What do we really know about the Higgs sector?

The "established" SM

- "Observed" fields:
  - Gauge bosons: $g_\mu^A \quad W_\mu^a \quad B_\mu$
  - Femions: $Q_i \quad u_i^c \quad d_i^c \quad L_i \quad e_i^c$
  - Scalar (Goldstones): G_a — from $SU(2)_L \times U(1)_Y \to U(1)_{em}$; long. part of massive gauge bosons
  - Scalar (?) (physical): h — custodial symmetry singlet

$\boxed{\text{Assumes H is elementary}} \to$

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \bar{\Psi}_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

The "established" lagrangian

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- Most general gauge invariant lagrangian for the observed fields
  - $L_{SM} = L_{EW} + L_{EWSB} + L_h$
  - L_{EW} = Gauge bosons, fermions, gauge interactions
  - L_{EWSB} = Goldstone effective lagrangian and interactions
  - L_h = Higgs ("h") lagrangian (including interactions with what above)
- L_{EWSB} has an approximate $SU(2)_L \times SU(2)_R$ symmetry (spontaneously broken by EWSB to the "custodial" $SU(2)_V$)
- The SM Higgs is a special, especially appealing case, with
  - ✓ exact unitarization
  - ✓ agreement with EWPT
  - ✓ understanding of custodial symmetry as accidental symmetry
  - ✗ hierarchy problem (see below)

$$\mathrm{L}_{\mathrm{EW}} = -\frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \sum_{j=1}^{3} \bar{\Psi}^{(j)} i \not{D} \Psi^{(j)}$$

$$\Sigma(x) = \exp(i\sigma^a \chi^a(x)/v) \qquad \Sigma \to U_L(x)\, \Sigma\, U_Y^\dagger(x)$$

$$\mathrm{L}_{\mathrm{EWSB}} = \frac{v^2}{4} \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger \, (D^\mu \Sigma) \right] - \frac{v}{\sqrt{2}} \sum_{i,j} \left(\bar{u}_L^{(i)} d_L^{(i)} \right) \Sigma \begin{pmatrix} \lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)} \end{pmatrix} + h.c.$$

$$+\, a_T\, v^2\, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma\, \sigma^3 \right]^2 \qquad \rho \approx 1 \Rightarrow a_T \approx 0$$

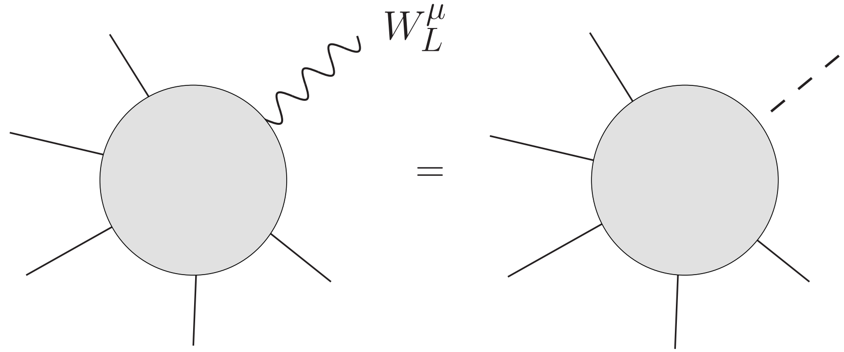
$$SU(2)_L \times SU(2)_R$$

$$+\, O(p^4)$$

$$\Sigma \to U_L\, \Sigma\, U_R^\dagger$$

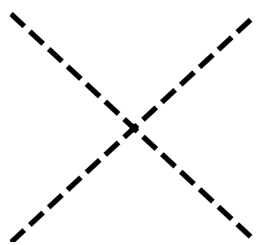
2 problems:

1) The theory is strongly interacting at TeV



☞ Goldstone bosons

$$\times \left(1 + O\left(\frac{m_W^2}{E^2}\right)\right)$$



$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}(s+t)$$

(while EWPT seem to indicate that strong interactions can appear only above about 5 TeV)

