JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MBI, 2 September 2015

Composite Higgs models and their implications for EW measurements at the LHC

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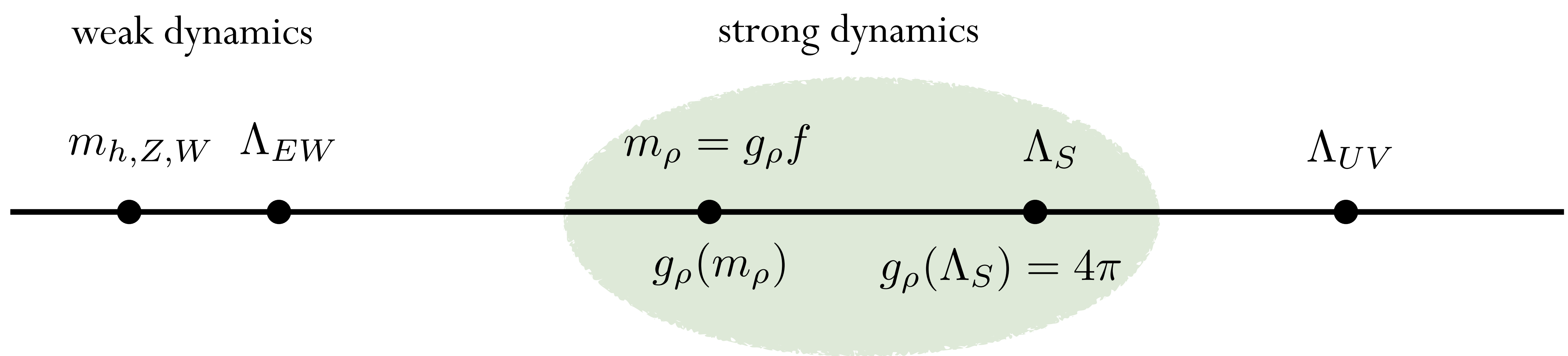
JGU Mainz

Composite Higgs models

Composite Higgs Models

strongly coupled heavy sector at scale m_ρ



heavy resonances expected in the strong sector

above Λ_S H no longer elementary d.o.f. → solves hierarchy problem

still large separation between Λ_{EW} and Λ_S which requires some tuning

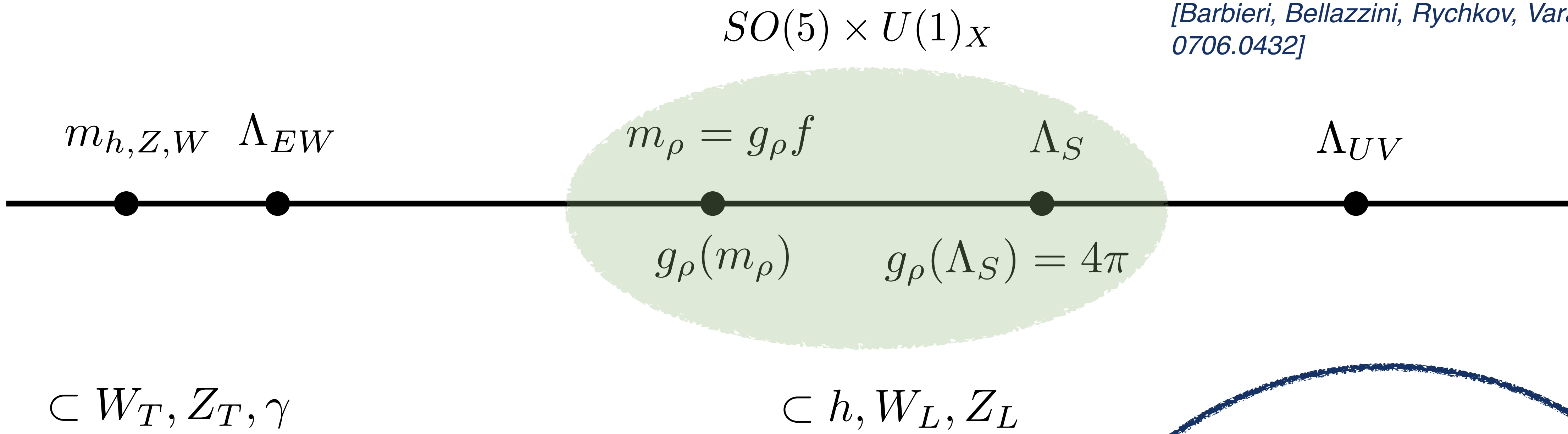
light Higgs present accidentally (e.g. light dilation)

or related to longitudinal polarisation of gauge bosons (pNGB)

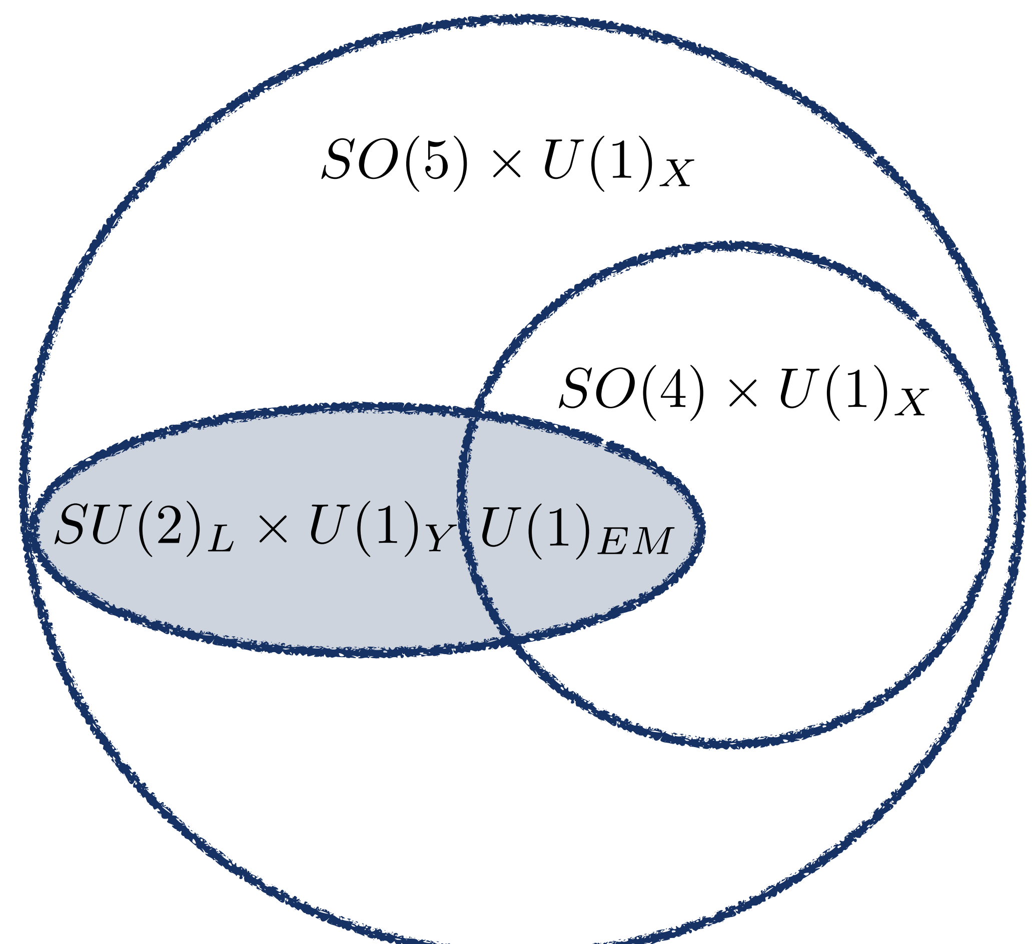
Minimal Composite Higgs Models

strongly coupled heavy sector at scale m_ρ

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]



at scale $f > v$ spontaneously broken
to $SO(4) \times U(1)_X$
quadruplet of pNGB appears: H
→ to guarantee its lightness

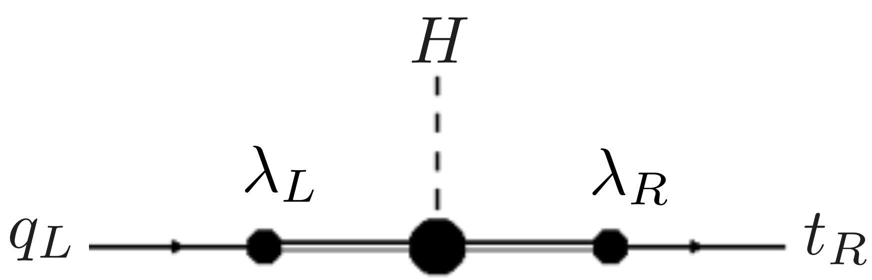


Minimal Composite Higgs

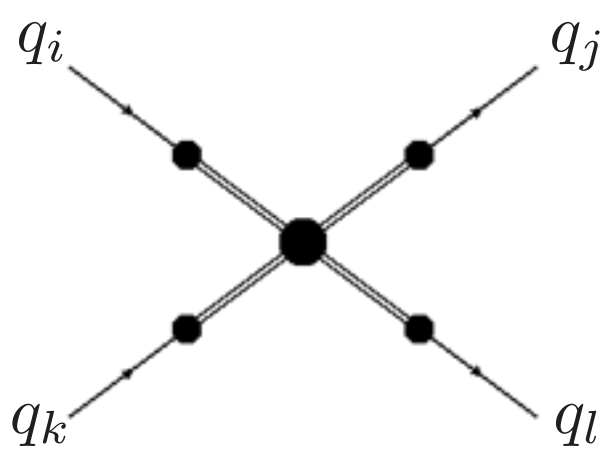
partial compositeness:
linear mixing between elementary and composite states

$$\mathcal{L}_{\rm mix} = \lambda_L\, q_L \mathcal{O}_L^q + \lambda_R\, t_R \mathcal{O}_R^t + \text{h.c.} + g\, A_\mu \mathcal{J}^\mu$$

yields attractive flavour picture
[Csaki, Falkowski, Weiler: arXiv:0804.1954]



$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} = \epsilon_L \epsilon_R g_\psi$$



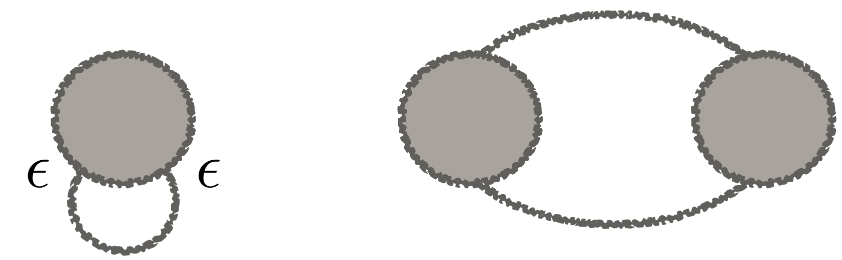
$$\sim \epsilon^i \epsilon^j \epsilon^k \epsilon^l \frac{g_\psi^2}{m_\psi^2}$$

couplings to elementary states → break SO(5)
generate potential

$$V(h) = f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \ldots\right) + \ldots$$

Minimal Composite Higgs

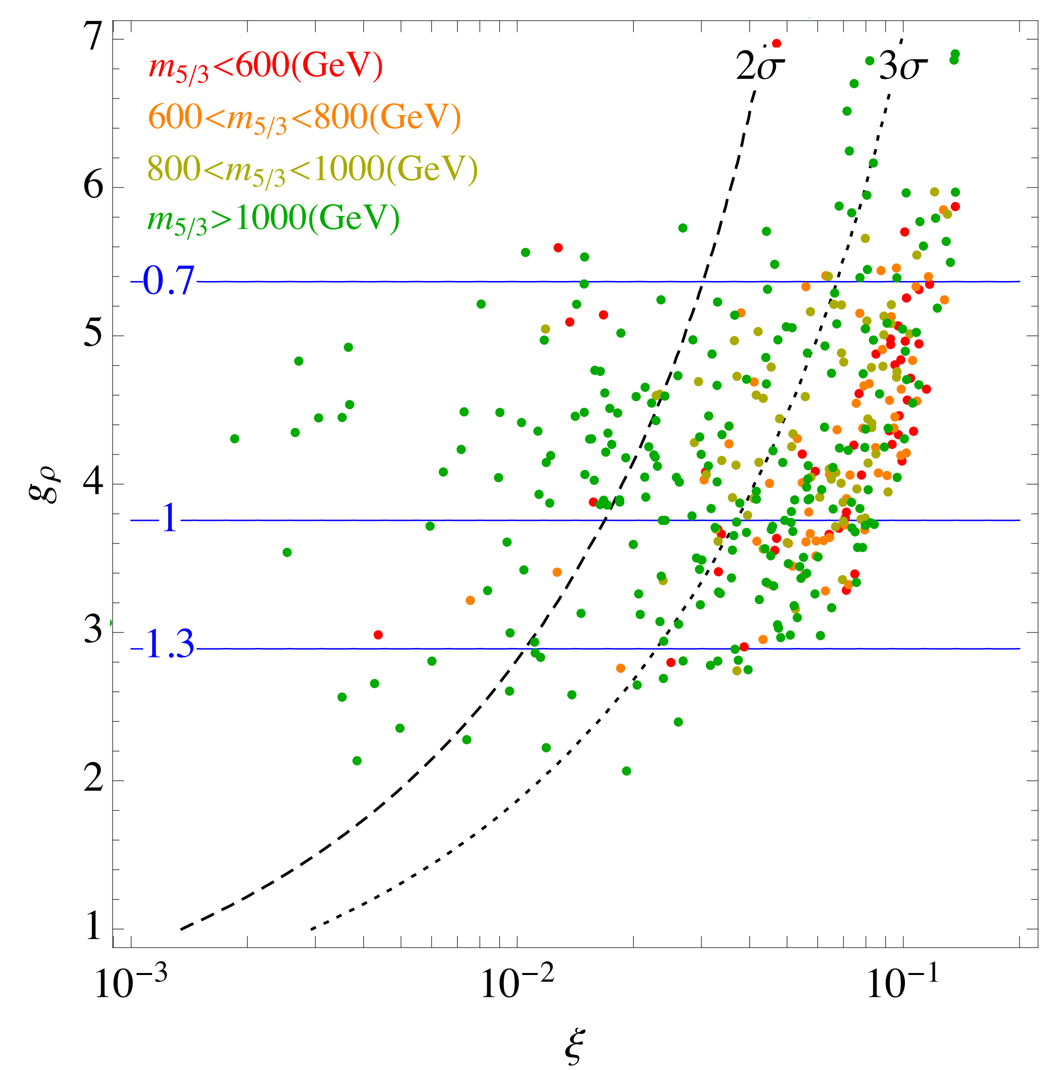
$$V(h) = f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \dots\right) + \dots$$



