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Physics Beyond the Standard Model

The 2011 Hadron Collider Physics Summer School

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Everything you always wanted to know...

- S. Dawson "SM & Higgs" lect #1 ➲ lect #2 ➲ lect #3 ➲
- M. Strassler "BSM" lect #1 ➲ lect #2 ➲ lect #3 ➲

- D. Zeppenfeld "EW & Higgs" lect #1 ➲ lect #2 ➲ lect #3 ➲
- D.E. Kaplan "BSM" lect #1 ➲ lect #2 ➲ lect #3 ➲

- G. Altarelli "SM & EW" lect #1 ➲ lect #2 ➲ lect #3 ➲
- H. Haber "Higgs" lect #1 ➲ lect #2 ➲
- S. Martin "SUSY" lect #1 ➲ lect #2 ➲ lect #3 ➲
- E. Ponton "Extra dimensions" lect #1 ➲ lect #2 ➲
- S. Chivukula "Strong dynamics" lect #1 ➲ lect #2 ➲

- A. Djouadi "EW & Higgs" lect #1-#4 ➲
- G. Giudice "BSM" lect #1-#4 ➲

- Y. Grossman "SM" lect #1 ➲ lect #2 ➲ lect #3 ➲ lect #4 ➲ lect #5 ➲
- H. Logan "SUSY" lect #1 ➲ lect #2 ➲ lect #3 ➲ lect #4 ➲
- M. Luty "BSM" lect #1 ➲ lect #2 ➲ lect #3 ➲

To help you reading these notes...

- Some exercises

  - do them by yourself!
  - ... or ask the discussion leaders to help you

- Some hyperlinks
  - "➲"
  - text written in "green" (in particular all the references)

Lecture Outline

1 First Lecture ➲

- Standard Model and EW symmetry breaking ➲
- Higgs mechanism ➲
- EW precision tests ➲
- Higgs as a UV moderator ➲
- UV behaviour of the Higgs ➲

2 Second Lecture ➲

- Supersymmetry ➲
- Little Higgs ➲

3 Third Lecture ➲

- Gauge-Higgs unification ➲, Higgsless ➲
- Composite Higgs models (I) ➲

4 Fourth Lecture ➲

- Composite Higgs models (II) ➲
- GUT: SM vs MSSM vs Composite Higgs ➲

Experimental/Theoretical Needs for BSM

- Precisions measurements
  (g_μ-2, LR asymmetries, top A_{FB} etc)
- Neutrino masses
- Dark matter
- Dark energy
- Matter-antimatter asymmetry
- Inflation
- Stability of Higgs potential
- Fermion mass and mixing hierarchies
- Strong CP problem
- Charge quantization & GUT
- Quantization of gravity

the LHC won't answer all these puzzles!

The questions addressed in these lectures

we expect new physics to play a crucial role in
the mechanism of electroweak symmetry breaking (EWSB).

- What is the scale of new physics in the EWSB sector?
- What is the population at this new scale? Which particles?
- Which interactions?

Identifying the new spectroscopy should allow to decipher the organization principle that governs the EWSB sector

vector bosons	$\longleftrightarrow$	gauge principle
Higgs/EWSB sector	$\longleftrightarrow$	? strong dynamics, susy, xdims

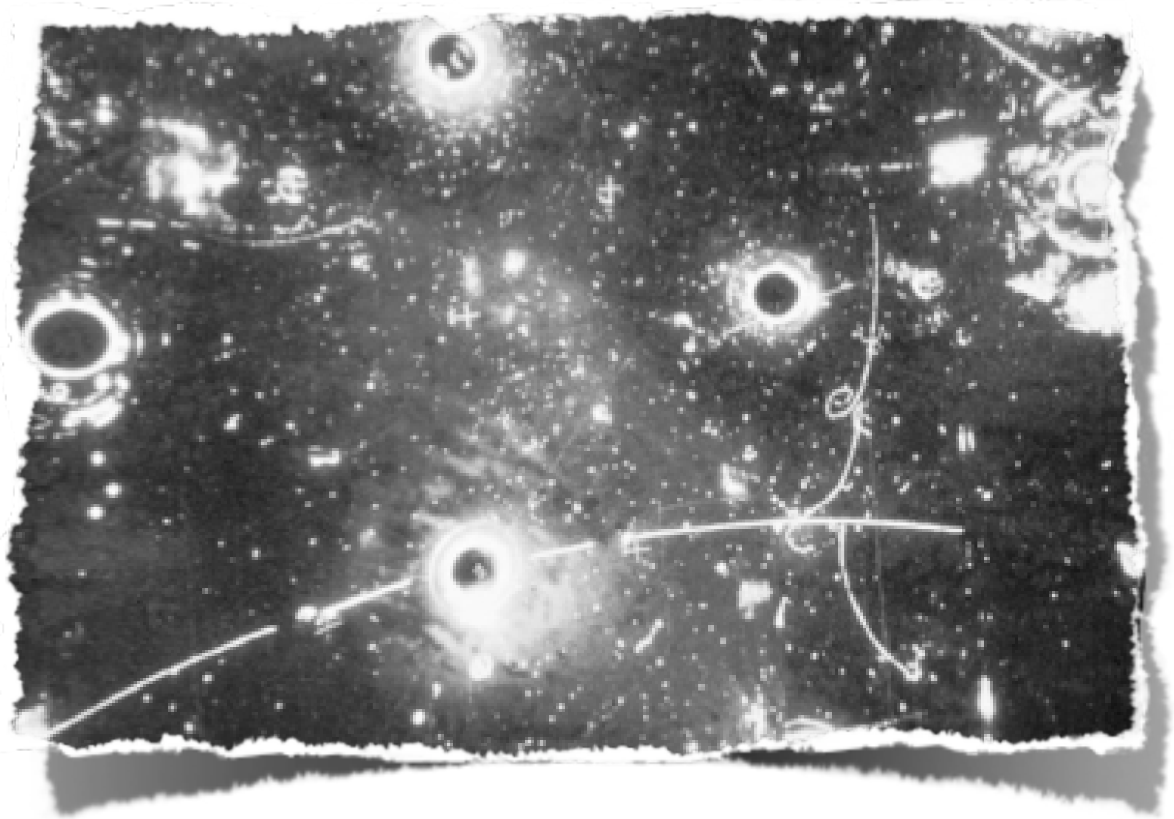
See also A. Pich's lecture #1

Standard Model & EW Symm. Breaking

The Standard Model

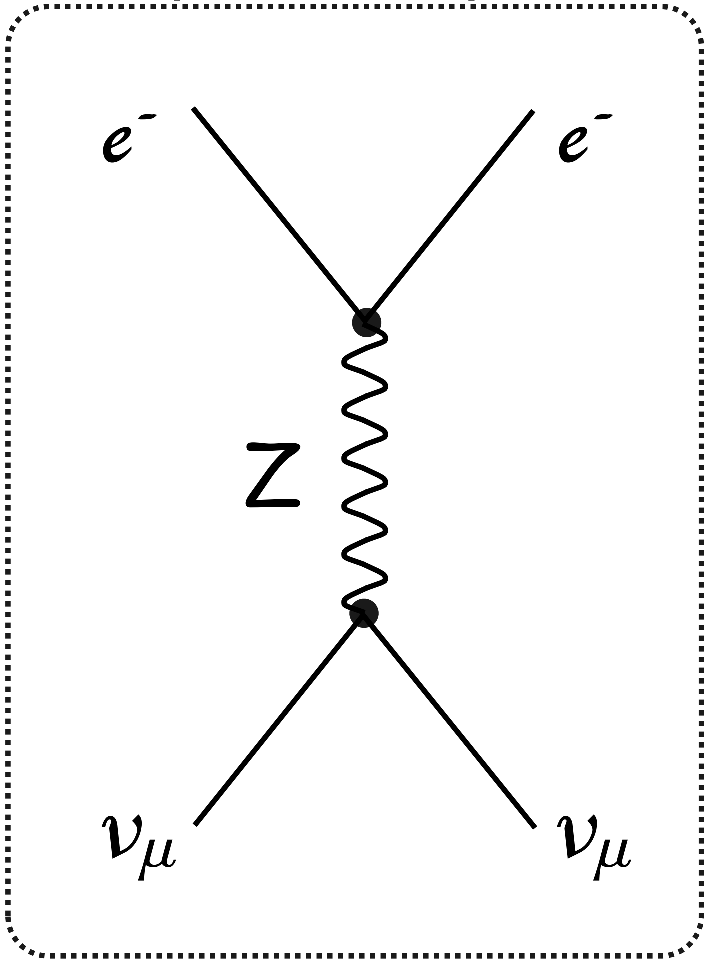
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$



Gargamelle collaboration, '73

$\nu_\mu e^- \to \nu_\mu e^-$



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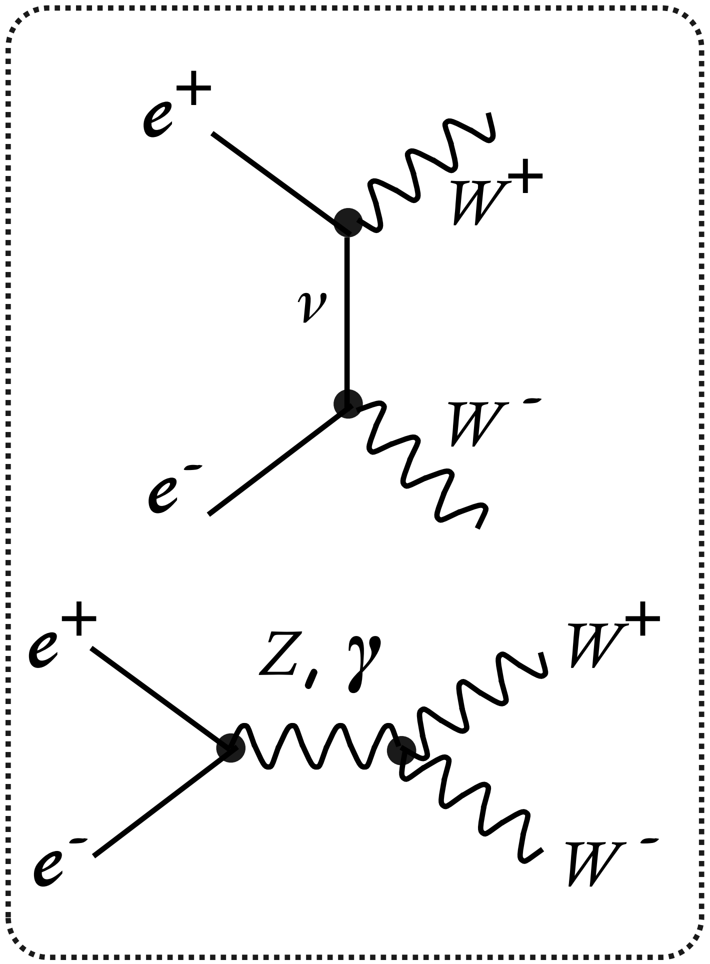
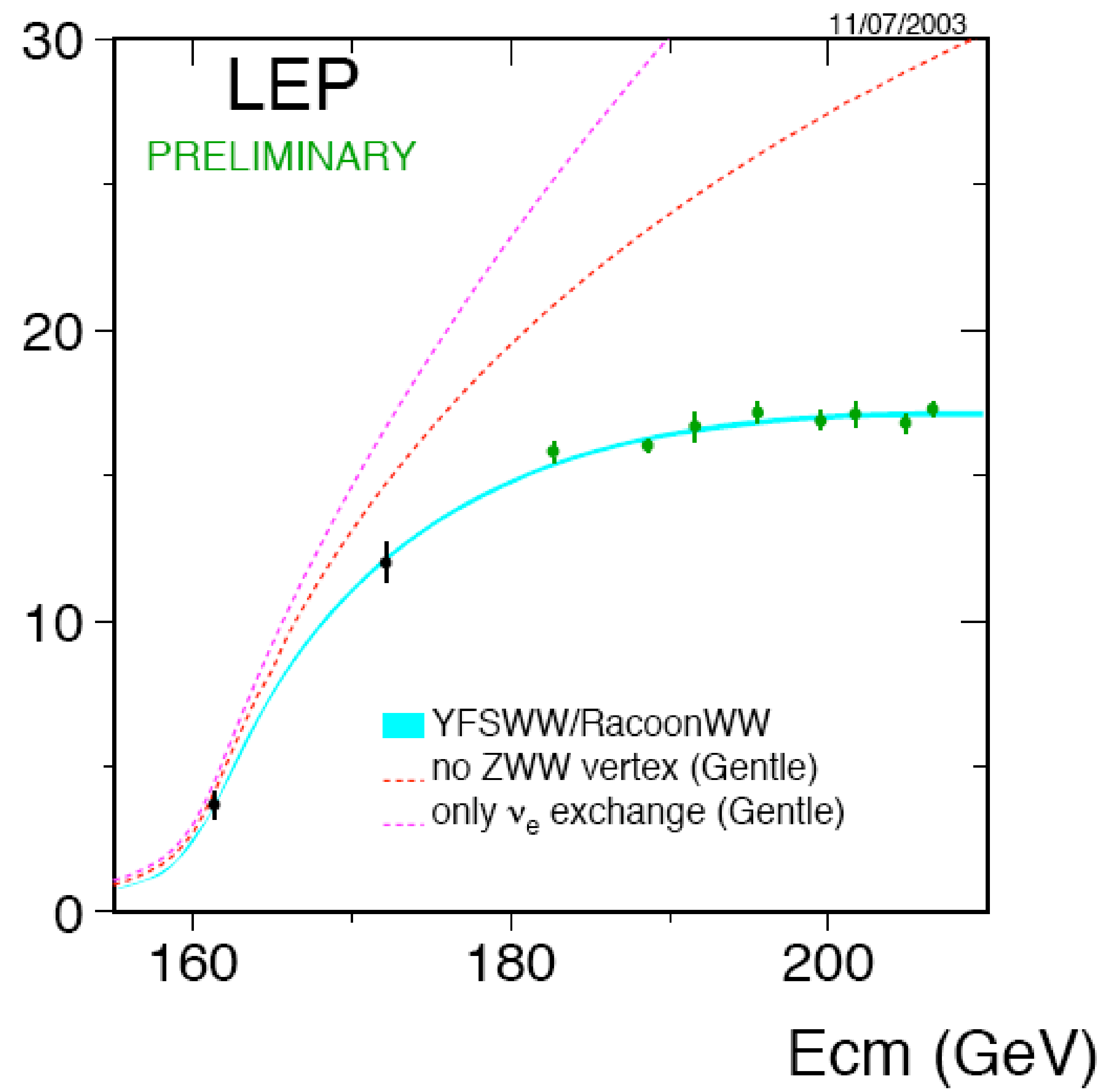
$e^+e^- \to W^+W^-$





The Standard Model and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

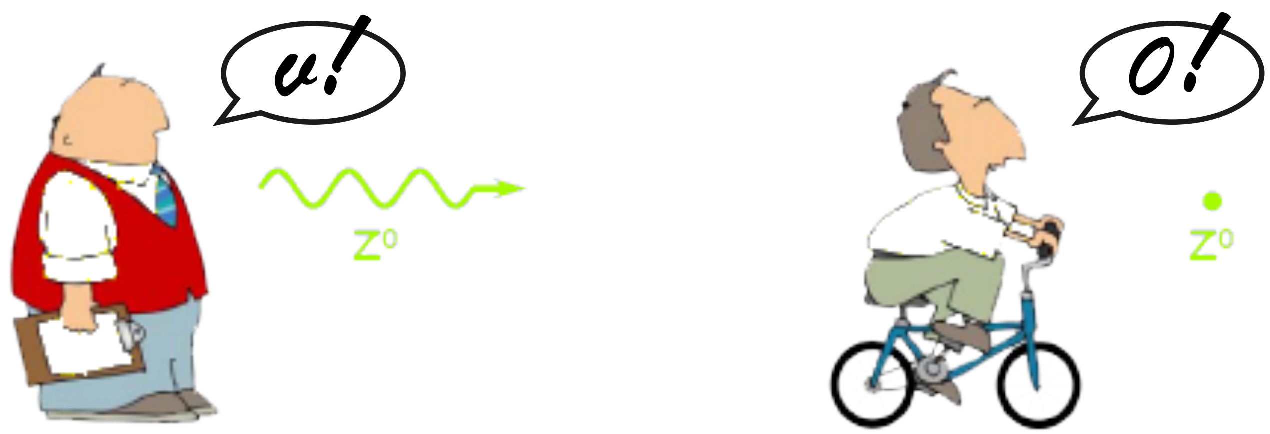
the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ is a doublet of $SU(2)_L$ but $m_{\nu_e} \ll m_e$
- a mass term for the gauge field isn't invariant under gauge transformation $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ spontaneous breaking of gauge symmetry ⇐

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{||} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rightarrow$ Where are these Goldstone's coming from? $\Leftarrow$

what is the sector responsible for the breaking $SU(2)_L \times SU(2)_R$ to $SU(2)_V$?

with which dynamics? with which interactions to the SM particles?

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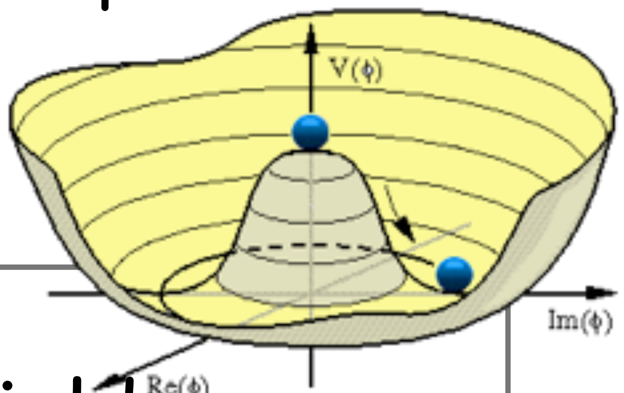
common lore: from a scalar Higgs doublet



$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

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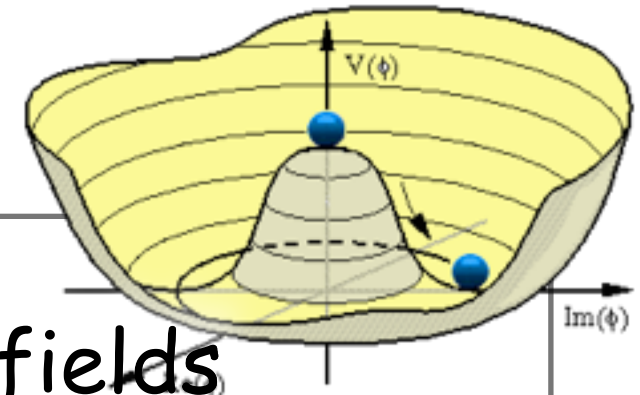

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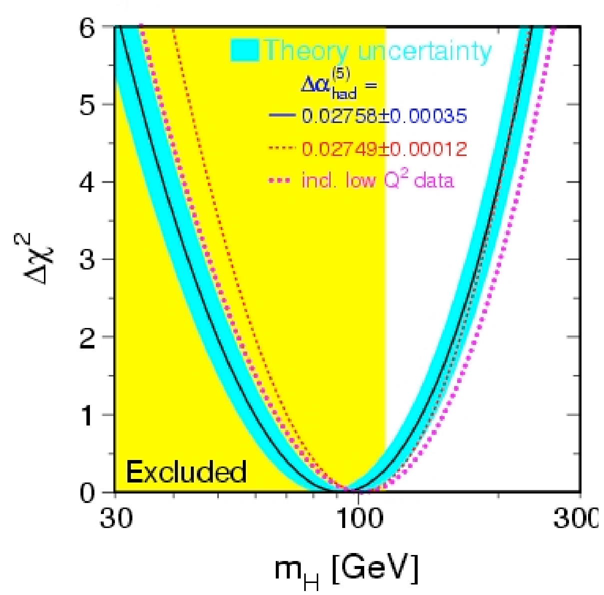
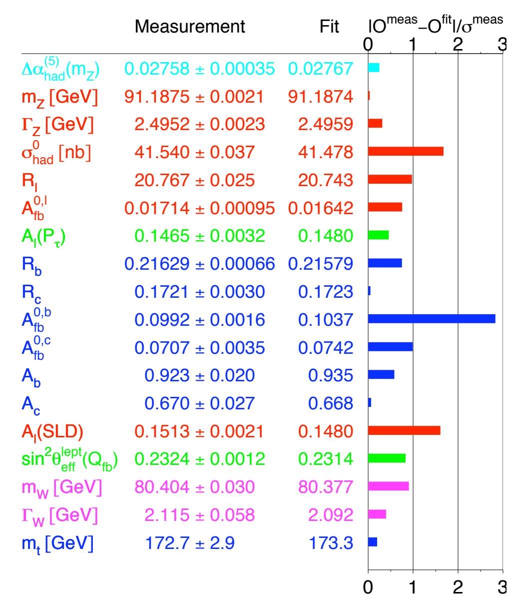
Higgs doublet = 4 real scalar fields

Good agreement with EW data

(doublet $\Leftrightarrow$ ρ=1)





But the Higgs hasn't been seen yet...

The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

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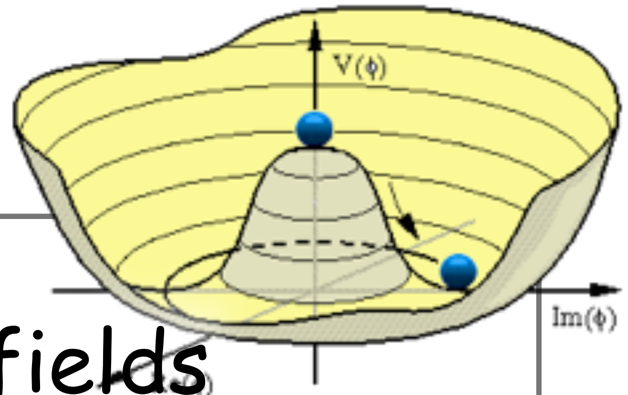

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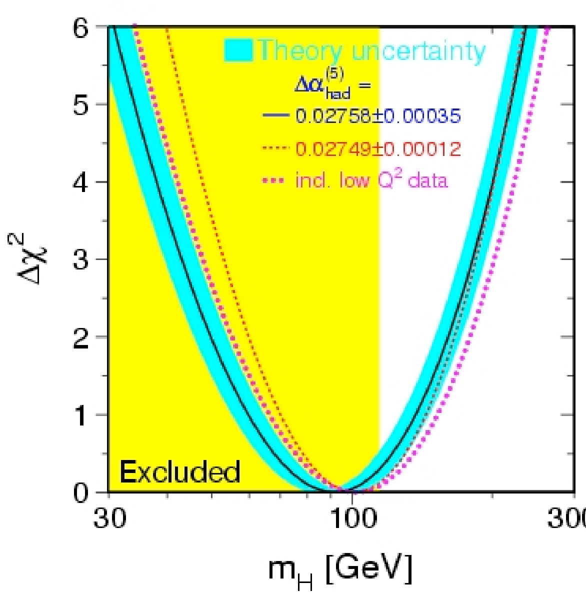
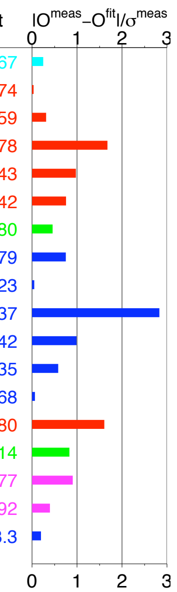


	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.377
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.7 ± 2.9	173.3



But the Higgs hasn't been seen yet...

"Myth or fact?"

How close to reality is the SM Higgs boson?

Bounds on (Dangerous) New Physics

Heavy Particles ⇛ new interactions for SM particles

broken symmetry	operators	scale Λ
B, L	$(QQQL)/\Lambda^2$	10^{13} TeV
flavor (1,2$^{\text{nd}}$ family), CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000 TeV
flavor (2,3$^{\text{rd}}$ family)	$m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

At colliders, it will be difficult to find direct evidence of new physics in these sectors...

New Physics in the EW sector

$\left((H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}\right) / \Lambda^2$	$\left\lvert H^\dagger D_\mu H \right\rvert^2 / \Lambda^2$	$\left(H^\dagger H\right)^3 / \Lambda^2$

Λ ~ few TeV only

high potential for direct detection at LHC, ILC !!!

See also A. Pich's lecture #2

Higgs Mechanism. Custodial symmetry

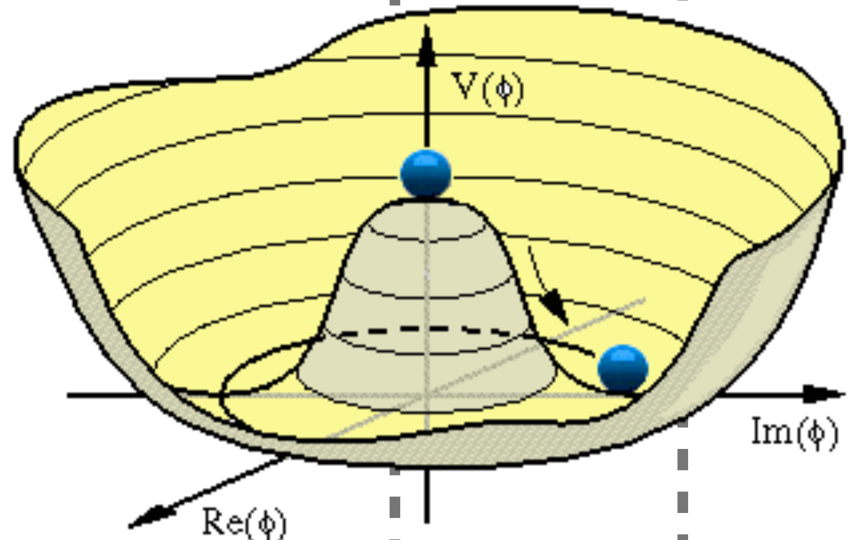
Higgs Mechanism

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} g W^3_\mu + g' B_\mu & \sqrt{2} g W^+_\mu \\ \sqrt{2} g W^-_\mu & -g W^3_\mu + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}^\pm_\mu = \tfrac{1}{\sqrt{2}} \left(\mathrm{W}^1_\mu \mp \mathrm{W}^2_\mu \right)$$

$$|D_\mu H|^2 = \tfrac{1}{4}\, g^2 v^2\, W^+_\mu W^{-\,\mu} + \tfrac{1}{8} \left(W^3_\mu \; B_\mu \right) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons

$$Z_\mu = c W^3_\mu - s B_\mu$$
$$\gamma_\mu = s W^3_\mu + c B_\mu$$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2 + g'^2}} \qquad s = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$M_Z^2 = \tfrac{1}{4}(g^2 + g'^2) v^2$$

$$M_\gamma = 0$$

Custodial Symmetry

Sikivie et al, '80

- Rho parameter

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4} g^2 v^2}{\frac{1}{4}(g^2+g'^2)v^2 \frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$ Higgs doublet = 4 real scalar fields

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$ is invariant under the rotation of the four real components

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

$SU(2)_R$

$SU(2)_L$ ➡ $\left(i\sigma^2 H^\star \quad H \right) = \Phi$

2x2 matrix

$$\Phi^\dagger \Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4} \left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2 \right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Sikivie et al, '80

Higgs vev

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad \langle \Phi \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

unbroken symmetry in the broken phase

$(W^1_\mu, W^2_\mu, W^3_\mu)$ transforms as a triplet

$$(Z_\mu \, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W^3_\mu \, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

$\rho = 1$

The hypercharge gauge coupling and the Yukawa couplings break the custodial $SU(2)_V$, which will generate a (small) deviation to $\rho = 1$ at the quantum level.

General expression of the ρ parameter

If $SU(2)_L \times U(1)_Y$ is broken not only by a doublet vev, but also through a collection of scalar fields in the $2s_i+1$ representation of $SU(2)_L$, carrying a hypercharge y_i and acquiring a vev v_i, the ρ parameter is given by

$$\rho = \frac{\sum_i (s_i(s_i+1) - y_i^2) v_i^2}{\sum_i 2 y_i^2 v_i^2}$$

See also A. Pich's lecture #3

SM & EW precision data

(S & T oblique parameters)

TH vs. EXP: SM @ the classical level

How good is the agreement of the SM with exp. data?

SM has 3 parameters: g, g' and v (forgetting the fermions)

several observables

α (Coulomb potential), G_F (μ decay), m_Z, m_W, $s^2_{\rm eff}$ (LR asymmetry in Z decay), $\Gamma(Z \to l^+ l^-)$

g, g' and v are extracted from α, G_F and m_Z

$\alpha = 1/137.03599911(46)$ $\qquad G_F = 1.16637(1) \times 10^{-5}\ \text{GeV}^{-2}$ $\qquad m_Z = 91.181876(21)\ \text{GeV}$

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SM at the classical level

$$\alpha = \frac{e^2}{4\pi}\ , \quad e = \frac{g g'}{\sqrt{g^2 + g'^2}}\ , \quad G_F = \frac{1}{\sqrt{2} v^2}\ , \quad m_Z^2 = \frac{1}{4}(g^2 + g'^2) v^2$$

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⇓ ⇓ ⇓

SM at the classical level

$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} \qquad g = \frac{\sqrt{8\pi\alpha}}{\sqrt{1-\sqrt{1-4\pi\alpha/(\sqrt{2}G_F m_Z^2)}}} \qquad g' = \frac{\sqrt{8\pi\alpha}}{\sqrt{1+\sqrt{1-4\pi\alpha/(\sqrt{2}G_F m_Z^2)}}}$$

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and we can predict the values of other observables

$$m_W = \tfrac{1}{2} g v$$

$$g_L = -1/2 + s^2, \quad g_R = s^2 \quad A_{LR} = \frac{(-1/2 + s^2_{eff})^2 - s^4_{\text{eff}}}{(-1/2 + s^2_{eff})^2 - s^4_{\text{eff}}} \quad s^2_{\text{eff}} = s^2_W = \frac{g'^2}{g^2 + g'^2}$$

$$\Gamma(Z \to l^+ l^-) = \frac{\sqrt{2} G_F}{6\pi} m_Z^3 (g_L^2 + g_R^2)$$

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and we can predict the values of other observables

$$m_W^2 = \frac{\sqrt{2}\pi\alpha G_F^{-1}}{1 - \sqrt{1 - 4\pi\alpha/(\sqrt{2} G_F m_Z^2)}}$$

$$s^2_{\rm eff} = 1/2 - \sqrt{1/4 - \pi\alpha/(\sqrt{2} G_F m_Z^2)}$$

$$\Gamma(Z \to l^+ l^-) = \frac{\sqrt{2} G_F m_Z^3}{12\pi} \left(\left(1/2 - \sqrt{1 - 4\pi\alpha(\sqrt{2} G_F m_Z^2)} \right)^2 + 1/4 \right)$$

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and we can predict the values of other observables

SM at tree-level

$m_W = 80.938\ \mathrm{GeV}$ $s^2_{\rm eff} = 0.21215$ $\Gamma(Z \to l^+ l^-) = 84.841\ \mathrm{MeV}$

experiment (LEPEWWG'05)

$m_W = 80.425 \pm 0.034\ \mathrm{GeV}$ $s^2_{\rm eff} = 0.23153 \pm 0.00016$ $\Gamma(Z \to l^+ l^-) = 83.992 \pm 0.010\ \mathrm{MeV}$

15 σ 120 σ 9 σ

TH vs. EXP: importance of quantum corrections

Quantum corrections have to be included in the previous analysis

accuracy in EW data: 1‰

typical size of EW loops:
$\mathcal{O}(g^2/16\pi^2) \sim \text{few ‰}$

new physics corrections:
$\mathcal{O}(v^2/M_{NP}^2)$

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new physics corrections:
$\mathcal{O}(v^2/M_{NP}^2)$

$$
\begin{aligned}
m_W &= m_W\big|^{\rm SM}_{\rm tree} + \Delta m_W\big|^{\rm SM}_{\rm loop} + \Delta m_W\big|_{\rm New\ Physics}\\
s^2_{\rm eff} &= s^2_{\rm eff}\big|^{\rm SM}_{\rm tree} + \Delta s^2_{\rm eff}\big|^{\rm SM}_{\rm loop} + \Delta s^2_{\rm eff}\big|_{\rm New\ Physics}\\
\Gamma_{l^+l^-} &= \Gamma_{l^+l^-}\big|^{\rm SM}_{\rm tree} + \Delta\Gamma_{l^+l^-}\big|^{\rm SM}_{\rm loop} + \Delta\Gamma_{l^+l^-}\big|_{\rm New\ Physics}
\end{aligned}
$$

SM loop corrections:
Many physicists have devoted their lives to compute them.
Require a deep knowledge of all areas of high energy physics

Test of SM:
Are these NP comtributions needed to fit EW data?

TH vs. EXP: EW fit

SM at tree-level

$m_W = 80.938$ GeV $\quad s^2_{\rm eff} = 0.21215 \quad \Gamma(Z \to l^+ l^-) = 84.841$ MeV

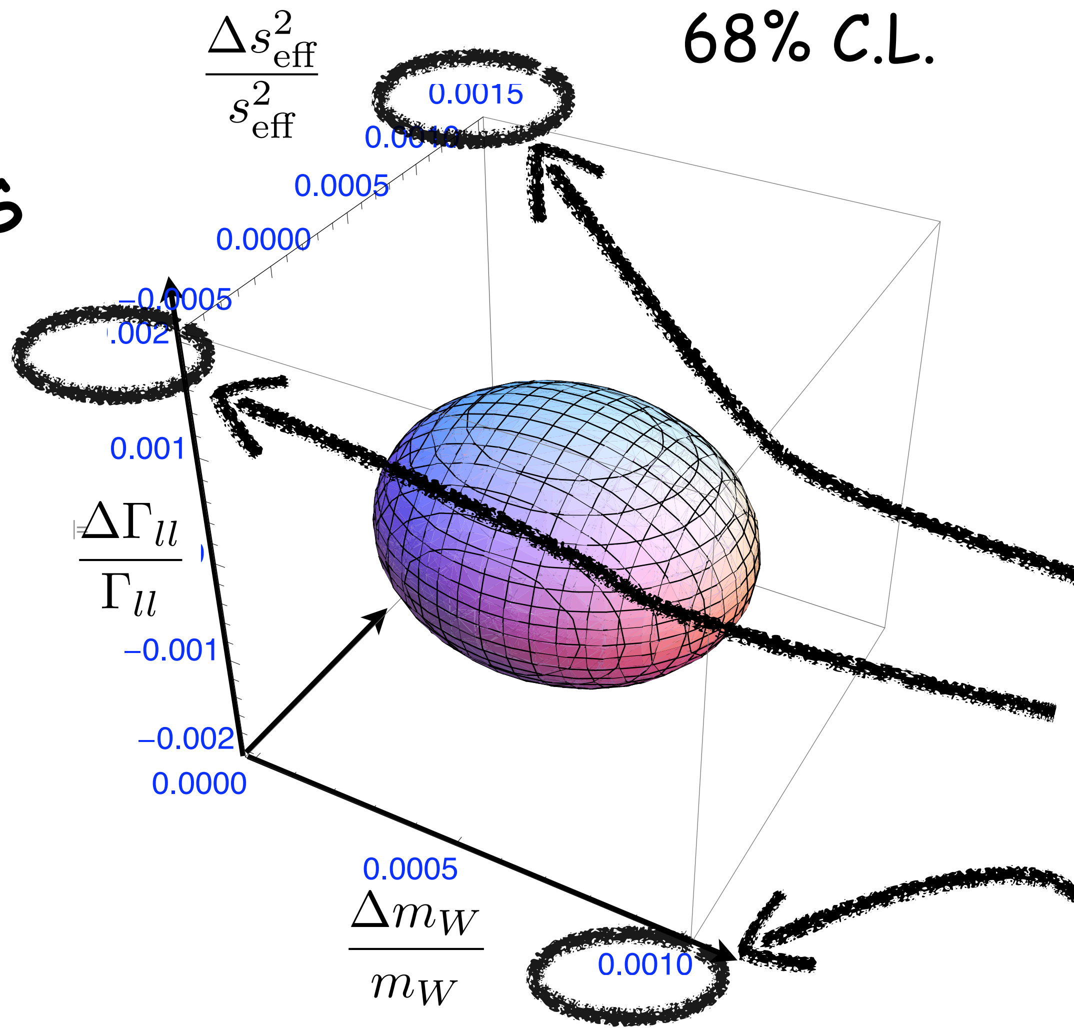
SM with loops (best fit, LEPEWWG'05)

$m_W = 80.389$ GeV $\quad s^2_{\rm eff} = 0.2314 \quad \Gamma(Z \to l^+ l^-) = 84.0325$ MeV

experiment (LEPEWWG'05)

$m_W = 80.425 \pm 0.034$ GeV $\quad s^2_{\rm eff} = 0.23153 \pm 0.00016 \quad \Gamma(Z \to l^+ l^-) = 83.992 \pm 0.010$ MeV

New Physics Contributions



68% C.L.

$$\chi^2 = \sum_{i=m_W, s^2_{\rm eff}, \Gamma_{ll}} \frac{\left(\mathcal{O}_i^{\rm exp} - \mathcal{O}_i^{\rm th}\right)^2}{\Delta \mathcal{O}_i{}^2}$$

$\chi^2=1 \Leftrightarrow$ 68% C.L.

The SM at quantum level fits the EW data at the 1‰ level

TH vs. EXP: EW fit - II

Usually, EW fits don't use $\Delta m_{W|\text{NP}}, \Delta s^2_{\text{eff}|\text{NP}}, \Delta\Gamma_{l^+l^-|\text{NP}}$

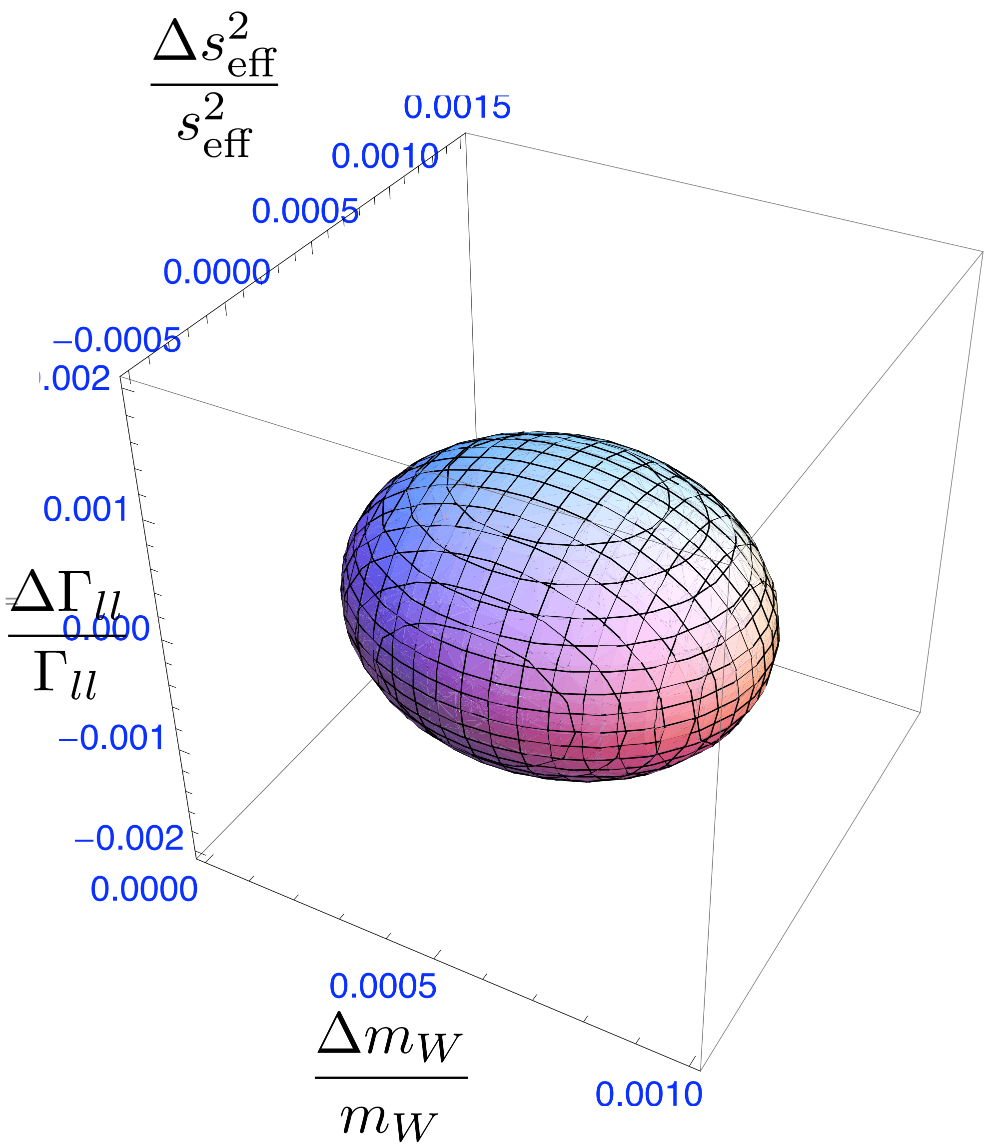
instead introduce perverse linear combinations S, T, U

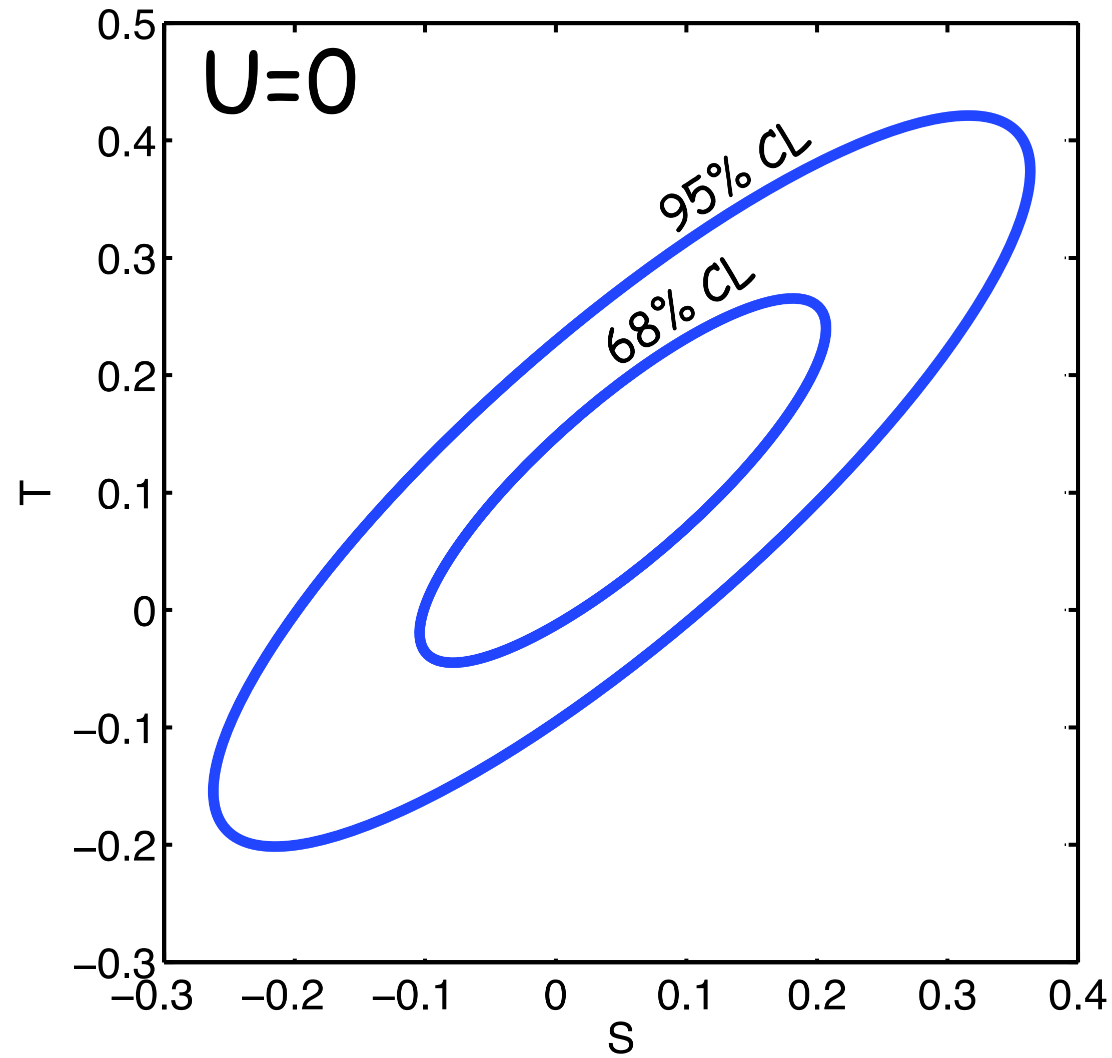
$$\Delta m_W = -\frac{\alpha m_W}{4(c_0^2 - s_0^2)} S + \frac{\alpha c_0^2 m_W}{2(c_0^2 - s_0^2)} T + \frac{\alpha m_W}{8 s_0^2} U$$

$$\Delta s^2_{\text{eff}} = \frac{\alpha}{4(c_0^2 - s_0^2)} S - \frac{\alpha c_0^2 s_0^2}{c_0^2 - s_0^2} T$$

$$\Delta\Gamma_{ll} = -\frac{2(1-4s_0^2)\alpha\Gamma^0_{ll}}{(1+(1-4s_0^2)^2)(c_0^2 - s_0^2)} S + \left(1 + \frac{8(1-4s_0^2)s_0^2 c_0^2}{(1+(1-4s_0^2)^2)(c_0^2 - s_0^2)}\right)\alpha\Gamma^0_{ll} T$$

