STRONG DOUBLE HIGGS PRODUCTION

Roberto Contino

based on:

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

work in progress with A.Pomarol, R.Rattazzi

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Motivation:

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

EVIDENCE FOR A LIGHT HIGGS-LIKE SCALAR

- EWSB sector described by an $SU(2)_L \times U(1)_Y \to U(1)_{em}$ chiral Lagrangian:

$$\Sigma = \exp\left(i\sigma^a \chi^a / v\right) \qquad D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W^a_\mu \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

$$\begin{aligned}\mathcal{L} = & \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \\ & + a_T \frac{v^2}{8} \left[\mathrm{Tr}\left(\Sigma^\dagger D_\mu \Sigma\, \sigma^3\right)\right]^2 + a_S\, \mathrm{Tr}\left(W_{\mu\nu} \Sigma\, B^{\mu\nu} \Sigma^\dagger\right) \\ & - \frac{v}{\sqrt{2}} \sum_{i,j} \left(u_L^{(i)}\ d_L^{(i)}\right) \Sigma \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.\end{aligned}$$

- For $a_T = 0$, in the limit $g_1 = 0$, $\lambda^u = \lambda^d$, there is an $SU(2)_L \times SU(2)_R \to SU(2)_V$ global symmetry

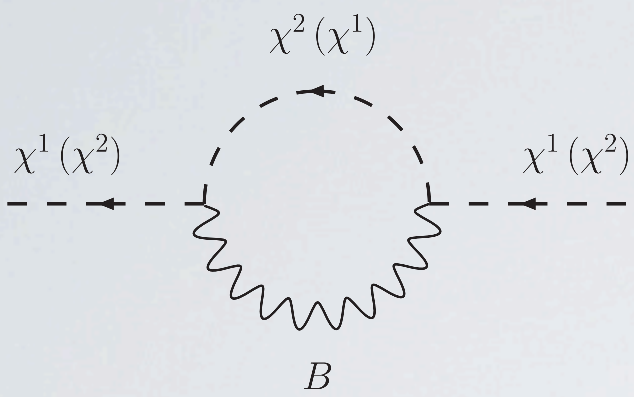
$$\Sigma \to U_L \Sigma U_R^\dagger$$

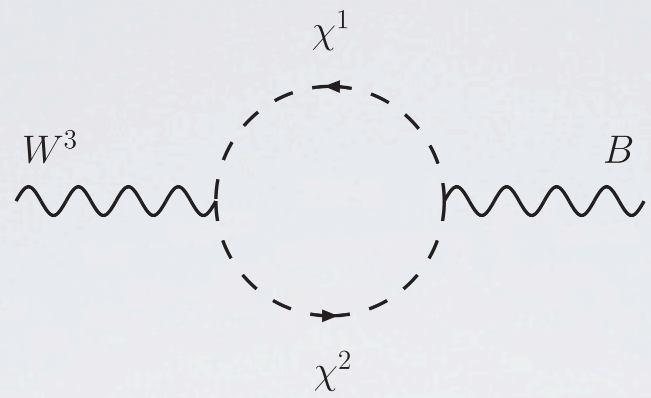
the NG bosons χ^a transform as a triplet under the custodial $SU(2)_V$ → $M_W = M_Z$ for $g_1 = 0$

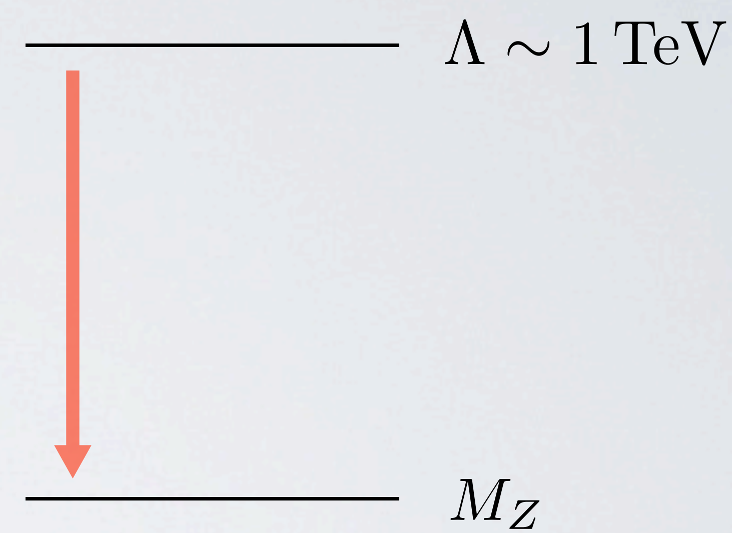
- For $a_{S,T}(\Lambda) = 0$ the fit to LEP data is not good

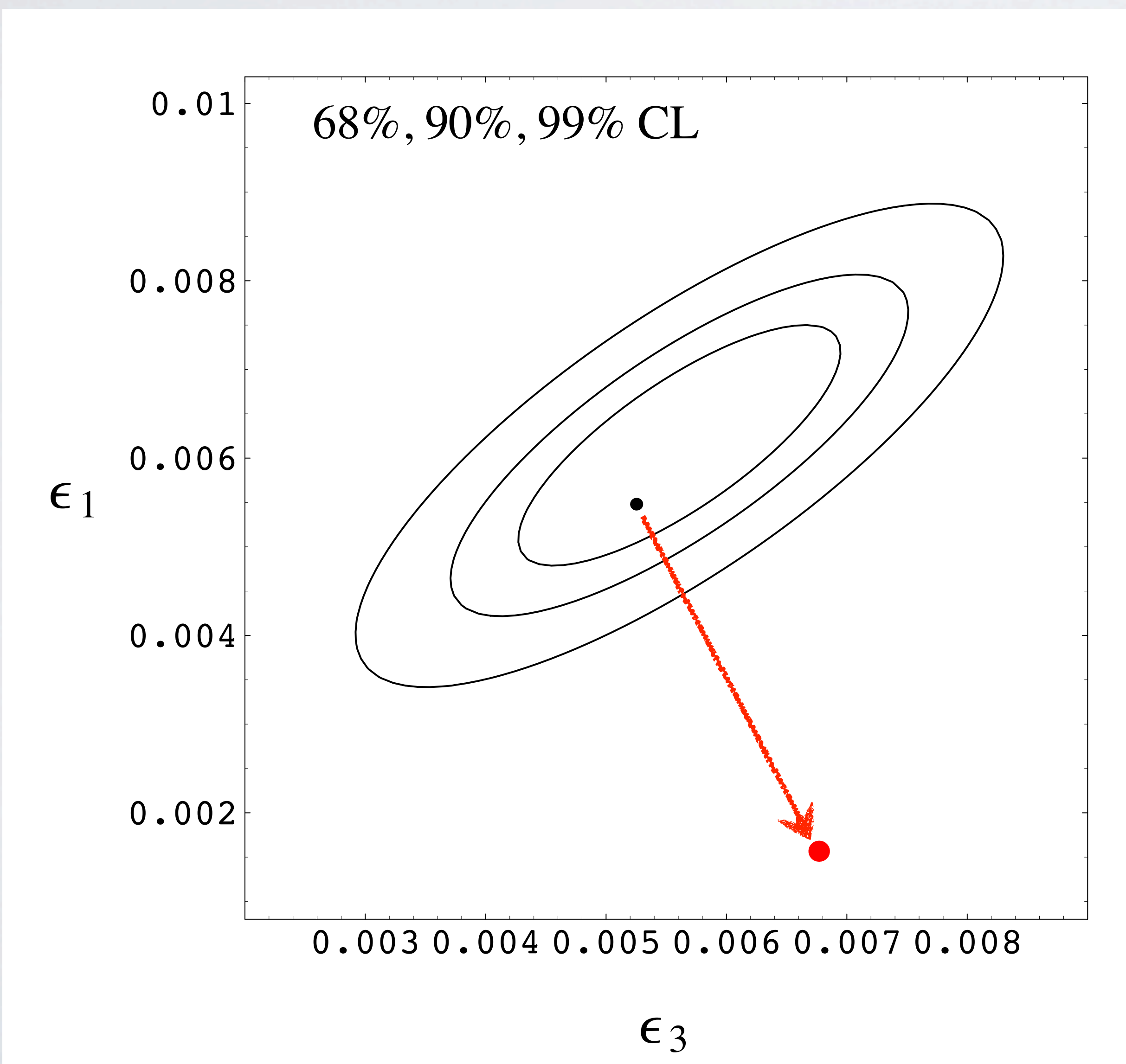
$$\Delta\epsilon_3 = \frac{g_2}{g_1} a_S(M_Z)$$

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









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

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

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

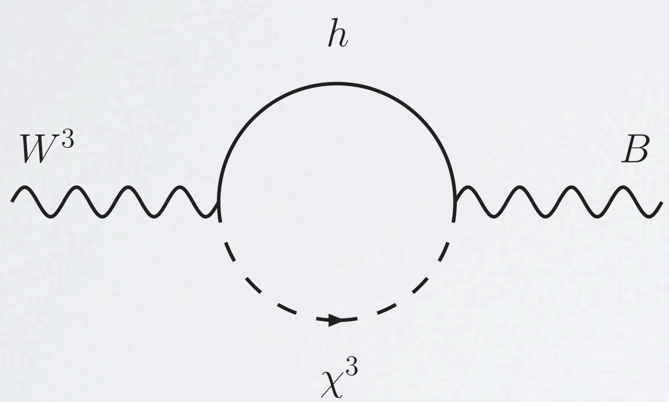
- Adding an extra scalar, singlet of the custodial SU(2)$_V$

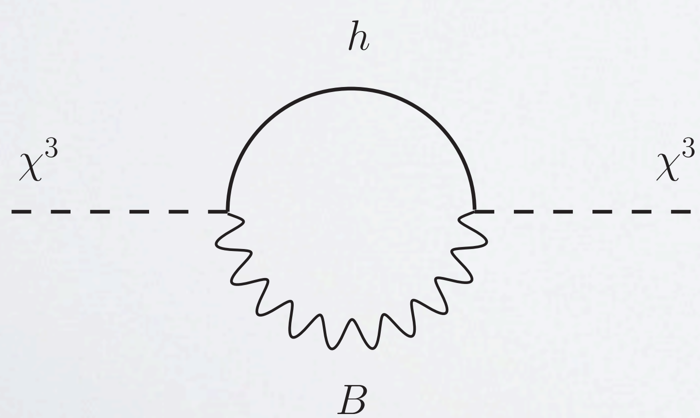
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D^\mu\Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) + V(h)$$

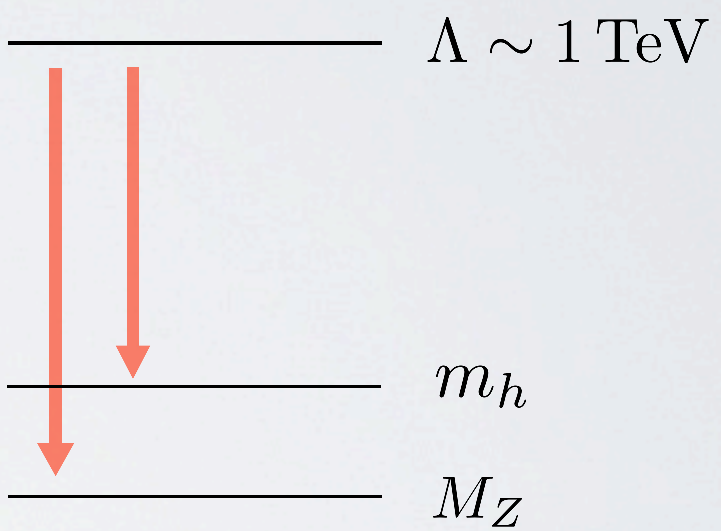
$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ d_L^{(i)}\right)\Sigma\left(1 + c\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