Higgs mass

$$m_h^2 = (125\,\mathrm{GeV})^2 \frac{1}{\epsilon_R^2} \left(\frac{m_\psi}{1\,\mathrm{TeV}}\right)^2 \frac{\xi}{0.1}$$

need light top partners to obtain light Higgs



[Matsedonskyi, Panico, Wulzer 1204.6333]
[Marzocca, Serone, Shu 1205.0770]
[Pomarol, Riva 1205.6434]
[Panico, Redi, Tesi, Wulzer 1210.7114]
[Barbieri, Buttazzo, Sala, Straub, Tesi 1211.5085]
[Pappadopulo, Thamm, Torre 1303.3062]

Beyond the Minimal Model

can build larger cosets with additional physical salars

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$	
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$	[Agashe, Contino, Pomarol,…]
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$	[Gripaios, Pomarol, Riva, Serra 0902.1485]
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}}+\bar{\mathbf{4}}_{\mathbf{-2}}=2\times(\mathbf{2},\mathbf{2})$	[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$	
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$	[Chala 1210.6208]
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0}=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$	
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$	
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$	[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{\mathbf{+5}}=2\times(\mathbf{2},\mathbf{2})$	
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$	

larger freedom for fermion representations

Composite Higgs Model

- predicts direct and indirect effects

- production of EW vector resonances

$$\hat{S} = \frac{m_W^2}{m_\rho^2} \qquad m_\rho > 2.6\,\mathrm{TeV}$$

- production of top partners
  light to reproduce m_h

[Mrazek, Wulzer: arXiv:0909.3977]
[De Simone, Matsedonskyi, Rattazzi, Wulzer: arXiv:1211.5663]

- modification of Higgs couplings

$$a = g_{WWh} = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

- EWPT
  (sensitive to effects only computable in specific models)

- Flavour

Direct measurements

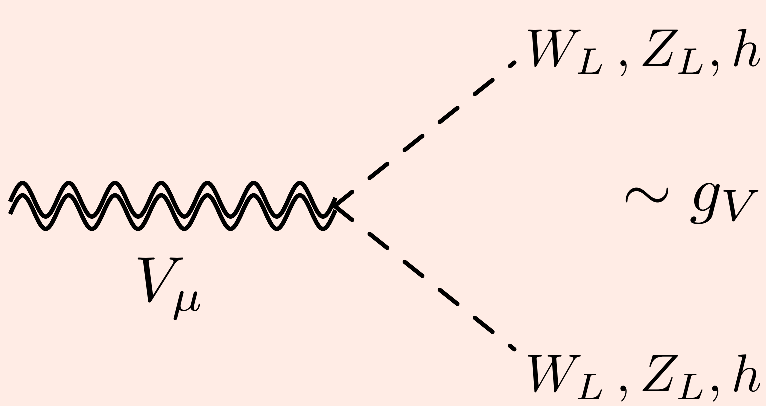
- heavy vectors
- heavy fermions (top partners)

Heavy vectors resonances

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]\,a} + \frac{m_V^2}{2} V^a_\mu V^{\mu\,a}$$
$$+\, i\, g_V c_H V^a_\mu H^\dagger \tau^a \overleftrightarrow{D}^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^{\mu\,a}_F$$
$$+ \frac{g_V}{2} c_{VVV}\, \epsilon_{abc} V^a_\mu V^b_\nu D^{[\mu} V^{\nu]\,c} + g_V^2 c_{VVHH} V^a_\mu V^{\mu\,a} H^\dagger H - \frac{g}{2} c_{VVW} \epsilon_{abc} W^{\mu\,\nu\,a} V^b_\mu V^c_\nu$$

$$V = \left(V^+, V^-, V^0\right)$$

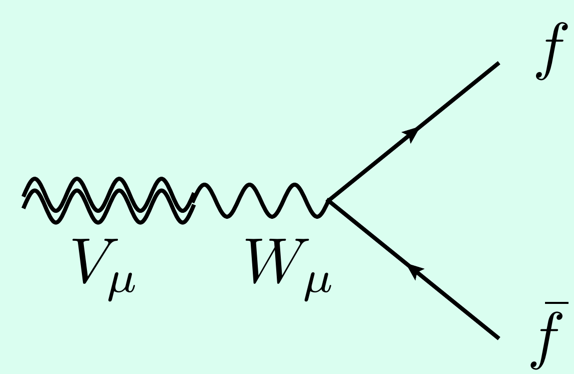
Coupling to SM Vectors



$$\sim g_V c_H$$

Coupling to SM fermions

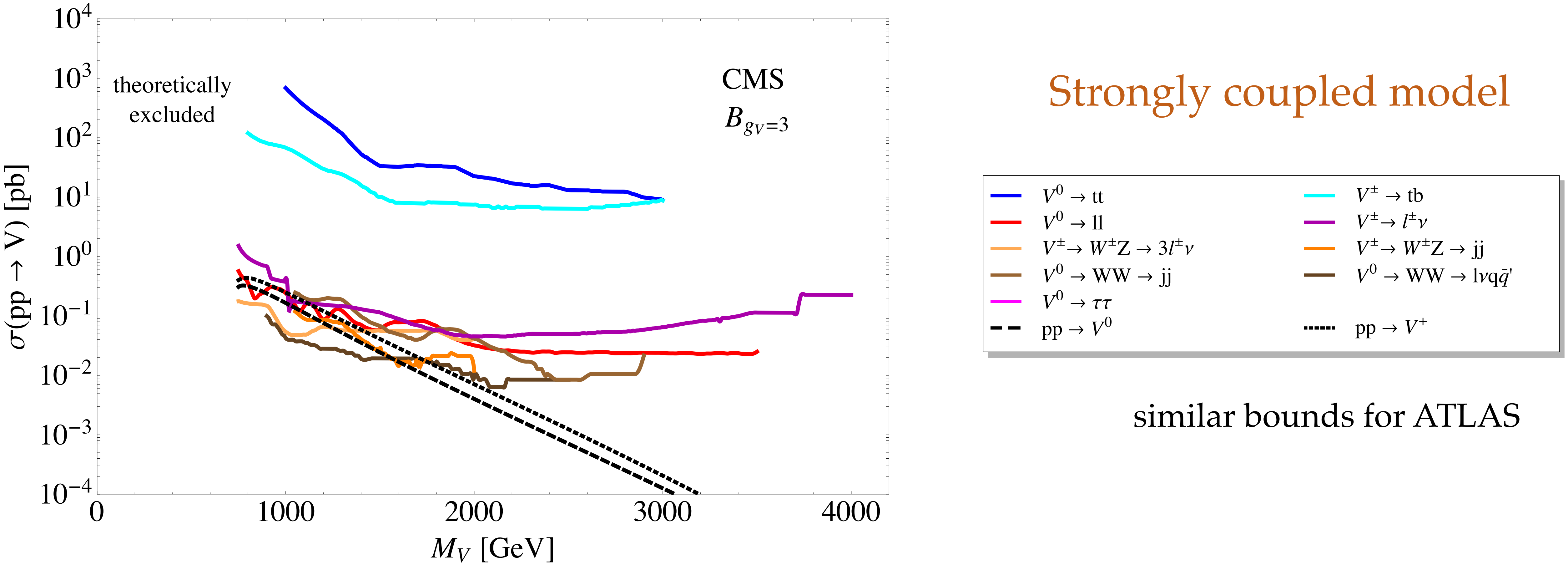
$$J^{\mu\,a}_F = \sum_f \bar{f}_L \gamma^\mu \tau^a f_L$$



$$\sim \frac{g}{g_V} \times g\, c_F$$

$$c_F V \cdot J_F \;\rightarrow\; c_l V \cdot J_l + c_q V \cdot J_q + c_3 V \cdot J_3$$

Heavy vectors: LHC bounds



Strongly coupled model

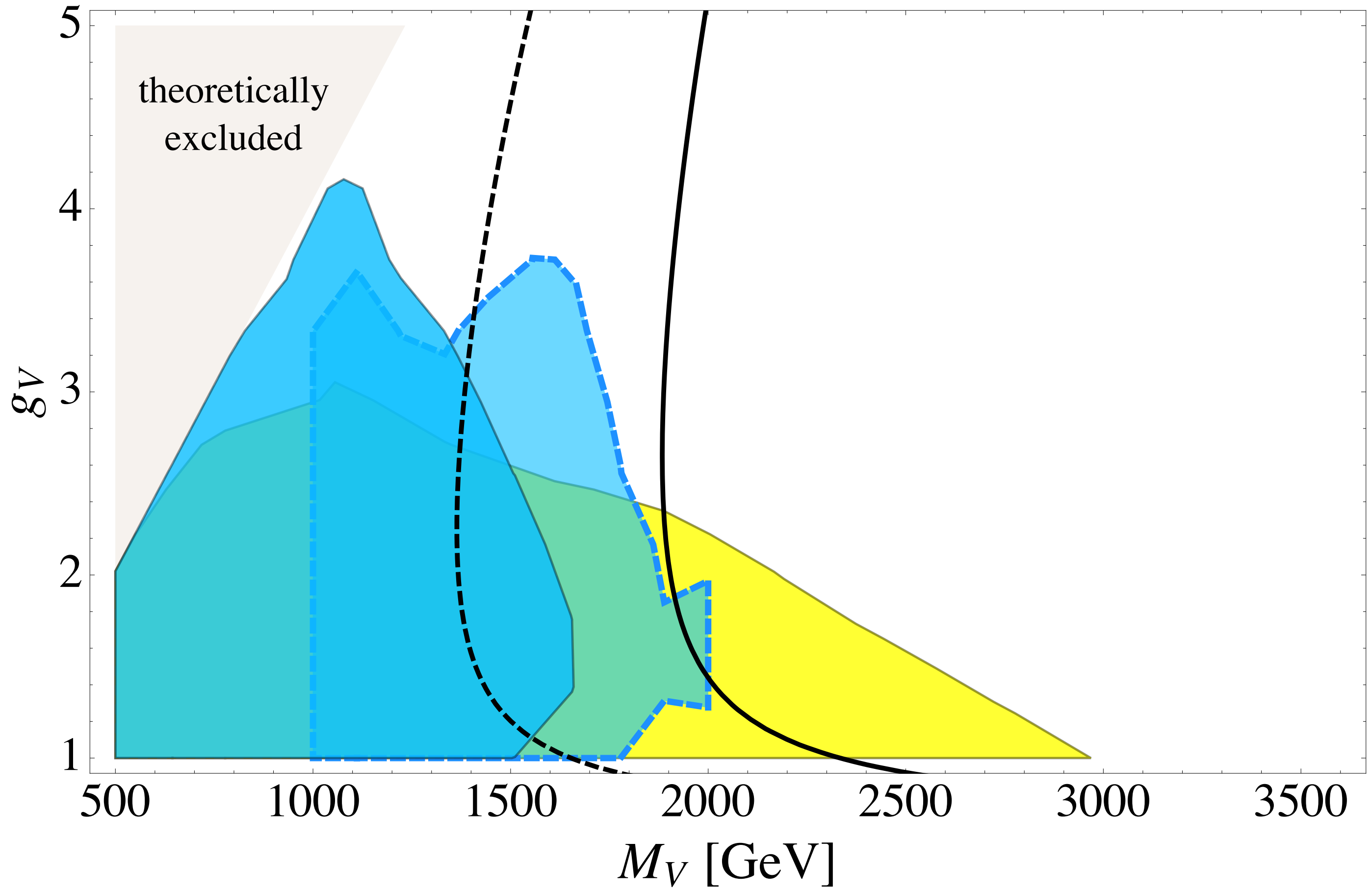
similar bounds for ATLAS

- excluded for masses < 1.5 TeV
  unconstrained for larger g_V
- di-boson most stringent
- in excluded region G_F, m_Z not reproduced

