WW Scattering
in Higgsless and Composite Higgs Models

based on works in collaboration with

G. Giudice, A. Pomarol and R. Rattazzi

hep-ph/0703164 = JHEP06(2007)045

C. Csáki, H. Murayama, L. Pilo and J. Terning

hep-ph/0305237 = PRD69(2004)055006

hep-ph/0308038 = PRL92(2004)10802

Christophe Grojean

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Main Question for the LHC

What is the mechanism of EW symmetry breaking?

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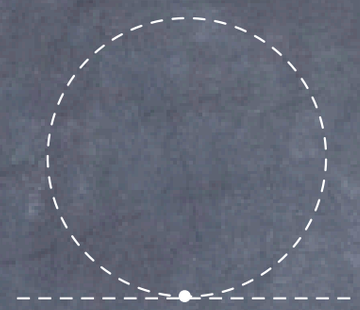
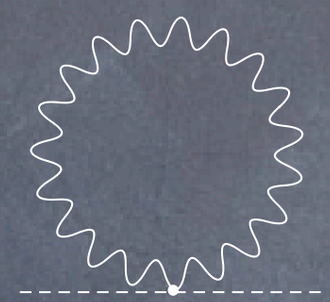
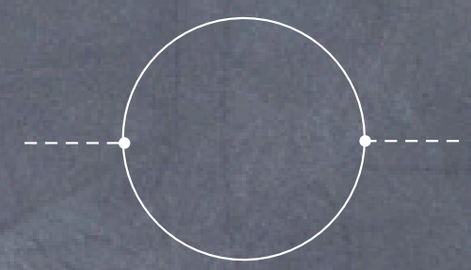
what we usually mean by that question is really

what is canceling these infamous diagrams?







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

supersymmetry, gauge-Higgs, Little Higgs

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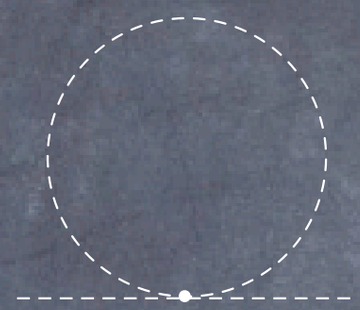

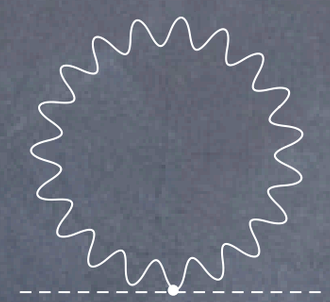

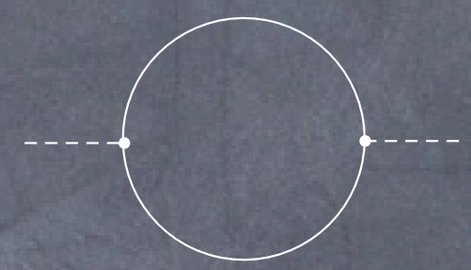

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supersymmetry, gauge-Higgs, Little Higgs

But this is assuming that we already know the answer to

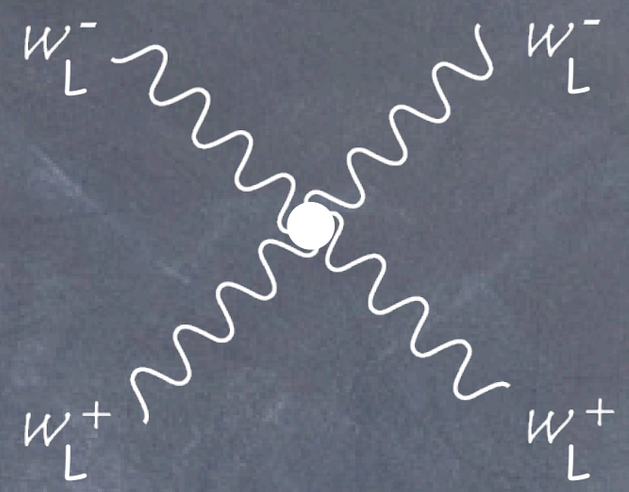
Main Question for the LHC

What is unitarizing the WW scattering amplitudes?

W_L & Z_L part of EWSB sector ⊃ W scattering is a probe of Higgs sector interactions

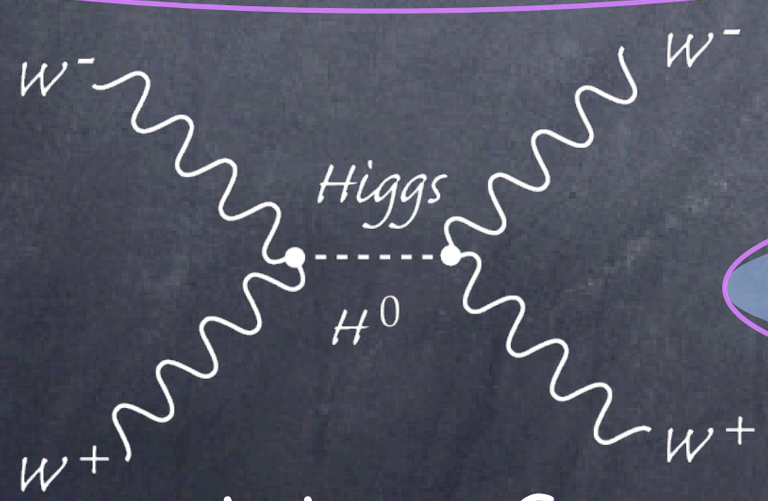
$$\epsilon_l = \left(\frac{|\vec{k}|}{M}, \frac{E}{M}\frac{\vec{k}}{|\vec{k}|}\right)$$

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



W_L & Z_L part of EWSB sector (we have already discovered 75% of the Higgs doublet!) ⊃ WW scattering is a probe of Higgs sector interactions

Weakly coupled models

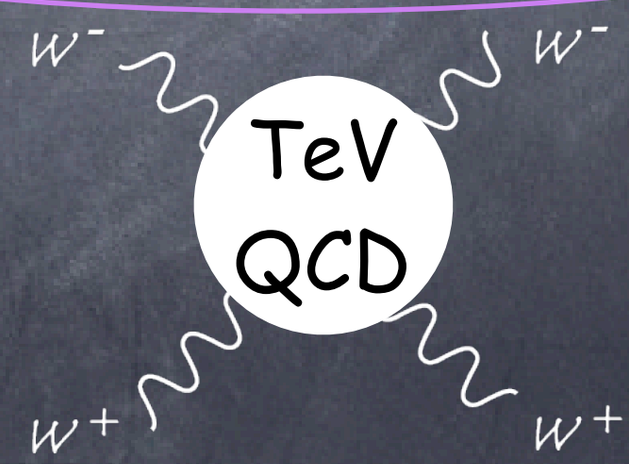


prototype: Susy

susy partners ~ 100 GeV

other ways?

Strongly coupled models



prototype: Technicolor

rho meson ~ 1 TeV

Back to "Technicolor" from Xdims

"AdS/CFT" correspondence for model-builder

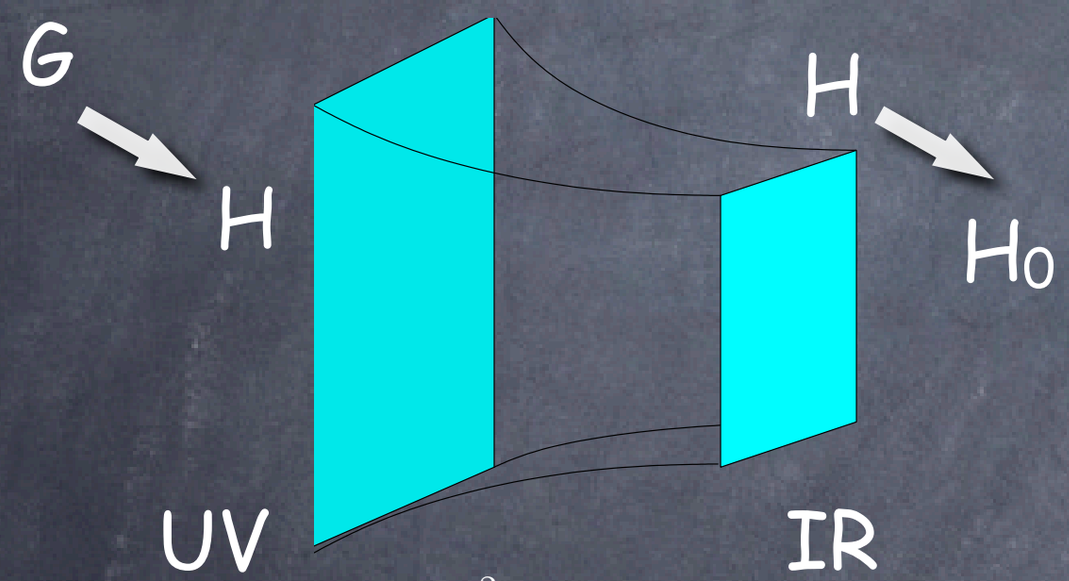
Warped gravity with fermions and gauge field in the bulk and Higgs on the brane

$$A_5 \to A_5 + \partial_5 \epsilon$$

Strongly coupled theory with slowly-running couplings in 4D

$$h \to h + a$$

pseudo-Goldstone of a strong force



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

5D	4D
KK modes	vector resonances (ρ mesons in QCD)
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

