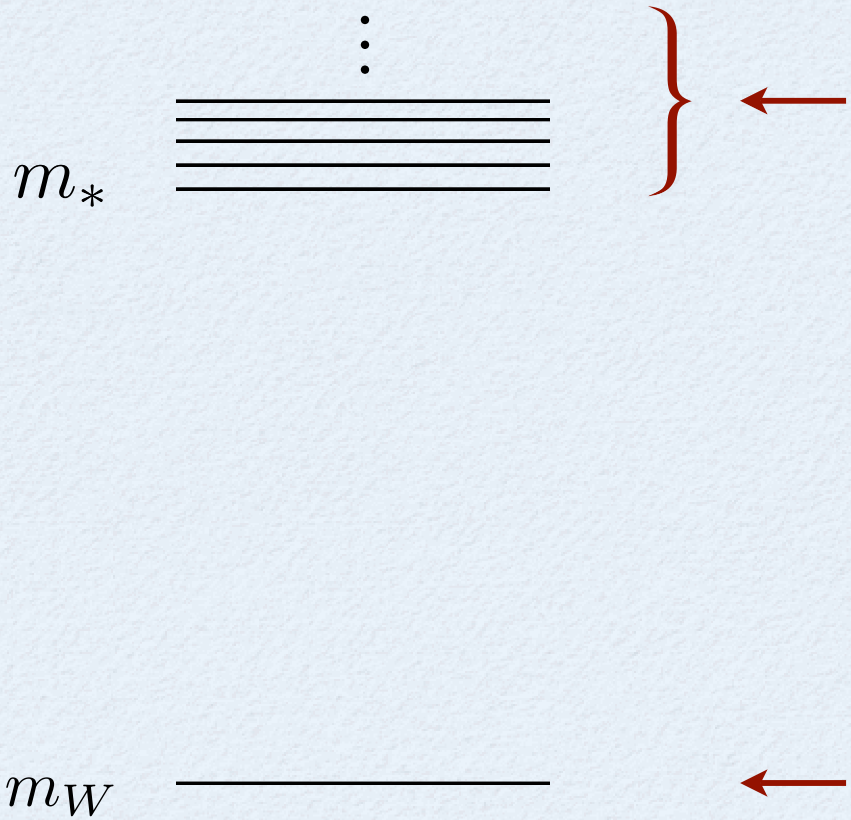
WARPED/COMPOSITE PHENOMENOLOGY SIMPLIFIED

Roberto Contino

CERN - TH

R.C. , T. Kramer, M. Son, R. Sundrum, JHEP 0705:074 (2007)

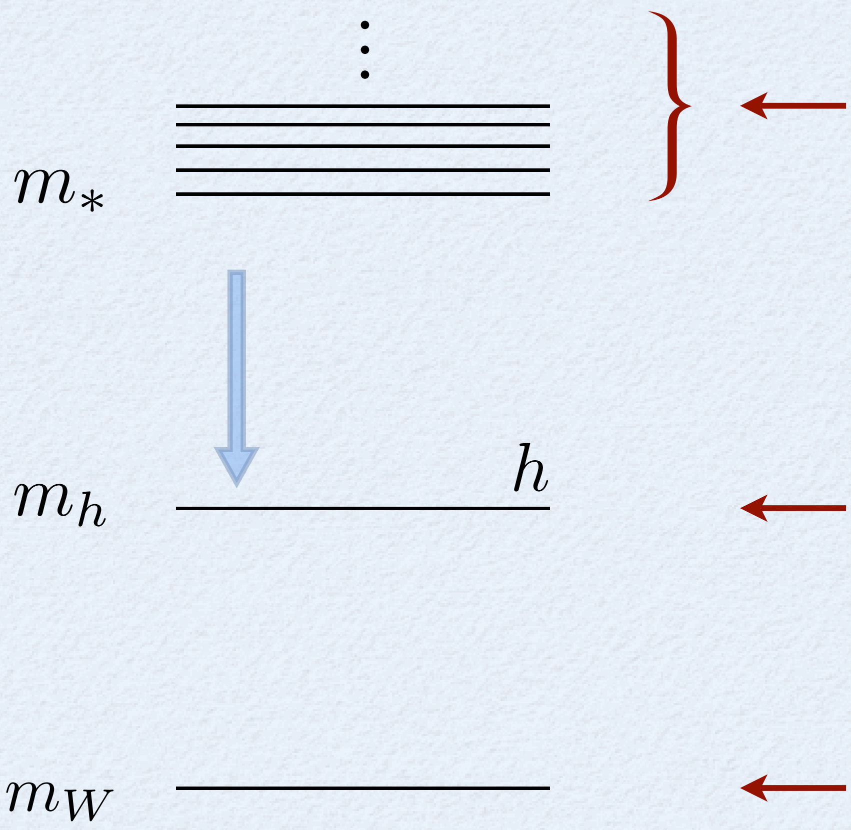
The case for a composite Higgs



a new strongly-interacting dynamics with heavy resonances is responsible for EWSB

W_L , Z_L are Goldstone bosons of the new dynamics

The case for a composite Higgs



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composite Higgs

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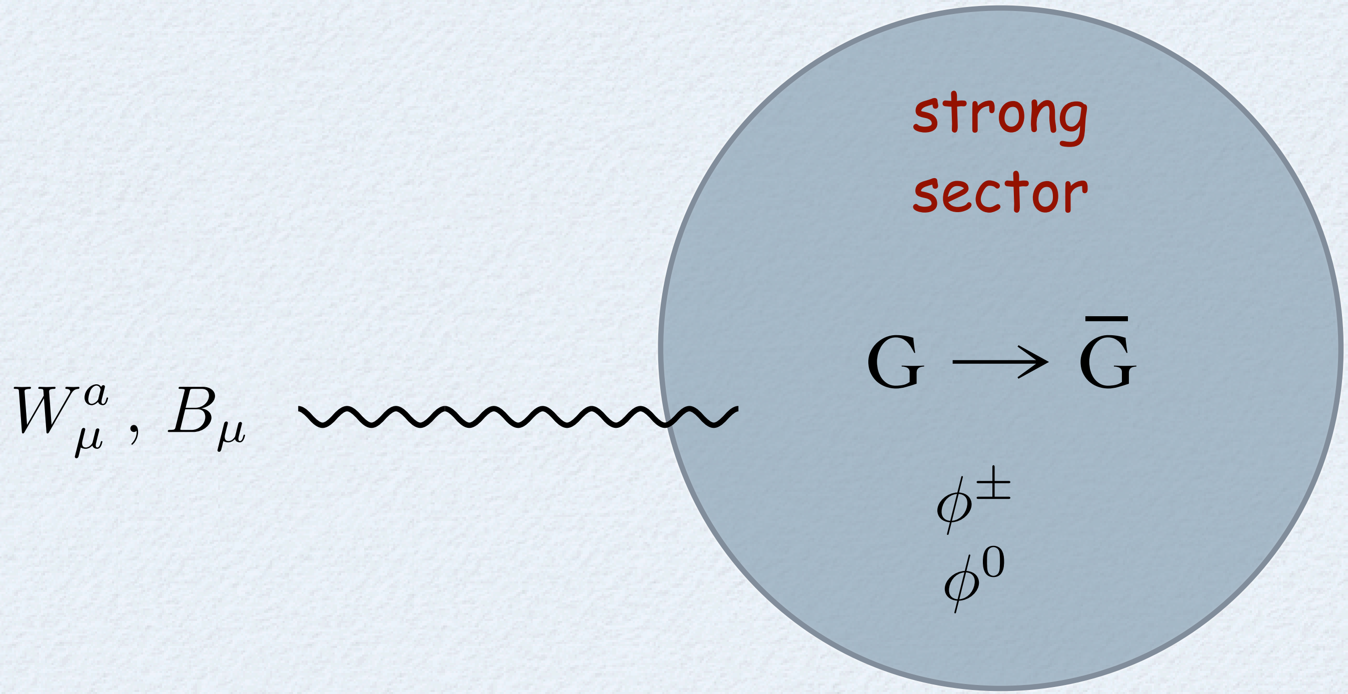

