

A LIGHT DYNAMICAL SCALAR BOSON

Luca Merlo

based on

Alonso,Gavela,LM,Rigolin&Yepes, 1201.1511
Alonso,Gavela,LM,Rigolin&Yepes, 1212.3305
Alonso,Gavela,LM,Rigolin&Yepes, 1212.3307



Origin of the EWSB?

- If the resonance is the **Brout-Englert-Higgs (SMS) Boson** (fundamental), then NP @TeV scale should be present to stabilize its mass (HP).

Origin of the EWSB?

- If the resonance is the **Brout-Englert-Higgs (SMS) Boson** (fundamental), then NP @TeV scale should be present to stabilize its mass (HP).
- Alternatively, this resonance could be related to a **strong dynamics** at the scale $\Lambda_s \sim \mathcal{O}(\text{TeV})$
- **Technicolor:** only the usual 3 GBs are accounted for, but no light scalar particle is present.
- **Composite Higgs:** a larger global symmetry is considered and the SM scalar particle arises as a (massless) GB. In this case the resonance corresponds to a composite object.

Formalism



The SM scalar boson $\Phi(x)$ \longrightarrow gauge $SU(2)_L \times U(1)_Y$

Formalism

- The SM scalar boson $\Phi(x)$ \longrightarrow gauge $SU(2)_L \times U(1)_Y$
- The symmetry of the scalar potential is easier to see writing

[Longhitano, PRD22 (1980)]

$$\mathbf{M}(x) \equiv \sqrt{2} \begin{pmatrix} \tilde{\Phi}(x) & \Phi(x) \end{pmatrix}$$

$$V(\mathbf{M}) = \frac{1}{4} \lambda \left(\frac{1}{2} \text{Tr}[\mathbf{M}^\dagger \mathbf{M}] + \frac{\mu^2}{\lambda} \right)^2$$

invariant under a global $SU(2)_L \times SU(2)_R \sim O(4)$

$$\mathbf{M} \rightarrow L \mathbf{M} R^\dagger$$

Formalism

- The SM scalar boson $\Phi(x) \longrightarrow$ gauge $SU(2)_L \times U(1)_Y$
- The symmetry of the scalar potential is easier to see writing
[Longhitano, PRD22 (1980)]
$$\mathbf{M}(x) \equiv \sqrt{2} \begin{pmatrix} \tilde{\Phi}(x) & \Phi(x) \end{pmatrix}$$
$$V(\mathbf{M}) = \frac{1}{4} \lambda \left(\frac{1}{2} \text{Tr}[\mathbf{M}^\dagger \mathbf{M}] + \frac{\mu^2}{\lambda} \right)^2$$
invariant under a global $SU(2)_L \times SU(2)_R \sim O(4)$
$$\mathbf{M} \rightarrow L \mathbf{M} R^\dagger$$
- When \mathbf{M} develops VEV $\langle \mathbf{M}^\dagger \mathbf{M} \rangle = v^2 \mathbf{1}$
$$O(4) \rightarrow SU(2)_V \quad \text{custodial symmetry}$$
$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$$

The non-linear σ -model notation

- Thinking at a very **heavy SMS particle**, all the remaining d.o.f. are the longitudinal components of the gauge bosons and are described by

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

$$\mathbf{U}(x) \rightarrow L \mathbf{U}(x) R^\dagger \quad \text{under} \quad SU(2)_L \times U(1)_Y$$

The non-linear σ -model notation

- Thinking at a very **heavy SMS particle**, all the remaining d.o.f. are the longitudinal components of the gauge bosons and are described by

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

$$\mathbf{U}(x) \rightarrow L \mathbf{U}(x) R^\dagger \quad \text{under} \quad SU(2)_L \times U(1)_Y$$

- Writing the covariant derivative as:

$$\mathbf{D}_\mu \mathbf{U}(x) \equiv \partial_\mu \mathbf{U}(x) + \frac{ig}{2} W_\mu^a(x) \sigma_a \mathbf{U}(x) - \frac{ig'}{2} B_\mu(x) \mathbf{U}(x) \sigma_3$$

we can define the vector and the scalar chiral fields

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U}) \mathbf{U}^\dagger \quad \mathbf{V} \rightarrow L \mathbf{V} L^\dagger$$

$$\mathbf{T} \equiv \mathbf{U} \sigma_3 \mathbf{U}^\dagger \quad \mathbf{T} \rightarrow L \mathbf{T} L^\dagger$$

- Making use of these objects, it is possible to construct a basis of independent operators describing all the $SU(2)_L \times U(1)_Y$ interactions

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

- $\mathbf{U}(x)$ is a 2x2 adimensional matrix. Only derivatives bring dimensions.
- This leads to a fundamental different wrt the SM in constructing the effective Lagrangian:

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

- $\mathbf{U}(x)$ is a 2x2 adimensional matrix. Only derivatives bring dimensions.
- This leads to a fundamental different wrt the SM in constructing the effective Lagrangian:

SM

- The GBs are in the SMS doublet Φ
- Φ has dimension 1 in mass
- $d=4+n$ operators are suppressed by Λ_{NP}^n
[see Eboli's talk]

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

- $\mathbf{U}(x)$ is a 2x2 adimensional matrix. Only derivatives bring dimensions.
- This leads to a fundamental different wrt the SM in constructing the effective Lagrangian:

SM

- The GBs are in the SMS doublet Φ
- Φ has dimension 1 in mass
- $d=4+n$ operators are suppressed by Λ_{NP}^n
[see Eboli's talk]

σ -model

- The $\mathbf{U}(x)$ matrix is adimensional and any its extra insertions do not lead to any suppression

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v}$$

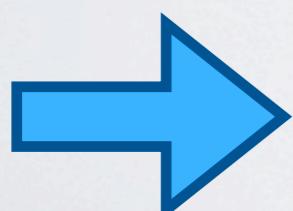
- $\mathbf{U}(x)$ is a 2x2 adimensional matrix. Only derivatives bring dimensions.
- This leads to a fundamental different wrt the SM in constructing the effective Lagrangian:

SM

- The GBs are in the SMS doublet Φ
- Φ has dimension 1 in mass
- $d=4+n$ operators are suppressed by Λ_{NP}^n
[see Eboli's talk]

σ -model

- The $\mathbf{U}(x)$ matrix is adimensional and any its extra insertions do not lead to any suppression



The dimension of the leading low-energy operators differs for a purely linear and a non-linear regime



Making use of these objects, it is possible to construct a basis of independent operators describing all the $SU(2)_L \times U(1)_Y$ interactions

$$\mathcal{L}^{<4} = \frac{v^2}{4} \text{Tr} [\mathbf{V}^\mu \mathbf{V}_\mu] + c_T \frac{v^2}{4} \text{Tr} [\mathbf{T} \mathbf{V}^\mu] \text{Tr} [\mathbf{T} \mathbf{V}_\mu] - \left(\frac{v}{2\sqrt{2}} \bar{Q}_L \mathbf{U}(x) \mathcal{Y} Q_R + \text{h.c.} \right)$$

Custodial breaking
 $-1.7 \times 10^{-3} < \Delta\rho \equiv c_T < 1.9 \times 10^{-3}$

W, Z masses GBs Kin terms Custodial breaking Yukawa terms

[see Kogler's talk]



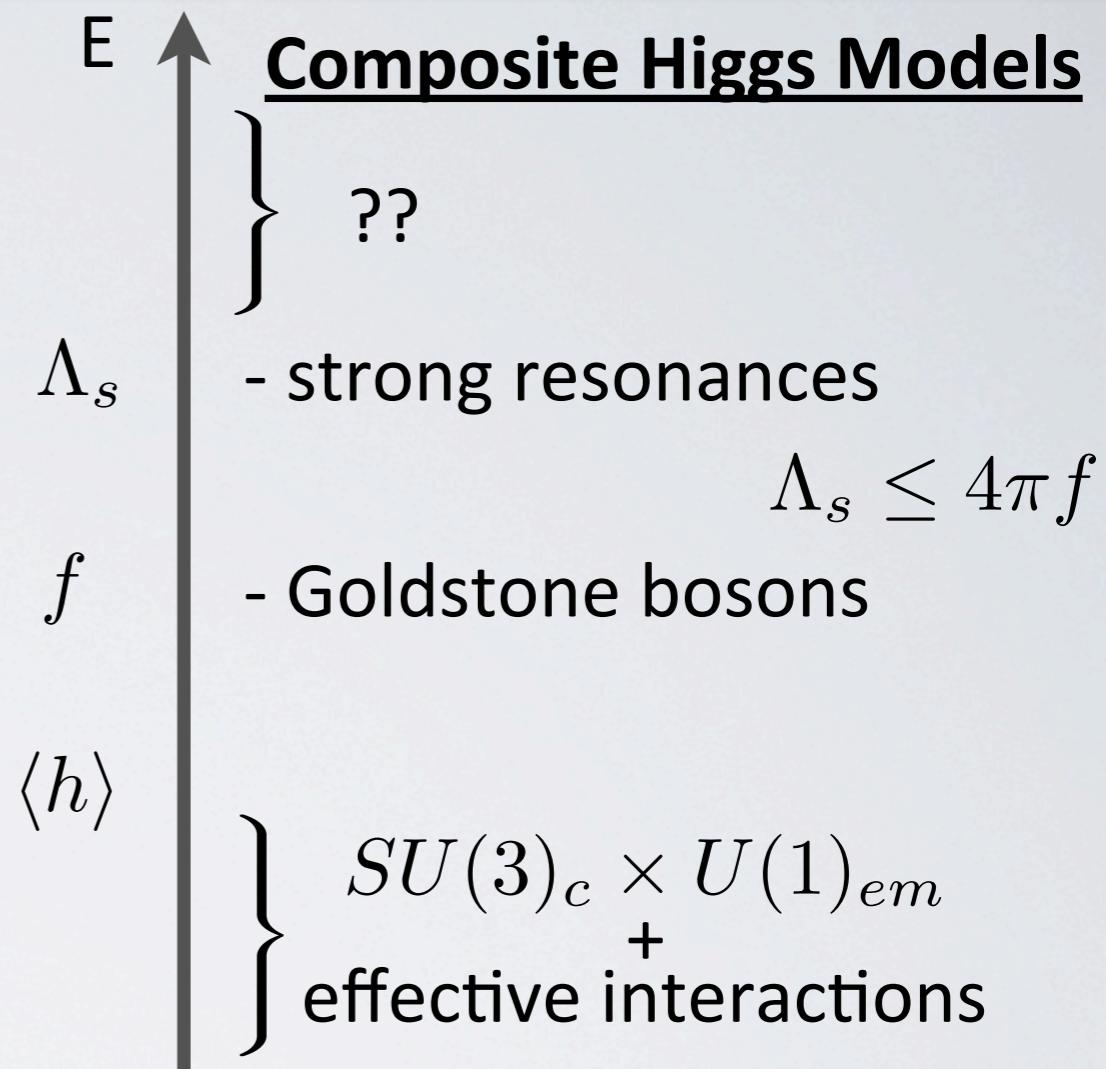
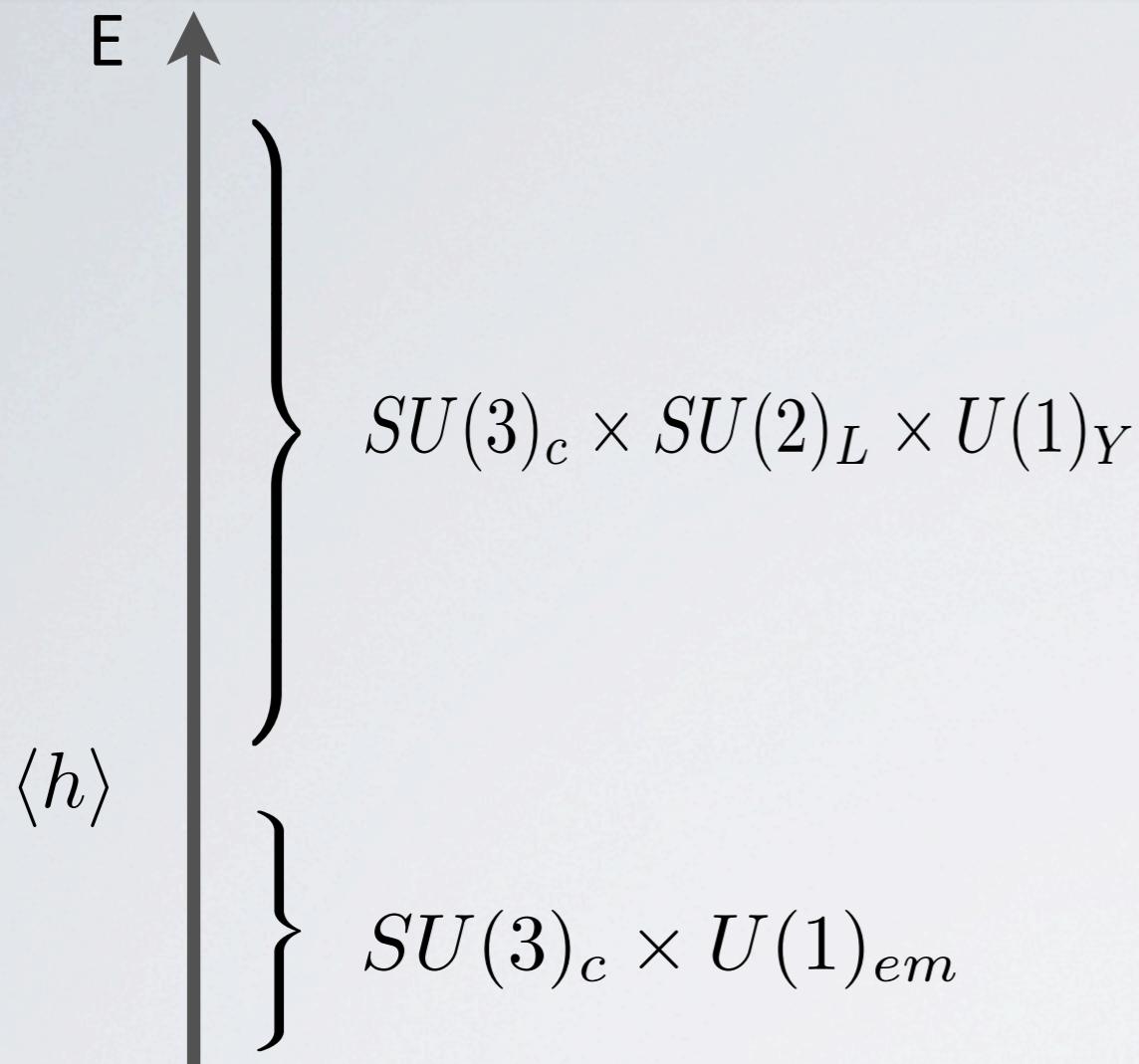
$$\mathcal{L}^4 = -\frac{g_s^2}{4} G_{\mu\nu}^a G_a^{\mu\nu} - \frac{g^2}{4} W_{\mu\nu}^a W_a^{\mu\nu} - \frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} + \sum_{i=1}^{14} c_i \mathcal{A}_i$$