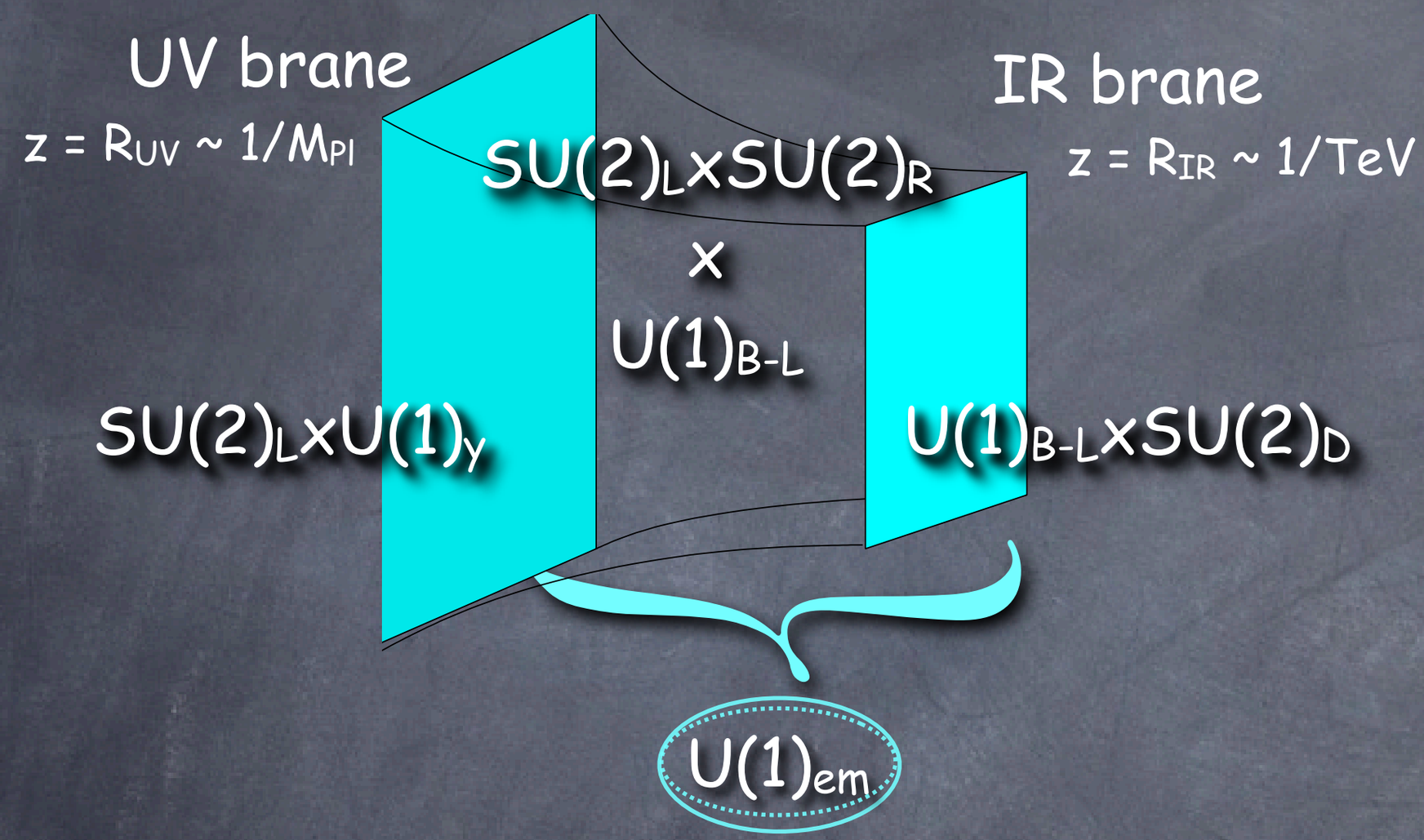
Advantages

- weakly coupled description ⊃ calculable models
- new approach to fermion embedding and flavor problem

Higgsless Models

Warped Higgsless Model

Csaki, Grojean, Pilo, Terning '03



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

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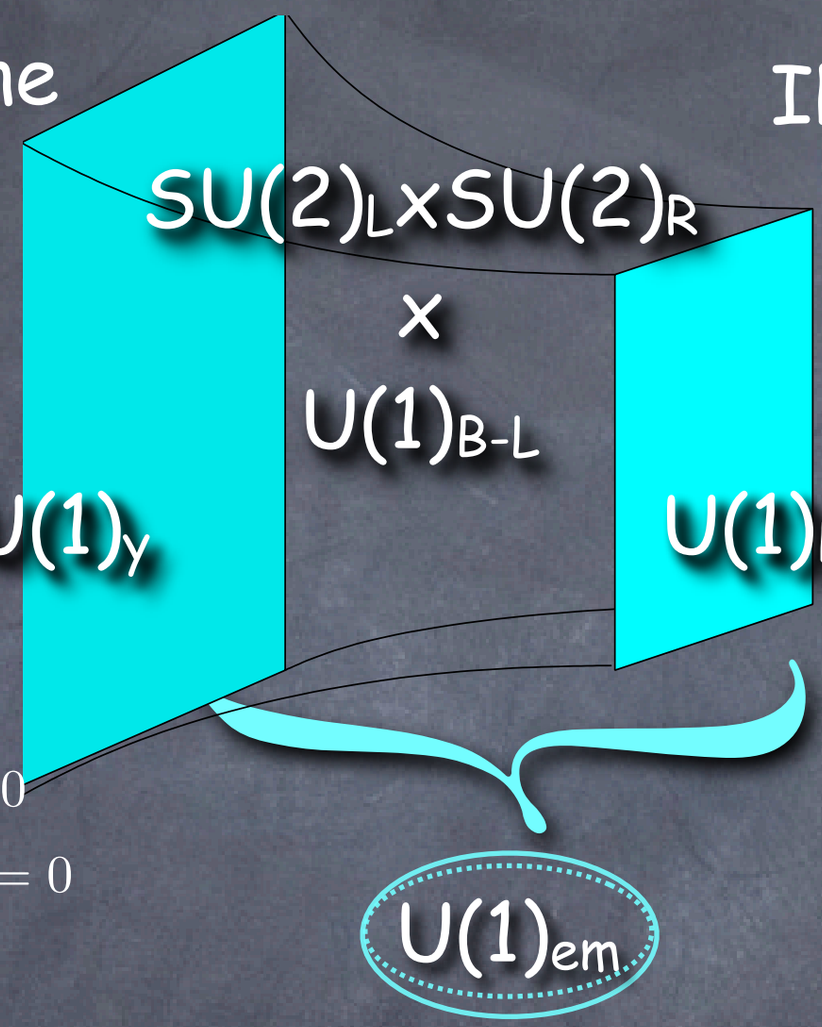
UV brane

