HOW '*WEAK*' IS ELECTROWEAK ?

— PROBING STRONG EWSB AT THE LHC —

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RC, C. Grojean, M. Moretti, F. Piccinini, R. Rattazzi JHEP 05(2010) 089

RC, D. Marzocca, D. Pappadopulo, R. Rattazzi, to appear

Motivation:

After a light scalar is discovered, how can we test the role it plays in the EWSB ?

EVIDENCE FOR A LIGHT HIGGS-LIKE SCALAR

- EWSB sector described by the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ Chiral Lagrangian:

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{mass}$$

$\mathcal{L}_{mass}$: mass spectrum is $U(1)_{em}$ invariant

$\mathcal{L}_{kin}$: interactions are $SU(2)_L \times U(1)_Y$ invariant

$$\mathcal{L}_{mass} \rightarrow \mathcal{L}_{EWSB} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) + a_T \frac{v^2}{8} \left[\mathrm{Tr}\left(\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right)\right]^2 \quad \leftarrow O(p^2)$$

$$+\, a_S\, \mathrm{Tr}\left(W_{\mu\nu}\, \Sigma\, B^{\mu\nu}\, \Sigma^\dagger\right) + \dots \quad \leftarrow O(p^4)$$

$$- \frac{v}{\sqrt{2}} \sum_{i,j} \left(\overline{u_L^{(i)}}, \overline{d_L^{(i)}}\right) \Sigma \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.$$

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

$$\Sigma \rightarrow U_L\, \Sigma\, U_Y^\dagger$$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W^a_\mu \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

$$U_Y(x) = \exp(i\, \alpha_Y(x) \sigma^3 / 2)$$

$$U_L(x) = \exp(i\, \alpha^a_L(x) \sigma^a / 2)$$

- EWSB sector described by the $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ Chiral Lagrangian:

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{mass}$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{1}{1+a_T}$$

$$\mathcal{L}_{mass} \rightarrow \mathcal{L}_{EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) + a_T \frac{v^2}{8}\left[\mathrm{Tr}\left(\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right)\right]^2$$

$$+ a_S\, \mathrm{Tr}\left(W_{\mu\nu}\, \Sigma\, B^{\mu\nu}\, \Sigma^\dagger\right) + \ldots$$

$$- \frac{v}{\sqrt{2}} \sum_{i,j} \left(\overline{u_L^{(i)}}, \overline{d_L^{(i)}}\right) \Sigma \begin{pmatrix} \lambda_{ij}^u\, u_R^{(j)} \\ \lambda_{ij}^d\, d_R^{(j)} \end{pmatrix} + h.c.$$

- Experimentally: $(\rho - 1) \lesssim 2 \times 10^{-3}$

$a_T(m_Z)$ must be very small

- EWSB sector described by the SU(2)$_L$×U(1)$_Y$→U(1)$_{em}$ Chiral Lagrangian:

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$$\mathcal{L}_{mass} \to \mathcal{L}_{EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right) + a_T\frac{v^2}{8}\left[\mathrm{Tr}\left(\Sigma^\dagger D_\mu\Sigma\,\sigma^3\right)\right]^2$$

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- For $a_T = 0$, in the limit $g_1 = 0$, $\lambda^u = \lambda^d$, there is a larger SU(2)$_L$ x SU(2)$_R$→SU(2)$_V$ global symmetry:

$$\Sigma \to U_L \Sigma U_R^\dagger$$

The NG bosons χ^a transform as a triplet under the custodial SU(2)$_V$:

$$M_W = M_Z \qquad \text{for } g_1 = 0$$

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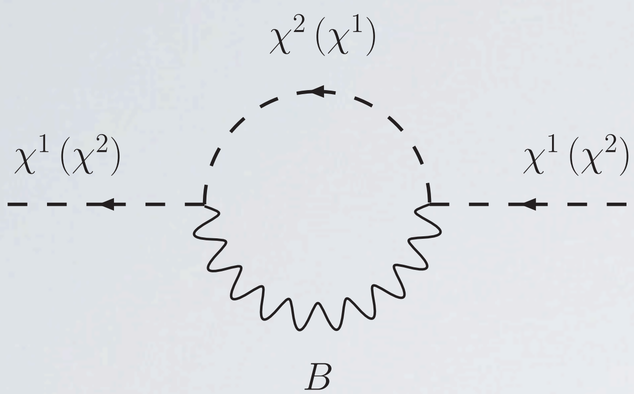
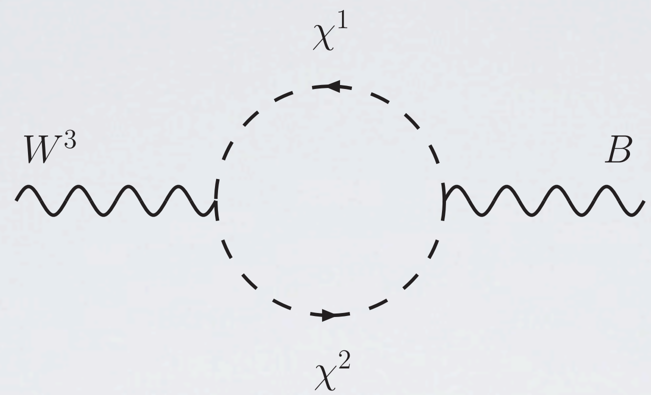
Data suggest the global coset: SU(2) × SU(2)→SU(2) ↔ SO(4)→SO(3)

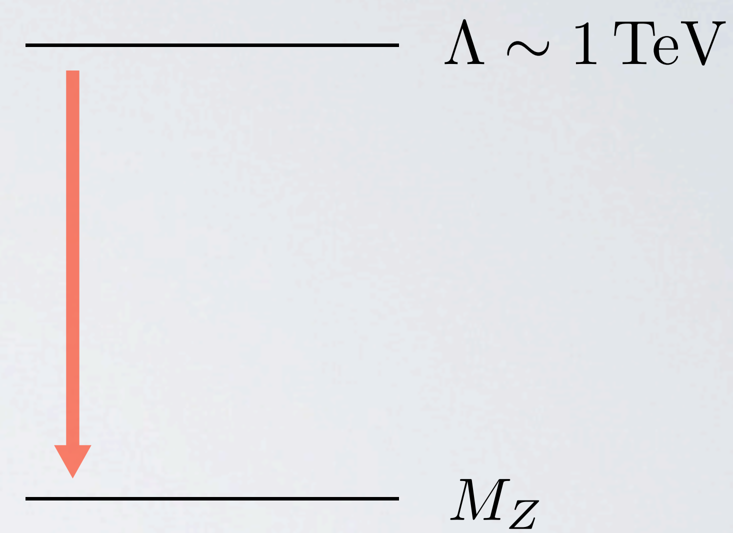
- For $a_{S,T}(\Lambda) = 0$ the fit to LEP data is not good

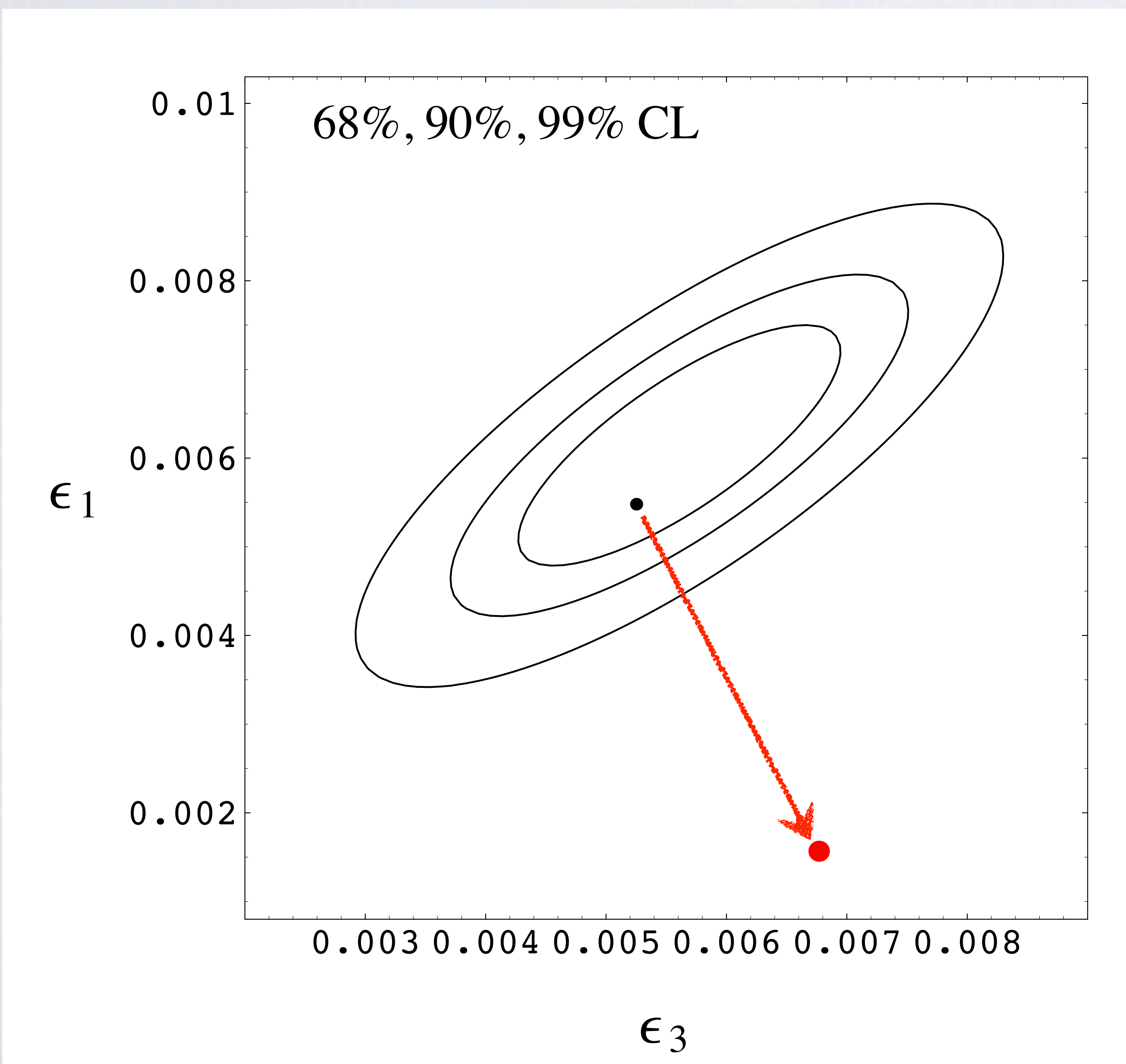
$$\Delta\epsilon_3 = \frac{g_2}{g_1} a_S(M_Z)$$

$$\Delta\epsilon_1 = a_T(M_Z)$$









$$\Delta\epsilon_{1,3} = c_{1,3} \log \frac{\Lambda^2}{M_Z^2}$$

$$c_1 = -\frac{3}{16\pi^2} \frac{\alpha(M_Z)}{\cos^2\theta_W}$$

$$c_3 = +\frac{1}{12\pi} \frac{\alpha(M_Z)}{4\sin^2\theta}$$

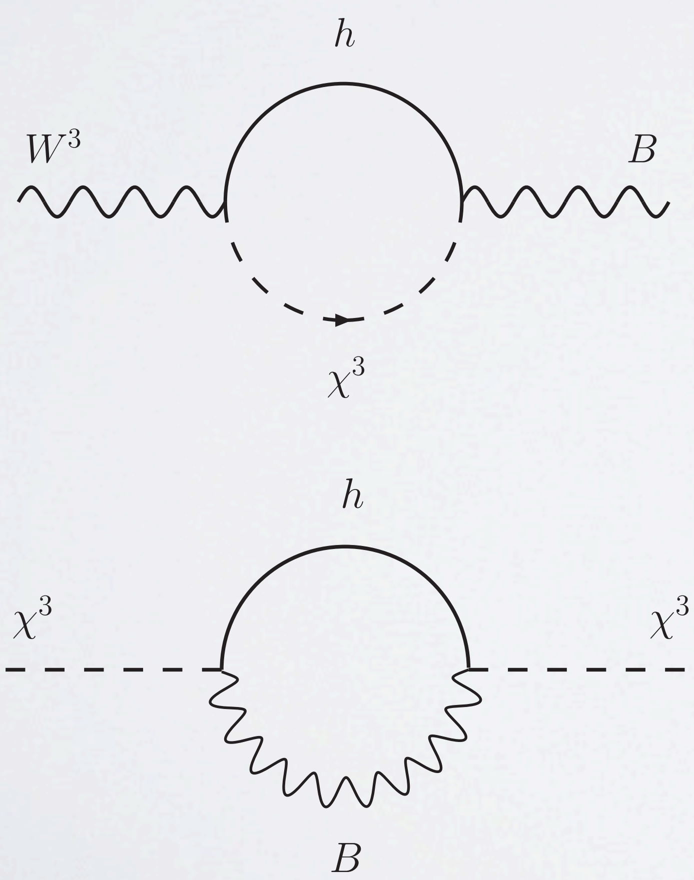
- Adding an extra scalar, singlet of the custodial $SU(2)_V$

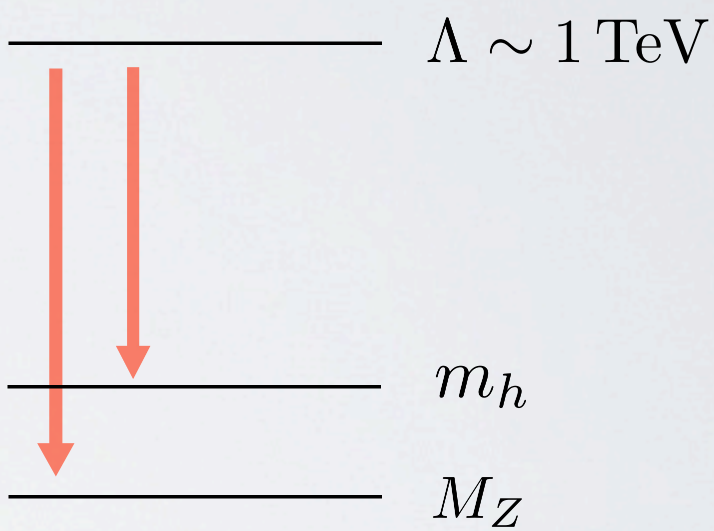
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) + V(h)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ d_L^{(i)}\right)\Sigma\left(1 + c\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

a, b, c are free parameters

[for a SM Higgs: a=b=c=1]





$$\Delta\epsilon_{1,3} = -c_{1,3}\ a^2\ \log\frac{\Lambda^2}{m_h^2}$$

see: Barbieri et al. PRD 76 (2007) 115008

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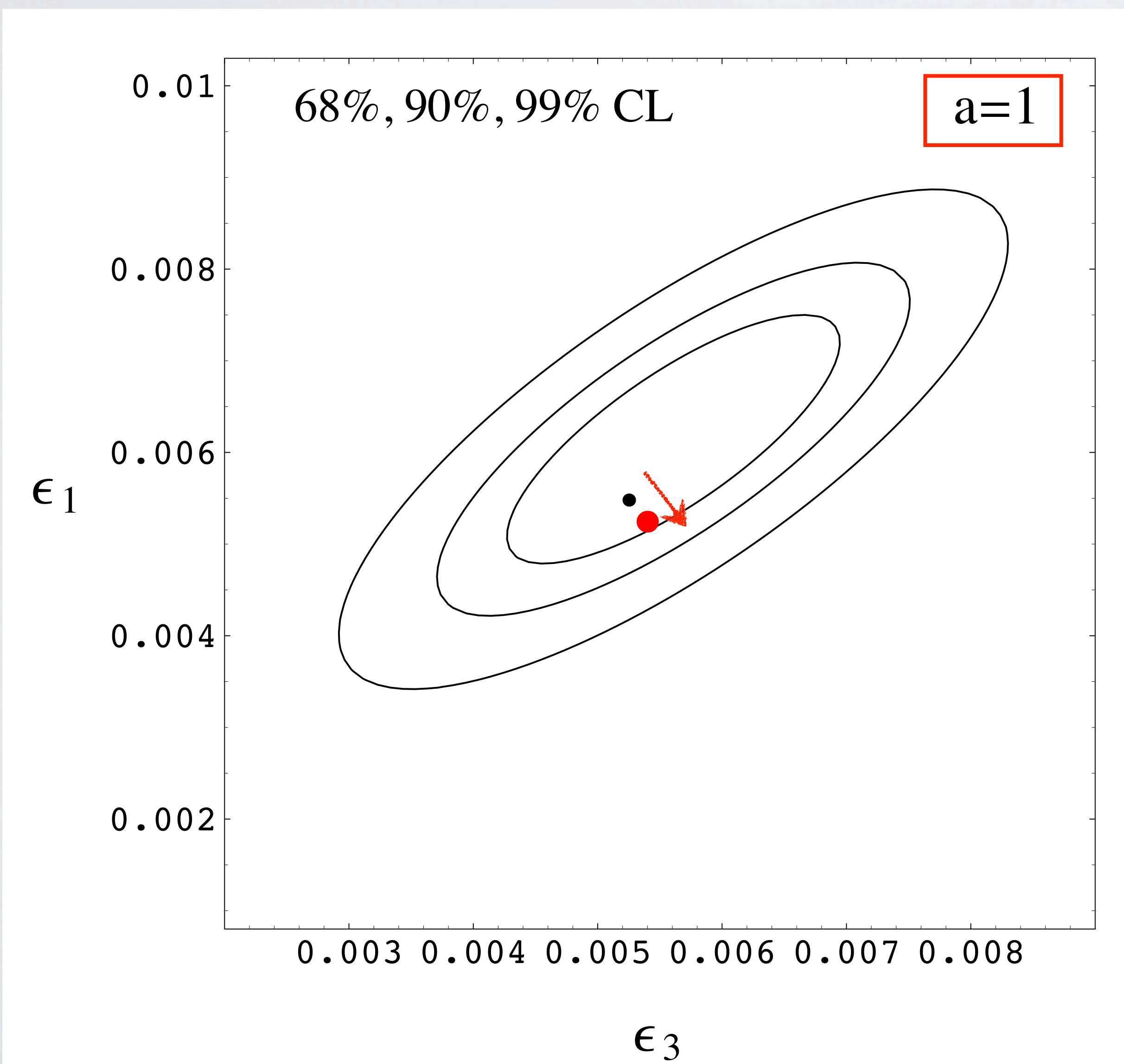