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

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

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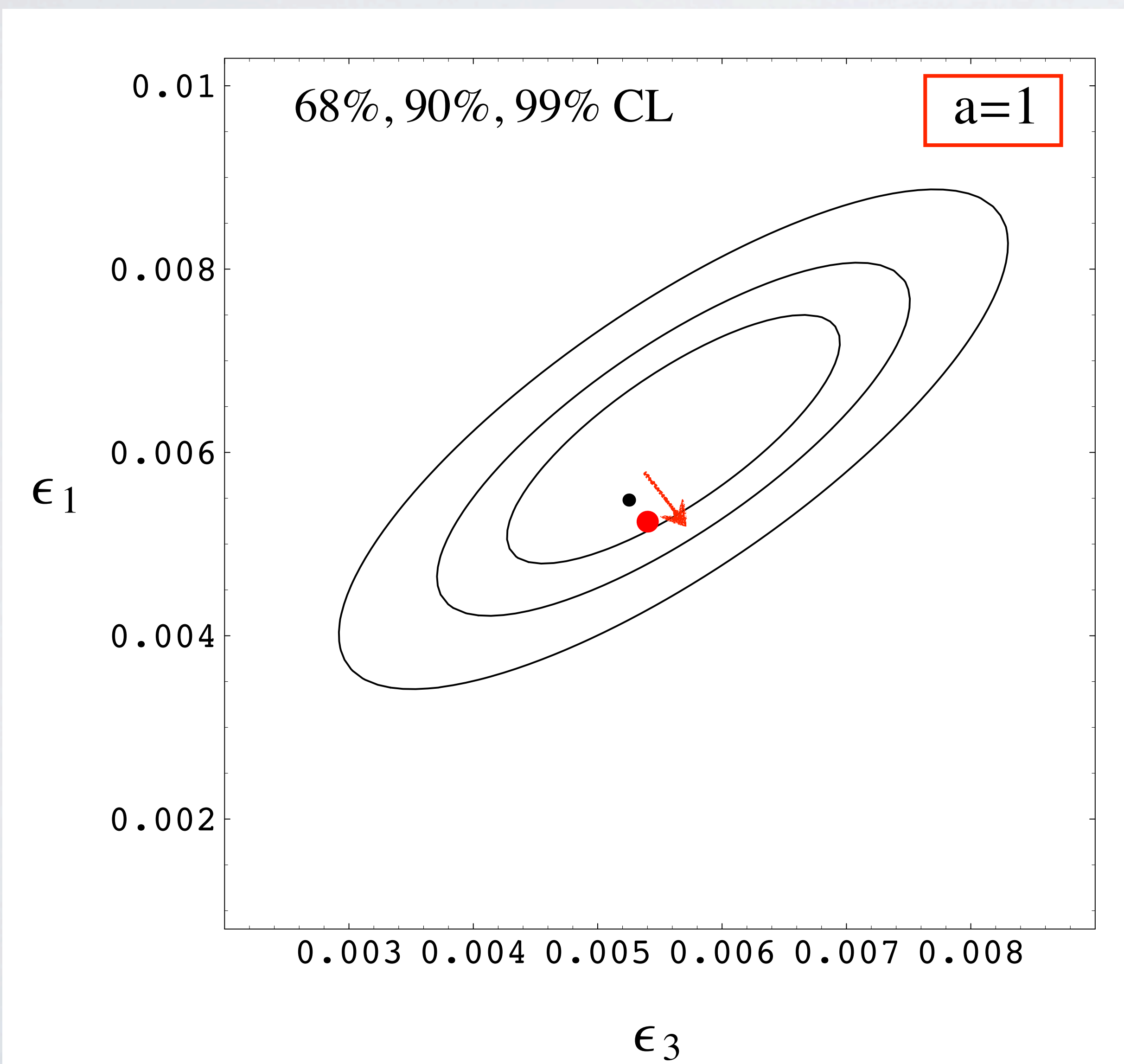
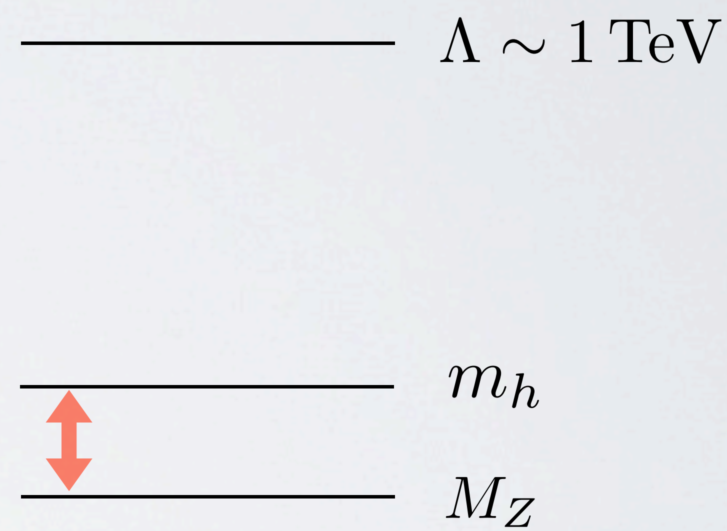
$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(u_L^{(i)}\ \ d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$





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

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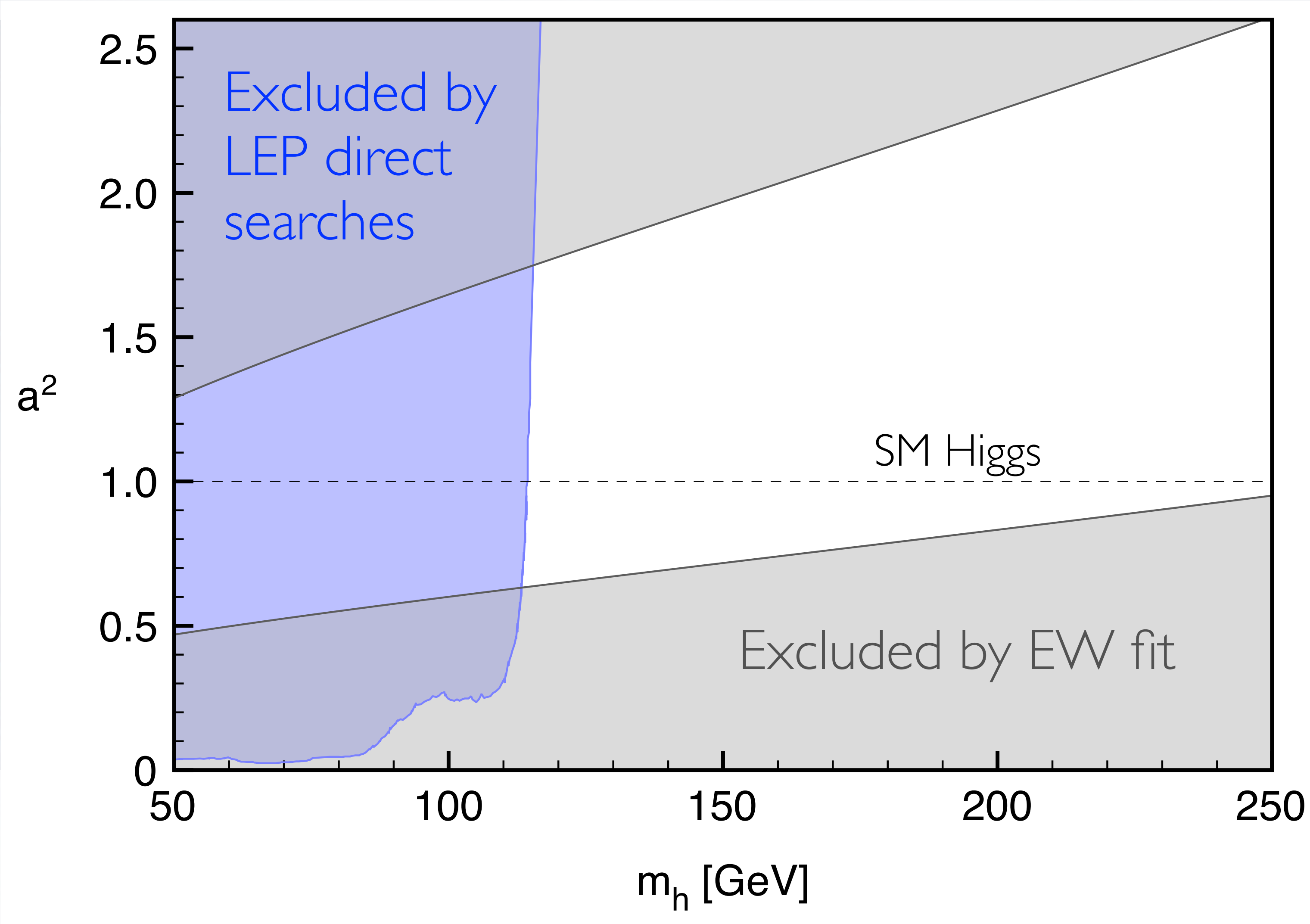
HOW `STANDARD` THE HIGGS MUST BE ?



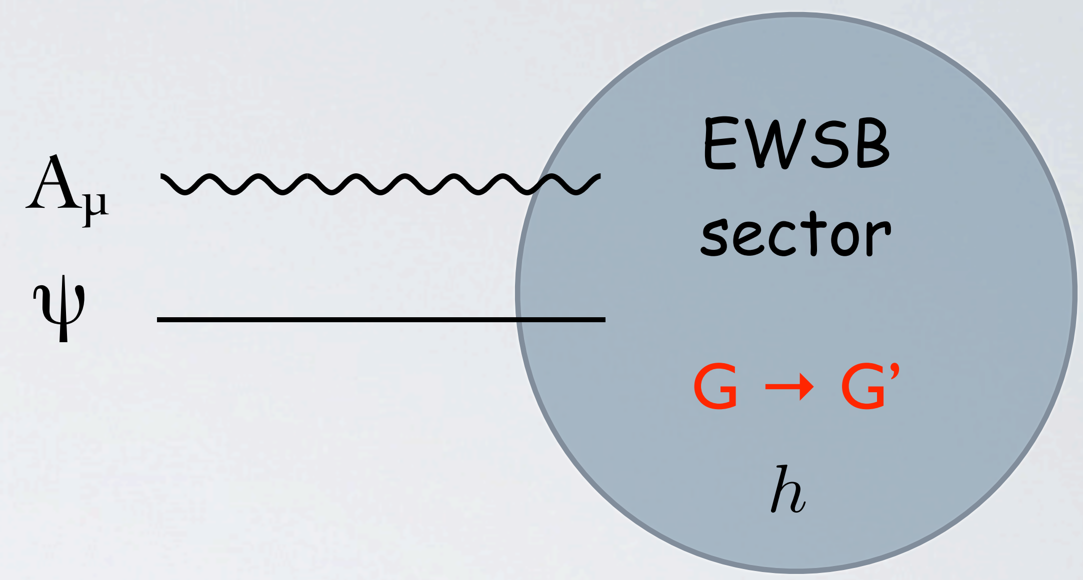
- Large deviations from a=1 still allowed for a light Higgs
- Presently <u>no</u> constraint on b,c

