Beyond the Standard Model (Except for SUSY)

John Terning
UC Davis

Outline for 3 Days

* Extra Dimensions
* Hidden Valleys/Quirks/Unparticles
* Monopoles and EWSB

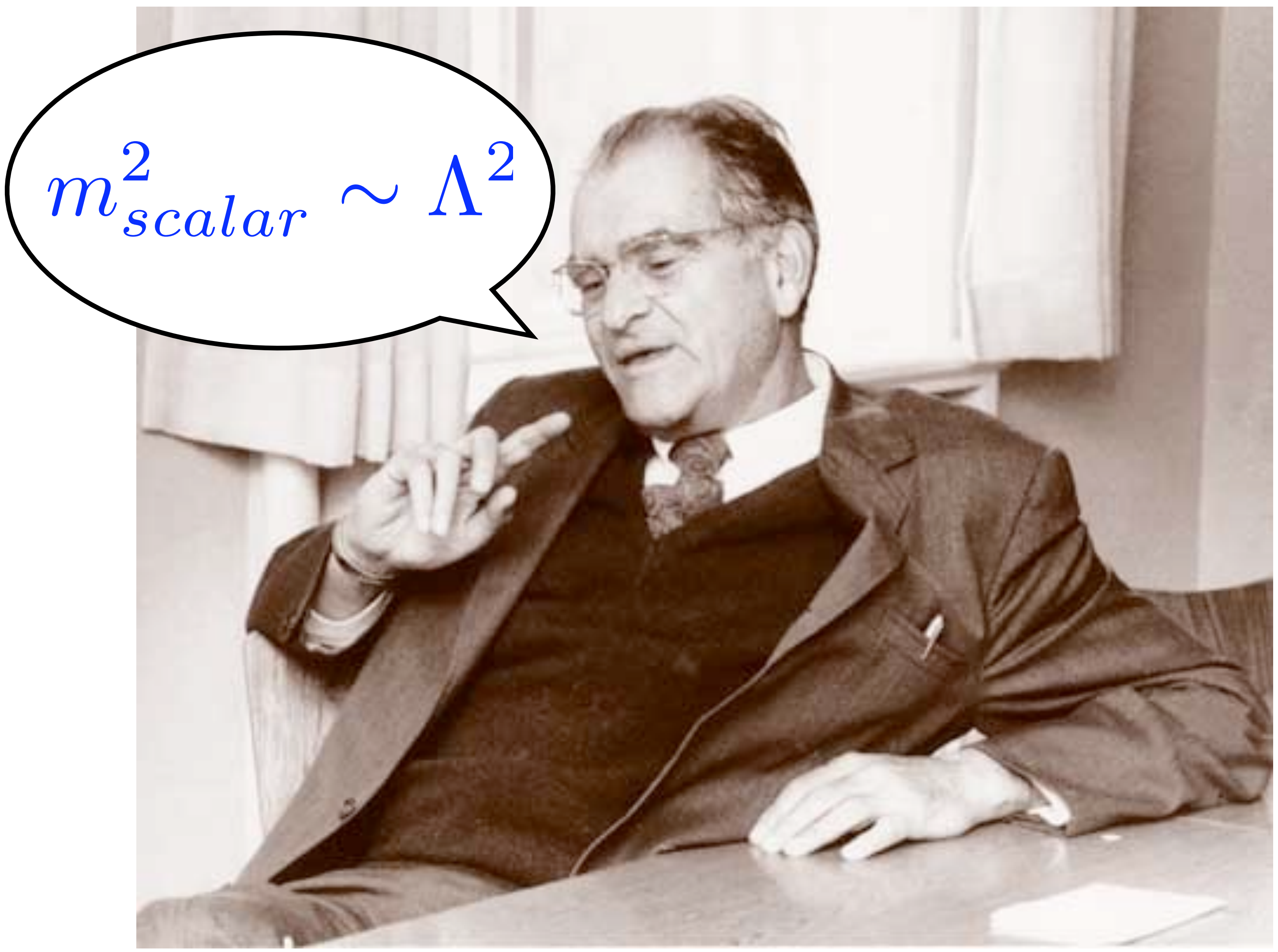
Extra Dimensions Outline

* Motivation: the Hierarchy Problem
* ADD, Little Higgs
* RS, MCH, Higgless, Gaugephobic Higgs
* Conclusions

What's the problem?

Weisskopf Phys. Rev.56 (1939) 72

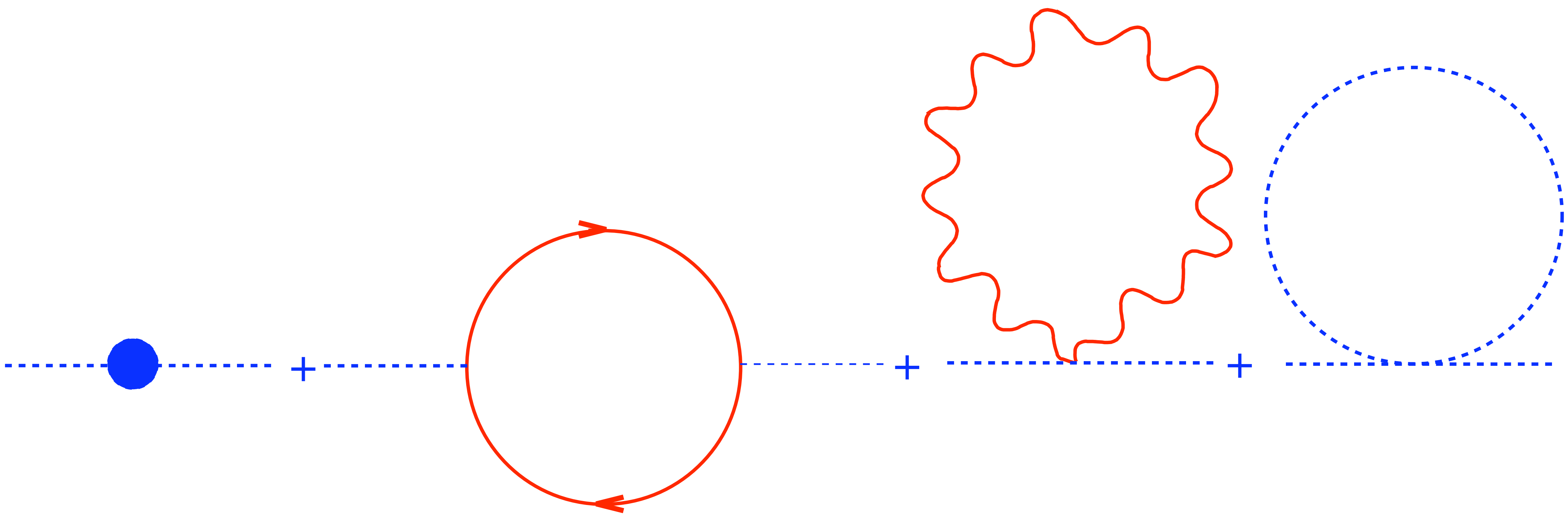
What's the problem?



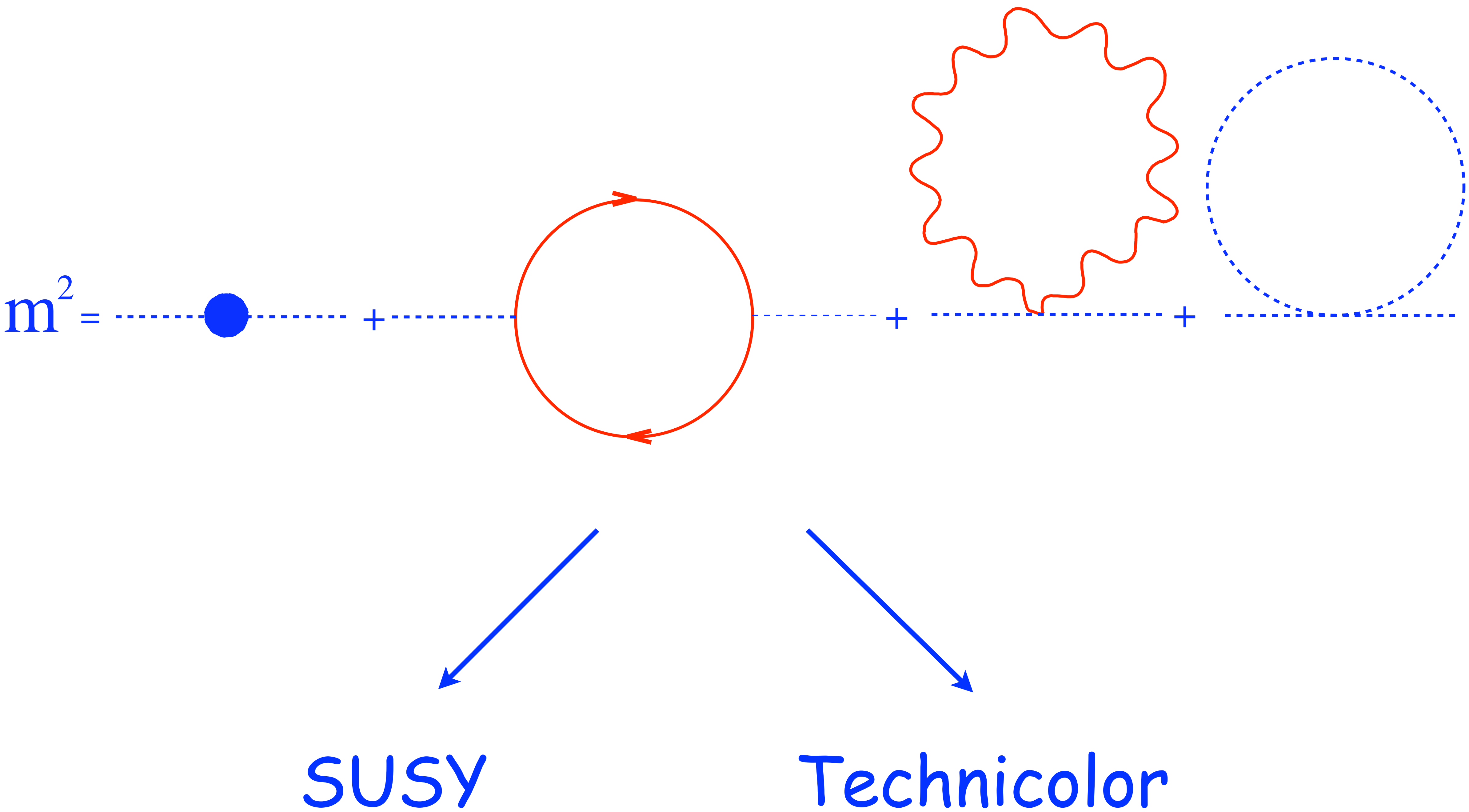
Weisskopf Phys. Rev.56 (1939) 72

Electroweak Symmetry

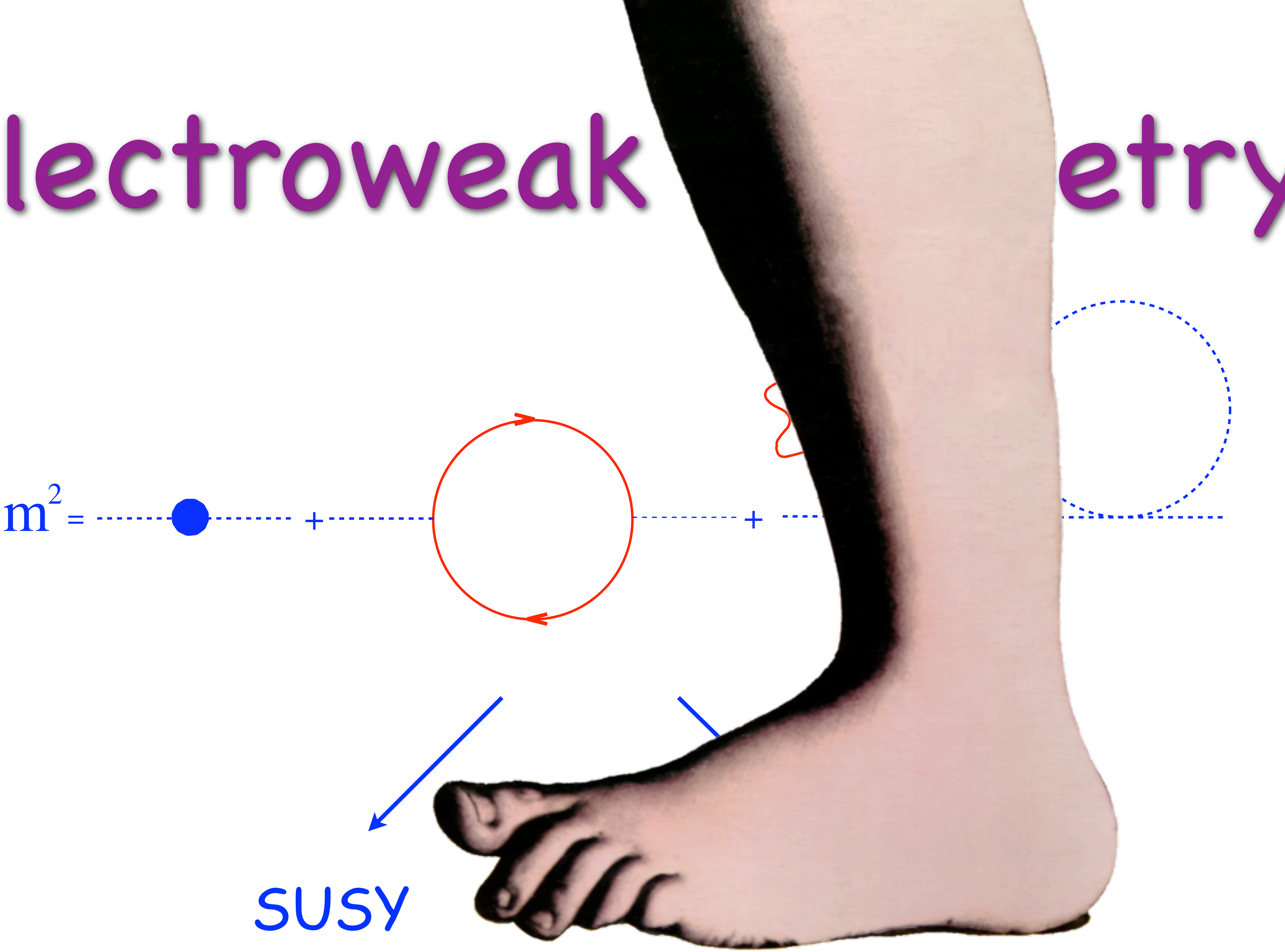
$m^2 =$



Electroweak Symmetry



Electroweak etry



Hierarchy Problem Now

SUSY

Technicolor

Hierarchy Problem Now

SUSY

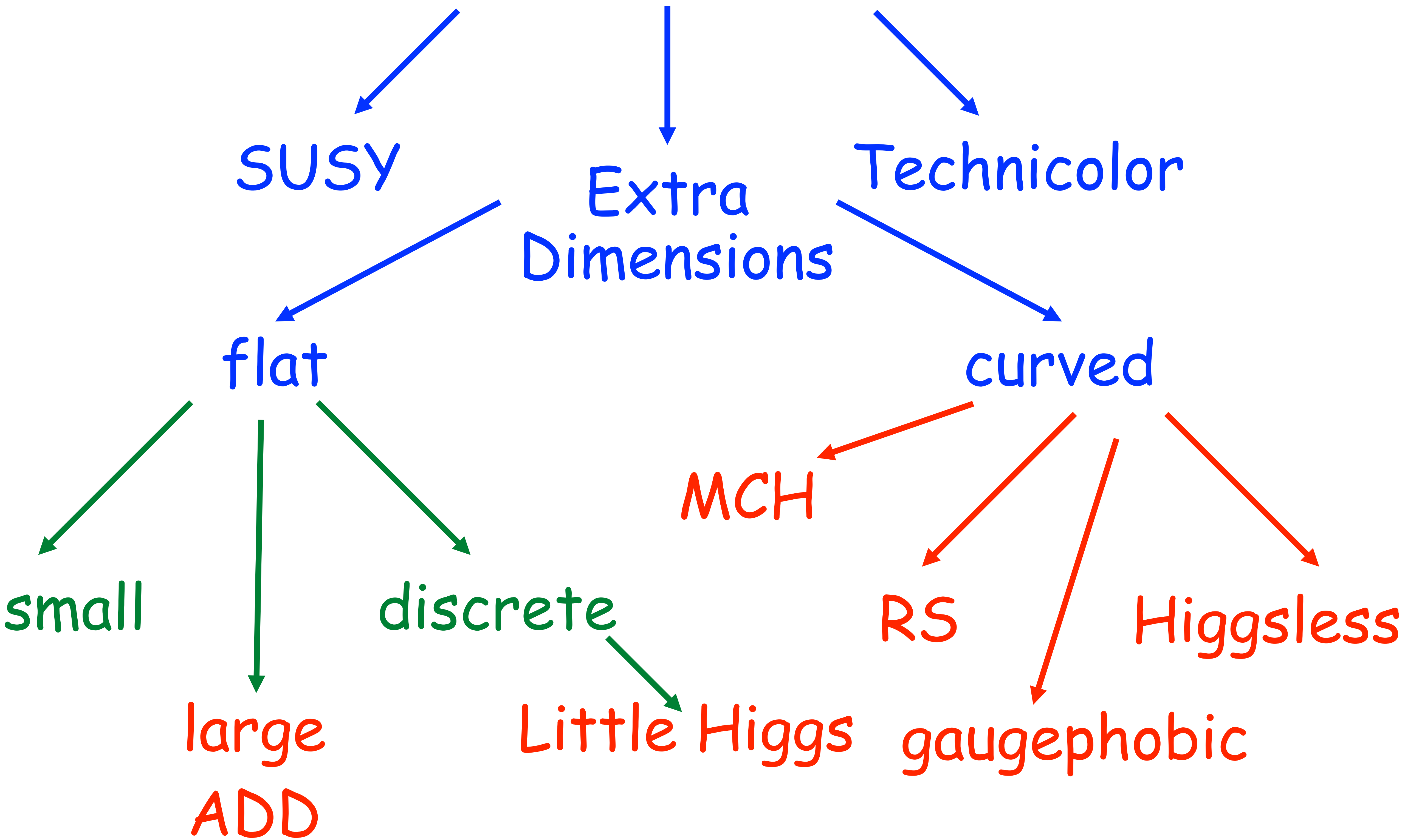
Extra Dimensions

Technicolor

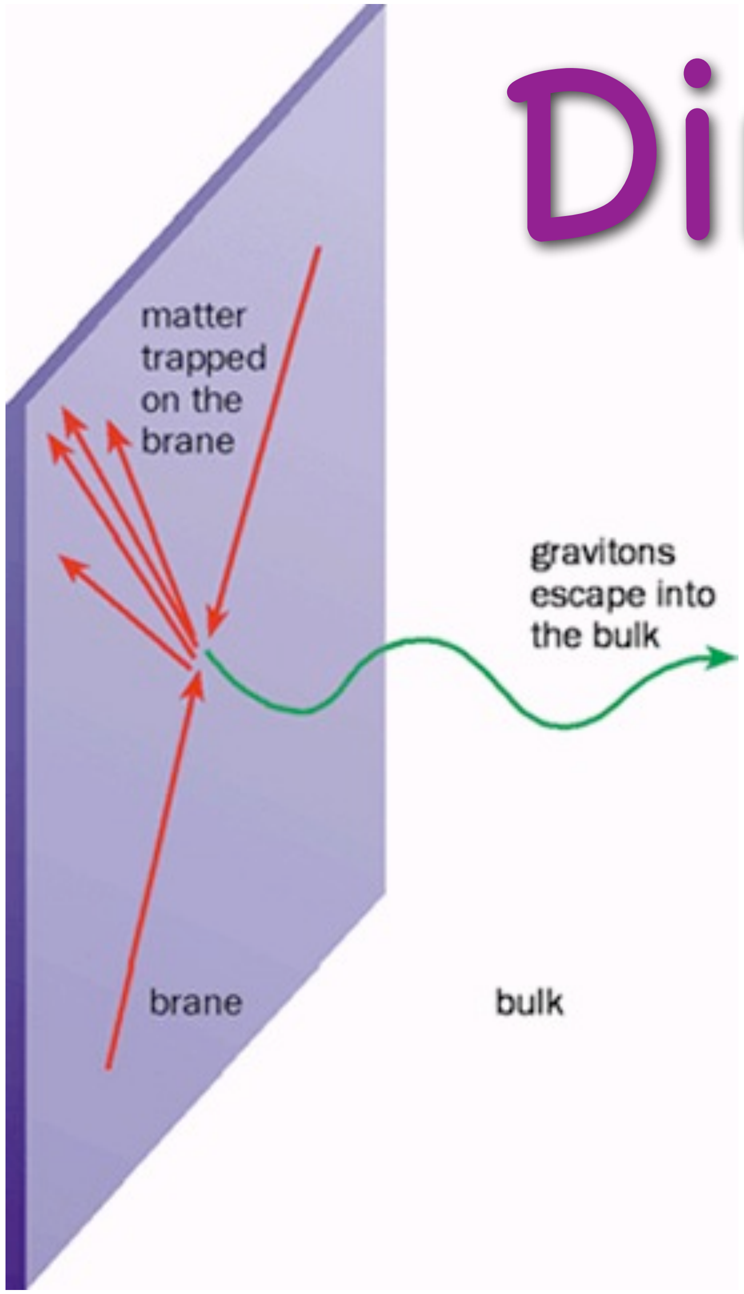
Hierarchy Problem Now

- SUSY
- Extra Dimensions
  - flat
  - curved
- Technicolor

Hierarchy Problem Now



Large Extra Dimensions

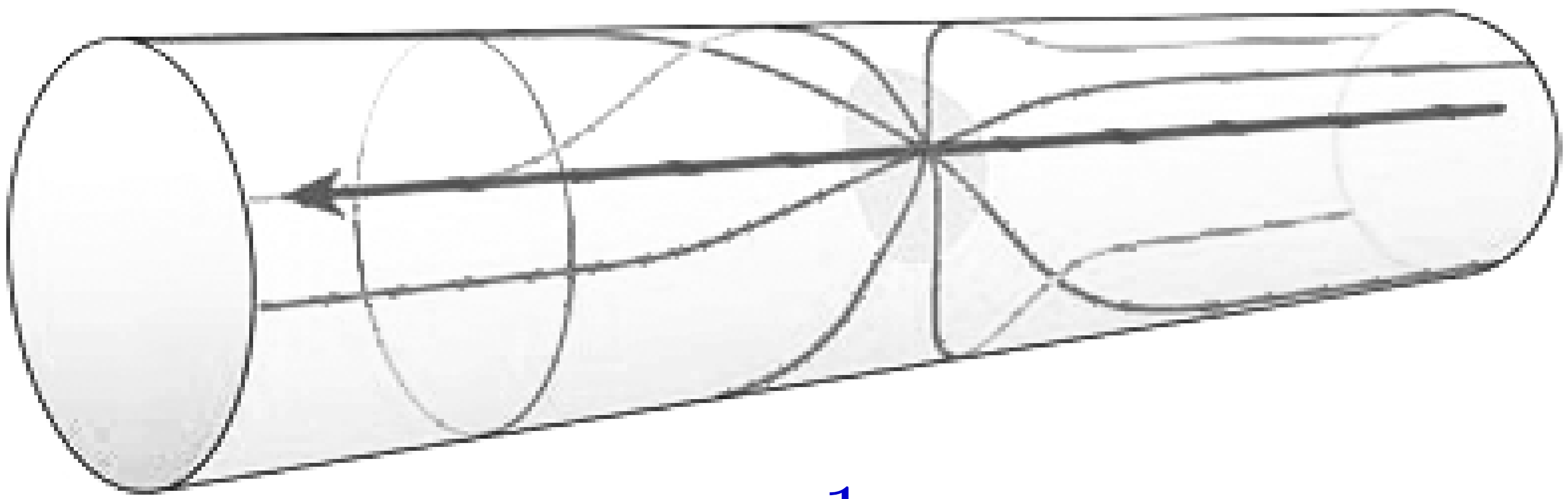


$$M_* = 1\,\mathrm{TeV}$$

Gravity gets strong at TeV
missing Energy signatures

Arkani-Hamed, Dimopoulos, Dvali   hep-ph/9803315

n Large Extra Dimensions



$$F_{\text{Grav}} = \frac{1}{M_*^{2+n}} \frac{m_1 m_2}{R^{2+n}}$$

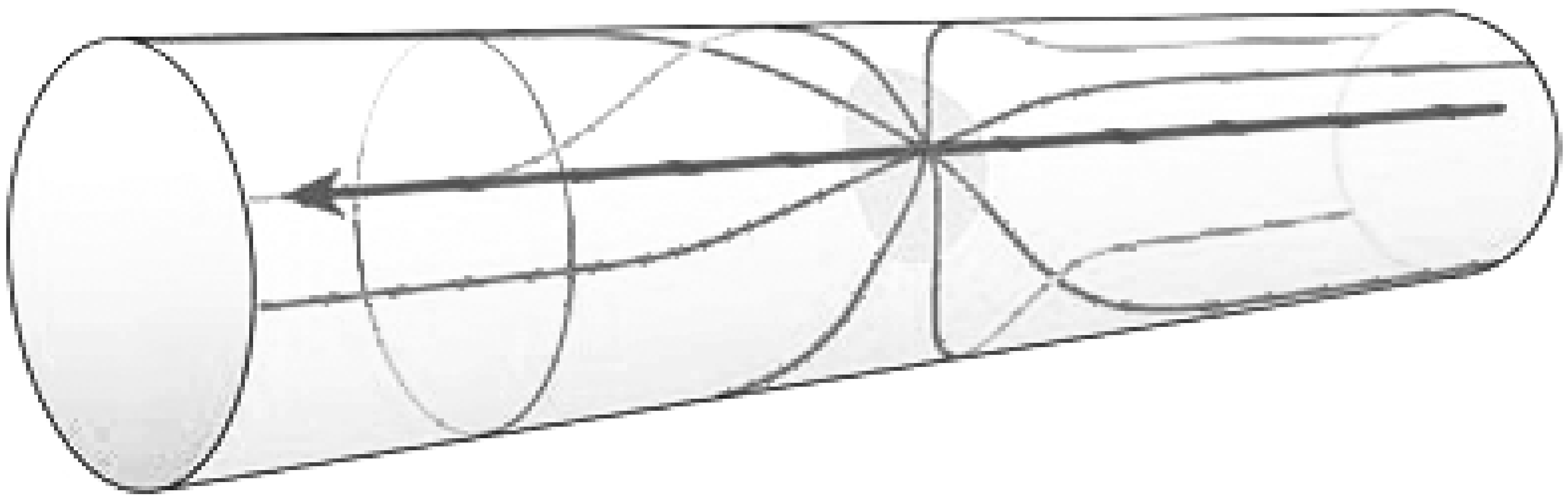
$r \gg L$

$$F_{\text{Grav}} = \frac{1}{M_*^{2+n}} \frac{m_1 m_2}{\text{Vol}_n \, r^2}$$

$$G_N = \frac{1}{M_*^{2+n} \text{Vol}_n}$$

Arkani-Hamed, Dimopoulos, Dvali hep-ph/9803315

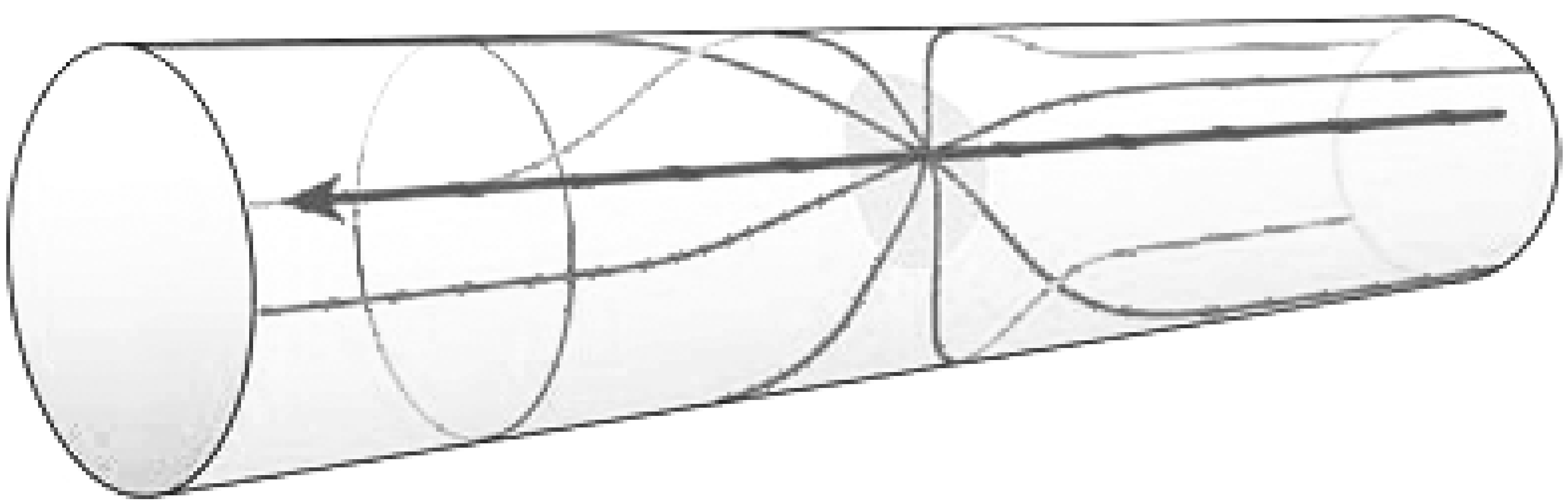
n Large Extra Dimensions



$$M_* = 1\,\mathrm{TeV}$$

$$\begin{aligned} n &= 1 \Rightarrow L \sim 10^{13}\,\mathrm{m} \\ n &= 2 \Rightarrow L \sim 1\,\mathrm{mm} \\ n &= 3 \Rightarrow L \sim 10^{-8}\,\mathrm{m} \\ &\vdots \end{aligned}$$

n Large Extra Dimensions



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$$\begin{aligned} n &= 1 \Rightarrow L \sim 10^{13}\,\mathrm{m} \\ n &= 2 \Rightarrow L \sim 1\,\mathrm{mm} \\ n &= 3 \Rightarrow L \sim 10^{-8}\,\mathrm{m} \\ &\vdots \end{aligned}$$