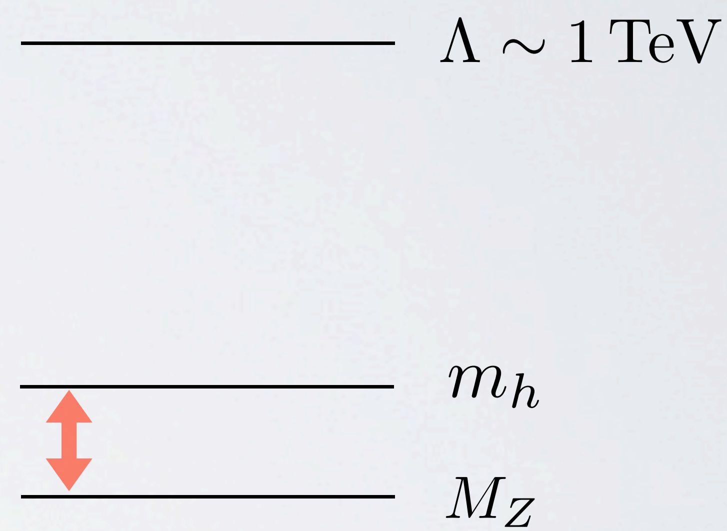

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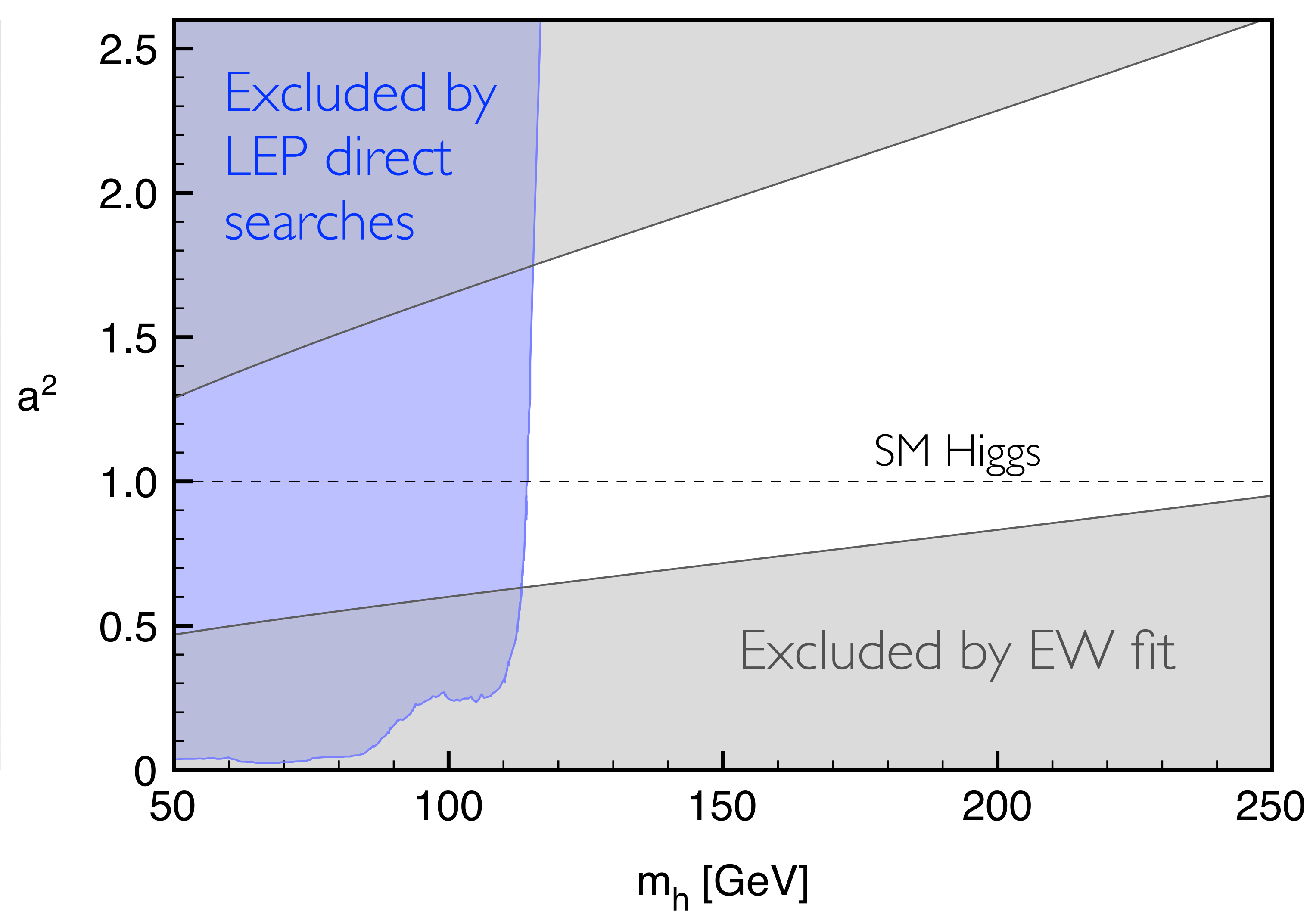
HOW `STANDARD` THE HIGGS MUST BE ?



- Large deviations from a=1 still allowed for a light Higgs
- Presently <u>no</u> constraint on b,c

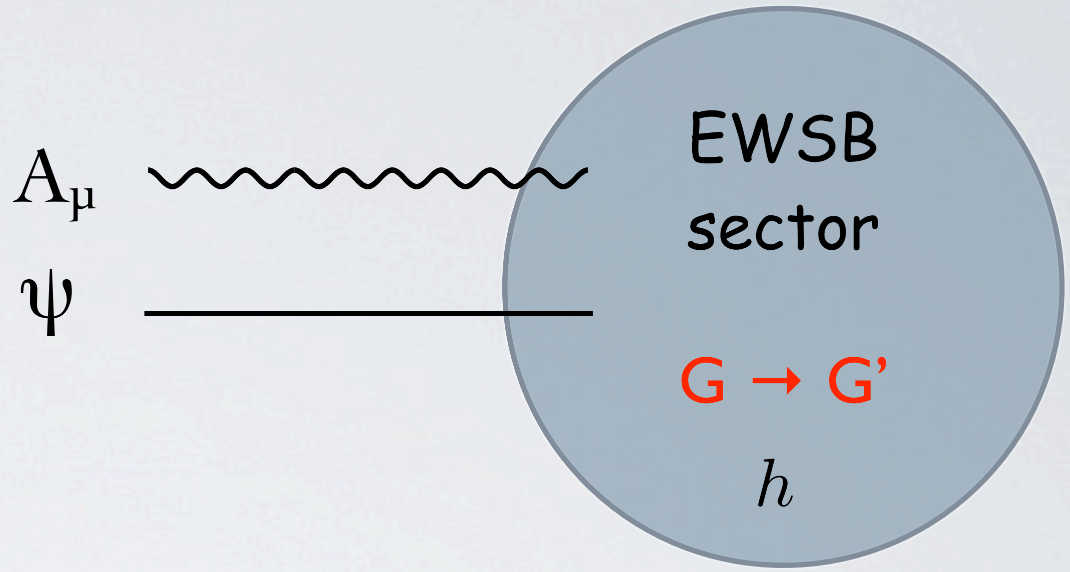
THE HIGGS AS A COMPOSITE NAMBU-GOLDSTONE BOSON

THE HIGGS AS A COMPOSITE PSEUDO-NG BOSON

[Georgi & Kaplan, `80]

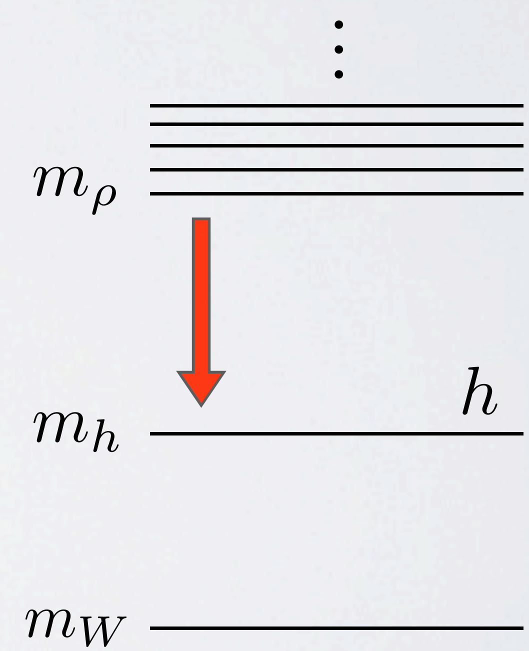
Motivations:

- light Higgs naturally



Higgs = NG boson of G→G' at the scale f

At tree level: $m_h = 0$ $m_\rho \approx 4\pi f$



THE HIGGS AS A COMPOSITE PSEUDO-NG BOSON

[Georgi & Kaplan, `80]

Motivations:

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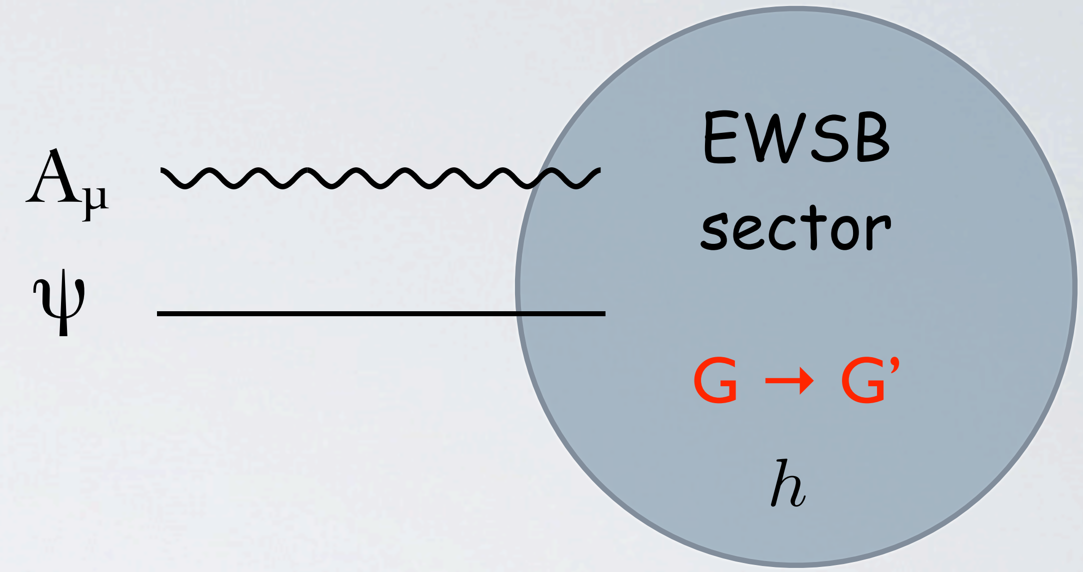
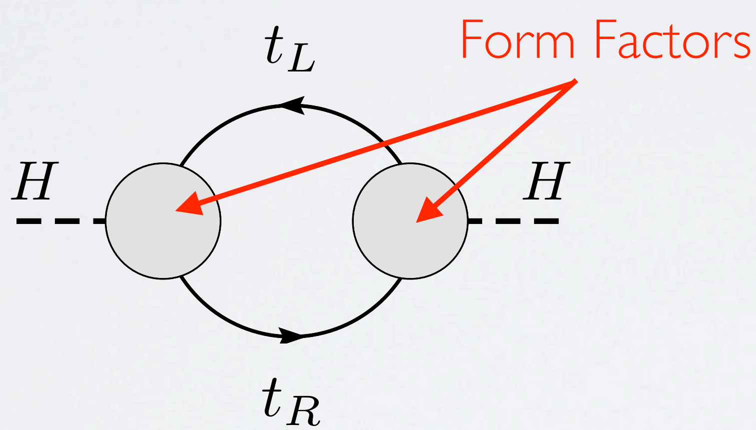
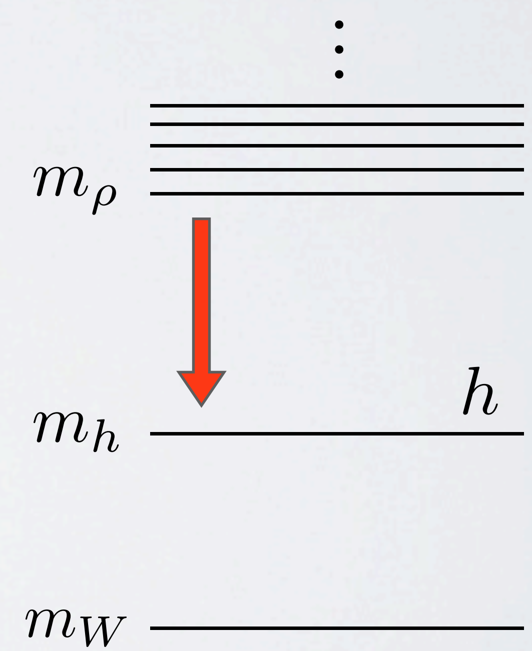


Higgs = NG boson of G→G' at the scale f

At 1-loop level:





periodic function

$$V(h) \approx \frac{3\, y_t^2}{16\pi^2}\, m_\rho^2\, f^2\, \zeta(h/f)$$

$$m_h \approx m_t \times \left(\frac{m_\rho}{4\pi f}\right)$$

THE HIGGS AS A COMPOSITE PSEUDO-NG BOSON

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Motivations:

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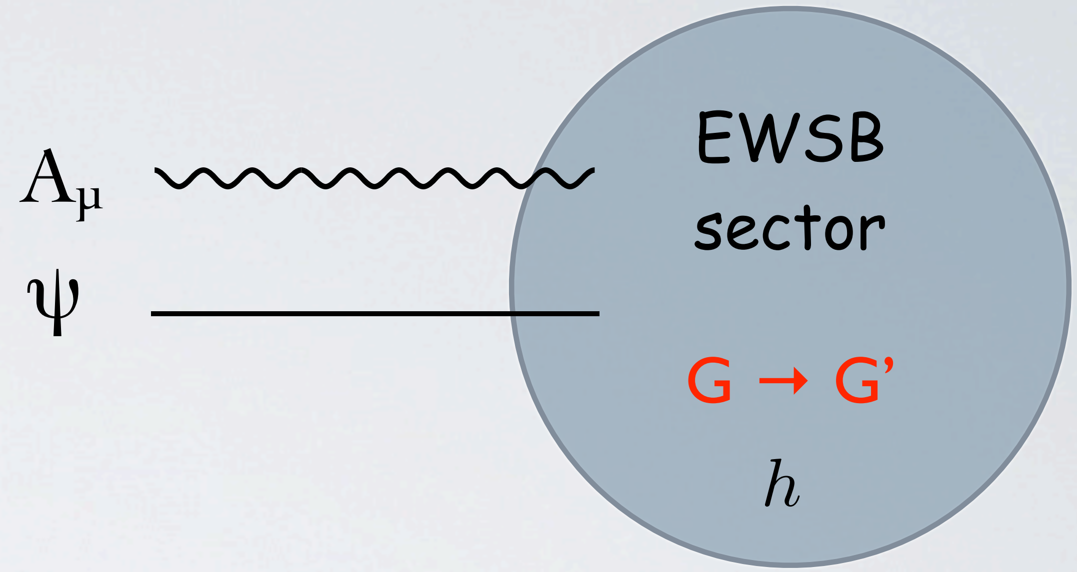