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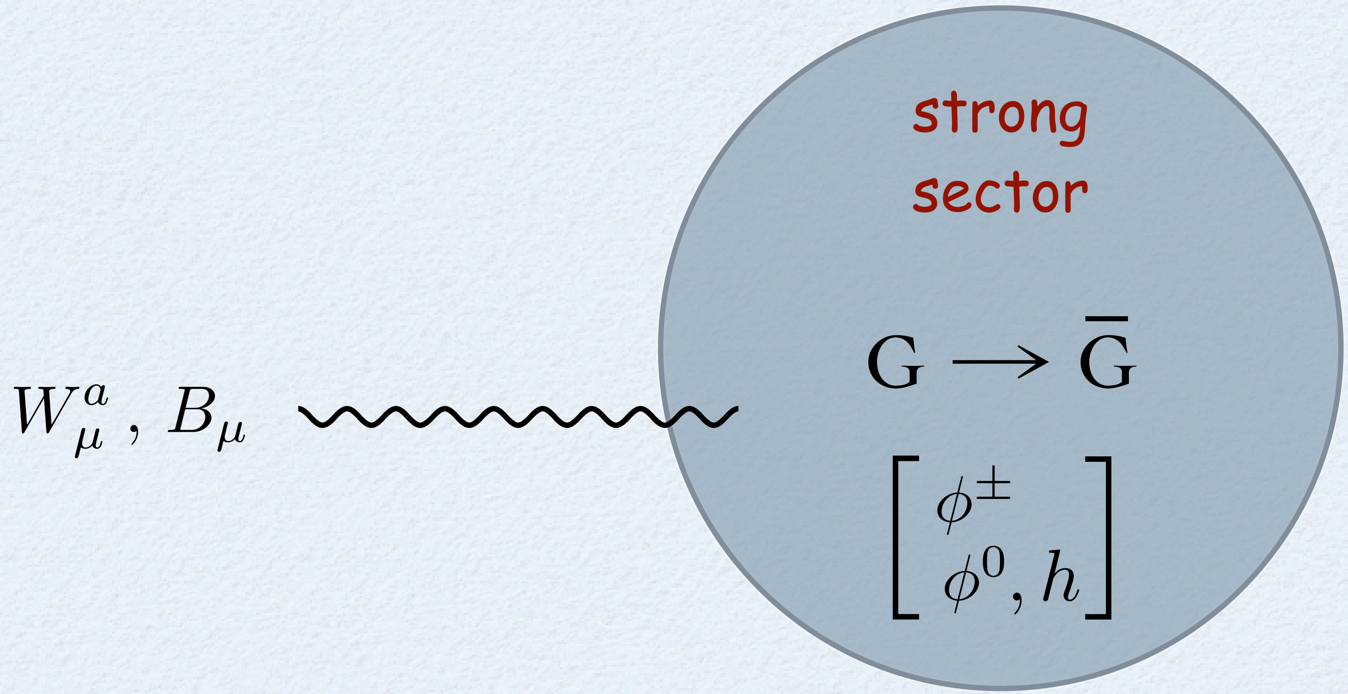

← enlarge the global symmetry to have a full SU(2) doublet

ex: $\mathrm{SO}(5) \to \mathrm{SO}(4)$

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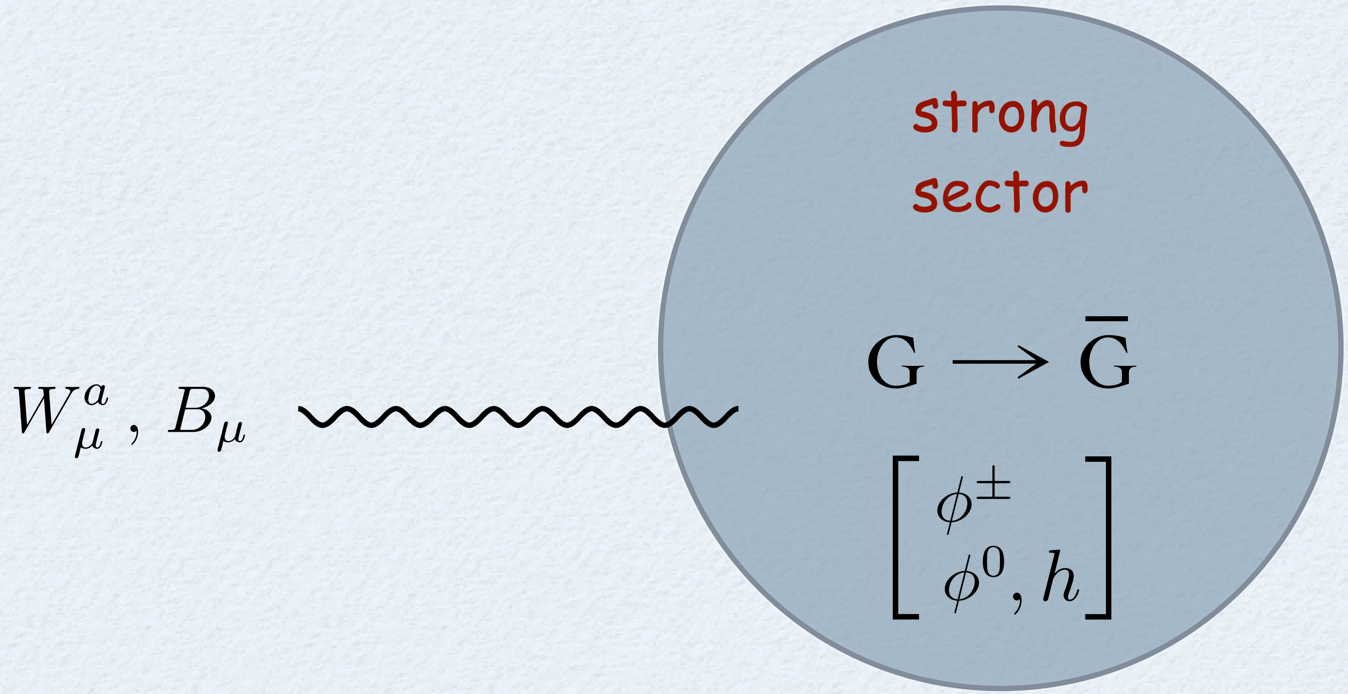

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the explicit breaking of the global symmetry by a weak interaction leads to a light Higgs

$$m_h^2 \sim \frac{\lambda^2}{16\pi^2} m_*^2$$

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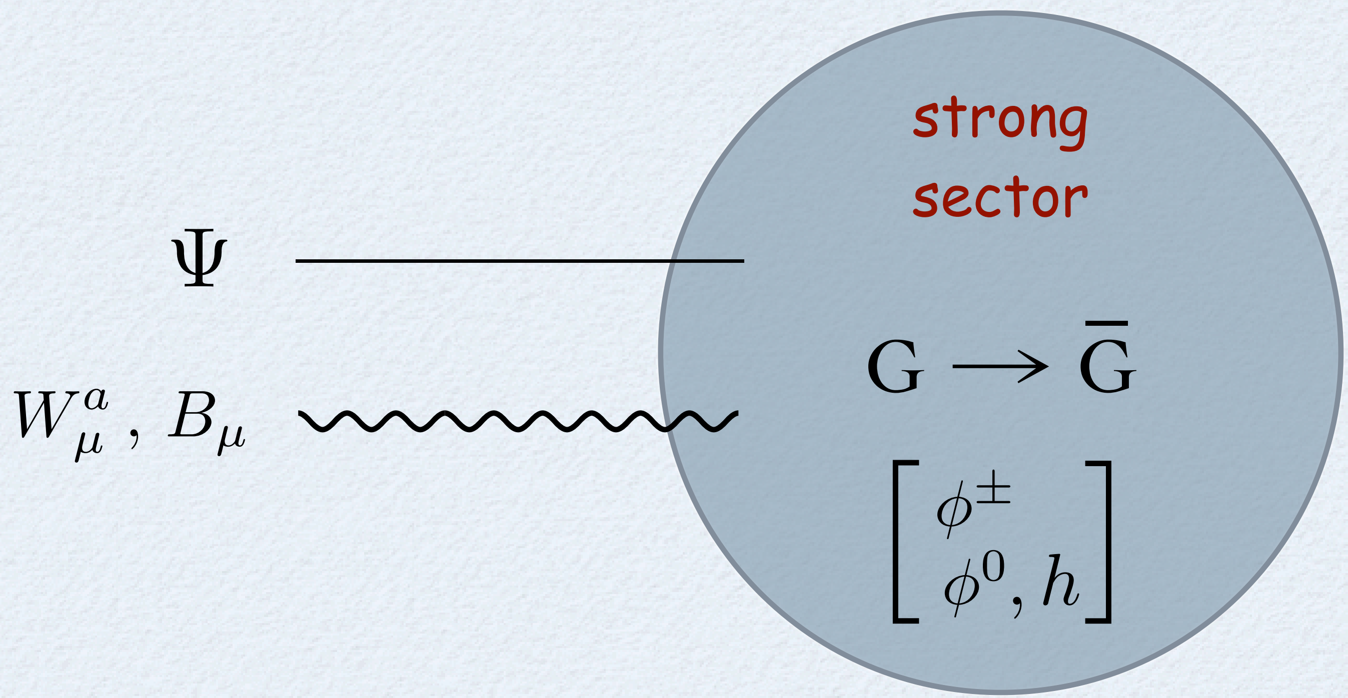

