Laboratoire d'Annecy-le-Vieux de Physique Théorique

mini-workshop, “New Paths towards New Physics”

Continuum Naturalness

Seung J. Lee

With B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning; PRX 2016
With C. Csaki, S. Lombardo; work in progress
With C. Csaki, S. Lombardo, G. Lee, O. Telem; 1811.06019 & to appear soon
With M. Park and Z. Qian; 1812.02679

KOREA UNIVERSITY

Jan. 15, 2019

Naturalness Paradigm Under Pressure

♦ Naturalness "typically" implies new colored top partners

~TeV scale to cut off the top contribution to the Higgs potential

not too many theoretical frameworks;

two major ones

AdS/CFT
warped extra dimension

Supersymmetry
stop

Composite Higgs:
Fermionic top partners
(partial compositeness)

Higgs is a fundamental scalar, just like many other SUSY partners

Higgs is a composite resonance, just like many composite resonances in the theory of strong dynamics

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*Neutral Naturalness is not discussed in this talk

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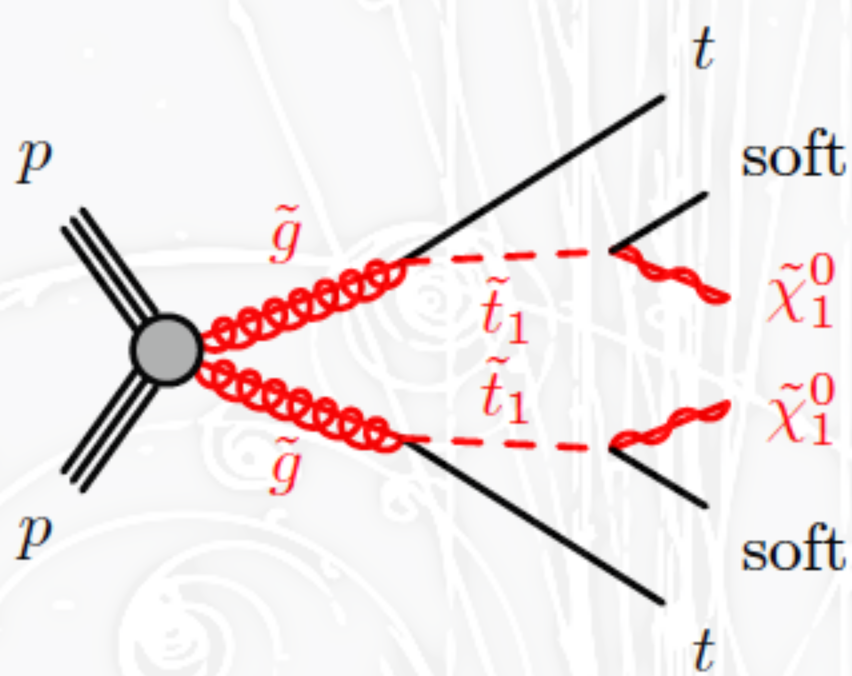
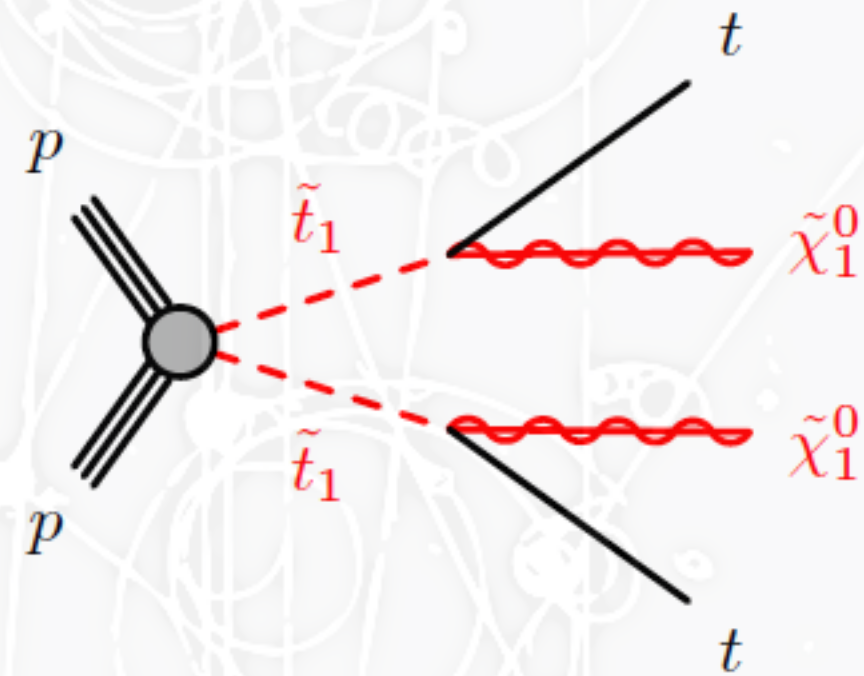
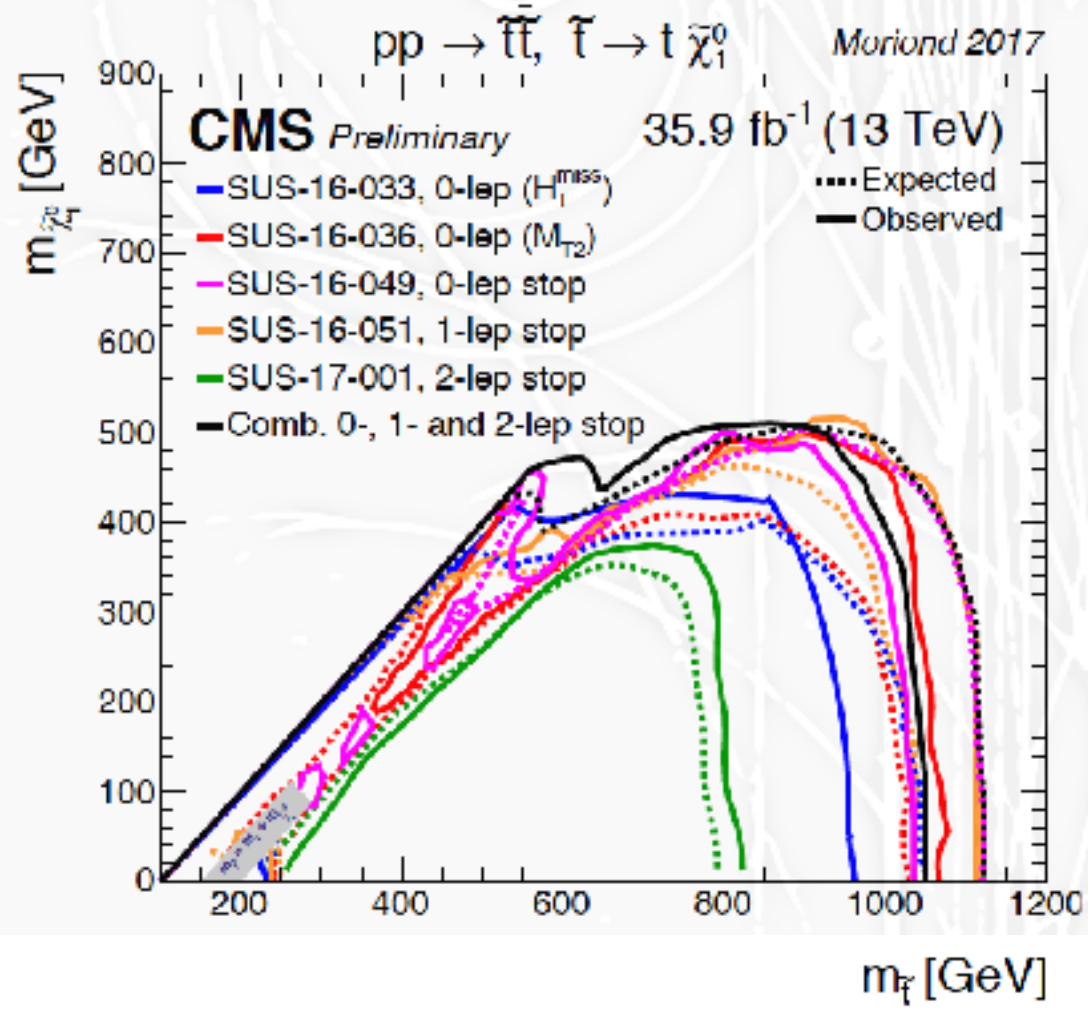
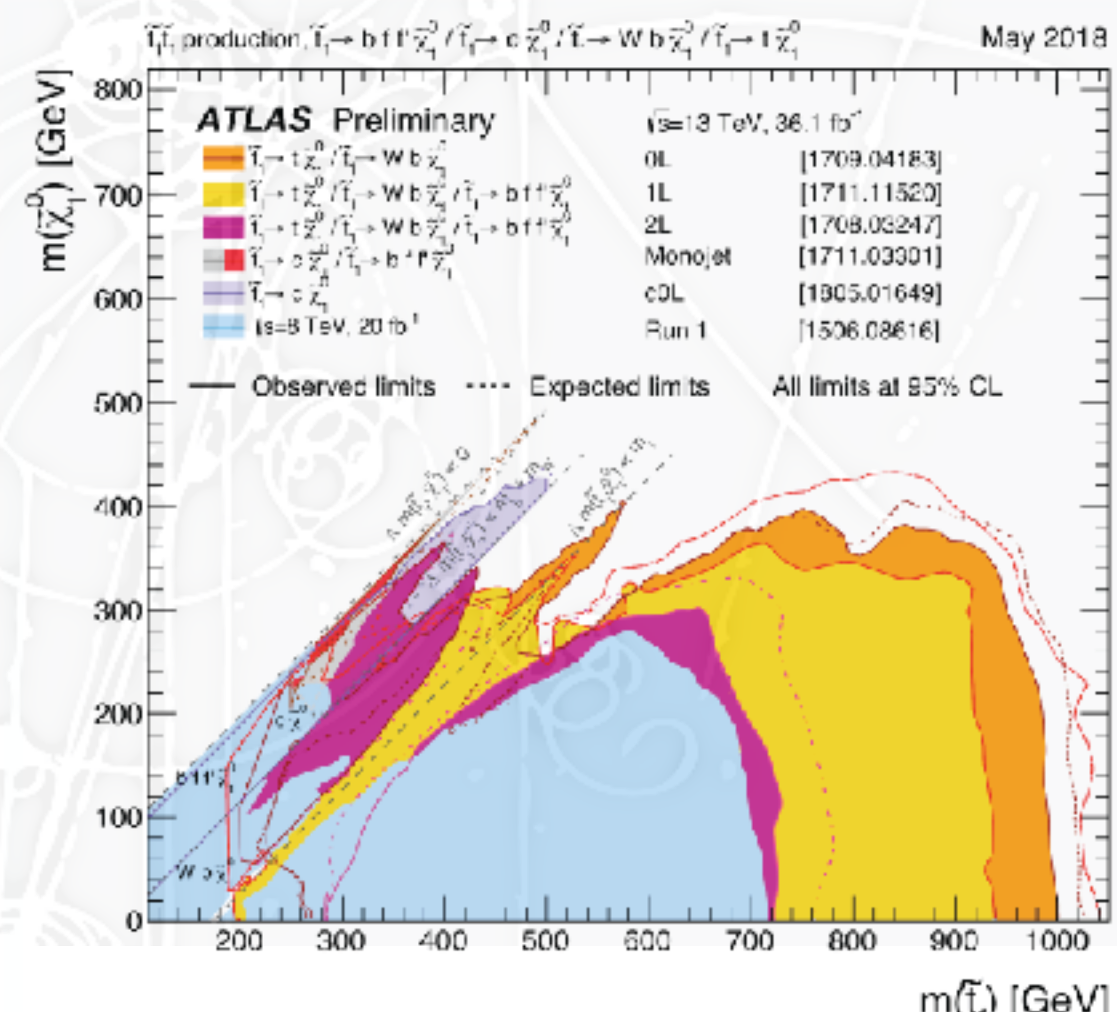
SUSY top partner searches





