Alternatives to the SM Higgs
a review

XLVIth Rencontres de Moriond

La Thuile, March 14th 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

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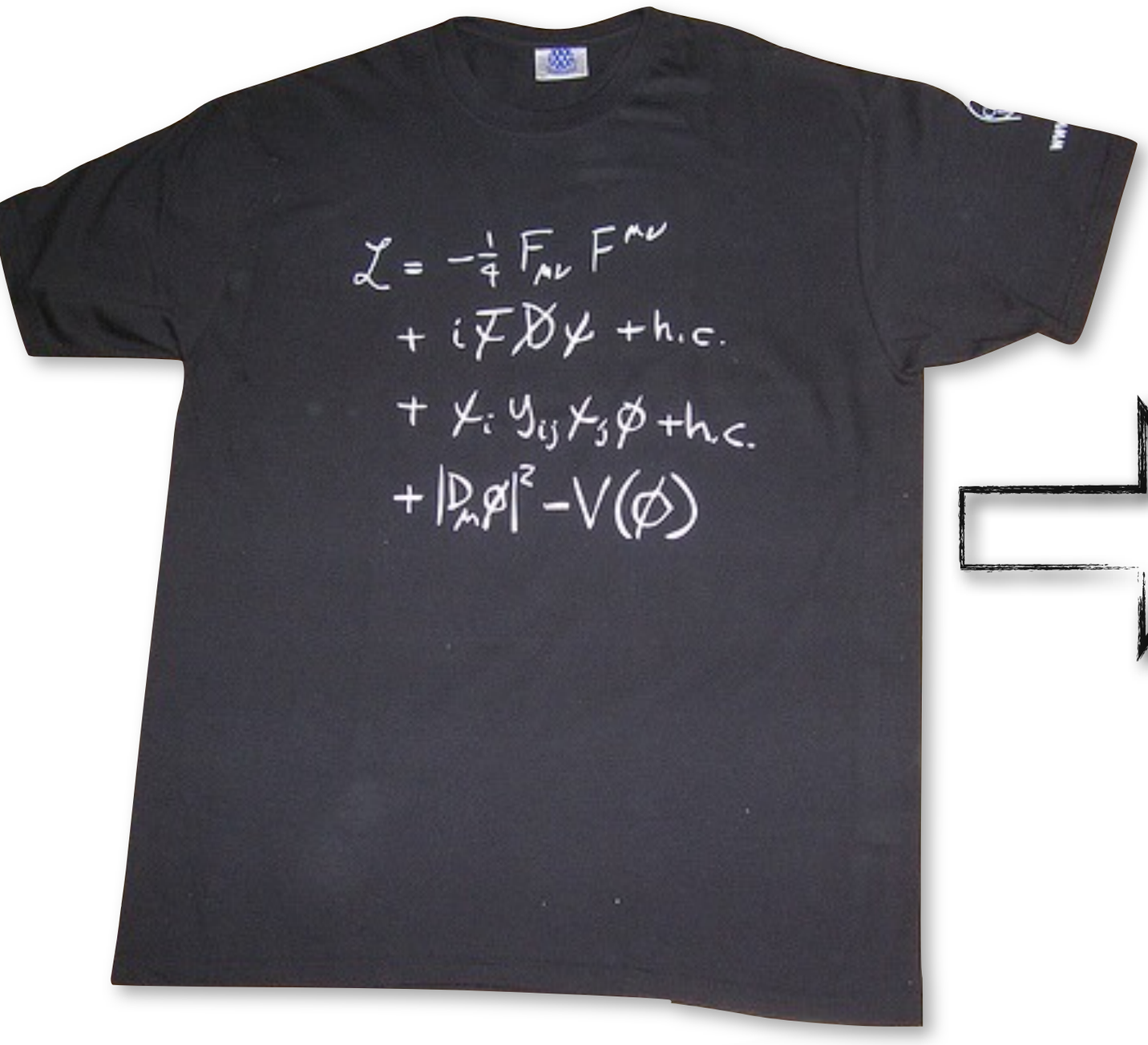
John Ellis' tee-shirt



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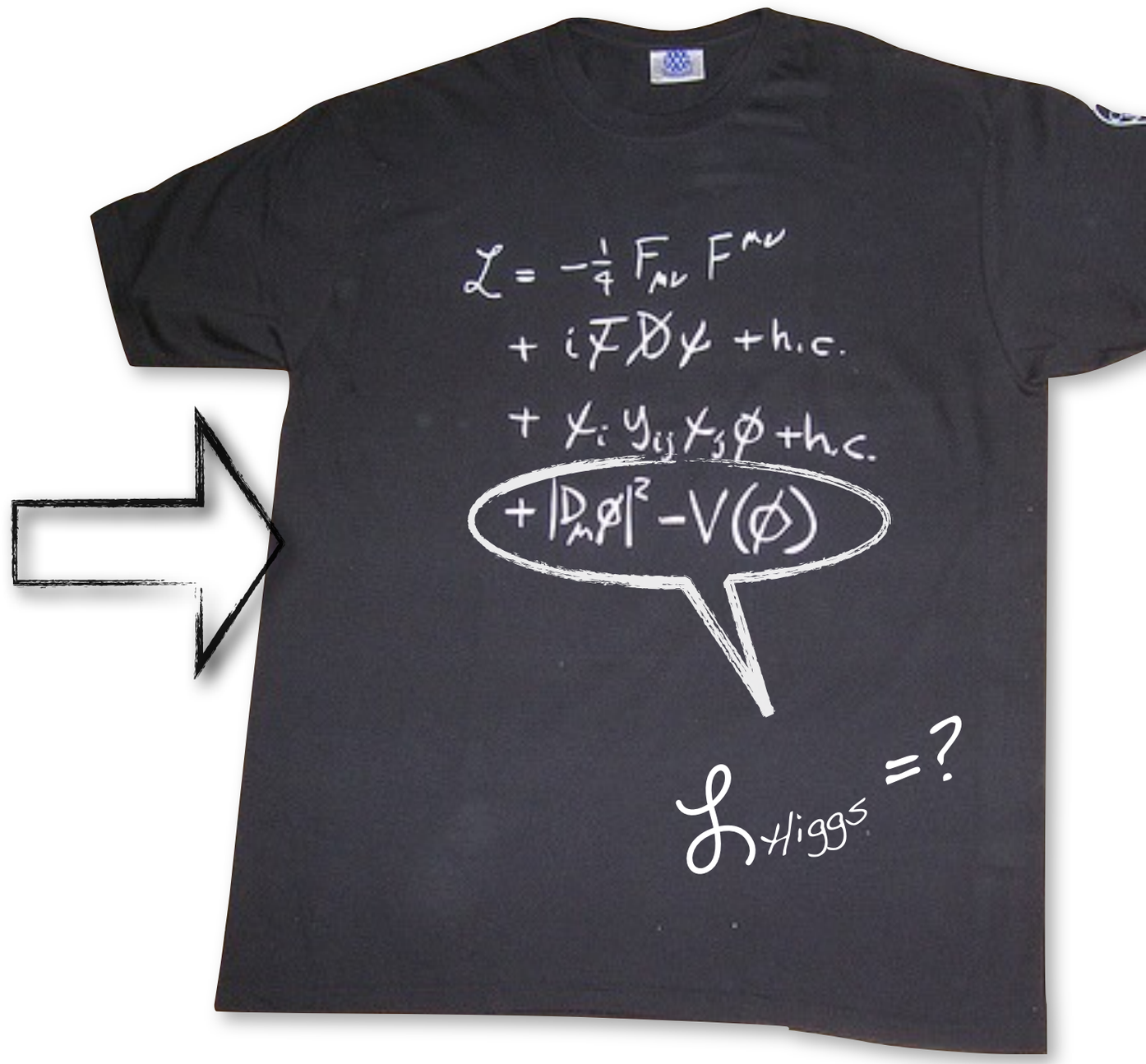
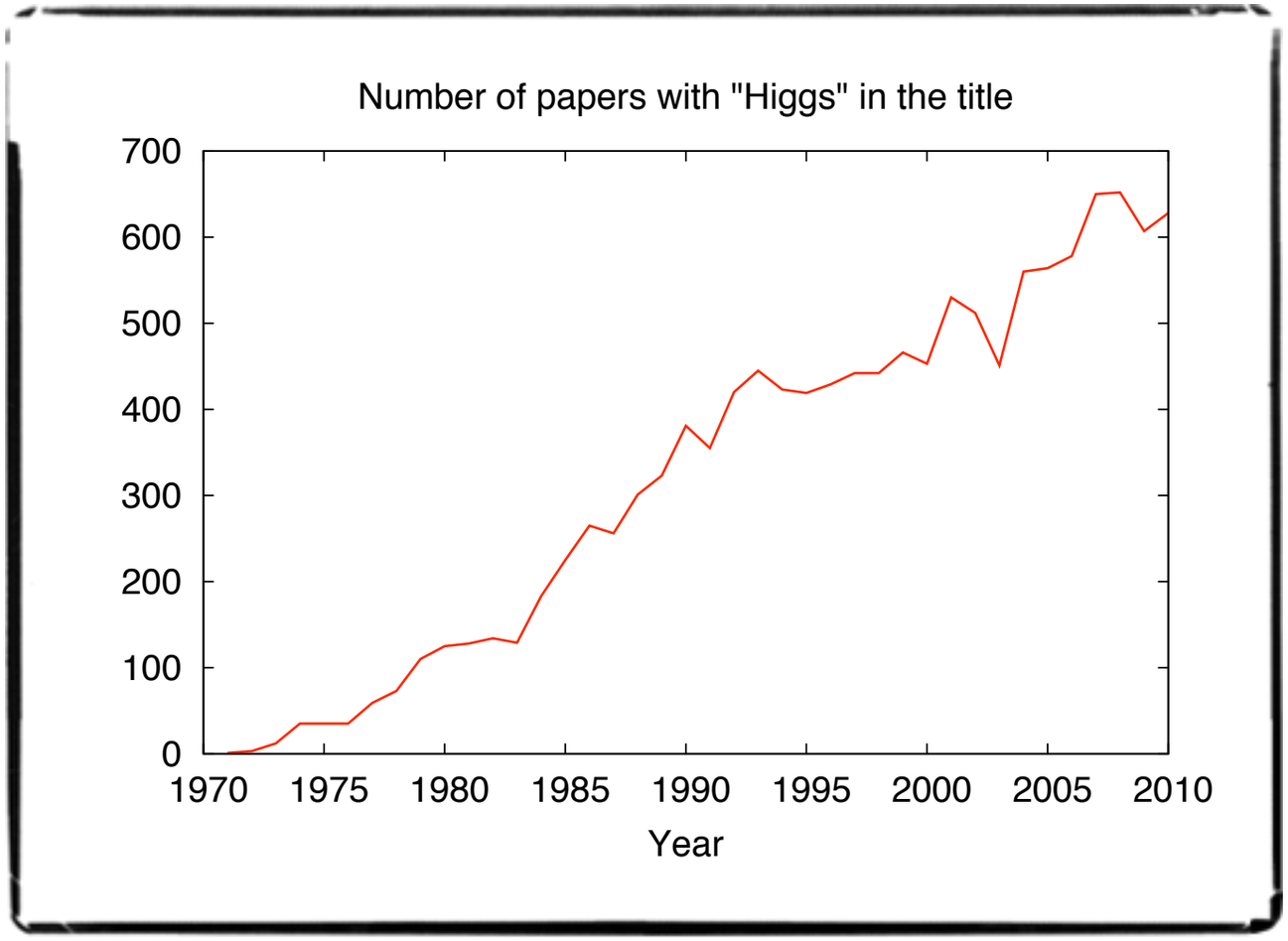


