University of Glasgow

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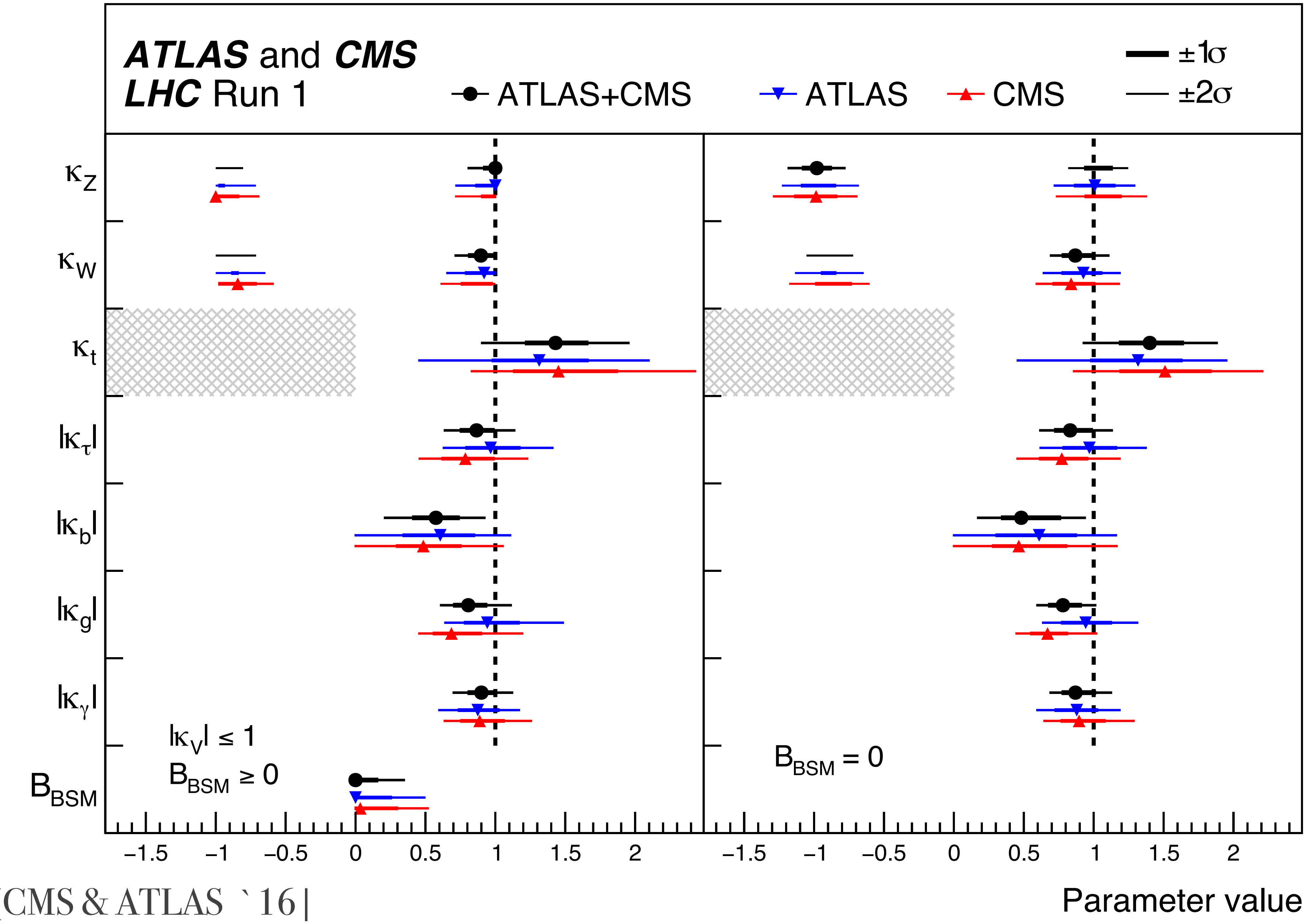
Higgs BSM Models

Heidelberg, 10.10.2017

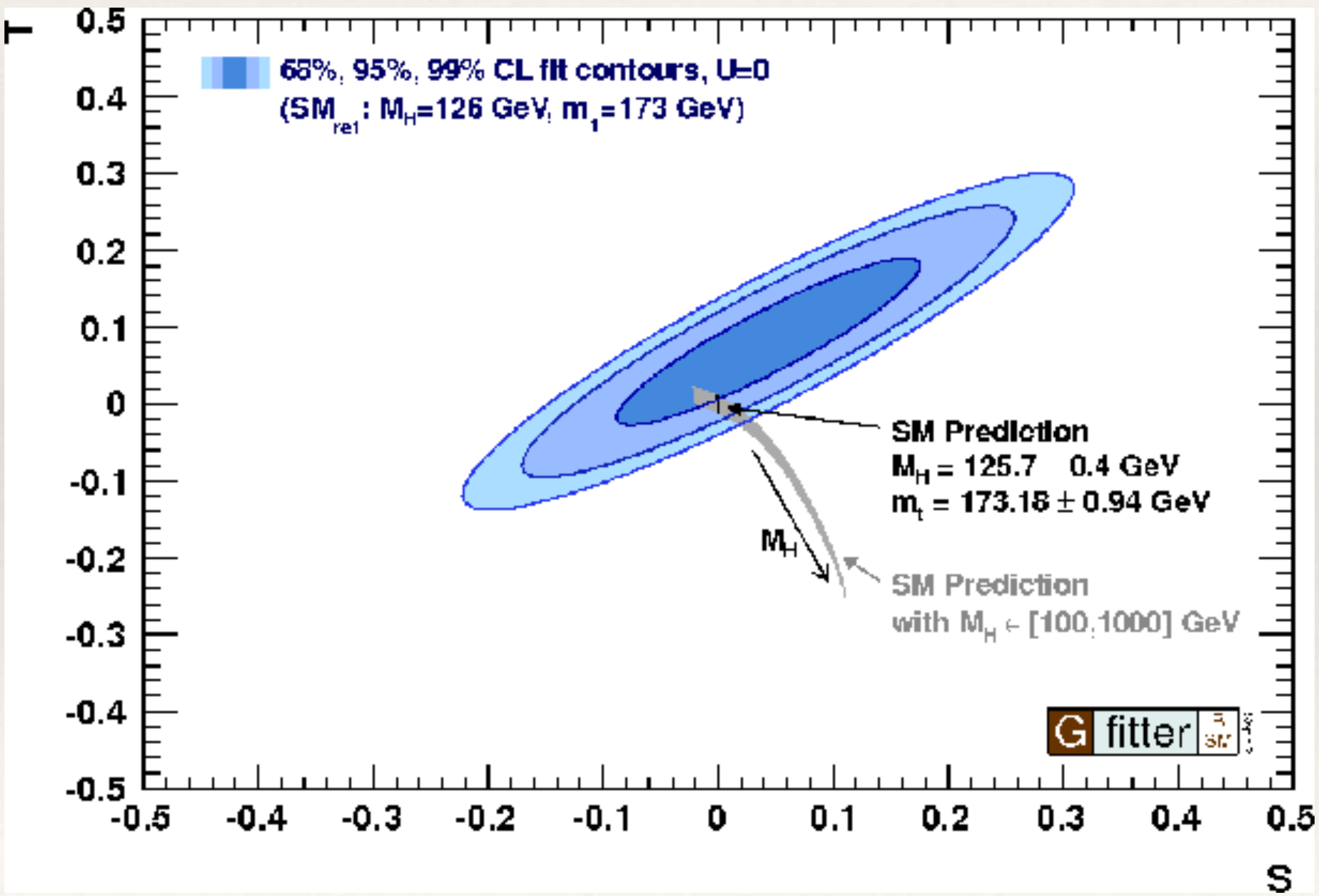
(B)SM Higgs



[CMS & ATLAS `16]

☛ everything is consistent with the SM Higgs hypothesis (so far)

- perturbativity **tightly bound** to the Higgs mass parameter (= unitarity, Higgs width, reliability of oblique corrections,...)
- Higgs discovery seems to fall into this perturbative QFT paradigm



could we be misled?

- perturbativity **tightly bound** to the Higgs mass parameter (= unitarity, Higgs width, reliability of oblique corrections,…)
- Higgs discovery seems to fall into this perturbative QFT paradigm

give up perturbativity

Compositeness

Luigi's & Ramona's talks

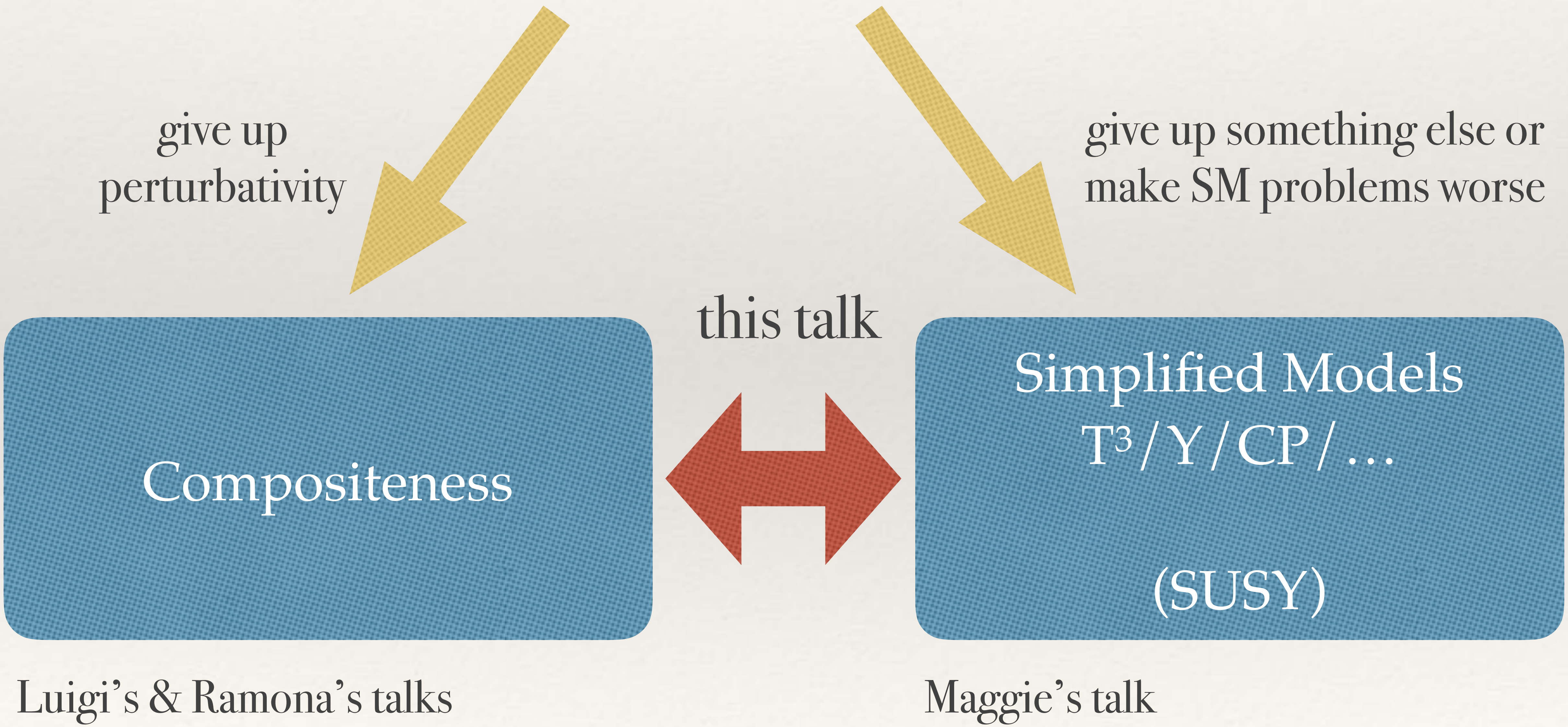
give up something else or make SM problems worse