Higgs = NG boson of G→G' at the scale f

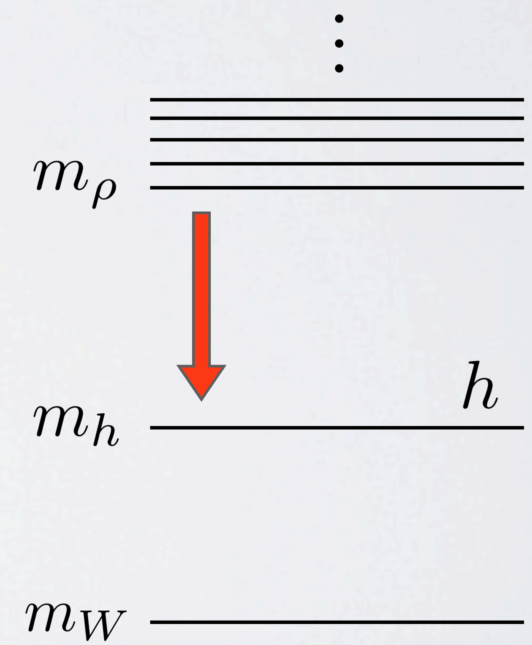
$$\xi = \left(\frac{v}{f}\right)^2$$

new parameter compared to TC
(fixed by dynamics)

$$\xi \to 0$$
$$[\, f \to \infty \,]$$

decoupling limit

All ρ's become heavy and
one reobtains the SM

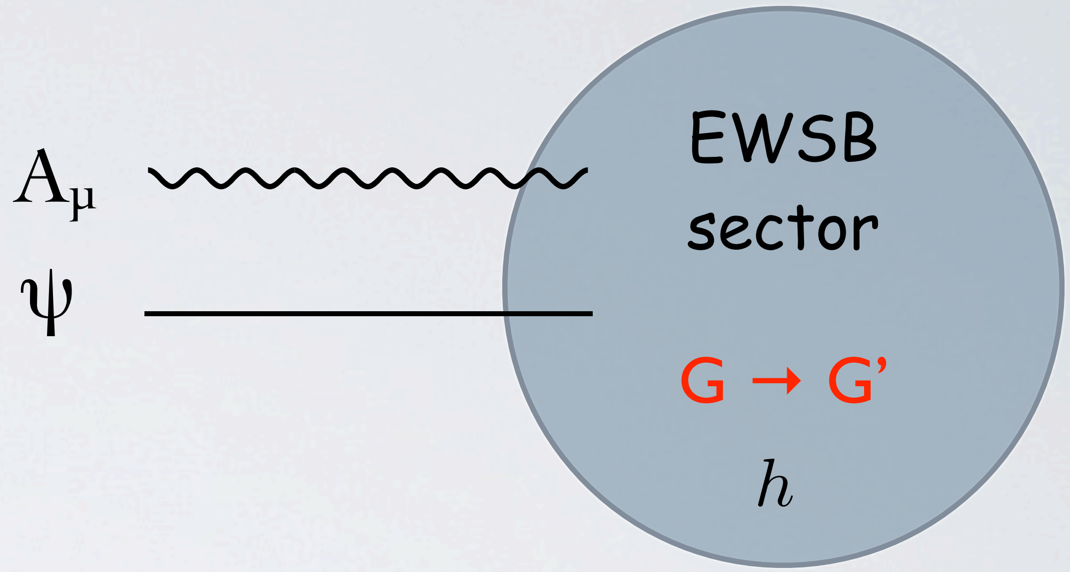


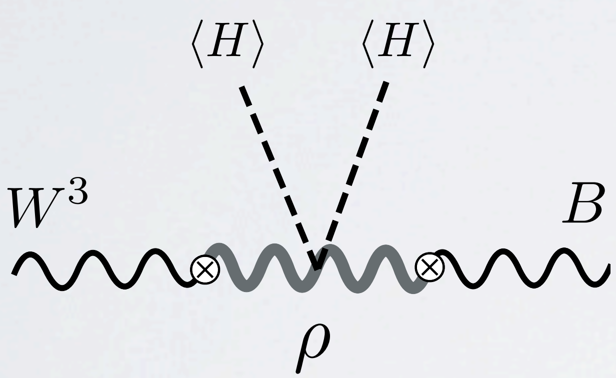
THE HIGGS AS A COMPOSITE PSEUDO-NG BOSON

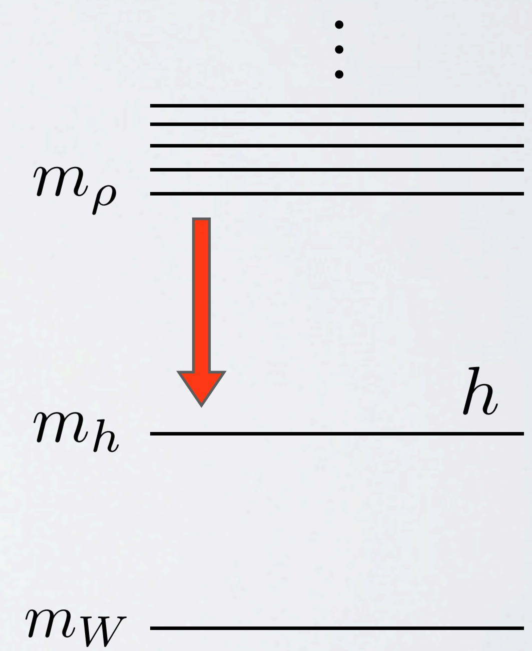
[Georgi & Kaplan, `80]

Motivations:

- contribution to EWPO from heavier resonances parametrically suppressed





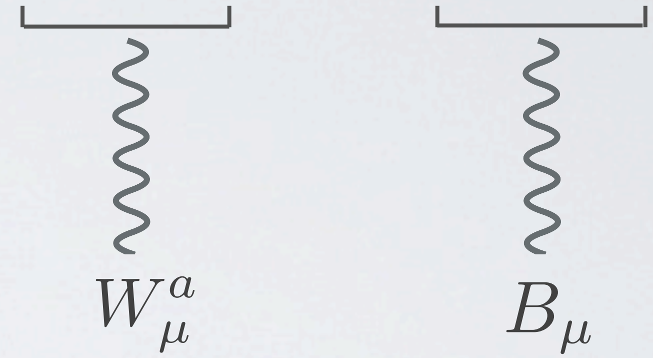


$$\Delta\epsilon_3 \equiv \hat{S} \sim \frac{m_W^2}{m_\rho^2} \sim \frac{g^2}{g_\rho^2} \times \frac{v^2}{f^2}$$

A MINIMAL COMPOSITE HIGGS MODEL:

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

$$SO(5)\times U(1)_X \rightarrow SO(4)\times U(1)_X \sim SU(2)_L\times SU(2)_R\times U(1)_X$$



$Y = T_{3R} + X$

$$\mathrm{Dim}\left[\frac{SO(5)}{SO(4)}\right] = 4$$

4 real Nambu-Goldstone bosons transforming as:

- a 4 of SO(4)
- a real (2,2) of $SU(2)_L \times SU(2)_R$
- a complex doublet of $SU(2)_L$

A MINIMAL COMPOSITE HIGGS MODEL:

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

$$\mathcal{L} = \frac{f^2}{2}(D_\mu \phi)^T (D^\mu \phi)$$

$$\phi^T \phi = 1$$

gauged SO(4)

unbroken custodial SO(3)

$$\phi = e^{i\pi^{\hat{a}} T^{\hat{a}}/f} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\pi/f) \times \begin{pmatrix} \hat{\pi}^1 \\ \hat{\pi}^2 \\ \hat{\pi}^3 \\ \hat{\pi}^4 \end{pmatrix} \\ \cos(\pi/f) \end{pmatrix} \xrightarrow{\text{vacuum}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ \sin(\langle \pi \rangle / f) \\ \cos(\langle \pi \rangle / f) \end{pmatrix}$$

$$T^{\hat{a}} \in \mathrm{Alg}\{SO(5)/SO(4)\} \qquad \pi \equiv \sqrt{(\pi^{\hat{a}})^2}$$

$$\hat{\pi}^{\hat{a}} \equiv \pi^{\hat{a}}/\pi$$

The $SU(2)_L \times U(1)_Y$ gauging and the couplings to the elementary fermions break SO(5) explicitly:

$$\langle \pi \rangle \neq 0$$

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3 NG bosons eaten to form W and Z longitudinal

'radial' excitation h(x) not eaten since SO(4) invariant

$$T^{\hat{a}} \in \mathrm{Alg}\{SO(5)/SO(4)\} \qquad \pi \equiv \sqrt{(\pi^{\hat{a}})^2}$$

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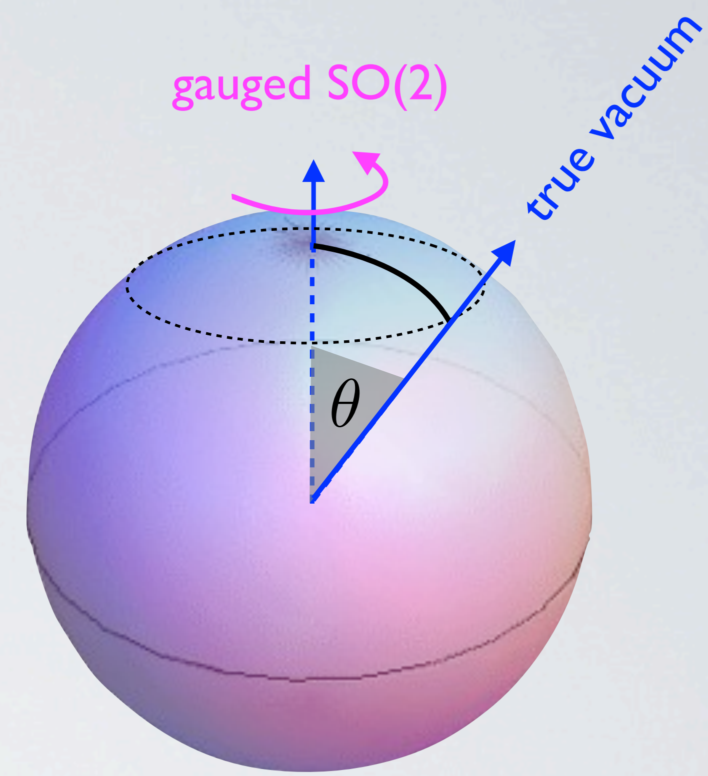
A TWO-STEP SYMMETRY BREAKING:

$$SO(5) \xrightarrow{f} SO(4) \xrightarrow{v} SO(3)$$

SU(2)L doublet H — EWSB

$$\frac{v}{f} = \sin\left(\frac{\langle\pi\rangle}{f}\right)$$

A SIMPLIFIED EXAMPLE: SO(3)→SO(2)



$$\mathrm{Dim}\left[\frac{SO(3)}{SO(2)}\right] = 2$$

$$\frac{SO(3)}{SO(2)} = S^2$$

← 2 real NG bosons transforming as a 2 of SO(2) and living on a 2-sphere

$$A_1 = -i\begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \quad A_2 = -i\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \quad V = -i\begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

gauged SO(2)

$$\phi = e^{i(\pi^1 A_1 + \pi^2 A_2)/f}\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \sin(\theta + h/f) \times \begin{pmatrix} \sin\varphi \\ \cos\varphi \end{pmatrix} \\ \cos(\theta + h/f) \end{pmatrix} \xrightarrow{\text{vacuum}} \begin{pmatrix} 0 \\ \sin\theta \\ \cos\theta \end{pmatrix}$$

gauged SO(2) fully broken

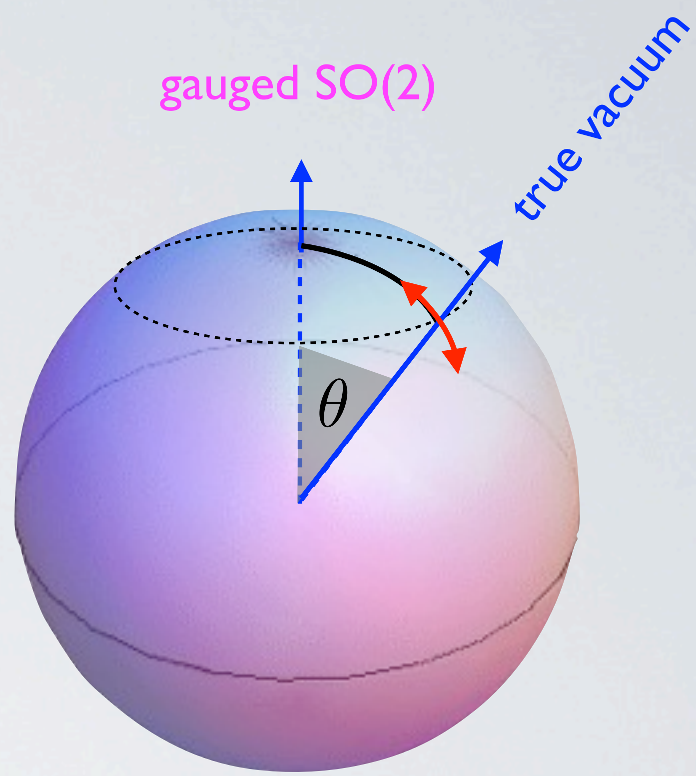
turning on a vev for the NG vector:

$$\langle \pi \rangle = \theta \cdot f$$

$$\begin{pmatrix} \pi^1(x) \\ \pi^2(x) \end{pmatrix} = (\theta f + h(x)) \begin{pmatrix} \sin\varphi(x) \\ \cos\varphi(x) \end{pmatrix}$$

The angle θ measures the degree of misalignment between the gauged SO(2) and the SO(2)' preserved in the true vacuum

A SIMPLIFIED EXAMPLE: SO(3)→SO(2)



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eaten NG boson

'radial' excitations = pNG Higgs

EW CHIRAL LAGRANGIAN FOR SO(5)→SO(4)

$$\phi = \begin{pmatrix} \sin(\theta + h(x)/f) \;\; e^{i\chi^i(x)A^i/v} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \\ \cos(\theta + h(x)/f) \end{pmatrix}$$

$$A^i \in \mathrm{Alg}\left\{\frac{SO(4)}{SO(3)}\right\}$$

$$\Sigma = e^{i\sigma^i \chi^i(x)/v}$$

$$\begin{aligned} \mathcal{L} =& \frac{f^2}{2}(D_\mu \phi)^T (D^\mu \phi) \\ =& \frac{1}{2}(\partial_\mu h)^2 + \frac{f^2}{2}\mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] \sin^2\left(\theta + \frac{h(x)}{f}\right) \end{aligned}$$

Notice: no covariant derivative acts on the Higgs field h(x)

(fluctuation of an SO(4) invariant)

I) $m_W^2 = \dfrac{g^2 f^2}{4} \sin^2\theta$

$$\xi = \left(\frac{v}{f}\right)^2 = \sin^2\theta$$

II) $a_T(\Lambda) = 0$ hence $\rho = 1$ up to 1-loop corrections

Expanding around the vacuum: $\xi = \left(\frac{v}{f}\right)^2 = \sin^2\theta$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left[\partial_\mu\Sigma^\dagger\partial^\mu\Sigma\right]\left(1 + 2\sqrt{1-\xi}\,\frac{h}{v} + (1-2\xi)\left(\frac{h}{v}\right)^2 + \dots\right)$$

$$a = \sqrt{1-\xi}\,, \qquad b = (1 - 2\,\xi)$$

- Higgs couplings to gauge bosons fixed by the coset, and predicted in terms of 1 parameter (ξ)

- For a composite Higgs doublet the small ξ behavior is universal

$$\mathcal{L} = \frac{1}{2}(D_\mu H)^\dagger(D^\mu H) + c_H\xi\,\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2 + \cdots$$

[Giudice et al. JHEP 0706:045 (2007)]

$$a = \left(1 - \frac{c_H\xi}{2}\right) \qquad b = (1 - 2\,c_H\xi)$$

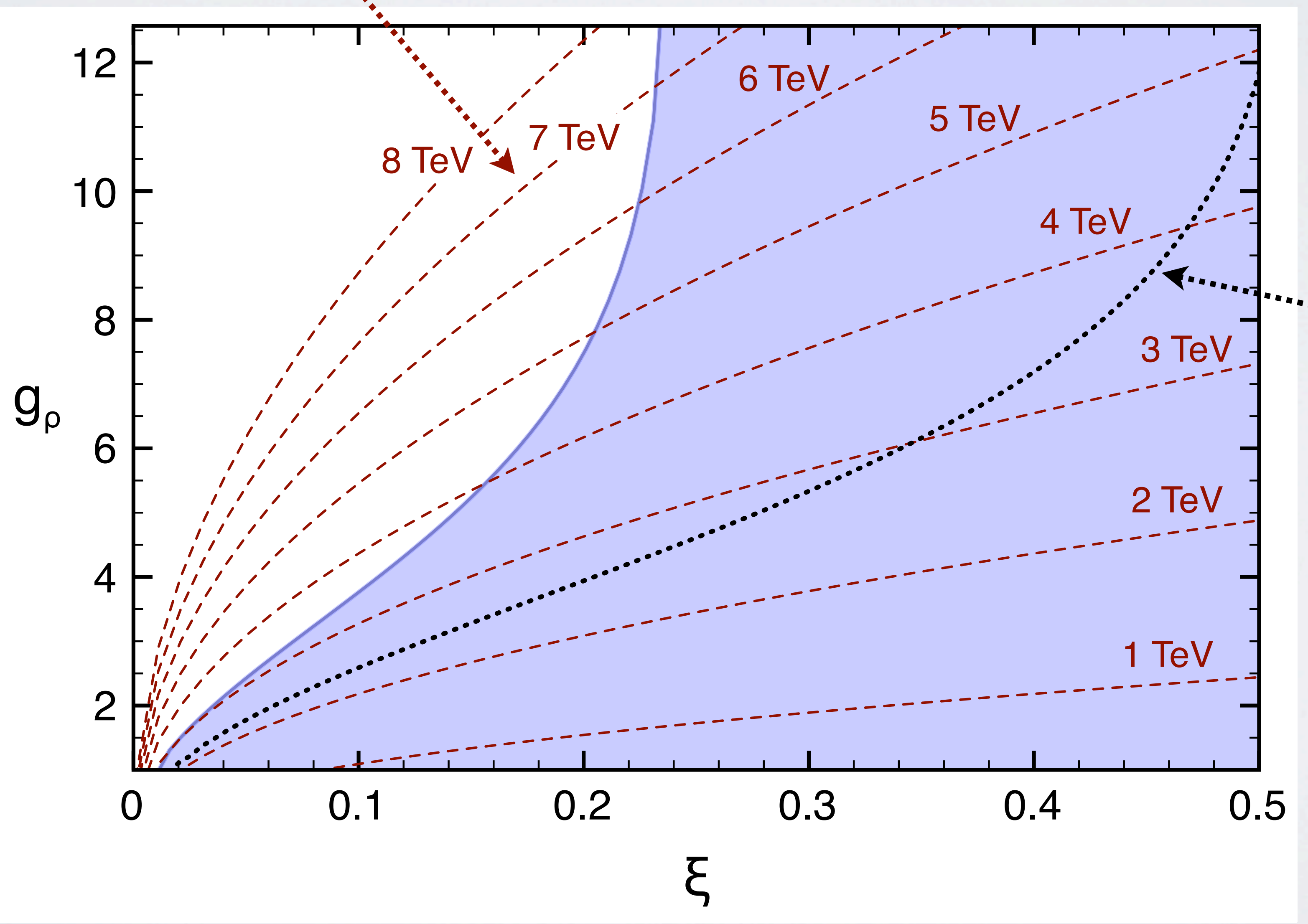
HOW MUCH COMPOSITE THE pNG HIGGS CAN BE ?