Higgs = "raison d'être" of LHC

- ≈500 physics papers over the last 5 years have an introduction starting like *"the (main) goal of the LHC is to discover the Higgs boson"*

- ≈9000 papers in Spires contain "Higgs" in their title



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- ≈500 physics papers over the last 5 years have an introduction starting like *"the (main) goal of the LHC is to discover the Higgs boson"*

- ≈9000 papers in Spires contain "Higgs" in their title
- ≈3×10^6 references in google (≈1% of M. Jackson)
- ... no Nobel prize (so far)

Reasons of a success

- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes
- screening of gauge boson self-energies

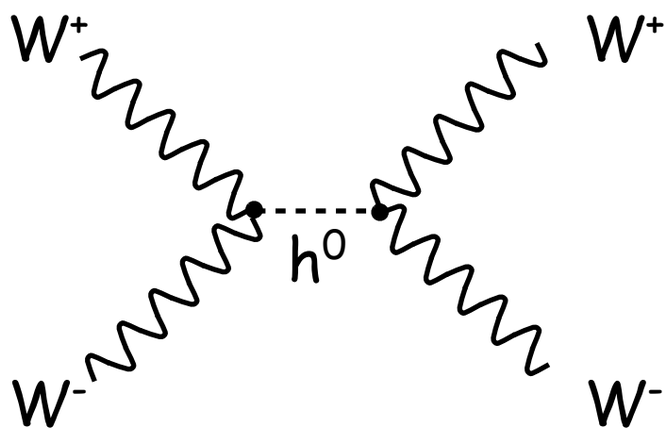
"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

Weak vs. Strong EWSB

what is unitarizing the WW scattering amplitude?

Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

need new particles to stabilize the Higgs mass

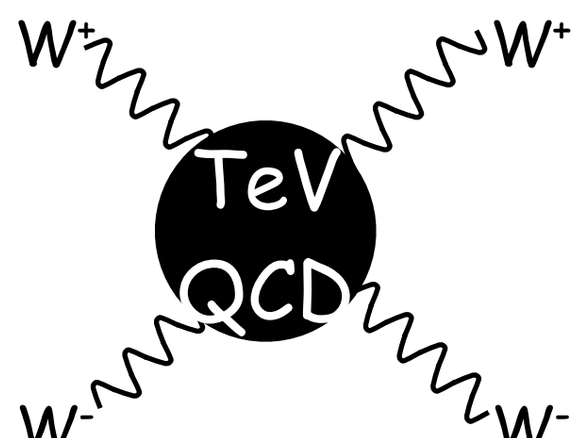
bounds on the masses of these particles

⇓

fine-tuning O(1%)

other ways?

Strongly coupled models



prototype: Technicolor

rho meson ~ 1 TeV

resonances needed for unitarization

generate EW oblique corrections

$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \xrightarrow[@95\%\ \mathrm{CL}]{|\hat{S}| < 10^{-3}} m_\rho > 2.5\ \mathrm{TeV}$$

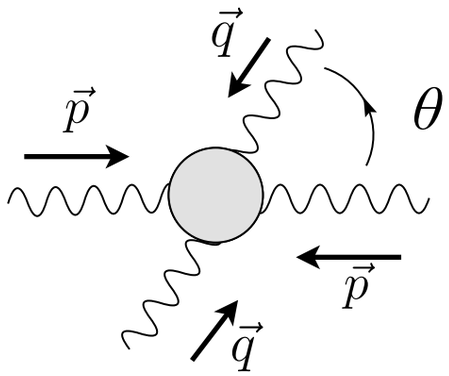
Higgsless Models

Unitarization of (Elastic) Scattering Amplitude

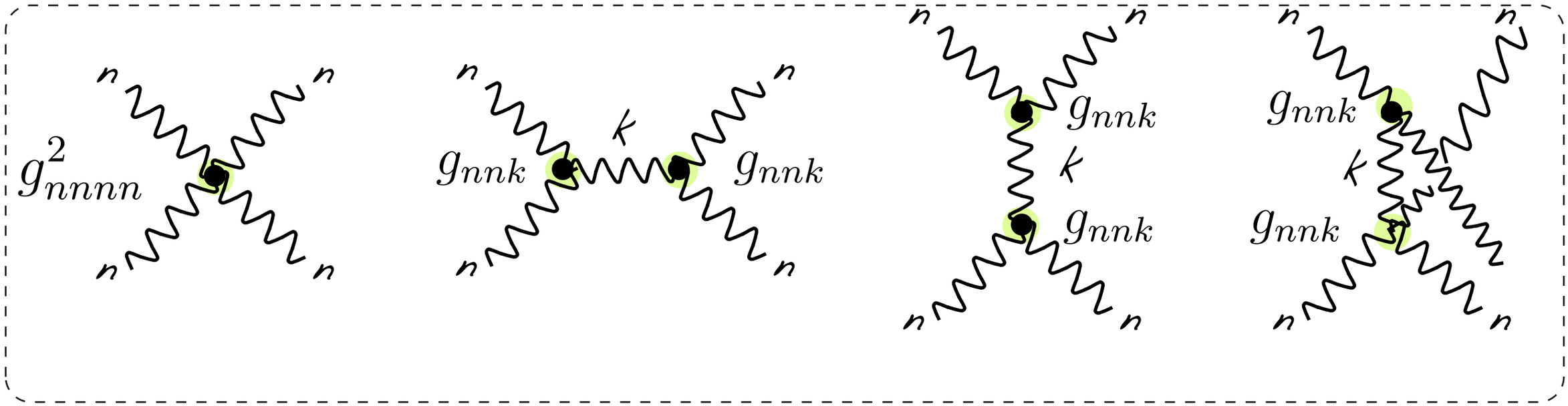
Same KK mode 'in' and 'out'

$$\epsilon_\parallel = \left(\frac{|\vec{p}|}{M}, \frac{E}{M}\frac{\vec{p}}{|\vec{p}|}\right)$$

Csaki, Grojean, Murayama, Pilo, Terning '03



$$\mathcal{A} = \mathcal{A}^{(4)}\left(\frac{E}{M}\right)^4 + \mathcal{A}^{(2)}\left(\frac{E}{M}\right)^2 + \dots$$



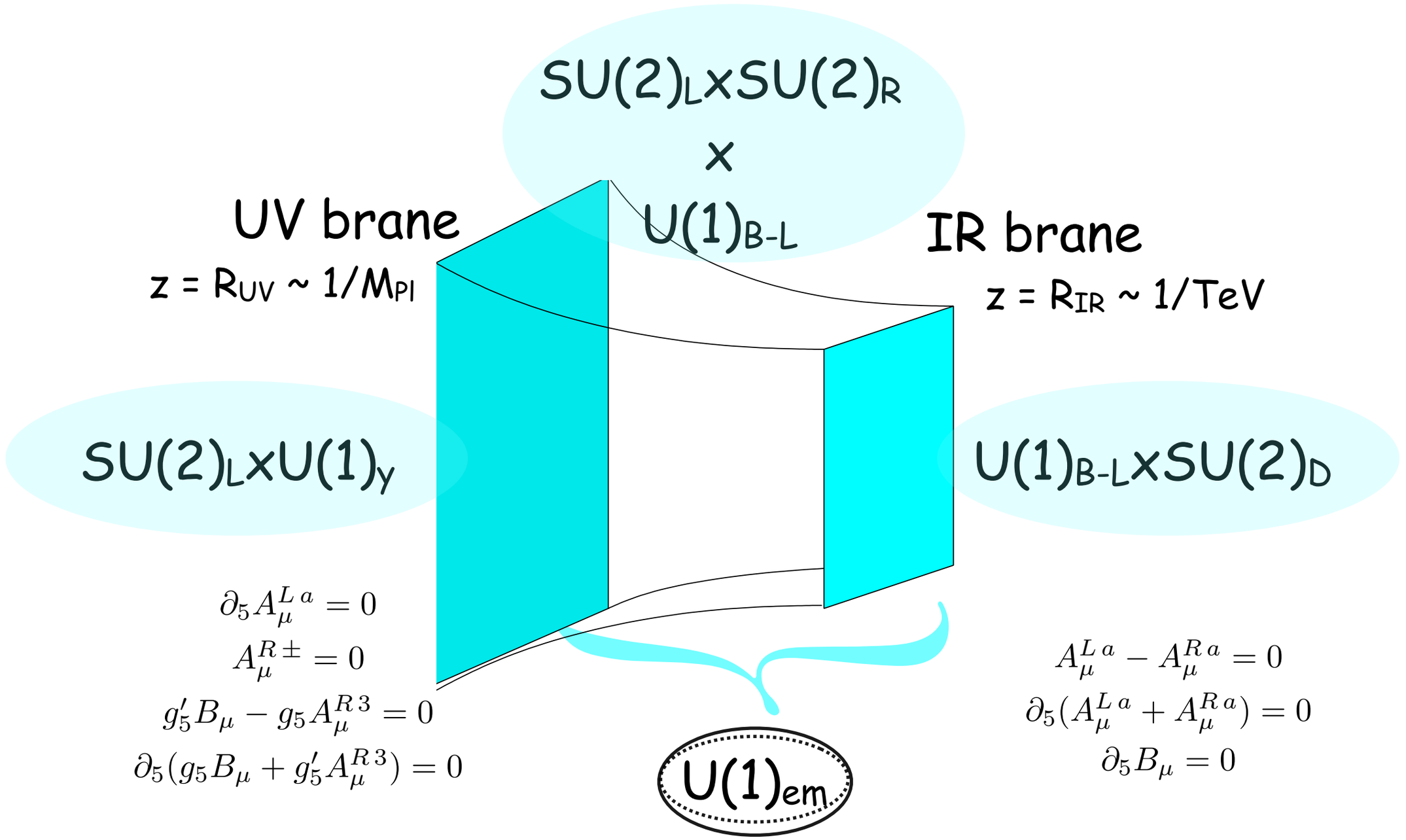
$$\mathcal{A}^{(4)} = i\left(g^2_{nnnn} - \sum_k g^2_{nnk}\right)\left(f^{abe}f^{cde}(3+6c_\theta-c_\theta^2)+2(3-c_\theta^2)f^{ace}f^{bde}\right)$$