TH vs. EXP: EW fit - II





Oblique Parameters

$\Delta m_{W|\mathrm{NP}}$, $\Delta s^2_{\mathrm{eff}|\mathrm{NP}}$, $\Delta\Gamma_{l^+l^-|\mathrm{NP}}$ are useful to perform a EW fit but cumbersome to compute explicitly in a given model

S,T (and U) are directly related to the Lagrangian (=friendly objects for theorists)

oblique parameters=modified propagators of $W^\pm$ and Z

$$\mathcal{L} = W_+^\mu\, \Pi_{+-}(p^2)\, W_{-\,\mu} + \tfrac{1}{2} W_3^\mu\, \Pi_{33}(p^2)\, W_{3\,\mu} + W_3^\mu\, \Pi_{3B}(p^2)\, B_\mu + \tfrac{1}{2} B^\mu\, \Pi_{BB}(p^2)\, B_\mu$$

Coefficients	Dim. 6 Operators	$SU(2)_c$	$SU(2)_l$
$\widehat{S} = \frac{g}{g'}\Pi'_{3B}(0)$	$\mathcal{O}_{WB} = (H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}/gg'$	$+$	$-$
$\widehat{T} = \frac{1}{M_W^2}(\Pi_{33}(0) - \Pi_{+-}(0))$	$\mathcal{O}_H = \lvert H^\dagger D_\mu H\rvert^2$	$-$	$-$
$\widehat{U} = \Pi'_{+-}(0) - \Pi'_{33}(0)$	dim. 8	$-$	$-$

$$\left(S = 4 s_w^2 \widehat{S}/\alpha_{em} \approx 119\,\widehat{S},\ T = \widehat{T}/\alpha_{em} \approx 129\,\widehat{T},\ U = -4 s_w^2 \widehat{U}/\alpha_{em} \approx -119\,\widehat{U}\right)$$

Barbieri, Pomarol, Rattazzi, Strumia '04

S & T from higher dimensional Operators

$$\mathcal{L} = \frac{1}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2$$

unitary gauge

$$\mathcal{L} = \frac{(g^2+g'^2)v^4}{16\Lambda^2} Z_\mu^2 \Rightarrow \Delta\Pi_{33} = -\frac{g^2 v^4}{8\Lambda^2} \Rightarrow T = -\frac{1}{2\sqrt{2}\alpha G_F \Lambda^2}$$

$$\begin{cases} m_Z^2 = \frac{1}{4}(g^2+g'^2)v^2 + \frac{1}{8\Lambda^2}(g^2+g'^2)v^4 \\ m_W^2 = \frac{1}{4}g^2 v^2 \end{cases}$$

- we need to write observables in terms of α, G_F and m_Z

$$\Delta m_W = \frac{c_0^2 m_W}{4\sqrt{2}(c_0^2 - s_0^2) G_F \Lambda^2}$$

$$s_{\text{eff}}^2 = \frac{g'^2}{g^2+g'^2} \Rightarrow \Delta s_{\text{eff}}^2 = -\frac{-s_0^2 c_0^2}{2\sqrt{2}(s_0^2 - c_0^2) G_F \Lambda^2}$$

$$\Bigg\} \; T = -\frac{1}{2\sqrt{2}\alpha G_F \Lambda^2}$$

- T measured the deviation to ρ=1:

$$\rho = \frac{m_W^2}{c_W^2 m_Z^2} \approx 1 + \alpha T$$

S & T from higher dimensional Operators

$$\mathcal{L} = \frac{1}{\Lambda^2} H^\dagger W_{\mu\nu} H B_{\mu\nu}$$

unitary gauge $\mathcal{L} = -\frac{v^2}{2\Lambda^2} B_{\mu\nu} W^3_{\mu\nu}$ kinetic mixing ⇨ $\Delta\Pi'_{30} = -\frac{v^2}{\Lambda^2}$ ⇨ $S = \frac{4 s_0 c_0}{\sqrt{2}\alpha G_F \Lambda^2}$

- because of the kinetic mixing, the Z and the γ are not obtained from the usual weak rotation from W_3 and B

$$Z = \frac{g}{\sqrt{g^2+g'^2}} \left(1 - \frac{gg'}{g^2+g'^2}\frac{v^2}{\Lambda^2}\right) W_3 - \frac{g'}{\sqrt{g^2+g'^2}} \left(1 - \frac{gg'}{g^2+g'^2}\frac{v^2}{\Lambda^2}\right) B$$

$$\gamma = \frac{g'}{\sqrt{g^2+g'^2}} \left(1 + \frac{g^3}{g'(g^2+g'^2)}\frac{v^2}{\Lambda^2}\right) W_3 - \frac{g}{\sqrt{g^2+g'^2}} \left(1 - \frac{g'^3}{g(g^2+g'^2)}\frac{v^2}{\Lambda^2}\right) B$$

$$m_Z^2 = \frac{1}{4}(g^2+g'^2)\left(1 + \frac{2gg'}{\sqrt{2}(g^2+g'^2)\Lambda^2}\right)$$

- the definition of the electric charge is also affected (check that the γ still couples to $Q=T_{3L}+Y$!)

$$e = \frac{gg'}{\sqrt{g^2+g'^2}}\left(1 - \frac{gg'}{g^2+g'^2}\frac{v^2}{\Lambda^2}\right)$$

- expressing m_W in terms of α, G_F and m_Z, we arrive at

$$\Delta m_W = -\frac{s_0 c_0 m_W}{\sqrt{2}(c_0^2 - s_0^2)\Lambda^2} \Rightarrow S = \frac{4 s_0 c_0}{\sqrt{2}\alpha G_F \Lambda^2}$$

EW Precision Measurements & Higgs Mass

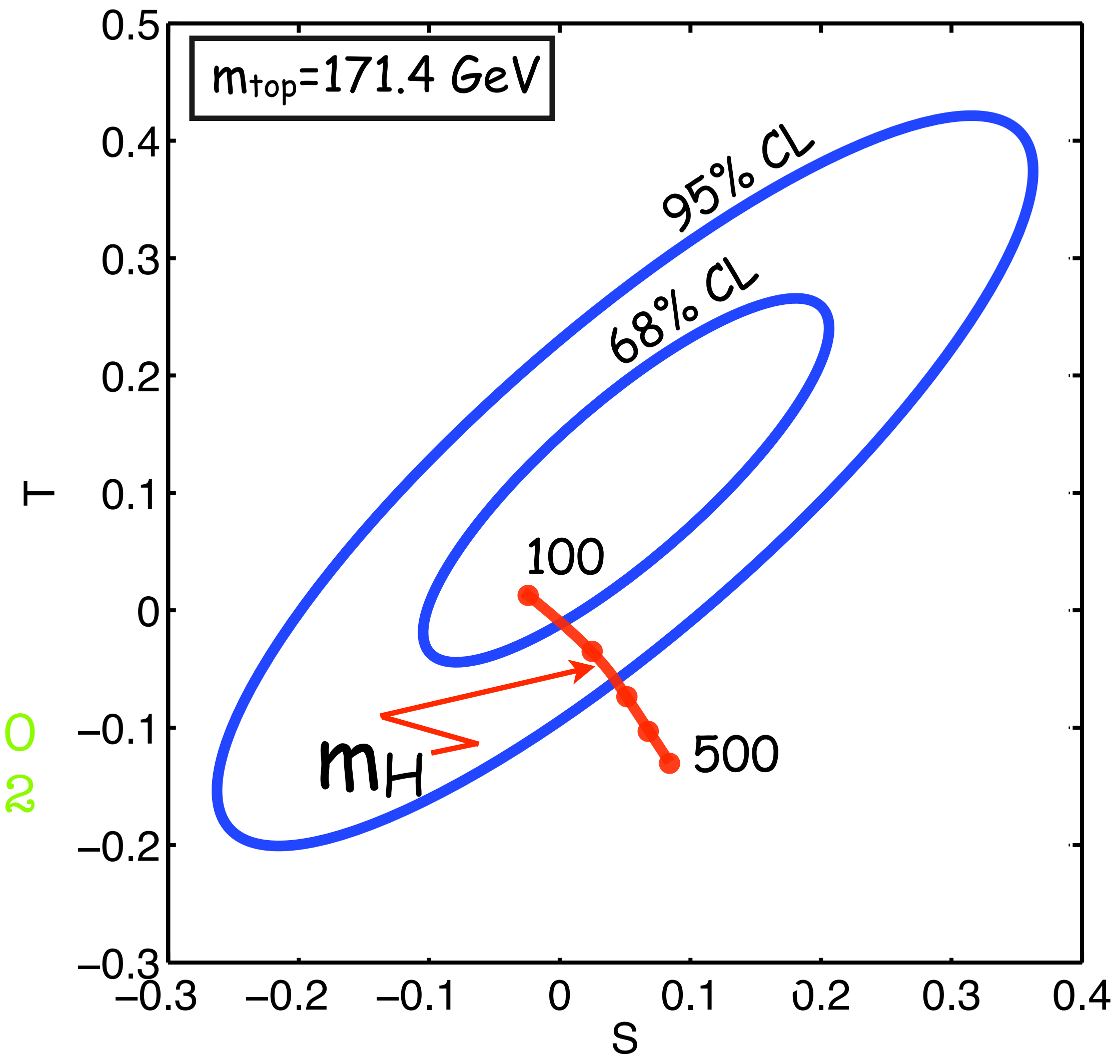
The SM 1-loop corrections are computed for a reference Higgs mass.
A variation of the Higgs mass can be seen as a contribution to S and T.

$\Rrightarrow$ constraints on the Higgs mass

Higgs contribution

$$\delta S = \frac{1}{12\pi} \log \frac{m_h^2}{m_{h_0}^2}$$

$$\delta T = -\frac{3}{16\pi\, c_W^2} \log \frac{m_h^2}{m_{h_0}^2}$$



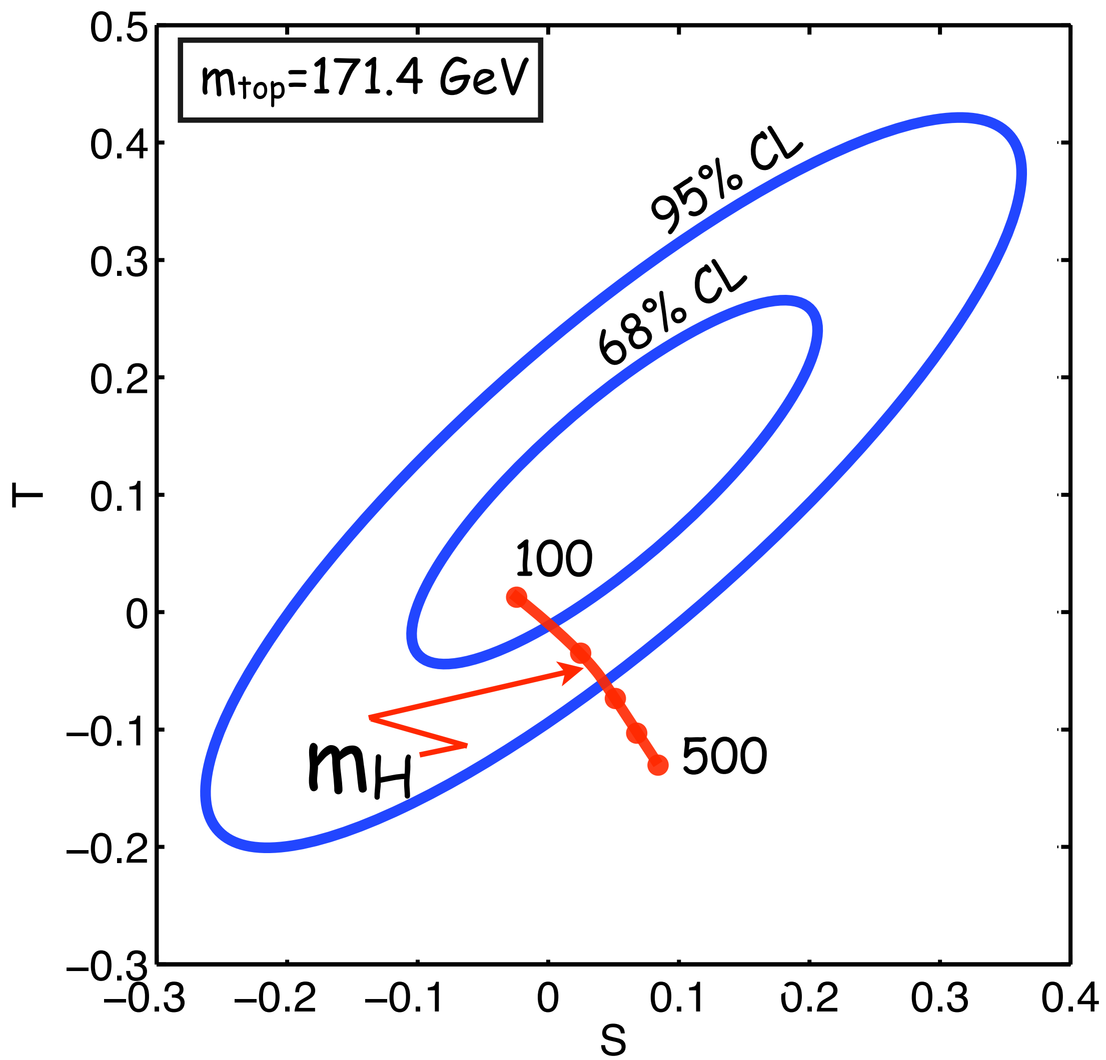
Peskin, Takeuchi '90
Peskin, Takeuchi '92

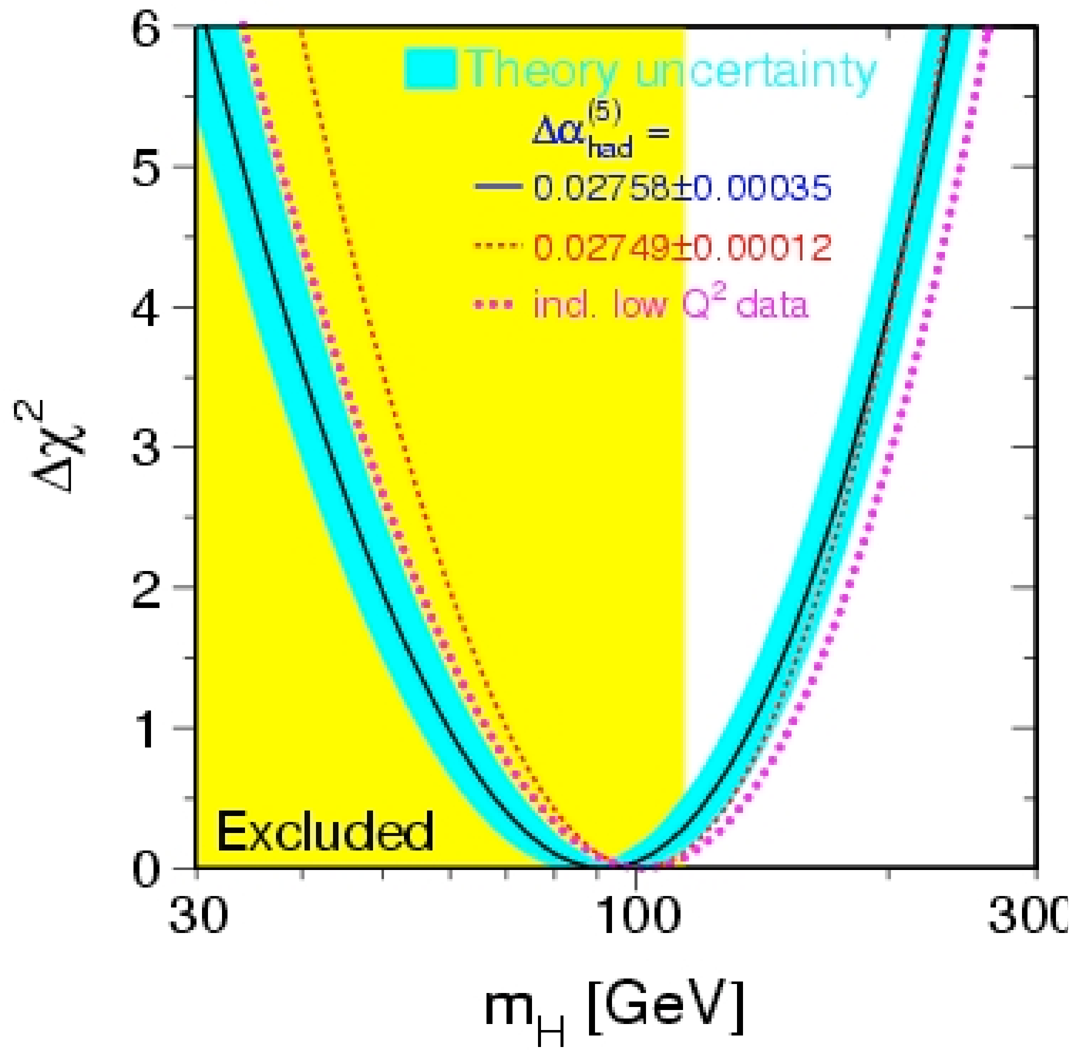
The SM Higgs cannot get too heavy
unless there exist other
(tuned) contributions to S and T

EW Precision Measurements & Higgs Mass

The SM 1-loop corrections are computed for a reference Higgs mass.
A variation of the Higgs mass can be seen as a contribution to S and T.

⇛ constraints on the Higgs mass





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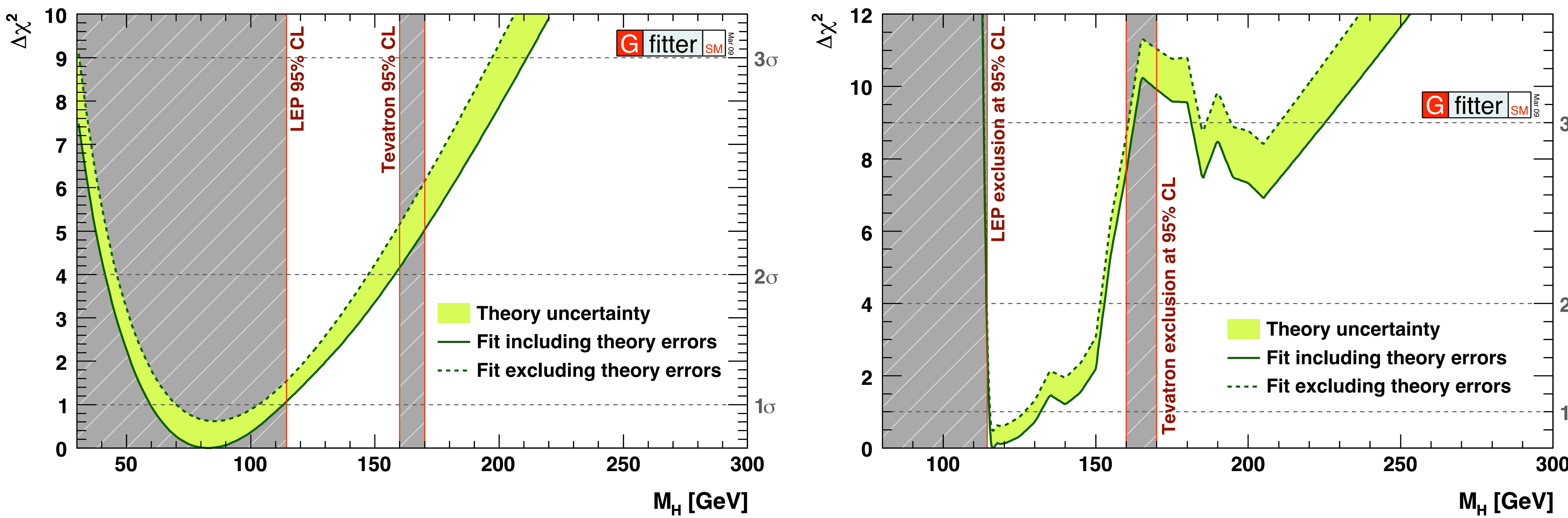
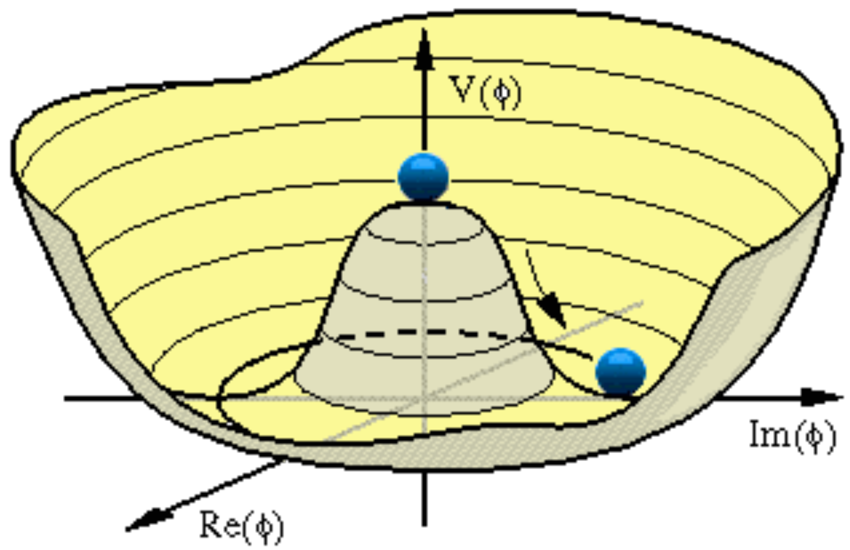


Higgs Mechanism: a model without dynamics

Why is EW symmetry broken ?
Because μ^2 is negative

Why is μ^2 negative ?
Because otherwise, EW symmetry won't be broken

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$



The Higgs mechanism is a description of EWSB. It is not an explanation. No dynamics to explain the instability at the origin.

See also A. Pich's lecture #4

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons ← → One physical degree of freedom the Higgs boson

Higgs as a UV moderator

(unitarity bound)

Why do we need a Higgs ?

The W and Z masses are inconsistent with the known particle content! Need more particles to soften the UV behavior of massive gauge bosons.

Indeed a massive spin 1 particle has 3 physical polarizations:

$$k^\mu = (E, 0, 0, k)$$

with $k_\mu k^\mu = E^2 - k^2 = M^2$

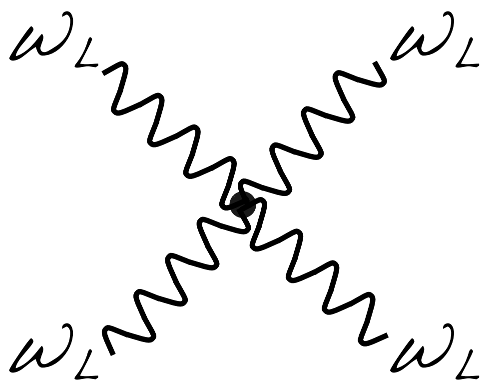
$$A_\mu = \epsilon_\mu \; e^{i k_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$
- 1 longitudinal: $\epsilon_\parallel^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

Bad UV behavior for the scattering of the longitudinal polarizations



Why do we need a Higgs ?

Bad UV behavior for
the scattering of the longitudinal
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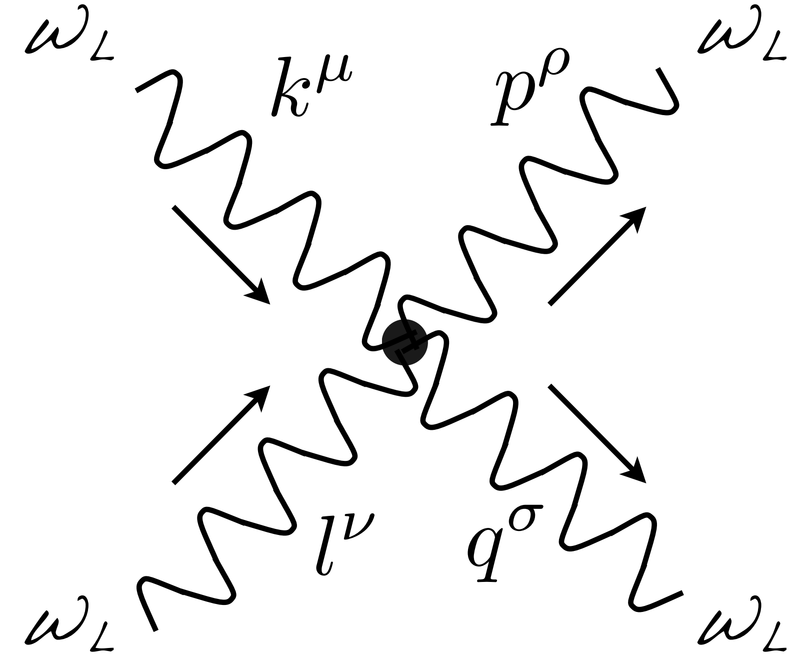


$$\mathcal{A} = \epsilon^\mu_{\|}(k)\epsilon^\nu_{\|}(l)\, ig^2(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho})\, \epsilon^\rho_{\|}(p)\epsilon^\sigma_{\|}(q)$$

$$\mathcal{A} = g^2 \frac{E^4}{4M_W^4}$$

violations of perturbative unitarity around E ~ M

A QCD antecedent

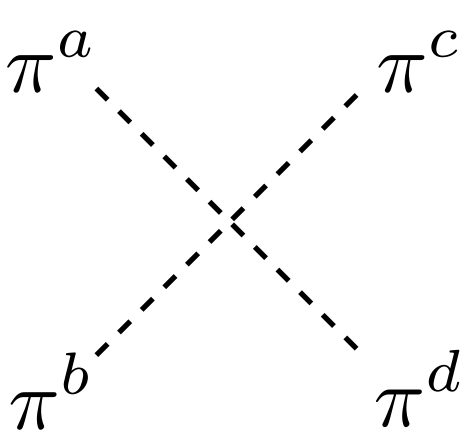
QCD pions are Goldstone bosons associated to $SU(2)_L \times SU(2)_R / SU(2)_V$

$$U = e^{i\pi^a \sigma^a / f_\pi} \begin{pmatrix} 0 \\ \frac{f_\pi}{\sqrt{2}} \end{pmatrix}$$

kinetic terms for U $\Leftrightarrow$ interaction terms for π^a

$$\mathcal{L} = |\partial_\mu U|^2 = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6 f_\pi^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



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

$$\mathcal{A}(s,t,u) = \frac{s}{f_\pi^2}$$

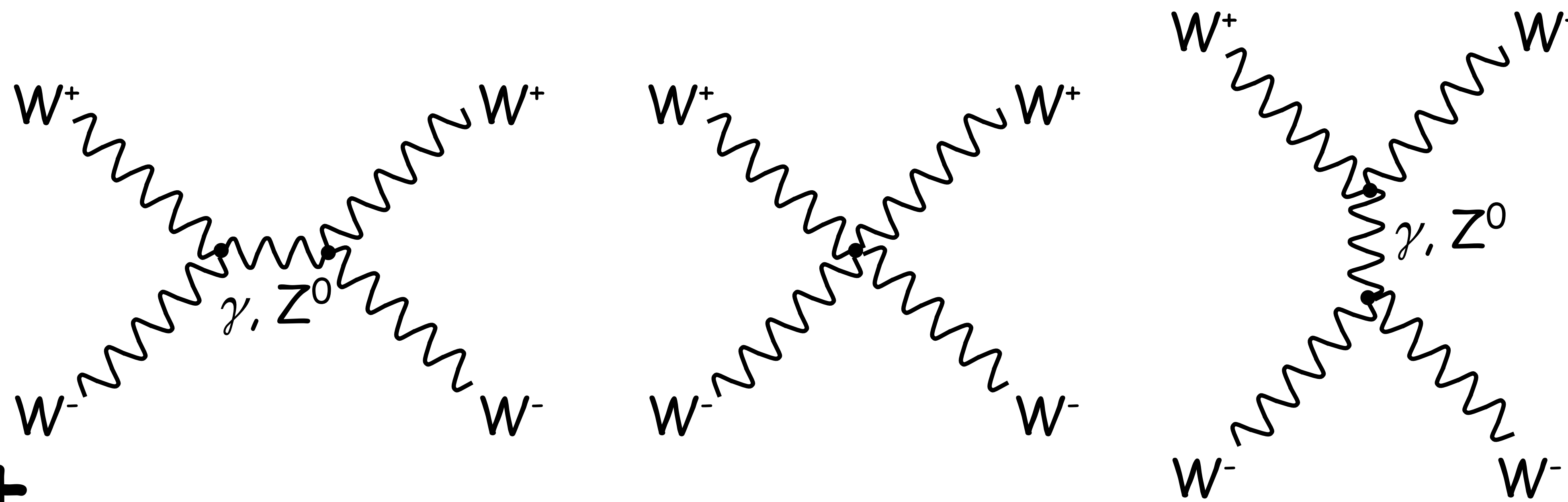
$$f_\pi = 93 \text{ MeV}$$

⇒ unitarity bound

$$\sqrt{s} \sim 4\sqrt{\pi} f_\pi = 660 \text{ MeV}$$

rho meson (m=770 MeV) is restoring unitarity

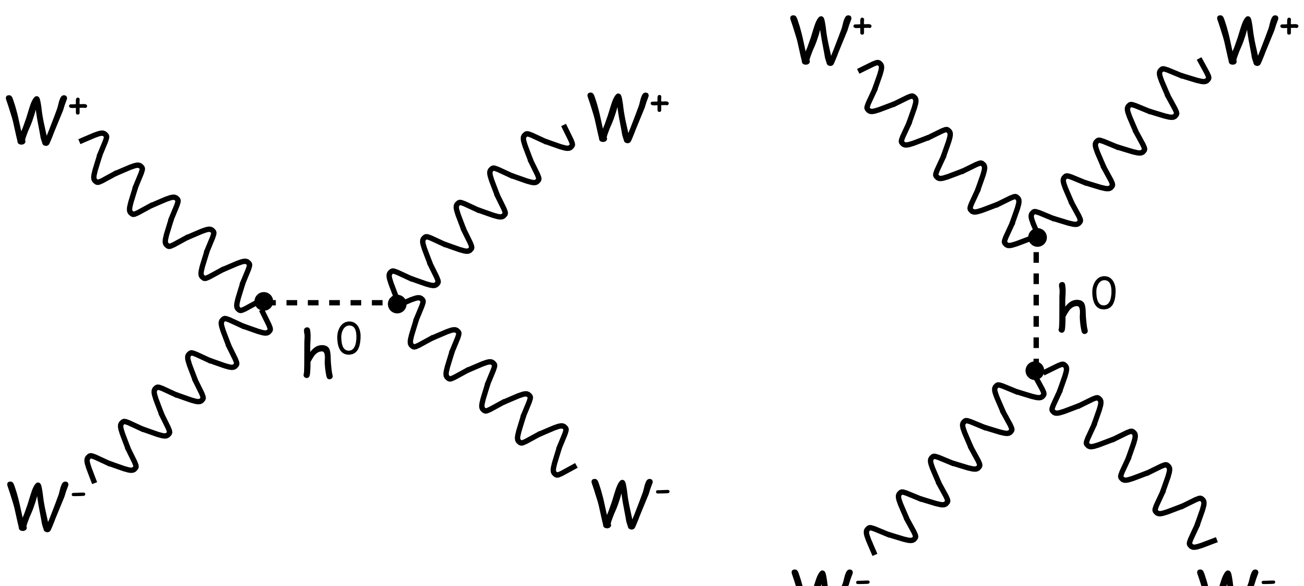
Why do we need a Higgs ?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W} \right)^2$$

+

+



$$\mathcal{A} = -g^2 \left(\frac{E}{M_W} \right)^2$$

$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W} \right)^2$$

The Higgs boson unitarize the W scattering (if its mass is below ~ 700 GeV)

W_L scattering = pion scattering

Goldstone equivalence theorem

Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73
Lee, Quigg, Thacker '77

Higgs as UV moderator

massless W, Z ⟷ gauge invariance

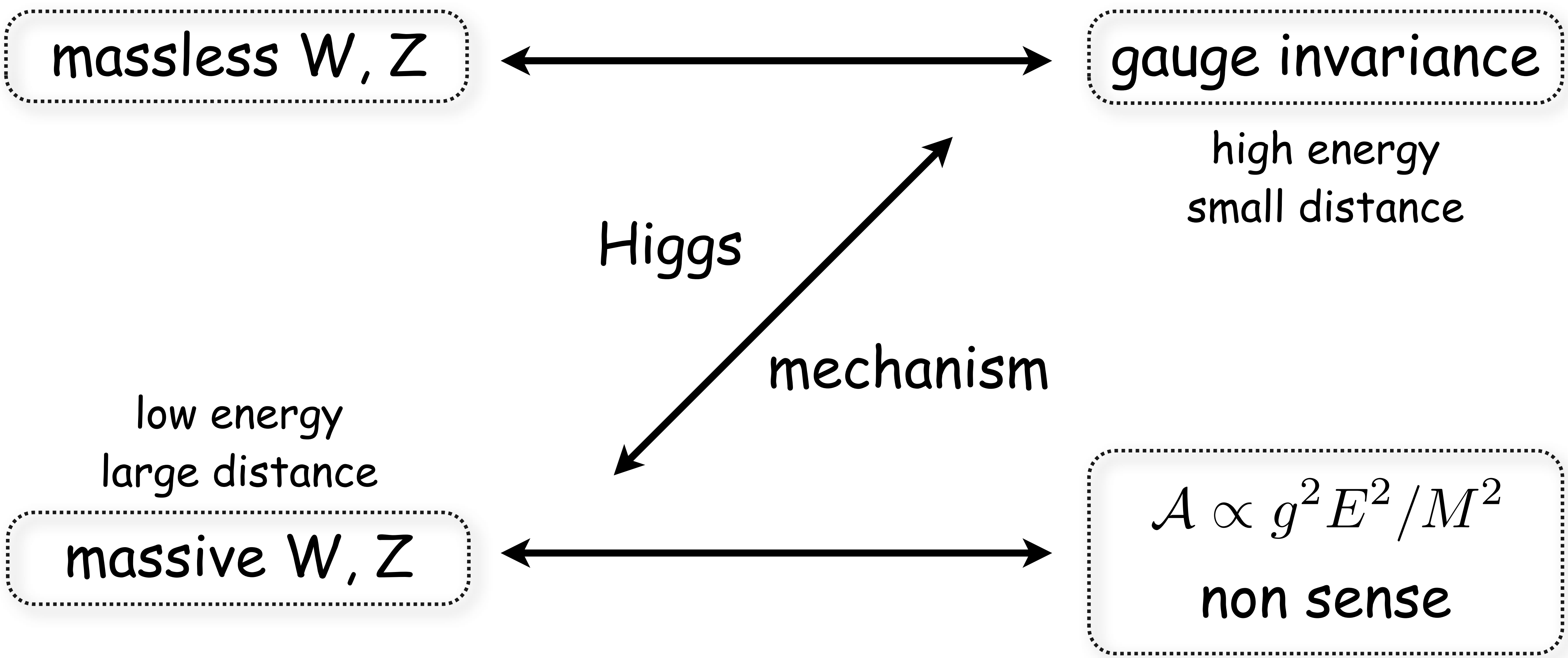
high energy
small distance

Puzzle:
compatiblity between
high and low energy

low energy
large distance

massive W, Z ⟷ $\mathcal{A} \propto g^2 E^2/M^2$
non sense

Higgs as UV moderator



Physics Beyond the Higgs?

Is the Standard Model with a Higgs a UV finite theory?
i.e. valid to arbitrarily high energies

Of course, the SM will fail around the Planck scale

but the real question is

Is there any reason to think there is new physics
between the weak scale and the Planck scale?

UV behaviour of the Higgs boson

(triviality, stability, hierarchy)

Quantum Behavior of the Higgs^4 Coupling (I)

$$V(h) = -\tfrac{1}{2}\mu^2 h^2 + \tfrac{1}{4}\lambda h^4$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$

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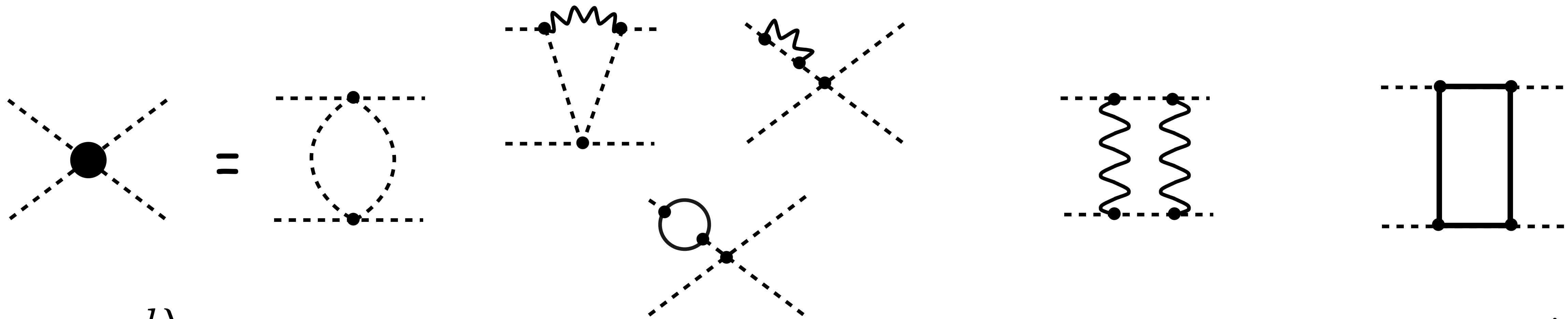

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

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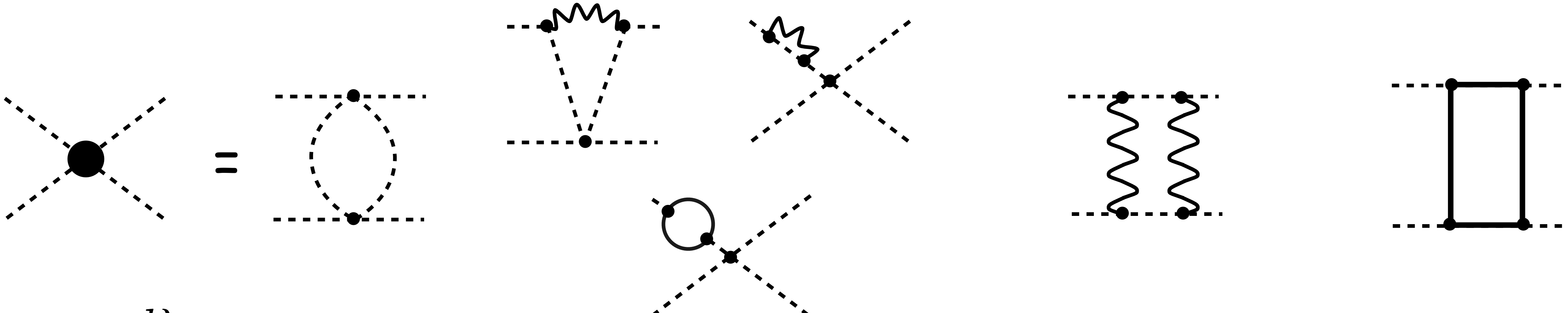

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Large mass (λ dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2$$

λ increases with Q: IR-free coupling

$$\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

Quantum Behavior of the Higgs^4 Coupling (I)

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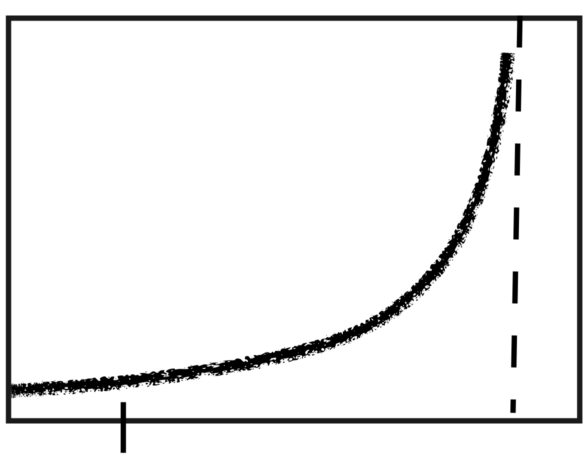
Wilson '71
Wilson, Kogut '74



Landau pole

Triviality bound

$$\Lambda \leq v\, e^{4\pi^2 v^2/3m_H^2}$$

New physics should appear before that point to restore stability

for m_H fixed, upper bound on Λ
for Λ fixed, upper bound on m_H

No microscopic description: for $\Lambda \to \infty$, trivial theory (λ=0)

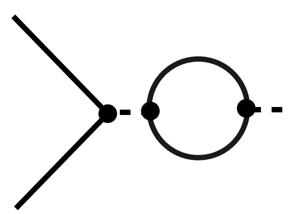
Quantum Behavior of the Higgs^4 Coupling (II)

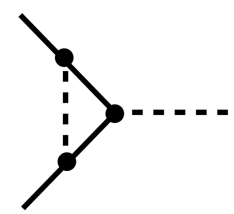
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Small mass (y_t dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4$$

λ decreases with Q.





$$\left(16\pi^2 \frac{dy_t}{d\ln Q} = \frac{9}{2}\, y_t^3 + \right.$$ Higher loops Small Yukawa $$\left. y^2(Q) = \frac{y^2(Q_0)}{1 - \frac{9}{16\pi^2} y^2(Q_0) \ln \frac{Q}{Q_0}}\right)$$

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

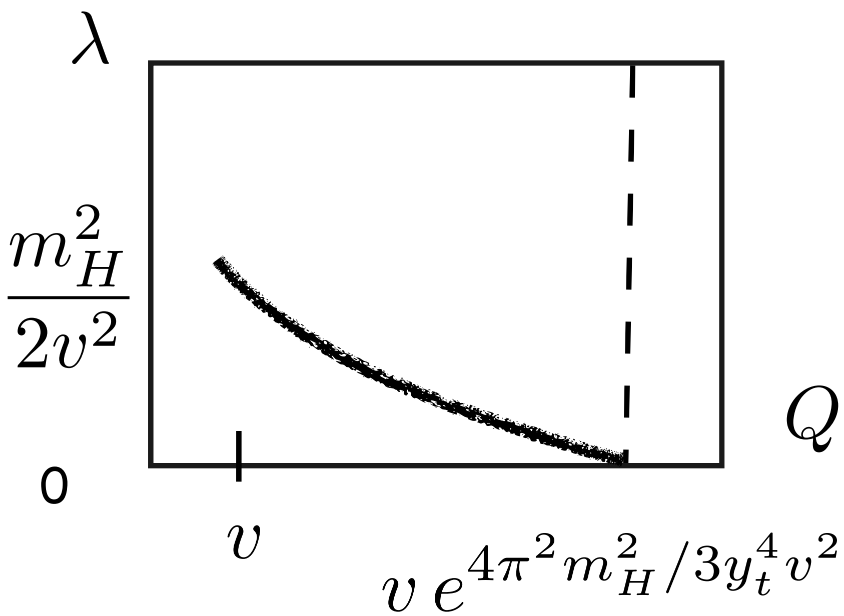
Quantum Behavior of the Higgs^4 Coupling (II)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$