Simplified Models
CP / T^3 / Y
…
SUSY

Maggie's talk

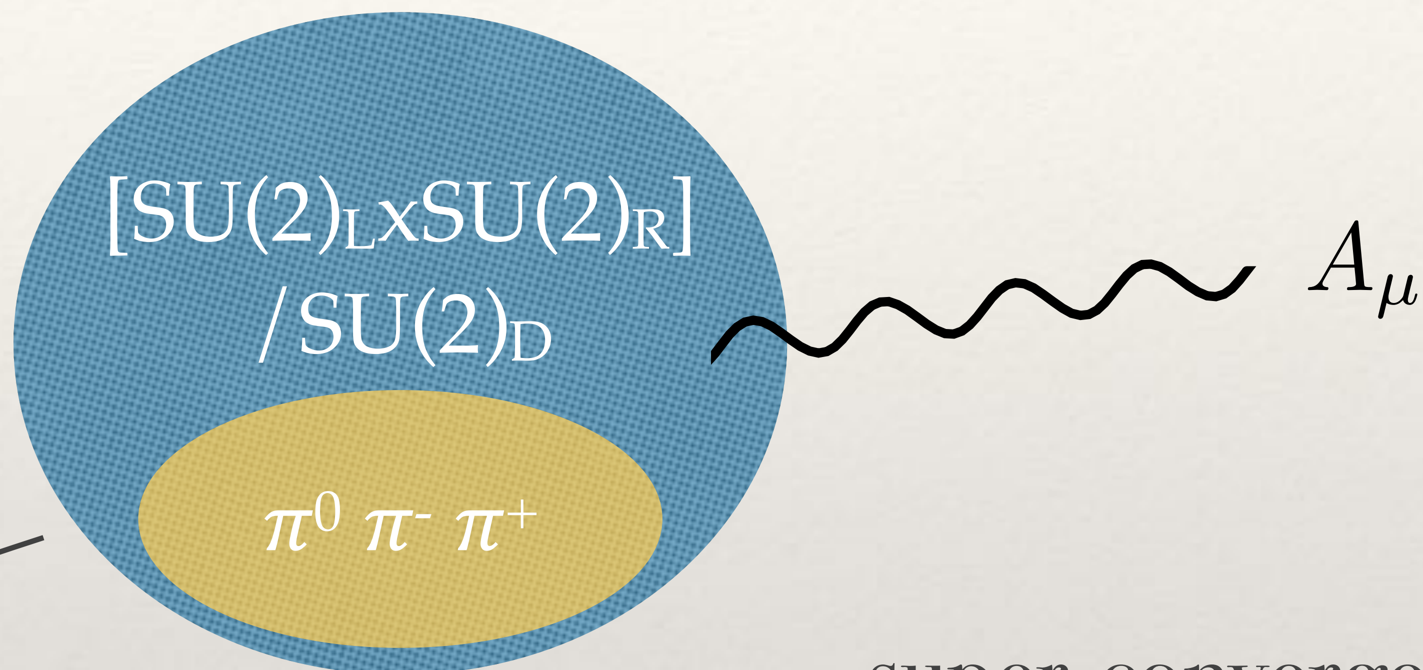
(B)SM Higgs

- perturbativity **tightly bound** to the Higgs mass parameter (= unitarity, Higgs width, reliability of oblique corrections,…)
- Higgs discovery seems to fall into this perturbative QFT paradigm



Compositeness in a nutshell

- interpret the electroweak scale as a radiative phenomenon, analogous to the pion mass splitting



effective potential

[Coleman, Weinberg `73]...

super-convergent

[Weinberg `67]
[Witten `83]
...

$$V(\pi) \simeq \frac{3}{8\pi^2}\alpha_{em}\frac{\sin^2(\pi/f_\pi)}{\pi^2}(\pi^+\pi^-)\int_0^\infty dQ^2\, \Pi_{LR}(Q^2)\,.$$

$$(m_{\pi^\pm} - m_{\pi_0})|_{\rm TH} \simeq 5.8\,{\rm MeV} \quad \text{vs} \quad (m_{\pi^\pm} - m_{\pi_0})|_{\rm EXP} \simeq 4.6\,{\rm MeV}$$

Compositeness in a nutshell

- not straightforward to this adapt to the Higgs case e.g. [Contino ` 10]

trigger ELW symmetry breaking not just CW masses

respect global symmetries in the Higgs sector

LEP precision measurements

…….

Compositeness in a nutshell

- not straightforward to this adapt to the Higgs case e.g. [Contino ` 10]

trigger ELW symmetry breaking not just CW masses

respect global symmetries in the Higgs sector

LEP precision measurements

....

- **complete vacuum mis-alignement** from $SU(2)_L$ x $U(1)_Y$ direction requires the presence of heavy fermions

$$V(h) \propto \alpha \cos(2h/f) - \beta \sin^2(2h/f)$$

fermions

gauge + fermions

Generic hints of compositeness

- write down a non-linear Sigma model with scale f

[CCWZ `69]
[Gasser, Leutwyler `85]
....

- gauge boson masses through symmetry choices
- fermion masses through mixing with baryonic matter (part. compositeness)

[Kaplan `91]

- minimal pheno model SO(5)→ SO(4) ≃ SU(2)$_L$ x SU(2)$_R$

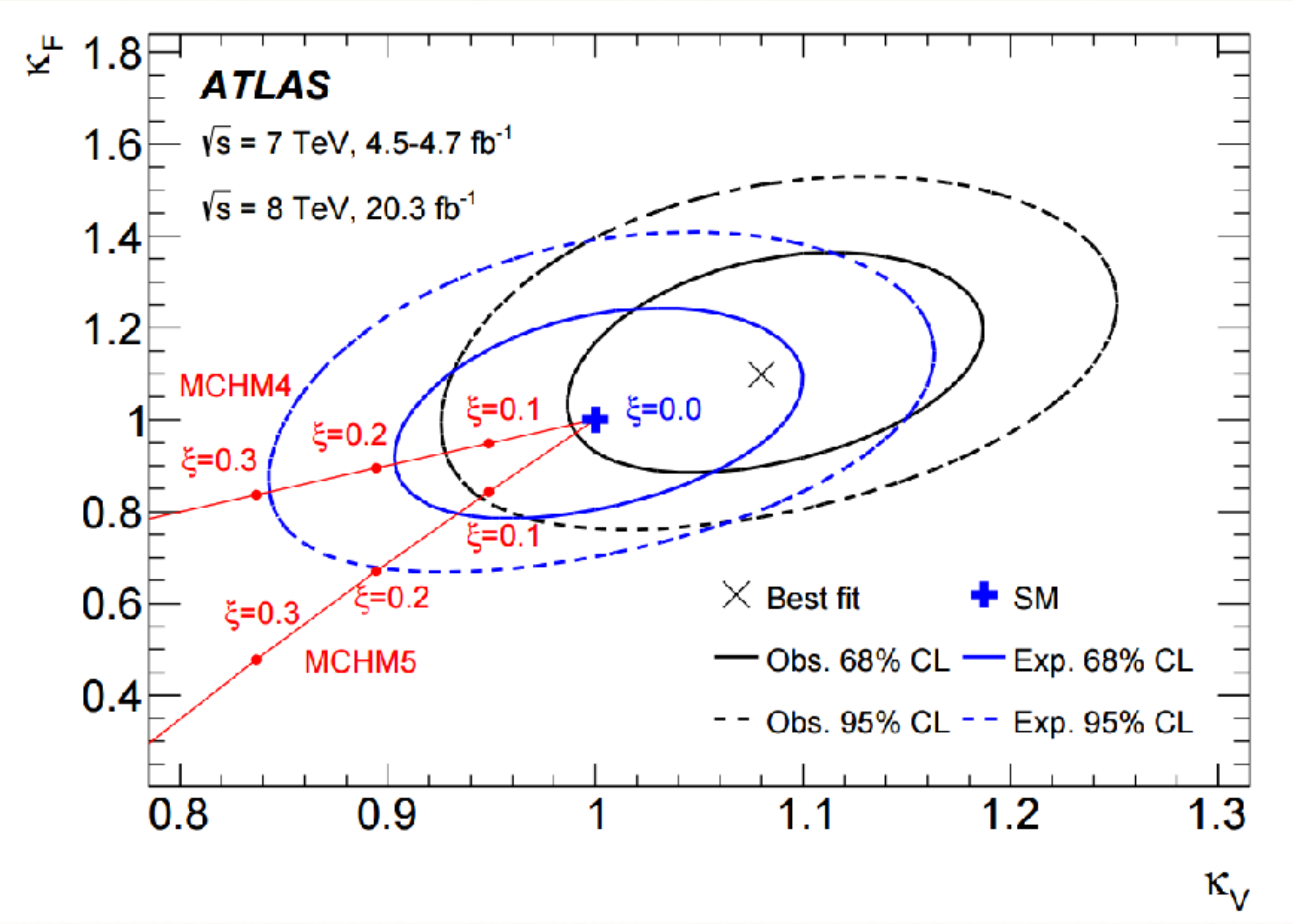
	MCHM4	MCHM5
$g_{hVV}/g_{hVV}^{\rm SM}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$g_{hf\bar f}/g_{hf\bar f}^{\rm SM}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
$g_{hhh}/g_{hhh}^{\rm SM}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
$g_{hhf\bar f}$	$-\xi m_f/v^2$	$-4\xi\, m_f/v^2$
g_{hgg} and g_{hhgg}	0	0

$\xi = v^2/f^2$

[Agashe, Contino, Pomarol `04]
[Contino, Da Rold, Pomarol `06]

- top quark couplings depend on baryonic symmetry embedding

Generic hints of compositeness



Generic hints of compositeness

- write down a non-linear Sigma model with scale f
- gauge boson masses through symmetry choices
- fermion masses through mixing with baryonic matter (part. compositeness)
- minimal pheno model $SO(5) \rightarrow SO(4) \simeq SU(2)_L \times SU(2)_R$

UV completion ?

Compositeness vs. Simplified Models

- write down a non-linear Sigma model with scale *f*
- gauge boson masses through symmetry choices
- fermion masses through mixing with baryonic matter (part. compositeness)
- minimal pheno model SO(5)→ SO(4) ≃ $SU(2)_L$ x $SU(2)_R$

UV completion ?