Little Hierarchy

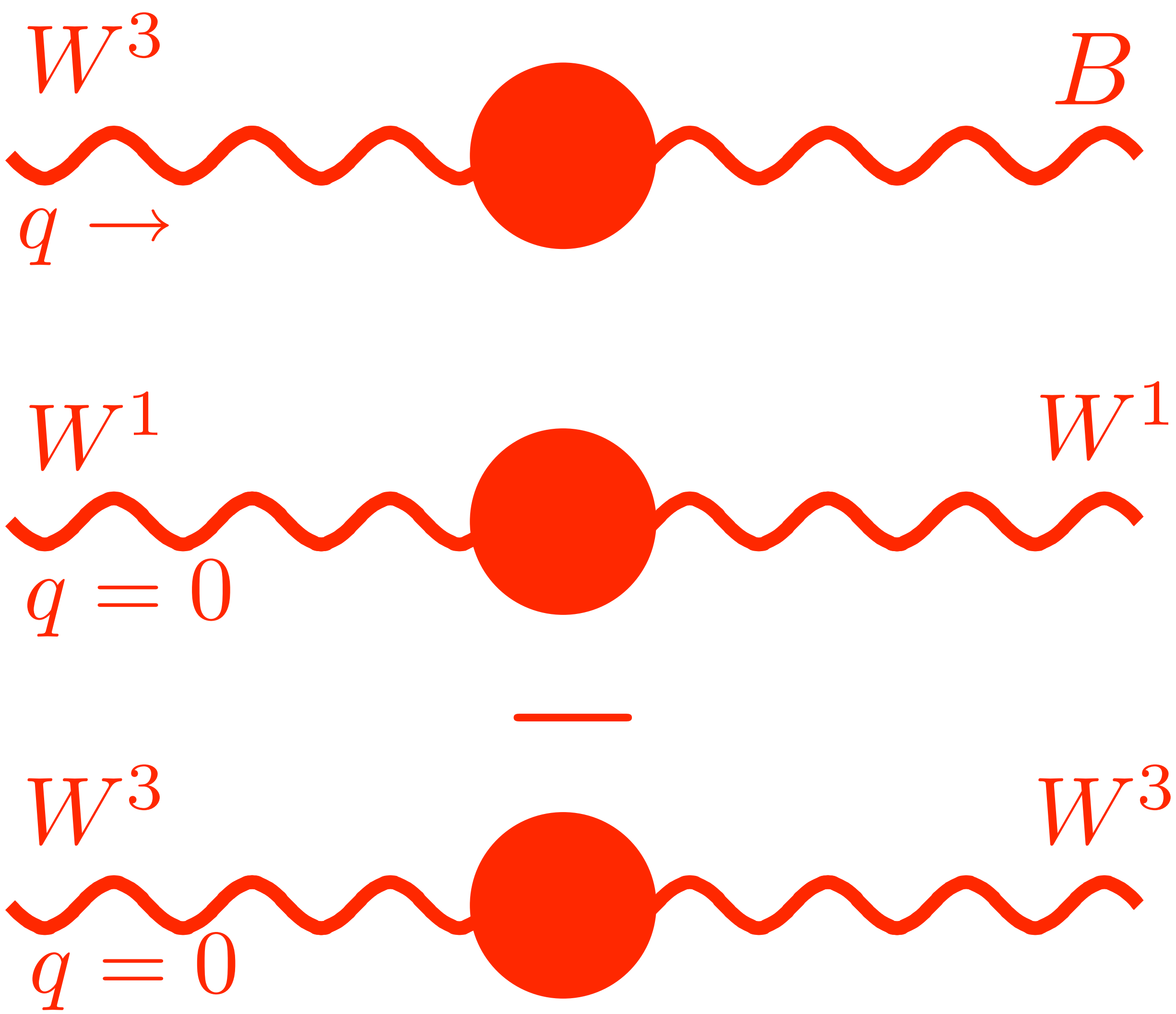
$$\mathcal{L}_{\rm eff} = \sum_i \frac{c_i}{\Lambda_i^2} \mathcal{O}_i$$

	c=+1	c=-1
$H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	9.0	13
$\lvert H^\dagger D_\mu H \rvert^2$	4.2	7.0
$(\overline{L} \gamma^\mu \sigma^a L)^2$	4.1	4.4
$i \overline{L} \gamma^\mu L H^\dagger D_\mu H$	14	8.0

Barbieri, Strumia hep-ph/0007265

Precision Tests

new physics changes vacuum polarizations



$$-\frac{gg'}{16\pi}\, S\, F^3_{\mu\nu} F_B^{\mu\nu}$$

$$-\frac{v^2}{4} T Z^\mu Z_\mu$$

Precision Tests

$$-\frac{gg'}{16\pi}\,S\,F^3_{\mu\nu}F^{\mu\nu}_B$$

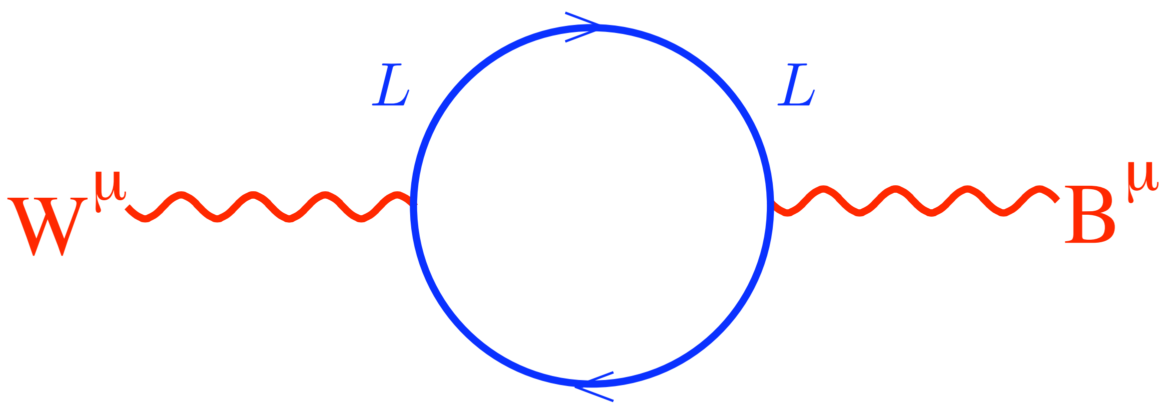
$$-\frac{v^2}{4}T\,Z^\mu Z_\mu$$

$$S = 16\pi\,\frac{d}{dq^2}\left(\Pi_{33}(q^2) - \Pi_{33}(q^2)\right)$$

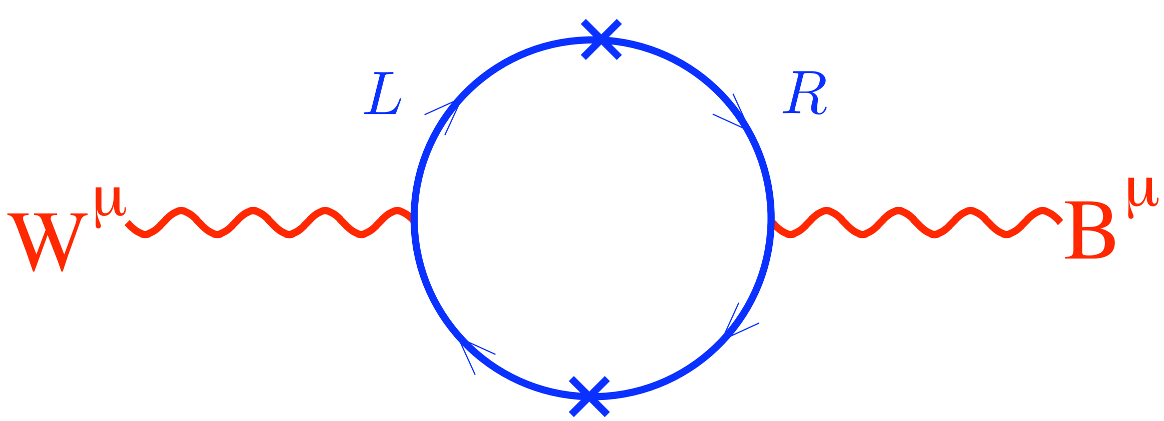
$$T = \frac{\Delta\rho}{\alpha} = \frac{e^2}{s_w^2\,M_W^2}\left(\Pi_{11}(0) - \Pi_{33}(0)\right)$$

Perturbative Estimate

degenerate fermions



$$\mathrm{Tr}\, T_L^3 Y_L = Y_L \,\mathrm{Tr}\, T_L^3 = 0$$



$$\mathrm{Tr}\, T_L^3 Y_R = \frac{1}{2}\left(Y_R^u - Y_R^d\right) = \frac{1}{2}$$

$$S_{deg.} = \frac{N}{6\pi}$$

Perturbative Estimate

non-degenerate fermions

$$S = \frac{N}{6\pi}\left(Y_L \ln\left(\frac{m_u^2}{m_d^2}\right) + 1\right)$$

$$T = \frac{N}{16\pi s_W^2 M_W^2}\left(m_u^2 + m_d^2 - 2\frac{m_u^2 m_d^2}{m_u^2 - m_d^2}\ln\left(\frac{m_u^2}{m_d^2}\right)\right)$$

for $m_u \gg m_d$

$$T \approx \frac{N}{16\pi s_W^2}\frac{m_u^2}{M_W^2}$$

Non-Perturbative

$$\mathcal{L}_2 = \frac{f_\pi^2}{4}\mathrm{Tr}\, D_\mu \Sigma^\dagger D^\mu \Sigma$$

$$\mathcal{L}_4 = L_{10}\mathrm{Tr}\, \Sigma^\dagger F_{L\mu\nu}\Sigma F_R^{\mu\nu} + \ldots$$

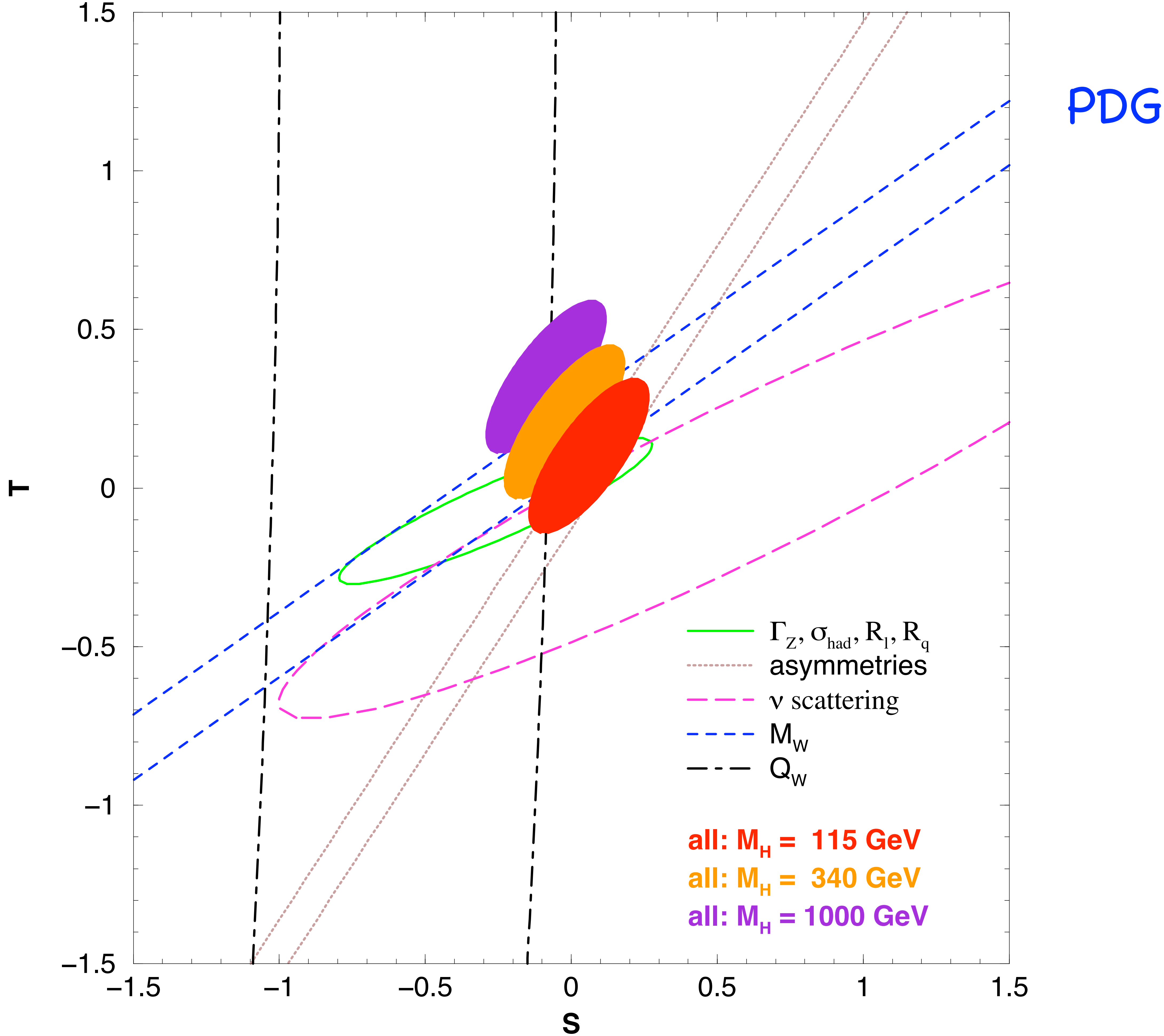
measure L_{10} in $\pi \to \gamma e \nu$

$$S_{\mathrm{non-pert.}} \approx 2 \times S_{\mathrm{pert.}}$$

for one doublet and $N = 2$

$$S \sim \frac{1}{3\pi} \text{ to } \frac{2}{3\pi} = 0.1 \text{ to } 0.2$$

Holdom, JT Phys. Lett. B 247 (1990) 88


PDG
T
S
$\Gamma_Z, \sigma_{had}, R_l, R_q$
asymmetries
ν scattering
M_W
Q_W
all: M_H = 115 GeV
all: M_H = 340 GeV
all: M_H = 1000 GeV

Custodial Symmetry

$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

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

custodial symmetry can forbid T

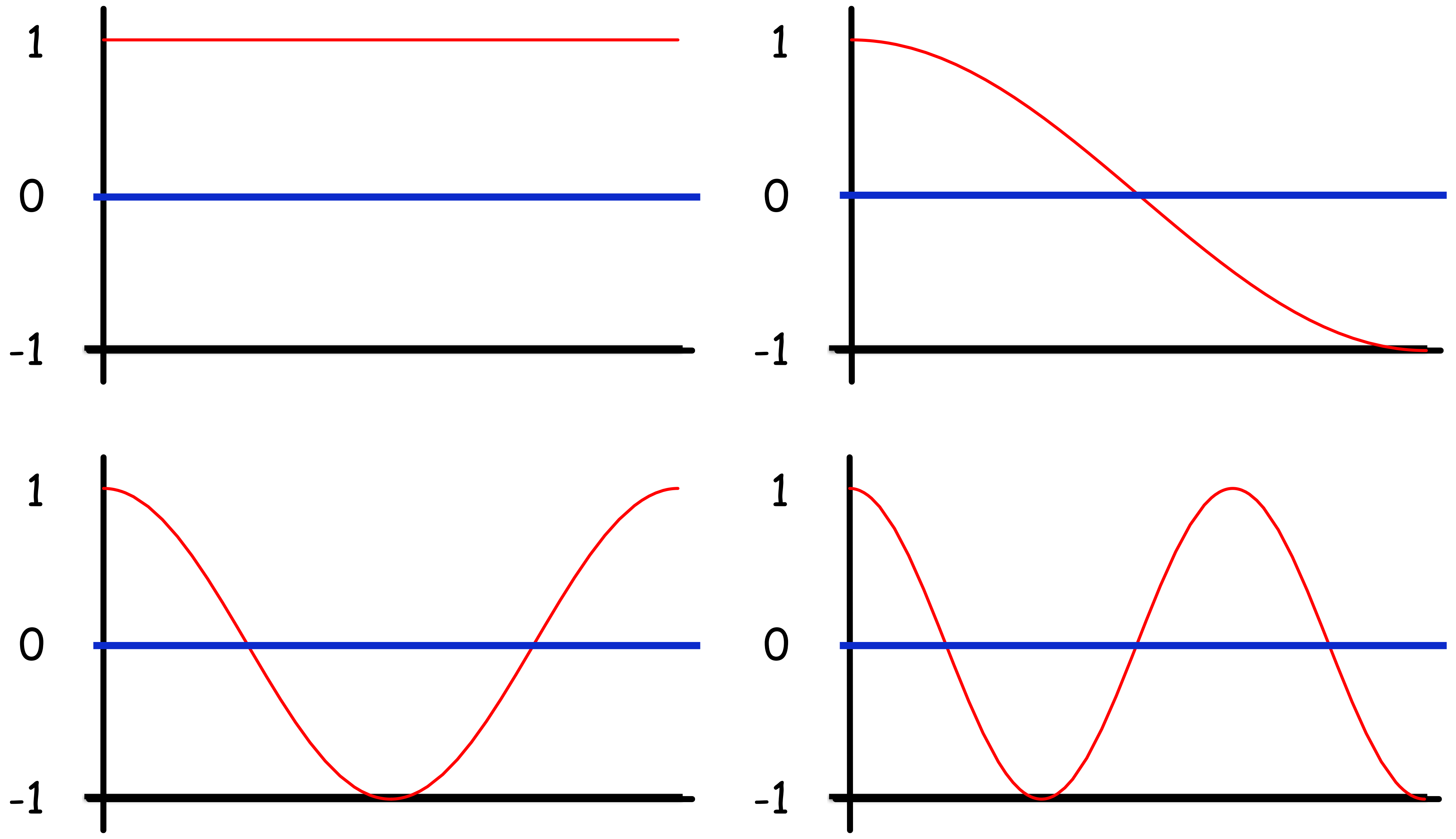
what symmetry can forbid S?

Little Higgs

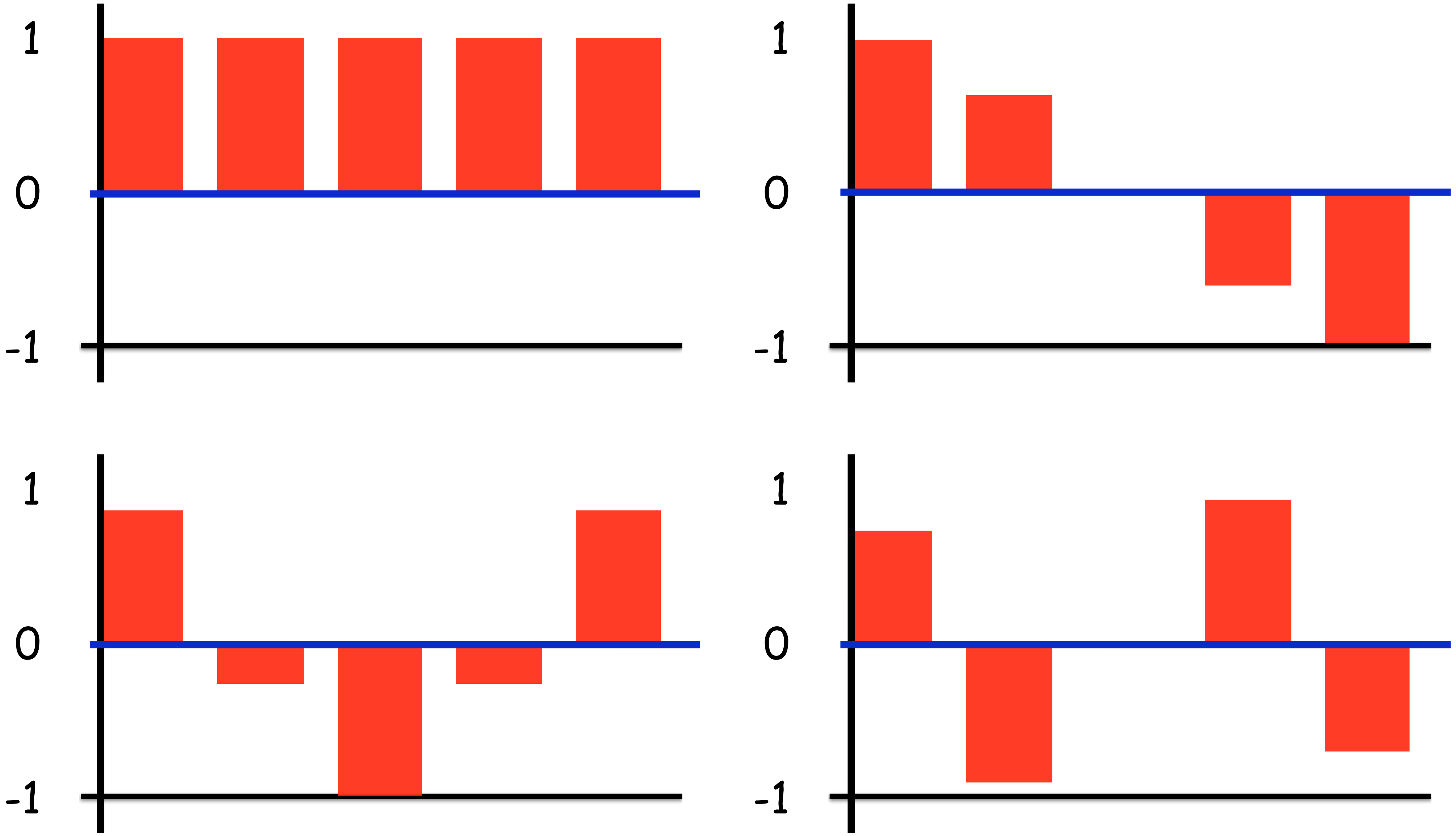
5D gauge boson has an extra polarization
in 4D it is a scalar
5D gauge invariance keeps it massless

can we use this for the Higgs?

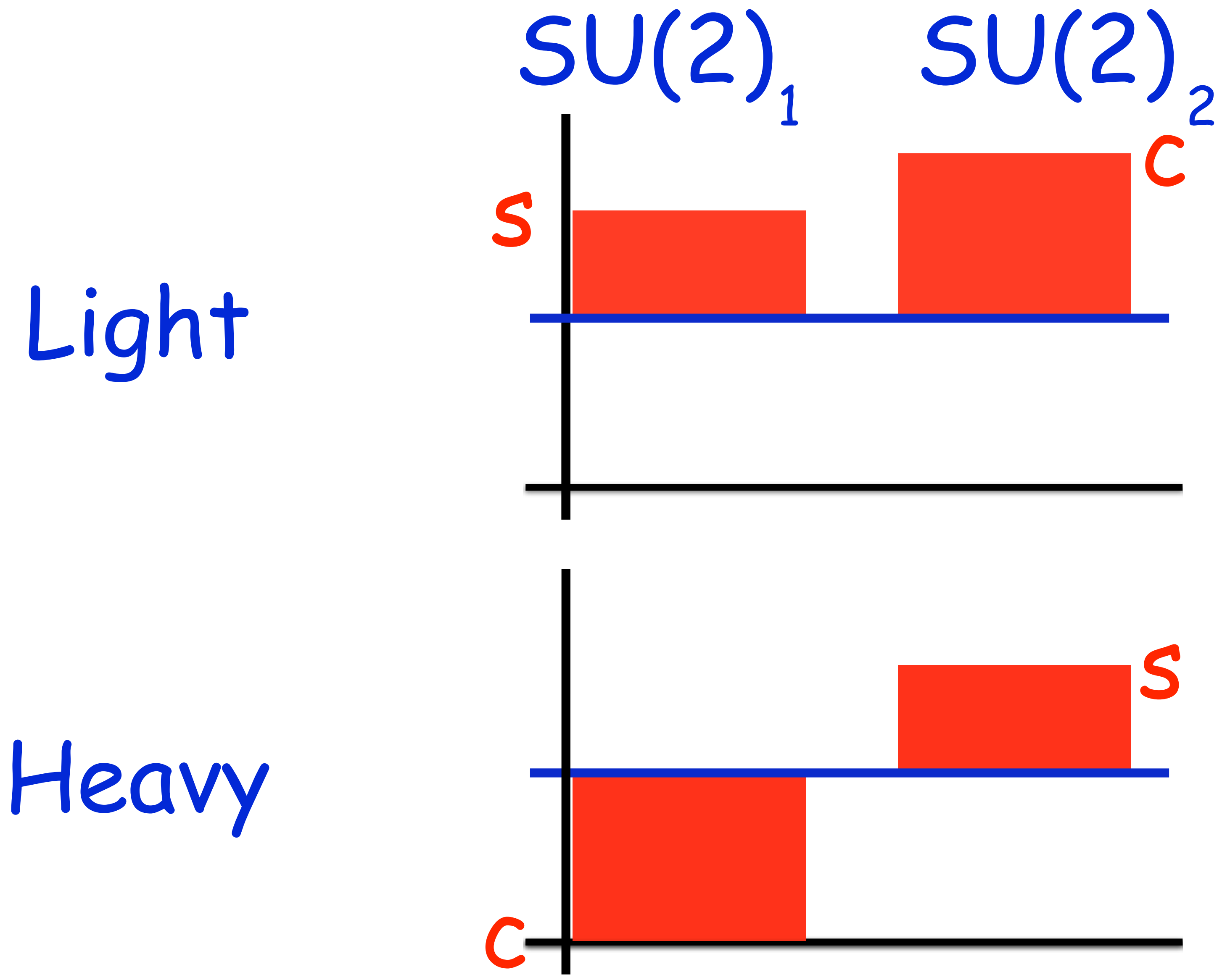
Kaluza-Klein Modes



Discrete Extra Dim.



