Searching for the origin of mass at LHC

P. Ko (KIAS)

RHIC: Present and Future
KIAS,Seoul, Korea
(Sep. 28-29, 2006)

Searching for the origin of mass at LHC (and ILC): Models for EWSB

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Plan of the Talk

- Why EWSB ?
- Symmetries and Symmetry Breaking
- Old models for EWSB
- New models for EWSB
- Outlook

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

- Gauge theory (renormalizable)
- SM=gauge bosons + chiral fermions + Higgs sector (or EWSB sector)
- Extremely succesful to describe Nature down to $\sim 10^{-18}$ m (upto ~200 GeV)
- Higgs boson yet to be found
- Origin of mass is not known yet

Elementary Particle Zoo (표준모형)

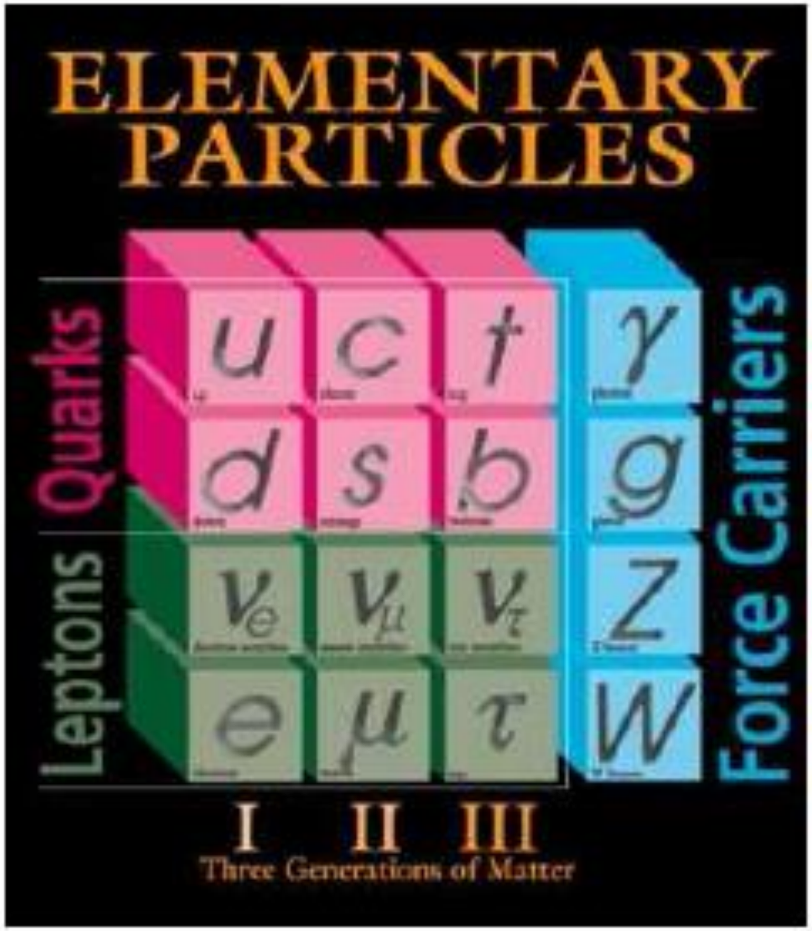


Figure 1: The ubiquitous chart of quarks, leptons, and force carriers.

In the massless limit, LH particle and RH particle are different species.