$z = R_{UV} \sim 1/M_{Pl}$

IR brane

$z = R_{IR} \sim 1/\mathrm{TeV}$



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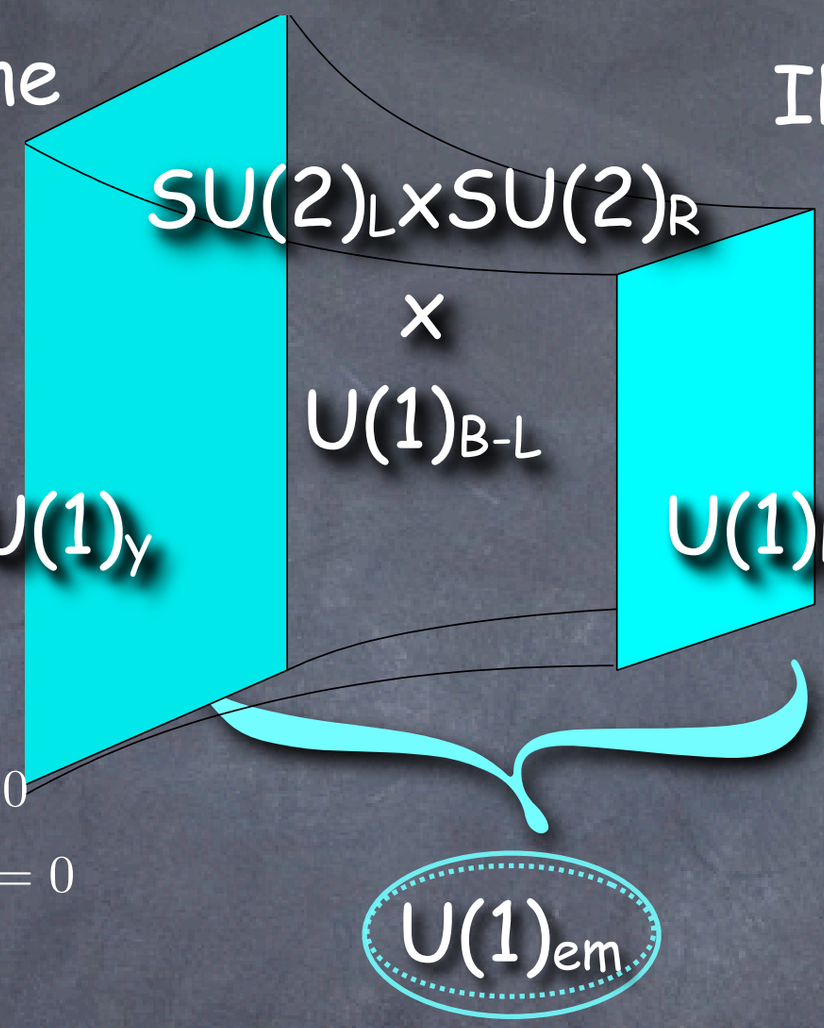

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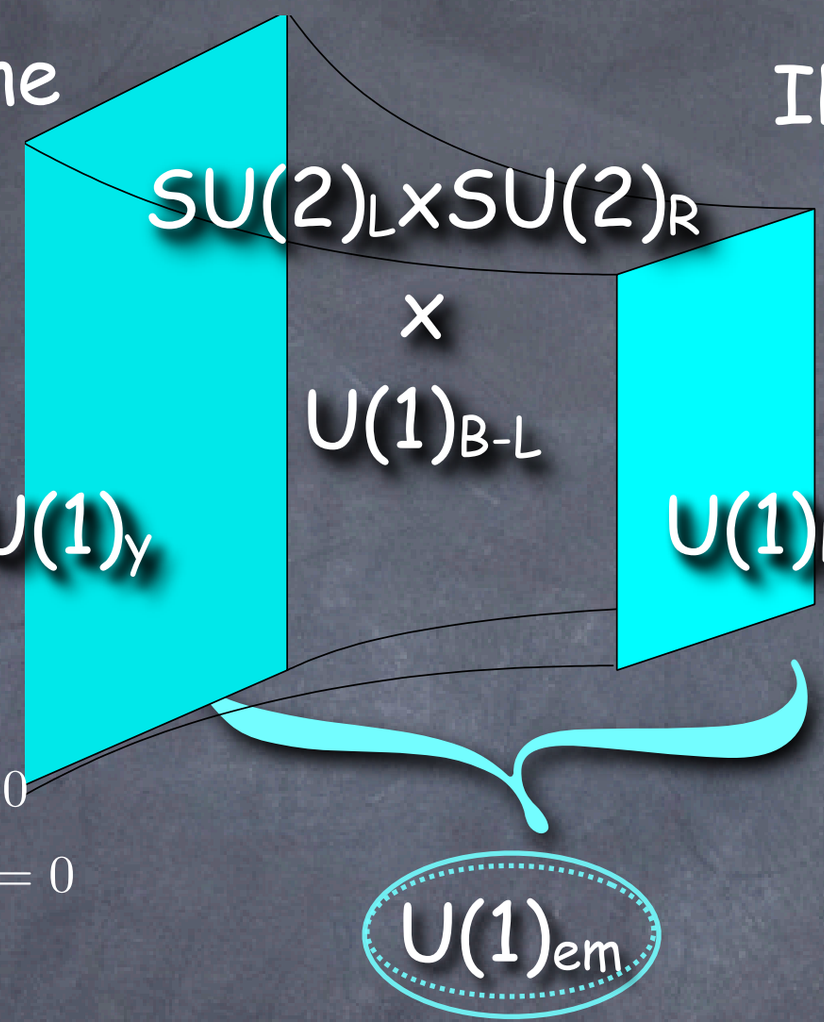

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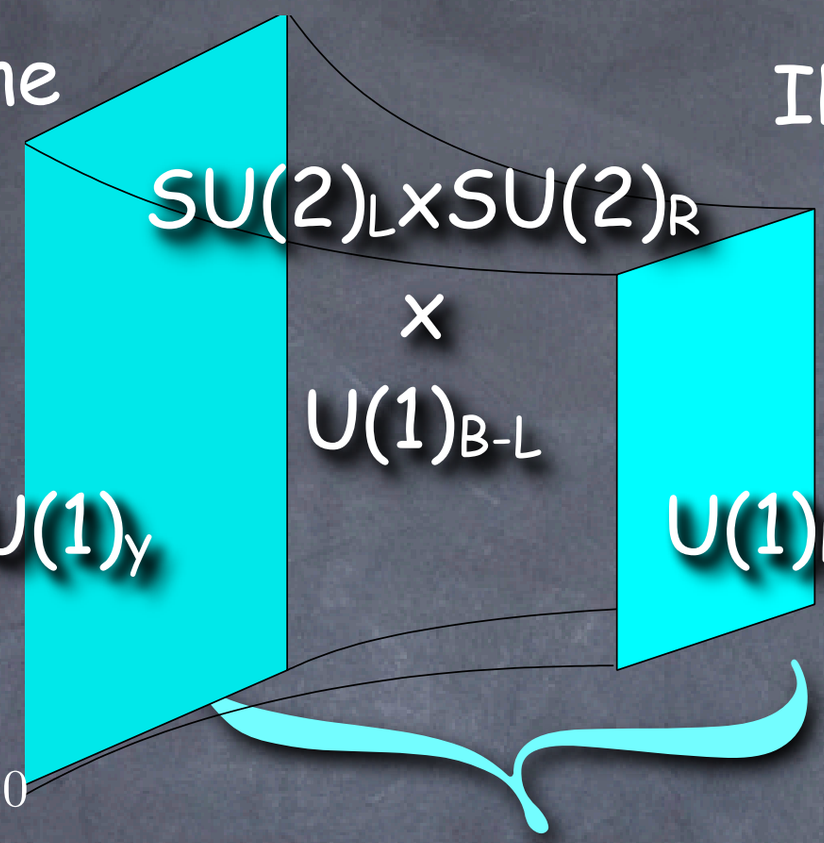

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$U(1)_{em}$

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

"light" mode:

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

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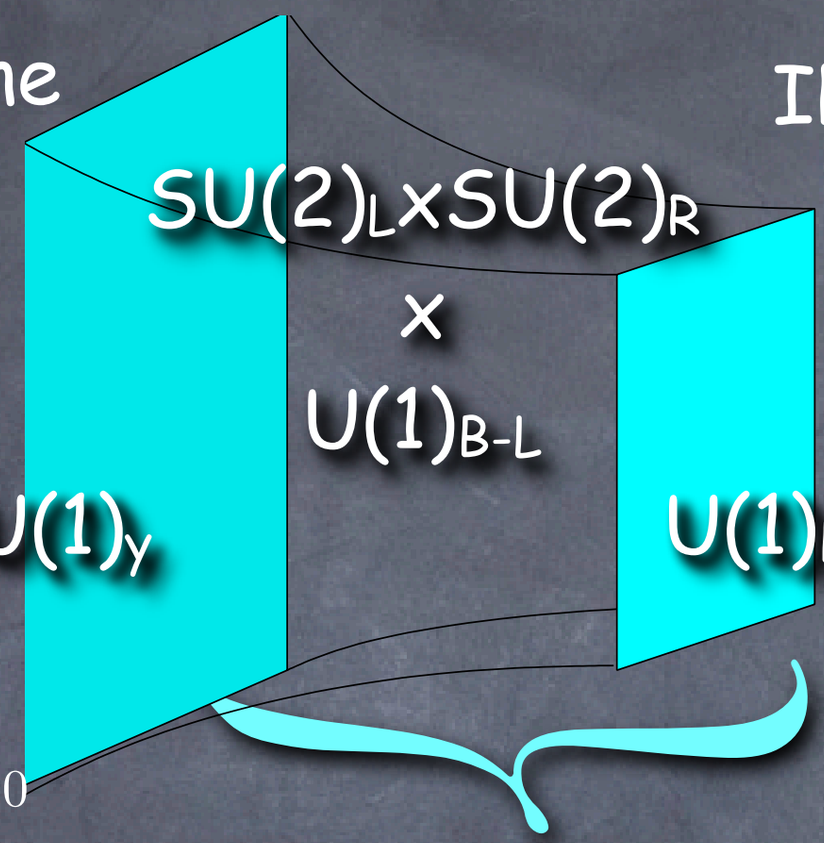

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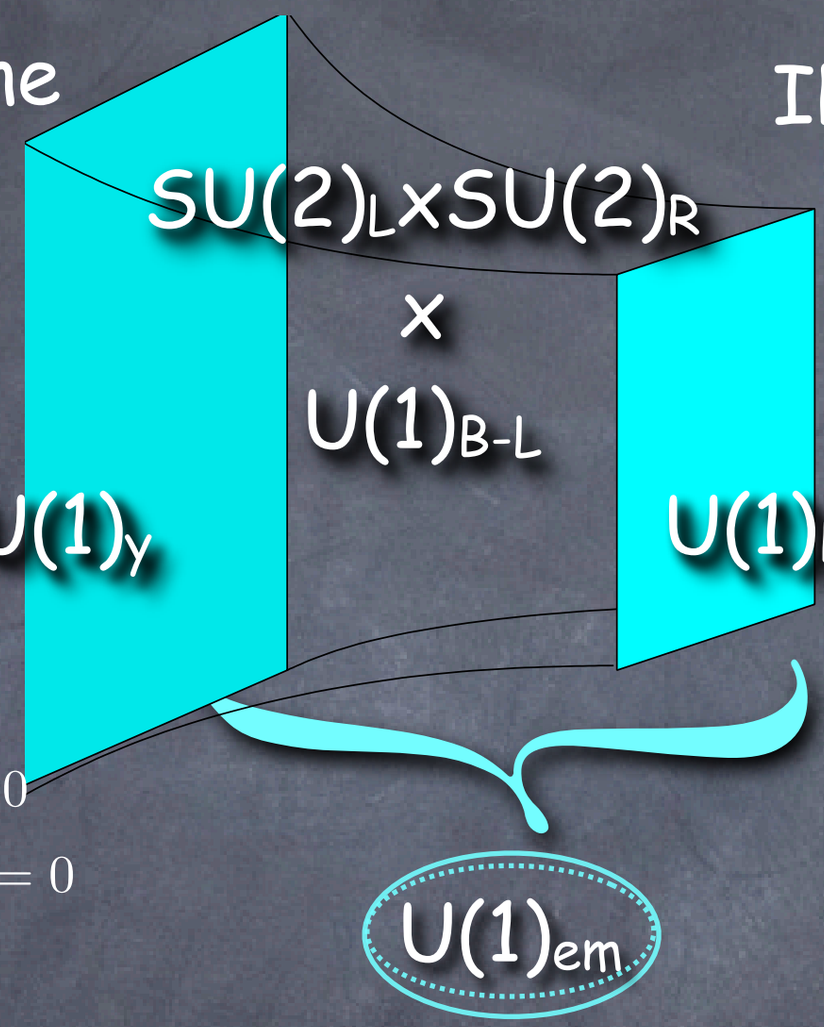

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log suppression

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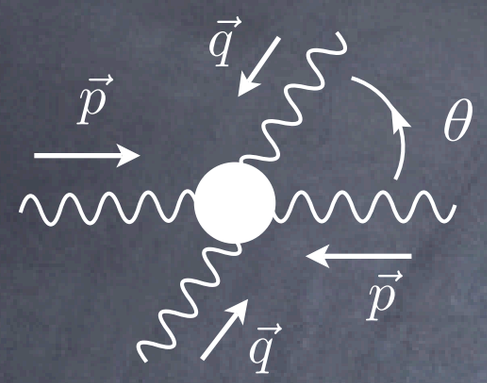
Unitarization of (Elastic) Scattering Amplitude

Same KK mode
'in' and 'out'

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



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

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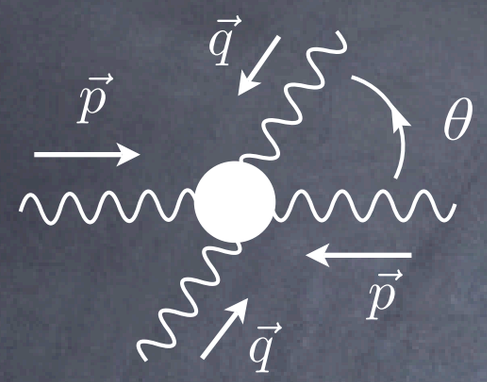

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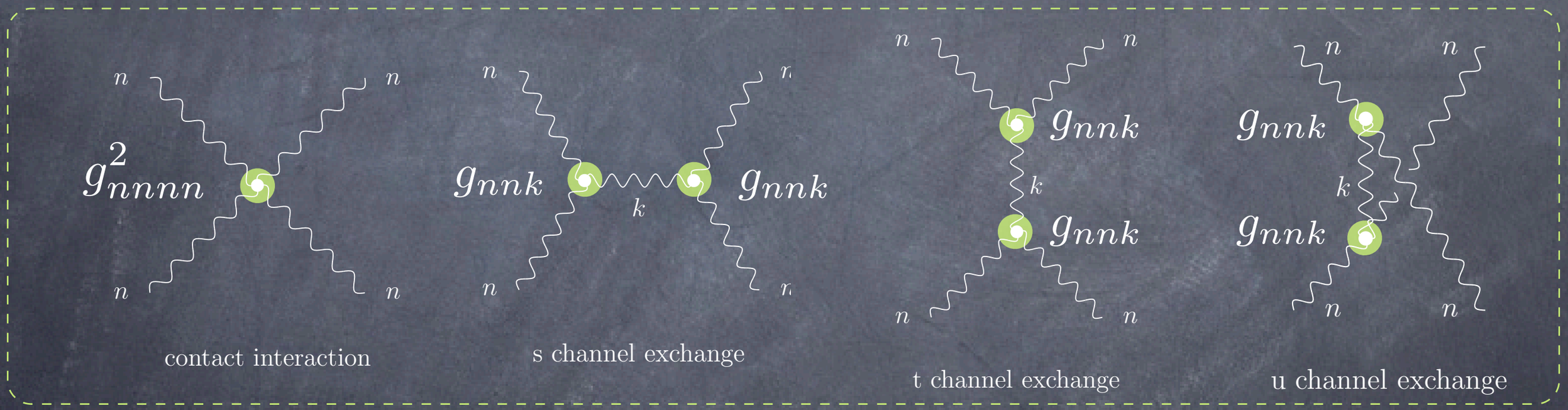

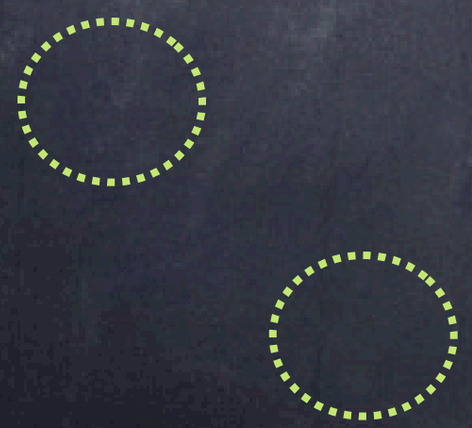

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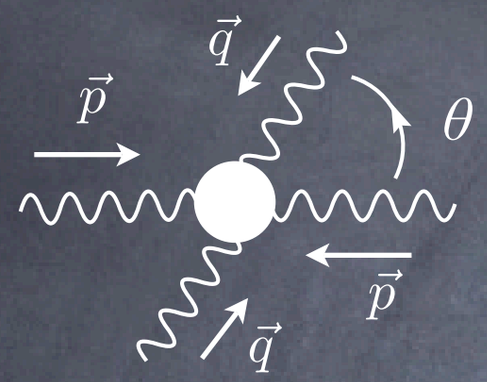