$= 0$ **KK sum rules** (enforced by 5D Ward identities)

$$\mathcal{A}^{(2)} = i\left(4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}\right)\left(f^{ace}f^{bde} - s^2_{\theta/2}f^{abe}f^{cde}\right)$$

Warped Higgsless Model

Csaki, Grojean, Pilo, Terning '03



$$\partial_5 A_\mu^{L\,a} = 0$$
$$A_\mu^{R\,\pm} = 0$$
$$g_5' B_\mu - g_5 A_\mu^{R\,3} = 0$$
$$\partial_5 (g_5 B_\mu + g_5' A_\mu^{R\,3}) = 0$$

$$A_\mu^{L\,a} - A_\mu^{R\,a} = 0$$
$$\partial_5 (A_\mu^{L\,a} + A_\mu^{R\,a}) = 0$$
$$\partial_5 B_\mu = 0$$

$$ds^2 = \left(\frac{R}{z}\right)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

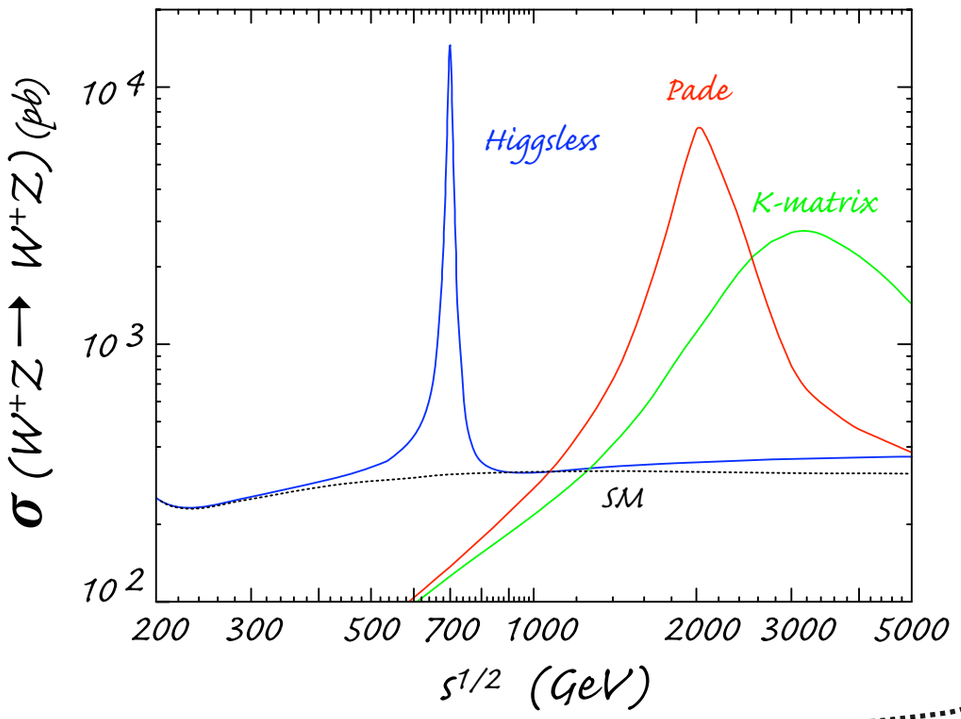
$$\Omega = \frac{R_{IR}}{R_{UV}} \approx 10^{16}\ \text{GeV}$$

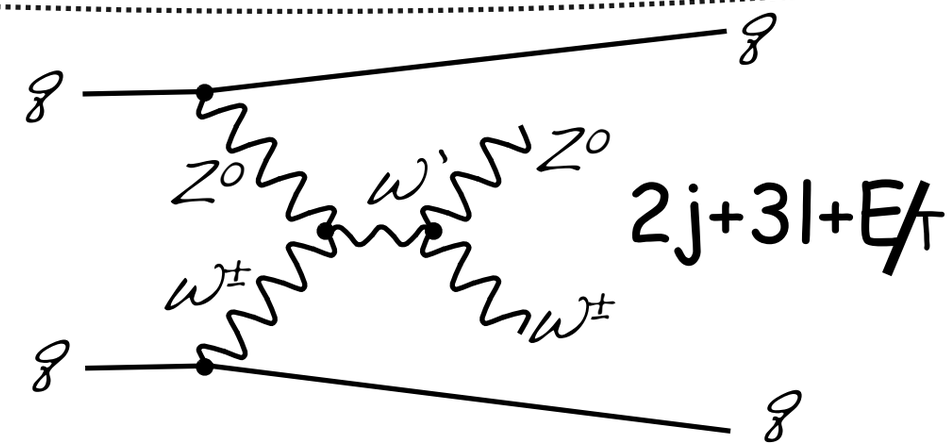
Collider Signatures

unitarity restored by vector resonances whose masses and couplings are constrained by the unitarity sum rules

Birkedal, Matchev, Perelstein '05
He et al. '07

WZ elastic cross section



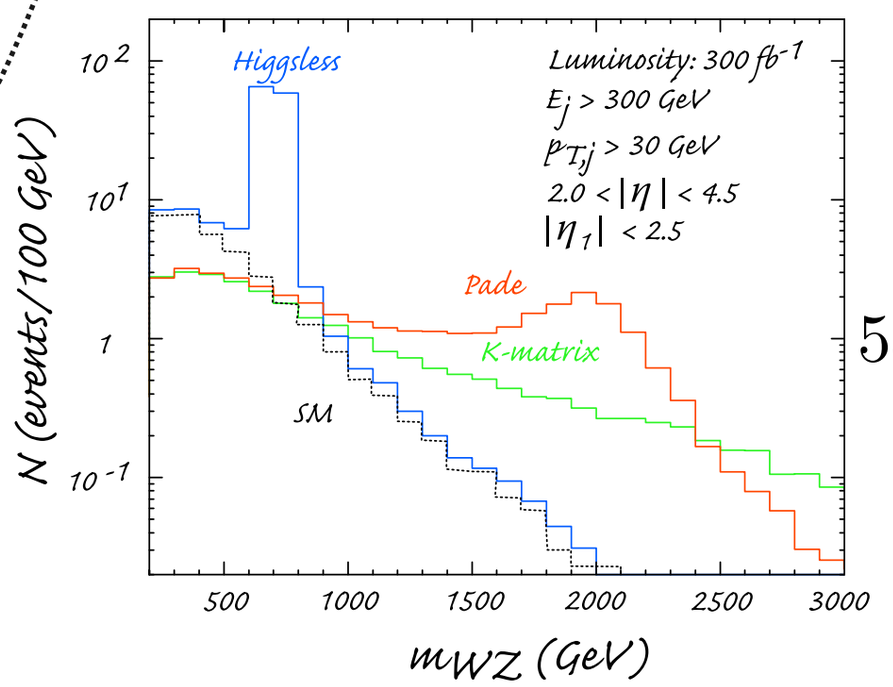


VBF (LO) dominates over DY since couplings of q to W' are reduced

$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \quad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance
no resonance in WZ for SM/MSSM

W' production



Number of events at the LHC, 300 fb^{-1}

discovery reach
@ LHC
(10 events)

$$550 \text{ GeV} \rightarrow 10 \text{ fb}^{-1}$$
$$1 \text{ TeV} \rightarrow 60 \text{ fb}^{-1}$$