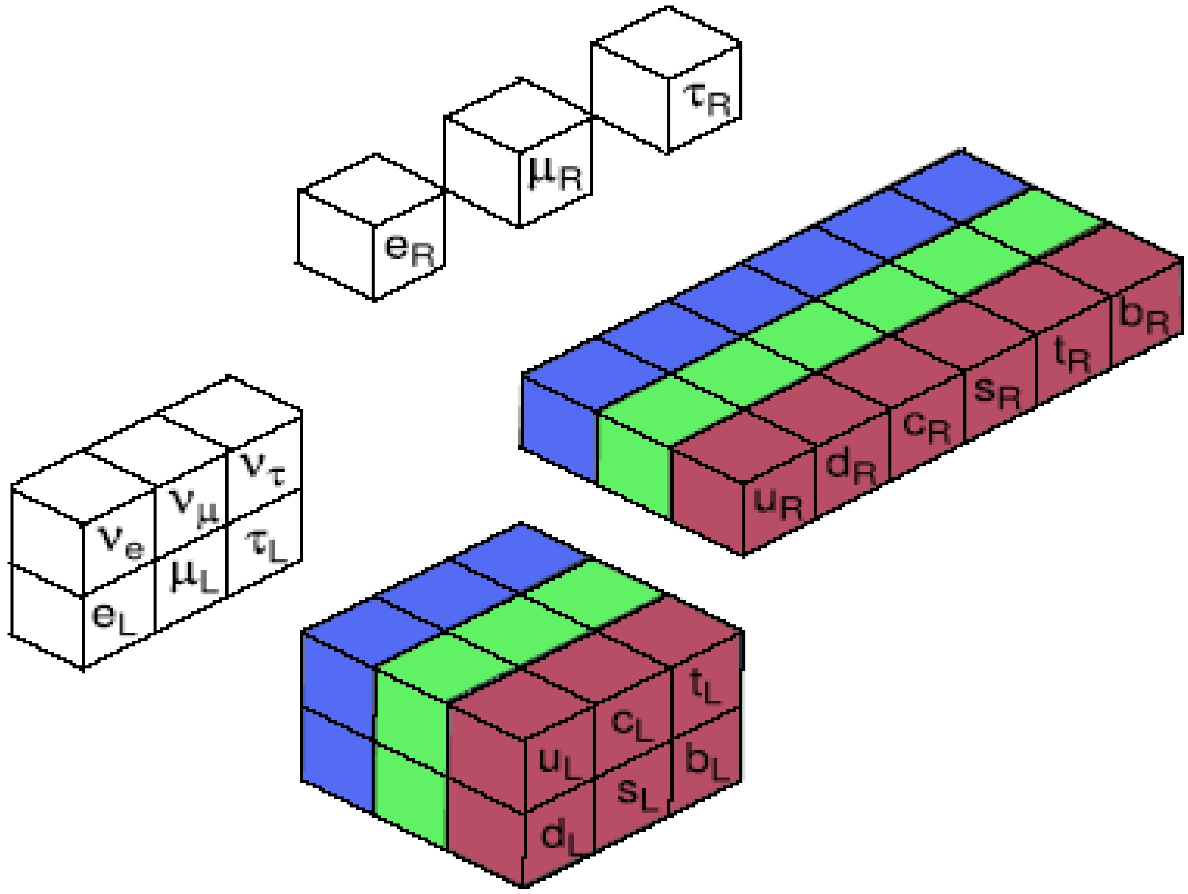
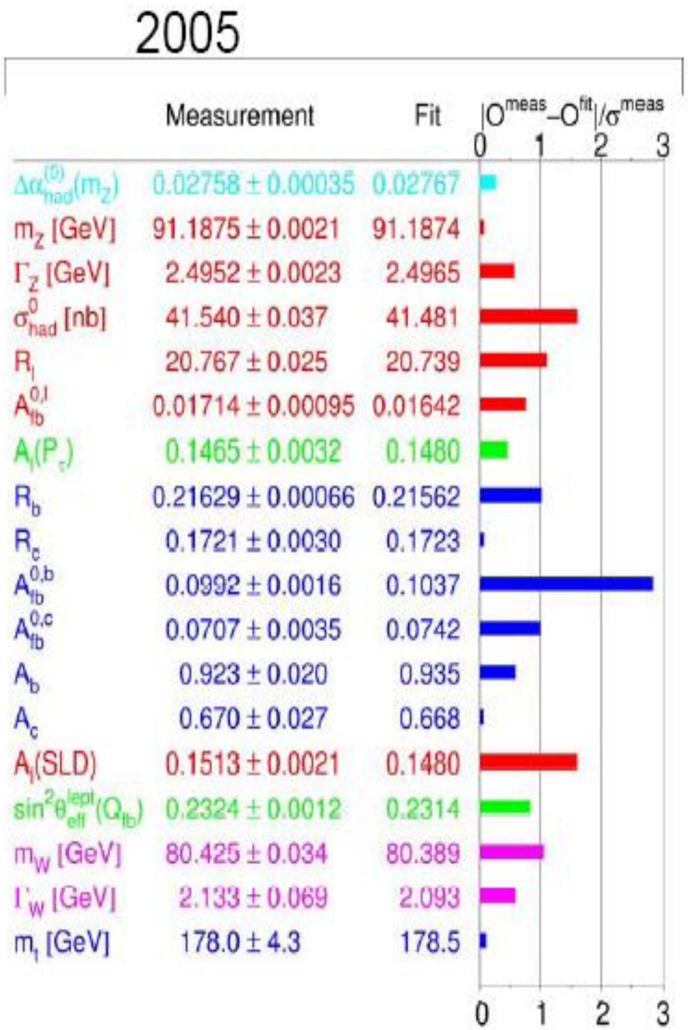
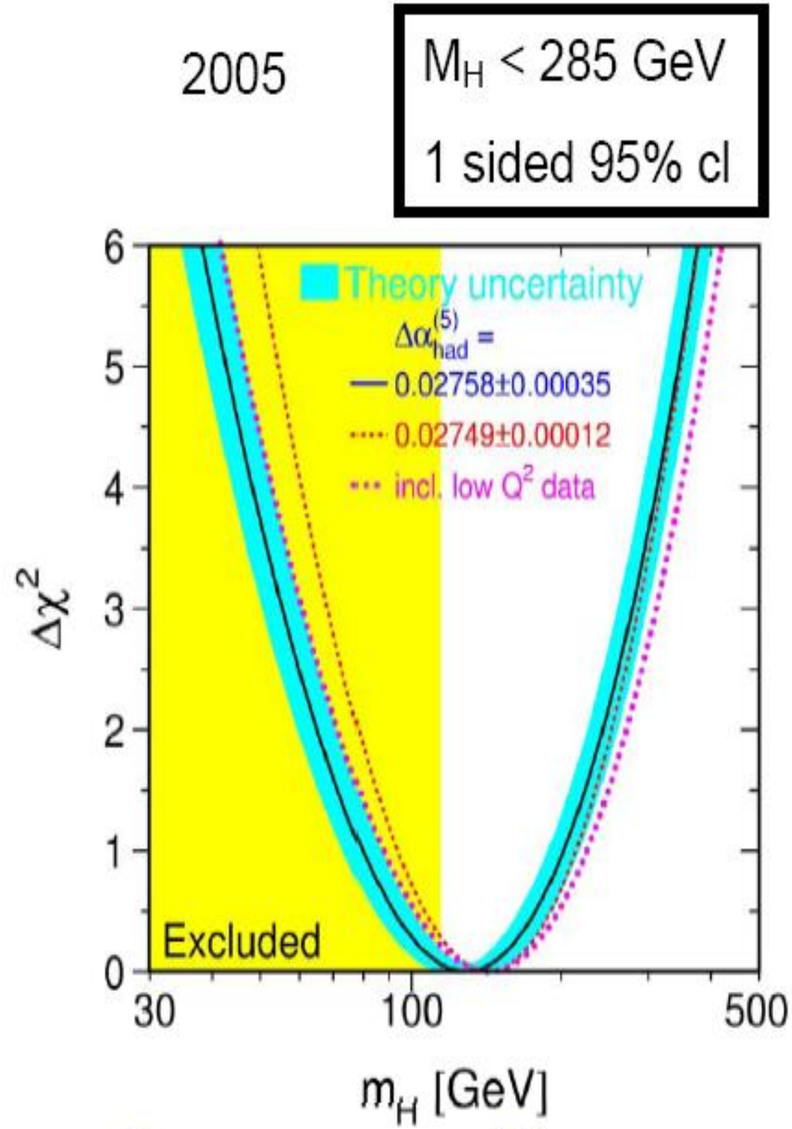


Figure 4: Left-handed doublets, right-handed singlets of quarks and leptons.





SM with light Higgs works pretty well!

Why EWSB ?

- Origin of masses of EW gauge bosons (W,Z), chiral fermions, their mixings, and CP violation within the SM
- Higgs sector has not been tested yet, unlike the gauge sectors
- LHC : a machine for studying EWSB sector of the SM or its various extensions
- ILC : precision tests of EWSB sector

Old models for EWSB (Before Mid 1990's)

- Standard model Higgs
- Technicolor
- Top condensate
- Many others

New models (After Mid 90's)

- Extra dimensional origin
  - EWSB by boundary conditions
  - Higgsless EWSB
  - Dynamical EWSB due to KK gluons
  - Cocktail Solution ??
  - Warped spacetime (RS-I)
  - Gauge-Higgs Unification, …….
- Little Higgs : Higgs~Goldstone boson
- Fat Higgs, String motivated,…..

SYMMETRIES
AND
SYMMETRY BREAKING

Symmetries of the Nature

	Exact	Broken
Internal Global	Baryon Number Lepton Number	Isospin, Flavor SU(3), etc.
Internal Local	U(1)em SU(3)c	$SU(2)_L \times U(1)_Y$ SU(5), SO(10),... (?)
Spacetime Global	Translation : P Rotation : J Boost : K	SUSY (?)
Spacetime Local	General Rel.	SUGRA (?)

Symmetry Breaking

- Explicit SB : global symmetry

  – isospin, flavor SU(3), etc.

- Spontaneous Breaking of global symmetry

  → massless Nambu-Goldstone boson

  – chiral symmetry in QCD : massless pion

  – translational symmetry in lattice : acoustic phonon

  – rotational symmetry in ferromagnet : magnon

Symmetry Breaking (Cont'd)

- Spontaneous Breaking of local sym. → Higgs mechanism :

  massless NG boson eaten by massless gauge boson → massive gauge bosons

- – $U(1)_{em}$ symmetry in BCS SC
- – $\rho - a_1$ mass difference in chiral models with $SU(2)_L \times SU(2)_R$ chiral symmetry
- – Weinberg model for lepton

  $SU(2)_L \times U(1)_Y$ → Massive M_W, M_Z …

Symmetry Breaking (Cont'd)

- Anomalous breaking of global sym
  - $\pi^o \rightarrow \gamma\gamma$
  - Chiral $U(1)_A$ and η' mass ($m_{\eta'} >> m_\pi$)
- Anomalous breaking of local sym
  - Inconsistent, if present
  - Anomaly cancellation in chiral gauge theories (→ Important constraint on model buildings)
  - SM : OK

History on Symmetry Breaking

- Explicit Symmetry Breaking (Isospin) (Heisenberg; ~1930)
- BCS superconductivity (1957)
- Nambu-Jona-Lasinio model (1961)
- Goldstone Theorem (1961, 1962)
- Higgs-Kibble mechanism (1964)
- Weinberg Model of Leptons (1967)

($U_A(1)$ problem, Chiral Lagrangian (CA and PCAC), many other examples)

BEFORE MID 1990’s

SM Higgs

- Single Higgs Doublet $\Phi(x)$

  $V(\Phi) = \lambda (|\Phi|^2 - v^2)^2$

  Mexican Hat Potential

- Linear Sigma model of Gell-Mann-Levy
- $M_H^2 \sim \lambda v^2$ and $M_W^2 \sim (g v)^2$
- Essential Ingredient : 3 NG bosons, i.e., some underlying theory that breaks global $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$

SM Higgs

- One unknown parameter : λ
- → Determines M_H and H^3 , H^4 couplings
- → One unknown parameter : λ (or M_H)
- → Can be measured at ILC
- SM Higgs picture is not a new one:

  "Old wine in a new bottle."
- Severe fine tuning problem

  $\delta M_H^2 \sim \Lambda^2$ at one loop level

  Λ : new physics scale

  $\sim M_{Pl}$, M_{GUT}, or M_{TeV} ….

