The Composite Higgs Alternative

Alex Pomarol (Univ. Autonoma Barcelona)

EW precision test favors a light Higgs

EW precision test favors a light Higgs

→ Higgs as an elementary particle

But it comes with
a naturalness problem → Need of supersymmetry

EW precision test favors a light Higgs

Higgs as an elementary particle

But it comes with
a naturalness problem → Need of supersymmetry

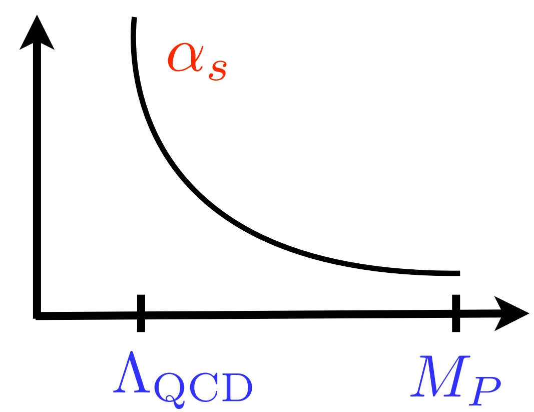
Higgs as a composite particle

does not suffer from naturalness problems

Example in QCD:

$$m_\pi << M_P$$

spin=0 composite states at $\Lambda_{\rm QCD} << M_P$



Composite Higgs scenario is inspired by QCD:

$$m_\pi < m_\rho, m_{a_1}, ... << M_P$$

The (pseudo)scalars are the lightest resonances

They are Pseudo-Goldstone Bosons

Global QCD symmetry:
(for two massless quarks)

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

3 Goldtones: π^+, π^-, π^0

Not a symmetry of the EW sector,
and therefore a potential for the pion
is induced at the loop-level:

$$V(\pi) = m_\pi^2 \pi^2 + ...$$

Can the light Higgs be a kind of a pion
from a new strong QCD-like sector?

Georgi,Kaplan 80s

Differences with QCD:

1) **Larger global symmetry of the new strong sector:**

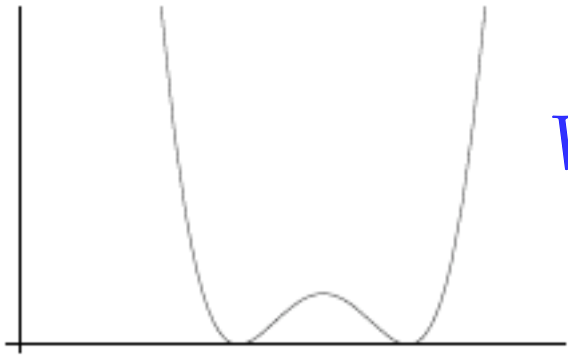
$$\mathbf{SO(5) \longrightarrow SO(4) \sim SU(2) \text{ x } SU(2)}$$

4 Goldstones = a doublet of SU(2) = Higgs

2) **The Higgs must get a VEV**

EW interactions + Yukawas breaks the global SO(5):

Higgs potential induced by gauge loops + top loops



$$V(h) = -m^2 h^2 + \ldots$$

One finds EWSB minimums thanks to the fact that the SM have a heavy top:

EWSB $\leftrightarrow$ heavy top

The Higgs will be light since its mass arises at the one-loop level

Main problem with this scenario:

Main problem with this scenario:

How to go further: Calculate spectrum, check consistency with EWPTs, fermion sector (flavor problem),...

i.e. how to calculate within strongly coupled theories

Lack of predictability !!

Recent progress: explicit weakly-coupled examples

- Little Higgs — Arkani-Hamed, Cohen, Katz, Nelson
- Holographic Higgs: Extra dimensions — Agashe, Contino, AP

Predictive models!

Recent progress: explicit weakly-coupled examples

- Little Higgs

Arkani-Hamed, Cohen, Katz, Nelson

- Holographic Higgs: Extra dimensions

Agashe, Contino, AP

Predictive models!

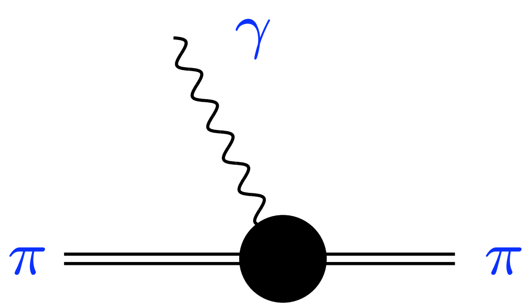
Lets have a brief look
at this possibility
and its implications

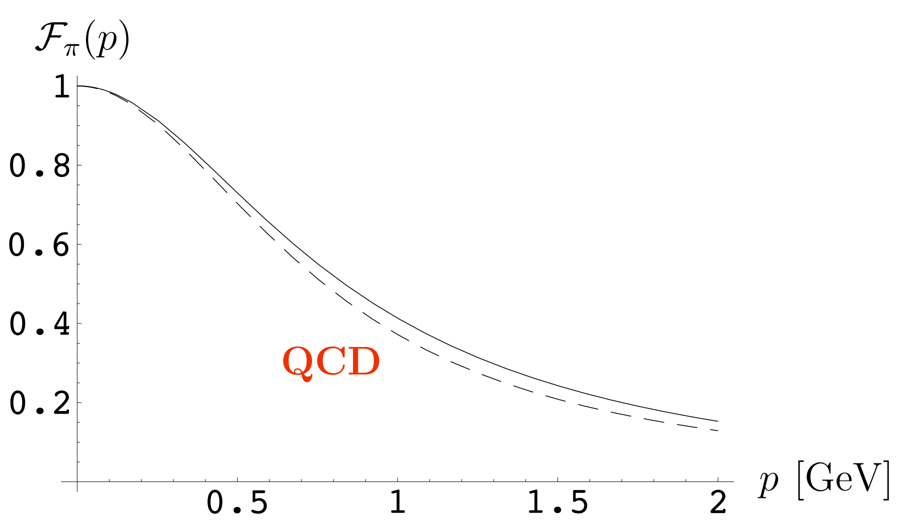
Why extra dimensions can give rise to a composite Higgs scenario?

An educated answer : AdS/CFT correspondence: Strongly coupled 4D theories are equivalent to 5D weakly-coupled theories in AdS

A more pedestrian answer : Just go on and calculate the Higgs properties, e.g., form factors:

Composite state:
(such as pions in QCD)



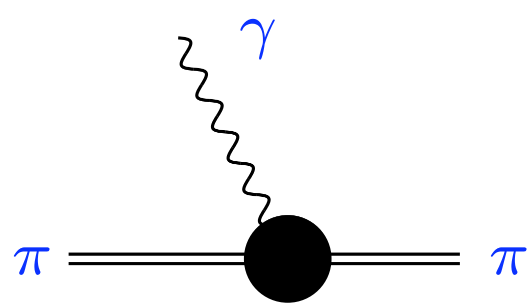


Why extra dimensions can give rise to a composite Higgs scenario?

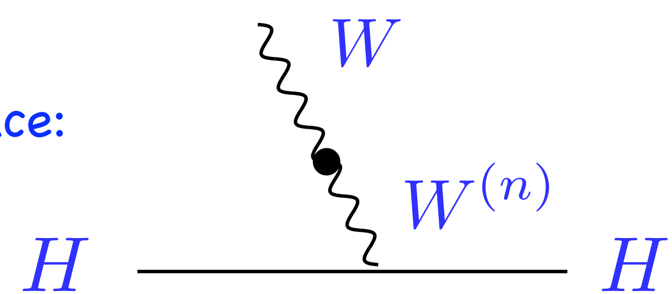
An educated answer : AdS/CFT correspondence: Strongly coupled 4D theories are equivalent to 5D weakly-coupled theories in AdS

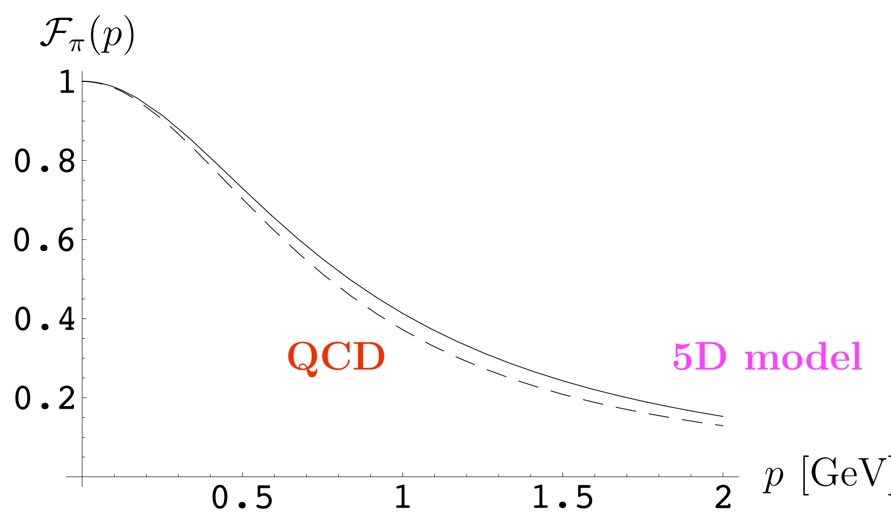
A more pedestrian answer : Just go on and calculate the Higgs properties such as form factors:

Composite state:
such as pions in QCD



Higgs inside
a 5D curved space:



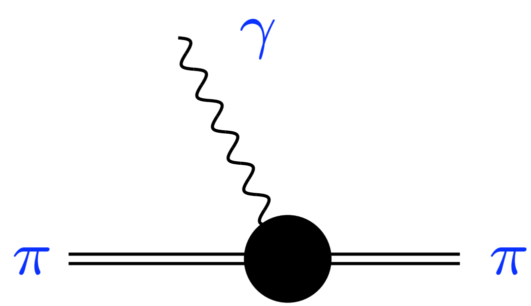


Why extra dimensions can give rise to a composite Higgs scenario?