Two Sites



$M_{Heavy} \sim f$

Little Higgs

The "little hierarchy" problem is why is the Higgs light compared to a 10 TeV cutoff

If the Higgs is a Pseudo-Goldstone boson it should have a suppressed mass

If symmetry is restored when either of two interactions vanish

$$m_H^2 \propto g_1^2 g_2^2$$

No quadratic divergence at one loop

Littlest Higgs

$$SU(5) \to SO(5)$$

$$(5^2 - 1) - \frac{1}{2} 5 \cdot 4 = 14 \text{ GB's}$$

$$\Sigma(x) = e^{2i\Pi/f} \begin{pmatrix} & & & 1 & \\ & & & & 1 \\ & & 1 & & \\ 1 & & & & \\ & 1 & & & \end{pmatrix}$$

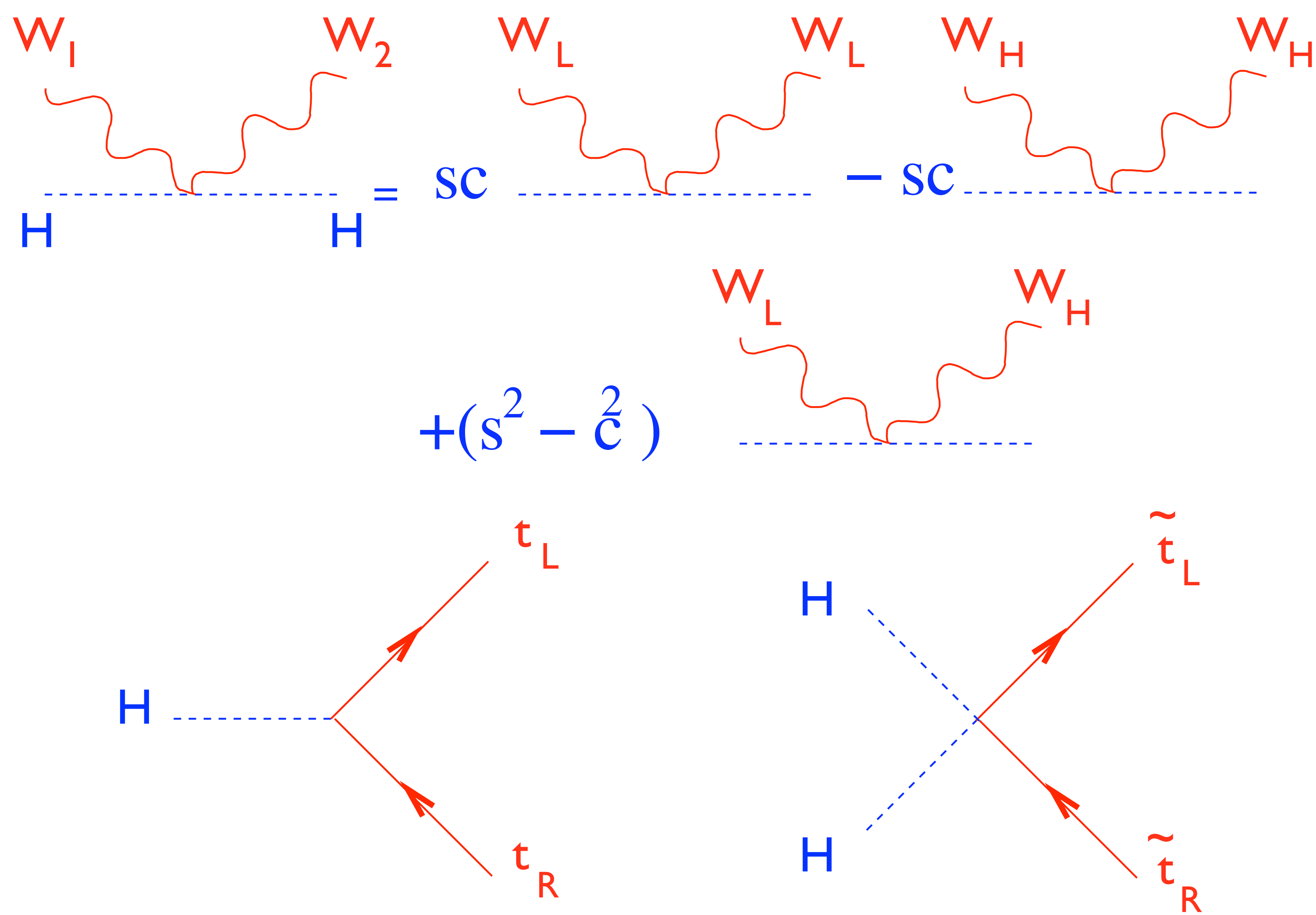
$$SU(2)_1 \quad SU(2)_2$$

$$SU(2)_1 \times SU(2)_2 \to SU(2)_L$$

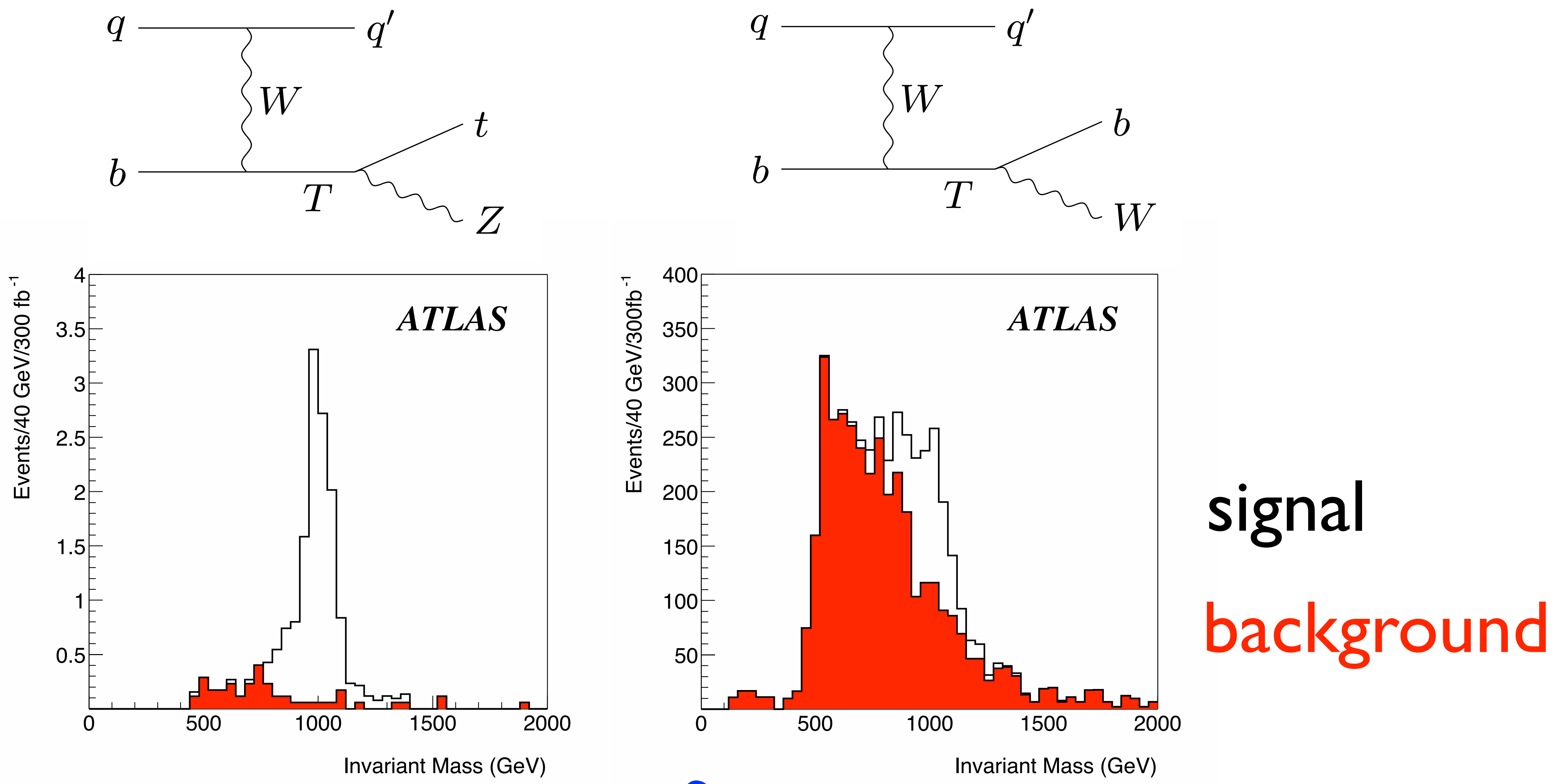
$$U(1)_1 \times U(1)_2 \to U(1)_Y$$

Arkani-Hamed, Cohen, Katz, Nelson hep-ph/0206021

Littlest Higgs Mass



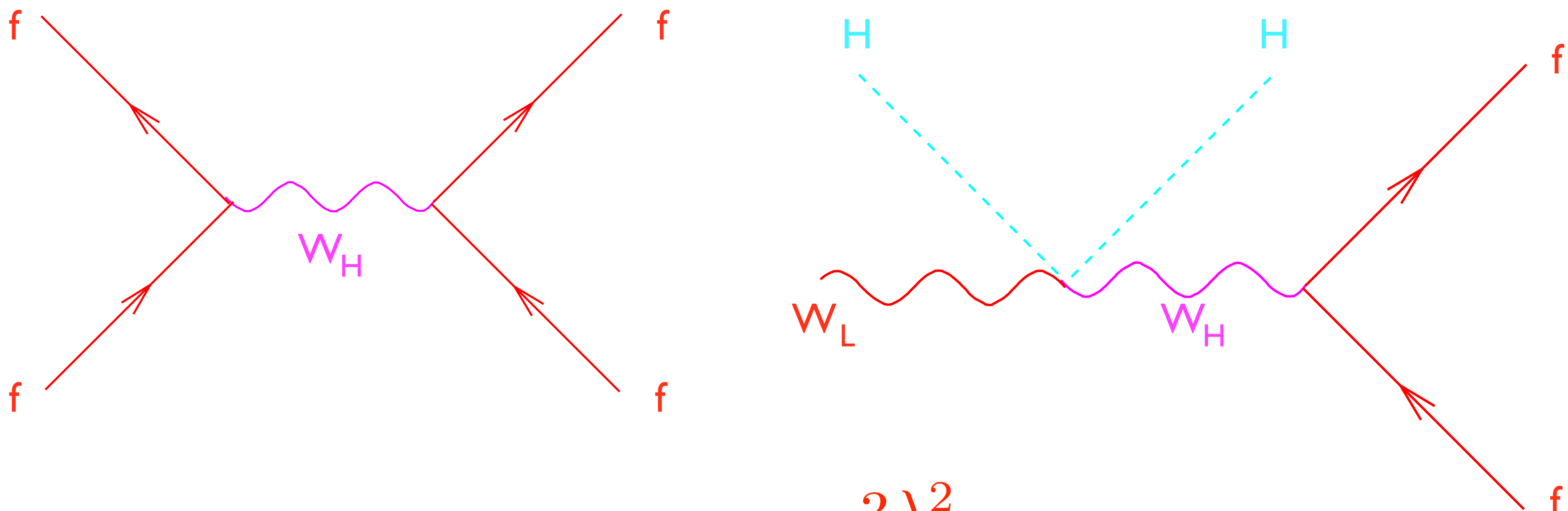
Top Partner



reach of 2 TeV

Azuelos et. al. hep-ph/0402037

Low Energy Effects



$$\Delta m_H^2 \sim -\frac{3\lambda_t^2}{2\pi^2} f^2$$

% level fine tuning

Csaki, Hubisz, Kribs, Mead JT hep-ph/0211124

T-Parity

$$\begin{aligned} SM &\rightarrow +SM \\ W_H, Z_H, A_H, \phi &\rightarrow -(W_H, Z_H, A_H, \phi) \end{aligned}$$

bonus: dark matter candidate

Cheng, Low hep-ph/0308199

UV Completion

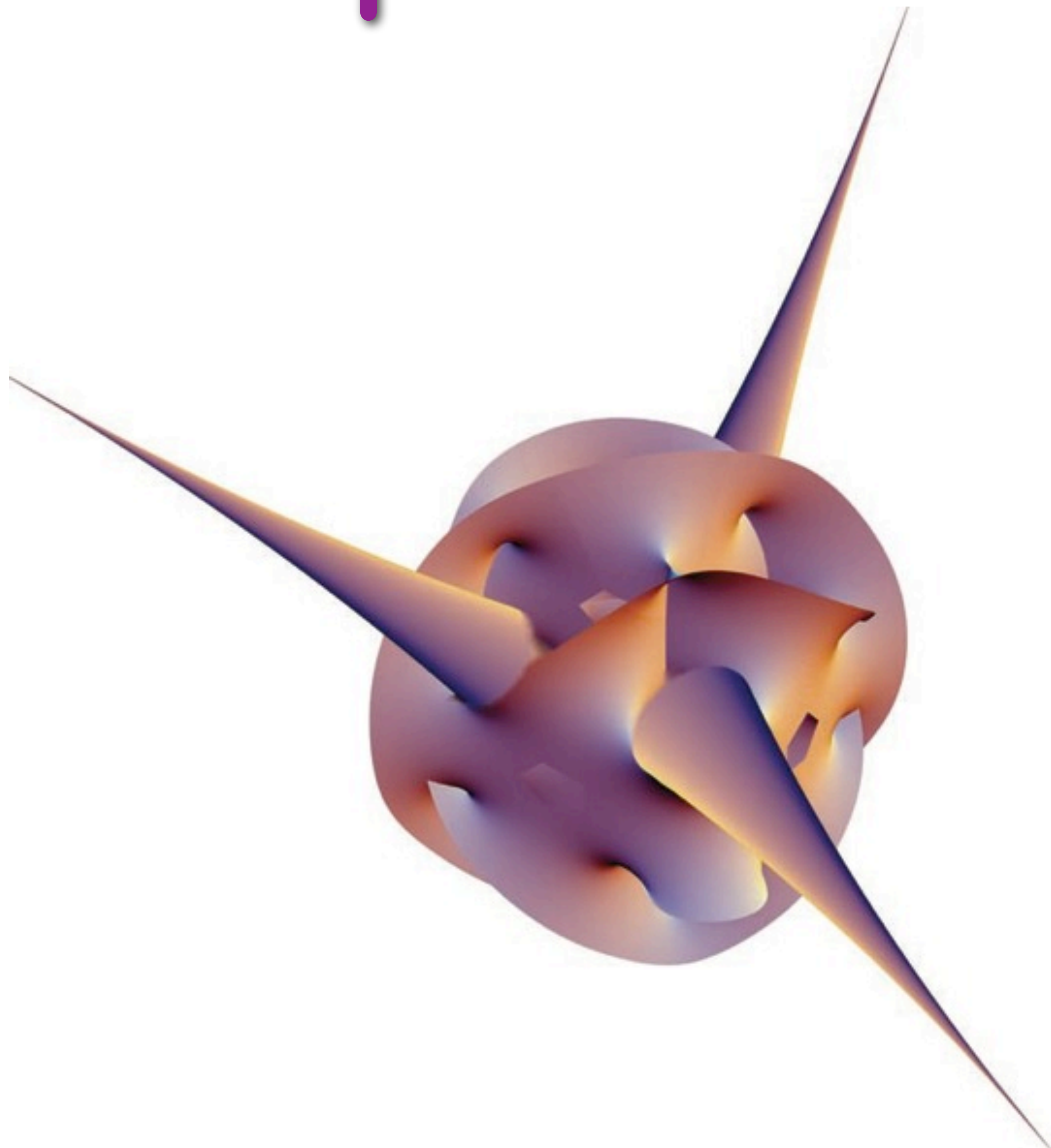
one generation:

a)	$SU(5)$	$SU(2)_3$	$U(1)_3$	b)	$SU(5)$	$SU(2)_3$	$U(1)_3$	c)	$SU(5)$	$SU(2)_3$	$U(1)_3$
Q_1	$\bar{\square}$	1	$+2/3$	Q'_1	$\bar{\square}$	1	$-2/3$	L_1	$\bar{\square}$	1	0
Q_2	$\square$	1	$+2/3$	Q'_2	$\square$	1	$-2/3$	L_2	$\square$	1	0
q_3	1	$\square$	$-1/6$	q'_3, q''_3	1	$\square$	$+1/6$	ℓ_3	1	$\square$	$+1/2$
q_4	1	$\square$	$-7/6$	q'_4	1	$\square$	$+7/6$	ℓ_4	1	$\square$	$-1/2$
q_5	1	$\square$	$-7/6$	q'_5	1	$\square$	$+7/6$	ℓ_5	1	$\square$	$-1/2$
U_{R1}	1	1	$-2/3$	U'_{R1}	1	1	$+2/3$	E_{R1}	1	1	0
U_{R2}	1	1	$-2/3$	U'_{R2}	1	1	$+2/3$	E_{R2}	1	1	0
u_R	1	1	$-2/3$					e_R	1	1	$+1$
d_R	1	1	$+1/3$					$(\nu_R$	1	1	$0\ )$

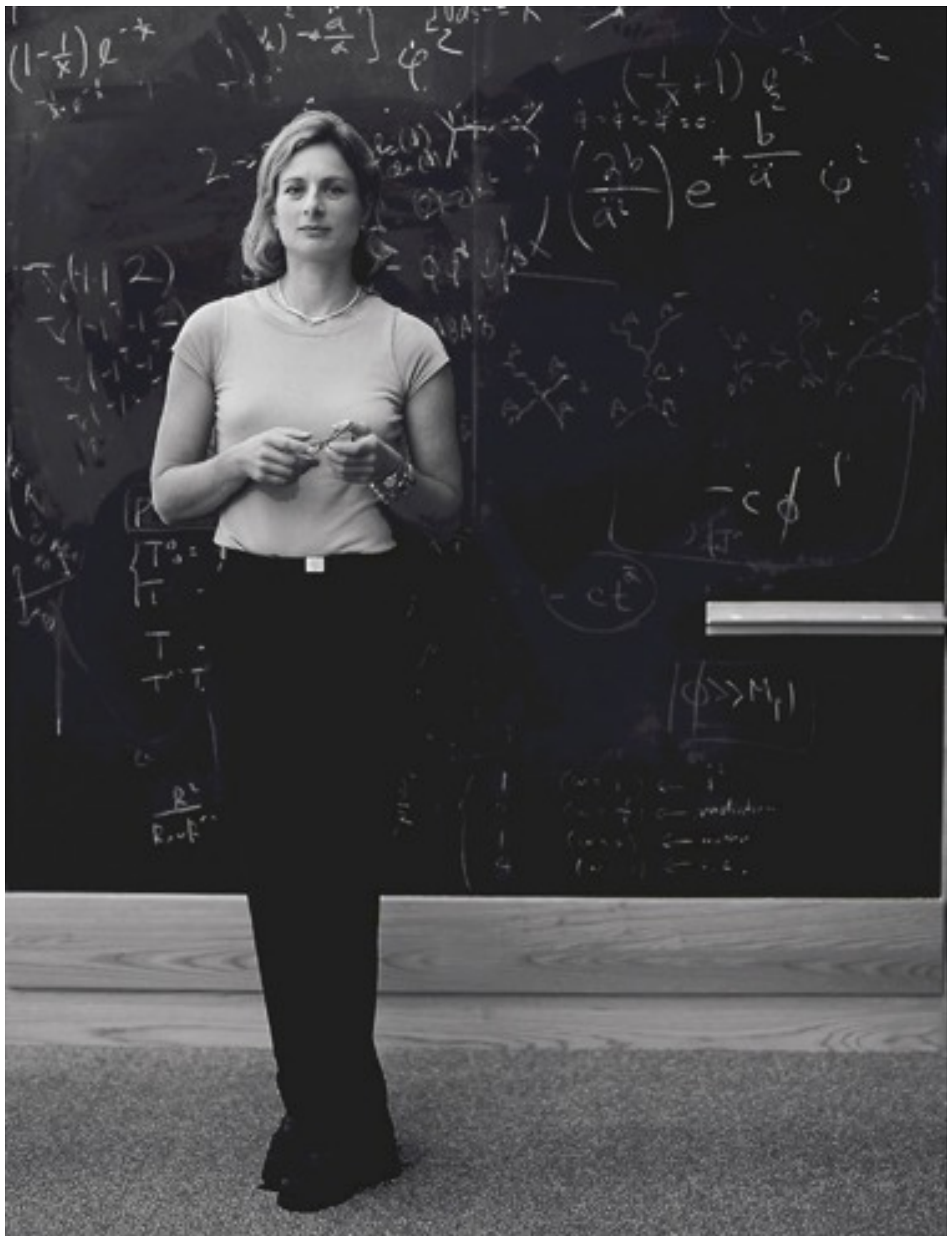
then add SUSY or
Warped Extra Dimensions

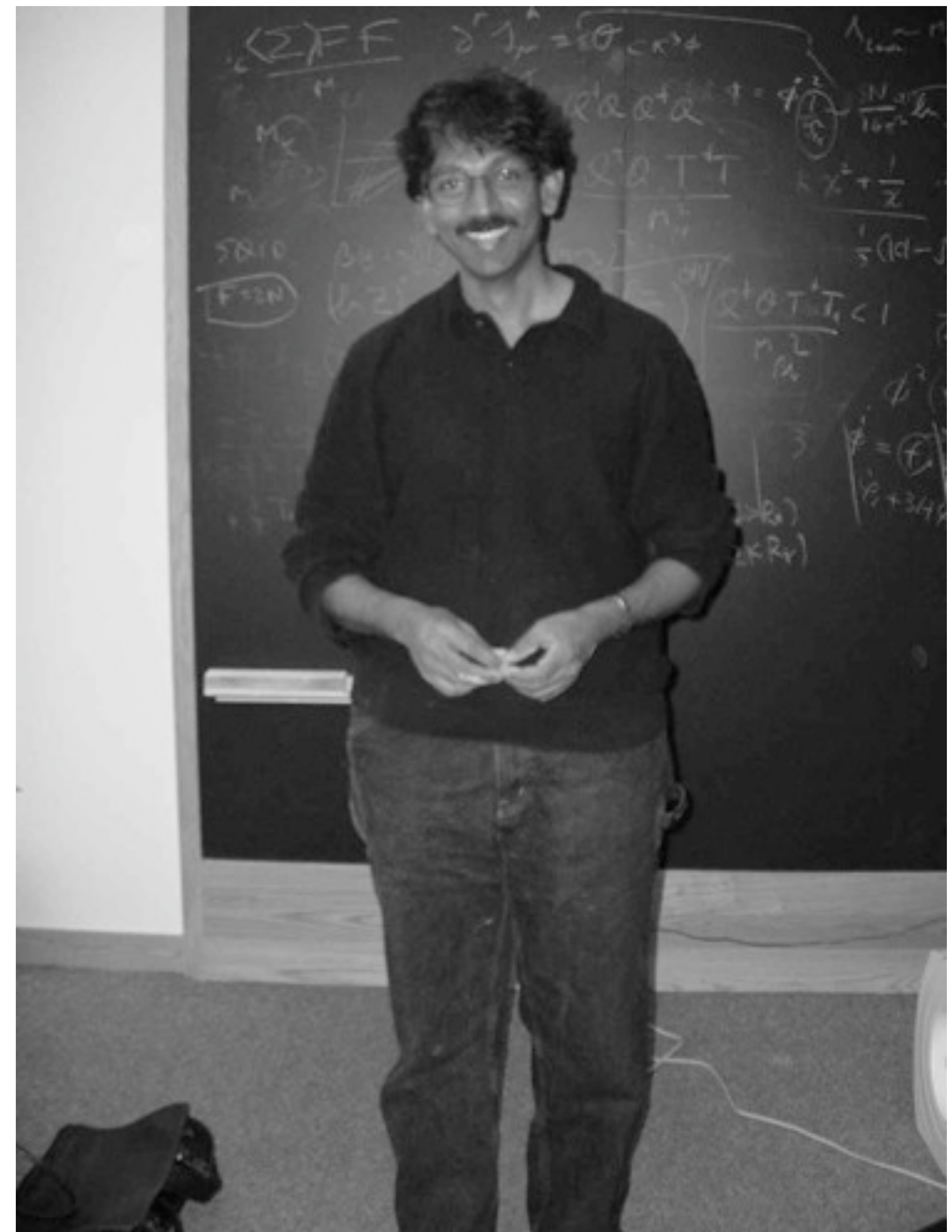
Csaki, Heinonen, Perelstein,
Spethmann hep-ph/0804.0622