Extensions with more Higgs

- Extend with more Higgs multiplets

SM Singlet or Doublet Higgs :

OK with EW precision measurements at tree level (T or $\Delta\rho$ parameter)

- Two Higgs Doublet model (including MSSM case) : still consistent with EW precision test
- Spontaneous EWSB due to two VEV's of neutral Higgs doublets (~SM Higgs)

Fine Tuning Problem for M_H

- One loop correction to M_H

$$\delta M_H^2 \sim \Lambda^2$$

Λ : new physics scale

$\sim M_{Pl}$, M_{GUT}, or M_{TeV} ….

- EW Precision Test : $M_H < \sim 200$ GeV
- Has to fine tune quadratic divergence order by order in perturbation theory to get $M_H \sim$ EW scale

→ Naturalness Problem

Solving Fine Tuning Problem

- Dimensional Transmutation (e.g. QCD)
  $M_{proton} \sim M_{Pl} \exp(-8\pi^2 / g_s^2 b) << M_{Pl}$
  without any severe fine tuning
  → Technicolor, Composite Higgs,…
- SUSY : quantum corrections under control, but has the μ–problem (tree level)
- Warped spacetime AdS_5 (RS–I)
- Little Higgs (Talk by J. Song),
- Other ideas (conformal sym, ….)

Technicolor (Susskind, Weinberg, Fahri, ...)

- Analogy to QCD with chiral symmetry breaking : $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$
- New confining strong interaction (Technicolor) acting on New Fermions
  (Techniquarks and Technileptons)
- 3 N.G. Bosons (~ π's)

$$F_T \sim \sqrt{\frac{N_T}{3}}\left(\frac{\Lambda_T}{\Lambda_{QCD}}\right) f_\pi; \qquad v_0 = \sqrt{N_D} F_T \sim \sqrt{\frac{N_D N_T}{3}}\left(\frac{\Lambda_T}{\Lambda_{QCD}}\right) f_\pi$$

Technicolor (Cont'd)

- When gauged, these techni pions are eaten by gauge bosons (Higgs mechanism)
- Difficult to construct realistic models
- – Strongly interacting theory : perturbative method does not work
- – Especially for the fermion masses (Extended, Walking,....) without FCNC problem
- EW precision test : strong constraint
- Naïve versions are excluded by EW precision tests (Peskin, Takeuchi)

Technicolor (Cont'd)

- Predictions：many TC resonance around weak scale – TeV → Collider Signals

state	$I(J^{PC})$	mass (TeV)	decay width (GeV)
$\pi_T^{\pm}, \pi_T^0 \rightarrow W_L^{\pm}, Z_L$	$1(0^{-+})$	M_W, M_Z (eaten)	Γ_W , Γ_Z
η_T^0 (a)	$0(0^{-+})$	$\sim r m_\eta \sim 0.4 \rightarrow 0.8$	$\Gamma_{t\bar{t}} \sim 8.0 - 64.0$, $\Gamma_{gg} \sim 0.3 - 3.0$
$\rho_T^{\pm}, \rho_T^0$	$1(1^{--})$	$q m_\rho / s \sim 1.2$	$\Gamma_{\rho_T}(WW) \sim \Gamma_\rho(\pi\pi)/sq^2 \sim 350$
ω_T^0	$0(1^{--})$	$\sim q m_\omega / s \sim 1.2$	$\Gamma_{\omega_T}(WWZ) \sim \Gamma_\omega(\pi\pi\pi)/sq^2 \sim 80$
${a_{0T}}^{\pm}, {a_{0T}}^0$	$1(0^{++})$	$r m_{a_0} \sim 1.5$	$\eta_T W^{\pm}$, $\eta_T Z^0$; $\Gamma \sim \Gamma_{a_0}/s \sim 100$
$f_{0T}^0 \sim \sigma_T$	$0(0^{++})$	$q f_0 / s \sim 2$	$\Gamma \sim \Gamma_{f_0}/s \sim 1000$
${a_{1T}}^{\pm}, {a_{1T}}^0$	$1(1^{++})$	$q m_{a_1} / s \sim 2$	$\Gamma(WW) \sim \Gamma_{a_1}/s \sim 700$
f_{1T}	$0(1^{++})$	$q m_{f1} / s \sim 2$	$\Gamma(4W) \sim \Gamma_{f_1}/s \sim 100$

Table 1: Estimated properties of lowest-lying (pseudo-) scalar and (axial-) vector mesons in the minimal TC model with a single electroweak doublet of techniquarks $N_D = 1$, $N_T = 4$, and $q = \sqrt{3/N_T} = 0.86$. We take $r \equiv \Lambda_T/\Lambda_{QCD} = 1.5 \times 10^3$, and $\Lambda_{QCD} = 200$ MeV, and $s \equiv f_\pi/F_T = 5.7 \times 10^{-4}$, where $f_\pi = 100$MeV, $F_T = 175$ GeV. The combination $r^3 s^2 = 1.1 \times 10^3$ frequently occurs. (a) These are estimates from the discussion of [104] .