Ex: SO(5) → SO(4)

$$m_\rho = \frac{3}{8\pi}\frac{g_\rho v}{\sqrt{\xi}} \qquad a = \sqrt{\xi - 1} \qquad m_h = 120\,\mathrm{GeV}$$

[Agashe, RC, Pomarol, NPB 719 (2005) 165]

isocurves of constant m_ρ



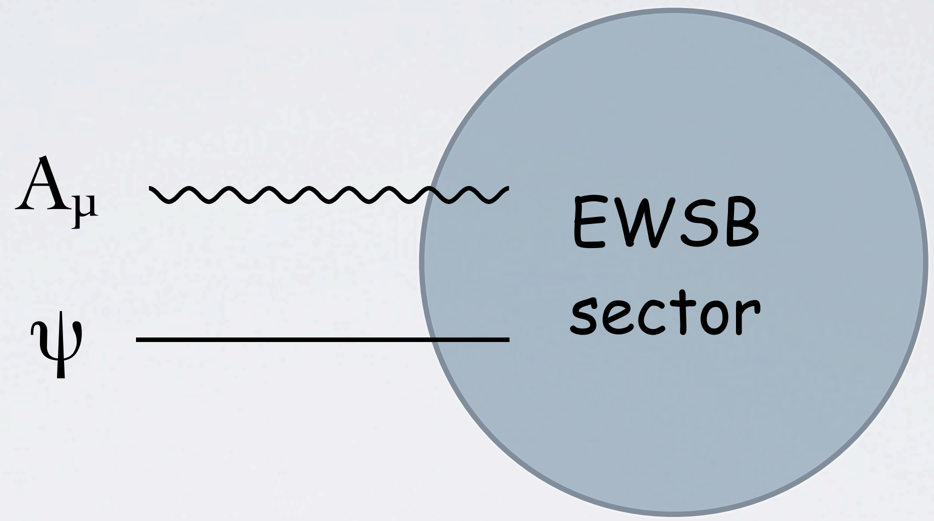
adding an extra

$$\Delta\rho = +2 \times 10^{-3}$$

A LIGHT SCALAR FAKING THE HIGGS: THE DILATON

[Goldberger et al. PRL 100 (2008) 111802]

If the EWSB sector has a spontaneously broken scale invariance the corresponding NG boson (the dilaton) can be light :



$$= \left\{ \chi^a,\ \phi,\ \ldots \right\}$$

Invariance under dilatations fixes the couplings of the dilaton:

$$x \to e^{-\lambda} x \qquad \phi(x) \to \phi(x e^{\lambda}) + \lambda f_D \qquad \chi^a(x) \to \chi^a(e^{\lambda} x) \qquad \psi(x) \to e^{3\lambda/2} \psi(e^{\lambda} x)$$

$$\mathcal{L} = e^{2\phi/f_D} \left[\frac{1}{2} \left(\partial_\mu \phi\right)^2 + \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \right] - m_i\, \bar{\psi}_{Li} \Sigma \psi_{iR}\, e^{\phi/f_D} + h.c.$$

A LIGHT SCALAR FAKING THE HIGGS: THE DILATON

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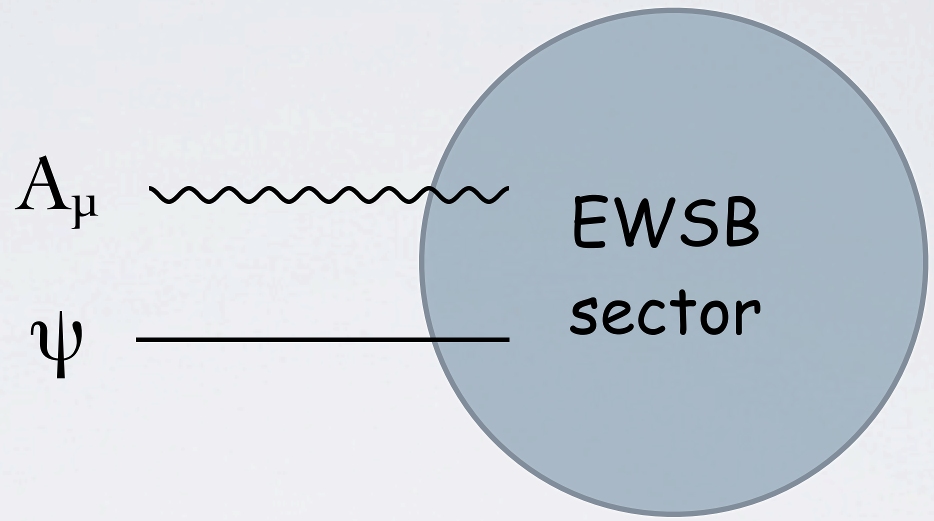


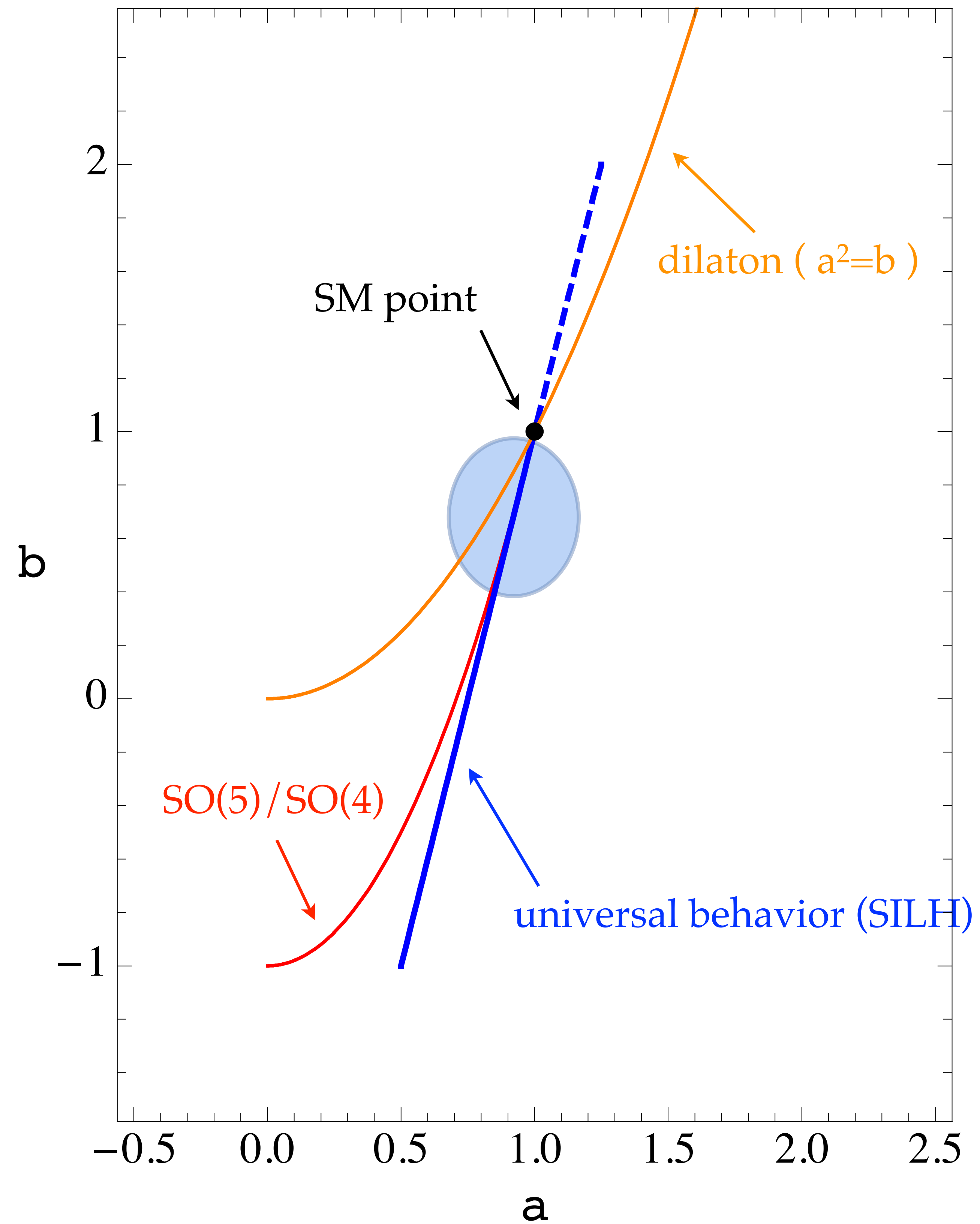
$$= \left\{ \chi^a, \, \phi, \, \ldots \right\}$$

By setting $e^{\phi/f_D} \equiv 1 + \frac{\chi}{f_D}$ one has:

$$\mathcal{L} = \left[\frac{1}{2} \left(\partial_\mu \phi\right)^2 + \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \right] \left(1 + \frac{\chi}{f_D}\right)^2 - m_i \, \bar{\psi}_{Li} \Sigma \psi_{iR} \left(1 + \frac{\chi}{f_D}\right) + h.c.$$

→ same as a light composite Higgs with:

$$a^2 = b = c^2 \qquad a = \frac{v}{f_D}$$



SM point
dilaton (a²=b)
SO(5) / SO(4)
universal behavior (SILH)
b
a
2
1
0
−1
−0.5
0.0
0.5
1.0
1.5
2.0
2.5

WW SCATTERING

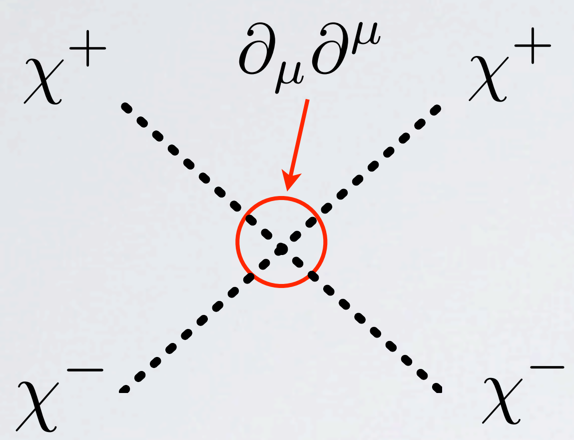
- By the Equivalence Theorem $\chi\chi \to \chi\chi$ equal to $W_L W_L \to W_L W_L$ at large energy

Comparing with

$$A(W_T W_T \to W_T W_T) = g^2$$

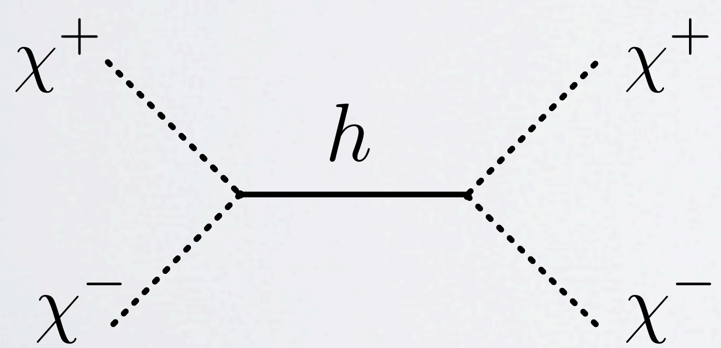
$$g \to (E/v)$$

strong coupling at $(E/v) \sim 4\pi$



$$A(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}(s+t)$$

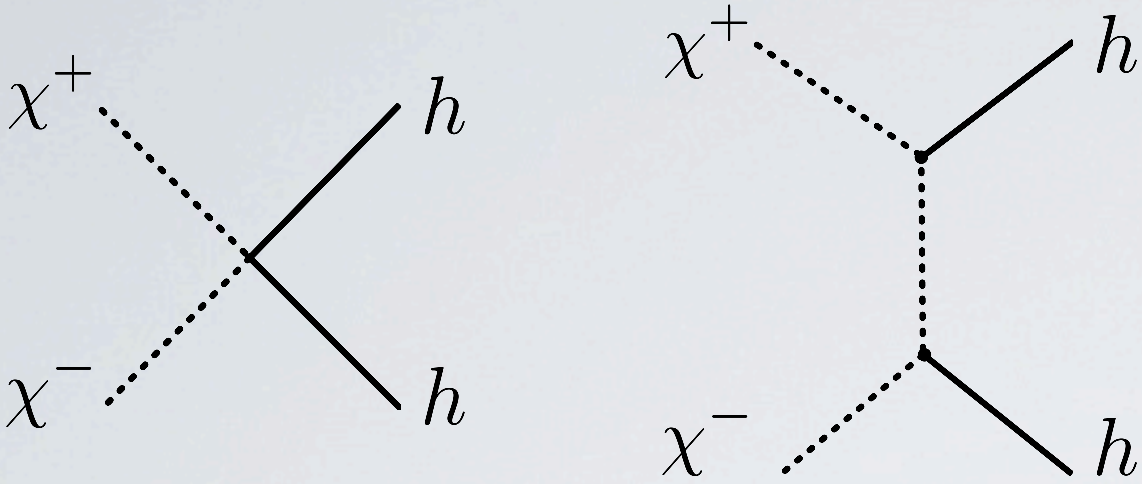
- The Higgs contributes to the scattering



unitarity for: a=1

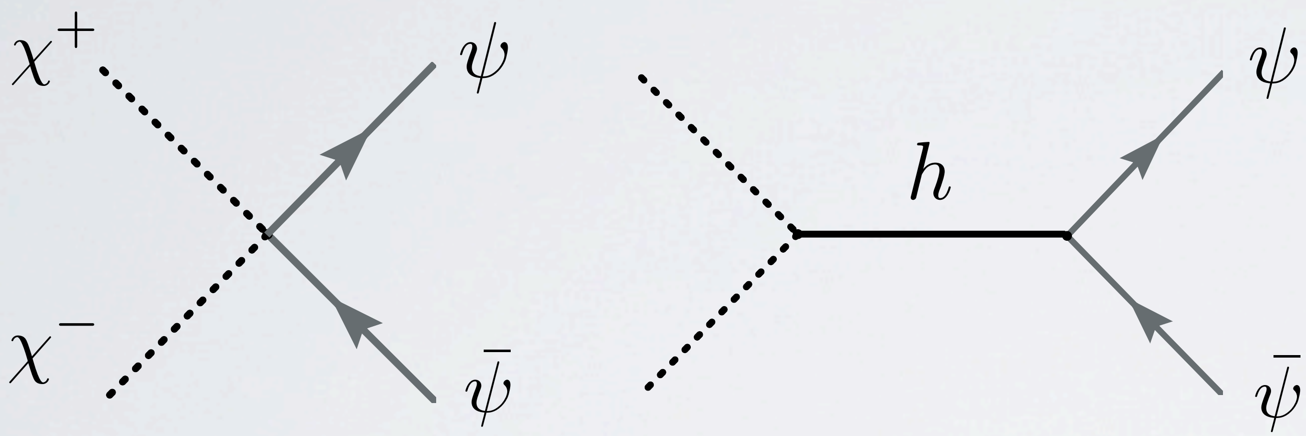
$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) \simeq \frac{1}{v^2}\left[s - \frac{a^2 s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