Warped Throats



Randall-Sundrum





Randall-Sundrum

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

fermions
gauge bosons
Higgs

Planck

TeV

hep-ph/9905221

Randall-Sundrum

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

fermions
gauge bosons

Higgs

Planck

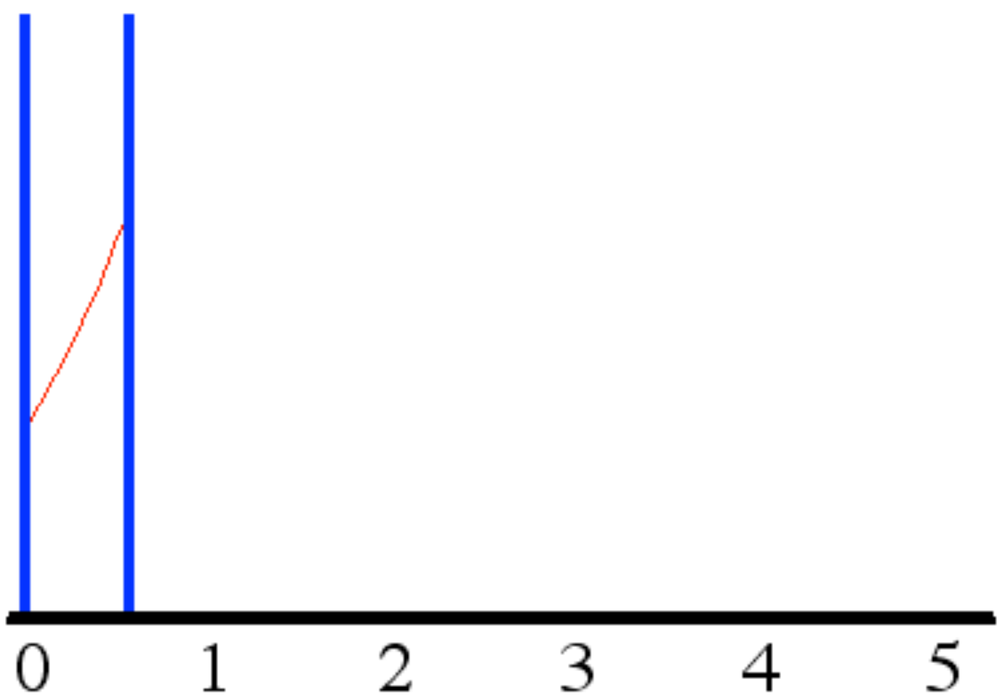
TeV

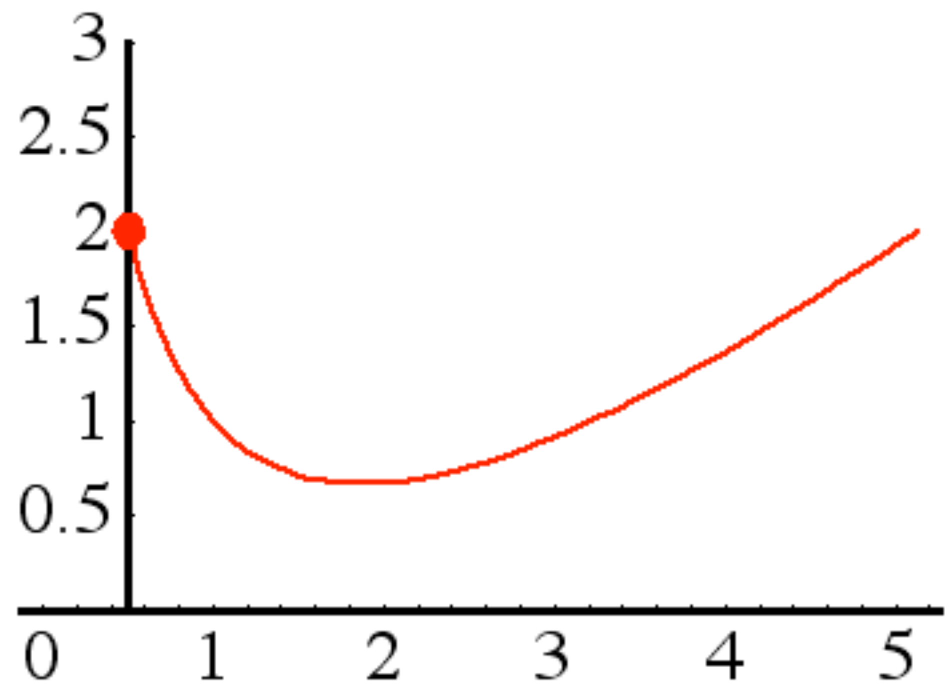
Stabilization

Planck

Goldberger, Wise hep-ph/9907218

Stabilization

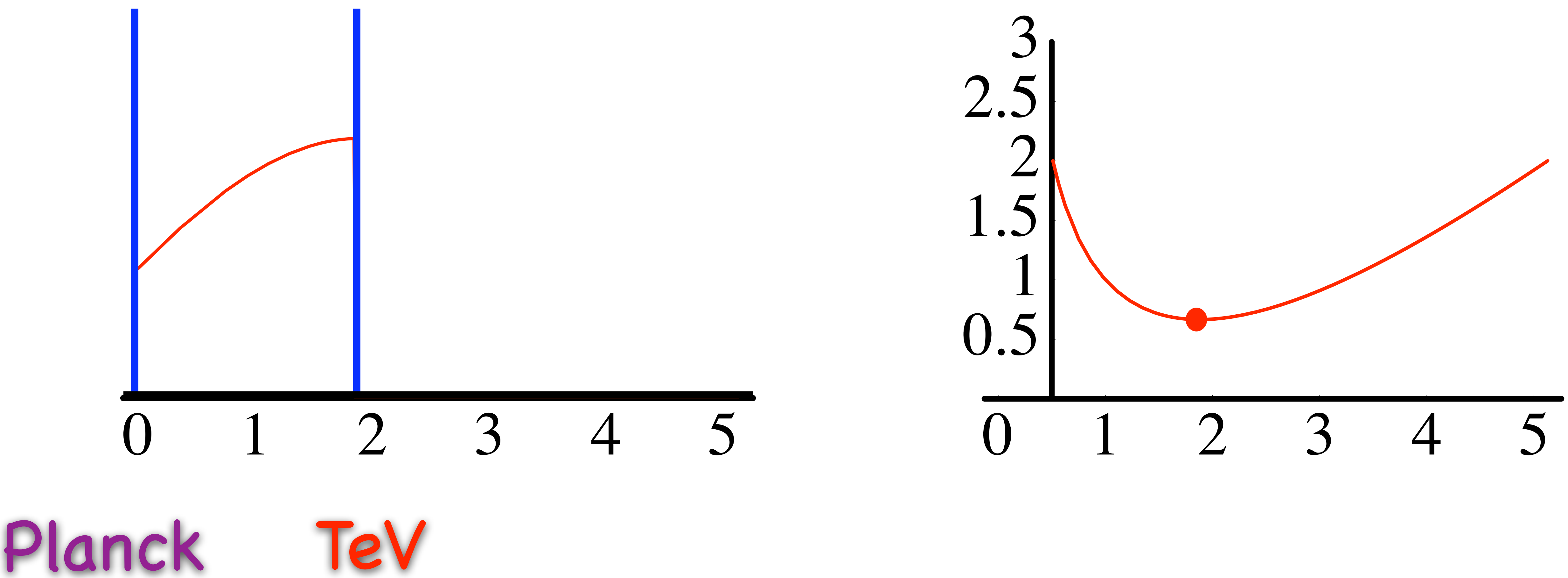




Planck

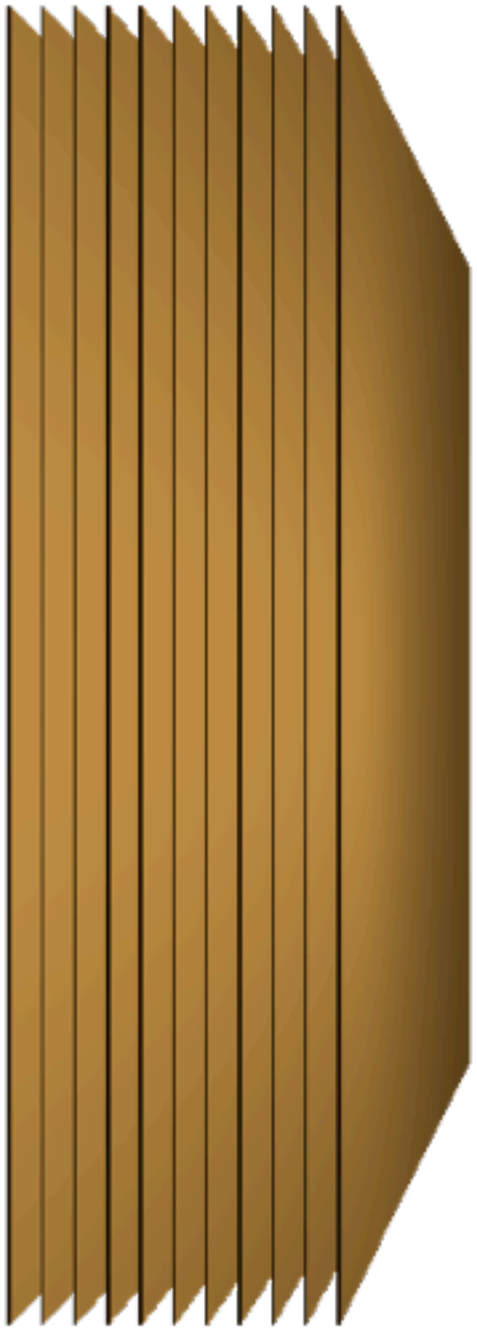
Goldberger, Wise hep-ph/9907218

Stabilization



Goldberger, Wise hep-ph/9907218

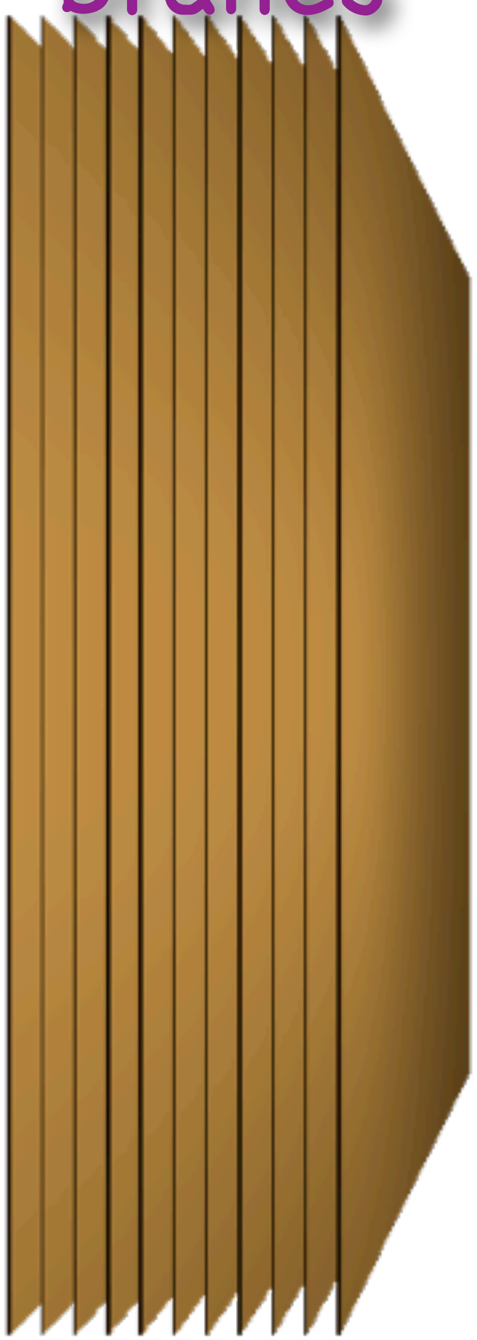
Maldacena Conjecture



Maldacena Conjecture

3-dimensional

branes



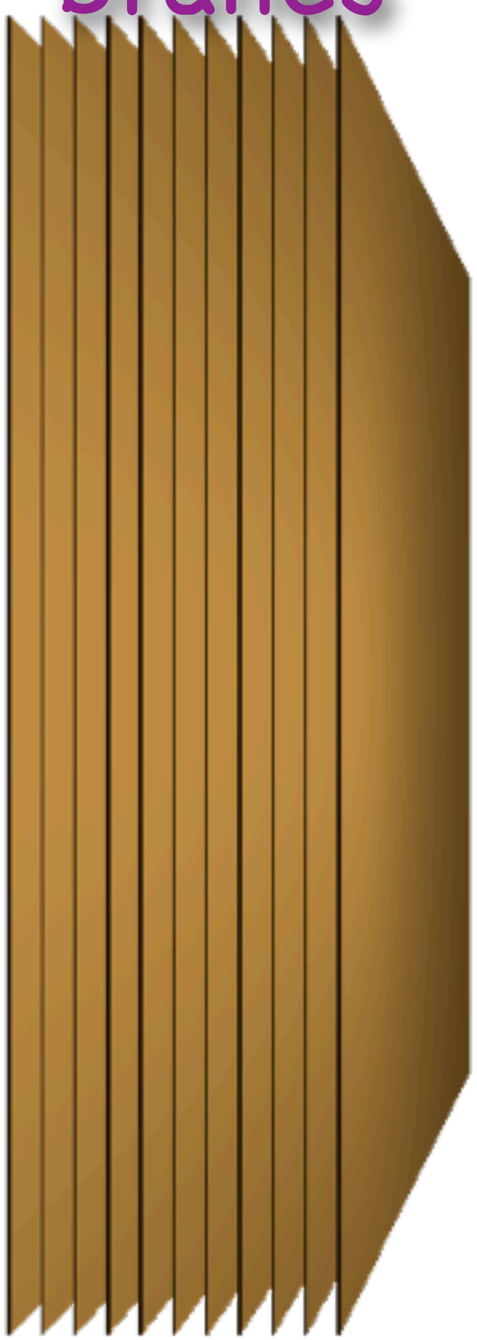
Four Dimensional strongly coupled SU(N) gauge theory

Low Energy

Large N, g^2 N

Maldacena Conjecture

3-dimensional branes



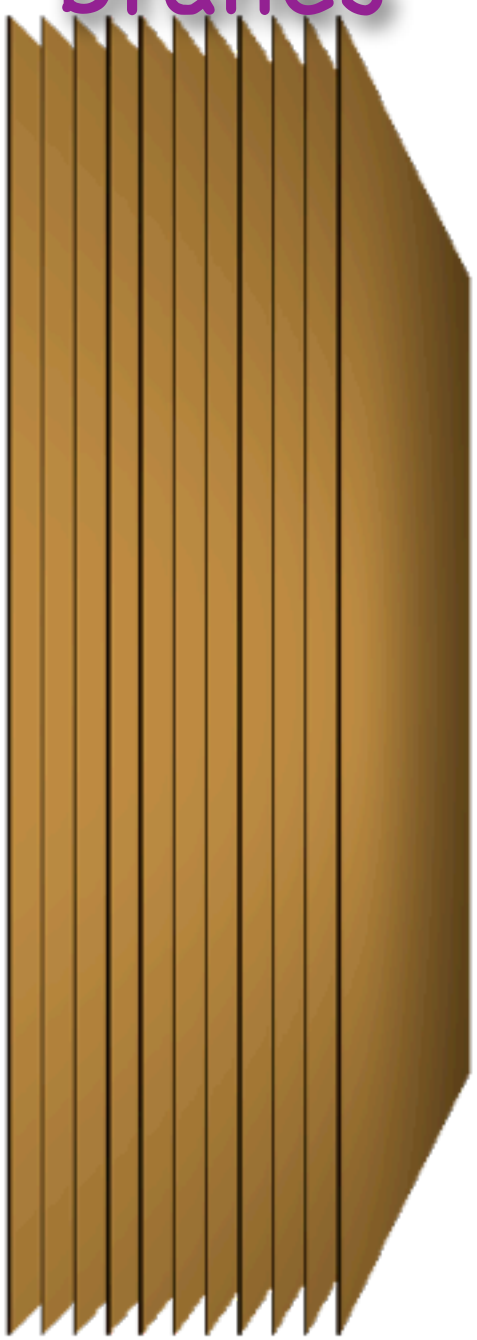
Four Dimensional strongly coupled SU(N) gauge theory

Low Energy
Large N, $g^2 N$

Five Dimensional weakly coupled Supergravity on $AdS_5 \times \mathbf{S}^5$

Maldacena Conjecture

3-dimensional
branes



Four Dimensional
strongly coupled
SU(N) gauge theory

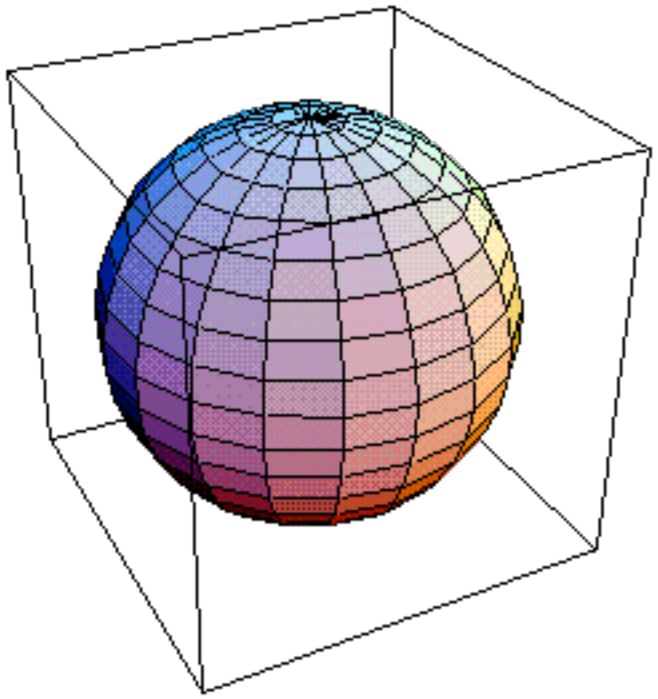
Low Energy
Large N, g^2 N

same
universality
class

Five Dimensional
weakly coupled
Supergravity on $AdS_5 \times S^5$

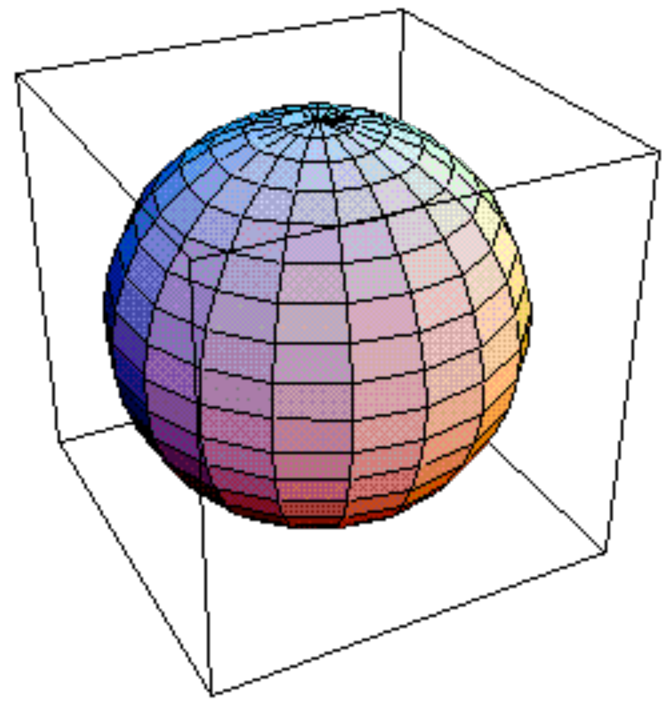
Anti-de Sitter x Sphere

S^5: $R^2 = x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 + x_6^2$

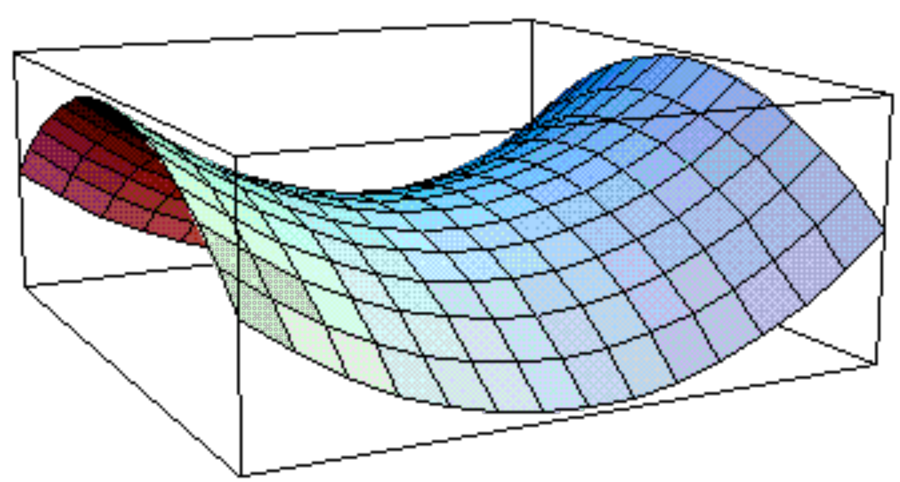


Anti-de Sitter x Sphere

S⁵: $R^2 = x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 + x_6^2$



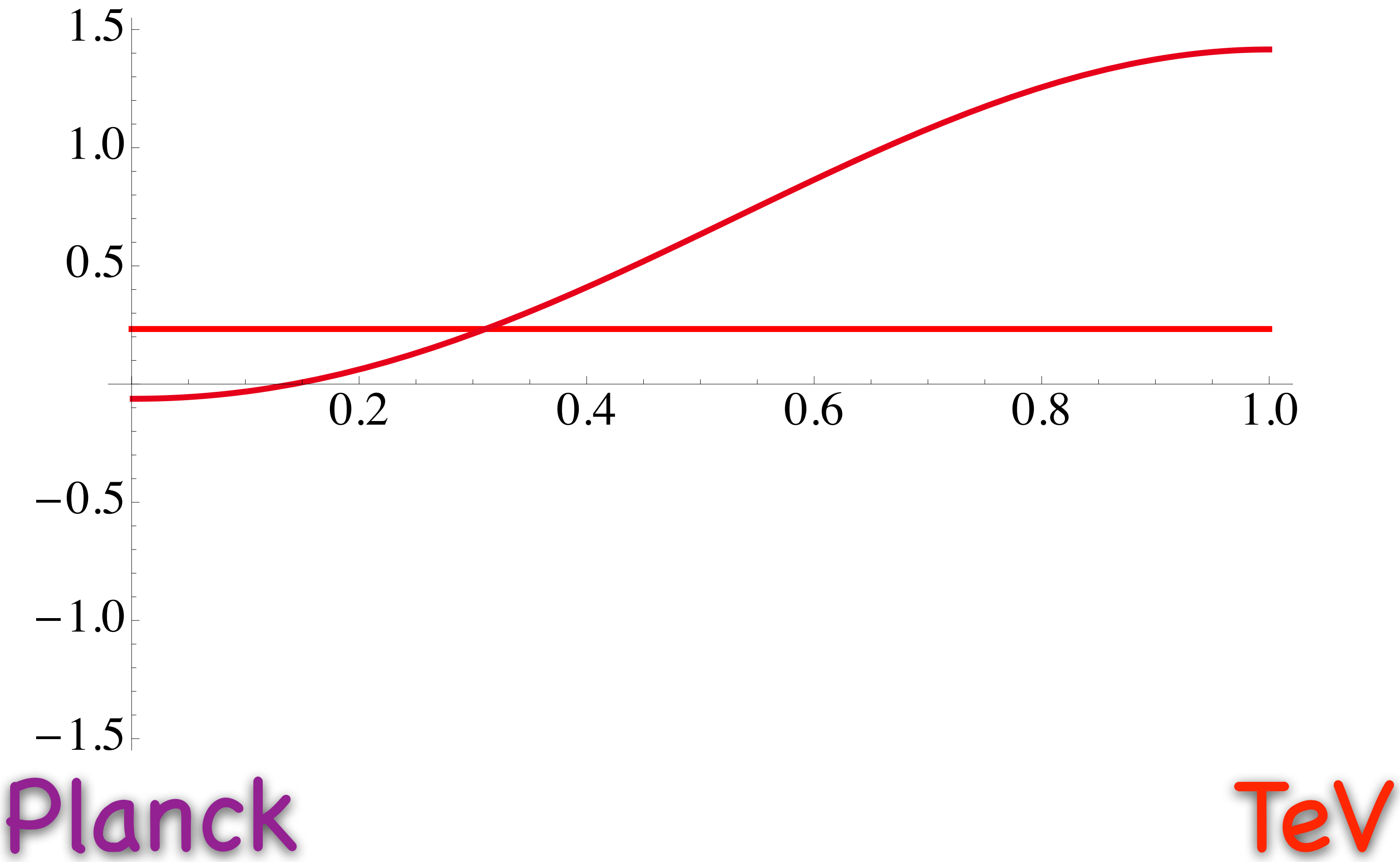
AdS$_5$: $-R^2 = -u\,v - x_1^2 + x_2^2 + x_3^2 + x_4^2$



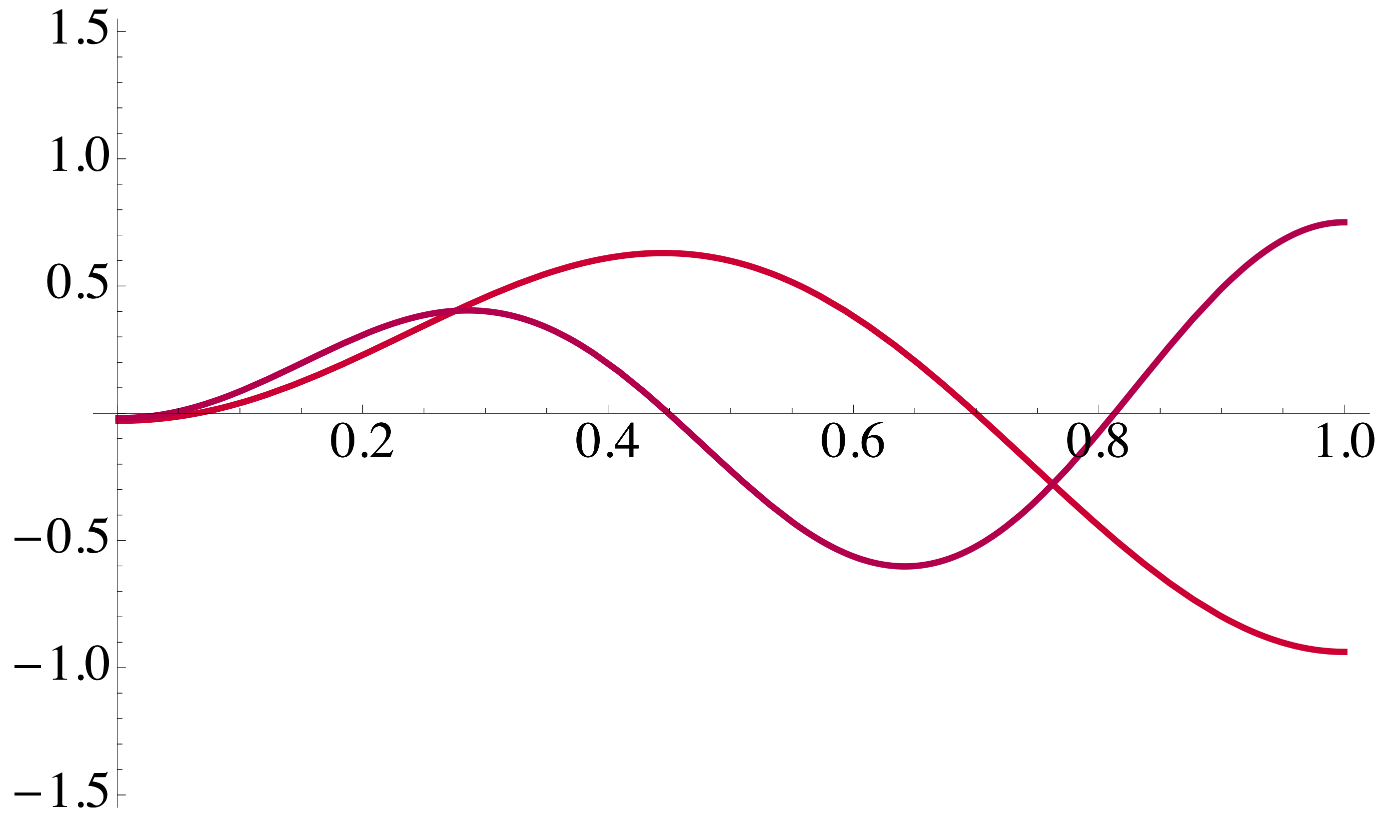
Gauge KK Modes

$$(\partial_z^2 - \frac{1}{z}\partial_z + q^2)\psi(z) = 0$$

$$\psi_k(z) = z\left(a_k J_1(q_k z) + b_k Y_1(q_k z)\right)$$



Gauge KK Modes



Planck TeV

Bulk fermions

$$
\begin{aligned}
S_{bulk,f} &= \int d^5x \left(\frac{R}{z}\right)^4 \Big(-i\bar{\chi}\bar{\sigma}^\mu\partial_\mu\chi - i\psi\sigma^\mu\partial_\mu\bar{\psi} \\
&\quad + \frac{1}{2}(\psi\overleftrightarrow{\partial_z}\chi - \bar{\chi}\overleftrightarrow{\partial_z}\bar{\psi}) + \frac{c}{z}\left(\psi\chi + \bar{\chi}\bar{\psi}\right)\Big) \\
\chi &= g(pz)\chi_4 \\
\bar{\psi} &= f(pz)\bar{\psi}_4 \\
g(pz) &= z^{\frac{5}{2}}\left(A(p)J_{c+\frac{1}{2}}(pz) + B(p)J_{-c-\frac{1}{2}}(pz)\right) \\
f(pz) &= z^{\frac{5}{2}}\left(A(p)J_{c-\frac{1}{2}}(pz) + B(p)J_{-c+\frac{1}{2}}(pz)\right)
\end{aligned}
$$