Techni rho production

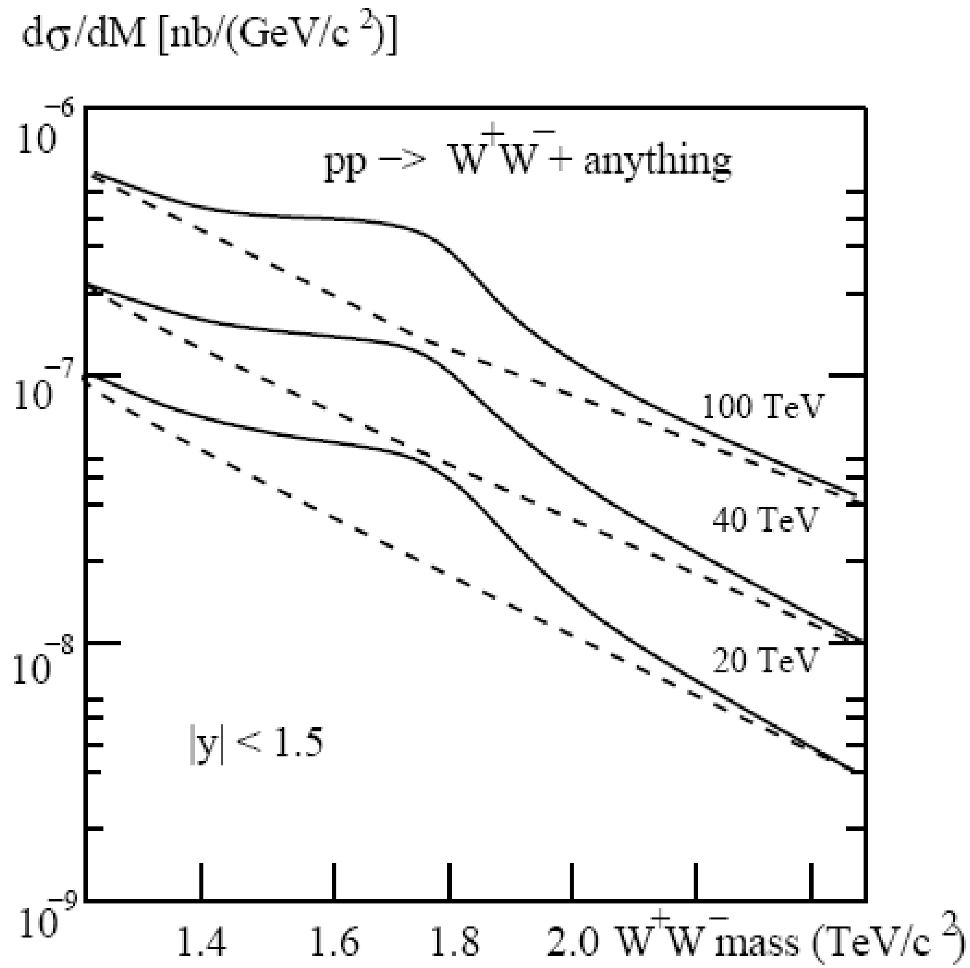


Figure 3: Vector Meson Dominance production of techni-ρ with subsequent decay to W^+Z in pp collider with center-of-mass energies, 20, 40 and 100 TeV (from EHLQ [157]).

Composite Higgs (Mid 80's by Georgi and Kaplan)

- Higgs ~ Goldstone boson of some spontaneously broken global symmetry
- Again analogy to low energy QCD
- Higgs is composite → No hierarchy problem
- Again, difficult to construct realistic model (especially fermion mass problem)
- Reincarnation in form of Little Higgs

Bardeen-Hill-Lindner Model

- Top quark is very heavy → can be sensitive to the EWSB mechanism
- Assume Nambu-Jona-Lasinio (NJL) type attractive 4-fermion interaction, which make ttbar condenses and breaks chiral symmetry of SM

  (cf. Similar to qqbar condensates break chiral symmetry of QCD)
- Higgs ~ t tbar bound state

BHL Model (Cont'd)

$$L = L_{kinetic} + G(\bar{\Psi}^i_L t_R \bar{t}_R \Psi_{iL})$$

$$m_t = -\frac{1}{2} G \langle \bar{t} t \rangle$$

$$G^{-1} = \frac{N_c}{8\pi^2}\left(\Lambda^2 - m_t^2 \ln(\Lambda^2/m_t^2)\right)$$

$$L = L_{kinetic} + g_{t0}(\bar{\Psi}_L t_R H + h.c.) - m_0^2 H^\dagger H$$

$$\begin{aligned} L &= L_{kinetic} + g_{t0}(\bar{\Psi}_L t_R H + h.c.) + \Delta L_{gauge} \\ &\quad + Z_H |D_\mu H|^2 - m_H^2 H^\dagger H - \frac{\lambda_0}{2}(H^\dagger H)^2 \end{aligned}$$

Fig. 1

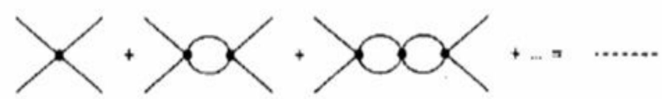


Fig. 2

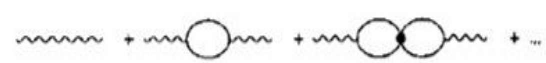


Fig. 3

Predictions of BHL model

3 generation case

$\Lambda[GeV]$	10^{19}	10^{17}	10^{15}	10^{13}	10^{11}	10^{10}	10^{9}	10^{8}	10^{7}	10^{6}	10^{5}	10^{4}
$m_t^{phys}[GeV]$	220	225	231	239	250	257	266	279	295	320	362	458
pert.	± 2	± 3	± 3	± 3	± 5	± 6	± 7	± 9	± 12	± 16	± 25	± 45
$m_H^{phys}[GeV]$	241	248	258	270	287	298	312	331	356	394	458	609
pert.	± 3	± 3	± 4	± 5	± 8	± 9	± 11	± 15	± 21	± 32	± 56	± 142

4 generation case

$\Lambda[GeV]$	10^{19}	10^{17}	10^{15}	10^{13}	10^{11}	10^{10}	10^{9}	10^{8}	10^{7}	10^{6}	10^{5}	10^{4}
$m_4^{phys}[GeV]$	200	203	207	213	222	228	235	245	259	279	314	391
pert.	± 1	± 2	± 2	± 2	± 3	± 4	± 5	± 7	± 10	± 14	± 22	± 39
$m_H^{phys}[GeV]$	237	243	250	260	274	284	296	312	335	368	425	557
pert.	± 1	± 2	± 2	± 3	± 4	± 6	± 7	± 10	± 15	± 22	± 39	± 99

BHL model (Cont'd)

- Two Main Problems

* Too heavy m_t (> 200 GeV)

→ Can be solved if there is a fundamental Higgs in addition to DynEWSB

→Partially composite Higgs (Talk by D.Jung)

* NJL interactions : ad hoc in BHL model

→ Can be generic in extra dimension scenarios (Dobrescu et al ; Yamawaki et al , for flat extra dim case ; Rius and Sanz for RS scenario ; Realistic model building in progress)

BHL model (Cont'd)

- Some extensions

– Two Higgs Doublet Model (Luty)

– SUSY Version (Carena et al.) : can accommodate realistic top mass

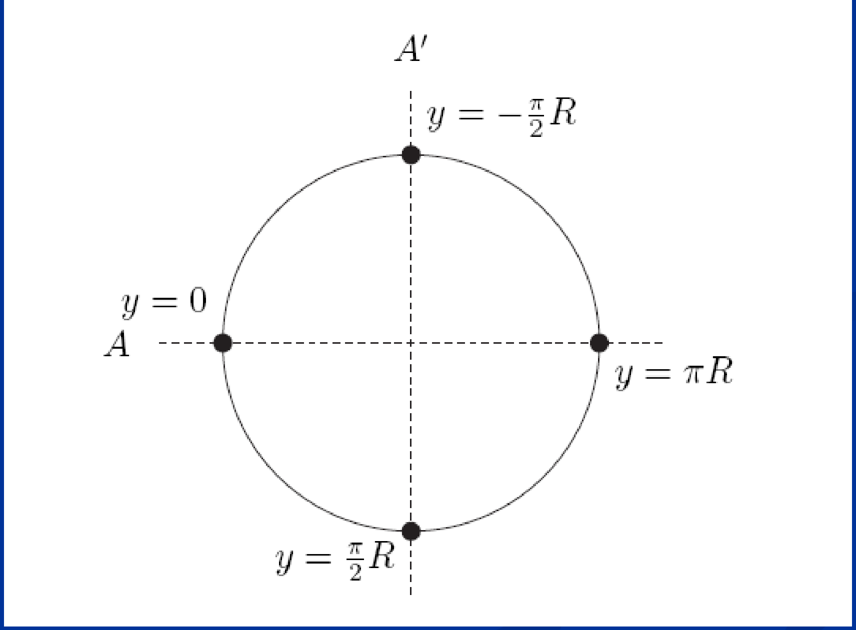
– BHL + One Fundamental Higgs (Chung,Jung,Ko,Lee, JHEP (2006))

Cf) For Other Dyn EWSB models, see Phys. Rep. by C.Hill and E.Simmons.