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A new fundamental parameter:

being a Goldstone, the composite Higgs behaves like an "angle" :

$$V(h) = F_\pi^2 m_*^2 \frac{\lambda^2}{16\pi^2}\, g(h/F_\pi)$$

$F_\pi =$ scale at which $G \to \bar{G}$

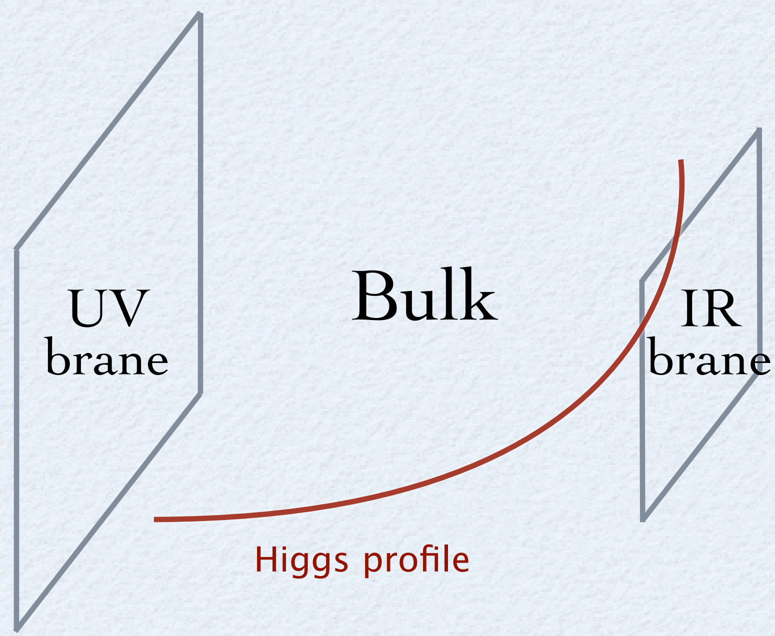
$g(x) =$ periodic function

new parameter:

$$\epsilon = \frac{v}{F_\pi}$$

$$0 \leq \epsilon \leq 1$$

Composite Higgs from an extra warped dimension



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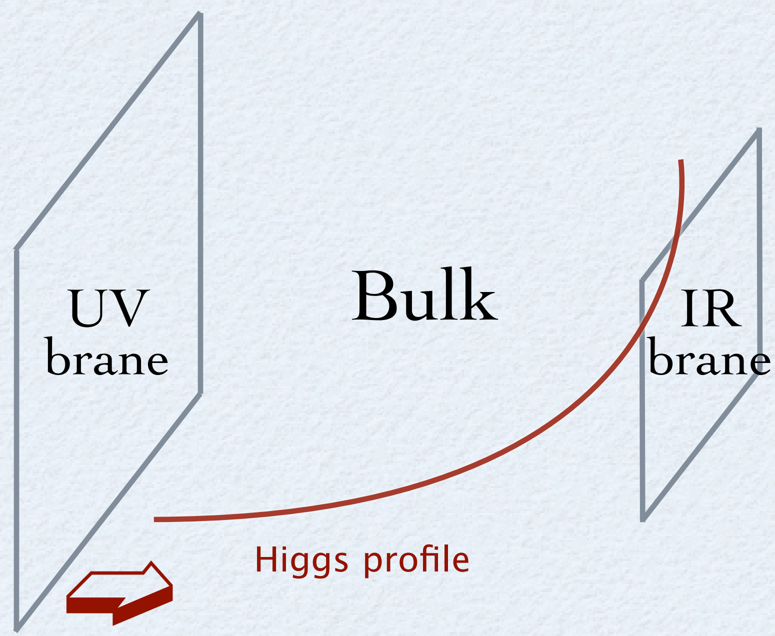

the Higgs structure along the extra dimension

appears like a form factor

for an observer on the UV brane

... ok, suppose we discover the Higgs:
how can we tell it is composite ?

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① Measuring its couplings

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② Probing its strong interaction in the WW scattering

the composite Higgs alone fails to fully unitarize WW scattering at high energy

$$\mathcal{A}(s,t) = \frac{s}{v^2}\epsilon^2 - \frac{s\, m_h^2}{s - m_h^2}(1-\epsilon^2) + \left(s \leftrightarrow t\right)$$

see: Giudice, Grojean, Pomarol, Rattazzi, JHEP 0706:045 (2007)

These signals would give direct evidence for the Higgs compositeness

- theoretically clean

- experimentally challenging

required:

full control of the detector and of background

large integrated luminosity

Indirect evidence can come from the production of the new resonances of the strong sector

- experimentally easier

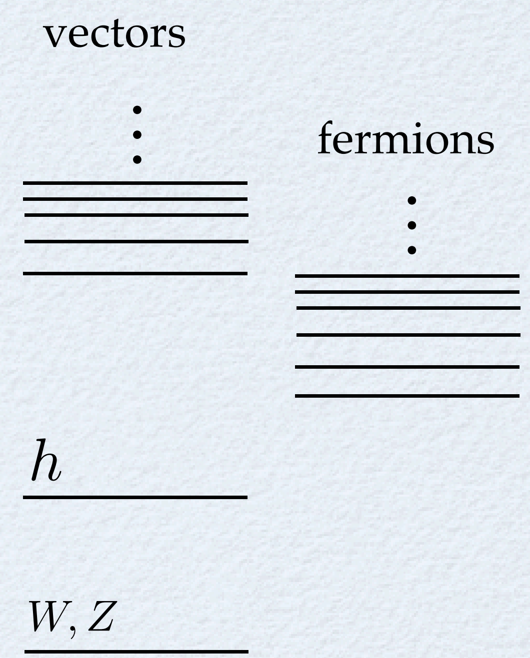
- more model dependent

Partners of the top

(resonances that cut off the loop of the top)

- ✔ Naturalness requires these new states to be light(er)

ex: $m_h = 200\,\mathrm{GeV}$ and NO tuning $\longrightarrow$ $m_* \sim 700\,\mathrm{GeV}$



- ✔ These states are colored fermions (no SUSY)

expected to be strongly coupled to t, b, W_L, Z_L

Need a low-energy effective description

of the lowest-lying resonances

to study their phenomenology

we focus on the class of models with

- no T-parity

- linear couplings between composite and elementary sector

  - ✔ Flavor
  - ✔ Fermion masses

this includes extra-dimensional warped (Randall-Sundrum) theories we focus on the class of models with

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effective description of the lowest-lying resonances given by a

Two-site model

R.C., Kramer, Son, Sundrum JHEP 0705:074 (2007)

RULES

- Elementary sector: {SM - Higgs}

  inter-elementary coupling: $g_{el} \sim 1$

- Composite sector: $\{\rho, \chi + \text{Higgs}\}$

  [$\supset$ excited massive copy of the SM]