Higher loops
Small Yukawa

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$



$\lambda < 0$ ⇛ potential unbounded from below

$\lambda(Q) = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2} y_0^4 \log \frac{Q}{Q_0}$

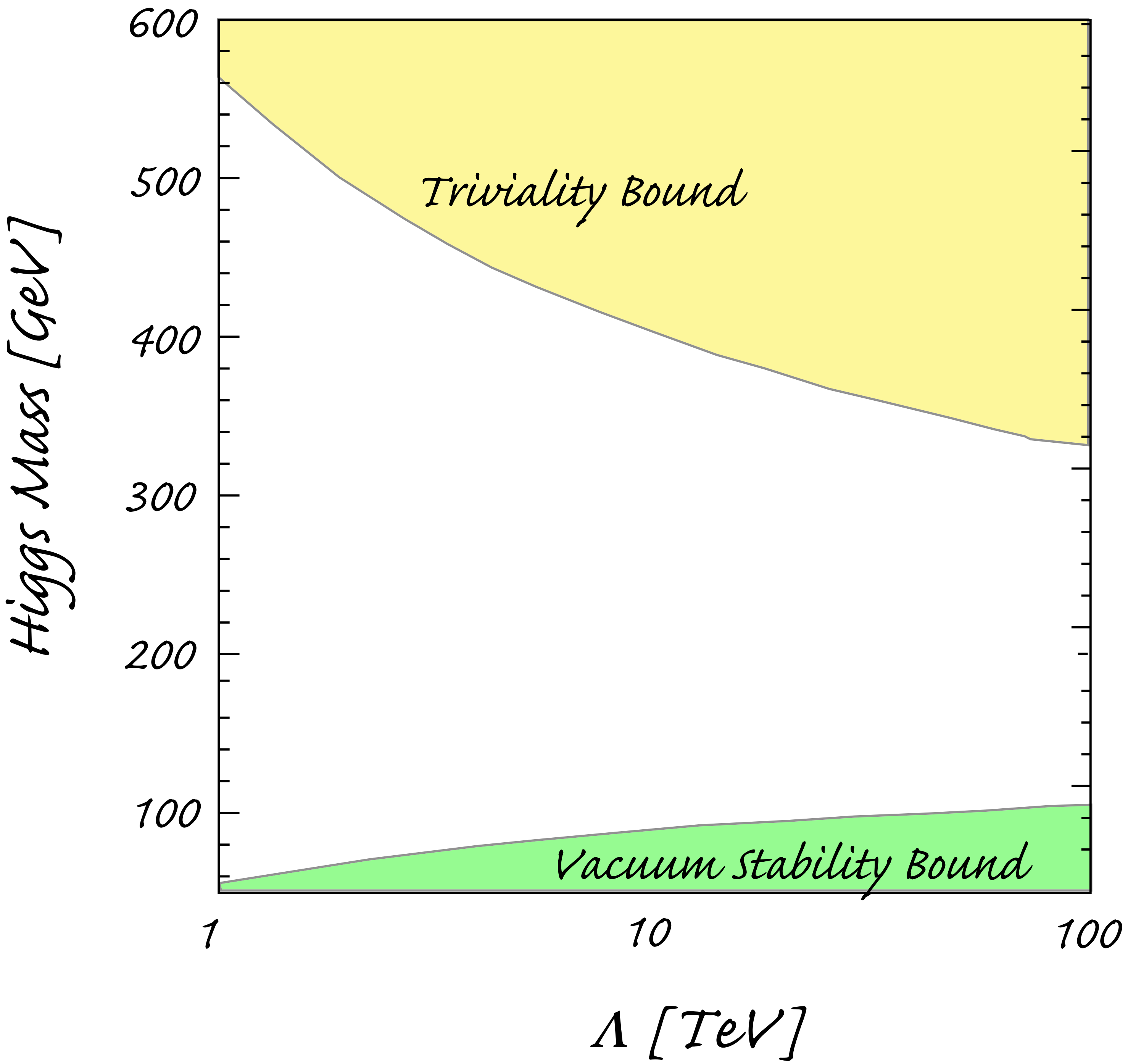
New physics should appear before that point to restore stability

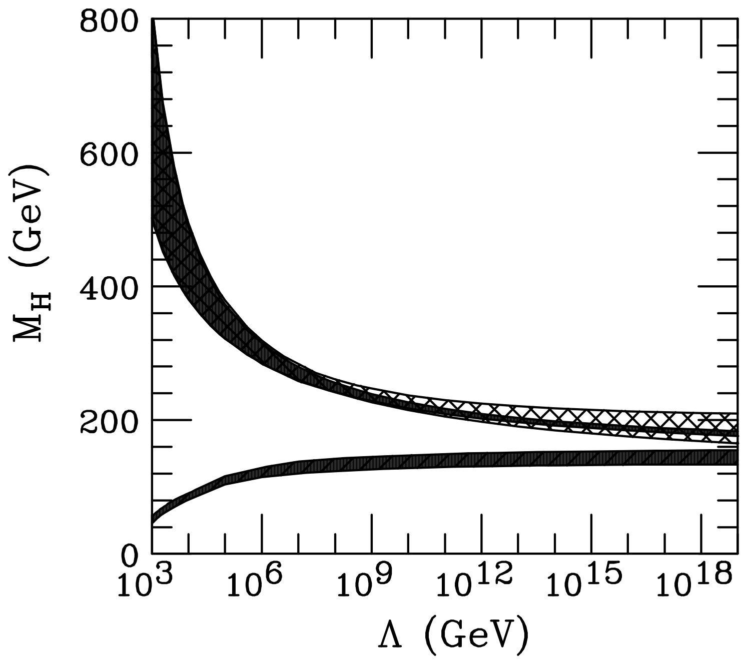
Stability bound

$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

for Λ fixed, lower bound on m_H

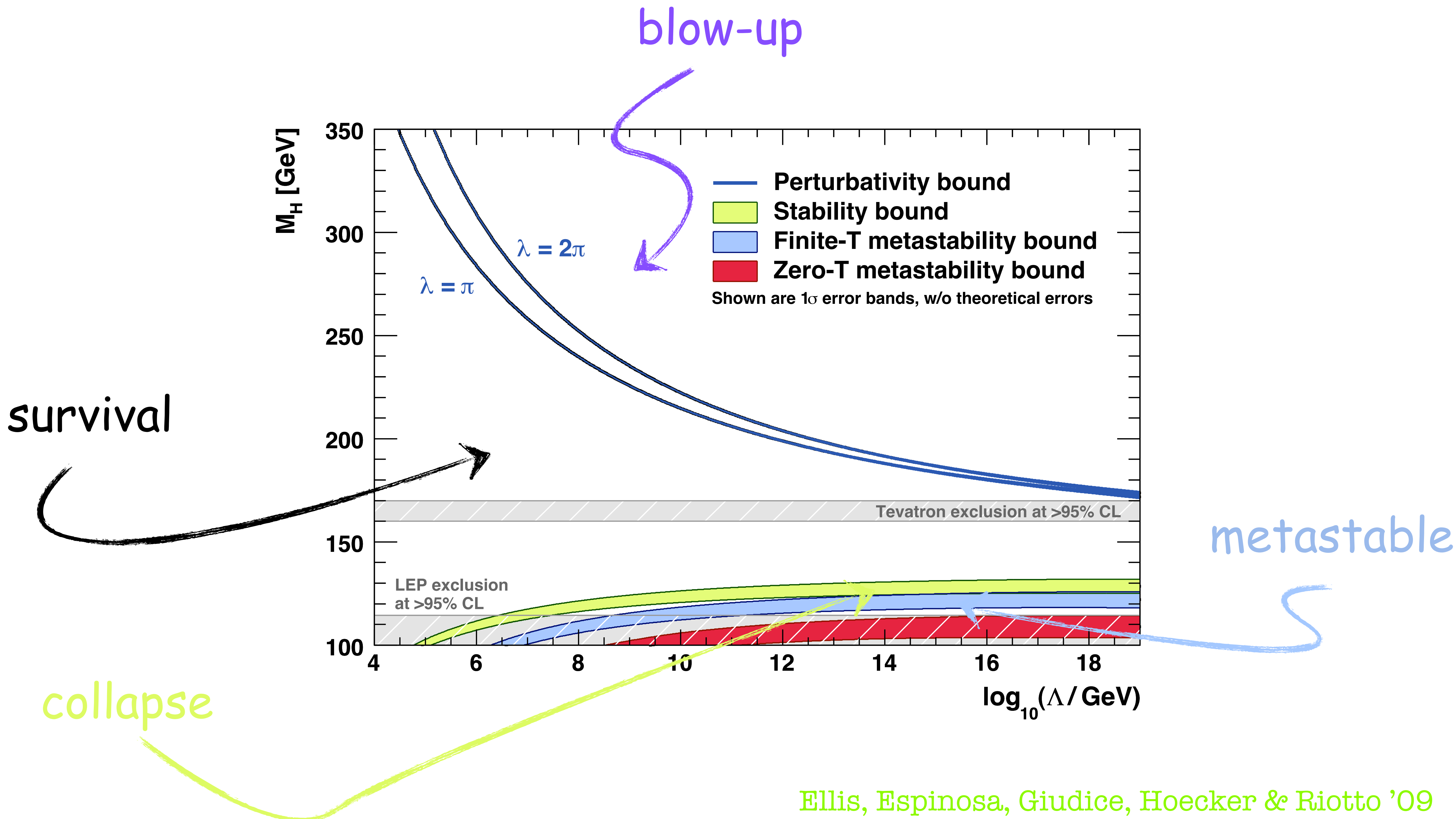
Linde '76
Weinberg '76





Hambye, Riesselmann '97

Only a light Higgs (160 GeV<m_H<180 GeV) allows for the absence of New Physics at low energy



Ellis, Espinosa, Giudice, Hoecker & Riotto '09

Only a light Higgs (130 GeV<m_H<170 GeV) allows for the absence of New Physics at low energy

Solution to the Higgs^4 Coupling Instabilities

find a symmetry such that

$$\lambda \equiv g^2$$

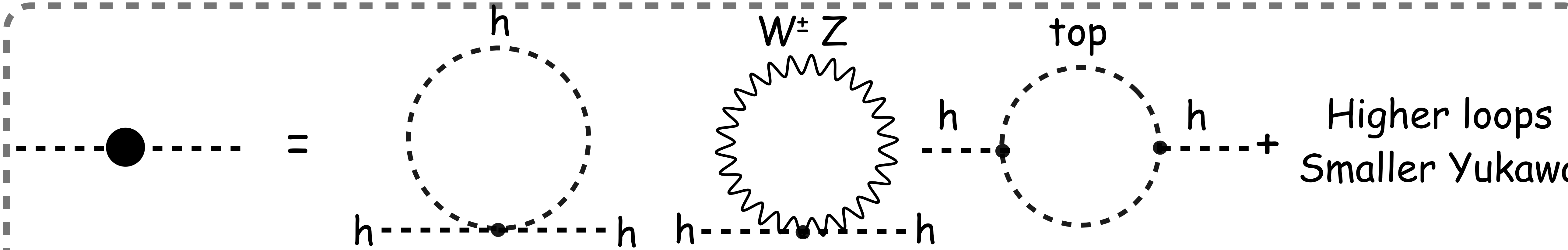
the Higgs quartic will inherit the good UV asymptotically free behavior of the gauge coupling

Examples of such symmetry:

- supersymmetry
- gauge-Higgs unification: the Higgs is identified as a component of the gauge field along some extra-dimensions.

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is higly dependent on the UV physics, which leads to the so called hierarchy problem



$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2$$

Weisskopf '39
't hooft '79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \frac{3G_F\Lambda^2}{16\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115 \text{ GeV})^2 \left(\frac{\Lambda}{400 \text{ GeV}}\right)^2$$

Λ^2 from the Coleman-Weinberg Potential

$$V(h) = \int \frac{d^4 k_E}{2(2\pi)^4} \mathrm{STr} \ln \left(k_E^2 + M^2(h)\right)$$

$$V(h) = -\frac{\Lambda^4}{128\pi^2}\mathrm{STr}1 + \frac{\Lambda^2}{64\pi^2}\mathrm{STr}M^2(h) + \frac{1}{64\pi^2}\mathrm{STr}M^4(h)\ln\frac{M^2(h)}{\Lambda^2}$$

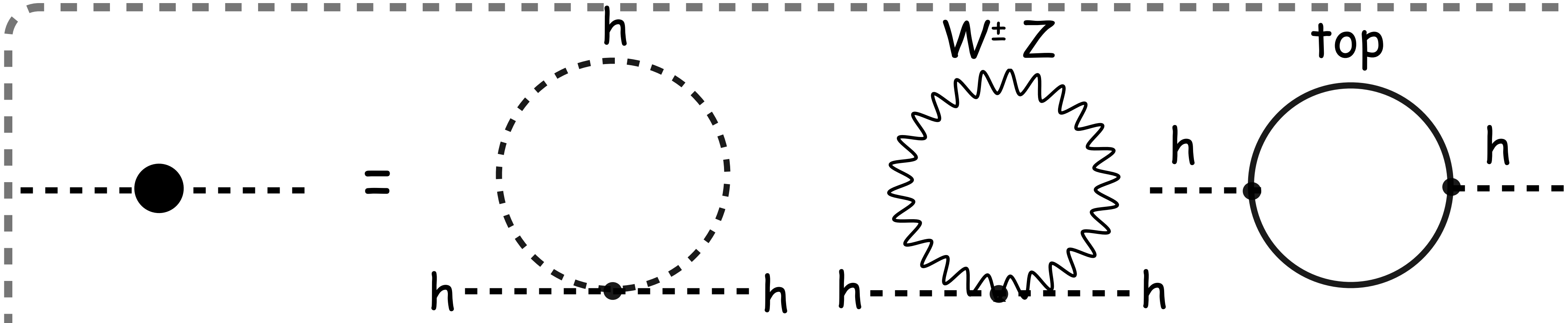
$M_W^2 = \frac{1}{4}g^2h^2$	$M_Z^2 = \frac{1}{4}(g^2+g'^2)h^2$	$M_t^2 = \frac{1}{2}y_t^2h^2$	$M_H^2 = \lambda\left(3h^2 - v^2\right)$	$M_G^2 = \lambda\left(h^2 - v^2\right)$
2x3	3	4x3	1	3

h dependent masses away from the true vacuum
(for h=v, we recover the usual expression
for the Higgs mass
and the Goldstone are massless)

$$V(h) = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{32\sqrt{2}\pi^2}h^2$$

in agreement with the loop computation

Quantum Instability of the Higgs Mass

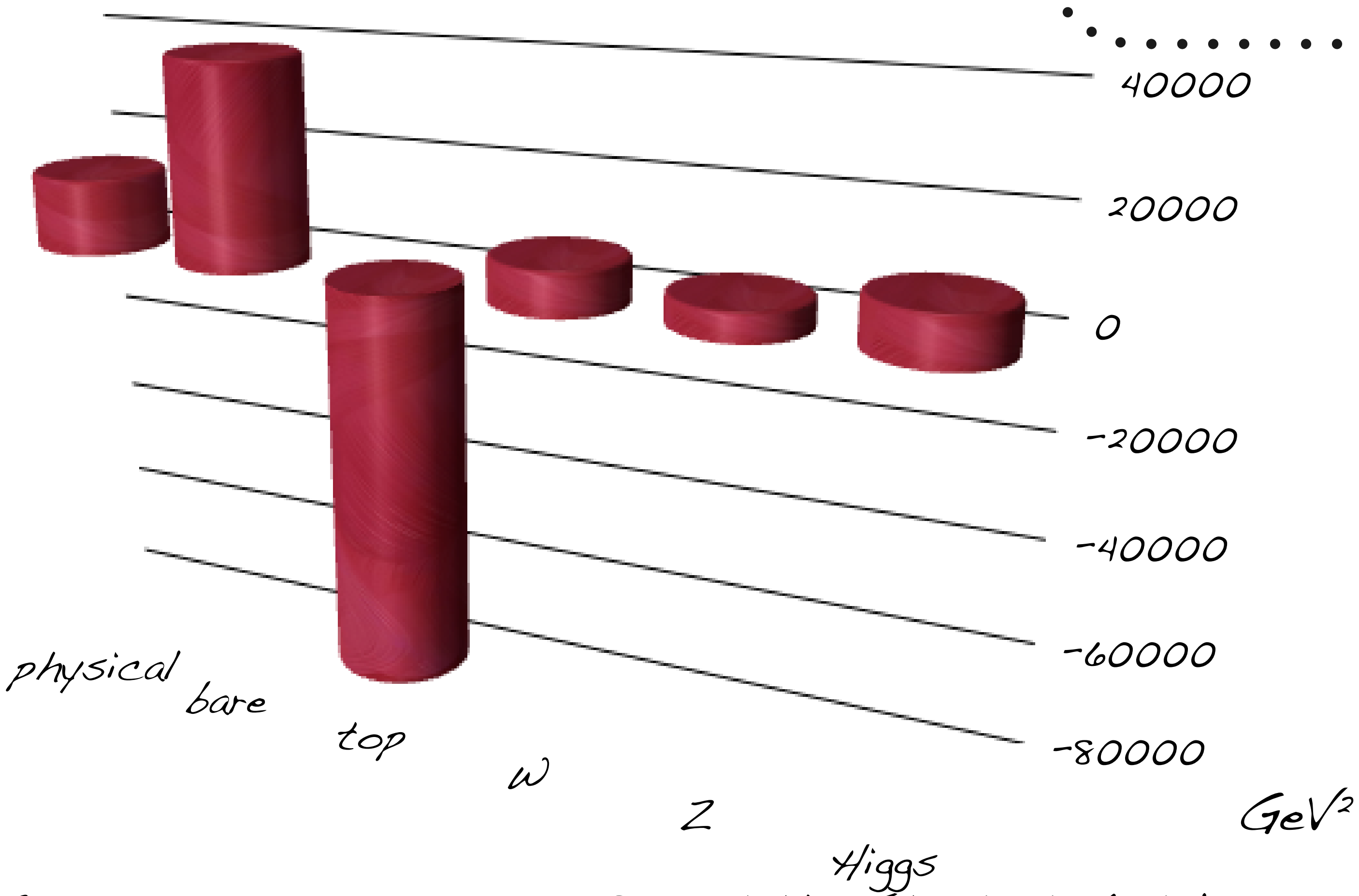


Higher loops
Smaller Yukawa

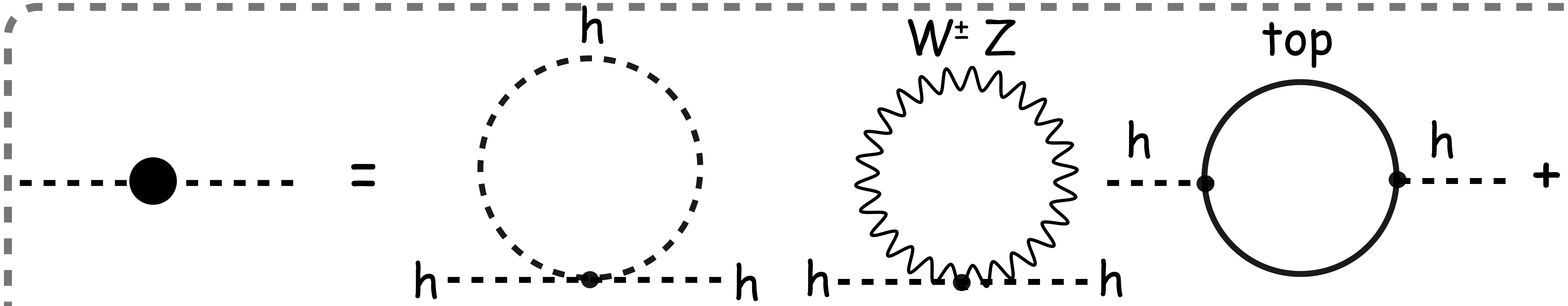
$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2$$

$$m_H^2 \sim m_0^2 - (115 \text{ GeV})^2 \left(\frac{\Lambda}{400 \text{ GeV}} \right)^2$$

Λ = 1 TeV



Quantum Instability of the Higgs Mass



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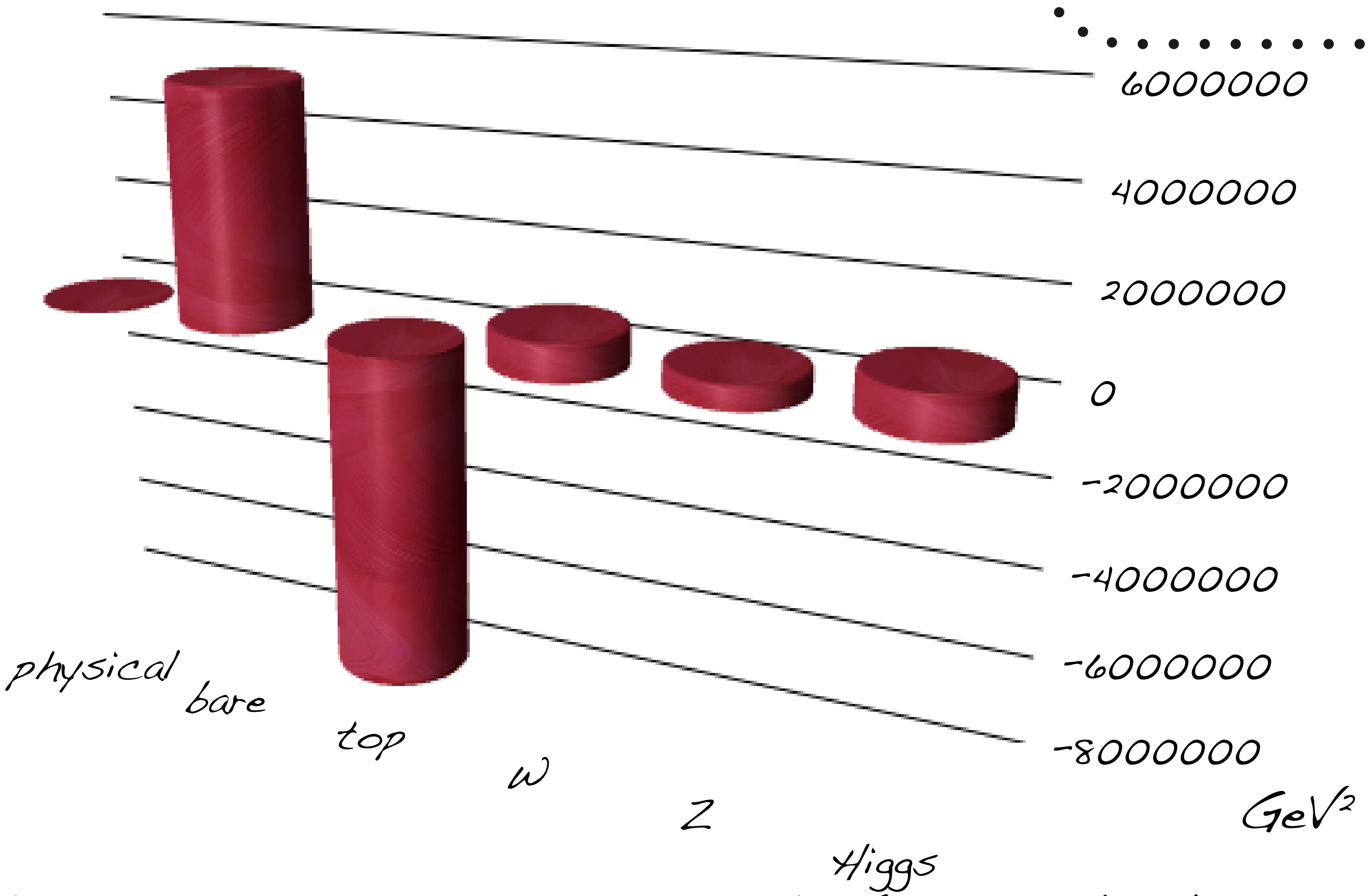
$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{400\ \text{GeV}} \right)^2$$

Λ = 10 TeV



Symmetries for a natural EWSB

How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry ⇨ massless scalar

... but the Higgs has sizable non-derivative couplings

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance ⟶ no longitudinal polarization ↘

Spin 1/2 Chiral symmetry ⟶ only one helicity ↗

m=0

... but the Higgs is a spin 0 particle

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

⇚ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1 ↗ A_μ 4D spin 0 ↖ A_5

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other symmetries?

Ghost symmetry

Grinstein, O'Connell, Wise '07

SM particle ~ ghost

It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60's proposed a trick to stabilize the ghosts (at the price of of a violation of causality at the microscopic scale).

Conclusions #1

- Why do we expect to find a Higgs?
  1. discovery already announced to journalists and politics
  2. simplest parametrization of EWSB
  3. unitarity of WW scattering amplitude
  4. EW precision tests
- Why do we expect more than the Higgs?
  1. dark matter and matter-antimatter asymmetry → new physics not necessarily coupled to SM
  2. triviality
  3. stability

  } new physics might be heavy if the Higgs is light

  4. naturality ➲ new physics has to be light if the Higgs is light

new particles/symmetries are expected to populate the TeV scale to trigger the breaking of the EW symmetry

what is the organization principle that governs this new sector?

1 2 3 4

Physics Beyond the Standard Model

The 2011 Hadron Collider Physics Summer School

CERN, June 8-17, 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

Lecture Outline

1 First Lecture ➲

- Standard Model and EW symmetry breaking ➲
- Higgs mechanism ➲
- EW precision tests ➲
- Higgs as a UV moderator ➲
- UV behaviour of the Higgs ➲

2 Second Lecture ➲

- Supersymmetry ➲
- Little Higgs ➲

3 Third Lecture ➲

- Gauge-Higgs unification ➲, Higgsless ➲
- Composite Higgs models (I) ➲

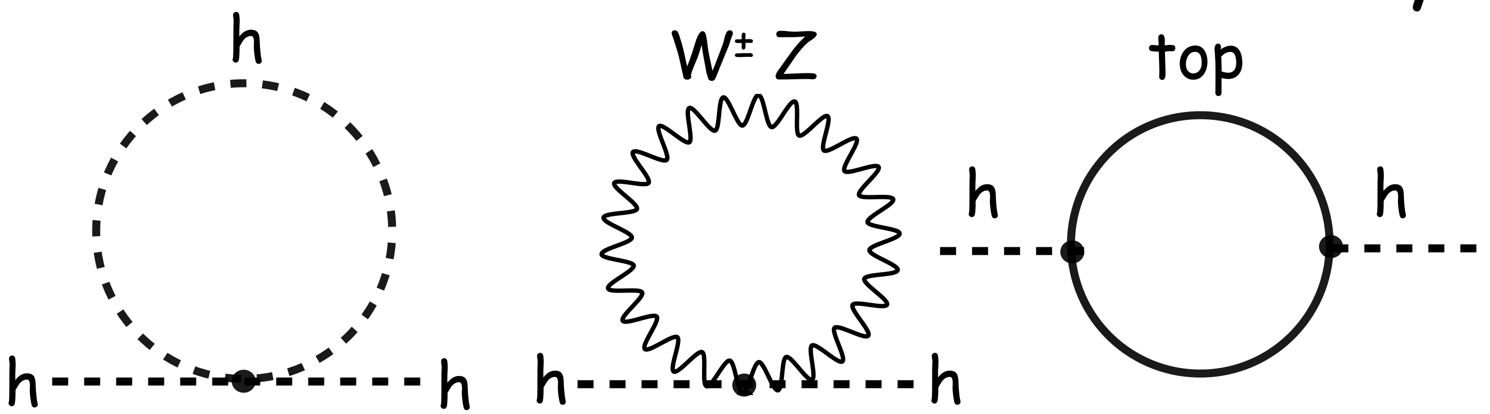
4 Fourth Lecture ➲

- Composite Higgs models (II) ➲
- GUT: SM vs MSSM vs Composite Higgs ➲

1 2 3 4

Beyond the Higgs: The hierarchy problem

need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale



$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{400\ \text{GeV}}\right)^2$$

1 add a sym. such that a Higgs mass is forbidden until this sym. is broken

- supersymmetry [Witten, '81]
- gauge-Higgs unification [Manton, '79, Hosotani '83]
- Higgs as a pseudo Nambu-Goldstone boson [Georgi-Kaplan, '84]

2 lower the UV scale

- large extra-dimensions [Arkani-Hamed-Dimopoulos-Dvali, '98]
- 10^{32} species [Dvali '07]

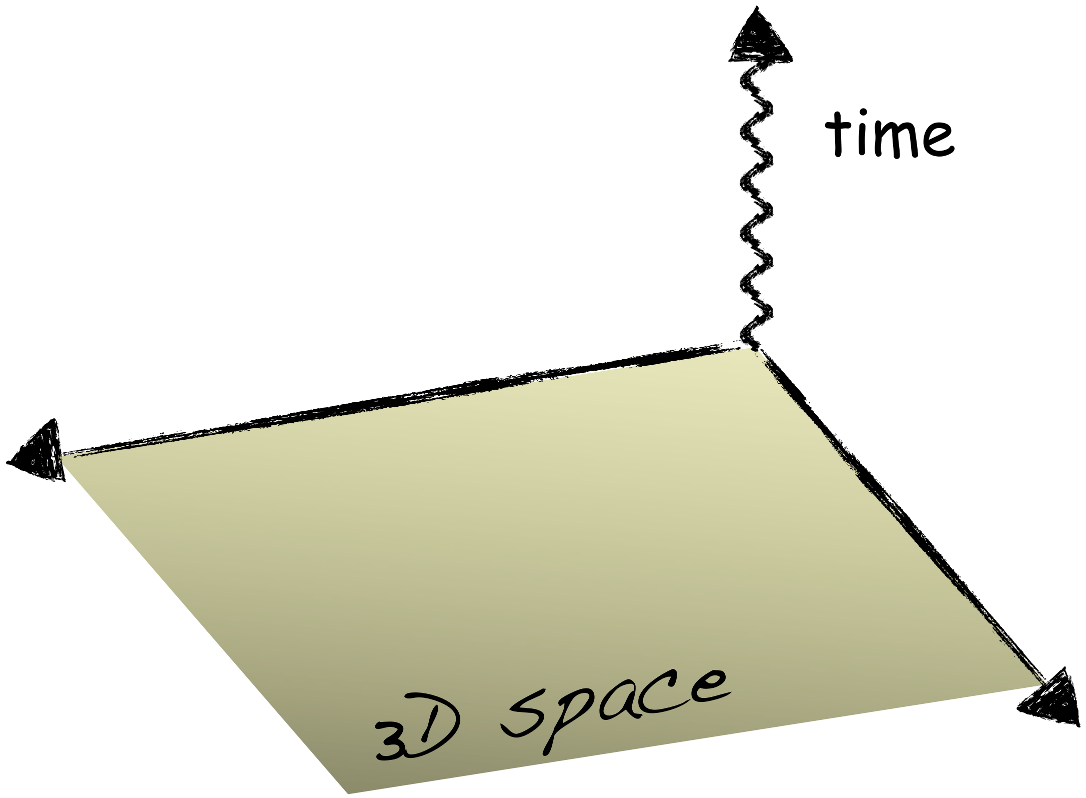
3 remove the Higgs

- technicolor [Weinberg '76, Weinberg '79, Susskind '79]

Supersymmetry

SUSY: a quantum space-time

(G. Giudice HCPSS'09)



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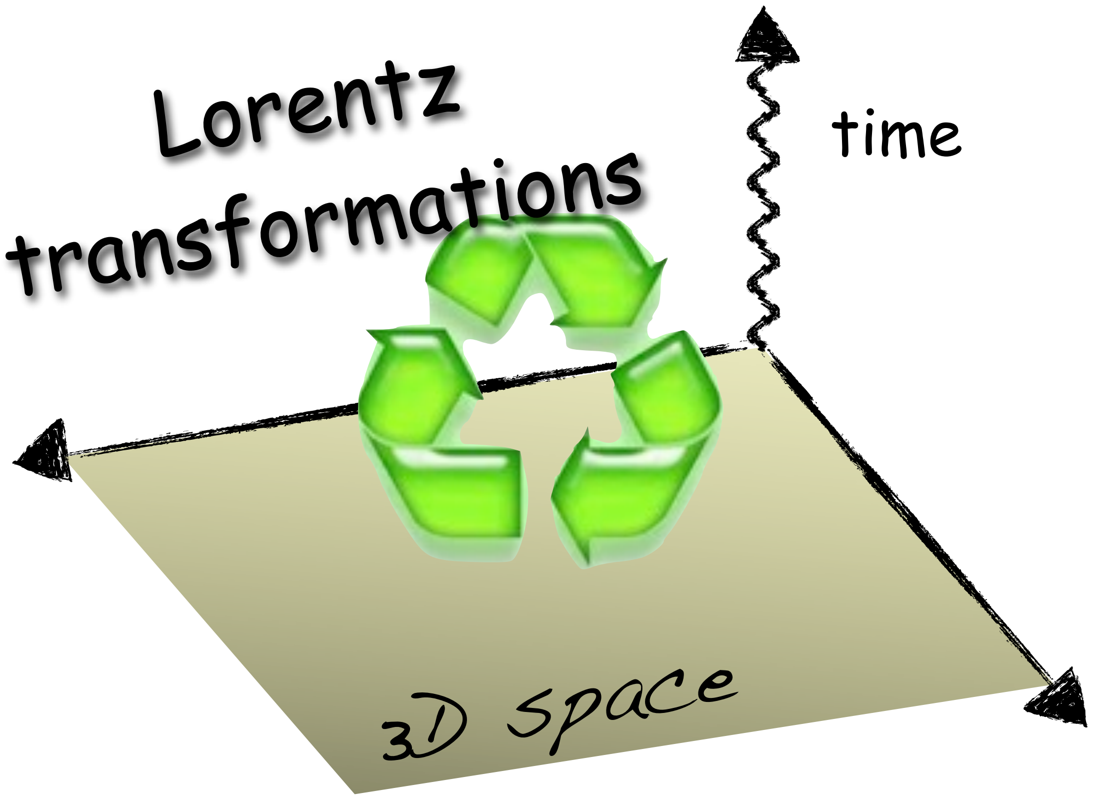
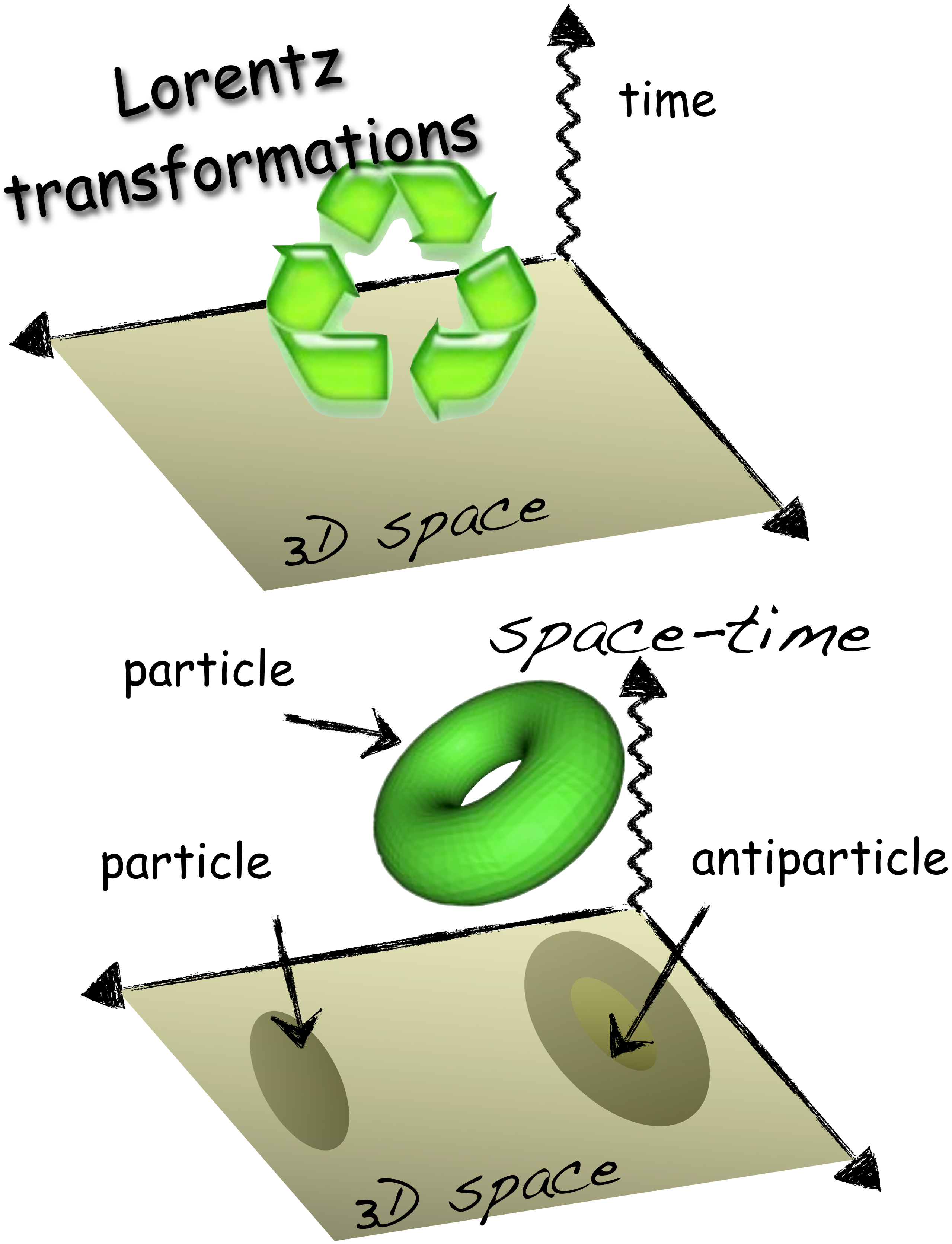


SUSY: a quantum space-time

(G. Giudice HCPSS'09)



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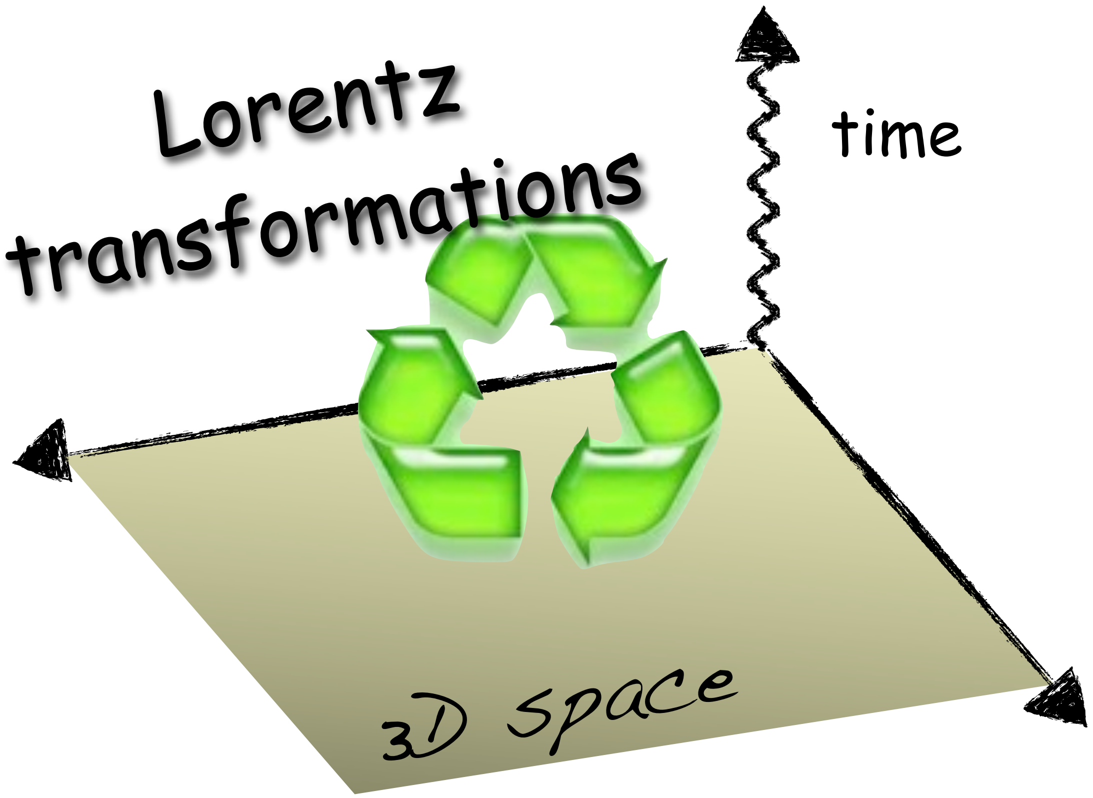