Limits on parameter space

- experimental limits converted into (M_V, g_V) plane

Strongly coupled model



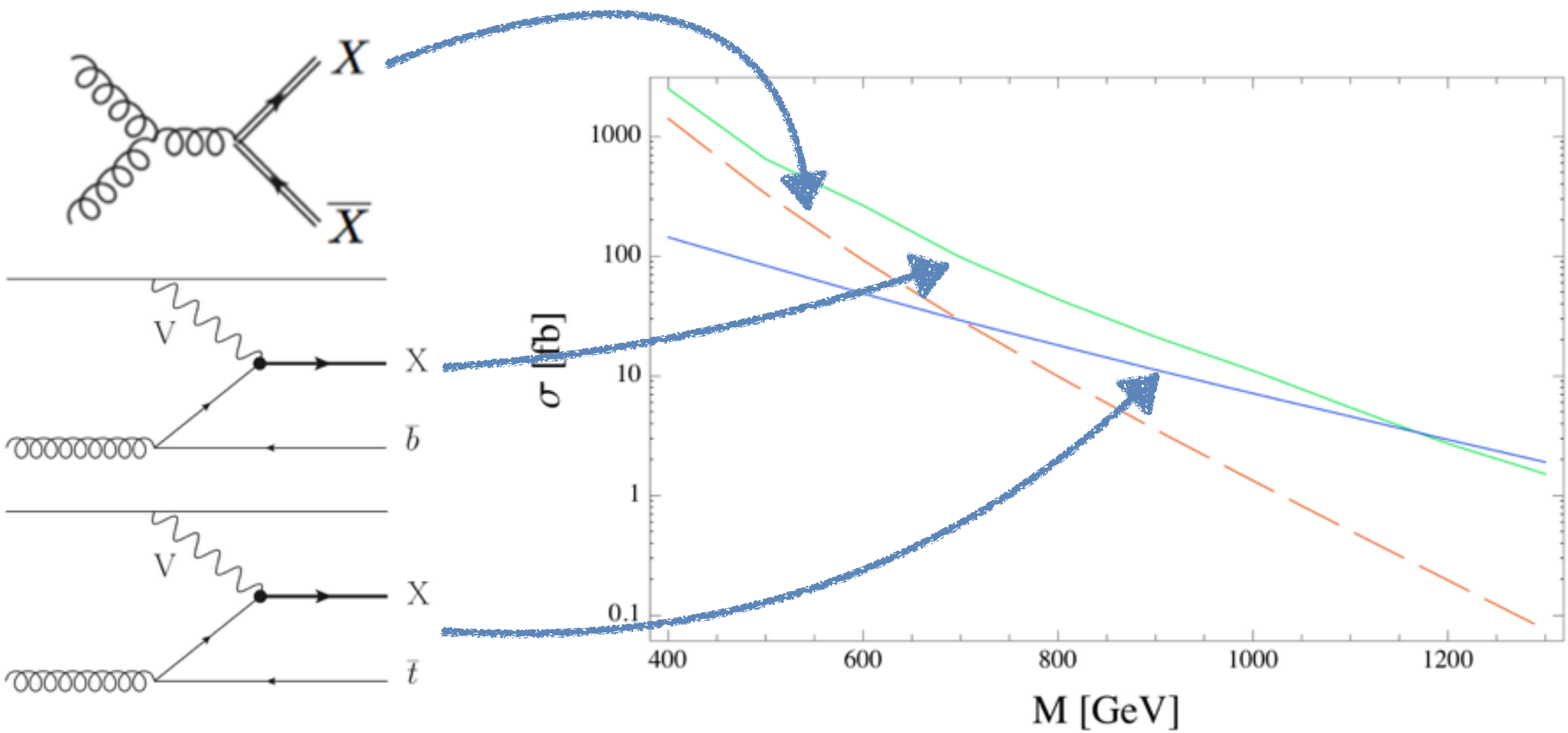
yellow: CMS $l^+\nu$ analysis
dark blue: CMS $WZ \to 3l\nu$
light blue: CMS $WZ \to jj$
black: bounds from EWPT

- leptonic final state dominates
- very different for larger coupling
- weaker limits if top partner decays are open

[Pappadopulo, Thamm, Torre, Wulzer: arXiv:1402.4431]
[Greco, Liu: arXiv:1410.2883]
[Chala, Juknevich, Perez, Santiago :arXiv:1411.1771]

Top partners

- expect new vector-like fermions at the TeV scale
- minimal case: top-like state and heavy charge 5/3 coloured state
- non-minimal cases: top-, bottom-like states, charge -4/3, 5/3, 8/3
- either pair production, or single production in association with a b or t



[De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663]

Limits on parameter space

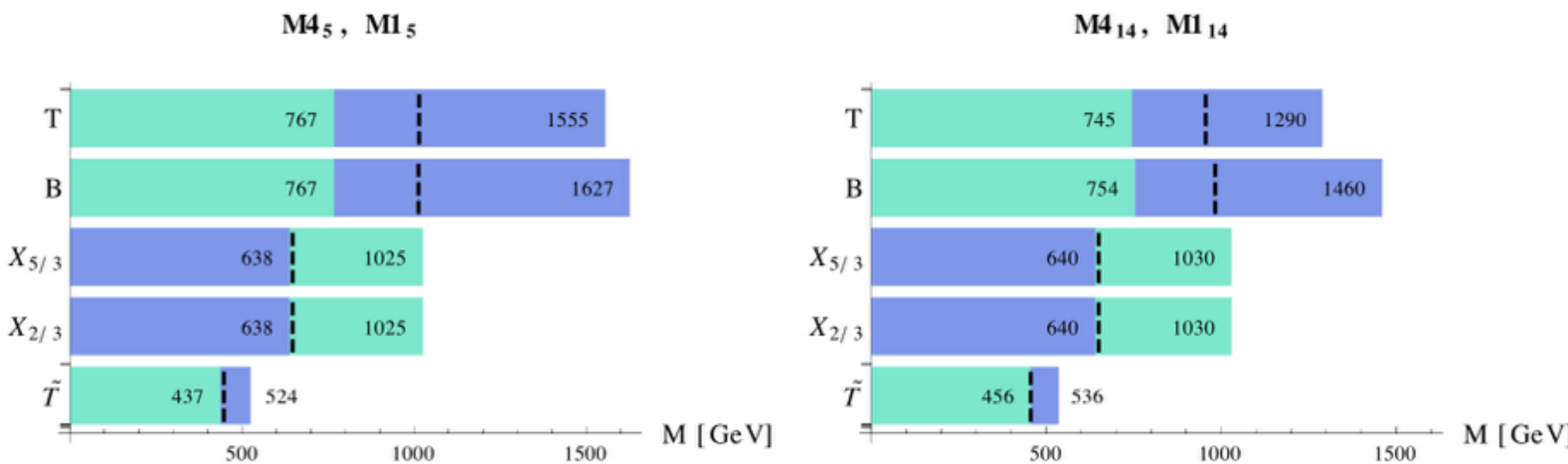
lightest

- effective approach with only one top partner present
- typical decay channels: $X_{5/3} \to tW$

$$X_{2/3} \to tZ \qquad X_{2/3} \to th$$

$$T \to X_{2/3}Z \qquad T \to X_{2/3}h \qquad T \to X_{5/3}W$$

$$B \to tW \qquad B \to TW \qquad B \to bh$$



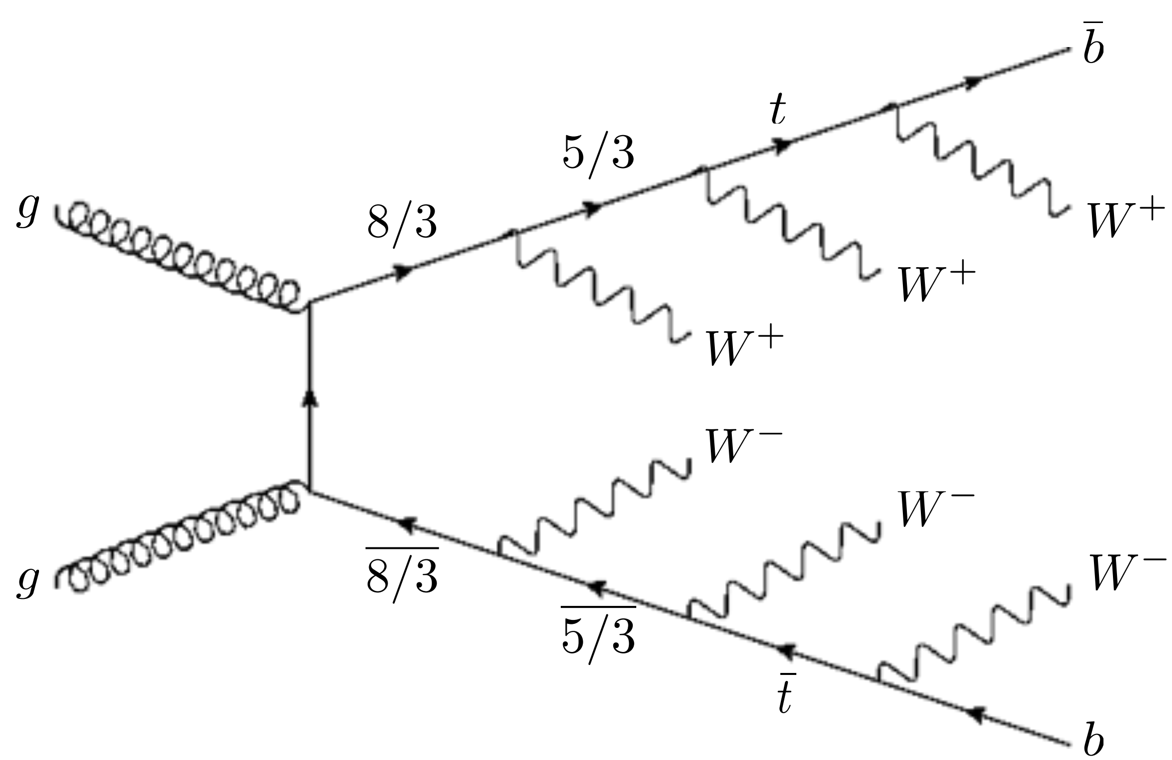
[De Simone, Matsedonskyi, Rattazzi, Wulzer 1211.5663]

Exotic states

- consider different representation, exotic quarks are predicted to be very light
  e.g. in the 14: quark with charge 8/3
- very interesting phenomenology: 3W and b
- signatures in two-same sign lepton searches
- current bounds

$$m_{8/3} > 700\,\mathrm{GeV}$$

[ATLAS-CONF-2012-130]
[CMS-PAS-SUS-12-027]



[Pappadopulo, Thamm, Torre: 1303.3062]
[Matsedonskyi, Riva, Vantalon: 1401.3740]

Indirect measurements

- Anomalous Higgs couplings
- EWPT

Parameterisation I

singlet

most general parameterisation, assumptions $m_h \ll m_\rho$

custodial symmetry

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \dots\right)$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\left(\frac{m_h^2}{2v}\right)h^3 + d_4\left(\frac{m_h^2}{8v^2}\right)h^4 + \dots$$

SM limit $a = b = d_3 = d_4 = 1$ $b_3 = 0$ $\Sigma(x) = \exp\left(i\sigma^a \chi^a(x)/v\right)$

Parameterisation I

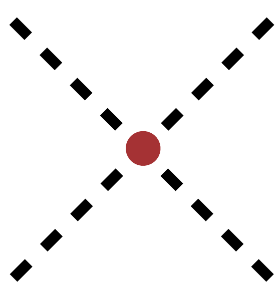
singlet

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \ldots\right)$$

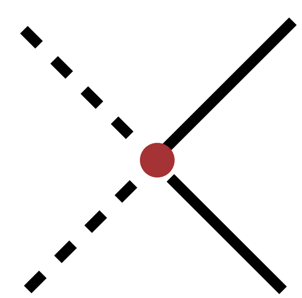
$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\left(\frac{m_h^2}{2v}\right)h^3 + d_4\left(\frac{m_h^2}{8v^2}\right)h^4 + \ldots$$

$$\Sigma(x) = \exp\left(i\sigma^a \chi^a(x)/v\right)$$

deviations in couplings ⟷ energy growing amplitudes



$$\sim \left(1 - a^2\right)\frac{s}{v^2} + \ldots$$



$$\sim \left(a^2 - b\right)\frac{s}{v^2} + \ldots \qquad \equiv \bar{g}(\sqrt{s})^2$$

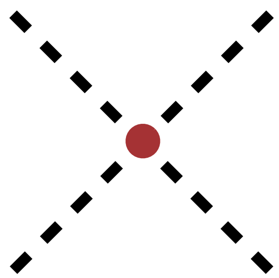
perturbativity lost at $\sqrt{s_*}$ where $\bar{g}(\sqrt{s_*}) \sim 4\pi$

expect new states at $m_* \leq \sqrt{s_*}$ with coupling $\bar{g}\left(m_*\right) \leq 4\pi$