  inter-composite coupling: $4\pi \gg g_* \gg 1$

- Mixing: only mass mixings allowed

- Higgs: H couples only to ρ and χ

$$\mathcal{L}_{mix} = \sum_n \Delta_n \, \bar{\Psi} \chi_n + h.c.$$

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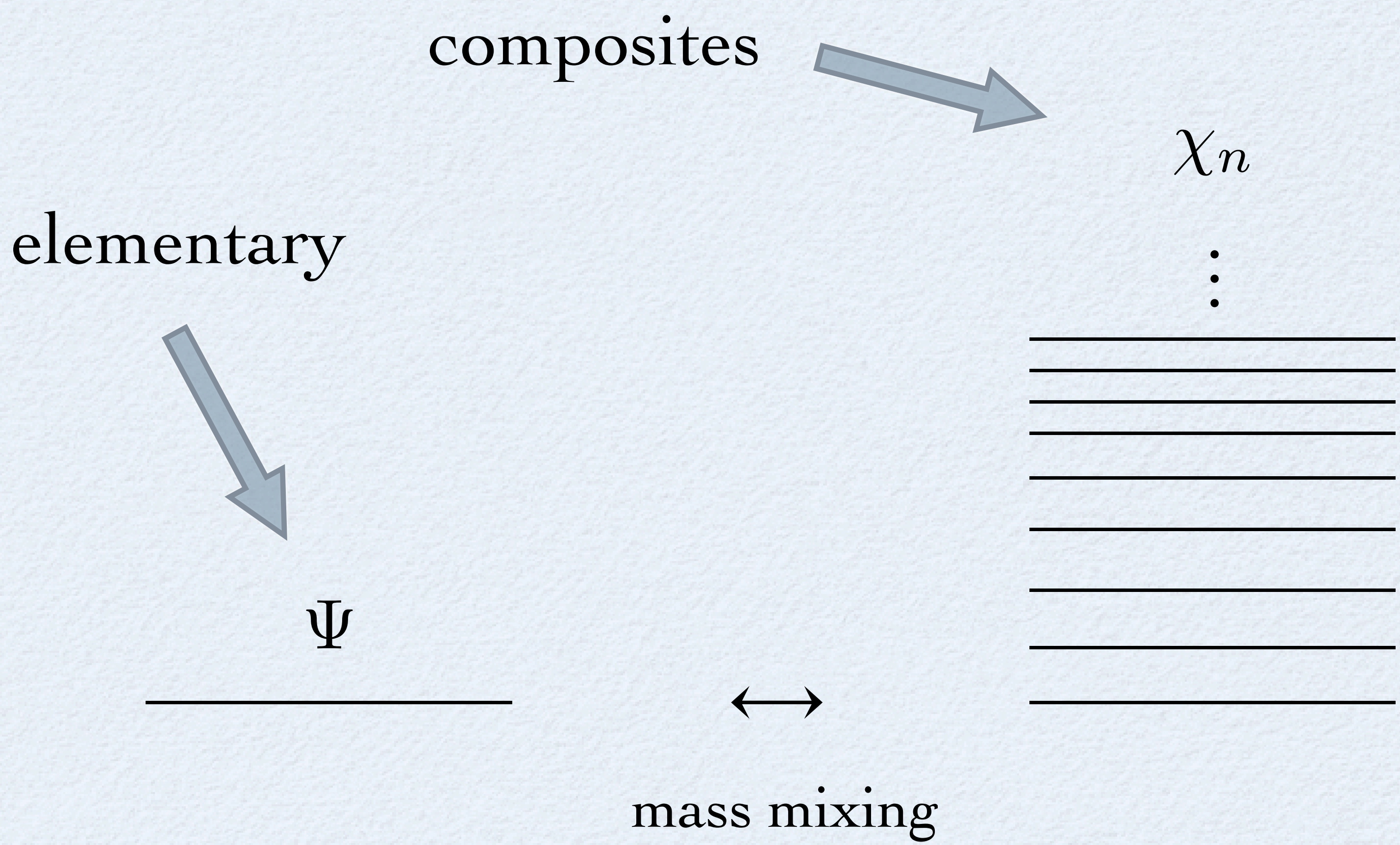

$$\mathcal{L}_{mix} = \sum_n \Delta_n \, \bar{\Psi} \chi_n + h.c.$$

☞ Keep only the first resonance of each tower

Ψ $\longleftrightarrow$ χ

mass mixing

$$\mathcal{L}_{mix} = \Delta\,\bar{\Psi}\chi + h.c.$$

example:

A simple Two-Site SO(5)/SO(4) model

$$\mathrm{SO}(5) \times \mathrm{U}(1)_X \to \mathrm{SO}(4) \times \mathrm{U}(1)_X$$

$$\Sigma_0 = (0, 0, 0, 0, 1)$$

$$\mathrm{SO}(4) \sim \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

$$Y = T_{3R} + X$$

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4 Goldstones

$$\Sigma = \Sigma_0 \, e^{T^{\hat{a}} h^{\hat{a}} / F_\pi}$$

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1 Heavy composite fermion multiplet

$\mathbf{5_{2/3}}$ of $\mathrm{SO}(5) \times \mathrm{U}(1)_X$

$[\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})]$

$$\chi = \begin{bmatrix} \begin{pmatrix} Q' \\ Q \end{pmatrix} \\ \tilde{T} \end{bmatrix}$$

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Q — q_L

$\tilde{T}$ — t_R

composite sector

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$$\chi = \begin{bmatrix} \begin{pmatrix} Q' \\ Q \end{pmatrix} \\ \tilde{T} \end{bmatrix}$$

q_L

t_R

elementary sector

composite sector

$$\chi = \begin{bmatrix} \begin{pmatrix} Q' \\ Q \end{pmatrix} \\ \tilde{T} \end{bmatrix}$$

$$[\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})]$$

$$Q = \begin{bmatrix} T \\ B \end{bmatrix}$$

$$Q' = \begin{bmatrix} T_{5/3} \\ T_{2/3} \end{bmatrix}$$

$$Y[Q] = 1/6$$

$$Y[Q'] = 7/6$$

$$
\begin{aligned}
\mathcal{L} =& \bar{\chi}\left(i\partial\!\!\!/ - m\right)\chi - m_\Sigma\, \bar{\chi}_i \Sigma_i \Sigma_j \chi_j \\
& + \bar{q}_L i\partial\!\!\!/ q_L + \bar{t}_R i\partial\!\!\!/ t_R \\
& + \Delta_q\, \bar{q}_L Q_R + \Delta_{t_R}\, \bar{t}_R \tilde{T}_L + h.c.
\end{aligned}
$$

$$\mathcal{L} = \bar{\chi}\left(i\partial\!\!\!/ - m\right)\chi - m_\Sigma\, \bar{\chi}_i \Sigma_i \Sigma_j \chi_j$$

source of explicit SO(5) breaking →

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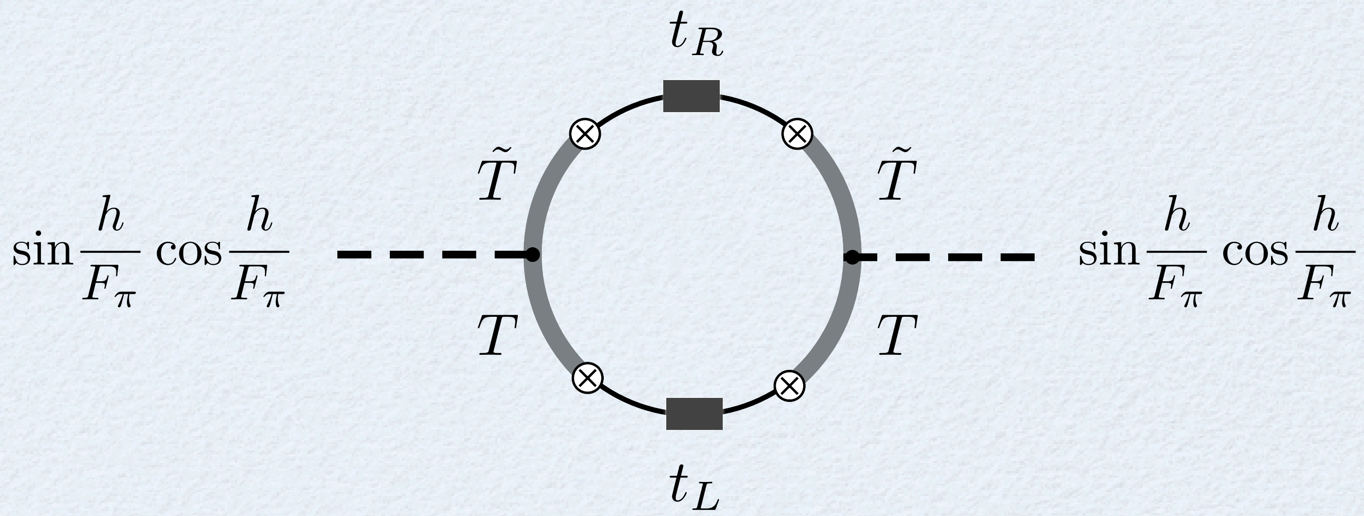
$$\begin{aligned} \mathcal{L} = &+ \bar{Q}\left(i\partial\!\!\!/ - m - m_\Sigma \frac{s^2}{2}\,\hat{H}\hat{H}^\dagger\right) Q + \bar{Q}'\left(i\partial\!\!\!/ - m - m_\Sigma \frac{s^2}{2}\,\hat{H}^c\hat{H}^{c\,\dagger}\right) Q' \\ &+ \bar{\tilde{T}}\left(i\partial\!\!\!/ - \tilde{m} + m_\Sigma\, s^2\right)\tilde{T} - m_\Sigma \frac{s^2}{2}\,\bar{Q}'\hat{H}\hat{H}^{c\,\dagger} Q + h.c. \\ &- m_\Sigma \frac{sc}{\sqrt{2}}\left(\bar{Q}\hat{H}^c\tilde{T} + \bar{Q}'\hat{H}\tilde{T} + h.c.\right) \\ &+ \bar{q}_L i\partial\!\!\!/ q_L + \bar{t}_R i\partial\!\!\!/ t_R + \Delta_q\, \bar{q}_L Q_R + \Delta_{t_R}\, \bar{t}_R \tilde{T}_L + h.c. \end{aligned}$$