The Appelquist-Longhitano Basis

$Z^{\mu\nu} Z_{\mu\nu}$ $\swarrow \quad \searrow$
 $W^{+\mu\nu} W^{-}_{\mu\nu}$

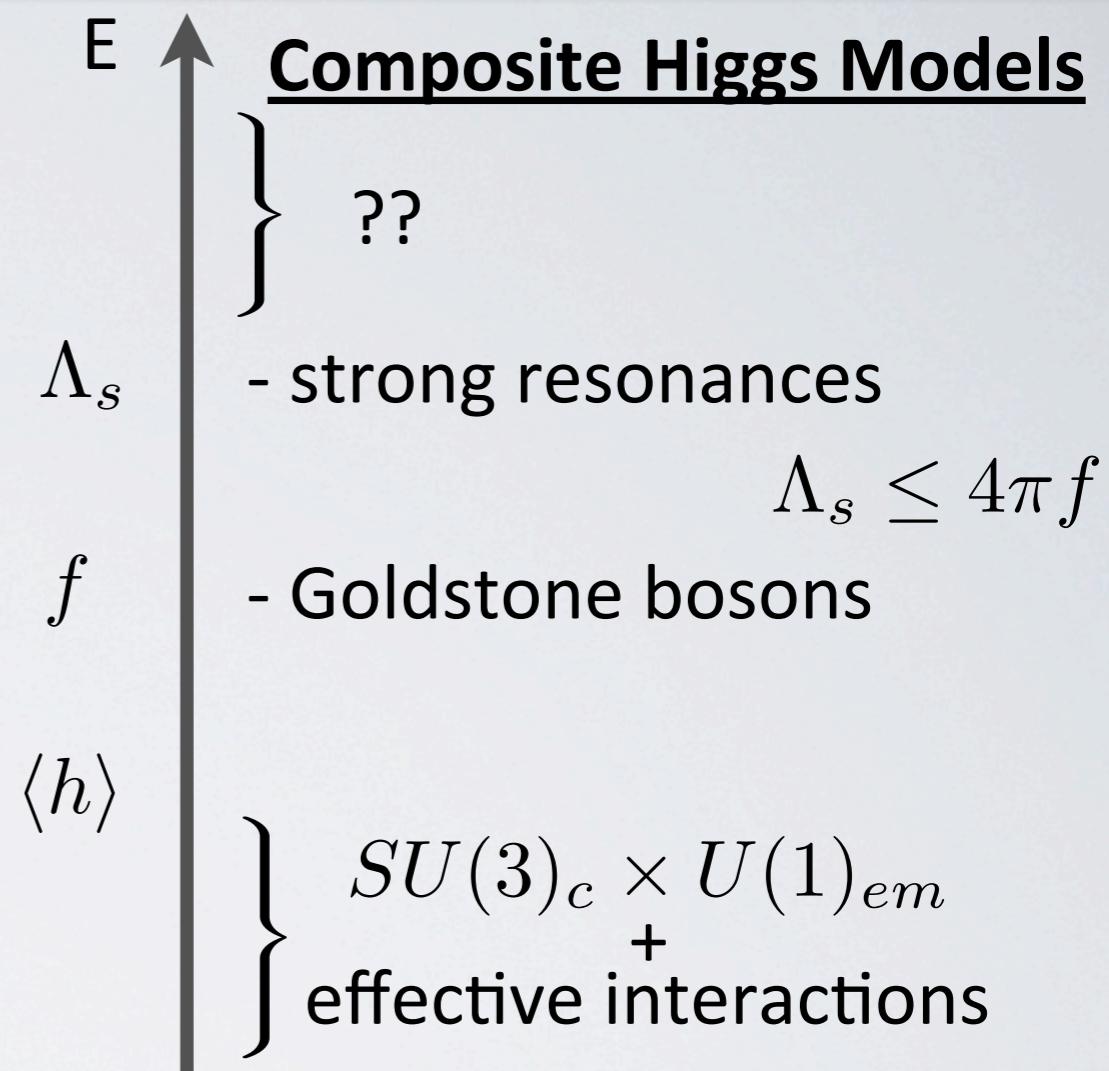
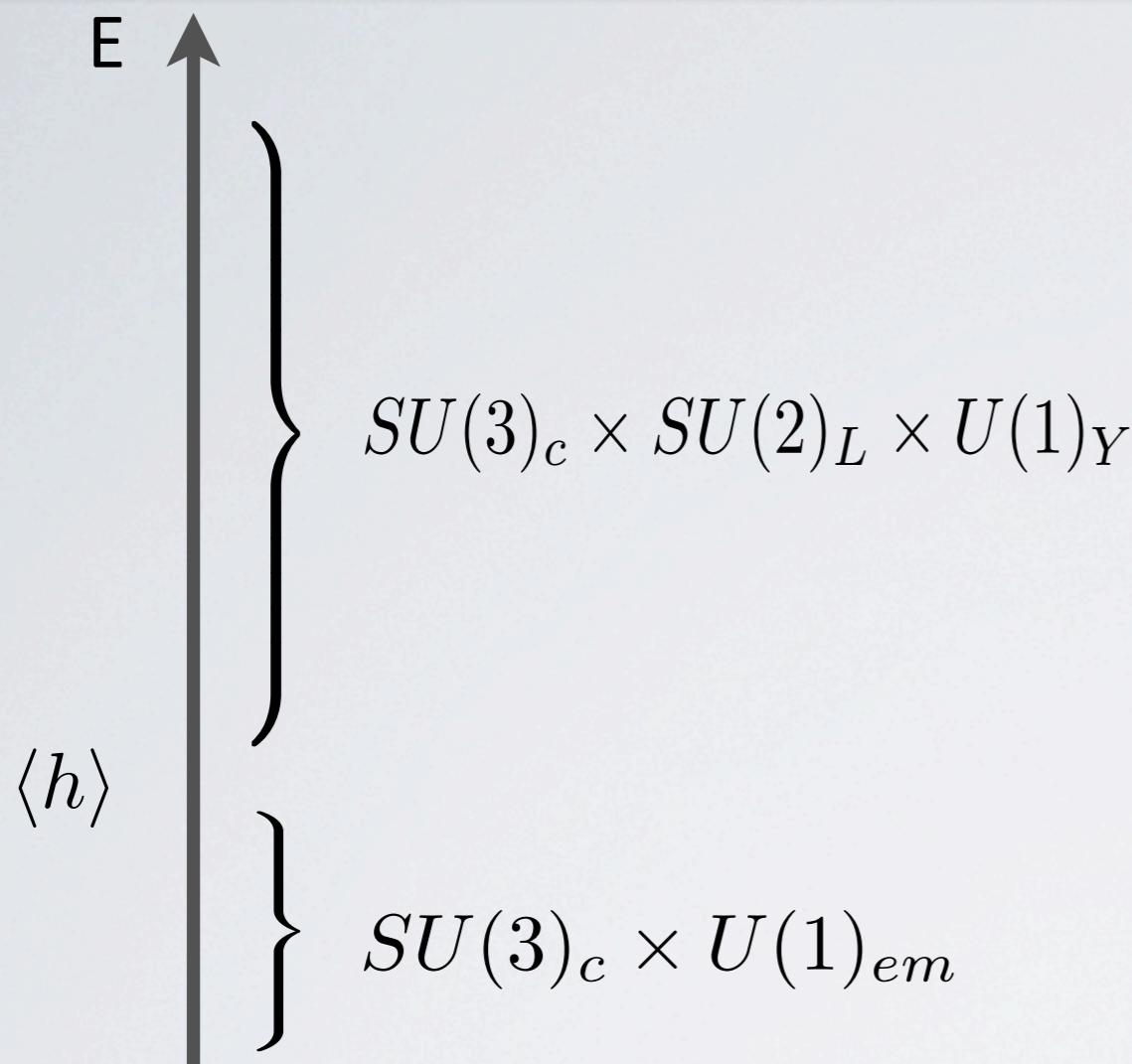
$\mathcal{A}_1 = g g' B_{\mu\nu} \text{Tr}(\mathbf{T} W^{\mu\nu})$	[Appelquist&Bernard, Phys. Rev. D22 (1980) 200]
$\mathcal{A}_2 = i g' B_{\mu\nu} \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu])$	[Longhitano, Phys. Rev. D22 (1980) 1166]
$\mathcal{A}_3 = i g \text{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu])$	[Longhitano, Nucl. Phys. B188 (1981) 118]
$\mathcal{A}_4 = (\text{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2$	[Feruglio, Int.J.Mod.Phys. A8 (1993) 4937–4972, hep-ph/9301281]
$\mathcal{A}_5 = (\text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2$	[Appelquist&Wu, Phys.Rev. D48 (1993) 3235–3241, hep-ph/9304240]
$\mathcal{A}_6 = g^2 (\text{Tr}(\mathbf{T} W^{\mu\nu}))^2$	
$\mathcal{A}_7 = i g \text{Tr}(\mathbf{T} W_{\mu\nu}) \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu])$	
$\mathcal{A}_8 = g \epsilon^{\mu\nu\rho\lambda} \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{V}_\nu W_{\rho\lambda})$	
$\mathcal{A}_9 = \text{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\text{Tr}(\mathbf{T} \mathbf{V}_\nu))^2$	
$\mathcal{A}_{10} = \text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\nu)$	
$\mathcal{A}_{11} = (\text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{T} \mathbf{V}_\nu))^2$	
$\mathcal{A}_{12} = \text{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2)$	
$\mathcal{A}_{13} = \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathcal{D}_\nu \mathbf{V}^\nu)$	
$\mathcal{A}_{14} = \text{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\nu)$	

What with a physical Scalar?!



[Georgi & Kaplan, 1984;
Dimopoulos, Georgi & Kaplan 1984;
Banks, 1984;
Galison, Georgi,& Kaplan, 1984;
Dugan, Georgi & Kaplan 1985;
Agashe, Contino & Pomarol 2005;
Gripaios, Pomarol, Riva & Serra 2009;
...]

What with a physical Scalar?!



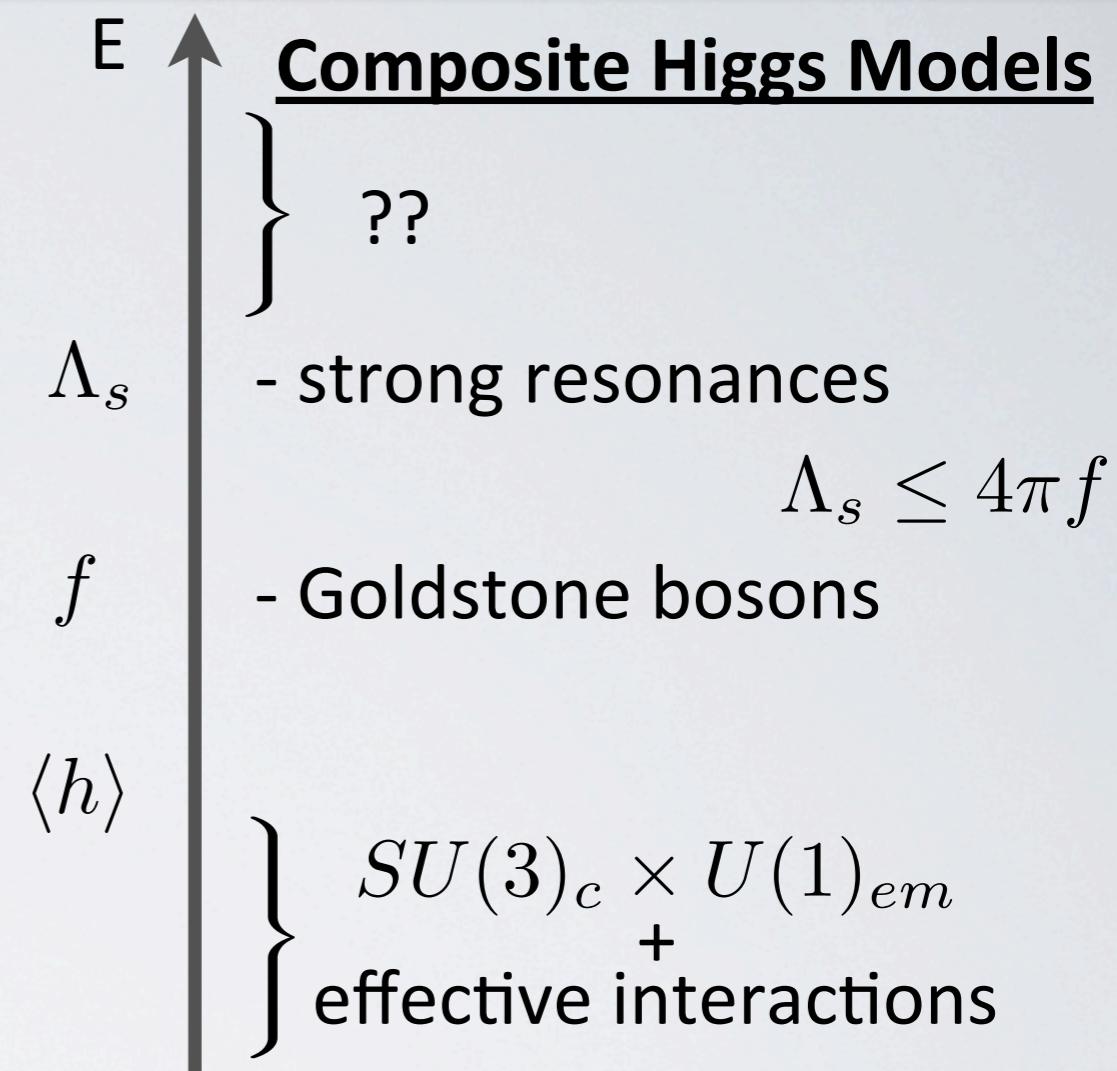
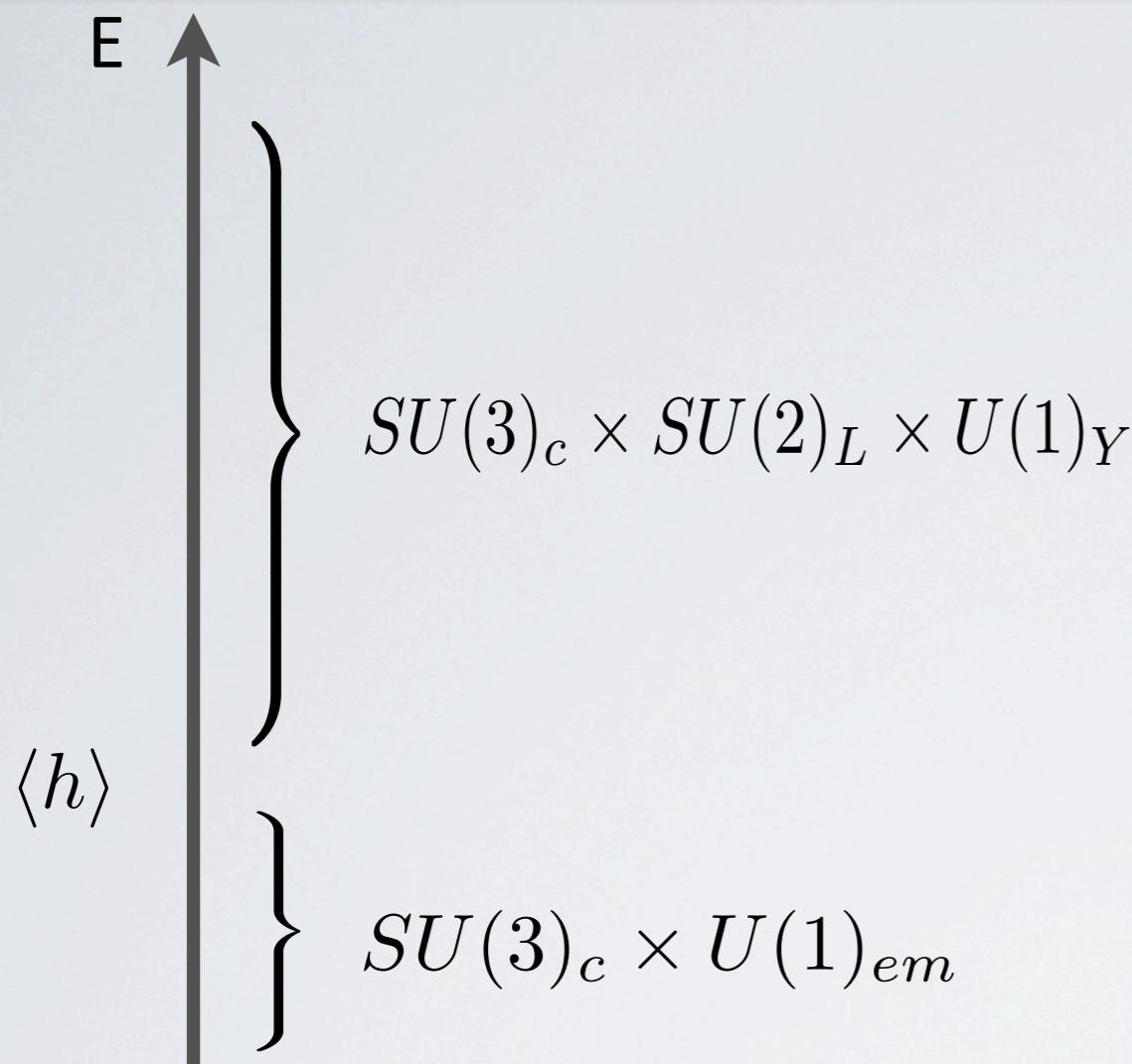
■ Higher order operators are suppressed by:

f for extra Goldstone leg (Goldstone-Higgs included)

Λ_s for extra derivatives and gauge field strength

[Manohar&Georgi, 1984]

What with a physical Scalar?!



- Higher order operators are suppressed by:
 - f for extra Goldstone leg (Goldstone-Higgs included)
 - Λ_s for extra derivatives and gauge field strength
- The degree of non-linearity is described by $\xi \equiv (v/f)^2$

[Manohar&Georgi, 1984]

Pure gauge and gauge- h operator

$$\mathcal{L}_{gauge-h}^{d \leq 5} = \mathcal{L}_{\chi=0}^h + \mathcal{L}_{\chi=2}^h + \mathcal{L}_{\chi=3}^h + \mathcal{L}_{\chi=4}^h$$

$$\mathcal{L}_{\chi=0}^h = \frac{1}{2} (\partial_\mu h) (\partial^\mu h) (1 + c_H \xi \mathcal{F}_H(h)) - V(h)$$

[see Azatov's talk]

$$\mathcal{L}_{\chi=2}^h = \frac{v^2}{4} \text{Tr} [\mathbf{V}^\mu \mathbf{V}_\mu] \boxed{\mathcal{F}_C(h)} + c_T \xi \frac{v^2}{4} \text{Tr} [\mathbf{T} \mathbf{V}^\mu] \text{Tr} [\mathbf{T} \mathbf{V}_\mu] \boxed{\mathcal{F}_T(h)}$$

$$\mathcal{L}_{\chi=3}^h = - \left(\frac{v}{2\sqrt{2}} \bar{Q}_L \mathbf{U}(x) \mathbf{Y} Q_R \boxed{\mathcal{F}_Y(h)} + \text{h.c.} \right)$$

$$\longrightarrow \mathcal{F}(h) = g_0(h, v) + \xi g_1(h, v) + \xi^2 g_2(h, v) + \dots$$

$$\mathcal{F}_C(h) = \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \dots \right)$$

[Contino et al. 2010,
Azatov et al. 2012,
...]

Pure gauge and gauge- h operator

$$\mathcal{L}_{gauge-h}^{d \leq 5} = \mathcal{L}_{\chi=0}^h + \mathcal{L}_{\chi=2}^h + \mathcal{L}_{\chi=3}^h + \mathcal{L}_{\chi=4}^h$$

$$\mathcal{L}_{\chi=0}^h = \frac{1}{2} (\partial_\mu h) (\partial^\mu h) (1 + c_H \xi \mathcal{F}_H(h)) - V(h)$$

[see Azatov's talk]

$$\mathcal{L}_{\chi=2}^h = \frac{v^2}{4} \text{Tr} [\mathbf{V}^\mu \mathbf{V}_\mu] \boxed{\mathcal{F}_C(h)} + c_T \xi \frac{v^2}{4} \text{Tr} [\mathbf{T} \mathbf{V}^\mu] \text{Tr} [\mathbf{T} \mathbf{V}_\mu] \boxed{\mathcal{F}_T(h)}$$

$$\mathcal{L}_{\chi=3}^h = - \left(\frac{v}{2\sqrt{2}} \bar{Q}_L \mathbf{U}(x) \mathbf{Y} Q_R \boxed{\mathcal{F}_Y(h)} + \text{h.c.} \right)$$

$$\longrightarrow \mathcal{F}(h) = g_0(h, v) + \xi g_1(h, v) + \xi^2 g_2(h, v) + \dots$$

$$\begin{aligned} \mathcal{L}_{\chi=4}^h = & - \frac{g_s^2}{4} G_{\mu\nu}^a G_a^{\mu\nu} \boxed{\mathcal{F}_G(h)} - \frac{g^2}{4} W_{\mu\nu}^a W_a^{\mu\nu} \boxed{\mathcal{F}_W(h)} - \frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} \boxed{\mathcal{F}_B(h)} + \\ & + \xi \sum_{i=1}^5 c_i \mathcal{P}_i(h) + \xi^2 \sum_{i=6}^{20} c_i \mathcal{P}_i(h) + \xi^3 \sum_{i=21}^{23} c_i \mathcal{P}_i(h) + \xi^4 c_{24} \mathcal{P}_{24}(h) \end{aligned}$$

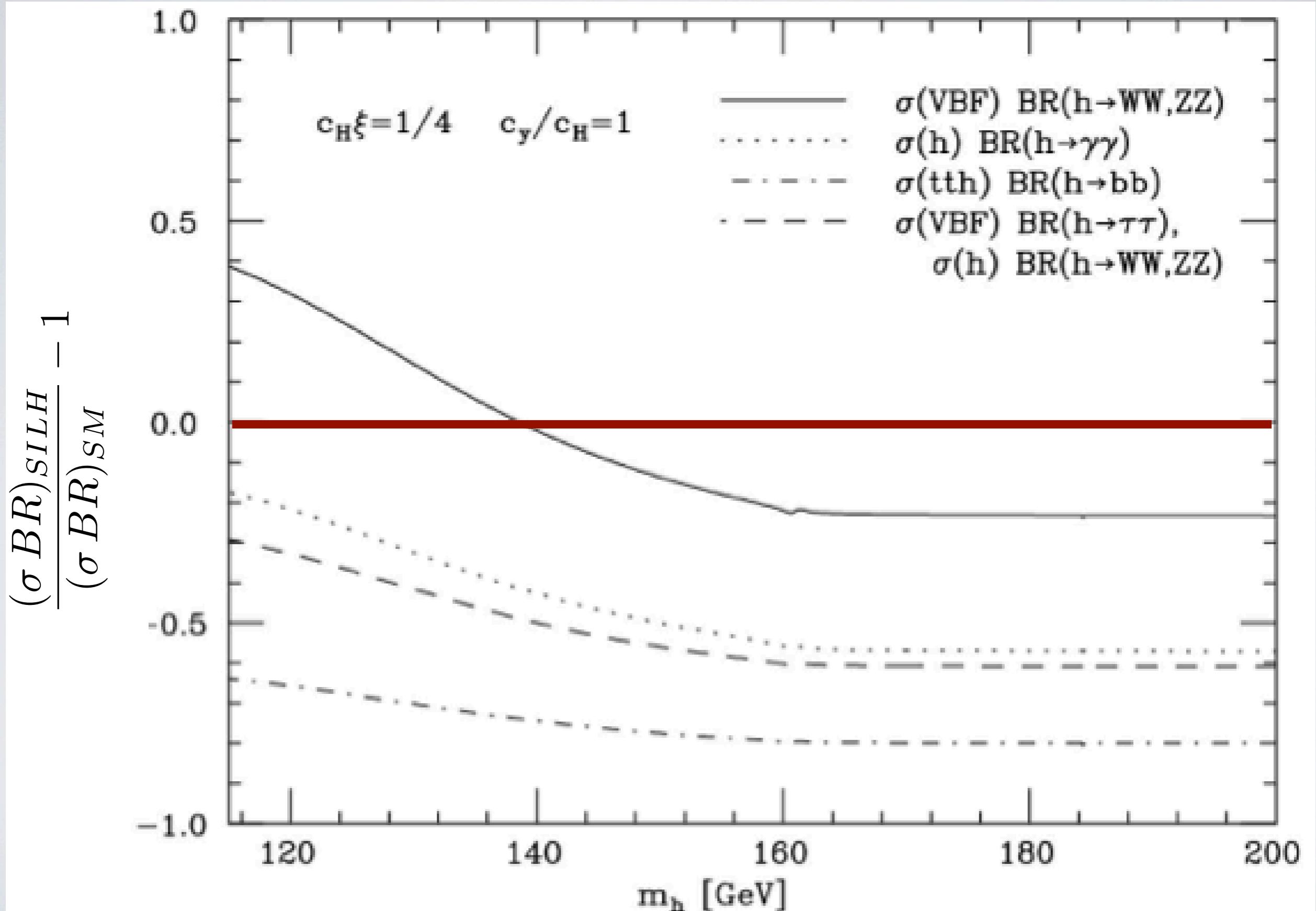
[Alonso,Gavela,LM,Rigolin&Yepes, 1212.3305]