Luigi Del Debbio

$$\underbrace{SU(4)}_{G_{\rm HC}} \times \underbrace{SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'}_{G_F}$$

[Ferretti `14, `16]
[Agugliaro et al. `16]

could work with

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3) \times SU(3)'}{SU(3)} \times U(1)'$$

[Rabi, Dimopoulos, Susskind `80]
[Preskill, Weinberg `81]

A concrete model of compositeness

- model predicts a number of exotics phenomenological implications

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3)\times SU(3)'}{SU(3)} \times U(1)'$$

[CE, Schichtel, Spannowsky `17]

doubly charged, singly charged and extra neutral Higgs bosons

top partners

hyperpions

[Belyaev et al. `17]

[Matsedonskyi, Panico, Wulzer `15]

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

similarities with [Georgi, Machacek `85]

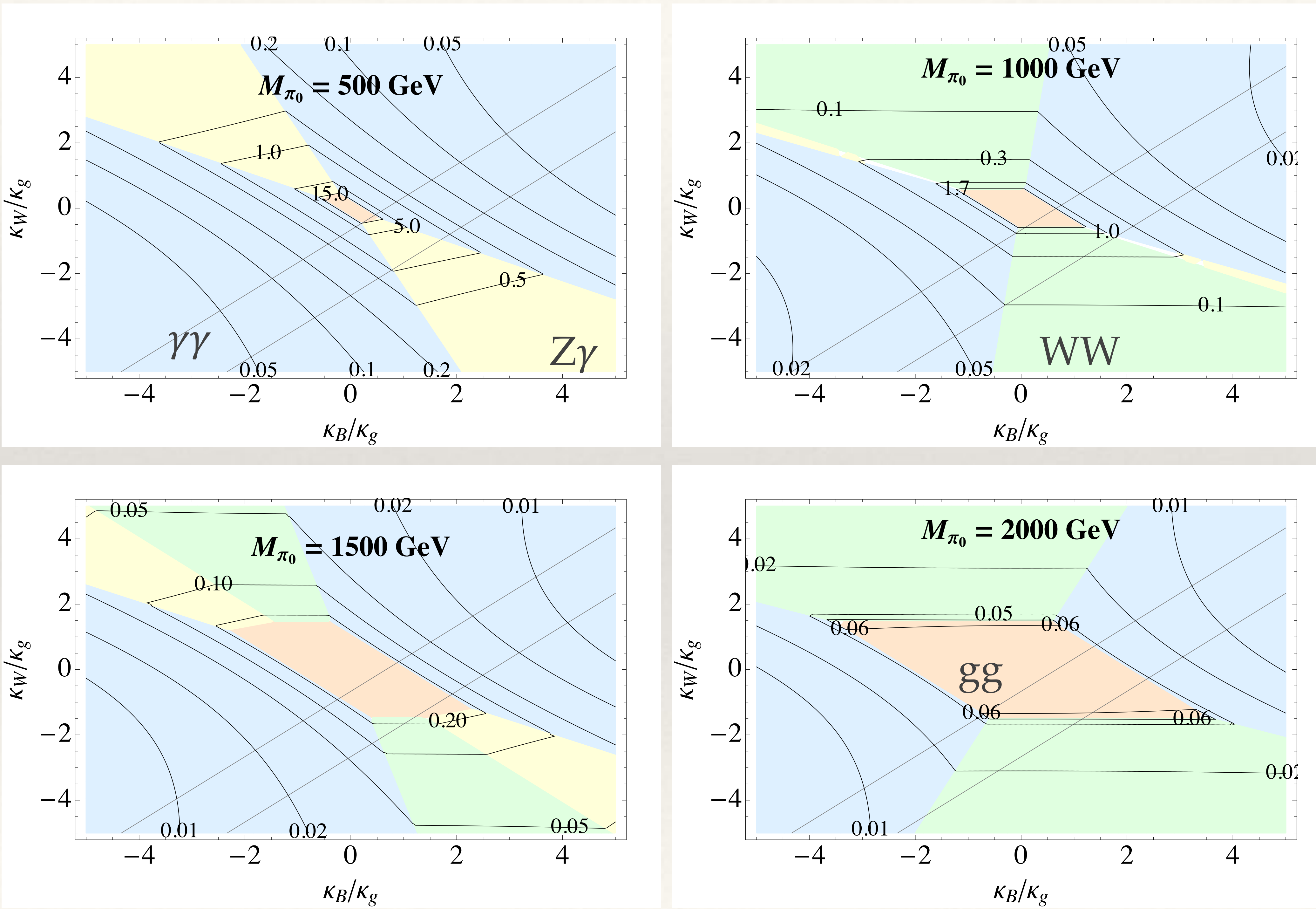
- partial compositeness: expect modifications in association with heavy fermions

Simplified models

[Wess, Zumino `71]
[Witten `83]

$$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$$

$$\mathcal{L}_{\rm WZW} \supset \frac{\alpha_A}{8\pi} c_5 \frac{C_A^r}{f_{a_r}} \delta^{ab} \; a_r \; \varepsilon^{\mu\nu\alpha\beta} A^a_{\mu\nu} A^b_{\alpha\beta}$$



σBR contours in [pb]

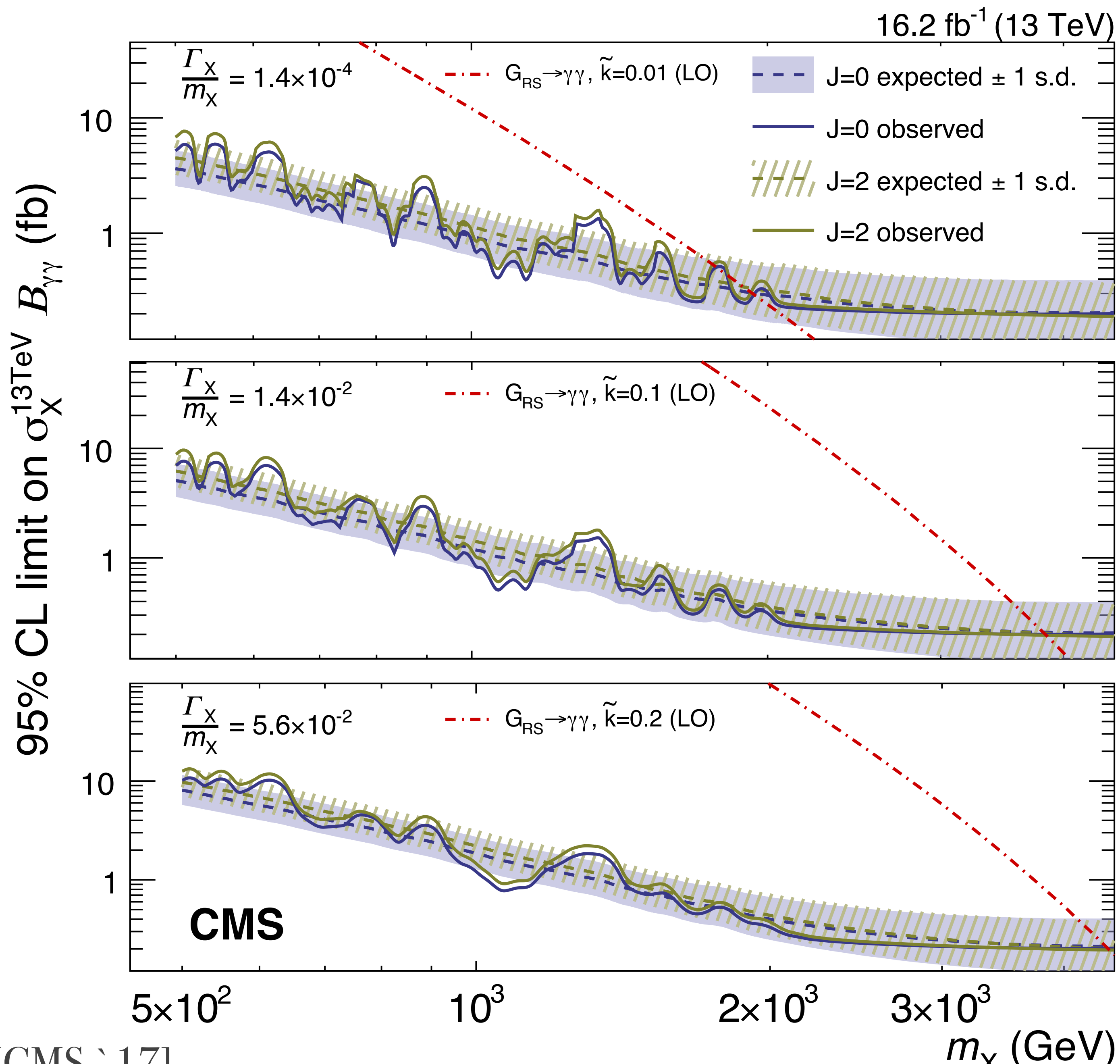
[Belyaev et al. `16]

$Q = T_3 + Y$

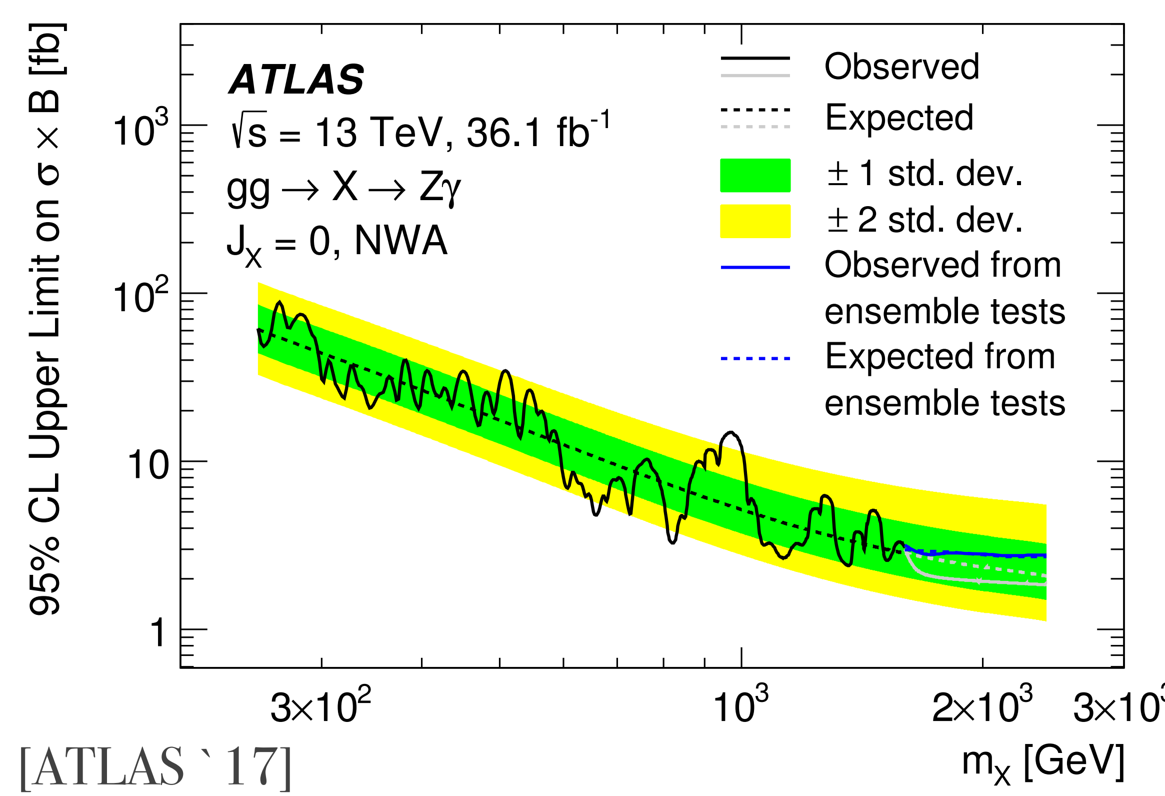
Simplified models

$$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$$

H^0



[CMS ` 17]



[ATLAS ` 17]