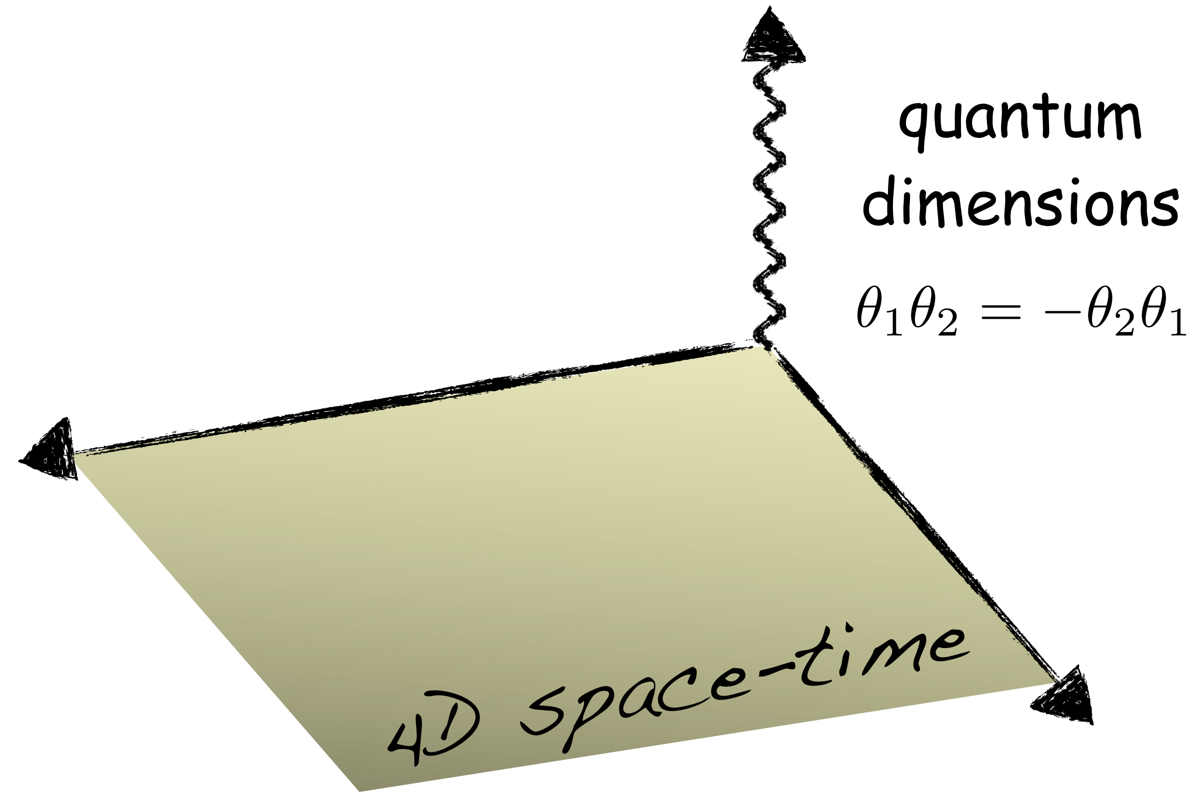

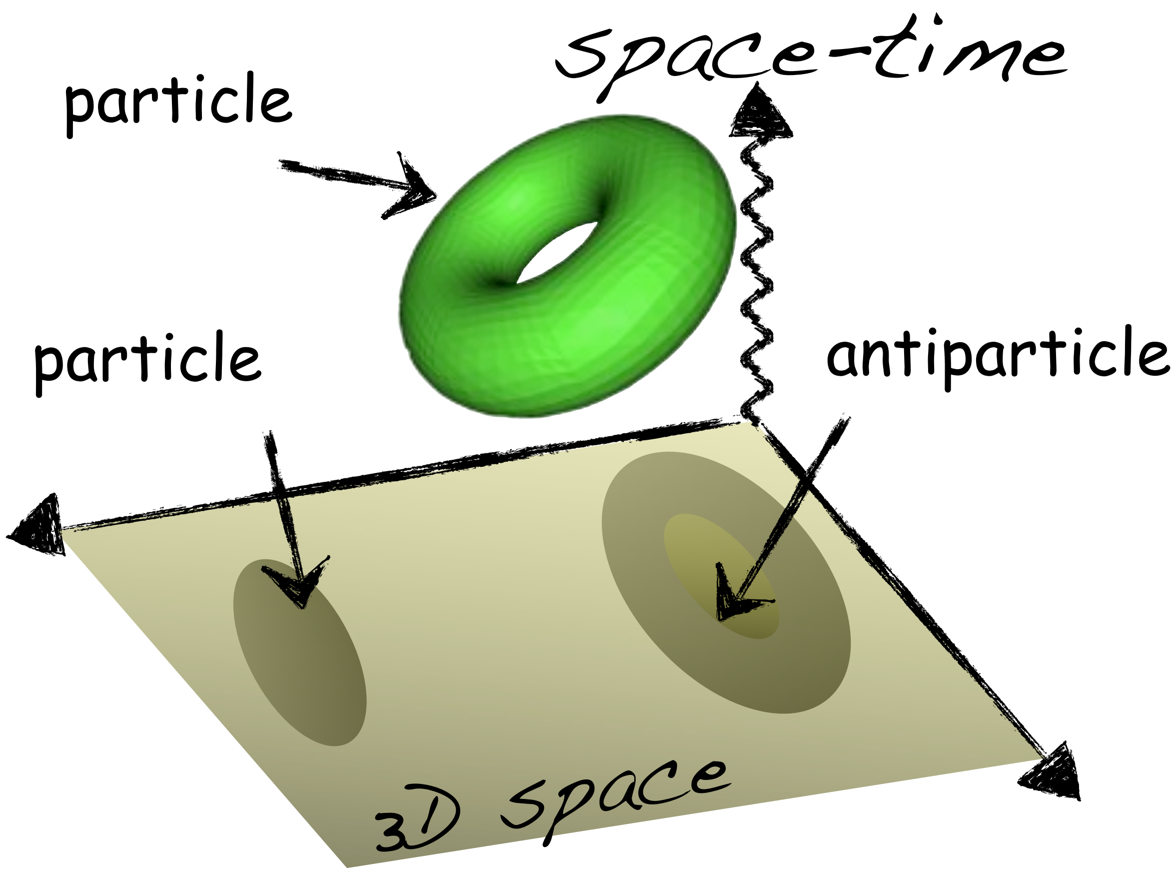

SUSY: a quantum space-time

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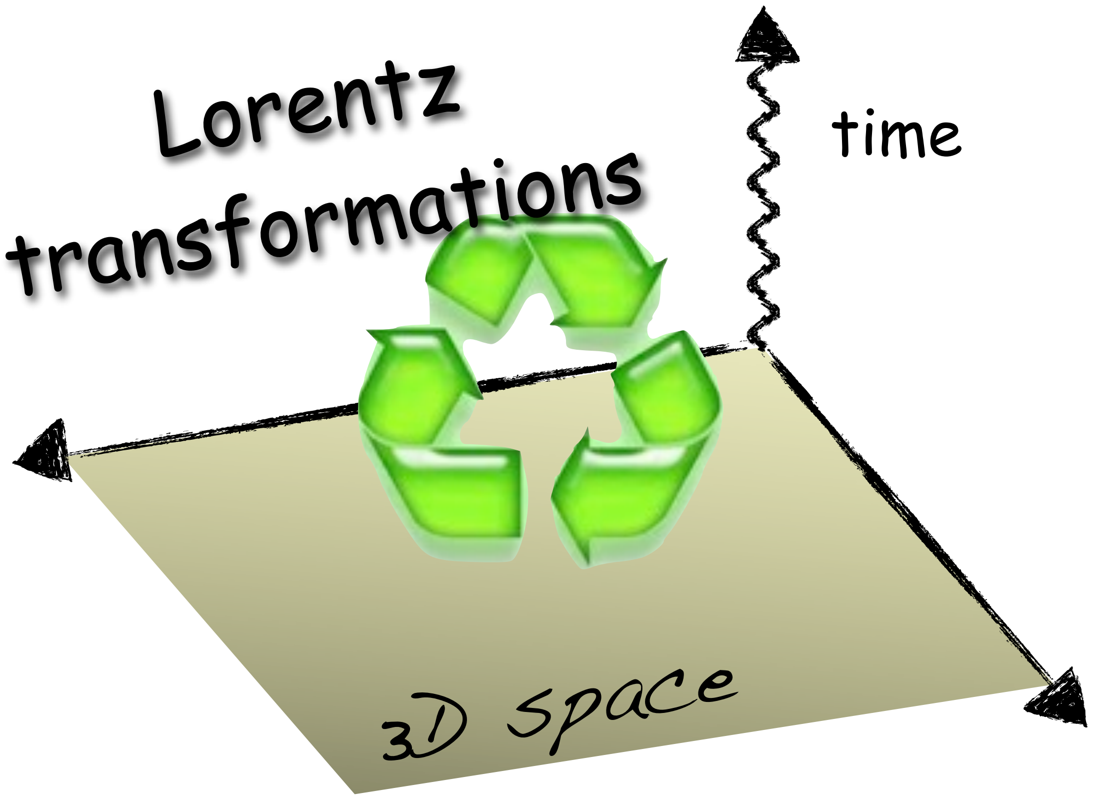

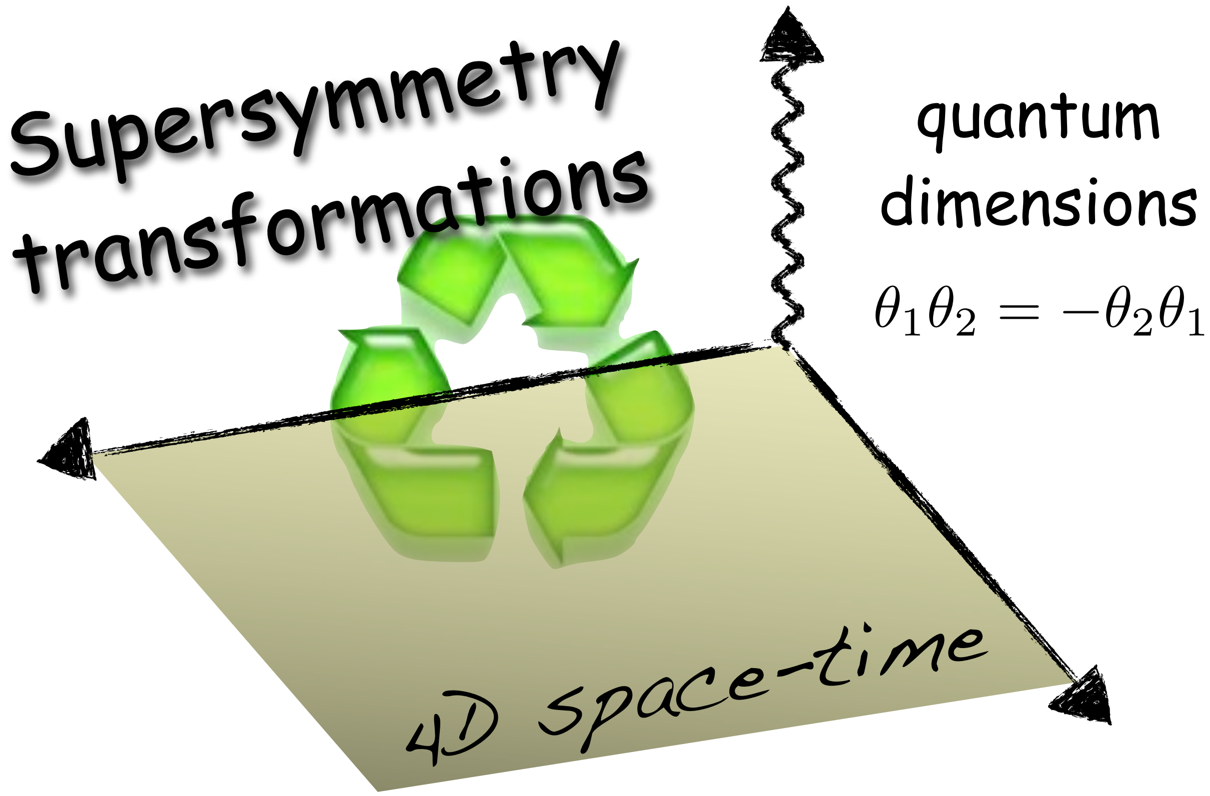

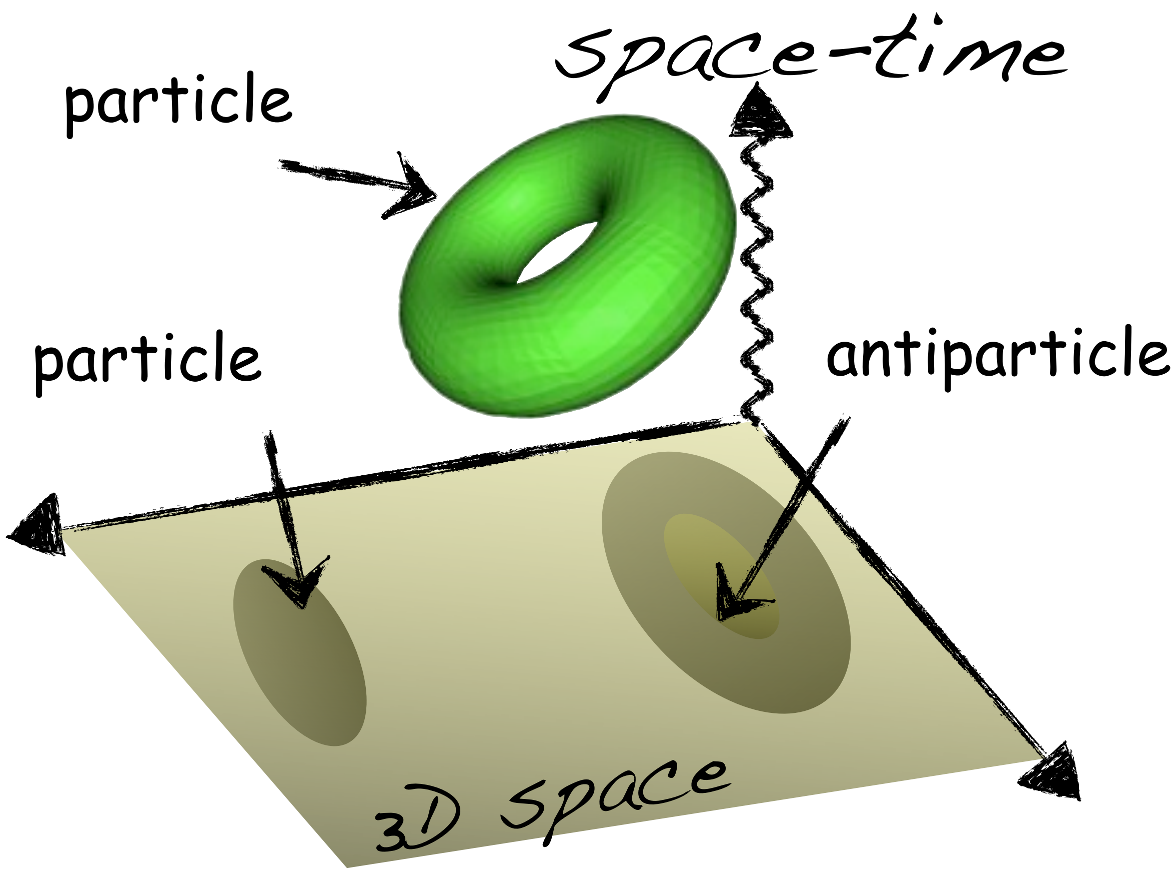

SUSY: a quantum space-time

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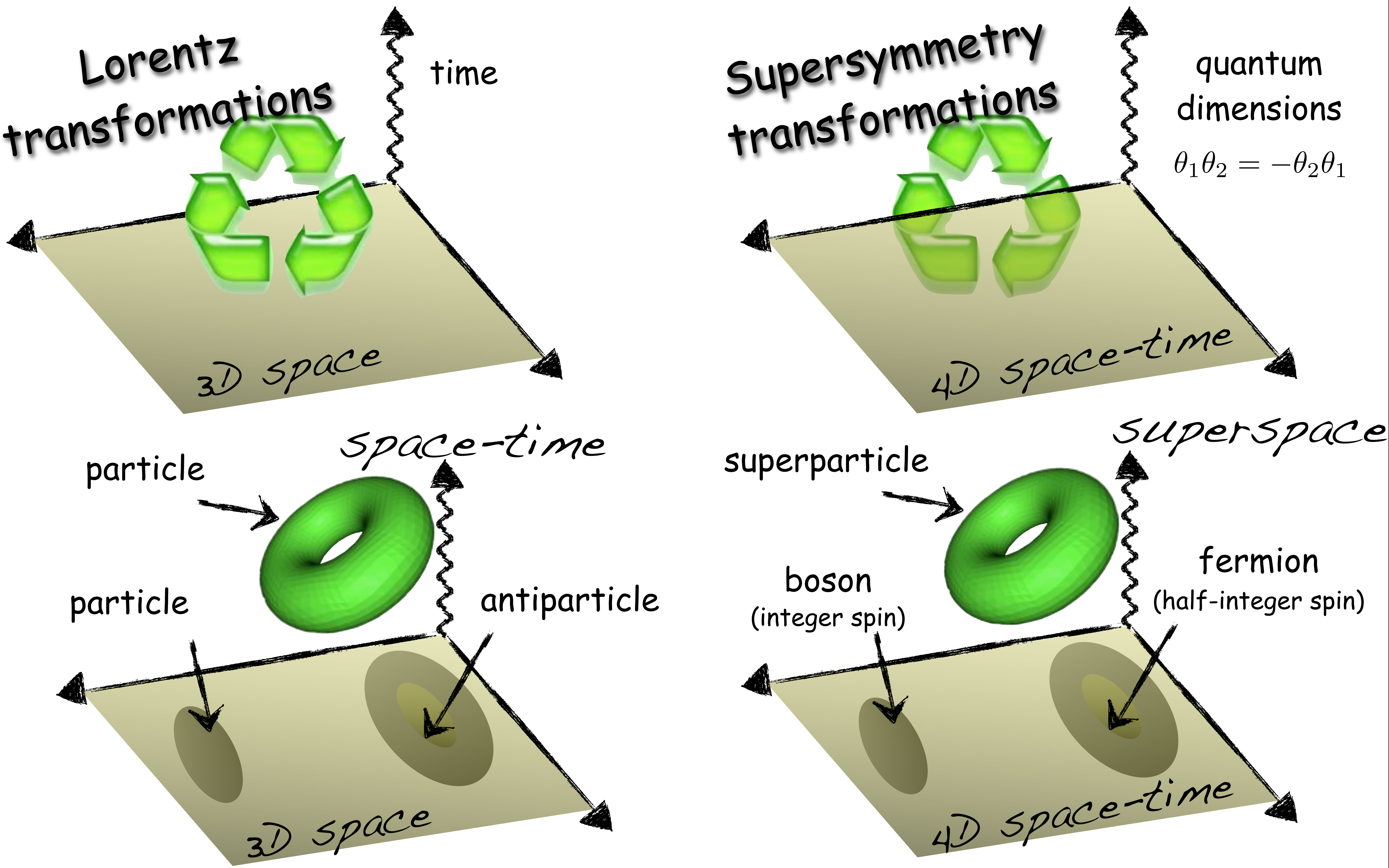


SUSY 1.0.1

Wess, Zumino '74

fermion ⇔ boson

$$\mathcal{L} = \partial^\mu \phi^\dagger \partial_\mu \phi + i\bar{\psi}\gamma^\mu \partial_\mu \psi$$

- susy transformations:

$$\delta\phi = \bar{\epsilon}\psi$$
$$\delta\psi = -i\left(\gamma^\mu \partial_\mu \phi\right)\epsilon$$

$$\delta\mathcal{L} = \text{total derivative}$$

- susy algebra:

$$[\delta_{\epsilon_1}, \delta_{\epsilon_2}] \begin{pmatrix} \phi \\ \psi \end{pmatrix} = -i\left(\bar{\epsilon}_2\gamma^\mu \epsilon_1\right)\partial_\mu \begin{pmatrix} \phi \\ \psi \end{pmatrix}$$

susy^2 = 4D translation

How to introduce interactions?

Superspace

$$\left(x^\mu, \theta, \bar\theta\right)$$

usual 4D space-time coordinates → x^μ

new fermionic/Grassmanian coordinates → $\theta, \bar\theta$

A general superfield can be Taylor-expanded in the superspace

$$F(x,\theta,\bar\theta) = f(x) + \theta\chi(x) + \bar\theta\bar\chi(x) + \theta\theta m(x) + \bar\theta\bar\theta\bar m(x) + \theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$$

complex spin-0 fields: $f(x), m(x), \bar m(x), d(x)$ — 4x2=8 real off-shell degrees of freedom

complex spin-1 fields: $v_\mu(x)$ — 1x8=8 real off-shell degrees of freedom

Weyl spin-1/2 fields: $\chi(x), \bar\chi, \lambda(x), \bar\lambda(x)$ — 4x4=16 real off-shell degrees of freedom

- **Chiral superfield** $\bar D_{\dot\alpha} F = 0$

  covariant derivative
  ie commute with supersymmetry

  ⇒ $F = \phi(x) + \theta\psi(x) + \theta\theta f(x)$

	$\phi(x)$	$\psi(x)$	$f(x)$
off-shell dof	2	4	2
on-shell dof	2	2	0

- **Vector superfield**

  $F = F^\dagger$

  ⇒ $F = \theta\sigma^\mu\bar\theta v_\mu(x) + i\theta\theta\bar\theta\bar\lambda(x) - i\bar\theta\bar\theta\theta\lambda(x) + \frac{1}{2}\theta\theta\bar\theta\bar\theta d(x)$

	$v_\mu(x)$	$\lambda(x)$	$d(x)$
off-shell dof	3	4	1
on-shell dof	2	2	0

MSSM - Matter Content

		particles			Sparticles	
Chiral superfields	quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R		squarks	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ $\tilde{u}_R$ $\tilde{d}_R$	
	leptons	$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$ e_R		sleptons	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$ $\tilde{e}_R$	
	Higgs doublets	H_1 (hypercharge $= -1$) H_2 (hypercharge $= +1$)		Higgsinos	$\tilde{H}_1$ $\tilde{H}_2$	
vector superfields		$W^{\pm}_{\mu}, W^3_{\mu}$		winos	$\tilde{\omega}^{\pm}, \tilde{\omega}^3$	
		B_{μ}		bino	$\tilde{b}$	
		G^A_{μ} $A = 1, \ldots, 8$		gluinos	$\tilde{g}^A$	

(G. Giudice HCPSS'09)

SUSY Interactions - Superpotential

superpotential W = holomorphic fct of chiral superfields

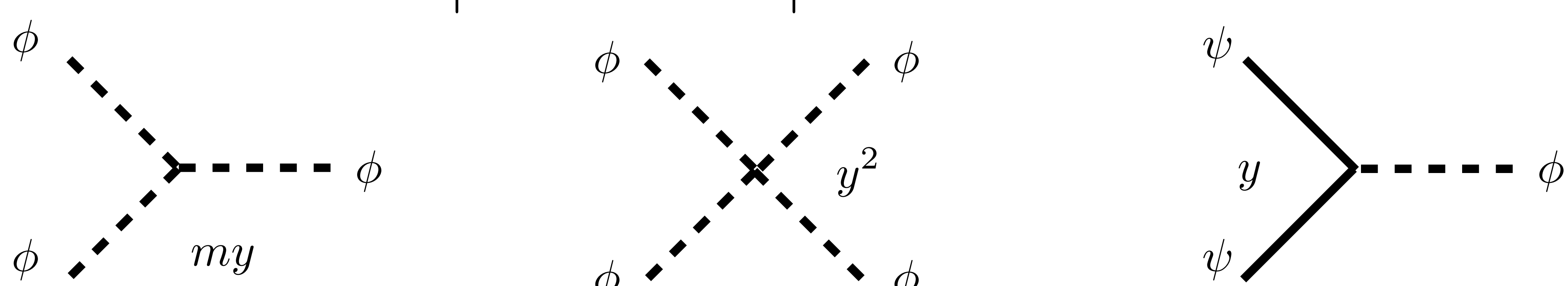
$$\mathcal{L} = \mathcal{L}_{\rm kin} - \left|\frac{\partial W}{\partial \phi}\right|^2_{|\theta=0} - \frac{1}{2}\frac{\partial^2 W}{\partial \phi^2}_{|\theta=0} \psi\psi + h.c.$$

is invariant under susy

example: susy Yukawa interaction

$$W = \frac{1}{2} m\phi^2 + \frac{1}{3!} y\phi^3 \qquad \partial_\phi W = m\phi + \frac{1}{2} y\phi^2 \qquad \partial^2_\phi W = m + y\phi$$

$$\mathcal{L} = \mathcal{L}_{\rm kin} - \left| m\phi + \frac{1}{2} y\phi^2 \right|^2 - \frac{1}{2}\left(m + y\phi\right)\psi\psi + h.c.$$



will be modified by soft susy breaking

will survive soft susy breaking

MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u Q D + H_u Q U + H_d L E + \mu H_u H_d + L Q D + U D D + L L E + \mu_L L H_u$$

MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u Q D + H_u Q U + H_d L E + \mu H_u H_d + LQD + UDD + LLE + \mu_L L H_u$$

$\not{B}, \not{L}$

lead to fast p decay

MSSM Superpotential

the most general ("renormalizable") superpotential of the MSSM

$$W = H_u Q D + H_u Q U + H_d L E + \mu H_u H_d + LQD + UDD + LLE + \mu_L L H_u$$

$\not B, \not L$

lead to fast p decay

R parity forbids all the dangerous terms

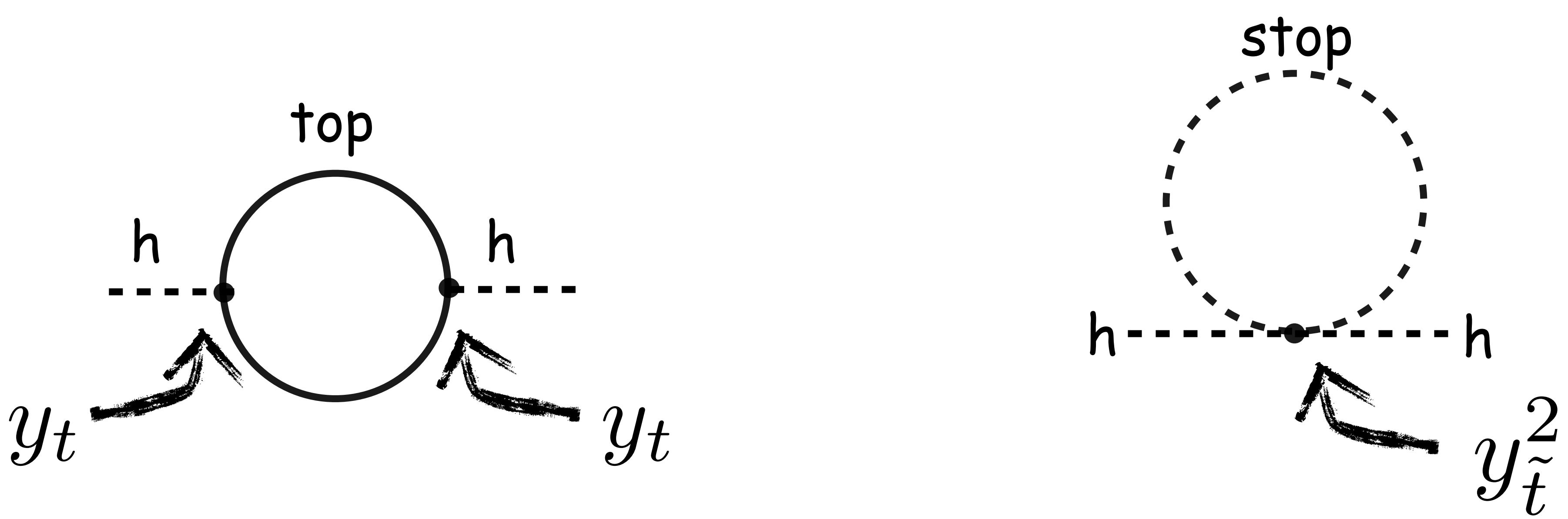
superfields	R-parity	fields
$Q, D, U, L : -1$	doesn't commute with susy	$\phi_{\rm SM} : +1$
$H_u, H_d : +1$	$\theta : -1$	$\phi_{\rm superpartner} : -1$

nice consequences:

- superpartners are pair-produced
- Lightest Supersymmetric Particle is stable → DM?

SUSY and the (big) hierarchy problem

(DE Kaplan HCPSS'07)



$$\delta m_H^2 \propto \left(y_t^2 - y_{\tilde{t}}^2\right)\Lambda^2 + \left(m_t^2 - m_{\tilde{t}}^2\right)\ln\Lambda$$

SUSY and the (big) hierarchy problem

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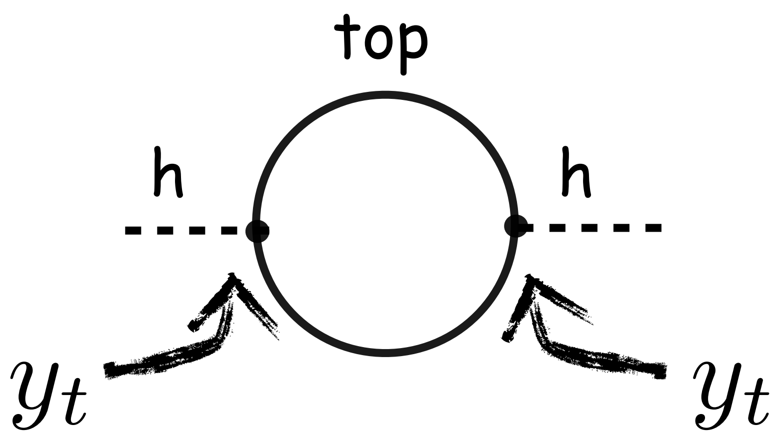
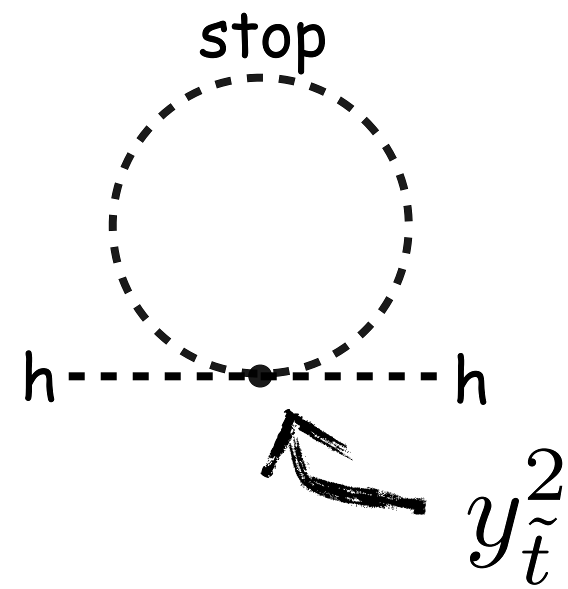




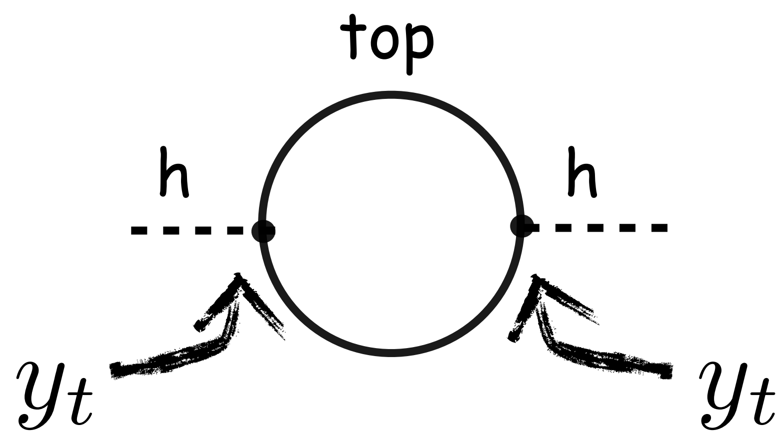
$$\delta m_H^2 \propto \left(y_t^2 - y_{\tilde{t}}^2\right)\Lambda^2 + \left(m_t^2 - m_{\tilde{t}}^2\right)\ln\Lambda$$

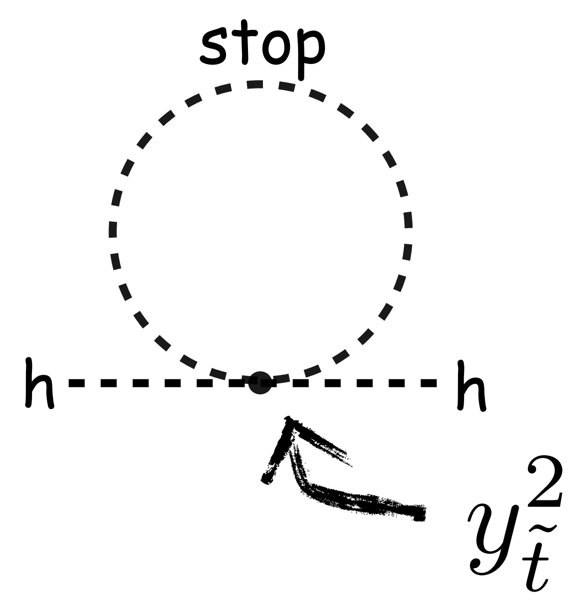
$y_t \neq y_{\tilde{t}}$ ⇓ Λ^2 dv — hard susy breaking

$m_t \neq m_{\tilde{t}}$ ⇓ $\ln\Lambda$ dv — soft susy breaking

SUSY and the (big) hierarchy problem

(DE Kaplan HCPSS'07)





$$\delta m_H^2 \propto \left(y_t^2 - y_{\tilde{t}}^2\right)\Lambda^2 + \left(m_t^2 - m_{\tilde{t}}^2\right)\ln\Lambda$$

$y_t \neq y_{\tilde{t}}$	$m_t \neq m_{\tilde{t}}$
⇩	⇩
Λ^2 dv	$\ln\Lambda$ dv
hard susy breaking	soft susy breaking

SUSY biggest pb: how to dynamically generate soft breaking terms compatible with exp constraints?

SUSY little hierarchy problem

SUSY need new (super)particles that haven't been seen yet

SUSY (at least MSSM) predicts a very light Higgs

$$V = (|\mu|^2 + m_{H_u}^2)\left|H_u^0\right|^2 + (|\mu|^2 + m_{H_d}^2)\left|H_d^0\right|^2 - B(H_u^0 H_d^0 + c.c.) + \frac{g^2+g'^2}{8}\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

tree-level

$$m_h^2 = m_Z^2 \cos^2 2\beta$$

$$m_Z^2/2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

excluded

SUSY little hierarchy problem

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$$V = (|\mu|^2 + m^2_{H_u})\left|H_u^0\right|^2 + (|\mu|^2 + m^2_{H_d})\left|H_d^0\right|^2 - B(H_u^0 H_d^0 + c.c.) + \frac{g^2 + g'^2}{8}\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

one-loop level

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

$$m_Z^2/2 = -\mu^2 + \frac{m^2_{H_d} - m^2_{H_u} \tan^2\beta}{\tan^2\beta - 1}$$

$m_H > 115$ GeV $\Rightarrow \tilde{m}_t > 1$ TeV

fine-tuned

$$\delta m^2_{H_u} = -\frac{3\sqrt{2} G_F m_t^2 m_{\tilde{t}}^2}{4\pi^2} \log \frac{\Lambda}{m_{\tilde{t}}}$$

requires some fine-tuning O(1%) in m_Z

susy little hierarchy problem

Solving the susy little hierarchy pb

Various proposals on the market:

- singlet extensions of the Higgs sector: NMSSM and friends
  Fayet '76 + O(500) papers
- gauge extensions with new non-decoupled D-terms:
  Batra, Delgado, Kaplan, Tait '03 + O(10) papers
- low scale susy breaking mediation (Λ~100 TeV)
- double protection: (super-little) Higgs as a Goldstone boson
  Birkedal, Chacko, Gaillard '04 + O(20) papers
- add higher dimensional terms: BMSSM Dine, Seiberg, Thomas '07

$$W_{\mathrm{BMSSM}} = \frac{\lambda_1}{M}(H_u H_d)^2 + \frac{\lambda_2}{M}\mathcal{Z}_{\mathrm{soft}}(H_u H_d)^2)$$

  - allow for much lighter susy particles
  - window for MSSM baryogenesis extended and more natural
  - LSP can account for DM relic density in larger region of parameter space

- ... your own model?

Little Higgs

Which symmetry for the Higgs sector

the symmetries of the EWSB sector can help to preserve the SM structure, i.e., to keep the oblique corrections under control

- Contribution to T

$$\frac{SU(2)_L \times U(1)_Y}{U(1)_{\rm em}} \rightarrow \frac{SU(2)_L \times SU(2)_R}{SU(2)_V} = \frac{SO(4)}{SO(3)}$$

the custodial symmetry ⇨ no T parameter

- Contribution to S

$SU(2)_L$ preserves S, but it has to be broken: $S \sim \frac{v^2}{\Lambda^2}$

need $v \ll \Lambda$. How? Hierarchy problem again.

Higgs as a Goldstone boson

$$\frac{SO(4)}{SO(3)} \rightarrow \frac{SO(5)}{SO(4)}, \frac{SU(5)}{SO(5)} \ldots$$

Little Higgs Models

Arkani-Hamed, Cohen, Georgi '01

Higgs as a pseudo-Nambu-Goldstone boson

QCD: π^+, π^0 are Goldstone associated to $\frac{SU(2)_L \times SU(2)_R}{SU(2)_{\text{isospin}}}$

$\alpha_{em} \to 0, m_q \to 0$

LxR exact

$m_\pi = 0$

$\alpha_{em} \neq 0$

$$m^2_{\pi^\pm} \approx \frac{\alpha_{em}}{4\pi} \Lambda^2_{QCD}$$

EW pions

$\alpha_{top} \to 0,\ g, g' \to 0$

exact global sym.

$m_H = 0$

$\alpha_{top} \neq 0$

$$m^2_H \approx \frac{\alpha_{top}}{4\pi} \Lambda^2_{\text{strong}}$$

would require

$\Lambda_{\text{strong}} \sim 1$ TeV

...too low !

Little Higgs = PNGB + Collective Breaking

$$m^2_H \approx \frac{\alpha_i \alpha_j}{(4\pi)^2} \Lambda^2_{\text{strong}}$$

Little Higgs Models

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QCD: π^+, π^0 are Goldstone associated to $\frac{SU(2)_L \times SU(2)_R}{SU(2)_{\text{isospin}}}$

$\alpha_{em} \to 0, m_q \to 0$

LxR exact

$m_\pi = 0$

$\alpha_{em} \neq 0$

$$m^2_{\pi^\pm} - m^2_{\pi^0} \approx \frac{\alpha_{em}}{4\pi} \Lambda^2_{QCD} \approx (5 \text{ MeV})^2$$

EW pions

$\alpha_{top} \to 0,\ g, g' \to 0$

exact global sym.

$m_H = 0$

$\alpha_{top} \neq 0$

$$m^2_H \approx \frac{\alpha_{top}}{4\pi} \Lambda^2_{\text{strong}}$$

would require

$\Lambda_{\text{strong}} \sim 1 \text{ TeV}$

...too low !

Little Higgs = PNGB + Collective Breaking

$$m^2_H \approx \frac{\alpha_i \alpha_j}{(4\pi)^2} \Lambda^2_{\text{strong}}$$

Little Higgs = PNGB + Collective Breaking

Higgs ∈ G/H

The coset structure is broken by 2 sets of interactions

$$\mathcal{L} = \mathcal{L}_{G/H} + g_1 \mathcal{L}_1 + g_2 \mathcal{L}_2$$

each interaction preserves a subset of the symmetry
Higgs remains an exact PNGB when either g_1 or g_2 is vanishing

Arkani-Hamed et al. '02

littlest Higgs

SU(5)/SO(5)

24-10=14 PNGB

gauge $SU(2)_L \times SU(2)_R$ subgroup (broken to $SU(2)_D$)

14-3=11 PNGB left = 3_1, $2_{1/2}$, 1_0 Higgs?

if g_L or g_R vanishes, SU(3)/SU(2) global sym. and Higgs remains massless

Littlest Higgs: SU(5)/SO(5)

2x2 symmetric

$$\Sigma \to U \Sigma U^t$$

$$\langle \Sigma \rangle = \begin{pmatrix} 1_2 & & \\ & 1 & \\ & & 1_2 \end{pmatrix}$$

SO(5) unbroken symmetry

$$U U^t = 1$$

Goldstone parameterization:

$$\langle \Sigma \rangle = \begin{pmatrix} & & 1_2 \\ & 1 & \\ 1_2 & & \end{pmatrix}$$

H=doublet

ϕ =triplet

$$\Sigma = e^{i \begin{pmatrix} & H & \phi \\ -H^\dagger & & H^t \\ -\phi^\star & -H^\star & \end{pmatrix} / f} \langle \Sigma \rangle$$

gauge symm.

SU(2)$_L$

$$\left(\begin{array}{c|c|c} 2 \times 2 & & \\ \hline & 1 \times 1 & \\ \hline & & 2 \times 2 \end{array} \right)$$

SU(3) unbroken global sym.

$$H \to H + \epsilon \qquad \phi \to \phi - (H \epsilon^t + \epsilon H^t)/f$$

SU(2)$_R$

$$\left(\begin{array}{c|c|c} 2 \times 2 & & \\ \hline & 1 \times 1 & \\ \hline & & 2 \times 2 \end{array} \right)$$

$$H \to H - \epsilon \qquad \phi \to \phi + (H \epsilon^t + \epsilon H^t)/f$$

SU(3) unbroken global sym.

Littlest Higgs: Higgs potential

$$\frac{g_L^2}{16\pi^2}\Lambda^2\left|\phi + HH^t/f\right|^2 + \frac{g_R^2}{16\pi^2}\Lambda^2\left|\phi - HH^t/f\right|^2$$

the triplet acquires a Λ^2 divergent mass and can be integrated out

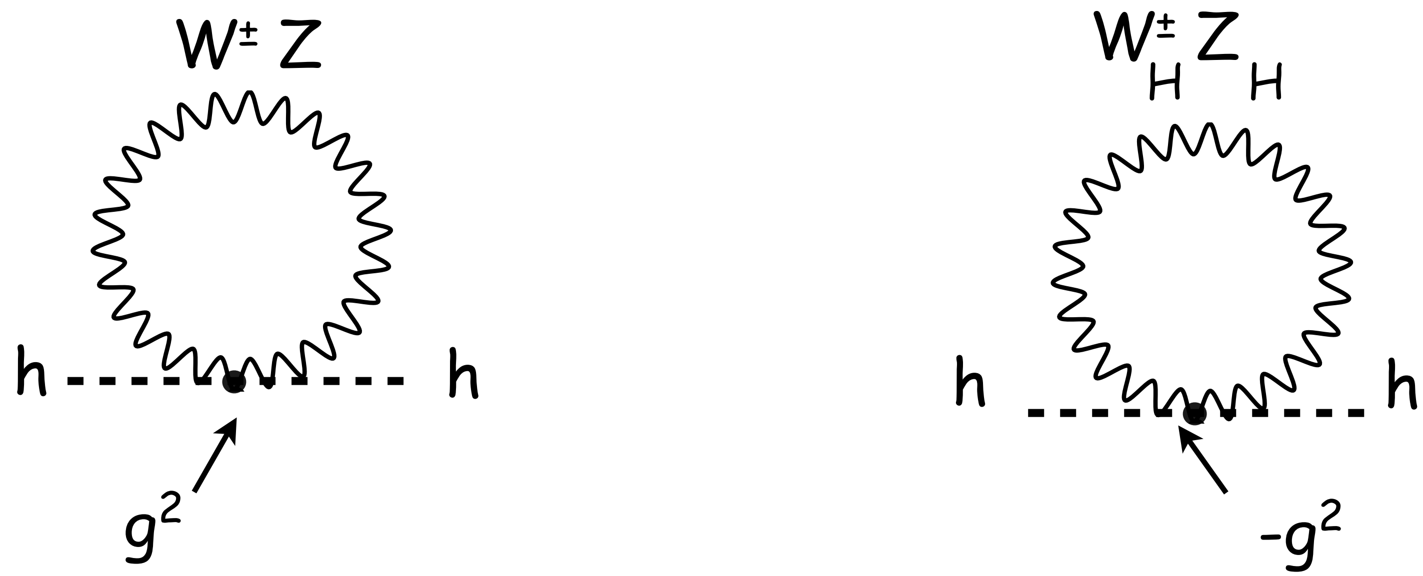
$$\phi = \frac{g_R^2 - g_L^2}{g_R^2 + g_L^2}\, HH^t/f$$

it generates a quartic Higgs coupling

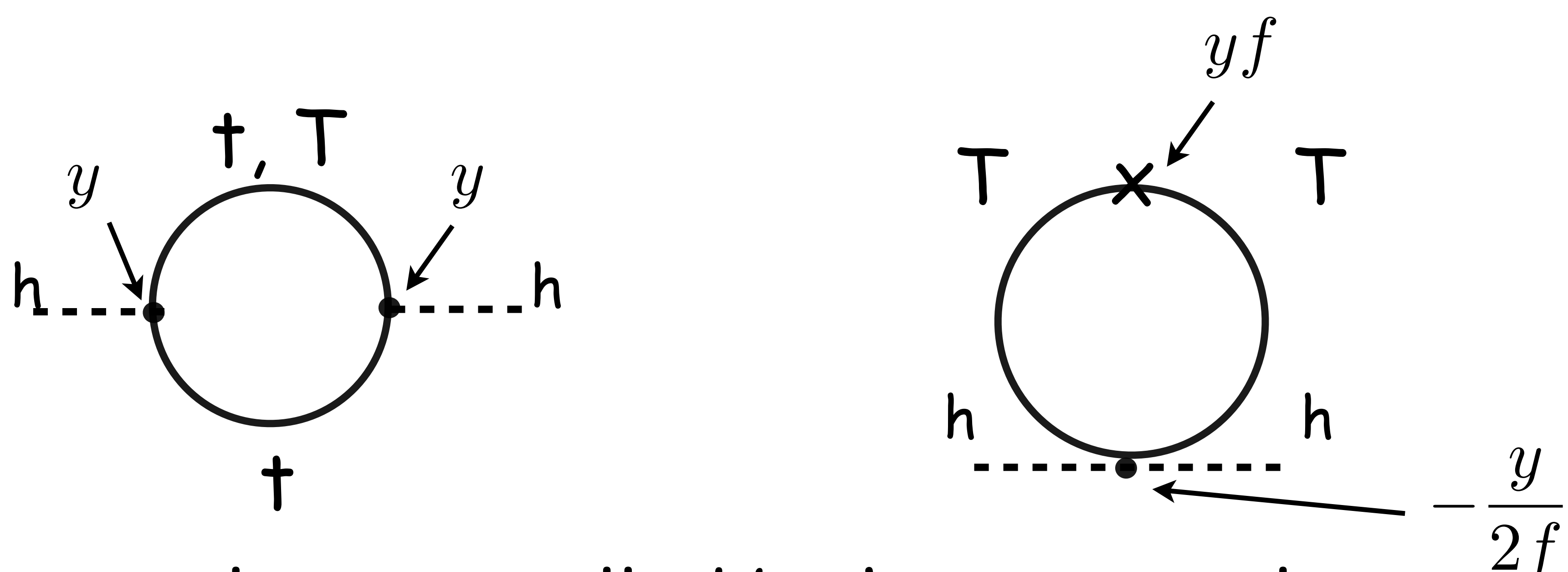
$$\frac{4g_L^2 g_R^2\,\Lambda^2}{16\pi^2(g_L^2 + g_L^2)f^2}\ \left|H\right|^4$$

need both g_L & g_R to generate the Higgs quartic: collective breaking

LH = Λ^2 cancelled by same spin partner



gauge boson loops cancelled by heavy gauge boson loops

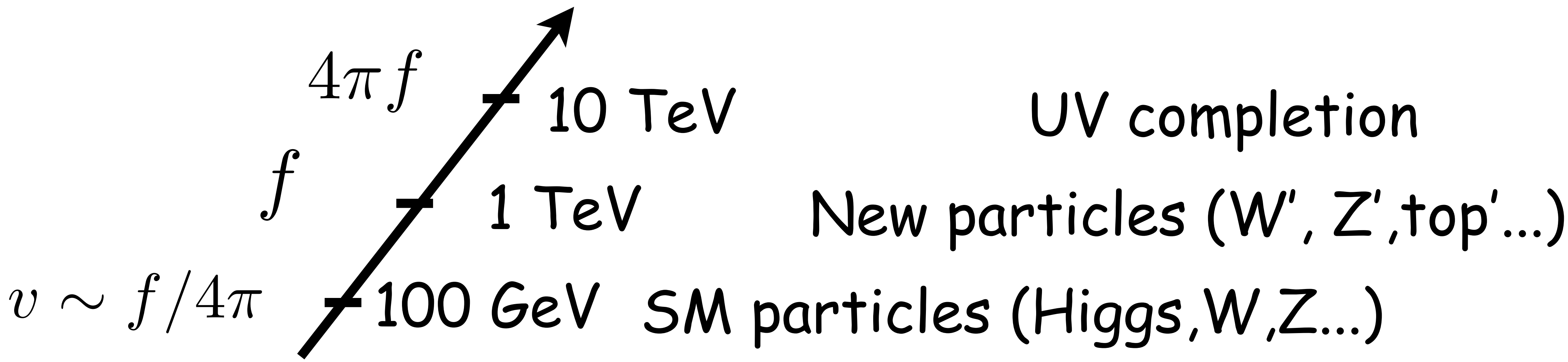


top loop cancelled by heavy toop loop

Relation among different couplings follows from global sym.

cancellation of div. occurs only at one-loop

Anatomy of Little Higgs models



cancellation of Higgs mass Λ^2 divergences

- W,Z loop cancelled by heavy W', Z' loops
- top loop cancelled by heavy top' loop
- Higgs loop cancelled by heavy scalar loops

T-parity

Cheng, Low '03

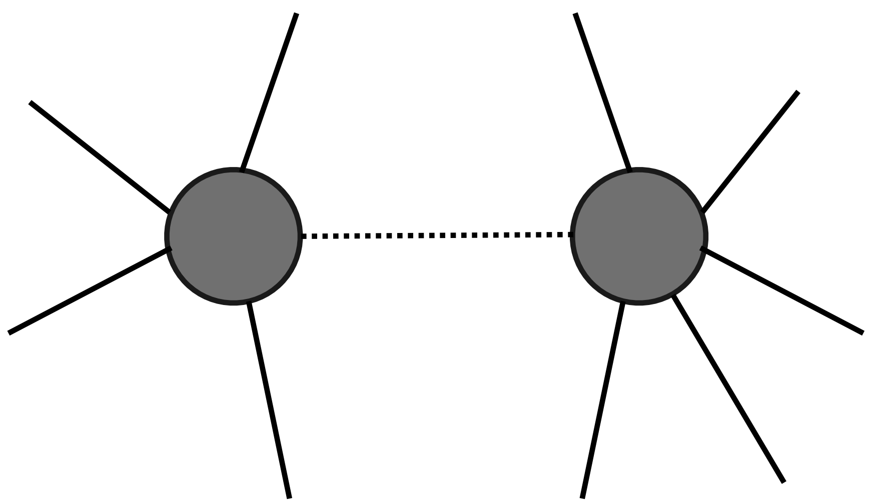
heavy particles = odd

light particles = even

at each vertex, an even number of heavy fields are required

no effective operator for light fields are generated
by tree-level exchange of heavy fields

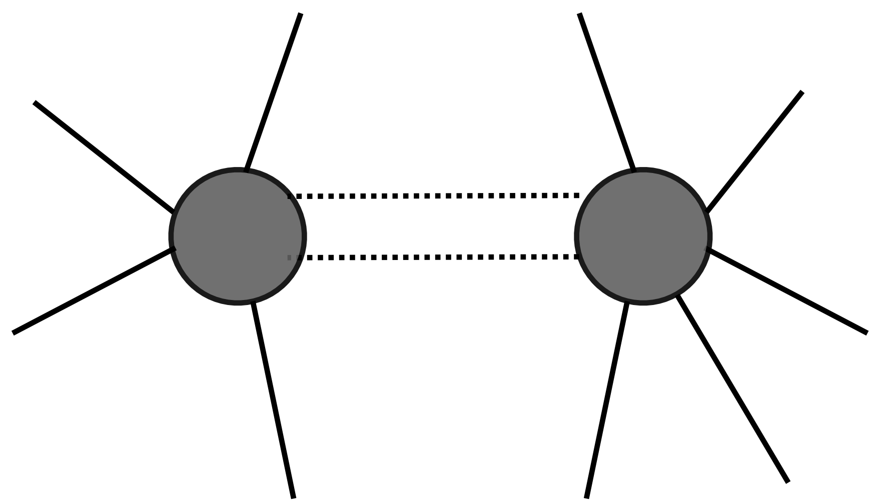
tree-level exchange



annoying for EW precision tests

forbidden by T-parity

loop exchange



needed to cancel SM Λ^2 divergences

allowed by T-parity

nice consequences:

- LH partners are pair-produced
- Lightest T-odd Particle is stable → DM?