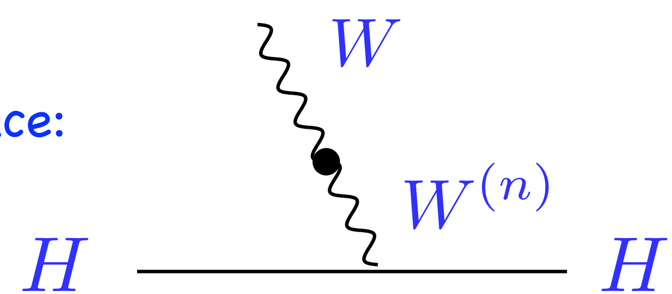
An educated answer : AdS/CFT correspondence: Strongly coupled 4D theories are equivalent to 5D weakly-coupled theories in AdS

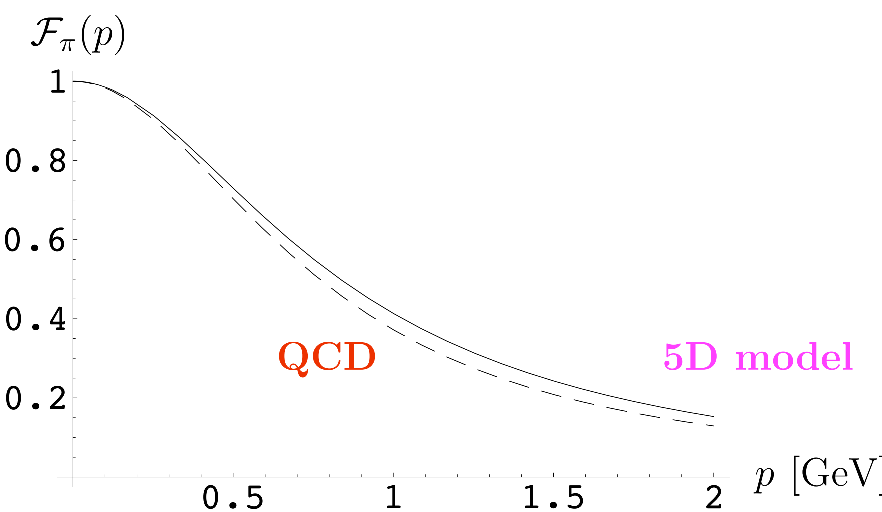
A more pedestrian answer : Just go on and calculate the Higgs properties such as form factors:

Composite state:
such as pions in QCD



Higgs inside
a 5D curved space:

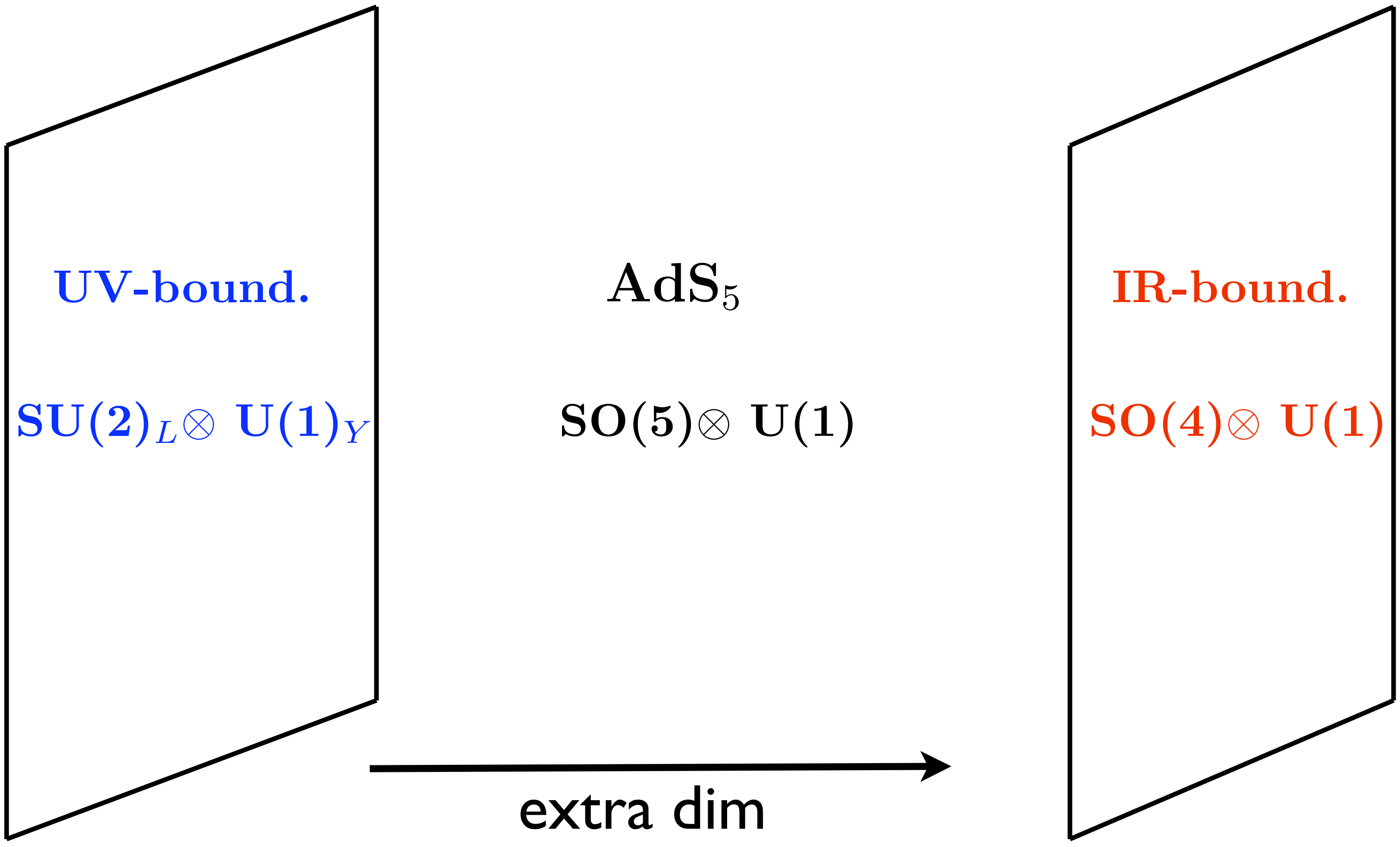




The extra dim must be warped!!

Minimal 5D composite Higgs

The bosonic sector:



Agashe,Contino,A.P.

Why this symmetry breaking pattern?

We are in 5D: $\mathbf{A_M} = (\mathbf{A}_\mu, \mathbf{A_5})$

Massless boson spectrum:

- $\mathbf{A}_\mu$ **of** $\mathbf{SU(2)}_L \otimes \mathbf{U(1)}_Y$ = **SM Gauge bosons**
- $\mathbf{A_5}$ **of** $\mathbf{SO(5)/SO(4)}$ = **2 of** $\mathbf{SU(2)}_L$ = **SM Higgs**

$\hookrightarrow$ **Higgs-gauge unification**

Hosotani mechanism

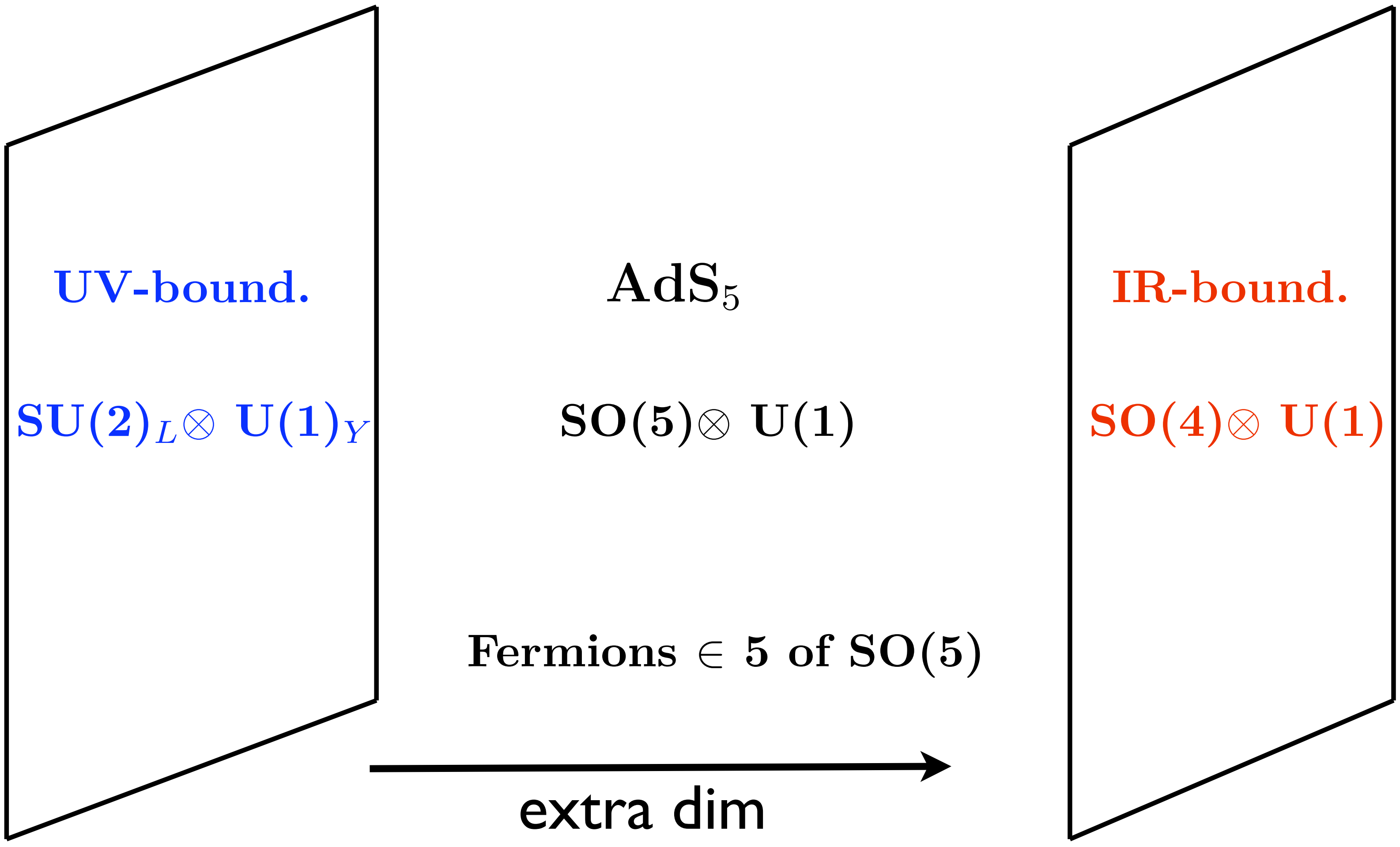
Higgs mass protected by 5D gauge invariance!

$$A_5 \rightarrow A_5 + \partial_5 \theta$$

shifts as a PGB

Minimal 5D composite Higgs

The fermionic sector: more model dependent



Agashe,Contino,A.P.

