Continuum Naturalness

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LBNL Particle Physics Seminar

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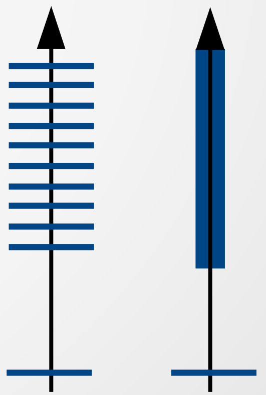
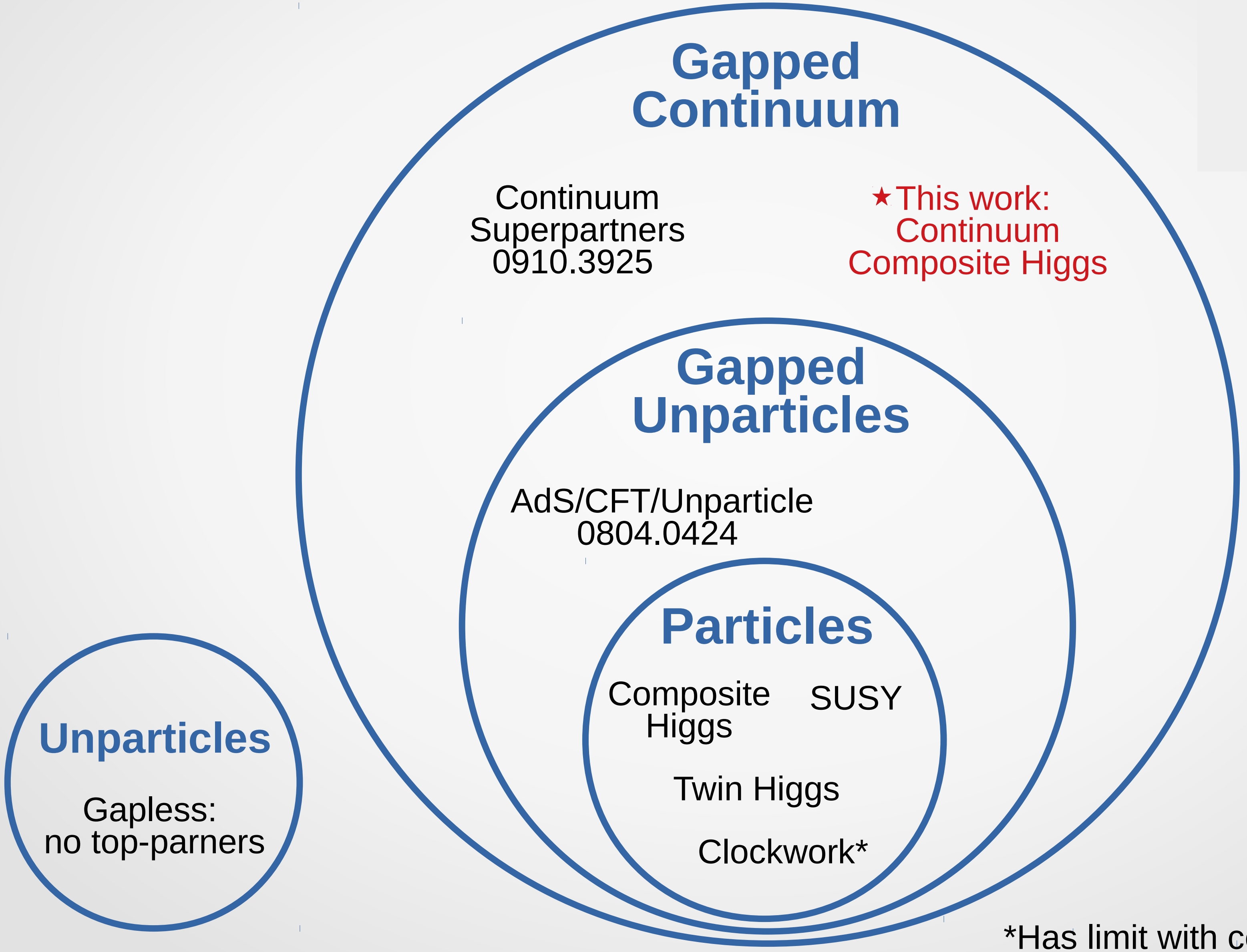


work in progress with C. Csaki, G. Lee, S. J. Lee and S. Lombardo

Motivation

- Higgs naturalness hints at top & gauge partners around the weak scale
  - Superpartners
  - Fermionic top partners and Z’
  - Other
- No new states have been observed so far for 136 fb^{-1} @ 13TeV. Searches involve:
  - Heavy resonances
  - Same sign dileptons
  - Opposite sign dileptons
  - b-tagging
  - MET
- Do the new states actually have to be particles?

A New Top Partner Road Map



*Has limit with continuum partners

What it is vs. what it isn't

What it is

- A composite Higgs models where the top & gauge partners are continuum states
- Solution to "big" Hierachy problem the same as RS
- A different model for the confining dynamics at Λ : a continuum of composites
- Group theory the same as regular CH: SO(5)/SO(4) or other
- Very different phenomenology

What it isn't

- A new solution to the "big" Hierarchy problem
- Completely hidden from the LHC

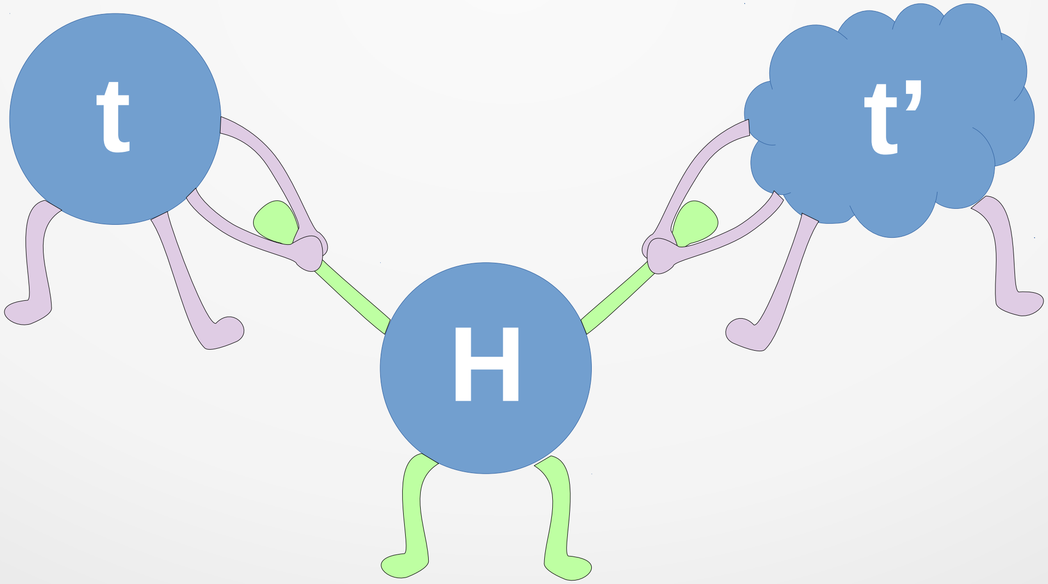
Outline

Part I: Continuum composite Higgs

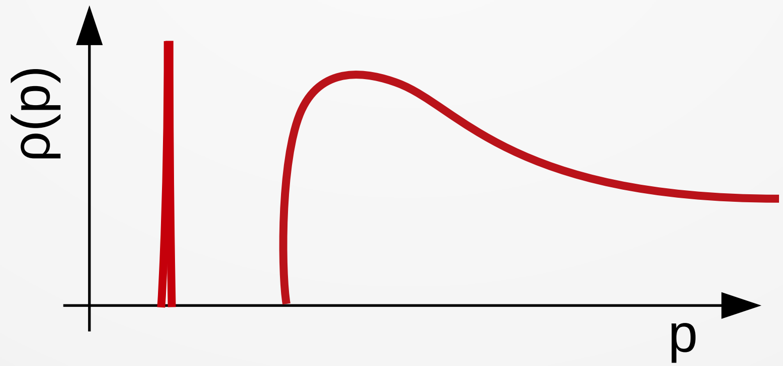
- The 4D action for continuum states: spectral densities
- Modeling a gapped continuum with a 5D Linear Dilaton
- Continuum composite Higgs: setting and results

- Part II: The pair-production CS for generic continuum states
  - A colorful continuum?
  - Dispersion relations
  - The generic result

Part I: Continuum Composite Higgs



The 4D action for continuum states



A 4D Weyl fermion

$$\mathcal{L}_{\mathrm{4D}} = -i\bar{\chi}\bar{\sigma}^{\mu}p_{\mu}\chi$$

Two point function:

$$\langle\bar{\chi}\chi\rangle = \frac{\sigma^{\mu}p_{\mu}}{p^2} \qquad \frac{1}{\bar{\sigma}^{\mu}p_{\mu}} = \frac{\sigma^{\mu}p_{\mu}}{p^2}$$

Has pole at p=0: massless Weyl fermion

A 4D non-local Weyl fermion

$$\mathcal{L}_{4\mathrm{D}} = -i\bar{\chi}\frac{\bar{\sigma}^{\mu}p_{\mu}}{p^2 G\left(p^2\right)}\chi$$

Two point function:

$$\langle\bar{\chi}\chi\rangle = \sigma^{\mu}p_{\mu}G(p^2)$$

Poles of $G(p^2)$ $\longrightarrow$ particles

Branch cut of $G(p^2)$ $\longrightarrow$ continuum

Can we describe the complex structure of G with a single real-valued function? Yes!