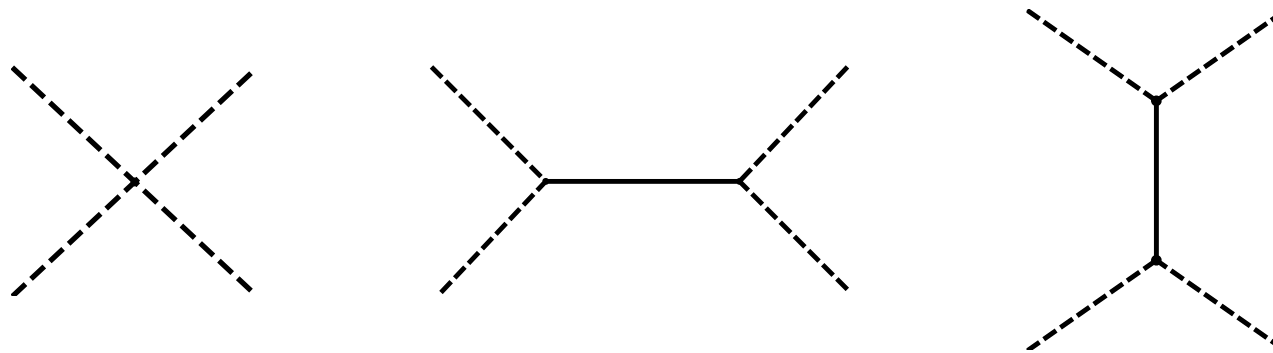
2) The H-like dof found at LHC is missing

Add scalar h, SU(2)LxSU(2)R singlet

$$\mathsf{L_h} = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^\dagger \left(D_\mu \Sigma\right)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + c\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda_{ij}^u\, u_R^{(j)} \\ \lambda_{ij}^d\, d_R^{(j)}\end{pmatrix} + h.c.$$

a ≈ 1



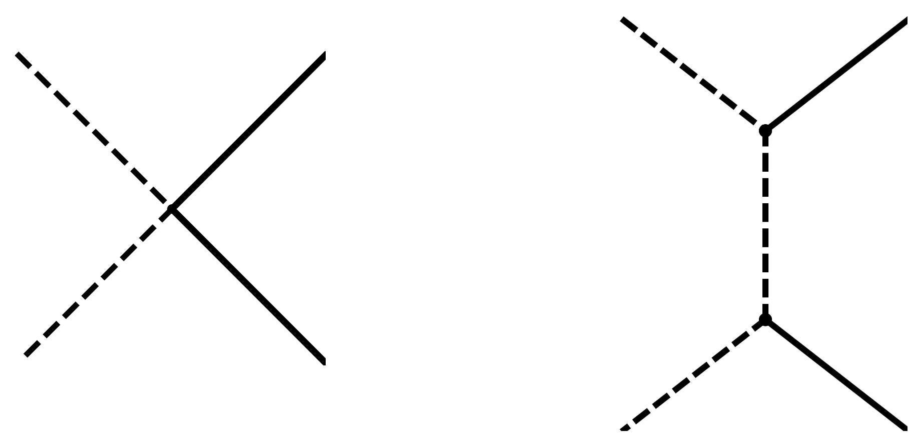
$$\mathcal{A}(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}\left[s - a^2\frac{s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

$$= \frac{s+t}{v^2}\left(1 - a^2\right) + O\left(\frac{m_h^2}{E^2}\right) .$$

Add scalar h, SU(2)$_L$xSU(2)$_R$ singlet

$$\mathcal{L}_H = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu \Sigma\right)^\dagger \left(D_\mu \Sigma\right)\right]\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right)$$
$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