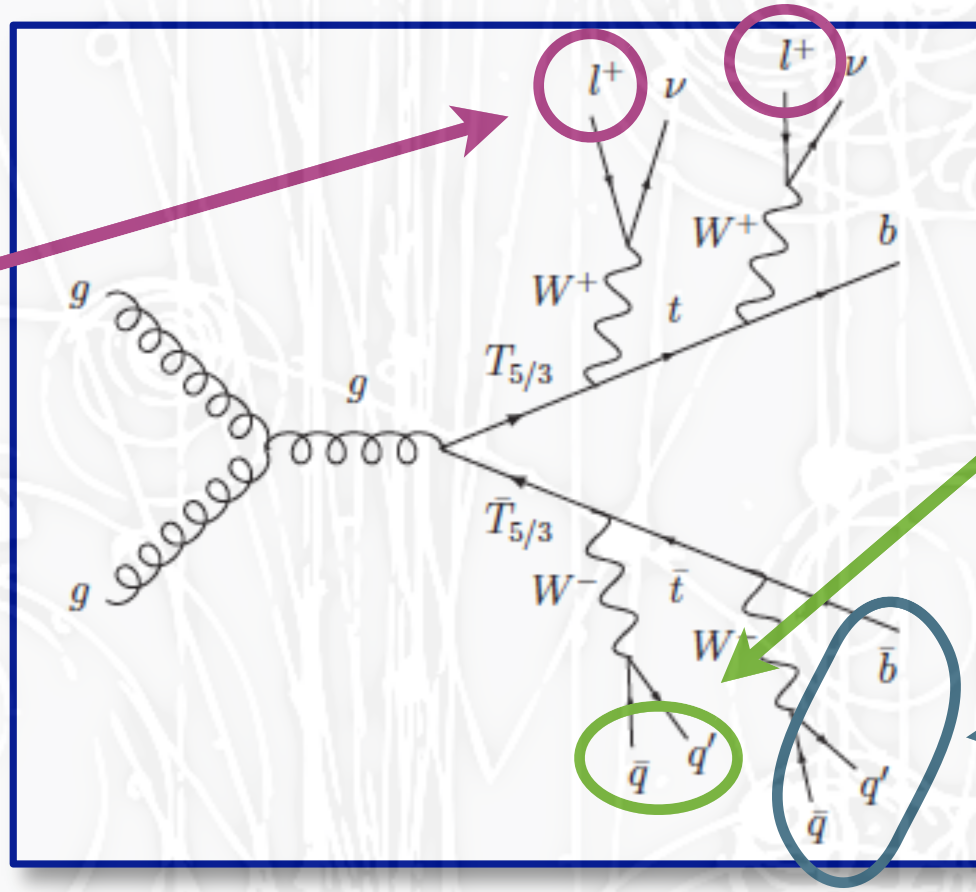




Composite Top Partner Searches

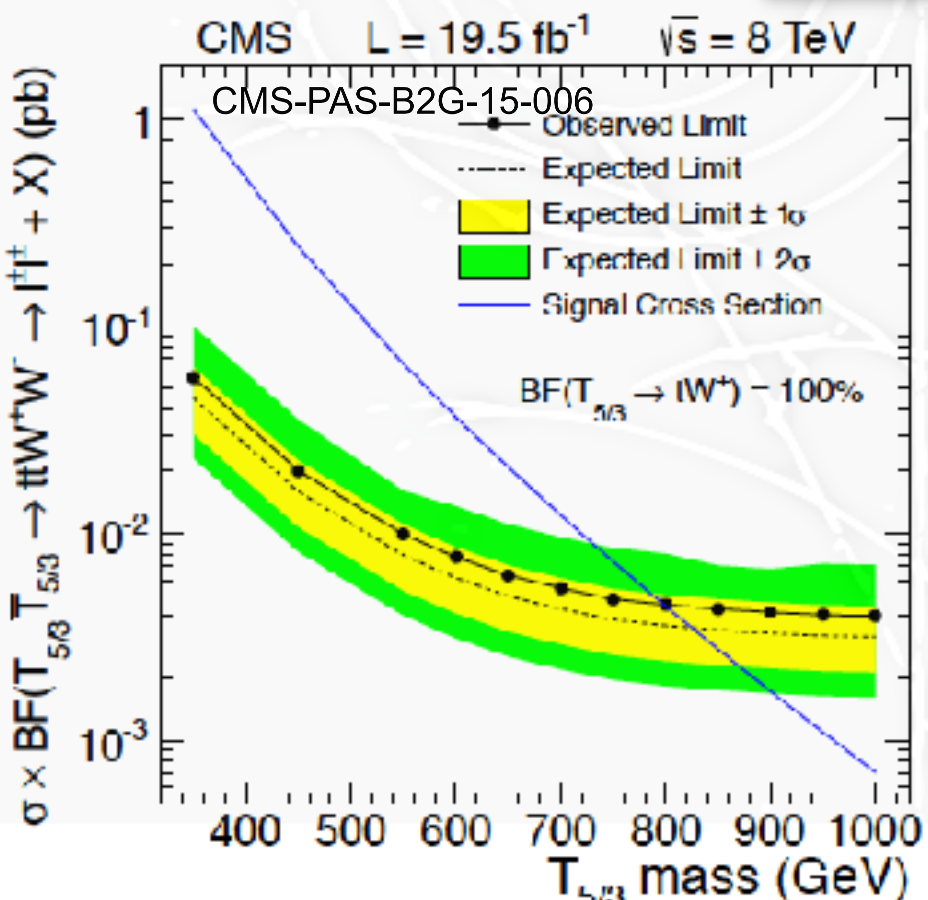
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