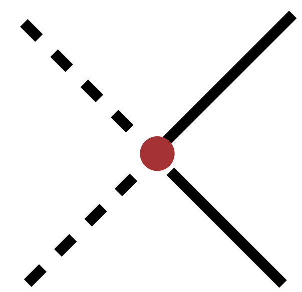
Parameterisation I

singlet

deviations in couplings ⟷ energy growing amplitudes



$\sim \left(1 - a^2\right) \frac{s}{v^2} + \ldots$



$\sim \left(a^2 - b\right) \frac{s}{v^2} + \ldots \qquad \equiv \bar{g}(\sqrt{s})^2$

can find lower bound on strong coupling

$$g_\rho > \bar{g}(\sqrt{s}) \sim \sqrt{\delta_{hh}}\,\frac{\sqrt{s}}{v}$$

set upper bound ϵ_{hh}

with enough precision include subleading corrections

$$\mathcal{A}(2 \to 2) = \delta_{hh} \frac{s}{v^2} \left(1 + O\left(\frac{s}{m_\rho^2}\right)\right)$$

no new states below $M \sim \sqrt{s}/\sqrt{\epsilon_{hh}}$

stronger bound

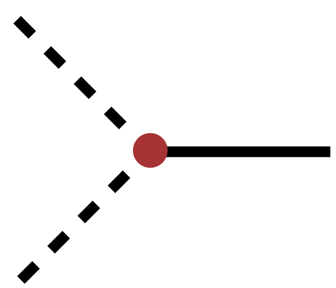
$$g_\rho > \bar{g}(M) \sim \sqrt{\frac{\delta_{hh}^{exp}}{\epsilon_{hh}}}\,\frac{\sqrt{s}}{v}$$

Parameterisation I

singlet

independent probe: single Higgs production

δ_h



$$\sim \frac{g_\rho^2 v^2}{M^2}$$

implies lower bound on coupling

$$g_\rho > \sqrt{\delta_h}\,\frac{M}{v}$$

Summary

We can distinguish whether Higgs is

elementary ⟷ composite

Parameterisation II

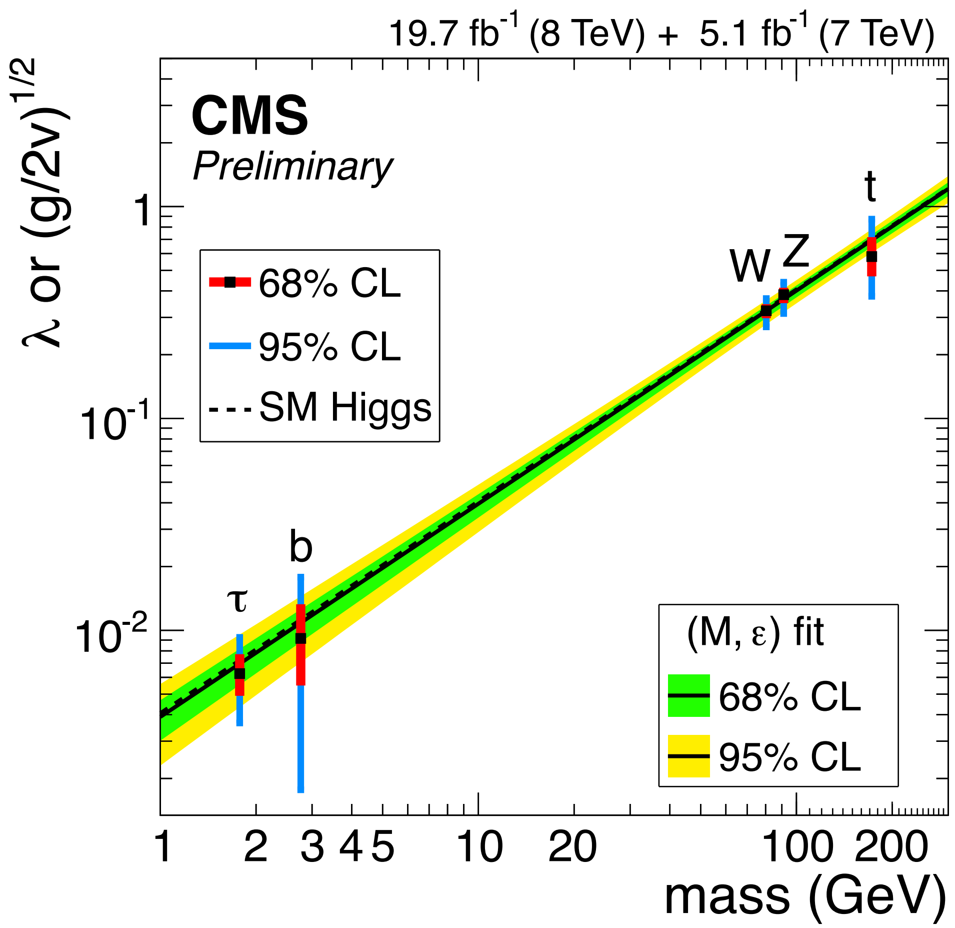
doublet

stronger assumptions

[Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]
[Elias-Miro, Espinosa, Masso, Pomarol: arxiv:1302.5661]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \text{dim-6 operators} + \ldots$$

current experimental evidence!



$$\Delta\mathcal{L} = \lambda h \bar{f} f$$

$$\Delta\mathcal{L} = m_V^2 \left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right) V_\mu V^\mu$$

in the non-linear realisation,
Higgs couplings to fermions and gauge bosons arbitrary,
but strong correlation observed

Parameterisation II

doublet

stronger assumptions

[Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]
[Elias-Miro, Espinosa, Masso, Pomarol: arxiv:1302.5661]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \text{dim-6 operators} + \ldots$$

$$O_H = \frac{c_H}{2f^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \qquad O'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu |H|^2 \partial^\mu |H|^2$$

$$O_6 = -\frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3 \qquad O_8 = -\frac{c_8 \lambda}{f^4}\left(H^\dagger H\right)^4$$

relation to Higgs anomalous Higgs couplings

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

$$b = 1 - 2c_H\frac{v^2}{f^2} + \left(3c_H^2 - \frac{3c'_H}{2}\right)\frac{v^4}{f^4} \qquad b_3 = -\frac{4c_H}{3}\frac{v^2}{f^2} + \left(\frac{14c_H^2}{3} - 2c'_H\right)\frac{v^4}{f^4}$$

$$d_3 = 1 + \left(c_6 - \frac{3c_H}{2}\right)\frac{v^2}{f^2} + \left(\frac{15c_H^2}{8} - \frac{5c'_H}{4} - \frac{c_6 c_H}{2} - \frac{3c_6^2}{2} + 2c_8\right)\frac{v^4}{f^4}$$

Parameterisation II

doublet

relation to Higgs anomalous Higgs couplings

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

$$b = 1 - 2c_H\frac{v^2}{f^2} + \left(3c_H^2 - \frac{3c'_H}{2}\right)\frac{v^4}{f^4} \qquad b_3 = -\frac{4c_H}{3}\frac{v^2}{f^2} + \left(\frac{14c_H^2}{3} - 2c'_H\right)\frac{v^4}{f^4}$$

at order $O\left(v^2/f^2\right)$ couplings given in terms of one parameter

relation

$$\Delta b = 2\Delta a^2\left(1 + O(\Delta a^2)\right)$$

$$\Delta a^2 \equiv a^2 - 1$$
$$\Delta b \equiv b - 1$$

from single Higgs production: measure Δa^2 with an error 10^{-2}

from double Higgs production: measure Δb with an error 10^{-2}

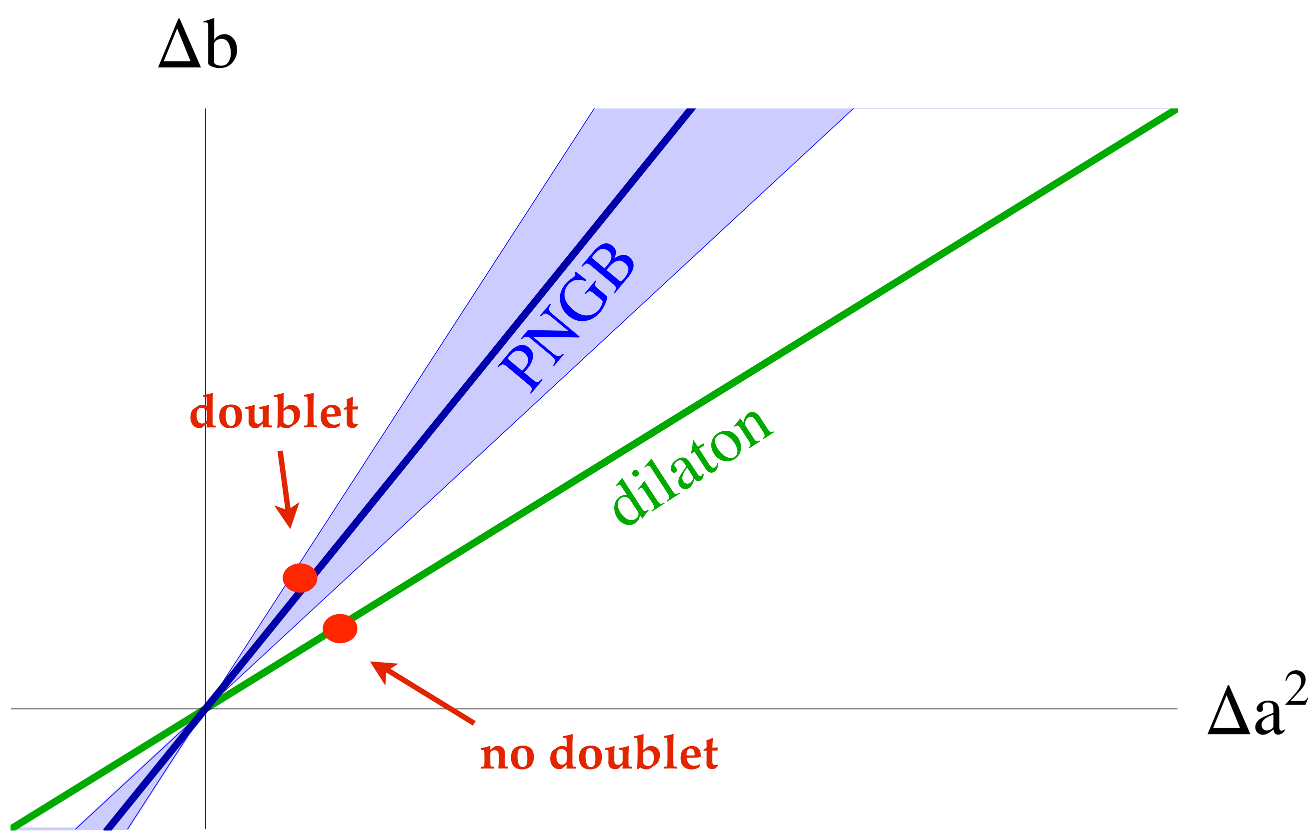
[Abramowicz: arXiv:1307.5288]
[Contino, Grojean, Pappadopulo, Rattazzi, Thamm: arXiv:1309.7038]

Parameterisation II

doublet

relation $\Delta b = 2\Delta a^2 \left(1 + O(\Delta a^2)\right)$

$\Delta a^2 \equiv a^2 - 1$
$\Delta b \equiv b - 1$



imagine we measure $\Delta a^2, \Delta b \sim 10^{-2}$ relation could not be respected

can distinguish doublet and singlet structure

theoretically not very motivated except for dilaton with $\Delta b = \Delta a^2$

Summary

We can distinguish whether Higgs is

elementary ⟷ composite

singlet ⟷ doublet

Parameterisation III

pNGB

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]

even stronger assumptions: MCHM SO(5)/SO(4)