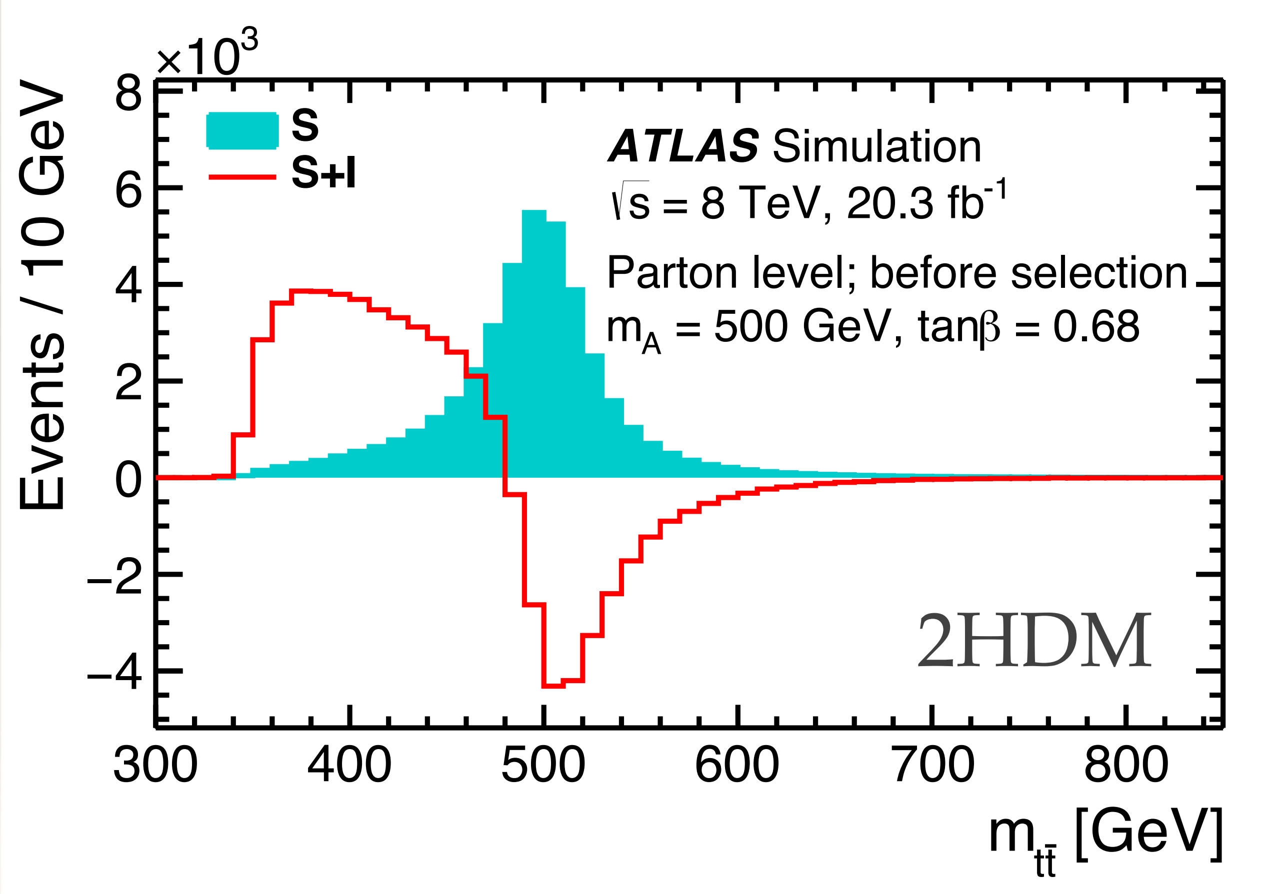
$Q = T_3 + Y$

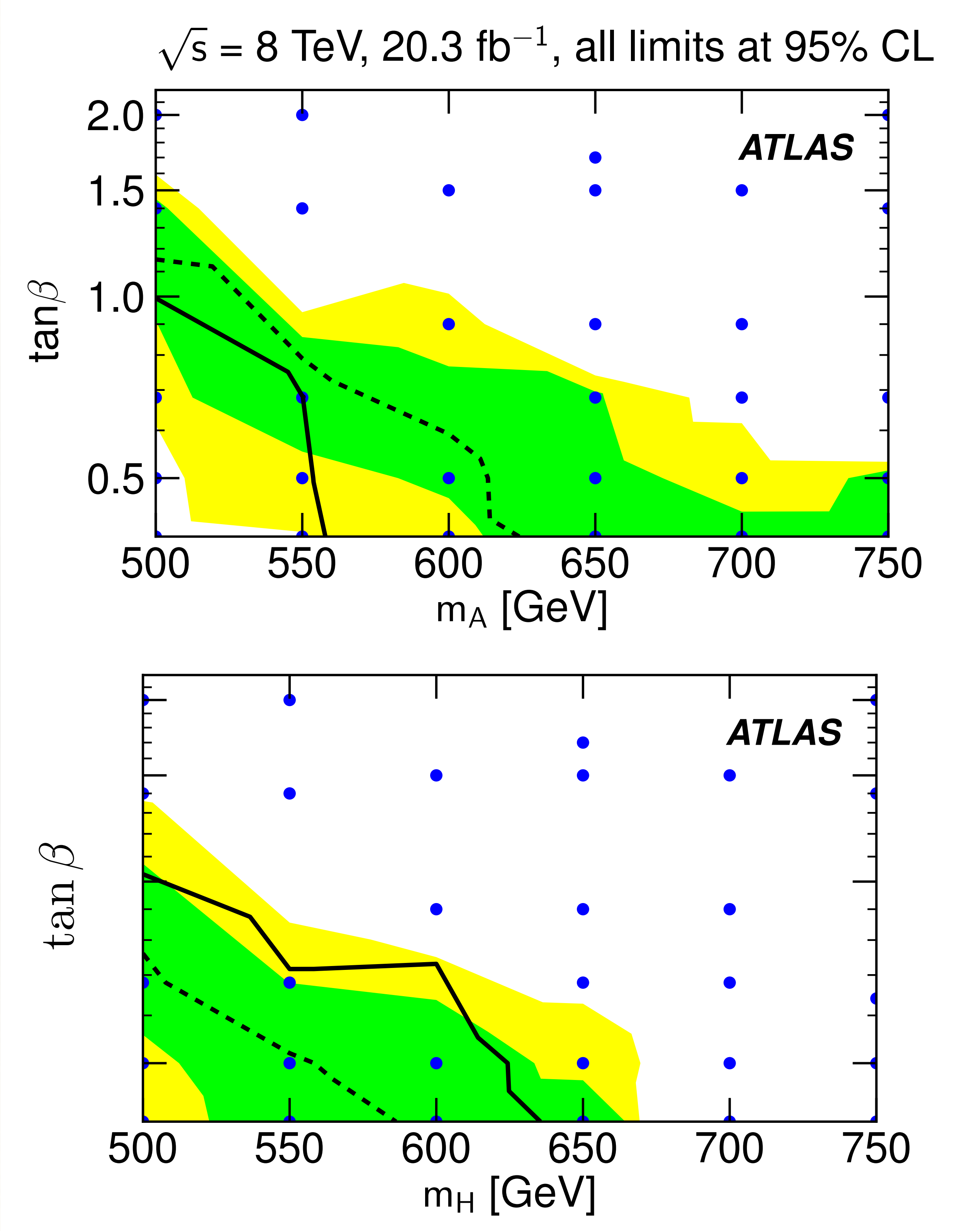
Simplified models

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

H^0/A^0

- model independent statements very difficult for top decays



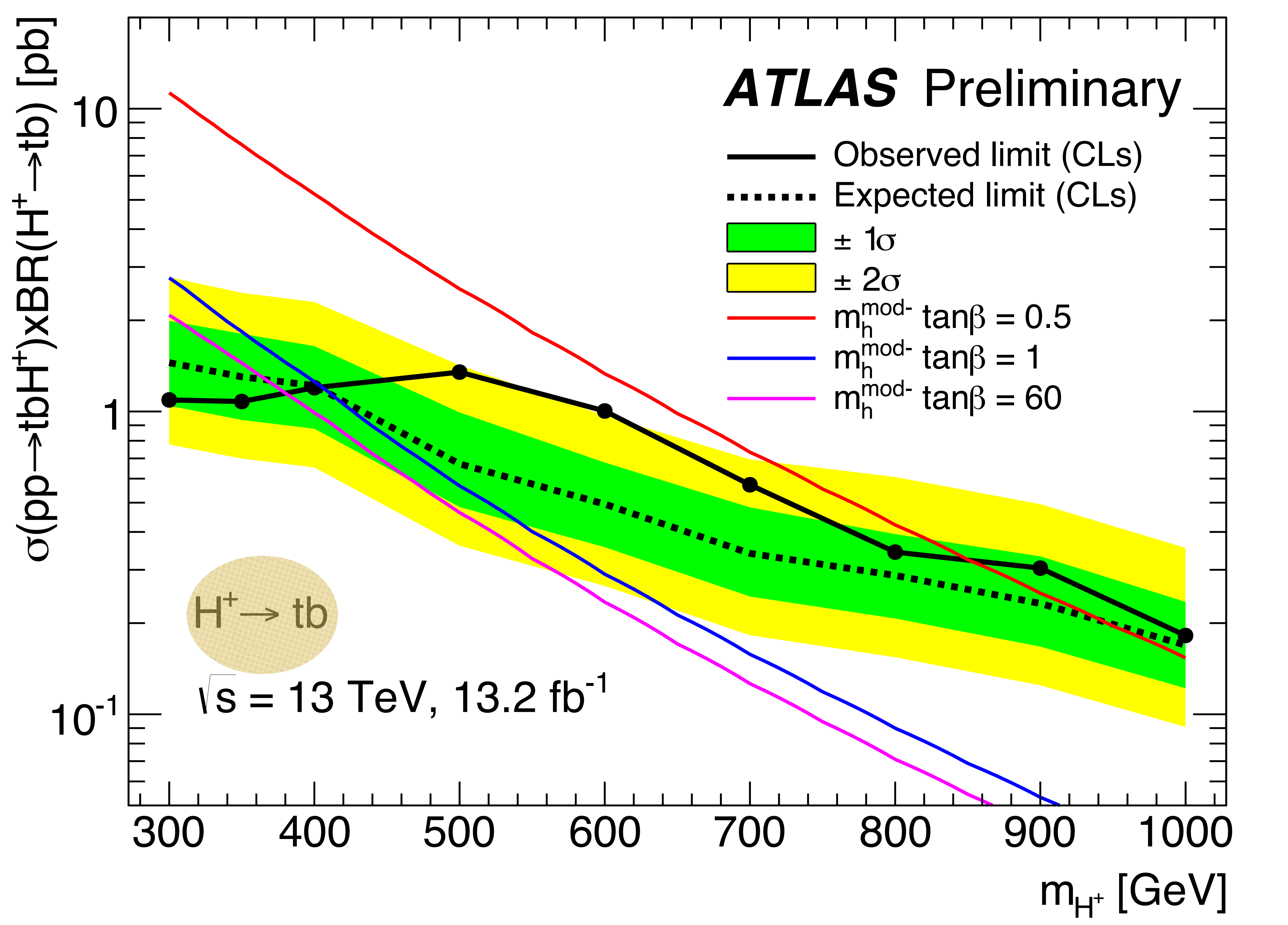


$Q = T_3 + Y$

Simplified models

$1_0 + 2_{\pm 1/2} + 3_0 + 3_{\pm 1}$

$H^{\pm}$



$Q = T_3 + Y$

Simplified models

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

$\mathbf{3}_0$ $\mathbf{3}_{\pm 1}$

$$\Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix}$$

$\Xi \to \mathrm{SU}(2)_L \quad \Xi \quad \mathrm{SU}(2)_R$

Y

vev

no vev

[Georgi, Machacek `85]
[Gunion et al. `91]