b ≈ 1



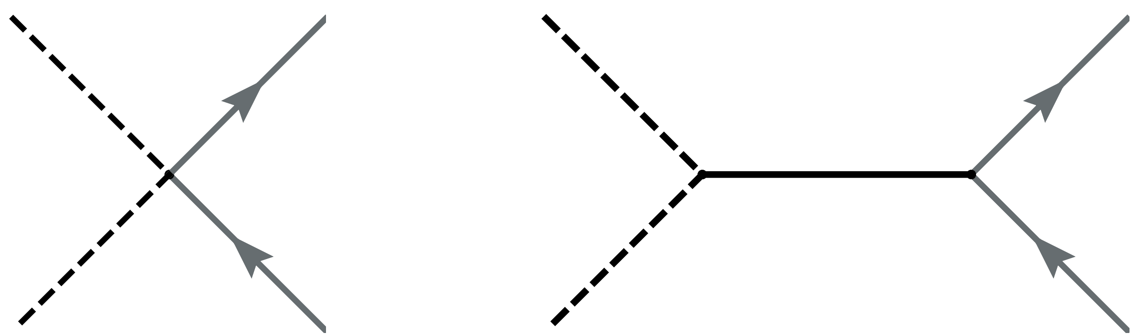
$$\mathcal{A}(\chi^+\chi^- \to hh) = \frac{s}{v^2}\left(b - a^2\right) + O\left(\frac{m_h^2}{E^2}\right)$$

Add scalar h, SU(2)$_L$xSU(2)$_R$ singlet

$$\mathcal{L}_H = \frac{1}{2}\left(\partial_\mu h\right)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[\left(D_\mu\Sigma\right)^\dagger\left(D_\mu\Sigma\right)\right]\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \dots\right)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^{(i)} d_L^{(i)}\right)\Sigma\left(1 + c\,\frac{h}{v} + \cdots\right)\begin{pmatrix}\lambda^u_{ij}\, u_R^{(j)} \\ \lambda^d_{ij}\, d_R^{(j)}\end{pmatrix} + h.c.$$

c ≈ 1



$$\mathcal{A}(\chi^+\chi^- \to \psi\bar{\psi}) = \frac{m_\psi\sqrt{s}}{v^2}\,(1 - ac) + O\left(\frac{m_h^2}{E^2}\right)$$

a = b = c = 1

$$H(x) = \frac{1}{\sqrt{2}}\, e^{i\sigma^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

L_H = SM Higgs + Yukawa lagrangian

Higgs as a pseudo-NGB

- $a \neq 1$, $b \neq 1$, $c \neq 1$ can be a sign of composite Higgs: Λ_{strong} just pushed higher than TeV (better for EWPT)

- Composite Higgs welcome as a solution of the hierarchy problem (trade-off between HP and EWPT)

- Why $m_H \ll \Lambda_{strong}$?

- Perhaps for the same reason why $m_\pi \ll \Lambda_{QCD}$
  H pseudo-NGB of approximate global symmetry
  of strong dynamics at $\Lambda_{strong} \gg m_H$

Composite Higgs and extra dimensions

Composite Higgs

- $Q_{\rm strong} \gtrsim \sqrt{c_i} \cdot 5\,{\rm TeV} \approx 5\,{\rm TeV}$
- Why $m_h \ll Q_{\rm strong}$? Because h is the pseudo-NGB of some global symmetry (protected by shift symmetry $h(x) \to h(x)+c$) [Georgi Kaplan 84]
  The global symmetry must however be explicitly broken by λ_t λ_H g:

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = m_h^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right) \quad \text{for } m_h = 115\,{\rm GeV}$$

- Little Higgs: keeping the effect of explicit breaking under control
  - no $Q^2_{\rm NP}$ ad 1-loop ("collective breaking") [Arkani-Hamed Cohen Georgi 01, Arkani-Hamed Cohen Katz Nelson Gregoire Wacker 02]
  - the top (gauge, Higgs) loop **must** be cancelled at a lower scale (= global symmetry breaking scale f « $Q_{\rm strong}$) by same statistics partners
  - Still not as nice as supersymmetry as far as EWPTs are concerned: T-parity + a partner for each SM fermion
  - UV completion? (see below) [Marandella Schappacher Strumia hep-ph/0502096]