1 2 3 4

Physics Beyond the Standard Model

The 2011 Hadron Collider Physics Summer School
CERN, June 8-17, 2011

Christophe Grojean
CERN-TH & CEA-Saclay/IPhT
(christophe.grojean@cern.ch)

Lecture Outline

1. First Lecture ➲
   - Standard Model and EW symmetry breaking ➲
   - Higgs mechanism ➲
   - EW precision tests ➲
   - Higgs as a UV moderator ➲
   - UV behaviour of the Higgs ➲
2. Second Lecture ➲
   - Supersymmetry ➲
   - Little Higgs ➲
3. Third Lecture ➲
   - Gauge-Higgs unification ➲, Higgsless ➲
   - Composite Higgs models (I) ➲
4. Fourth Lecture ➲
   - Composite Higgs models (II) ➲
   - GUT: SM vs MSSM vs Composite Higgs ➲

1 2 3 4

Gauge-Higgs Unification

How to Get a Doublet from an Adjoint

Consider a 5D gauge symmetry G $\quad H \sim A_5^a \quad$ will belong tho the adjoint rep. of G

The SM Higgs is not an adjoint of SU(2)xU(1), it is a doublet !

Consider a bigger gauge group

$$G \to SU(2)_L \times U(1)_Y$$

Adj $\longrightarrow$ doublet + other rep.

SU(3)

$$\frac{1}{2}\begin{pmatrix} W_3 + W_8/\sqrt{3} & W_1 - iW_2 & W_4 - iW_5 \\ W_1 + iW_2 & -W_3 + W_8/\sqrt{3} & W_6 - iW_7 \\ W_4 + iW_5 & W_6 + iW_7 & -2W_8/\sqrt{3} \end{pmatrix}$$

SU(2)xU(1)

Adj

$$2_{\sqrt{3}/2}$$

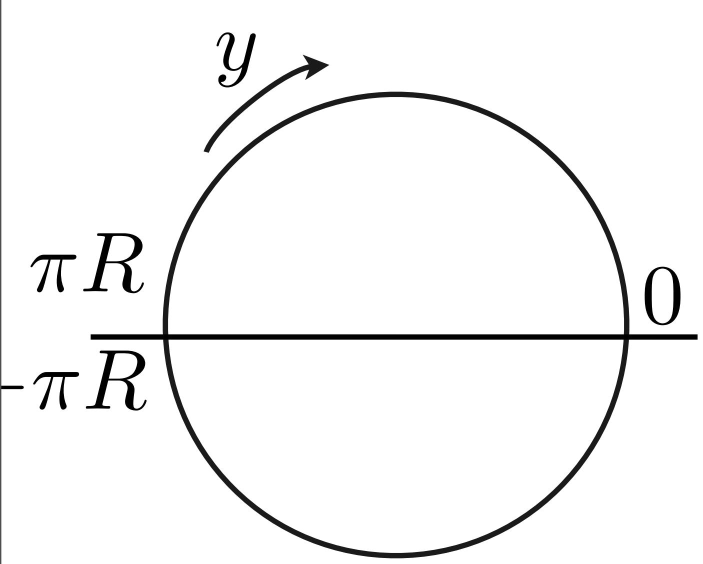
Towards a Complete Construction

so far we haven't broken any symmetry... we even enlarged the gauge group

We need to break G down to SU(2)xU(1)

we can achieve this breaking while compactifying the extra-dimension

Compactification on a Circle



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x, y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}} \pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

Towards a Complete Construction

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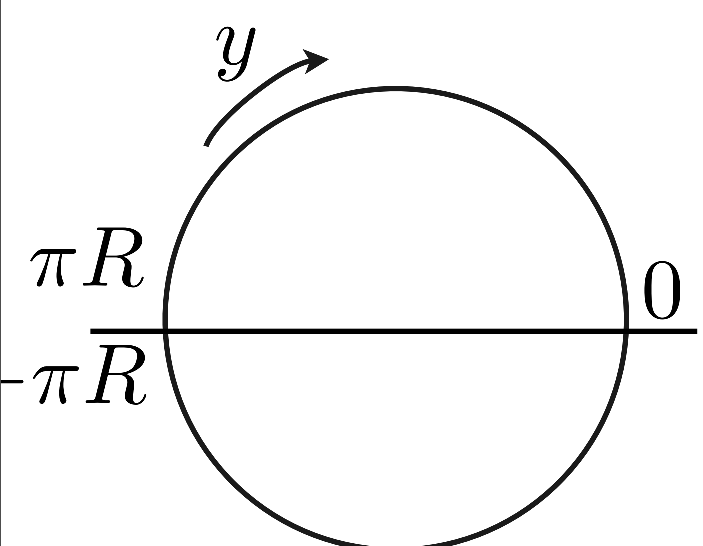
Compactification on a Circle



circle: $y \sim y + 2\pi R$

$$\phi(y+2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

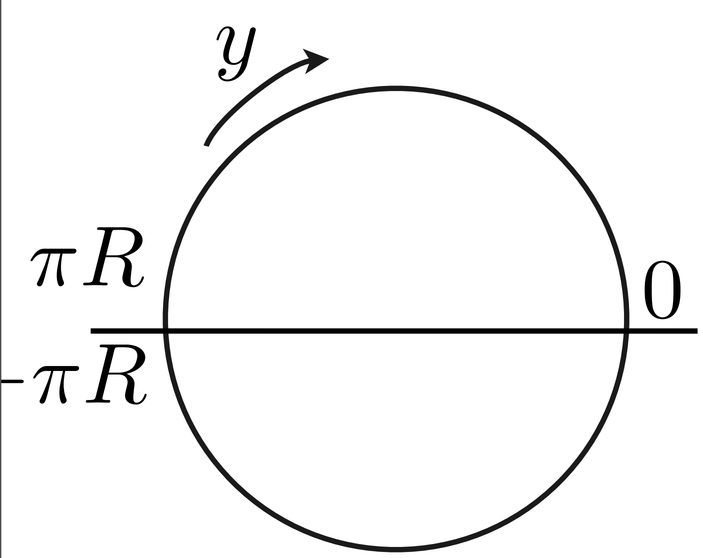
Towards a Complete Construction

so far we haven't broken any symmetry... we even enlarged the gauge group

We need to break G down to SU(2)xU(1)

we can achieve this breaking while compactifying the extra-dimension

Compactification on a Circle



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}} \pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

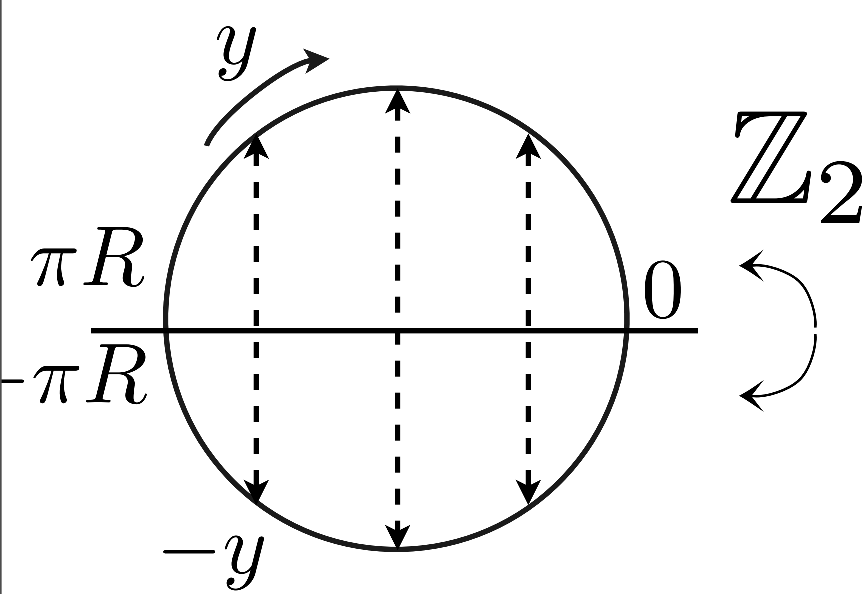
Towards a Complete Construction

so far we haven't broken any symmetry... we even enlarged the gauge group

We need to break G down to SU(2)xU(1)

we can achieve this breaking while compactifying the extra-dimension

Compactification on an Orbifold



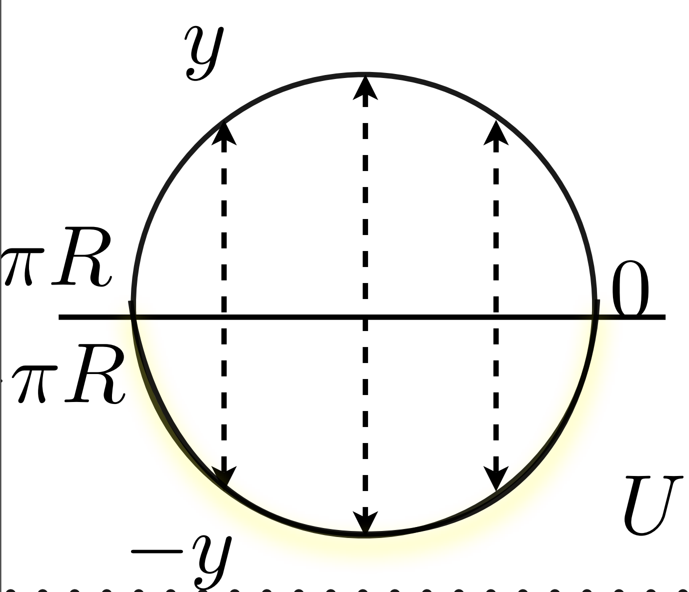
circle: $y \sim y + 2\pi R$ $\quad \phi(y + 2\pi R) = \phi(y)$

orbifold: $y \sim -y$ $\quad \phi(-y) = U\phi(y) \qquad U^2 = 1$

U=+1: $\cos\left(\frac{ny}{R}\right)$ wavefunctions $\quad \exists$ massless mode

U=-1: $\sin\left(\frac{ny}{R}\right)$ wavefunctions $\quad \nexists$ massless mode

Orbifold breaking



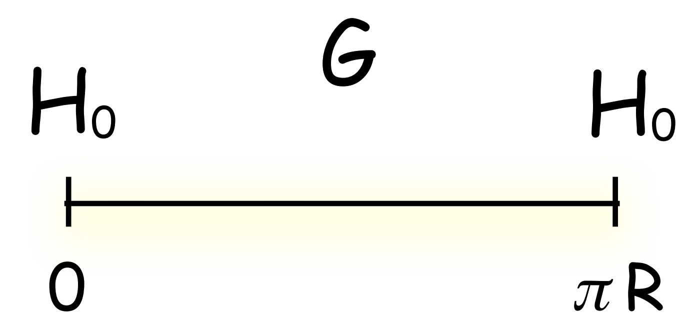
$\mathbb{Z}_2$

$U^2 = 1$

orbifold $\quad y \sim -y$

$$A_\mu(-y) = U A_\mu(y) U^\dagger$$

$$A_5(-y) = -U A_5(y) U^\dagger$$



Breaking of gauge group at the end-points of the orbifold $A_\mu(0) = U A_\mu(0) U^\dagger$

at the end-points, the surviving gauge group commute
with the orbifold projection matrix U

KK effective theory

zero mode: A_μ is independent of y

$$A_\mu = U A_\mu U^\dagger \qquad A_5 = -U A_5 U^\dagger$$

gauge symmetry breaking

(+ chiral fermions)

SU(3) → SU(2)xU(1) 5D Orbifold Breaking

$$U = \begin{pmatrix} -1 & & \\ & -1 & \\ & & 1 \end{pmatrix} \qquad U \in SU(3) \qquad U^2 = 1$$

massless vectors A_μ

$$[A_\mu, U] = 0 \qquad A_\mu = \frac{1}{2}\begin{pmatrix} A^3_\mu + A^8/\sqrt{3} & A^1_\mu - iA^2_\mu & \\ A^1_\mu + iA^2_\mu & -A^3_\mu + A^8_\mu/\sqrt{3} & \\ & & -2A^8_\mu/\sqrt{3} \end{pmatrix} \qquad SU(2)\times U(1)$$

massless scalars A_5

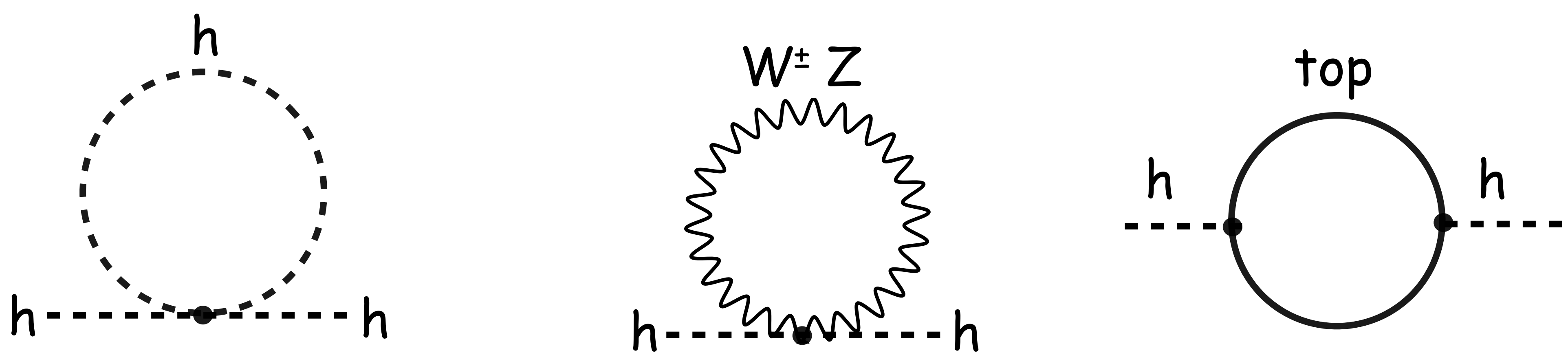
$$\{A_5, U\} = 0 \qquad A_5 = \frac{1}{2}\begin{pmatrix} & & A^4_5 - iA^5_5 \\ & & A^6_5 - iA^7_5 \\ A^4_5 + iA^5_5 & A^6_5 + iA^7_5 & \end{pmatrix} \qquad \frac{SU(3)}{SU(2)\times U(1)}$$

Susy, Little Higgs, gauge-Higgs unification:
three concrete classes of models with

new particles/symmetries that populate the TeV scale
to stabilize the EW scale and suppress dangerous Λ^2 quantum corrections
to the Higgs mass

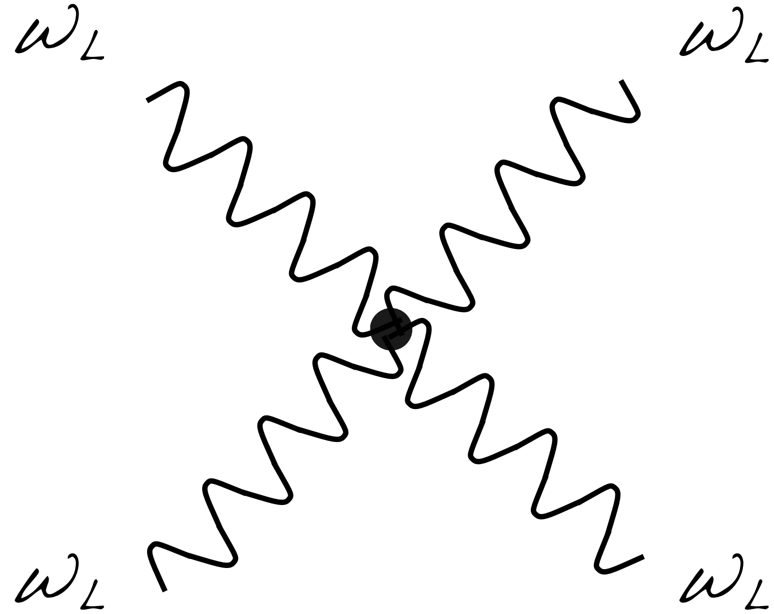
Models designed to address the question:

what is canceling the infamous divergent diagrams?



But this is assuming that we already know the answer to the central question of EW symmetry breaking

what is unitarizing the WW scattering amplitude?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^2 \quad \Rightarrow \quad \mathcal{A} \text{ finite}$$

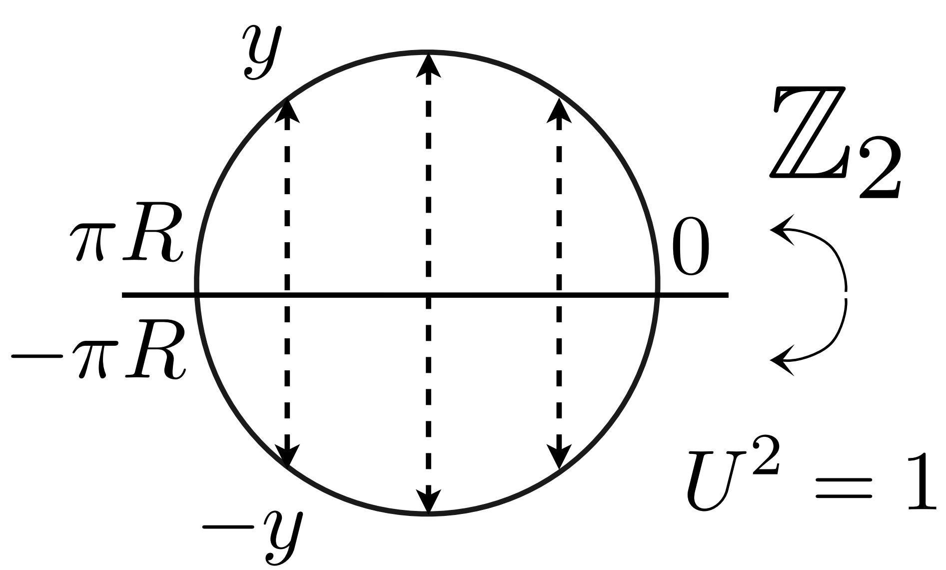
other way to unitarize the WW amplitude:

Higgsless models & composite Higgs

Higgsless Models

Higgsless Approach

Csaki, Grojean, Murayama, Pilo, Terning '03
Csaki, Grojean, Pilo, Terning '03



Gauge symmetry breaking

In the gauge-Higgs unification models, we have been breaking bigger gauge groups down to SU(2)xU(1) by orbifold.

Why can't we break directly SU(2)xU(1) to $U(1)_{em}$ by orbifold?

Higgsless Models

mass without a Higgs

$$m^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2$$

momentum along extra dimensions ~ 4D mass

quantum mechanics in a box

⇓

boundary conditions generate a transverse momentum

Is it better to generate a transverse momentum than introducing by hand a symmetry breaking mass for the gauge fields?

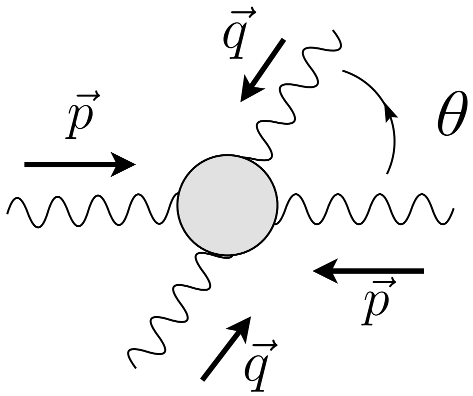
ie how is unitarity restored without a Higgs field?

Unitarization of (Elastic) Scattering Amplitude

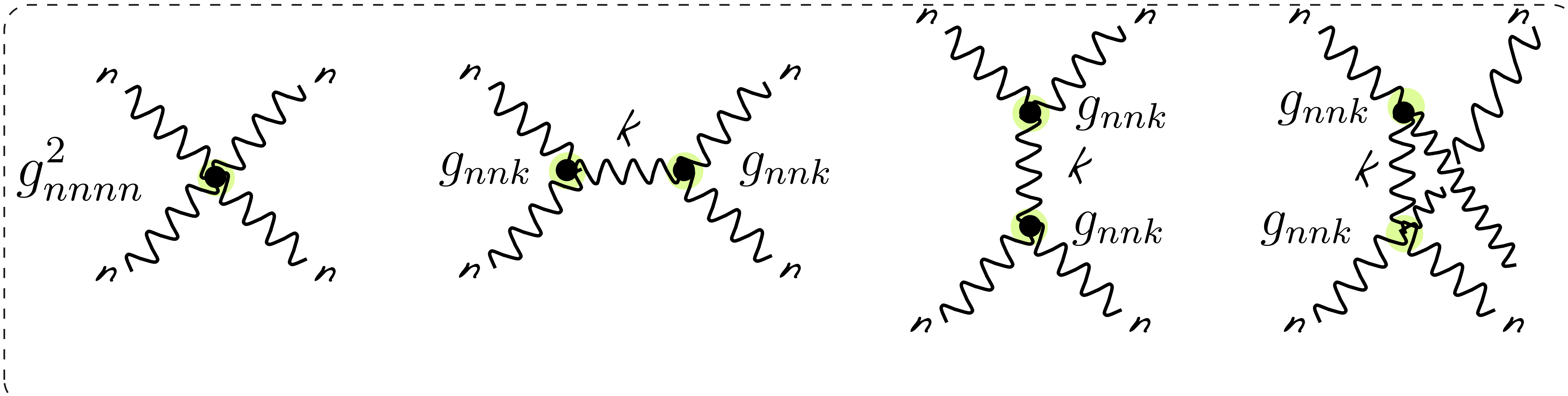
Csaki, Grojean, Murayama, Pilo, Terning '03

Same KK mode 'in' and 'out'

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



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

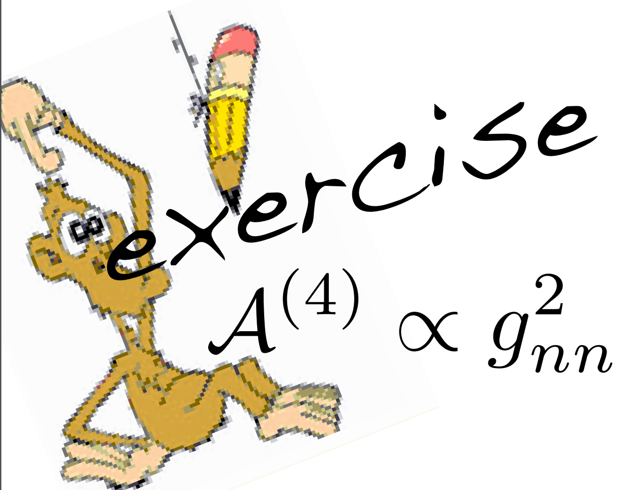


$$\mathcal{A}^{(4)} = i \left(g^2_{nnnn} - \sum_k g^2_{nnk} \right) \left(f^{abe} f^{cde} (3 + 6c_\theta - c^2_\theta) + 2(3 - c^2_\theta) f^{ace} f^{bde} \right)$$

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

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

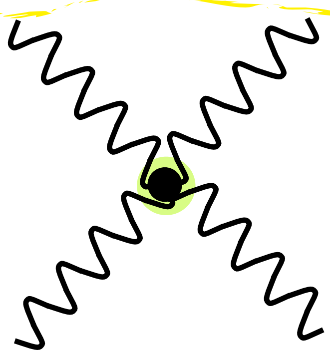
KK Sum Rules



Csaki, Grojean, Murayama, Pilo, Terning '03

$$\mathcal{A}^{(4)} \propto g^2_{nnnn} - \sum_k g^2_{nnk} \qquad\qquad \mathcal{A}^{(2)} \propto 4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}$$

In a KK theory, the effective couplings are given by overlap integrals of the wavefunctions



$$g^2_{mnpq} = g^2_{5D}\int_0^{\pi R} dy f_m(y) f_n(y) f_p(y) f_q(y)$$

$$g_{mnp} = g_{5D}\int_0^{\pi R} dy f_m(y) f_n(y) f_p(y)$$

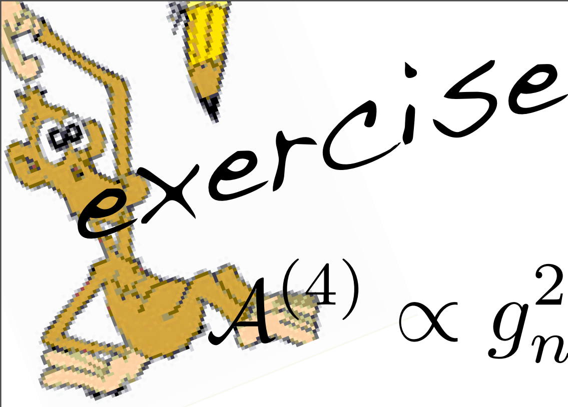
o E^4 Sum Rule

$$g^2_{nnnn} - \sum_k g^2_{nnk} = g^2_{5D}\int_0^{\pi R} dy f_n^4(y) - g^2_{5D}\int_0^{\pi R} dy \int_0^{\pi R} dz f_n^2(y) f_n^2(z) \sum_k f_k(y) f_k(z) = 0$$

$$\mathcal{A}^{(4)} = 0$$

$$\sum_k f_k(y) f_k(z) = \delta(y-z)$$

Completness of KK modes



KK Sum Rules

$$\mathcal{A}^{(4)} \propto g^2_{nnnn} - \sum_k g^2_{nnk} \qquad\qquad \mathcal{A}^{(2)} \propto 4g^2_{nnnn} - 3\sum_k g^2_{nnk}\frac{M_k^2}{M_n^2}$$

- E^2 Sum Rule

$$4g^2_{nnnn}M_n^2 - 3\sum_k g^2_{nnk}M_k^2 = 4g^2_{5D}M_n^2\int_0^{\pi R} dy f_n^4(y) - 3g^2_{5D}\int_0^{\pi R} dy\, dz\, f_n^2(y)f_n^2(z)\sum_k f_k(y)\underbrace{f_k(z)M_k^2}_{-f_k''(z)}$$

$$\int dz\, f_n^2(z)f_k''(z) \overset{\text{int. by part}}{=} -2\int dz\, f_n(z)f_n'(z)f_k'(z)$$

$$\overset{\text{int. by part}}{=} 2\int dz\, f_n(z)f_n''(z)f_k(z) + 2\int dz\, f_n'^2(z)f_k(z)$$

$$= -2M_n^2\int dz\, f_n^2(z)f_k(z) + 2\int dz\, f_n'^2(z)f_k(z)$$

$$\sum_k f_k(y)f_k(z) = \delta(y-z)$$

$$= 4g^2_{5D}M_n^2\int_0^{\pi R} dy\, f_n^4(y) - 6g^2_{5D}M_n^2\int_0^{\pi R} dy\, f_n^4(y) + 6g^2_{5D}\int_0^{\pi R} dy\, f_n^2(y)f_n'^2(y)$$

$$\int dy\, f_n^2(y)f_n'^2(y) \overset{\text{int. by part}}{=} -2\int dy\, f_n^2(y)f_n'^2(y) - \int dy\, f_n^3(y)f_n''(y)$$

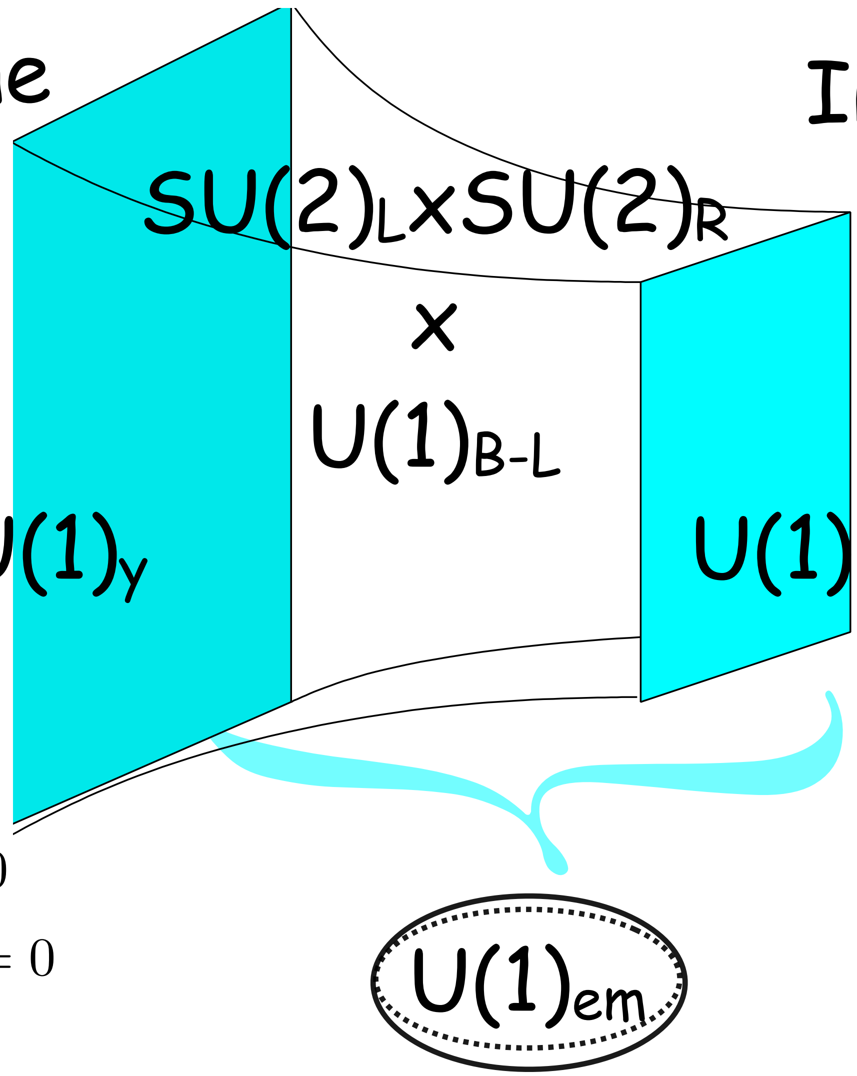
$$= \tfrac{1}{3}M_n^2\int dy\, f_n^4(y)$$

$$\mathcal{A}^{(2)} = 0$$

up to boundary terms...

Warped Higgsless Model

Csaki, Grojean, Pilo, Terning '03



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

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

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

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

BCs kill all A_5 massless modes: no 4D scalar mode in the spectrum

"light" mode:

$$M_W^2 = \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

$$M_Z^2 \sim \frac{g_5^2 + 2g_5'^2}{g_5^2 + g'^2} \frac{1}{R_{IR}^2 \log(R_{IR}/R_{UV})}$$

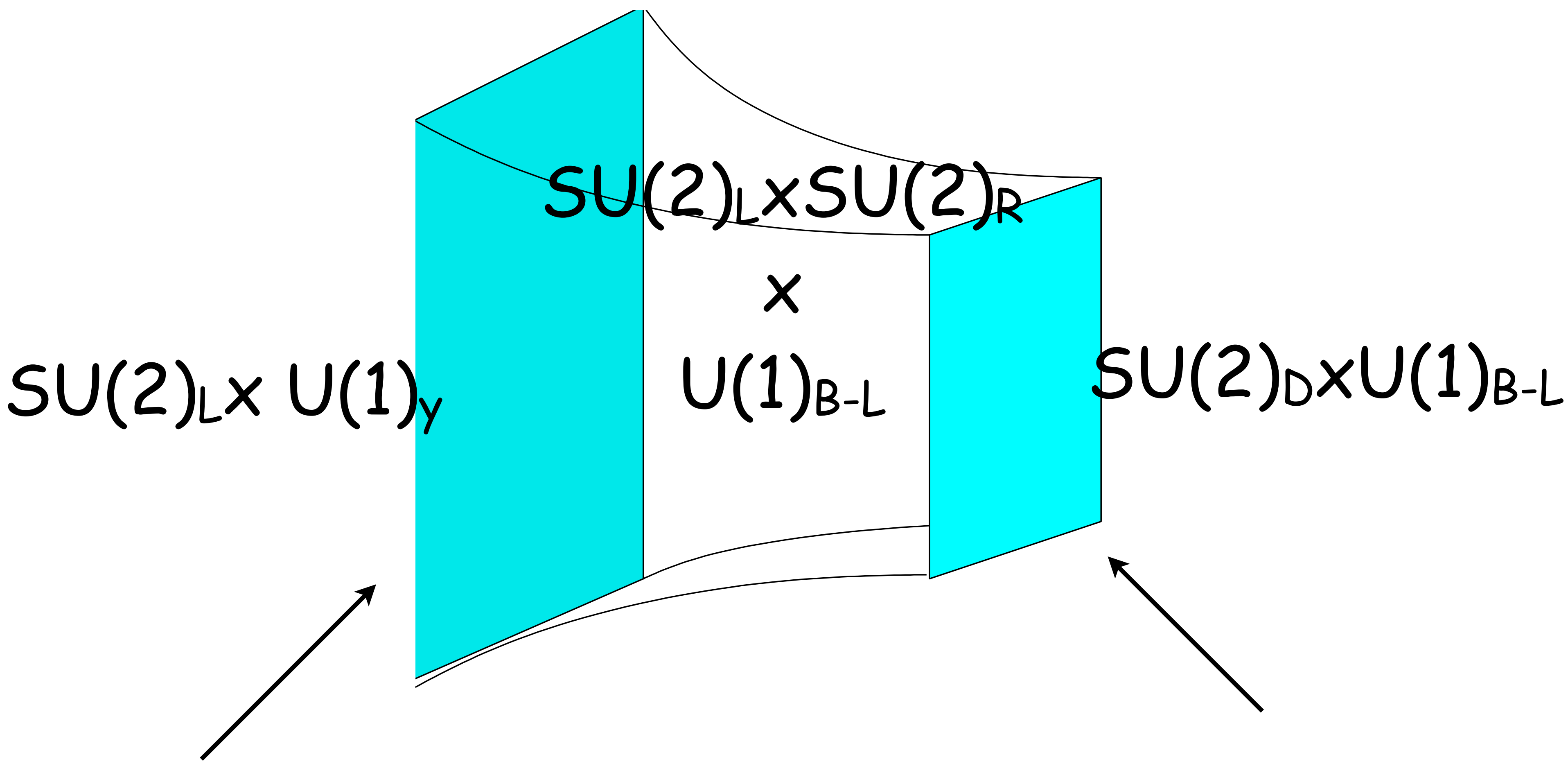
log suppression

KK tower:

$$M_{KK}^2 = \frac{\text{cst of order unity}}{R_{IR}^2}$$

SM Fermions in Higgsless Models

Csaki, Grojean, Hubisz, Shirman, Terning '03



Chiral brane
no possible mass term

vector-like brane
isospin invariant mass only
(same mass for the top and bottom or electron and neutrino)

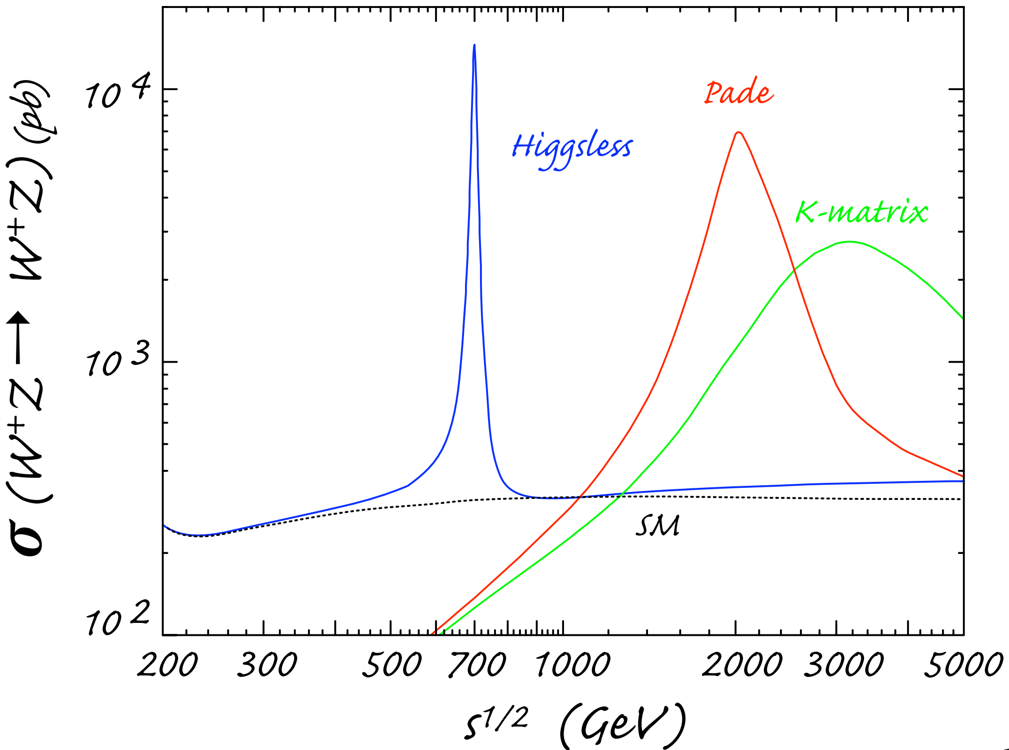
The fermions have to live in the bulk

Collider Signatures

Birkedal, Matchev, Perelstein '05
He et al. '07
Hirn, Martin, Sanz '07

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

WZ elastic cross section

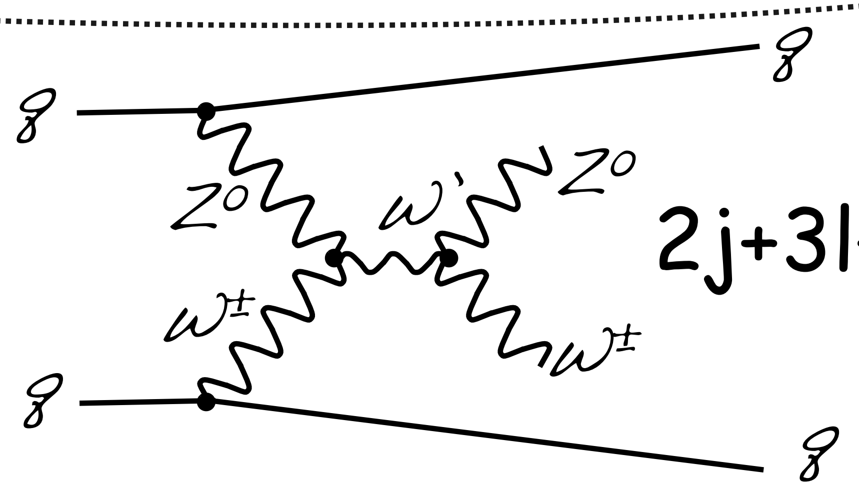


$$g_{WW'Z} \leq \frac{g_{WWZ} M_Z^2}{\sqrt{3} M_{W'} M_W} \quad \Gamma(W' \to WZ) \sim \frac{\alpha M_{W'}^3}{144 s_w^2 M_W^2}$$

a narrow and light resonance

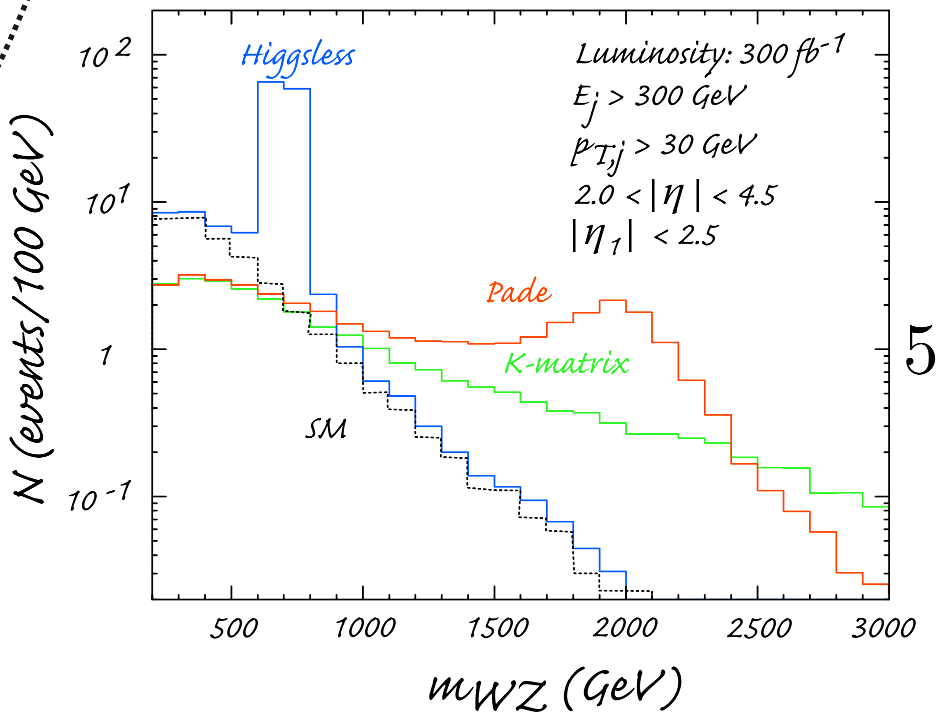
no resonance in WZ for SM/MSSM

W' production



2j+3l+$\not{E}_T$

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



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

discovery reach @ LHC (10 events)