The spectral function

Dispersion relation:

$$G(p^2) \;=\; \int_0^\infty \frac{\rho(s)}{s - p^2}\, ds$$

where $\rho(s) = \frac{1}{\pi}\mathrm{Im}\left[G(s)\right]$ is the *spectral function*

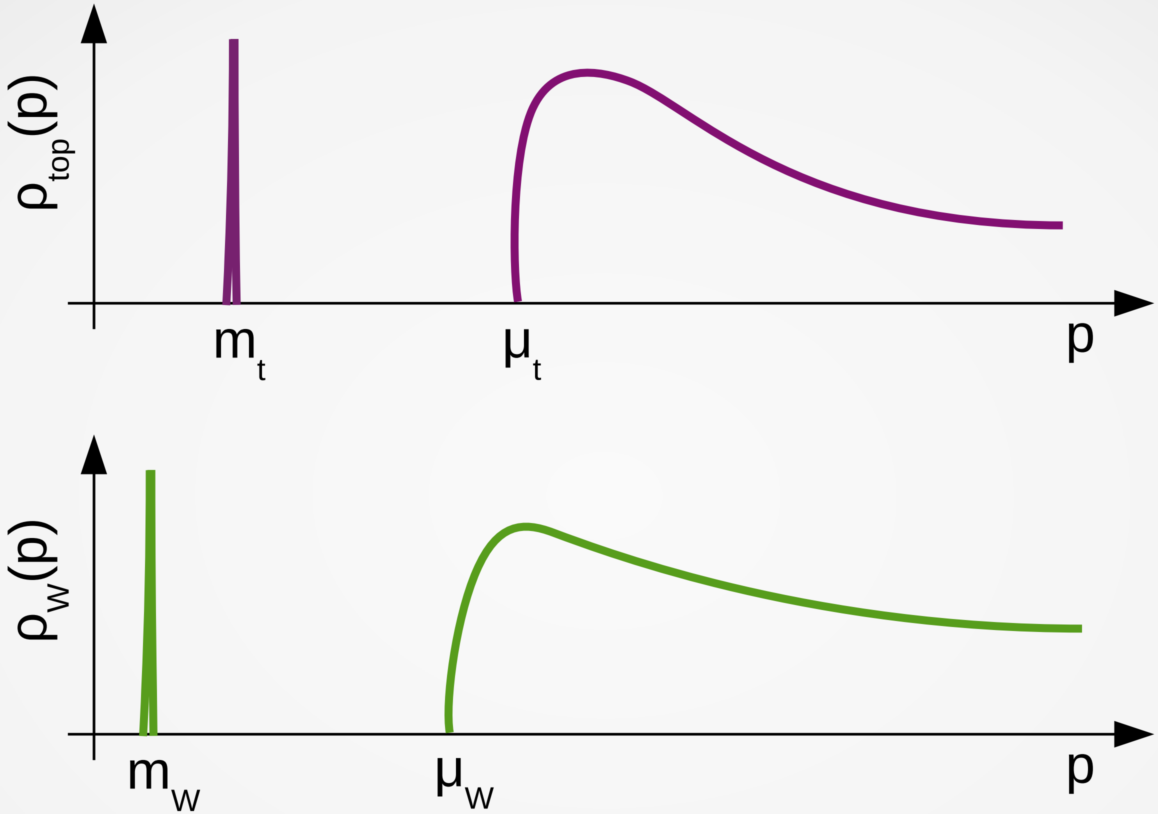
Generically:

$$\rho(s) = -\sum_i \delta(s - m_i) \;+\; \sigma(s)$$

Tower of particles

Continuum

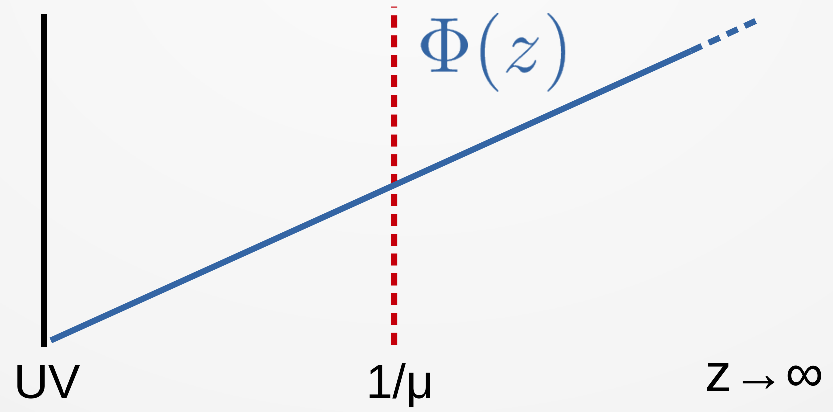
The SM + continuum partners



Goal: SM + continuum as the IR description of some “confining” strong dynamics. More ambitious: composite Higgs

Method: model strong dynamics in 5D Linear Dilaton background

Modeling gapped continua with a 5D Linear Dilaton



Modeling 4D Strong Dynamics in 5D

Green's function for a fermion in RS1

(AdS_5 with UV brane and IR brane)

$\updownarrow$

A tower of 4D composite fermions

Grossman, Neubert, hep/ph:9912408
Gherghetta, Pomarol, hep-ph/0003129

Green's function for a fermion in AdS_5

(RS2 with UV brane $\rightarrow$ z=0)

$\updownarrow$

Green's function for 4D ungapped continuum fermion

Cacciapaglia, Marandela,Terning, hep/ph:0804.0424

Ungapped continuum fermions (U.C.F)

A U.C.F is just a continuum particle with a specific spectral function:

$$\mathcal{L}_{4\mathrm{D}} = -i\bar{\chi}\frac{\bar{\sigma}^{\mu}p_{\mu}}{p^2 G\left(p^2\right)}\chi \qquad G(p^2) \propto \frac{\Gamma\left(\frac{5}{2}-d\right)}{4^{d-2}\Gamma\left(d-\frac{3}{2}\right)}\frac{1}{\left(-p^2\right)^{\frac{5}{2}-d}}$$

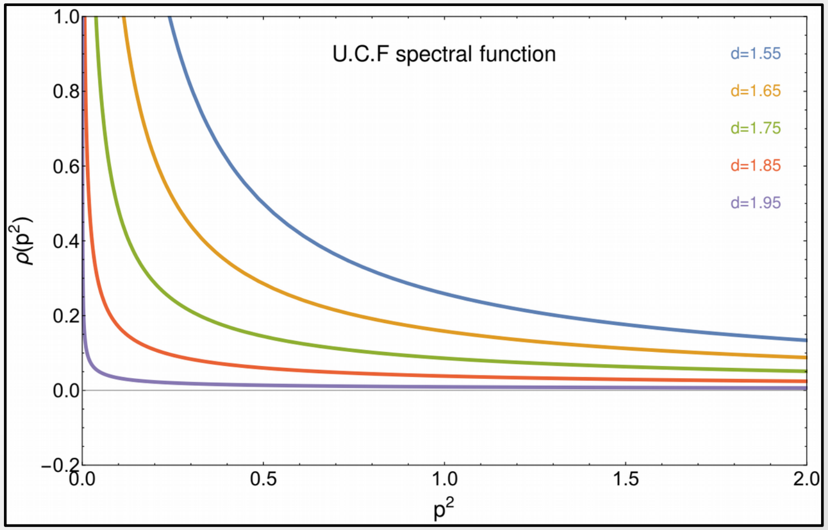
It can be regarded as either a continuum or a “fractional number of particles”

d is the scaling dimension of the U.C.F. When d → 3/2 it approaches a single Weyl fermion.

$G(p^2)$ has a branch cut starting from 0

↓

Gapless continuum

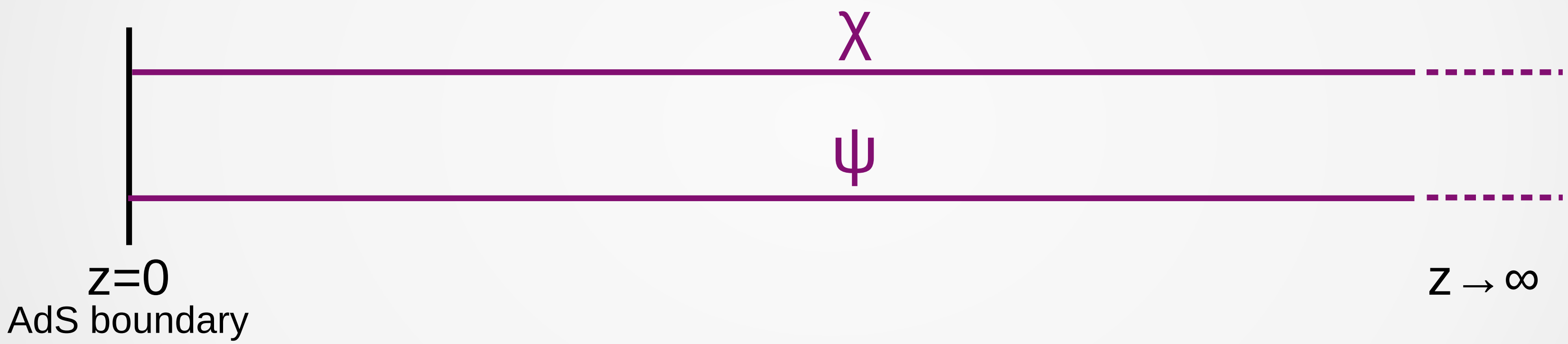


The AdS/U.C.F. correspondence

A fermion in AdS$_5$:

Metric: $ds^2 = a^2(z)\left(dx^\mu dx_\mu - dz^2\right)$

Warp factor: $a(z) = R/z$



Bulk fermion Lagrangian:

$$\mathcal{L}_{5\mathrm{D}} = a^4(z)\left[\mathcal{L}_{\mathrm{kin.}} + \frac{c}{z}\left(\psi\chi + \bar{\chi}\bar{\psi}\right)\right]$$

5D bulk mass ↔ 4D scaling dimension

Csáki et al. hep/ph:0310355

The AdS/U.C.F. correspondence

5D EOM:

$$\chi'(z) - p\,\psi(z) + \frac{c-2}{z}\chi(z) = 0$$

$$\psi'(z) + p\,\chi(z) - \frac{c+2}{z}\psi(z) = 0$$

"IR regular" solution:

$$\chi(z) = A\left(\frac{z}{R}\right)^{\frac{5}{2}} H^{(1)}_{c+\frac{1}{2}}(pz) \qquad \psi(z) = A\left(\frac{z}{R}\right)^{\frac{5}{2}} H^{(1)}_{c-\frac{1}{2}}(pz)$$

Green's function:

$$G(p^2) = \frac{1}{p}\,\bar{\lim}_{z\to 0}\frac{\psi(z)}{\chi(z)} \propto \frac{\Gamma\left(\frac{1}{2}-c\right)}{4^c\Gamma\left(\frac{1}{2}+c\right)}\frac{1}{(-p^2)^{\frac{1}{2}-c}}$$

What's so special about it?

This is the Green's function for a 4D U.CF !

The AdS/U.C.F. correspondence

AdS$_5$ fermion Green's function

$$G_{5\mathrm{D}}(p^2) \propto \frac{\Gamma\left(\frac{1}{2}-c\right)}{4^c\Gamma\left(\frac{1}{2}+c\right)}\frac{1}{(-p^2)^{\frac{1}{2}-c}}$$

$$\updownarrow$$

4D U.C.F

$$G_{4\mathrm{D}}(p^2) \propto \frac{\Gamma\left(\frac{5}{2}-d\right)}{4^{d-2}\Gamma\left(d-\frac{3}{2}\right)}\frac{1}{(-p^2)^{\frac{5}{2}-d}}$$

If we identify $d = 2 + c$

4D scaling dimension

5D bulk mass

Cacciapaglia, Marandela,Terning, hep/ph:0804.0424

A different viewpoint: the Schrodinger picture

We want to understand why AdS_5 gave rise to a continuum.

Best way: convert to effective Schrodinger eqn.

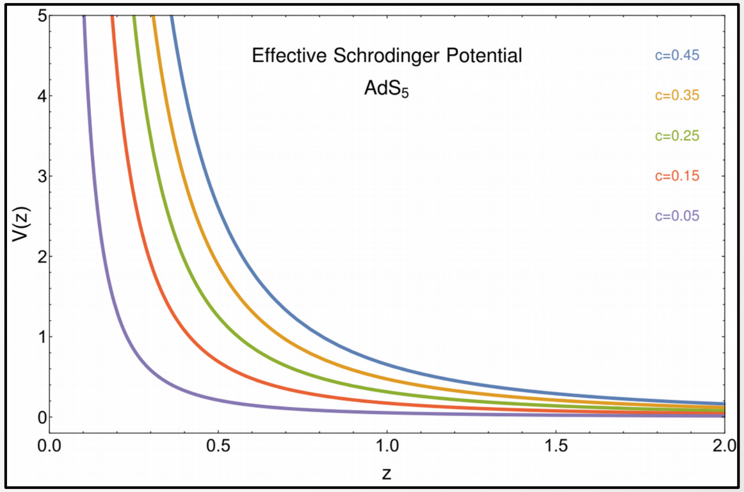
Bulk EOM: $$-\chi''(z) + \frac{4}{z}\chi'(z) + \frac{c^2+c-6}{z^2}\chi(z) = p^2\chi(z)$$

Define: $$\chi(z) = \left(\frac{z}{R}\right)^2 \hat{\chi}(z)$$

Schrodinger equation!

$$-\hat{\chi}''(z) + V(z)\hat{\chi}(z) = p^2\hat{\chi}(z)$$

$$V(z) = \frac{c(c+1)}{z^2}$$



Continuum = unbounded solutions to the effective Schrodinger problem

Falkowski, Perez-Victoria, hep/ph:0806.1737
0810.4940

Back to our story: a gapped continuum?

We've seen how to model ungapped Unparticles in AdS_5

For realistic model building, we need to model a gapped continuum

Method: introduce a dilaton in the 5D picture

$$\mathcal{L}_{5\mathrm{D}} = e^{\Phi(z)} a^4(z) \left[\mathcal{L}_{\mathrm{kin}} + \frac{c + y\,\Phi(z)}{z} \left(\psi\chi + \bar{\chi}\bar{\psi} \right) \right]$$

This modifies the bulk EOM and the effective Schrodinger potential

Falkowski, Perez-Victoria, hep/ph:0806.1737
Batell, Gherghetta, Sword, hep/ph:0808.3977
Gutsche et al. hep/ph:1108.0346

A gapped continuum!

Effective Schrodinger eqn. with dilaton

$$-\hat{\chi}''(z) + V(z)\hat{\chi}(z) \;=\; p^2\hat{\chi}(z)$$

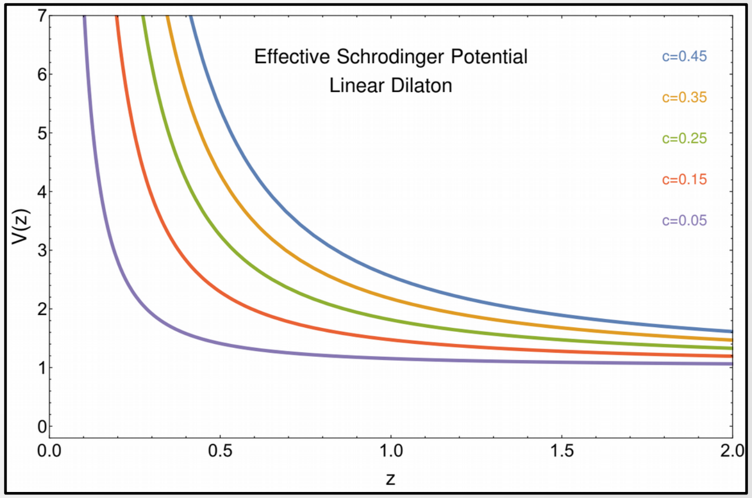
$$V(z) = \frac{c(c+1) + y\Phi(z)(2c + y\Phi(z) + 1) - yz\Phi'(z)}{z^2}$$

For a gapped continuum we need $V(z \to \infty) = \text{finite gap}$

An IR scale gap appears for a linear dilaton

$$\Phi(z) = \mu\,(z - R) \qquad \mu \sim \text{TeV}$$

the gap is yμ

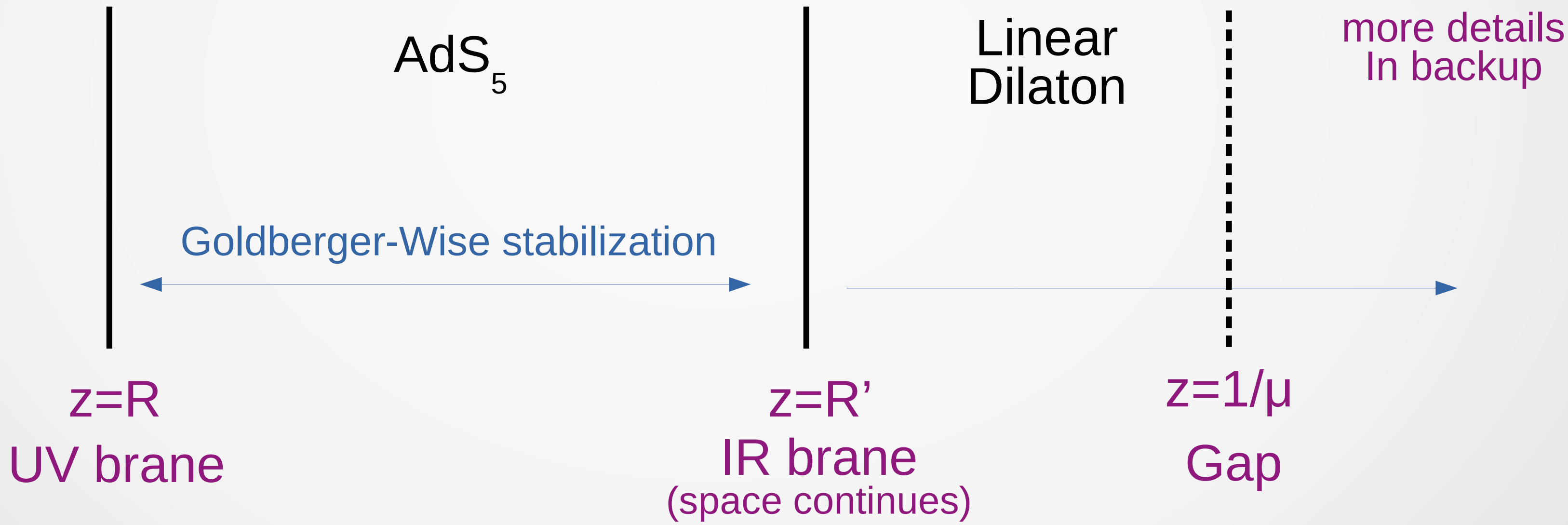


Stabilization – not our problem

A natural question is how the scale $\mu \sim$ TeV emerges and how the linear dilaton is stabilized.