Strong regime delayed to $(E/v) \sim \dfrac{4\pi}{\sqrt{1-a^2}}$



$$\mathcal{A}(\chi^+\chi^- \to hh) \simeq \frac{s}{v^2}(b - a^2)$$

unitarity for: $a^2=b$



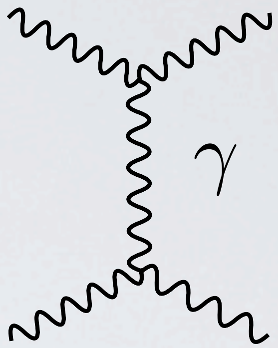
$$\mathcal{A}(\chi^+\chi^- \to \psi\bar{\psi}) \simeq \frac{m_\psi \sqrt{s}}{v^2}(1 - ac)$$

unitarity for: a=c=1

- No strong $W_L W_L \to hh$ for a dilaton ($a^2=b$)
- In general a,b,c control three different sectors of the theory

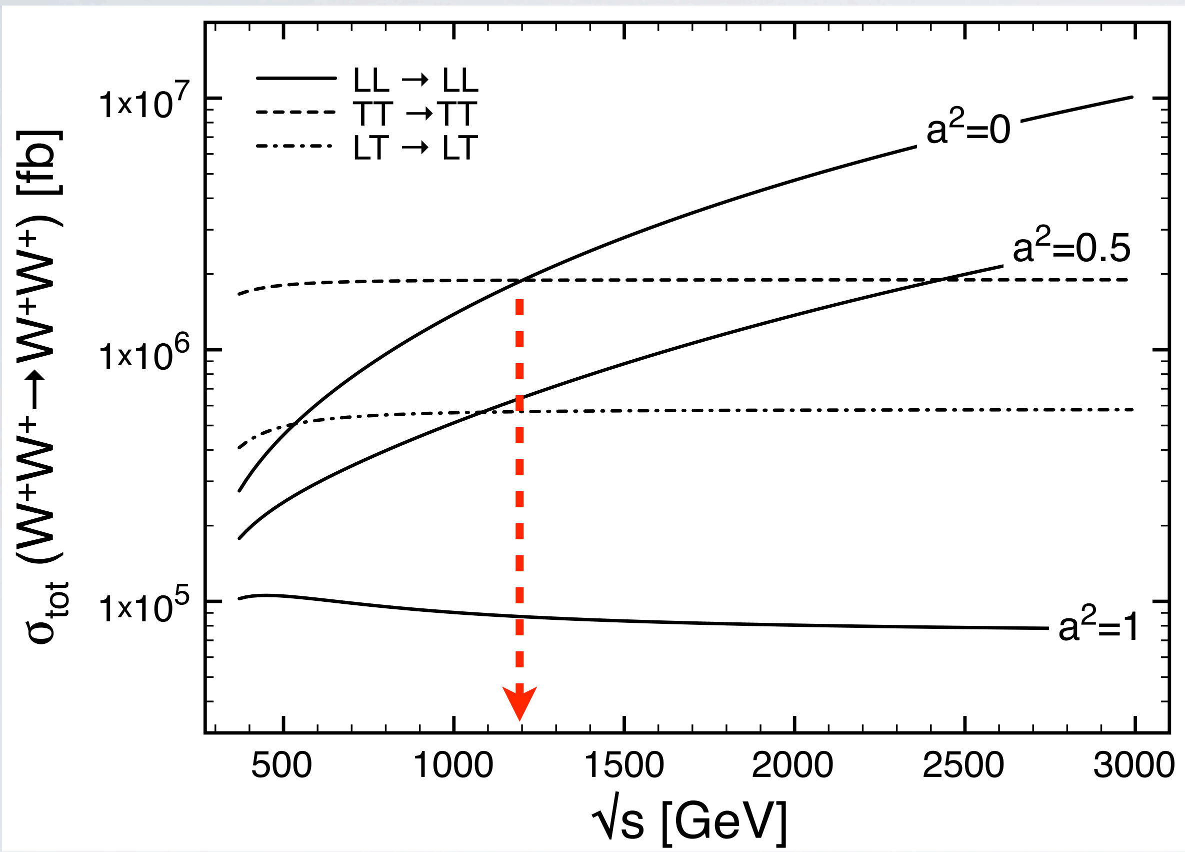
→ $W_L W_L \to hh$ only way to extract b

Extracting a from WW→WW scattering



Coulomb singularity enhances the TT scattering at small t

$$\sigma_{TT} \sim \frac{g^4}{8\pi}\frac{1}{t_{min}} \qquad \sigma_{LL} \sim \frac{(1-a^2)^2}{8\pi}\frac{s}{v^4}$$

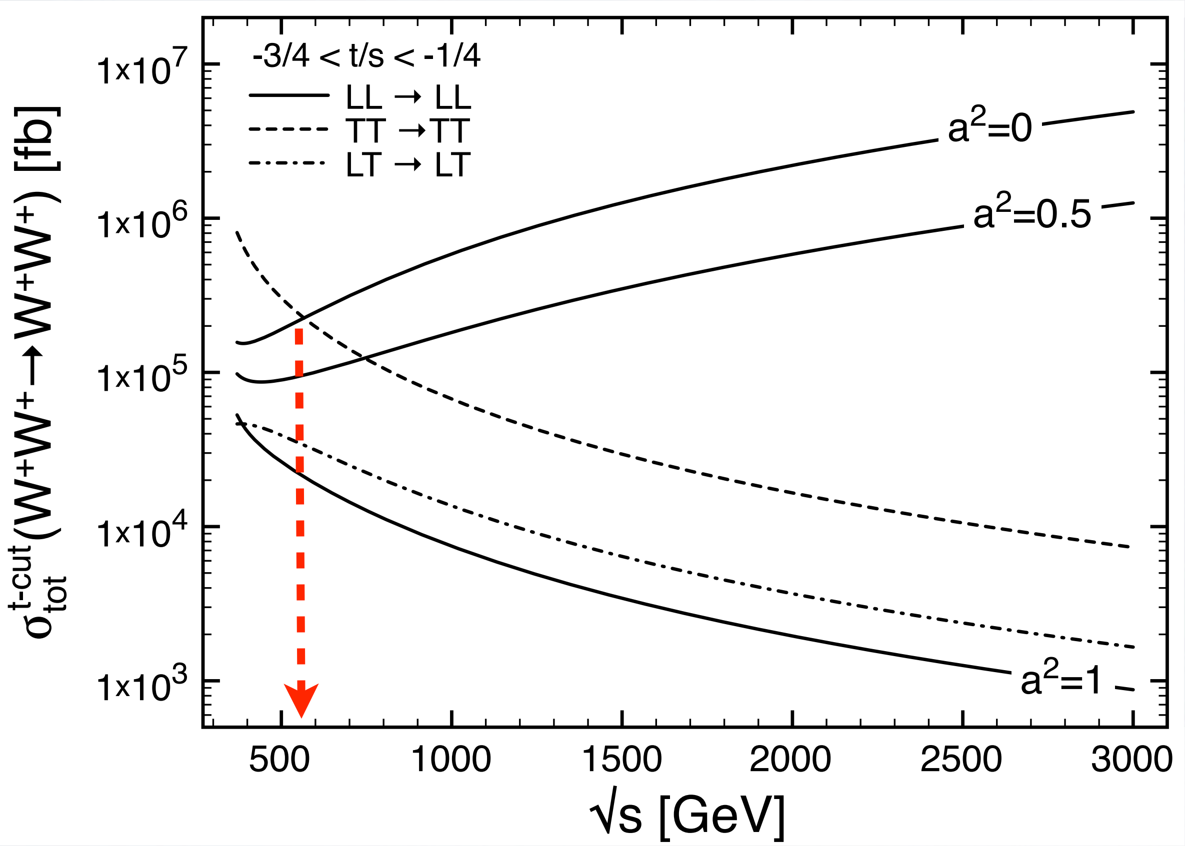


$$\frac{\sigma_{LL}}{\sigma_{TT}} \sim (1-a^2)^2\,\frac{s\,t_{min}}{M_W^4} \times \frac{1}{512}\frac{1}{(s_W^4+c_W^4)}$$

$$-s + 4M_W^2 < t < -M_W^2$$

TT scattering accidentally larger than NDA expectations: onset of strong scattering delayed

Extracting a from WW→WW scattering



Cutting on events with central final W's

$$t_{min} \sim s$$

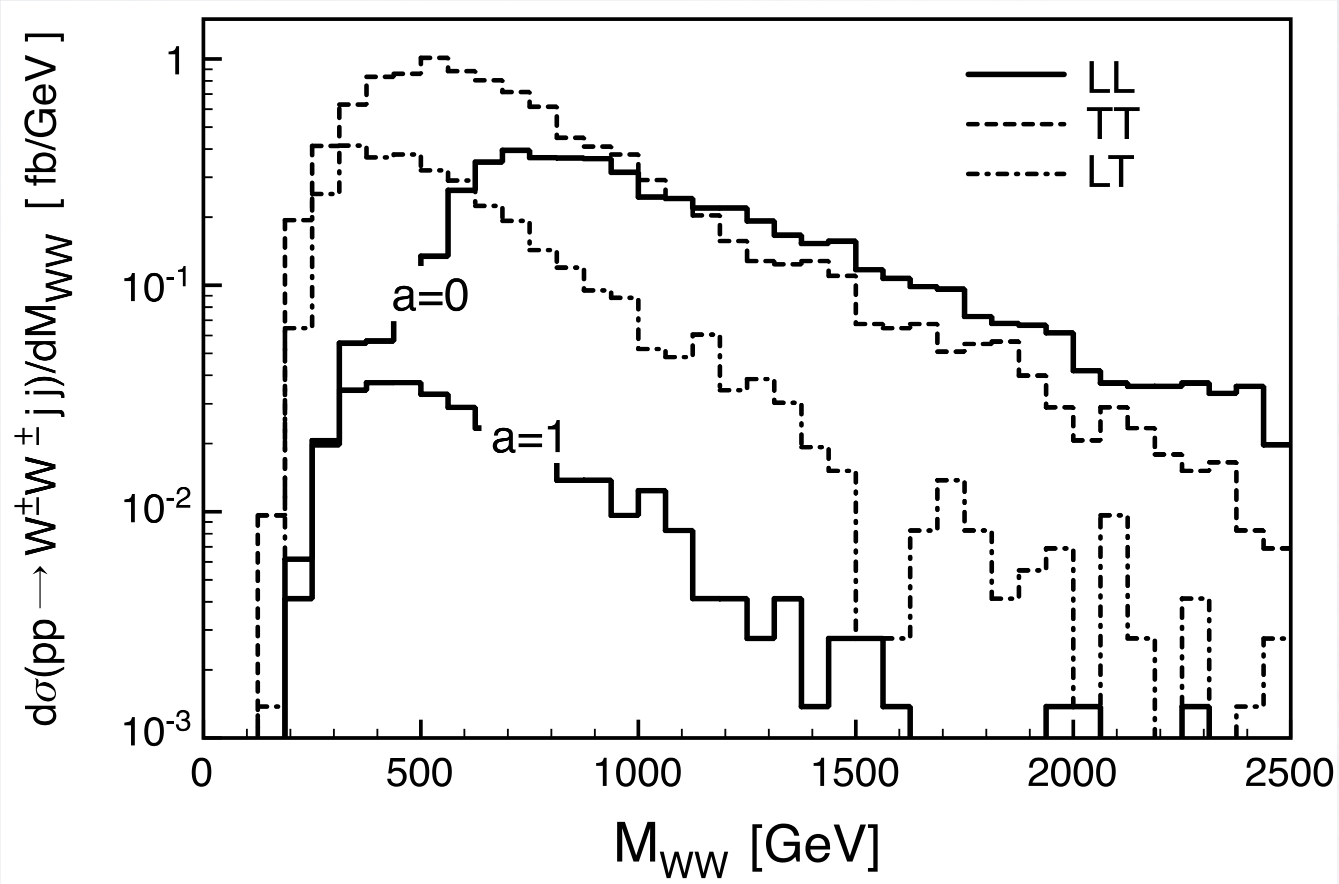
$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} \sim \frac{(1-a^2)^2}{2304}\frac{s^2}{M_W^4}$$

Still numerically larger than naive expectation

- Large pollution from transverse modes in hard scattering

Extracting a from WW→WW scattering

- Larger luminosity for longitudinal W's makes the signal even harder to identify



same as in Weizsacker-Williams photon spectrum

$$P_T(z) = \frac{g_A^2 + g_V^2}{4\pi^2} \frac{1+(1-z)^2}{2z} \log \frac{(p_{Tj}^{max})^2}{(1-z)M_W^2}$$

$$P_L(z) = \frac{g_A^2 + g_V^2}{4\pi^2} \frac{1-z}{z}$$

$$M_{jj} > 500 \text{ GeV}$$

$$p_{Tj} < 120 \text{ GeV}$$

$$p_{TW} > 300 \text{ GeV}$$

$$\sigma(signal) = \sigma(a \neq 1) - \sigma(SM)$$

- ~O(10) events in fully leptonic channel $W^\pm W^\pm \to l^\pm \nu l^\pm \nu$ with 100 fb^{-1} for a=0

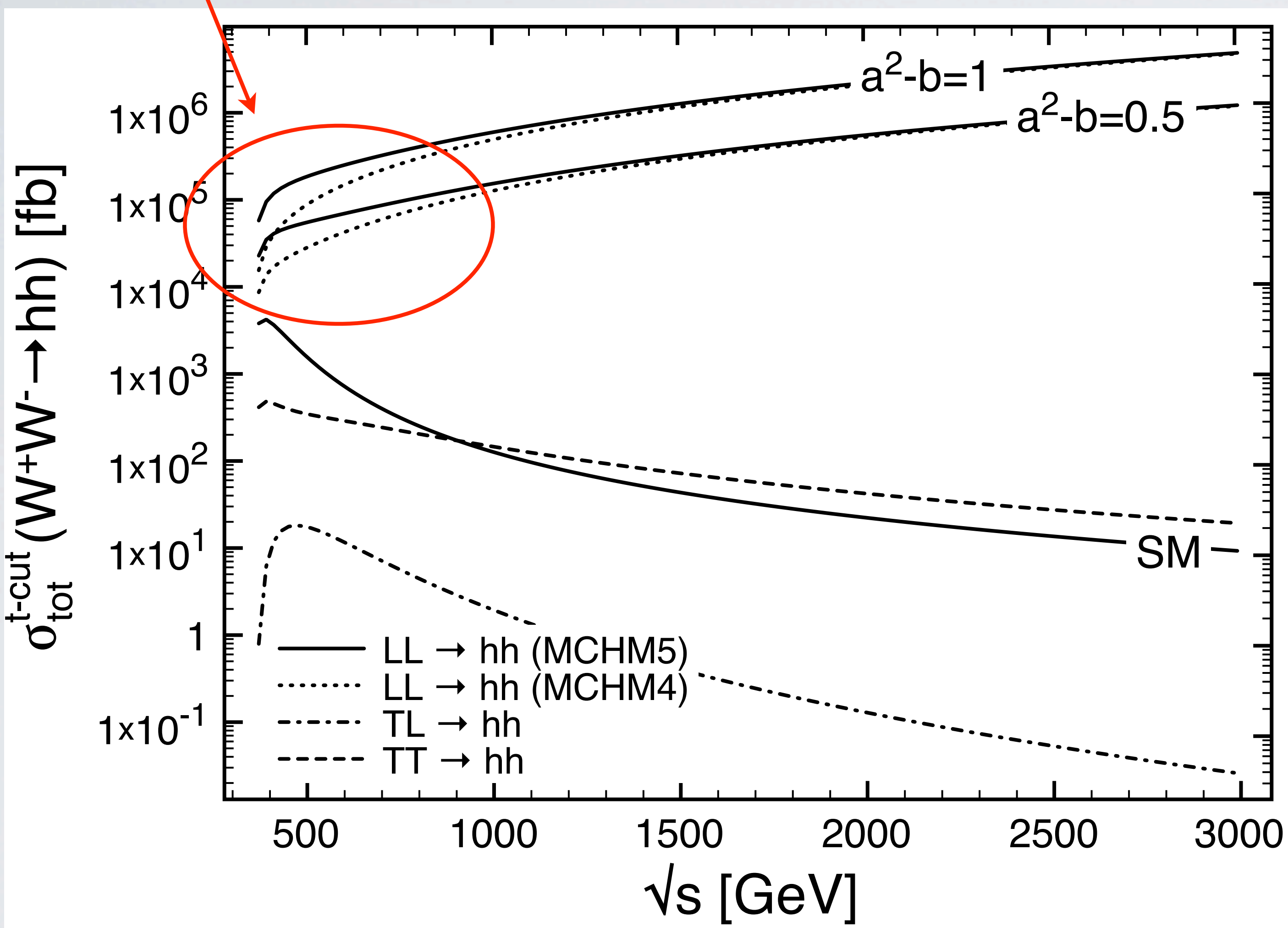
- LHC at 14 TeV sensitive to $a^2 \lesssim 0.5$ with 100 fb^{-1}