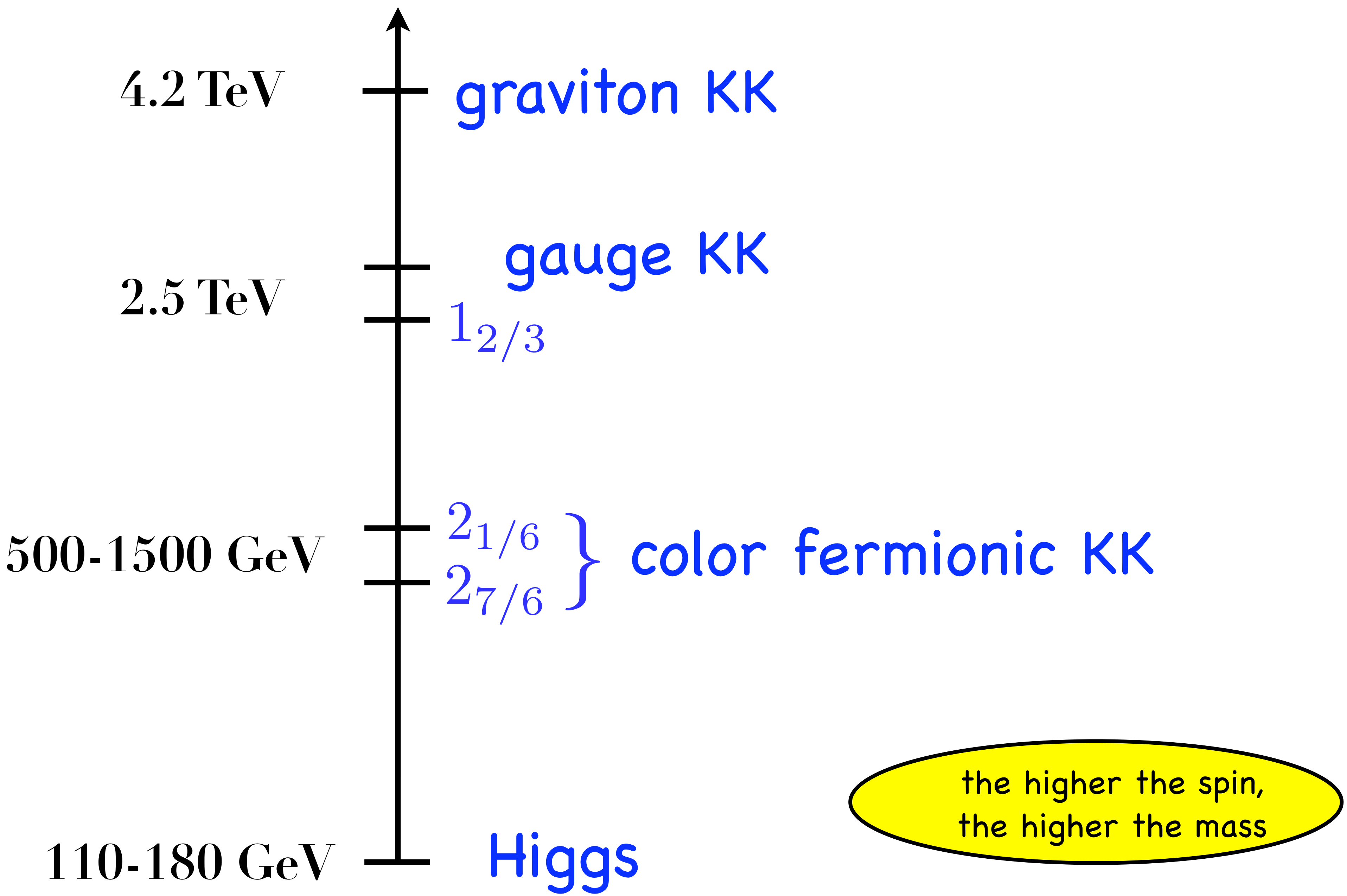
Predictions

Light Higgs $+$ **KK resonances for each SM field in complete reps of the bulk group SO(5)**

top: $5 = 2_{7/6} + 2_{1/6} + 1_{2/3}$

→ **exotic states of Q=5/3**

Spectrum


4.2 TeV
graviton KK
gauge KK
2.5 TeV
$1_{2/3}$
$2_{1/6}$
500-1500 GeV
color fermionic KK
$2_{7/6}$
110-180 GeV
Higgs
the higher the spin,
the higher the mass

What to expect at the LHC and, maybe, ILC?

Type of searches:

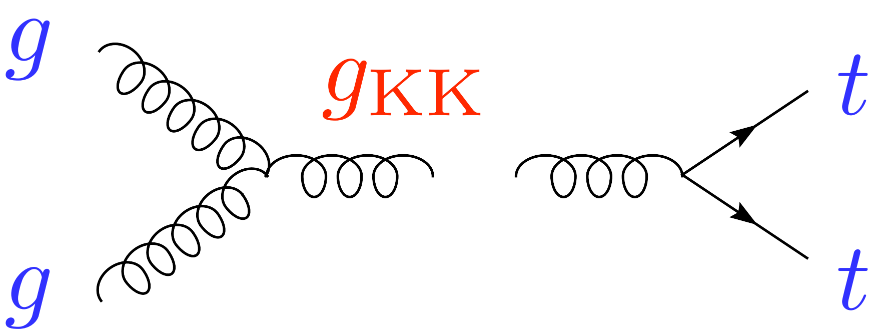
Direct: Detection of the heavy KK-particles

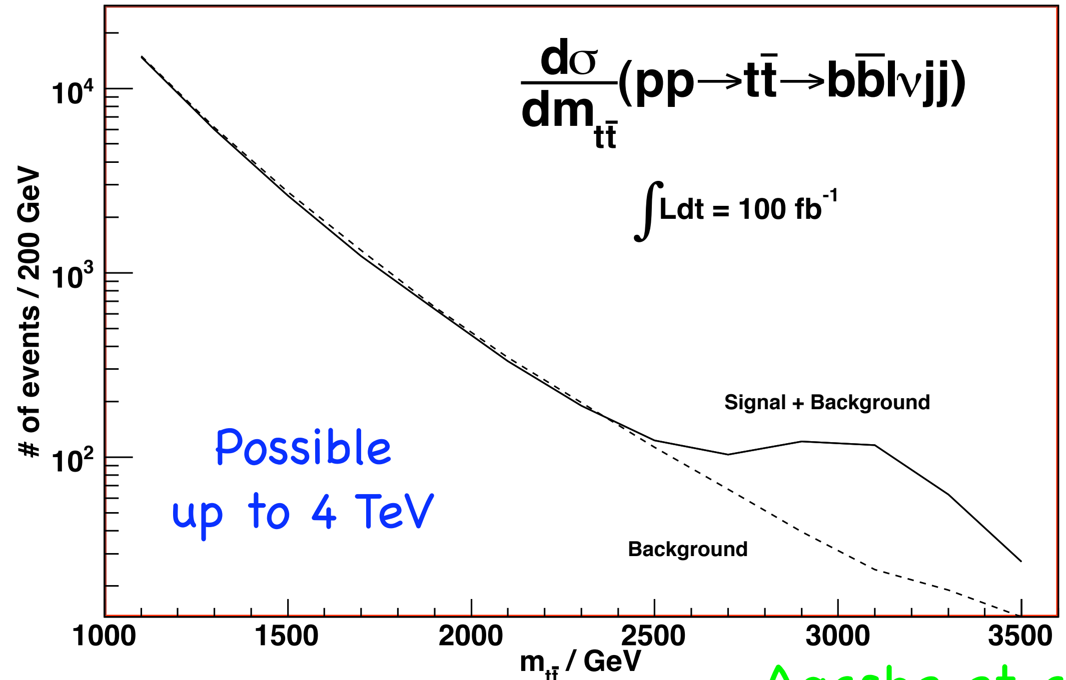
→ Very similar to detecting the "hadrons" of TC models

Indirect: The Higgs behaves as a composite particle: Expected deviations from a SM elementary Higgs