We don't claim to have a new solution to the "big" Hierarchy problem

Use regular RS – Goldberger – Wise stabilization



In 4D language:

The IR scale is generated as usual by "confinement" / dimensional transmutation.
The linear dilaton models the emergence of a gapped continuum below the IR scale 1/R'.

The Linear Dilaton/Gapped continuum Correspondence

"IR regular" solutions to bulk EOM: See also Cai, Cheng, Medina, Terning

$$\chi(z) = A\,a^{-2}(z)e^{\frac{4}{3}\Phi(z)}\,W\left(-\frac{c\mu y}{\Delta}, c+\frac{1}{2}, 2\Delta z\right)$$

$$\psi(z) = A\,a^{-2}(z)e^{\frac{4}{3}\Phi(z)}\,W\left(-\frac{c\mu y}{\Delta}, c-\frac{1}{2}, 2\Delta z\right)\frac{\mu y-\Delta}{p}$$

where $\Delta \equiv \sqrt{y^2\mu^2 - p^2}$ goes imaginary above the gap

Green's function:

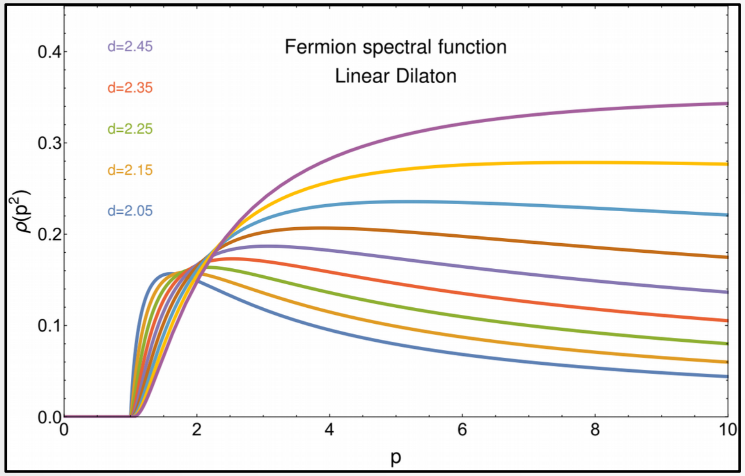
$$G(p) = \frac{1}{p}\,\bar{\lim}_{z\to 0}\,\frac{\psi(z)}{\chi(z)} = \frac{y\mu-\Delta}{p^2}\,\frac{\Gamma(1-2c)}{\Gamma(1+2c)}\,\frac{\Gamma\left(1-c\,\frac{y\mu-\Delta}{\Delta}\right)}{\Gamma\left(1-c\,\frac{y\mu+\Delta}{\Delta}\right)}(2\Delta)^{2c}$$

As expected, it has a pole at $p^2=0$ (zero mode)
and a branch cut (continuum) for $p^2 \geq y\mu$ when Δ is imaginary

Cai, Cheng, Medina, Terning, hep/ph:0910.3925

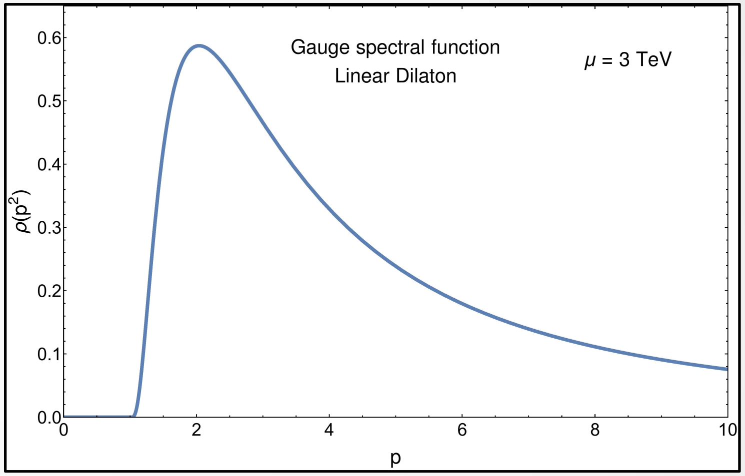
The Linear Dilaton/Gapped continuum Correspondence

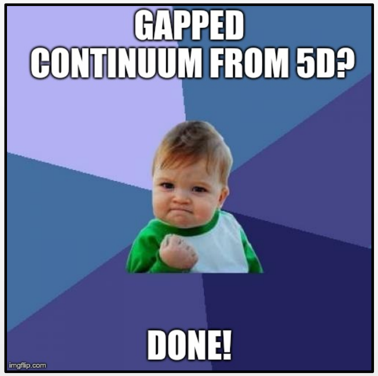
Fermion spectral functions:



(zero modes not depicted)

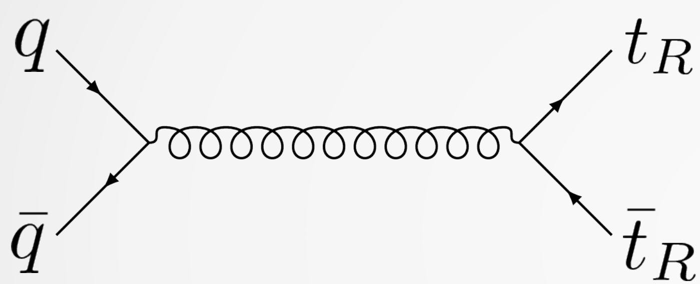
Gauge spectral function:



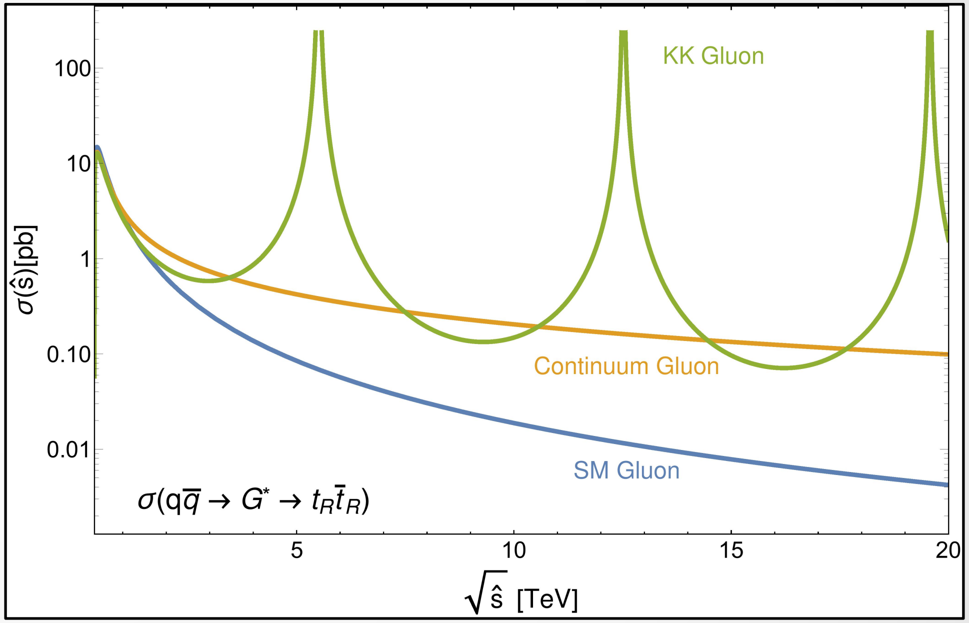


1st Phenomenology Result: No s-channel Resonances

Cross-section for s-channel vector resonance:



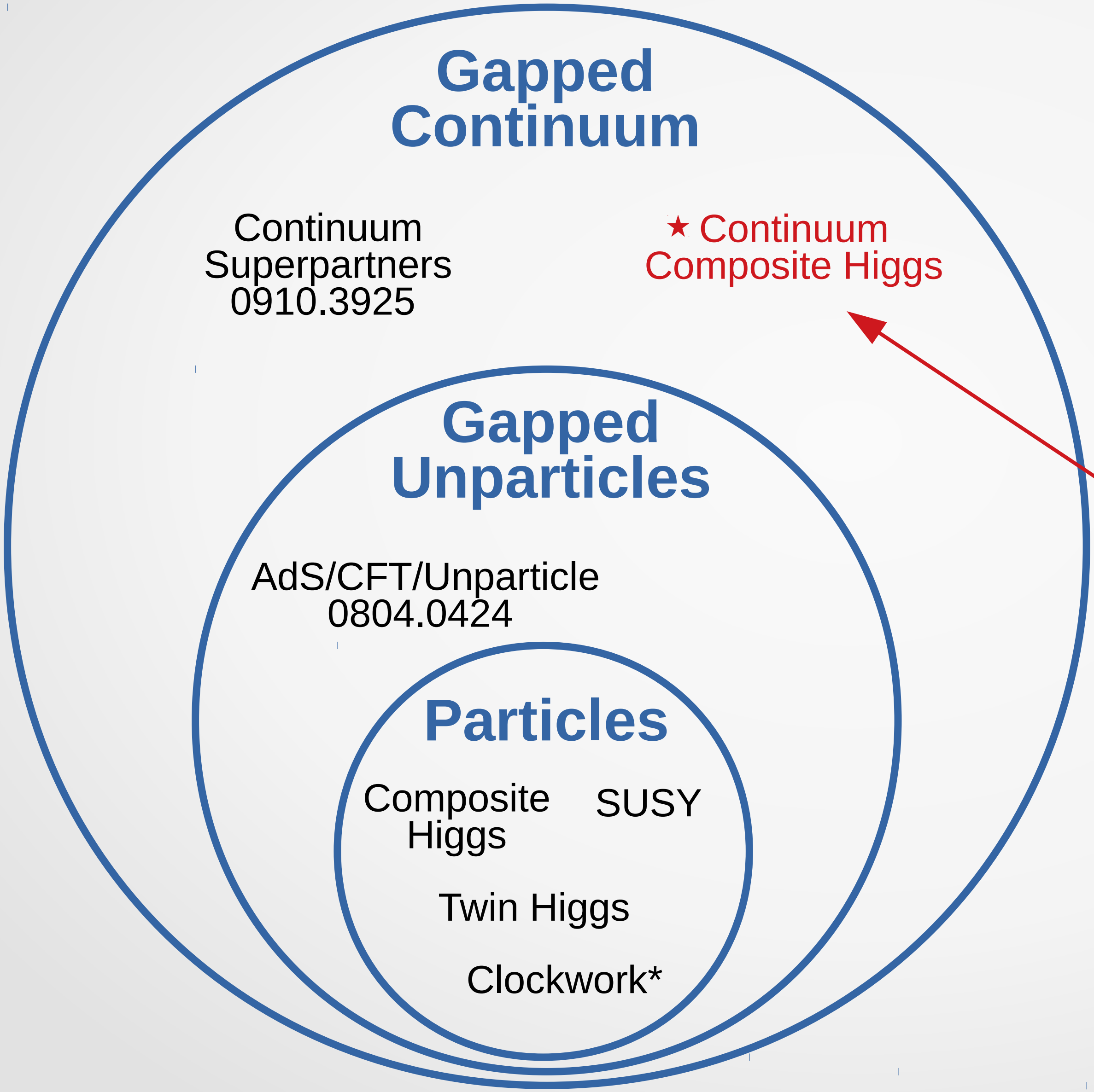
$$\sigma(\hat{s}) = \sigma(\hat{s})_{\mathrm{SM}} \times \hat{s}^2 \left|G(\hat{s})_{\text{UV-IR}}\right|^2$$



In standrad RS, the KK gluons show up as s-channel resonances.

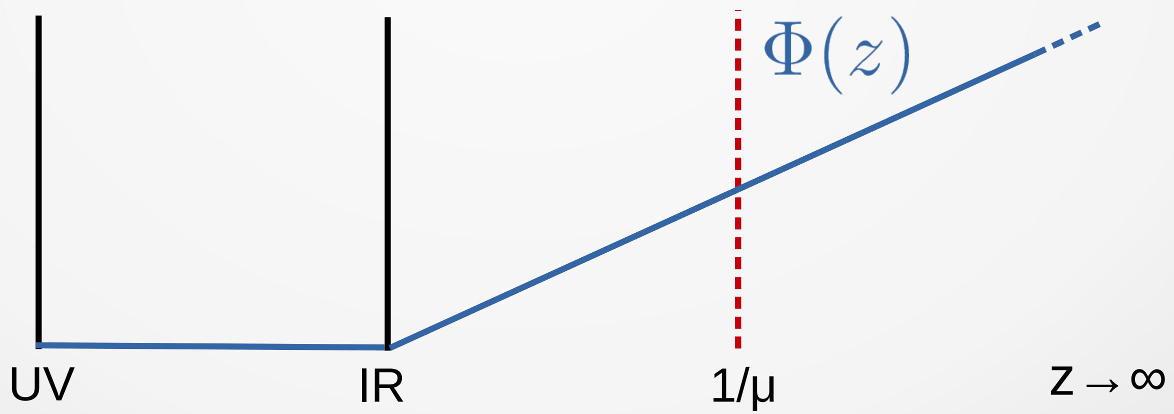
In our setting, the continuum gluon only yields a continuous execess above the SM background → no s-channel resonances!

Remember the Road Map?



Can we use our Linear Dilaton geometry to build this model?

Continuum composite Higgs: setting and results



Composite Higgs models

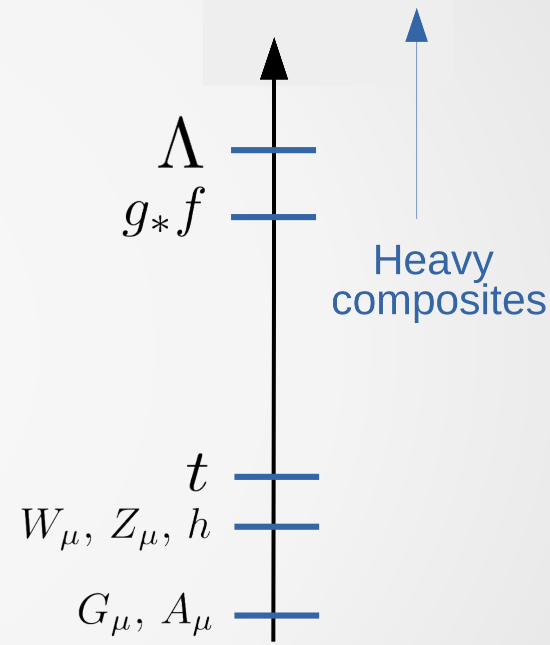
- A class of solutions to the hierarchy problem

- A strongly interacting sector confines at Λ~10 TeV
  → composite vectors and fermions
  → global symmetry G broken to a subgroup H

- SM fermions & gauge bosons:
  a mixture of composite and elementary states

- The Higgs is the pseudo-Goldstone of G/H
  → no tree level potential

- Higgs potential arises radiatively
  → quadratic divergences are cut off at $g_* f$
  → composite top & gauge partners at $g_* f$



Georgi, Kaplan, Phys.Lett. 136B (1984)
Contino, Nomura, Pomarol 0306259
Agashe, Contino, Pomarol 0412089

Composite Higgs models

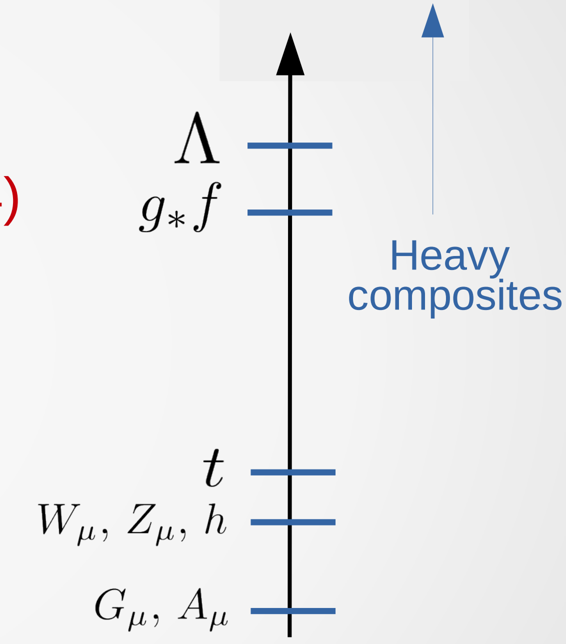
- A class of solutions to the hierarchy problem

- A strongly interacting sector confines at Λ~10 TeV
  → composite vectors and fermions
  → global symmetry SO(5) broken to a subgroup SO(4)

- SM fermions & gauge bosons:
  a mixture of composite and elementary states

- The Higgs is the pseudo-Goldstone of SO(5)/SO(4)
  → no tree level potential

- Higgs potential arises radiatively
  → quadratic divergences are cut off at $g_* f$
  → composite top & gauge partners at $g_* f$



This is why it works!
(as a solution to the hierarchy problem)

Georgi, Kaplan, Phys.Lett. 136B (1984)
Contino, Nomura, Pomarol 0306259
Agashe, Contino, Pomarol 0412089

Composite Higgs from 5D – Gauge Higgs Unification

In RS1:

$SU(2)_L \times U(1)_Y$ breaking by Dirichlet boundary conditions	**SO(5)** gauge symmetry (dual to 4D global symmetry)	**SO(4)** breaking by Dirichlet boundary conditions
z=R UV brane	AdS_5	z=R' IR brane