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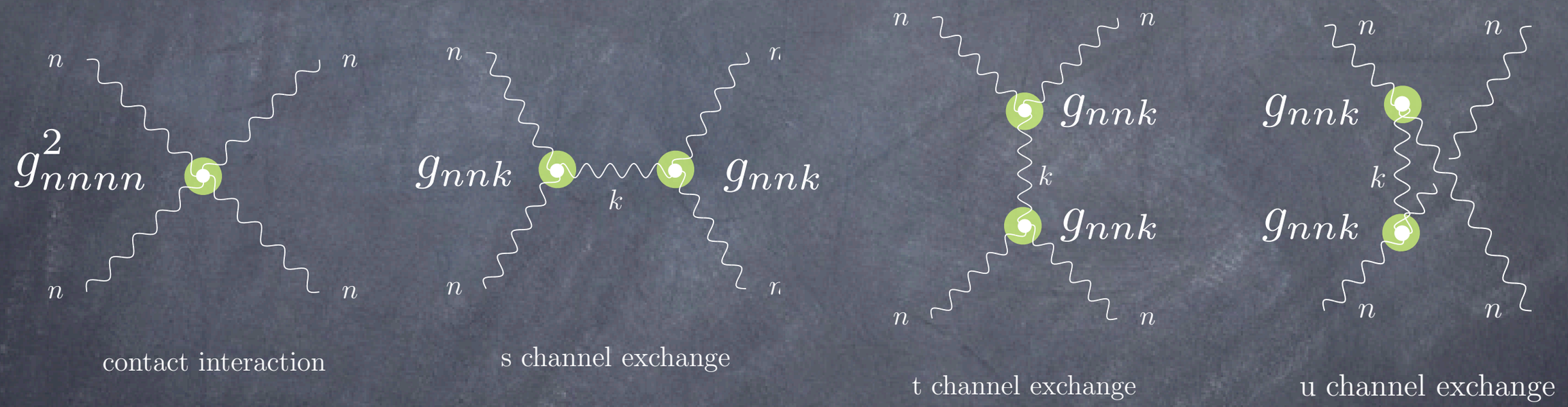

$$\mathcal{A}^{(4)} = i\left(g^2_{nnnn} - \sum_k g^2_{nnk}\right)\left(f^{abe}f^{cde}(3+6c_\theta - c_\theta^2) + 2(3-c_\theta^2)f^{ace}f^{bde}\right)$$

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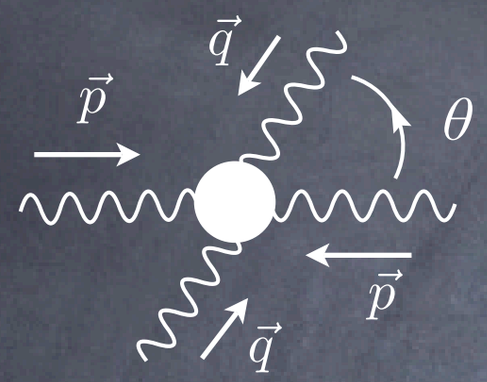

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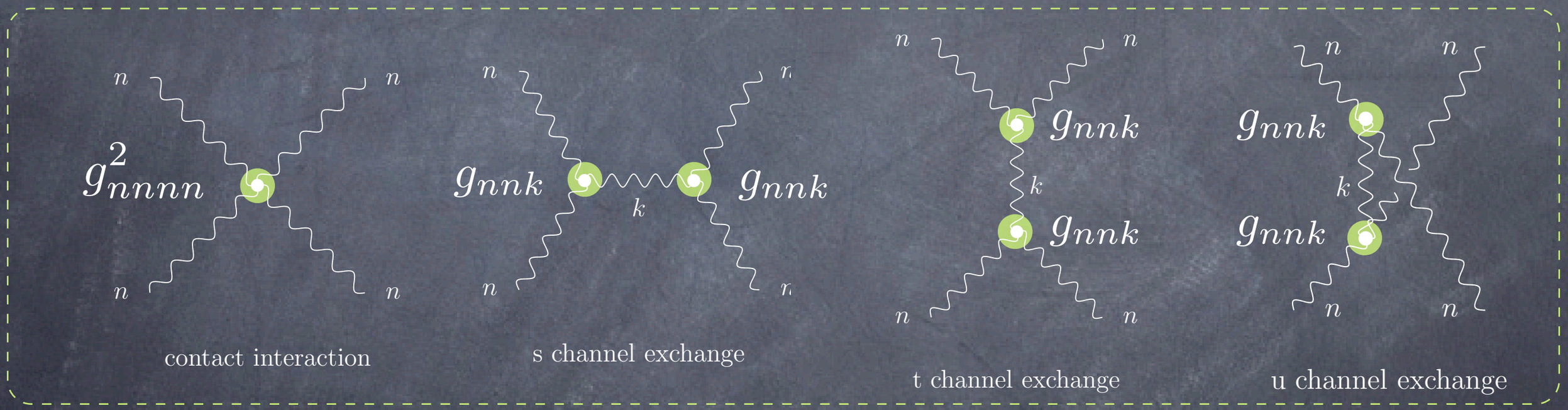

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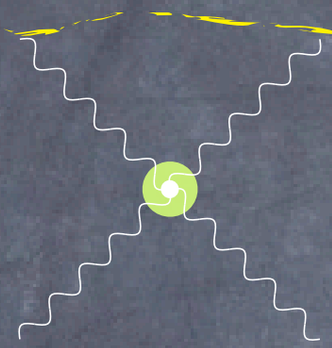
KK Sum Rules

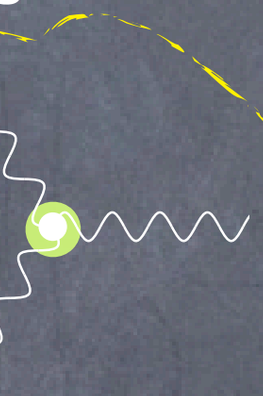
Csaki, Grojean, Murayama, Pilo, Terning '03

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

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



$$g^2_{mnpq} = g^2_{5D}\int_{R_{UV}}^{R_{IR}} dz\frac{R}{z} f_m(z) f_n(z) f_p(z) f_q(z)$$



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Completeness of KK modes

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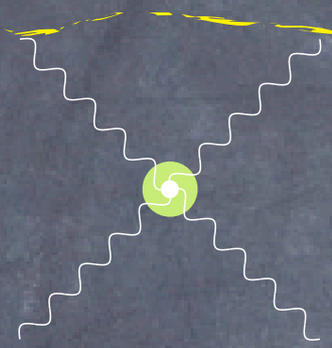

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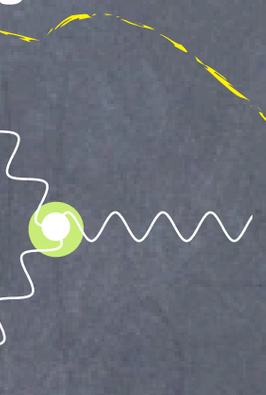

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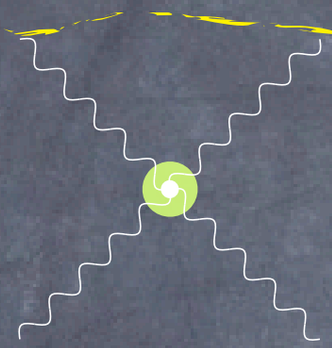