breaking scale $f > v$

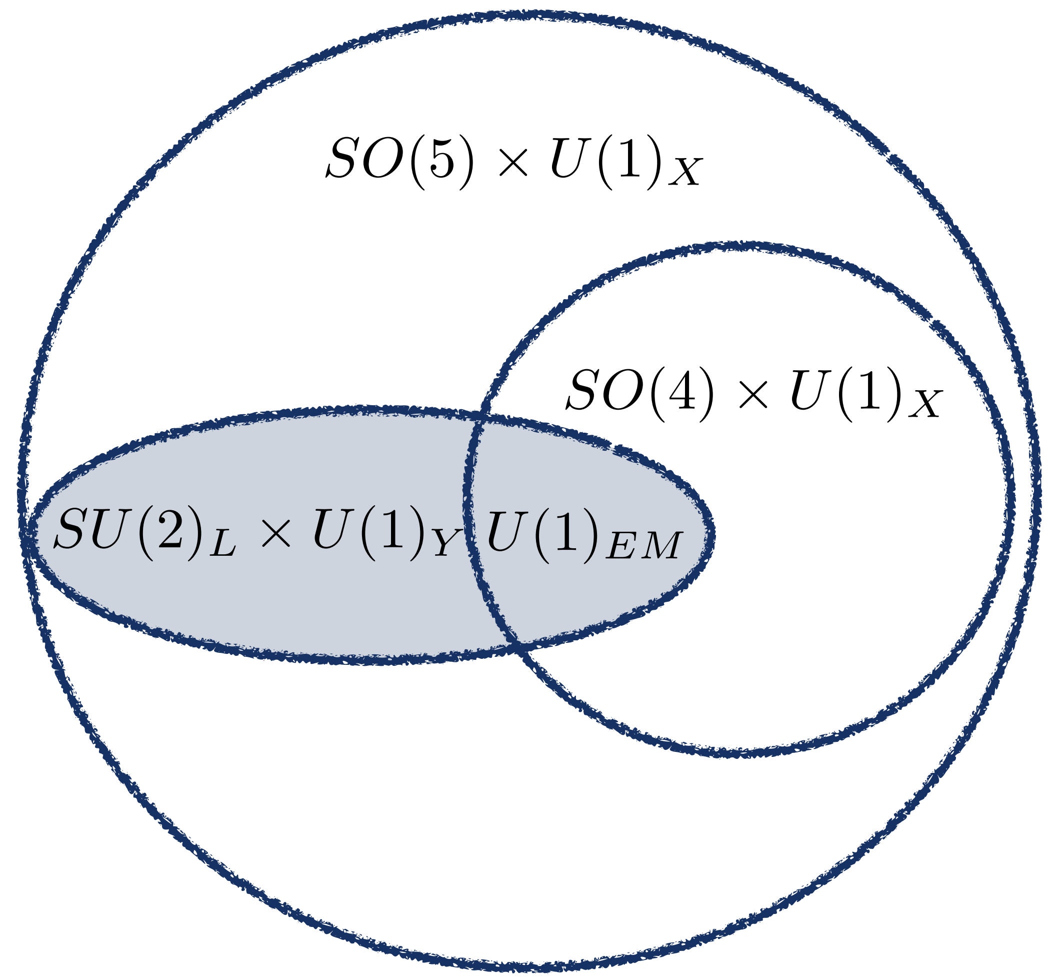
$$a = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$b_3 = -\frac{4}{3}\xi\sqrt{1-\xi}$$

$$d_3^{(4)} = \sqrt{1-\xi}$$

where $\xi = \frac{v^2}{f^2}$



at $O\left(v^2/f^2\right)$ can not distinguish a pNGB from a generic doublet

at $O\left(v^4/f^4\right)$ pNGB implies $c'_H = 2c_H^2$

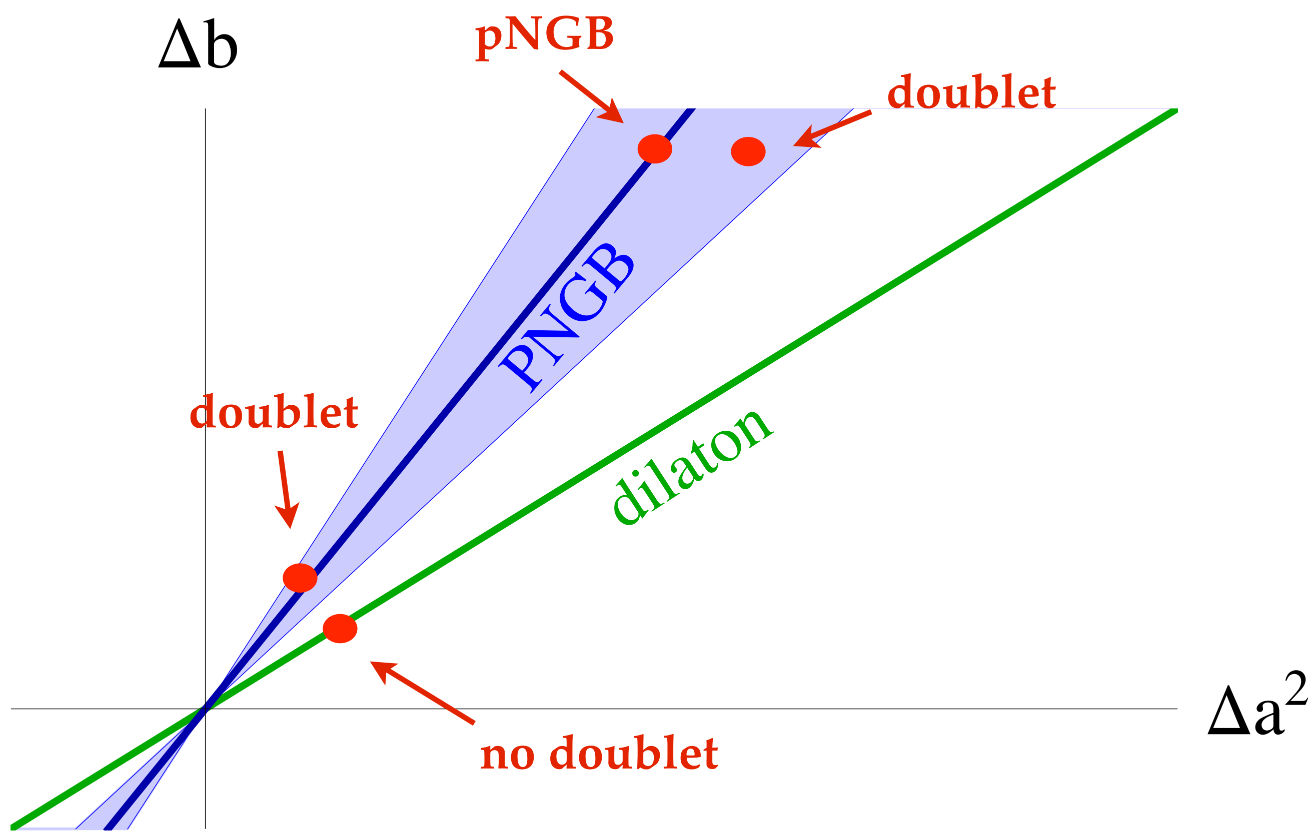
Parameterisation III

pNGB

relation
(to all orders)

$$\Delta b = 2\Delta a^2$$

$$\Delta a^2 \equiv a^2 - 1$$
$$\Delta b \equiv b - 1$$



imagine we measure $\Delta a^2, \Delta b \geq 0.1$ relation could not be respected

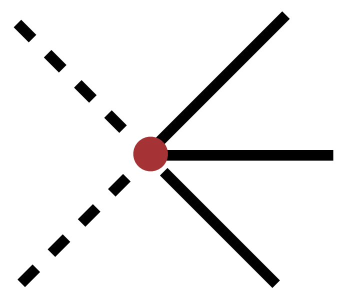
can distinguish pNGB and non-pNGB structure

imagine we measure $\Delta a^2, \Delta b < 0.1$, then we could not distinguish

Parameterisation III

pNGB

independent probe of pNGB nature: triple Higgs production



$$\sim \frac{is}{v^3}\left(4ab - 4a^3 - 3b_3\right)$$

0 for pNGB due to Z_2 symmetry

$$\pi^{\hat{a}}(x) \to -\pi^{\hat{a}}(x)$$

non-zero for generic doublet

Polarisation	Amplitude for	
	PNGB	SILH
$V_L V_L \to hhh$	$g^2 v/f^2$	$\hat{s} v/f^4$
$V_L V_T \to hhh$	$\sqrt{\hat{s}} g/f^2$	
$V_T V_T \to hhh$	$g^2 v/f^2$	

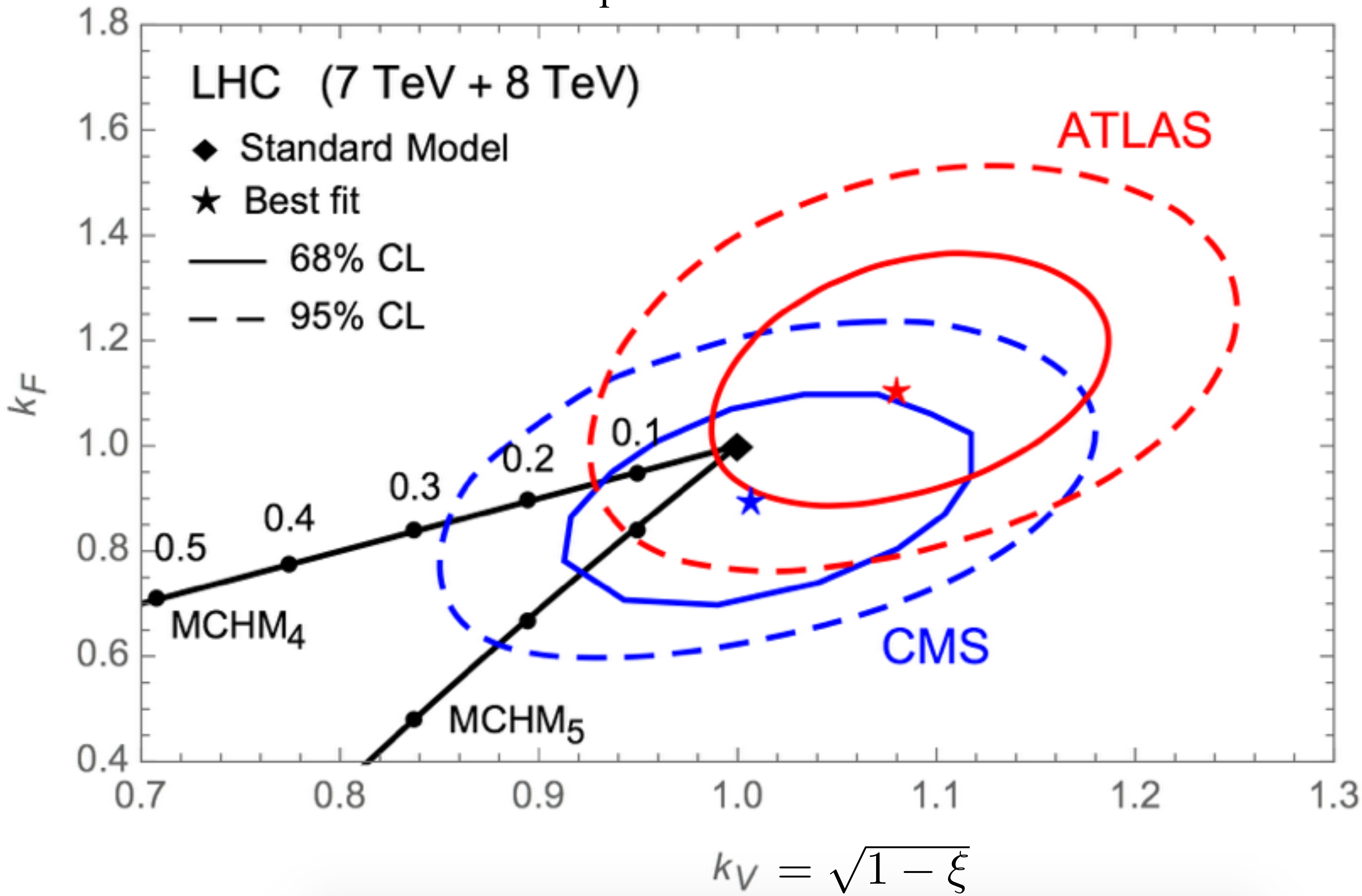
Summary

We can distinguish whether Higgs is

elementary	⟷	composite
singlet	⟷	doublet
pNGB	⟷	no pNGB

Indirect measurements

comparison with data



MCHM4: $k_F = \sqrt{1-\xi}$

MCHM5: $k_F = \dfrac{1-2\xi}{\sqrt{1-\xi}}$

Indirect measurements

Collider	Energy	Luminosity	ξ $[1\sigma]$
LHC	14 TeV	$300\,\text{fb}^{-1}$	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	$3\,\text{ab}^{-1}$	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	$250\,\text{fb}^{-1}$ $500\,\text{fb}^{-1}$	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	$500\,\text{fb}^{-1}$ $1.5\,\text{ab}^{-1}$ $2\,\text{ab}^{-1}$	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	$10\,\text{ab}^{-1}$ $2.6\,\text{ab}^{-1}$	2×10^{-3}

[CMS-NOTE-2012-006]
[ATL-PHYS-PUB-2013-014]
[Dawson et. al.1310.8361]
[CLIC 1307.5288]

EWPT

- set some of strongest constraints on CH models

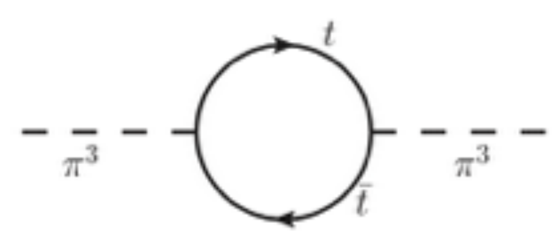
tree level exchange of vector resonances

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi\log\left(\frac{\Lambda}{m_h}\right) + \frac{m_W^2}{m_\rho^2} + \alpha\frac{g^2}{16\pi^2}\xi\,,$$