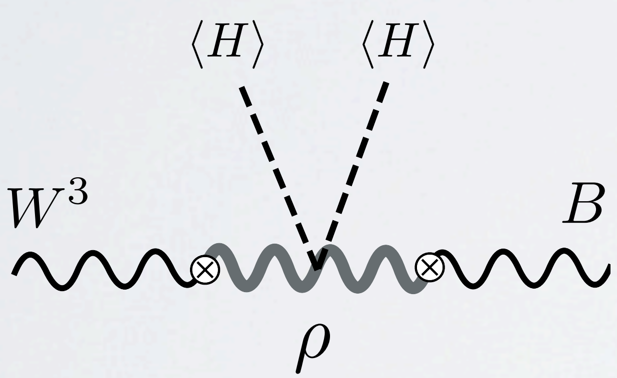
THE HIGGS AS A COMPOSITE PSEUDO-NG BOSON

[Georgi & Kaplan, `80]

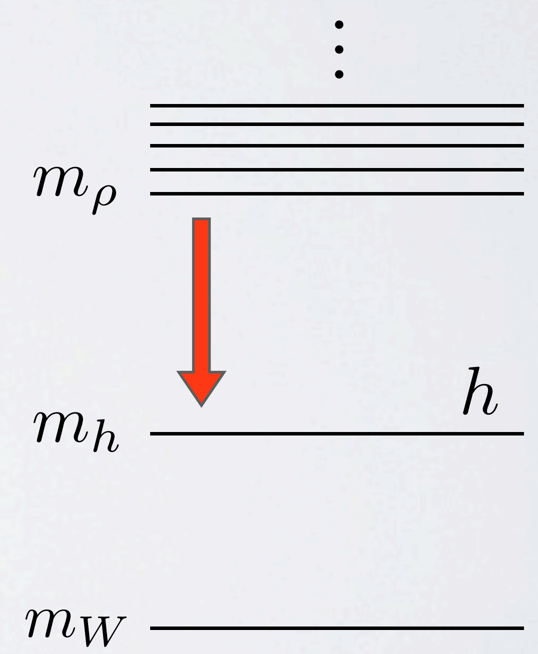
Motivations:

- light Higgs naturally
- contribution to EWPO from heavier resonances parametrically suppressed





$$\Delta\epsilon_3 \equiv \hat{S} \sim \frac{m_W^2}{m_\rho^2} \sim \frac{g^2}{16\pi^2} \times \frac{16\pi^2}{g_\rho^2} \times \frac{v^2}{f^2}$$



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

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

- Shifts in the Higgs couplings at $O(\xi)$

Given the σ-model Lagrangian a, b predicted in terms of ξ :

Ex: SO(5) → SO(4)

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

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

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

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

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

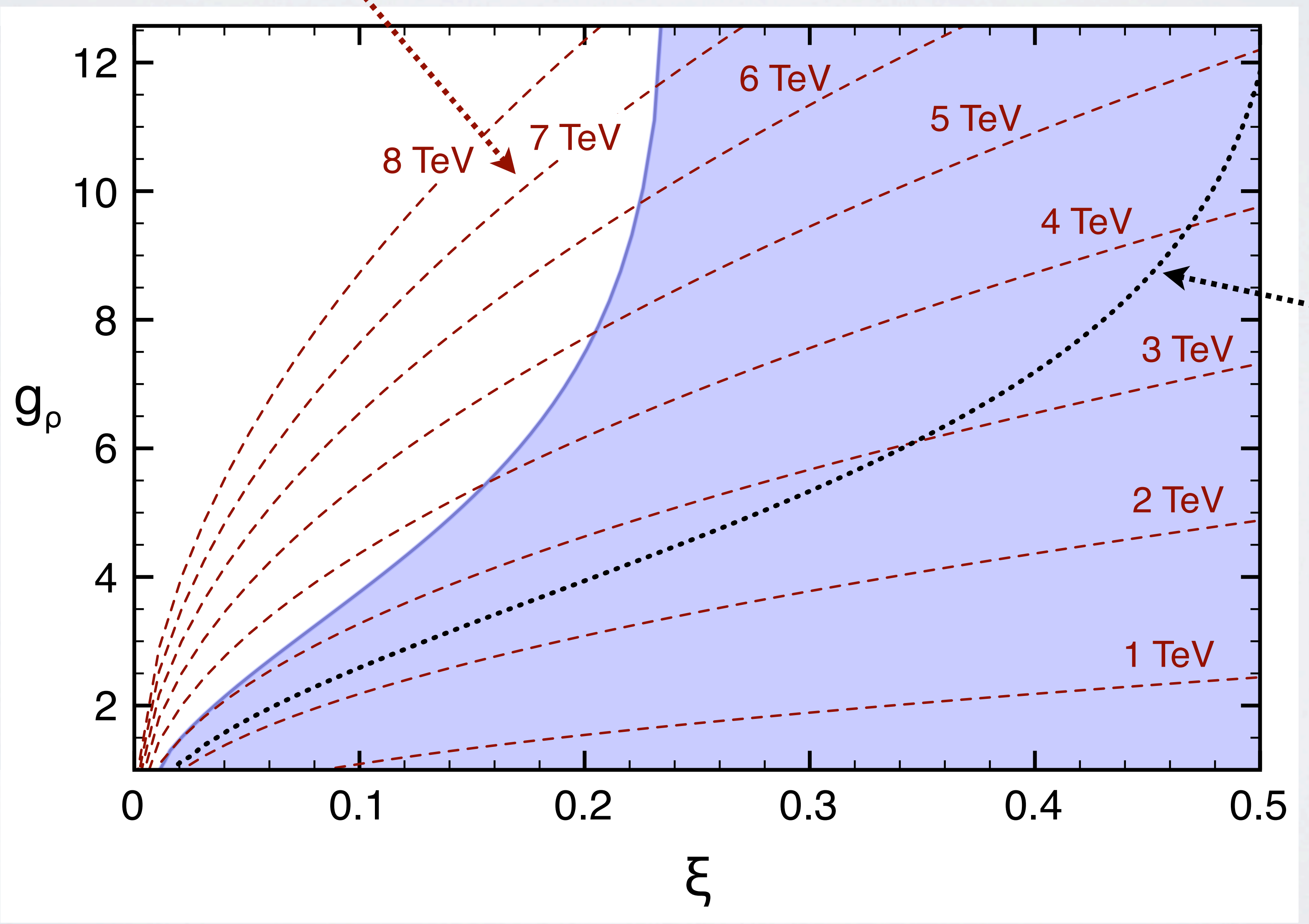
HOW MUCH COMPOSITE THE pNG HIGGS CAN BE ?

Ex: SO(5) → SO(4)

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

$$m_\rho = \frac{3}{8\pi}\frac{g_\rho v}{\sqrt{\xi}} \qquad a = \sqrt{\xi - 1}$$

isocurves of constant m_ρ

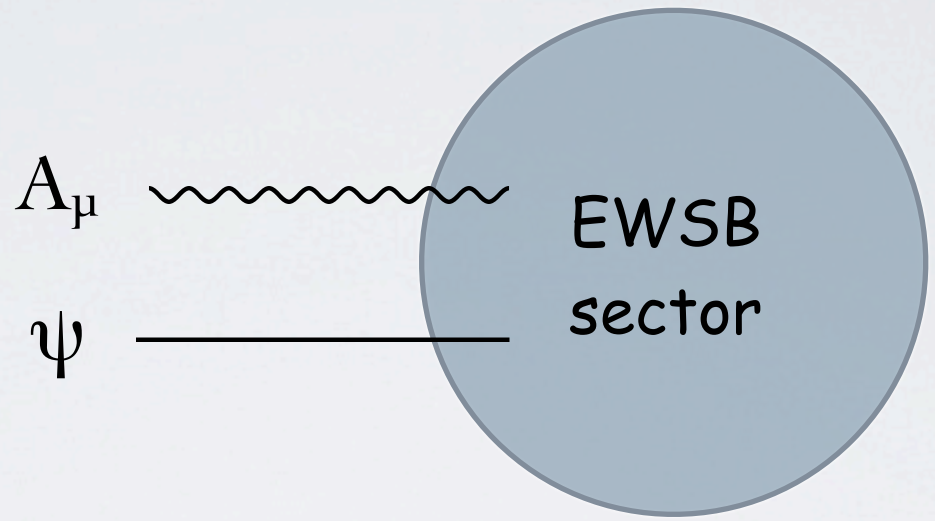


adding an extra
$\Delta\rho = +2 \times 10^{-3}$

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:

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

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

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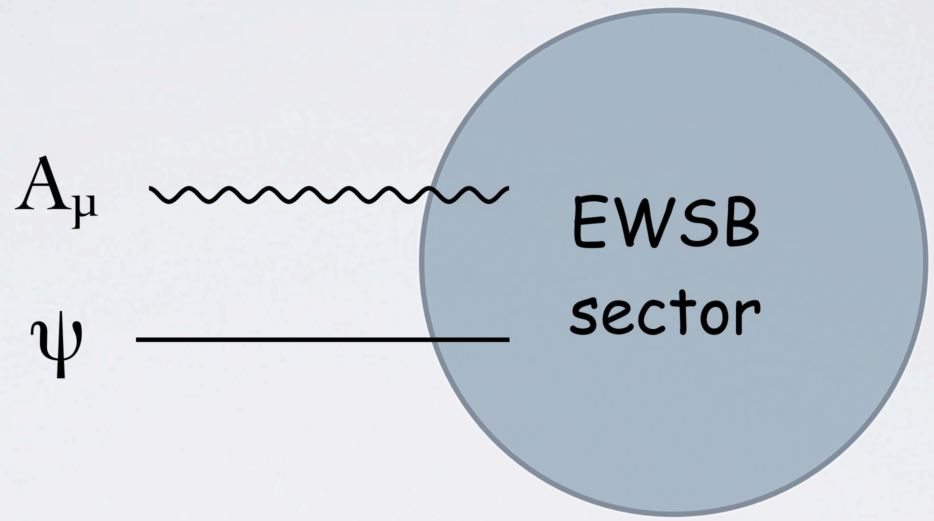