COMPLETE BASIS OF INDEPENDENT OPERATORS

24 CP-even operators

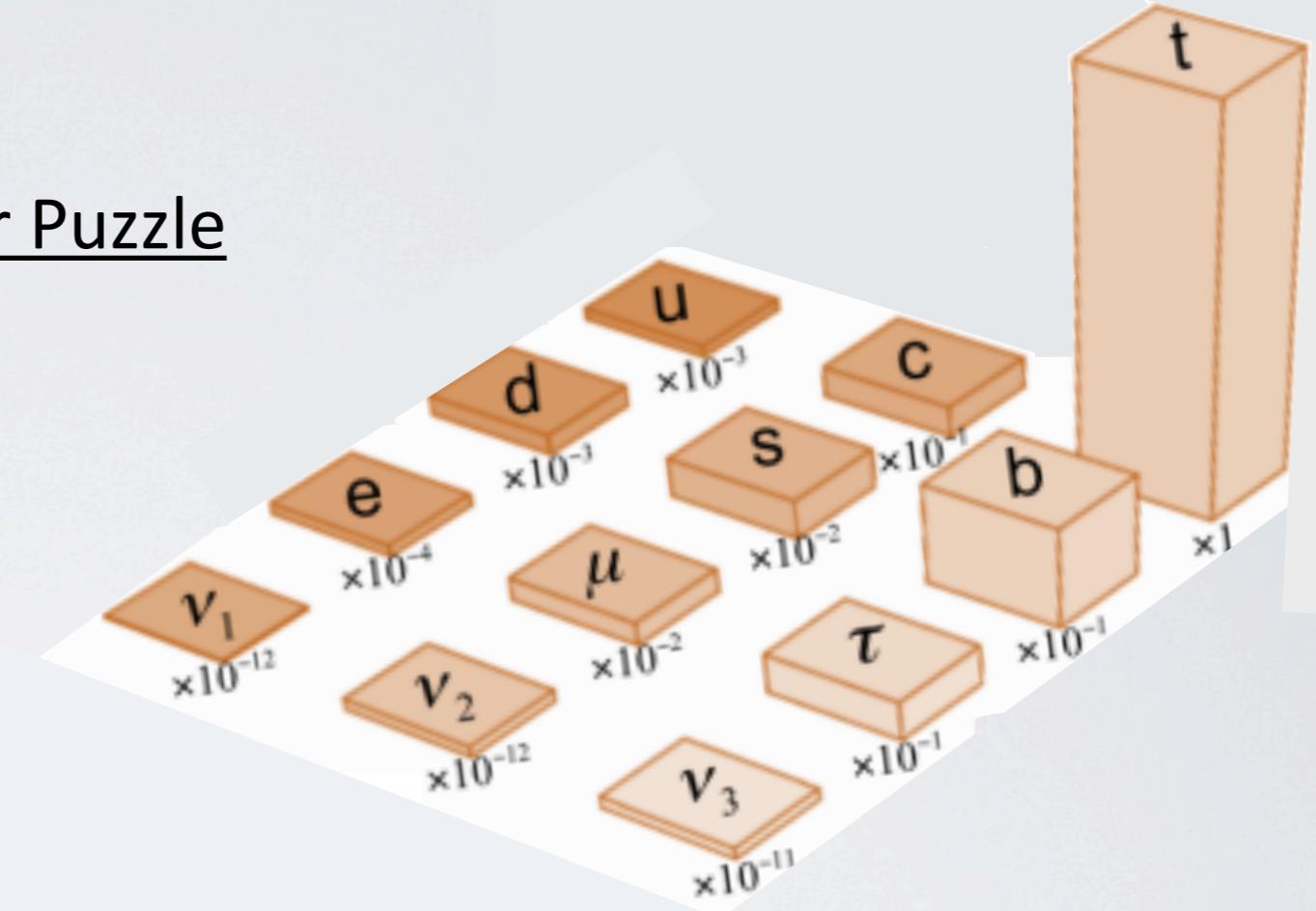
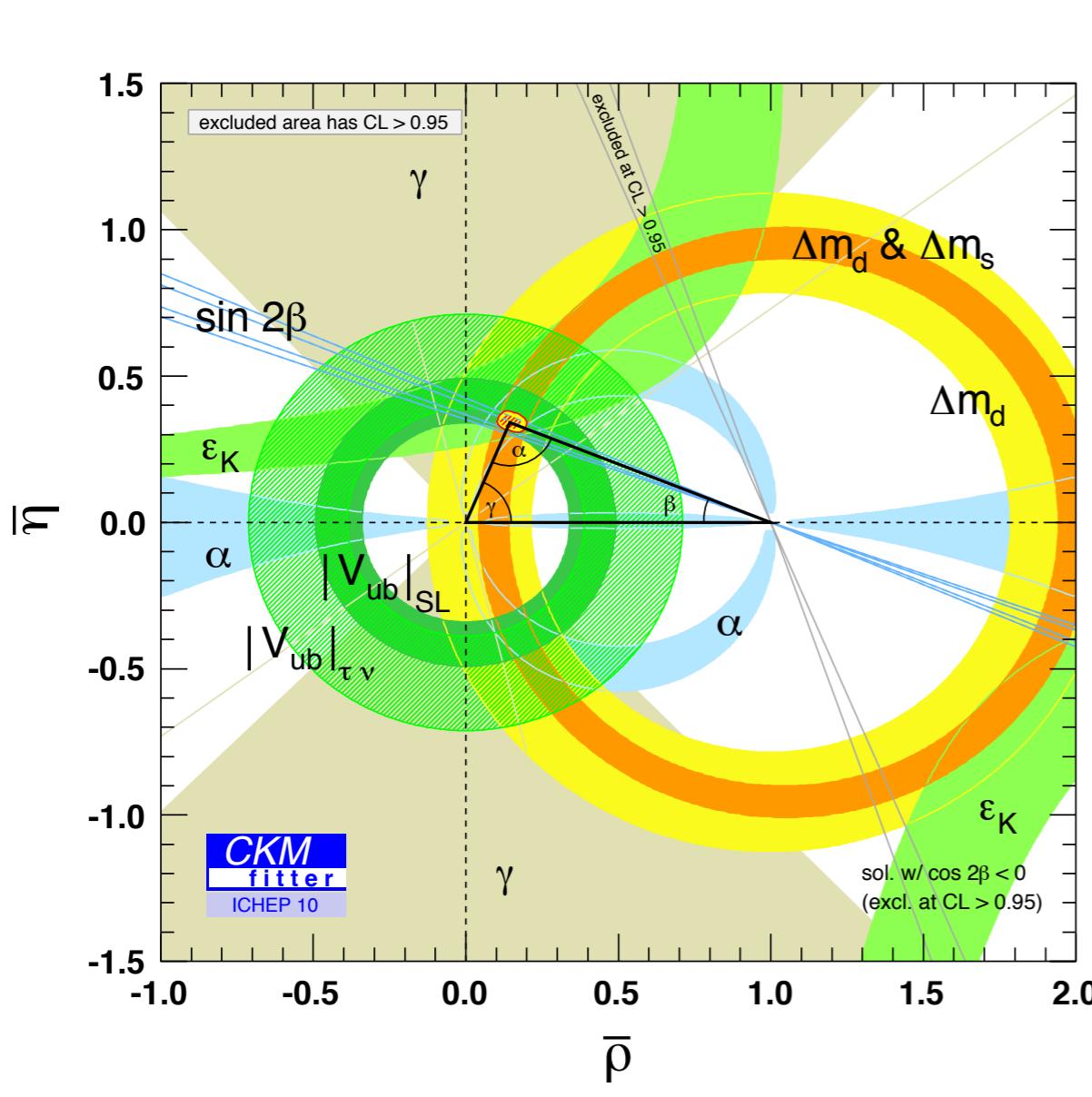
Appelquist-Longhitano basis
for $\mathcal{F}(h) \rightarrow \text{constant}$

$$\begin{aligned}
\mathcal{P}_1(h) &= g g' B_{\mu\nu} \text{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h) \\
\mathcal{P}_2(h) &= i g' B_{\mu\nu} \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h) \\
\mathcal{P}_3(h) &= i g \text{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h) \\
\mathcal{P}_4(h) &= i g' B_{\mu\nu} \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h) \\
\mathcal{P}_5(h) &= i g \text{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h) \\
\mathcal{P}_6(h) &= (\text{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu))^2 \mathcal{F}_6(h) \\
\mathcal{P}_7(h) &= (\text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu))^2 \mathcal{F}_7(h) \\
\mathcal{P}_8(h) &= g^2 (\text{Tr}(\mathbf{T} W^{\mu\nu}))^2 \mathcal{F}_8(h) \\
\mathcal{P}_9(h) &= i g \text{Tr}(\mathbf{T} W_{\mu\nu}) \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_9(h) \\
\mathcal{P}_{10}(h) &= g \epsilon^{\mu\nu\rho\lambda} \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{V}_\nu W_{\rho\lambda}) \mathcal{F}_{10}(h) \\
\mathcal{P}_{11}(h) &= \text{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_{11}(h) \\
\mathcal{P}_{12}(h) &= \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{12}(h) \\
\mathcal{P}_{13}(h) &= \text{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\nu) \mathcal{F}_{13}(h) \\
\mathcal{P}_{14}(h) &= i g \text{Tr}(\mathbf{T} W_{\mu\nu}) \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{14}(h) \\
\mathcal{P}_{15}(h) &= \text{Tr}(\mathbf{T} [\mathbf{V}_\mu, \mathbf{V}_\nu]) \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{15}(h) \\
\mathcal{P}_{16}(h) &= \text{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{16}(h) \\
\mathcal{P}_{17}(h) &= \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}_\nu) \partial^\nu \mathcal{F}_{17}(h) \\
\mathcal{P}_{18}(h) &= \text{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \partial_\nu \partial^\nu \mathcal{F}_{18}(h) \\
\mathcal{P}_{19}(h) &= \text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \partial^\mu \mathcal{F}_{19}(h) \partial^\nu \mathcal{F}_{19}(h) \\
\mathcal{P}_{20}(h) &= \text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{T} \mathbf{V}_\nu) \partial^\mu \mathcal{F}_{20}(h) \partial^\nu \mathcal{F}_{20}(h) \\
\mathcal{P}_{21}(h) &= \text{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) (\text{Tr}(\mathbf{T} \mathbf{V}_\nu))^2 \mathcal{F}_{21}(h) \\
\mathcal{P}_{22}(h) &= \text{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\nu) \mathcal{F}_{22}(h) \\
\mathcal{P}_{23}(h) &= (\text{Tr}(\mathbf{T} \mathbf{V}_\mu))^2 \partial_\nu \partial^\nu \mathcal{F}_{23}(h) \\
\mathcal{P}_{24}(h) &= (\text{Tr}(\mathbf{T} \mathbf{V}_\mu) \text{Tr}(\mathbf{T} \mathbf{V}_\nu))^2 \mathcal{F}_{24}(h)
\end{aligned}$$



The flavour Sector

The Flavour Puzzle



FCNC are suppressed in the SM

[See Maiani's and Gavela's talks]

Minimal Flavour Violation ansatz

[Chivukula & Georgi, 1987;

Hall & Randall, 1990;

Giudice,Isidori&Strumia, hep-ph/0207036]

$d = 4$ chiral operators with insertions of h

$$\mathcal{L}_{\chi=4}^f = \sum_{i=1}^4 a_i \mathcal{O}_i(h) = \xi \sum_{i=1,2,3} \hat{a}_i \mathcal{O}_i(h) + \xi^2 \hat{a}_4 \mathcal{O}_4(h)$$

$$\mathcal{O}_1(h) = \frac{i}{2} \bar{Q}_L \lambda_F \gamma^\mu \{\mathbf{T}, \mathbf{V}_\mu\} Q_L \mathcal{F}(h)$$

$$\mathcal{O}_2(h) = i \bar{Q}_L \lambda_F \gamma^\mu \mathbf{V}_\mu Q_L \mathcal{F}(h)$$

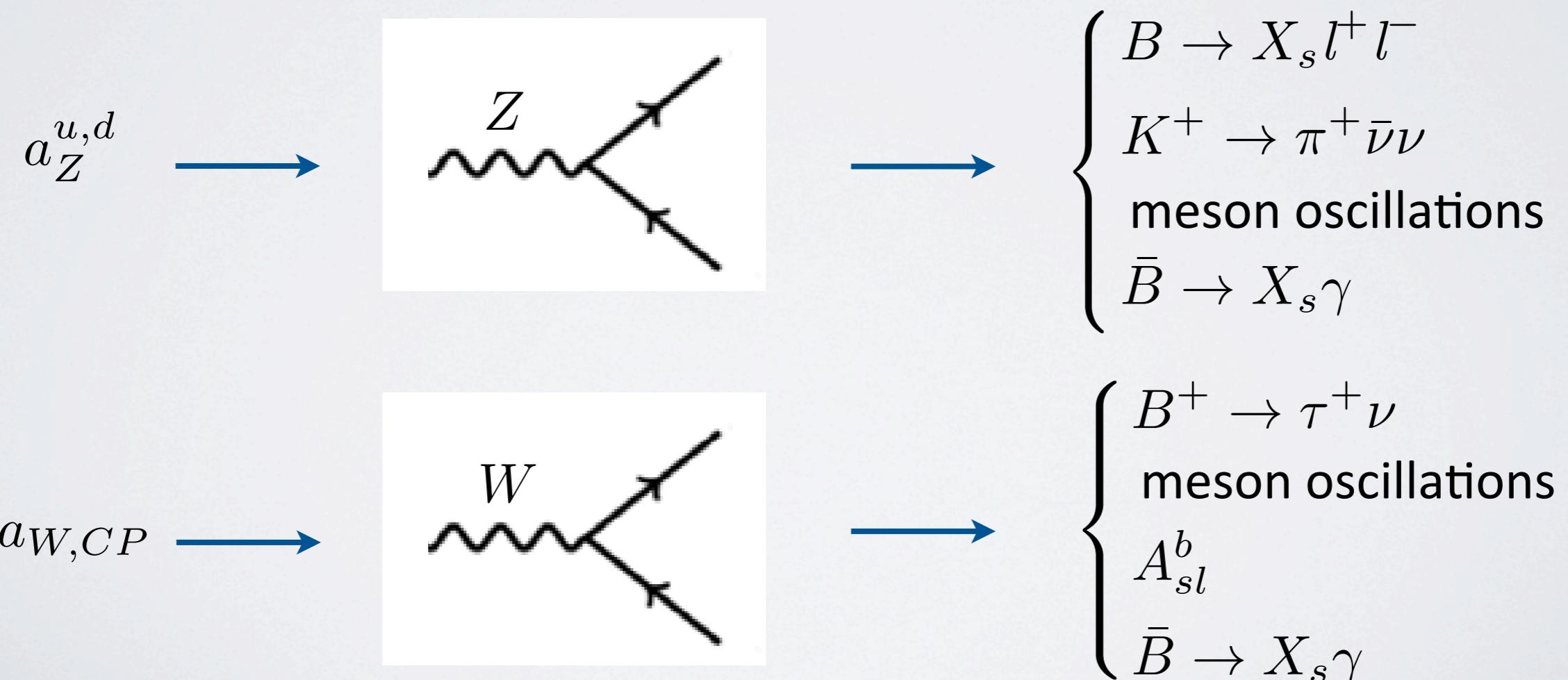
$$\mathcal{O}_3(h) = i \bar{Q}_L \lambda_F \gamma^\mu \mathbf{T} \mathbf{V}_\mu \mathbf{T} Q_L \mathcal{F}(h)$$

$$\mathcal{O}_4(h) = \frac{1}{2} \bar{Q}_L \lambda_F \gamma^\mu [\mathbf{T}, \mathbf{V}_\mu] Q_L \mathcal{F}(h)$$

$$\lambda_F \equiv Y_U Y_U^\dagger + Y_D Y_D^\dagger = V^\dagger \mathbf{y}_U^2 V + \mathbf{y}_D^2$$

It is easier to read the interaction vertices in the unitary gauge:

$$\begin{aligned}\mathcal{L}_{\chi=4}^f = & - \frac{g}{\sqrt{2}} [W_\mu^+ \bar{U}_L \gamma^\mu [a_W(1 + \beta_W h/v) + ia_{CP}(1 + \beta_{CP} h/v)] \times \\ & \quad \times (\mathbf{y}_U^2 V + V \mathbf{y}_D^2) D_L + \text{h.c.}] + \\ & - \frac{g}{2 \cos \theta_W} Z_\mu [a_Z^u \bar{U}_L \gamma^\mu (\mathbf{y}_U^2 + V \mathbf{y}_D^2 V^\dagger) U_L (1 + \beta_Z^u h/v) \\ & \quad + a_Z^d \bar{D}_L \gamma^\mu (\mathbf{y}_D^2 + V^\dagger \mathbf{y}_U^2 V) D_L (1 + \beta_Z^d h/v)]\end{aligned}$$



It is easier to read the interaction vertices in the unitary gauge:

$$\begin{aligned}\mathcal{L}_{\chi=4}^f = & -\frac{g}{\sqrt{2}} \left[W_\mu^+ \bar{U}_L \gamma^\mu [a_W(1 + \beta_W h/v) + ia_{CP}(1 + \beta_{CP} h/v)] \times \right. \\ & \quad \left. \times (\mathbf{y}_U^2 V + V \mathbf{y}_D^2) D_L + \text{h.c.} \right] + \\ & -\frac{g}{2 \cos \theta_W} Z_\mu \left[a_Z^u \bar{U}_L \gamma^\mu (\mathbf{y}_U^2 + V \mathbf{y}_D^2 V^\dagger) U_L (1 + \beta_Z^u h/v) \right. \\ & \quad \left. + a_Z^d \bar{D}_L \gamma^\mu (\mathbf{y}_D^2 + V^\dagger \mathbf{y}_U^2 V) D_L (1 + \beta_Z^u h/v) \right]\end{aligned}$$

The $\mathcal{O}_4(h)$ is CP-odd and introduce a source of CP violation. This is interesting since it introduces an exotic h -fermion couplings:

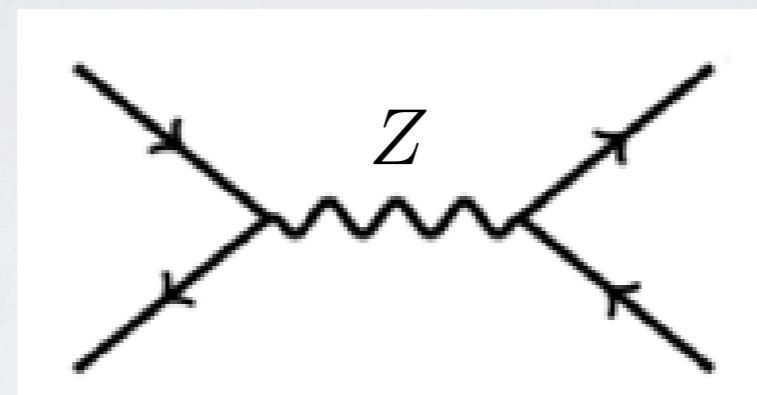
$$\delta \mathcal{L}_{\chi=4}^h \supset a_{CP} \left(1 + \beta_{CP} \frac{h}{v} \right) \mathcal{O}_4$$

If a_{CP} will turn out to be of order 1, then this would be a test of this framework once both low-energy flavour experiments and LHC precision on h -fermion couplings nears the 10^{-2} level.