[Giudice et al. JHEP 0706:045 (2007)]

Extracting b from WW→hh scattering

model dependency

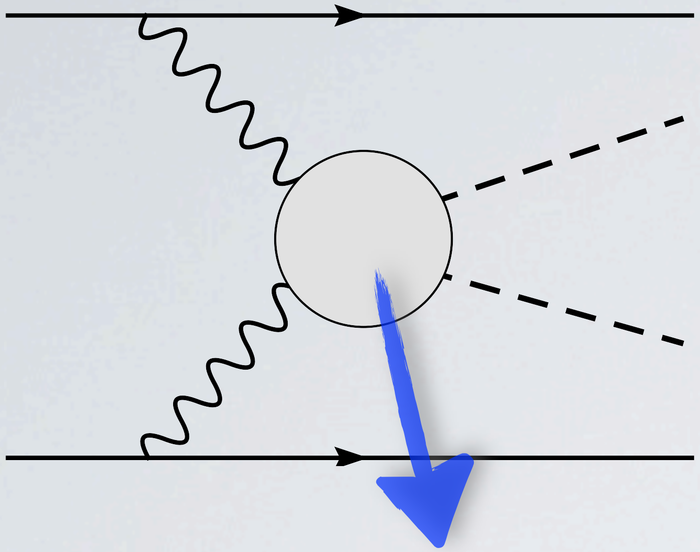
$m_h = 180\,\mathrm{GeV}$



Naive estimate works well

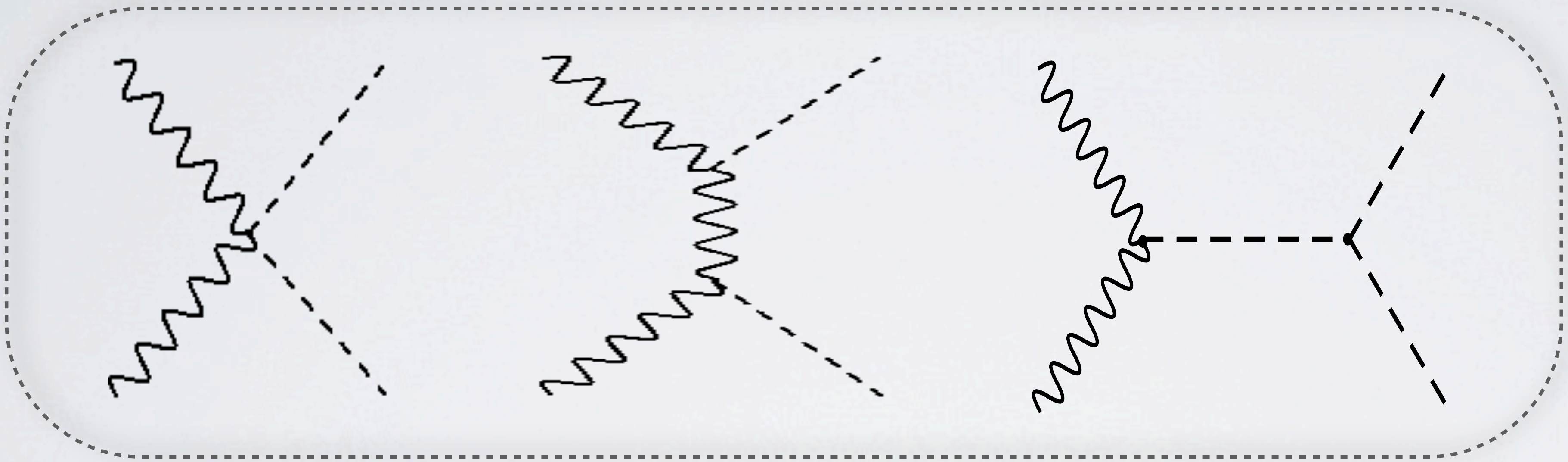
$$\frac{d\sigma_{LL\to hh}/dt}{d\sigma_{TT\to hh}/dt} \sim \frac{1}{8}\,\frac{(b-a^2)^2}{a^4+(b-a^2)^2}\,\frac{s^2}{M_W^4}$$

- No Coulomb singularity enhancement of transverse scattering
- Longitudinal scattering always dominating: cleaner than WW → WW



$\sigma(pp \to hhjj)$ [fb]	MCHM4	MCHM5
$\xi = 1$	9.3	14.0
$\xi = 0.8$	6.3	9.5
$\xi = 0.5$	2.9	4.2
$\xi = 0$ (SM)	0.5	0.5
dilaton $v/f_D = 1.5$	3.3	

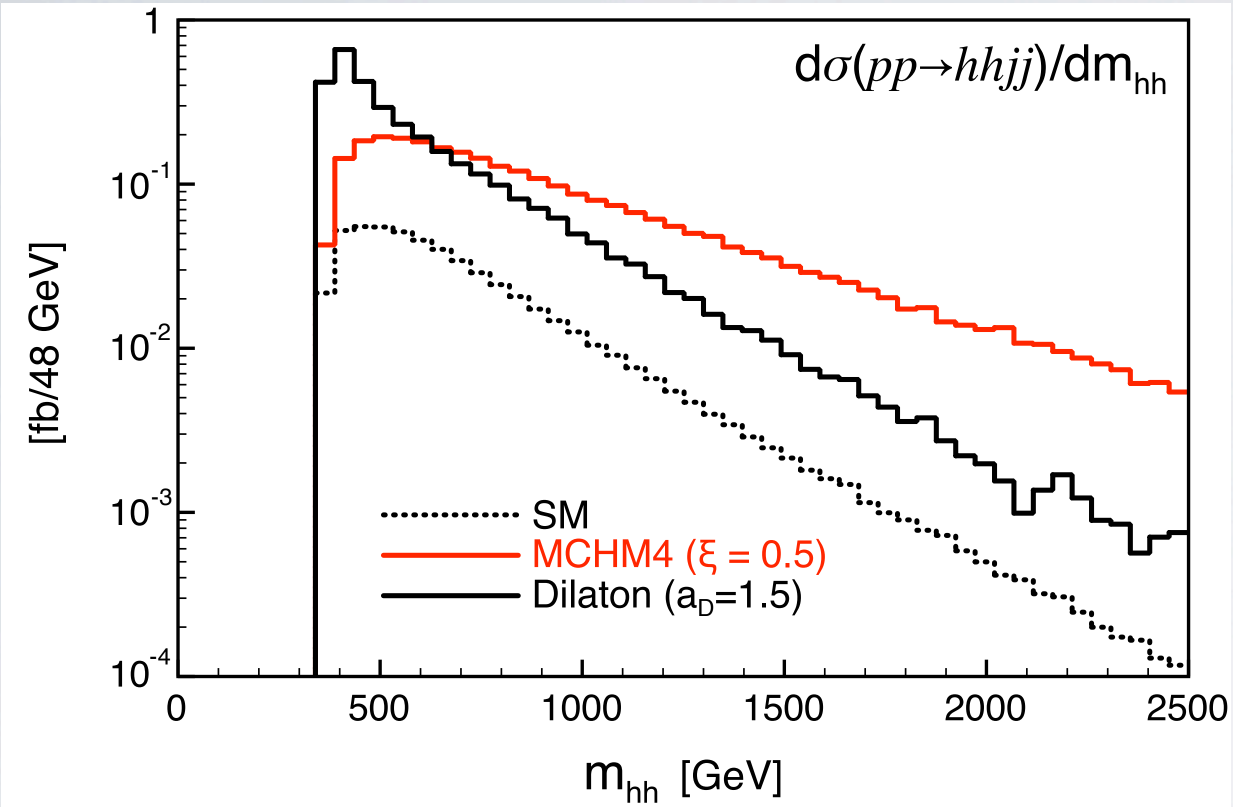
$m_h = 180\,\mathrm{GeV}$

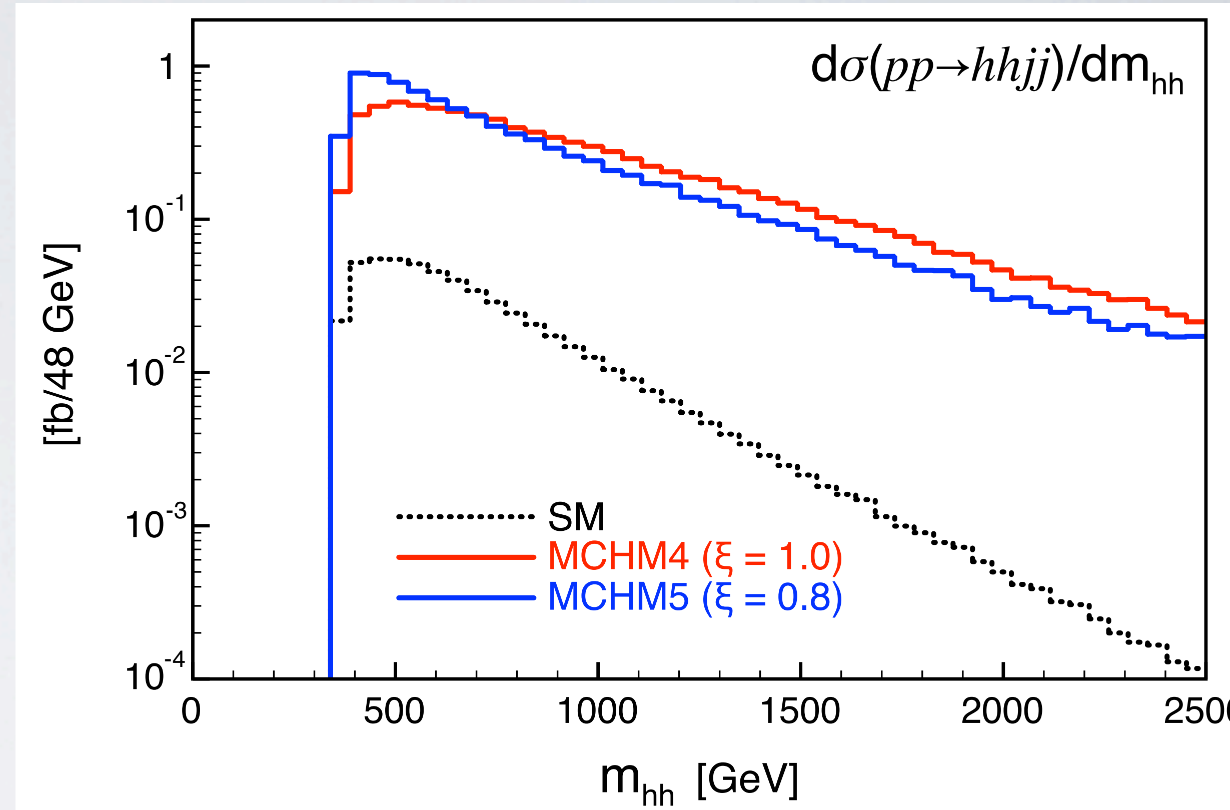


$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \dots$$

Coupling	MCHM4	MCHM5
$a = g_{hWW}/g_{hWW}^{SM}$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$b = g_{hhWW}/g_{hhWW}^{SM}$	$1-2\xi$	$1-2\xi$
$c = g_{hff}/g_{hff}^{SM}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
$d_3 = g_{hhh}/g_{hhh}^{SM}$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$