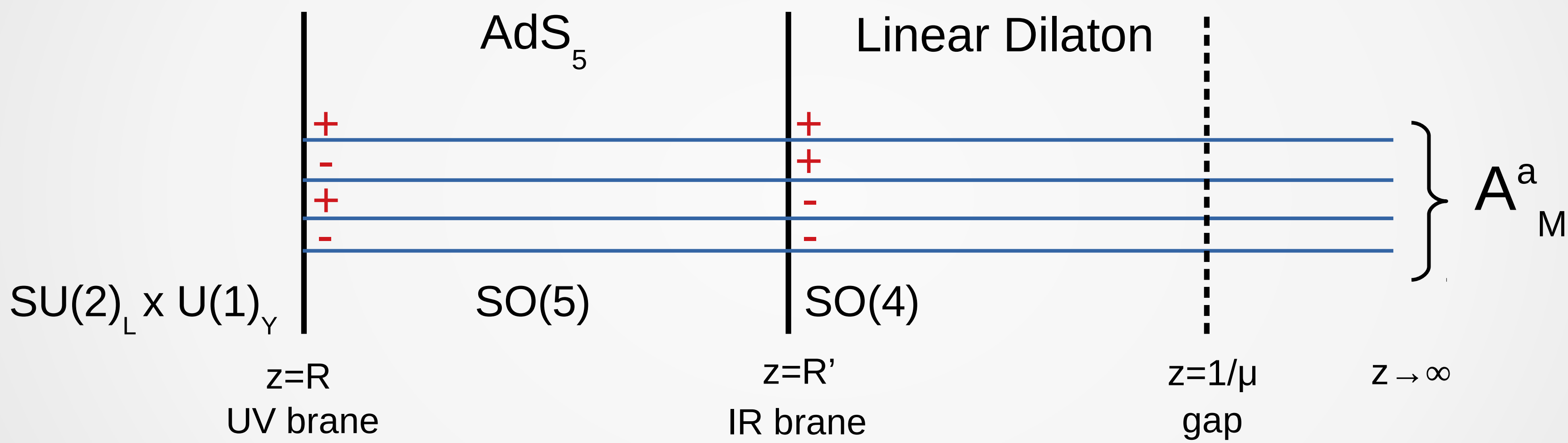
Where is the Higgs in all this? The 5D gauge fields A^a_m break to (A^a_μ, A^a_5).
The A_5 of the "Dirichlet" generators has a 4D scalar zero mode → the composite Higgs.

Bonus: we can calculate the radiative Higgs potential from the 5D Green's functions in the presence of $\langle A_5 \rangle$.

Continuum Composite Higgs

Can model gapped continua in 5D
Can construct composite Higgs models in 5D

Let's combine the two!



The gauge fields in SO(4) are continuous across the IR brane

The gauge fields in SO(5)/SO(4) get Dirichlet b.c. on the IR brane

The Higgs is the A5 of the (-,-) gauge field

Continuum Composite Higgs - Fermions

The bulk fermion reps. are $Q_L(5)$, $T_R(5)$, $B_R(10)$ of $SO(5)$

$q_L(2)_{1/6}$, $t_R(1)_{2/3}$ and $b_R(1)_{-1/3}$ get zero modes - the SM top sector

On the IR brane $\rightarrow$ SO(4) invariant mass terms:

$$M_1 Q^1_L T^1_R + M_4 Q^4_L T^4_R + M_d Q^4_L B^4_R$$

$\rightarrow$ SM Yukawa couplings

$\rightarrow$ Continuum Yukawa couplings

Feeling Lost? Here's a recap

We want to construct a continuum composite Higgs model

The 4D picture is confinement at Λ~10 TeV which breaks SO(5)→SO(4), with the Higgs a pNGB of SO(5)/SO(4). The low energy spectrum is the SM + continuum states above μ~2TeV.

The 5D picture is AdS with a bulk symmetry SO(5) and an IR brane where the symmetry is reduced to SO(4). Beyond the IR brane, a linear dilaton turns on and yields continuum spectra. The SM Green's functions have zero modes + branch cuts above μ~2TeV.

Continuum Compsite Higgs - Results

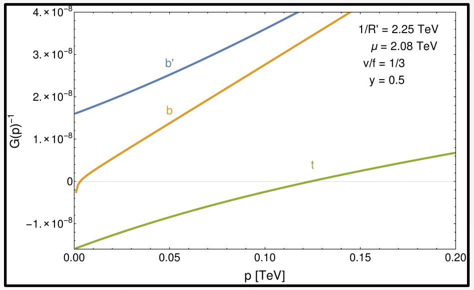
Parameters

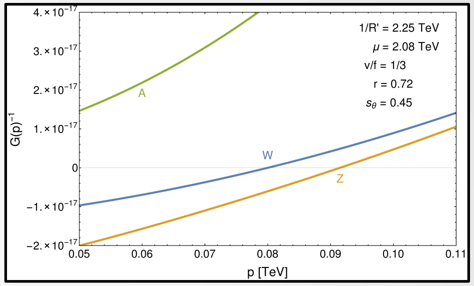
$R/R' = 10^{-16}$, $1/R' = 2.25$ TeV, $\mu = 2.08$ TeV