$\Delta F = 1$ Observables



Z-mediated

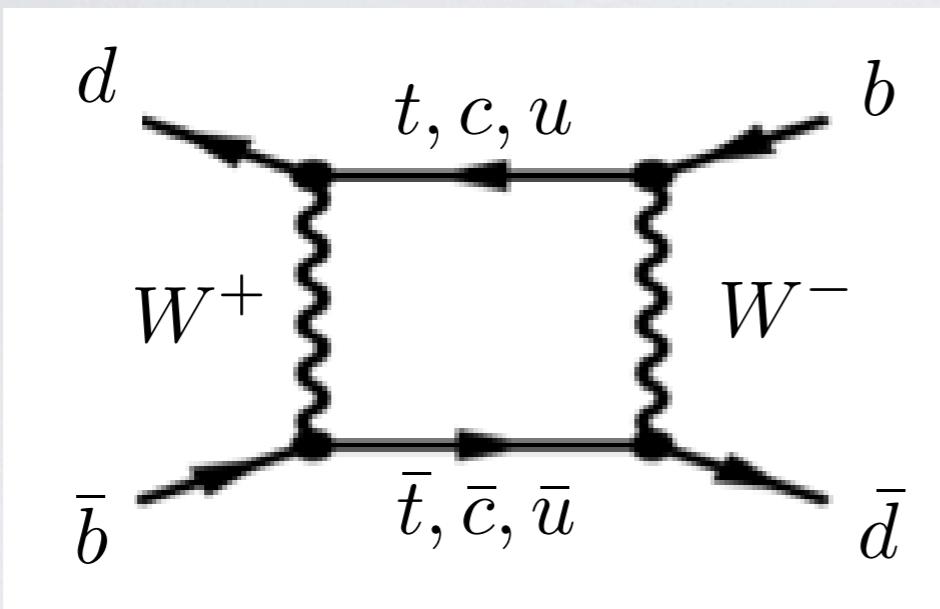


Observable	Bound (@ 95% C.L.)
$B \rightarrow X_s l^+ l^-$	$-0.050 < a_Z^d < 0.009$
$K^+ \rightarrow \pi^+ \bar{\nu}\nu$	$-0.044 < a_Z^d < 0.133$

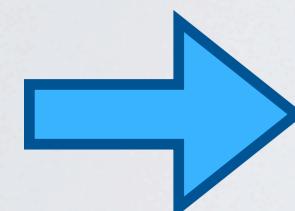
$\Delta F = 2$ Observables



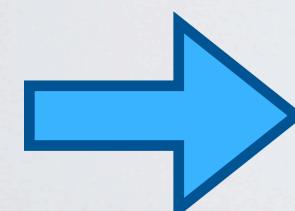
Meson Oscillations



The Z-mediated contributions is already much suppressed due to the $\Delta F = 1$ bounds.



Large deviations are expected in the K system

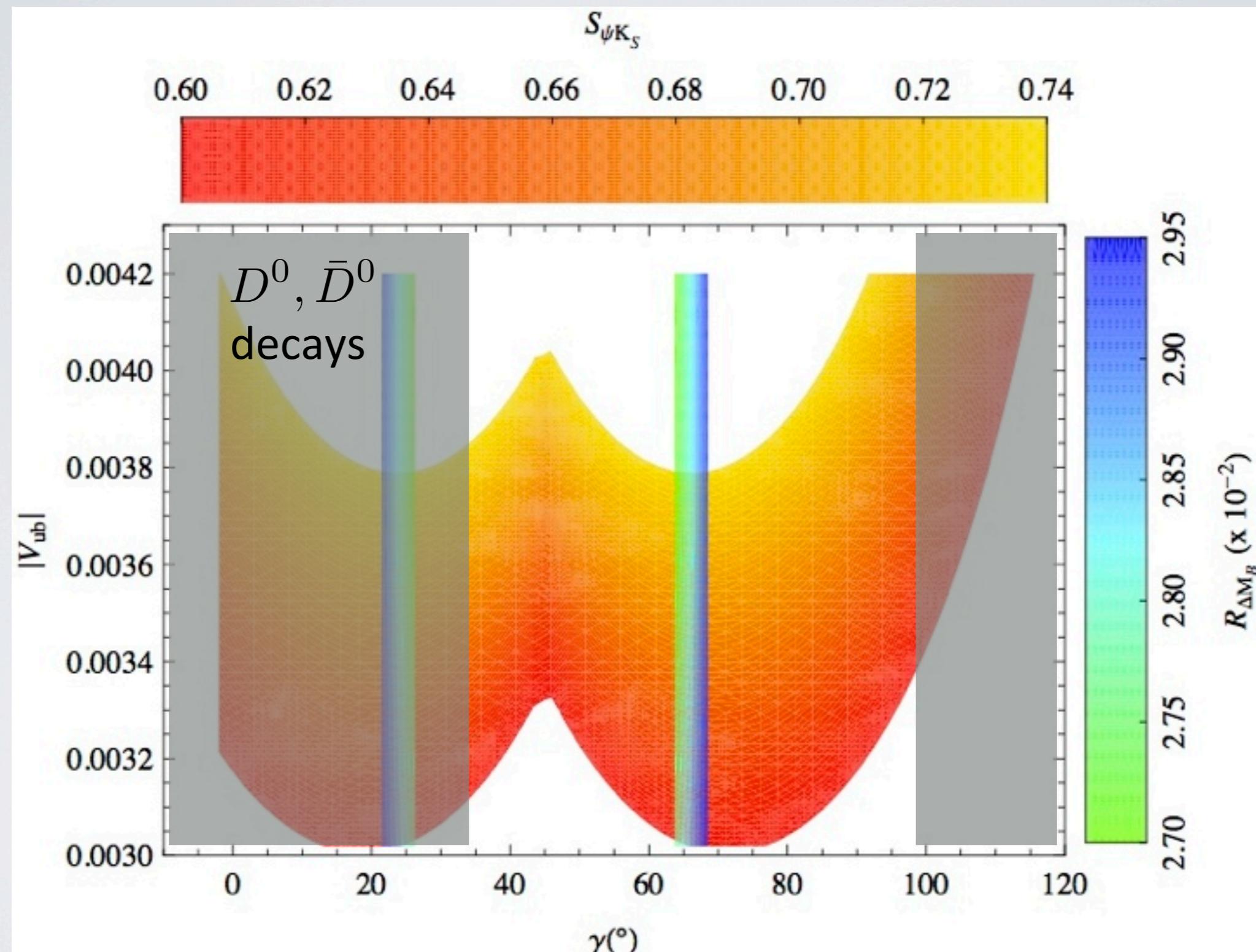


Large deviations are expected only in ΔM_q but

$$\frac{\Delta M_{B_d}}{\Delta M_{B_s}} = \frac{C_{B_d}}{C_{B_s}} \frac{\Delta M_{B_d}}{\Delta M_{B_s}} \Big|_{SM}$$

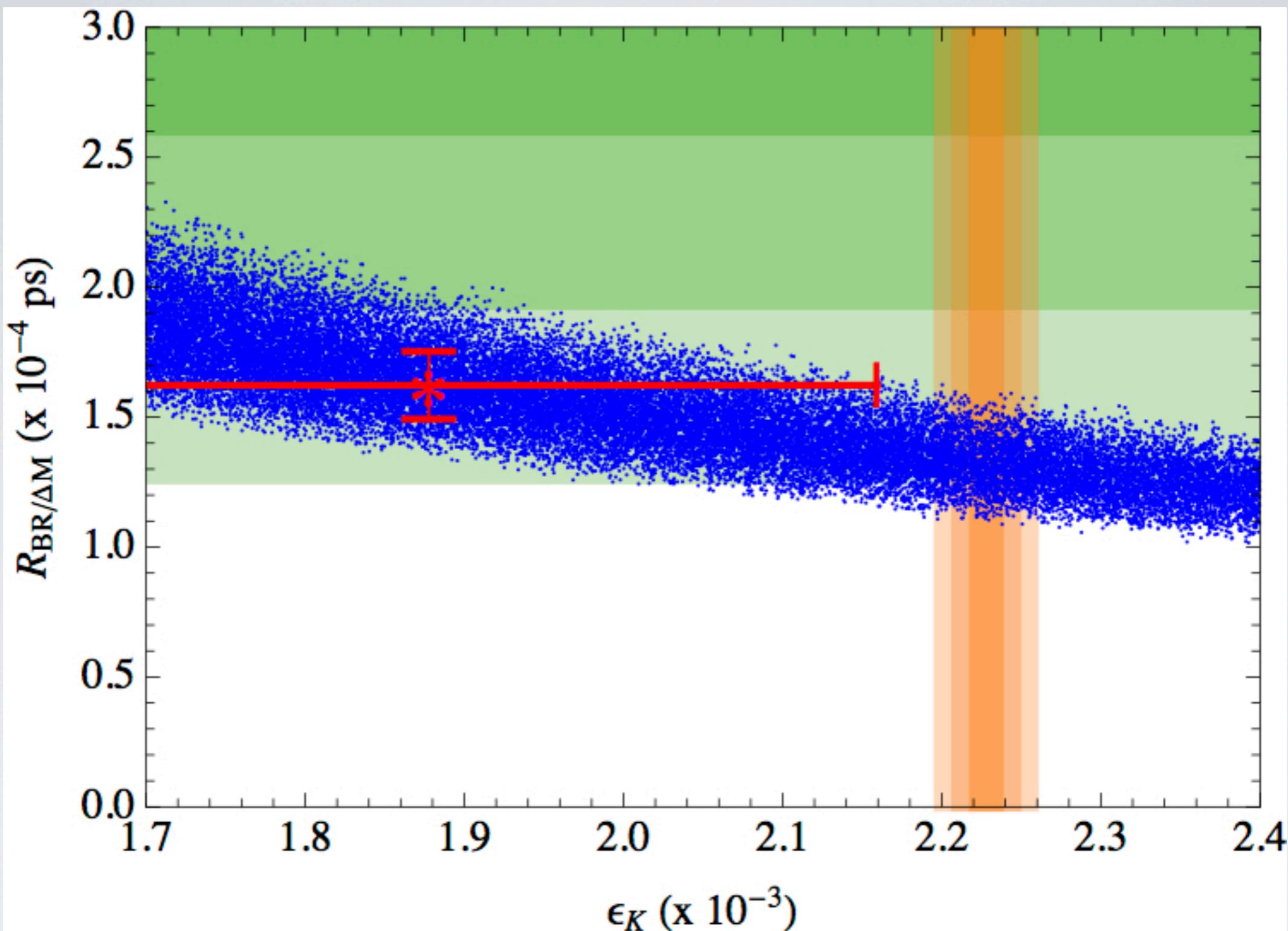
in particular $S_{\psi K_S}$ is expected to be SM like.

$S_{\psi K_S}$ and $R_{\Delta M_B} = \frac{\Delta M_{B_d}}{\Delta M_{B_s}}$ @ 3σ ranges



