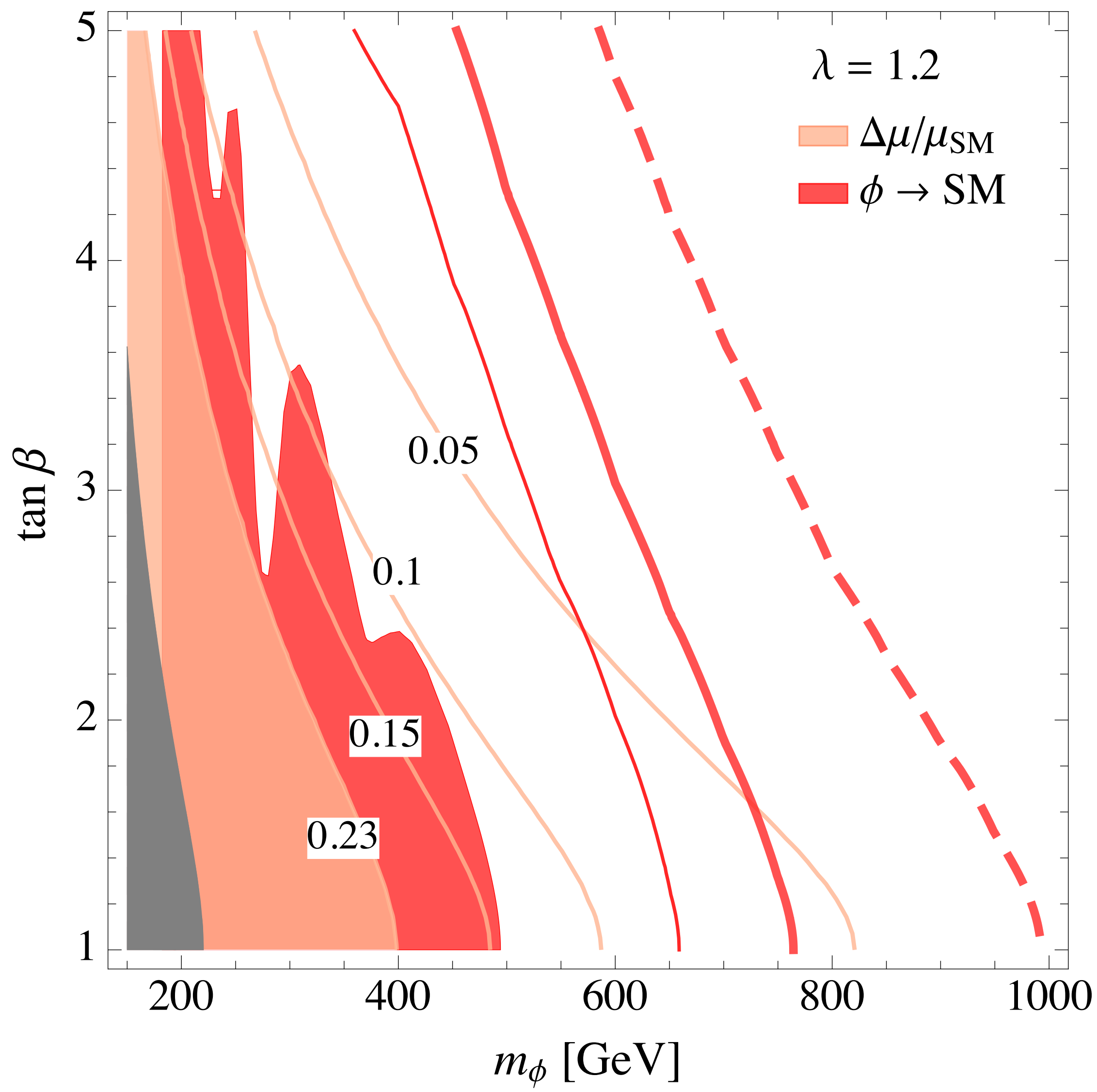
SUSY: the NMSSM

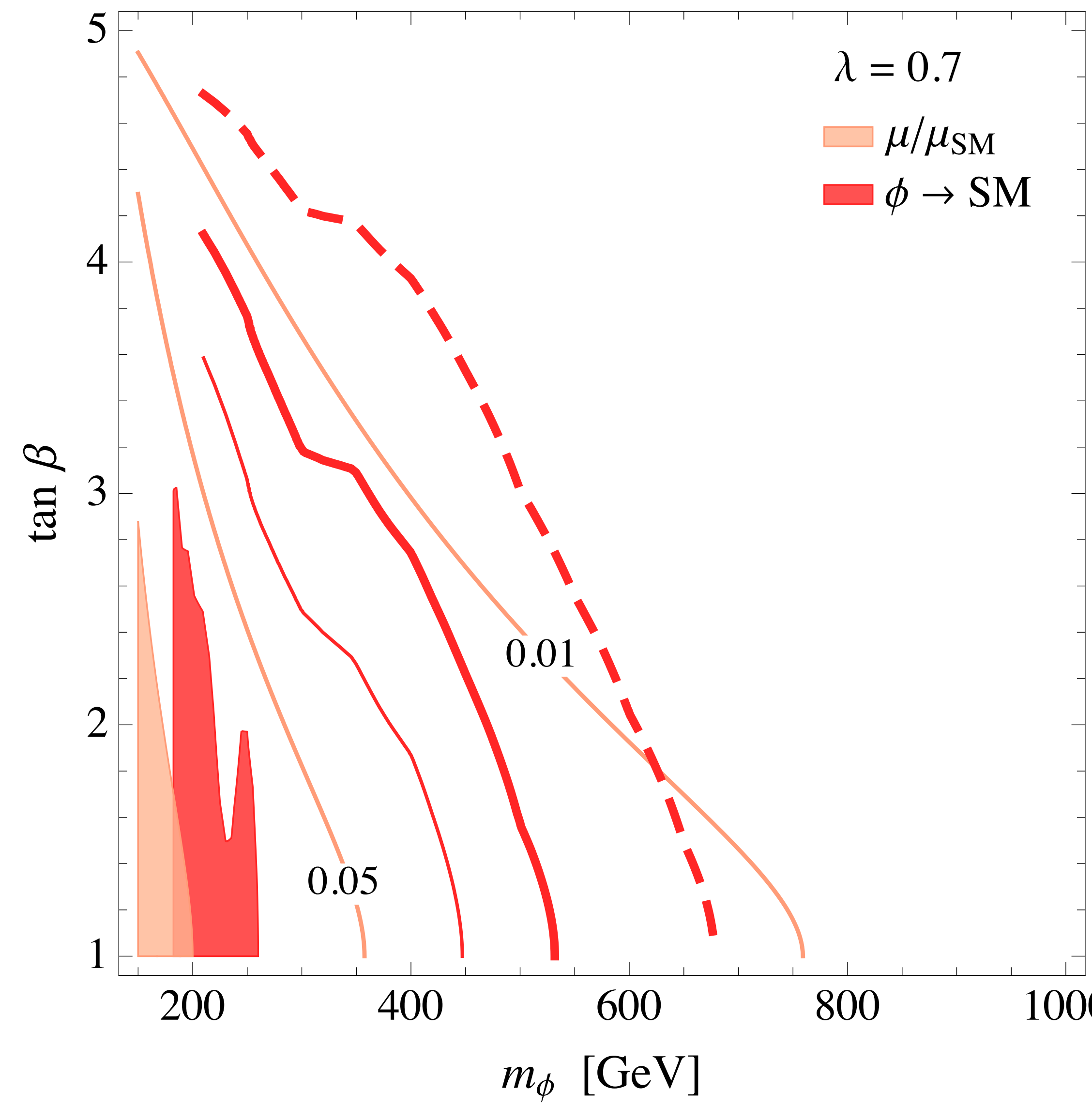
- Recast the bounds for a generic singlet in the (M_{hh}, m_ϕ) plane

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

Δ ~ 70 – 80 GeV
(fixed by stop masses
and A terms < TeV)

[DB, Sala, Tesi 1505.05488]





The NMSSM with vector-like matter

- Can the singlet of the NMSSM be responsible for the γγ excess?

➡ **Need for extra matter!** Can this be motivated by fundamental arguments?

★ SUSY particles in the loop not sufficient (unless more complicated final-state)

Add 1 generation of vector-like matter:

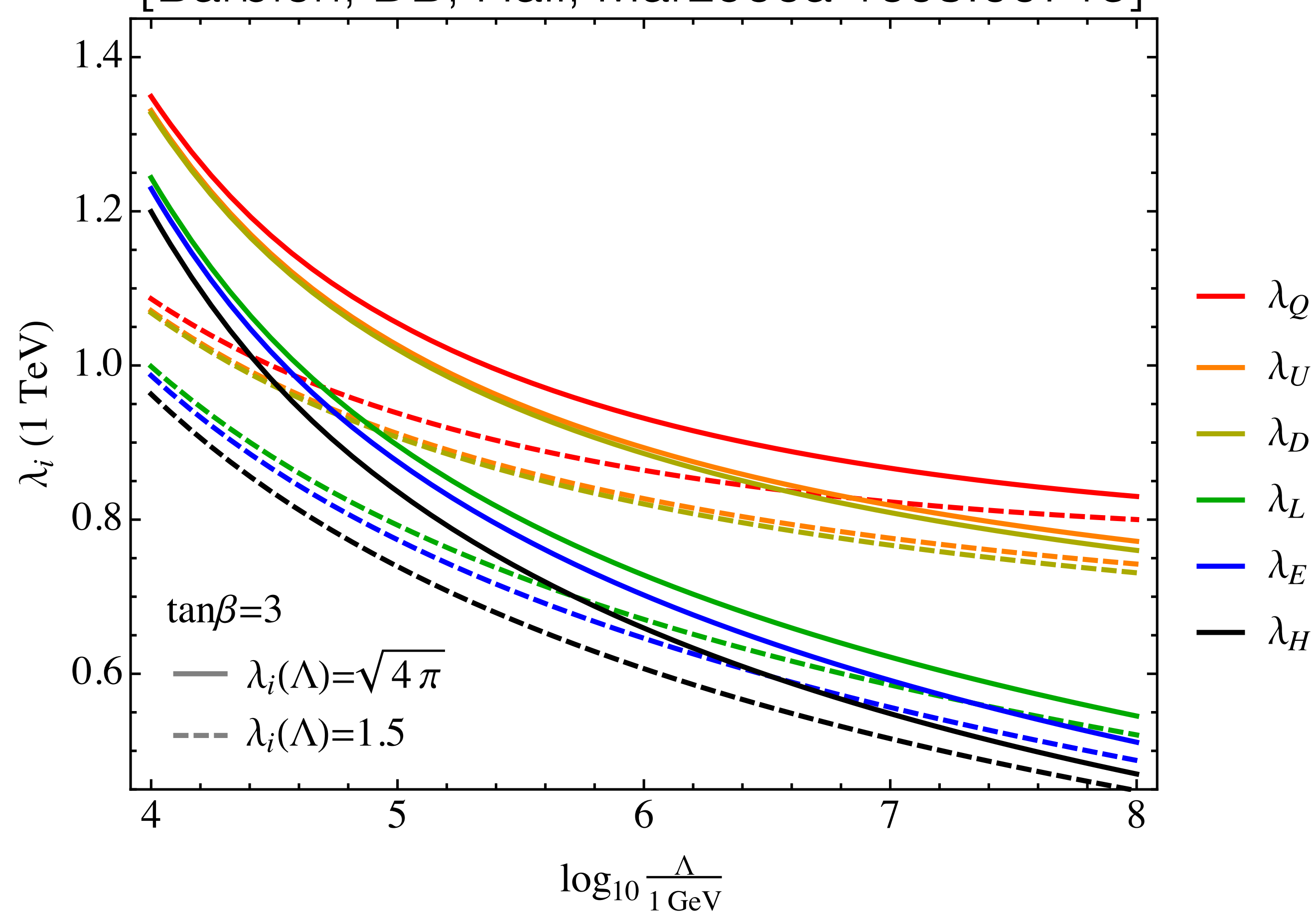
$$\Delta\mathcal{W} = \lambda_H S H_u H_d + \sum_i \lambda_i S \Phi_i \bar{\Phi}_i + \frac{\kappa}{3} S^3$$

scale invariant potential

- Masses of vector-like fermions $M_{\Phi_i} = \lambda_i v_s$ (and $\mu_H = \lambda_H v_s$)
- Assume all the Yukawa couplings get large at a common scale Λ