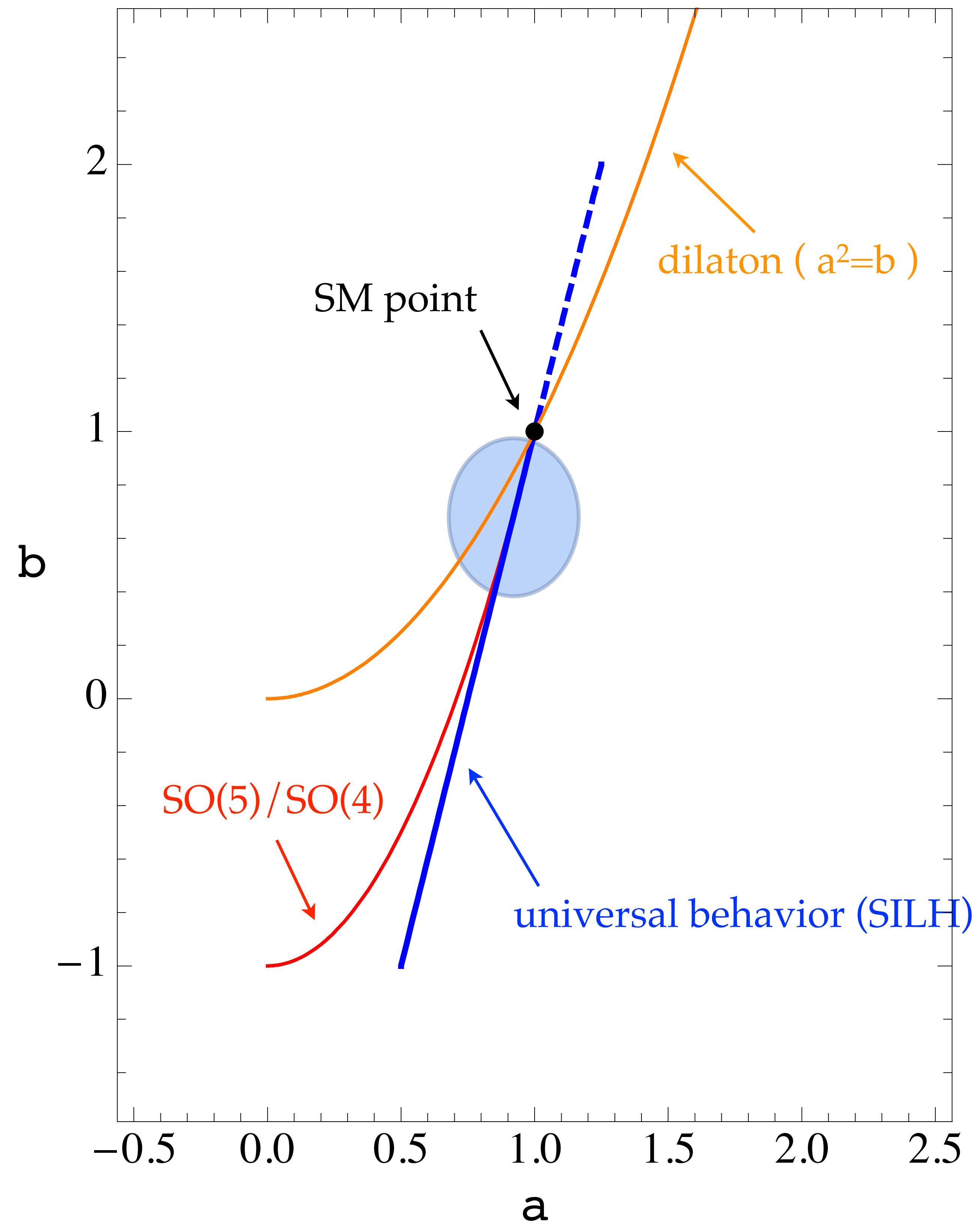
$$= \left\{ \chi^a,\ \phi,\ \ldots \right\}$$

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:

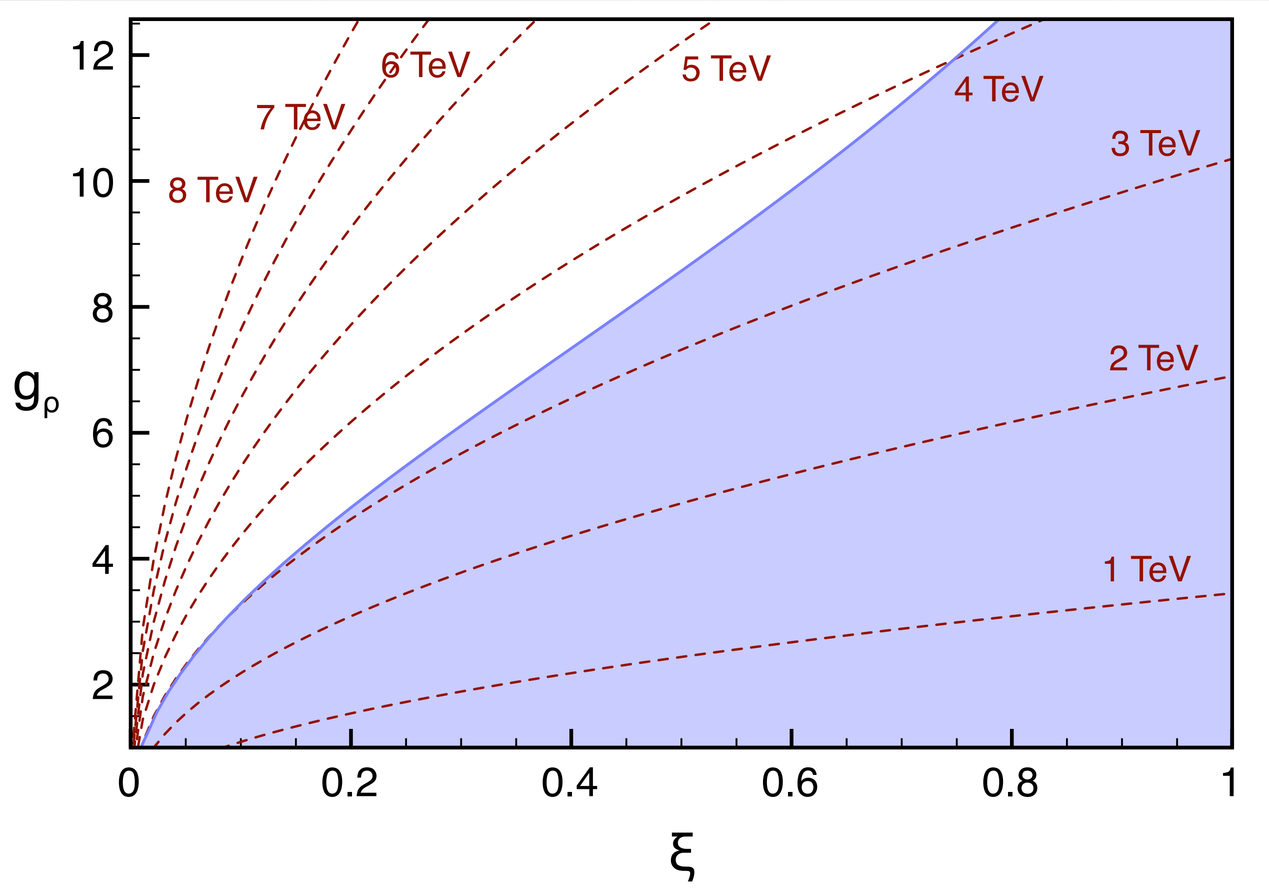
$$a^2 = b = c^2 \qquad a = \frac{v}{f_D}$$



dilaton (a²=b)
SM point
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

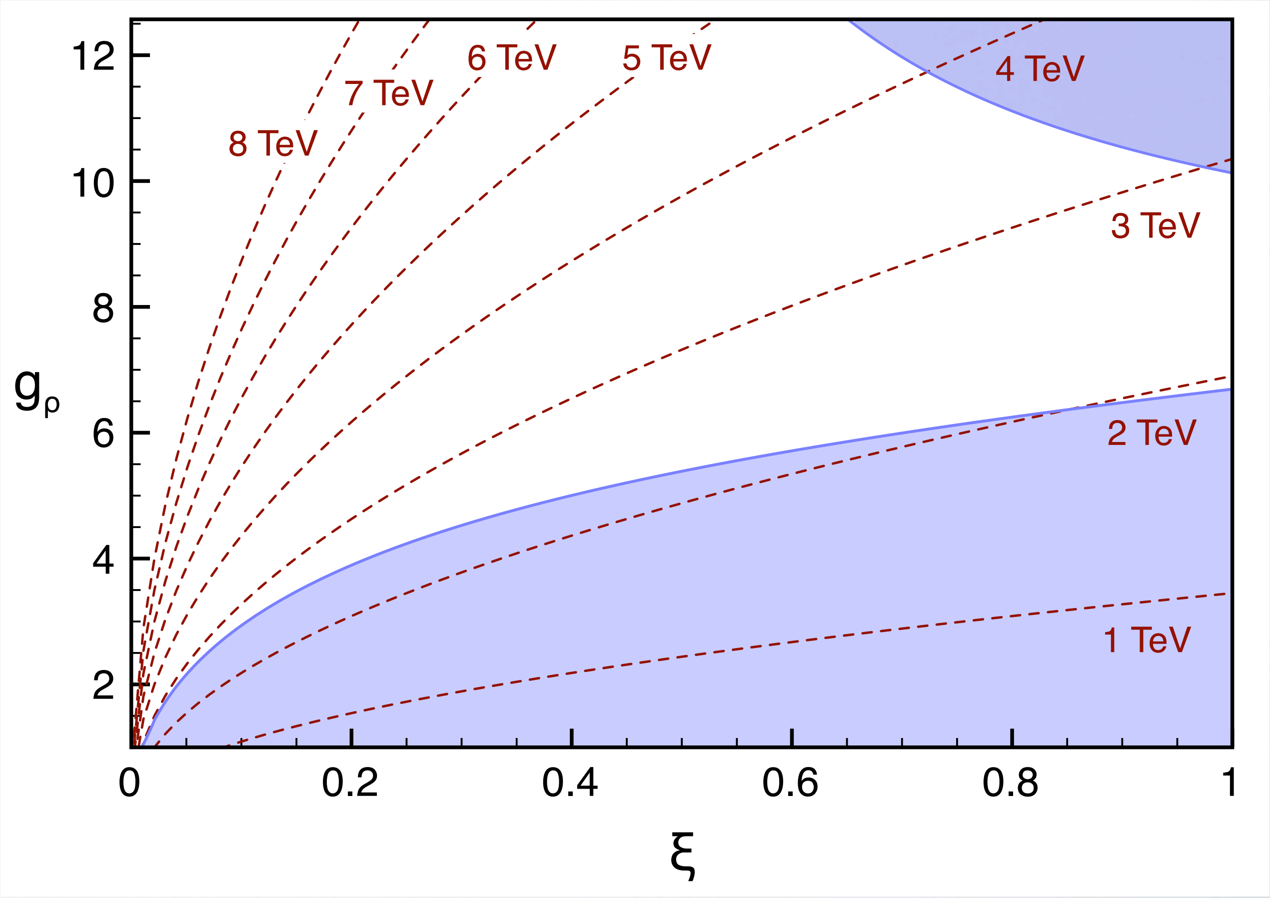
PNGB HIGGS + DILATON

[Work in progress with A. Pomarol and R. Rattazzi]



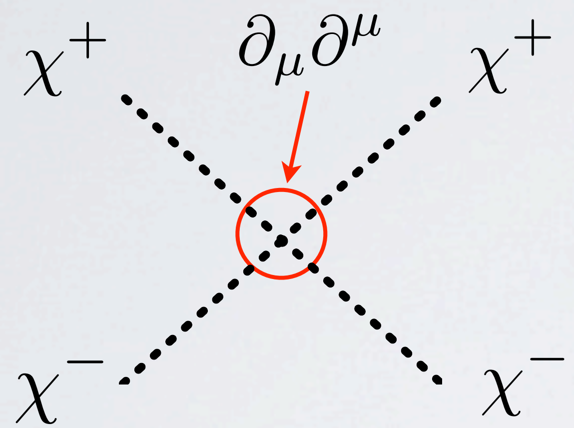
$m_h = 120\,\text{GeV} \quad m_D = 250\,\text{GeV} \quad f_D = f$