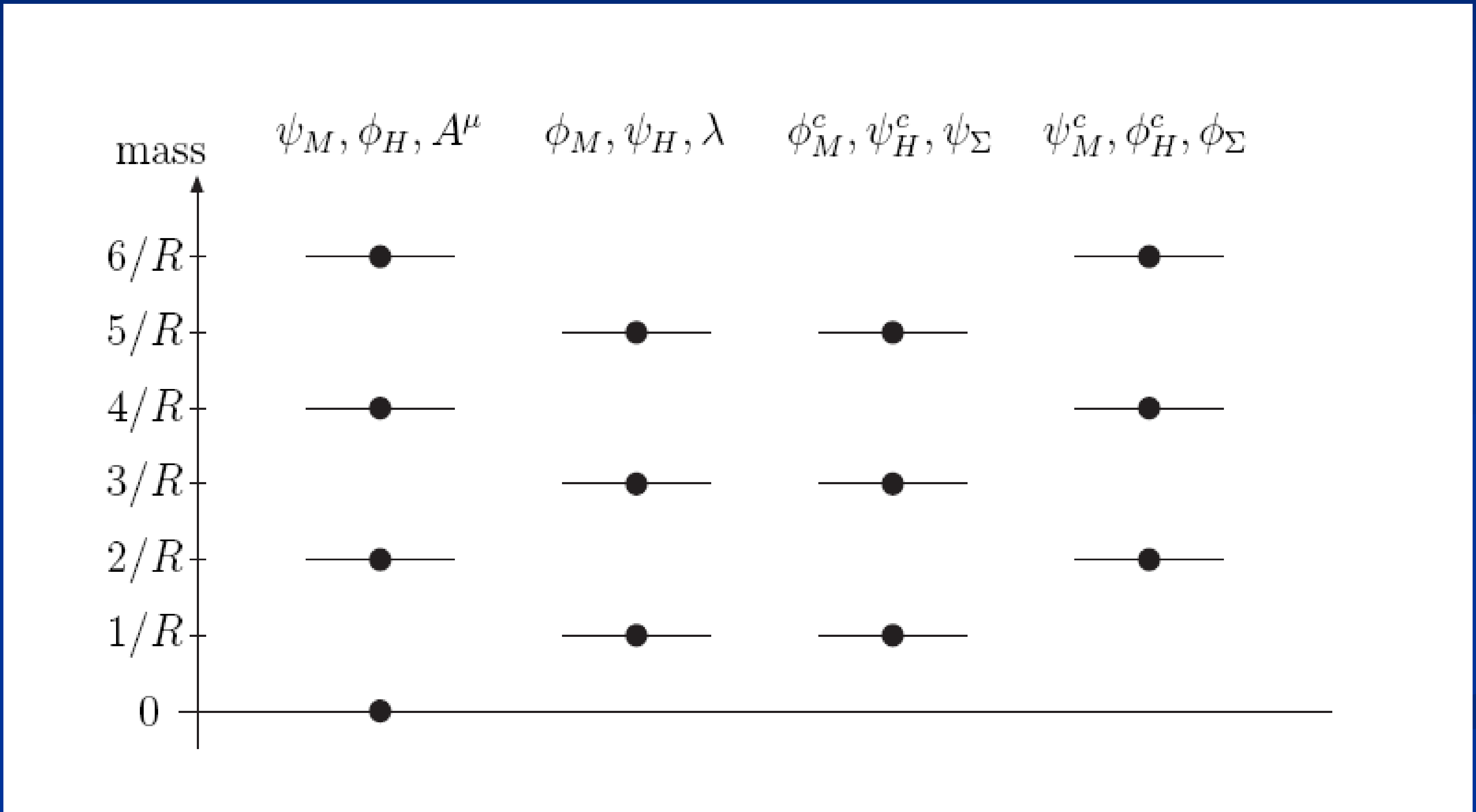
AFTER MID 1990’s

Barbieri–Hall–Nomura model

- 5 d N=1 SUSY with $S^1/Z_2 \times Z_2$ orbifold
- More symmetry (N=2 SUSY in 4d)
- More constraints
- Calculability of Higgs mass
- Radiative EWSB
- Many new states



Spectrum in BHN model



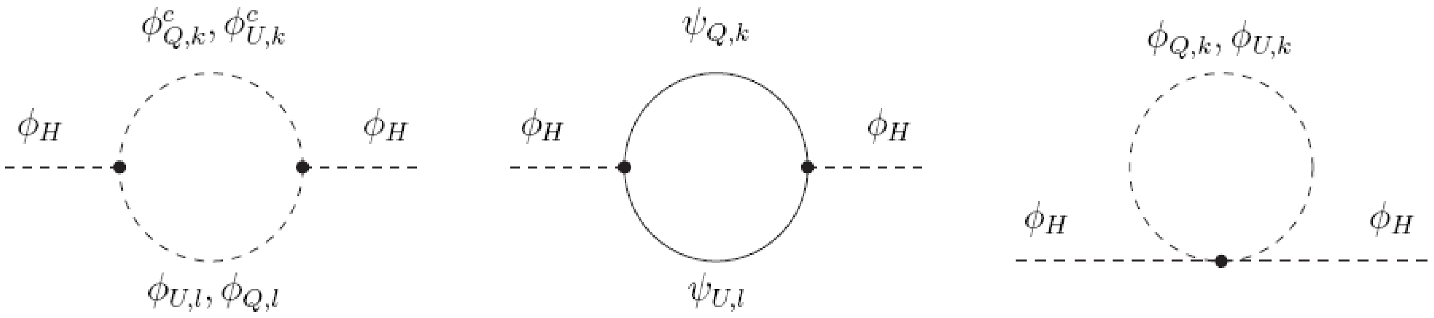


Figure 4: One-loop diagrams contributing to the mass squared of the Higgs boson.

$$\begin{aligned} m^2_{\phi_H} &= -\frac{N_c f_t^2}{128 R^2}\int_0^\infty dx\, x^3 \left\{\coth^2\left[\frac{\pi x}{2}\right] - \tanh^2\left[\frac{\pi x}{2}\right]\right\} \\ &= -\frac{21\,\zeta(3)}{64\pi^4}\frac{N_c f_t^2}{R^2}, \end{aligned}$$

$$\frac{1}{R} = \left(\frac{\pi^6}{18}\right)^{\frac{1}{4}} (M_Z v)^{\frac{1}{2}} \simeq 341 \text{ GeV}$$

$$m_H = \sqrt{2} M_Z \left(1 - \frac{1}{4}\cos[\pi R\, m_t]\right) \simeq 127 \text{ GeV}$$

BHN model (Cont'd)

- Including various uncertainties,
  1/R = (352 +- 20) GeV
  M_H = (127 +- 8 +- 2) GeV
- Low Energy EFT :
  One Higgs Doublet + 2 superpartners for each SM particles
  (Very different from MSSM)
- LSP and NLSP : stops with ~(197 +- 20) GeV
- 6 Charginos and 6 Neutralinos : heavier
  (1/R = 352 GeV, 364 GeV, 370 GeV)