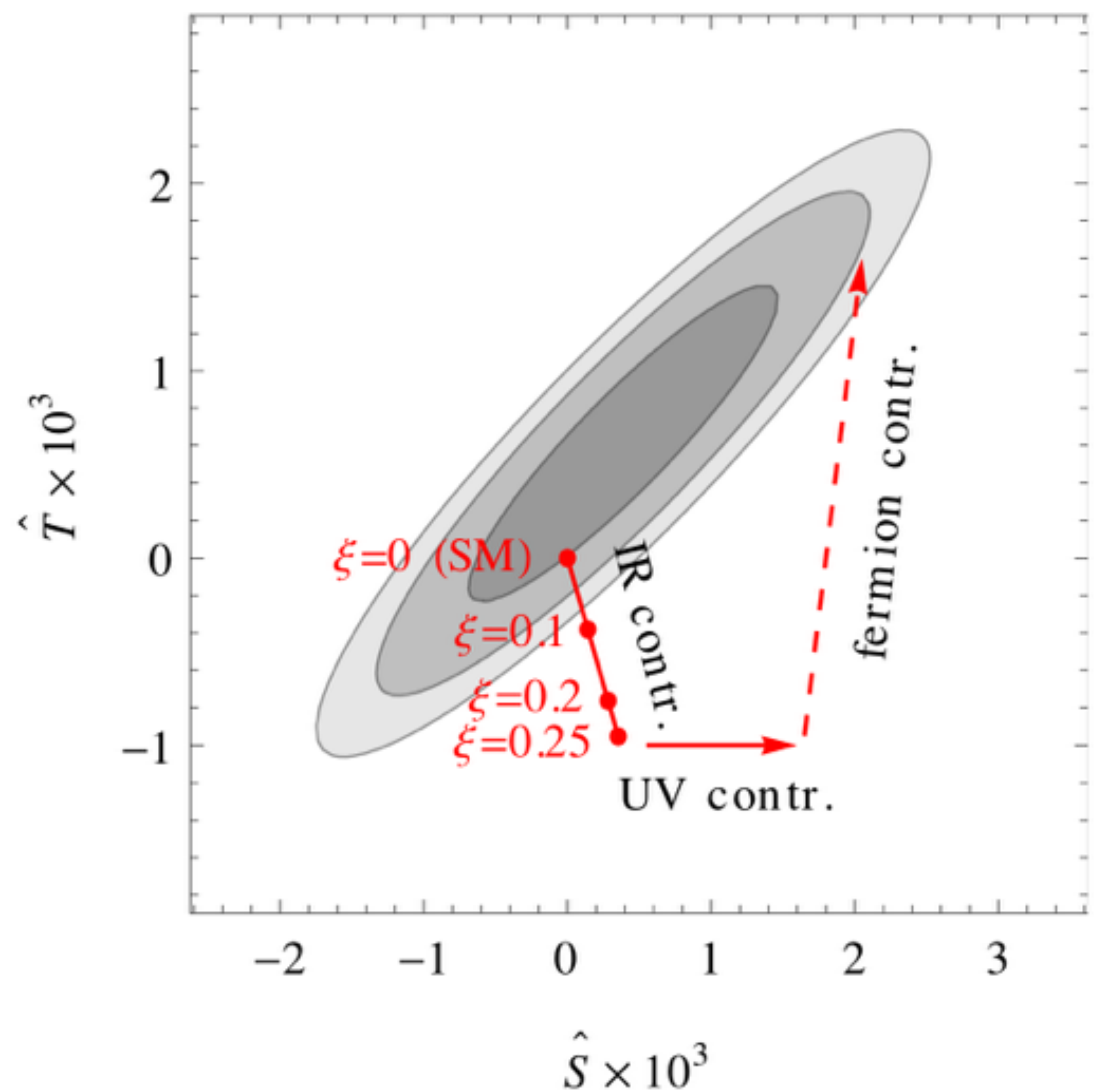
$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi\log\left(\frac{\Lambda}{m_h}\right) + \beta\frac{3y_t^2}{16\pi^2}\xi$$

short distance effects

IR contribution due to Higgs coupling modifications

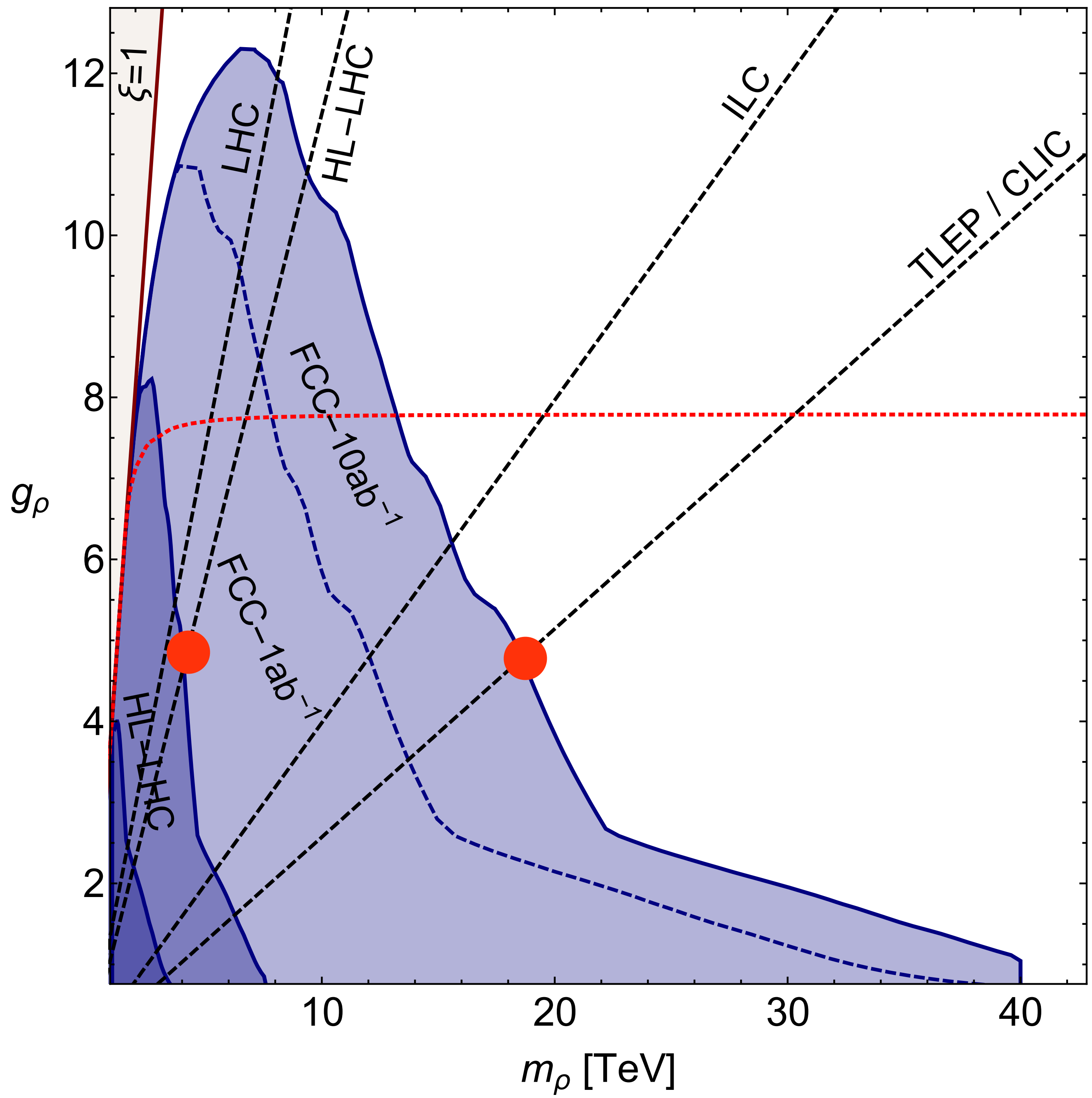


EWPT



2
1
0
−1
−2
−1
0
1
2
3
$\hat{T} \times 10^3$
$\hat{S} \times 10^3$
ξ=0 (SM)
ξ=0.1
ξ=0.2
ξ=0.25
IR contr.
UV contr.
fermion contr.

Direct vs indirect



95% C.L.

- theoretically excluded $\xi \leq 1$
- LHC8 at 8 TeV with 20 fb^{-1}
  HL-LHC at 14 TeV with 3 ab^{-1}
- increase in E: improves mass reach
- increase in L: improves g_ρ reach
- resonances too broad for large g_ρ

- direct: more effective for small g_ρ
  ineffective for large g_ρ
- indirect: more effective for large g_ρ

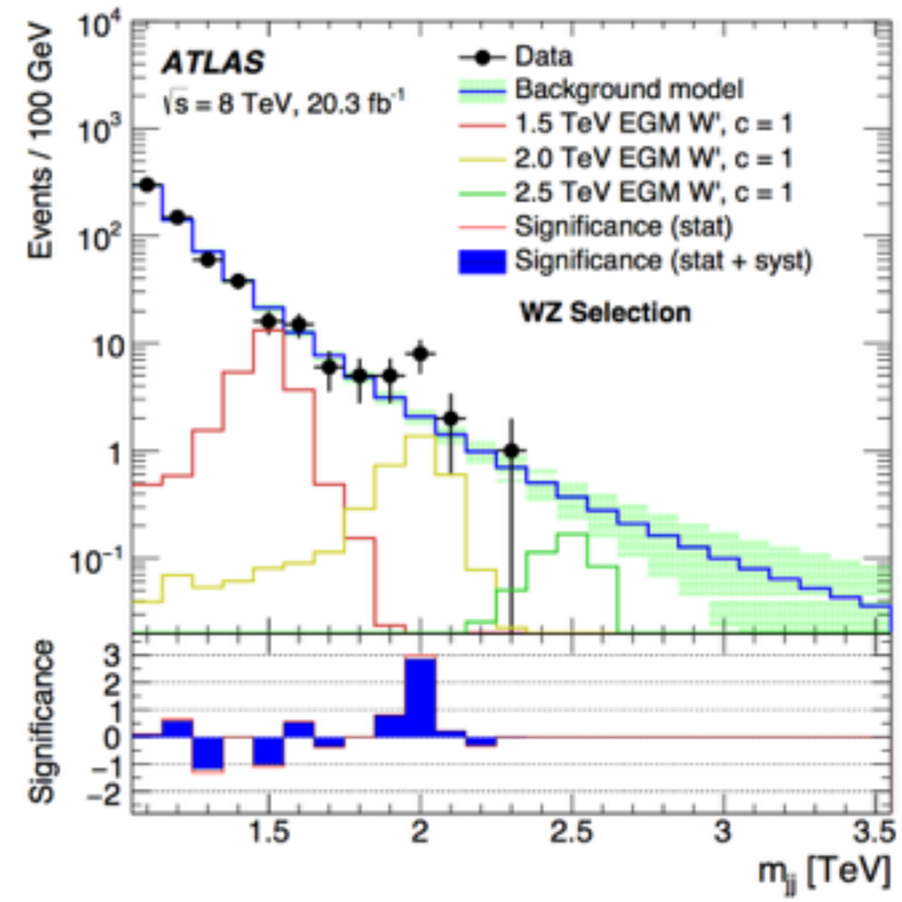
[Thamm, Torre, Wulzer: 1502.01701]

But maybe…

… we don't need to consider all of this!

- ATLAS excess in fully hadronic di-bosons at 2 TeV
- fits with a region in the mass coupling plane

m_V [TeV]	g_V	$(\sigma \times \mathrm{BR})_{V^\pm}$ [fb]	$(\sigma \times \mathrm{BR})_{V^0}$ [fb]
1.8	$3.95^{+1.65}_{-0.88}$	4.51	2.04
1.9	$3.37^{+1.63}_{-0.83}$	4.63	2.09
2.0	$2.81^{+1.54}_{-0.82}$	4.79	2.16



- also some other channels fluctuate up
- some others don't
- maybe this is what it should look like?

→ ATLAS and CMS will tell!