$m_h = 120\,\text{GeV} \quad m_D = 250\,\text{GeV} \quad f_D = f/1.5$



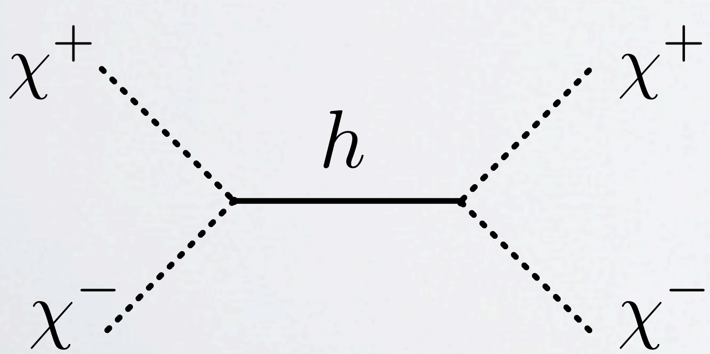
WW SCATTERING

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



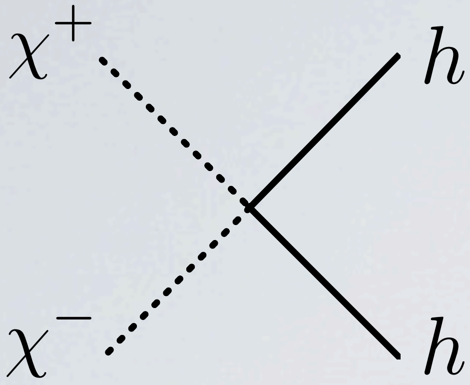
$$A(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}(s+t)$$

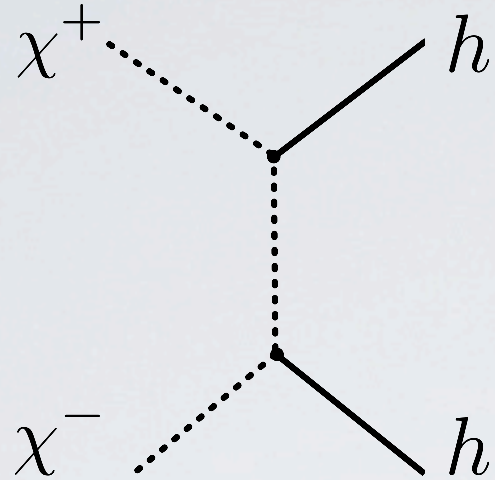
- The Higgs contributes to the scattering



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

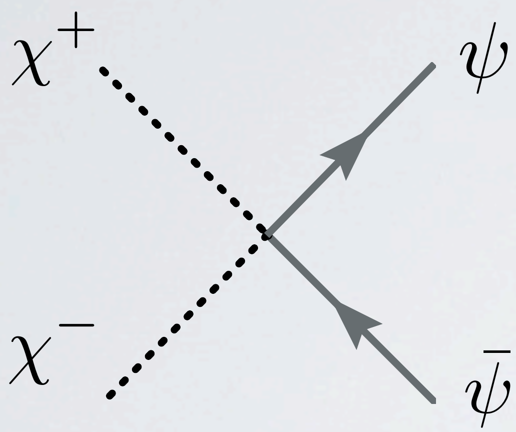
unitarity for: a=1

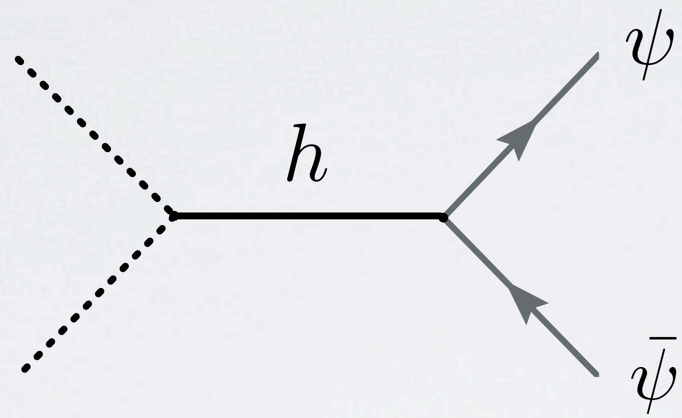




$$\mathcal{A}(\chi^+\chi^- \to hh) \simeq \frac{s}{v^2}(b - a^2)$$

unitarity for: $a^2=b$





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

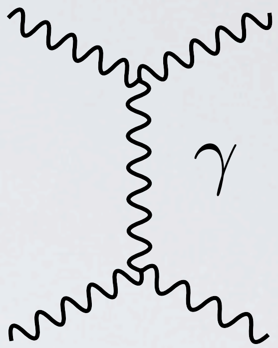
unitarity for: a=c

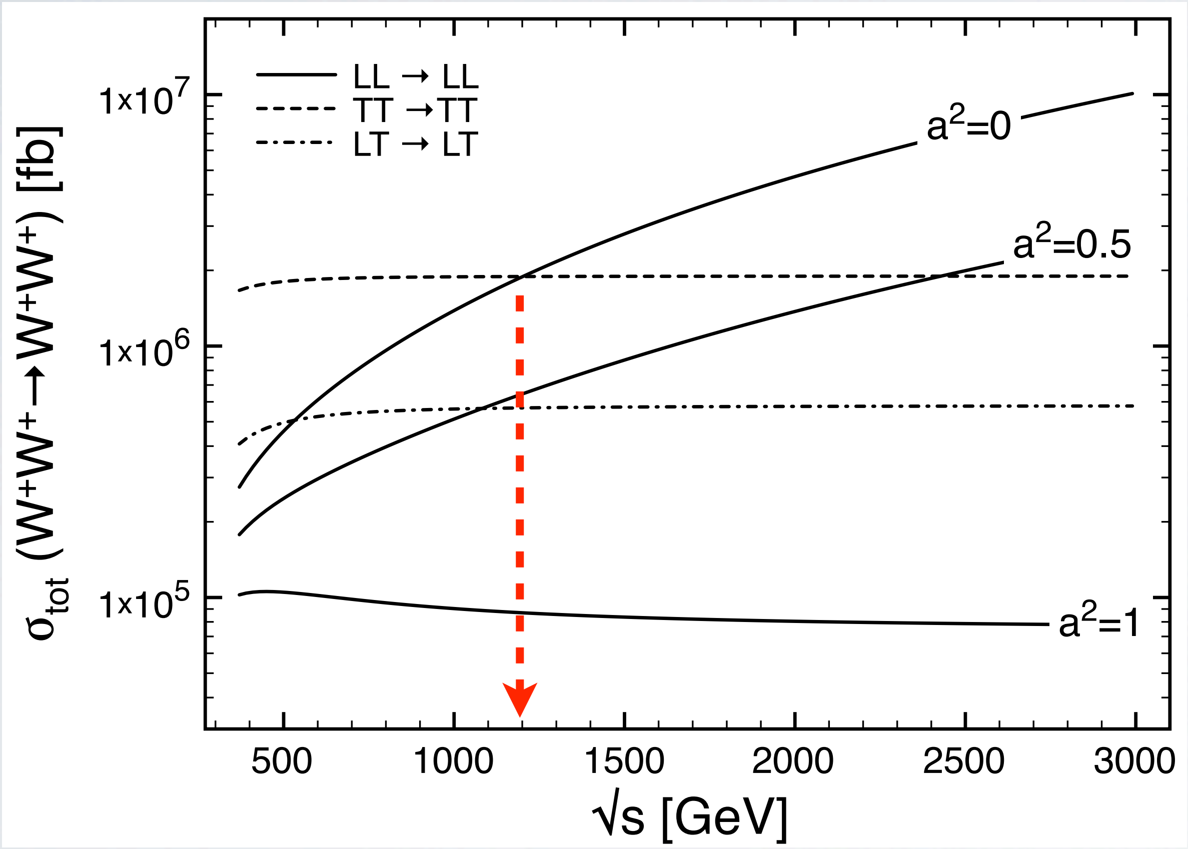
- No strong $W_L W_L \to hh$ for a dilaton ($a^2=b$)
- In general a,b,c control three different sectors of the theory

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

Extracting a from WW→WW scattering

Coulomb singularity enhances the TT scattering at small t





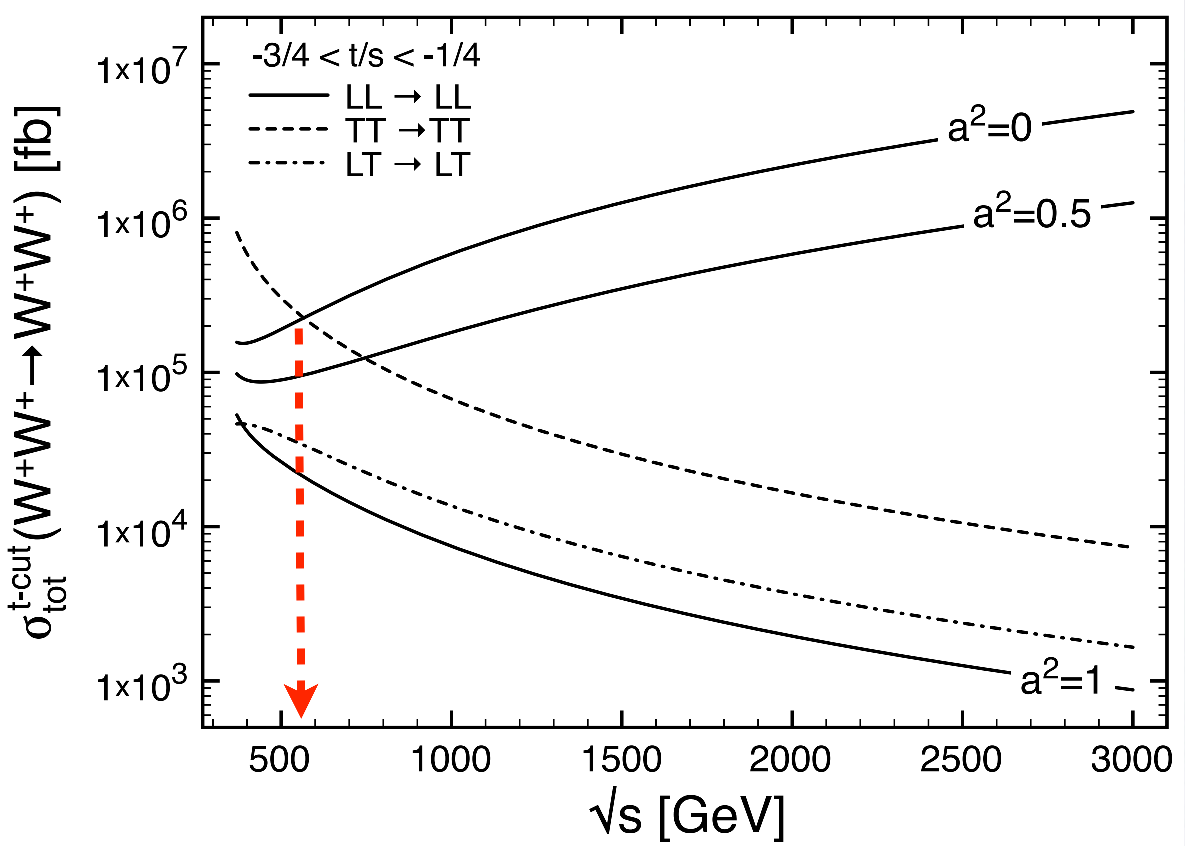
$$\sigma_{TT} \sim \frac{g^4}{8\pi} \frac{1}{t_{min}} \qquad \sigma_{LL} \sim \frac{(1-a^2)^2}{8\pi} \frac{s}{v^4}$$