Direct Searches

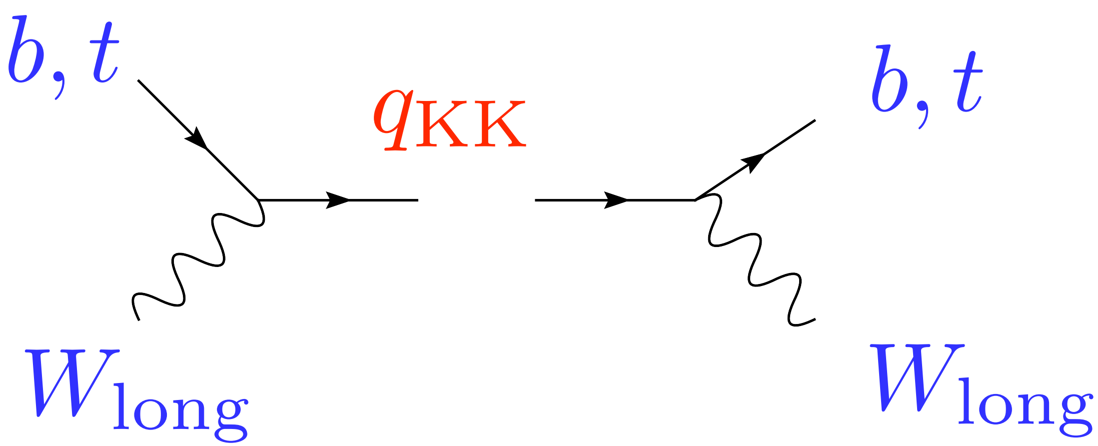
1) KK of the gluon:





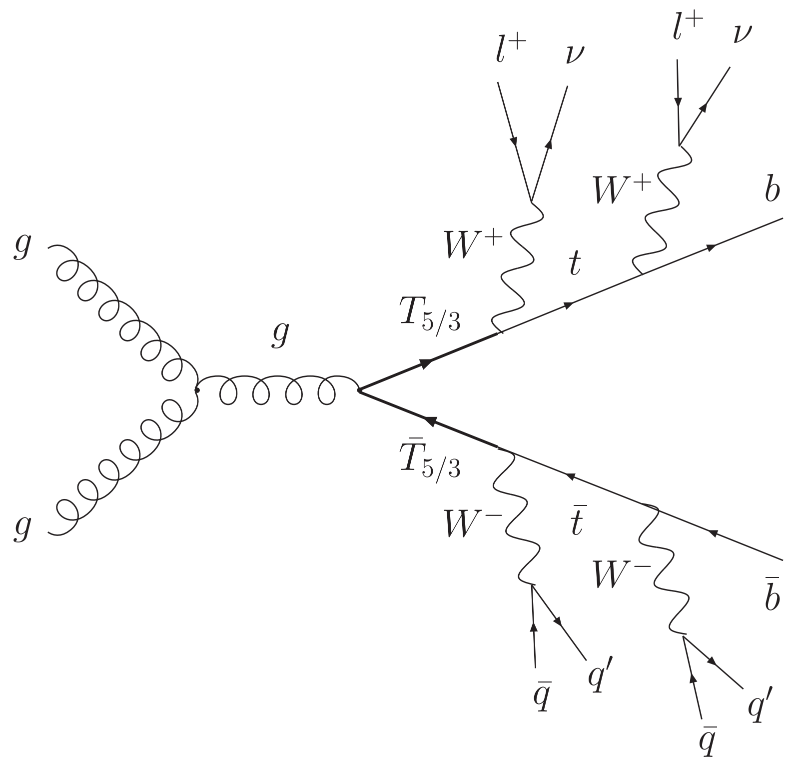
Agashe et al

2) KK of the top:



feasible to see up to 1-2 TeV

If the KK-fermion are light, they can be double produced:



masses up to 1 TeV reached with an integrated luminosity of 20/fb

Contino,Servant

Indirect Searches

Giudice,Grojean,A.P.,Rattazzi

Model independent approach:

Find the effective theory after integrating out the heavy states:

$$\mathcal{L}_{\rm SM+H} \quad + \quad \text{higher dimensional operators}$$

→ **what are they?**

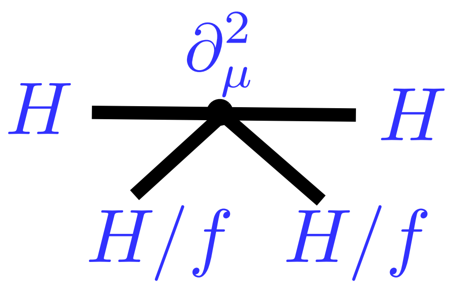
(equivalent of the chiral lagrangian in QCD)

Parametric counting for the higher-dim operator's coefficients:

Physics of two scales: $\begin{cases} f & = \text{decay constant} \\ m_\rho & = \text{resonance mass} \end{cases}$

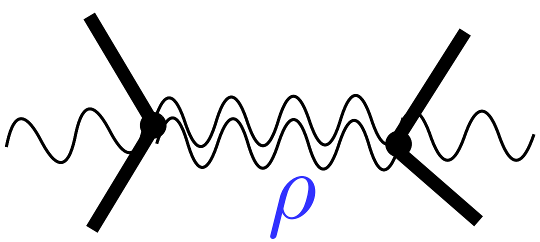
TREE-LEVEL:

leading:



e.g. $$\frac{1}{f^2}(\partial_\mu H^2)^2$$

subleading:



e.g. $$\frac{1}{m_\rho^2}(H^\dagger D^\mu H)(\partial^\nu B_{\mu\nu})$$

ONE-LOOP:

e.g. those suppressed by the Golstone symmetry $$\frac{g'^2}{16\pi^2}\frac{g^2}{m_\rho^2}H^\dagger H G_{\mu\nu}G^{\mu\nu}$$

DIMENSION-6 OPERATORS

leading:

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$

$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right)$$

tested at LEP: T-parameter
$c_T = 0$ **if the strong sector is custodial invariant**

The rest, not tested yet!

subleading:

$$\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i+\frac{ic_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

Tested by EWPT at LEP!

one-loop:

$$\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}+\frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$\frac{c_\gamma {g'}^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu}+\frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.$$

Contribution to the coefficients of the dim-6 operators from explicit models:

	Holographic Higgs Extra dim	Littlest Higgs
c_T	0	-1/16
c_H	1	1/4
c_y	1	
c_6	0	

From EWPT at LEP: $m_\rho > 2-3\ TeV \longrightarrow f > 500\ GeV$

Measuring the compositeness of the Higgs:

$$\xi \equiv \frac{v^2}{f^2}$$

Definite modifications of Higgs decay widths:

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

$$\Gamma\left(h \to W^+W^-\right)_{\mathrm{SILH}} = \Gamma\left(h \to W^+W^{(*)-}\right)_{\mathrm{SM}}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_W\right)\right]$$

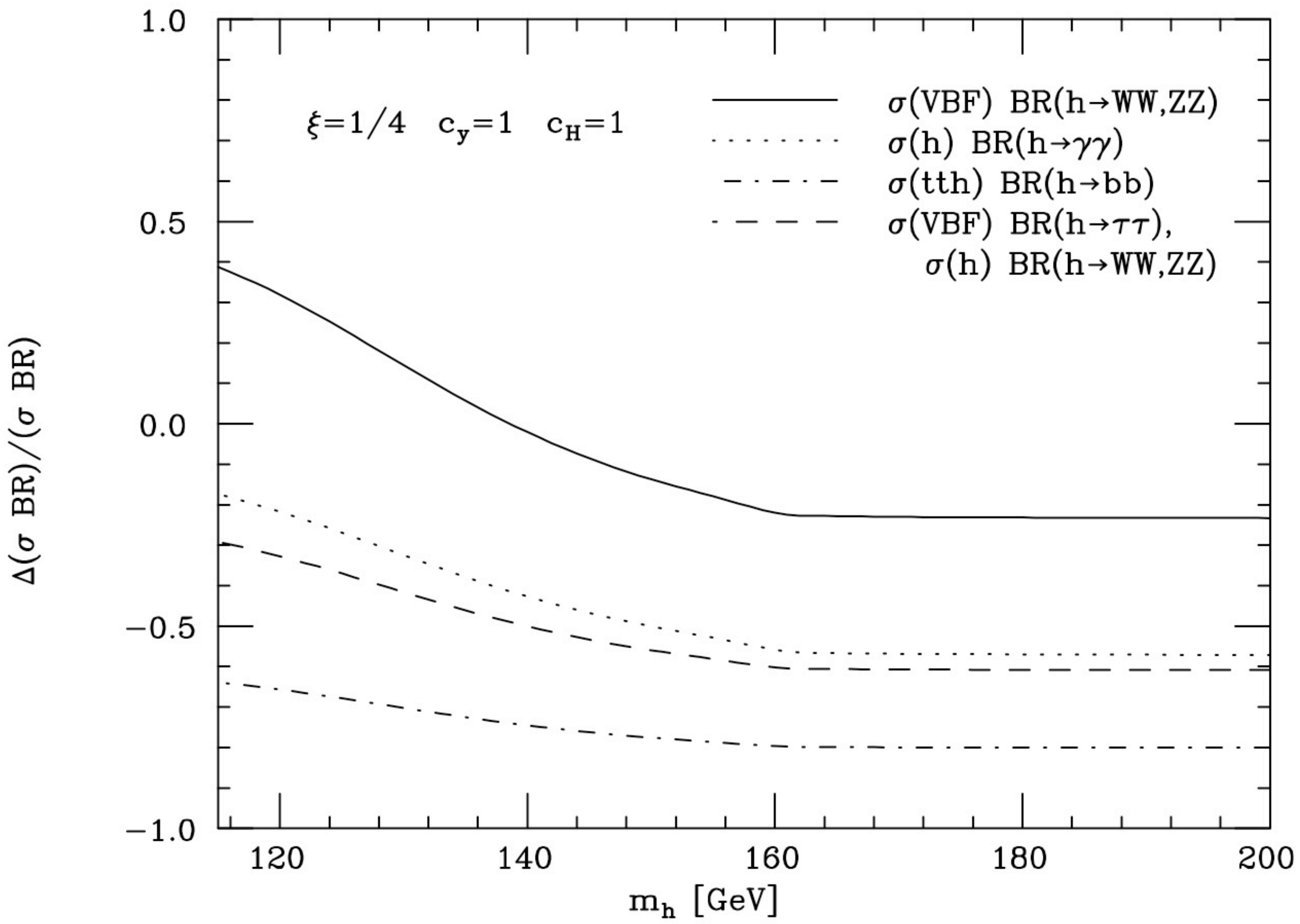
$$\Gamma\left(h \to ZZ\right)_{\mathrm{SILH}} = \Gamma\left(h \to ZZ^{(*)}\right)_{\mathrm{SM}}\left[1 - \xi\left(c_H - \frac{g^2}{g_\rho^2}\hat{c}_Z\right)\right]$$

$$\Gamma\left(h \to gg\right)_{\mathrm{SILH}} = \Gamma\left(h \to gg\right)_{\mathrm{SM}}\left[1 - \xi\,\mathrm{Re}\left(2c_y + c_H + \frac{4y_t^2 c_g}{g_\rho^2 I_g}\right)\right]$$