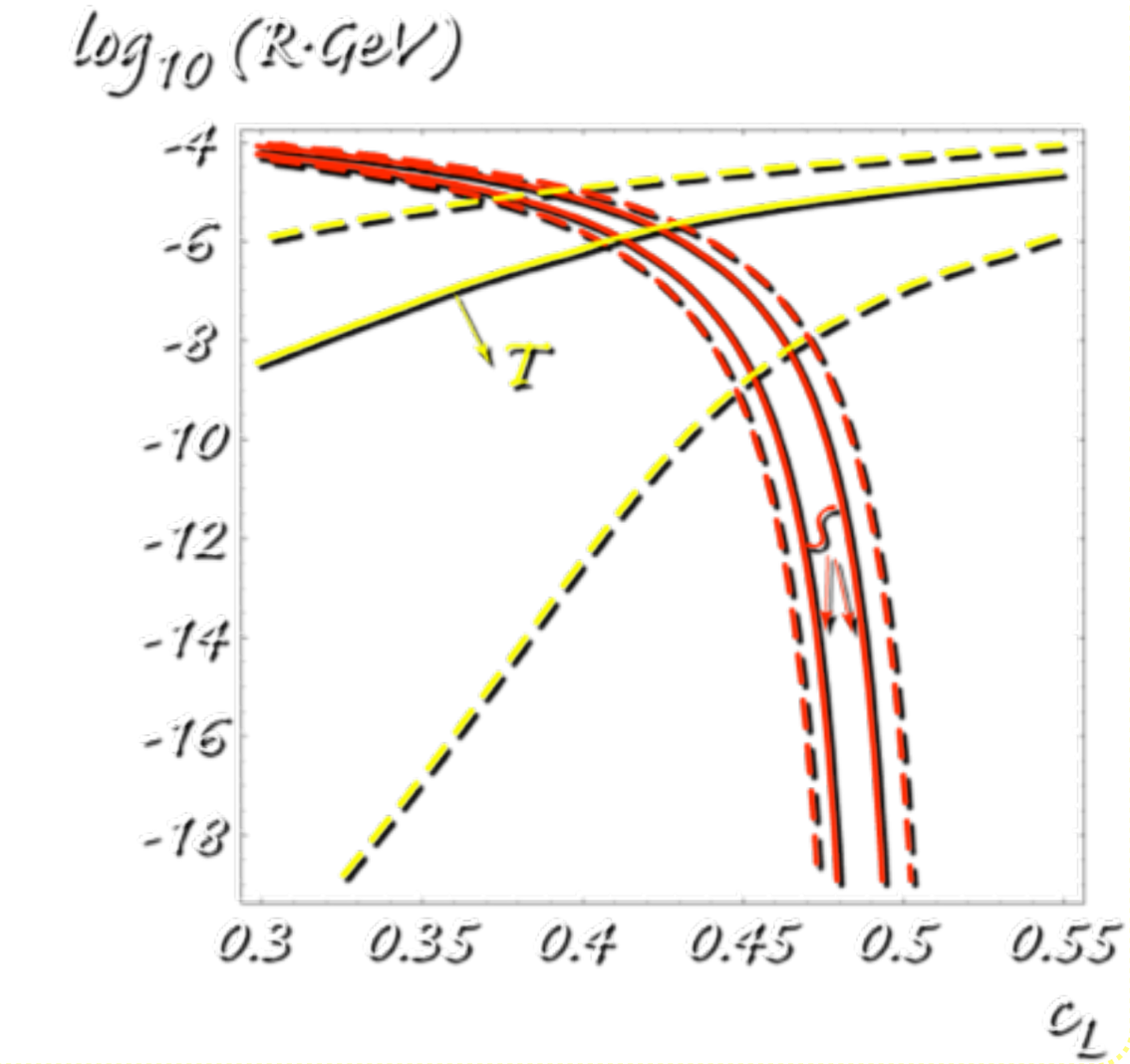
should be seen
within one/two year

EW Precision Data

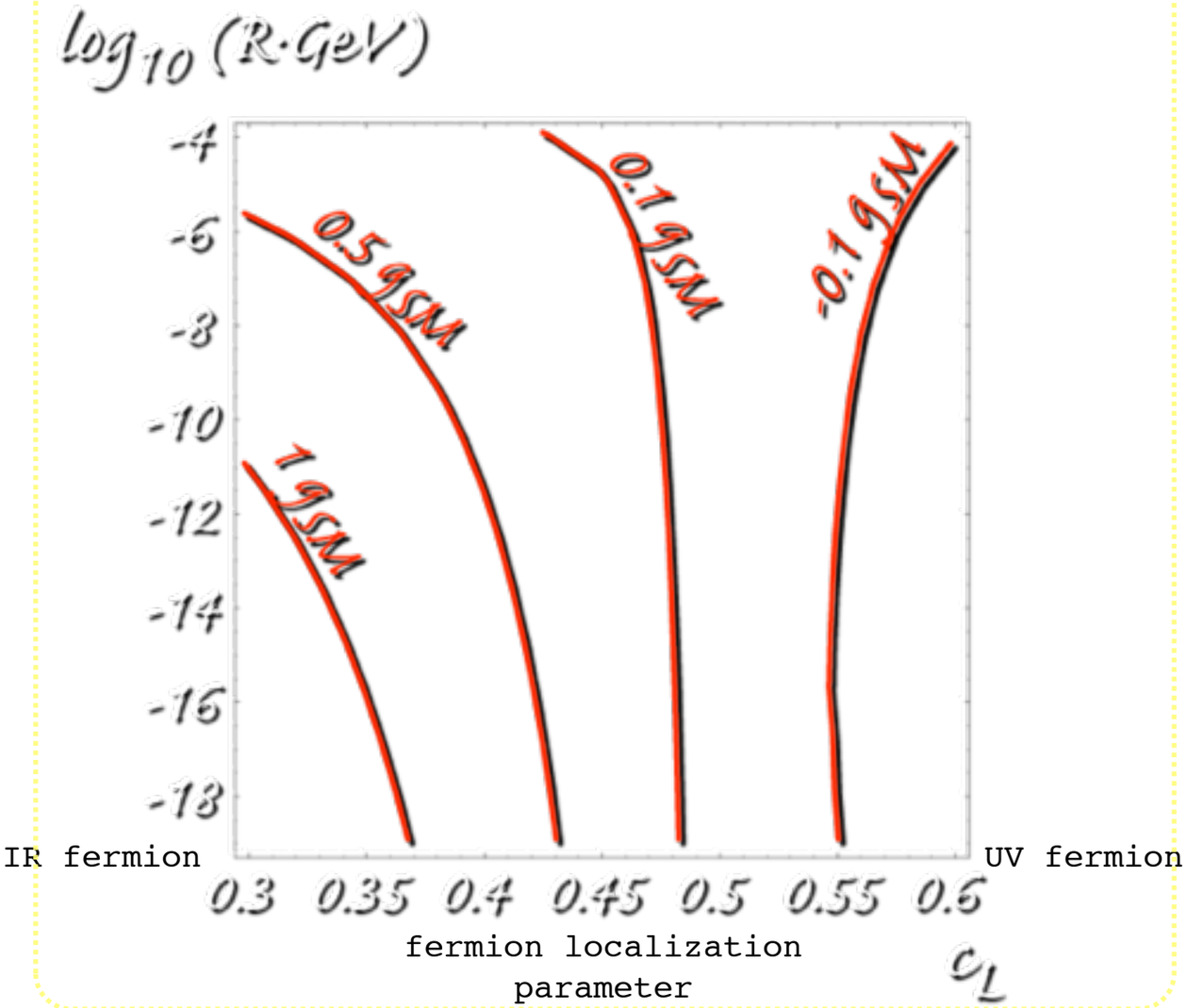
Cacciapaglia, Csaki, Grojean, Terning '04

Oblique parameters (S,T,W,Y) can be tuned away
by delocalizing the fermions in the bulk.
the fermions decouple from W', Z' etc

oblique corrections



W' and Z' couplings to fermions



Open Questions

- 5D models provide a (weakly) coupled description of resonances of the strong sector... but:
- we don't know the UV dynamics,
- we don't know what the resonances are made of,
- we don't know what shape the geometry/topology of the extra dimension
- etc...
- still need some tuning to pass EW constraints!

See also von Gersdorff's talk

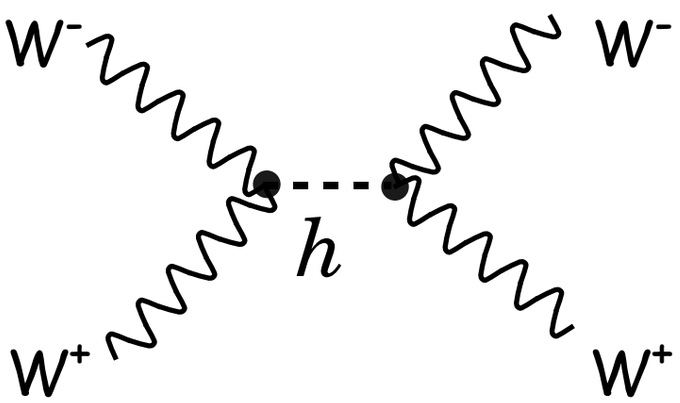
Composite Higgs Models

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R/SU(2)_L$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1+c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s-m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

What is the SM Higgs?

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$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

For ac=1: perturbative unitarity in inelastic $WW \to \psi\,\psi$

'a=1', 'b=1' & 'c=1' define the SM Higgs

$\mathcal{L}_{\rm EWSB}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

Higgs properties depend on a single unknown parameter (m_H)

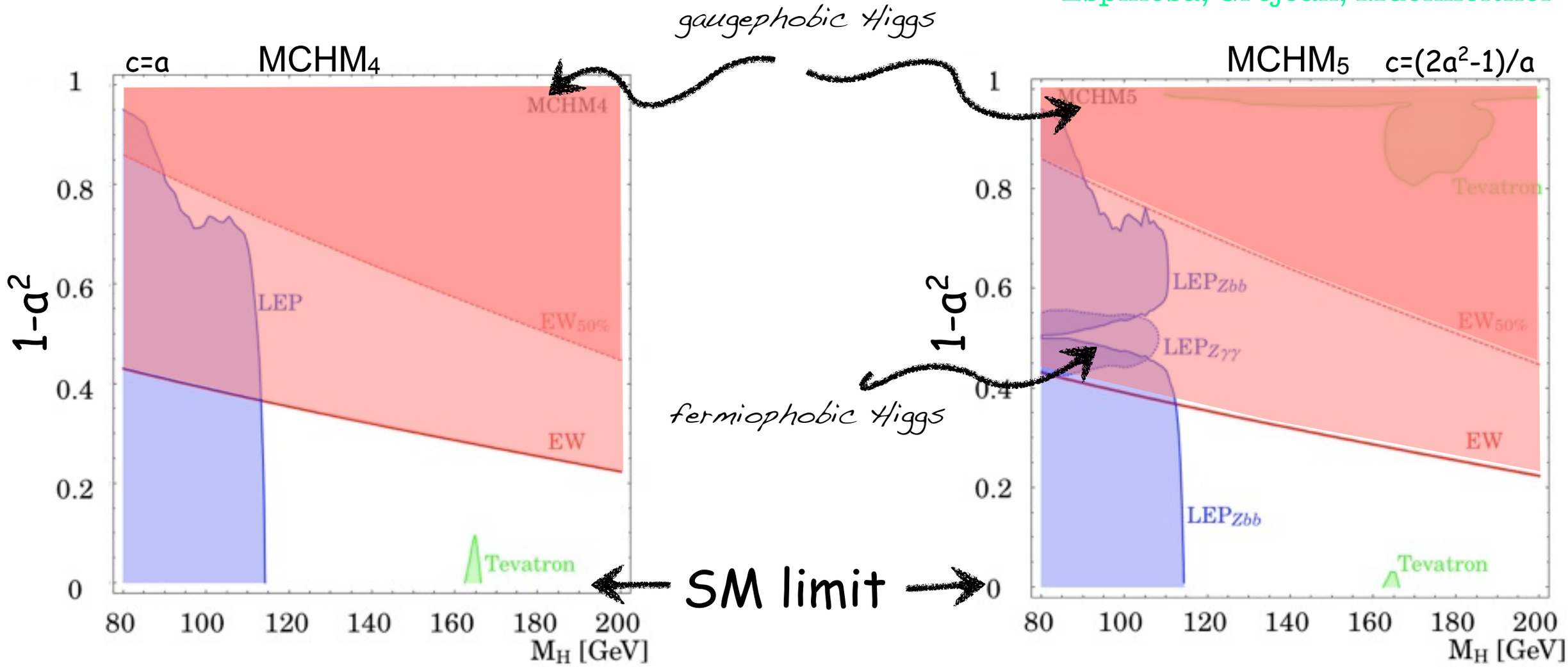
Deformation of the SM Higgs

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

generic 'a', 'b' & 'c'