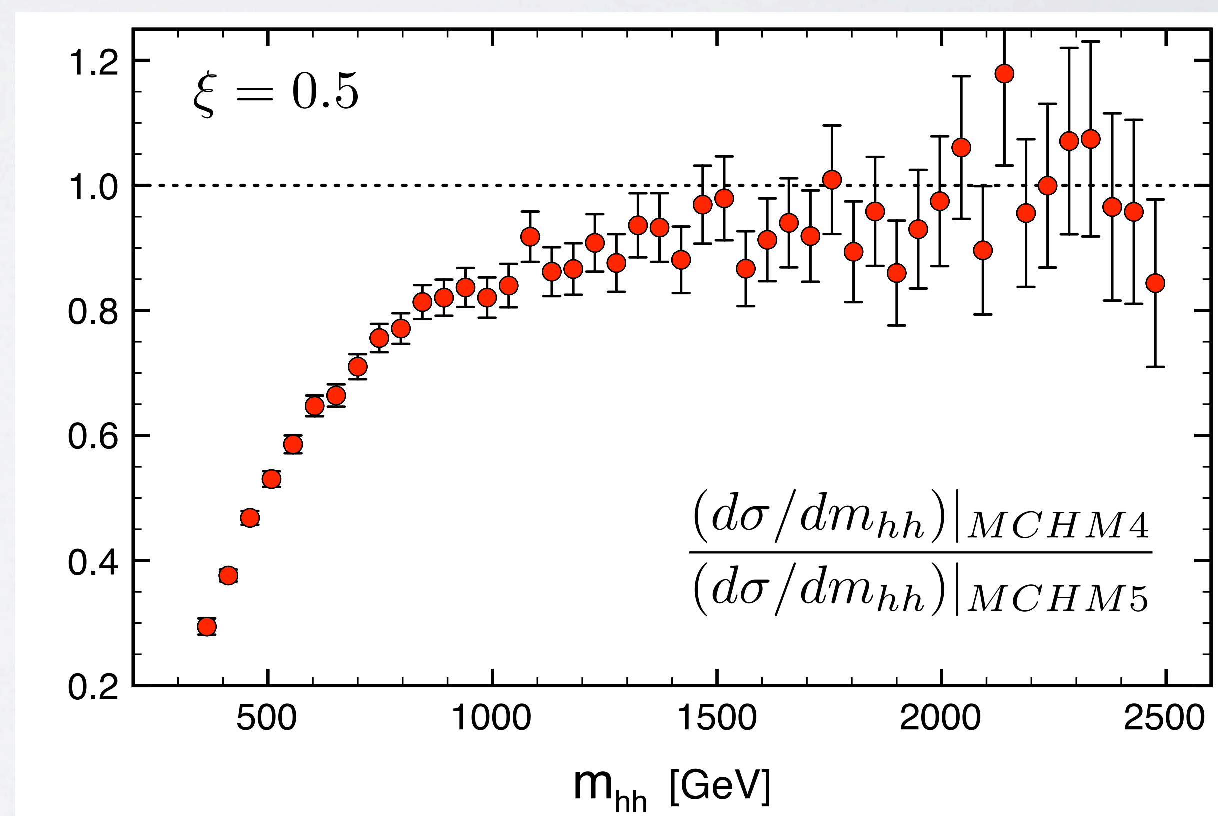
Breaking the model degeneracy



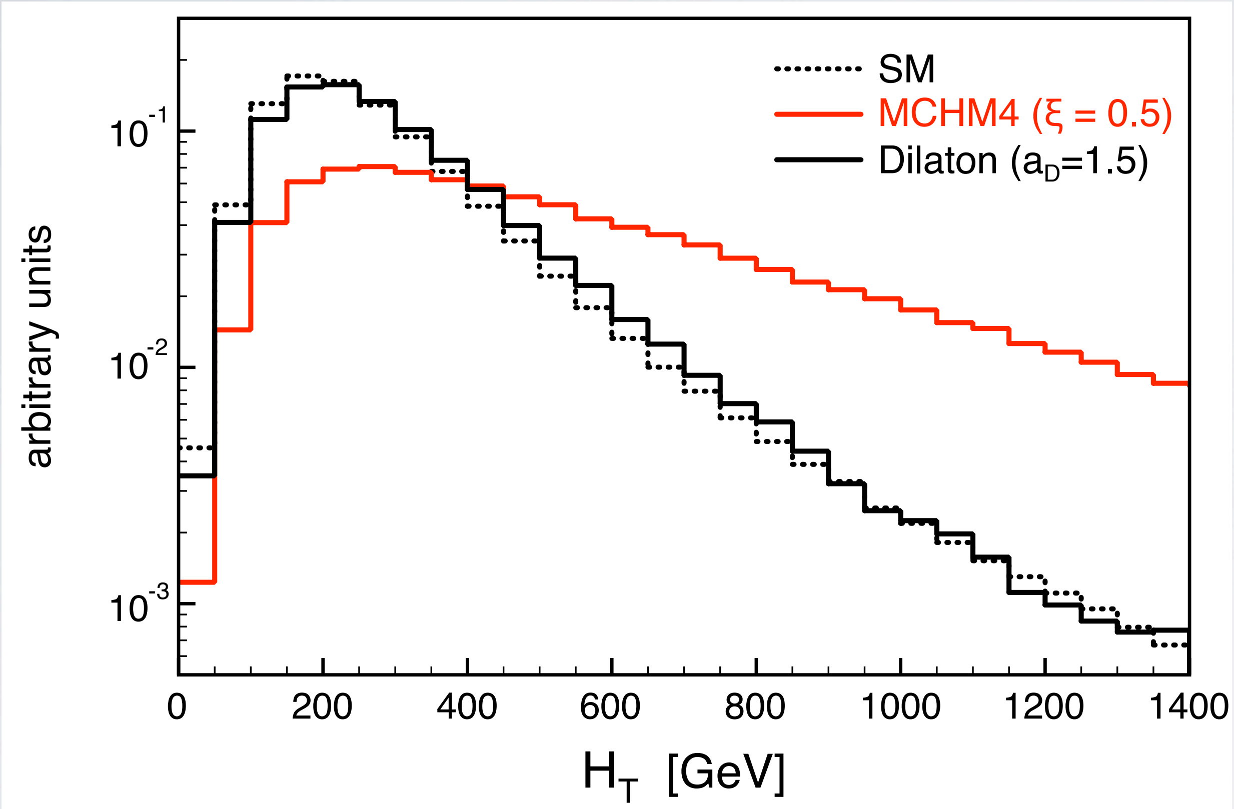


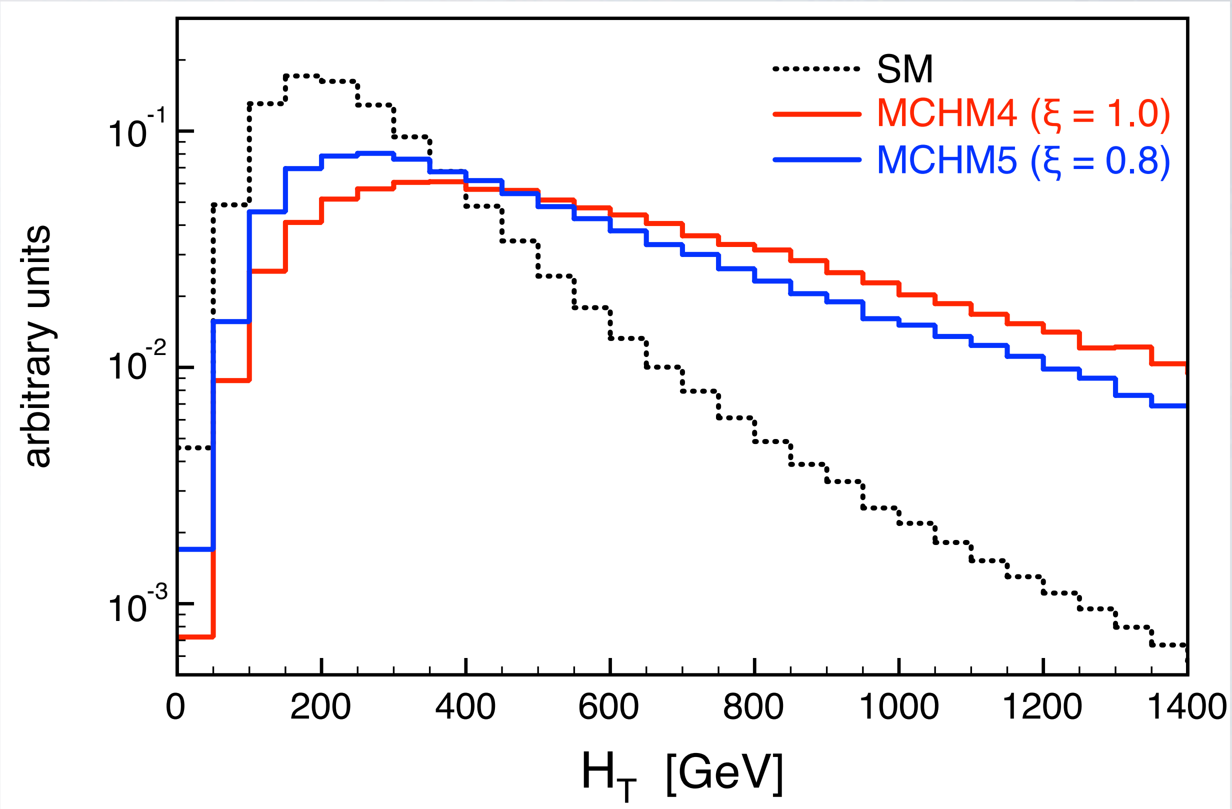
$$\frac{d\sigma}{dm_{hh}^2} = \frac{1}{m_{hh}^2}\,\hat{\sigma}(W_iW_j \to hh)\,\rho_W^{ij}(m_{hh}^2/s, Q^2)$$

$$\rho_W^{ij}(\tau,Q^2) = \tau\int_0^1 dx_1\int_0^1 dx_2\; f_{q_A}(x_1,Q^2)f_{q_B}(x_2,Q^2) \times \int_0^1 dz_1\int_0^1 dz_2\; P_A^i(z_1)P_B^j(z_2)\,\delta(x_1x_2z_1z_2-\tau)$$

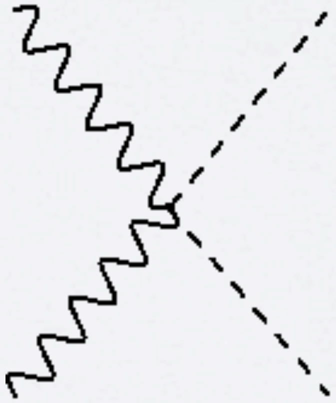


Breaking the model degeneracy





$$H_T = \sum_{i=1,2} |p_{T H_i}|$$



More central Higgses (larger H_T)

Signal pure s-wave

- Moral: extracting (a^2-b) requires studying events at large m_{hh} / H_T

Problem: very few events:

$$pp \to hhjj \to 4Wjj \to \begin{cases} l^+l^+l^-l^- \not{E}_T + 2j \\ l^+l^-l^\pm \not{E}_T + 4j \\ l^{+(-)}l^{+(-)} \not{E}_T + 5j\,(6j) \end{cases}$$

# Events with 300 fb^{-1}		3 leptons		2 SS leptons		4 leptons	
		signal	bckg.	signal	bckg.	signal	bckg.
MCHM4	$\xi = 1$	4.9	1.1	15.0	16.6	1.3	0.08
	$\xi = 0.8$	3.3	1.2	10.1	18.3	0.9	0.14
	$\xi = 0.5$	1.5	1.4	4.9	21.0	0.4	0.23
MCHM5	$\xi = 0.8$	4.5	1.8	14.3	26.0	1.1	0.19
	$\xi = 0.5$	2.3	1.2	7.6	18.4	0.6	0.21
SM	$\xi = 0$	0.2	1.7	0.8	25.4	0.05	0.37

	Total		3 leptons		Acceptance cuts passed		Final
# events:	2790	$\longrightarrow$	61	$\longrightarrow$	9.1	$\longrightarrow$	4.9
		2.2%		15%		54%	

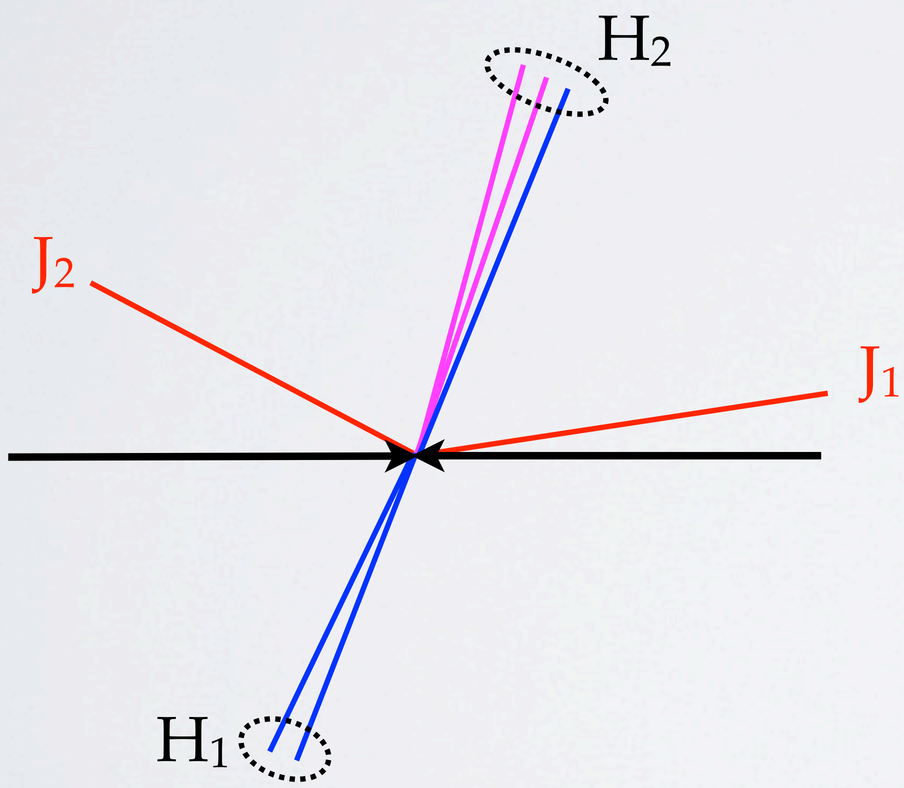
[last step for Bckg: $\sim 3 \times 10^{-4}$]

- Efficiency of `standard` cuts drastically drops for energetic (boosted) events

$$p_{Tj} > 30\,\text{GeV} \qquad |\eta_j| < 5 \qquad \Delta R_{jj'} > 0.7$$

$$p_{Tl} > 20\,\text{GeV} \qquad |\eta_l| < 2.4 \qquad \Delta R_{jl} > 0.4 \qquad \Delta R_{ll'} > 0.2$$

The larger m(hh), the more boosted the Higgses, the more collimated its decay products



	4 jets	3 jets (1 'fat')
No cut on m_{hh}	40%	17%
$m_{hh} > 750\,\text{GeV}$	36%	32%
$m_{hh} > 1500\,\text{GeV}$	18%	59%

These events are lost with a standard analysis

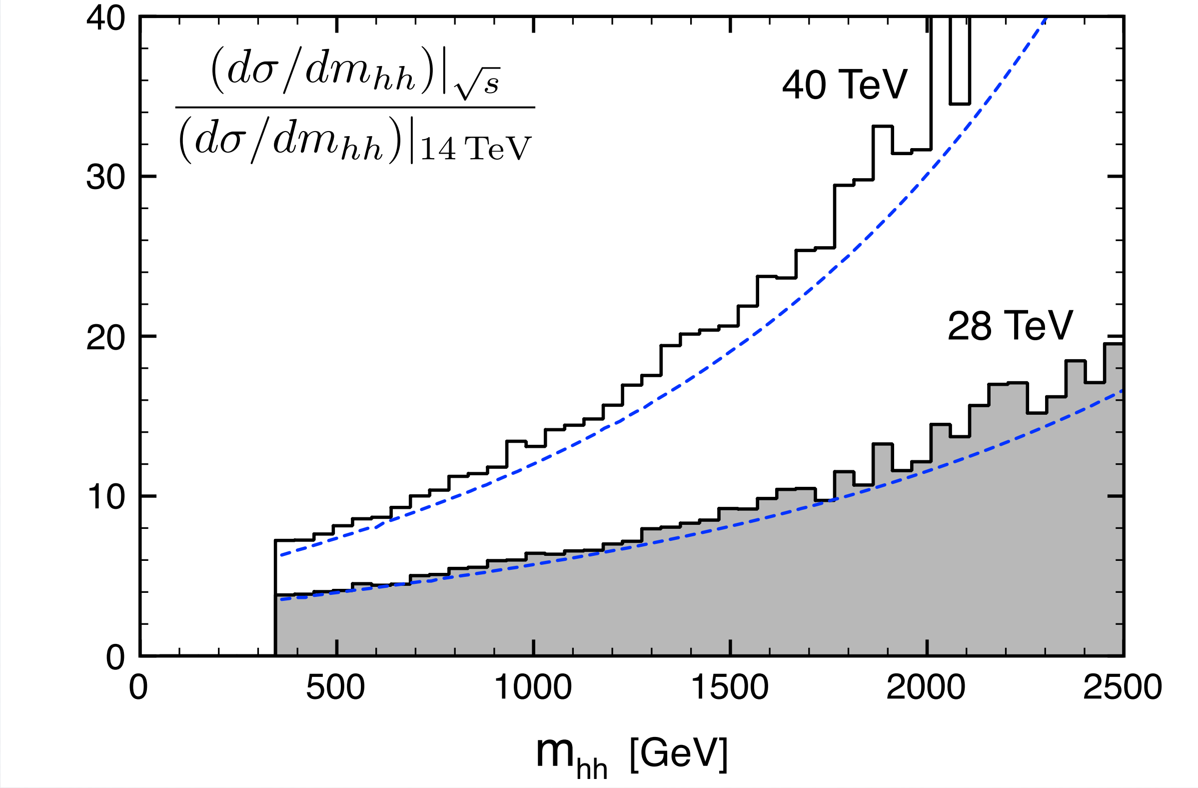
LUMINOSITY vs ENERGY UPGRADE

- With a tenfold Luminosity upgrade (3 ab^{-1}) our analysis predicts:

~ 50 three-lepton events
~150 two same-sign lepton events

even with a standard strategy should be possible to extract the energy growing behavior of the signal

- With a higher-energy collider one can probe larger values of m_{hh}



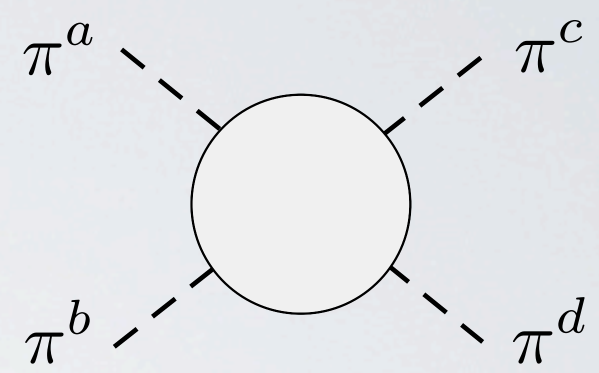
Luminosity upgrade as effective as a 28 TeV collider to study the signal

Full optimized analysis required to properly estimate the background

$$\frac{d\sigma}{dm_{hh}^2} = \frac{1}{m_{hh}^2}\,\hat{\sigma}(W_iW_j \to hh)\,\rho_W^{ij}(m_{hh}^2/s, Q^2)$$

EFFECT OF RESONANCES IN WW SCATTERING

Amplitude for the scattering of four Goldstones:



$$\pi^i = \chi^i + \dots \quad (i = 1,2,3)\,, \qquad \pi^4 = h + \dots$$

$$A(\pi^a\pi^b \to \pi^c\pi^d) = A(s,t,u)\,\delta^{ab}\delta^{cd} + A(t,s,u)\,\delta^{ac}\delta^{bd} + A(u,t,s)\,\delta^{ad}\delta^{bc} + B(s,t,u)\,\epsilon^{abcd}$$

two kinematical functions

Violates LR parity

$$\chi^i \to -\chi^i$$

$$h \to +h$$

Mediates: WW $\rightarrow$ Zh

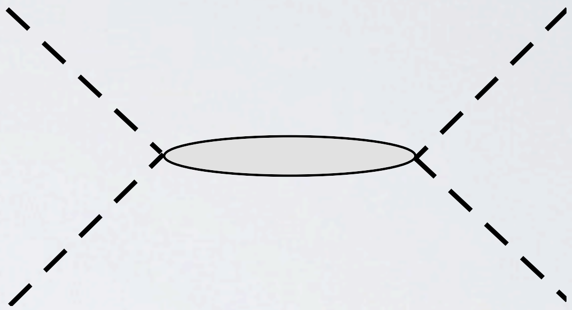
Consider the possibility:

one resonance accidentally lighter than the cutoff scale

$$m_\rho \ll \Lambda \sim 4\pi f$$

→ It must be included in the low-energy chiral Lagrangian

Quantum numbers of resonances:



SO(4) | $SU(2)_L \times SU(2)_R$

$\pi = 4$ of SO(4) → $\pi\pi = 4 \times 4 = 1 + 6 + 9 \;= (1,1) + [(1,3) + (3,1)] + (3,3)$

- 1 → spin=0, isospin=0 (η)
- 6 → spin=1, isospin=1 (ρ_L, ρ_R)
- 9 → spin 0, isospin 0+1+2 (Δ)

- Consider for example a light $\rho_L = (3,1)$:

The Callan-Coleman-Wess-Zumino (CCWZ) formalism is most convenient to construct its Lagrangian:

$$U(x) = e^{i\pi^{\hat{a}}(x)T^{\hat{a}}} \qquad U^\dagger(x)\partial_\mu U(x) = i\, d_\mu^{\hat{a}} T^{\hat{a}} + i\, E_\mu^a T^a$$

$$d_\mu \sim \partial_\mu \pi + \cdots \qquad E_\mu \sim \pi\partial_\mu\pi + \cdots$$

Under a global transformation $g \in G$

(with $h \in H$ local)