$\langle \chi_3 \rangle \sim \langle \xi_2 \rangle \neq 0$

- fine-tuning in T
- WBF single production of H^{++}

$\langle \chi_3 \rangle = \langle \xi_2 \rangle = 0$

- massive scalar degrees
- DY pair production of H^{++}

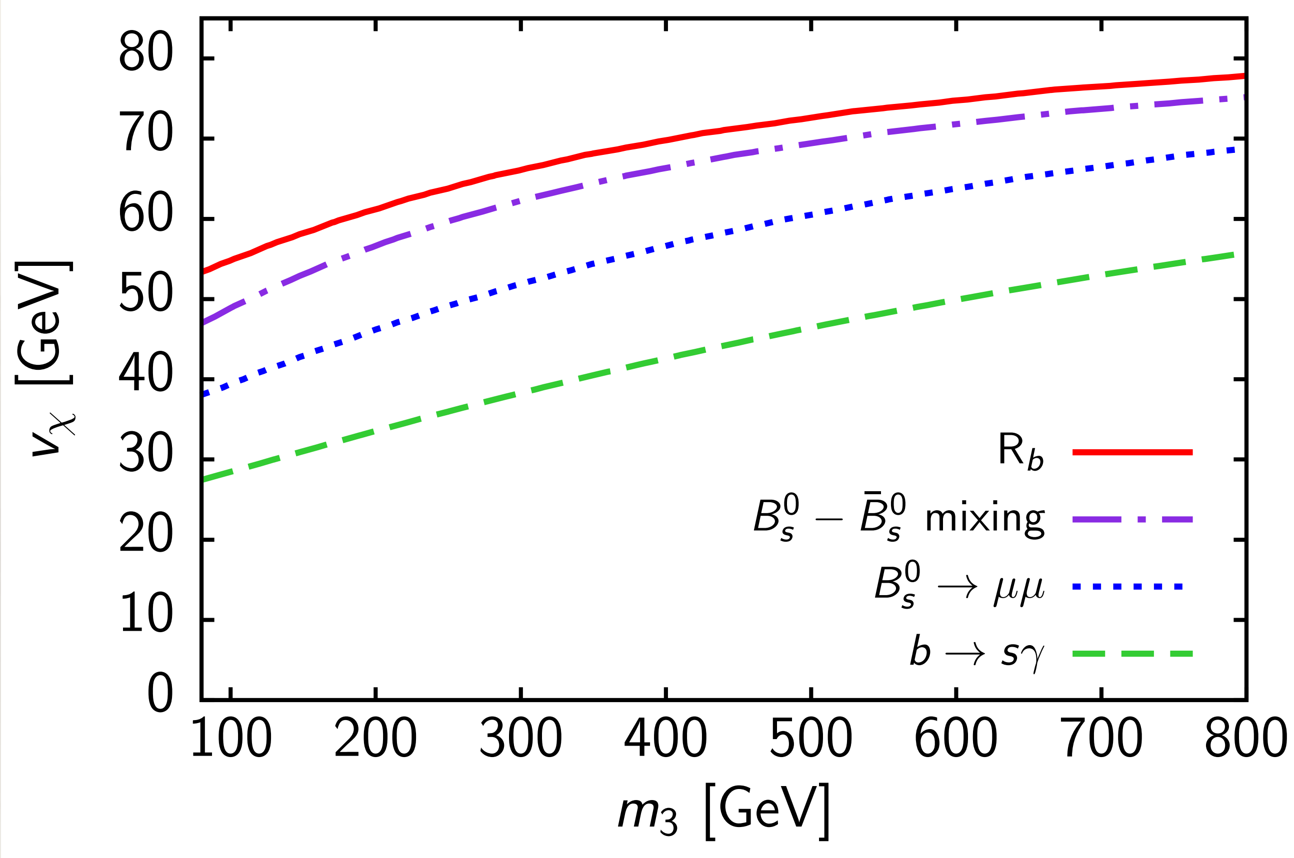
$Q = T_3 + Y$

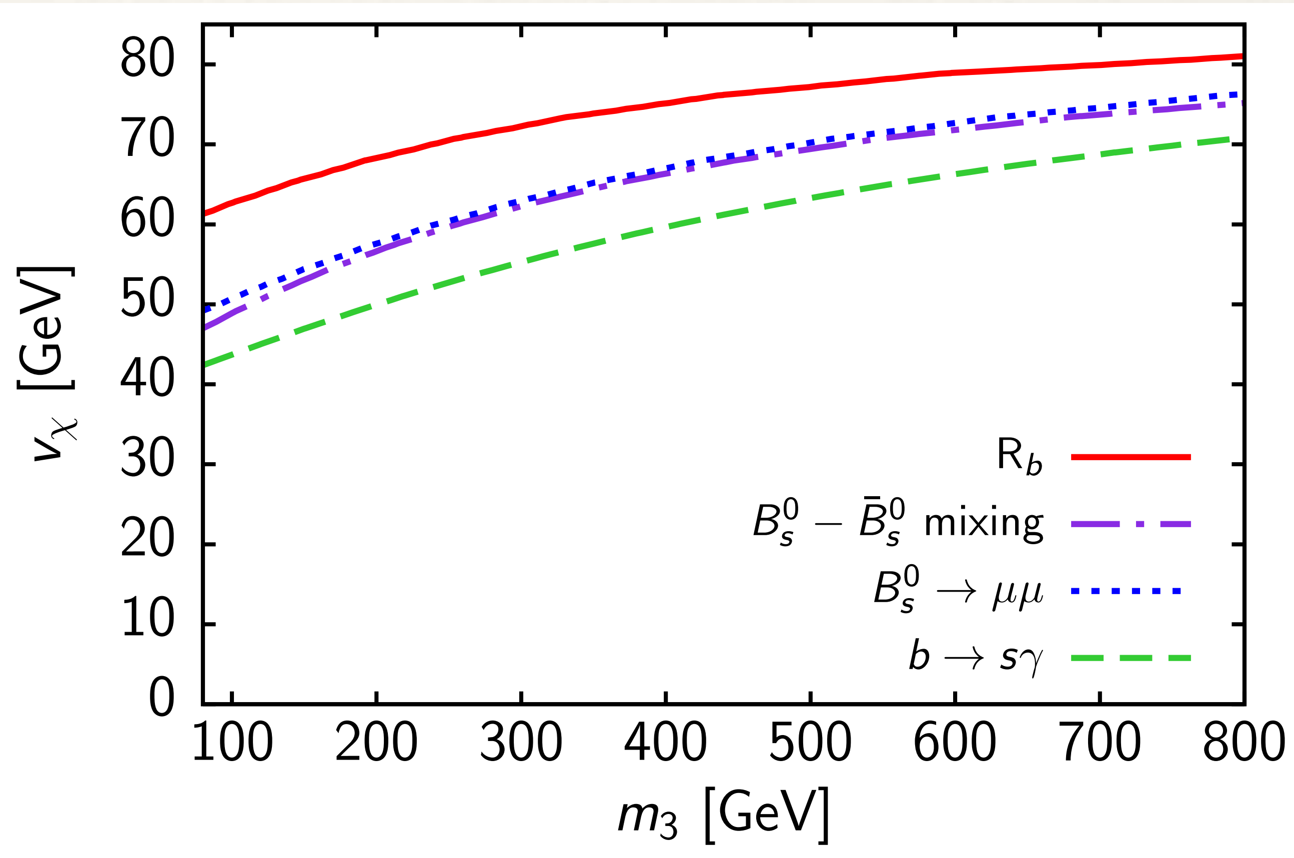
Simplified models

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

$$v_\chi = \langle \chi_3 \rangle \sim \langle \xi_2 \rangle \neq 0$$

[Hartling, Kumar, Logan `14]





$$s_H = \frac{2\sqrt{2}v_\chi}{v} \lesssim 0.25 \qquad v = \sqrt{v_\phi^2 + 8v_\chi^2} \simeq 246 \text{ GeV}$$