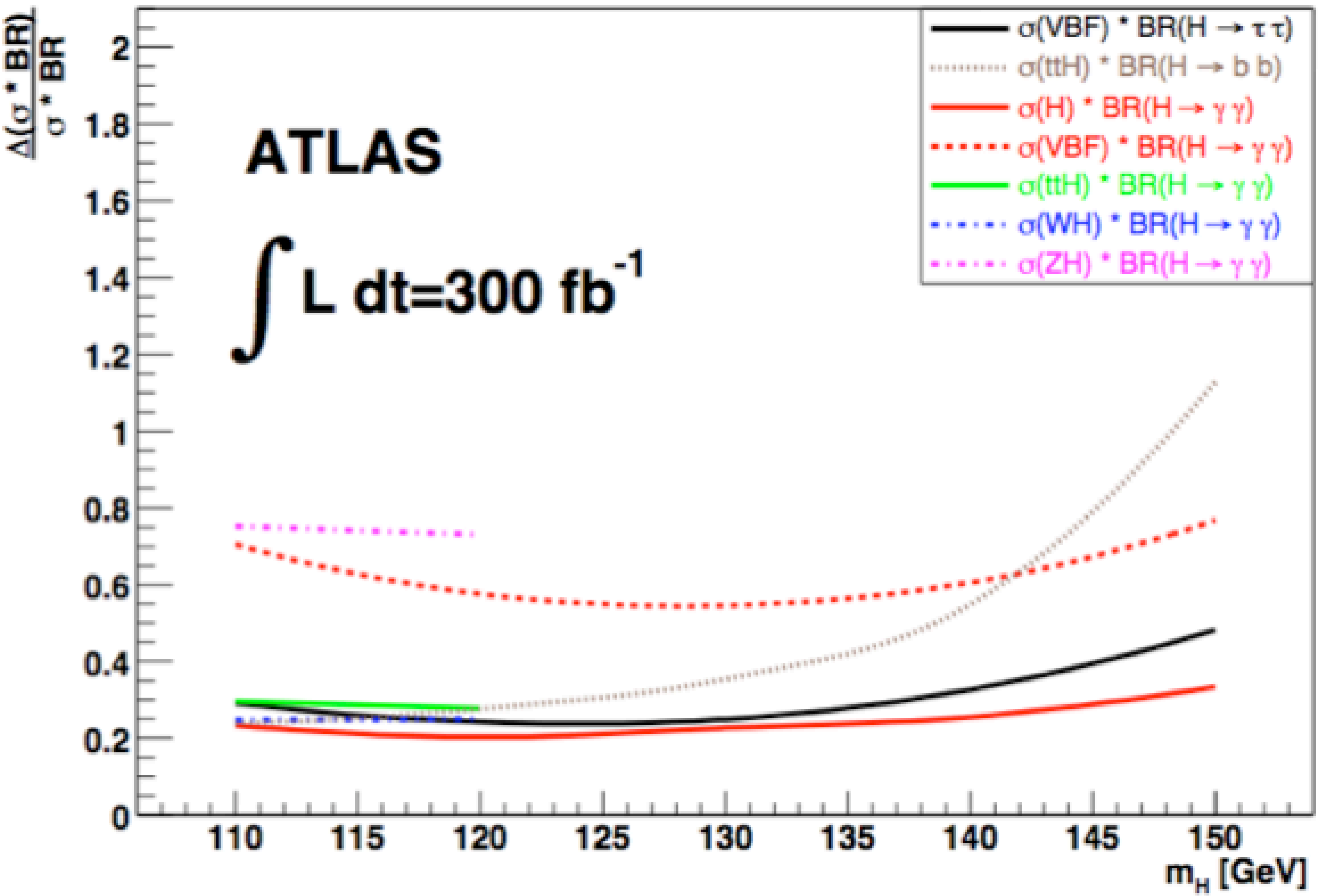
$$\Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma\gamma\right)_{\mathrm{SM}}\left[1 - \xi\,\mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_\gamma/I_\gamma} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_\gamma/J_\gamma} + \frac{\frac{4g^2}{g_\rho^2}c_\gamma}{I_\gamma + J_\gamma}\right)\right]$$

$$\Gamma\left(h \to \gamma Z\right)_{\mathrm{SILH}} = \Gamma\left(h \to \gamma Z\right)_{\mathrm{SM}}\left[1 - \xi\,\mathrm{Re}\left(\frac{2c_y + c_H}{1 + J_Z/I_Z} + \frac{c_H - \frac{g^2}{g_\rho^2}\hat{c}_W}{1 + I_Z/J_Z} + \frac{4c_{\gamma Z}}{I_Z + J_Z}\right)\right]$$

Deviations from the SM:



Visible at LHC?

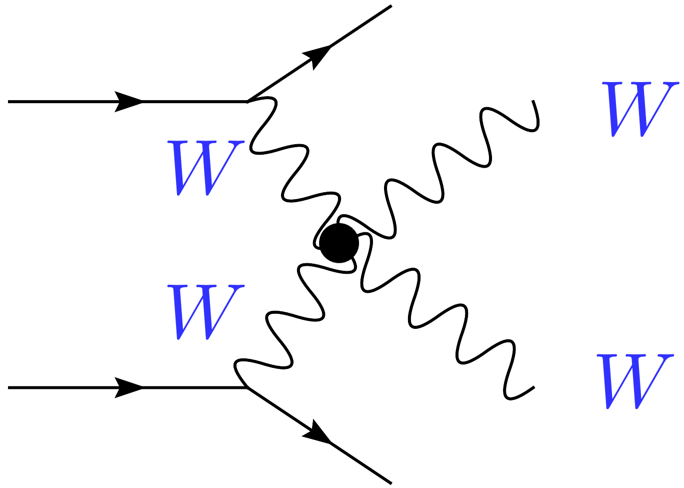


Duhrssen 03

...certainly if they are of order 20-40%

ILC would be a perfect machine to test these scenarios: effects could be measured up to a few %

Best test of composite Higgs: WW-scattering



even that the Higgs is light, it grows with s

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

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

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

Difficult to see. From Higgsless studies possible to see if

Bagger et al

$$\frac{c_H v^2}{f^2} \sim 0.5 - 0.7$$

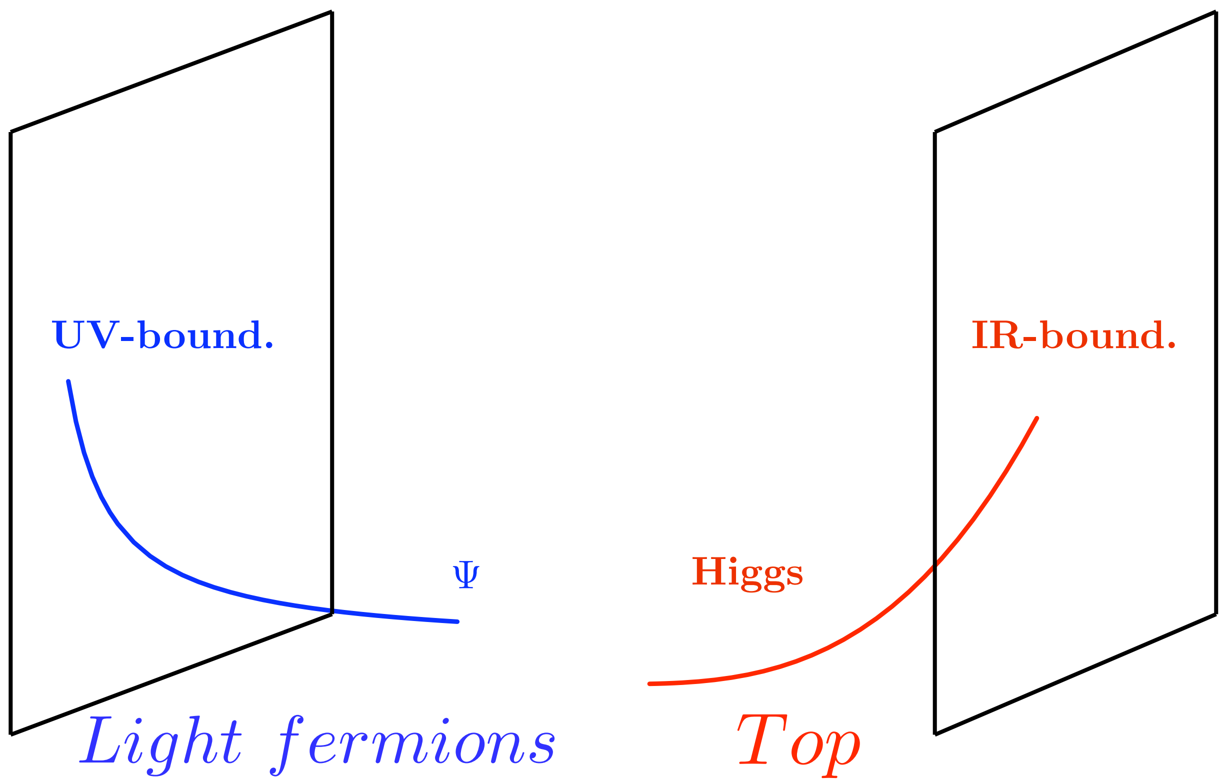
Composite Higgs suggests Composite top

Since large top mass implies large coupling of the top
to the Higgs (strong sector or extra dim)