$$s \equiv \sin\frac{h}{F_\pi} \quad , \quad c \equiv \cos\frac{h}{F_\pi}$$

$$\hat{H} \equiv \frac{1}{h} H = \frac{1}{h}\begin{bmatrix} h^1 - i h^2 \\ h^3 - i h^4 \end{bmatrix} \qquad h = \sqrt{h^{\hat{a}} h^{\hat{a}}}$$

$$\tilde{m} = m + m_\Sigma$$

Higgs potential



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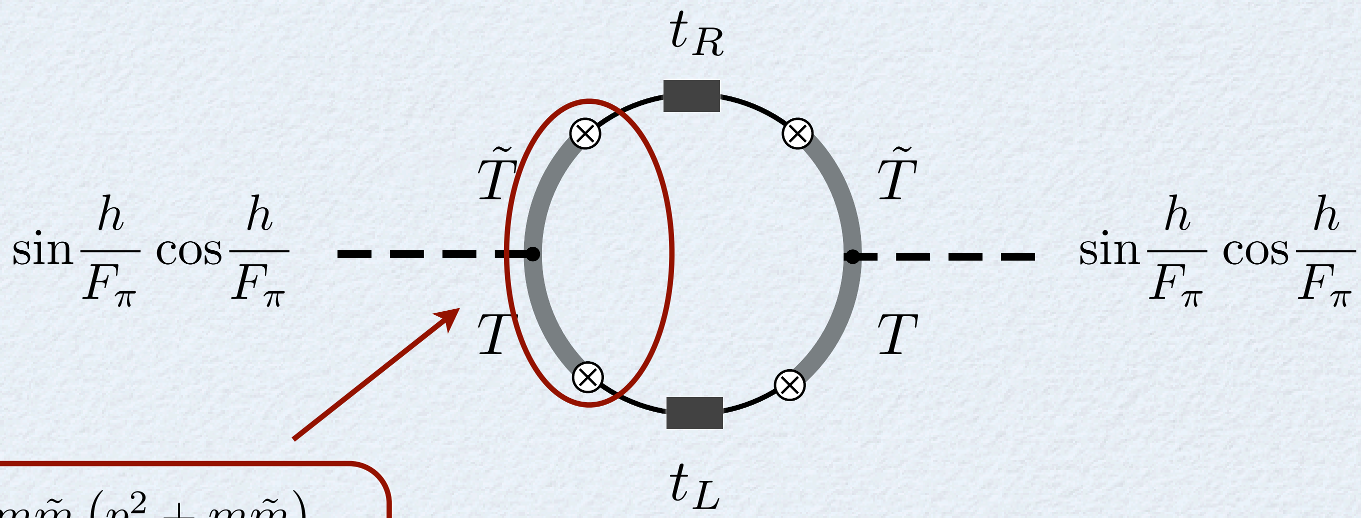
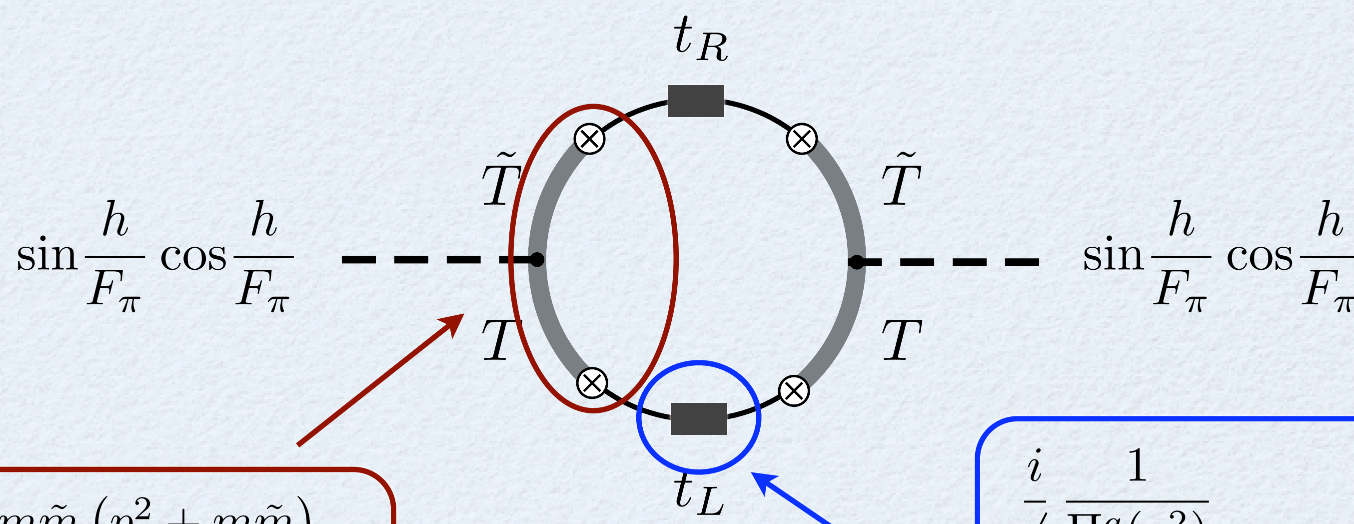


$$F(p^2) = y_t \, \frac{m\tilde{m}\left(p^2 + m\tilde{m}\right)}{(p^2 - m^2)(p^2 - \tilde{m}^2)}$$

Higgs potential



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$$\frac{i}{\not{p}}\;\frac{1}{\Pi^q(p^2)}$$

$$\Pi^q(p^2) = \frac{1 + p^2\,(m^2 + \Delta_q^2)^{-1}}{1 + p^2\,m^{-2}}$$

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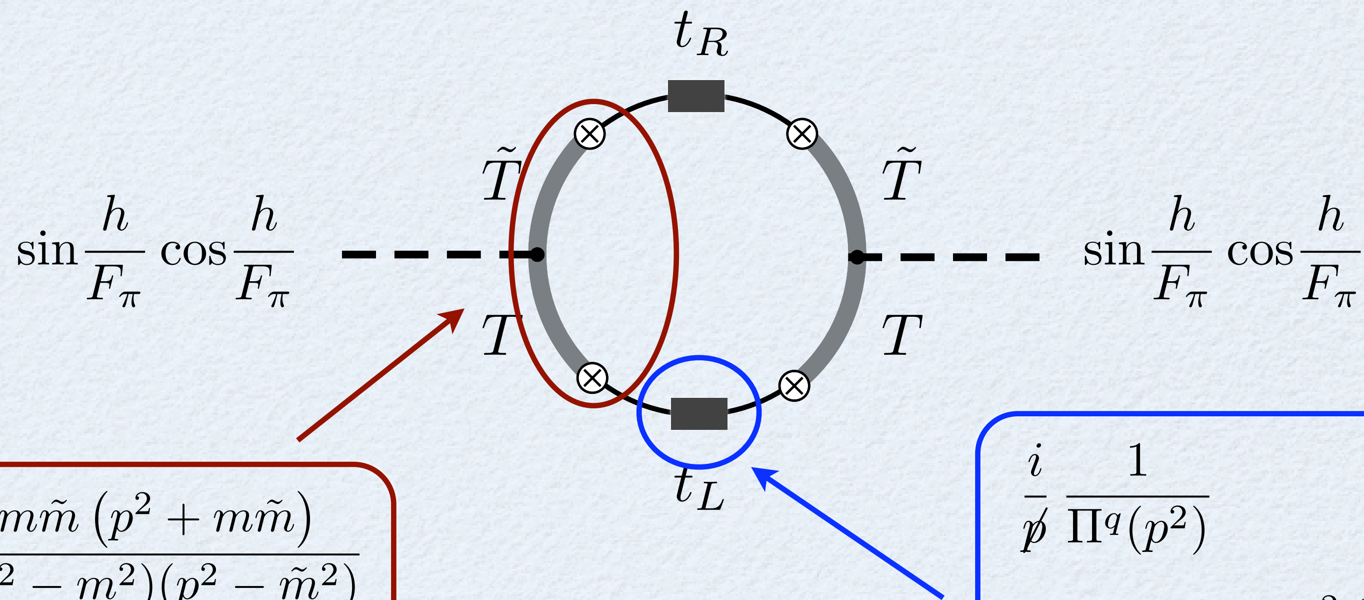

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$$\Delta V(h) = -\frac{2N_c}{8\pi^2}F_\pi^2\int_0^\infty dp\;p\,\frac{F^2(-p^2)}{\Pi^q(-p^2)\Pi^{t_R}(-p^2)}\;\sin^2\frac{h}{F_\pi}\cos^2\frac{h}{F_\pi}$$

$$\simeq -\frac{2N_c}{8\pi^2}y_t^2\frac{m^2}{6}F_\pi^2\;\sin^2\frac{h}{F_\pi}\cos^2\frac{h}{F_\pi}$$