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

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

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

$$t_{min} \sim s$$

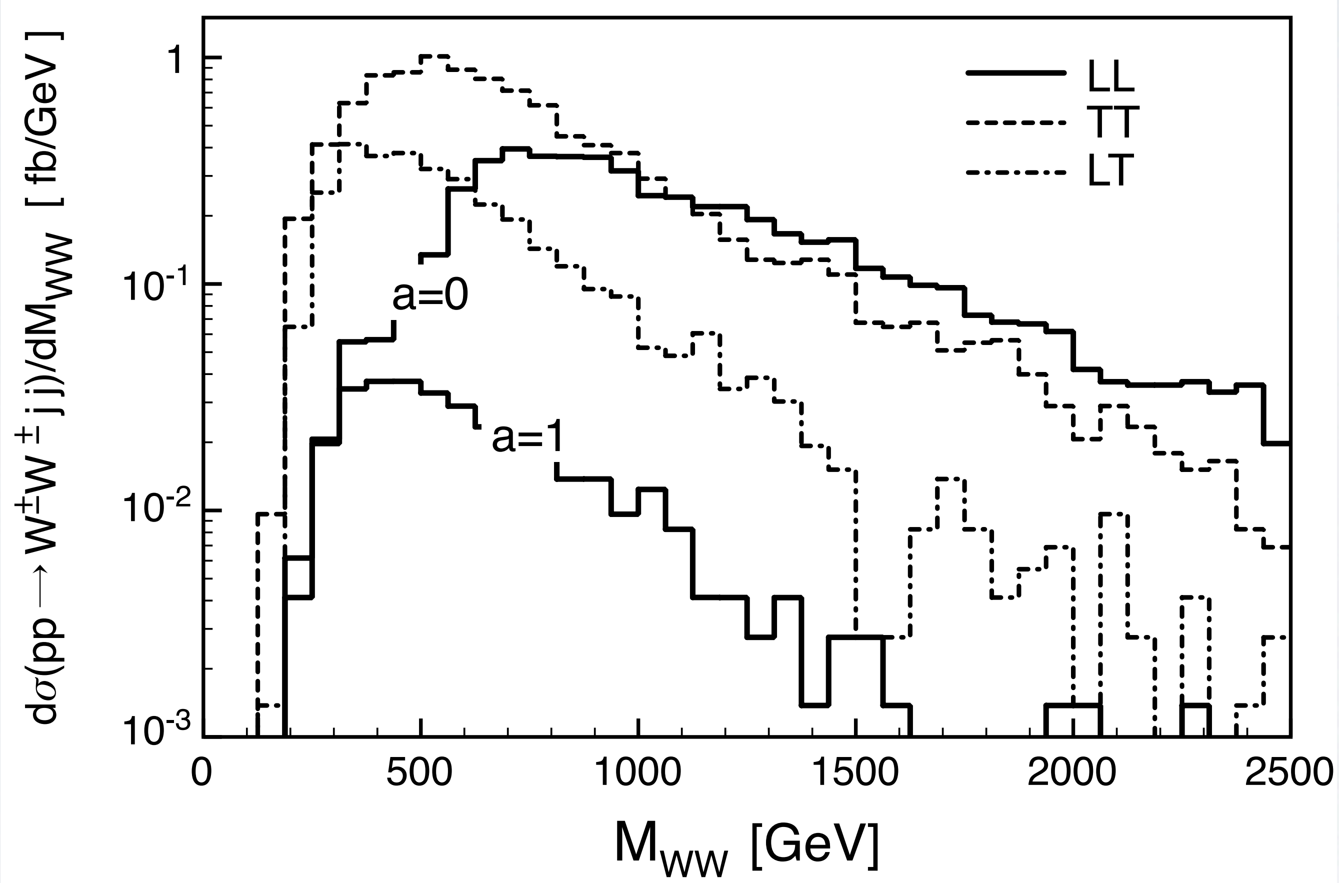
$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} \sim \frac{(1-a^2)^2}{2304}\,\frac{s^2}{M_W^4}$$

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

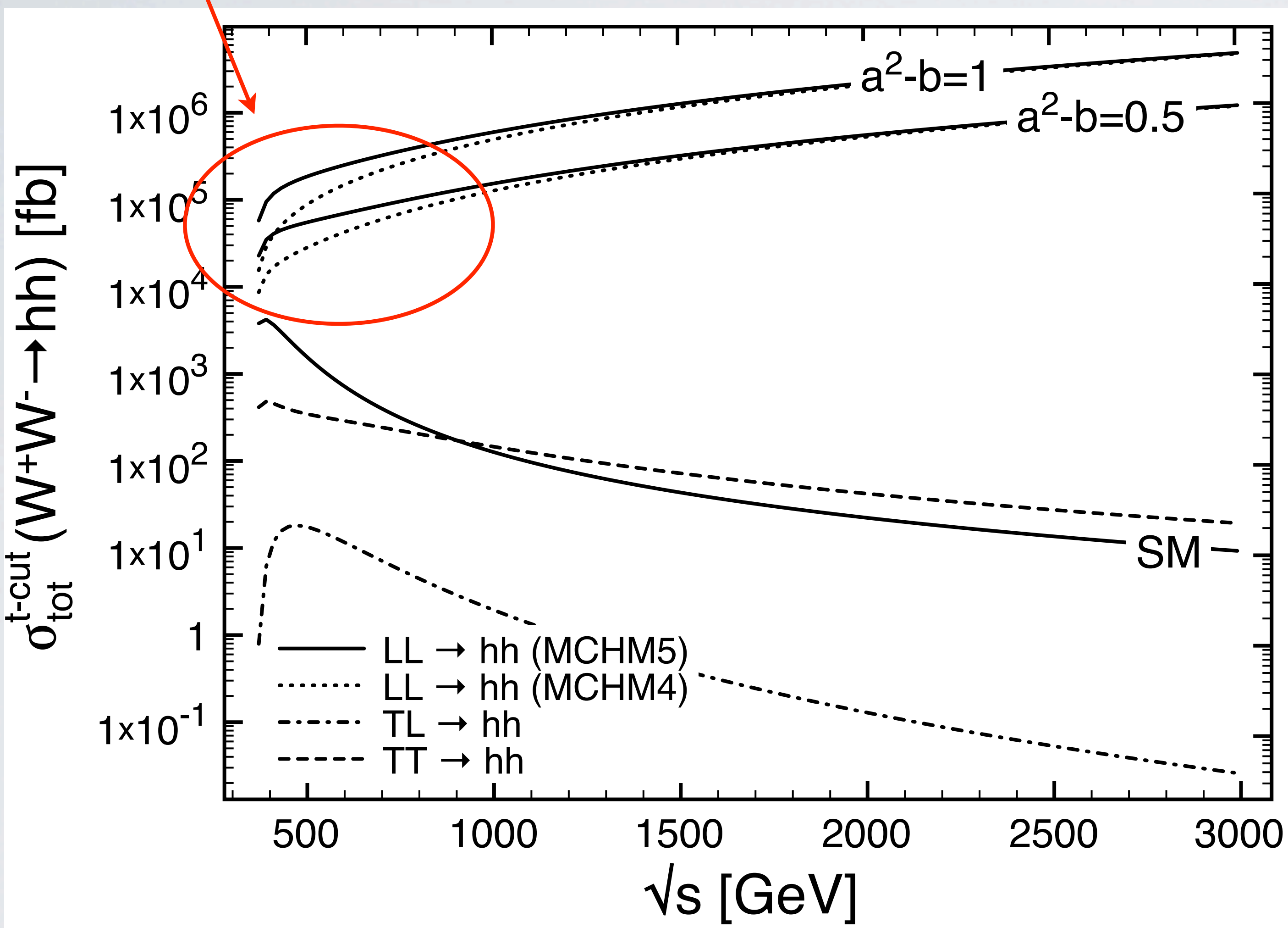
- LHC at 14 TeV sensitive to $a^2 \lesssim 0.5$ with 100 fb^{-1}

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

Extracting b from WW→hh scattering

model dependency

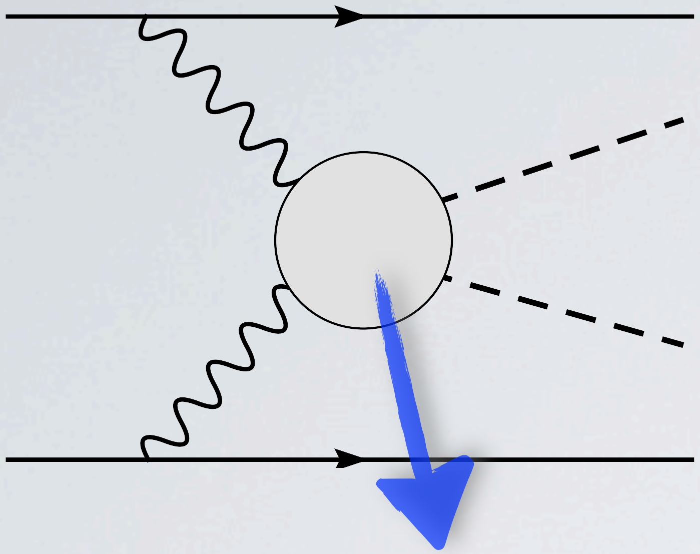
$m_h = 180\,\mathrm{GeV}$



Naive estimate works well

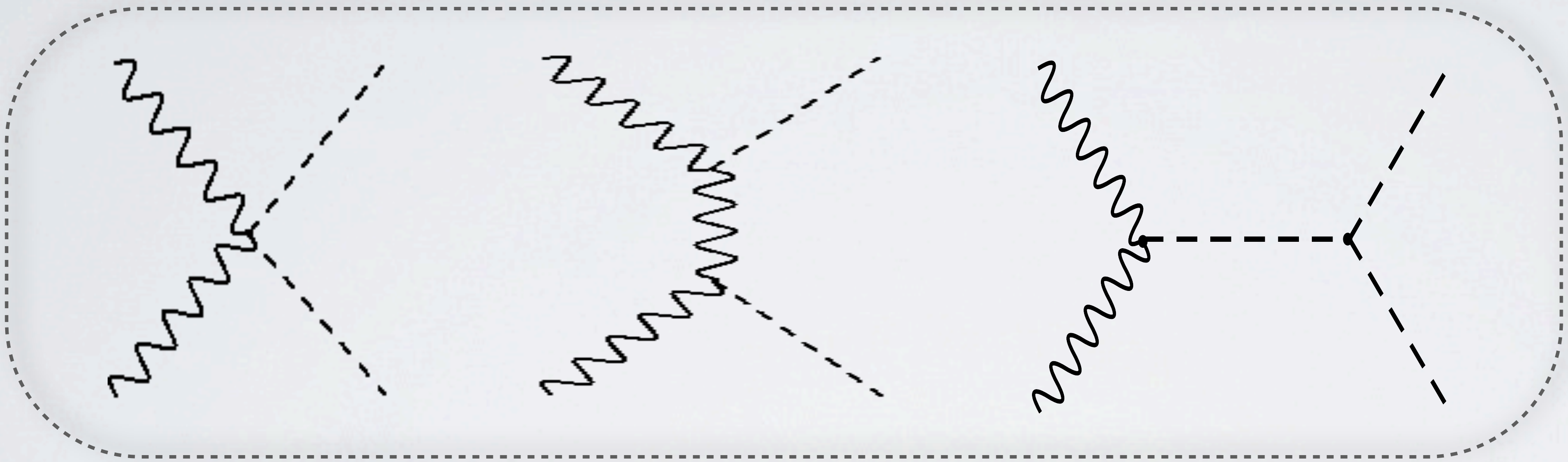
$$\frac{d\sigma_{LL\to hh}/dt}{d\sigma_{TT\to hh}/dt} \sim \frac{1}{8}\,\frac{(b-a^2)^2}{a^4+(b-a^2)^2}\,\frac{s^2}{M_W^4}$$