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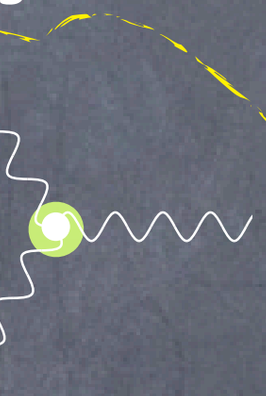


$$g_{mnp} = g_{5D}\int_{R_{UV}}^{R_{IR}} dz\frac{R}{z} f_m(z) f_n(z) f_p(z)$$

- E^4 Sum Rule

$$g^2_{nnnn} - \sum_k g^2_{nnk} = g^2_{5D}\int_{R_{UV}}^{R_{IR}} dz\frac{R}{z} f_n^4(z) - g^2_{5D}\int_{R_{UV}}^{R_{IR}} dz\frac{R}{z}\int_{R_{UV}}^{R_{IR}} dz' f_n^2(z) f_n^2(z')\sum_k \frac{R}{z'} f_k(z) f_k(z') = 0$$

$$\cdot \sum_k \frac{R}{z'} f_k(z) f_k(z') = \delta(z - z')$$

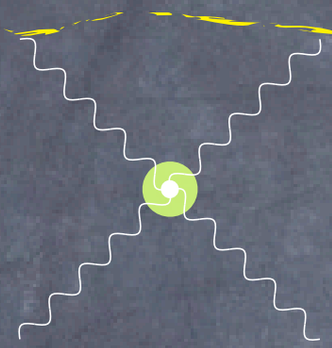
Completness of KK modes

KK Sum Rules

Csaki, Grojean, Murayama, Pilo, Terning '03

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

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



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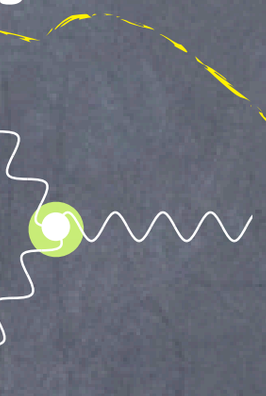

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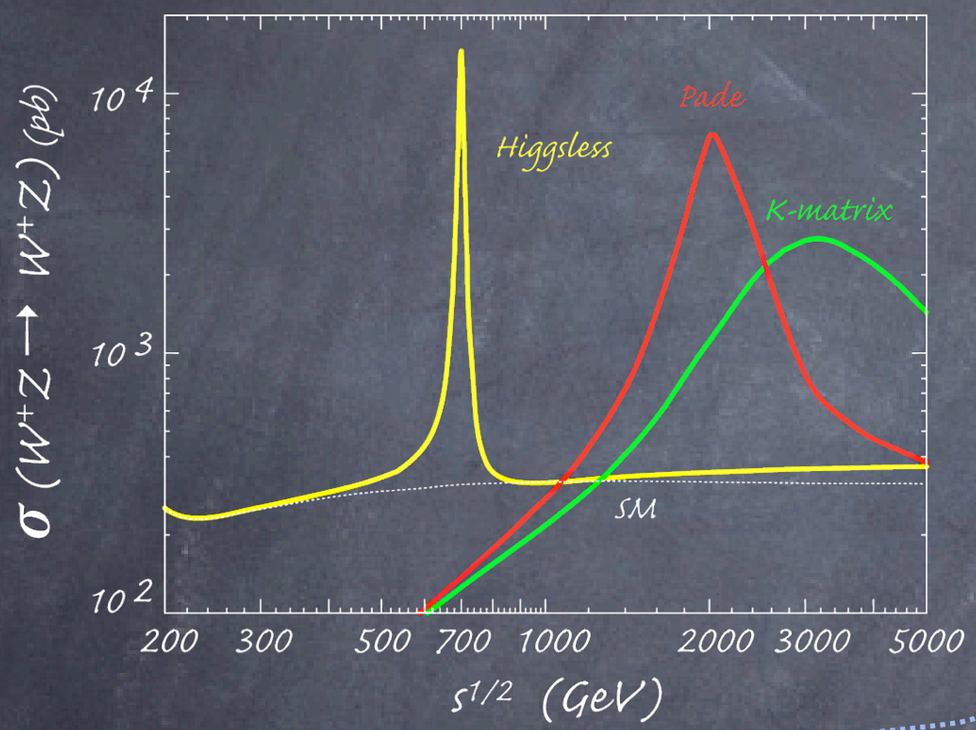
Completness of KK modes

Collider Signatures

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

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

WZ elastic cross section



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

a narrow and light resonance

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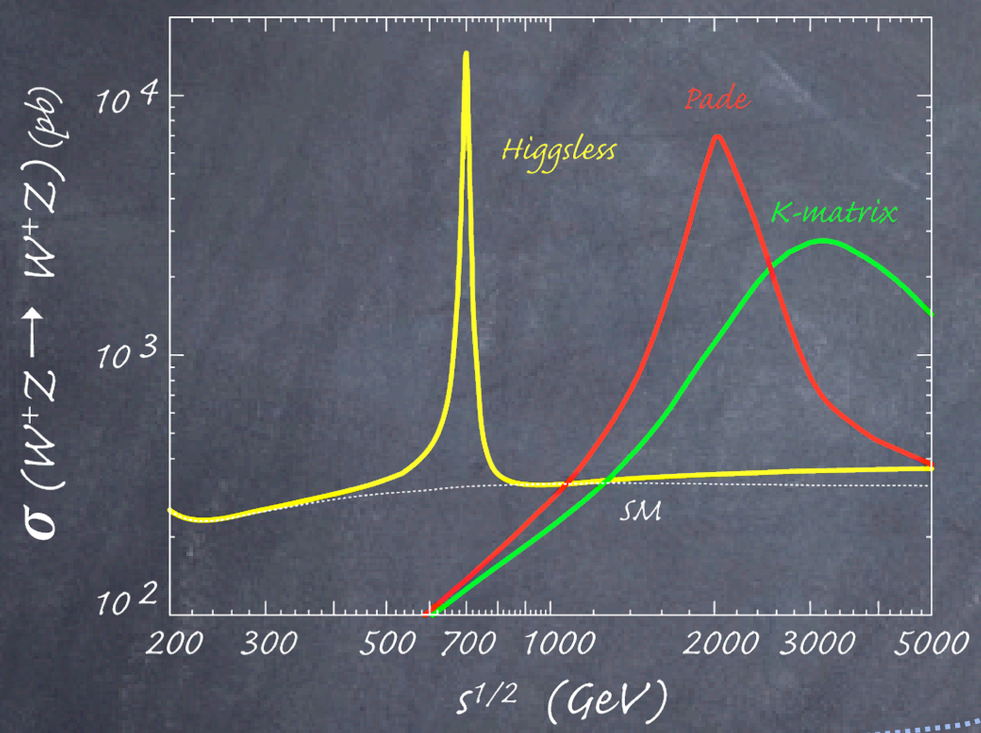

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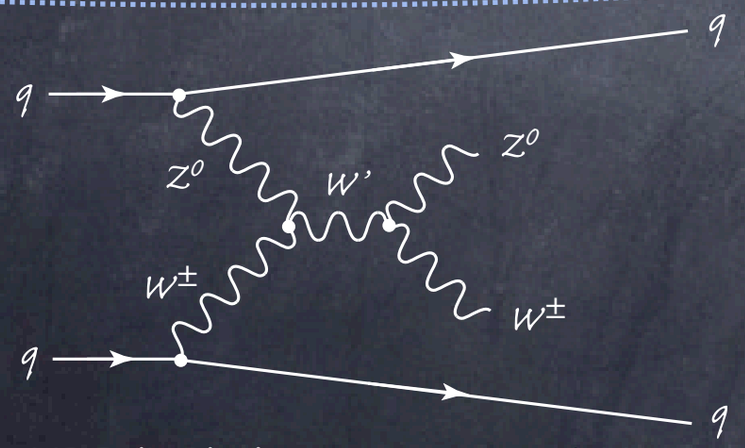
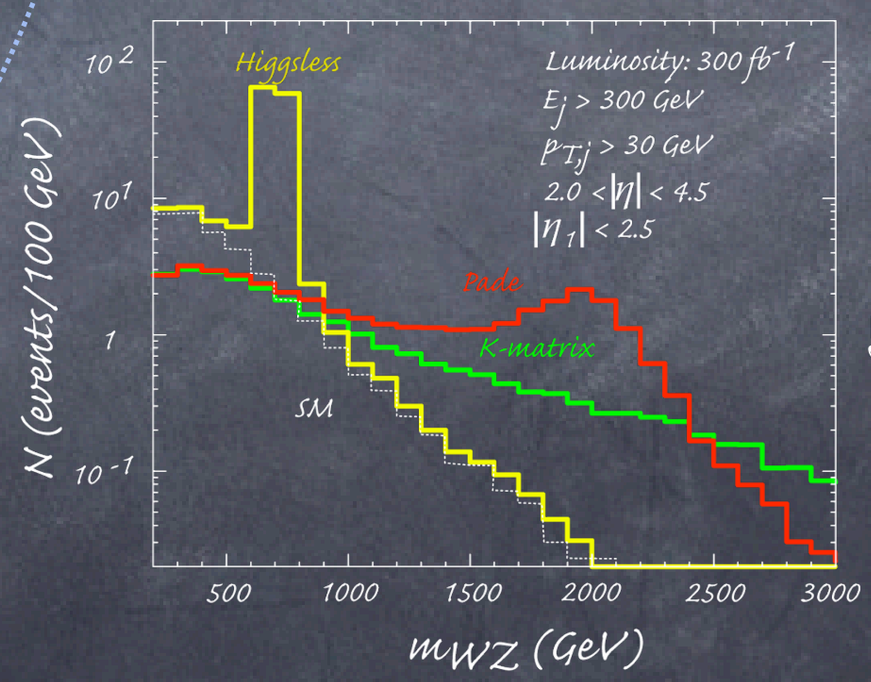