W tag:
2 subjets,
M_j[60,130]

CMS top tag



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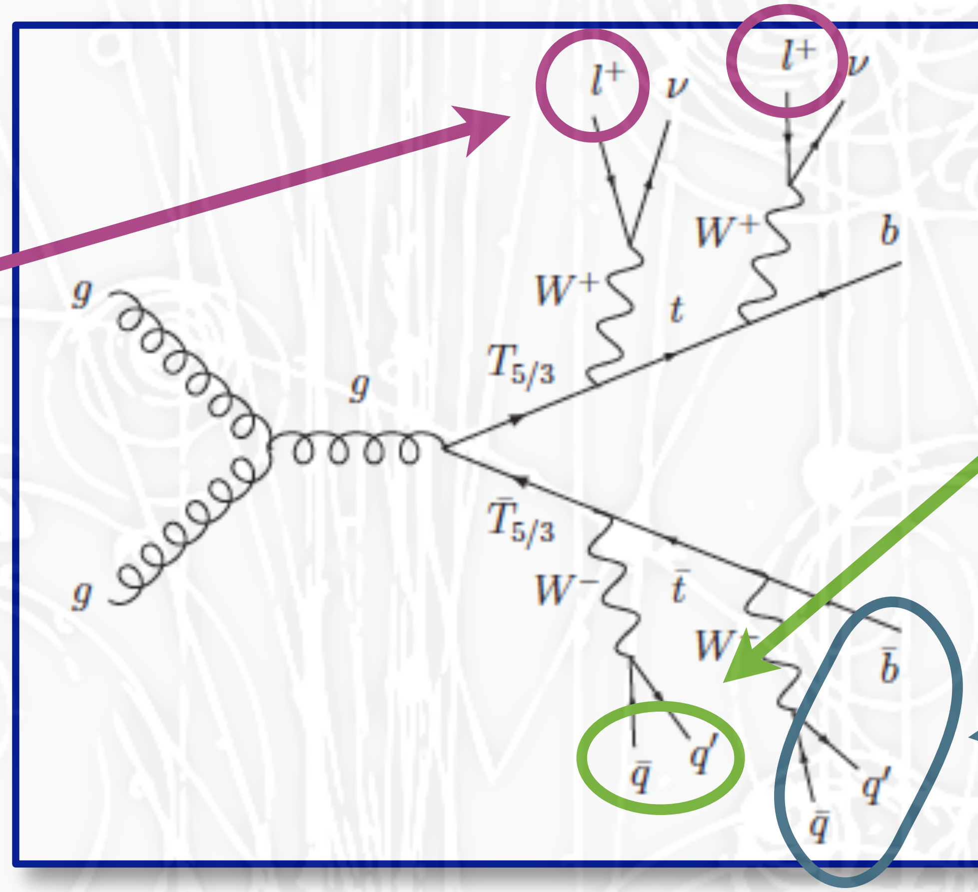

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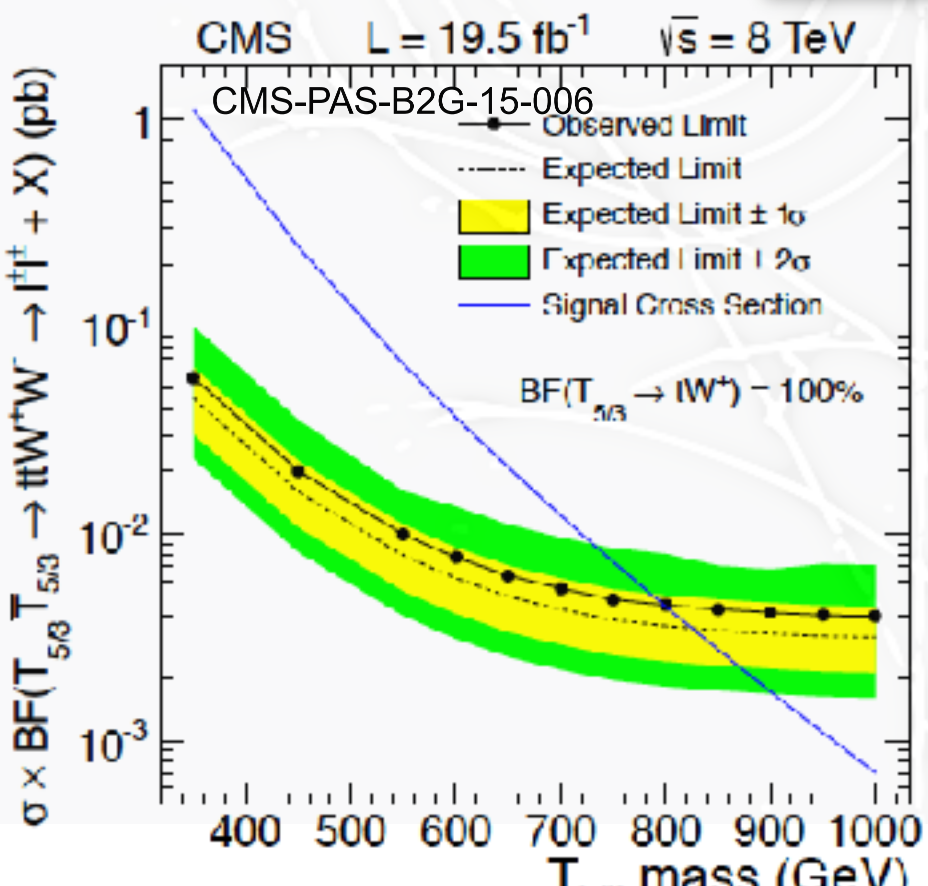