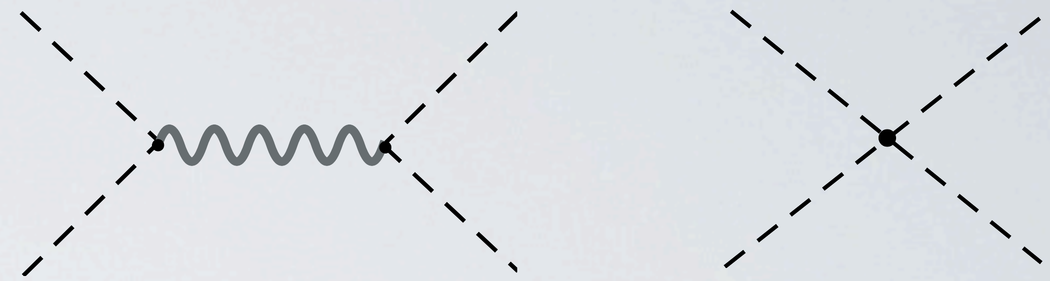
$$d_\mu \to h(\pi,g)\, d_\mu\, h^{-1}(\pi,g)$$

$$E_\mu \to h(\pi,g)\, E_\mu\, h^{-1}(\pi,g) + i\,[\partial_\mu h(\pi,g)]h^{-1}(\pi,g)$$

$$\rho_\mu \to h(\pi,g)\rho_\mu h^{-1}(\pi,g) + \frac{i}{g_{\rho_L}}\,[\partial_\mu h(\pi,g)]\, h^{-1}(\pi,g)$$

$$\mathcal{L} = -\frac{1}{4}\rho_{\mu\nu}^{a_L}\rho^{a_L\,\mu\nu} + \frac{m_\rho^2}{2}\left(\rho_\mu^{a_L} - \frac{1}{g_{\rho_L}}E_\mu^{a_L}\right)^2 + \ldots$$

- Contribution of the resonance to the scattering amplitude:

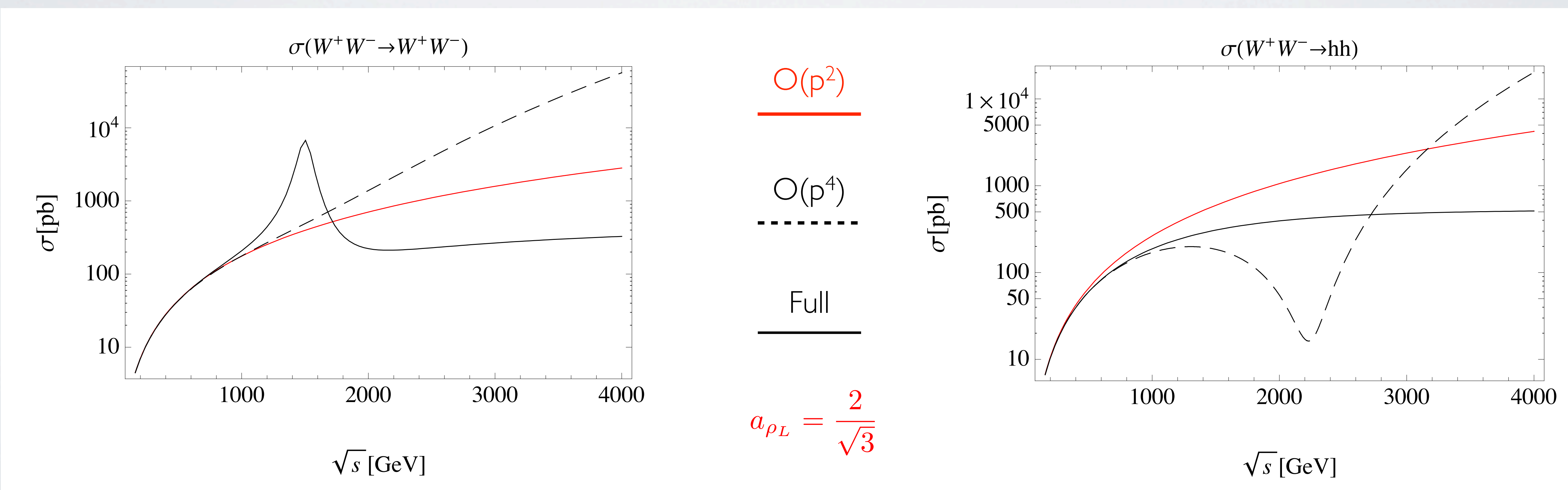


from contact term unitarizes for $a_{\rho_L} = \frac{2}{\sqrt{3}}$

$$A(s,t,u) = \frac{s}{f^2}\left(1 - \frac{3}{4}a_{\rho_L}^2\right) - \frac{1}{4}a_{\rho_L}^4 g_{\rho_L}^2 \left[\frac{s-u}{t-m_{\rho_L}^2} + (u \leftrightarrow t)\right]$$

$$m_{\rho_L} \equiv a_{\rho_L} g_{\rho_L} f$$

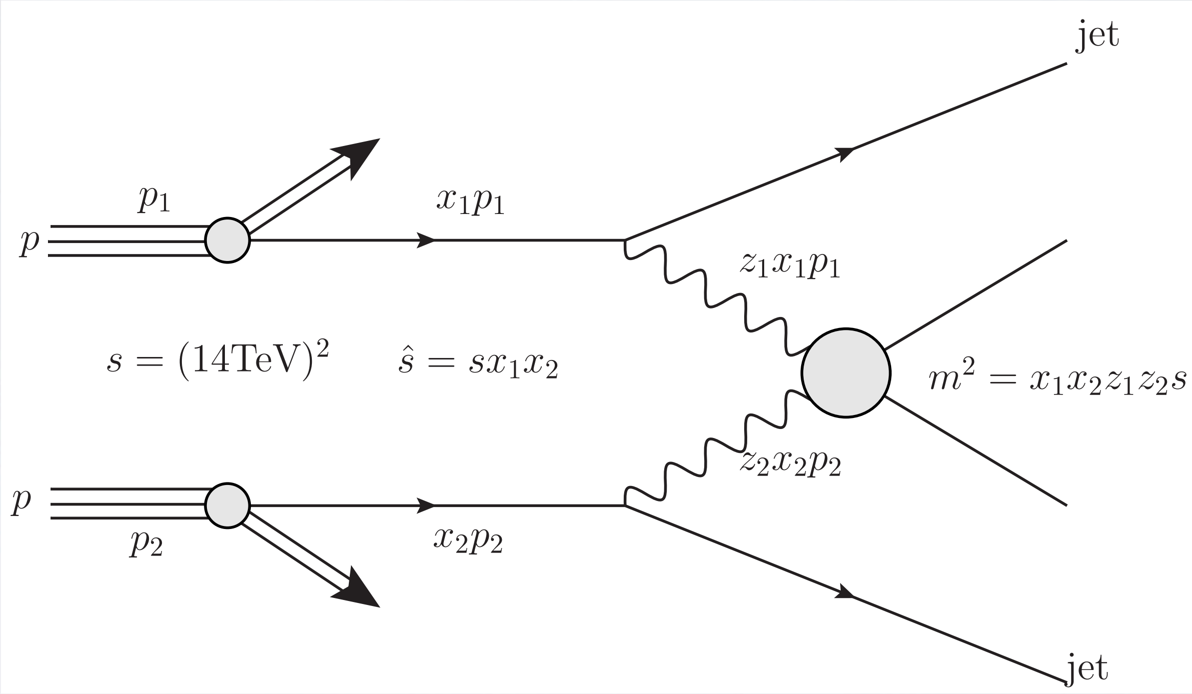
$$B(s,t,u) = \frac{1}{4}a_{\rho_L}^4 g_{\rho_L}^2 \left[\frac{u-t}{s-m_{\rho_L}^2} + \frac{s-u}{t-m_{\rho_L}^2} + \frac{t-s}{u-m_{\rho_L}^2}\right] \longrightarrow O\left(\frac{E^6}{m_{\rho_L}^6}\right)$$



EFFECT OF RESONANCES AT THE LHC

We make the following simplifying assumptions:

- Effective W approximation
- Neglect $m_h, m_W \ll m_{WW}$



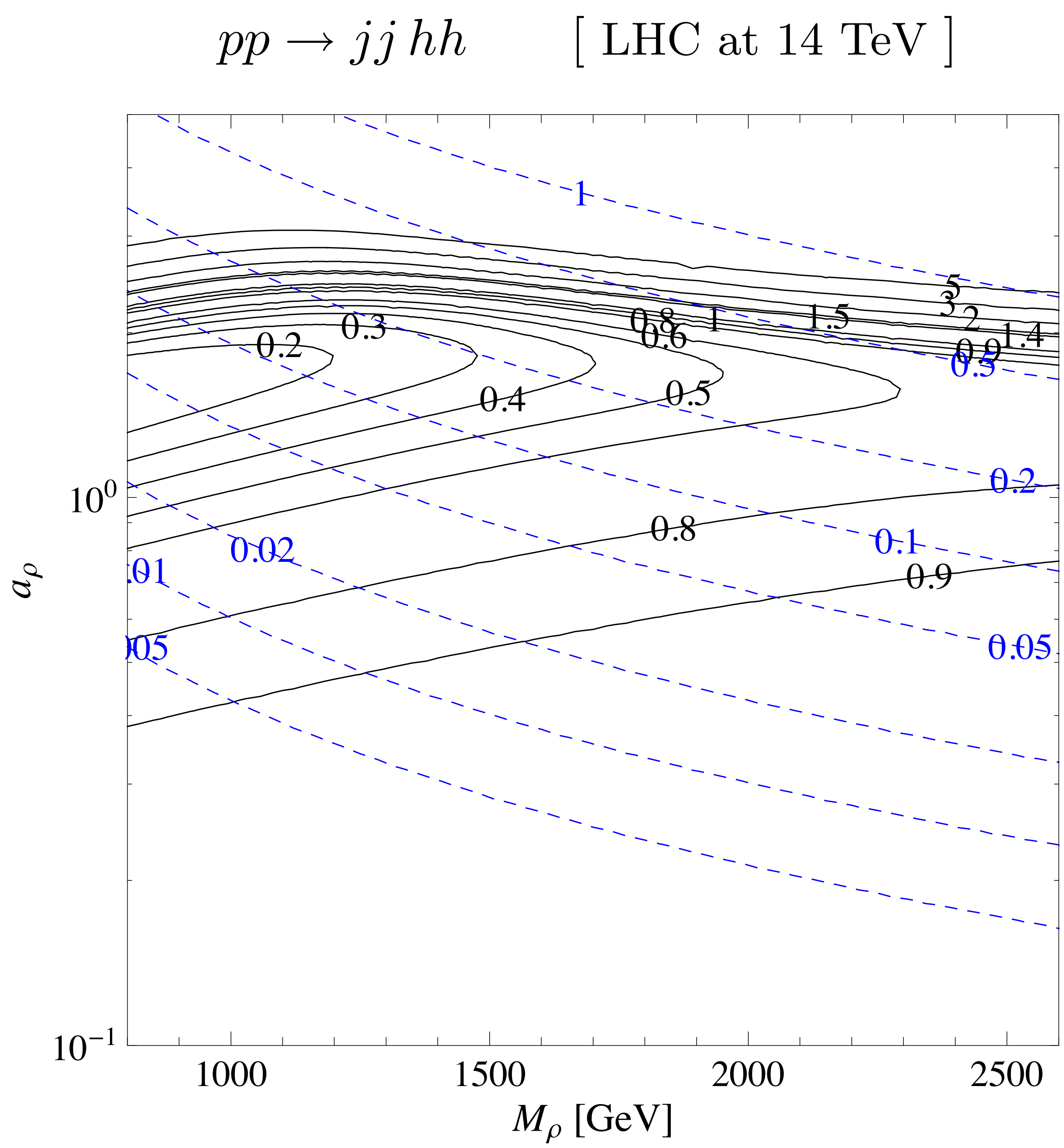
Effect of the resonance monitored through the ratio:

$$R(\Phi, \xi, m_{\mathrm{cut}}) = \frac{\sigma(\Phi, \xi, m_{\mathrm{cut}})}{\sigma(\mathrm{LET}, \xi, m_{\mathrm{cut}})}$$

kinematical cut:

$$m_{WW} > m_{\mathrm{cut}}$$

Results for a ρ_L [spin=1, (3,1) of $SU(2)_L \times SU(2)_R$, isospin=1]



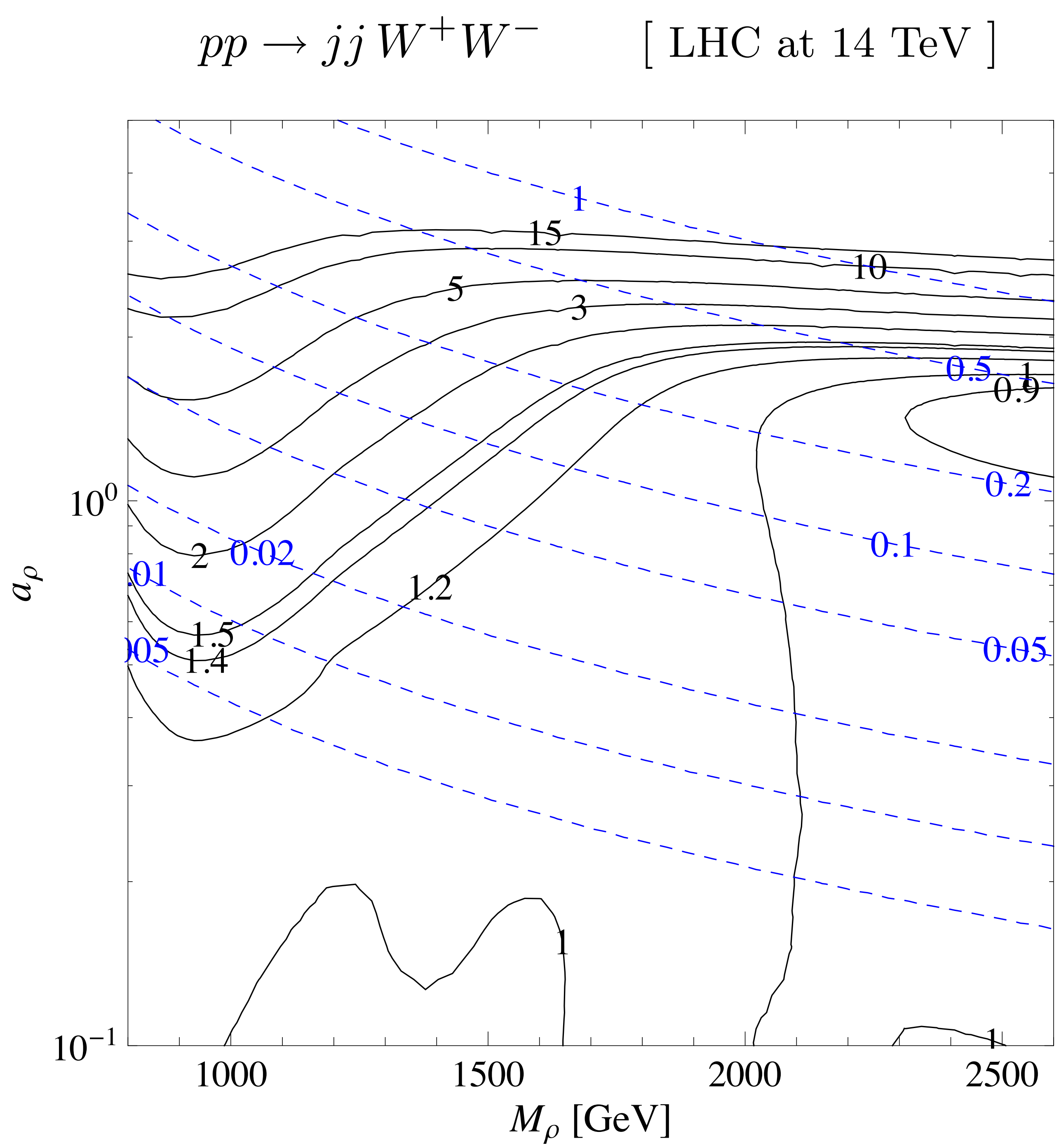
$\xi = 0.5$

$m_{\rm cut} = 800\,\text{GeV}$

$$R = \frac{\sigma(\rho_L)}{\sigma(\text{LET})}$$

$$\frac{\Gamma_{\rho_L}}{m_{\rho_L}}$$

Results for a ρ_L [spin=1, (3,1) of $SU(2)_L \times SU(2)_R$, isospin=1]



$\xi = 0.5$

$m_{\rm cut} = 800\,{\rm GeV}$

$$R = \frac{\sigma(\rho_L)}{\sigma({\rm LET})}$$

$$\frac{\Gamma_{\rho_L}}{m_{\rho_L}}$$

CONCLUSIONS

- LHC goal: Unraveling the mechanism of EWSB

  main question: weak or strong ?

- WW→hh only process to probe the (hhWW) coupling

  LHC reach (3σ) with 300 fb^{-1}: $\xi \sim 1$

  3 ab^{-1}: $\xi \sim 0.5$

- Model dependency due to the trilinear coupling important

- Effect of resonances in general negligible for $m_{\rm res} \gtrsim 2\,{\rm TeV}$

- For $m_{\rm res} \lesssim 1.5\,{\rm TeV}$ pattern of enhancement/suppression in the various channels gives information on the quantum numbers of the resonance and thus on the strong sector