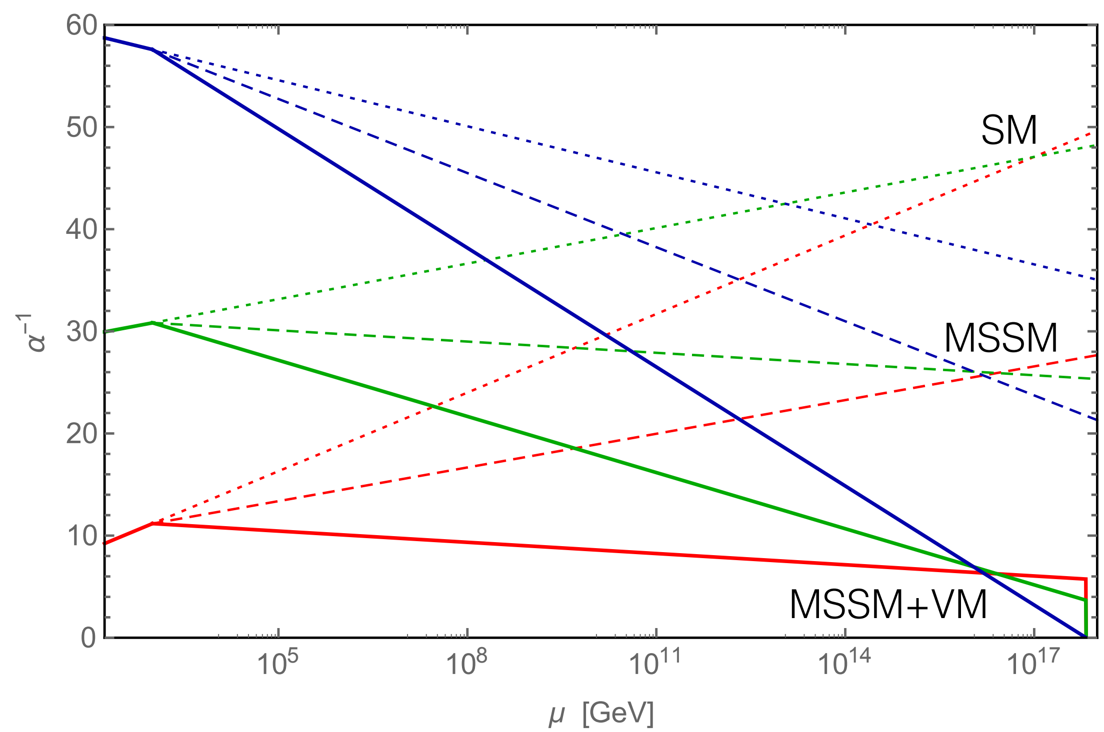
unification not necessarily spoiled

[Barbieri, DB, Hall, Marzocca 1603.00718]



The NMSSM with vector-like matter

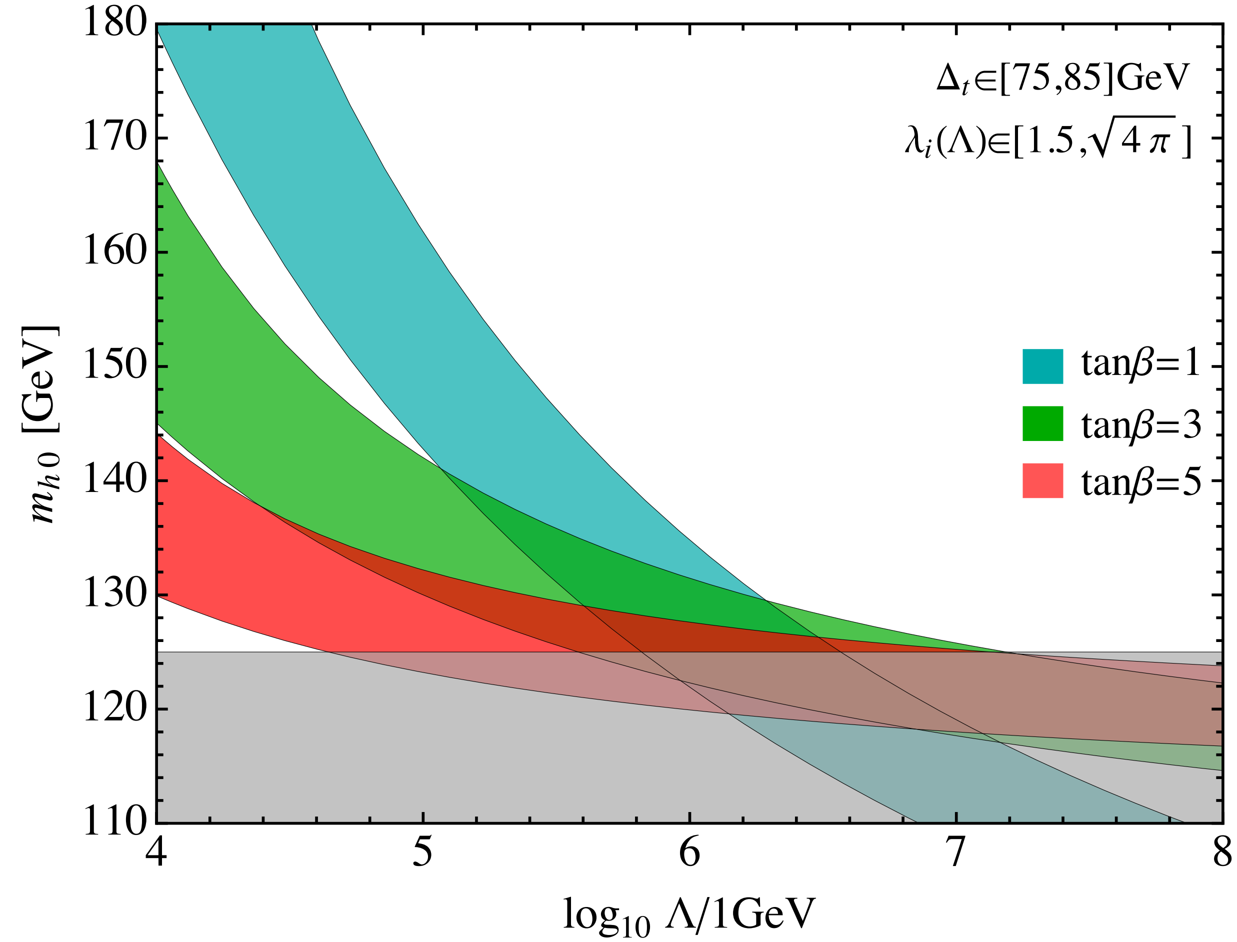
➡ The gauge couplings unify at a semi-perturbative value



[Barbieri, DB, Hall, Marzocca 1603.00718]

➡ If $\Lambda \sim 10^4 - 10^7$ GeV, from RGE running one gets $\lambda_H \sim 0.6 - 1$

Higgs mass naturally reproduced!

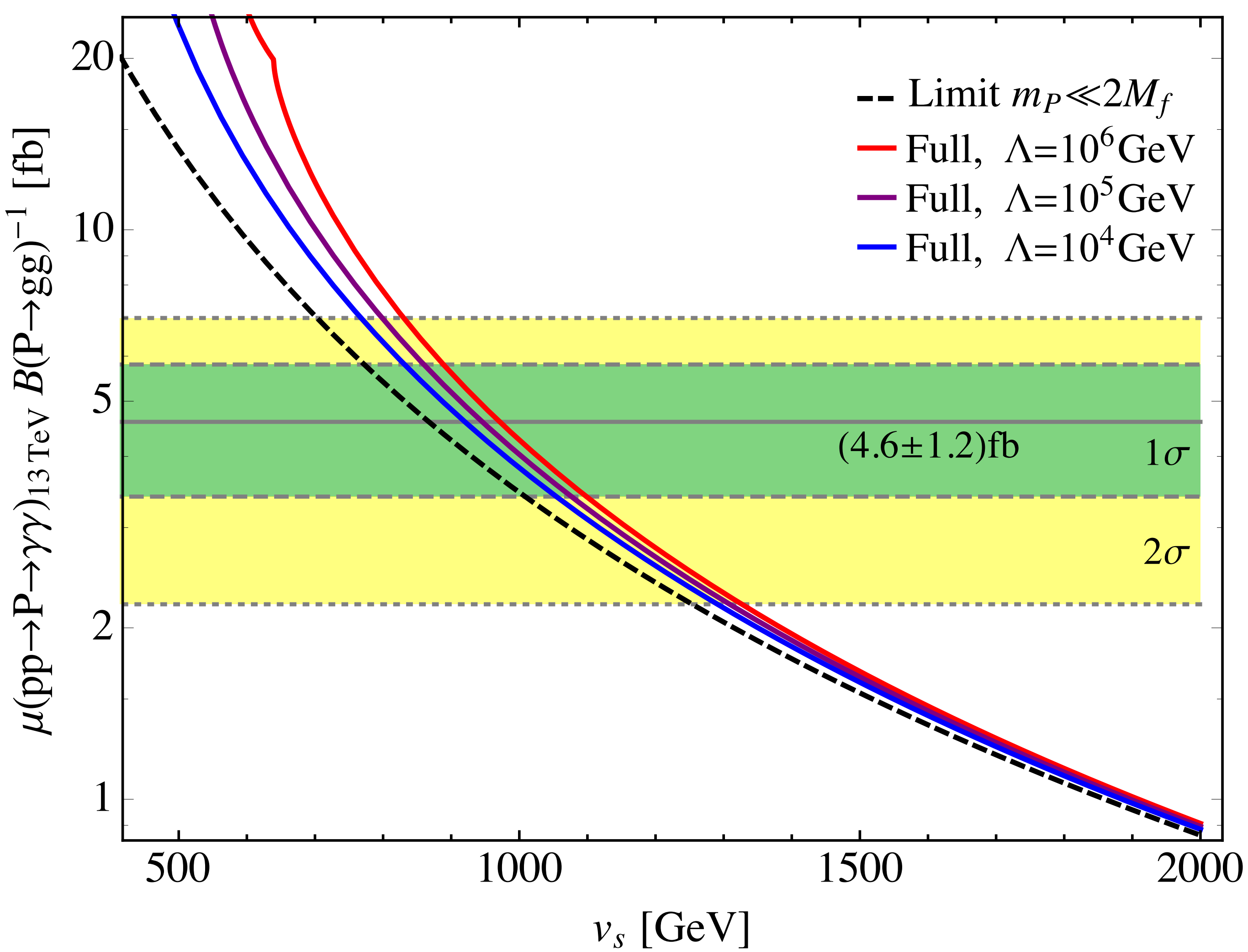


Pseudo-scalar phenomenology: diphoton

- Diphoton: scalar or pseudo-scalar?