Fermion KK modes

$$\chi = \sum_n g_n(z)\chi_n(x) \quad \psi = \sum_n f_n(z)\psi_n(x)$$

$$f_n' + m_n\, g_n - \frac{c+2}{z} f_n = 0,$$

$$g_n' - m_n\, g_n + \frac{c-2}{z} g_n = 0.$$

zero modes:

$$f_0 = C_0 \left(\frac{z}{R}\right)^{c+2},$$

$$g_0 = A_0 \left(\frac{z}{R}\right)^{2-c},$$

Fermion KK modes

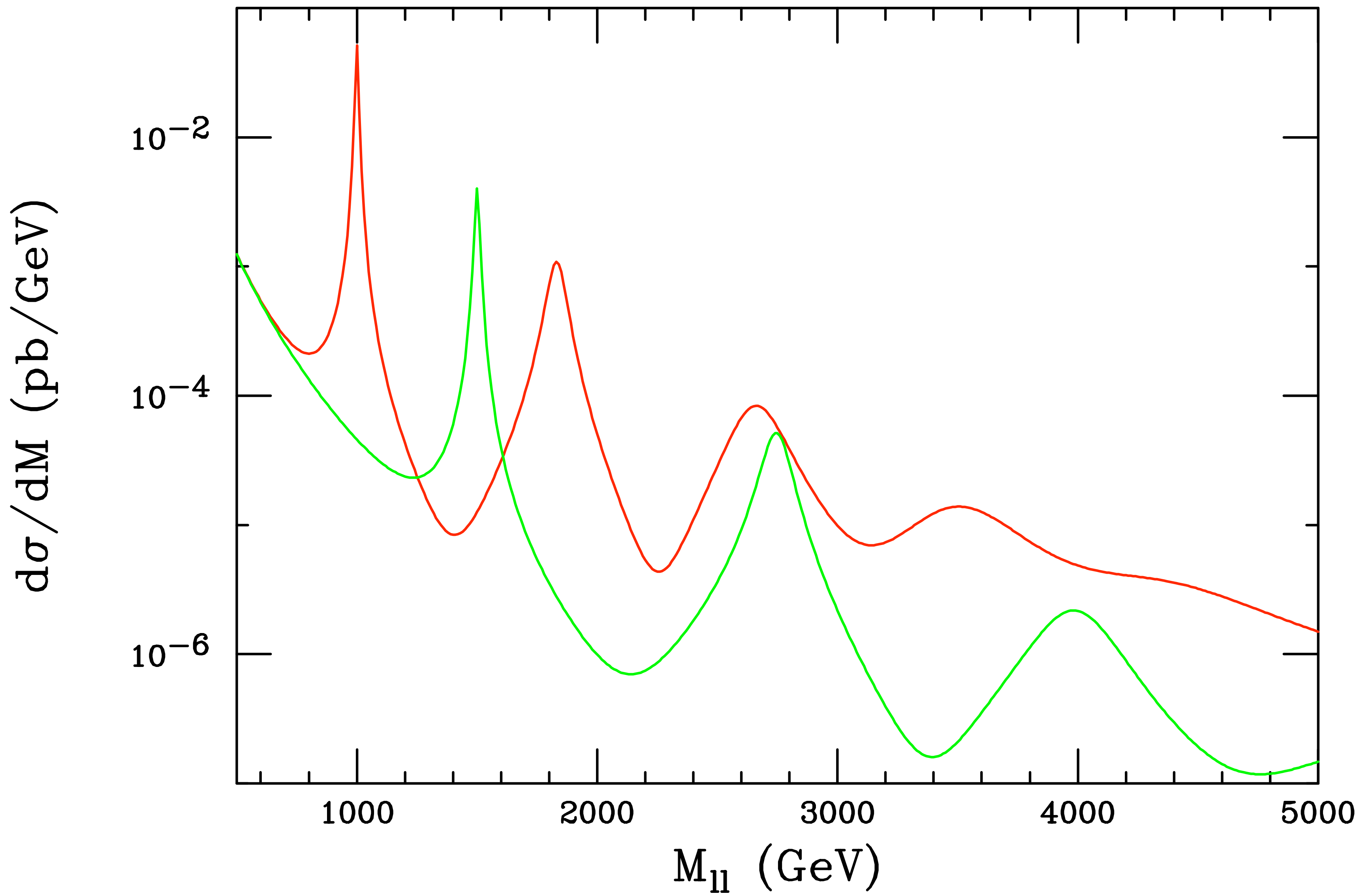
coefficient of zero mode kinetic term

$$\chi^\dagger \bar{\sigma}^\mu \partial_\mu \chi$$

$$\int_R^{R'} dz\, z^{-2c} \sim R'^{1-2c} - R^{1-2c}$$

	$R' \to \infty$	$R \to 0$
converges:	$c > 1/2$	$c < 1/2$
	localized on Planck brane	localized on TeV brane

Randall-Sundrum

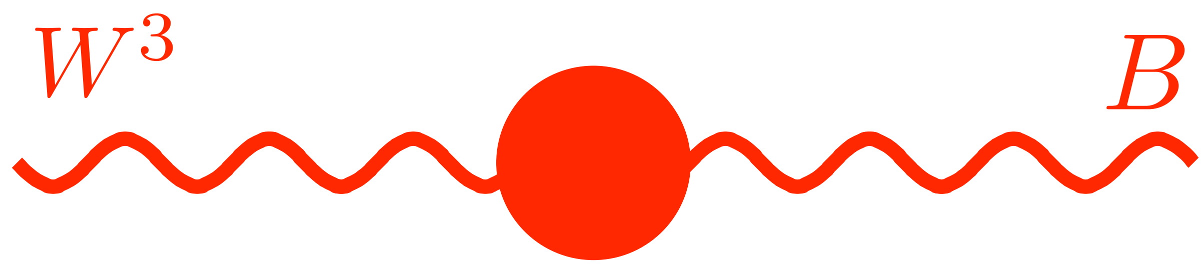


Drell-Yan graviton production

Davoudiasl, Hewett, Rizzo hep-ph/0006041

Randall-Sundrum

S:



make gauge resonances heavy, but then doesn't solve the "little hierarchy" problem

$$
\begin{aligned}
\Delta m_H^2 &= \frac{3\lambda_t^2}{8\pi^2}(10\,\mathrm{TeV})^2 \\
&\sim 3.8\mathrm{TeV}^2 \\
m_H^2 &\sim 0.01\mathrm{TeV}^2
\end{aligned}
$$

0.3% fine tuning

Gauge-Higgs Unification

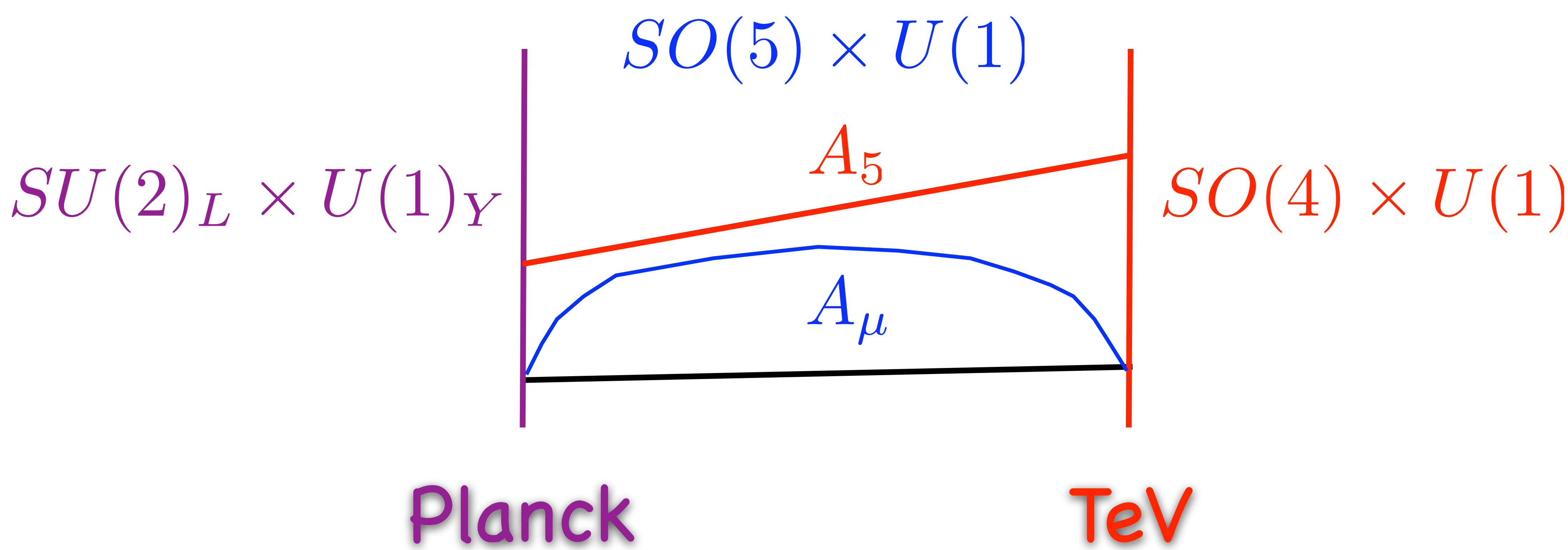
$SO(5) \times U(1)$

$SU(2)_L \times U(1)_Y$ | gauge bosons | $SO(4) \times U(1)$

Planck TeV

Agashe, Contino, Pomarol hep-ph/0412089

Minimal Composite Higgs



$\partial_z(A_5/z) = 0$, zero mode $\sim \mathbf{4}$ of $SO(4)$

Agashe, Contino, Pomarol hep-ph/0412089

New Custodial Symmetry

to protect $Zb\bar{b}$

$$O(4) \sim SU(2)_L \times SU(2)_R \times P_{LR}$$

$$T_L = T_R, \qquad T_R^3 = T_L^3$$

Q_{L+R} charge is protected

$$\delta Q_L + \delta Q_R = 0, \qquad \delta Q_L = \delta Q_R$$

$$\delta Q_L = 0$$

Agashe, Contino, Da Rold, Pomarol hep-ph/0605341

Carena, Ponton, Santiago, Wagner hep-ph/0701055

New Custodial Symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_X$$

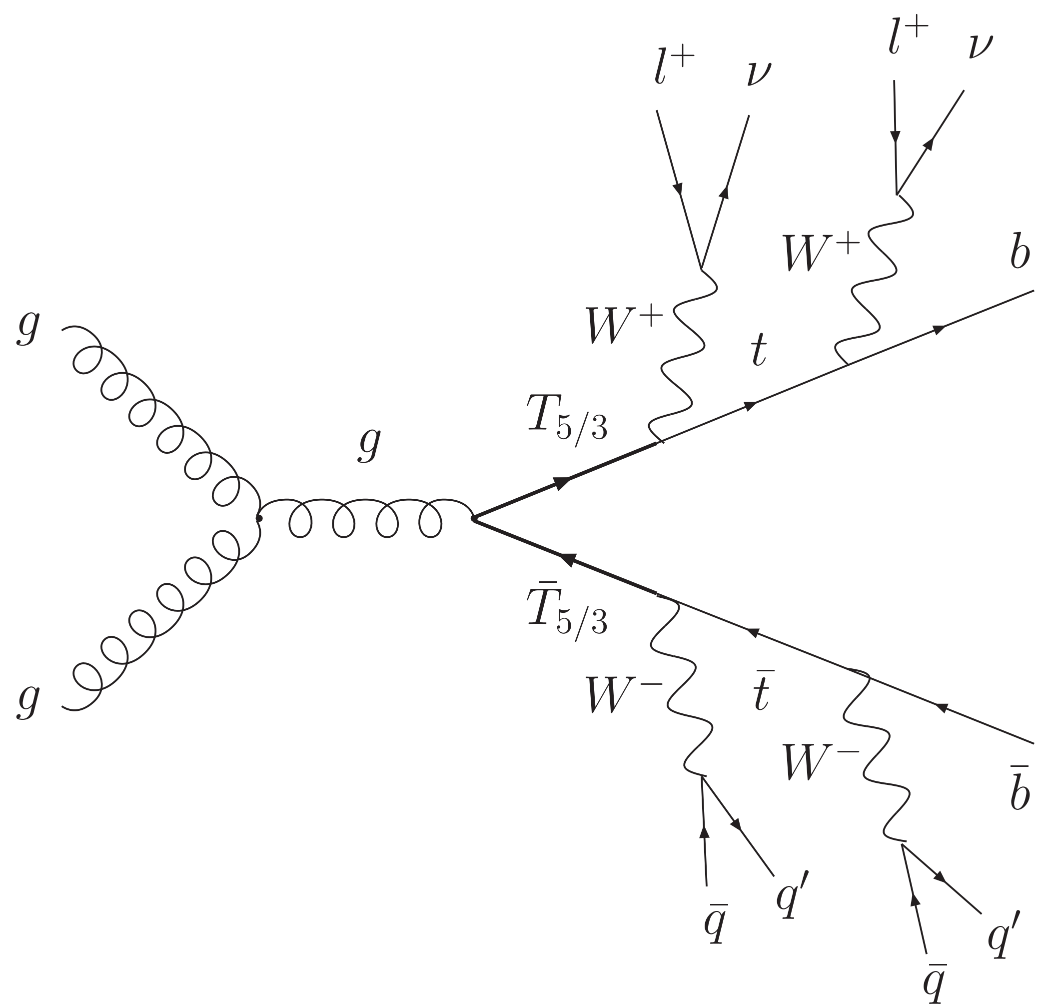
$$Y = T_R^3 + X \ , Q = T_L^3 + Y$$

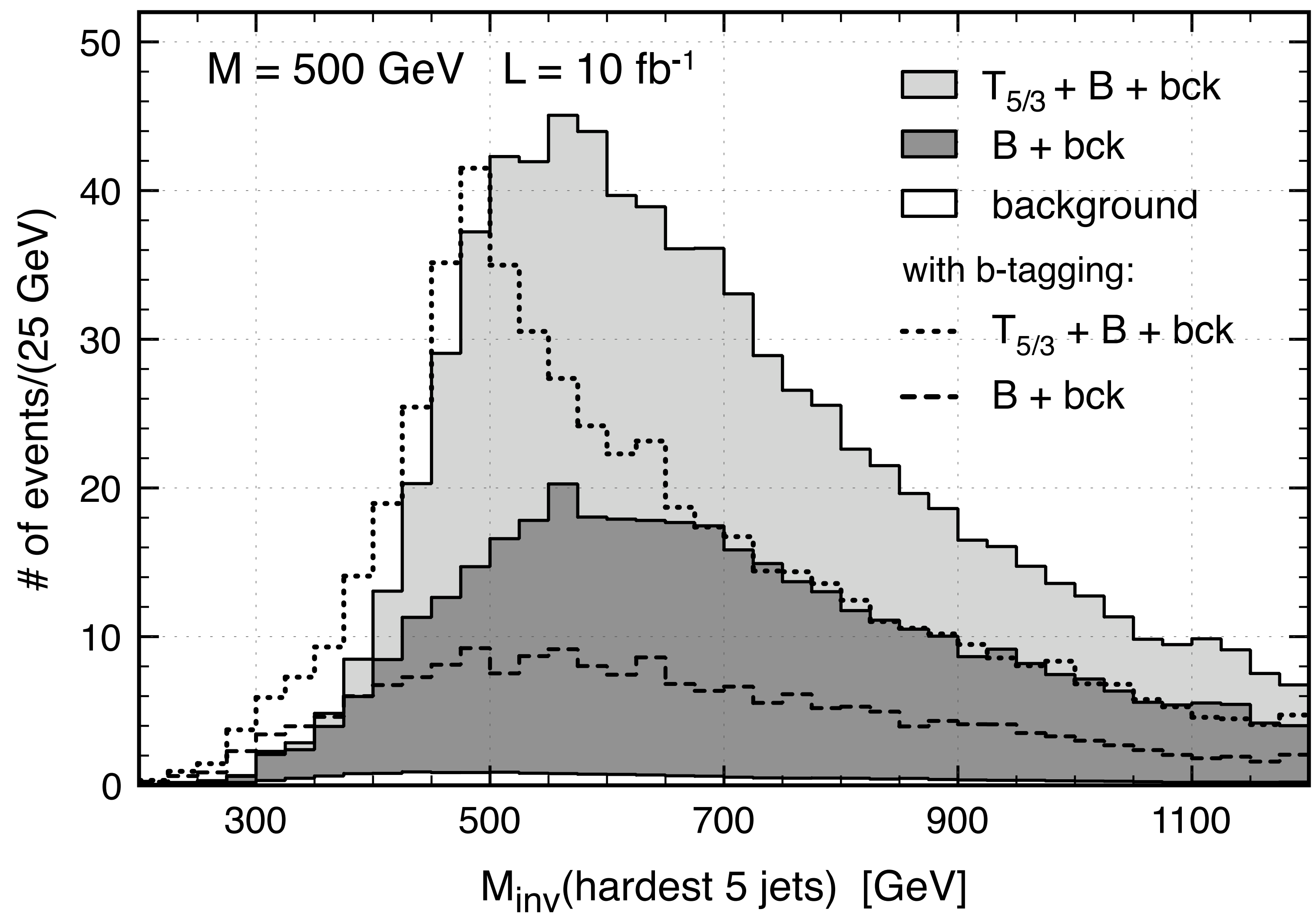
$$\begin{aligned} \Psi_L &\sim (\mathbf{2},\mathbf{2})_{2/3} \\ \Psi_R &\sim (\mathbf{1},\mathbf{3})_{2/3} \\ t_R &\sim (\mathbf{1},\mathbf{1})_{2/3} \end{aligned}$$

$$\Psi_L = \left(\begin{array}{cc} t & T \\ b & \tilde{t} \end{array}\right)_L , \qquad \Psi_R = \left(\begin{array}{c} T \\ \tilde{t} \\ b \end{array}\right)_R , \quad t_R$$