Current EW data constrain only 'a' (and marginally 'c')

Espinosa, Grojean, Muehlleitner '10

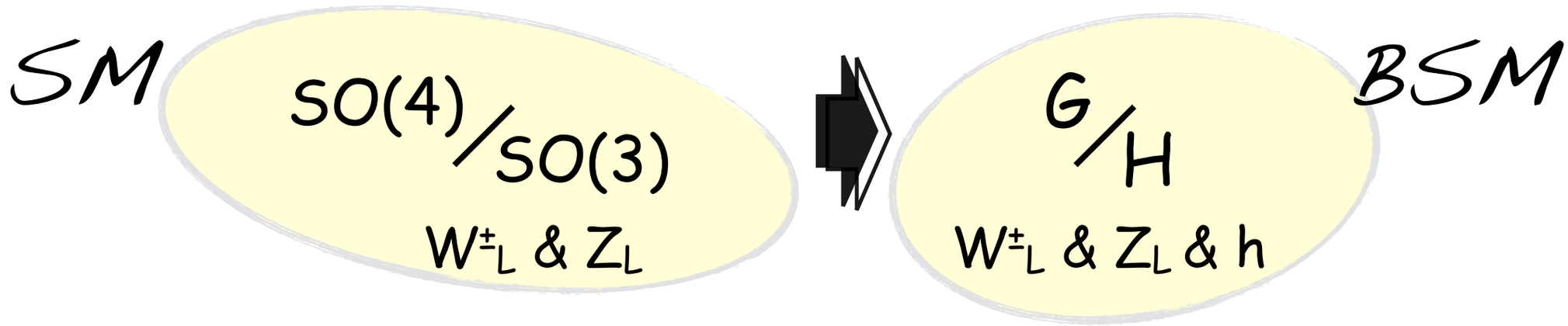


One Motivated Example: Higgs as a PGB

One solution to the hierarchy pb:

Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)



Examples:

SO(5)/SO(4): 4 PGBs=$W^{\pm}_L$, Z_L, h ← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

SO(6)/SO(5): 5 PGBs=H, a ← Next MCHM

Gripaios, Pomarol, Riva, Serra '09

SU(4)/Sp(4,$\mathbb{C}$): 5 PGBs=H, s

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '??

SO(6)/SO(4)xSO(2): 8 PGBs=H_1+H_2

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '??

Composite Higgs: Strong EWSB with 2 Scales

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

SM limit

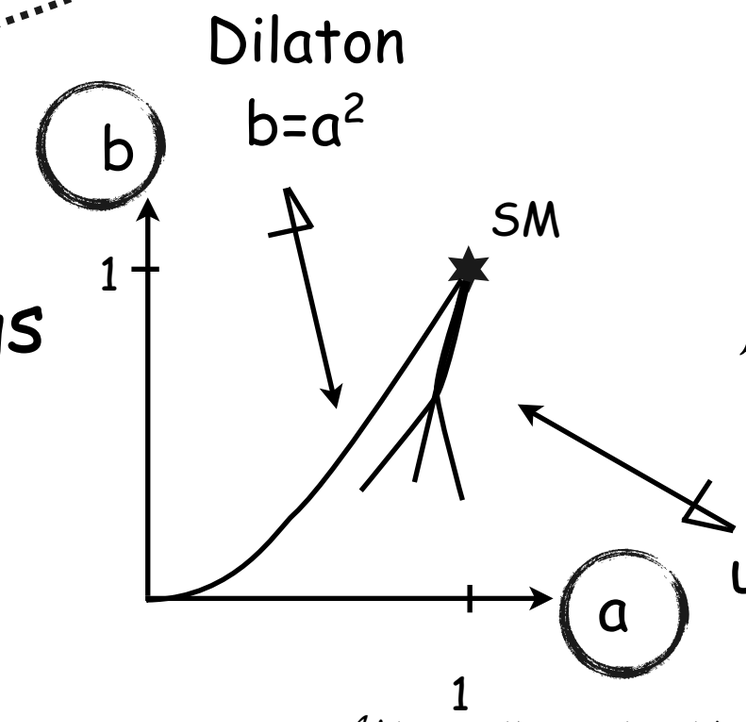
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. SM Higgs



$$\mathcal{L}_{\text{EWSB}} = \left(a\,\frac{v}{2}\,h \;+ b\,\frac{1}{4}\,h^2 \right) \text{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

Composite Higgs
universal behavior for large f
a=1-v/2f b=1-2v/f

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

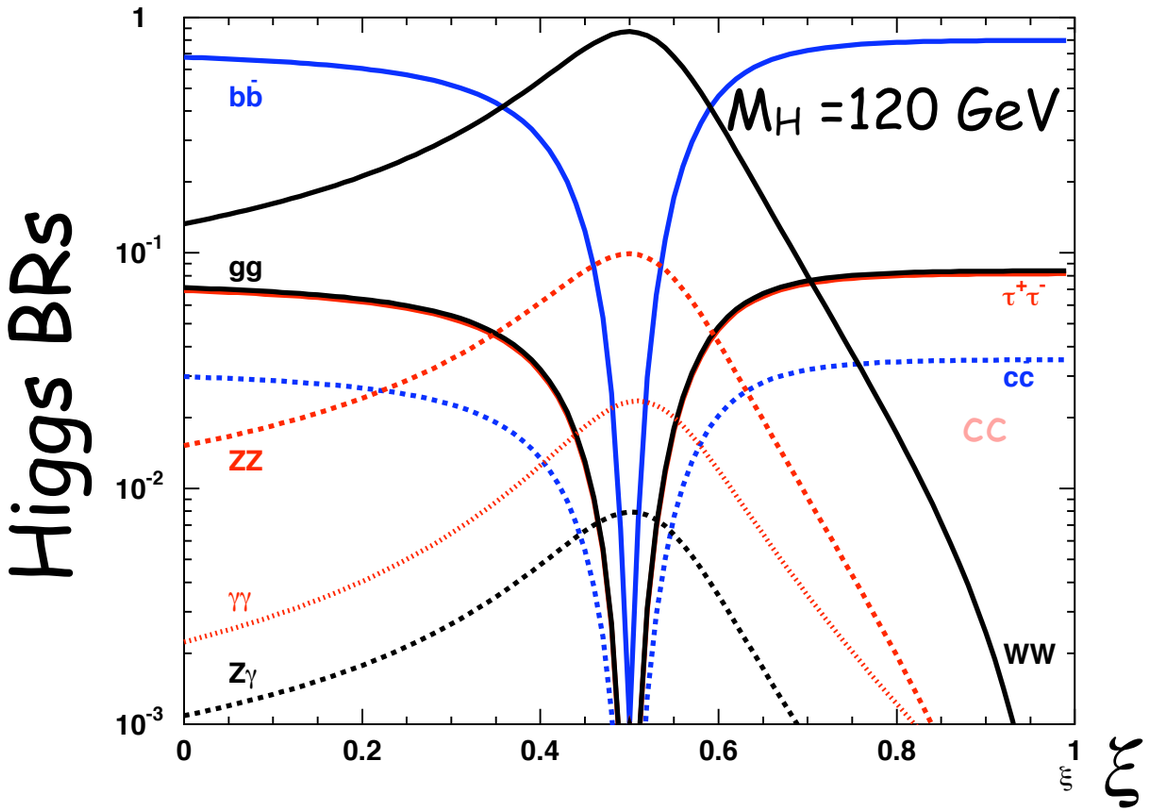
$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \dots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1 - \xi/2$

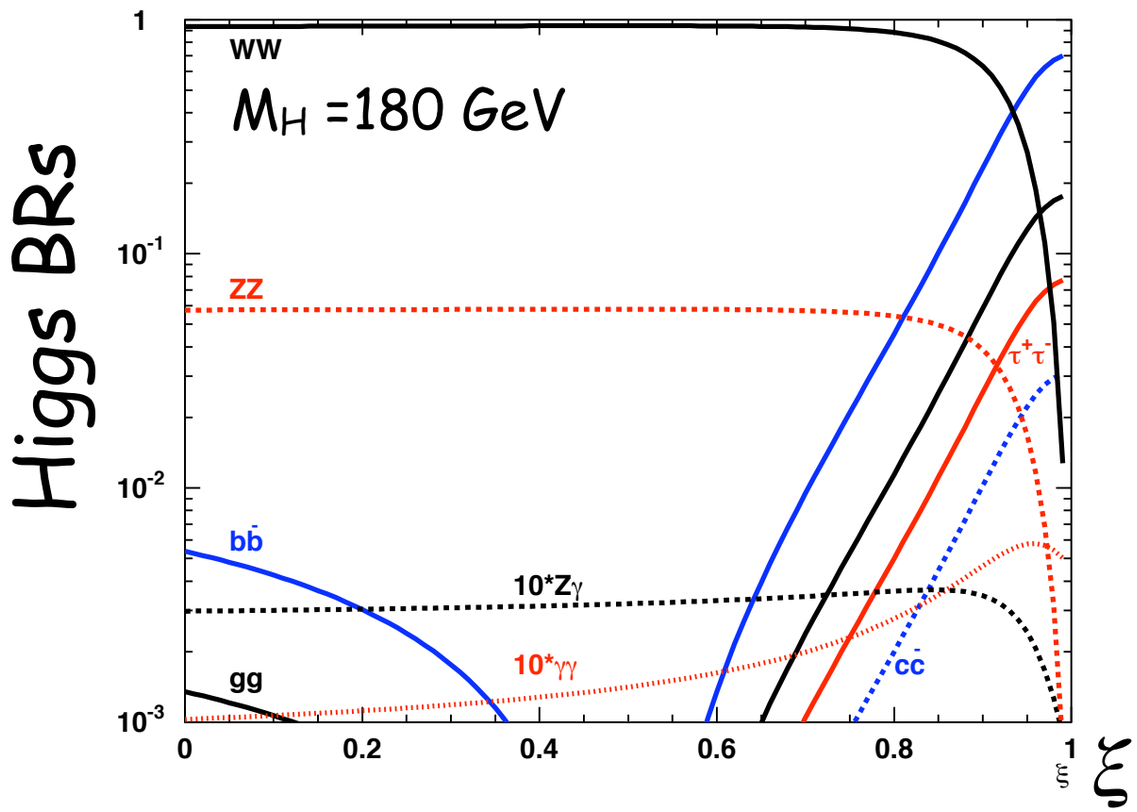
Anomalous Higgs BRs

Fermions embedded in 5+10 of SO(5)