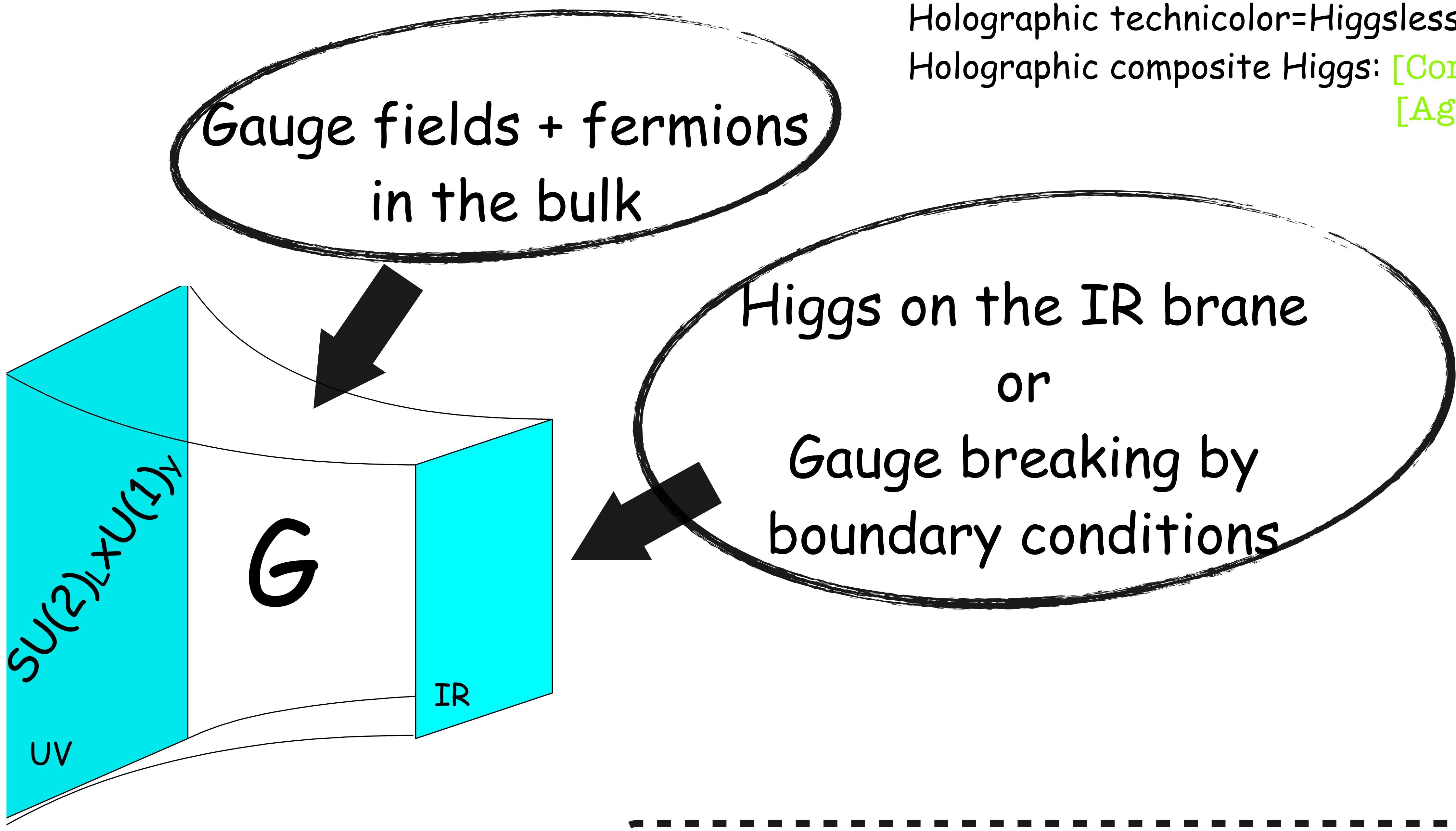
$550\ \text{GeV} \to 10\ \text{fb}^{-1}$

$1\ \text{TeV} \to 60\ \text{fb}^{-1}$

should be seen within one/two year

Holographic Models of EWSB

Bulk gauge fields: [Pomarol, '00]
Holographic technicolor=Higgsless: [Csaki et al., '03
Holographic composite Higgs: [Contino et al., '03]
[Agashe et al., '04]



$G=SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$G=SO(5) \times U(1)_X$
$G=SO(6) \times U(1)_X$

- UV completion: log running of gauge couplings
- Custodial symmetry from bulk $SU(2)_R$

Composite Higgs Models (1)

what is the SM Higgs? ➲

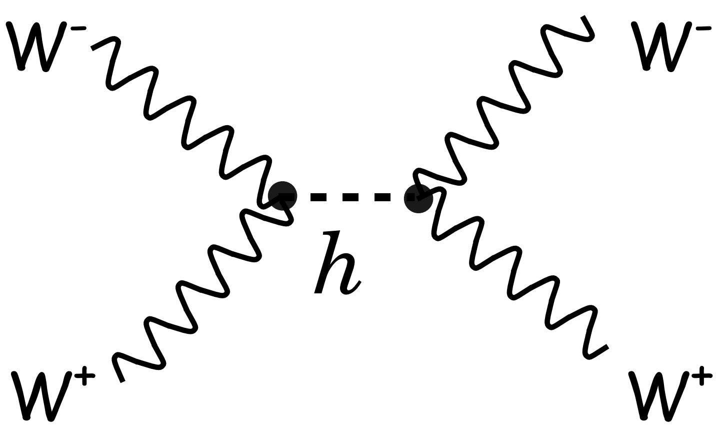
what is a composite Higgs? ➲,

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

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

What is the SM Higgs?

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

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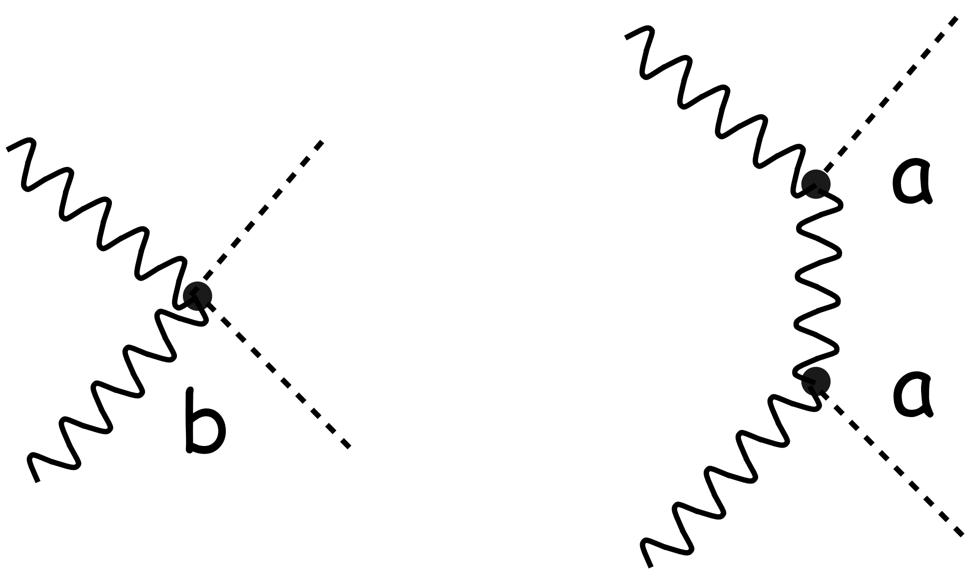
For a=1: perturbative unitarity in elastic channels $WW \to WW$

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

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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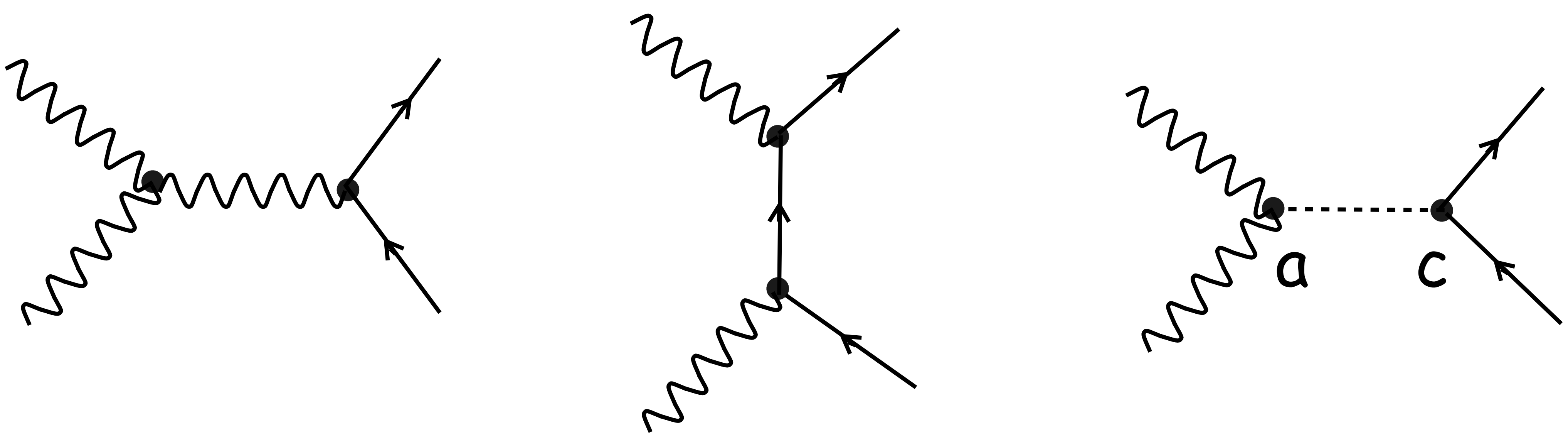
Cornwall, Levin, Tiktopoulos '73 Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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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

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\rm EWSB}$ 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 $SU(2)_L \times U(1)_Y$

What is a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet

renormalizable level = uniqueness

$SU(2)_L x U(1)_Y$ linearly realized $\Leftrightarrow$ Standard Model $\Leftrightarrow$ a=b=c=1

What is a composite Higgs?

A σ particle that combines with W_L and Z_L to form a SU(2) doublet

renormalizable level = uniqueness

$SU(2)_L \times U(1)_Y$ linearly realized ⇔ Standard Model ⇔ a=b=c=1

non-renormalizable level

$SU(2)_L \times U(1)_Y$ linearly realized & a, b, c ≠ 1 ⇔ Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

$$\left(\partial_\mu |H|^2\right)^2 \quad |H|^2 \bar{\psi} H \psi \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}$$

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

$\xi = v^2/f^2$

$a = 1-\xi/2 \qquad b = 1-2\xi \qquad c = 1-\xi/2$

Deformation of the SM Higgs: current constraints

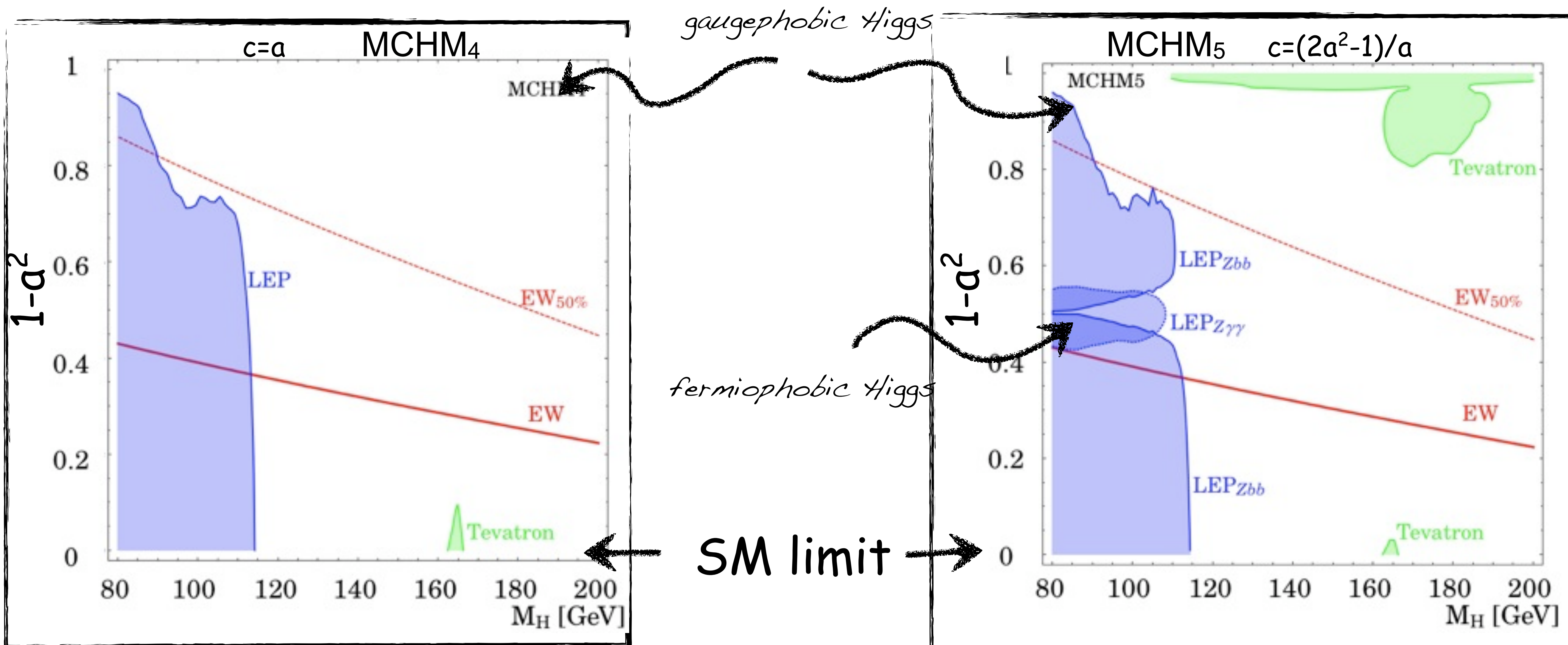
$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda\bar\psi_L\Sigma\psi_R\left(1+c\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

SM 'a=1', 'b=1' & 'c=1'

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

Espinosa, Grojean, Muehlleitner '10



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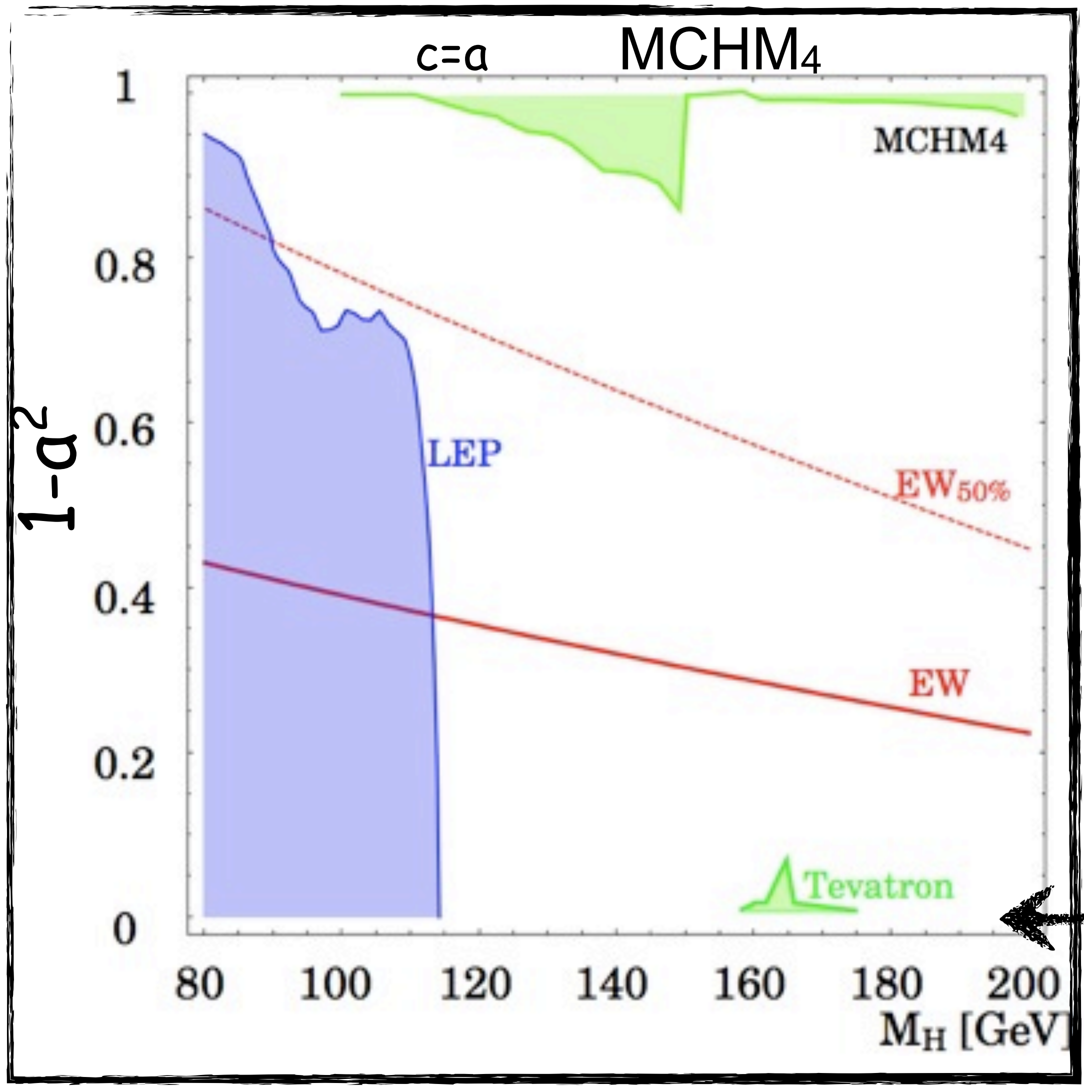
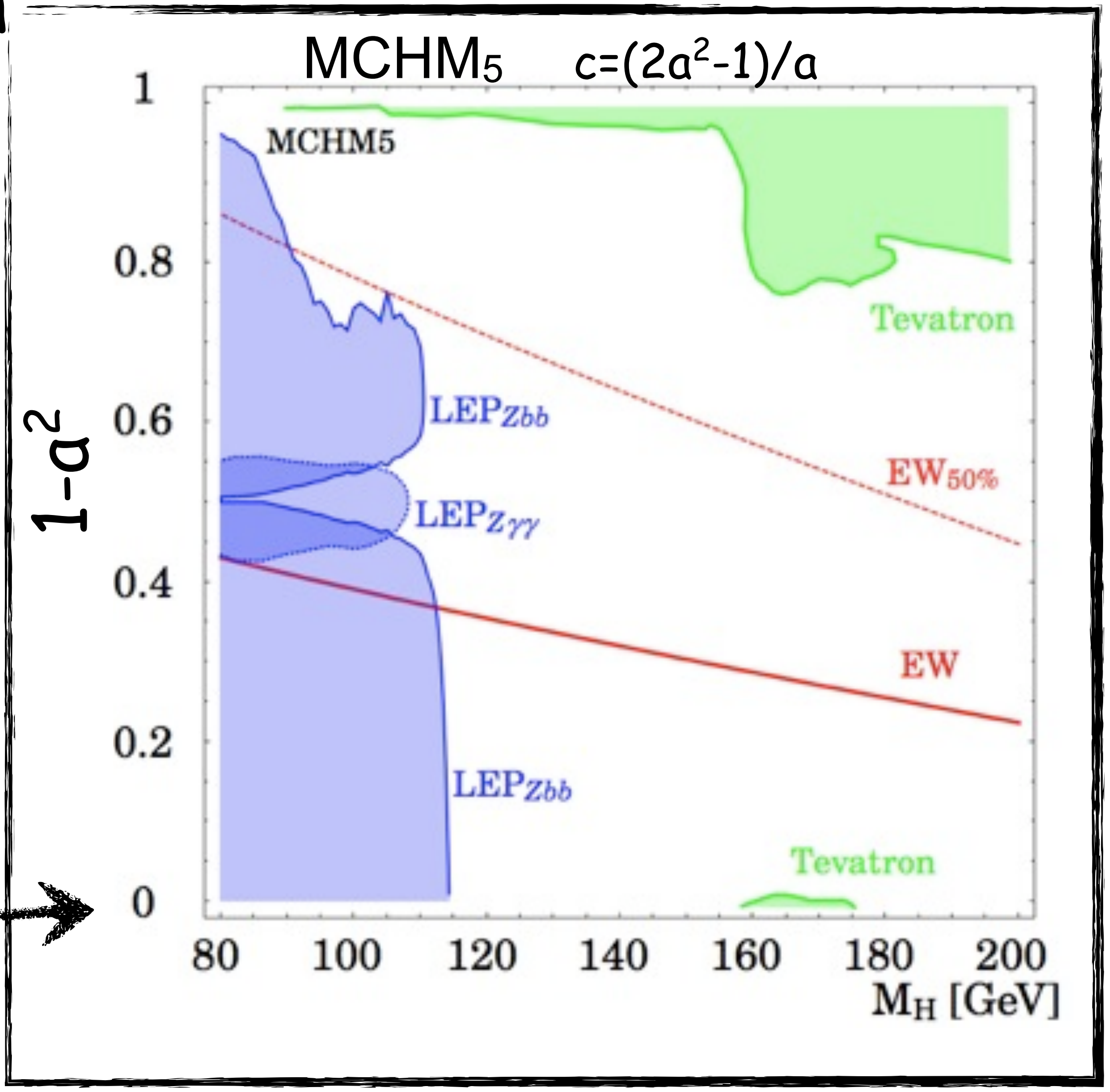
Espinosa '11



New Tevatron constraints

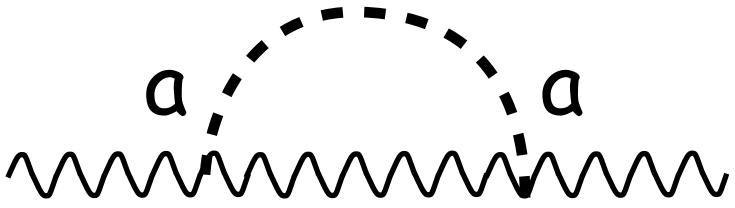
SM limit



For a recent analysis, see also Bonnet, Gavela, Ota, Winter '11

Deformation of the SM Higgs: EW constraints

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables



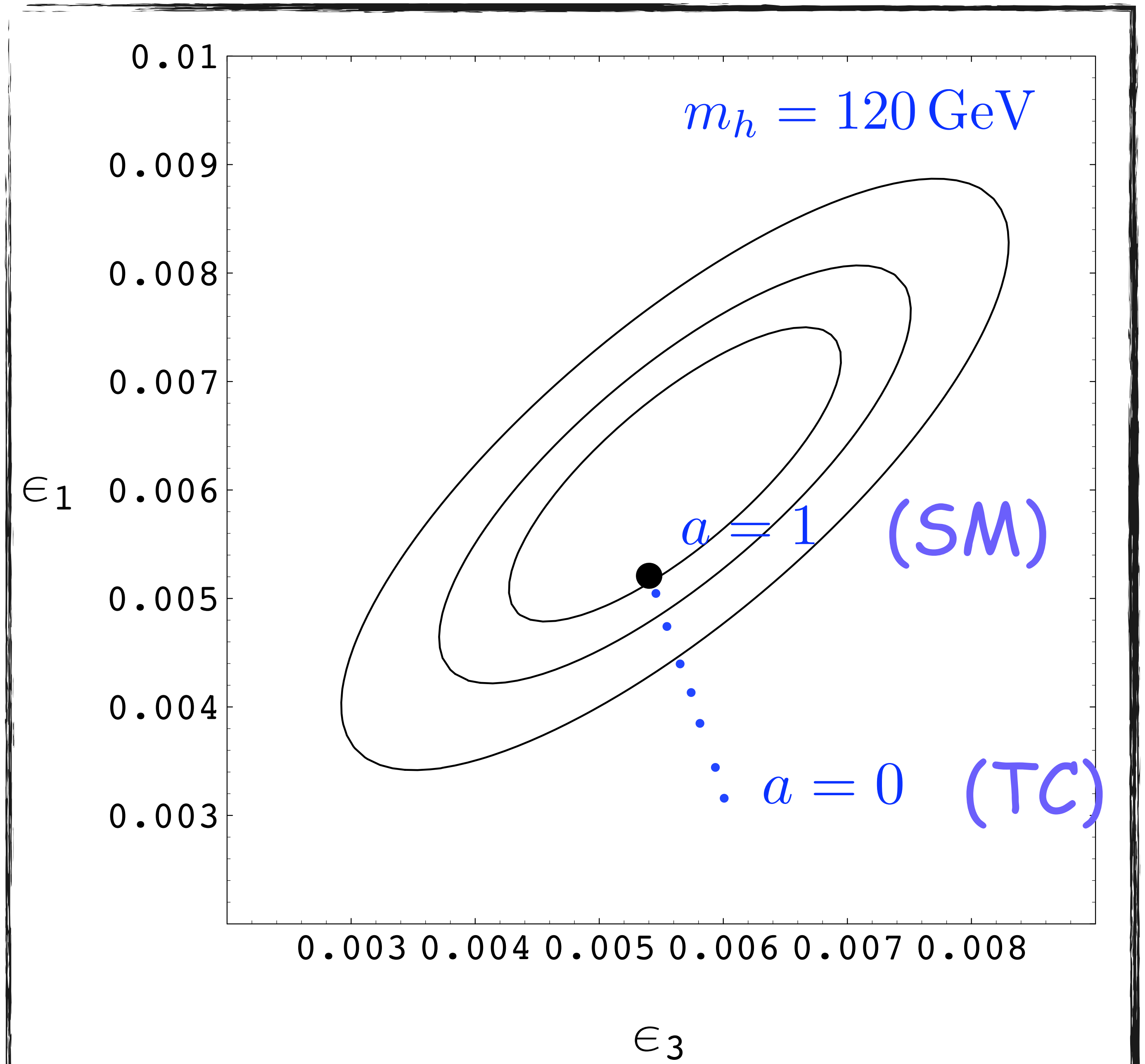
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\,a^2\log(m_h^2/\mu^2) - c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

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

$$c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\,\left(1-a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07



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Physics Beyond the Standard Model

The 2011 Hadron Collider Physics Summer School

CERN, June 8-17, 2011

Christophe Grojean

CERN-TH & CEA-Saclay/IPhT

(christophe.grojean@cern.ch)

Lecture Outline

1 First Lecture ➲
- Standard Model and EW symmetry breaking ➲
- Higgs mechanism ➲
- EW precision tests ➲
- Higgs as a UV moderator ➲
- UV behaviour of the Higgs ➲

2 Second Lecture ➲
- Supersymmetry ➲
- Little Higgs ➲

3 Third Lecture ➲
- Gauge-Higgs unification ➲, Higgsless ➲
- Composite Higgs models (I) ➲

4 Fourth Lecture ➲
- Composite Higgs models (II) ➲
- GUT: SM vs MSSM vs Composite Higgs ➲

1 2 3 4

Composite Higgs Models (2)

Higgs anomalous couplings ➲ strong scatterings ➲

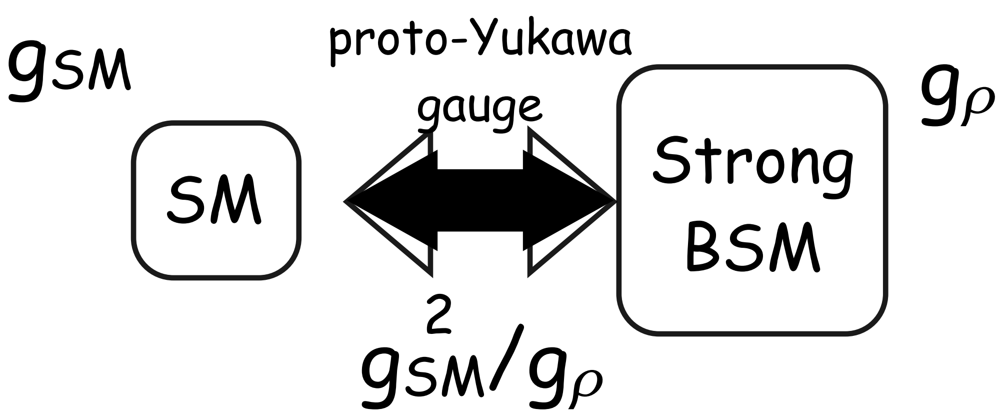
triple Higgs production ➲ heavy resonances ➲

How to obtain a light composite Higgs?

Georgi, Kaplan '84 Giudice, Grojean, Pomarol, Rattazzi '07

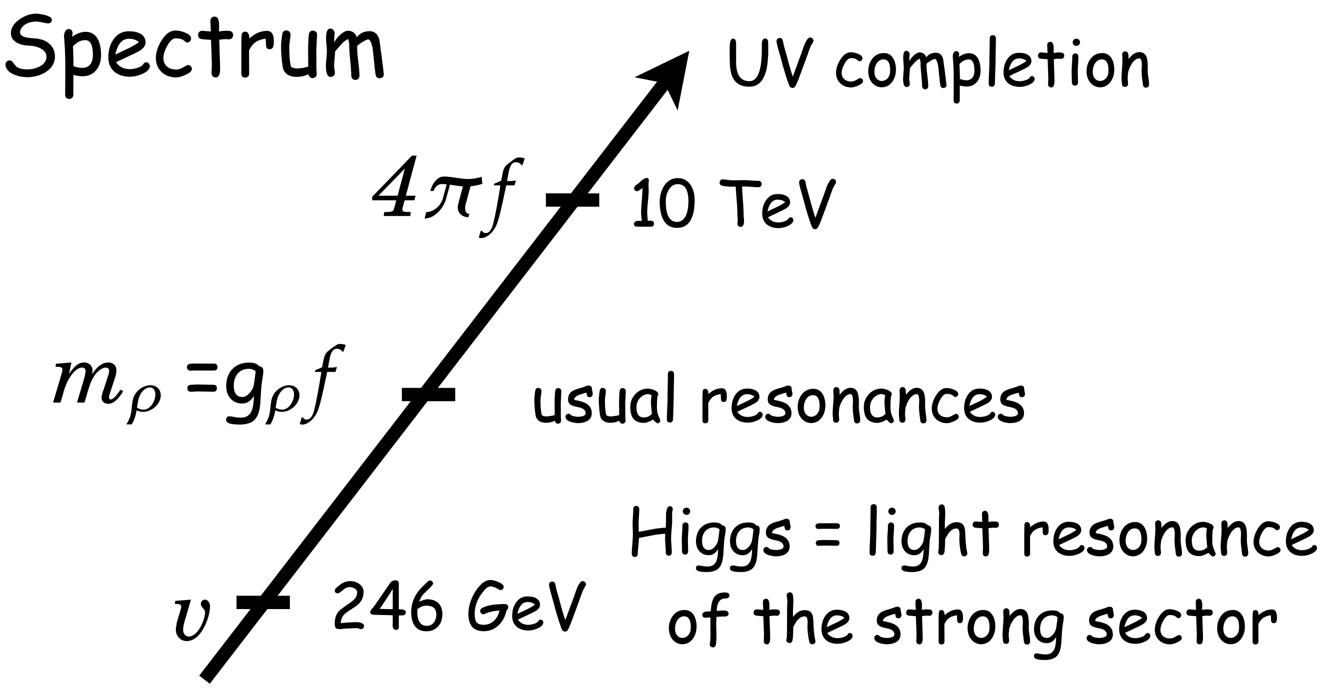
Higgs=Pseudo-Goldstone boson of the strong sector

$m_{Higgs}=0$ when $g_{SM}=0$



global symmetry → G/H ← residual global symmetry

Spectrum



Coset broken by SM couplings

⇛ Higgs potential

v/f≈0.2÷0.3 generated dynamically

(might require mild-tuning in explicit models)

strong sector broadly characterized by 2 parameters

m_ρ = mass of the resonances

g_ρ = coupling of the strong sector or decay cst of strong sector $f = m_\rho / g_\rho$

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:

Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM: $SO(4)/SO(3)$ — $W^{\pm}_L$ & Z_L ⇒ BSM: G/H — $W^{\pm}_L$ & Z_L & h

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

$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ← Minimal Composite Two Higgs Doublets
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Continuous interpolation between SM and TC

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

$$\xi = 0$$

SM limit

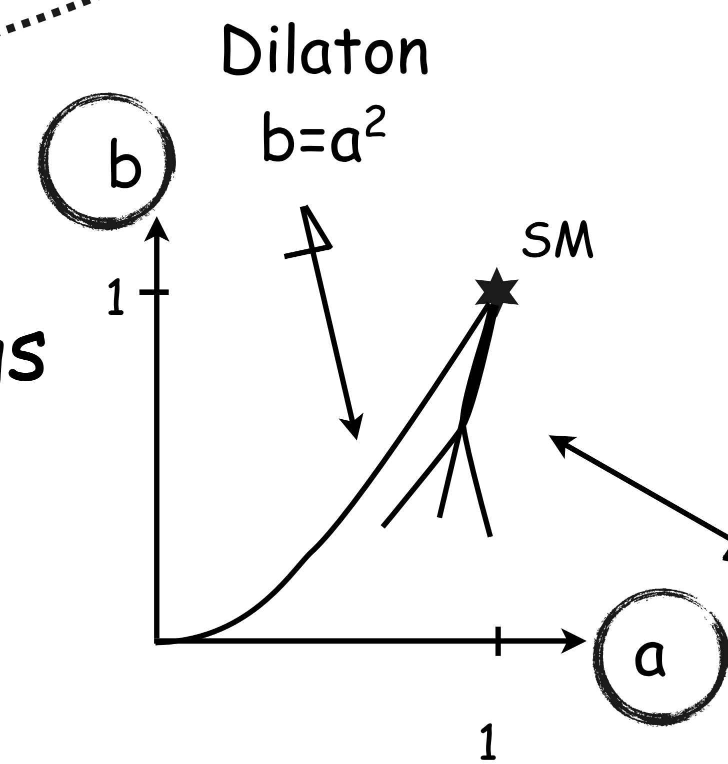
all resonances of strong sector, except the Higgs, decouple

$$\xi = 1$$

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
$a=1-v/2f$ $b=1-2v/f$

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$$

$$\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6\lambda}{f^2}|H|^6$$

Form factor operators (sensitive to the scale m_ρ)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i$$

$$\frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$$

$$\frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed
by custodial symmetry

$$\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2} \Longrightarrow m_\rho \geq (c_W + c_B)^{1/2}\, 2.5\,\mathrm{TeV}$$

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There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\hat{S}, \hat{T} = a \left((1 - c_H \xi) \log m_h + c_H \xi \log \Lambda \right) + b$$

effective Higgs mass

$$m_h^{\mathit{eff}} = m_h \left(\frac{\Lambda}{m_h} \right)^{c_H v^2/f^2} > m_h$$

LEPII, for m_h~115 GeV: $c_H v^2/f^2 < 1/3 \div 1/2$

IR effects can be cancelled by heavy fermions (model dependent)

Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right) y_{ij}\bar{f}_{Li}Hf_{Rj} = \left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

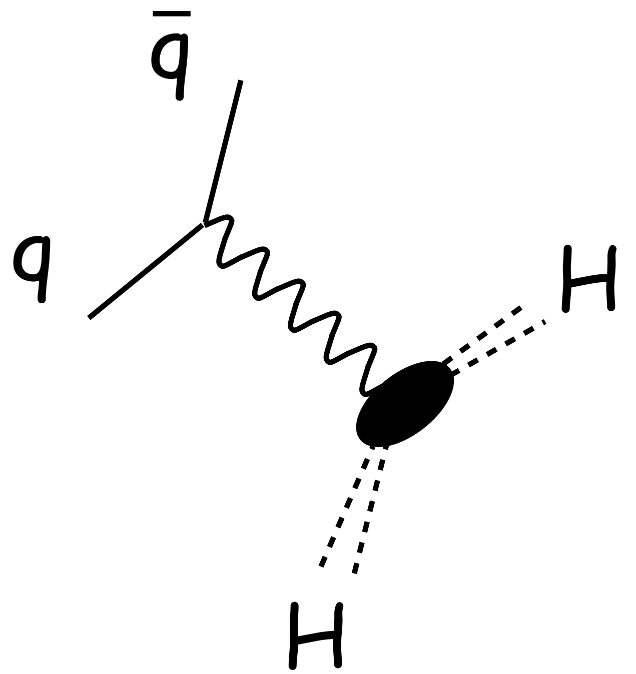
mass and interaction matrices are not diagonalizable simultaneously if c_{ij} are arbitrary

$\Rrightarrow$ FCNC

SILH: c_y is flavor universal

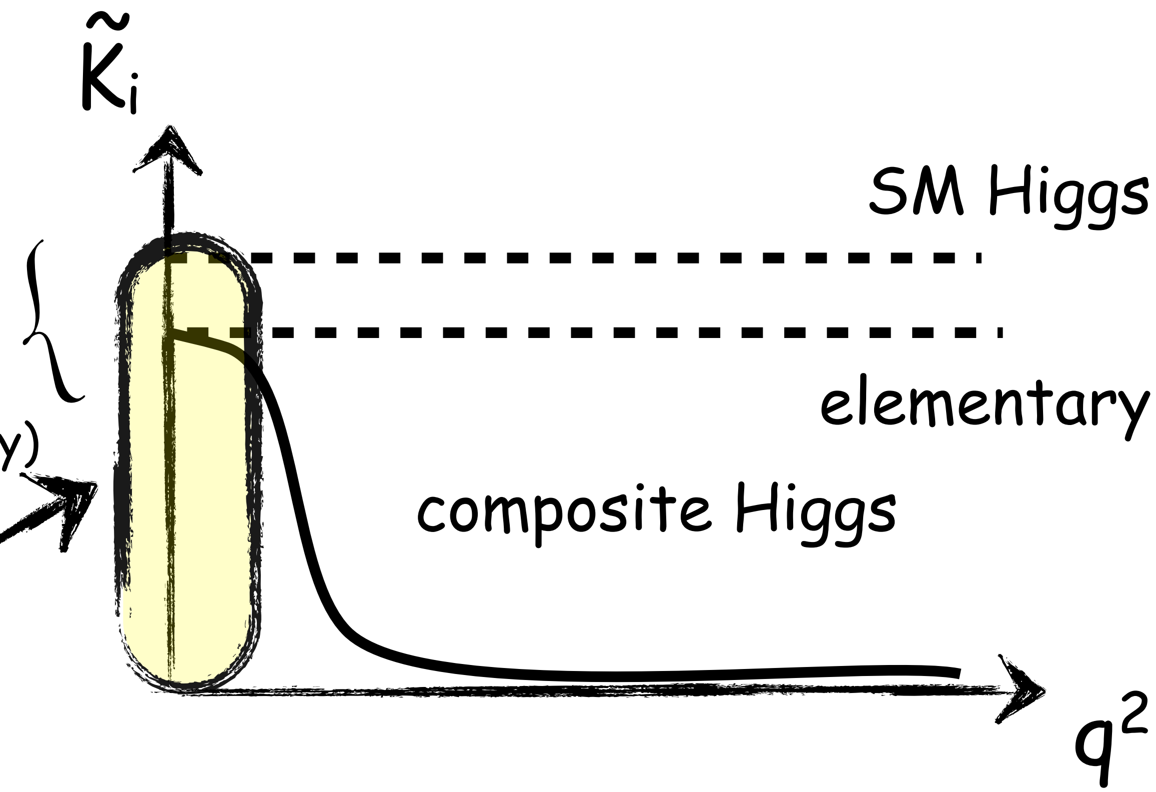
$\Rrightarrow$ Minimal flavor violation built in

How to probe the compositeness of the Higgs?



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2}\frac{E'}{E^3}\left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2\cos^2\theta/2\right)$$

Rosenbluth-type cross-section



anomalous couplings
(accessible @ LHC with 20-40% accuracy)

LHC reach ?
(accessible @ LHC with 20-40% accuracy)

Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

} identify interesting processes

How to probe the composite nature of the Higgs?