S mixes with h: $\frac{\Gamma(S\to ZZ)}{\Gamma(S\to\gamma\gamma)} = 3\times10^6 \frac{s_\gamma^2}{|c_{\gamma\gamma}|^2} \lesssim 6 \quad \Rightarrow \quad s_\gamma \lesssim 10^{-3}|c_{\gamma\gamma}|$ ✗

P mixes with A: $\frac{\Gamma(P\to t\bar{t})}{\Gamma(P\to\gamma\gamma)} = 2\times10^6 \frac{s_\theta^2}{t_\beta^2|c_{\gamma\gamma}|^2} \lesssim 300 \quad \Rightarrow \quad s_\theta \lesssim 10^{-2}t_\beta|c_{\gamma\gamma}|$ ✓



$$c_{gg,\gamma\gamma} \sim \sum \lambda_i \frac{m_P}{M_i} = \sum \frac{m_P}{v_s}$$

➡ Diphoton signal can be reproduced for v_s ~ TeV

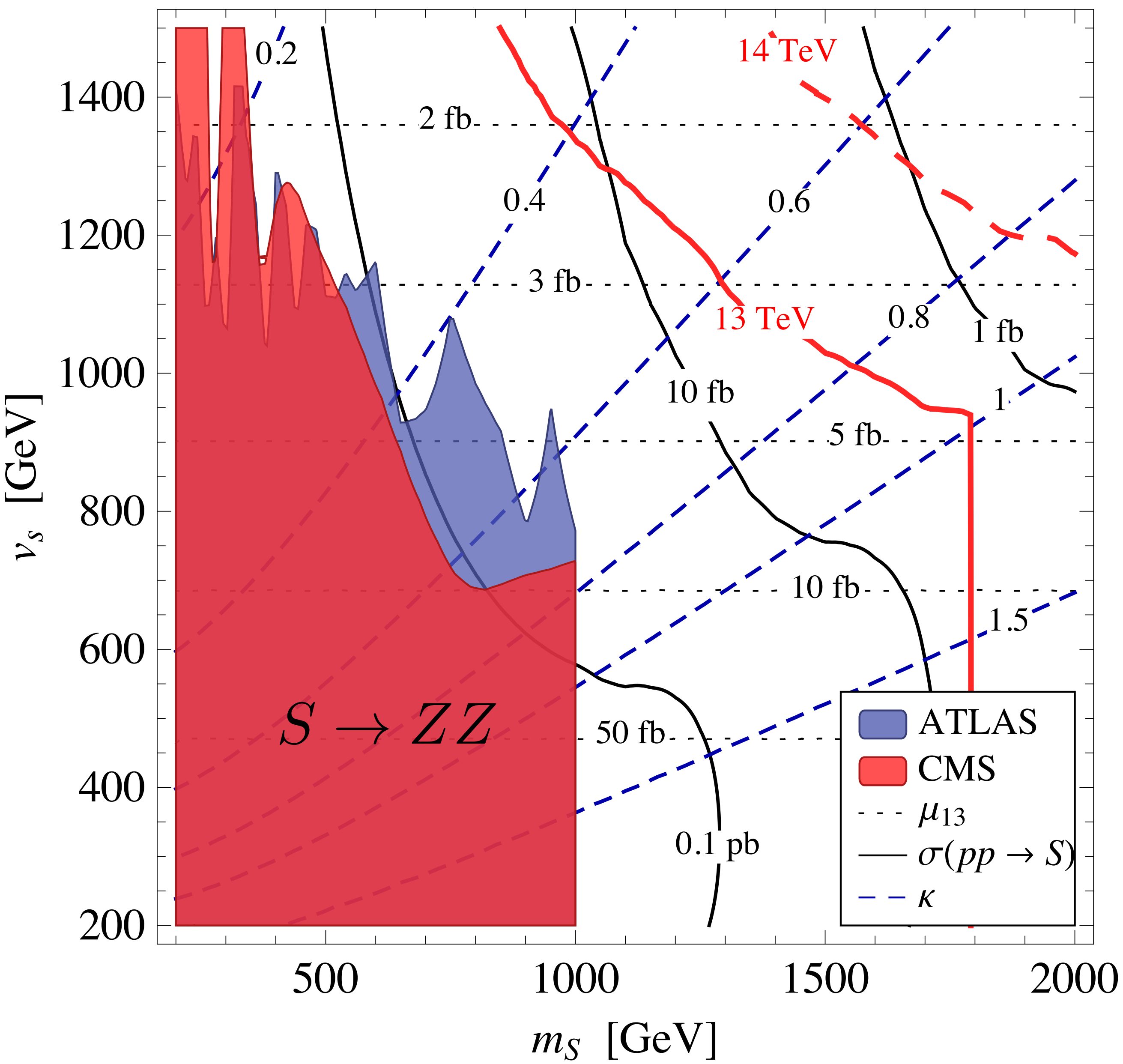
$$s_\theta \lesssim 0.05 \quad \Rightarrow \quad \mathrm{BR}(P\to t\bar{t}) \lesssim 20\%$$

$$\mu_{WW} \sim 25\,\mathrm{fb}$$
$$\mu_{ZZ} \sim 10\,\mathrm{fb}$$
$$\mu_{Z\gamma} \sim 1.5\,\mathrm{fb}$$

Scalar phenomenology: diboson

- The real scalar mixes with the Higgs, $s_\gamma^2 = \frac{M_{hh}^2 - m_h^2}{m_S^2 - m_h^2} \approx 10^{-2} \div 10^{-3}$
- Mass predicted in terms of the parameters of the potential (v_s, κ)

[Barbieri, DB, Hall, Marzocca 1603.00718]



$$m_S^2 = 4\kappa^2 v_s^2 - \frac{m_P^2}{3}$$

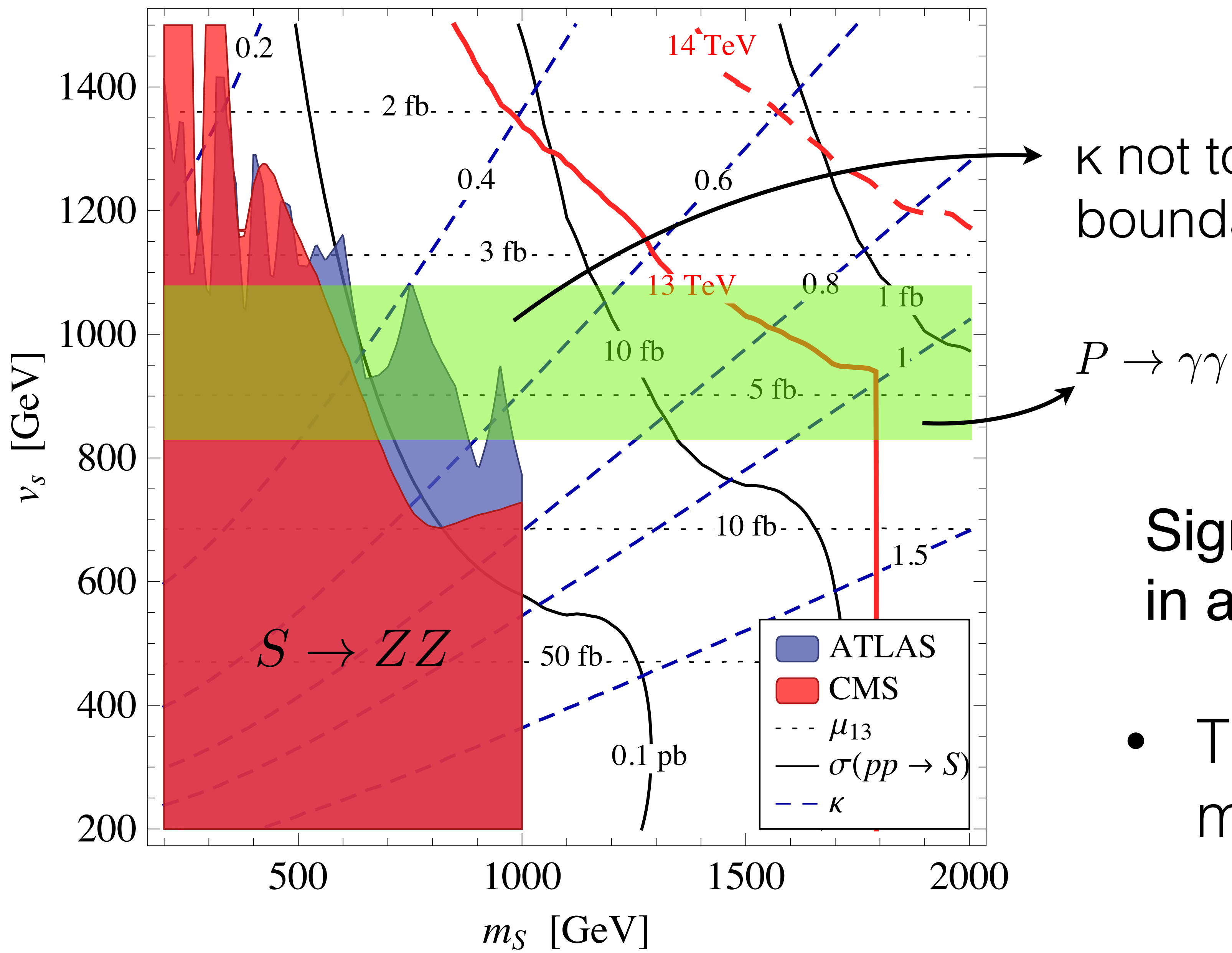
Scalar phenomenology: diboson

- The real scalar mixes with the Higgs, $s_\gamma^2 = \frac{M_{hh}^2 - m_h^2}{m_S^2 - m_h^2} \approx 10^{-2} \div 10^{-3}$

- Mass predicted in terms of the parameters of the potential (v_s, κ)

$$m_S^2 = 4\kappa^2 v_s^2 - \frac{m_P^2}{3}$$

[Barbieri, DB, Hall, Marzocca 1603.00718]



Signal in ZZ expected soon, in any case in Run-II!

- The other doublet is heavy, m_A ~ 1 – 2 TeV

Composite scalars and vectors

Heavy vectors

- Simple parametrisation: HVT

[Pappadopulo, Thamm, Torre, Wulzer 2014]

$$\mathcal{L}_{\mathrm{HVT}} = -\frac{1}{4} D_{[\mu} V_{\nu]}^{a} D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V_\mu^a V^{\mu a} + g_H V_\mu^a (H^\dagger \tau^a i \overleftrightarrow{D}_\mu H) + V_\mu^a J^{\mu a} + \cdots$$

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bounded by LEP data:

- S parameter
- Zff couplings

- If Vff couplings flavour-universal, no effect on Z fermion couplings

  [see e.g. 1402.4431]

- If V couples mainly to 3rd gen. strongest bound from Zbb

  [see e.g. 1506.01705]

Heavy vectors

- Simple parametrisation: HVT

[Pappadopulo, Thamm, Torre, Wulzer 2014]

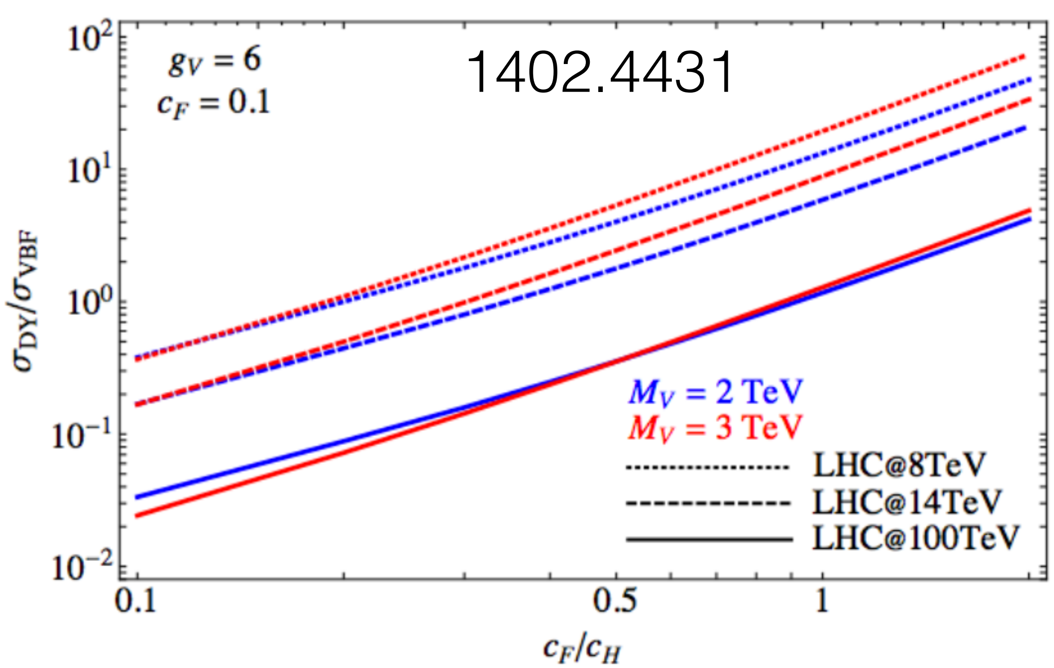
$$\mathcal{L}_{\rm HVT} = -\frac{1}{4} D_{[\mu}V^a_{\nu]} D^{[\mu}V^{\nu]a} + \frac{m_V^2}{2} V^a_\mu V^{\mu a} + g_H V^a_\mu (H^\dagger \tau^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^{\mu a} + \cdots$$

only term responsible for V-diboson couplings (g_H)

bounded by LEP data ($V^a_\mu (H^\dagger \tau^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^{\mu a}$):
- S parameter
- Zff couplings

$$\Gamma(V \to WW) \simeq \Gamma(V \to Zh) \simeq \frac{g_V m_V}{192\pi} + \cdots$$

Main production mechanisms: VBF and Drell-Yan
(the details depend on the model)