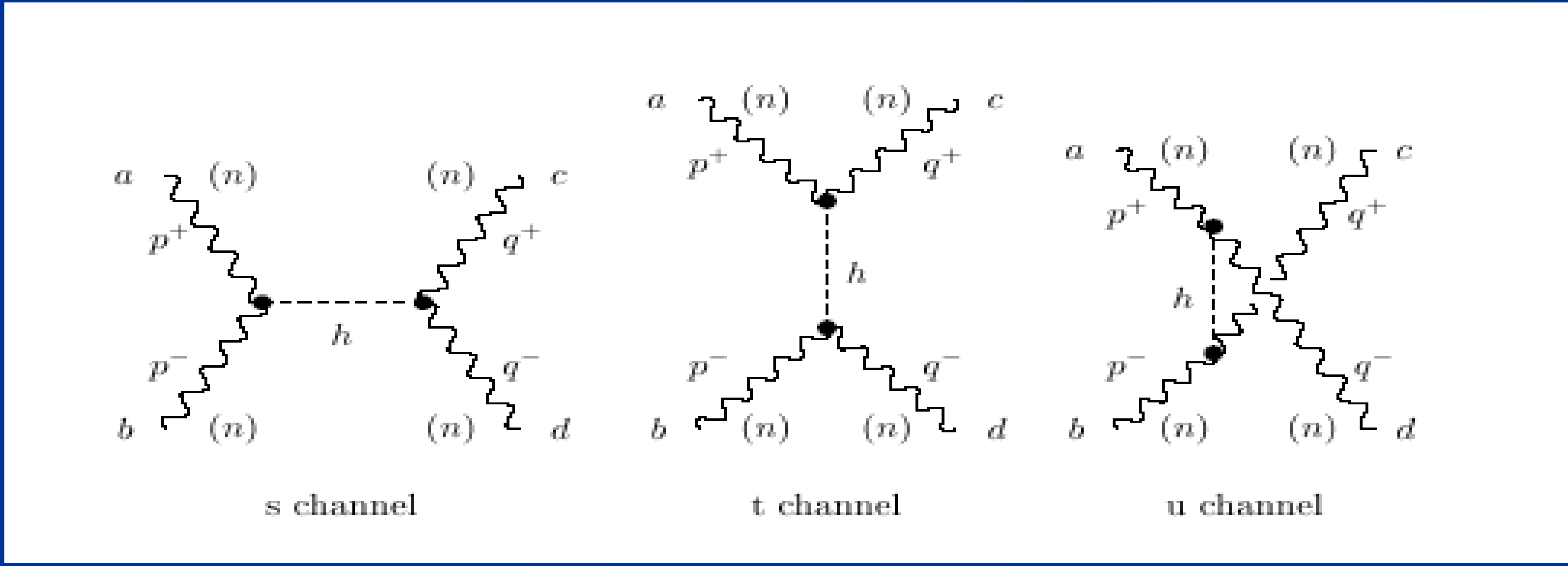
BHN model (Cont'd)

- Exotic hadrons with stops are collider signatures of this model
- Similar to GMSB with stop NLSP
- Current bound from Tevatron > 150 GeV
- Many works in similar approaches

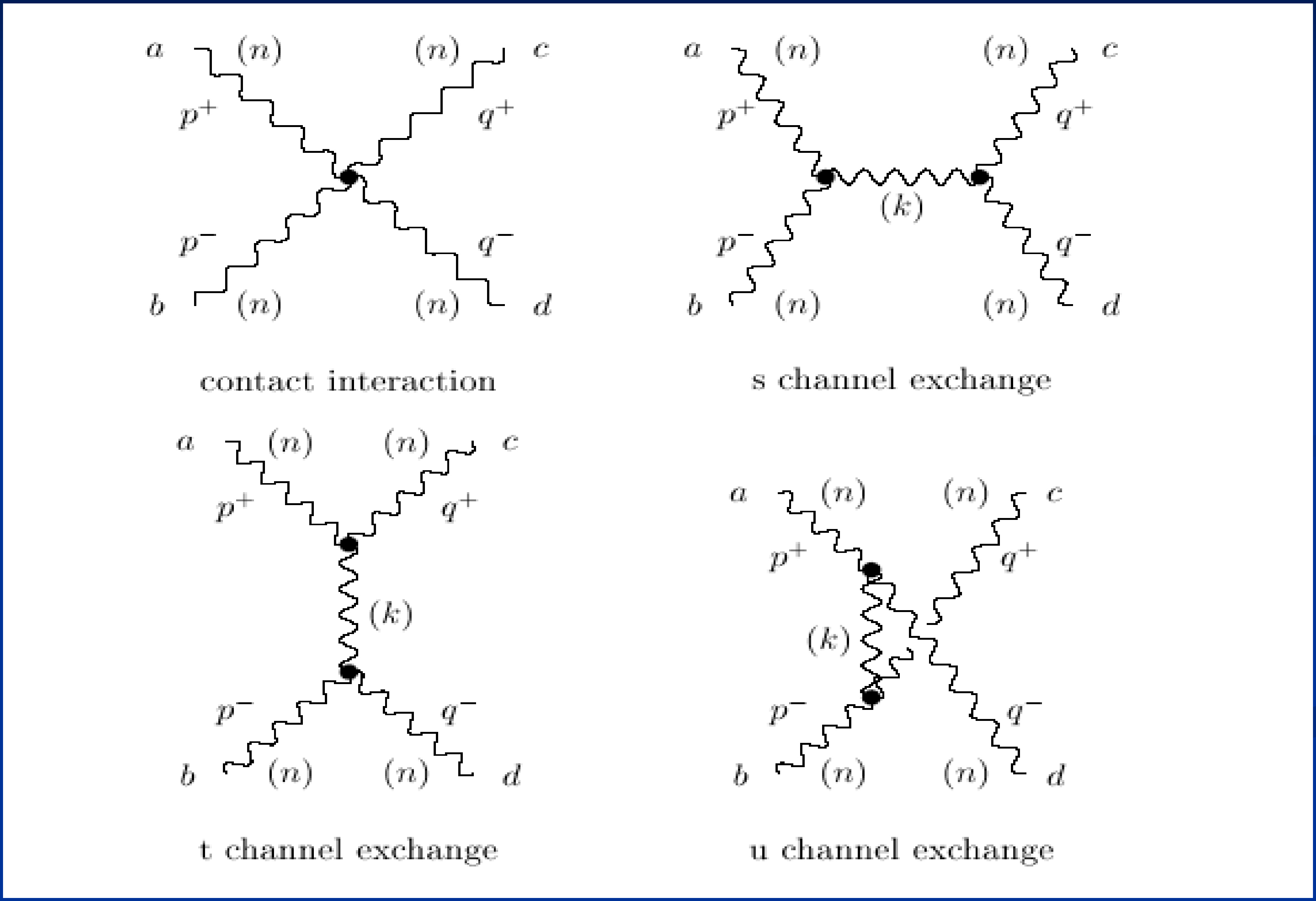
  (BHN ; Arkani-Hamed et al. ; Nilles et al.; Dobado et al ; Quiros et al, Many others ......)

Higgsless EWSB in Extra dim (EWSB by boundary conditions)

- Folklore : Tree level unitarity in WL WL elastic scattering is achieved by Higgs boson : B.W.Lee, C. Quigg, H.B.Thacker (1977)



Gauge boson scattering



Sum Rules

$$\mathcal{A} = A^{(4)} \frac{E^4}{M_n^4} + A^{(2)} \frac{E^2}{M_n^2} + A^{(0)} + \mathcal{O}\left(\frac{M_n^2}{E^2}\right).$$

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

$$A^{(2)} = \frac{i}{M_n^2}\left(4 g_{nnnn} M_n^2 - 3 \sum_k g_{nnk}^2 M_k^2\right)\left(f^{ace} f^{bde} - \sin^2\frac{\theta}{2}\, f^{abe} f^{cde}\right)$$

$$g_{nnnn}^2 = \sum_k g_{nnk}^2.$$

$$4 g_{nnnn}^2 M_n^2 = 3 \sum_k g_{nnk}^2 M_k^2.$$

Higgless EWSB (cont'd)

- So, the folklore is evaded, if there are infinitely many KK modes and the sum rules are satisfied (Csaki, Gorjean, Murayama, Pilo and Terning (2003))
- Tree level unitarity violation is delayed
- Realistic Model Building by Caski et al.
- W,Z : the 1st KK modes of the gauge fields in the bulk, and the 0th KK modes are projected out by suitable BC's