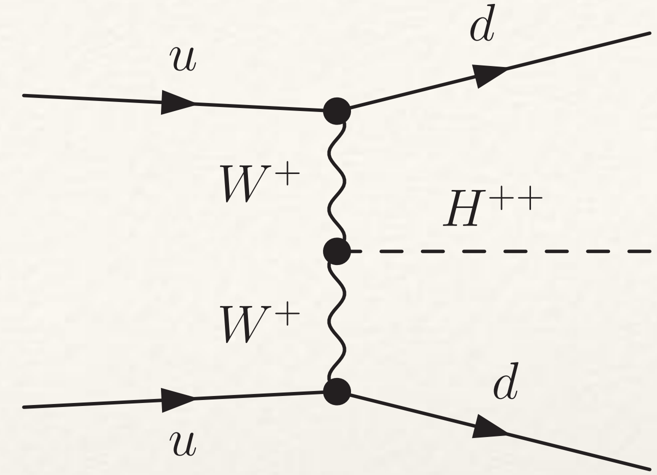
$Q = T_3 + Y$

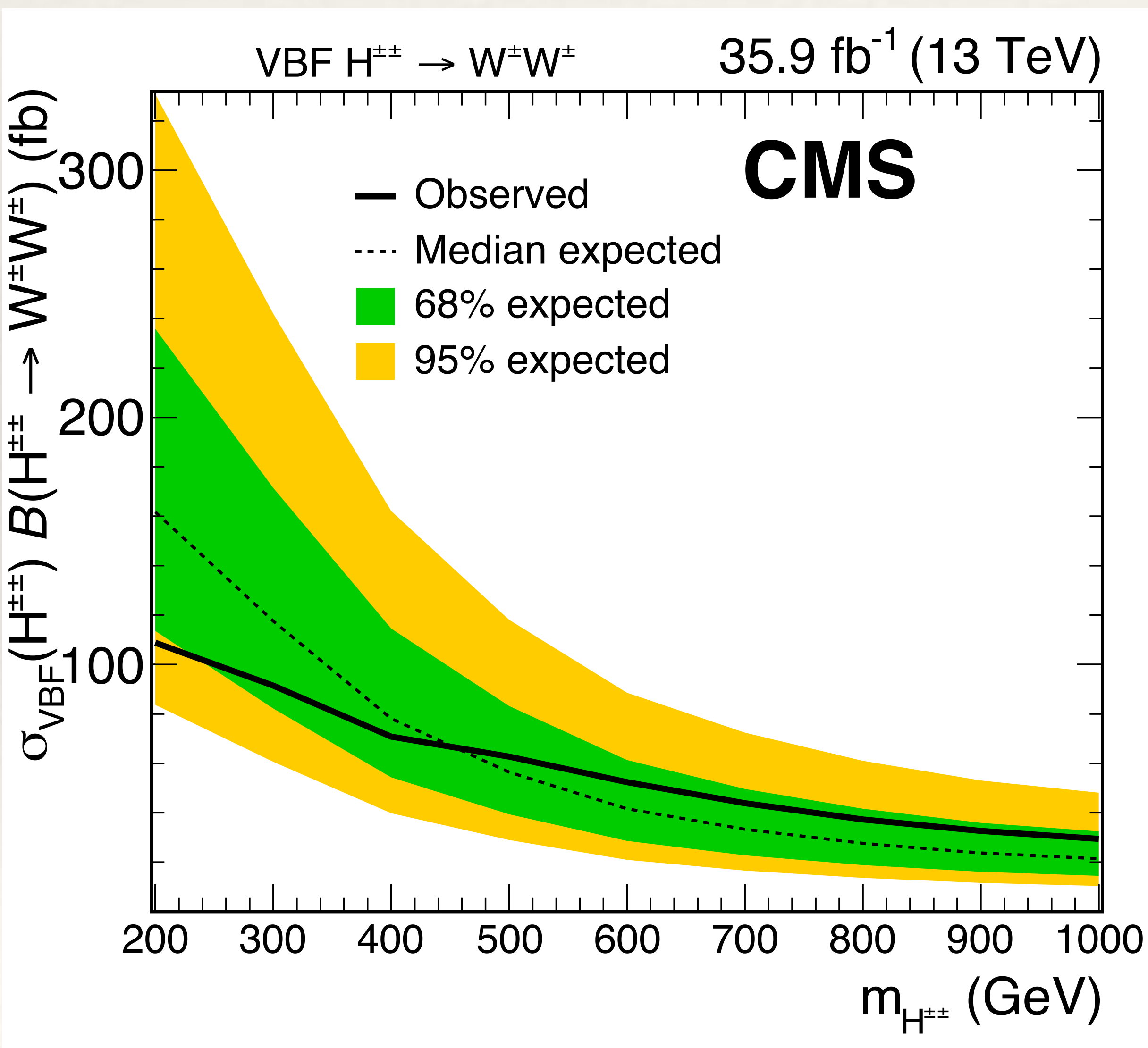
Simplified models

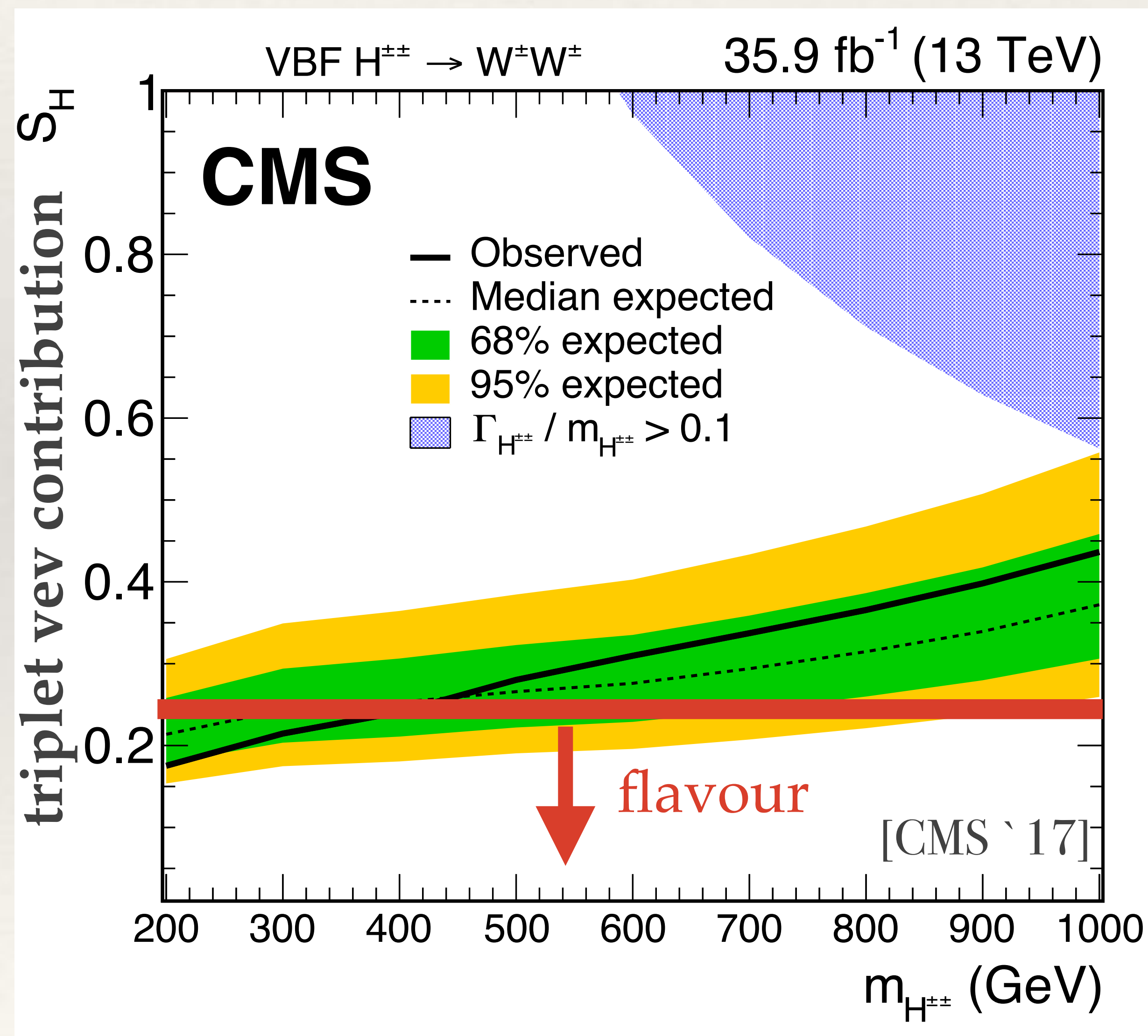
$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

$\langle \chi_3 \rangle \sim \langle \xi_2 \rangle \neq 0$

[Cheung, Gosh `02]
[Godfrey, Moats `10]
[CE, Re, Spannowsky `13]
[Hartling, Kumar, Logan `14]