- If Vff couplings flavour-universal, no effect on Z fermion couplings [see e.g. 1402.4431]
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Heavy vectors

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only term responsible for V-diboson couplings

bounded by LEP data:
- S parameter
- Zff couplings

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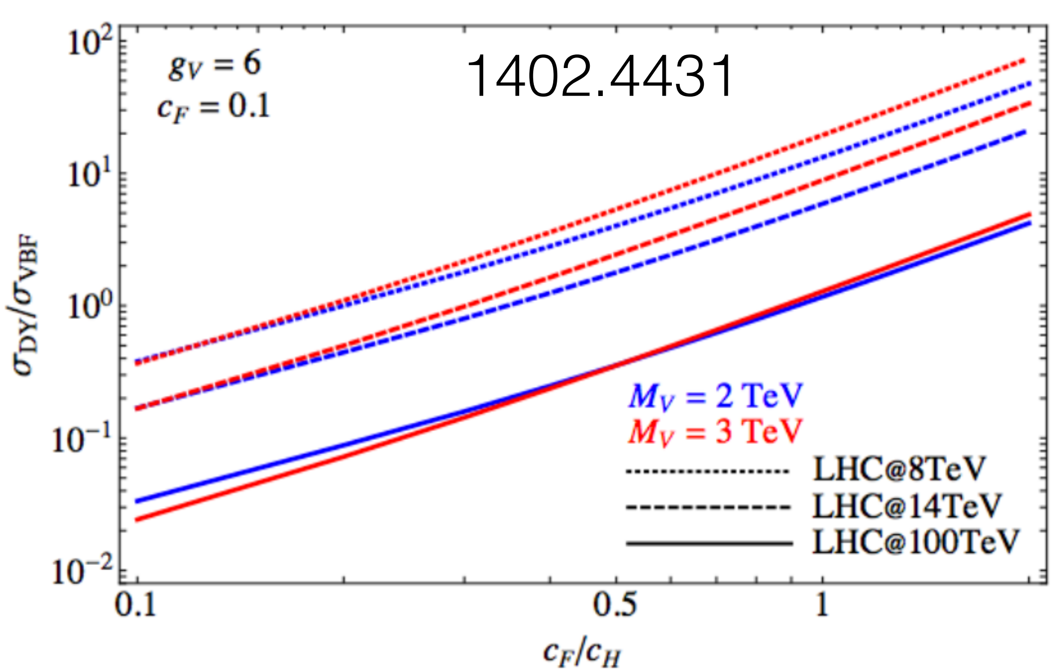


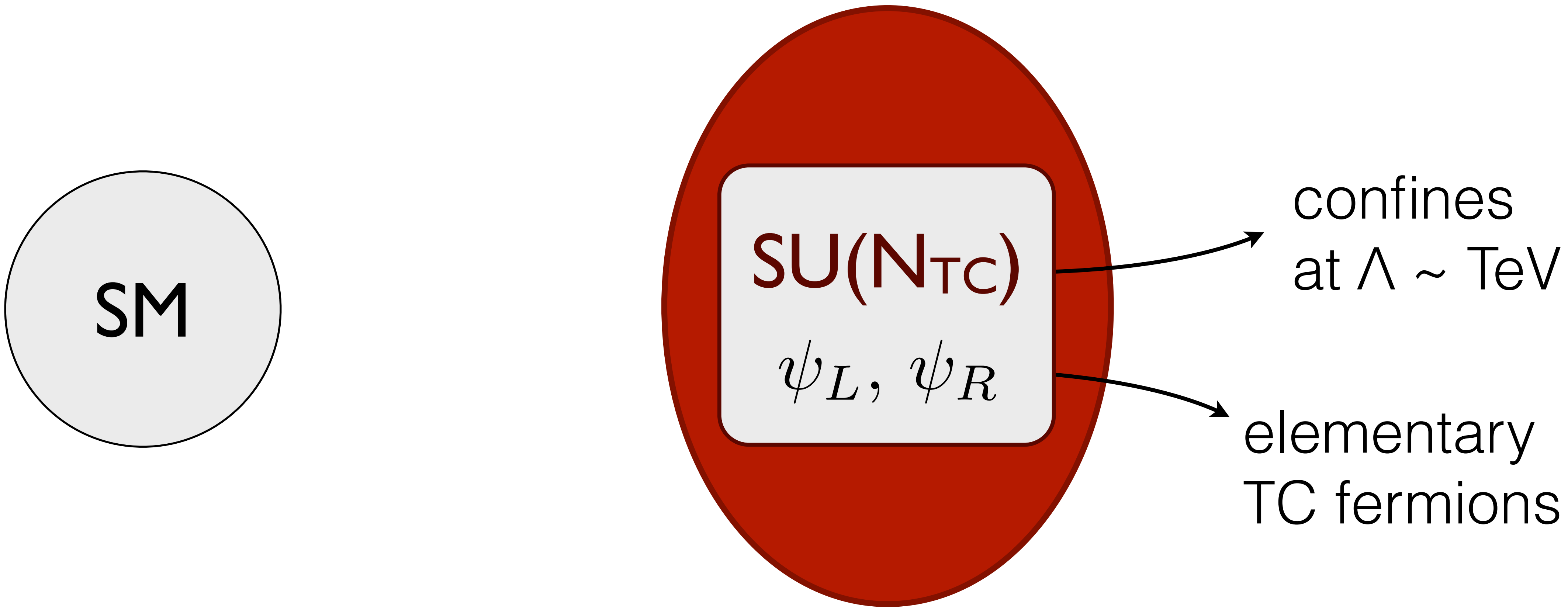
- If Vff couplings flavour-universal, no effect on Z fermion couplings [see e.g. 1402.4431]
- If V couples mainly to 3rd gen. strongest bound from Zbb [see e.g. 1506.01705]

LHC is now really starting to probe the interesting region of masses > 2 TeV

see previous 2 talks

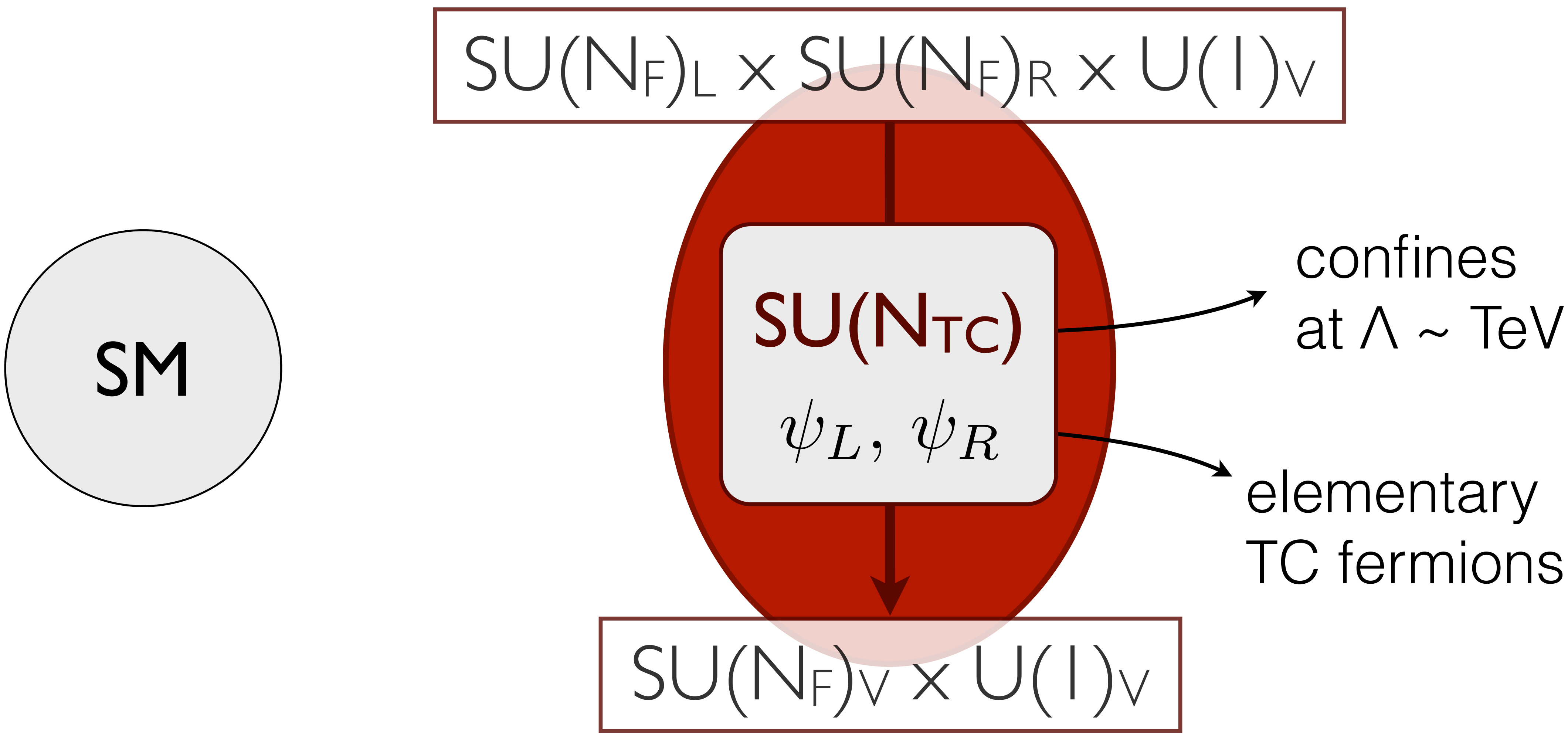
Vector-like confinement

- A new strongly interacting sector with confining gauge group SU(N_{TC})



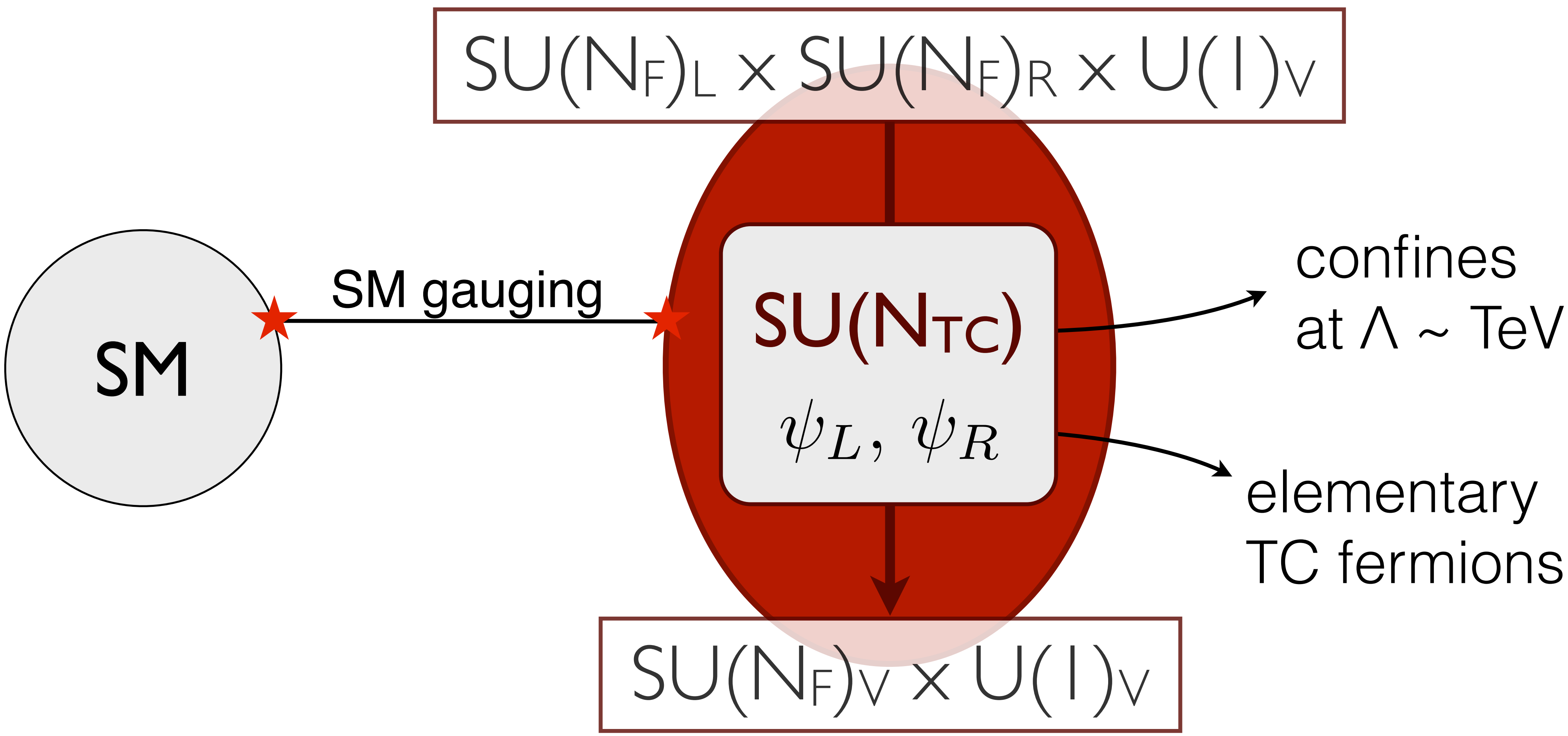
Vector-like confinement

- A new strongly interacting sector with confining gauge group SU(N_{TC})
- Global flavour symmetry SU(N_F) x SU(N_F), spontaneously broken