MCHM5



h→WW can dominate even for low Higgs mass



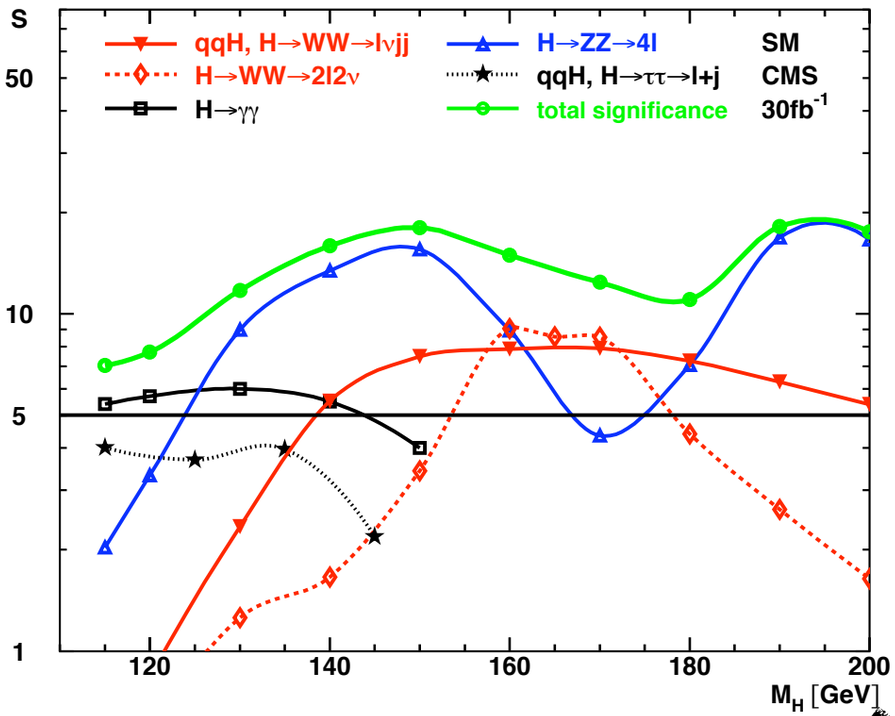
BRs remain SM like except for very large values of v/f