→ $|V_{ub}| = 3.5 \times 10^{-3}$ $\gamma = 66^\circ$

$$R_{BR/\Delta M} \equiv BR(B^+ \rightarrow \tau^+ \nu) / \Delta M_{B_d}$$



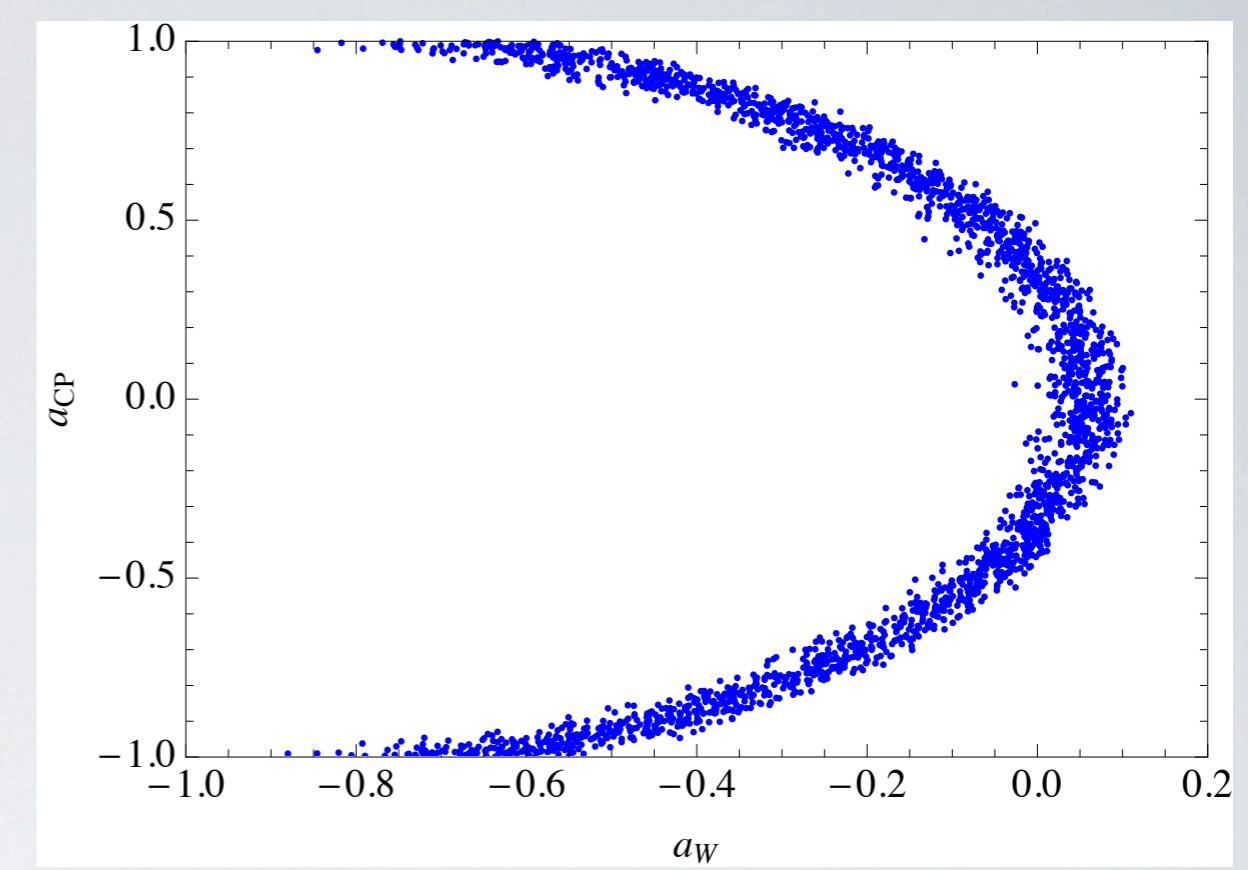
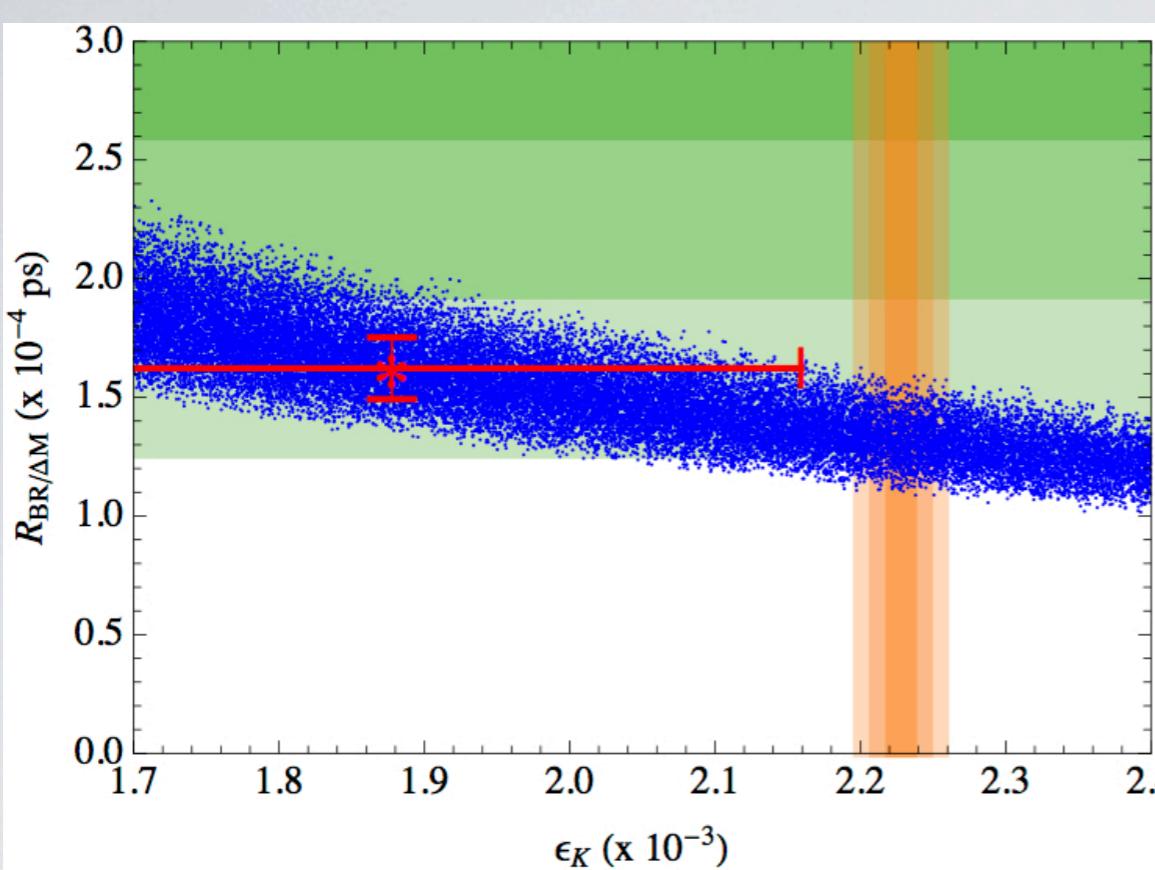
SM values:

$$\epsilon_K \sim (1.88 \pm 0.3) \times 10^{-3}$$

$$R_{BR/\Delta M} \sim (1.62 \pm 0.13) \times 10^{-4}$$

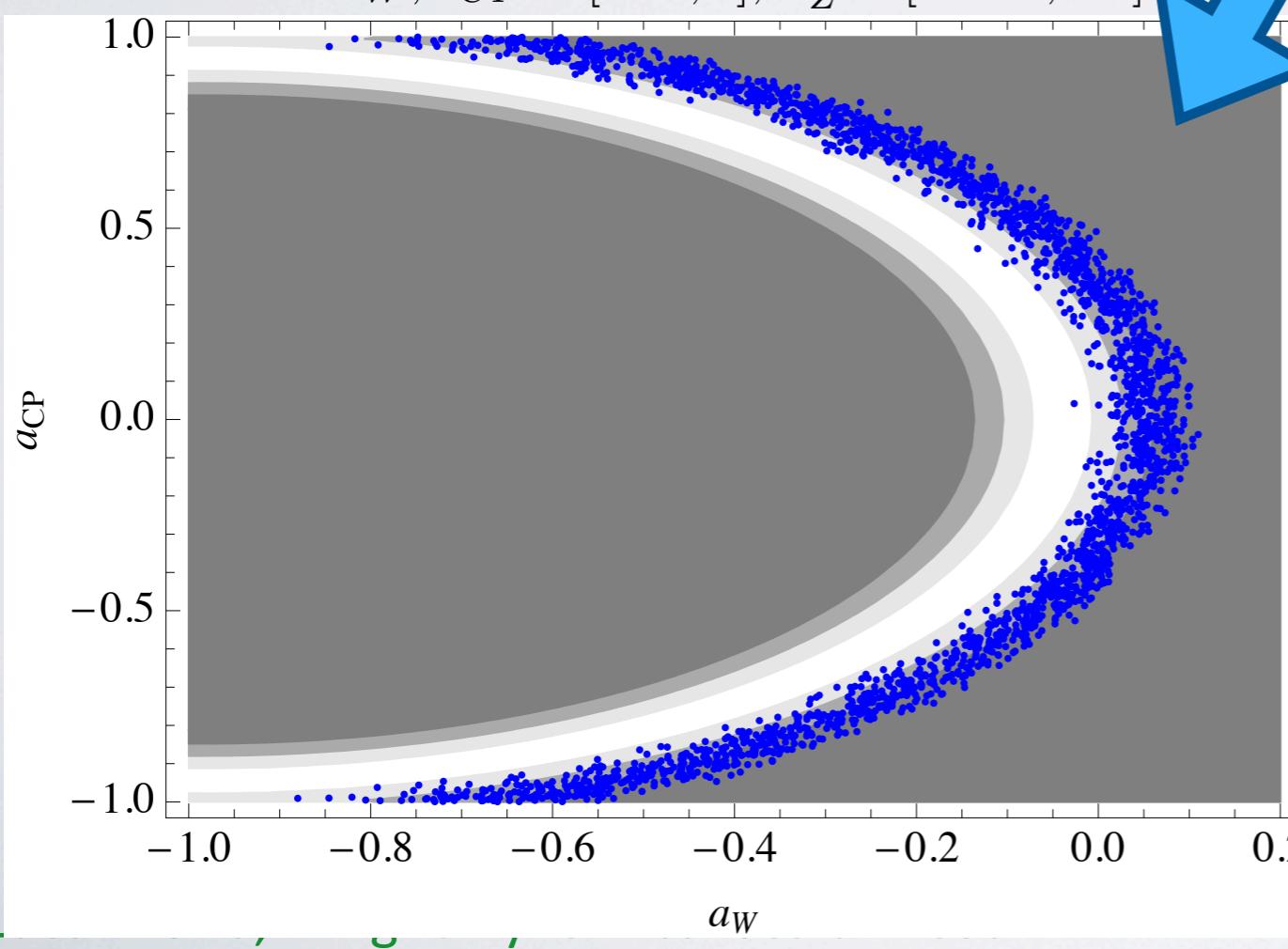
$$a_W, a_{CP} \in [-1, 1]$$

$$a_Z^d \in [-0.1, 0.1]$$



Correlation plot between ε_K and $R_{BR/\Delta M}$.
 $a_W, a_{CP} \in [-1, 1]$, $a_Z^d \in [-0.1, 0.1]$

$a_W - a_{CP}$ parameter space for the observables inside their 3σ error ranges and $a_Z^d \in [-0.0087, 0.0440]$.



Considering $\bar{B} \rightarrow X_s \gamma$

Final Remarks

- No striking evidence of NP associated to scalar sector has been found
 - we should live with the idea of a fine-tuning (Hierarchy Problem)
 - NP is still waiting to be discovered
- NP could consist in a strong interacting dynamics at the TeV scale:
 - Strong resonances at Λ_s , not seen yet
 - Deviation from the SM couplings of the SMS particle
- We constructed the effective Lagrangian up to $d = 5$ in both the gauge and flavour bases
- We studied the phenomenology mainly of the flavour sector and it turns out that the Lagrangian parameters can be as large as 1, even with NP at the TeV scale
- A correlation is established between the possible signals in low-energy searches of CP-violation and anomalous h -fermion couplings at the LHC

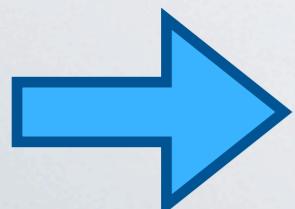
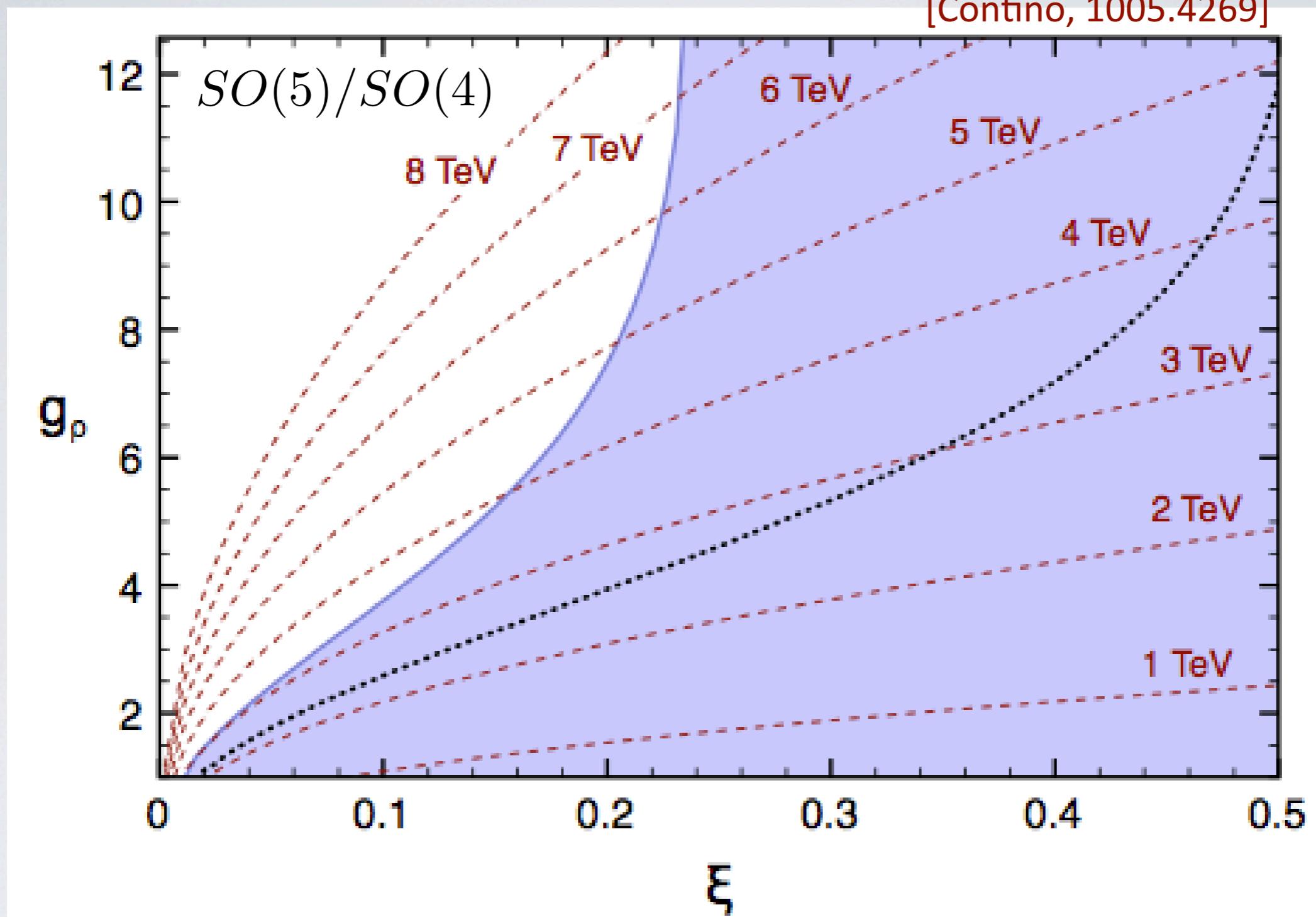
Thank you