[Thamm, Torre, Wulzer: 1506.08688]

Conclusions

- CH is a very compelling framework
- many ways to look for it:

  direct: vector resonance and top partners

  indirect: coupling modifications
- we will definitely learn something from Run2 of LHC

Backup

EWPT

- set some of strongest constraints on CH models

tree level exchange of vector resonances

$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \frac{m_W^2}{m_\rho^2} + \alpha\frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{\Lambda}{m_h}\right) + \beta\frac{3y_t^2}{16\pi^2}\xi$$

short distance effects

IR contribution due to Higgs coupling modifications

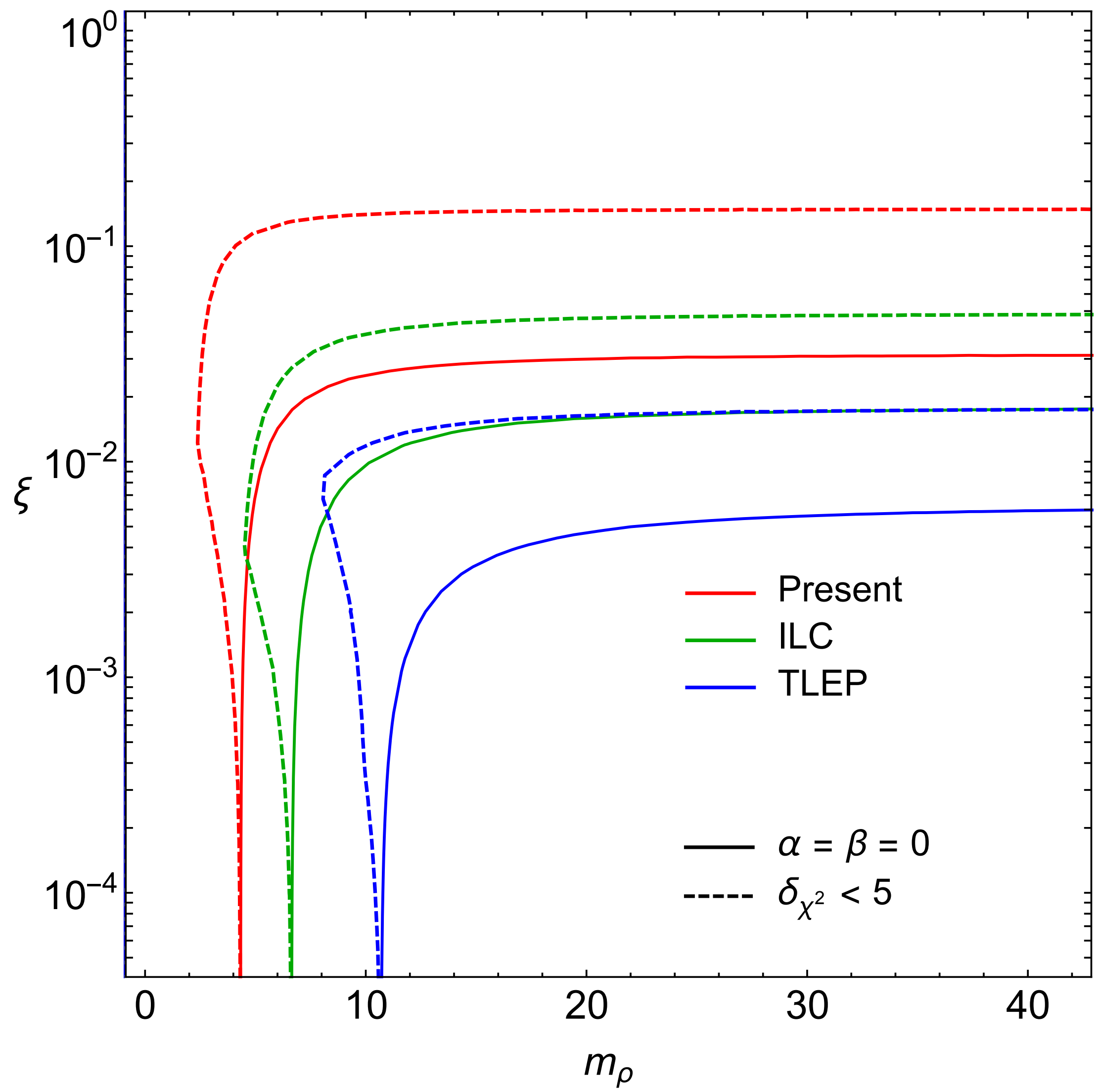
[Grojean, Matsedonskyi, Panico: 1306.4655]

- incalculable UV contributions can relax constraints
- α and β constants of order 1
- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise

EWPT

- define $\chi^2(\xi, m_\rho, \alpha, \beta)$ and marginalise
- to avoid unnatural cancellations

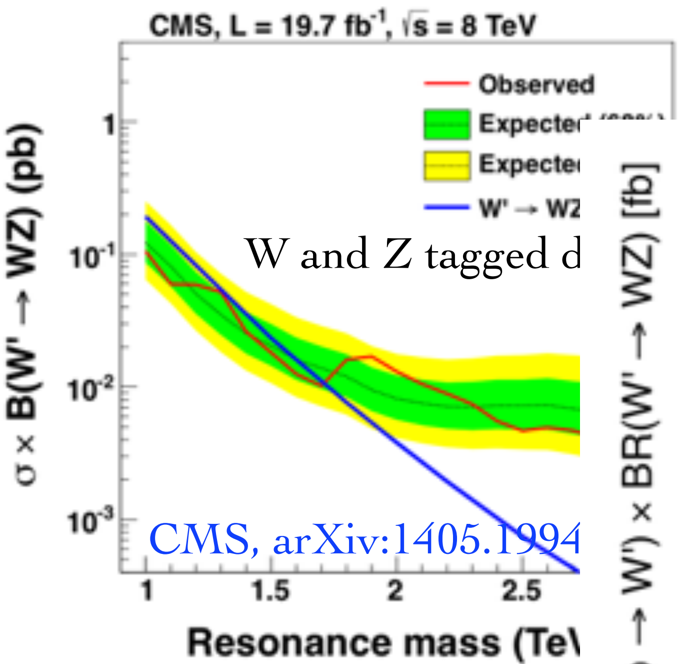
$$\delta_{\chi^2} = \frac{\chi^2(\xi, m_\rho, \alpha = 0, \beta = 0)}{\chi^2(\xi, m_\rho, \alpha, \beta)}$$

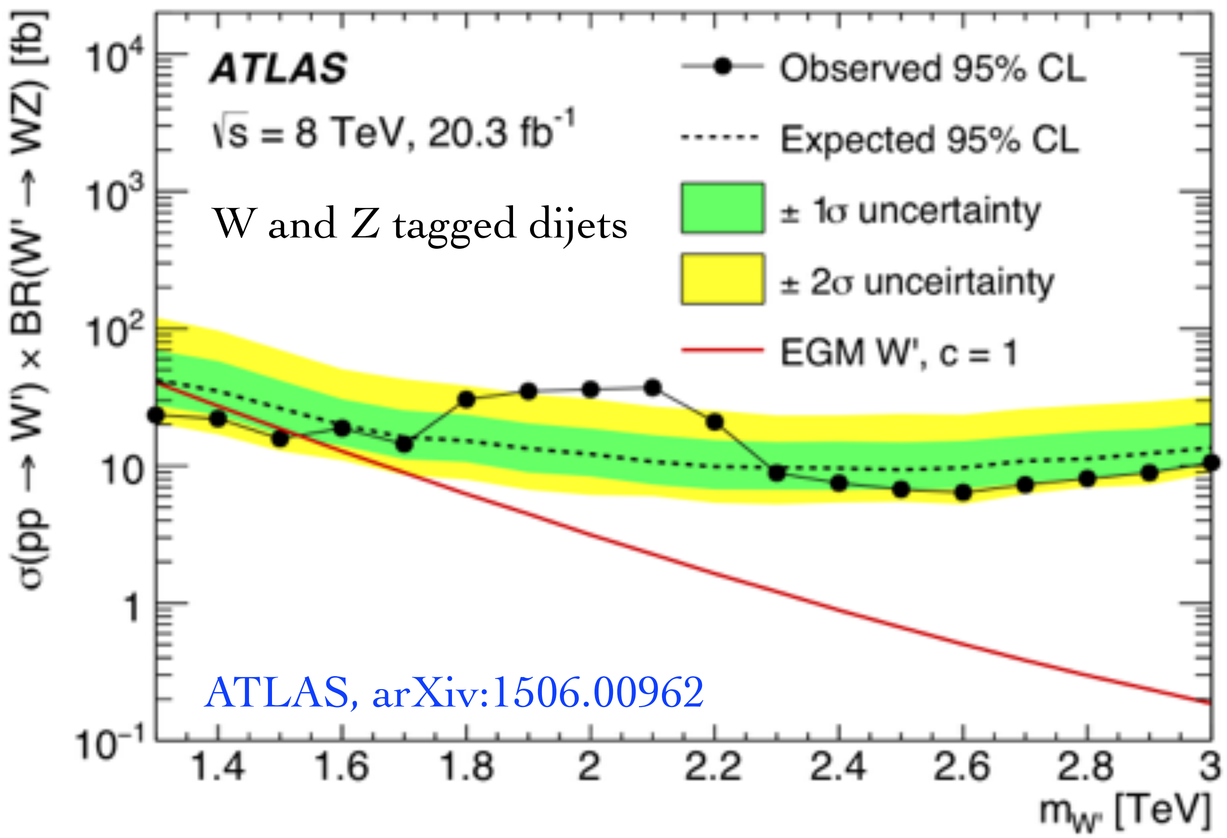


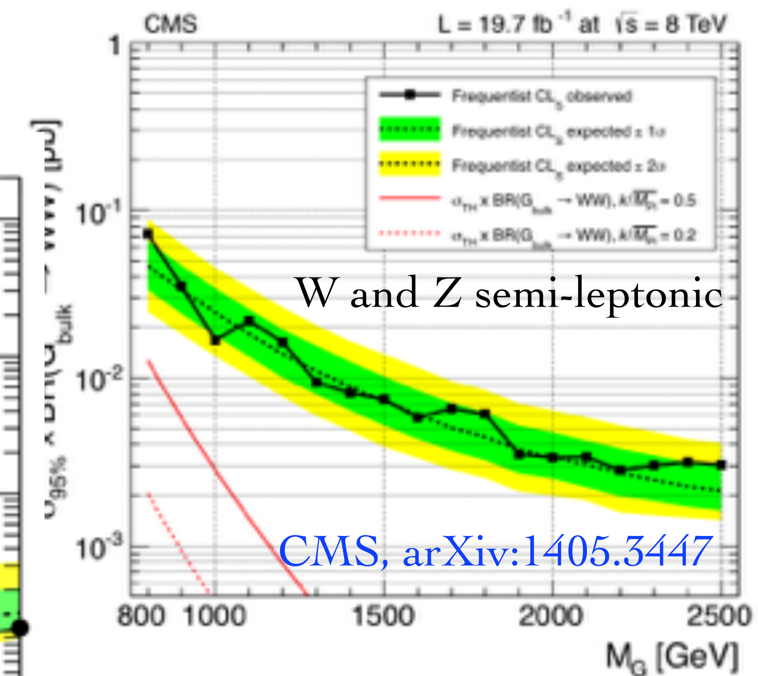
[Baak et al: 1209.2716]
[Baak et al: 1407.3792]