Composite Higgs suggests Composite top

Since large top mass implies large coupling of the top
to the Higgs (strong sector or extra dim)

In warped extra dimension this means the top must be localized close to the Higgs



Composite Higgs suggests Composite top

Since large top mass implies large coupling of the top
to the Higgs (strong sector)

After integrating out the heavy resonances:

NEW DIMENSION-6 OPERATORS

leading terms:

$$\frac{c_t y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R + \frac{c_{4t}}{f^2} (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R) .$$

$$\frac{c_q y_b}{f^2} H^\dagger H \bar{q}_L H b_R + \frac{c_q y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_L^{(1)}}{f^2} H^\dagger D_\mu H \bar{q}_L \gamma^\mu q_L$$
$$+ \frac{i c_L^{(3)}}{f^2} H^\dagger \sigma^i D_\mu H \bar{q}_L \gamma^\mu \sigma^i q_L + \frac{c_{4q}}{f^2} (\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) .$$

Experimental implications of the compositeness of the top

Right-handed top:

$$\frac{c_t y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R + \frac{c_{4t}}{f^2} (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)\,.$$

↓

Modifications of $Z t_R t_R$

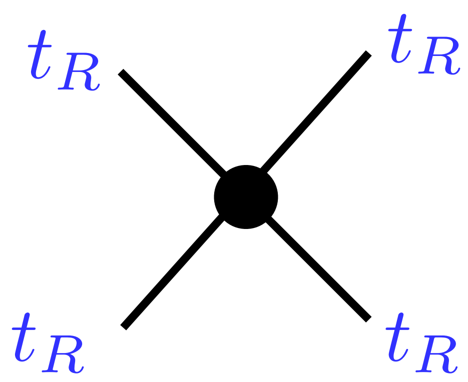
But not possible to be seen at LHC!

Experimental implications of the compositeness of the top

Right-handed top:

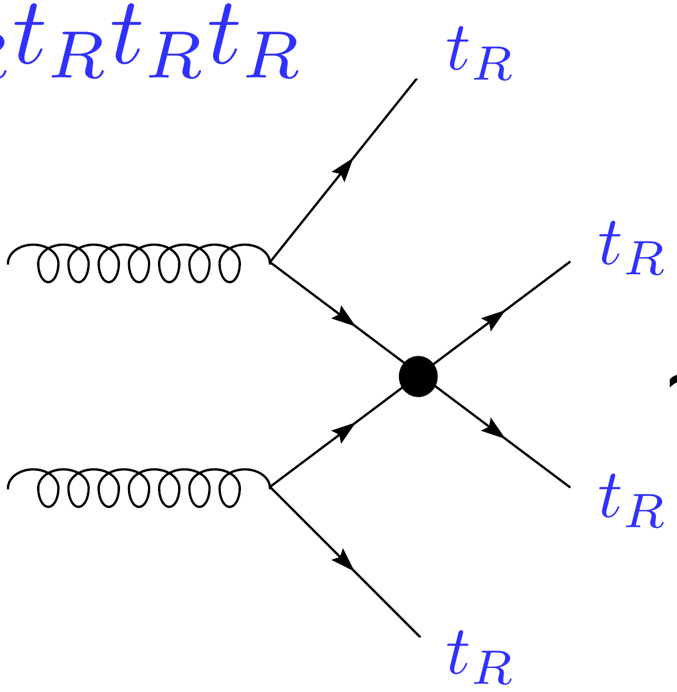
$$\frac{c_t y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R + \frac{c_{4t}}{f^2} (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R) \, .$$

4-top interaction



Enhances the 4-top production at the LHC:

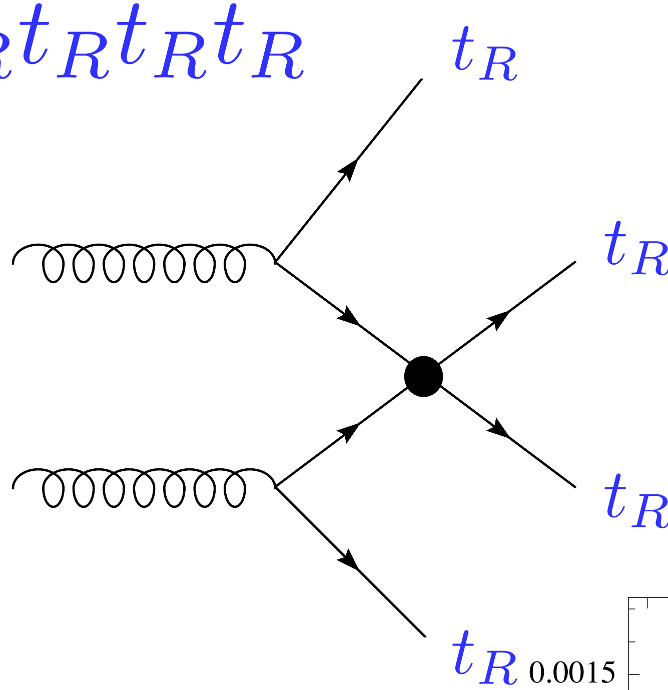
$pp \rightarrow t_R \bar{t}_R t_R \bar{t}_R$



~ grows with $(E/f)^2$

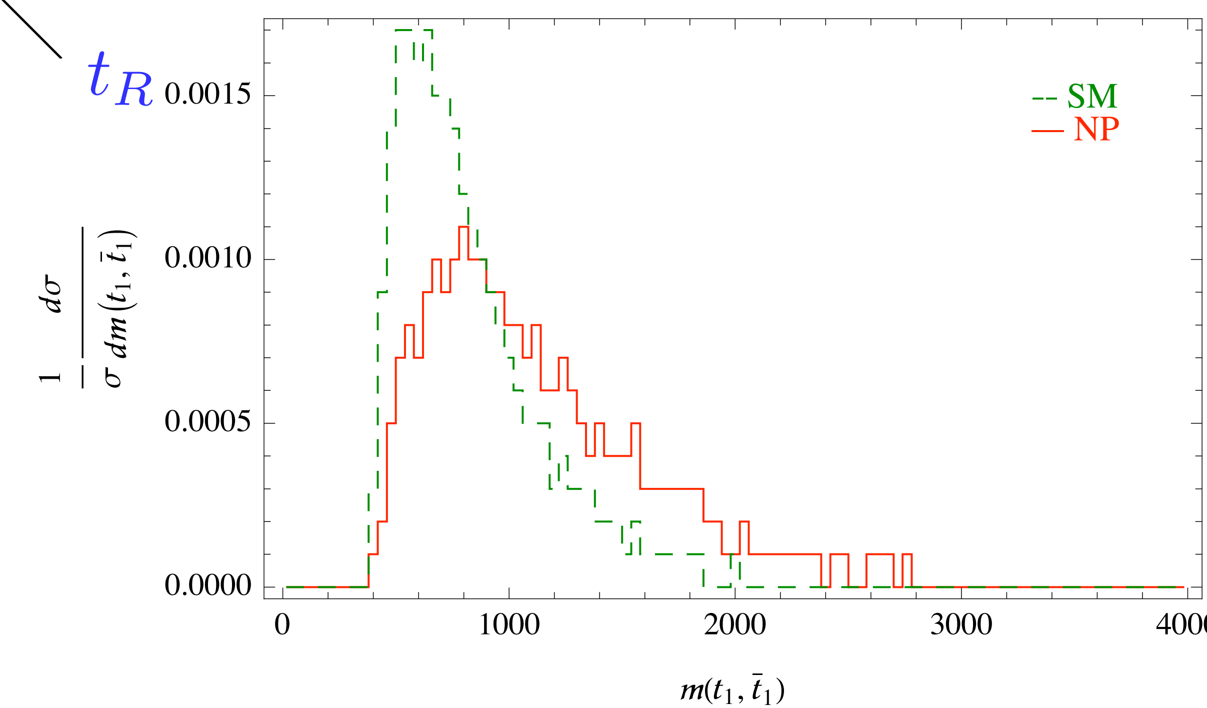
Enhances the 4-top production at the LHC:

$$pp \to t_R \bar{t}_R t_R \bar{t}_R$$



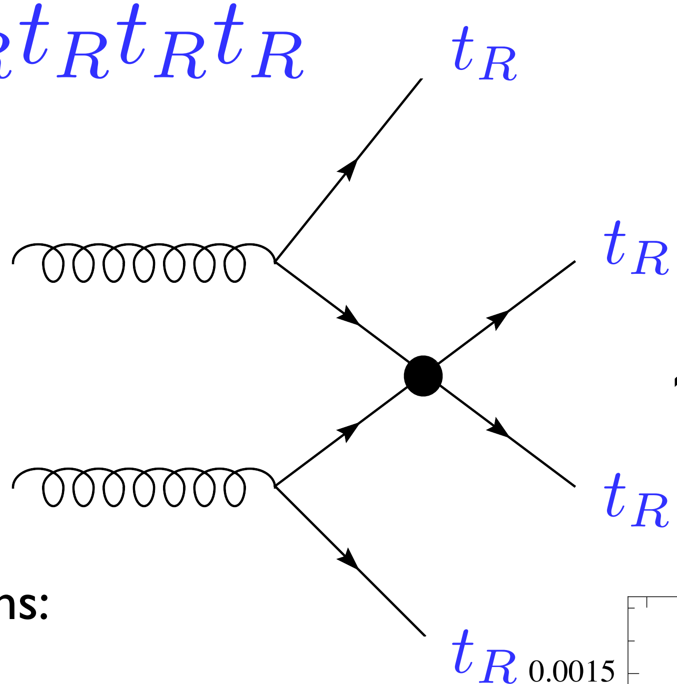
~ grows with $(E/f)^2$

A.P., J.Serra



Enhances the 4-top production at the LHC:

$$pp \to t_R \bar{t}_R t_R \bar{t}_R$$



~ grows with $(E/f)^2$

A.P., J.Serra

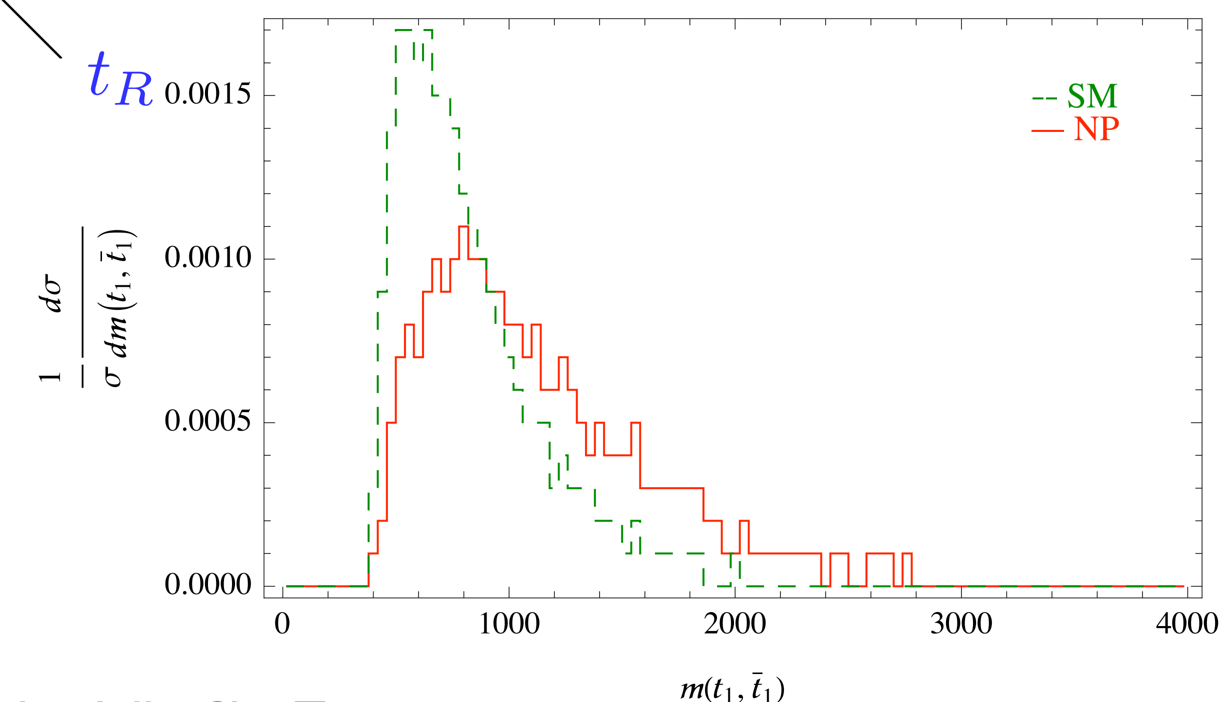
But small cross sections:

In the SM:

$$\sigma(4t) \sim 4.5\ fb$$

Composite top: ↓

$$6\ fb$$



See also Lillie,Shu,Tait

Experimental implications of the compositeness of the top

Left-handed top:

$$\frac{c_q y_b}{f^2} H^\dagger H \bar{q}_L H b_R + \frac{c_q y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_L^{(1)}}{f^2} H^\dagger D_\mu H \bar{q}_L \gamma^\mu q_L$$

$$+ \frac{i c_L^{(3)}}{f^2} H^\dagger \sigma^i D_\mu H \bar{q}_L \gamma^\mu \sigma^i q_L + \frac{c_{4q}}{f^2} (\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) \,.$$

Modifications of $W t_L b_L$

Measured in top single-production at LHC with an accuracy of 10%

Conclusions

The legacy of LEP+Tevatron seems to indicate that the main effort should go for the search of

Ligh Higgs

Conclusions

The legacy of LEP+Tevatron seems to indicate that the main effort should go for the search of

Ligh Higgs ⟶ look for supersymmetry

Conclusions

The legacy of LEP+Tevatron seems to indicate that the main effort should go for the search of

Ligh Higgs $\longrightarrow$ look for supersymmetry

.. but also, it is possible:

Ligh Higgs $\longrightarrow$ not look for supersymmetry, but for extra resonances: G′,W′ Z′,t′,...

Higgs can be composite:
In this case we expect deviations from a point-like Higgs

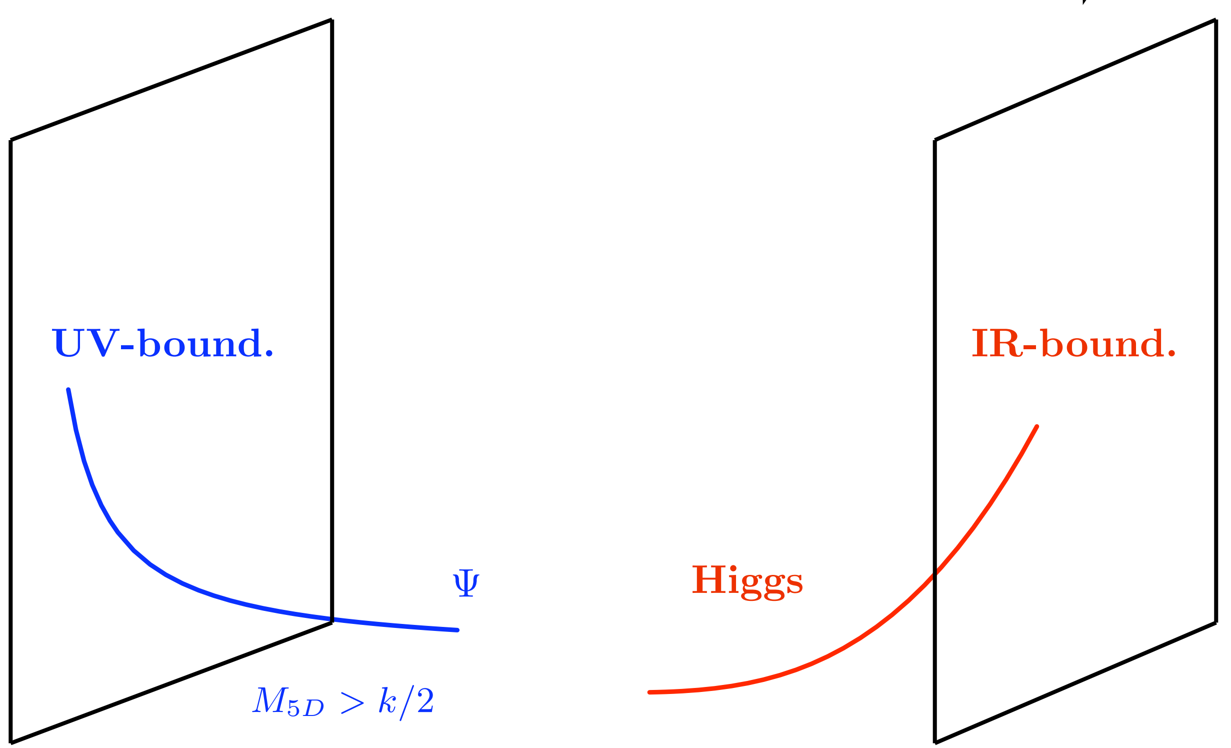
- Precise effects on Higgs decays, strong WW-scattering, strong WW $\longrightarrow$ hh
- Possibility of the top also composite

Back slides

If the space is Anti-de-Sitter (AdS) nice "geometrical" solution to the flavor problem:

The wave-functions of the massless fermion (to be associated to the SM fermions) depends on the 5D mass. For certain values the fermion wave-functions can have a small overlapping with the Higgs wave-function

➡ **Small fermion masses are natural in these models**



Gherghetta, AP

From 5D masses of order one (in units of the AdS curvature)

$$
\begin{aligned}
c_{Q1} &= 0.643, & c_{D1} &= 0.643, & c_{U1} &= 0.671,\\
c_{Q2} &= 0.583, & c_{D2} &= 0.601, & c_{U2} &= 0.528,\\
c_{Q3} &= 0.317, & c_{D3} &= 0.601, & c_{U3} &= -0.460.
\end{aligned}
$$

Huber

... one can fit all the SM fermionic spectrum

→ from a 5D perspective no flavor structure

Flavor violations: Surprisingly, and contrary to flat space, they are smaller than the experimental bounds:

	gluon	Z	exp.
Δm_K :	1.5×10^{-14}	1.2×10^{-17}	3.5×10^{-12}
Δm_B :	5.1×10^{-11}	3.0×10^{-14}	3.2×10^{-10}
Δm_D :	3.8×10^{-13}	5.2×10^{-15}	4.6×10^{-11}
ϵ_K :	1.1×10^{-3}	1.1×10^{-6}	2.3×10^{-3}.