Backup



The parameter ξ

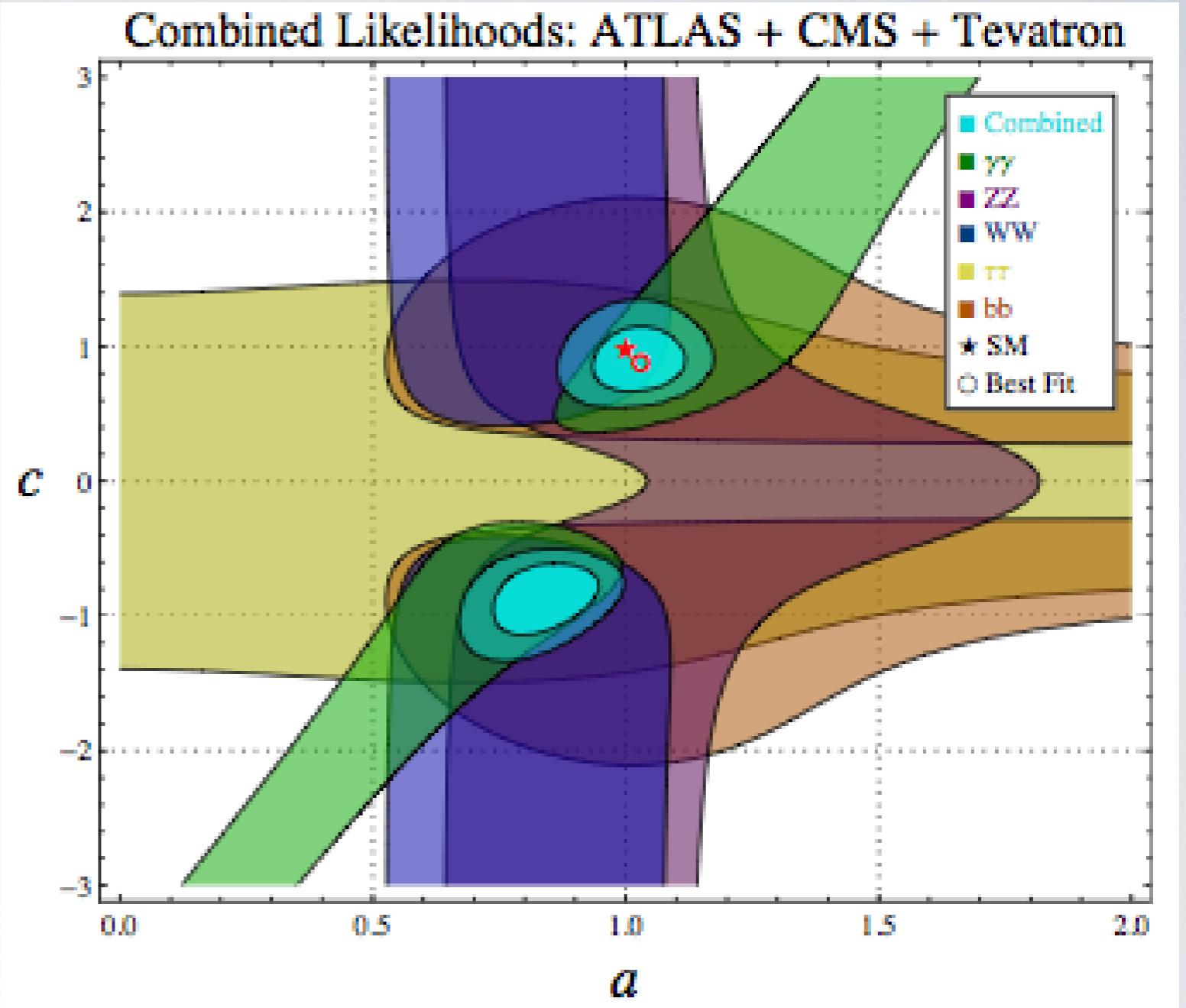
[Contino, 1005.4269]



In the general effective approach, ξ could be even larger than 0.2, but a specific UV completion is necessary.

The parameters a and c

[Azatov&Galloway, 1212.1380]



The operator proportional to c_T violates custodial symmetry and gives a contribution to the ρ parameter:

$$-1.7 \times 10^{-3} < \Delta\rho \equiv c_T \xi < 1.9 \times 10^{-3}$$

[Giudicea,Grojeana,Pomarol&Rattazzi, hep-ph0703164]

Operators in ξ

$$\begin{aligned}
 \mathcal{P}_1(h) &= g g' B_{\mu\nu} \text{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h) \\
 \mathcal{P}_2(h) &= i g' B_{\mu\nu} \text{Tr}(\mathbf{T} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h) \\
 \mathcal{P}_3(h) &= i g \text{Tr}(W_{\mu\nu} [\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_3(h) \\
 \mathcal{P}_4(h) &= i g' B_{\mu\nu} \text{Tr}(\mathbf{T} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h) \\
 \mathcal{P}_5(h) &= i g \text{Tr}(W_{\mu\nu} \mathbf{V}^\mu) \partial^\nu \mathcal{F}_5(h)
 \end{aligned}$$

It is interesting to make connection with the linear regime: we define the **linear siblings** those operators written in terms of the Higgs doublet H , that includes the pure gauge part of the operators $\mathcal{P}_i(h)$.

The lowest dimensional siblings of $\mathcal{P}_{1-5}(h)$ have $d = 6$ and have been pointed out in [Giudice, Grojean, Pomarol & Rattazzi, arXiv:hep-ph/0703164]

$$(\mathcal{D}^\mu H)^\dagger W_{\mu\nu} (\mathcal{D}^\nu H) \quad (\mathcal{D}^\mu H)^\dagger (\mathcal{D}^\nu H) B_{\mu\nu}$$

Operators that are related to the quark masses

$$\mathcal{P}_{11}(h) = \text{Tr}((\mathcal{D}_\mu \mathbf{V}^\mu)^2) \mathcal{F}_{11}(h)$$

$$\mathcal{P}_{12}(h) = \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathcal{D}_\nu \mathbf{V}^\nu) \mathcal{F}_{12}(h)$$

$$\mathcal{P}_{13}(h) = \text{Tr}([\mathbf{T}, \mathbf{V}_\nu] \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}^\nu) \mathcal{F}_{13}(h)$$

$$\mathcal{P}_{16}(h) = \text{Tr}(\mathbf{V}_\nu \mathcal{D}_\mu \mathbf{V}^\mu) \partial^\nu \mathcal{F}_{16}(h)$$

$$\mathcal{P}_{17}(h) = \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) \text{Tr}(\mathbf{T} \mathbf{V}_\nu) \partial^\nu \mathcal{F}_{17}(h)$$

$\mathcal{P}_{11-13}(h)$ were already known in the context without a scalar Higgs

Using: $(D^\mu W_{\mu\nu})_j = i \frac{g}{4} v^2 \text{Tr}[\mathbf{V}_\nu \sigma_j] + \frac{g}{2} \bar{Q}_L \gamma_\nu \sigma_j Q_L$

$$\partial^\mu B_{\mu\nu} = -i \frac{g'}{4} v^2 \text{Tr}[\mathbf{T} \mathbf{V}_\nu] + \sum_{i=L,R} g' \bar{Q}_i \gamma_\nu \mathbf{h}_i Q_i$$

→
$$\begin{cases} \frac{iv}{\sqrt{2}} \text{Tr}(\sigma_j \mathcal{D}_\mu \mathbf{V}^\mu) = i \bar{Q}_L \sigma_j \mathbf{U} \mathbf{Y} Q_R + \text{h.c.} \\ \frac{iv}{\sqrt{2}} \text{Tr}(\mathbf{T} \mathcal{D}_\mu \mathbf{V}^\mu) = i \bar{Q}_L \mathbf{T} \mathbf{U} \mathbf{Y} Q_R + \text{h.c.} \end{cases}$$

Minimal Flavour Violation

[D'Ambrosio, Giudice, Isidori & Strumia, hep-ph/0207036]

- The flavour symmetry is the symmetry of the kinetic terms

$$G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

$$Q_L \sim (3, 1, 1) \quad U_R \sim (1, 3, 1) \quad D_R \sim (1, 1, 3)$$

- Lagrangian invariant under G_f if $Y_D \sim (3, 1, \bar{3})$ and $Y_U \sim (3, \bar{3}, 1)$

- Masses and Mixings are reproduced, but NOT explained: for quarks

[Alonso, Gavela, LM&Rigolin, 1103.2915]

[Alonso, Gavela, Hernandez&LM, 1206.3167]

$$Y_d = \frac{\sqrt{2}}{v} \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

$$Y_u = \frac{\sqrt{2}}{v} V^\dagger \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

V CKM matrix

$\Delta F = 2$ Observables

$$M_{12}^K = (M_{12}^K)_{SM} + (M_{12}^K)_{NP}$$

$$(M_{12}^K)_{SM} = R_K \left[\eta_2 \lambda_t^2 S_0(x_t) + \eta_1 \lambda_c^2 S_0(x_c) + 2 \eta_3 \lambda_t \lambda_c S_0(x_c, x_t) \right]^*$$

$$(M_{12}^K)_{NP} = R_K \left[\eta_2 \lambda_t^2 (y_t^2 (2 a_W + y_t^2 a_{CP}^2) G(x_t) + \dots) + \right.$$

$$\left. + 2 \eta_3 \lambda_t \lambda_c (y_t^2 (2 a_W + a_{CP}^2 y_t^2) H(x_t, x_c) + \dots) + \dots \right]^*$$

large deviations

$$\left\{ \begin{array}{l} \Delta M_K = 2 \left[\mathcal{R}e(M_{12}^K)_{SM} + \mathcal{R}e(M_{12}^K)_{NP} \right] \\ \varepsilon_K = \frac{\kappa_\epsilon e^{i \varphi_\epsilon}}{\sqrt{2} (\Delta M_K)_{\text{exp}}} \left[\mathcal{I}m \left(M_{12}^K \right)_{SM} + \mathcal{I}m \left(M_{12}^K \right)_{NP} \right] \end{array} \right.$$

$$M_{12}^q = (M_{12}^q)_{\text{SM}} \mathcal{C}_{B_q} e^{2i\varphi_{B_q}}$$

$$(M_{12}^q)_{\text{SM}} = R_{B_q} [\lambda_t^2 S_0(x_t)]^*$$

$$\mathcal{C}_{B_d} = \mathcal{C}_{B_s} = \left| 1 + 2 a_W y_t^2 \frac{G(x_t)}{S_0(x_t)} + \dots \right|$$

large deviations

$$\varphi_{B_d} = \varphi_{B_s} = 2 a_W a_{CP} y_t^2 y_b^2 \frac{G(x_t)}{S_0(x_t)}$$

small deviations

$$\begin{cases} \Delta M_q = 2 |M_{12}^q| \equiv (\Delta M_q)_{\text{SM}} \mathcal{C}_{B_q} \\ S_{\psi K_S} = \sin(2\beta + 2\varphi_{B_d}) \\ S_{\psi\phi} = \sin(2\beta_s - 2\varphi_{B_s}) \end{cases}$$

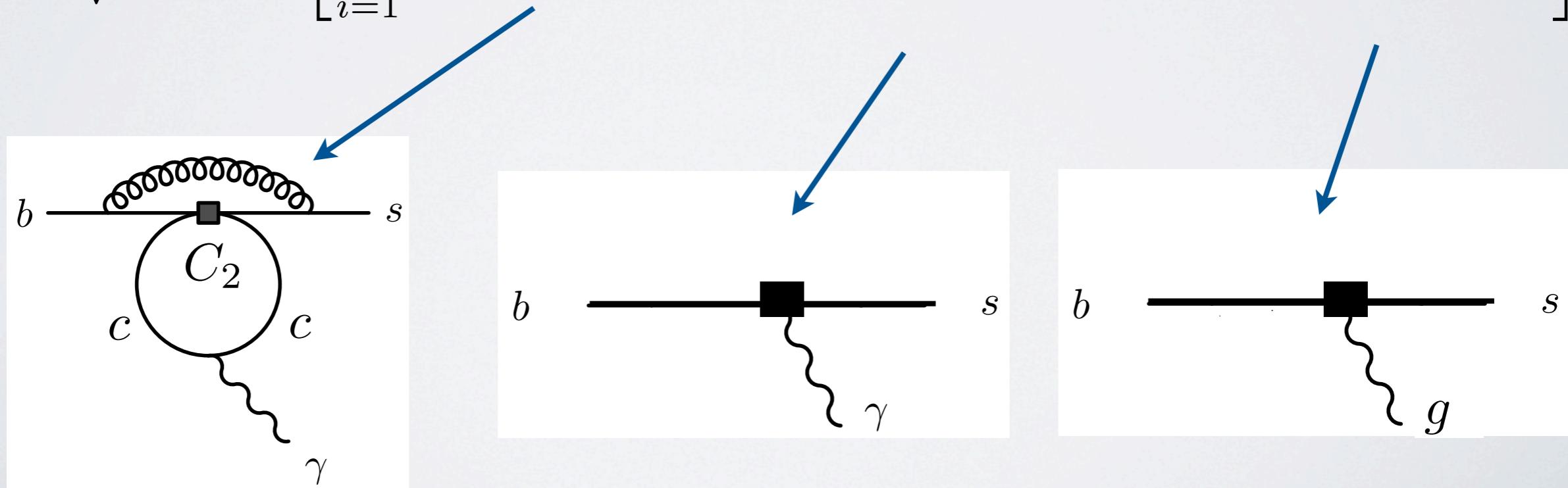
$$\bar{B} \rightarrow X_s \gamma$$

$$\left. \begin{aligned} Br(\bar{B} \rightarrow X_s \gamma)_{Exp} &= (3.55 \pm 0.24 \pm 0.09) \times 10^{-4} \\ Br(\bar{B} \rightarrow X_s \gamma)_{SM} &= (3.15 \pm 0.23) \times 10^{-4} \end{aligned} \right\} \text{ quite precise numbers!}$$

The modification of the CKM induces modification on $\bar{B} \rightarrow X_s \gamma$

The effective Lagrangian relevant for this decay at $\mu_b \approx m_b$:

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\sum_{i=1}^6 C_i(\mu_b) Q_i(\mu_b) + C_{7\gamma}(\mu_b) Q_{7\gamma}(\mu_b) + C_{8G}(\mu_b) Q_{8G}(\mu_b) \right]$$



To compute the $Br(\bar{B} \rightarrow X_s \gamma)$ we need to:

- Compute the Wilson coefficients C_i at the matching scale

$$C_i(\mu_W) = C_i^{SM}(\mu_W) + \Delta C_i^{d=4}(\mu_W)$$

$$\Delta C_i^{d=4}(\mu_W) \propto a_W y_t^2 + (a_W^2 + a_{CP}^2) y_t^4$$

large deviations

- Apply the running under QCD (mixings among operators arise) down to the low-energy scale $\mu_b \approx m_b$

$$\Delta C_{7\gamma}(\mu_b) = \eta^{\frac{16}{23}} \Delta C_{7\gamma}(\mu_W) + \frac{8}{3} \left(\eta^{\frac{14}{23}} - \eta^{\frac{16}{23}} \right) \Delta C_{8G}(\mu_W) + \Delta C_2(\mu_W) \sum_{i=1}^8 \kappa_i \eta^{\sigma_i}$$

$$\eta \equiv \frac{\alpha_s(\mu_W)}{\alpha_s(\mu_b)} = 0.45$$

Impact of the physical Scalar

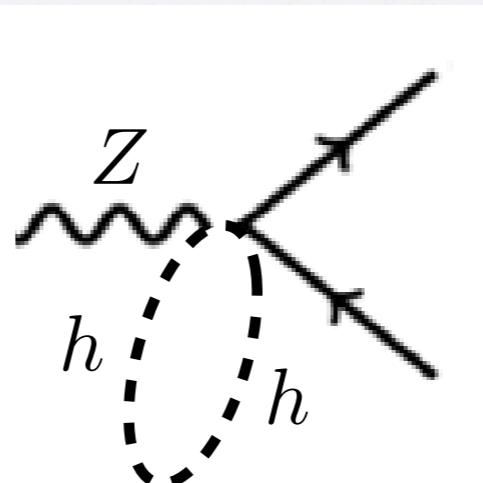
How the presence of a light SMS could modify the previous analysis?