Oblique parameter fits of LEP & Tevatron data gave
f ≳ 800GeV

Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

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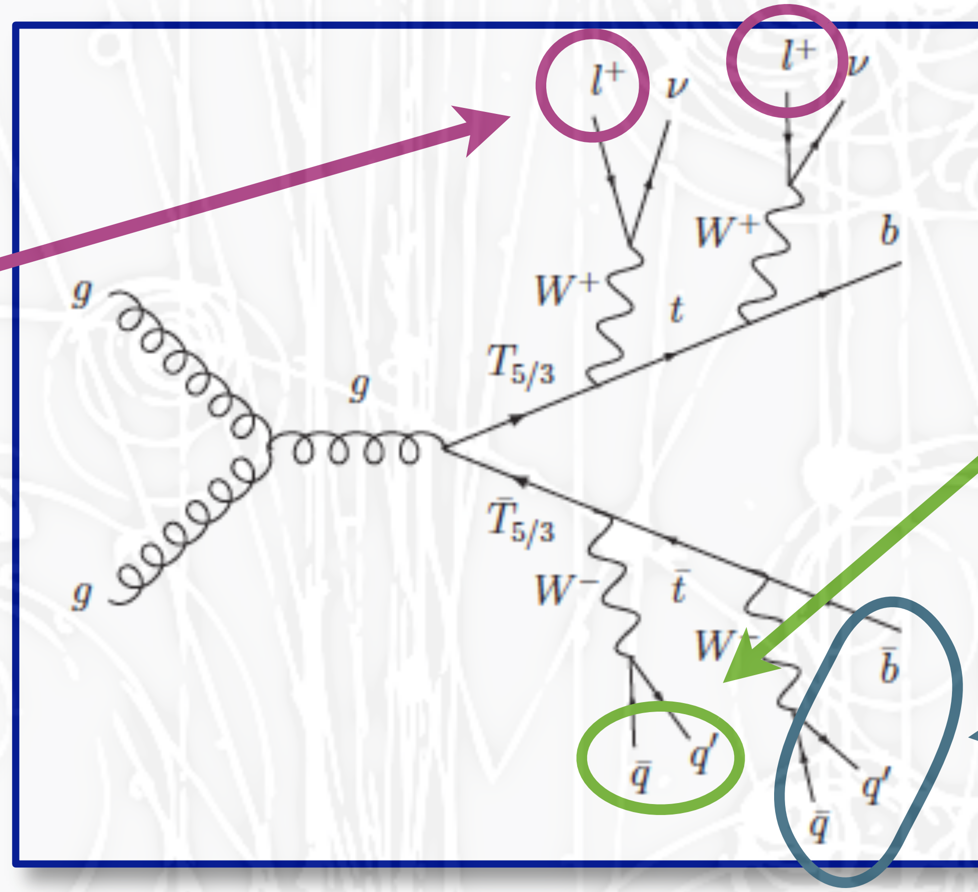

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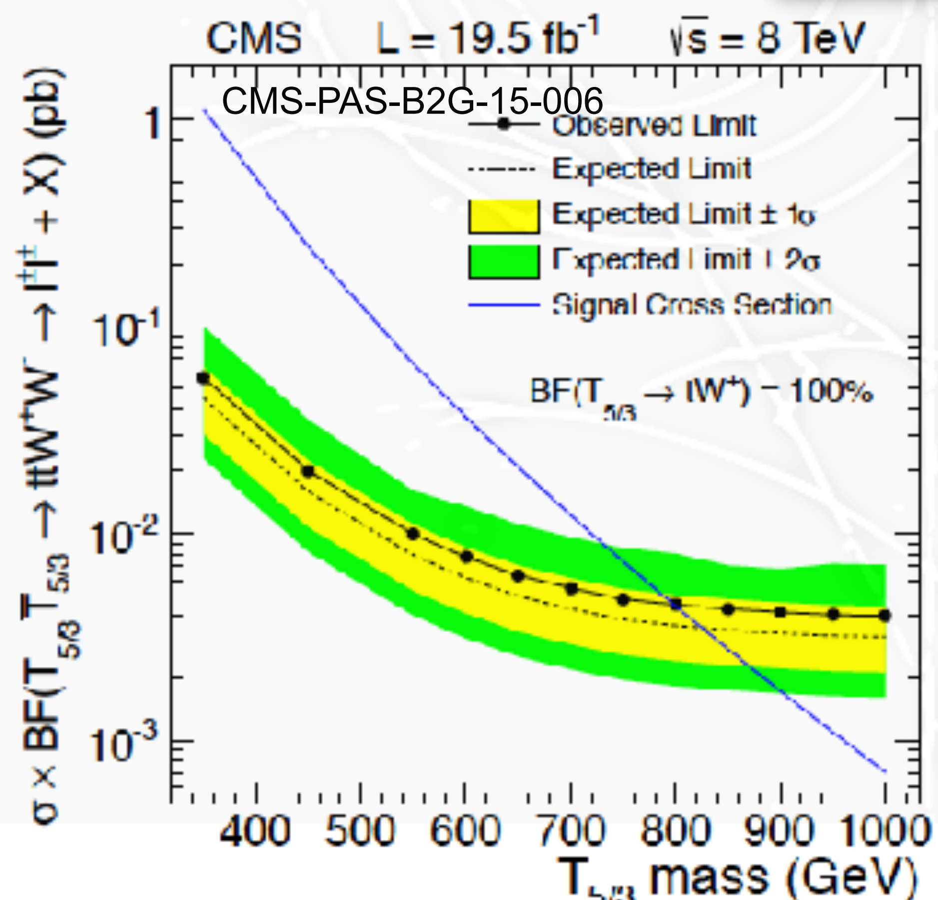