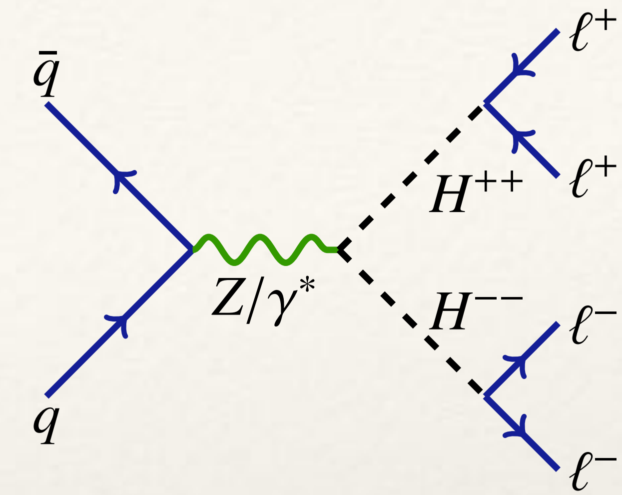


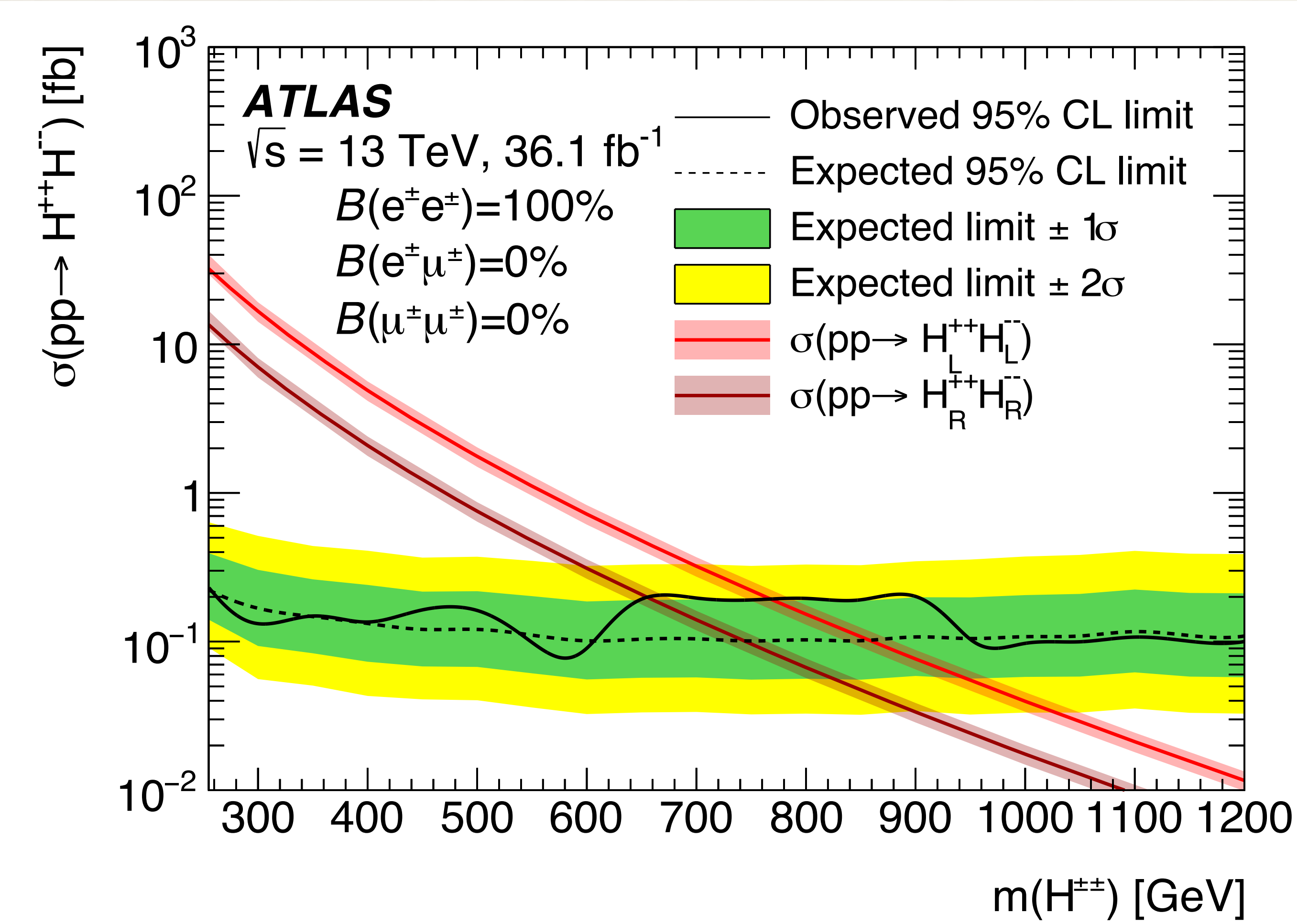
$Q = T_3 + Y$

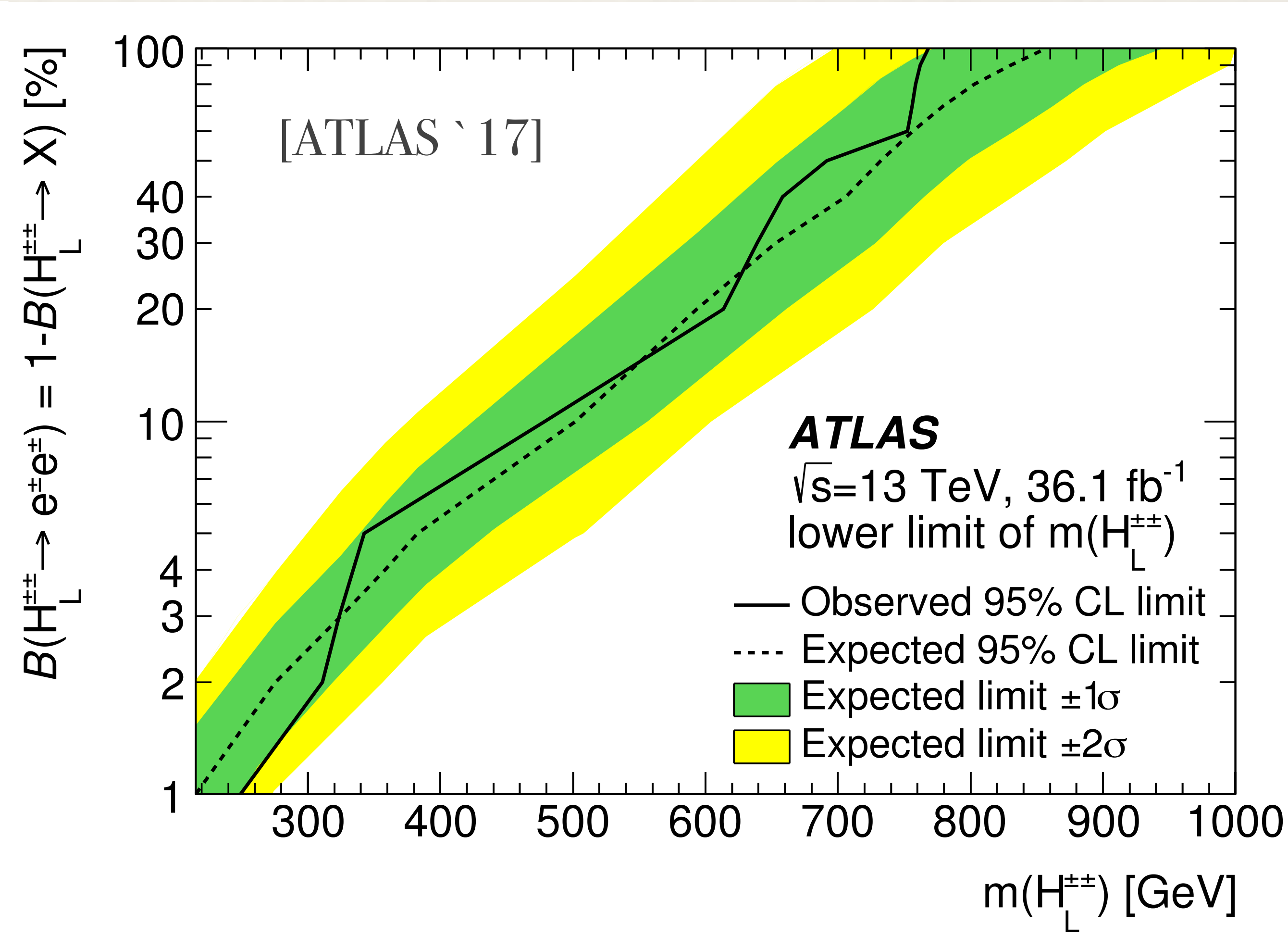
Simplified models

$$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$$

$$\langle \chi_3 \rangle = \langle \xi_2 \rangle = 0$$





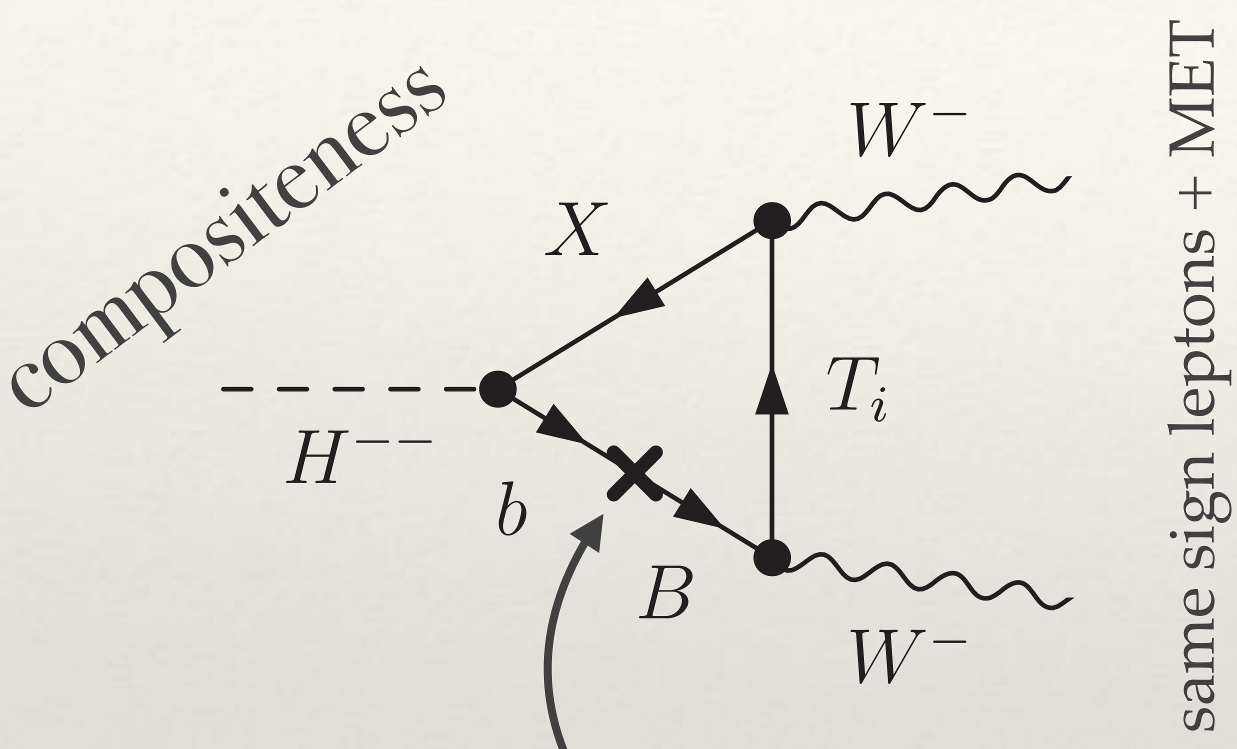


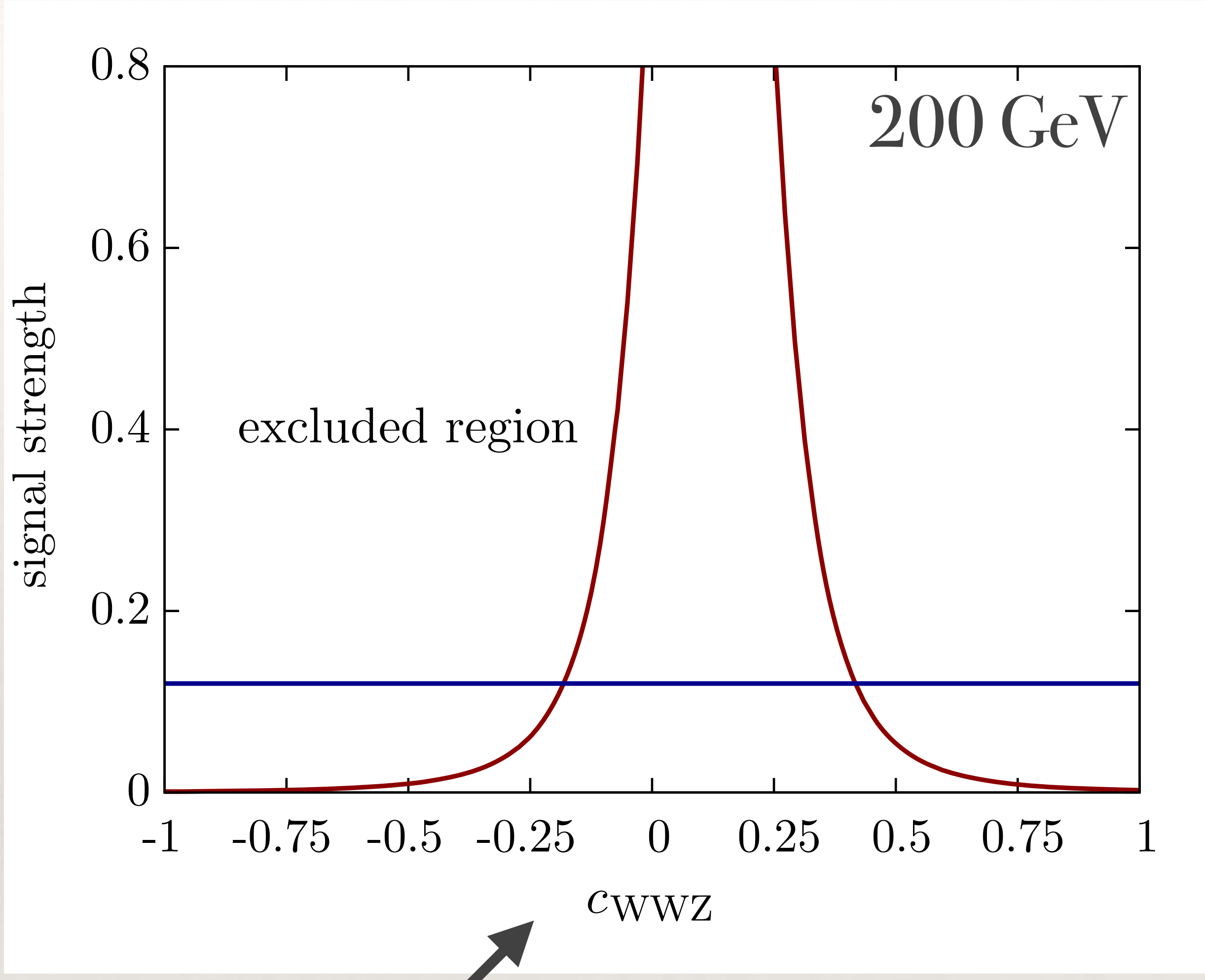
A concrete model of compositeness

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

[Kanemura, Yagyu, Yokoya ` 13]
[Kanemura, Kikuchi, Yagyu, Yokoya ` 13]
[CE, Schichtel, Spannowsky ` 17]

$H^{\pm\pm}$





partial compositeness in the b sector
vs
WWZ interactions

A concrete model of compositeness

- model predicts a number of exotics phenomenological implications

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3)\times SU(3)'}{SU(3)} \times U(1)'$$

[CE, Schichtel, Spannowsky `17]

doubly charged, singly charged and extra neutral Higgs bosons

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

top partners

[Matsedonskyi, Panico, Wulzer `15]

hyperpions

[Belyaev et al. `17]

similarities with [Georgi, Machacek `85]

- partial compositeness: expect modifications in association with heavy fermions triplet Higgs masses

$$V = \hat{C}_{\rm LR}\left(3g^2 + g'^2)(2H^\dagger H + \frac{16}{3}\phi_+^\dagger\phi_+) + 8g^2\phi_0\phi_0\right) + 8\hat{F}_{\rm LL}\phi_+^\dagger\phi_+$$