- Tree-level FV couplings of the SMS:

$$\begin{aligned}\mathcal{L}_h = & \frac{1}{2}(\partial_\mu h)(\partial^\mu h) (1 + c_H \xi \mathcal{F}_H(h)) - V(h) + \\ & + \frac{v^2}{4} \text{Tr} [\mathbf{V}^\mu \mathbf{V}_\mu] \mathcal{F}_C(h) + c_T \xi \frac{v^2}{4} \text{Tr} [\mathbf{T} \mathbf{V}^\mu] \text{Tr} [\mathbf{T} \mathbf{V}_\mu] \mathcal{F}_T(h) + \\ & - \left(\frac{v}{2\sqrt{2}} \bar{Q}_L \mathbf{U}(x) \mathbf{Y} Q_R \mathcal{F}_Y(h) + \text{h.c.} \right) + \dots\end{aligned}$$

$$\longrightarrow \mathcal{F}_Y(h) = \left(1 + c \frac{h}{v} + \dots \right) \quad \text{NO}$$

- Loop-level contributions:



Negligible

$d = 5$ chiral operators

There are no operators with 2 LH or 2 RH quark fields, but all the operators are written with 1 LH and 1 RH quark fields.

$$\begin{aligned}\mathcal{L}_{\chi=5}^f &= \sum_{i=1}^{18} b_i \frac{\mathcal{X}_i}{\Lambda_s} \\ &= \xi \sum_{i=1}^8 \hat{b}_i \frac{\mathcal{X}_i}{\Lambda_s} + \xi^2 \sum_{i=9}^{18} \hat{b}_i \frac{\mathcal{X}_i}{\Lambda_s}\end{aligned}$$



Integrating out the strong resonances

Dipole-type operators:

$$\begin{array}{ll} \mathcal{X}_1 = g' \bar{Q}_L \sigma^{\mu\nu} \mathbf{U} Q_R B_{\mu\nu} & \mathcal{X}_2 = g' \bar{Q}_L \sigma^{\mu\nu} \mathbf{T} \mathbf{U} Q_R B_{\mu\nu} \\ \mathcal{X}_3 = g \bar{Q}_L \sigma^{\mu\nu} \sigma_i \mathbf{U} Q_R W_{\mu\nu}^i & \mathcal{X}_4 = g \bar{Q}_L \sigma^{\mu\nu} \sigma_i \mathbf{T} \mathbf{U} Q_R W_{\mu\nu}^i \\ \mathcal{X}_5 = g_s \bar{Q}_L \sigma^{\mu\nu} \mathbf{U} Q_R G_{\mu\nu} & \mathcal{X}_6 = g_s \bar{Q}_L \sigma^{\mu\nu} \mathbf{T} \mathbf{U} Q_R G_{\mu\nu} \\ \mathcal{X}_7 = g \bar{Q}_L \sigma^{\mu\nu} \mathbf{T} \sigma_i \mathbf{U} Q_R W_{\mu\nu}^i & \mathcal{X}_8 = g \bar{Q}_L \sigma^{\mu\nu} \mathbf{T} \sigma_i \mathbf{T} \mathbf{U} Q_R W_{\mu\nu}^i \end{array}$$



$$\boxed{\bar{D}_L \sigma^{\mu\nu} D_R F_{\mu\nu} \quad \bar{D}_L \sigma^{\mu\nu} D_R G_{\mu\nu}}$$

Operators containing $\sigma^{\mu\nu}$:

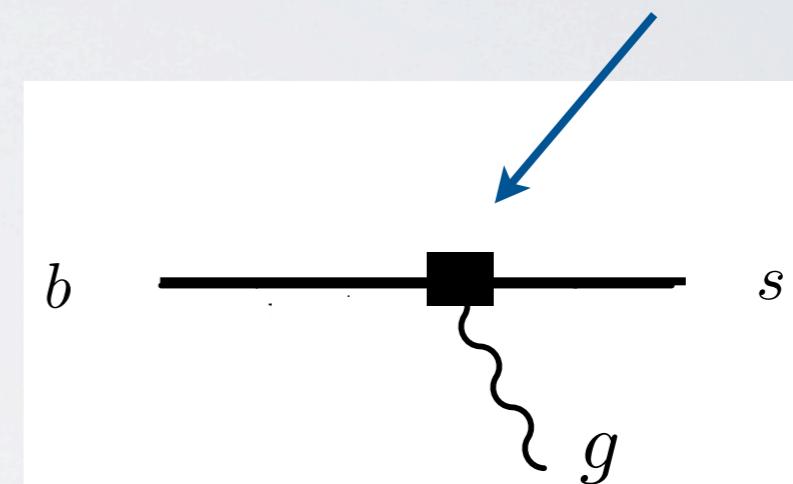
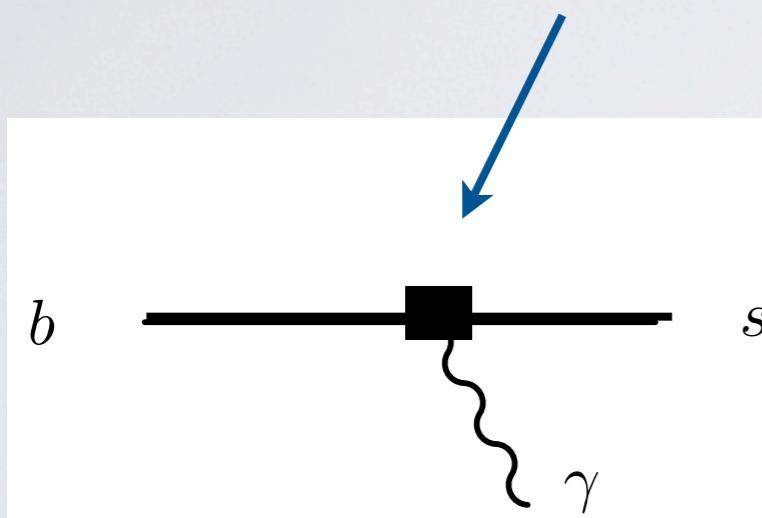
$$\begin{array}{ll} \mathcal{X}_9 = \bar{Q}_L \sigma^{\mu\nu} [\mathbf{V}_\mu, \mathbf{V}_\nu] \mathbf{U} Q_R & \mathcal{X}_{10} = \bar{Q}_L \sigma^{\mu\nu} [\mathbf{V}_\mu, \mathbf{V}_\nu] \mathbf{T} \mathbf{U} Q_R \\ \mathcal{X}_{11} = \bar{Q}_L \sigma^{\mu\nu} [\mathbf{V}_\mu \mathbf{T}, \mathbf{V}_\nu \mathbf{T}] \mathbf{U} Q_R & \mathcal{X}_{12} = \bar{Q}_L \sigma^{\mu\nu} [\mathbf{V}_\mu \mathbf{T}, \mathbf{V}_\nu \mathbf{T}] \mathbf{T} \mathbf{U} Q_R \end{array}$$

Other operators containing \mathbf{V}_μ :

$$\begin{array}{ll} \mathcal{X}_{13} = \bar{Q}_L \mathbf{V}_\mu \mathbf{V}^\mu \mathbf{U} Q_R & \mathcal{X}_{14} = \bar{Q}_L \mathbf{V}_\mu \mathbf{V}^\mu \mathbf{T} \mathbf{U} Q_R \\ \mathcal{X}_{15} = \bar{Q}_L \mathbf{V}_\mu \mathbf{T} \mathbf{V}^\mu \mathbf{U} Q_R & \mathcal{X}_{16} = \bar{Q}_L \mathbf{V}_\mu \mathbf{T} \mathbf{V}^\mu \mathbf{T} \mathbf{U} Q_R \\ \mathcal{X}_{17} = \bar{Q}_L \mathbf{T} \mathbf{V}_\mu \mathbf{T} \mathbf{V}^\mu \mathbf{U} Q_R & \mathcal{X}_{18} = \bar{Q}_L \mathbf{T} \mathbf{V}_\mu \mathbf{T} \mathbf{V}^\mu \mathbf{T} \mathbf{U} Q_R \end{array}$$

■ $d = 5$ chiral operators

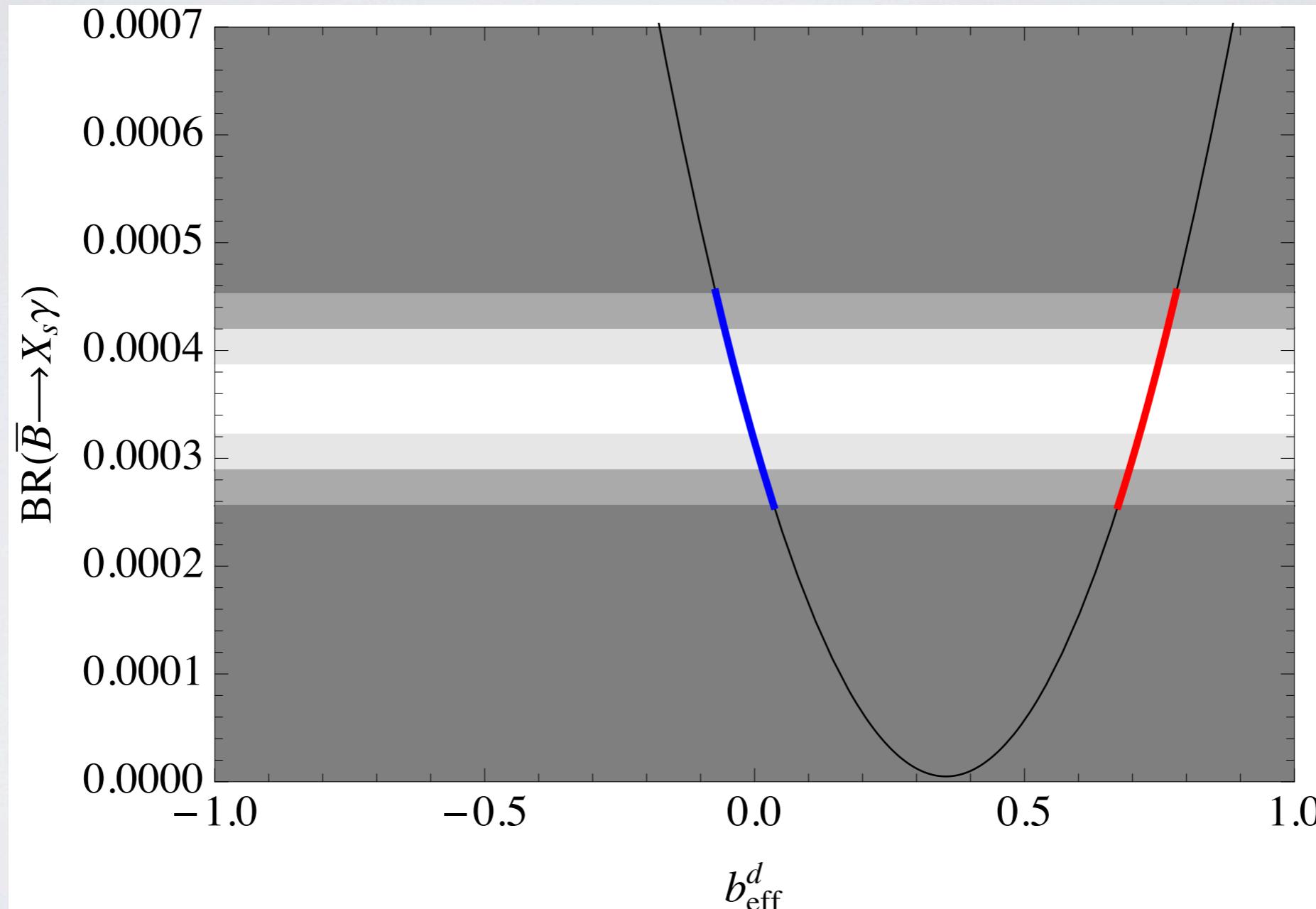
$$\delta\mathcal{L}_{\chi=5}^d = \frac{g^2}{4 \cos \theta_W^2} \frac{b_Z^d}{\Lambda_s} \bar{D}_L D_R Z_\mu Z^\mu + \frac{g^2}{2} \frac{b_W^d}{\Lambda_s} \bar{D}_L D_R W_\mu^+ W^{-\mu} + g^2 \frac{c_W^d}{\Lambda_s} \bar{D}_L \sigma^{\mu\nu} D_R W_\mu^+ W_\nu^- + \\ + e \frac{d_F^d}{\Lambda_s} \bar{D}_L \sigma^{\mu\nu} D_R F_{\mu\nu} + \frac{g}{2 \cos \theta_W} \frac{d_Z^d}{\Lambda_s} \bar{D}_L \sigma^{\mu\nu} D_R Z_{\mu\nu} + g_s \frac{d_G^d}{\Lambda_s} \bar{D}_L \sigma^{\mu\nu} D_R G_{\mu\nu} + \text{h.c.}$$



This effective Lagrangian is written at the matching scale $\mu_s \equiv \Lambda_s$ and in the following we take $\mu_s = 4\pi v$, that maximizes the contributions. The running is now two-step:

- a 6-flavour running from μ_s down to μ_W
- a 5-flavour running from μ_W down to μ_b (as before)

$$BR(b \rightarrow s\gamma) = 0.000315 - 0.00175 b_{eff}^d + 0.00247 (b_{eff}^d)^2$$



$$BR(b \rightarrow s\gamma) = 0.000315 - 0.00175 b_{eff}^d + 0.00247 (b_{eff}^d)^2$$

$$b_{eff}^d \equiv 3.8 b_F^d + 1.2 b_G^d$$