Anomalous Higgs Production

Espinosa, Grojean, Muehlleitner '10

the modification of Higgs couplings and BRs affects the Higgs search

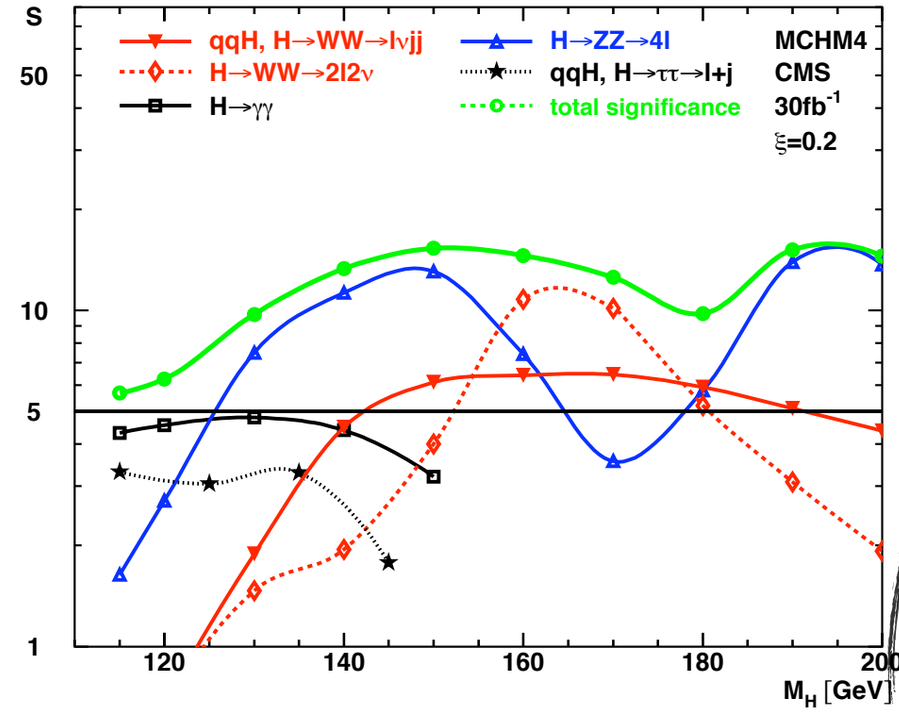
SM



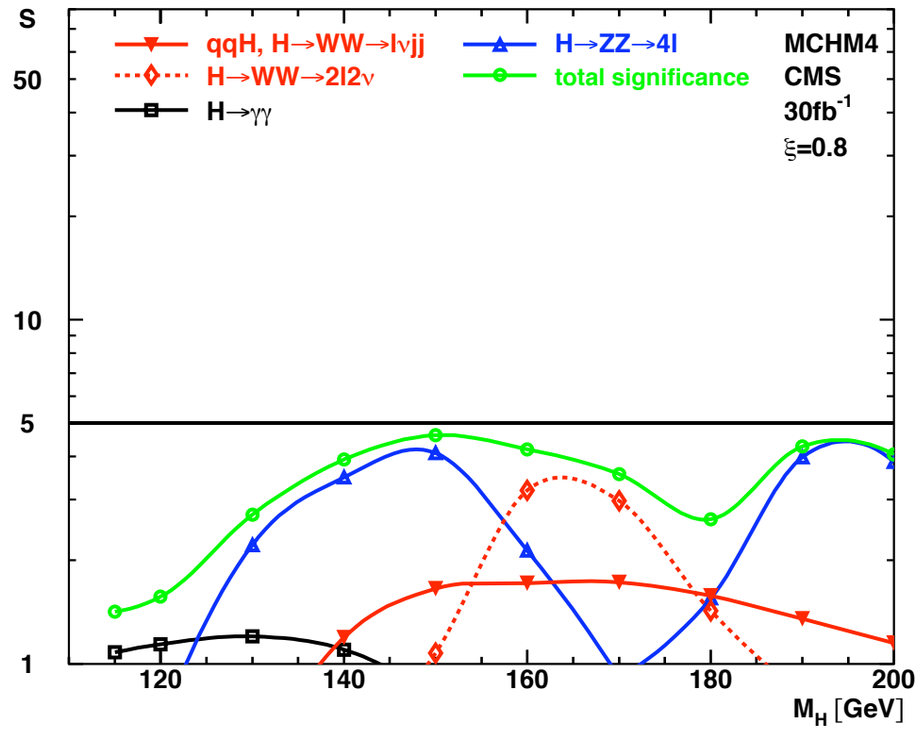
large compositeness scale

signal significance for L=30/fb

small compositeness scale



MCHM4



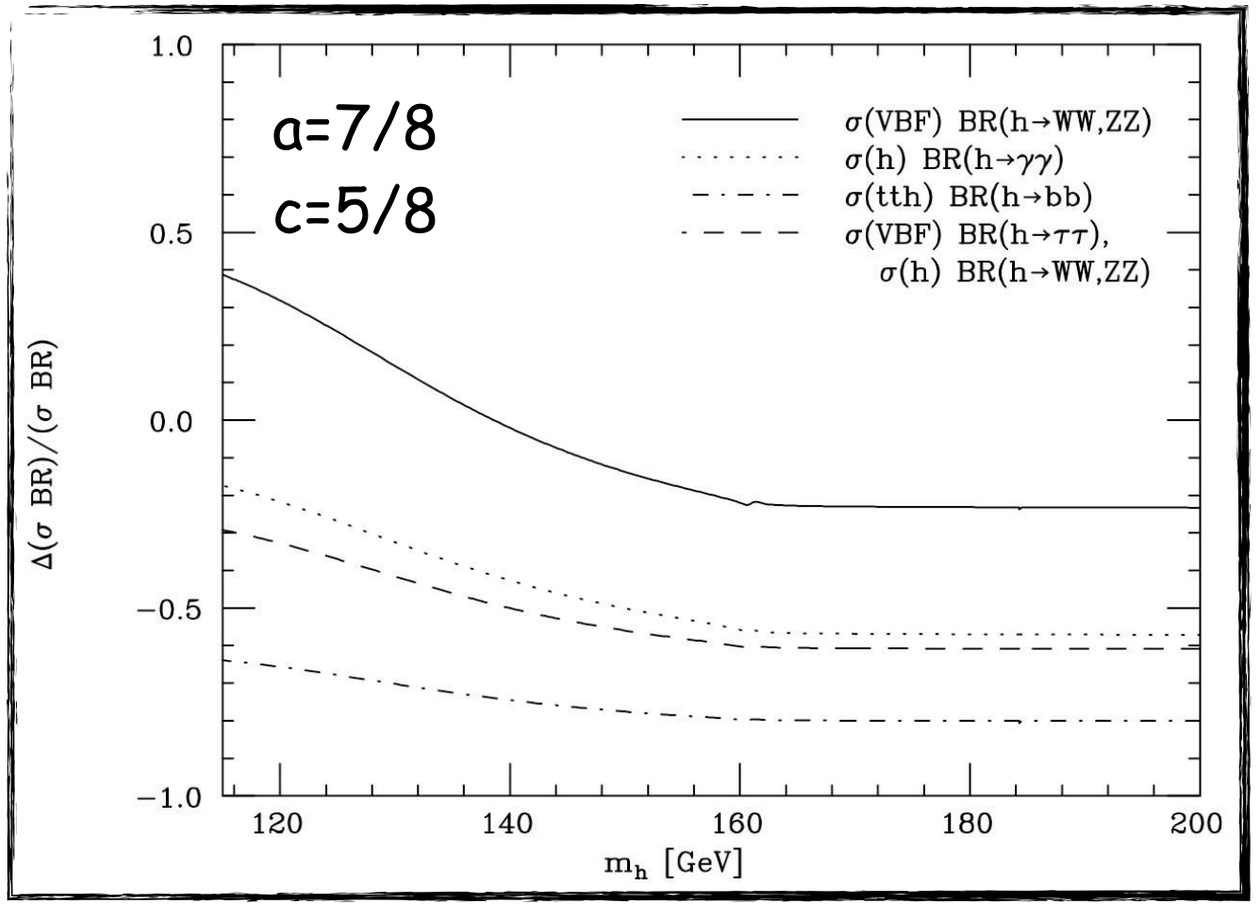
Higgs anomalous couplings @ LHC

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+b_3\frac{h^3}{v^3}+\dots\right) - \lambda\bar{\psi}_L\Sigma\psi_R\left(1+c\frac{h}{v}+c_2\frac{h^2}{v^2}+\dots\right)$$

$$a=\sqrt{1-\xi} \qquad b=1-2\xi \qquad b_3=-\frac{4}{3}\xi\sqrt{1-\xi} \qquad c=\left(\sqrt{1-\xi},\frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad c_2=-(\xi,4\xi)$$

Minimal composite Higgs model (MCHM): SO(5)/SO(4)

$$\Gamma(h\to f\bar{f}) = (2c-1)\,\Gamma(h\to f\bar{f})_{\rm SM} \quad \Gamma(h\to ZZ) = (2a-1)\,\Gamma(h\to ZZ)_{\rm SM}$$



SLHC can probe

Δa & Δc
up to ~ 0.1÷0.2
i.e. 4πf ~ 5÷7 TeV

compositeness scale of the Higgs

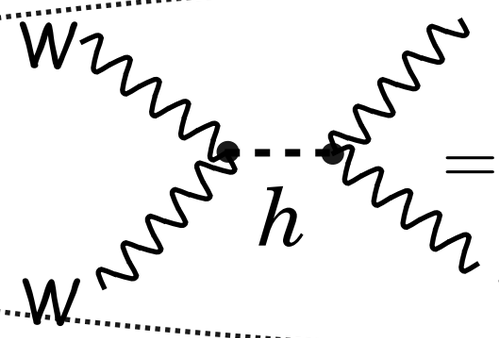
(ILC could go to few % ie
test composite Higgs up to 4πf ~ 5÷7 TeV)

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

strong WW scattering



$$= -(1-\xi)g^2\frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

strong double Higgs production

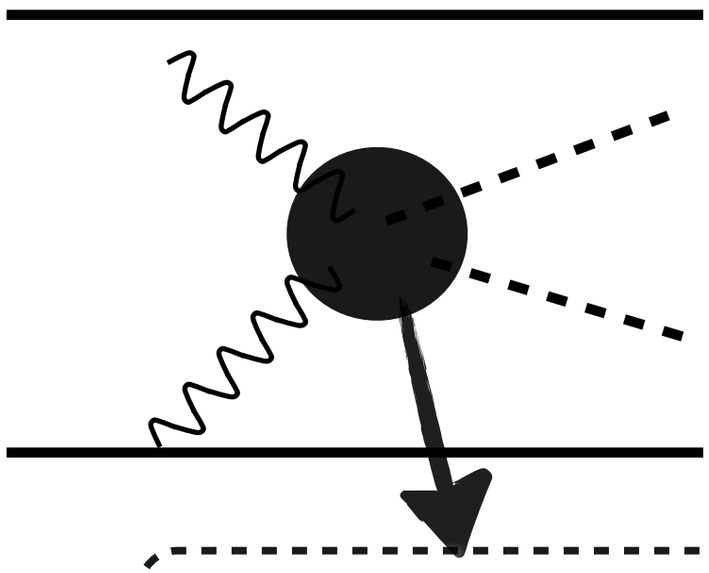
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \left(W_L^+ W_L^- \to hh\right) = \left(b - a^2\right)\frac{s}{v^2}$$

access to a new interaction, 'b'

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

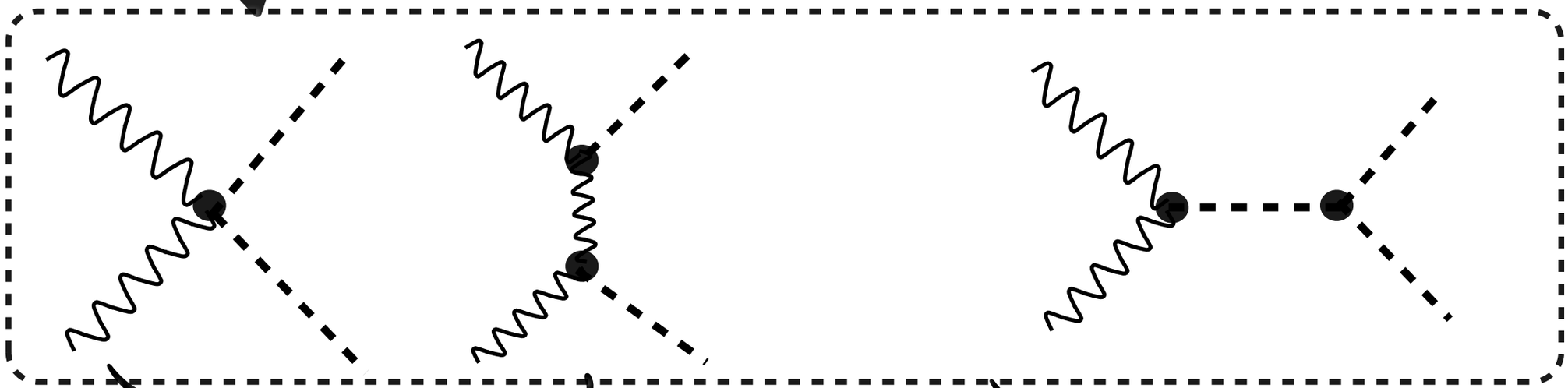
Double Higgs production: 'b' and 'd_3' couplings



$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right)$$

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

SM: $a=b=d_3=d_4=1$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b-a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

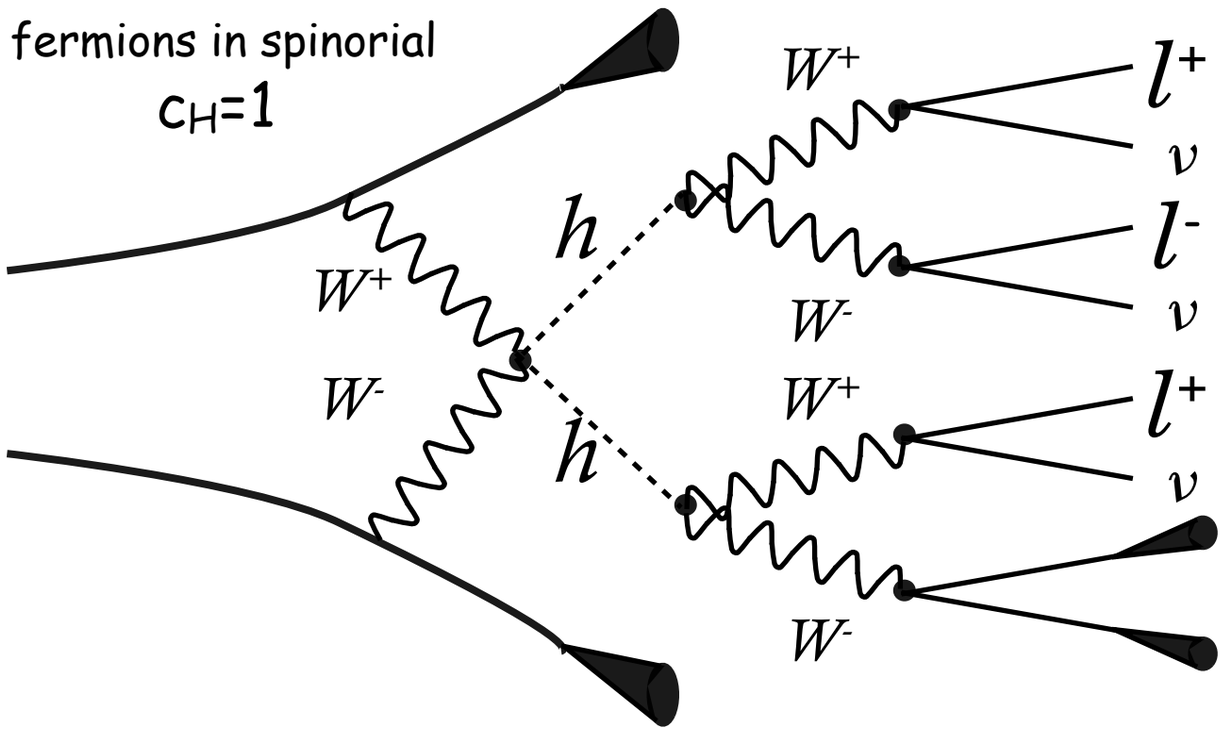
strong boson scattering ⇔ strong Higgs production

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}$$

$m_h = 180$ GeV

fermions in spinorial

c_H=1



acceptance cuts

jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

Dominant backgrounds: Wll4j, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

forward jet-tag, back-to-back lepton, central jet-veto

v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

⇐ good motivation to SLHC

Geometry of Coset from $W^+W^- \to 3h$

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Strong EWSB

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{E^2}{f^4}\frac{E^2}{(4\pi f)^2}$$