T has charge 5/3

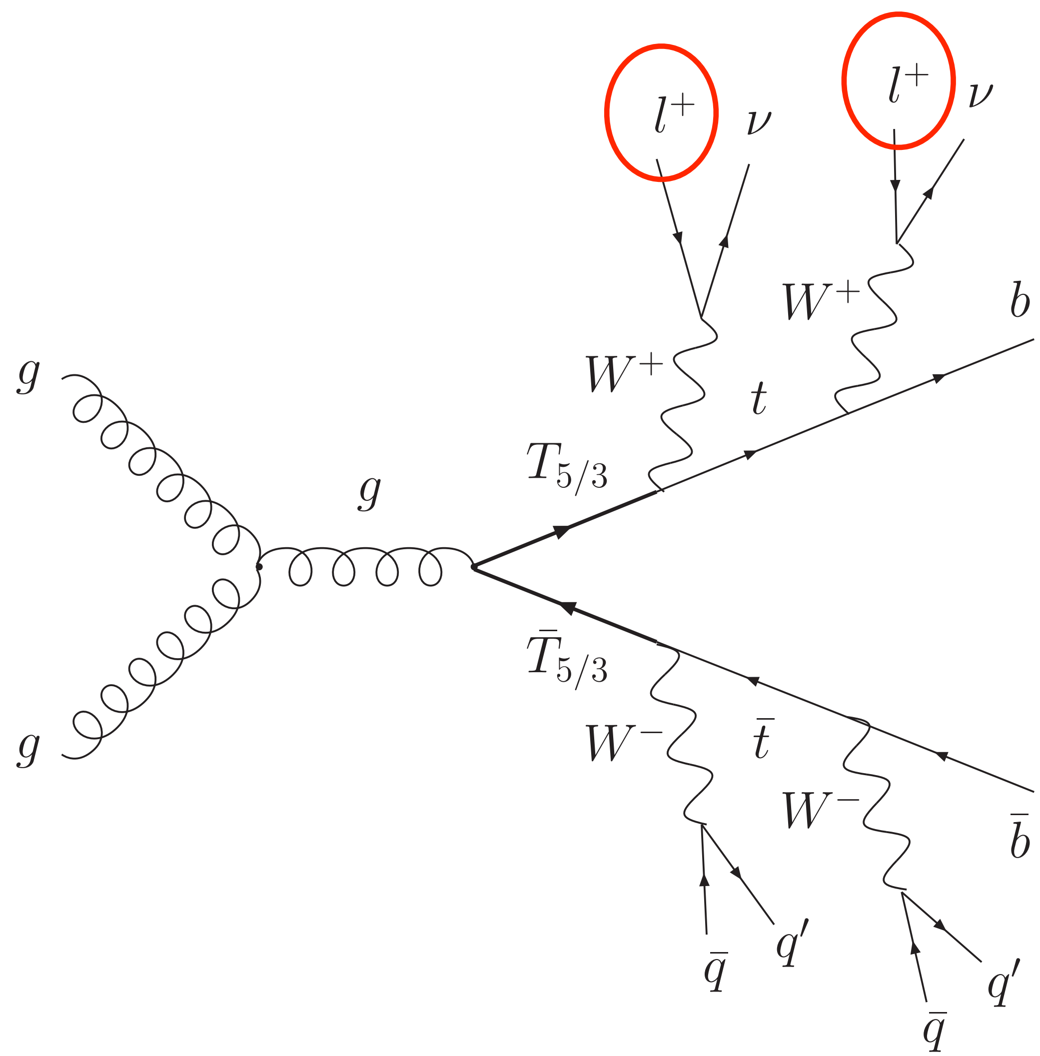
Custodial t Partner

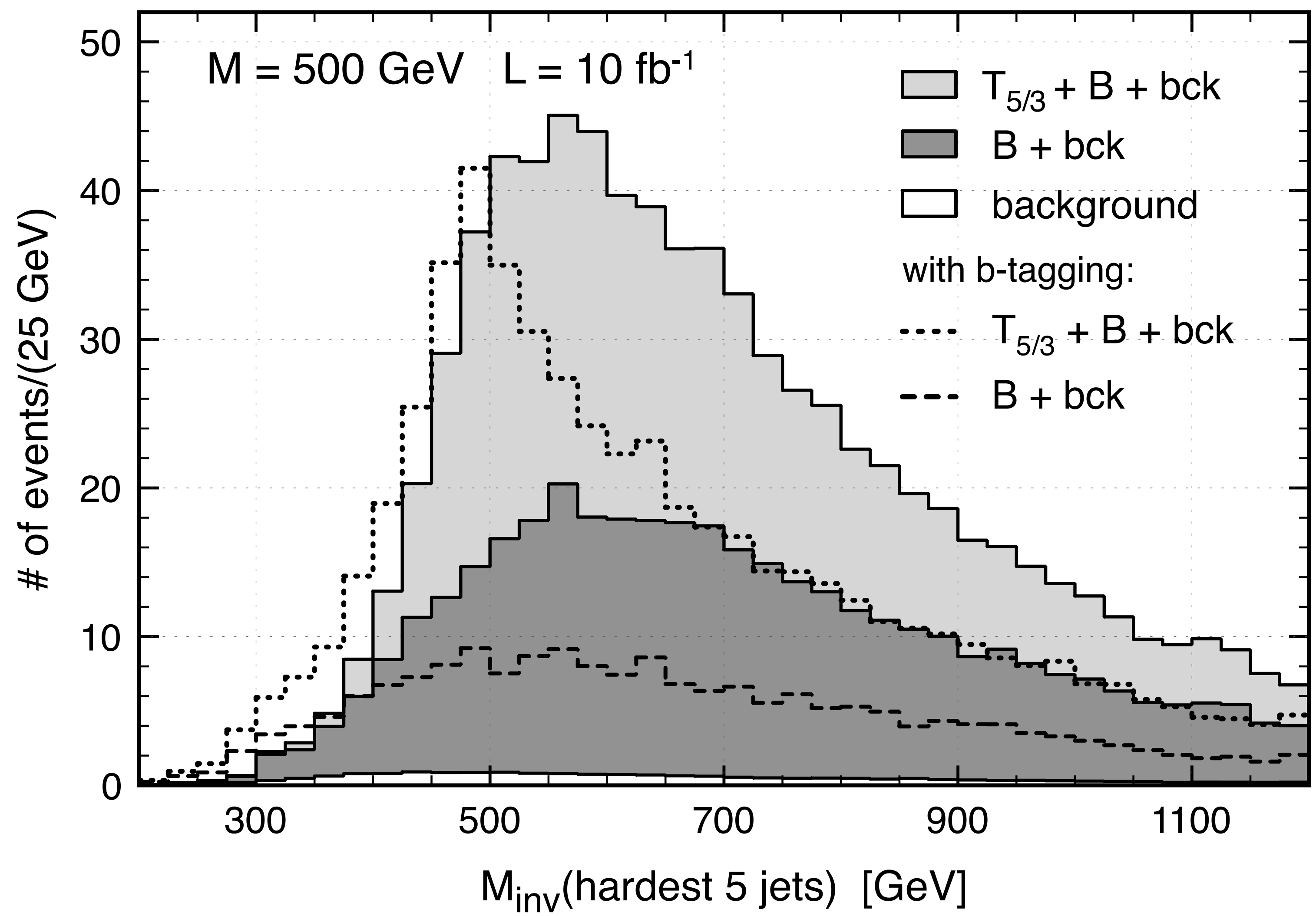




Contino, Servant hep-ph/0801.1679

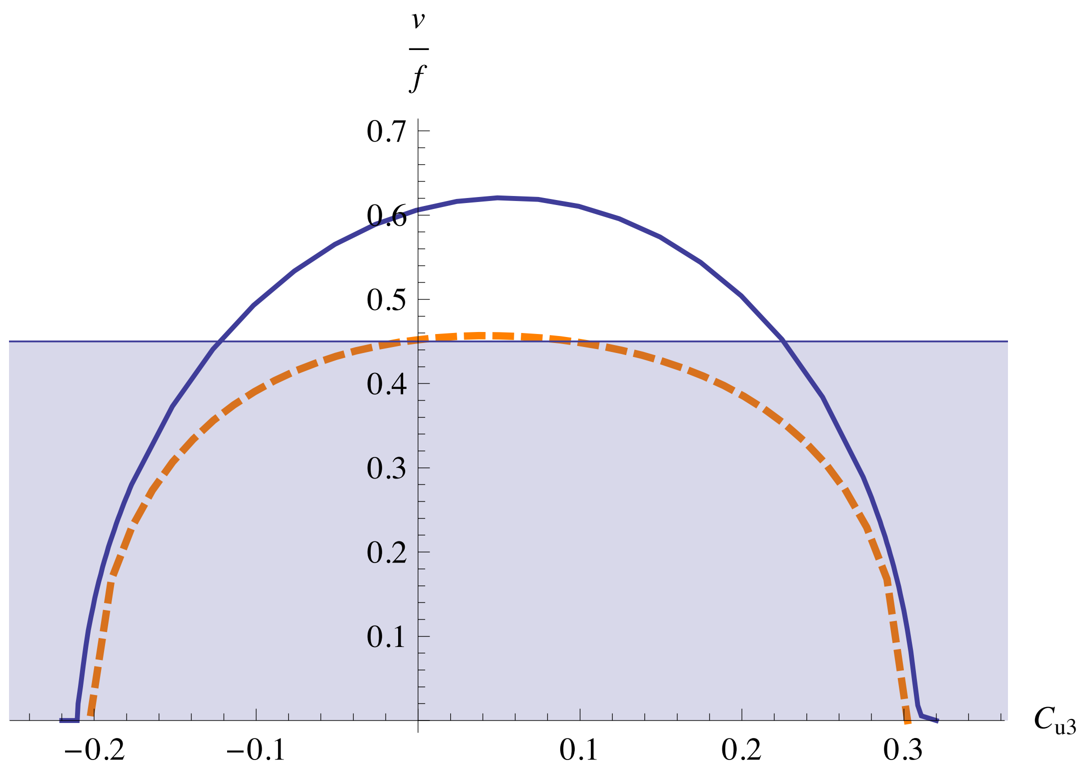
Custodial t Partner

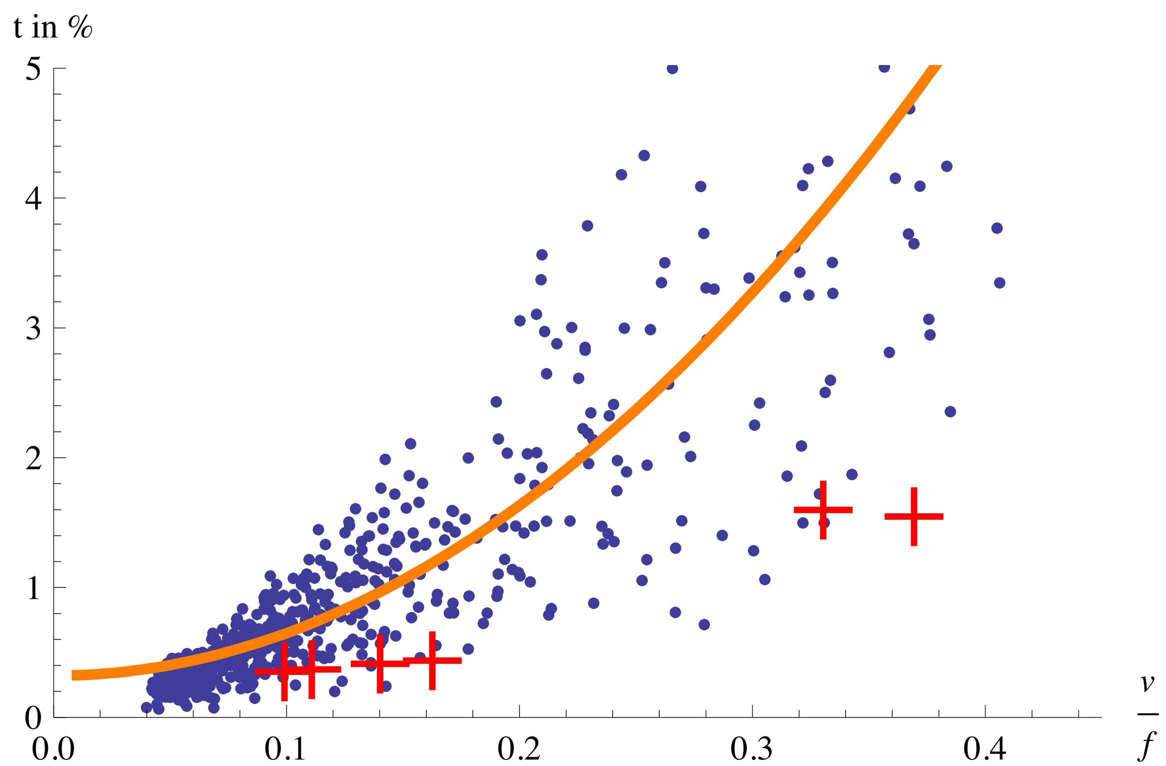




Contino, Servant hep-ph/0801.1679

Fine Tuning for EWSB

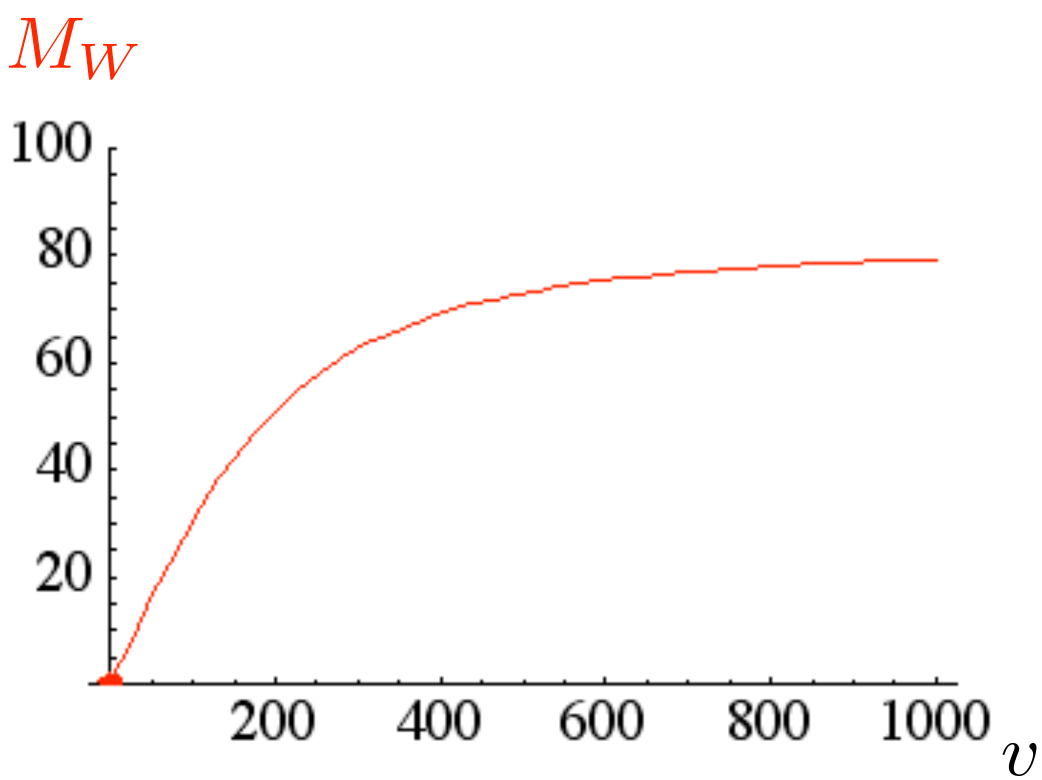


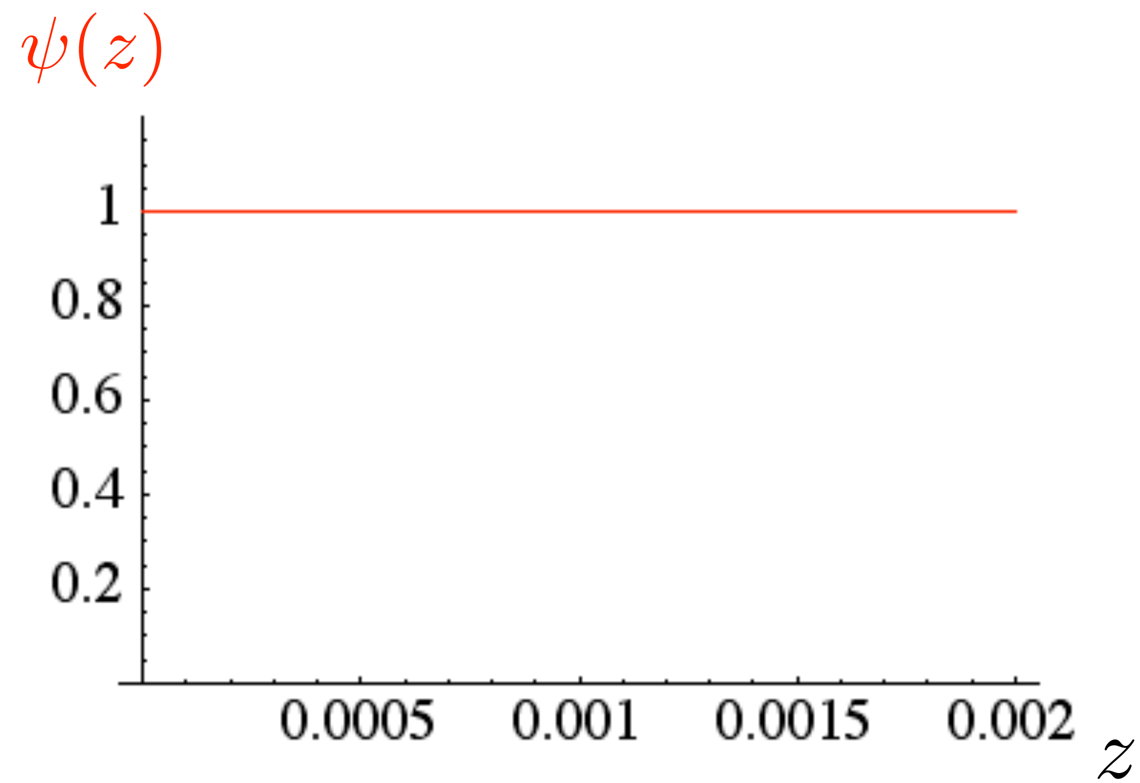


Csaki, Falkowski, Weiler hep-ph/0801.1679

Decoupling the Higgs

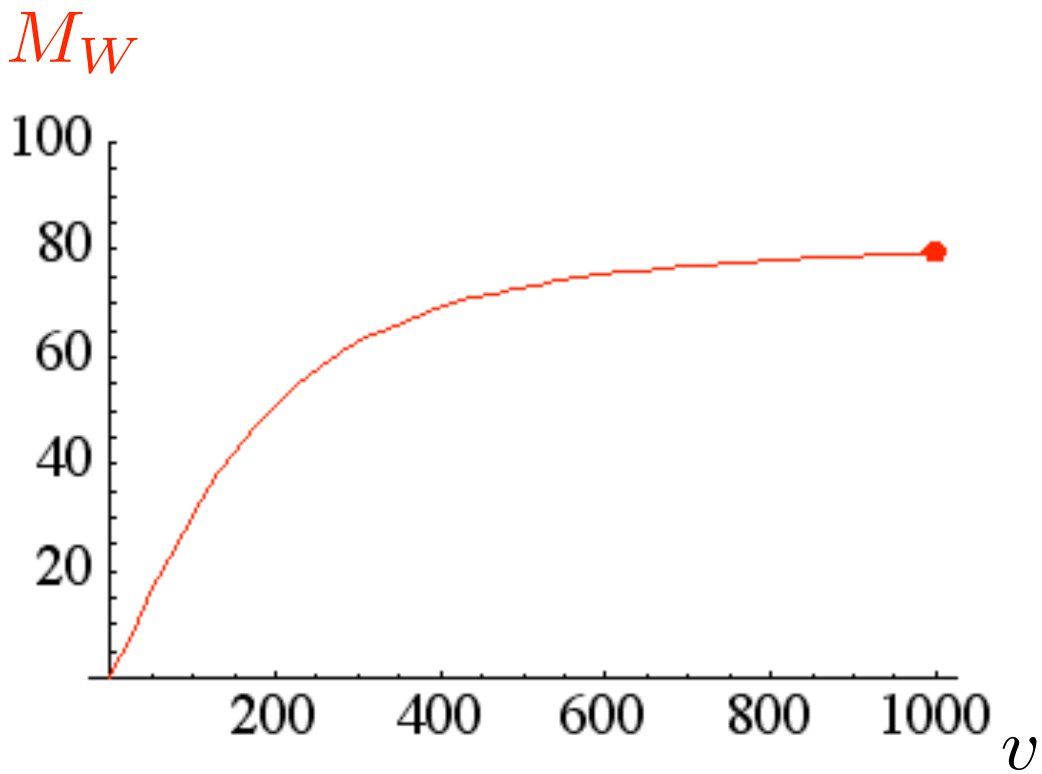
$$\partial_z \psi(z) = -\frac{g_5^2 v^2}{2}\psi(z)$$

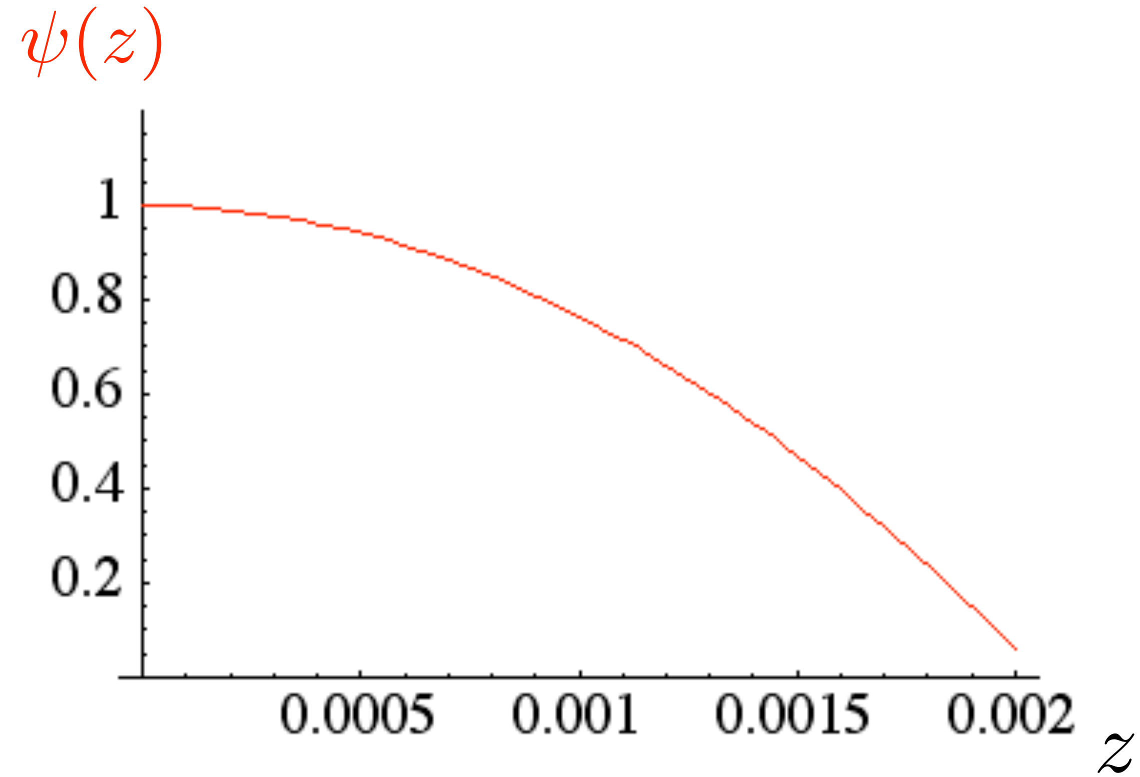




Decoupling the Higgs

$$\partial_z \psi(z) = -\frac{g_5^2 v^2}{2} \psi(z)$$



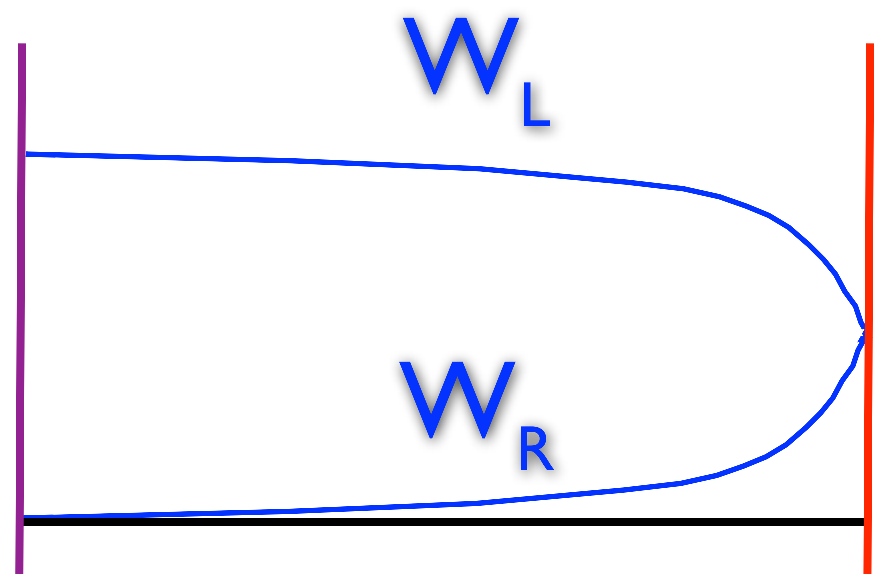


Higgs decouples from scattering as $v \to \infty$

Going Higgsless

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

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



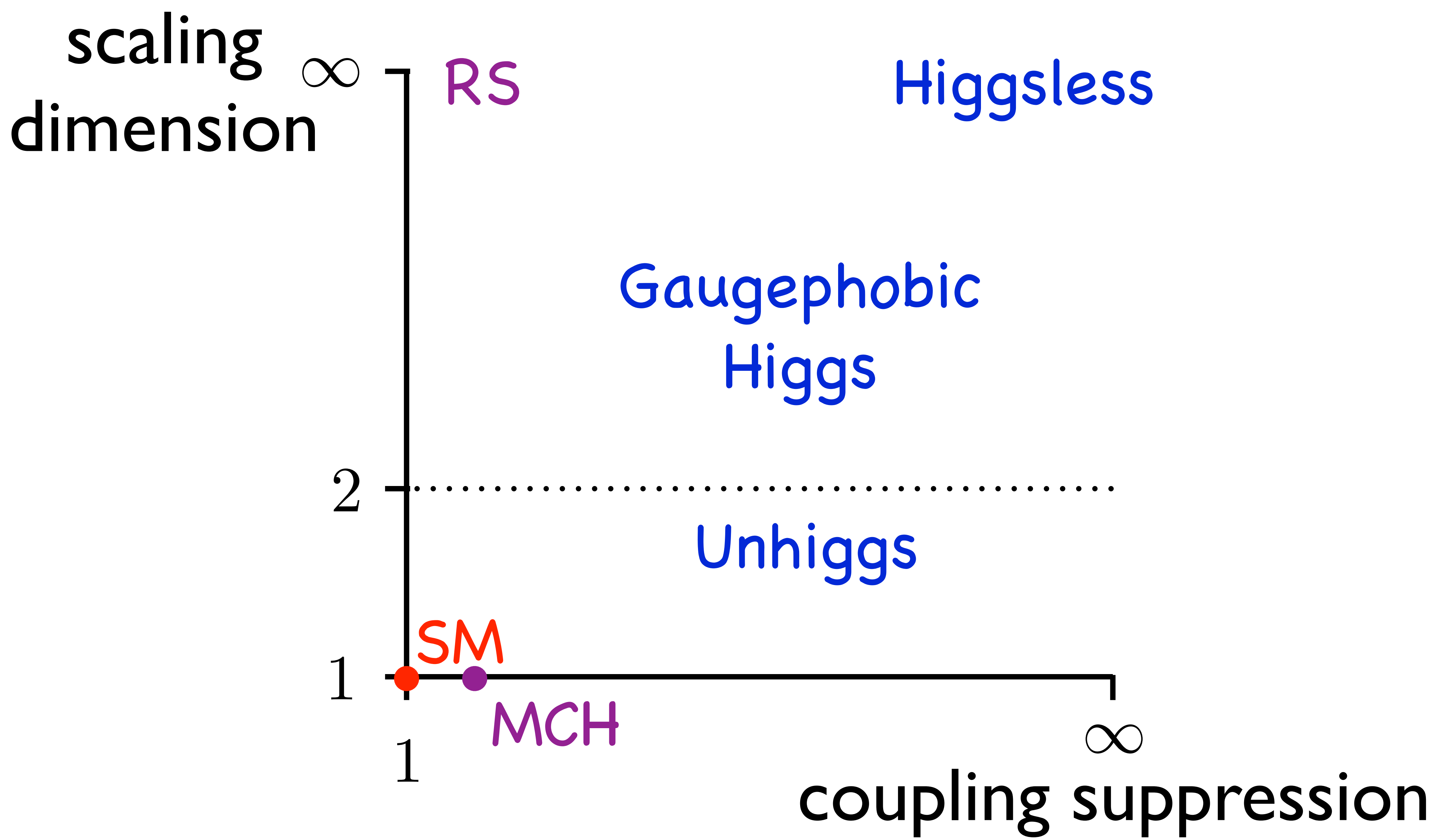
$SU(2)_D \times U(1)_{B-L}$

Planck

TeV

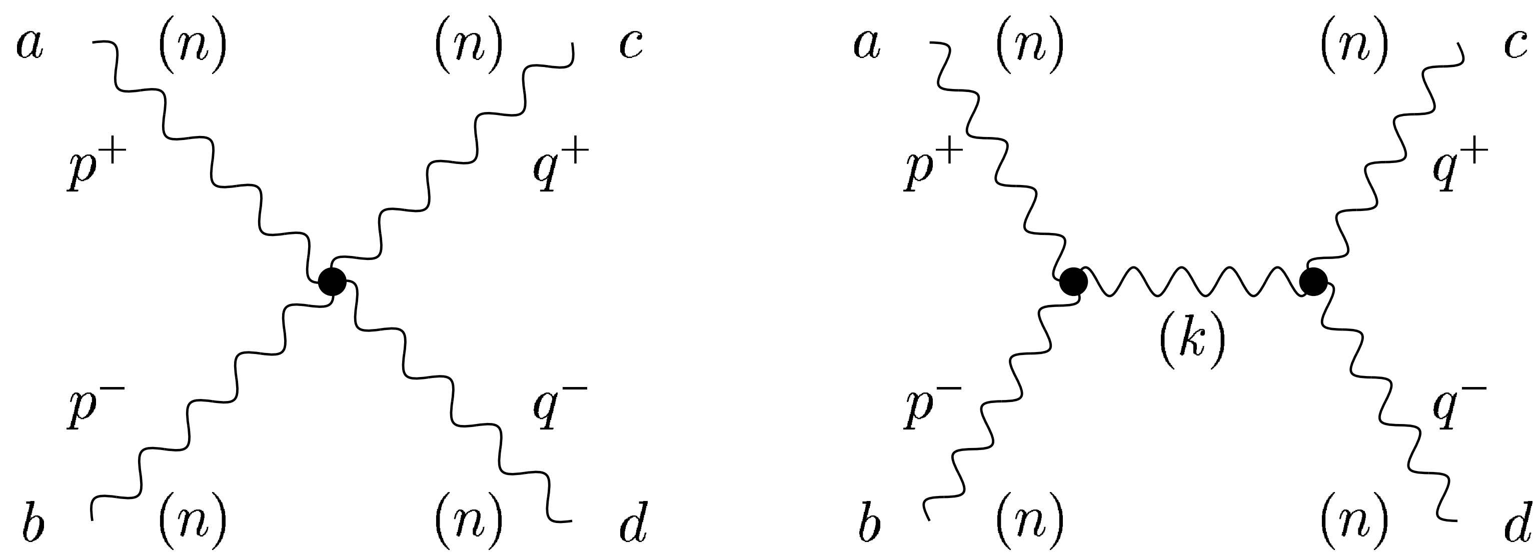
hep-ph/0305237, hep-ph/0308038

Model Landscape



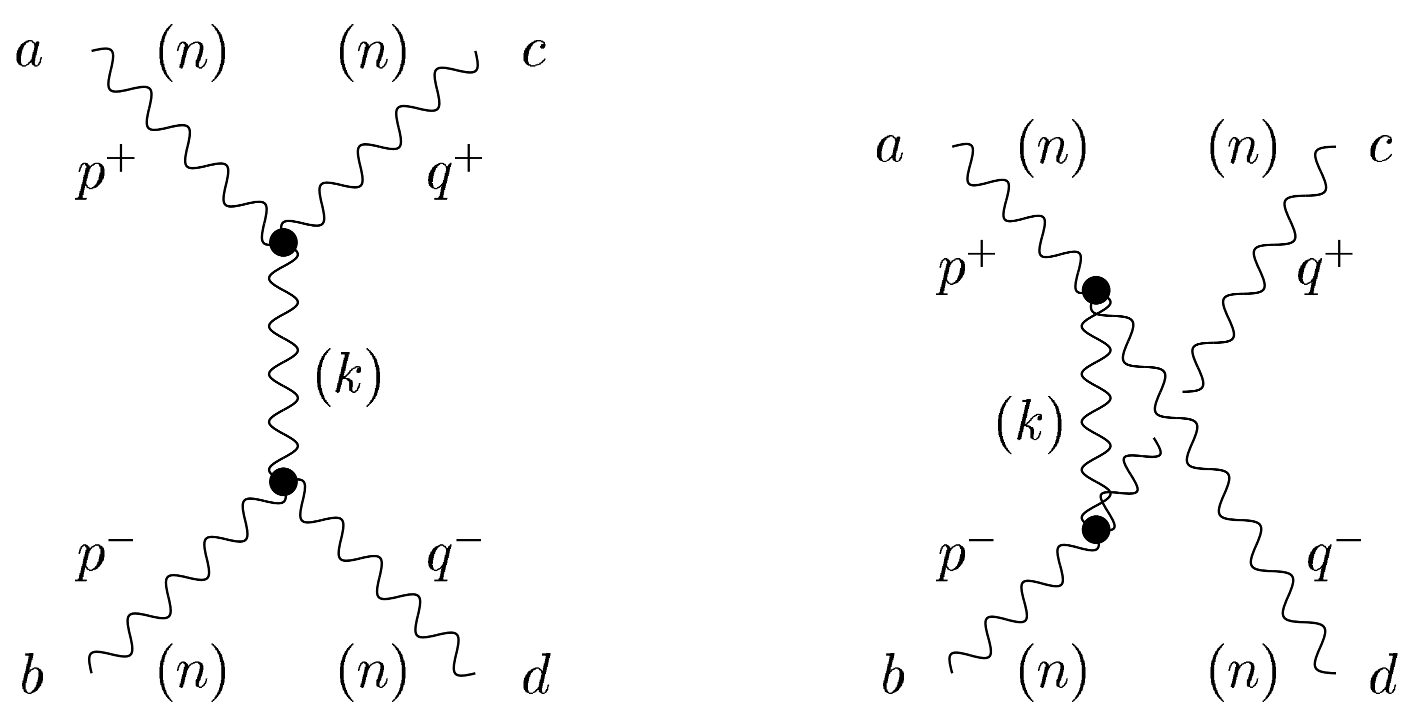
WW Scattering

amplitude grows like E^4



contact interaction

s channel exchange



WW Scattering

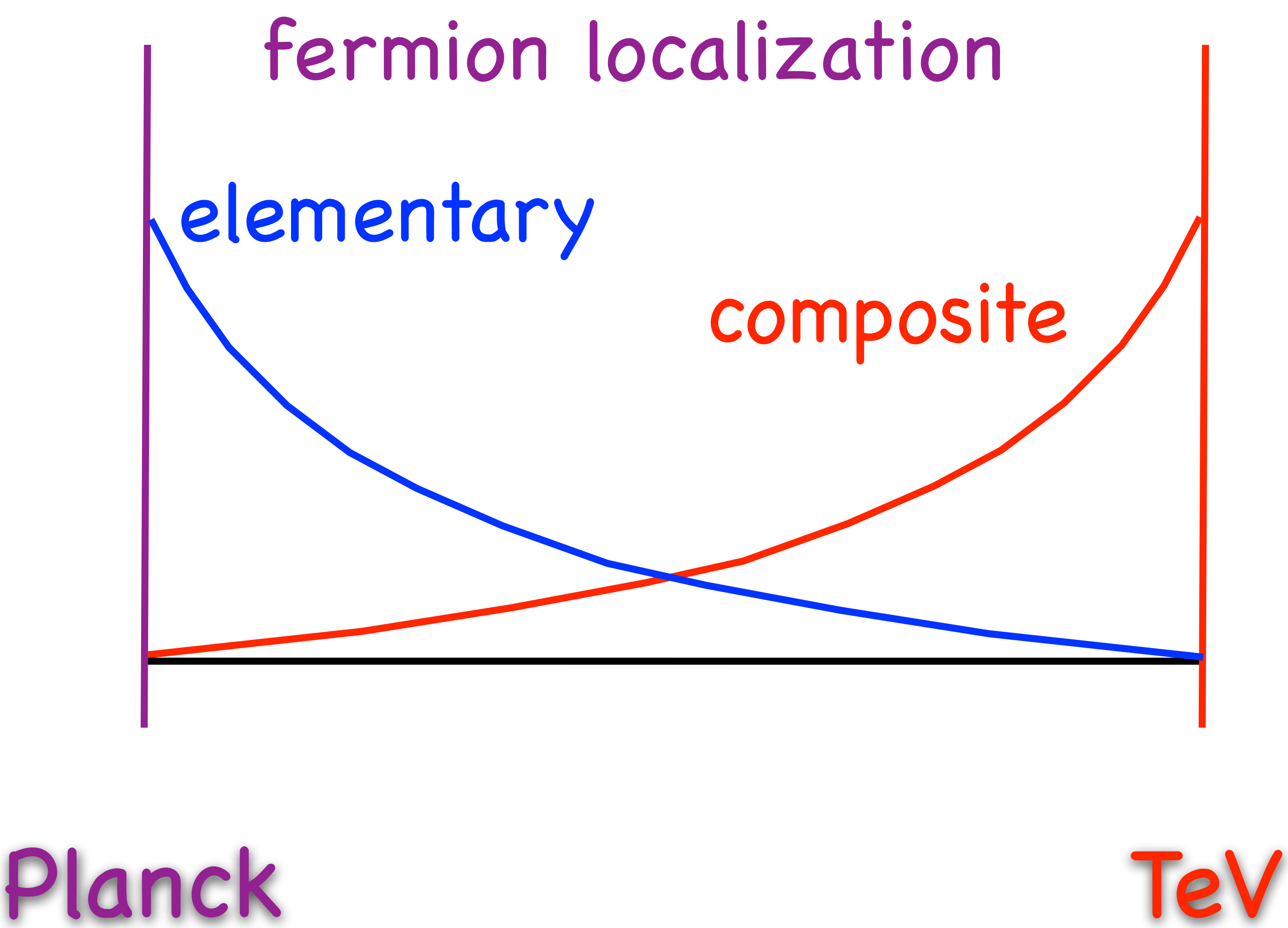
5D gauge invariance:

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

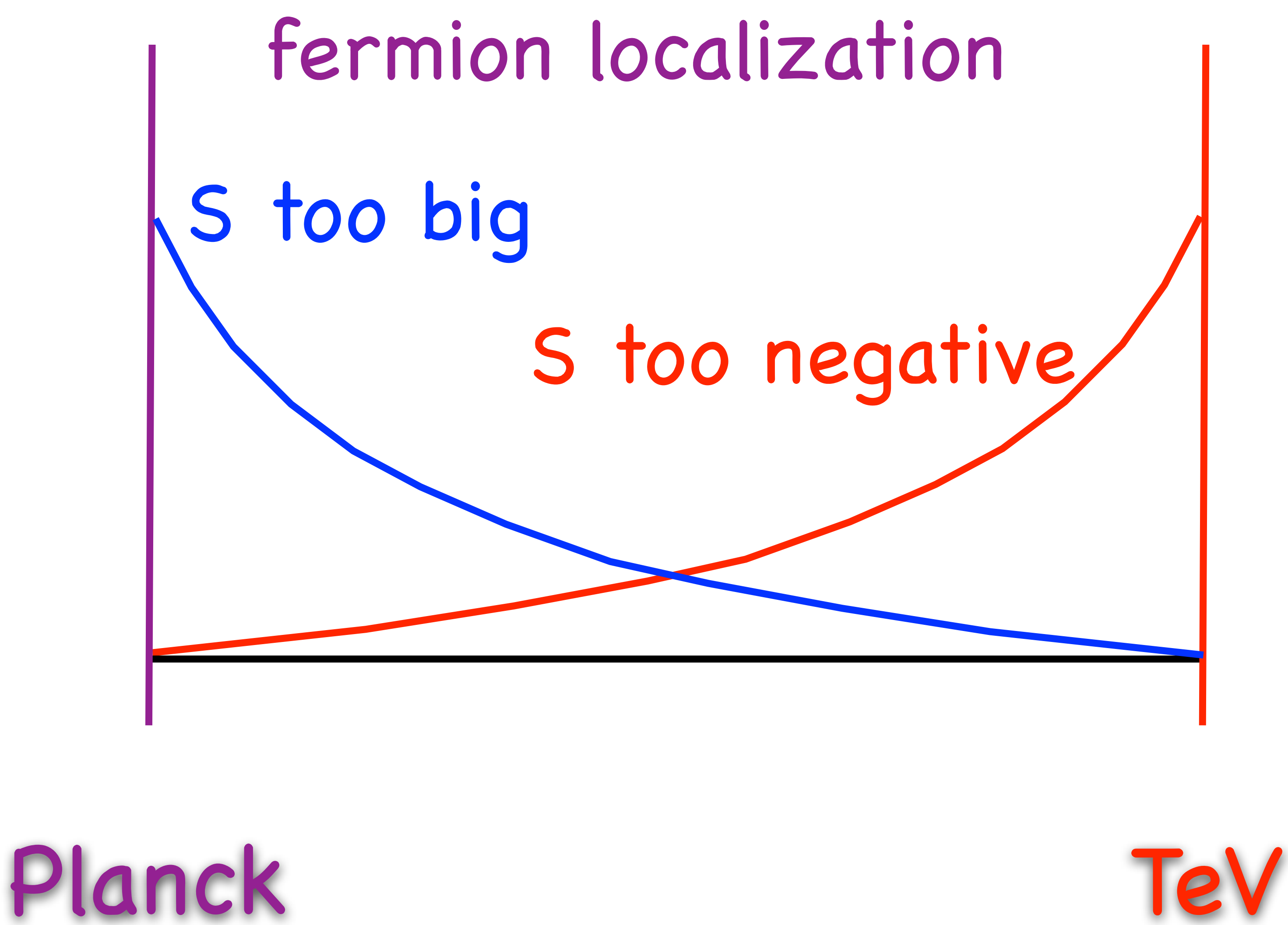
$$4g_{nnnn}^2 M_n^2 \quad = \quad 3\sum_k g_{nnk}^2 M_k^2$$

cancels E^4 and E^2 terms

Precision Electroweak

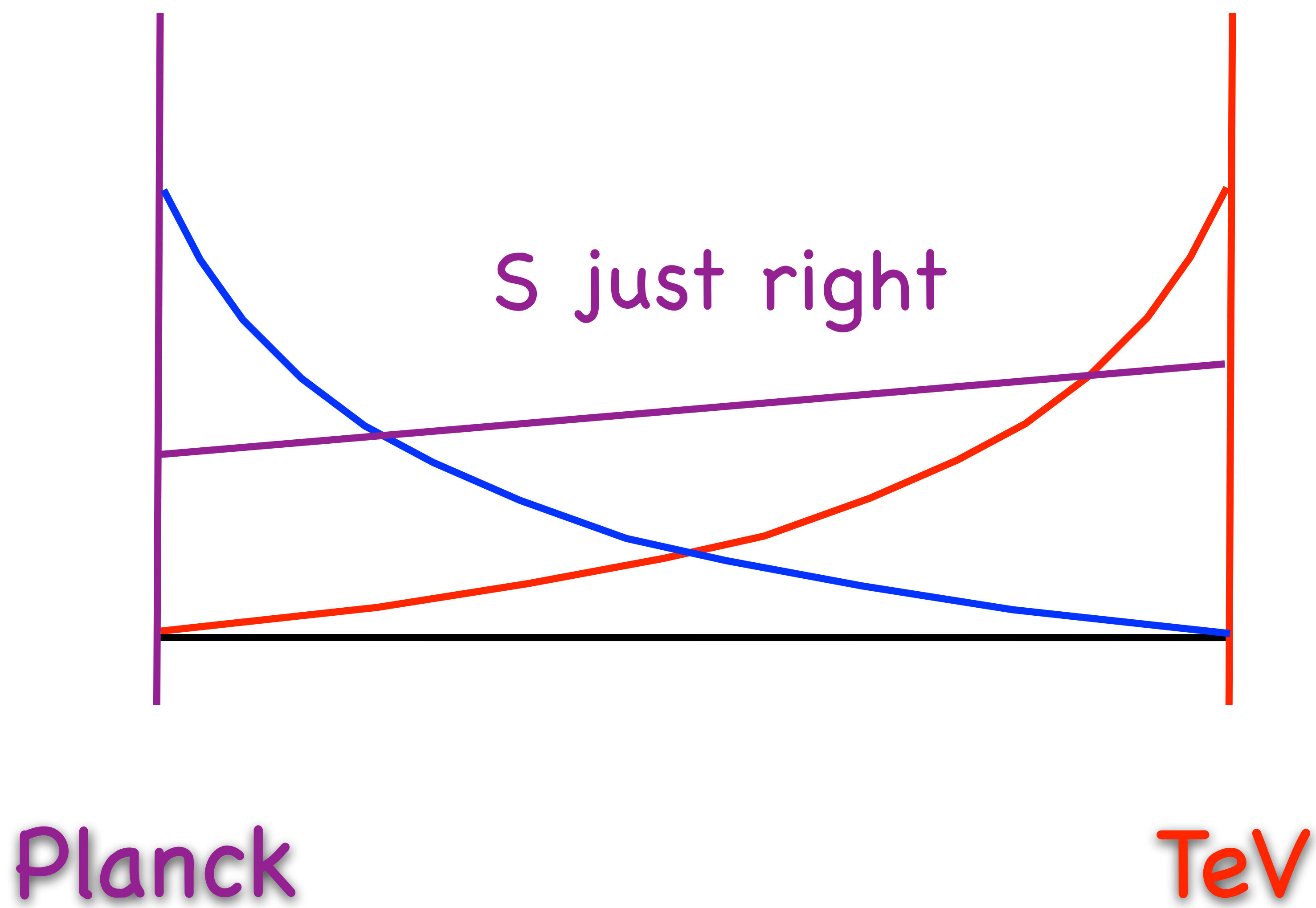


Precision Electroweak



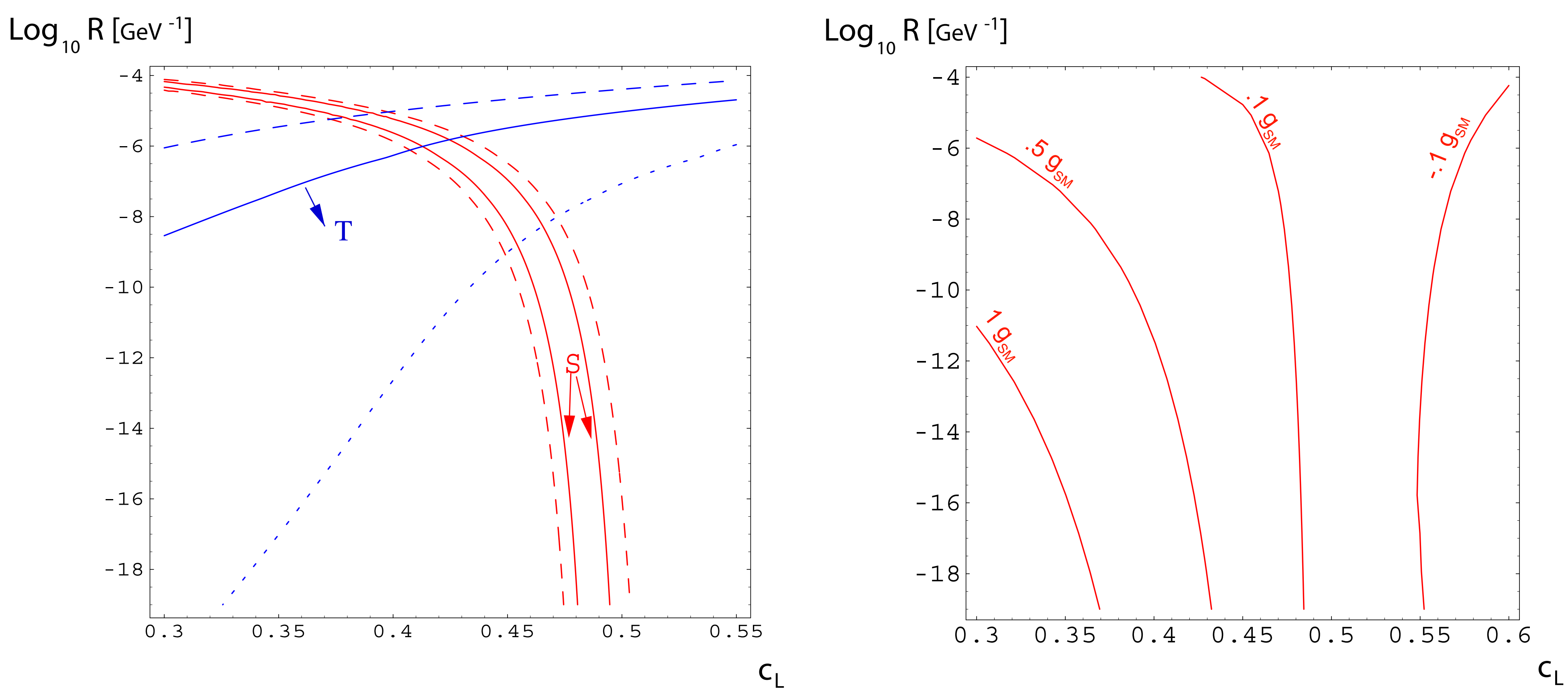
hep-ph/0308036, hep-ph/0203034

Precision Electroweak



Cacciapaglia, Csaki, Grojean JT hep-ph/0409126

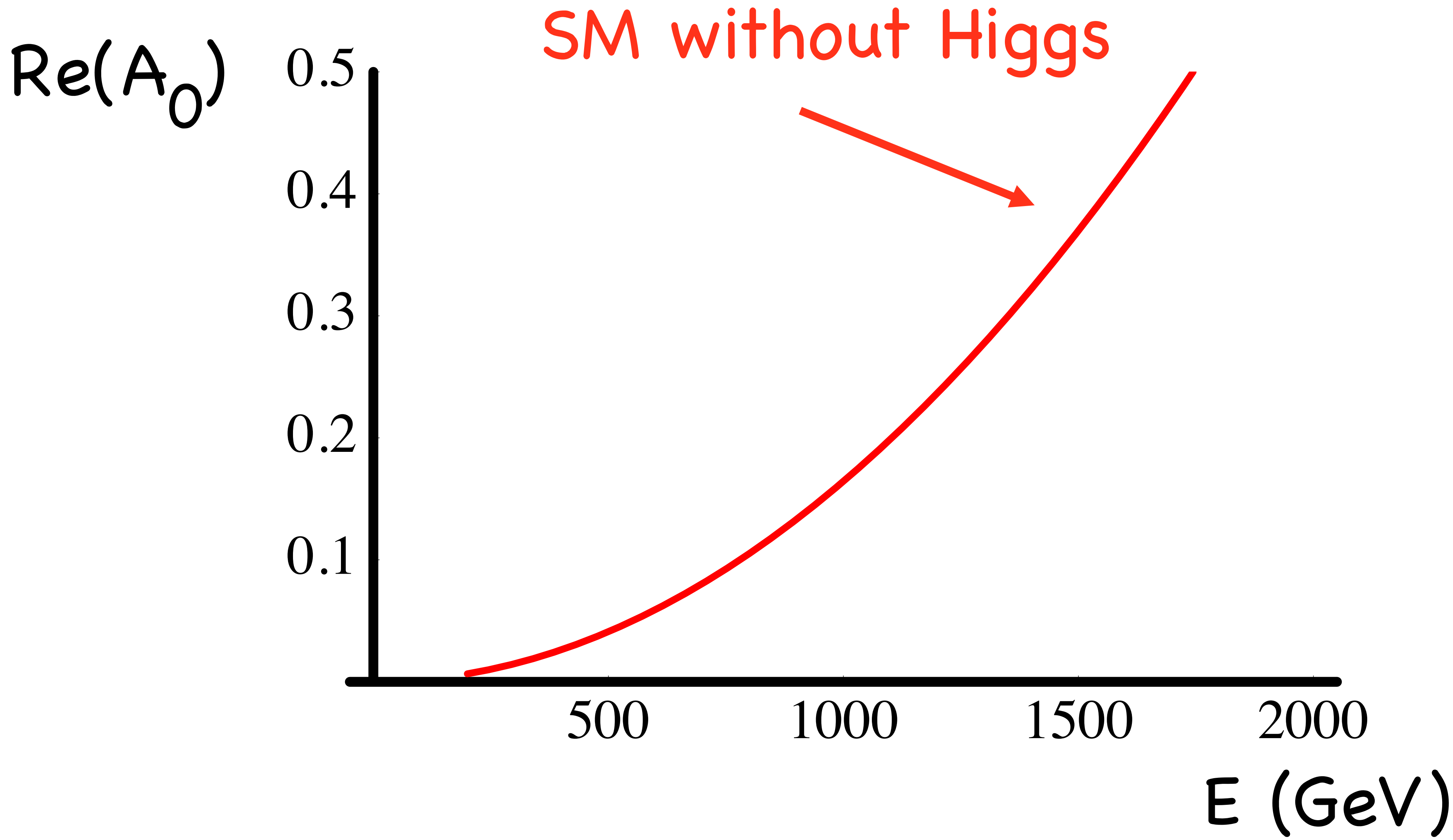
Fine Tuning for Small S



fermion localization parameter

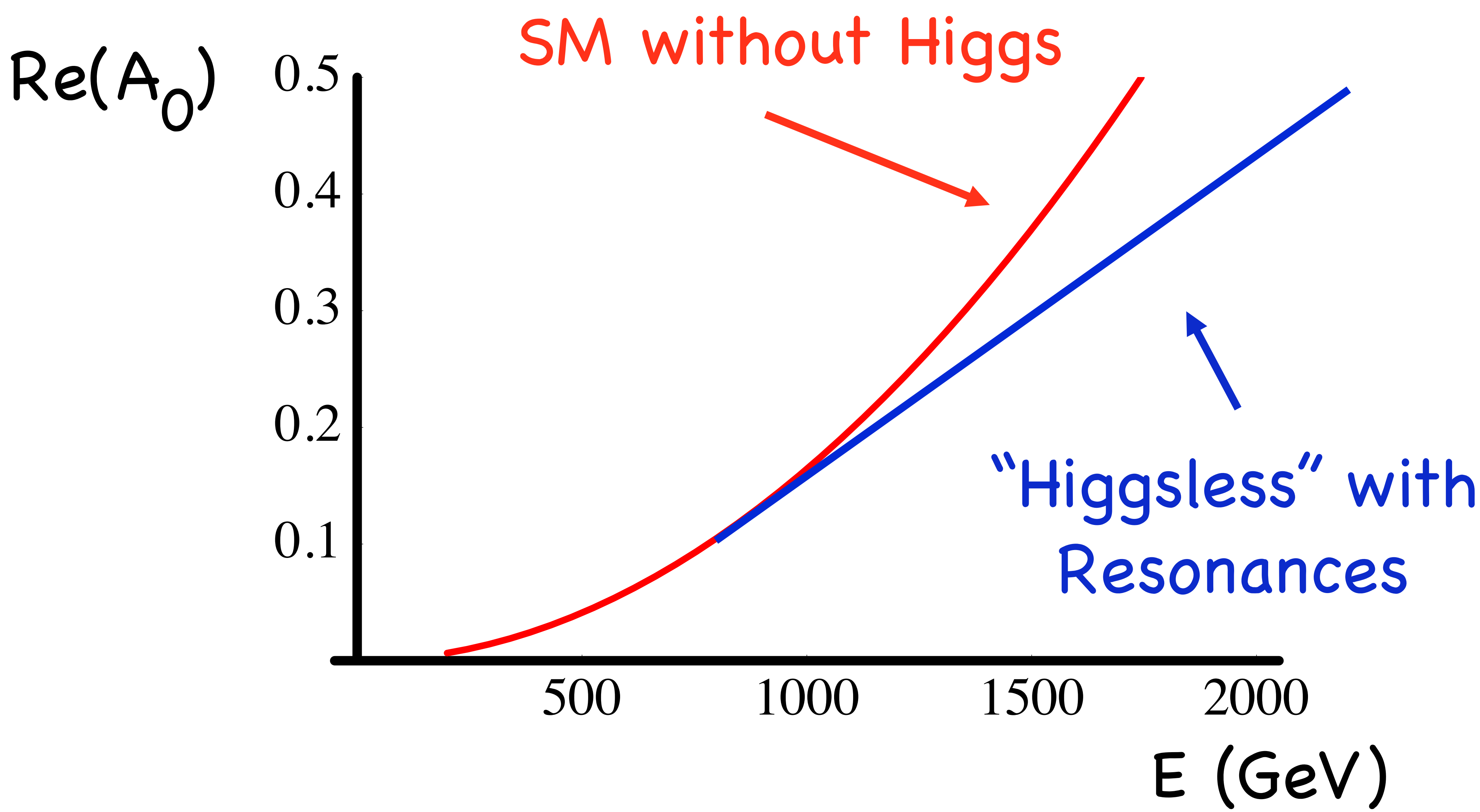
Why Build the LHC?

WW Scattering Amplitude

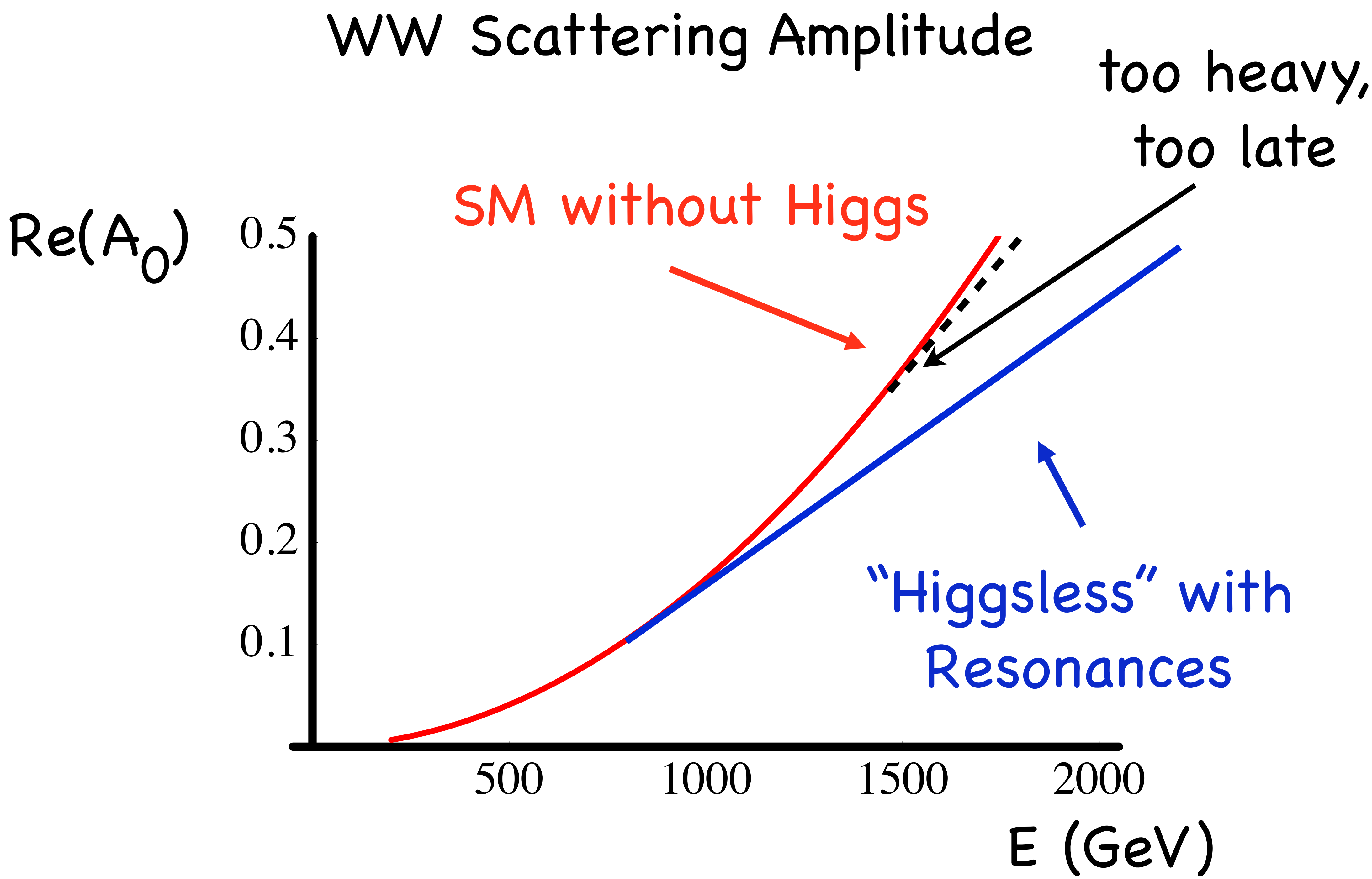


Why Build the LHC?

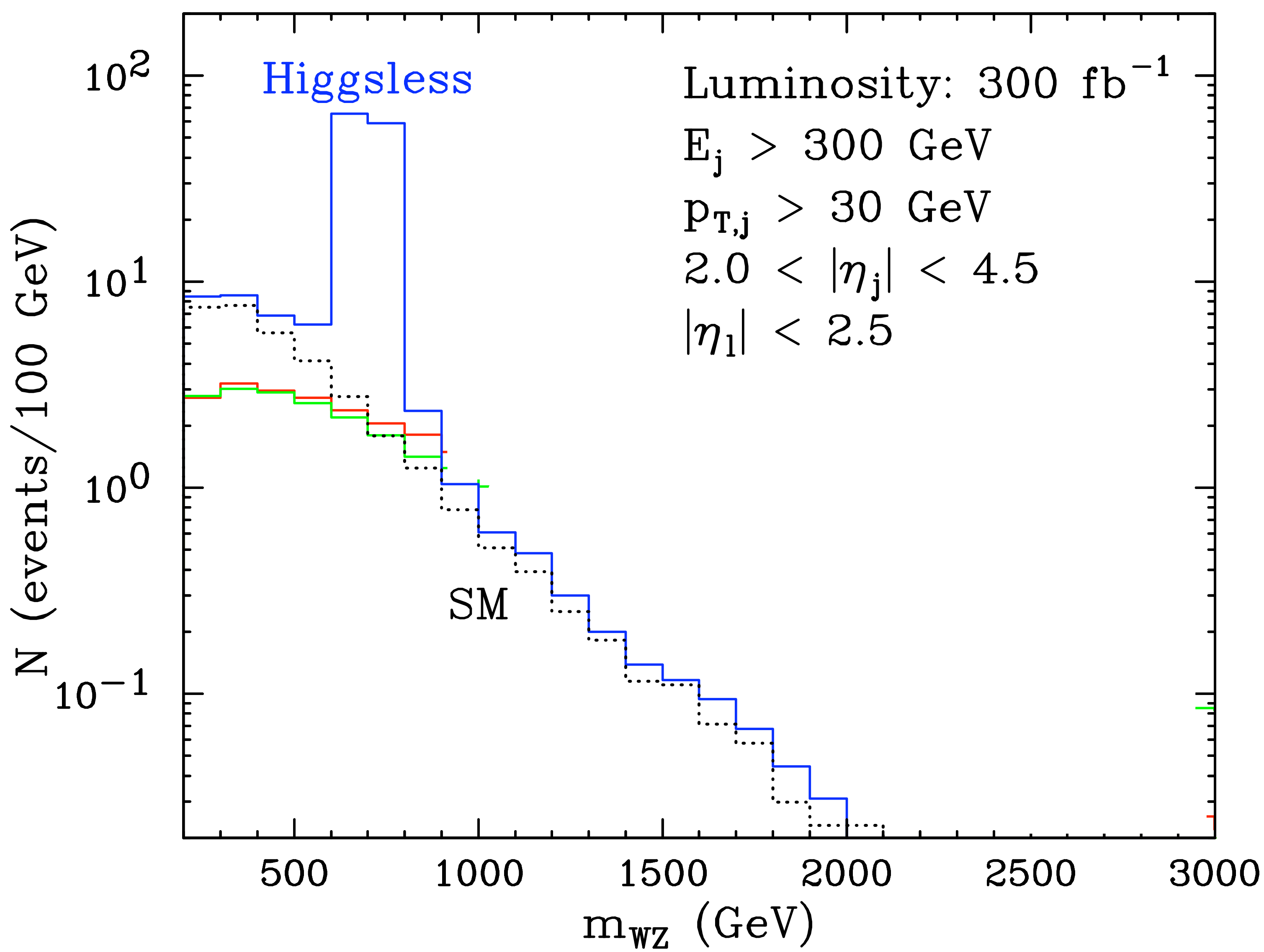
WW Scattering Amplitude



Why Build the LHC?