Realization in Extra Dimensions

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Serone 0909.5619
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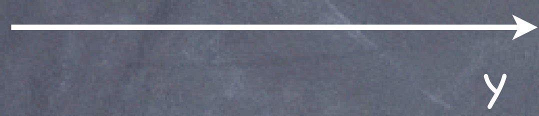
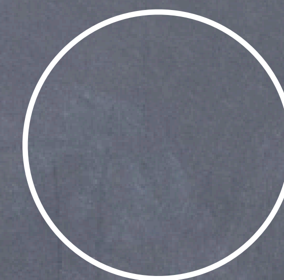
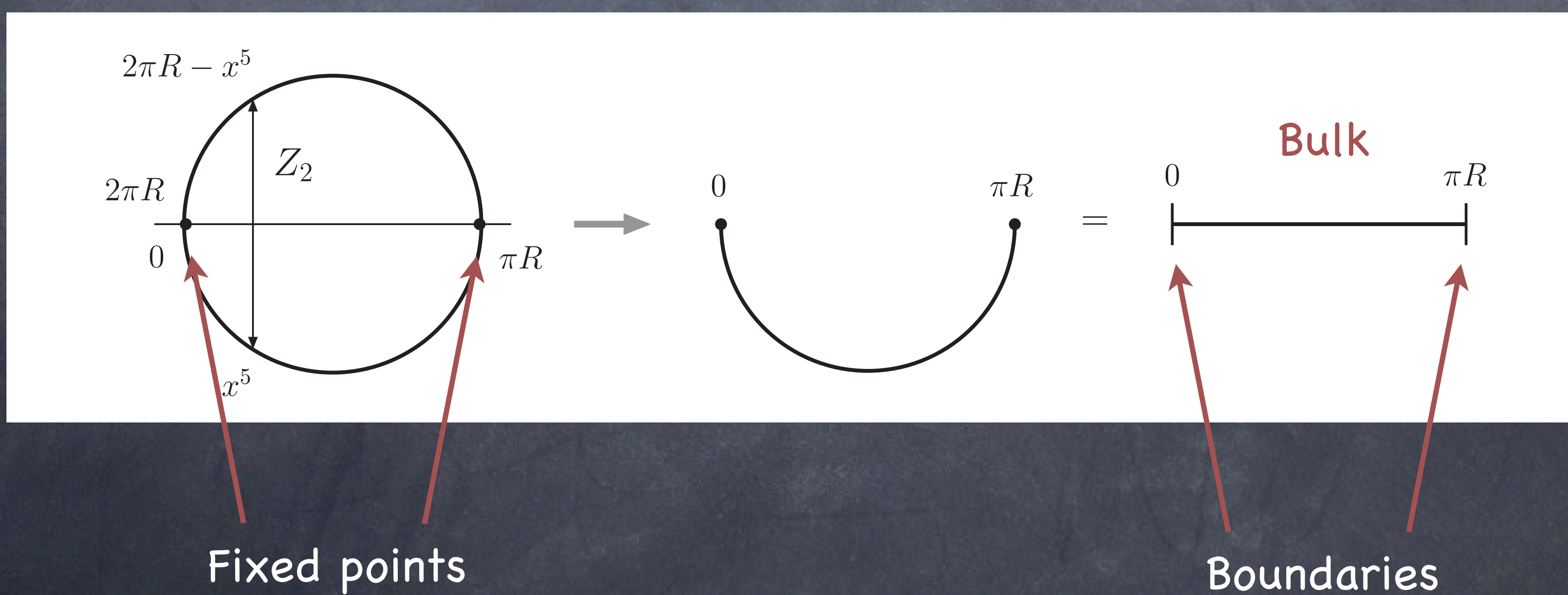
- S^1:



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



- S^1/Z_2: $\qquad S^1 + \quad y \sim -y$:



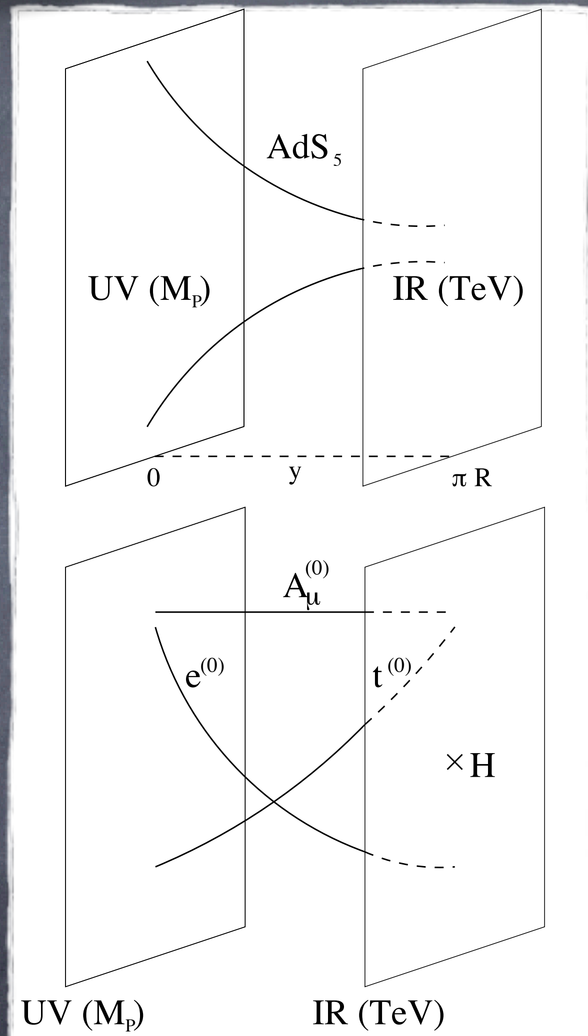
Z_2 parity (boundary conditions)

- Can be used to break symmetries in a novel way
- Gauge symmetries can be broken "on the boundaries"
- Boundary conditions for
  - 5D fermions: chirality
  - 5D vectors: massless (tree level) 4D scalars $\leftrightarrow$ broken generators $\leftrightarrow$ pseudo Goldstone bosons

RS

- S^1/Z_2 5D model with curved 5th dimension: $ds^2 = e^{-2ky} dx^2 + dy^2$
- IR redshift of energies: $y = \pi R$ (IR brane) wrt $y = 0$ (UV brane)
- All scales are $O(M_{Pl})$, including $k, 1/R$, within $O(10)$ factor
- Fields localized near UV see $O(M_{Pl})$, near IR see $O(M_{Pl})e^{-2\pi kR}$
- $kR \approx 12 \to O(M_{Pl})e^{-2\pi kR} \approx$ TeV
- Solution of hierarchy problem if the graviton is near UV, the Higgs is near IR
- SM in the bulk (instead of on the IR brane as in original RS)
  - eases FCNC problem
  - gives (very) hierarchical fermion masses
- Dual description: fields near IR are mostly composite