- 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	

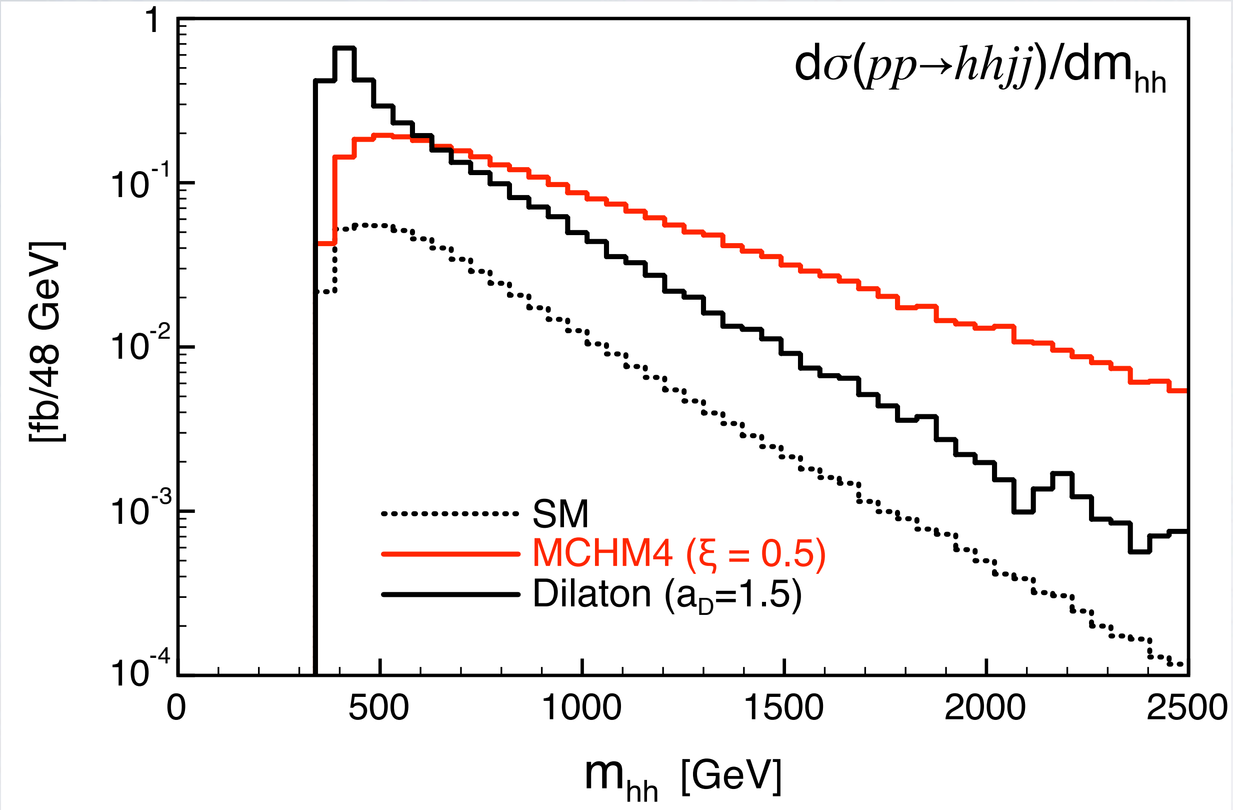
$m_h = 180\,\mathrm{GeV}$

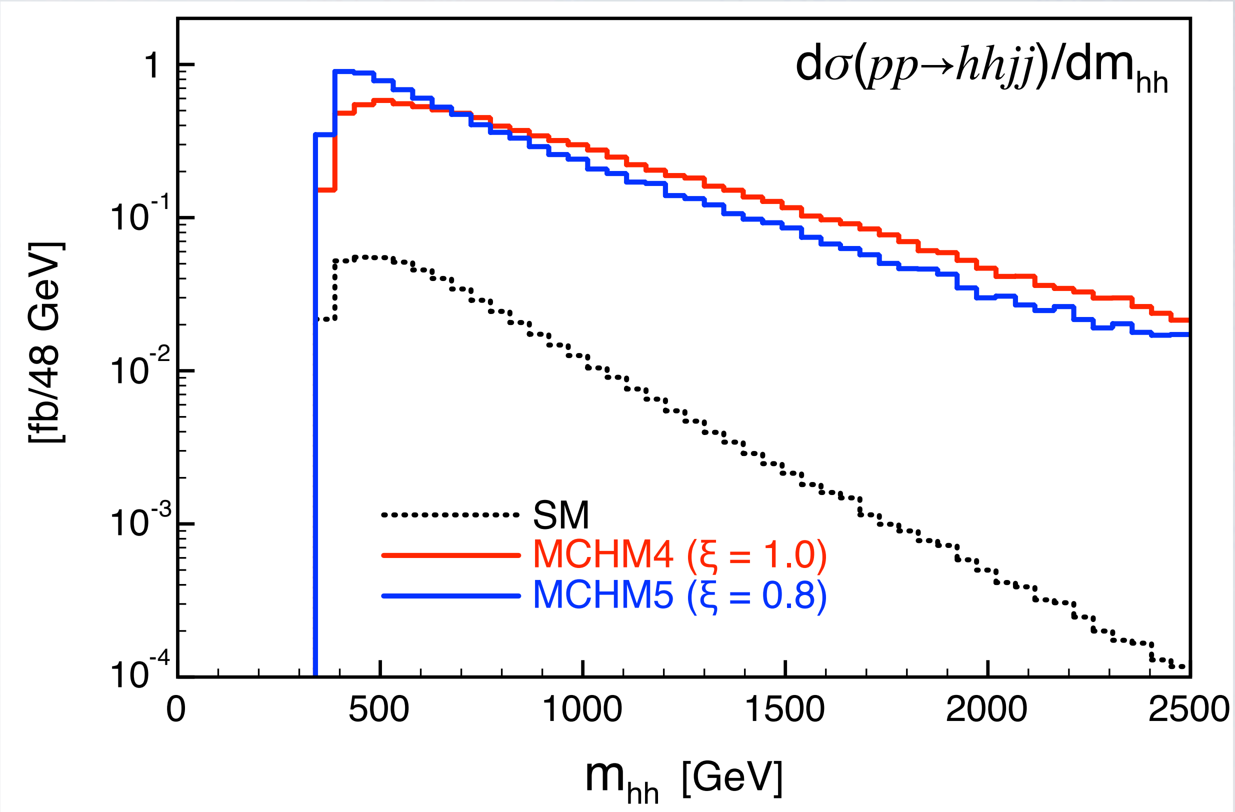


$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \dots$$

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

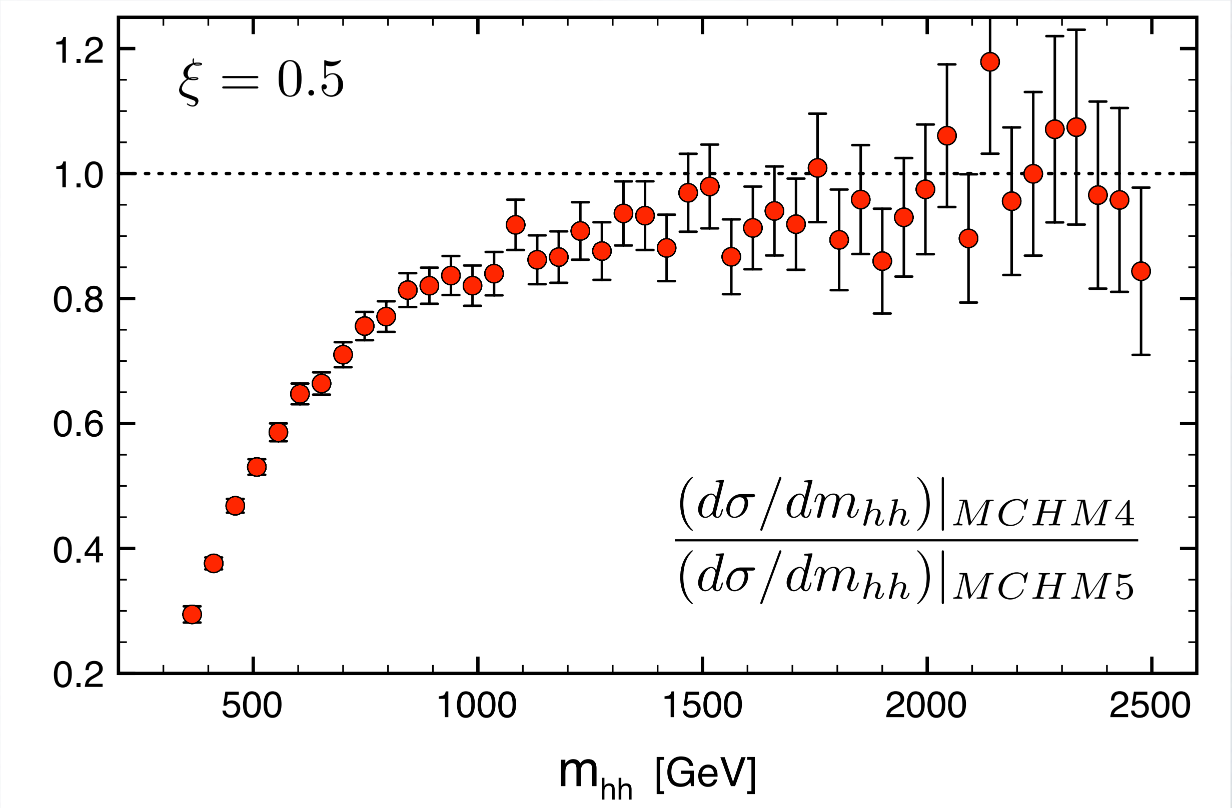
Breaking the model degeneracy



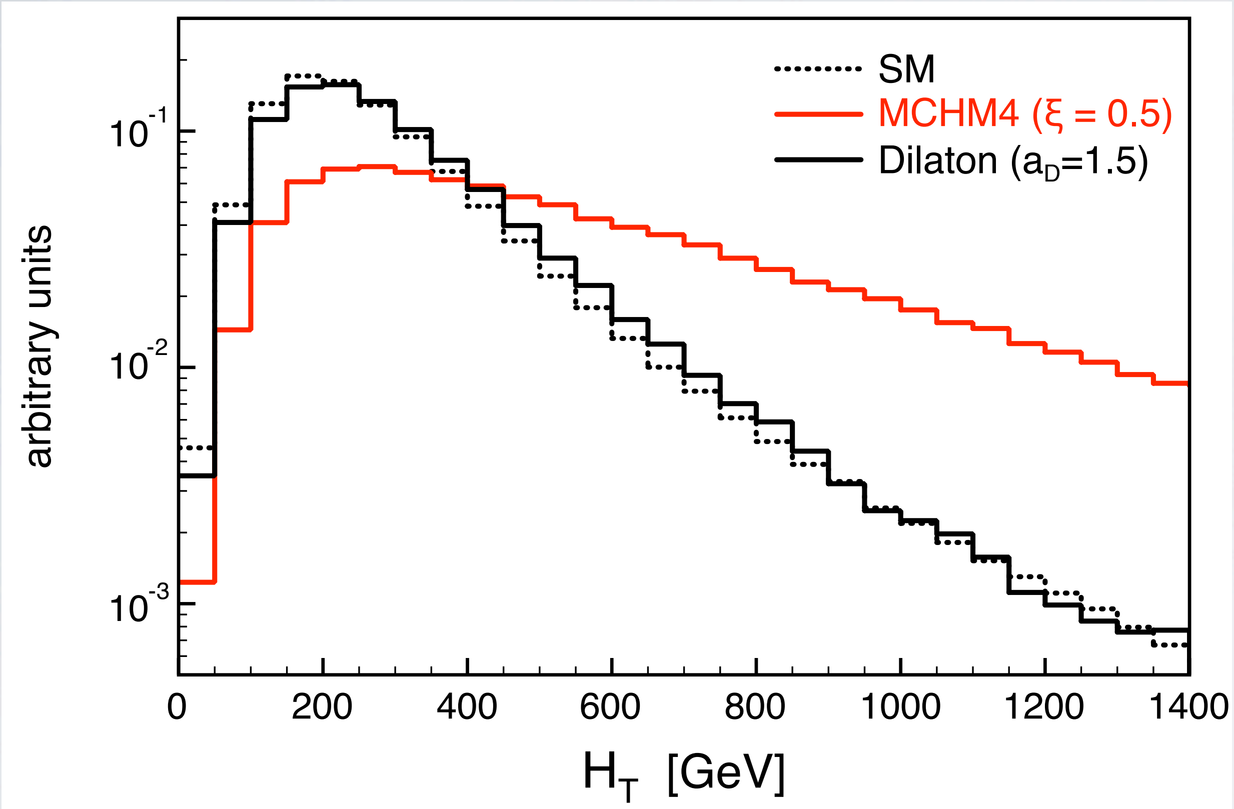


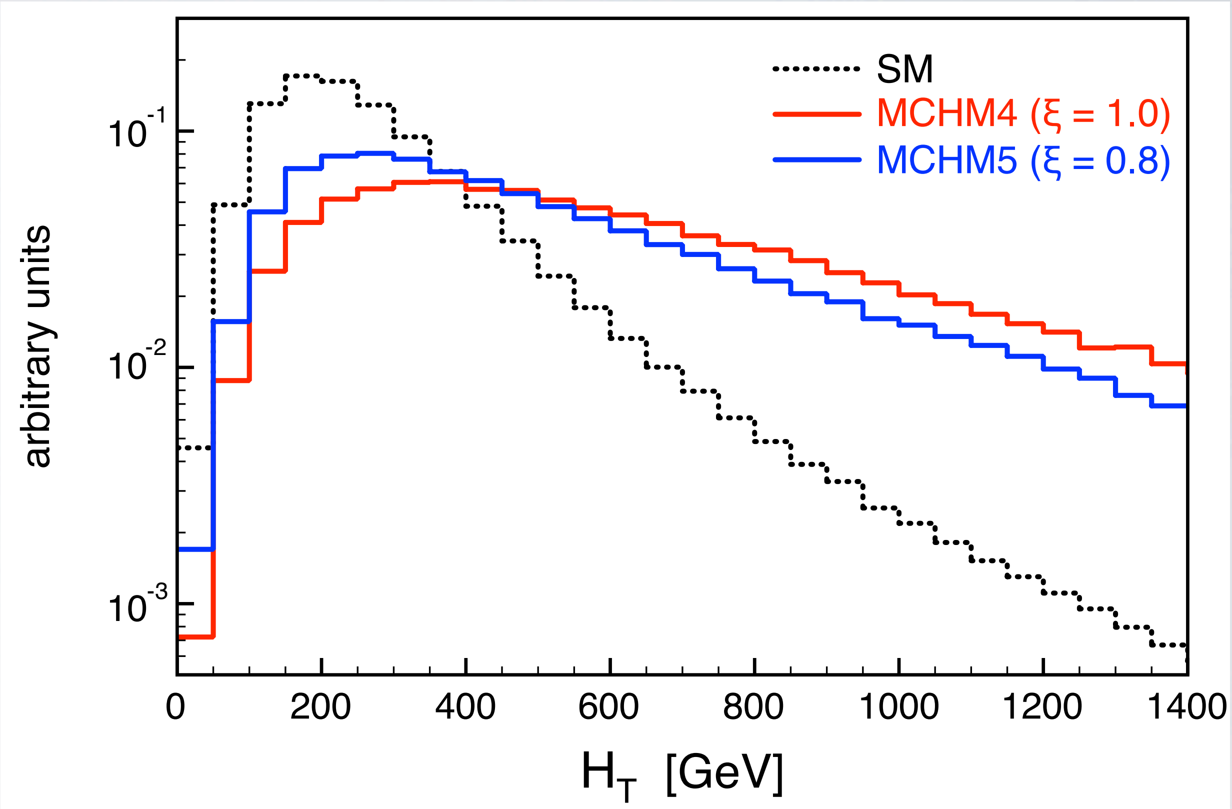
$$\frac{d\sigma}{dm_{hh}^2} = \frac{1}{m_{hh}^2}\,\hat{\sigma}(W_iW_j \to hh)\,\rho_W^{ij}(m_{hh}^2/s, Q^2)$$

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

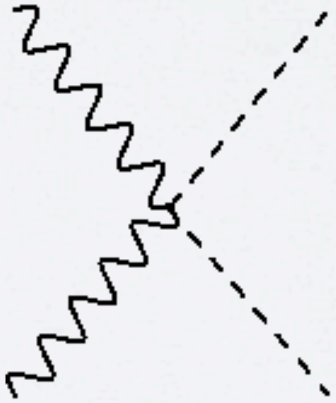