Higgless EWSB (cont'd)

- Detailed model buildings in flat and warped extra dimensions available
- EW precision tests stringent

– Too large S parameter : can be made small by modifying the light fermion structure

– Large shift in Zbbar coupling with heavy top mass : need to be resolved

Higgsless EWSB (cont'd)

Birkedal, Matchev, Perelstein, PRL (2005)

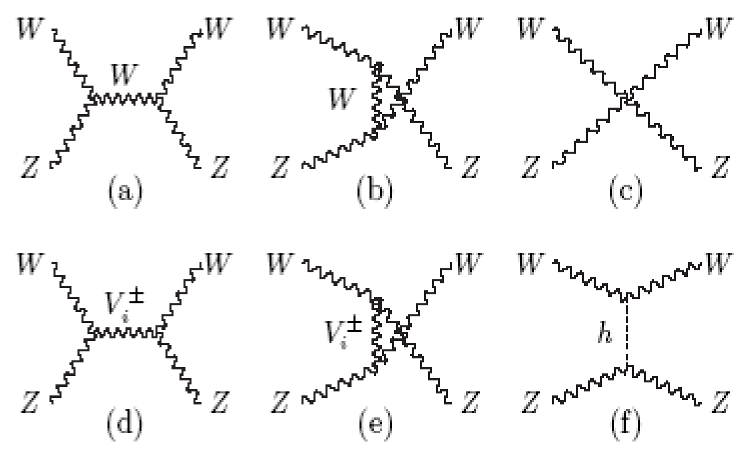


FIG. 1. Diagrams contributing to the $W^{\pm}Z \to W^{\pm}Z$ scattering process: (a), (b) and (c) appear both in the SM and in Higgsless models, (d) and (e) only appear in Higgsless models, while (f) only appears in the SM.

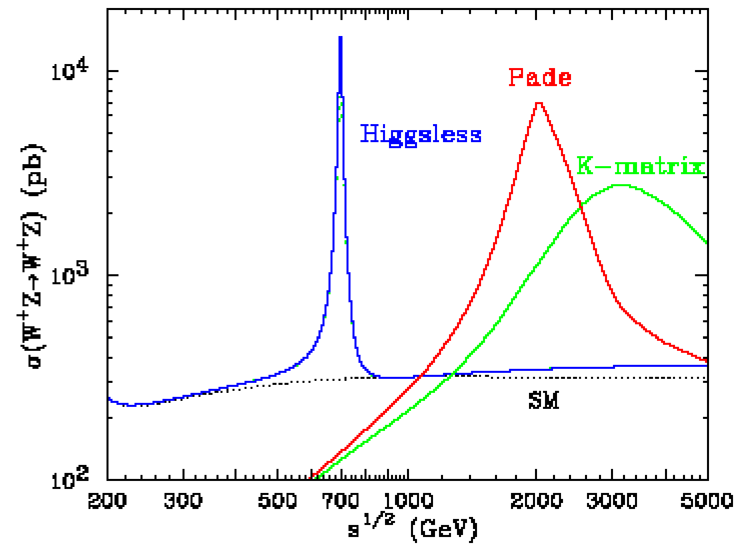


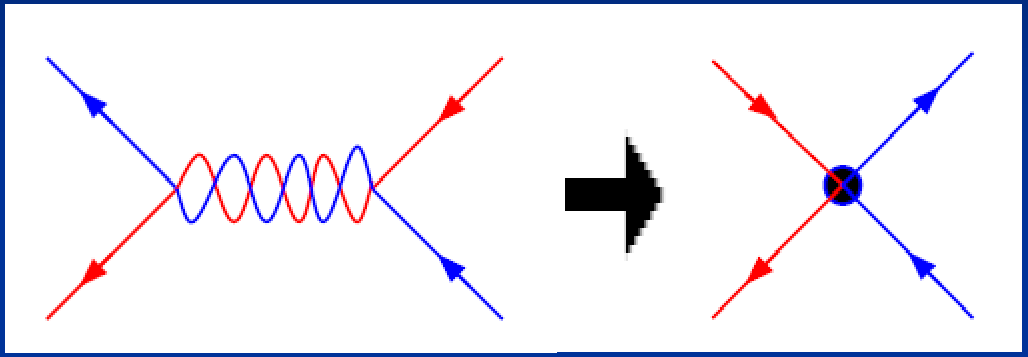
FIG. 2. WZ elastic scattering cross-sections in the SM (dotted), the Higgsless model (blue), and two "unitarization" models: Padé (red) and K-matrix (green).

Dynamical EWSB in Extra Dim

- NJL model assumes ad hoc 4-fermion interactions for triggering EWSB
- Natural if gauge fields live in the bulk

  due to KK gluon exchange (Dobrescu ; Cheng, Dobrescu, Hill ; Yamawaki et al.)
- BHL picture can work without introducing new interactions beyond the SM gauge interaction, if there are extra dimensional space with bulk gauge fields and the 3rd generation fermion in the bulk

Dyn. EWSB in Extra Dim (Cont'd)



$$\mathcal{L}^c_{\text{eff}} = -\frac{c g_s^2(M_1)}{2M_1^2}\left(\sum_q \bar{q}\gamma_\mu T^a q\right)^2$$

- "c" sums all the contributions from KK gluons, thus depends on the number of extra dim, and compactification radii.

Dyn. EWSB in Extra Dim (cont'd)

- Yamawaki et al. considered more careful analysis within flat extra dim.
- Rius and Sanz considered the same problem within RS-1 with gauge fields and t_R in the bulk, and other fields on the TeV brane.
- More realistic model building possible ?

Cocktail Solutions ?

- W/Z mass may be from
  - fundamental Higgs VEV
  - nontrivial BC
  - dynamical EWSB

  * All of them are generic within extra dimension scenarios

  (Similar to SUSY : SUGRA + GMSB + …)
- Difficult to distinguish from the dominance of a single source of EWSB

New (Non SUSY) Physics Search

- Well motivated New Physics Scenarios other than SUSY ?
- Guidelines (Prejudice ?)
  - Solve Hierarchy Problem (Longtime Holy Grail → Ignored in split SUSY)
  - Gauge Coupling Unification
  - Dark Matter Candidate (Neutralino, Gravitino, Axion, Axino, etc.)

Scores of some models

	SM	SUSY	RS-I
Quad Div.	Problem	Yes(SUSY)	Yes (warp factor)
$M_W << M_{Pl}$	Problem	Mu problem	Yes (warp factor)
G.C.U.	No	Yes	Yes
Cold DM	No (axion ?)	Neutralino, gravitino, axion ?	Yes , if grand unified