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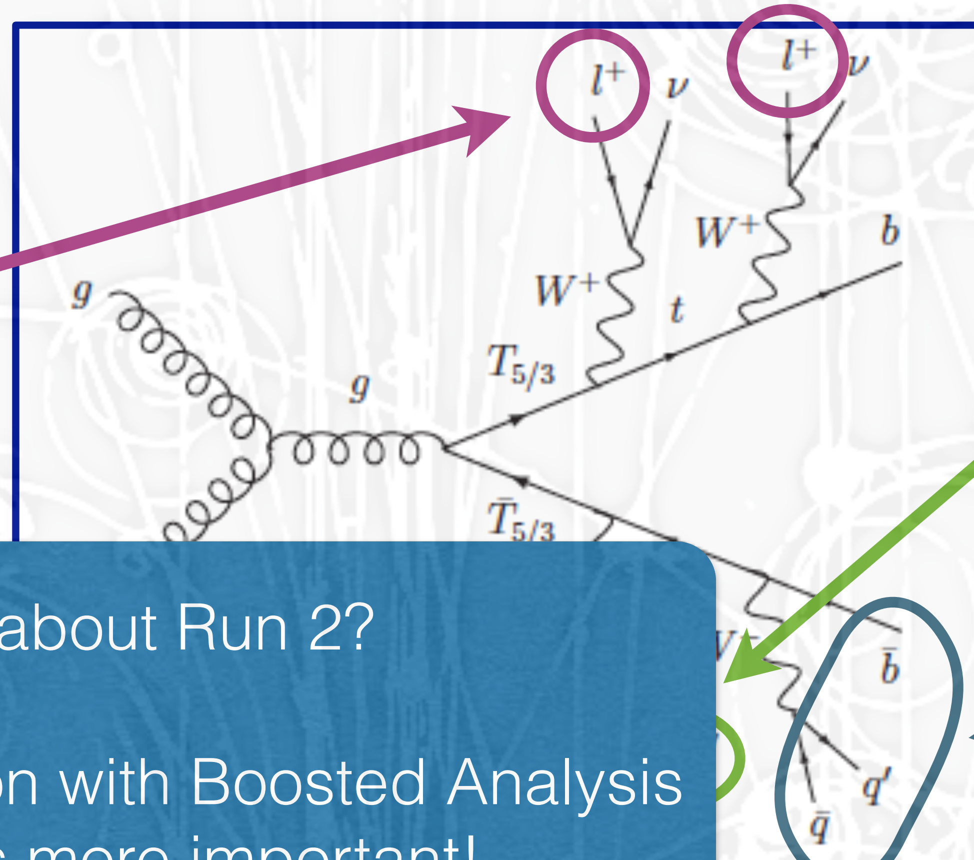

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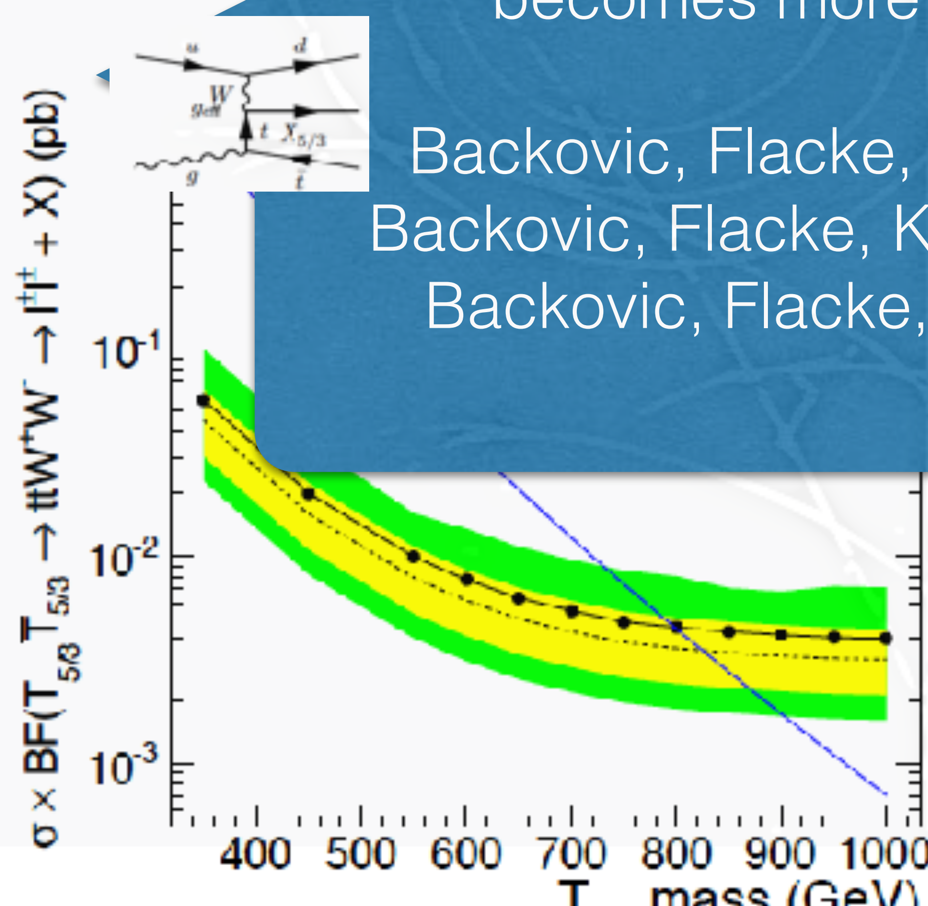
How about Run 2?