Breaking the model degeneracy





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



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%	

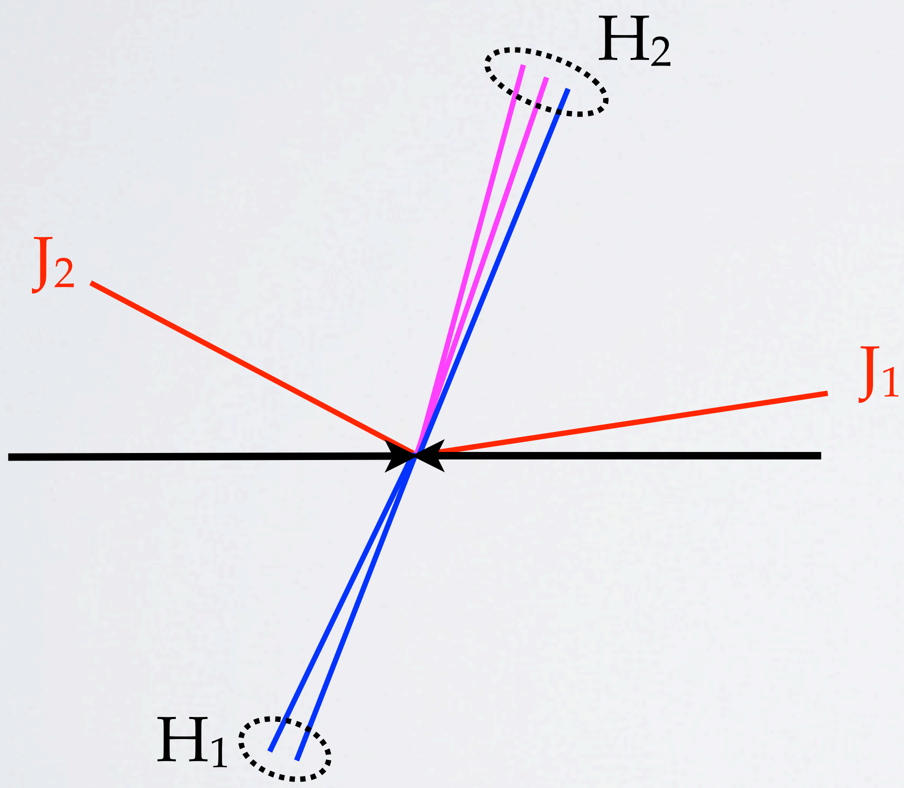
[last step for Bckg: $\sim 3 \times 10^{-4}$]

- 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

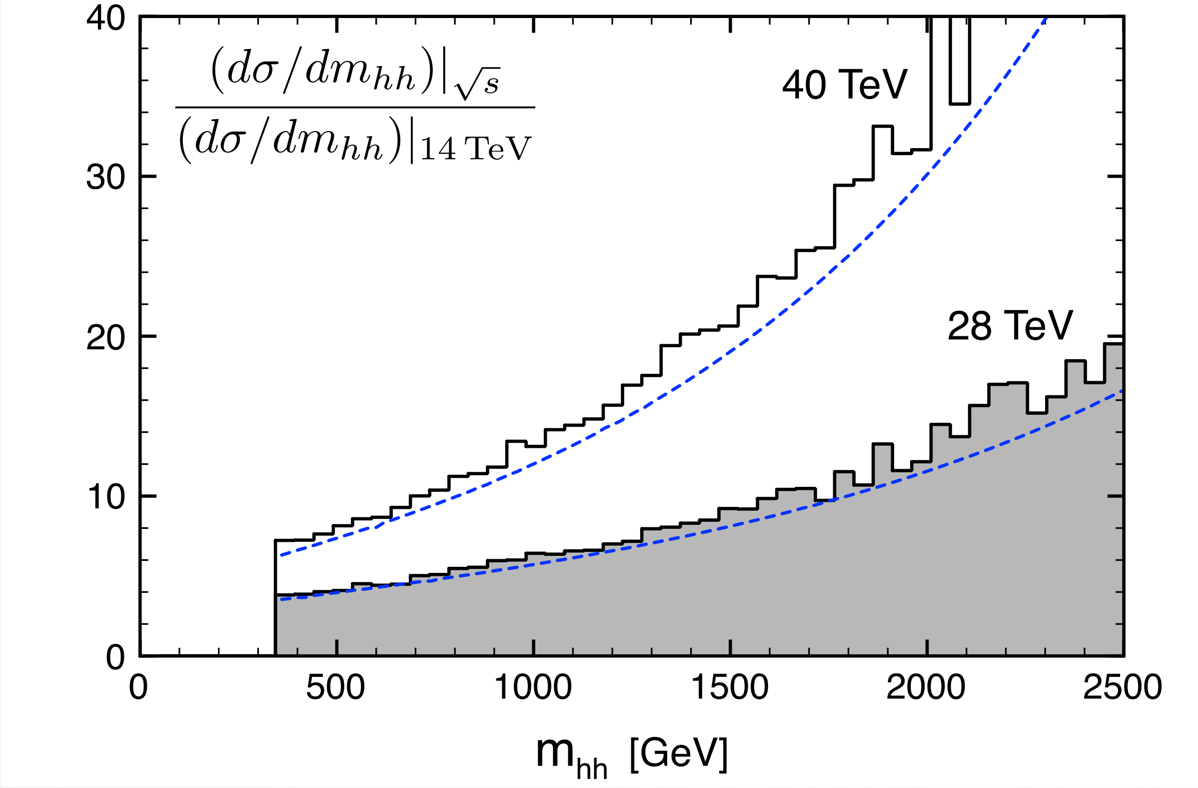
LUMINOSITY VS ENERGY UPGRADE

- 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

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

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

- New strategy (e.g. using jet substructure) required to study events at large m_{hh}

- Additional channels to be studied (ex: hh→bb$\tau\tau$)