4-point baryon correlator breaks SU(2)
triplet states not necessarily affected

$$m_{\phi_0}^2 = 16g^2\hat{C}_{\rm LR}\ ,$$

[Ferretti `14] [Golterman, Shamir `15, 17]

$$m_{\phi_+}^2 = 16(g^2 + \frac{g'^2}{3})\hat{C}_{\rm LR} + 8\hat{F}_{\rm LL}$$

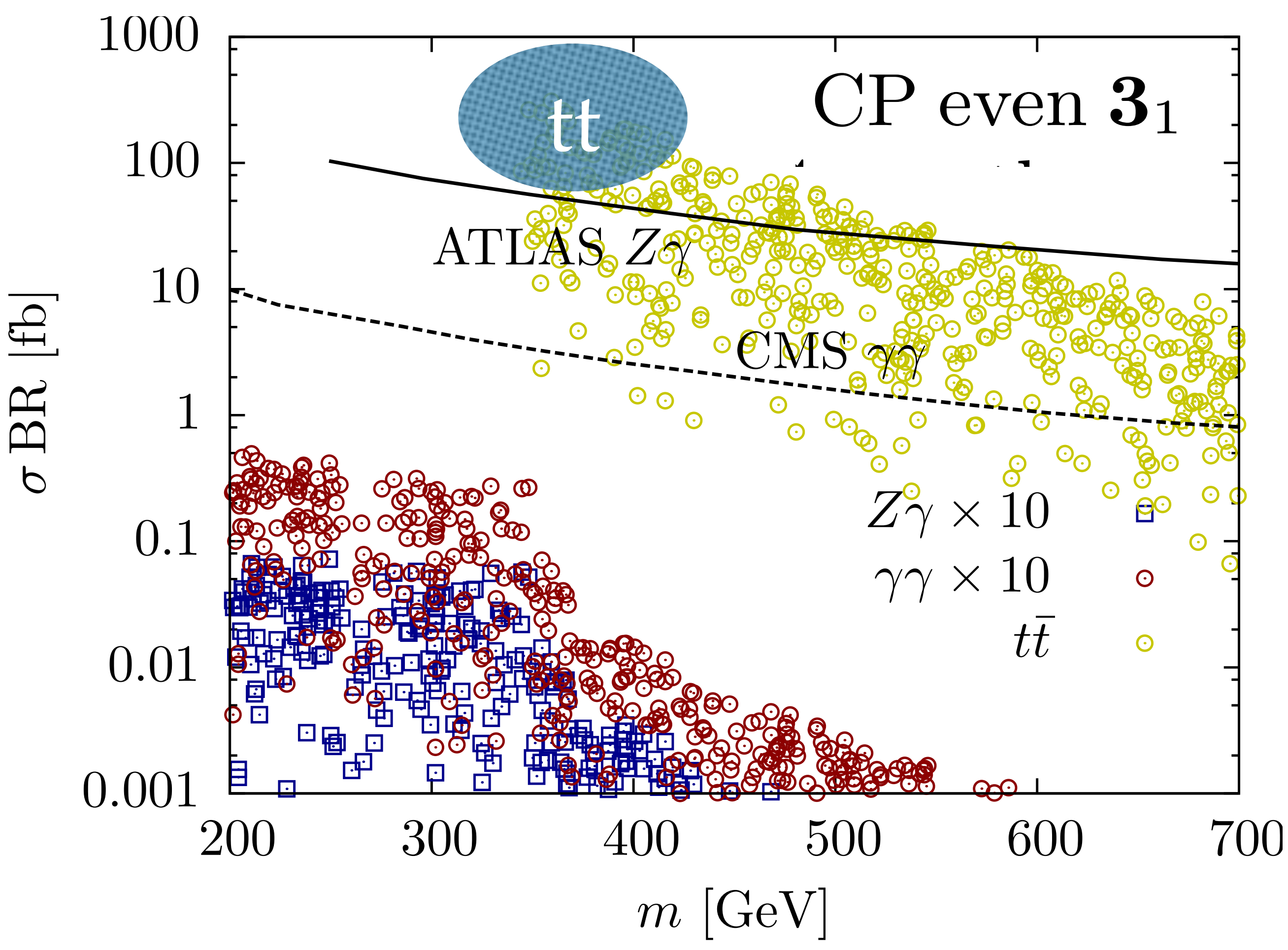
$$\hat{m}_\Phi = \left(\frac{32|\alpha|}{3}\right)^{\frac{1}{2}} = 4\left(\hat{C}_{\rm LR}\left(g^2 + \frac{g'^2}{3}\right)\right)^{\frac{1}{2}} \simeq 0.36\ ,$$

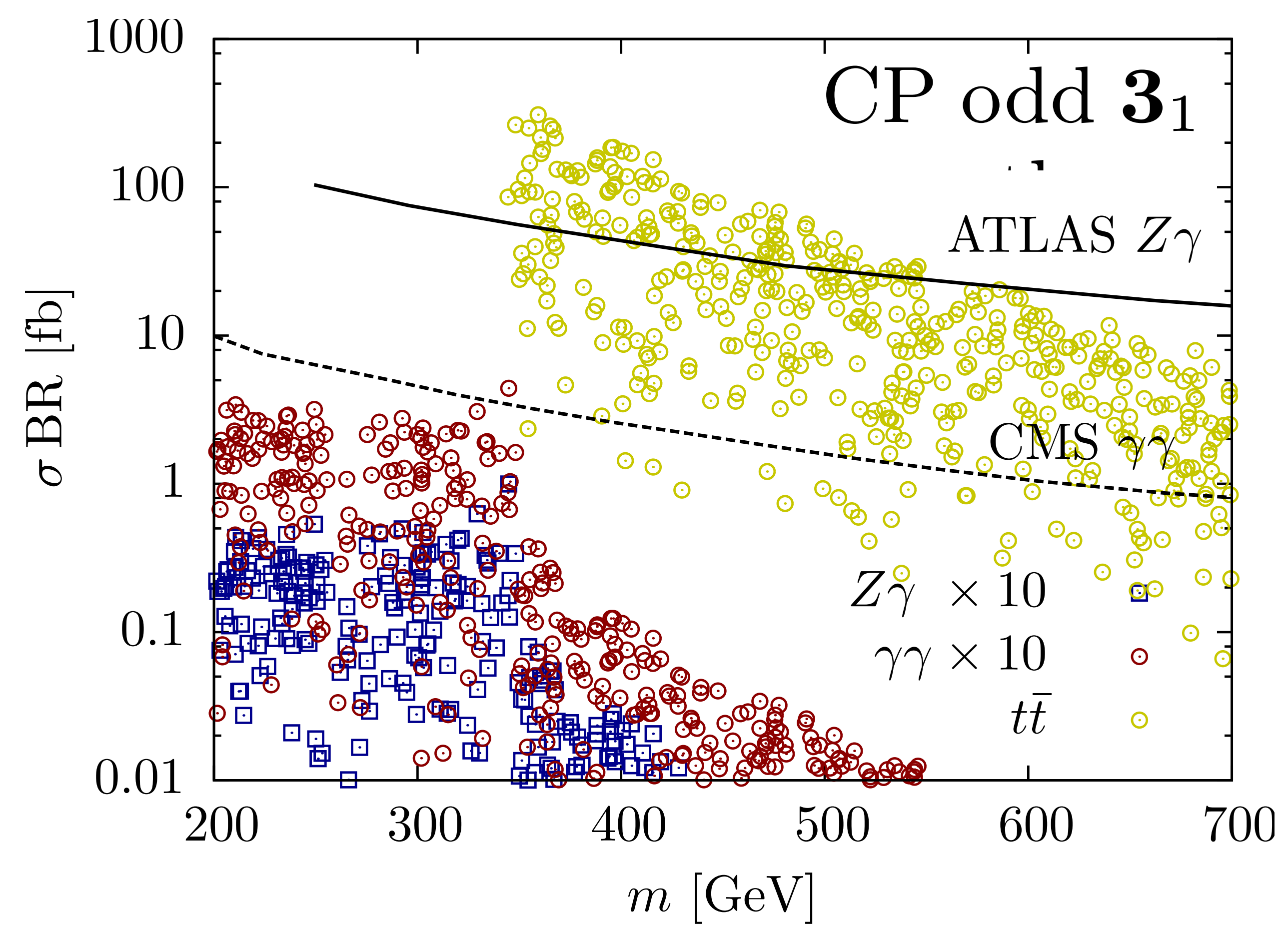
$$\hat{m}_{\Phi_0} = \left(\frac{32|\alpha|}{3}r_g\right)^{\frac{1}{2}} = 4(\hat{C}_{\rm LR}g^2)^{\frac{1}{2}} \simeq 0.34\,,$$

small mass splitting can expect small EWPD corrections compared to effective MCHM5 scenario

e.g. [Gilioz et al. `12]

- searches for extra scalar / pseudoscalar Higgs bosons with couplings to top quarks





- challenging phenomenology, but can expect sensitivity at large luminosity (within the LHC's kinematic coverage)

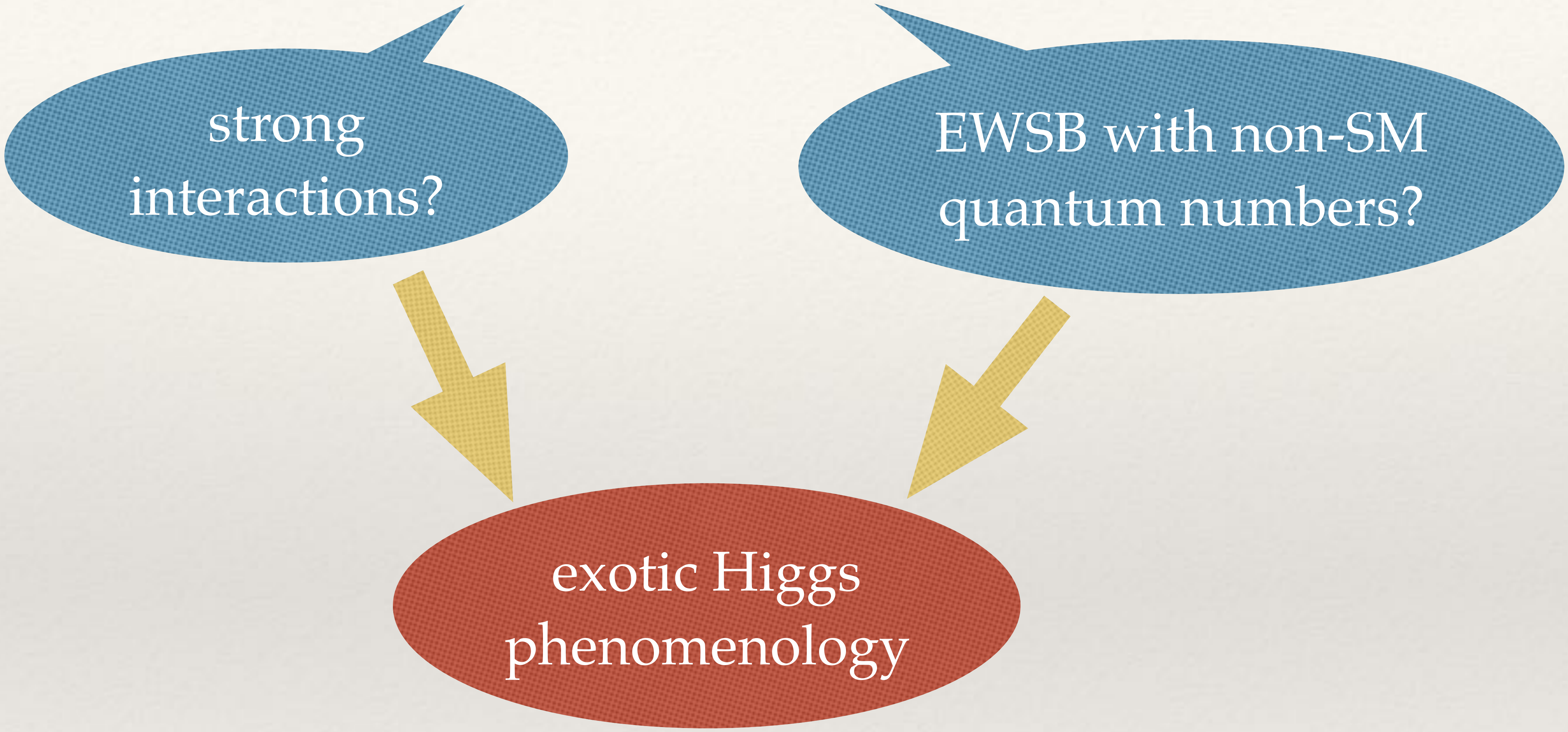
Summary

☛ **vast field of BSM Higgs theories**

strong interactions?

EWSB with non-SM quantum numbers?

- **vast field of BSM Higgs theories**



- **plenty of resonant opportunities in the “LHC precision era”**