VBF (LO) dominates over DY since couplings of q to W' are reduced

W' production



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

Composite Higgs Models

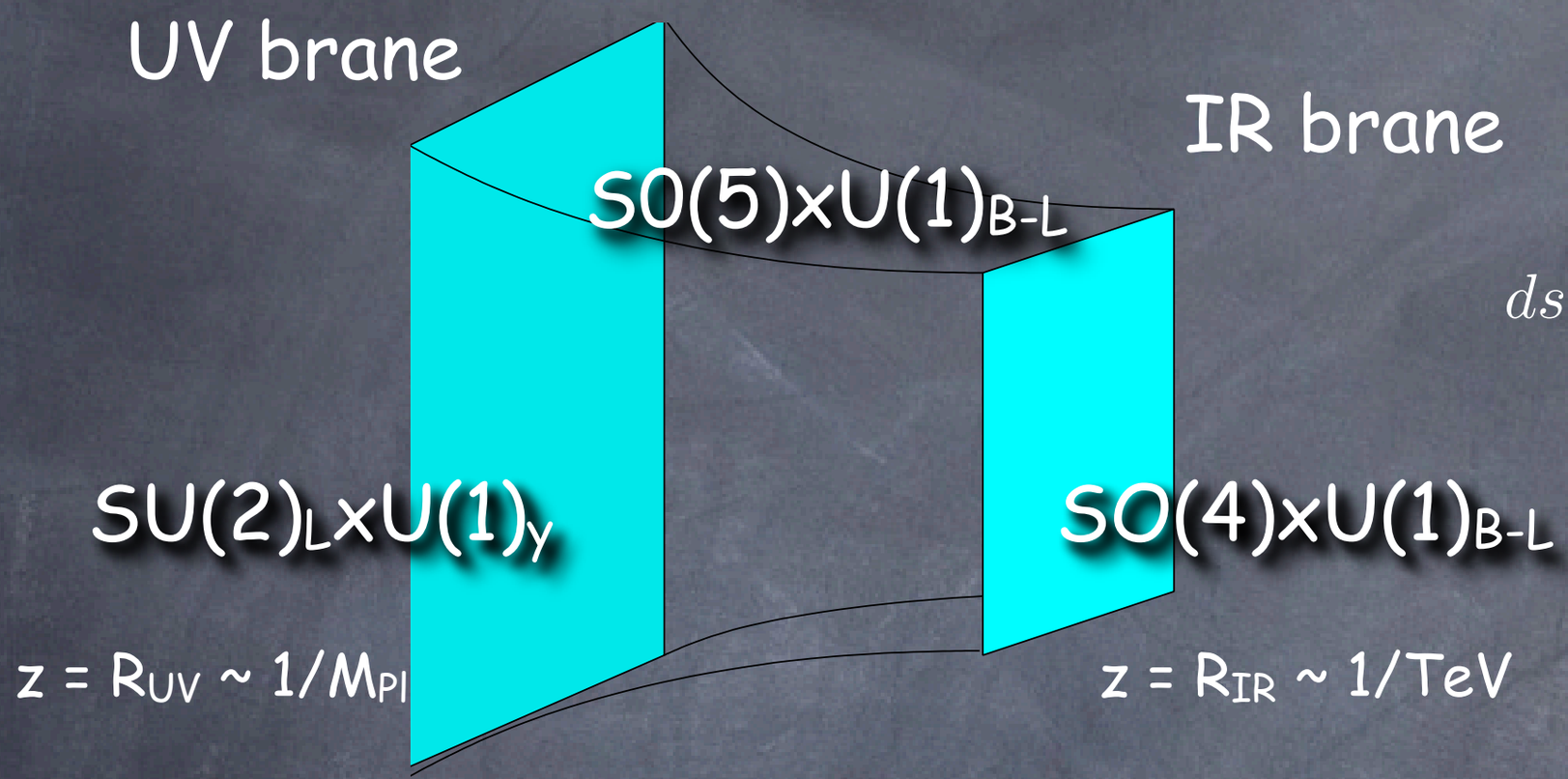
Christophe Grojean

SILH

Aspen January 15th 2008

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04



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

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

warped dual to composite Higgs model

SO(5)

SO(4)

$$\begin{pmatrix} \boxed{\quad SO(4) \quad} & \begin{matrix} h_1 \\ h_2 \\ h_3 \\ h_4 \end{matrix} \\ \begin{matrix} -h_1 & -h_2 & -h_3 & -h_4 \end{matrix} & 0 \end{pmatrix}$$

Adj ← A_μ

4 ← A_5

SO(5)/SO(4)
contains a doublet

Unitarity with Composite Higgs

Technicolor: W_L and Z_L are part of the strong sector

Higgs = composite object (part of the strong sector too)

its couplings deviate from a point-like scalar

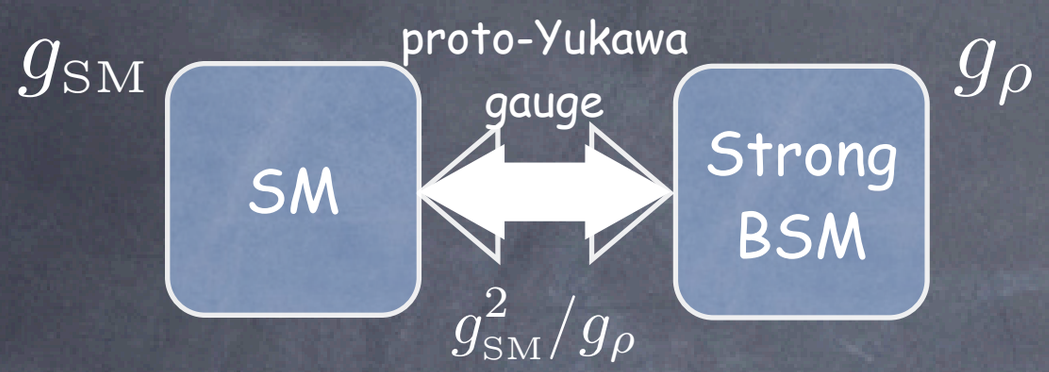
Georgi, Kaplan '84

unitarization halfway between weak and strong unitarizations!

- ≠ susy: no naturalness pb ⊃ no need for new particles to cancel Λ^2 divergences
- ≠ technicolor: heavier rho ⊃ smaller oblique corrections; one tunable parameter: v/f. $\hat{S}_{\rm UV} \sim \frac{g^2 N}{96\pi^2}\frac{v^2}{f^2}$

How to obtain a light composite Higgs?

Higgs=Pseudo-Goldstone boson of the strong sector



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

global symmetry → G/H ← residual global symmetry

UV completion

$4\pi f$ — 10 TeV

$m_\rho = g_\rho f$ — usual resonances of the strong sector

f —

v — 246 GeV Higgs = light resonance of the strong sector

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 $f = \dfrac{m_\rho}{g_\rho}$

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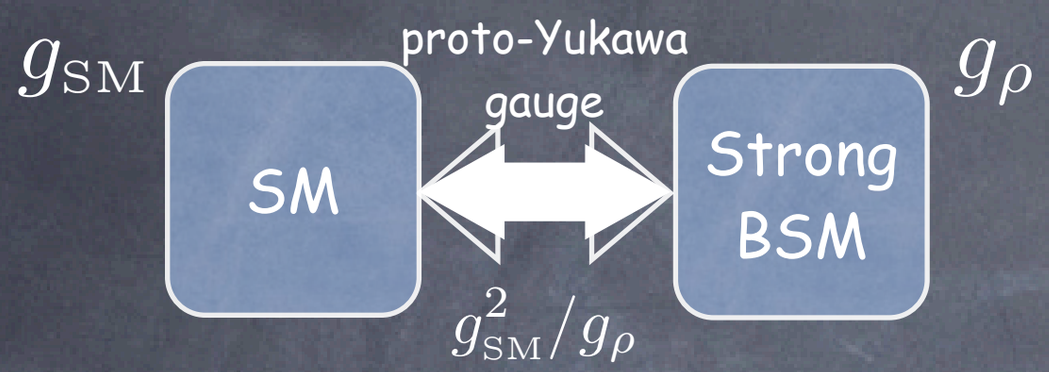

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SO(5)/SO(4) model

SM Higgs: a SO(4) global symmetry.