Vector-like confinement

- A new strongly interacting sector with confining gauge group $SU(N_{TC})$
- Global flavour symmetry $SU(N_F) \times SU(N_F)$, spontaneously broken
- Higgs not necessarily part of the composite sector (but could be)



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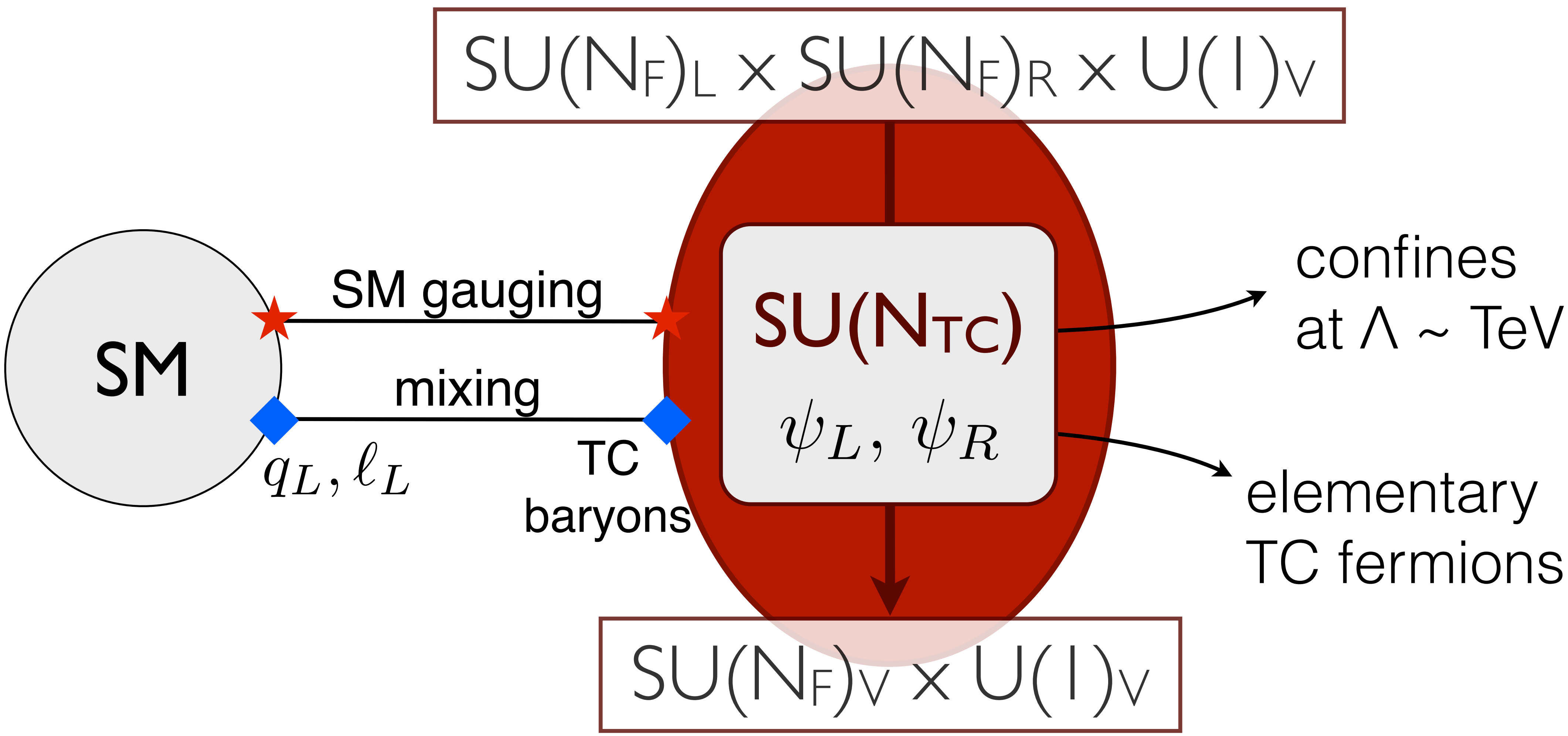


➡ pNGB: $\pi^{\pm}, \pi^0, \eta, \cdots$

➡ Vector mesons: $\rho^{\pm}, \rho^0, \omega, \phi, \cdots$

Diphotons from pions

- Chiral symmetry breaking $\mathrm{SU}(N_F) \times \mathrm{SU}(N_F) \longrightarrow \mathrm{SU}(N_F)$
  N_F^2 - 1 (pseudo) Goldstone bosons

$$\mathcal{L}_{\chi\mathrm{PT}} = \frac{f^2}{4}\left(\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right] + 2B_0(\mathrm{Tr}[M\Sigma] + \mathrm{Tr}[M^\dagger\Sigma^\dagger])\right)$$

$\Sigma = \exp\left(\frac{2i}{f}t^a\pi^a\right)$ Goldstone matrix, $M = \mathrm{diag}(m_{\psi_i})$ $\langle\psi_i\bar{\psi}_j\rangle = -f^2B_0\delta_{ij}$

[see also Redi et al. 1602.07297]

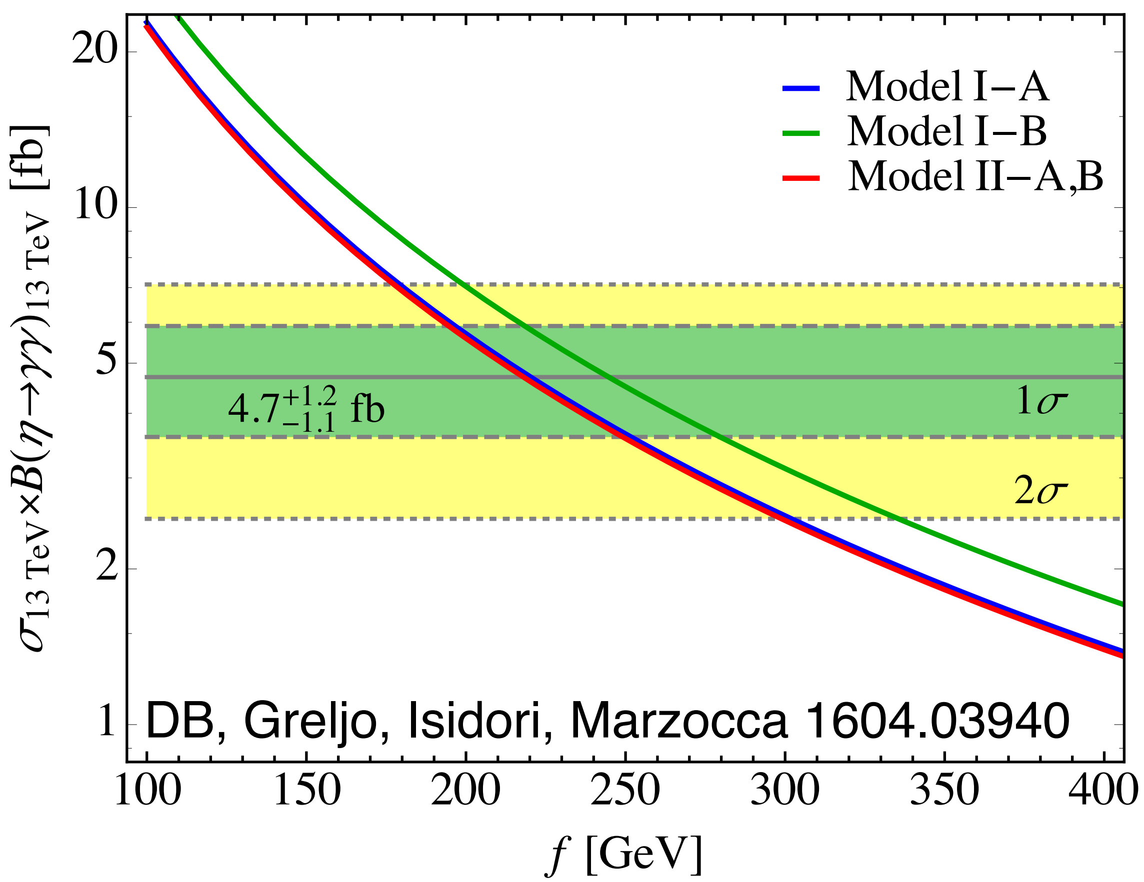
- Chiral anomaly: $\mathcal{L}_{\mathrm{WZW}} \supset -\frac{\eta}{16\pi^2 f}2N_{\mathrm{TC}}\mathrm{Tr}[t^\eta t^a t^b]F^a_{\mu\nu}\widetilde{F}^b_{\mu\nu}$

$$\Gamma_{\eta\to\gamma\gamma} = \frac{\alpha^2 N_{\mathrm{TC}}}{32\pi^3}\mathrm{Tr}[t^\eta Q^2]\frac{m_\eta^3}{f^2},$$

$$\Gamma_{\eta\to gg} = \frac{\alpha_3^2 N_{\mathrm{TC}}}{32\pi^3}\mathrm{Tr}[t^\eta t^A t^A]\frac{m_\eta^3}{f^2}$$

Fitting the diphoton signal

$$f \approx (70 \div 80\,\mathrm{GeV}) \times N_{\mathrm{TC}}$$

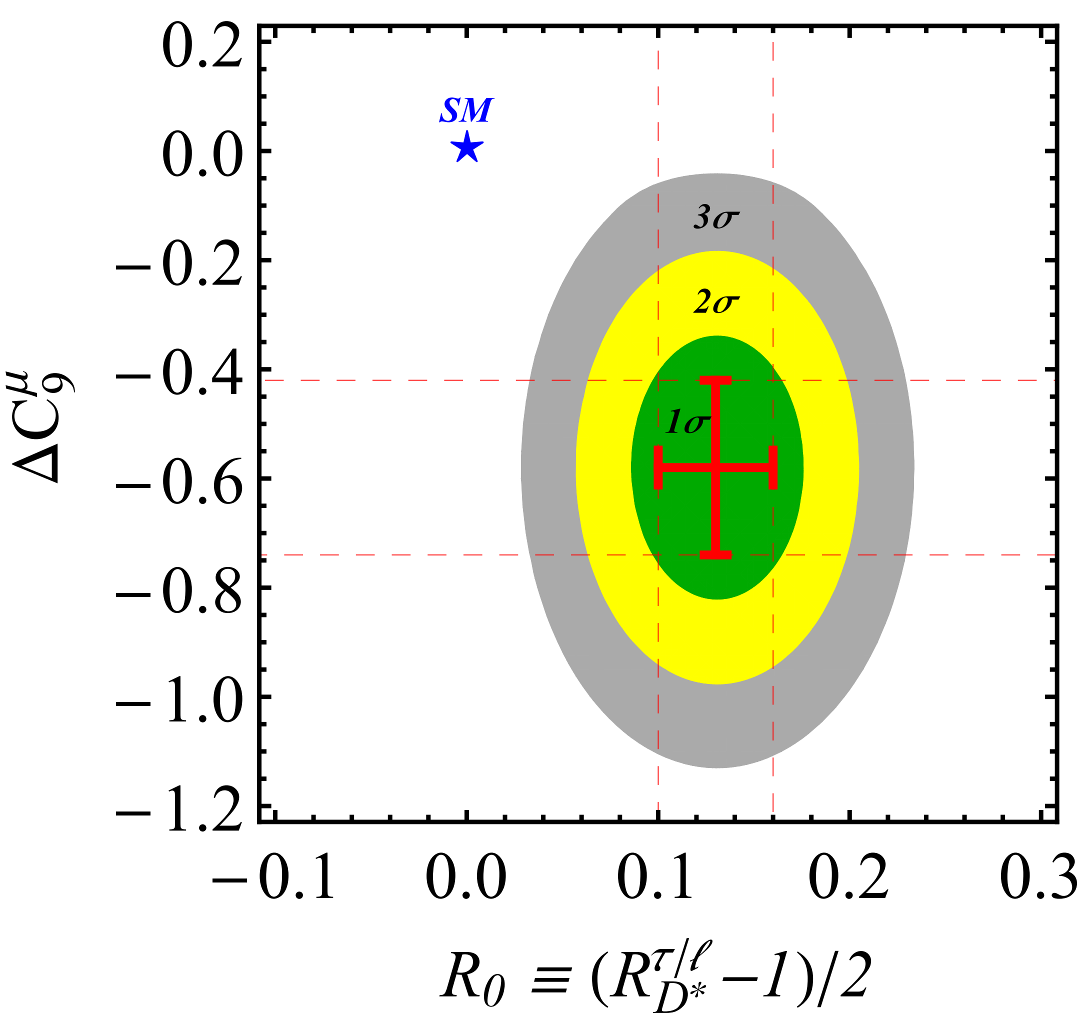


Interlude: flavour

- Other 3 recent anomalies, at the level of 3–4σ: violation of Lepton Flavour Universality in B decays (to D, D^*, and K)!