1. Anomalous Higgs couplings

Higgs anomalous couplings for large v/f

The SILH Lagrangian is an expansion for small v/f

5D MCHM give a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \;\Rrightarrow\; g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM} \;\Rrightarrow\; \begin{cases} a = \sqrt{1-\xi} \\ b = 1-2\xi \end{cases}$$

MCHM4

Fermions embedded in spinorial of SO(5)

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \sqrt{1-\xi}$$

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$m_f = M \sin 2v/f$$

$$\Downarrow$$

$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

BRs now depends on v/f

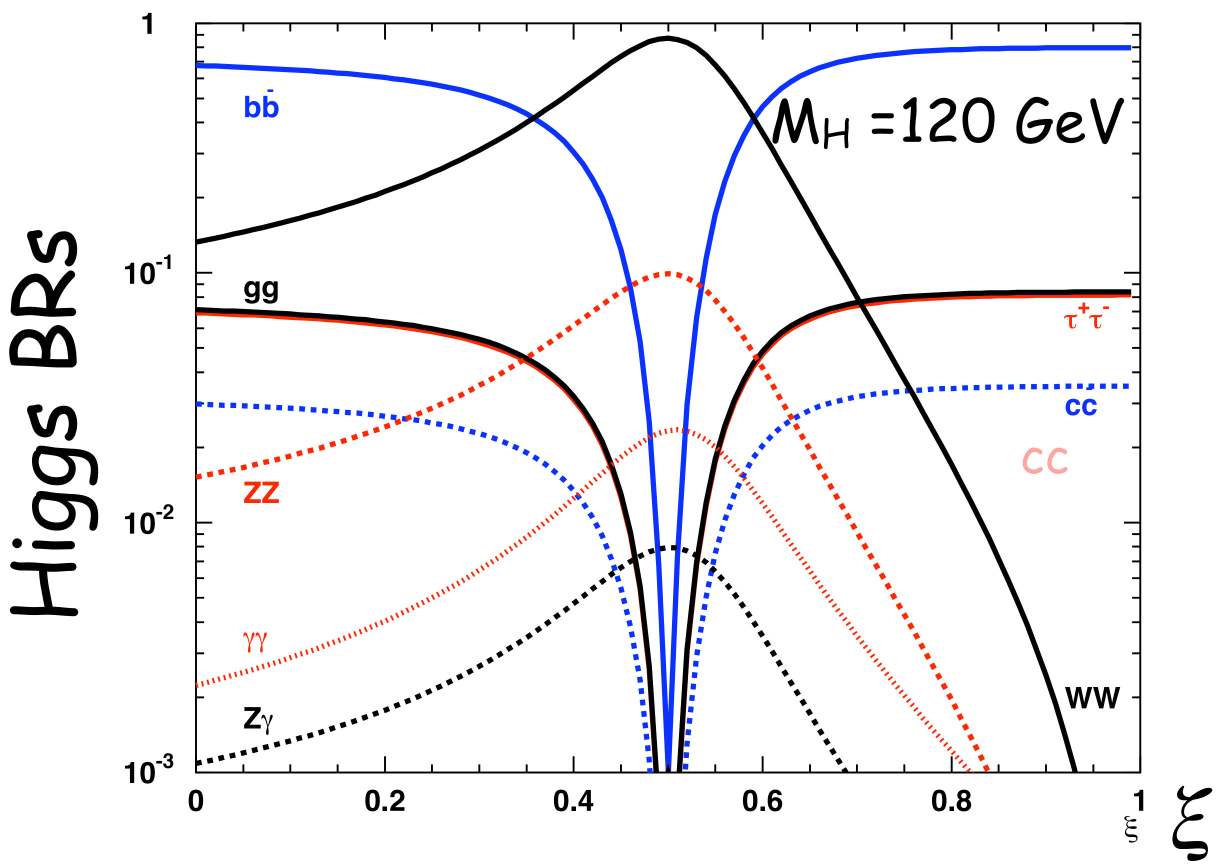
$$(\xi = v^2/f^2)$$

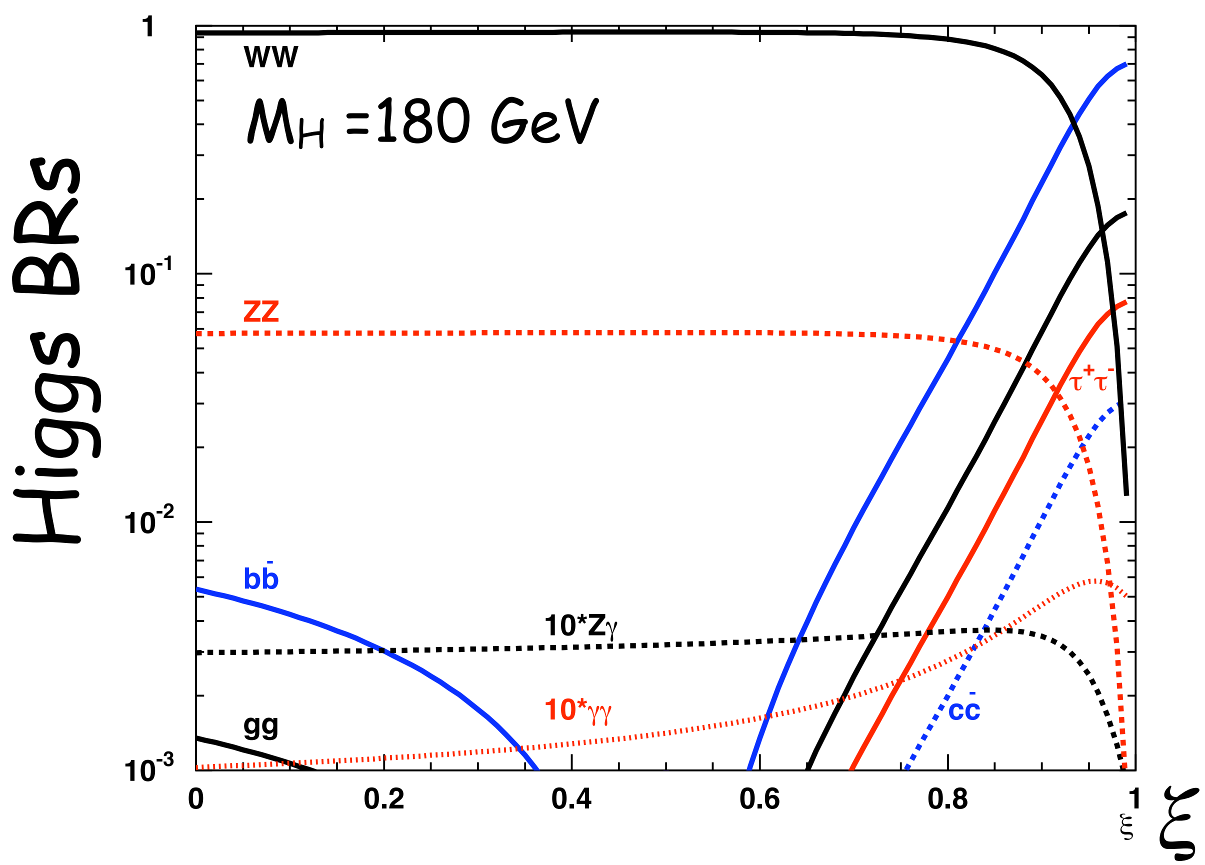
Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$a = \sqrt{1-\xi} \quad b = 1 - 2\xi \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$





h→WW can dominate even for low Higgs mass

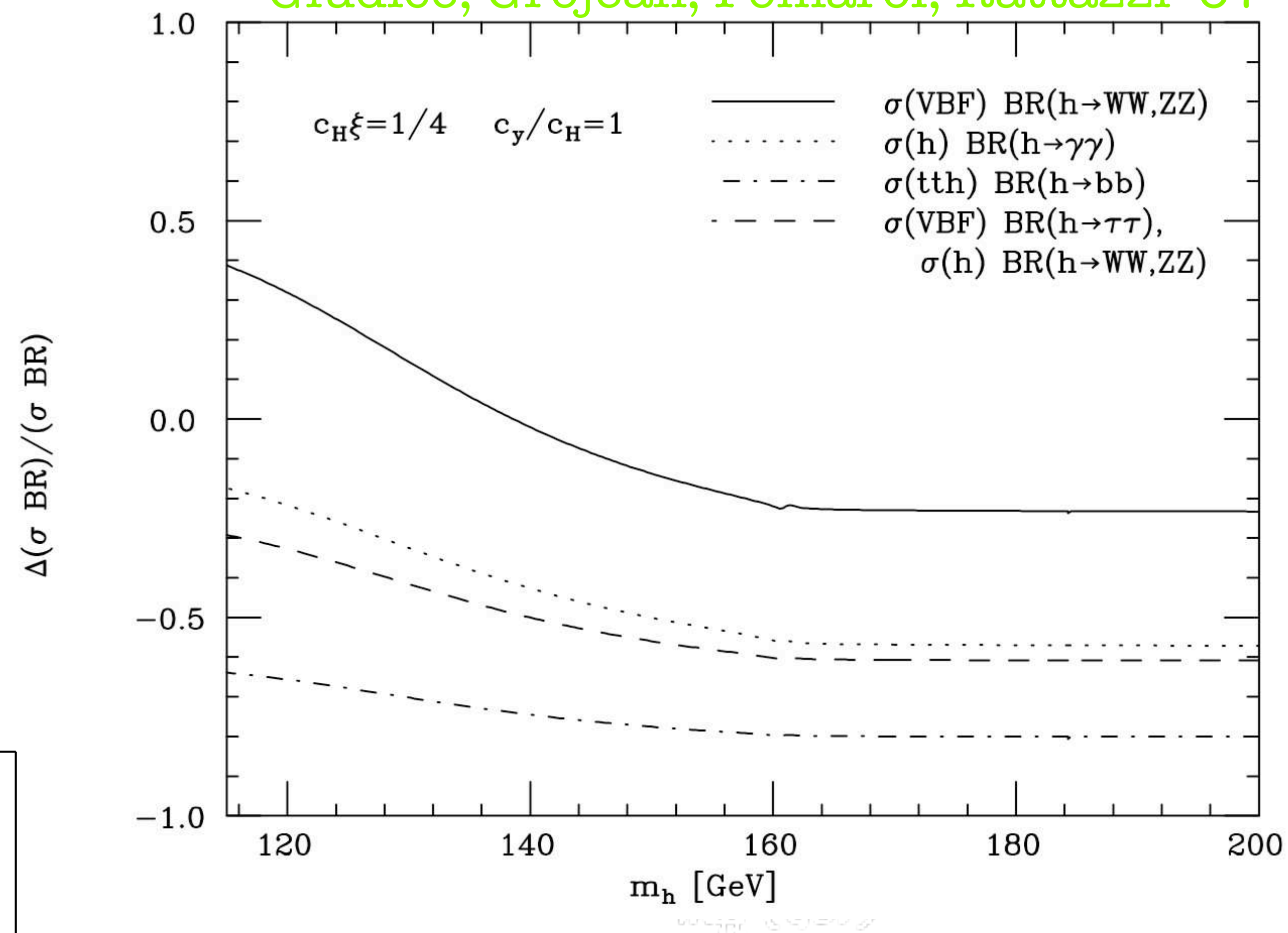
BRs remain SM like except for very large values of v/f

Higgs anomalous couplings @ LHC

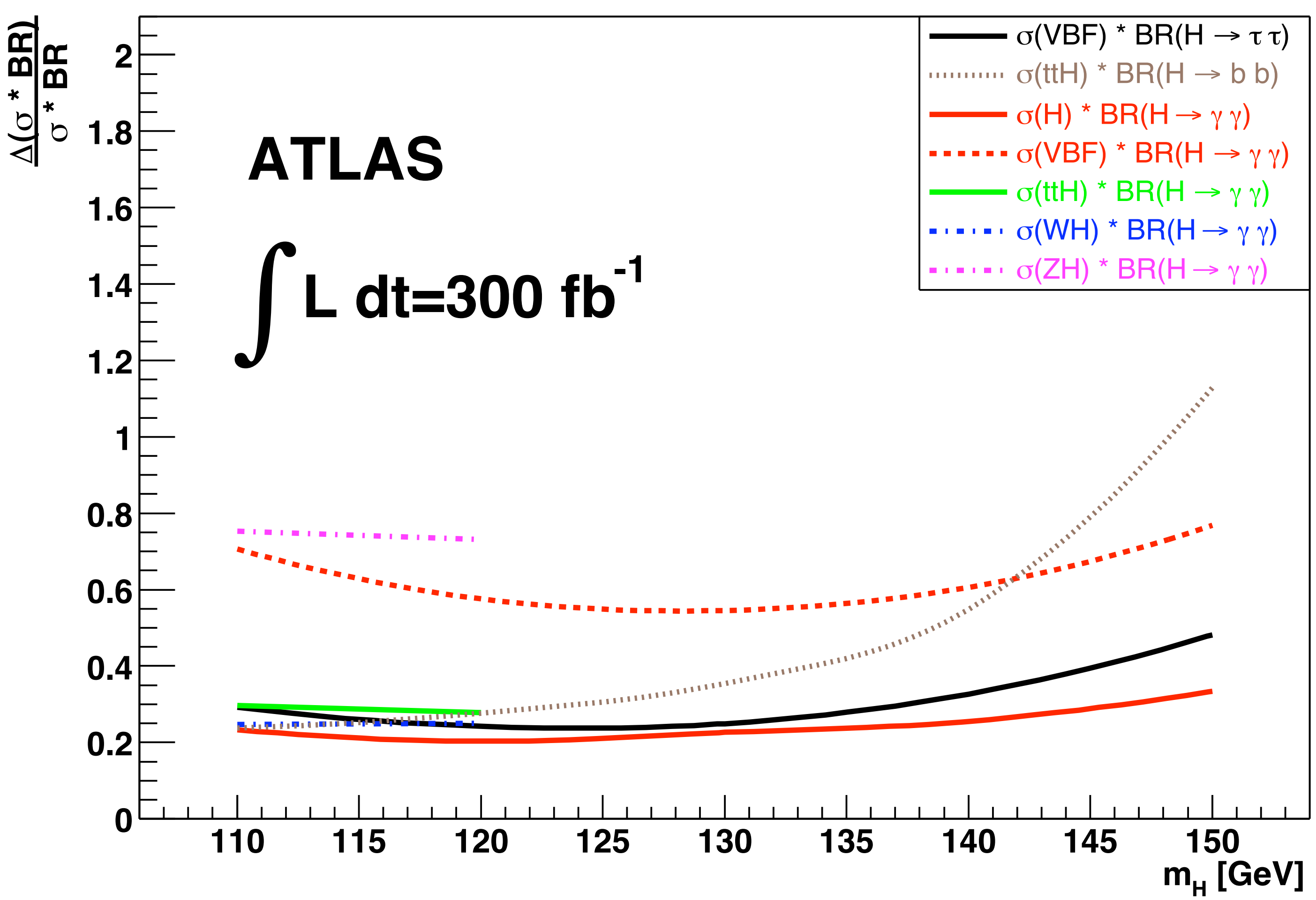
$$\Gamma\left(h\to f\bar{f}\right)_{\rm SILH}=\Gamma\left(h\to f\bar{f}\right)_{\rm SM}\left[1-\frac{v^2}{f^2}\left(2c_y+c_H\right)\right]$$

$$\Gamma\left(h\to gg\right)_{\rm SILH}=\Gamma\left(h\to gg\right)_{\rm SM}\left[1-\frac{v^2}{f^2}\left(2c_y+c_H\right)\right]$$

Giudice, Grojean, Pomarol, Rattazzi '07



observable @ LHC?



Duhrssen '03

LHC can measure

$$c_H\frac{v^2}{f^2},\ c_y\frac{v^2}{f^2}$$

up to 0.2-0.4

i.e. $4\pi f\sim 5-7\ \mathrm{TeV}$

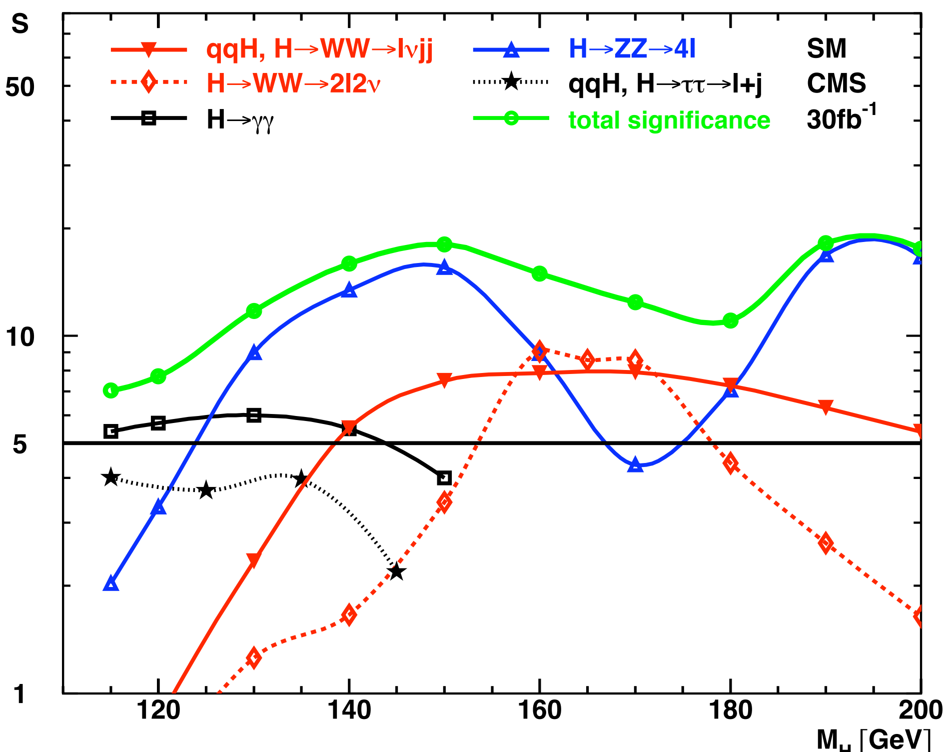
(ILC/CLIC could go to few %, ie, test composite Higgs up to $4\pi f$ ~ 30/60 TeV)

Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

the modification of Higgs couplings and BRs affects the Higgs search

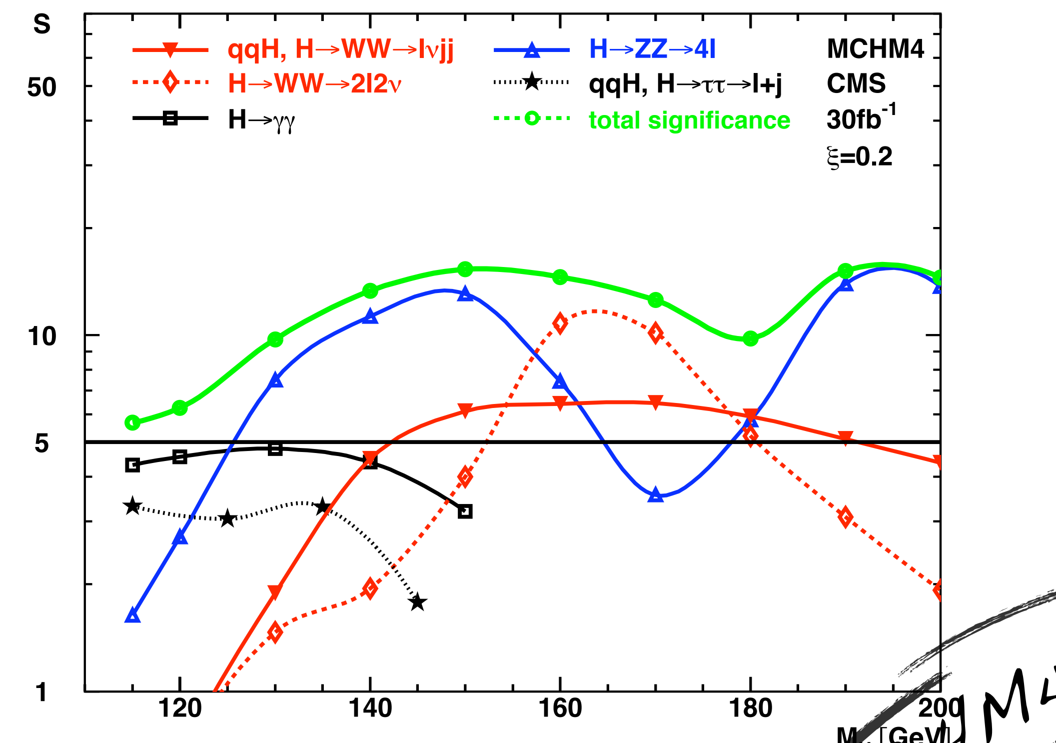
SM



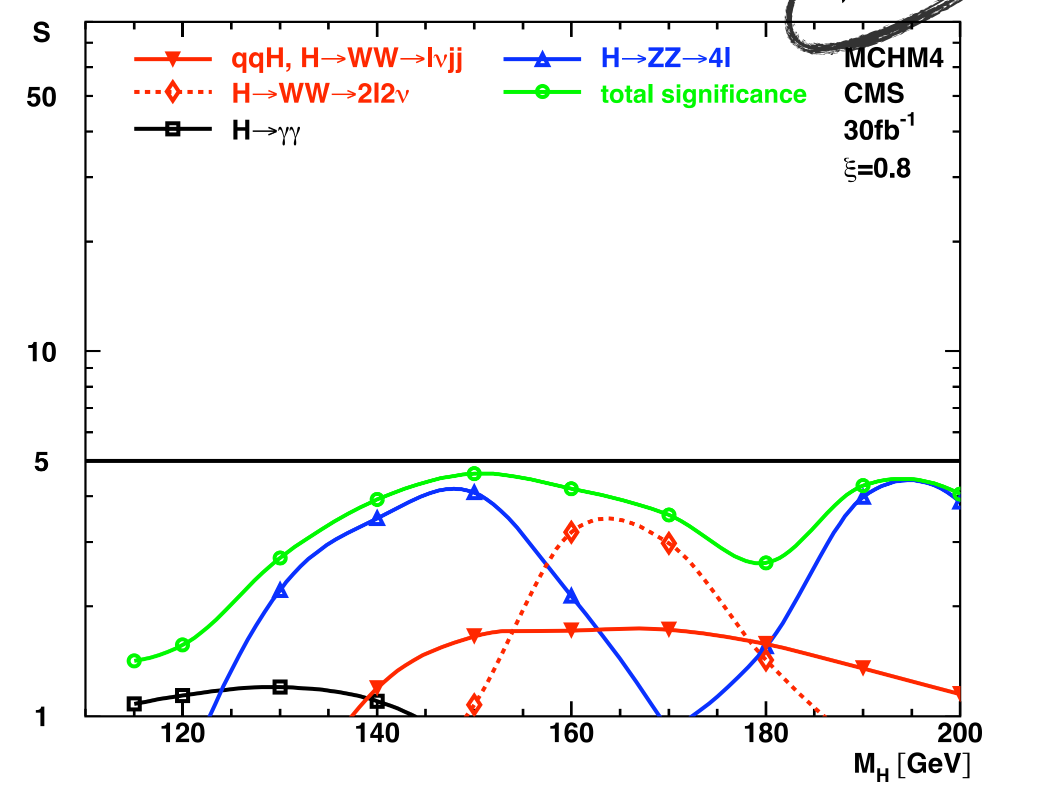
large
compositeness scale

signal significance
for L=30/fb

small
compositeness scale



MCHM4



How to probe the composite nature of the Higgs?

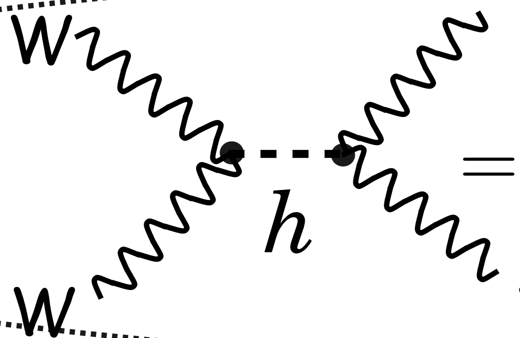
2. Processes probing the strong interactions

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

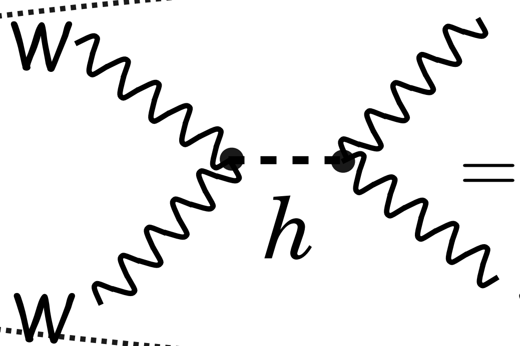
not competitive with the measurement of 'a' via anomalous couplings

How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

strong WW scattering



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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

Scale of Strong WW scattering?

$$\mathcal{A}_{TT\to TT} \sim g^2 f(t/s)$$

f is a rational fct
expected O(1) for t~-s/2

$$\mathcal{A}_{LL\to LL} \sim \frac{s}{v^2}$$

onset of strong scattering at the weak scale

hard cross-section

$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} = N_h \frac{s^2}{M_W^4}$$

'inclusive' cross-section

$(-s+Q^2_{\min} < t < -Q^2_{\min})$

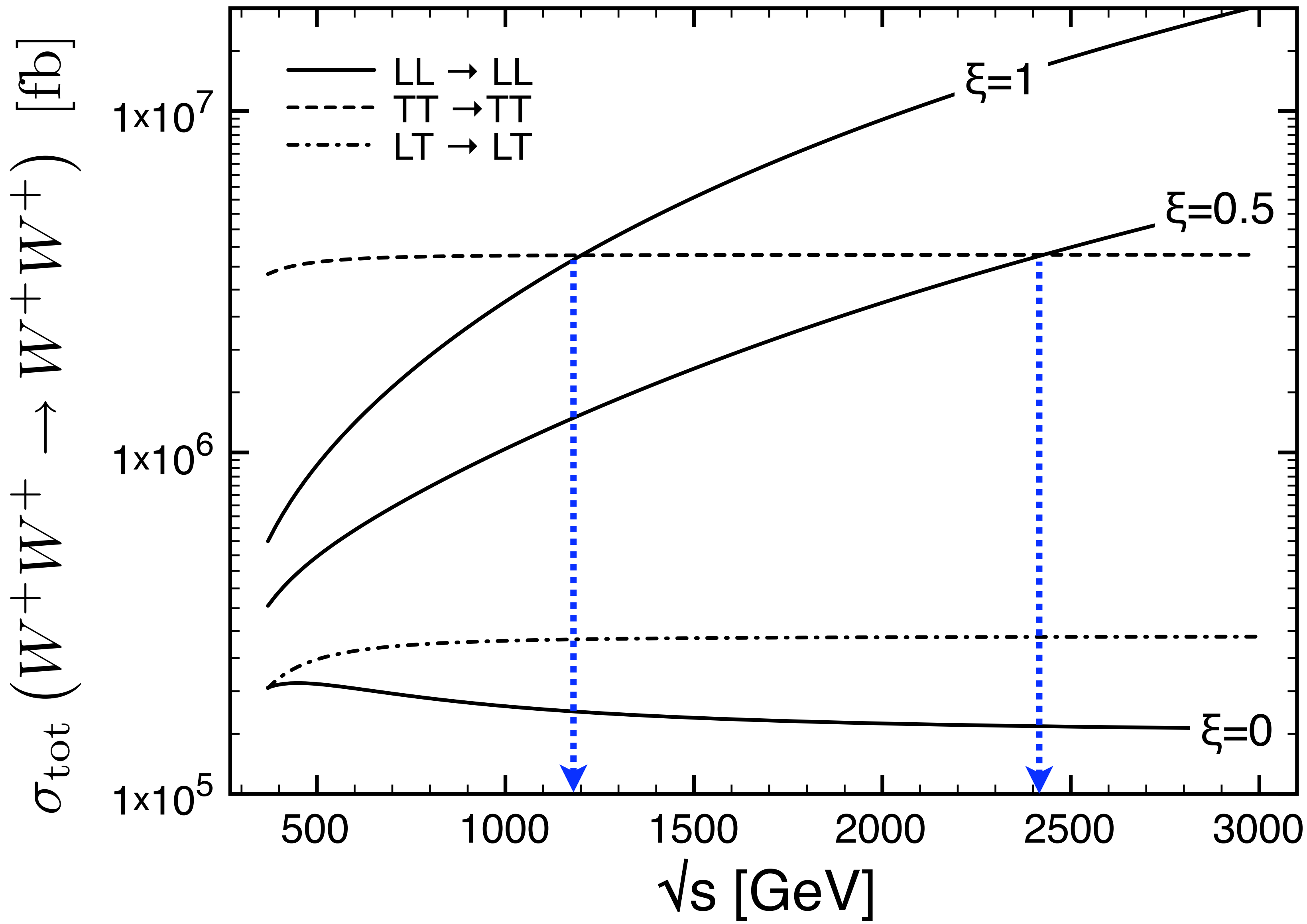
$$\frac{\sigma_{LL\to LL}(Q_{\min})}{\sigma_{TT\to TT}(Q_{\min})} = N_s \frac{s\, Q^2_{\min}}{M_W^4}$$

NDA estimates

$N_h \sim 1$ $N_s \sim 1$

Total cross sections

disentangling L from T polarization is hard



The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background

The dominance of T background will be further enhanced by the pdfs since the luminosity of W_T inside the proton is $\log(E/M_W)$ enhanced

Coulomb enhancement (SM)

$W^+W^+ \to W^+W^+$

the total cross section is dominated by the poles
in the exchange of γ and Z in the t- and u-channels

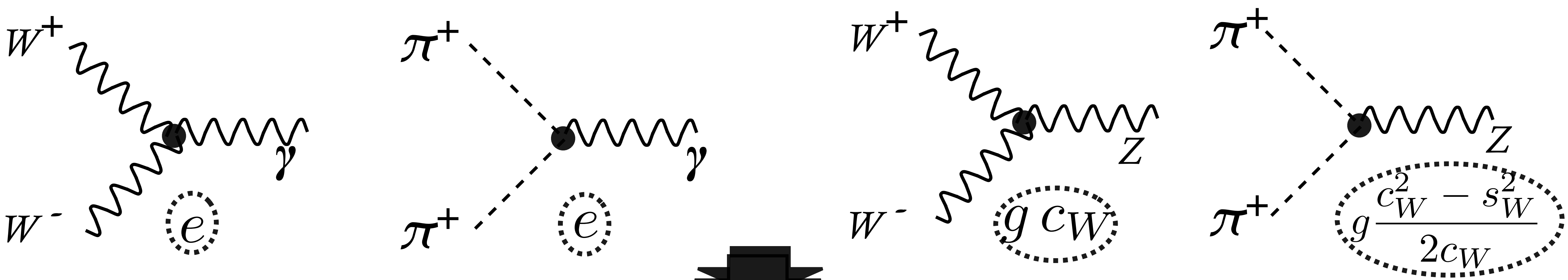
$$\mathcal{A} = \frac{a_\gamma^t\, s}{t} + \frac{a_Z^t\, s}{t - M_Z^2} + \frac{a_\gamma^u\, s}{u} + \frac{a_Z^u\, s}{u - M_Z^2} + \ldots \Longrightarrow \sigma \sim \frac{1}{16\pi}\left(\frac{{a_\gamma^t}^2 + {a_\gamma^u}^2}{M_\gamma^2} + \frac{{a_Z^t}^2 + {a_Z^u}^2}{M_\gamma^2 + M_Z^2} \right)$$

M_γ = regulateur of Coulomb singularity=off-shellness of W ~ M_W

eïkonal limit

$a_\gamma = 2 \cdot (\text{electric charge of } W^+)^2$
universal for T and L

$a_Z = 2 \cdot (\text{“SU(2) charge” of } W^+)^2$
different for T and L



SM $\frac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20$ (for $M_\gamma \sim M_Z$)

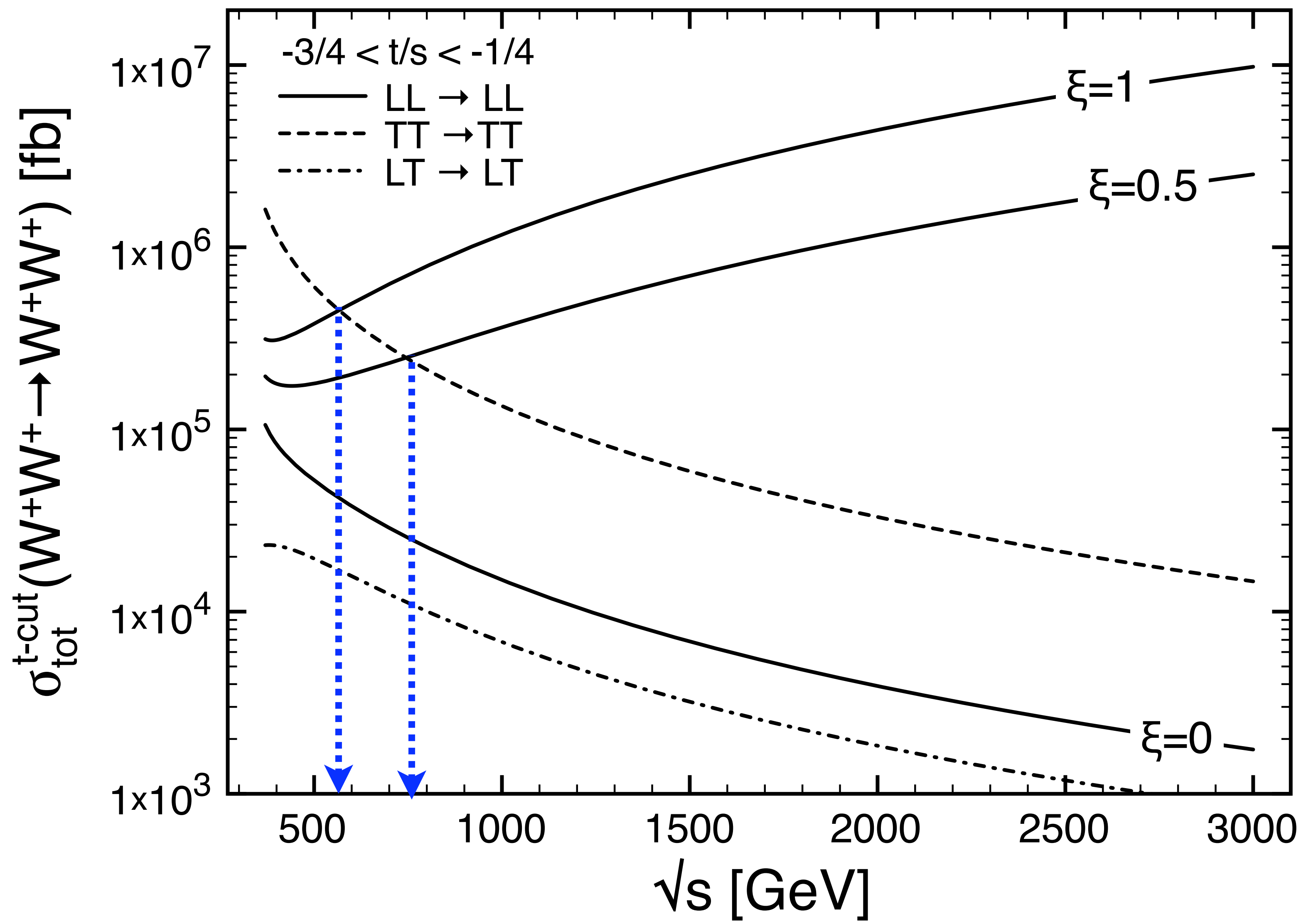
$N_s \sim 1/500$

$\Rrightarrow$ T-dominance is the result of multiplicity and larger SU(2) charges $\Lleftarrow$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Hard scattering (central region)

we need to look at the central region, i.e. large scattering angle, to be sensitive to strong EWSB

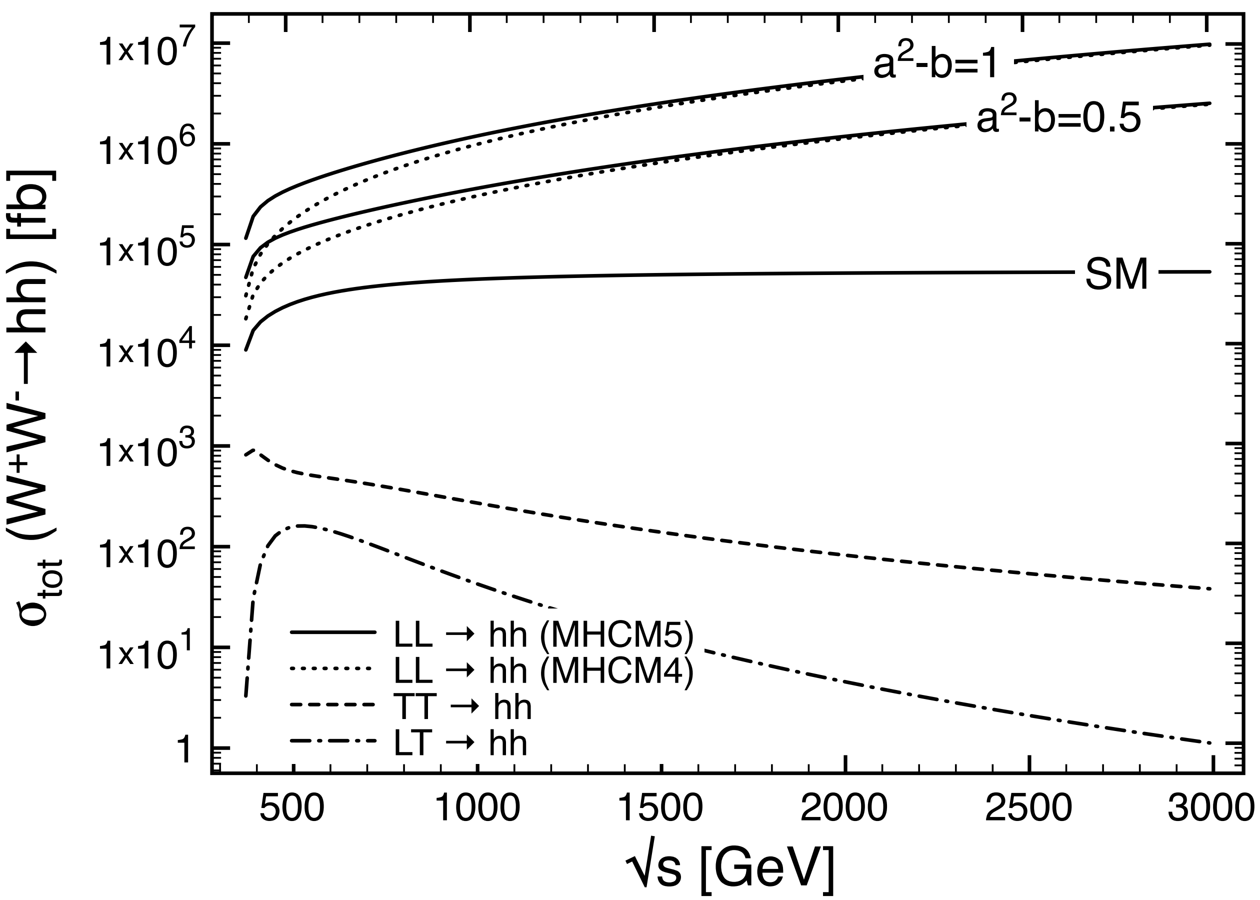


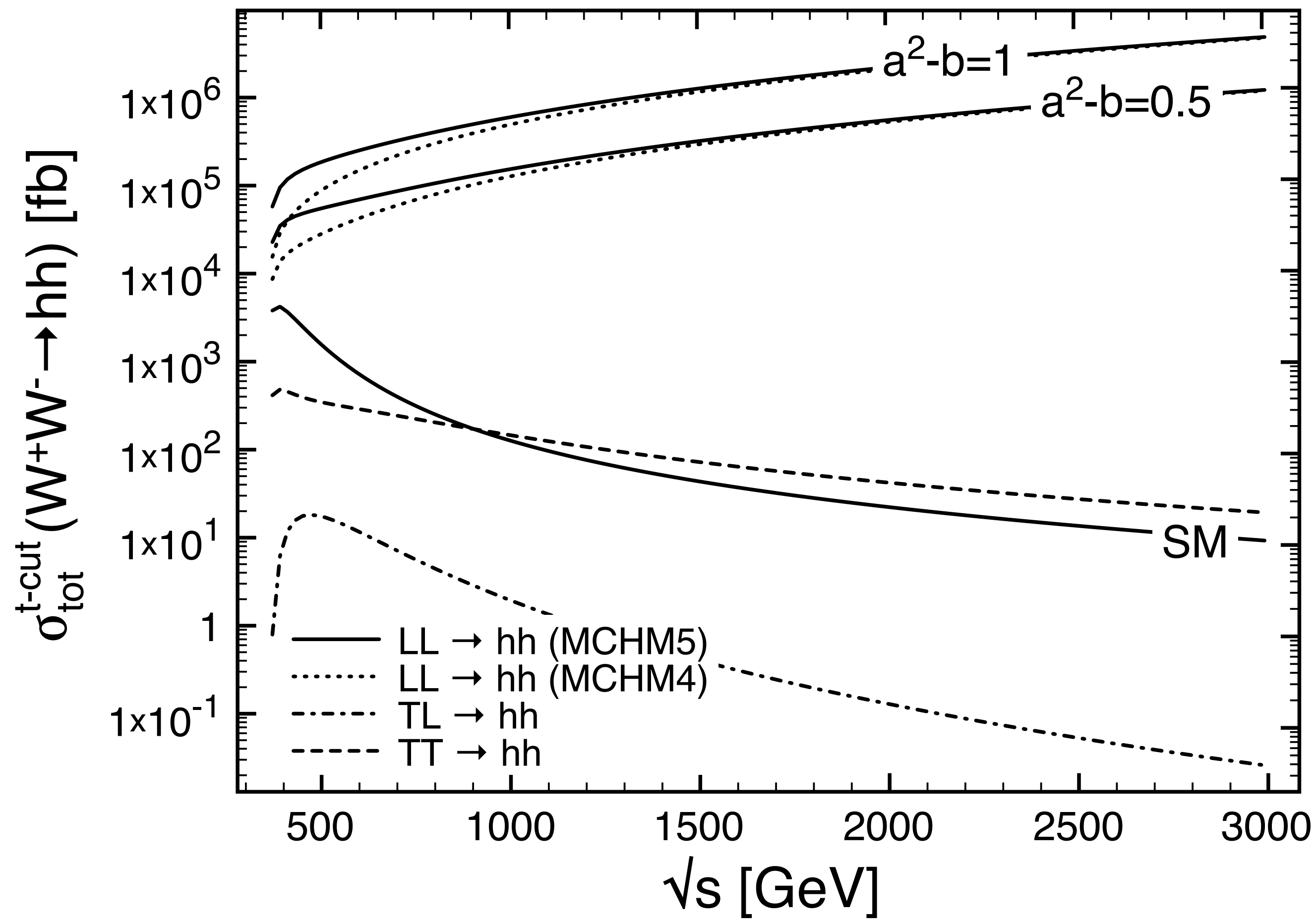
$$\frac{\sigma^{\rm hard}_{LL\to LL}}{\sigma^{\rm hard}_{TT\to TT}} \simeq \left(\frac{\sqrt{s}}{7.4 M_W}\right)^4 \xi^2$$

$$N_h = 1/2304$$

- hard cross-section = faster growth with energy
- onset of strong scattering still at high scale

EW bckg for WW → hh





$$\frac{d\sigma^{LL\to hh}/dt}{d\sigma^{TT\to hh}/dt} = \frac{1}{8}\frac{\xi^2}{\xi^2+(1-\xi)^2}\left(\frac{\sqrt{s}}{M_W}\right)^4$$

no T polarization pollution,
neither in the total cross section,
nor in the central region