Single production with Boosted Analysis becomes more important!

Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL (x2),`15
Backovic, Flacke, Kim, SL, `16



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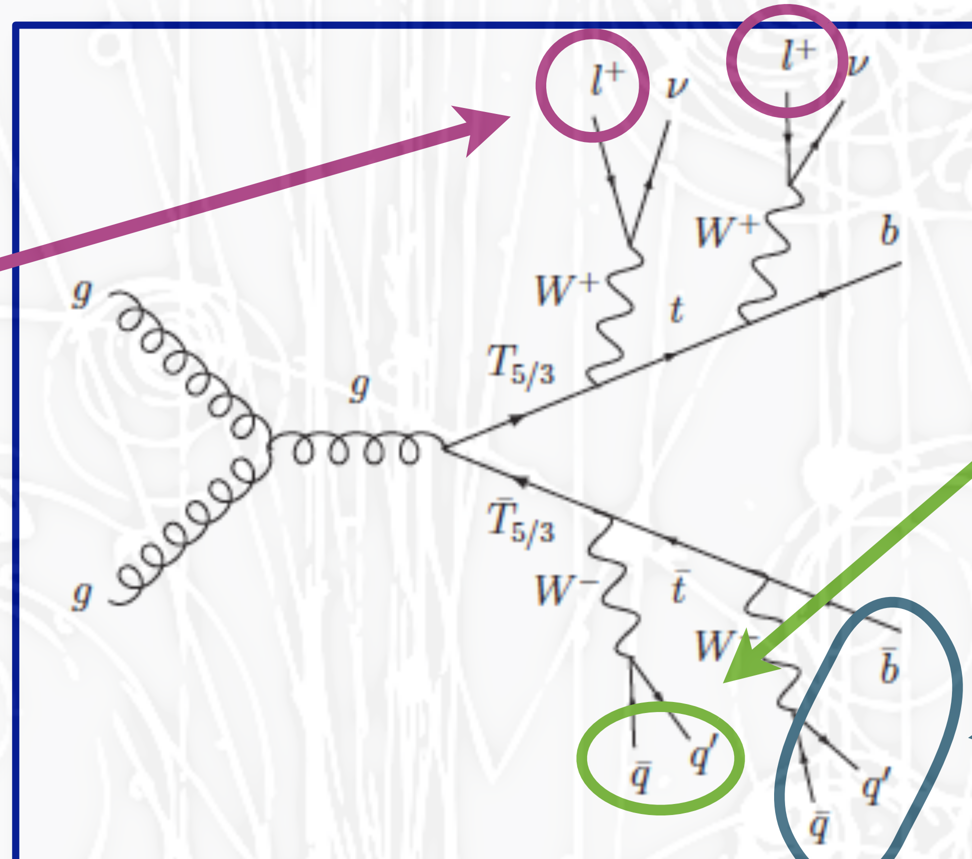

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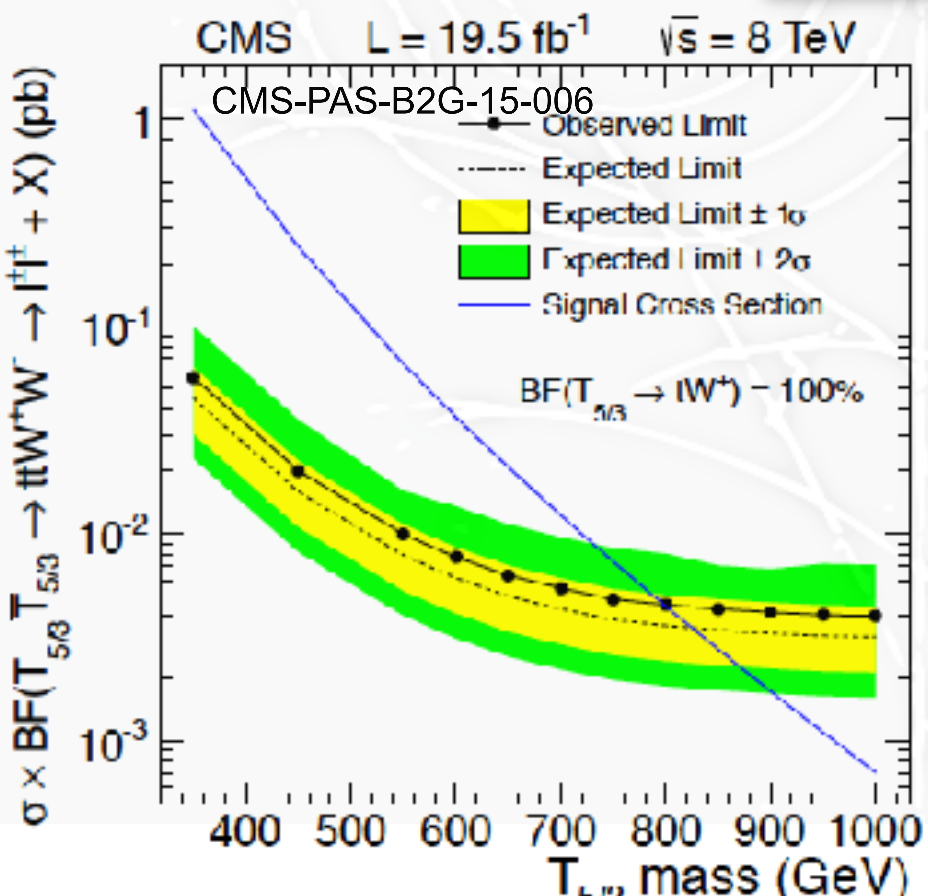