- Can be explained by the **tree-level exchange of vector resonances** coupled to third generation leptons and quarks [Greljo, Isidori, Marzocca 2015]

[DB, Greljo, Isidori, Marzocca 1604.03940]



- Perfect fit to experimental data (flavour + diphoton) in vector-like confinement

- Consistent with a weakly broken $U(2)^5$ flavour symmetry

- Large couplings to 3rd generation fermions required

An explicit example

- Fermion content: $Q \sim (\mathbf{N}, \mathbf{3}, \mathbf{1})_{Y_Q}, \qquad L \sim (\mathbf{N}, \mathbf{1}, \mathbf{2})_{Y_L}$
- Symmetry breaking: $\mathrm{SU}(5)_L \times \mathrm{SU}_R(5) \to \mathrm{SU}(5)_V$ 24 pNGB

	Flavour structure	$\mathcal{G}_{\mathrm{SM}}$ irrep	pNGB Mass m_π^2
$\mathcal{V}$	$(\bar{Q}Q)$	$(\mathbf{8}, \mathbf{1}, 0)$	$2B_0 m_Q$
U	$(\bar{L}Q)$	$(\mathbf{3}, \mathbf{2}, Y_Q - Y_L)$	$B_0(m_L + m_Q)$
π	$(\bar{L}L)$	$(\mathbf{1}, \mathbf{3}, 0)$	$2B_0 m_L$
η	$3(\bar{L}L) - 2(\bar{Q}Q)$	$(\mathbf{1}, \mathbf{1}, 0)$	$\frac{2}{5}B_0(3m_L + 2m_Q)$

- Baryons with SM-fermion quantum numbers:

$$|LLL\rangle_{(\mathbf{1},\mathbf{2},\pm\frac{1}{2})}, \qquad |QQL\rangle_{(\bar{\mathbf{3}},\mathbf{1},-\frac{1}{6})}$$

- Other decay channels

	(Y_Q, Y_L)	$R_{Z\gamma}$	R_{ZZ}	R_{WW}
A:	$(-\frac{1}{6}, \frac{1}{6})$	6.7	11	37
B:	$(0, -\frac{1}{6})$	5.0	9.1	34

all these predictions are model-dependent.

Vector mesons

$$|\rho^a\rangle_{(\mathbf{1},\mathbf{3},0)} = \frac{1}{\sqrt{2}}|\bar{\psi}\sigma^a\psi\rangle, \quad |\omega\rangle_{(\mathbf{1},\mathbf{1},0)} = \frac{1}{\sqrt{2}}|\bar{\psi}\psi\rangle, \quad \cdots$$

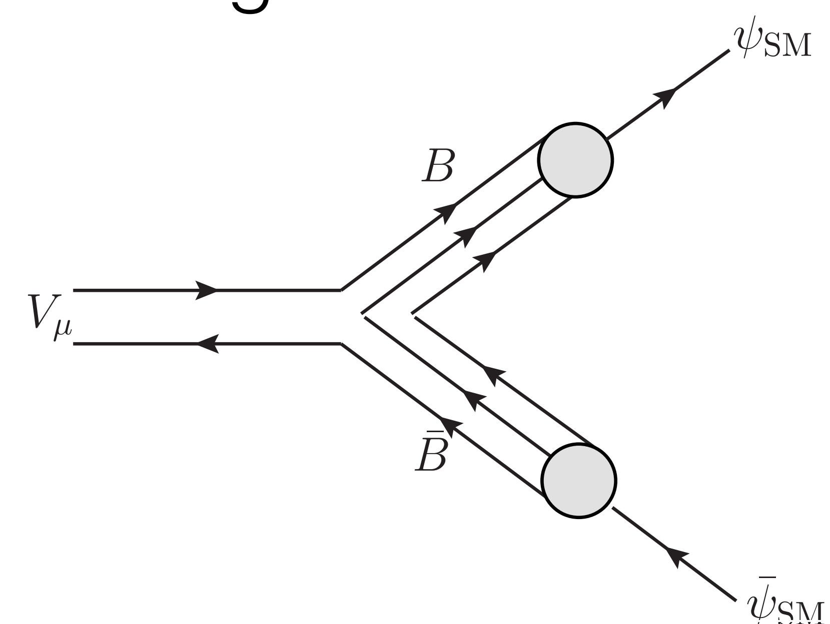
- Mass of the vectors: $m^2_{V_{ij}} = c_0^2(4\pi f)^2 + c_1^2 B_0(m_i + m_j), \qquad (c_{0,1} \lesssim 1)$

- Coupling between vectors and baryons in the strong sector

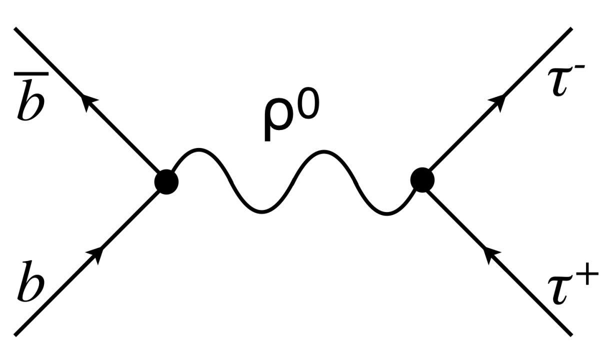
$$\mathcal{L}_\omega = g_\rho(a_q^\omega \bar{B}_q\gamma^\mu B_q + a_\ell^\omega \bar{B}_\ell\gamma^\mu B_\ell)\omega_\mu$$

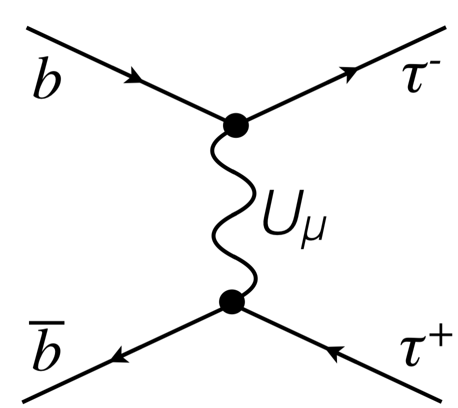
OZI rule

induces a coupling with SM fermions, if they mix with the TC-baryons



- Exchange of vectors contributes to processes involving heavy fermions, both at low (flavour observables) and high (LHC) energies



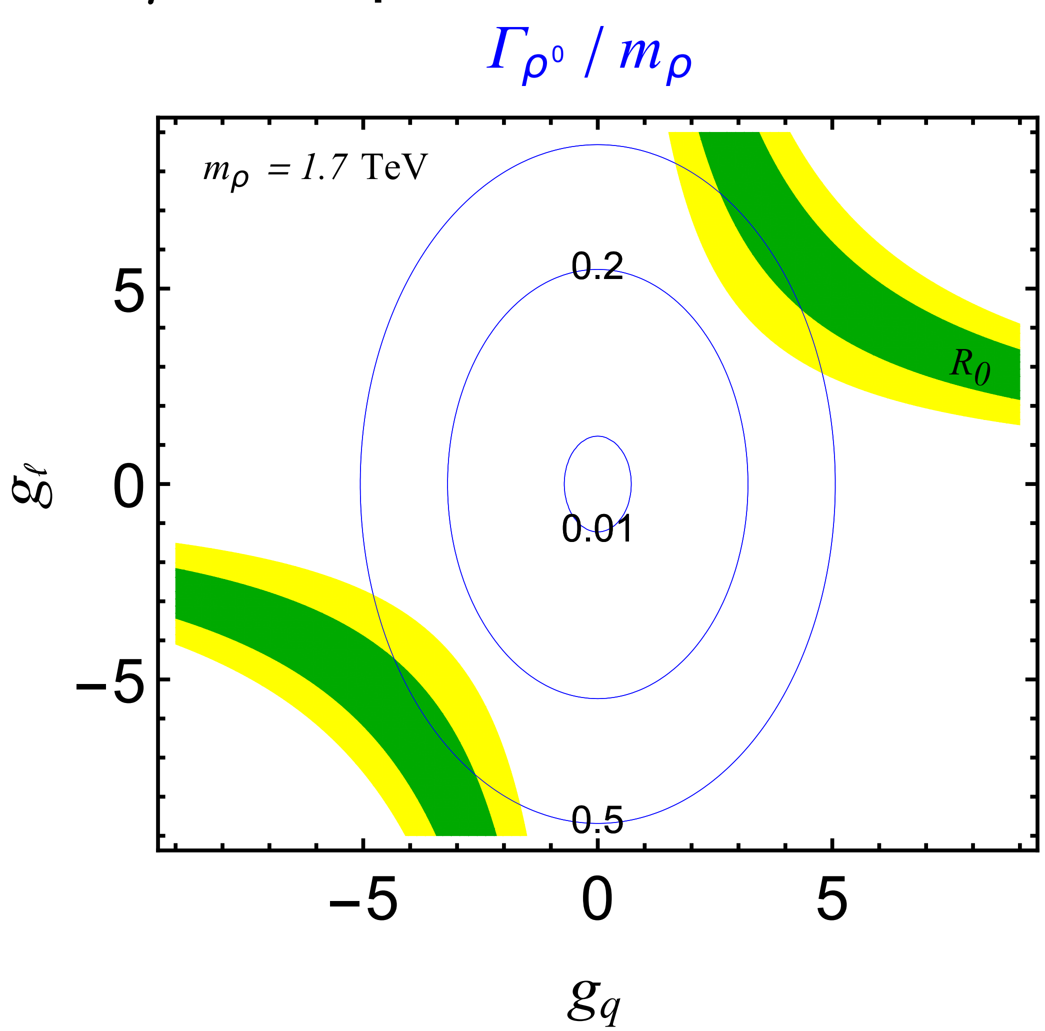


LHC phenomenology: ρ mesons

Due to large coupling, vector mesons decay mainly into 3rd gen. fermions.

$$\Gamma_{\rho^0\to\tau^+\tau^-\,(\nu_\tau\bar\nu_\tau)} = \frac{g_\ell^2}{96\pi} m_\rho\,, \qquad \Gamma_{\rho^0\to b\bar b\,(t\bar t)} = \frac{g_q^2}{32\pi} m_\rho .$$

- ρ is expected to be a broad resonance



Decays to pairs of pNGB through TC interaction can also be sizable:

$$\Gamma_{\rho\to\pi\pi} = \frac{g_{\rho\pi\pi}^2}{192\pi} m_\rho \left(1 - \frac{4m_\pi^2}{m_\rho^2}\right)^{\frac{3}{2}},$$