$y = 0.5$, $c_Q = 0.2$, $c_T = -0.22$, $c_B = -0.01$

$M_1 = 1.2$, $M_4 = 0$, $M_d = 0.01$

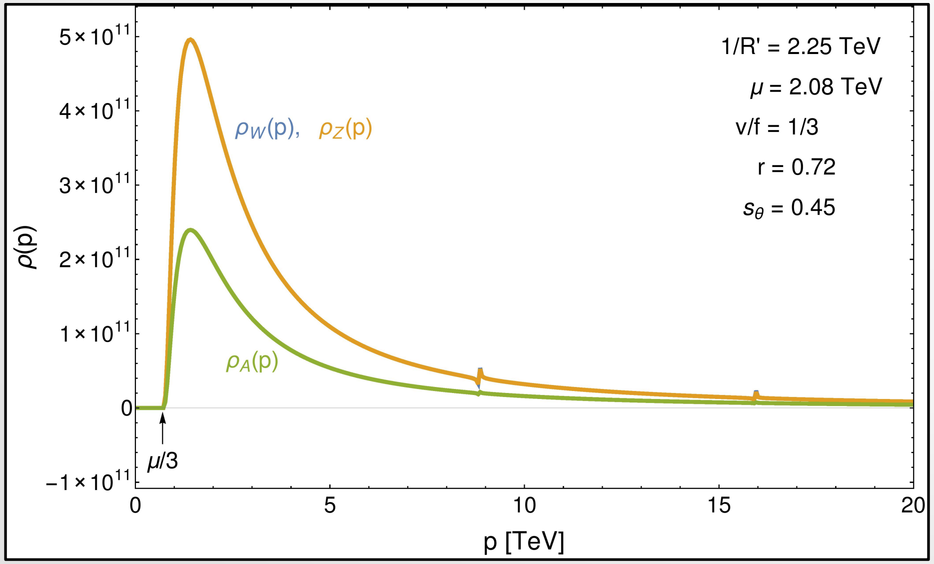
Inverse Green's functions



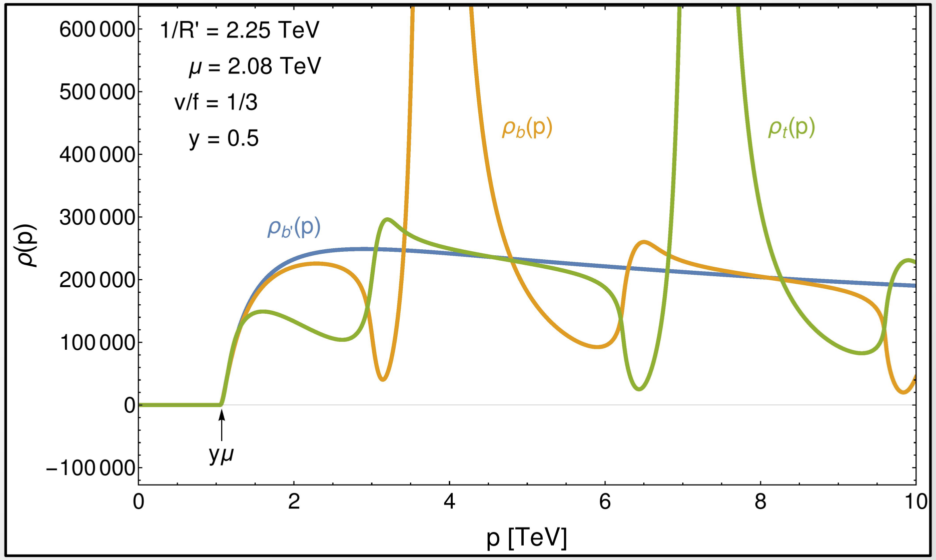


We get the right mt, mb, mW, mZ

Gauge spectral functions



Fermion spectral functions



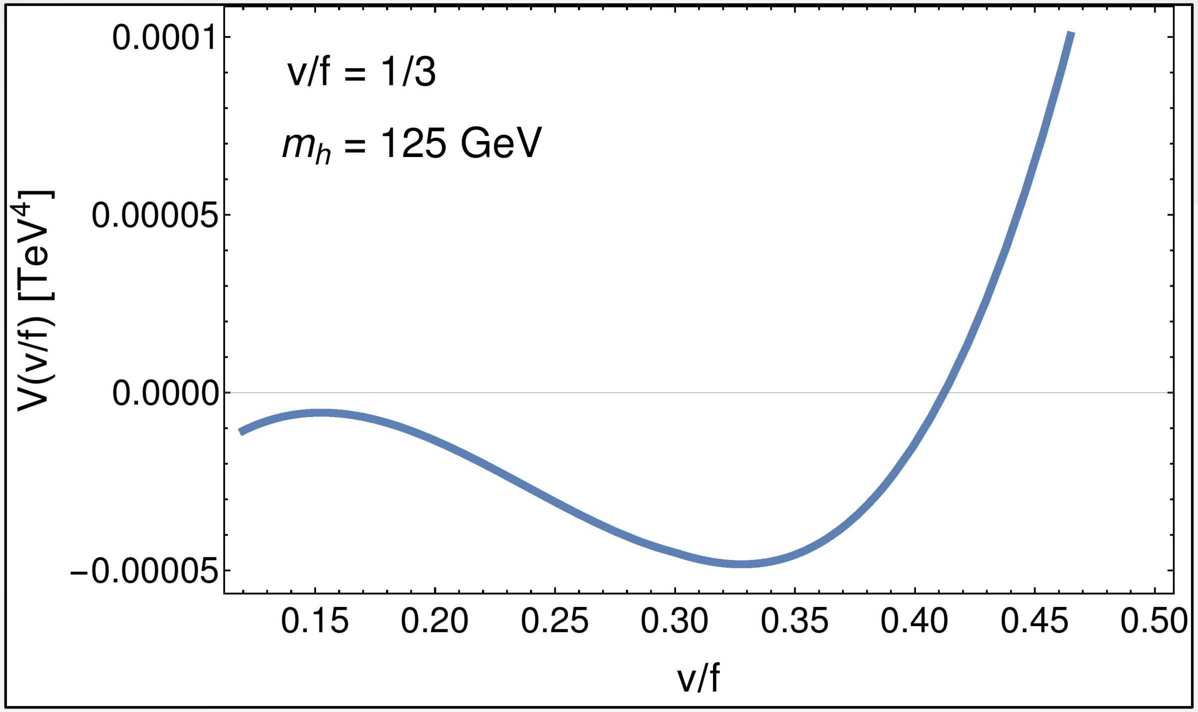
Continuum Compsite Higgs – the Higgs potential

The Higgs is a pNGB of SO(5)/SO(4):

- The potential is radiatively generated (Coleman-Weinberg potential)
- The radiative corrections are cut off at the global symmetry breaking scale $g_* f$ - this is the essence of composite Higgs as a solution to the Hierarchy problem
- We get the potential from the fermion & gauge boson Green's functions

$$V(h) = \frac{3}{16\pi^2} \int dp\, p^3 \left[-4 \sum_j \log G_{f_j}(ip) + \sum_k \log G_{g_k}(ip) \right]$$

The Higgs potential - results

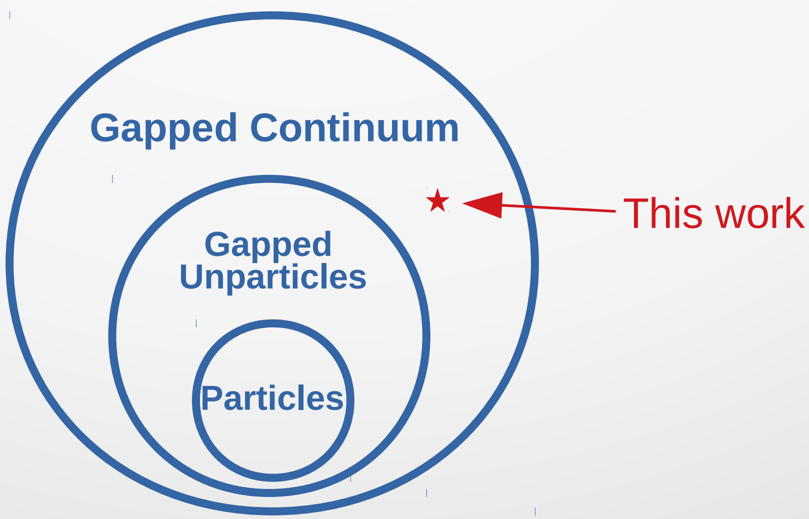


We exactly reproduce the Higgs mass and VEV for the compositeness scale f=3v

This is consistent with the bound v/f ≤ 3 for electroweak precision

Continuum Composite Higgs - Summary

- Found a way to model gapped continua in 5D
- Used our 5D setting to construct a fully realistic composite Higgs model
  - All SM masses and couplings are reproduced, consistent with EWP
  - The fermion & gauge continua start at ~1 TeV (can push higher at the cost of tuning)
  - Still need to check tuning (at least as good as regular CH)



Continuum Composite Higgs - Phenomenology

- Very different gauge partner pheno – no s-channel resonances!
- LHC pheno – no cascade decays. Work in progress for same-sign dilepton bounds (similar or better than CH)
- 100 TeV pheno – possible cascade decays between continuum fermions and gluons. Need to calculate total pair-production CS for continuum fermions.
- Flavor constraints – the same as standard CH models

Continuum Composite Higgs - Phenomenology

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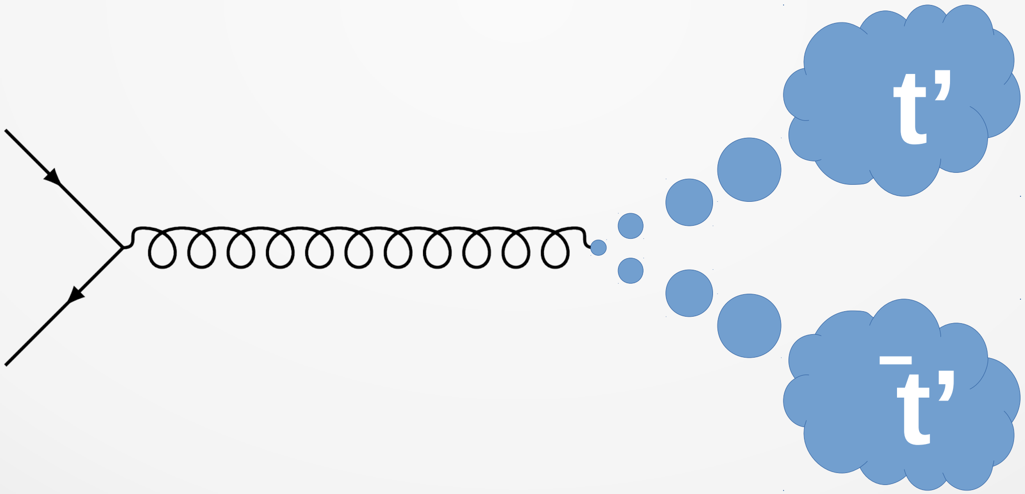
Part II Goal

- Flavor constraints – the same as standard CH models

Part II: Continuum Pair-Production



The Pair-production CS for Continuum Fermions

Looking for the tree-level CS

$$\sigma\left(q\bar{q} \to G \to T\bar{T}\right)$$

for a continuum fermion T with a generic 2-pt function G(p)

Looks easy, but is actually hard!

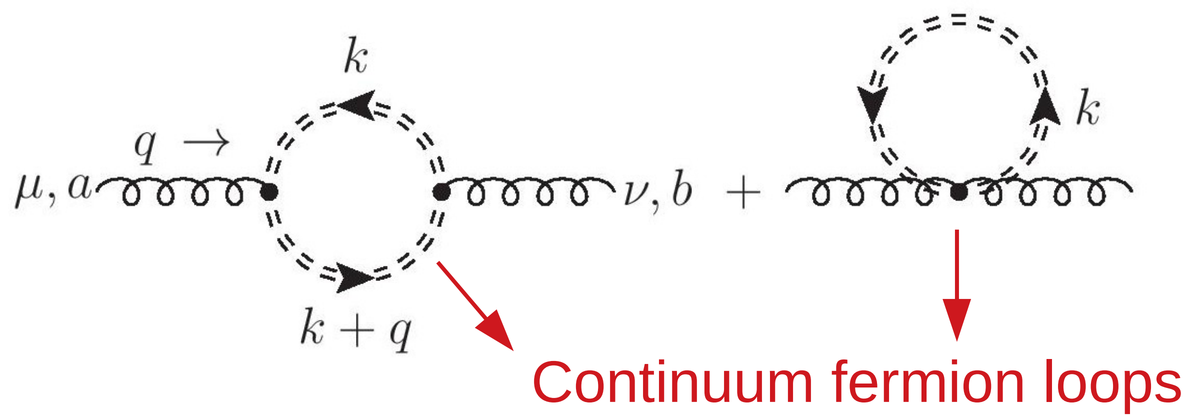
- TTG vertex has momentum dependence
- Final state phase space hard to calculate
  - For Unparticles, LIPS is like a fractional number of particles
  - For generic continuum?

Using the Optical Theorem in Reverse

$$\sigma\left(q\bar{q} \to G \to T\bar{T}\right) = -\frac{4\pi\alpha_S}{3s}\,\mathrm{Im}\,\Pi_g(s)$$

where

$$i\Pi_g(s) = P_T^{\mu\nu}\,\mathrm{Tr}$$



We need to:

- Get continuum fermion Feynman rules
- Calculate non-standard loops

Cacciapaglia, Marandella, Terning, hep/ph:0708.0005
0804.0424

Feynman Rules: A Colorful Continuum?