Diagonalization:

elementary / composite → light / heavy

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \to \begin{pmatrix} \cos\varphi_L & -\sin\varphi_L \\ \sin\varphi_L & \cos\varphi_L \end{pmatrix} \begin{pmatrix} q_L \\ Q_L \end{pmatrix} \qquad \tan\varphi_L = \frac{\Delta_{q_L}}{m}$$

$$\begin{pmatrix} t_R \\ \tilde{T}_R \end{pmatrix} \to \begin{pmatrix} \cos\varphi_{t_R} & -\sin\varphi_{t_R} \\ \sin\varphi_{t_R} & \cos\varphi_{t_R} \end{pmatrix} \begin{pmatrix} t_R \\ \tilde{T}_R \end{pmatrix} \qquad \tan\varphi_{t_R} = \frac{\Delta_{t_R}}{\tilde{m}}$$

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$$|\mathrm{SM}\rangle = \cos\varphi\,|\Psi\rangle + \sin\varphi\,|\chi\rangle$$

$$|\mathrm{heavy}\rangle = -\sin\varphi\,|\Psi\rangle + \cos\varphi\,|\chi\rangle$$

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☞ φ parametrizes the degree of partial compositeness

$$\begin{aligned}\mathcal{L} =& \bar{q}_L i\not{\partial} q_L + \bar{t}_R i\not{\partial} t_R \\ & + \bar{Q}\left(i\not{\partial} - m_Q\right) Q + \bar{Q}'\left(i\not{\partial} - m\right) Q' + \bar{\tilde{T}}\left(i\not{\partial} - m_{\tilde{T}}\right)\tilde{T} \\ & - Y_*\Big[\left(\sin\varphi_L\,\bar{q}_L + \cos\varphi_L\,\bar{Q}\right) H^c\left(\sin\varphi_{t_R}\,t_R + \cos\varphi_{t_R}\,\tilde{T}\right) \\ & \qquad + \bar{Q}' H\left(\sin\varphi_{t_R}\,t_R + \cos\varphi_{t_R}\,\tilde{T}\right) + h.c.\Big] + \dots\end{aligned}$$

$$m_{\tilde{T}} = \sqrt{\tilde{m}^2 + \Delta_{t_R}^2}$$

$$m_Q = \sqrt{m^2 + \Delta_{q_L}^2}$$

$$\tilde{m} = m + m_\Sigma$$

$$Y_* = \frac{m_\Sigma}{F_\pi\sqrt{2}}$$

$$
\begin{aligned}
\mathcal{L} =&\bar{q}_L i\partial\!\!\!/ q_L + \bar{t}_R i\partial\!\!\!/ t_R \\
&+ \bar{Q}\left(i\partial\!\!\!/ - m_Q\right)Q + \bar{Q}'\left(i\partial\!\!\!/ - m\right)Q' + \bar{\tilde{T}}\left(i\partial\!\!\!/ - m_{\tilde{T}}\right)\tilde{T} \\
&- Y_*\Big[\left(\sin\varphi_L\,\bar{q}_L + \cos\varphi_L\,\bar{Q}\right)H^c\left(\sin\varphi_{t_R}\,t_R + \cos\varphi_{t_R}\,\tilde{T}\right) \\
&\qquad + \bar{Q}'H\left(\sin\varphi_{t_R}\,t_R + \cos\varphi_{t_R}\,\tilde{T}\right) + h.c.\Big] + \ldots
\end{aligned}
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$$
m_{\tilde{T}} = \sqrt{\tilde{m}^2 + \Delta_{t_R}^2} \qquad \tilde{m} = m + m_\Sigma
$$

$$
m_Q = \sqrt{m^2 + \Delta_{q_L}^2} \qquad Y_* = \frac{m_\Sigma}{F_\pi\sqrt{2}}
$$

induced Yukawa coupling → $y_t = Y_* \sin\varphi_L \sin\varphi_{t_R}$

Heavy partners of the top

	charge
$T_{5/3}$	$+5/3$
$T_{2/3}$	$+2/3$
T	$+2/3$
B	$-1/3$
$\tilde{T}$	$+2/3$

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T	$+2/3$	} ⟵ partners of q_L
B	$-1/3$	}
$\tilde{T}$	$+2/3$	⟵ partner of t_R

Heavy partners of the top

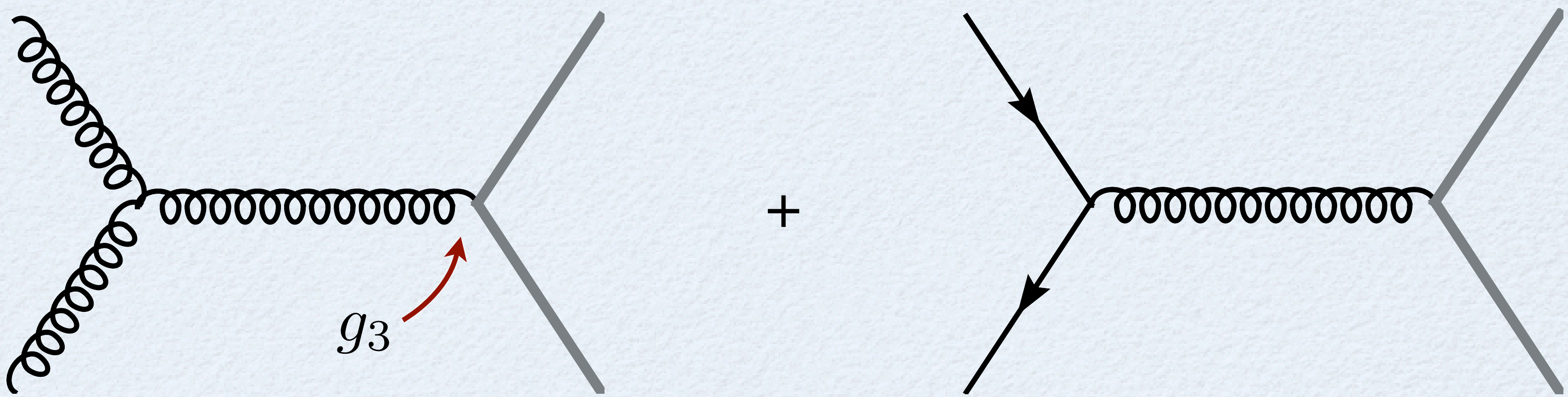
	charge	
$T_{5/3}$	$+5/3$	$\leftarrow$ $SU(2)_R$ partners of q_L (with $T_{2/3}$)
$T_{2/3}$	$+2/3$	
T	$+2/3$	$\leftarrow$ partners of q_L (with B)
B	$-1/3$	
$\tilde{T}$	$+2/3$	$\leftarrow$ partner of t_R

Heavy partners of the top

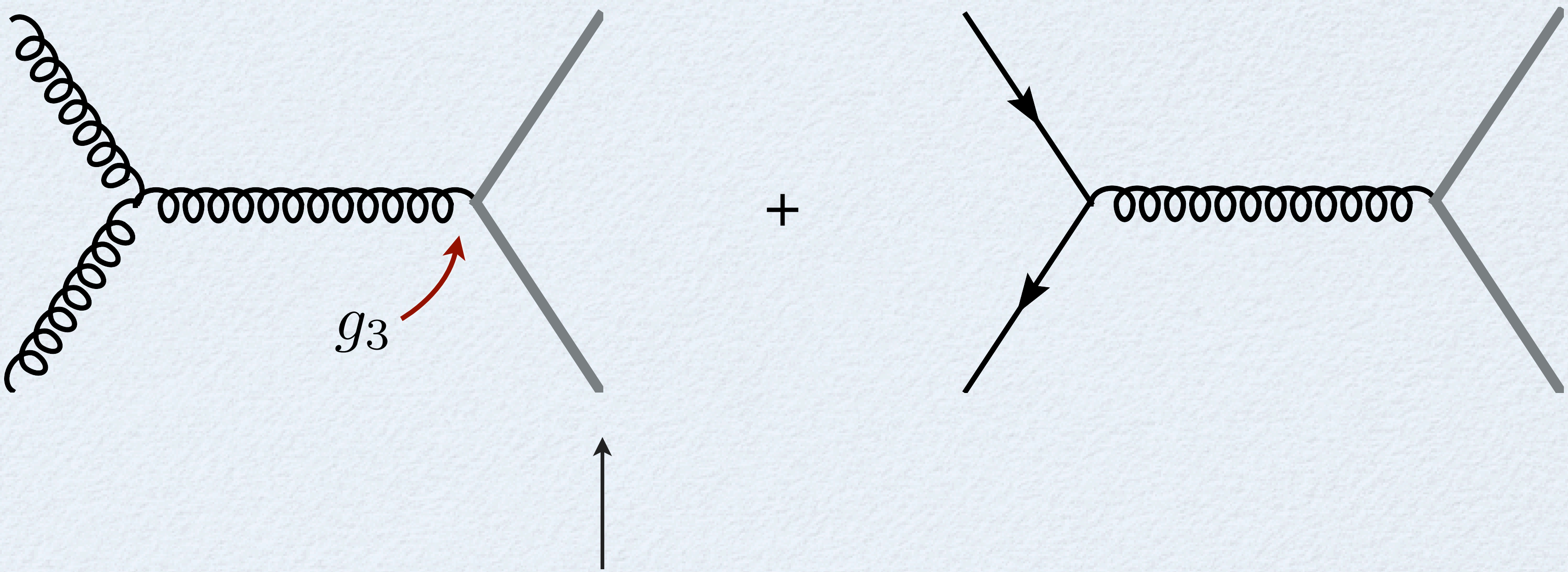
	charge	
$T_{5/3}$	$+5/3$	$\mathrm{SU}(2)_R$ partners of q_L
$T_{2/3}$	$+2/3$	
T	$+2/3$	partners of q_L
B	$-1/3$	
$\tilde{T}$	$+2/3$	partner of t_R