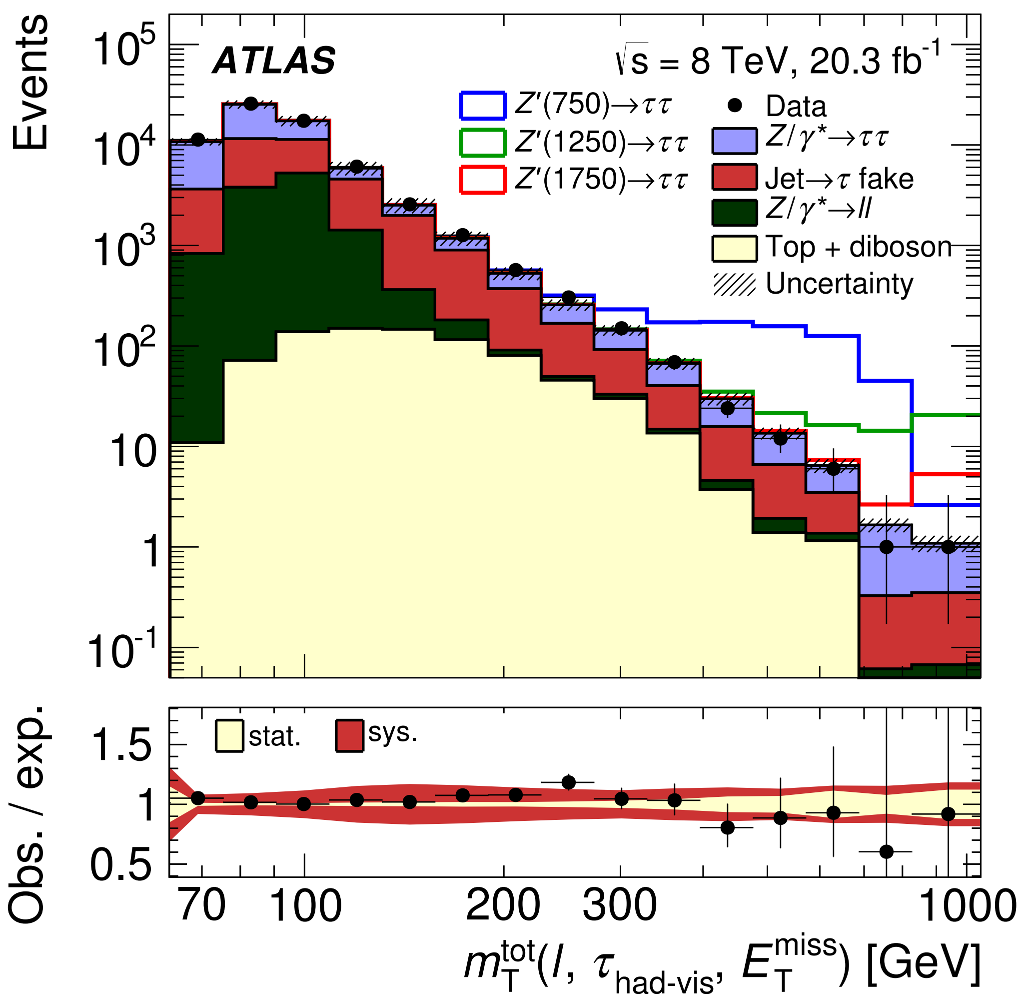
$$\left(\mathcal{L} = \frac{g_{\rho\pi\pi}}{2}\epsilon_{abc}\rho_\mu^a\pi^b\partial_\mu\pi^c\right)$$

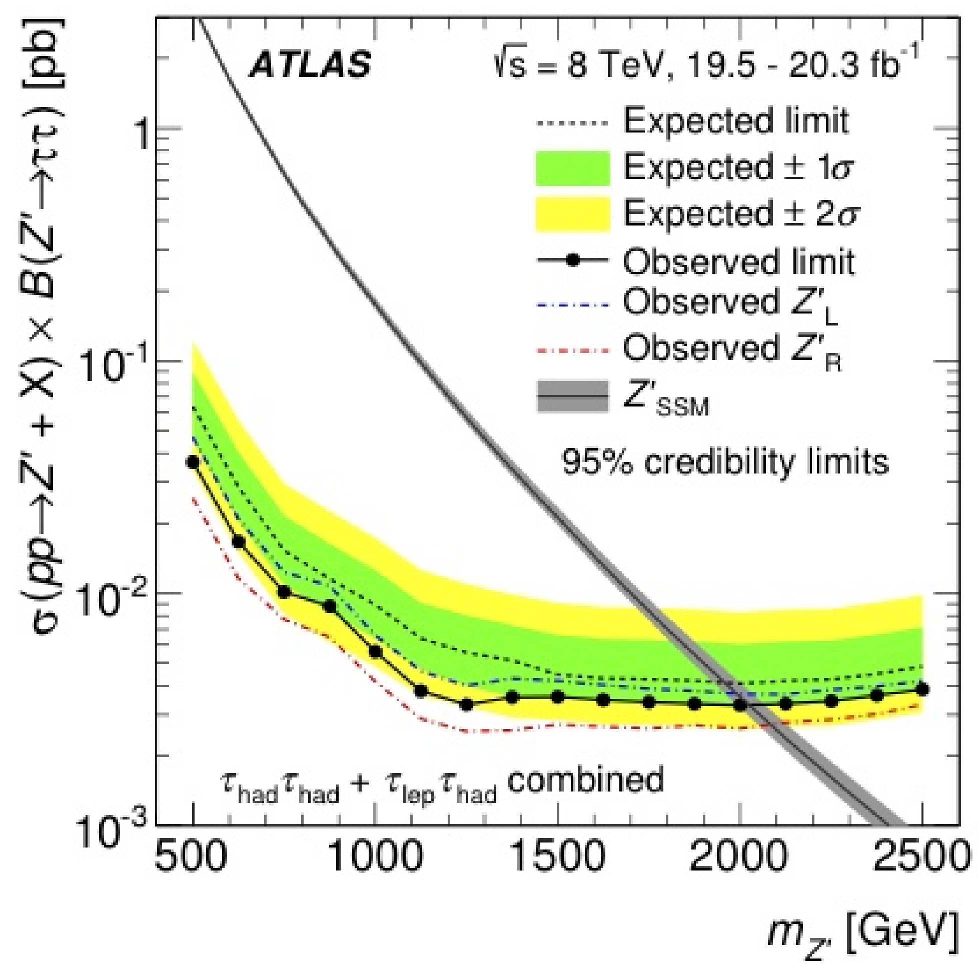
[DB, Greljo, Isidori, Marzocca 1604.03940]

- Main production channel: $b\bar b \to \rho^0$ single production.
  For $g_q = 5$, $m_\rho = 1.7\,\mathrm{TeV}$, one finds $\sigma_{b\bar b}/\sigma_{u\bar u} \approx 7$.

LHC phenomenology: $\rho^0 \to \tau\tau$

ATLAS search for Z' decaying into $\tau^+\tau^-$, 1502.07177



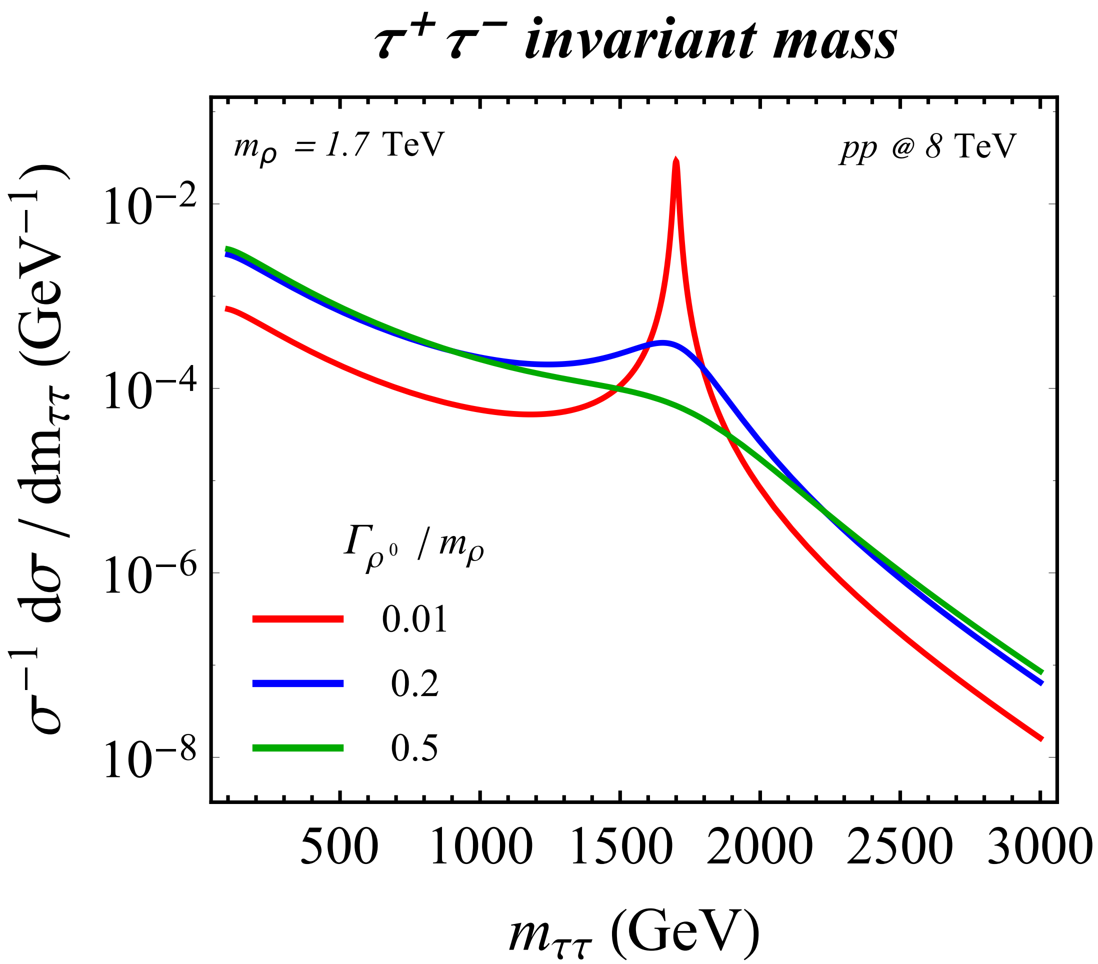


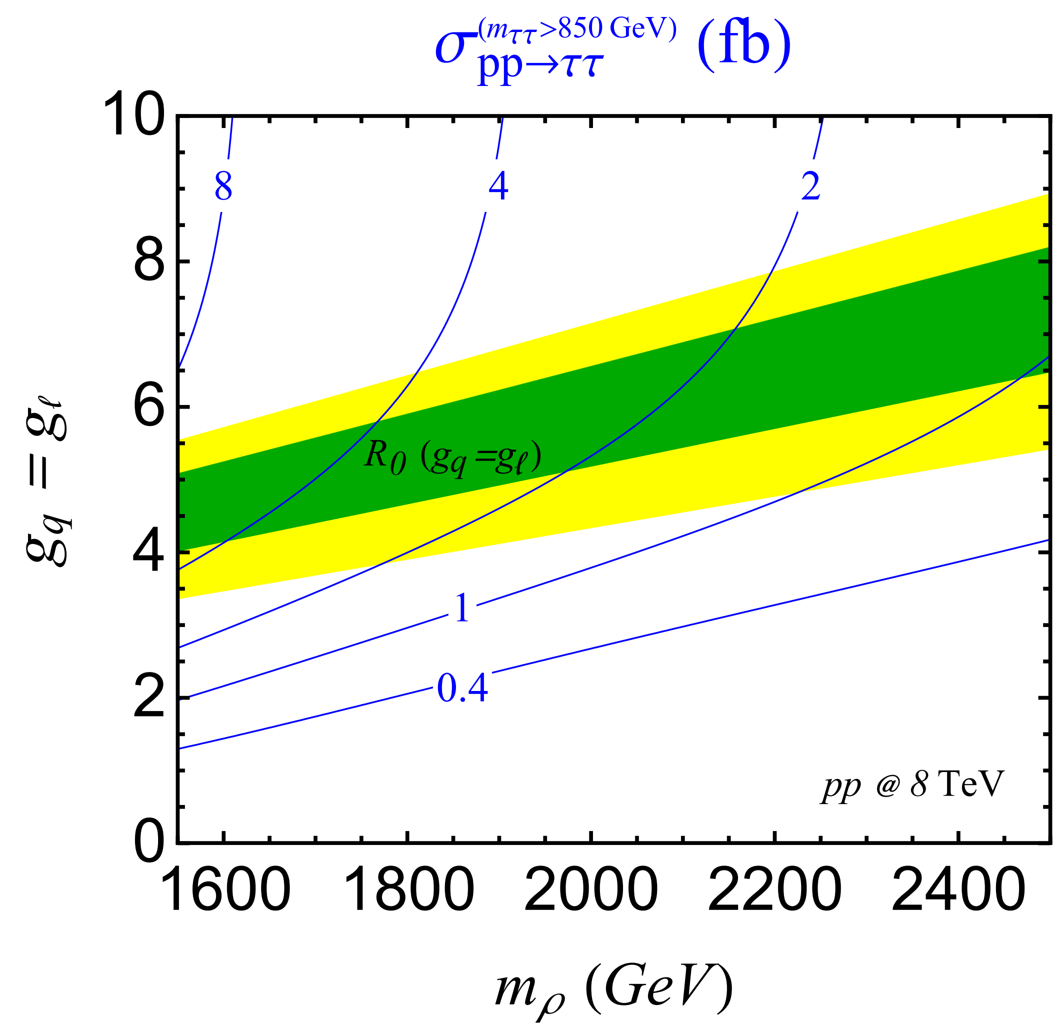
- ◇ For large masses (above ~ 1.5 TeV), basically one bin in total transverse mass: $m^T_{\text{tot}} > 850\,\text{GeV}$.
- ◇ 95% C.L. exclusion above 1.5 TeV: $\sigma < 4\,\text{fb}$ $(7\,\text{fb})$ for a narrow width (20% width).