Randall–Sundrum Scenario

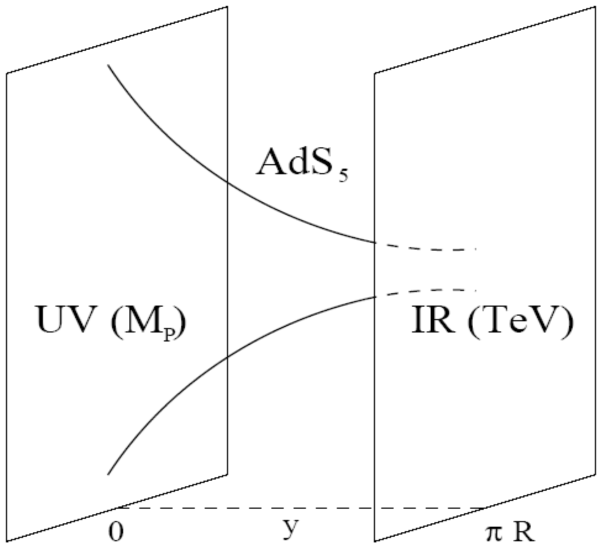


Figure 1: *A slice of* AdS_5*: The Randall-Sundrum scenario.*

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \equiv g_{MN}dx^M dx^N,$$

$$m_H^2|H|^2 \to (m_H e^{-\pi kR})^2|H|^2$$

SM in the bulk in RS

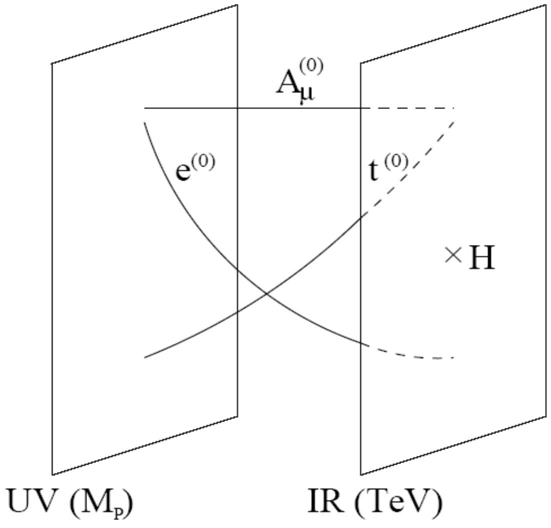


Figure 2: *The Standard Model in the warped five-dimensional bulk.*

- GCU without SUSY
- Fermion mass hierarchy from geometry with O(1) Yukawa couplings

G.C.U. without SUSY in RS-I (Agashe, Delgado and Sundrum)

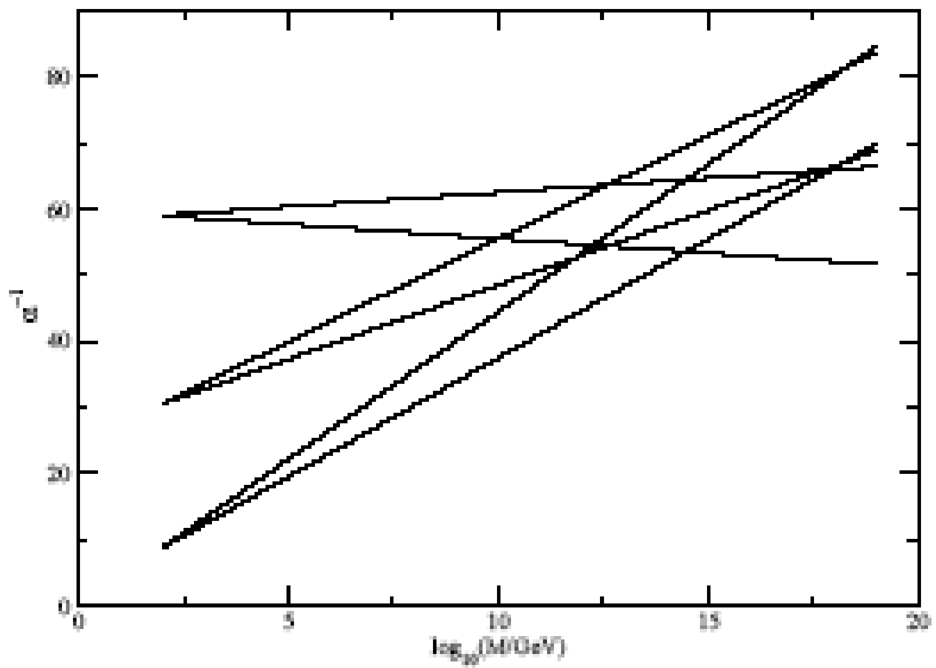


Figure 3: Running couplings (α^{-1}) with respect to energy scale (M) for RS1 with $\Delta_i = \pm O(10\%)$ of differential running contributions in the SM.

RS model

- Therefore I'd like to consider the RS scenario more seriously, since it has similar merits and less (?) drawbacks compared with MSSM
- Put gauge fields in the bulk → G.C.U.
- Put fermions in the bulk → G.C.U.
- Put Higgs on the TeV brane
- Extend the gauge group including $SU(2)_R$ → T parameter protected

RS–I model (cont'd)

- Kaluza Klein Graviton (with a few TeV mass) production at LHC and ILC
  (Hewett and Rizzo, …) →DY Dilepton
- Higgs – Radion Mixing
- Higgs pair production
- g_{KK} (~ a few TeV) production
  (work in progress)
- LZP : RHN with fractional baryon number (Agashe and Servant)
  Collider signature ?

Dilepton signals in RS scenario (Matthews, Ravindran, Sridhar)

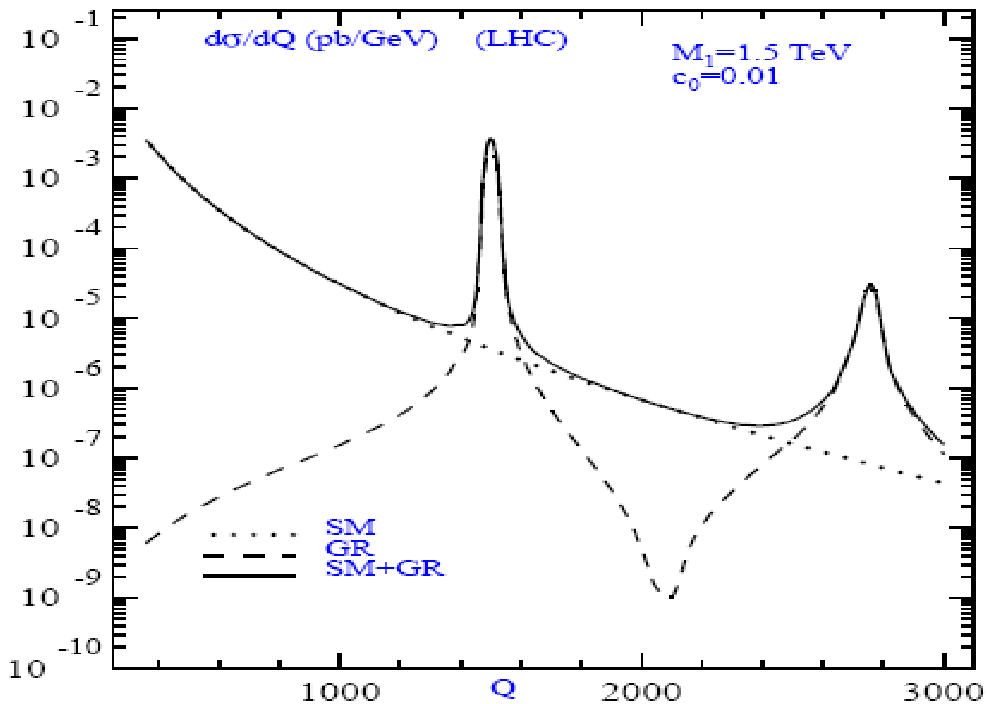


Fig. 1a

Outlooks

- Many interesting ideas proposed so far during the last few decades, but no experimental tests available yet, and not so compelling models
- Generation of fermion masses without FCNC is not so easy, like SUSY models
- Could be due to our limited imagination
- Nature could be smart enough to show the way of mass generation and EWSB in a completely unexpected way

Outlooks (Cont'd)

- LHC/ILC will be necessity to test these fascinating ideas, and deeper understanding of the origin of EWSB, namely masses, mixings and CPV
- New physics may be around the corner, but could be in a surprising disguise
- Let us hope to find something new and exciting at LHC and ILC