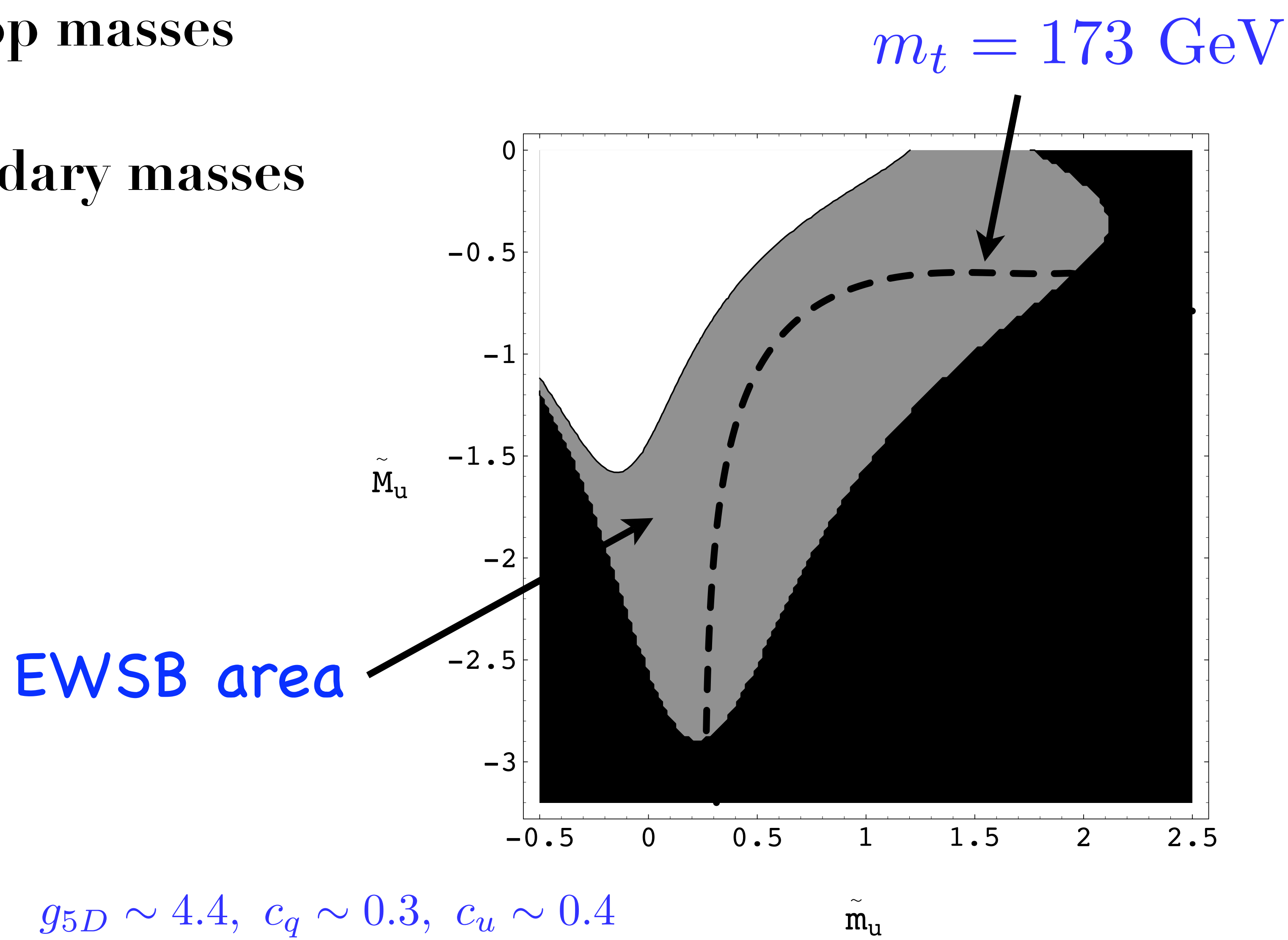
for KK-masses $\sim$ TeV

Parameters:

g_{5D} : **5D gauge coupling**

$c_{q,u}$: **5D top masses**

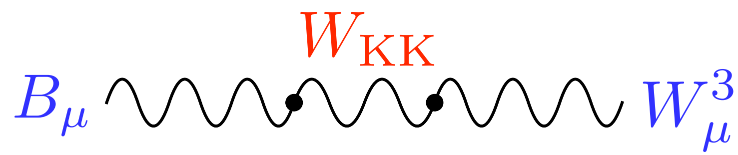
$\left.\begin{array}{l}\tilde{m}_u \\ \tilde{M}_u\end{array}\right\}$ **boundary masses**



$g_{5D} \sim 4.4,\ c_q \sim 0.3,\ c_u \sim 0.4$

Electroweak Precision Tests

Main effects on the gauge self-energies:



- $T \simeq 0$ **(KK-sector has a custodial SO(3) symmetry)**

- $S \simeq \dfrac{26\, v^2}{m^2_{\rm KK}} \leq 0.3 \quad \rightarrow \quad m_{\rm KK} \geq 2.3\ \text{TeV}$

In <u>flat</u> space this will rule out big portions of the parameter space

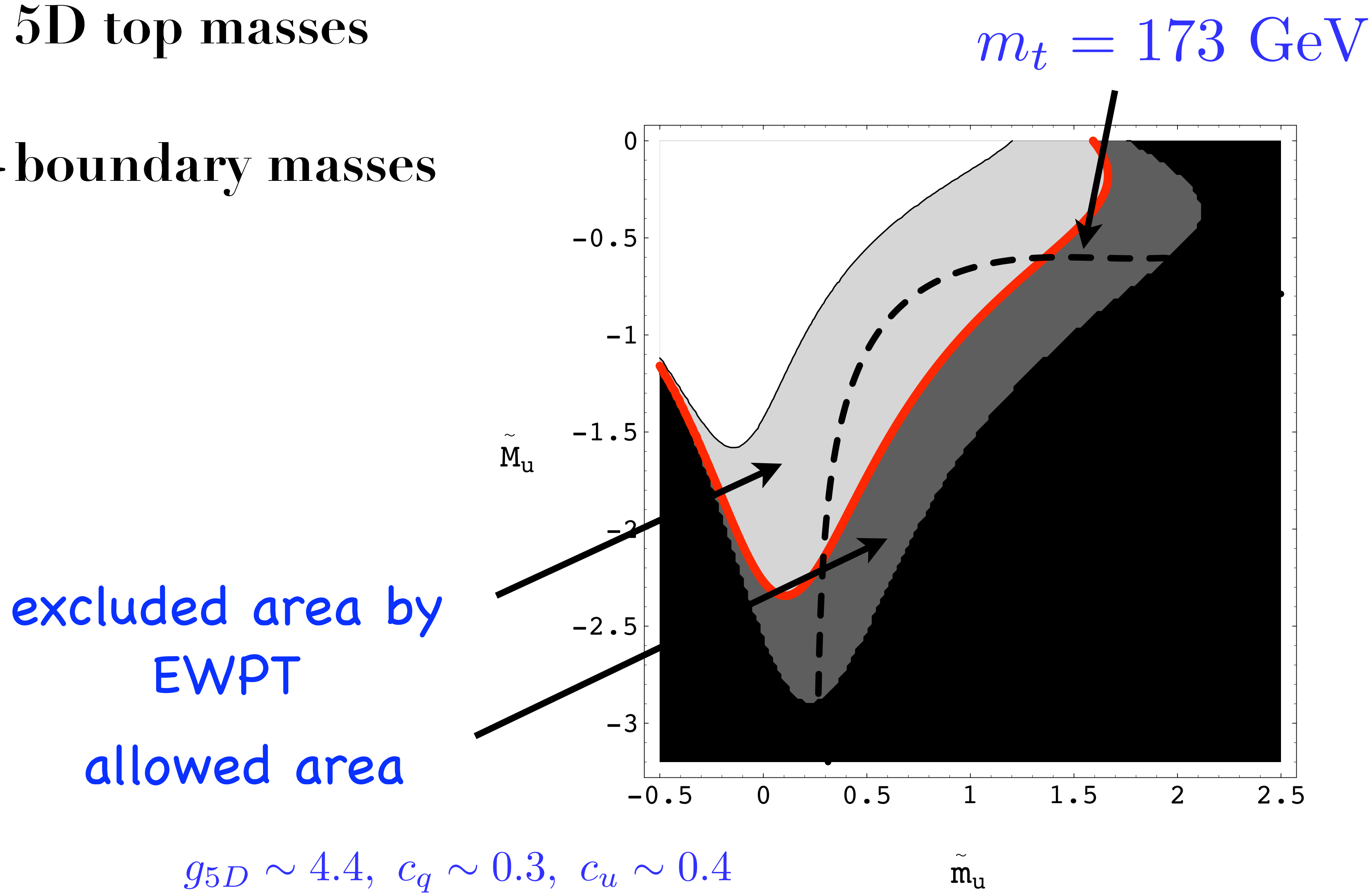
In <u>AdS</u> space only ~3/4 excluded

Parameters:

g_{5D} : **5D gauge coupling**

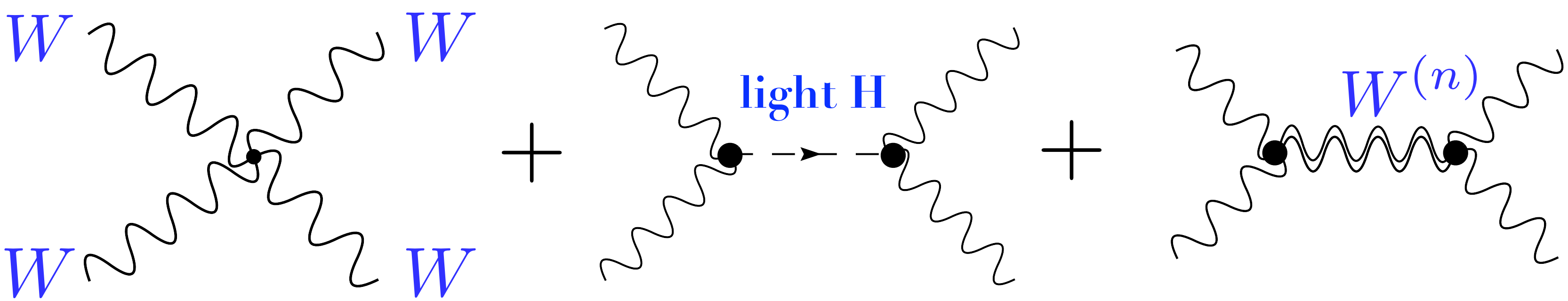
$c_{q,u}$: **5D top masses**

$\tilde{m}_u$, $\tilde{M}_u$ } **boundary masses**



$g_{5D} \sim 4.4,\ c_q \sim 0.3,\ c_u \sim 0.4$

To unitarize: → $m_{W^{(1)}} < 3\ TeV$



To avoid LEP constrains: → $m_{W^{(1)}} > 2.4\ TeV$