LHC phenomenology: $\rho^0 \to \tau\tau$

Recast the exclusion approximating $m^T_{\rm tot} \approx m_{\tau\tau}$:

[DB, Greljo, Isidori, Marzocca 1604.03940]





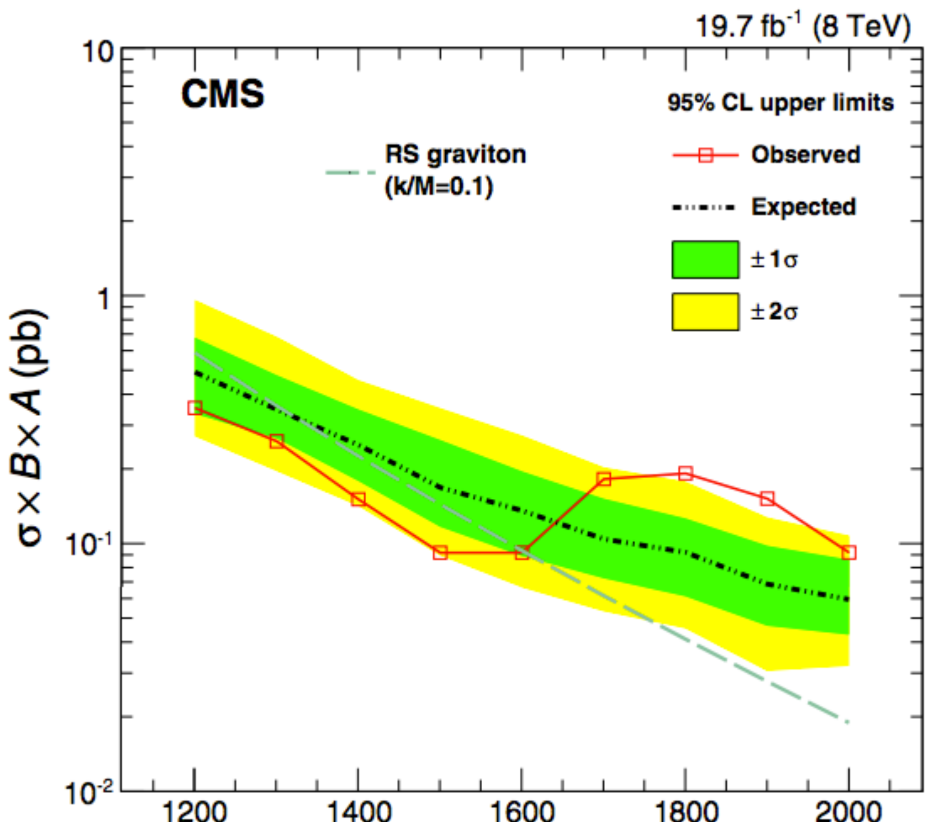
Cross-section $\sigma(pp \to \rho \to \tau\tau)$, for $m_{\tau\tau} > 850\,\text{GeV}$

ATLAS bound: $\sigma \gtrsim 4 \div 7\,\text{fb}$. The relevant region above $\sim 1.5\,\text{TeV}$ still allowed, but will be probed soon!

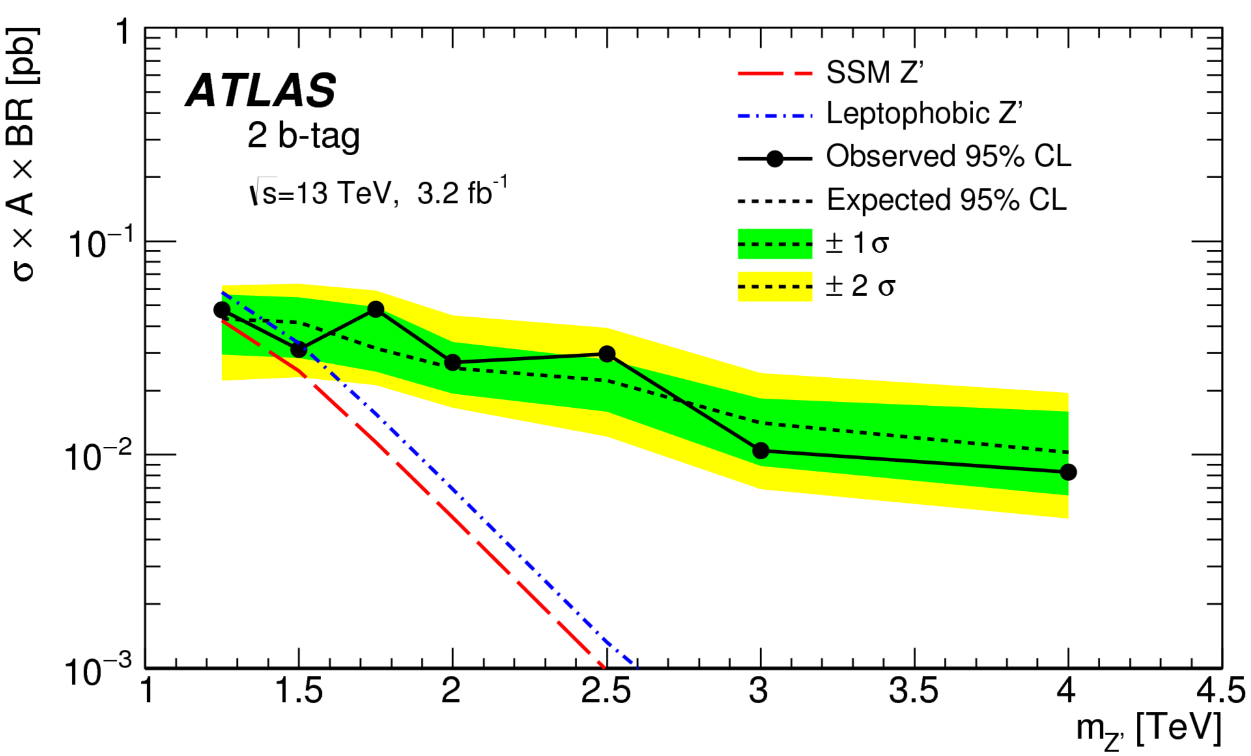
A detailed recast for large width would be useful to get precise bounds...

LHC phenomenology: ρ → bb

- Large coupling to t, b: $\rho^0 \to b\bar{b}$ can be another relevant channel



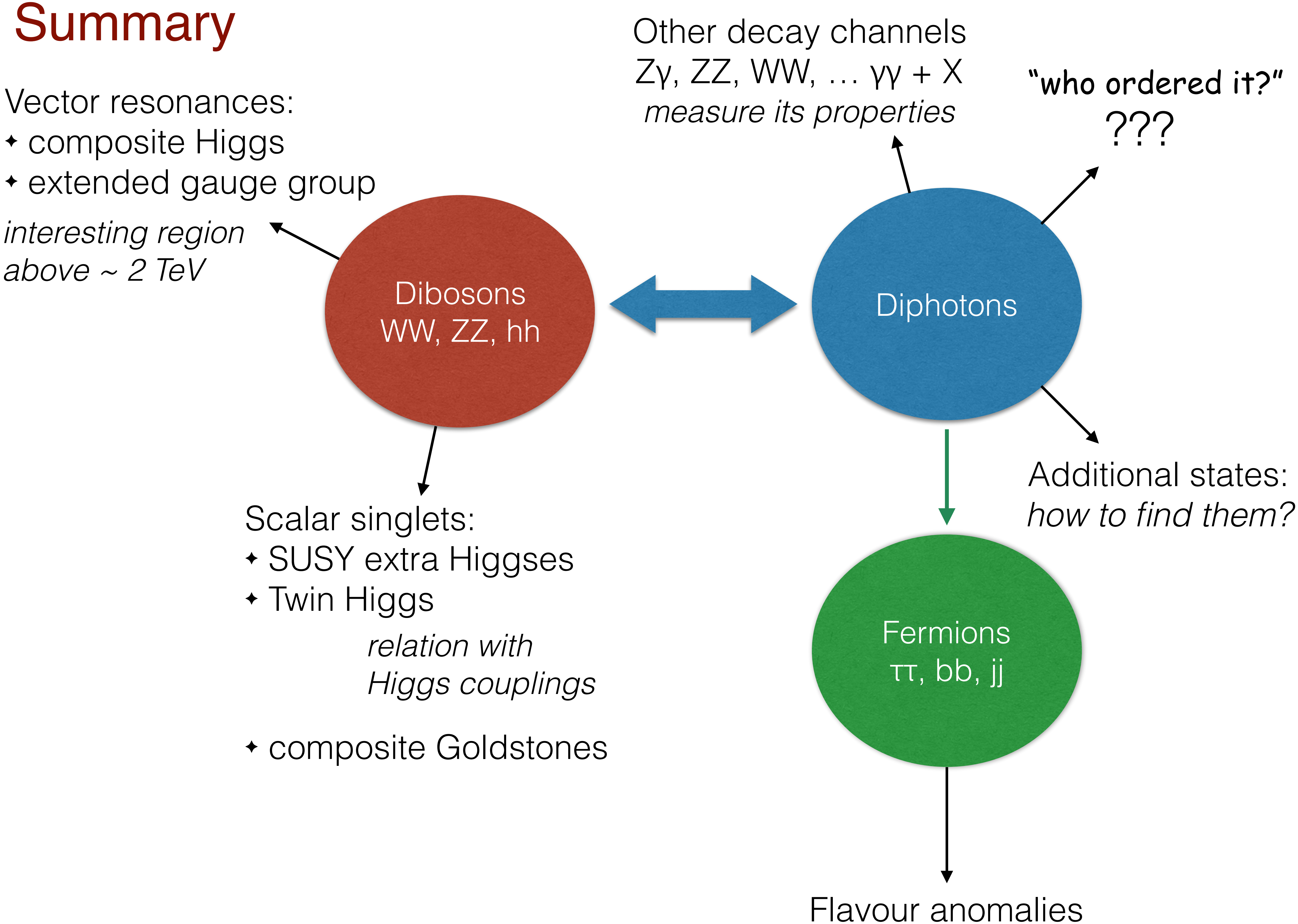
- ATLAS (13 TeV) and CMS (8 TeV) searches for heavy resonances $pp \to X \to bb/jb/jj$



- At present, limit not yet comparable with $\tau^+\tau^-$ channel, if $g_q > g_\ell$

- If $g_q \sim g_\ell$ it could become an interesting channel soon!

Summary


Vector resonances:
✦ composite Higgs
✦ extended gauge group
interesting region above ~ 2 TeV
Other decay channels
Zγ, ZZ, WW, … γγ + X
measure its properties
"who ordered it?"
???
Dibosons
WW, ZZ, hh
Diphotons
Additional states:
how to find them?
Scalar singlets:
✦ SUSY extra Higgses
✦ Twin Higgs
relation with Higgs couplings
✦ composite Goldstones
Fermions
ττ, bb, jj
Flavour anomalies