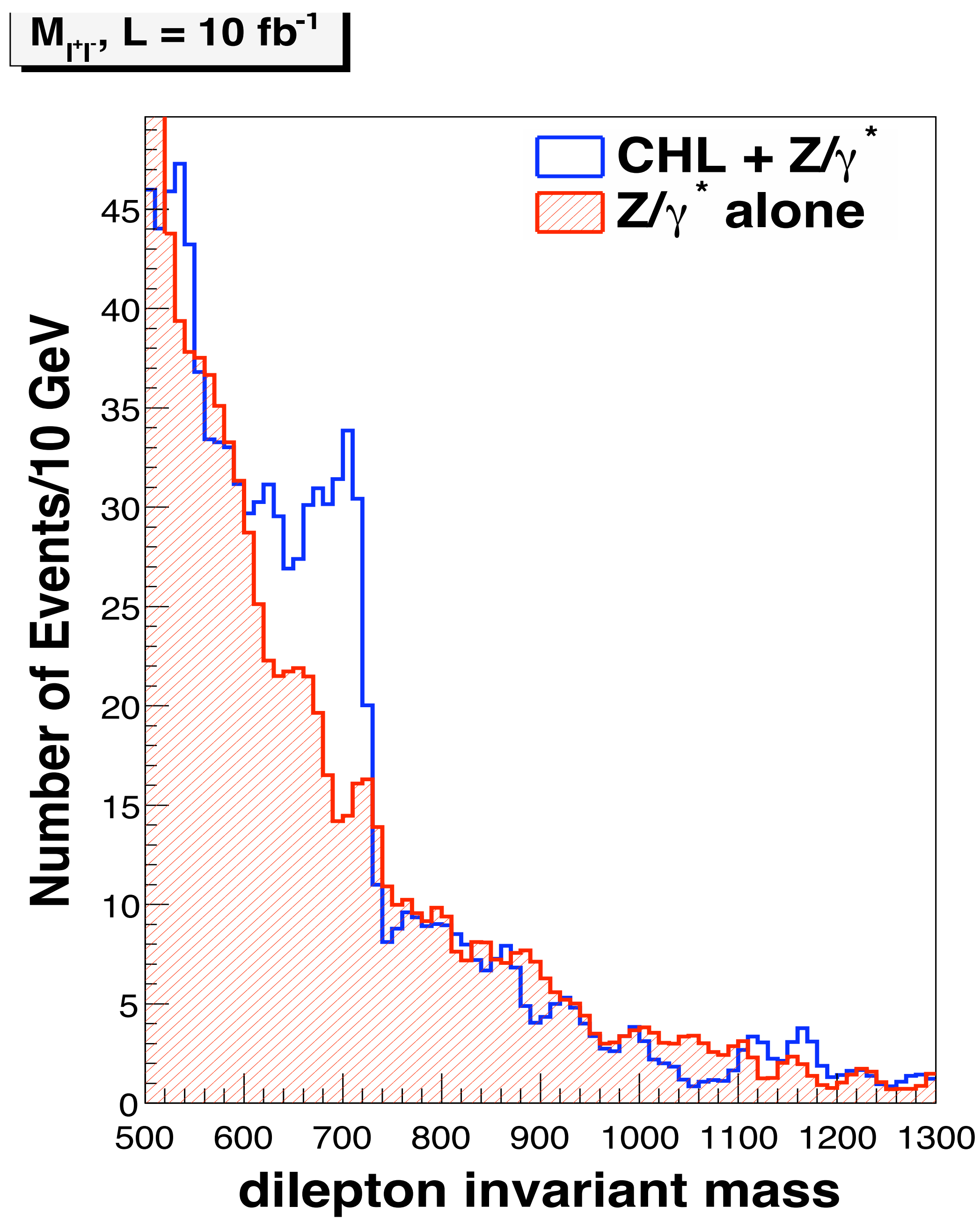


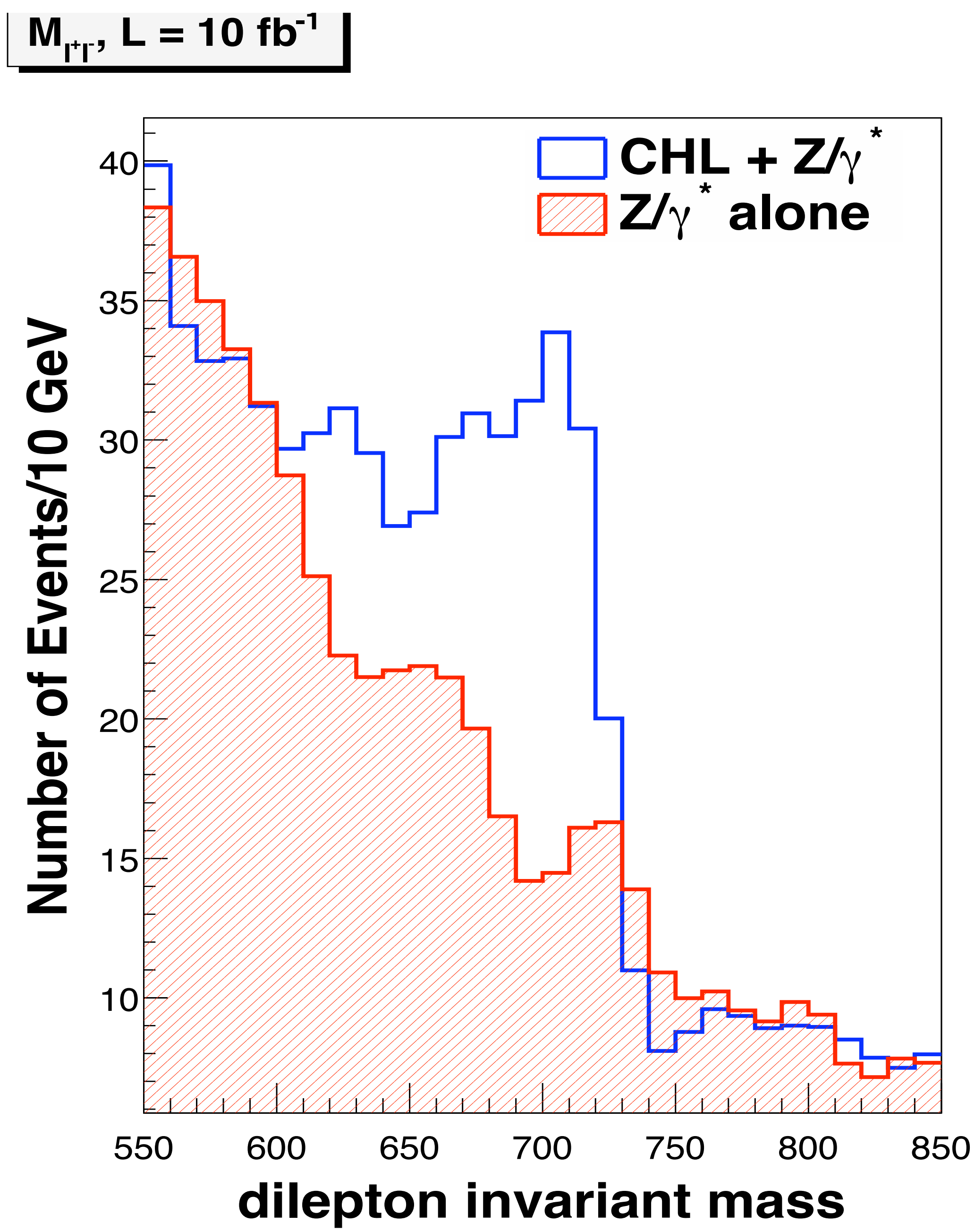
LHC Signal



Birkedal, Matchev, Perelstein hep-ph/0412278

Drell-Yan





Sanz, Martin hep-ph/0907.3931

Gauge-Phobic Higgs

AdS/CFT: a localized Higgs $\rightarrow$ $\mathcal{O}$ with $d[\mathcal{O}] = \infty$

$d[\mathcal{O}]$ finite $\rightarrow$ Higgs profile in bulk, finite VEV

Higgs profile in Bulk, finite VEV

Higgs has suppressed couplings

Cacciapaglia, Csaki, Marandella, JT hep-ph/0611358

Missing the Higgs

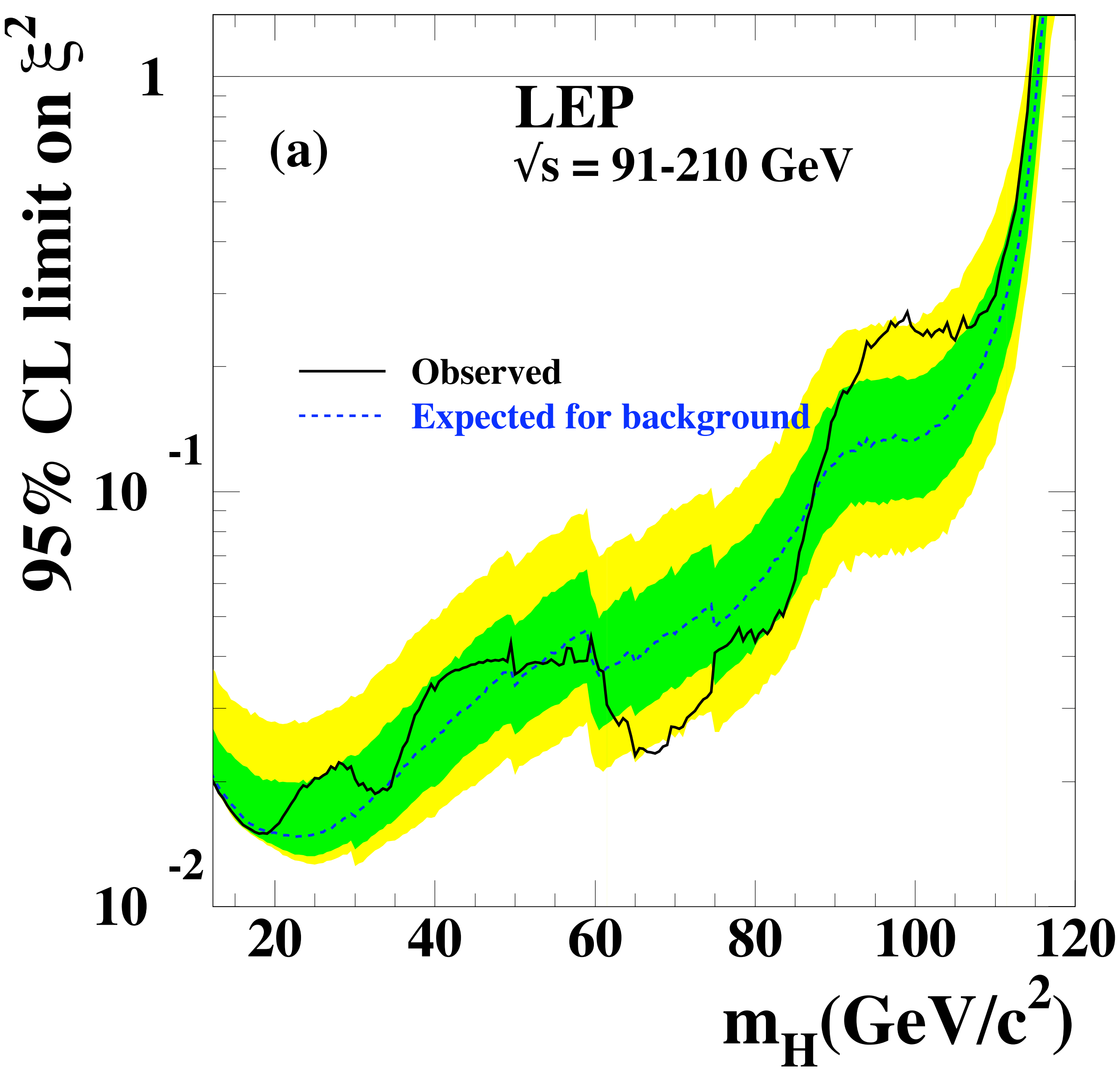
$$\xi^2 \equiv \frac{\sigma(e^+e^- \to HZ)}{\sigma_{SM}}$$

a light

Gaugephobic/Unhiggs

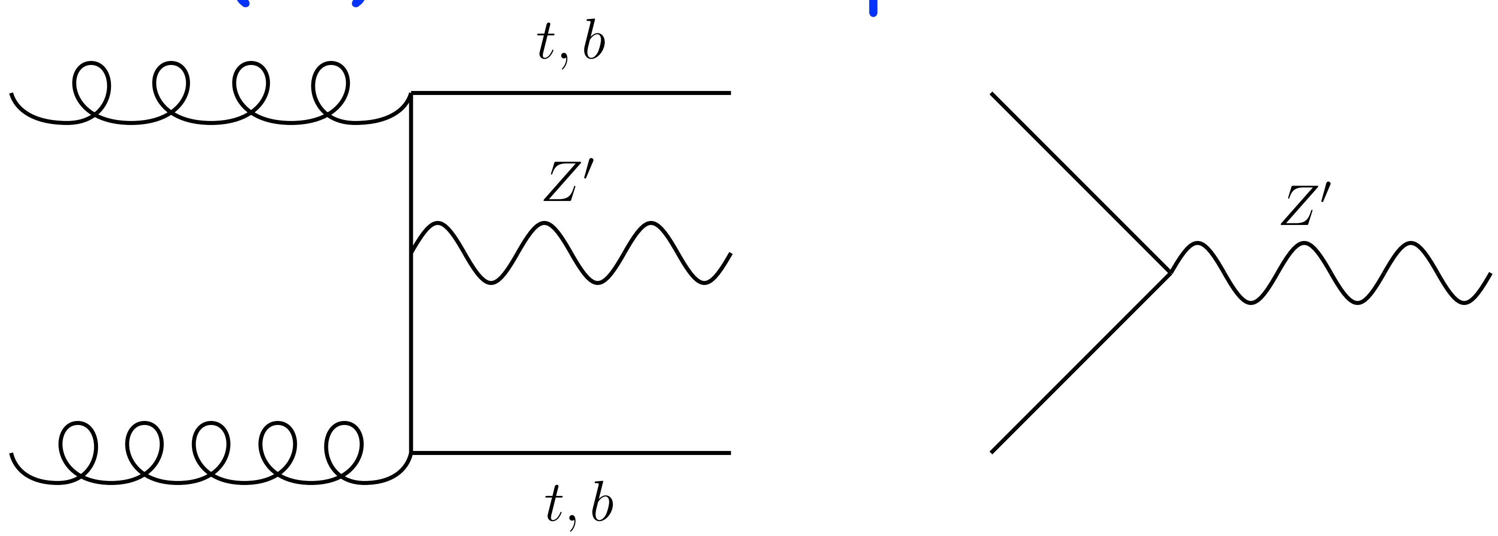
could have been

missed at LEP



G-Phobic Phenomenology

Production: tt (bb) associated production and Drell-Yan



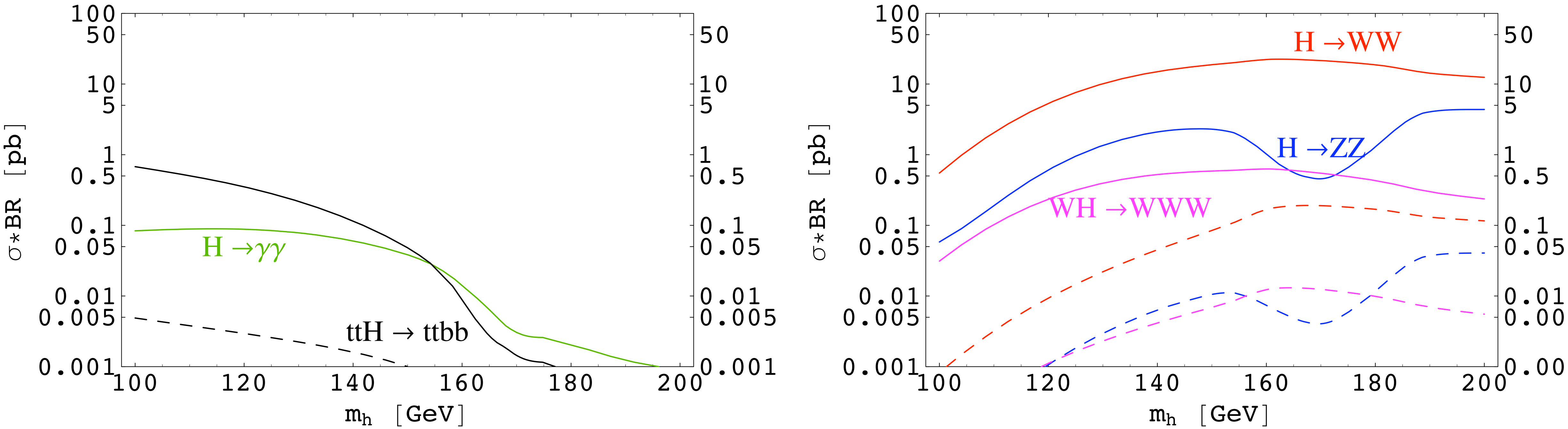
σ (pp -> Z_1 or A_1 -> W^+W^-) = 420 fb

σ (pp -> Z_1 or A_1 -> e^+e^-) = 6 fb

- WW: rescale Higgs studies, $\sim 5\sigma$ significance after 10 fb^{-1}
- Leptons: fewer events but clean

Cacciapaglia, Marandella

Gaugephobic Higgs

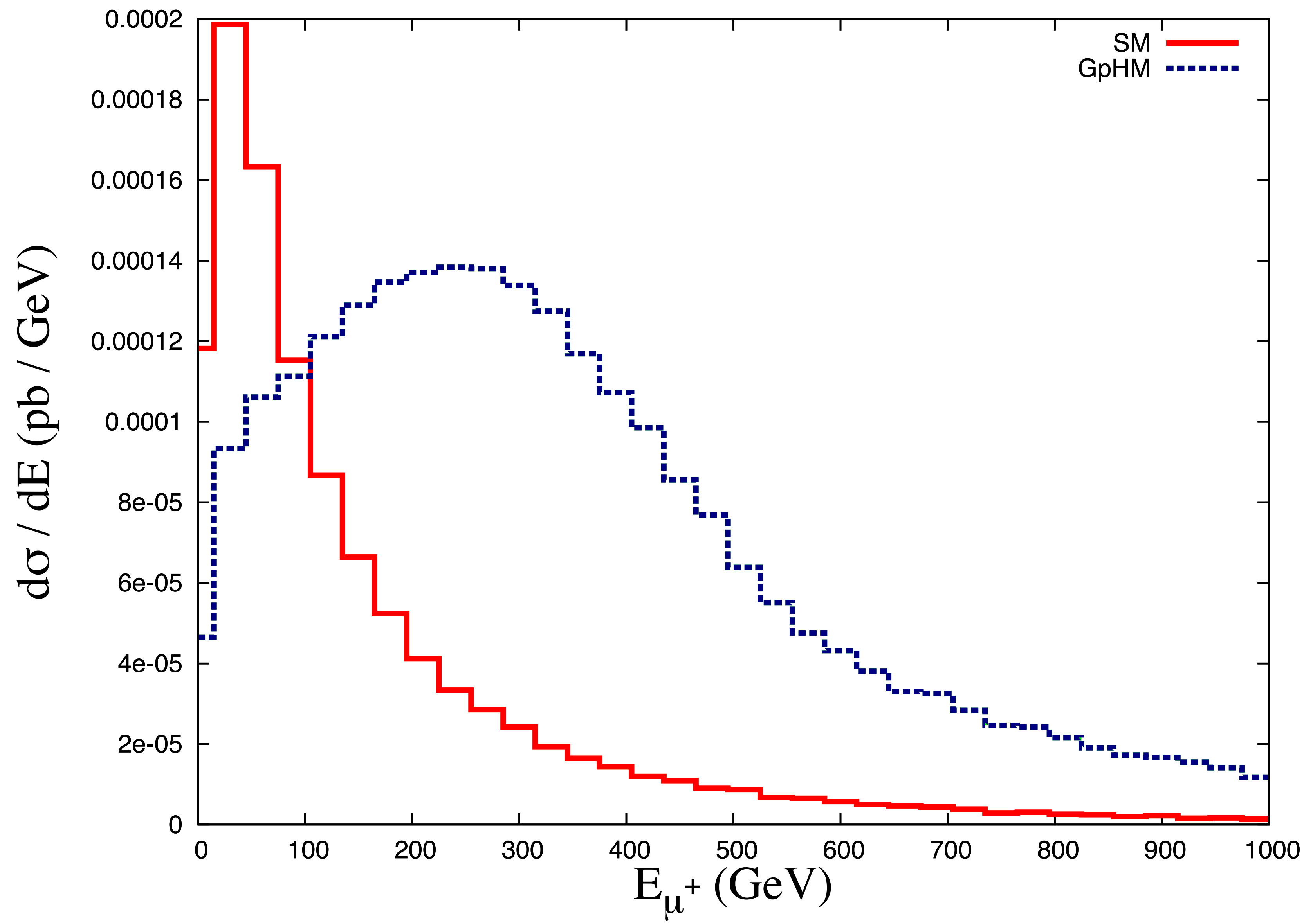


dashed lines: gaugephobic Higgs extremely difficult at LHC

Cacciapaglia, Csaki, Marandella, JT hep-ph/0611358

Gaugephobic Signal

$$pp \to W^{(2)} \to W^{+}\, h \to \mu^{+}\, \nu\, b\, \bar{b}$$



Galloway, McElrath, McRaven, JT hep-ph/0908.0532

Conclusions

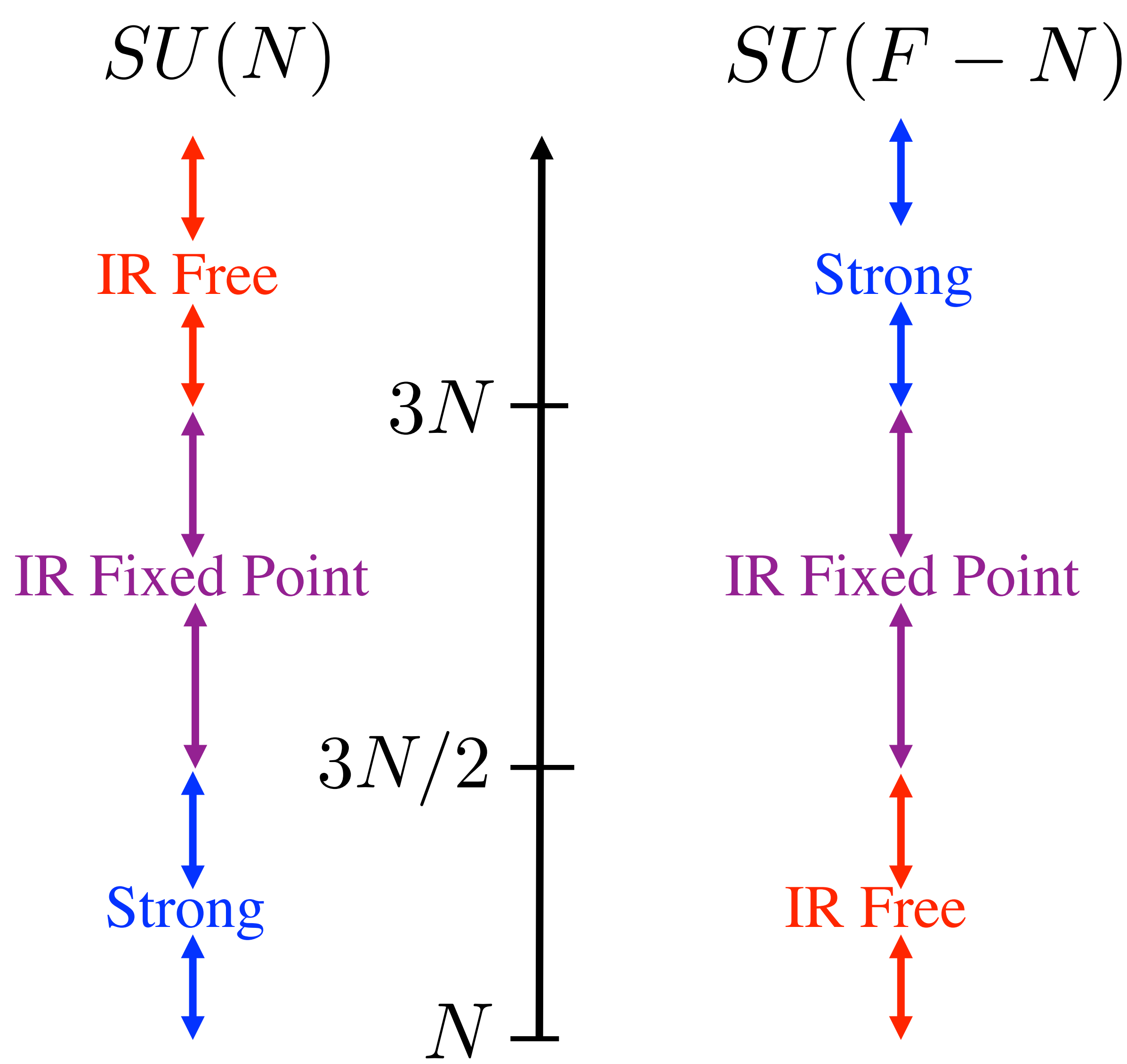
all the proposed solutions to the hierarchy problem are fine tuned

probably are other ways to address the hierarchy problem

luckily Nature is smarter than us, and will soon tell us the answer

if we ask the right questions

Duality for SUSY QCD



special cases:

F=N+1 → confinement without χSB

F=N → confinement with χSB

Toy-Model of EWSB

	$SU(2)_{\rm SC}$	$SU(2)_L$	$SU(2)_R$	$U(1)$	$U(1)_R$
T_L	$\Box$	$\Box$	$\mathbf{1}$	1	0
T_R	$\Box$	$\mathbf{1}$	$\Box$	-1	0
H	$\mathbf{1}$	$\Box$	$\Box$	0	1
S_L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-2	2
S_R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	2	2

$$W = \lambda_L S_L T_L T_L + \lambda_R S_R T_R T_R + \lambda_H H T_L T_R + \frac{1}{2}\mu H H$$

$$U(1)_Y \subset SU(2)_R,\ Y \propto \tau_{3R}$$

Two colors with Two flavors

Confinement

	$SU(2)_L$	$SU(2)_R$	$U(1)$	$U(1)_R$
$\Pi \sim (T_L T_R)$	$\square$	$\square$	0	0
$B_L \sim (T_L T_L)$	$\mathbf{1}$	$\mathbf{1}$	2	0
$B_R \sim (T_R T_R)$	$\mathbf{1}$	$\square$	-2	0
H	$\square$	$\square$	0	1
S_L	$\mathbf{1}$	$\mathbf{1}$	-2	2
S_R	$\mathbf{1}$	$\mathbf{1}$	2	2

$$W_{\text{eff}} = f\left[\lambda_L S_L B_L + \lambda_R S_R B_R + \lambda_H H \Pi\right] + \frac{1}{2}\mu H H$$

Confinement with χSB

$$\det(\Pi) - B_L B_R = \tfrac{1}{2} f^2$$

$$f = \frac{\Lambda}{4\pi}$$

$$W_{\text{eff}} = f\left[\lambda_L S_L B_L + \lambda_R S_R B_R + \lambda_H H \Pi\right] + \tfrac{1}{2}\mu H H$$

$$\Pi^j{}_k = \tfrac{1}{\sqrt{2}}(\Pi_0 \mathbf{1}_2 + i\Pi_A \tau_A)^j{}_k$$

$$\det(\Pi) = \tfrac{1}{2}\left(\Pi_0^2 + \Pi_A \Pi_A\right)$$

$$\Pi_0 = \left(f^2 + 2B_L B_R - \Pi_A \Pi_A\right)^{1/2}$$

Confinement with χSB

equations of motion:

$$
\begin{aligned}
H_0 &= -\frac{\lambda_H f}{\mu}\Pi_0 \\
f\lambda_H \Pi_A &= -\mu H_A \\
H_0 \Pi_A &= H_A \Pi_0
\end{aligned}
$$

3 linear combinations of Π_A and H_A are undetermined: Goldstone Bosons

Fat Higgs

$$W = \lambda_L S_L T_L T_L + \lambda_R S_R T_R T_R + \lambda_H H T_L T_R + \frac{1}{2} y (S_L + S_R) H H$$

$$\begin{aligned}
\langle H_0 \rangle &= \left(\frac{2\lambda_L \lambda_R}{9y^2} \right)^{1/4} f \\
\langle S_L \rangle &= \langle S_R \rangle = \pm \lambda_H \left(\frac{2}{9y^2 \lambda_L \lambda_R} \right)^{1/4} f \\
\langle B_L \rangle &= -\left(\frac{\lambda_R}{18y^2 \lambda_L} \right)^{1/2} f \\
\langle B_R \rangle &= -\left(\frac{\lambda_L}{18y^2 \lambda_R} \right)^{1/2} f
\end{aligned}$$

Luty, JT, Grant hep-ph/0006224

Murayama, Harnik, Kribs, Larsen hep-ph/0311349