Warping and compositeness



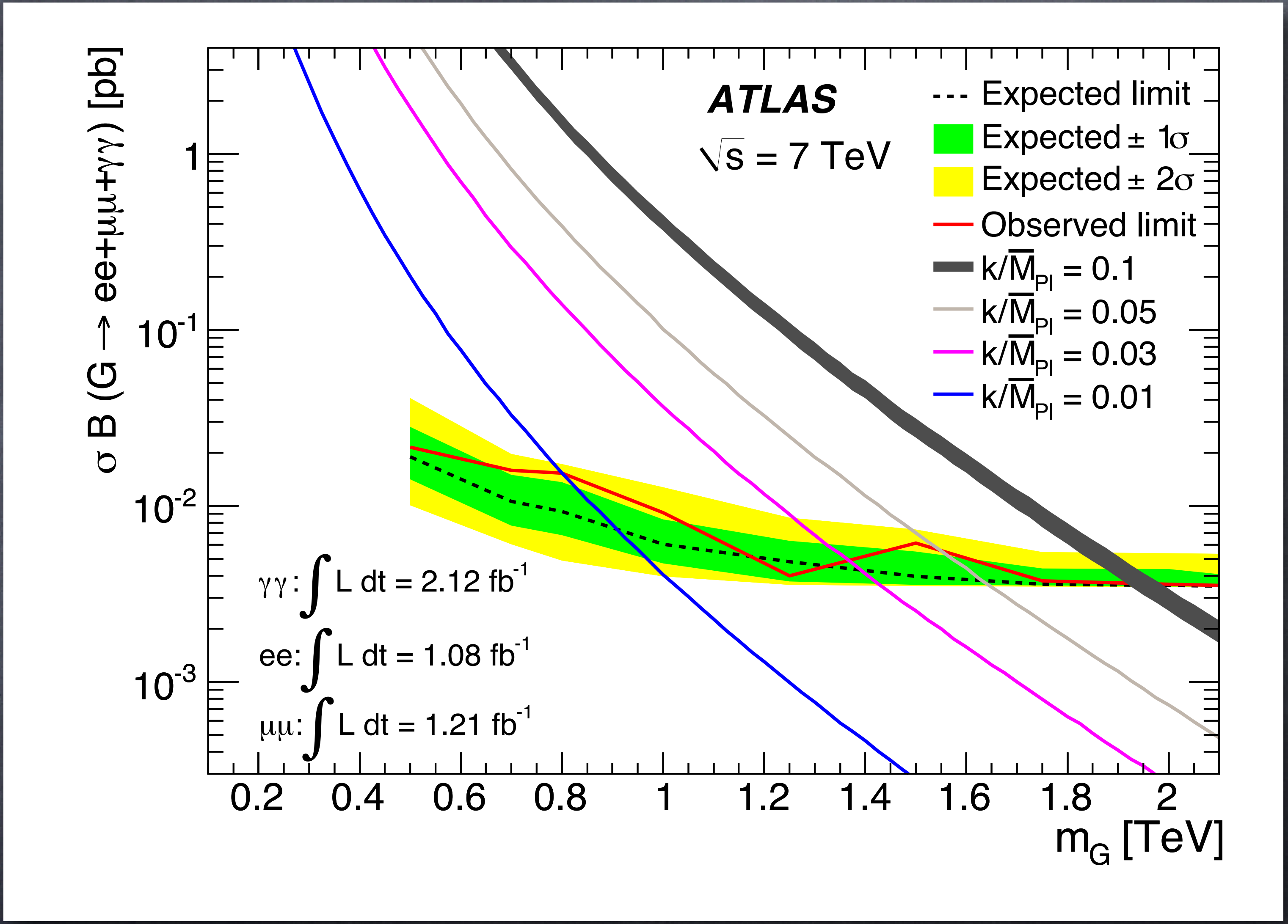
$$m_h \sim M_5 e^{-2\pi k R}$$

$$k = \text{curvature}$$

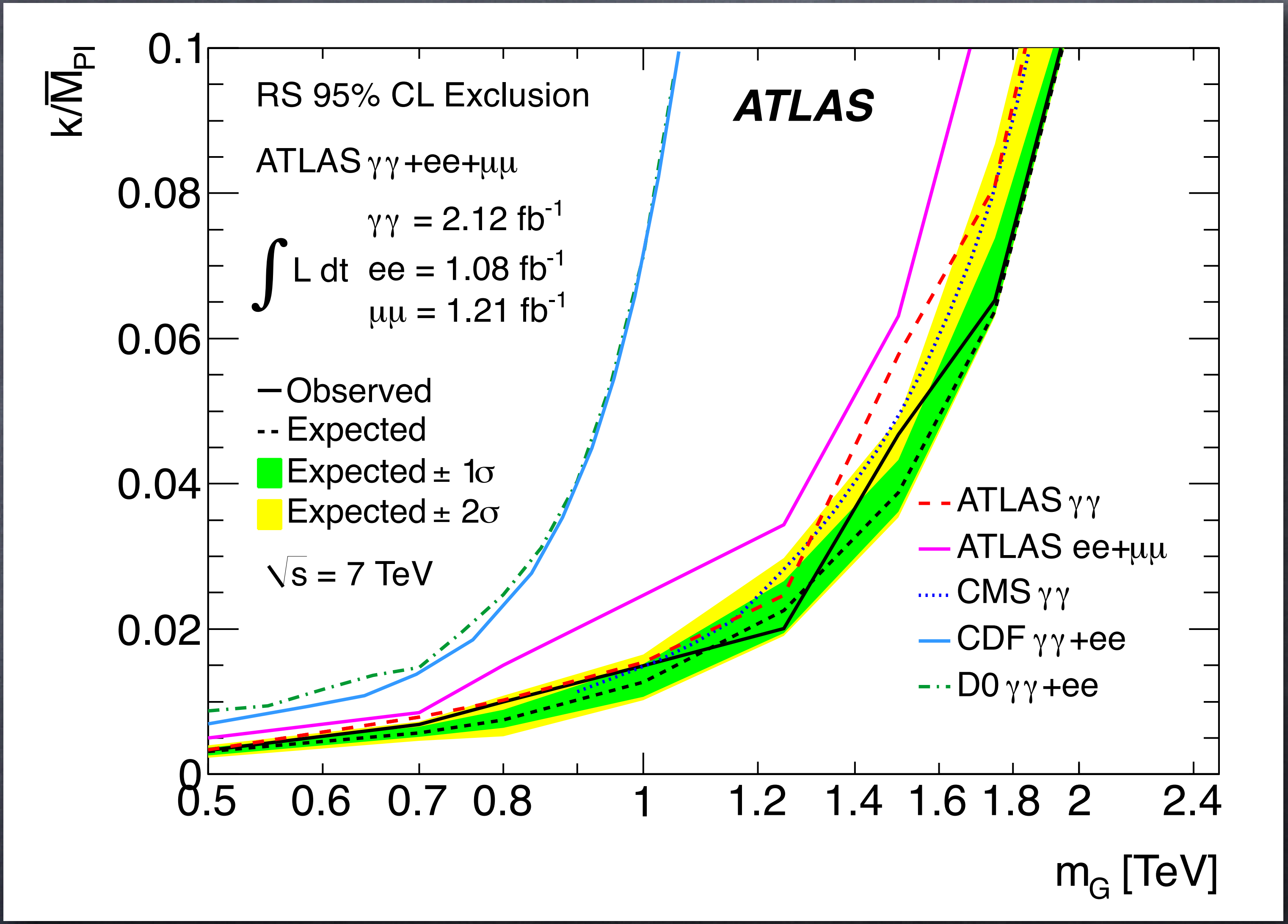
- Extra-dims accessible at LHC and compositeness together with high scale extrapolation
- RS + bulk fermions + H as $(A_5)_0$ + deconstruction = Little Higgs + UV completion
- Flavour, 4D dual
  UV brane: elementary dofs
  IR brane: composite dofs (H, t_R)
- Q_{strong} > 5 TeV as usual
  m_{KK} > TeV, watch $Z \to b\bar{b}$
- Gauge coupling unification in a novel way (but limited calculability)

[Contino Nomura Pomarol hep-ph/0306259
Agashe Contino Pomarol hep-ph/0412089
hep-ph/0605341]

$k/M_{Pl} = 0.1$:
$m_G > 1.85$ TeV ($\gamma\gamma$ only)
$m_G > 1.95$ TeV (combined)



Expected and observed 95% CL limits from the combination of $G_1 \rightarrow \gamma\gamma/ee/\mu\mu$ channels on the product of the RS graviton production cross section and the branching ratio for graviton decay via $G_1 \rightarrow \gamma\gamma/ee/\mu\mu$



RS 95% CL Exclusion
ATLAS
ATLAS γγ+ee+μμ
∫L dt γγ = 2.12 fb-1
ee = 1.08 fb-1
μμ = 1.21 fb-1
Observed
Expected
Expected ± 1σ
Expected ± 2σ
√s = 7 TeV
ATLAS γγ
ATLAS ee+μμ
CMS γγ
CDF γγ+ee
D0 γγ+ee
k/M̄Pl
0.1
0.08
0.06
0.04
0.02
0
0.5
0.6
0.7
0.8
1
1.2
1.4
1.6
1.8
2
2.4
mG [TeV]