The Continuum Propagator

Take a generic continuum fermion:

$$\mathcal{L}_f = -i\bar{\chi}\bar{\sigma}^\mu p_\mu \Sigma\left(p^2\right)\chi$$

The propagator is then

$$= \frac{i\sigma^\mu p_\mu}{p^2\Sigma(p^2)}$$

The Gluon-Continuum Vertex

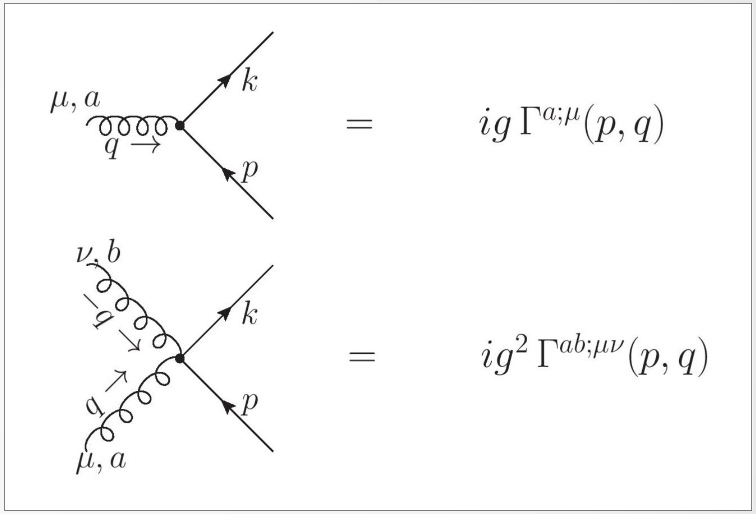
Gluon-Continuum interaction uniquely defined by gauge invariance

This is not your typical $-igT^a$, but two momentum dependent vertices

Exact form derived by:

- Switching to position space
- Inserting a Wilson line to preserve gauge invariance
- Switching back to momentum space

Mandelstam 62', Terning 91'



Vertices satisfy generalized Ward-Takahashi identities

$$q_\mu\,\Gamma^{a;\mu} = i\,T^a\,\bar{\sigma}^\mu\left[(p+q)_\mu\,\Sigma\,(p+q) - p_\mu \Sigma\,(p)\right]$$
$$q_\mu\,\Gamma^{ab;\mu\nu} = \Gamma^{b;\nu}(p,q)\,T^a - T^a\,\Gamma^{b;\nu}(p,-q)$$

Cacciapaglia, Marandella, Terning, hep/ph:0708.0005
0804.0424

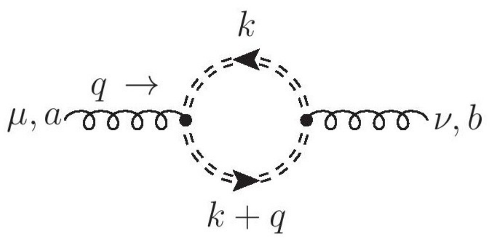
Calculating the Loops: Dispersion Relations

$$G(s) = \frac{1}{\pi} \int_0^\infty \frac{\operatorname{Im} G(s')}{s' - s} \, ds'$$

The Continuum Loop

Focus on:

$$i\Pi_3(s) \quad = \quad P_T^{\mu\nu}\,\mathrm{Tr}$$

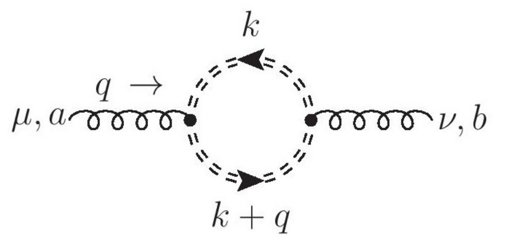


$$\mathrm{Im}\,\Pi_{\psi 3}(q) \;=\; -\frac{1}{2}\,\mathrm{Im}\int \frac{d^d k}{(2\pi)^d}\;\frac{1}{k^2 (k+q)^2 (q^2 + 2k\cdot q)^2}\;\left[\frac{\Sigma(k+q)}{\Sigma(k)}P_+ \;+\; \frac{\Sigma(k)}{\Sigma(k+q)}P_-\right]$$

The Continuum Loop

Focus on:

$$i\Pi_3(s) \quad = \quad P_T^{\mu\nu}\,\mathrm{Tr}$$



$$\mathrm{Im}\,\Pi_{\psi 3}(q) \;=\; -\frac{1}{2}\,\mathrm{Im}\int \frac{d^d k}{(2\pi)^d}\,\frac{1}{k^2(k+q)^2(q^2+2k\cdot q)^2}\left[\frac{\Sigma(k+q)}{\Sigma(k)}P_+ + \frac{\Sigma(k)}{\Sigma(k+q)}P_-\right]$$

Denominator linear in loop momentum (like HQET)
This is from the vertex momentum dependence

Model dependent continuum spectral density. We will mod it out using a dispersion relation

Uniquely defined polynomials in the loop momentum

The Continuum Loop

Defining the following

$$I\left[P\right] \;\equiv\; \int \frac{d^d k}{\left(q^2+2k\cdot q\right)^2} P \qquad\qquad \sigma_1(p) \;=\; \frac{\Sigma(p)}{p^2} \quad , \quad \sigma_2(p) \;=\; \frac{\Sigma(p)^{-1}}{p^2}$$

We get the “compact” form

$$\boxed{\mathrm{Im}\,\Pi_{\psi 3}(q) \;=\; -\frac{1}{2(2\pi)^d}\,\mathrm{Im}\,I\left[\,\sigma_1(k+q)\sigma_2(k)\,P_+ + \sigma_1(k)\sigma_2(k+q)\,P_-\,\right]}$$

The expressions in red are dependent on the particular spectral density

We want to get the out of the loop integral I[P]

A Dispersion Relation for $\sigma_{1,2}$

To mod out the model dependence from our loop integral, we use dispersion relations

$$\boxed{\begin{aligned}\sigma_1(p^2) &= \frac{c_{-2}}{p^4} + \frac{c_{-1}}{p^2} - \frac{1}{\pi}\int_{\mu^2}^{\infty} \frac{\mathrm{Im}\,\sigma_1(s)ds}{s-p^2} \\ \sigma_2(p^2) &= \sigma_2(p_0^2) - \frac{p^2-p_0^2}{\pi}\int_{\mu^2}^{\infty} \frac{\mathrm{Im}\,\sigma_2(s)\,ds}{(s-p_0^2)(s-p^2)}\end{aligned}}$$

Now all the p^2 (and loop momentum) dependence is contained in a Feynman numerator/denominator that we can integrate over

$$\mathrm{Im}\,\Pi_3(q) = -\frac{1}{2(2\pi)^d}\frac{1}{\pi^2}\,\mathrm{Im}\iint_{\mu^2}^{\infty} \frac{\mathrm{Im}\,\sigma_1(s)\,\mathrm{Im}\,\sigma_2(s')\,ds ds'}{s'-q_0^2}\underbrace{I_{\mathrm{kernel}}(q,q_0,s,s')}_{\text{Model independent Feynman integral (still non-trivial)}} + \ldots$$

The Pair-Production Cross Section – Summary

$$\sigma\left(q\bar{q}\to G\to T\bar{T}\right) \;=\; -\frac{4\pi\alpha_S}{3s}\,\mathrm{Im}\,\Pi_g(s)$$

$$\mathrm{Im}\,\Pi_g(q) \;=\; -\frac{1}{2(2\pi)^d}\frac{1}{\pi^2}\,\mathrm{Im}\iint_{\mu^2}^{\infty}\frac{\mathrm{Im}\,\sigma_1(s)\,\mathrm{Im}\,\sigma_2(s')\,ds\,ds'}{s'-q_0^2}\,I_{\mathrm{kernel}}\left(q,q_0,s,s'\right)+\ldots$$

- The model independent kernels I(q,q0,s,s') involve a linear denominator and are similar to 2-loop HQET
- We can* calculate them by Schwinger transformations and the Mellin-Barnes technique
- The result has a general significance beyond our model – valid for any continuum fermion (can generalize to any particle)

* Wrote our own 1-loop Mellin-Barnes code for linear denominators.
Currently struggling with double Harmonic sums using the Sigma package.

Conclusions

- Found a way to model gapped continua in a 5D Linear Dilaton setting

  See also Cai, Cheng, Medina, Terning, hep/ph:0910.3925

- Constructed a fully realistic composite Higgs model with continuum top & gauge partners

- Closing in on a generic formula for the pair production of continuum fermions

- Future study:
  - LHC pheno - no resonances, need to finish top partner bounds
  - 100 TeV pheno – cascade decays, spherical event shapes (?) and more
  - Cosmology – what does a continuum-populated universe look like?

Thank You!

Backup

Stabilizing a Linear Dilaton

- Stabilization by the superpotential method:

  → Solve Einstein-scalar equations by assuming a "superpotential"

One scalar: $W = R^{-1}\left(1 + e^{\phi/R}\right) \longrightarrow$ gapped continuum

Carber, von Gersdorff,Quiros, hep/ph: 0907.5361

2 scalars: $W(\Phi, T) \sim R^{-1}\left[2e^{\frac{T^2}{\Lambda_T^2}} - \left(1 - \frac{\Phi}{\Lambda_\Phi}\right)e^{\phi/\Lambda_\Phi}\right] \longrightarrow$ linear dilaton

Batell, Gherghetta, Sword, hep/ph: 0808.3977

- As a "little String theory" construction

Aharony, Berkooz, Kutasov, Seiberg, hep/ph:9808149
Antoniadis, Arvanitaki, Dimopoulos, Giveon, hep/ph:1102.4043

- Other:

Guidice, Kats, McCullough, Torre, Urbano, hep/ph:1711.08437