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

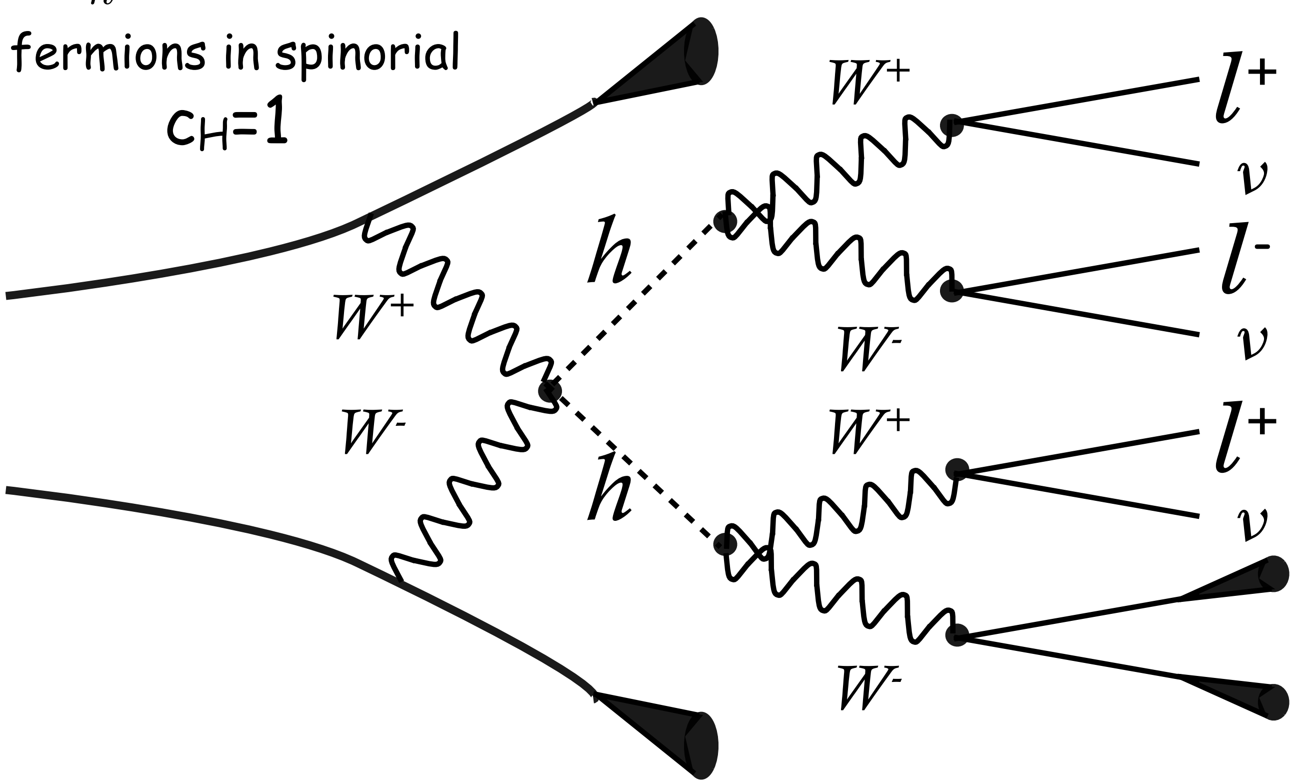
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ GeV

fermions in spinorial

c_H=1



acceptance cuts

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

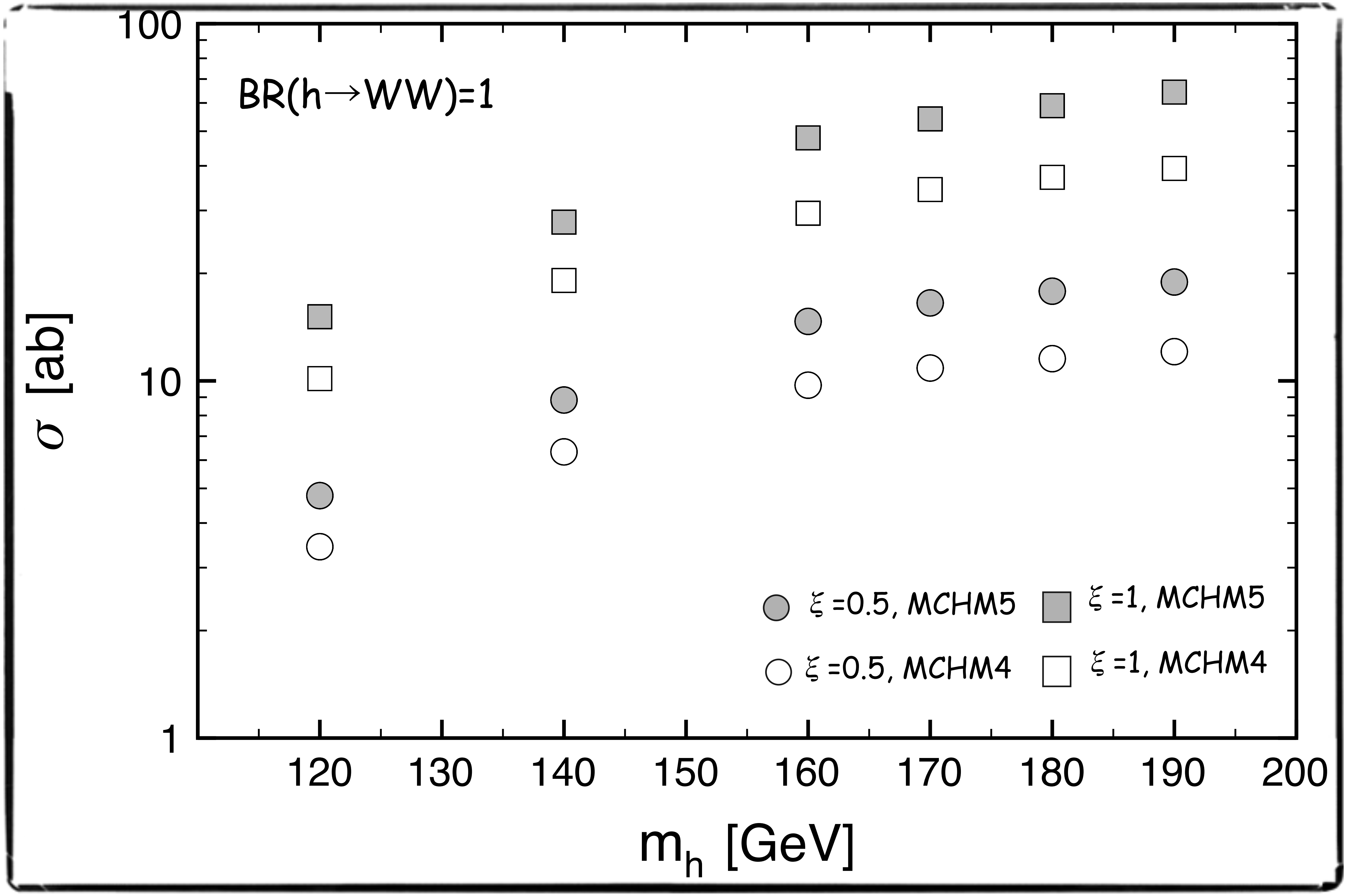
Dominant backgrounds: Wll4j, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

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

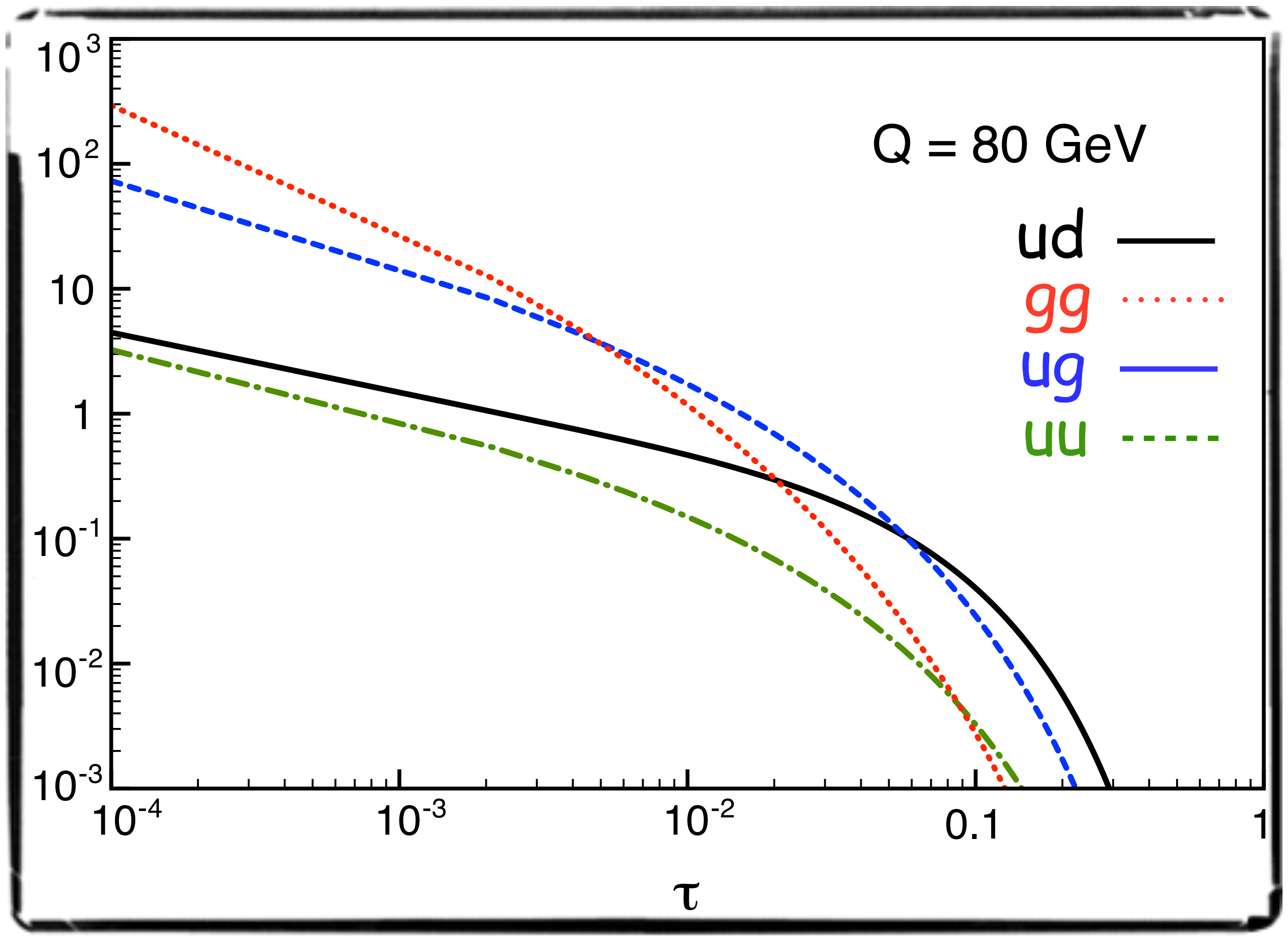
Higgs mass dependence



- production at threshold: $x_1 x_2 \sim 4 m_h^2/s$ σ↘ w/. m_h
- lighter Higgs, softer decay products, less effective cuts σ↗ w/. m_h
  (ie more signal killed)

Threshold production

$$\frac{d\sigma}{d\hat{s}} = \frac{1}{\hat{s}}\hat{\sigma}(q_A q_B \to hh)\rho_{AB}(\hat{s}/s, Q^2)$$



$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

integral is saturated at threshold

⇓ ⇓ ⇓

inclusive cross-section is not probing the asymptotic regime of hard scattering

sensitivity on Higgs self-coupling and not only on strong scattering (b-a^2)

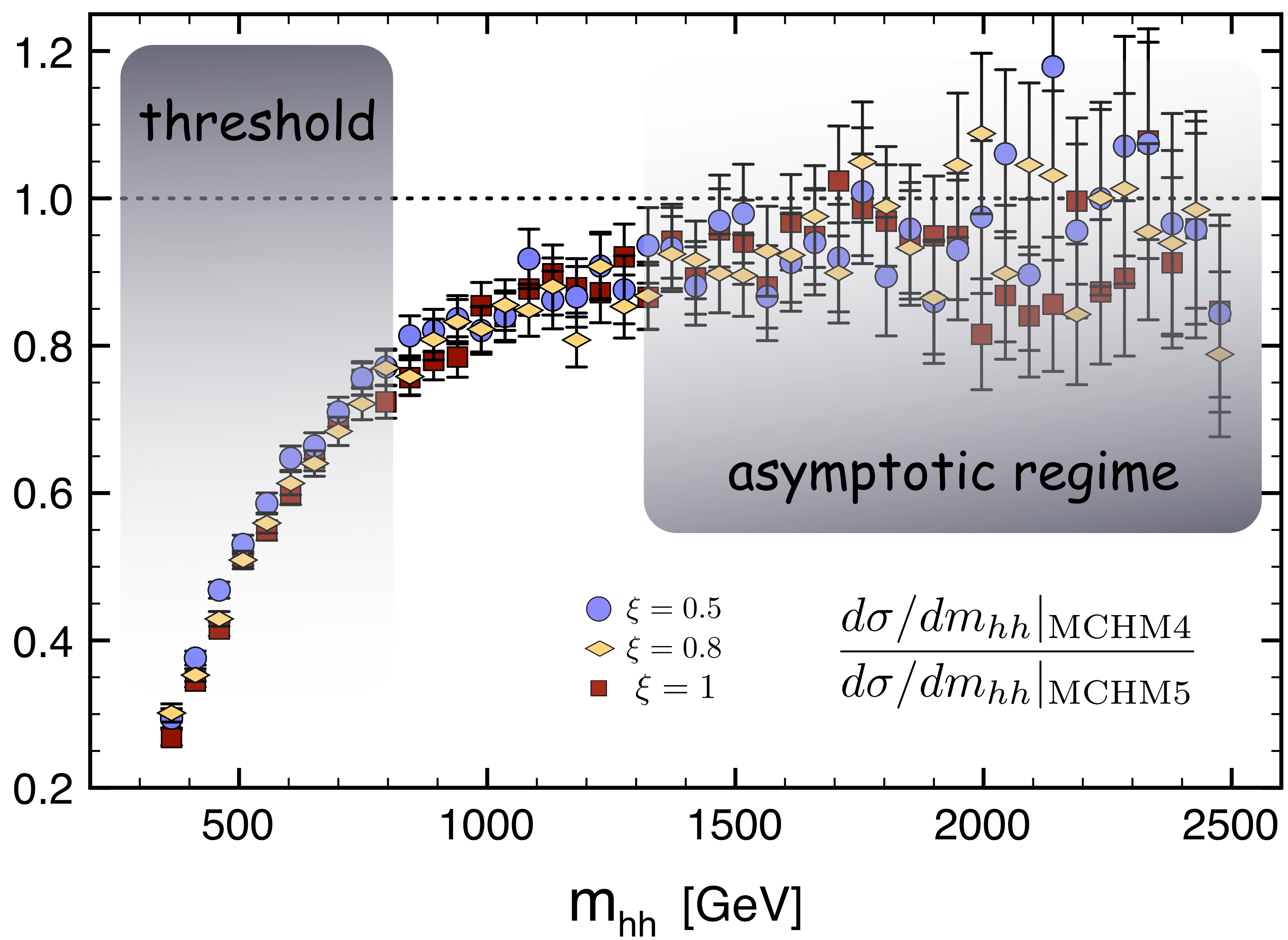
Isolating Hard Scattering

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

isolate events with large m_{hh}

luminosity factor drops out in ratios: extract the growth with m_{hh}

measure H^3 measure $(b-a^2)$



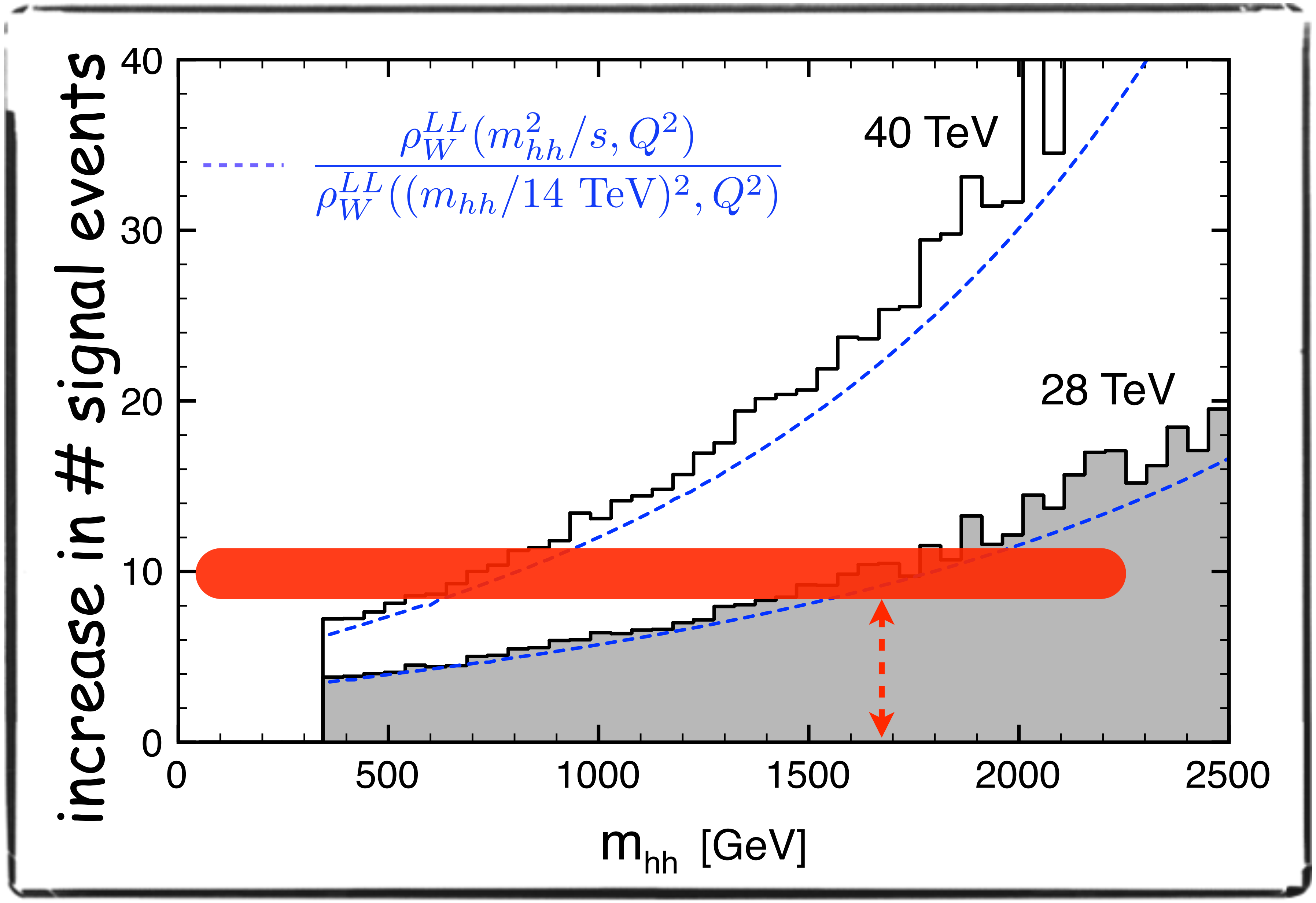
two models with same asymptotic regime but different higgs-self-coupling

Dependence on Collider Energy

$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

increase collider energy √s = sensitive to PDFs at smaller x

bigger cross-sections



sLHC vs. VLHC

10 x lum ≈ 10 x events

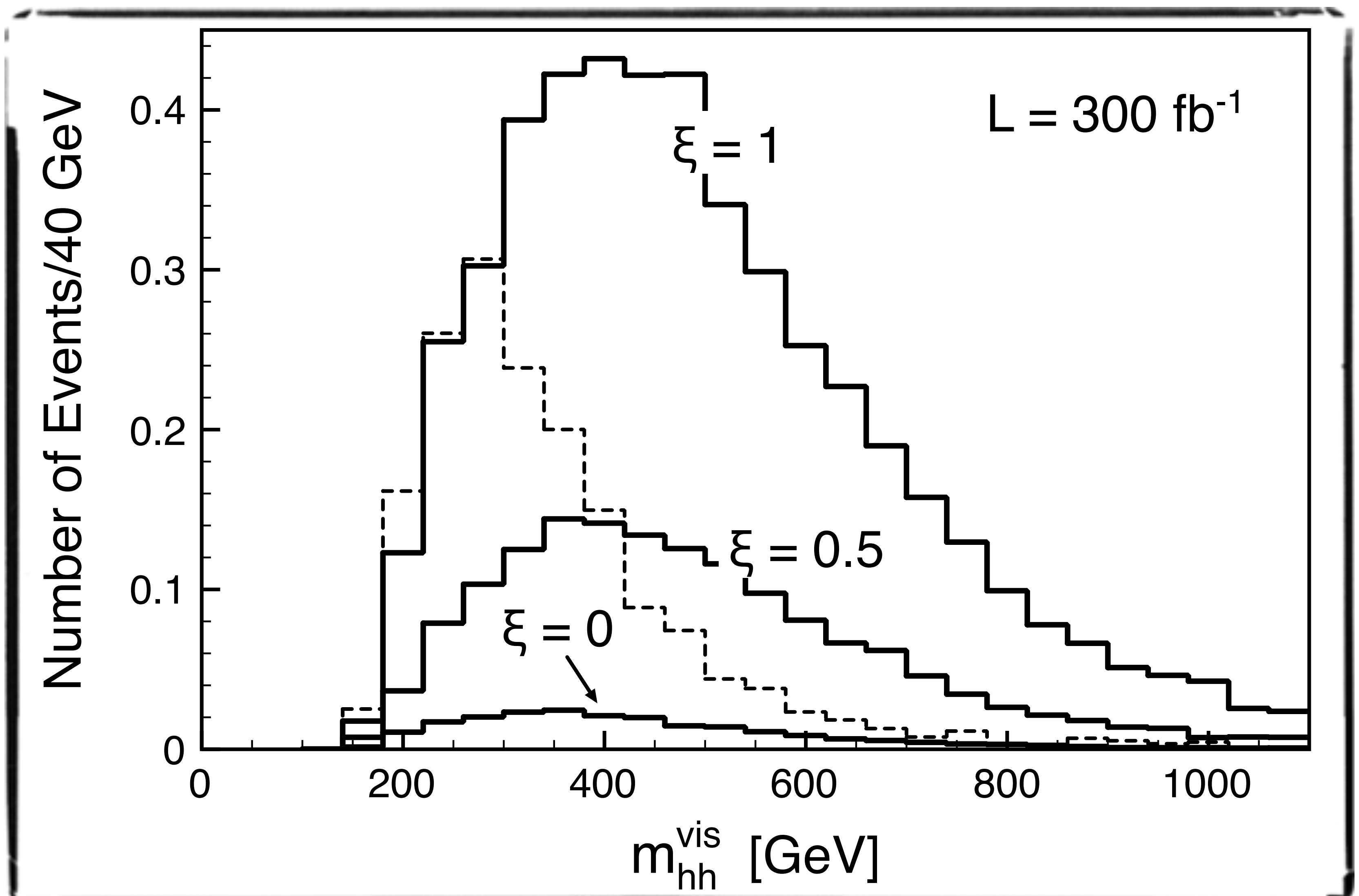
2 x √s = 10 x events

iif m_{hh}>1.6TeV

Dependence on Collider Energy

$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

increase collider energy √s = sensitive to PDFs at smaller x
bigger cross-sections



sLHC vs. VLHC

10 x lum ≈ 10 x events

2 x √s = 10 x events
iif m_{hh}>1.6TeV

... very few events

sLHC might be better

How to probe the composite nature of the Higgs?

3. Probing discrete symmetries of the strong sector

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

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

Strong EWSB

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

$$E/f \leftrightarrow g$$

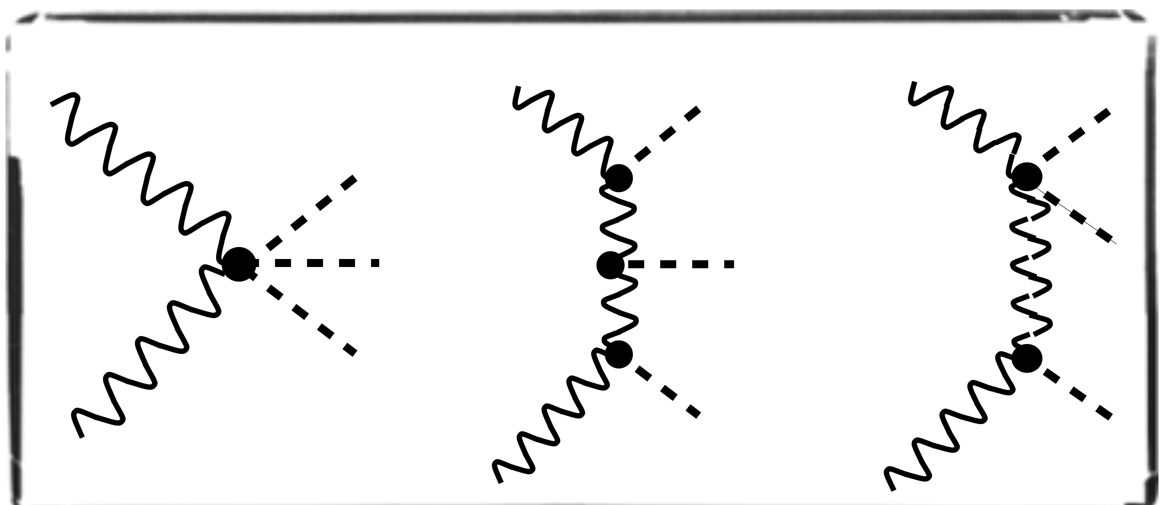
SM

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

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

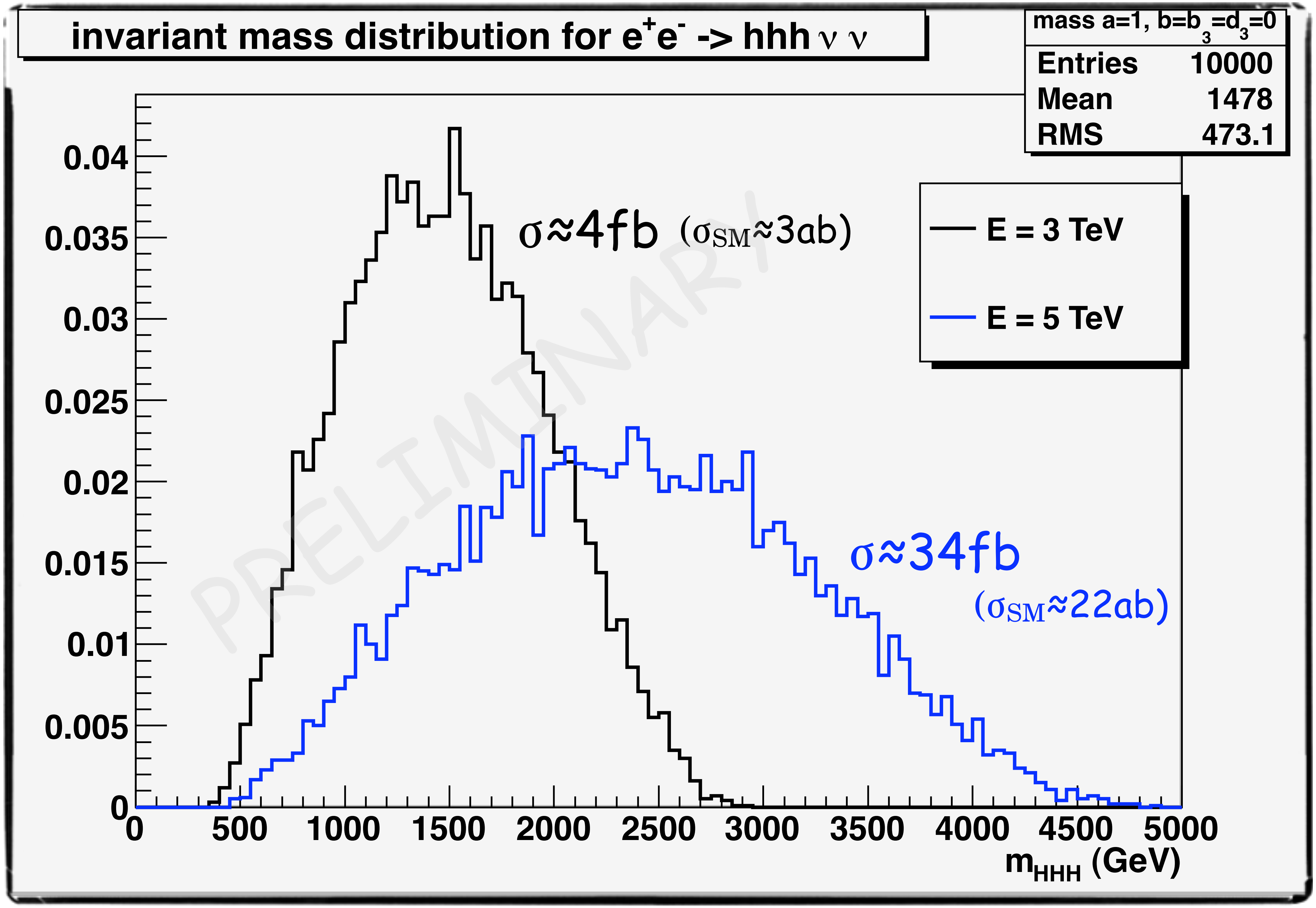


$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\underbrace{\left(a(b-a^2)-\frac{3}{4}b_3\right)}_{\text{=0 for symmetric coset}} + \underbrace{\sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

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

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

non-symmetric coset



How to probe the composite nature of the Higgs?

4. Detecting heavy resonances

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

elementary spin-1

$g=2 \Leftrightarrow \Lambda \gg M/e \Leftrightarrow W' \to W\gamma$ highly suppressed

gyromagnetic ratio of any elementary particle of mass M coupled to photon must be g=2 at tree-level to maintain perturbative unitarity up to energy $\Lambda \gg M/e$

Ferrara, Porrati, Telegdi '92

A heavy composite W'

Grojean, Salvioni, Torre '11

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only

How can we tell the difference between a massive gauge field and a resonance from a strong sector?

elementary spin-1

g=2 ⇔ Λ » M/e ⇔ W'→Wγ highly suppressed

gyromagnetic ratio of any elementary particle of mass M coupled to photon must be g=2 at tree-level to maintain perturbative unitarity up to energy Λ » M/e

Ferrara, Porrati, Telegdi '92

composite spin-1

g≠2 & Λ > 5÷10 M ⇔ W'→Wγ allowed and potentially large

$(g-1)B^{\mu\nu}W'^{+}_{\mu}W'^{-}_{\nu}$ dimension-4 operator mediating W' →Wγ after W-W' mixing

GUT: SM vs MSSM vs MCHM

SU(5) GUT: Gauge Group Structure

$SU(3)_c \times SU(2)_L \times U(1)_Y$: SM Matter Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6}, \quad u_R^c = (\bar{3},1)_{-2/3}, \quad d_R^c = (\bar{3},1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2}, \quad e_R^c = (1,1)_1$$

$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$

SU(5) Adjoint rep.

$$\left(\begin{array}{c|c} SU(2) & \\ \hline & SU(3) \end{array} \right)$$

$$\mathrm{Tr}(T^a T^b) = \frac{1}{2}\delta^{ab}$$

additional U(1) factor that commutes with SU(3)xSU(2)

$$T^{12} = \sqrt{\frac{3}{5}} \left(\begin{array}{cc|ccc} 1/2 & & & & \\ & 1/2 & & & \\ \hline & & -1/3 & & \\ & & & -1/3 & \\ & & & & -1/3 \end{array} \right)$$

$$\bar{5} = (1,2)_{-\frac{1}{2}\sqrt{\frac{3}{5}}} + (\bar{3},1)_{\frac{1}{3}\sqrt{\frac{3}{5}}}$$

$$\bar{5} = L + d_R^c$$

$$10 = (5\times 5)_A = (\bar{3},1)_{-\frac{2}{3}\sqrt{\frac{3}{5}}} + (3,2)_{\frac{1}{6}\sqrt{\frac{3}{5}}} + (1,1)_{\sqrt{\frac{3}{5}}}$$

$$10 = u_R^c + Q_L + e_R^c$$

$$T^{12} = \sqrt{\frac{3}{5}} Y \qquad g_5\sqrt{\frac{3}{5}} = g' \qquad g_5 = g = g_s$$

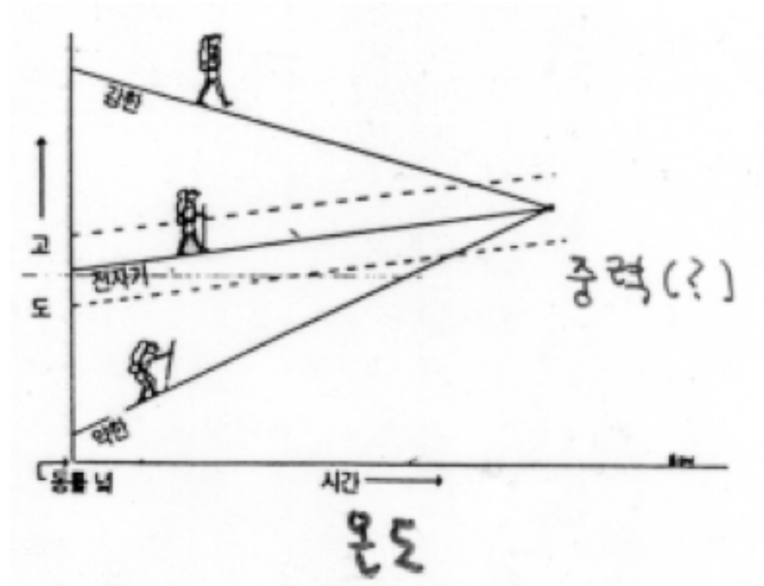
$$g_5 T^{12} = g' Y$$

$$\sin^2\theta_W = \frac{3}{8}$$ @ M_{GUT}

SU(5) GUT: SM β fcts

g, g' and g_s are different but it is a low energy artefact!

$$\beta = \frac{dg}{d\log\mu} = -\frac{1}{16\pi^2} b g^3 + \ldots$$



$$\frac{1}{g^2(Q)} = \frac{1}{g^2(Q_0)} + \frac{b}{16\pi^2}\ln\frac{Q^2}{Q_0^2}$$

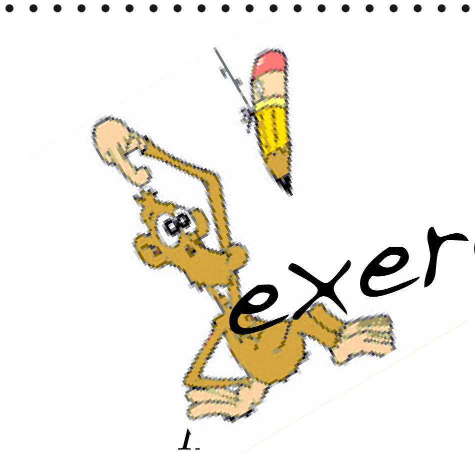
$$b = \frac{11}{3}T_2(\texttt{spin-1}) - \frac{2}{3}T_2(\texttt{chiral spin-1/2}) - \frac{1}{3}T_2(\texttt{complex spin-0})$$

$$\mathrm{Tr}\left(T^a(R)T^b(R)\right) = T_2(R)\delta^{ab} \qquad T_2(\texttt{fund}) = \frac{1}{2} \qquad T_2(\texttt{adj}) = N$$

$$b_{SU(3)} = \overset{g}{\frac{11}{3}\times 3} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{u_R^c}{\frac{1}{2}\times 1\times 3} + \overset{d_R^c}{\frac{1}{2}\times 1\times 3}\right) = 7$$

$$b_{SU(2)} = \overset{W^\pm, Z}{\frac{11}{3}\times 2} - \frac{2}{3}\left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H}{\frac{1}{3}\times\frac{1}{2}} = \frac{19}{6}$$

$$b_Y = -\frac{2}{3}\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{u_R^c}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{d_R^c}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{e_R^c}{(1)^2\times 3}\right) - \frac{1}{3}\left(\frac{1}{2}\right)^2\times 2 = -\frac{41}{6} \Rightarrow b_{T^{12}} = -\frac{41}{10}$$



exercise

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$ experimental inputs

b_3, b_2, b_1 predicted by the matter content

3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation for unification

$$\epsilon_{ijk} \frac{b_j - b_k}{\alpha_i(M_Z)} = 0 \quad \Rightarrow \quad \sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)}$$

$$\alpha_{em}(M_Z) \approx \frac{1}{128} \qquad \alpha_s(M_Z) \approx 0.1184 \pm 0.0007$$

$$\Downarrow$$

$$\sin^2\theta_W \approx 0.207$$

not so bad...

SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \qquad i = SU(3), SU(2), U(1)$$

$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$ ⟵ experimental inputs

b_3, b_2, b_1 ⟵ predicted by the matter content

3 equations & 2 unknowns (α_{GUT}, M_{GUT})

one consistency relation for unification

$$M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 7 \times 10^{14} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 41.5$$

self-consistent computation:

- $M_{GUT} < M_{Pl}$ safe to neglect quantum gravity effects
- $\alpha_{GUT} \ll 1$ perturbative computation

SU(5) GUT: SM vs MSSM β fcts

chiral superfield

complex spin-0
Weyl spin-1/2
in same representation R of gauge group

vector superfield

Weyl spin-1/2
real spin-1
in same representation V of gauge group

$$b = \frac{11}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{vector}) - \frac{2}{3}T_2(\texttt{chiral}) - \frac{1}{3}T_2(\texttt{chiral}) = 3\,T_2(\texttt{vector}) - T_2(\texttt{chiral})$$

MSSM Chiral Content

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2)_{1/6},\quad U = (\bar{3},1)_{-2/3},\quad D = (\bar{3},1)_{1/3},\quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1,2)_{-1/2},\quad E = (1,1)_1,\ H_u = (1,2)_{1/2},\quad H_d = (1,2)_{-1/2}$$

$$b_{SU(3)} = \overset{g}{3\times 3} - \left(\overset{Q_L}{\frac{1}{2}\times 2\times 3} + \overset{U}{\frac{1}{2}\times 1\times 3} + \overset{D}{\frac{1}{2}\times 1\times 3}\right) = 3$$

$$b_{SU(2)} = \overset{W^\pm, Z}{3\times 2} - \left(\overset{Q_L}{\frac{1}{2}\times 3\times 3} + \overset{L}{\frac{1}{2}\times 1\times 3}\right) - \overset{H_u}{\frac{1}{2}} - \overset{H_d}{\frac{1}{2}} = -1$$

$$b_Y = -\left(\overset{Q_L}{\left(\frac{1}{6}\right)^2 3\times 2\times 3} + \overset{U}{\left(-\frac{2}{3}\right)^2 3\times 3} + \overset{D}{\left(\frac{1}{3}\right)^2 3\times 3} + \overset{L}{\left(-\frac{1}{2}\right)^2 2\times 3} + \overset{E}{(1)^2\times 3}\right) - \overset{H_u}{\left(\frac{1}{2}\right)^2\times 2} - \overset{H_d}{\left(\frac{1}{2}\right)^2\times 2} = -11 \;\Rightarrow\; b_{T^{12}} = -\frac{33}{5}$$

SU(5) GUT: MSSM GUT

$$b_3 = 3, \quad b_2 = -1, \quad b_1 = -33/5$$

low-energy consistency relation for unification

$$\sin^2\theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1}\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.23$$

squarks and sleptons form complete SU(5) reps ➙ they don't improve unification!
gauginos and higgsinos are improving the unification of gauge couplings

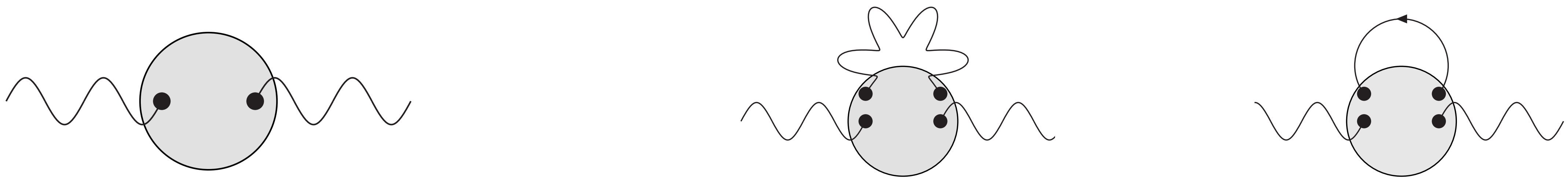
GUT scale predictions

$$M_{GUT} = M_Z \exp\left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 2 \times 10^{16}\ \text{GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 24.3$$

SU(5) GUT: Composite Higgs β fcts

Agashe, Contino, Sundrum '05
Frigerio, Serra, Varagnolo '11



strong sector
SU(5) invariant

interactions between strong & elementary sectors
SU(5) breaking

$$\frac{d\alpha_i}{d\ln Q} \in -\frac{b_{\rm comp}}{2\pi}\alpha_i^2 + \frac{B_{ij}}{2\pi}\frac{\alpha_j^3}{4\pi} + \frac{C_{if}}{2\pi}\frac{\lambda_f^2}{16\pi^2}$$

doesn't contribute to the differential running
cannot be computed
(non-perturbative)
but negative and bounded from below

affect the unification of the gauge couplings

Higgs = light composite state → may contribute to the differential running only below composite scale

t_R = light composite fermion → doesn't contribute to the running either

} substract H, t_R and t_R^c from the β fcts

SU(5) GUT: Composite Higgs β fcts

Agashe, Contino, Sundrum '05

Higgs = light composite state → may contribute to the differential running only below composite scale

t_R = light composite fermion → doesn't contribute to the running either

} substract H, t_R and t_R^c from the β fcts

$$b_{SU(3)} = b^{SM}_{SU(3)} + \frac{2}{3}\left(\frac{1}{2}+\frac{1}{2}\right) = \frac{23}{3}$$

$$b_{SU(2)} = b^{SM}_{SU(2)} + \frac{1}{3}\times\frac{1}{2} = \frac{10}{3}$$

$$b_Y = b_Y^{SM} + \frac{2}{3}\left(\left(-\frac{2}{3}\right)^2\times 3 + \left(-\frac{2}{3}\right)^2\times 3\right) + \frac{1}{3}\left(\frac{1}{2}\right)^2\times 2 = -\frac{44}{9} \Rightarrow b_{T^{12}} = -\frac{44}{15}$$

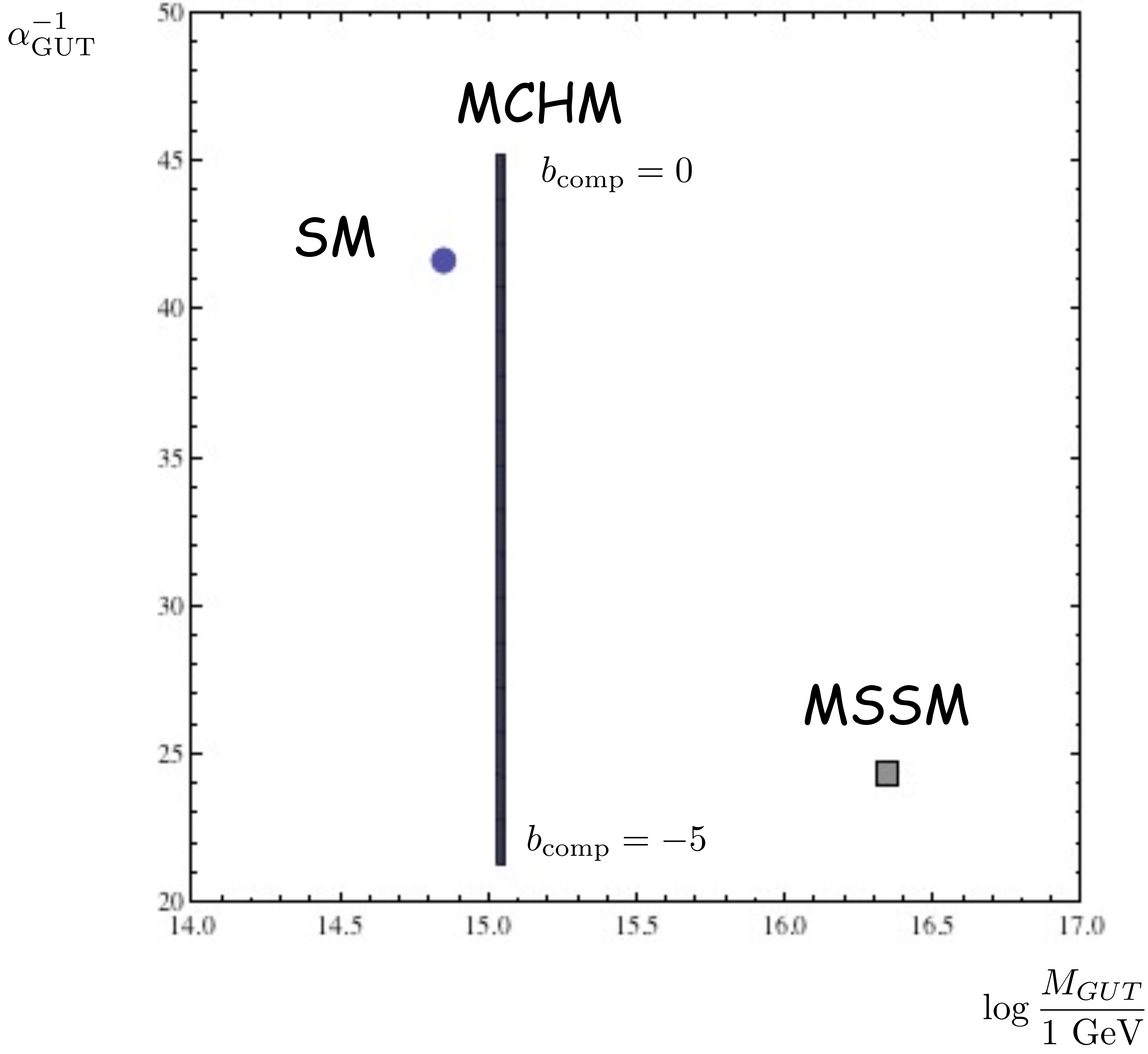
exercise

low-energy consistency relation for unification

$$\sin^2\theta_W = \frac{3(b_3-b_2)}{8b_3-3b_2-5b_1} + \frac{5(b_2-b_1)}{8b_3-3b_2-5b_1}\frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.228$$

improving the unification of gauge couplings by removing chiral matter!

SU(5) GUT: SM vs MSSM vs MCHM



Conclusions

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

$\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$

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 $\Leftrightarrow$ gauge principle
Higgs NC $\Leftrightarrow$?

LHC is prepared to discover the "Higgs"
collaboration EXP-TH is important to make sure
e.g. that no unexpected physics (unparticle, hidden valleys) is missed (triggers, cuts...)

Should not forget that the LHC will be a (quark) top machine
and there are many reasons to believe that the top is an important agent of the Fermi scale