Higgs=Goldstone ⇛ need to extend the symmetry, e.g. SO(5)

ϕ = 5 of SO(5) with the constraint $|\phi|^2=f^2$

weakly gauge $SU(2)_L \times U(1)_Y$ of $SO(4) \subset SO(5)$

$$\phi = (\vec{\phi}, \phi_5) \qquad \vec{\phi}^2 + \phi_5^2 = f^2$$

the dynamics will determine the alignement of the two SO(4)

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A SO(5) breaking potential is generated,
e.g., by interaction with gauge bosons or quarks and leptons

$$V = f^4 \delta(\phi^2 - f^2) - A f^2 \vec{\phi}^2 + B f^3 \phi_5$$

SO(5) inv. potential

Most general soft breaking potential dim≤2

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$$v^2 = \langle \vec{\phi}^{\,2} \rangle = f^2 \left(1 - \frac{B}{2A} \right).$$

⇐ v/f determines by the dynamics

Testing the composite nature of the Higgs?

if LHC sees a Higgs and nothing else*:

- evidence for string landscape???
- it will be more important then ever to figure out whether the Higgs is composite!

- Model-dependent: production of resonances at m_ρ
- Model-independent: study of Higgs properties & W scattering
  - Higgs anomalous coupling
  - strong WW scattering
  - strong HH production
  - gauge bosons self-couplings

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see Alex Pomarol's talk on thursday

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What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

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

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Modified Higgs propagator ~ Higgs couplings rescaled by

$$\frac{1}{\sqrt{1 + c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2}$$

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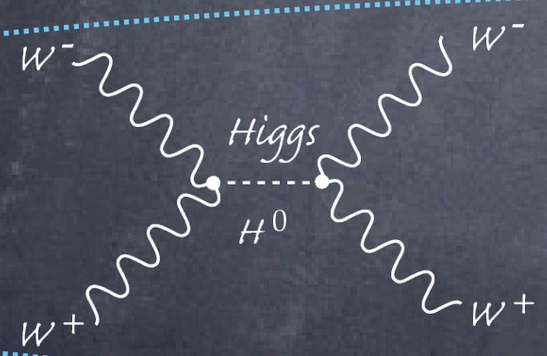

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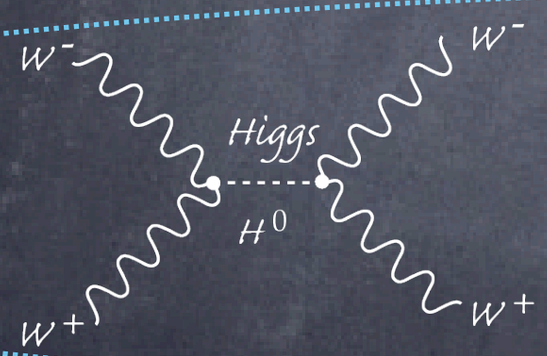

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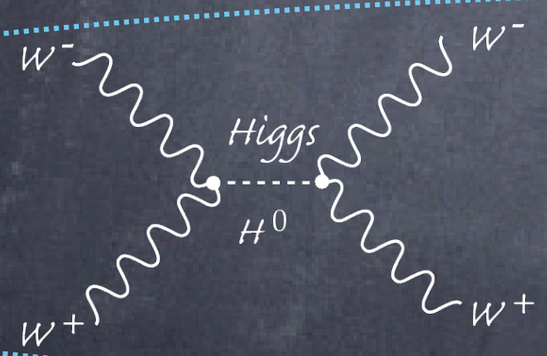

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Strong W scattering below m_ρ

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)

- **Form factor operators** (sensitive to the scale m_ρ)

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Genuine strong operators (sensitive to the scale f)

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

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

custodial breaking

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

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

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Form factor operators (sensitive to the scale m_ρ)

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

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

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

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

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.

Coset Structure

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↑

can be removed by field redefinition

$$H \to H + \sharp |H|^2 H/f^2$$

c_H and c_T are fully fixed by the σ-model structure

(up to the overall normalization of f)

(independent of the physics at the scale m_ρ)

SO(5)/SO(4): c_H=1/2, c_T=0 SU(3)/SU(2)xU(1): c_H=c_T=1/36

$$\lambda |H|^4 \to \frac{\sharp}{f^2}\lambda |H|^6 \qquad y \bar{f}_L H f_R \to \frac{\sharp}{f^2} y |H|^2 \bar{f}_L H f_R$$

c_6 and c_y receive contributions both from the σ-model structure and from the resonance at m_ρ

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

$$\Downarrow$$

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

effective
Higgs mass

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

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

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

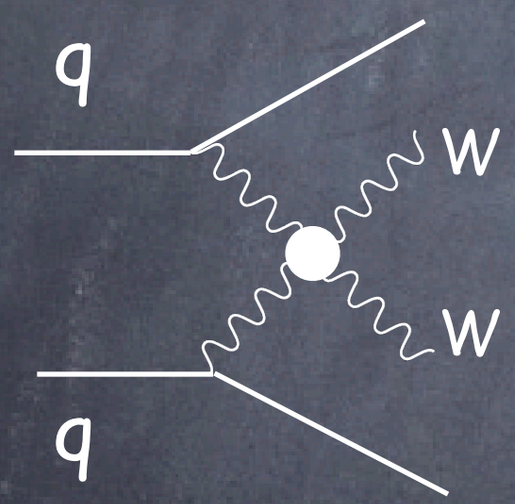
Strong W scattering

Even with a light Higgs, growing amplitudes (at least up to m_ρ)

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

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \qquad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0$$



$$\sigma\left(pp \to V_L V_L' X\right)_{c_H} = \left(c_H \frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\cancel{H}}$$

leptonic vector decay channels

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

with 300 fb^{-1}

30 signal-events and 10 background-events

Bagger et al '95
Butterworth et al. '02

LHC is sensitive to

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

bigger than

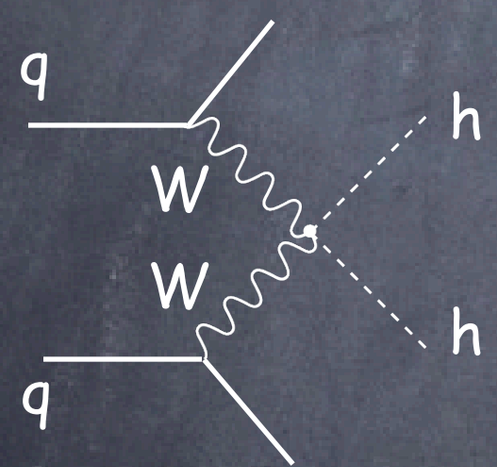
0.5 ~ 0.7

Strong Higgs production

O(4) symmetry between W_L, Z_L and the physical Higgs

strong boson scattering ⇔ strong Higgs production

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



signal:
- $hh \to bbbb$
- $hh \to 4W \to \ell^\pm\ell^\pm\nu\nu$jets

Sum rule (with cuts $|\Delta\eta| < \delta$ and $s < M^2$)

$$2\sigma_{\delta,M}\left(pp \to hhX\right)_{c_H} = \sigma_{\delta,M}\left(pp \to W_L^+ W_L^- X\right)_{c_H} + \frac{1}{6}\left(9 - \tanh^2\frac{\delta}{2}\right)\sigma_{\delta,M}\left(pp \to Z_L^0 Z_L^0 X\right)_{c_H}$$

Conclusions

The LHC should tell us what is the mechanism of EWSB

Oblique corrections are a test of new physics

WW scattering (and Higgs anomalous couplings) should be able to tell us if the EWSB sector is strongly or weakly coupled.