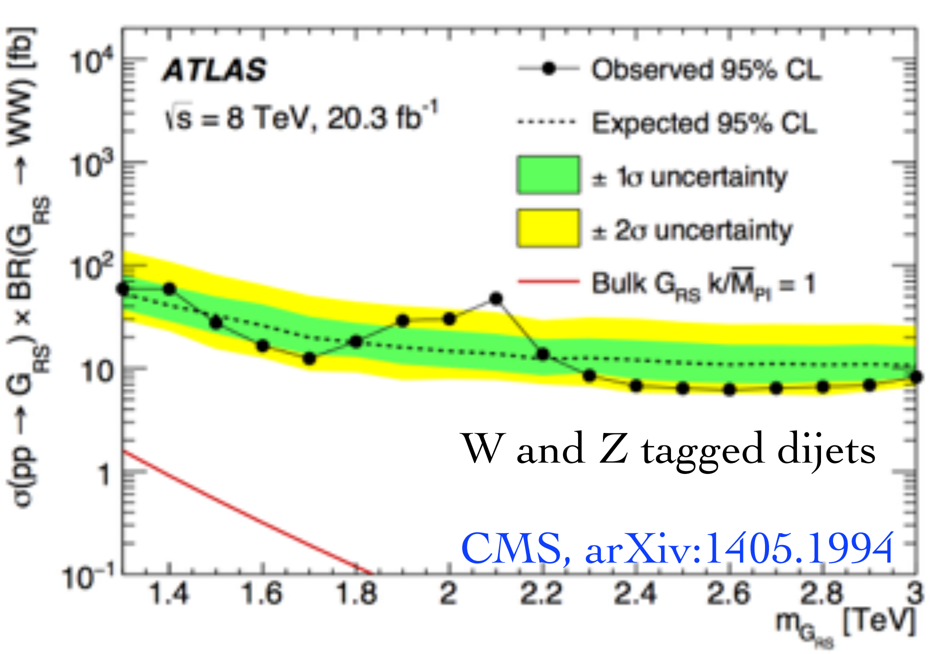
HVT IN THE DI-BOSON EXCESS

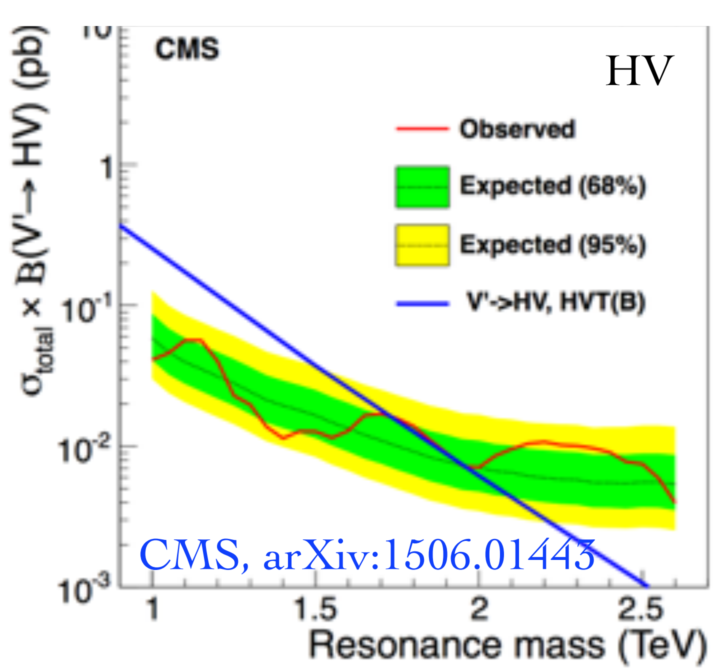
Thamm, Torre, Wulzer, arXiv:1506.08688

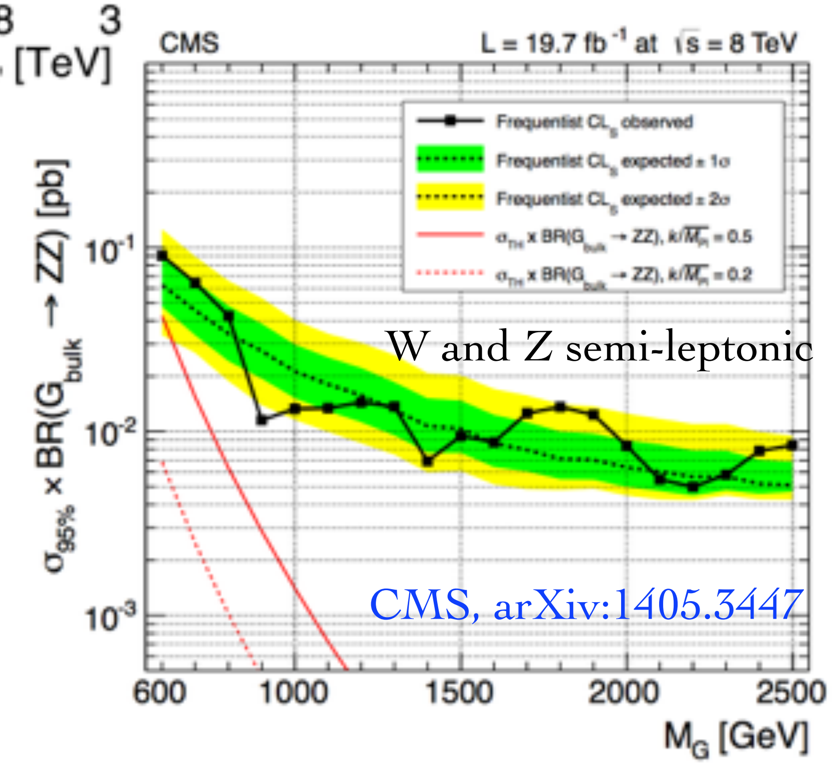








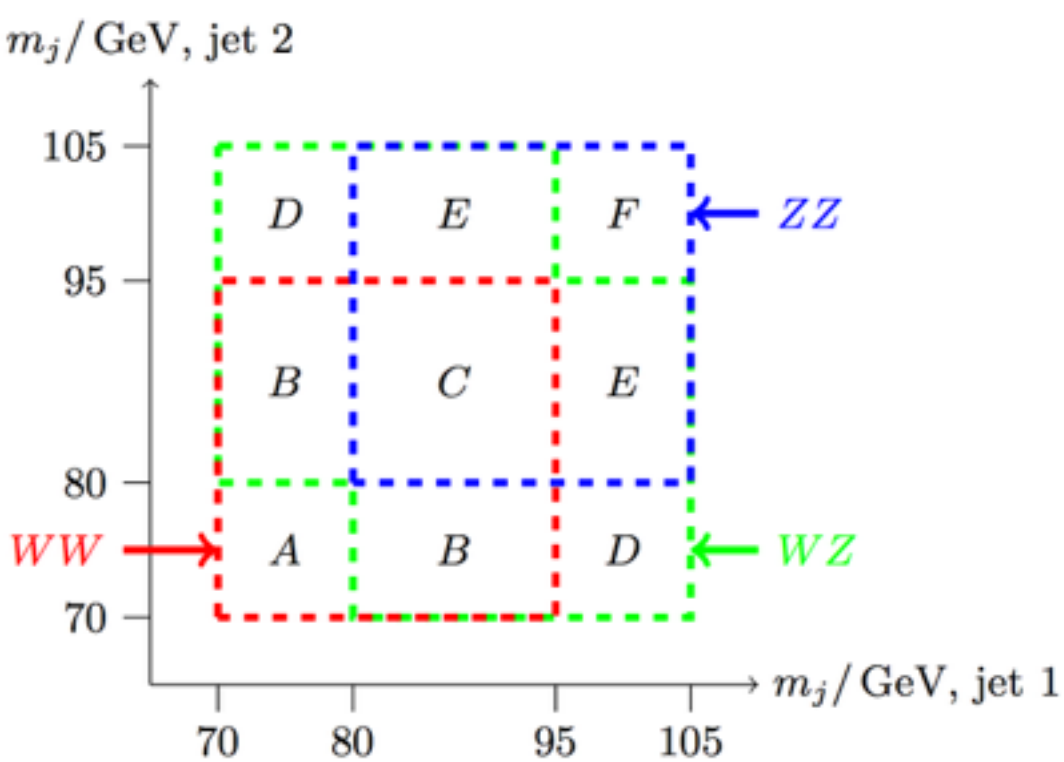




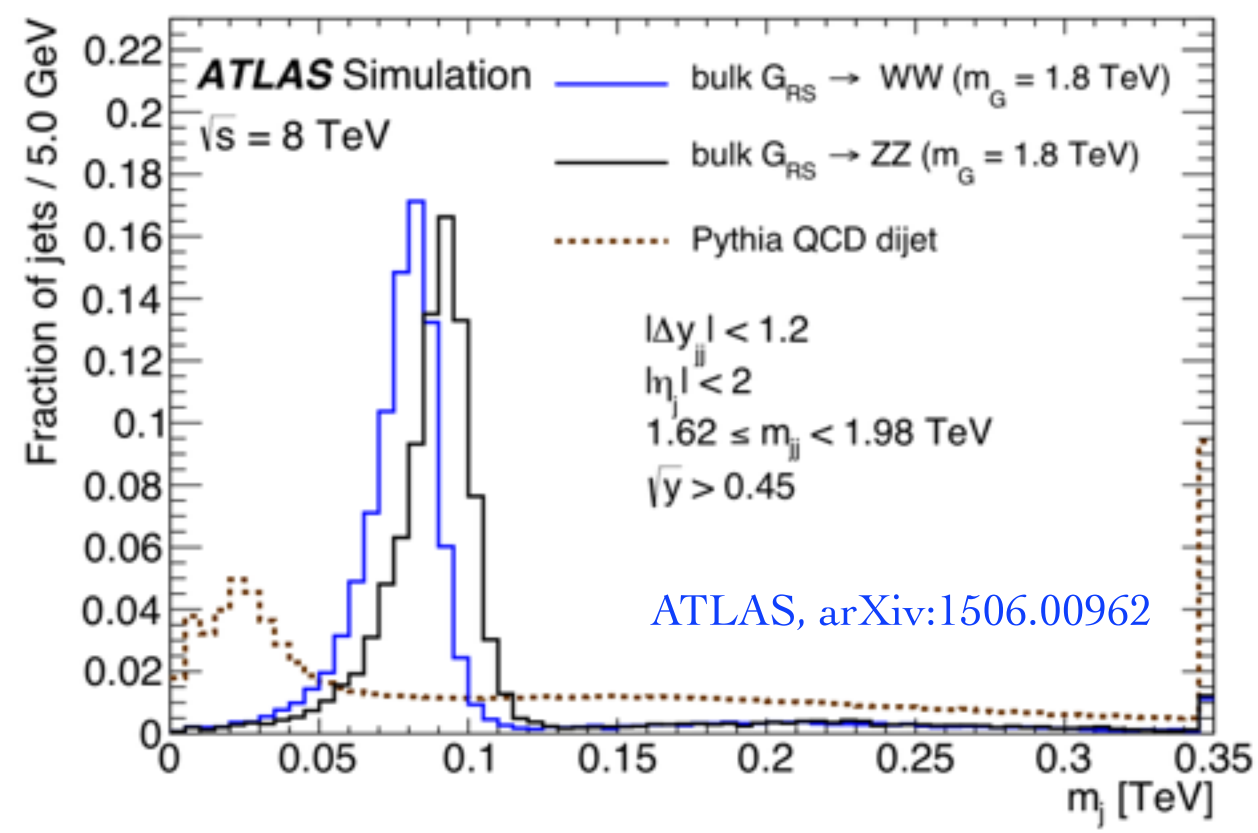
BOOSTED VECTORS TAGGING EFFICIENCIES

Thamm, Torre, Wulzer, arXiv:1506.08688

- W-jet: 69.4 GeV < m < 95.4 GeV
- Z-jet: 79.8 GeV < m < 105.8 GeV



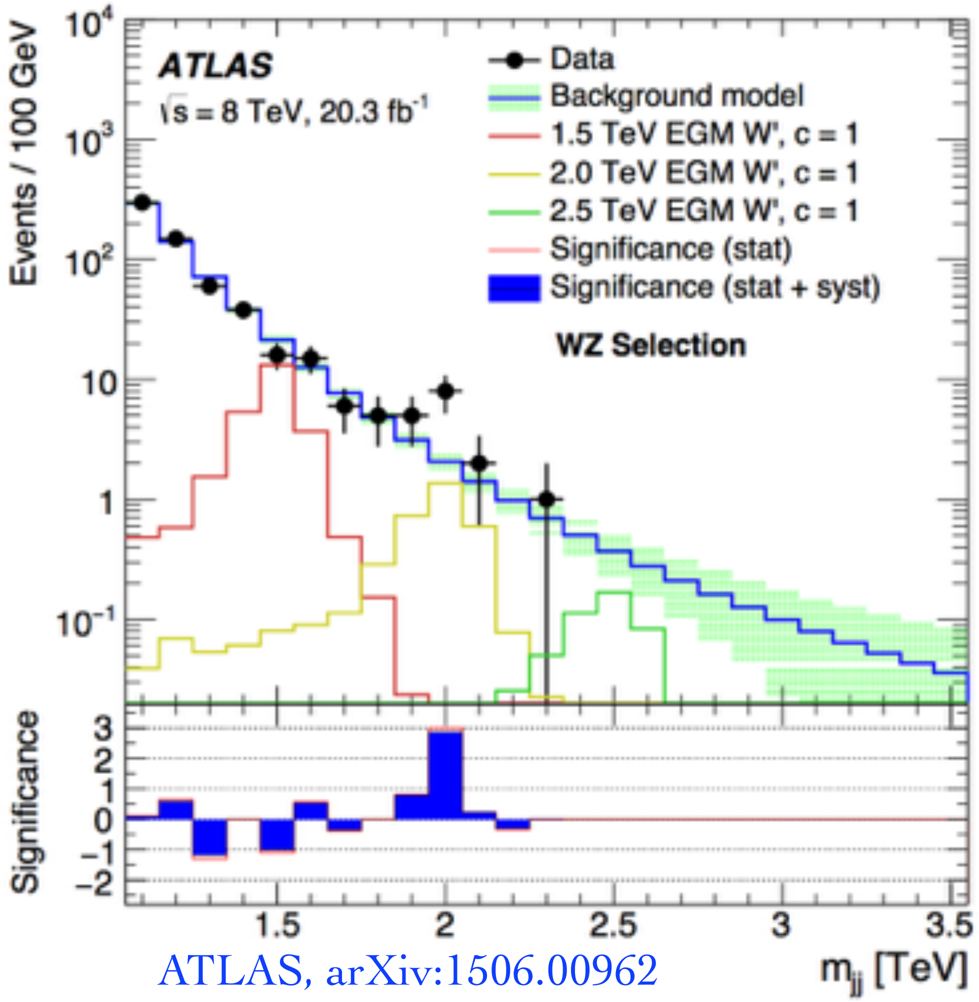
arXiv:1507.01638



$$\begin{bmatrix} \epsilon_{WW\to WW} & \epsilon_{WZ\to WW} \\ \epsilon_{WW\to WZ} & \epsilon_{WZ\to WZ} \\ \epsilon_{WW\to ZZ} & \epsilon_{WZ\to ZZ} \end{bmatrix} = \begin{bmatrix} 0.51 & 0.42 \\ 0.48 & 0.57 \\ 0.21 & 0.32 \end{bmatrix}$$

HVT SIGNAL CROSS SECTION

Thamm, Torre, Wulzer, arXiv:1506.08688



ATLAS, arXiv:1506.00962

- consider 5 bins [1.75, 2.25]
- total events: 20
- background: 13
- excess events: 7
- need 6.5 fb signal cross section

$$S_{WZ} = \mathcal{L}\mathcal{A}\left[(\sigma\times\mathrm{BR})_{V^\pm}\mathrm{BR}_{WZ\to\mathrm{had}}\epsilon_{WZ\to WZ} + (\sigma\times\mathrm{BR})_{V^0}\mathrm{BR}_{WW\to\mathrm{had}}\epsilon_{WW\to WZ}\right],$$

m_V [TeV]	g_V	$(\sigma\times\mathrm{BR})_{V^\pm}$ [fb]	$(\sigma\times\mathrm{BR})_{V^0}$ [fb]
1.8	$3.95^{+1.65}_{-0.88}$	4.51	2.04
1.9	$3.37^{+1.63}_{-0.83}$	4.63	2.09
2.0	$2.81^{+1.54}_{-0.82}$	4.79	2.16

COMPATIBILITY WITH OTHER SEARCHES

Thamm, Torre, Wulzer, arXiv:1506.08688