$E/f \leftrightarrow g$

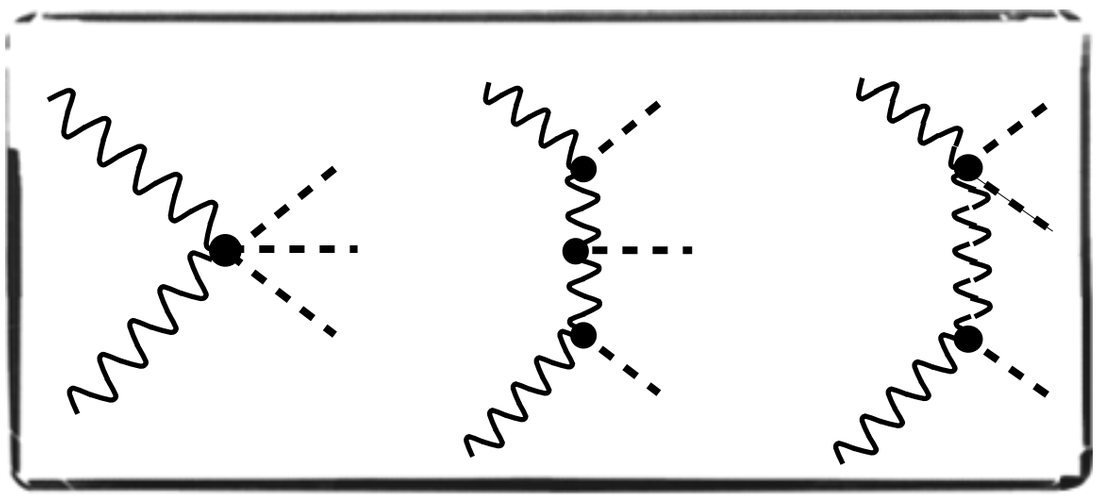
SM

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

a process with an odd # of PGBs
requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone



$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\left(\underbrace{a(b-a^2)-\frac{3}{4}b_3}_{=0 \text{ for symmetric coset}}\right) + \underbrace{\sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

$W^+W^- \to 3h$ @ CLIC

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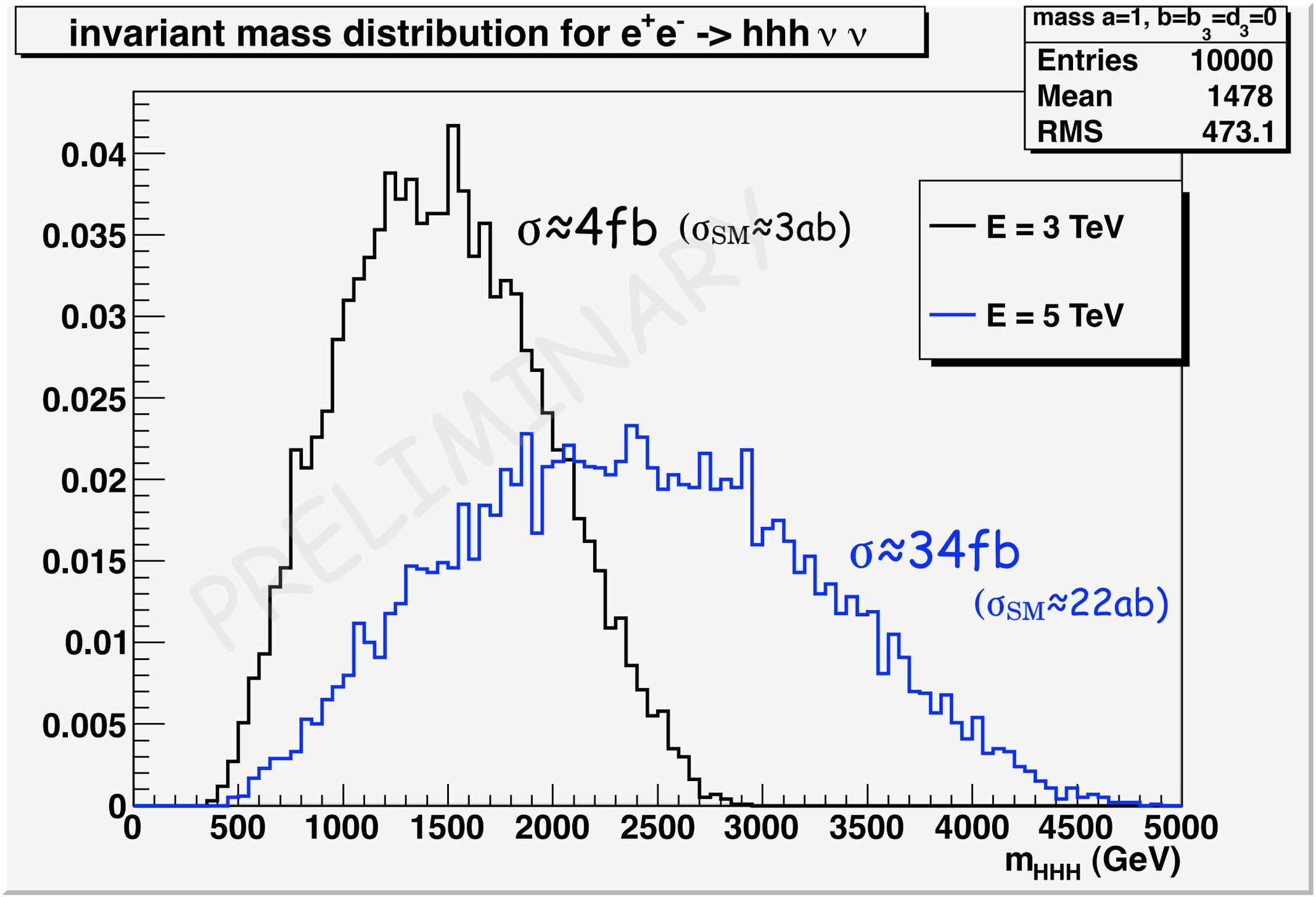
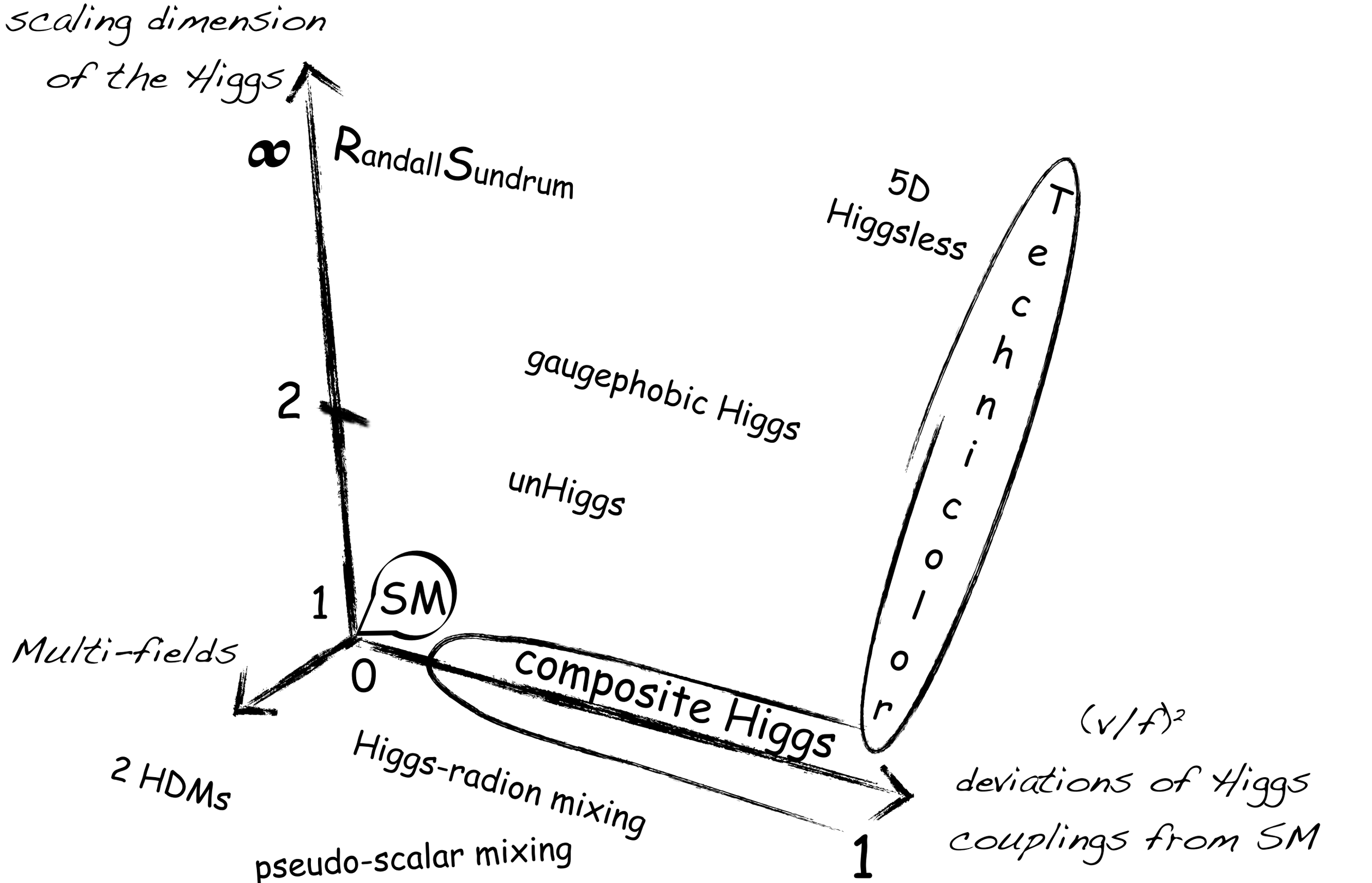
non-symmetric coset



Conclusions



Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z

⇓ ⇓ ⇓ ⇓

EW interactions also need a UV moderator/new physics
to unitarize WW scattering amplitude

We'll need another Gargamelle experiment
to discover the still missing neutral current of the SM: the Higgs
weak NC ⇔ gauge principle
Higgs NC ⇔ ?

Strong EWSB w/o an elementary Higgs can be very similar to SM
it might take some time to decipher the true dynamics of EWSB!

An Emergency Tire Even Beyond the SM

[picture courtesy to Andreas Weiler]