most studies focused on

PAIR PRODUCTION

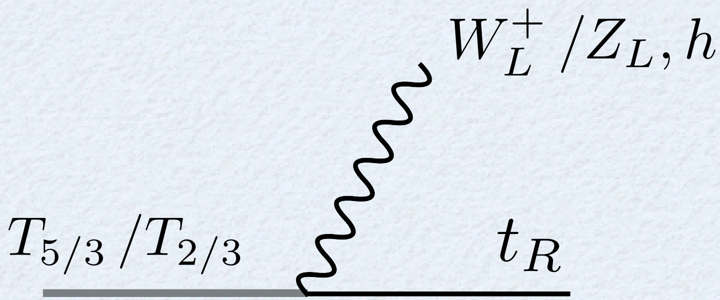


PAIR PRODUCTION

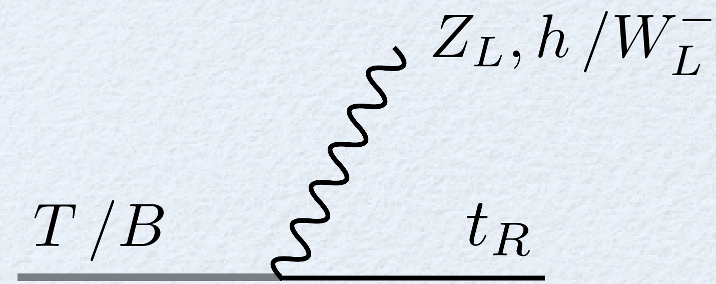


any of T, B, $T_{5/3}$, $T_{2/3}$, $\tilde{T}$

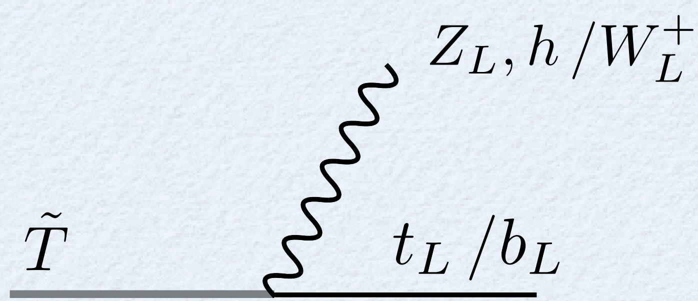
DECAYS



$$\lambda_{Q'} = Y_* \sin\varphi_{t_R}$$



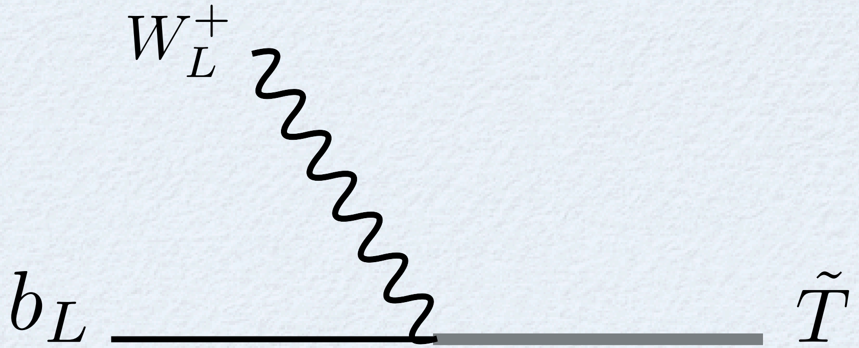
$$\lambda_Q = Y_* \sin\varphi_{t_R} \cos\varphi_L$$



$$\lambda_{\tilde{T}} = Y_* \sin\varphi_L \cos\varphi_{t_R}$$

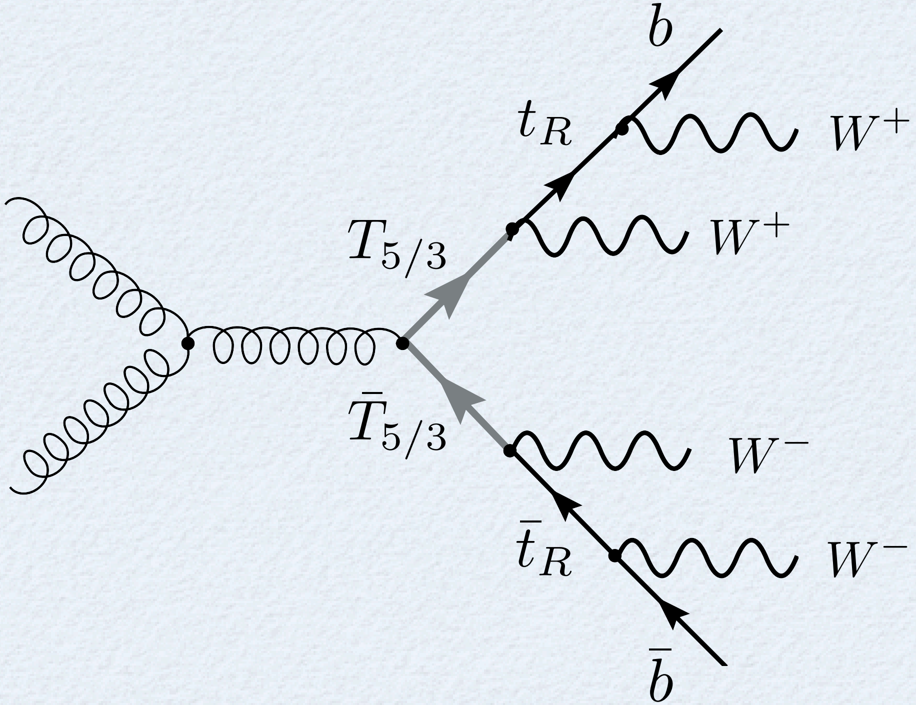
single production

ex:



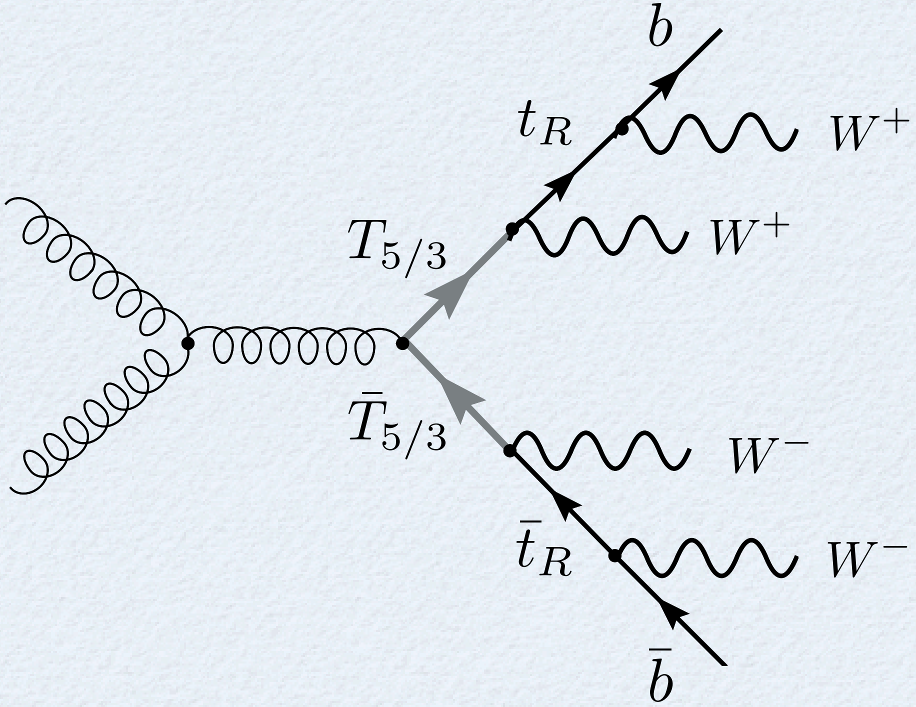
Discovering the exotic $T_{5/3}$

work in progress
with G. Servant



Discovering the exotic $T_{5/3}$

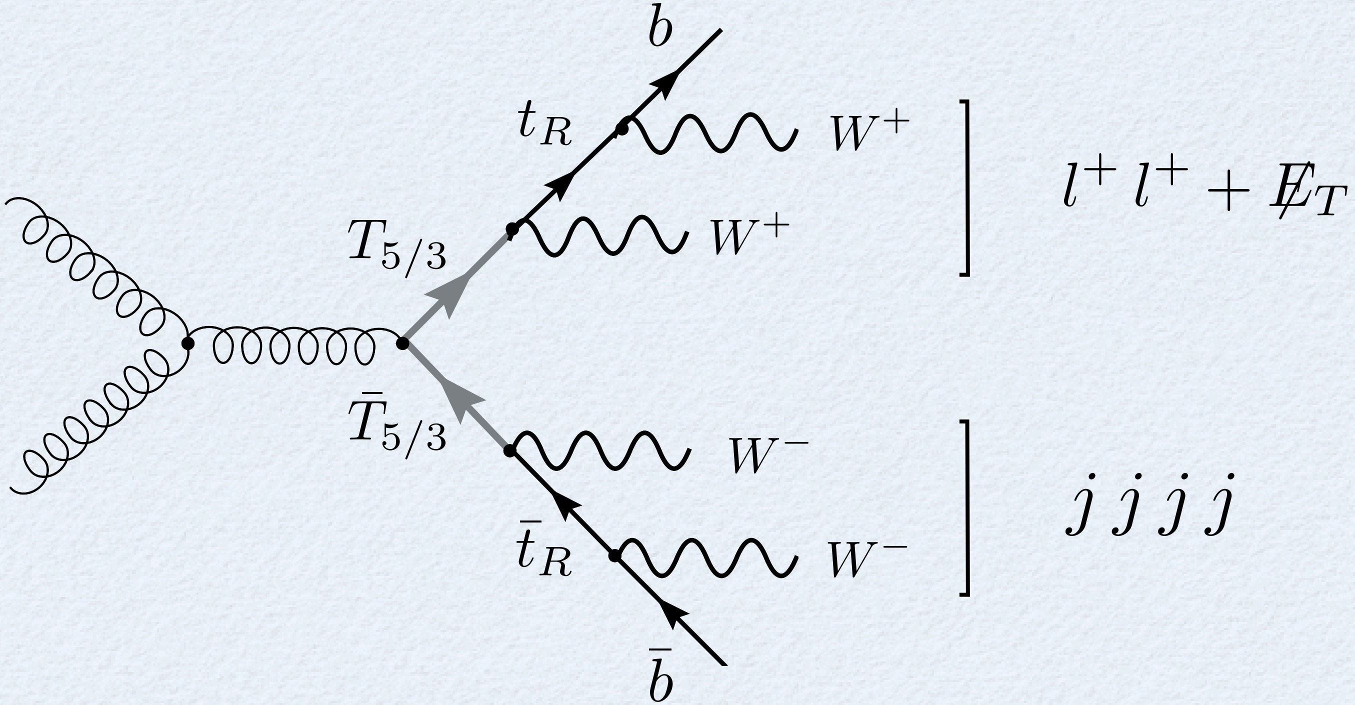
work in progress
with G. Servant



$$l^+ l^+ + \not{E}_T$$

Discovering the exotic $T_{5/3}$

work in progress
with G. Servant



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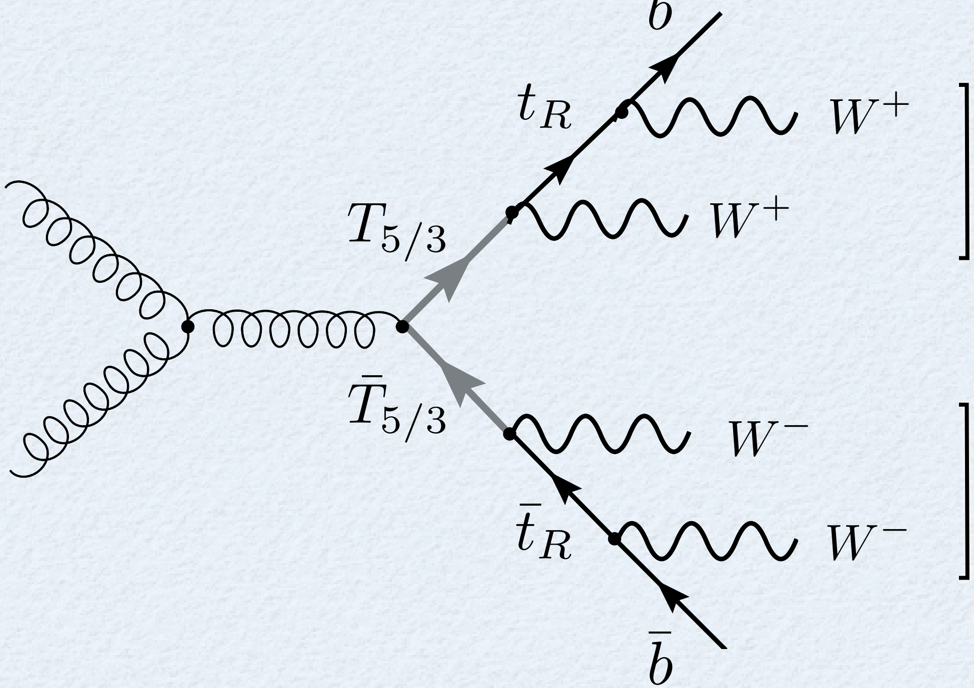
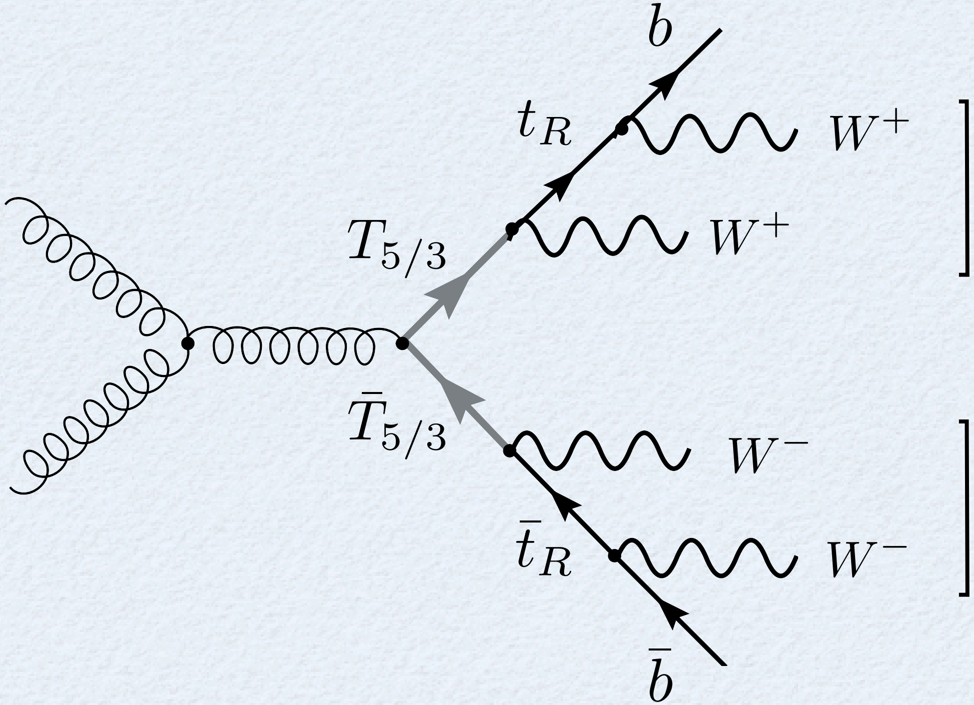


$l^+ l^+ + \not{E}_T$ ← same-sign leptons

$j\,j\,j\,j$

Discovering the exotic $T_{5/3}$

work in progress
with G. Servant



$l^+ l^+ + \not{E}_T$ ← same-sign leptons

$j\,j\,j\,j$ ← invariant mass

Conclusions

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- Direct evidence from shifts in the couplings of the Higgs and WW scattering $\longrightarrow$ challenging

- Indirect evidence might come much earlier by producing the partners of the top