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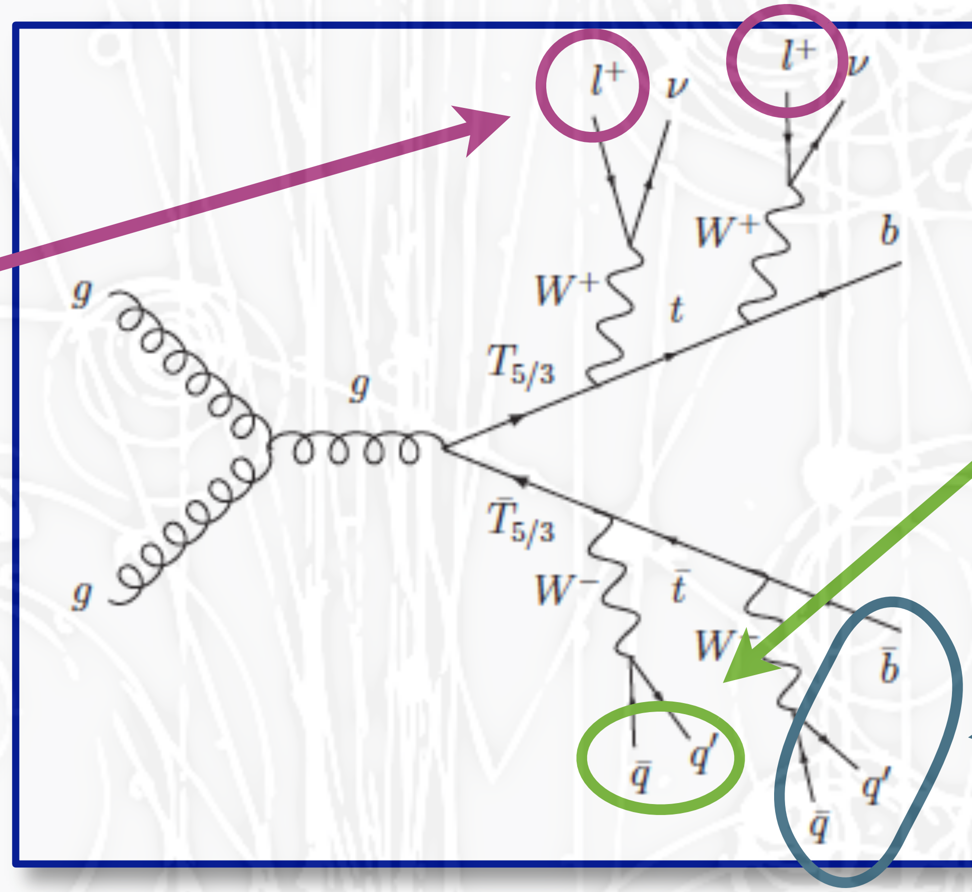

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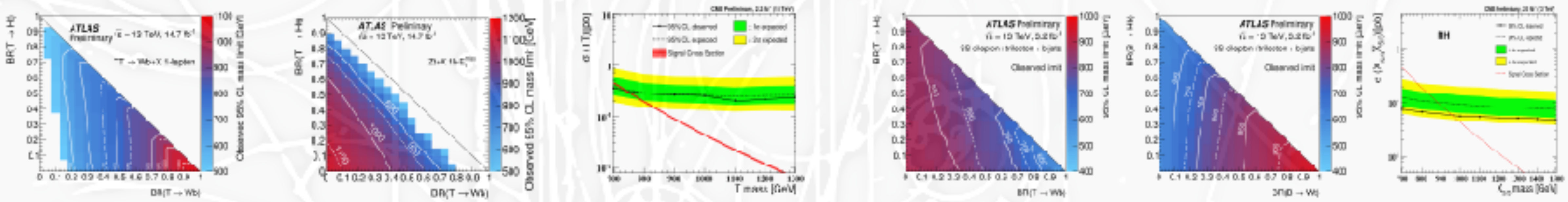
$M_j[60,130]$

CMS top tag

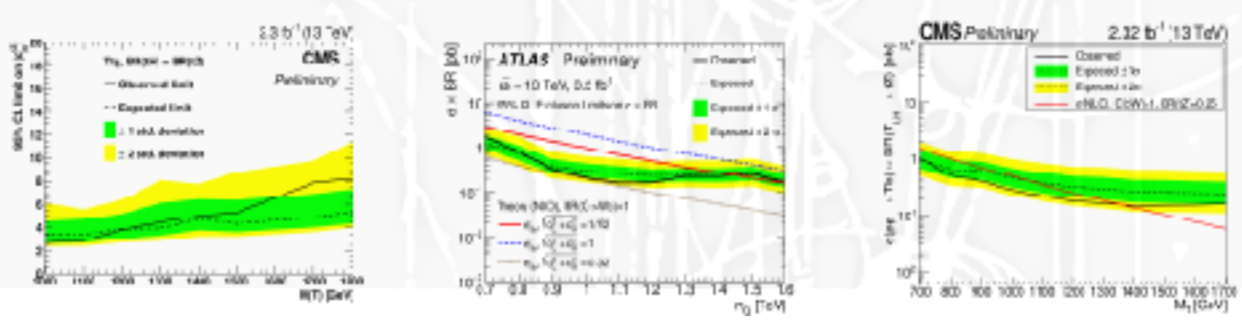
TT→bW+x | TT→tZ+x | TT (T→tW,bZ,bH) | TT→tH+x | BB→tH+x | XX→tWtW

pair VLQ



T→tH | T/Y→bW | T→tZ, B→bZ

single VLQ



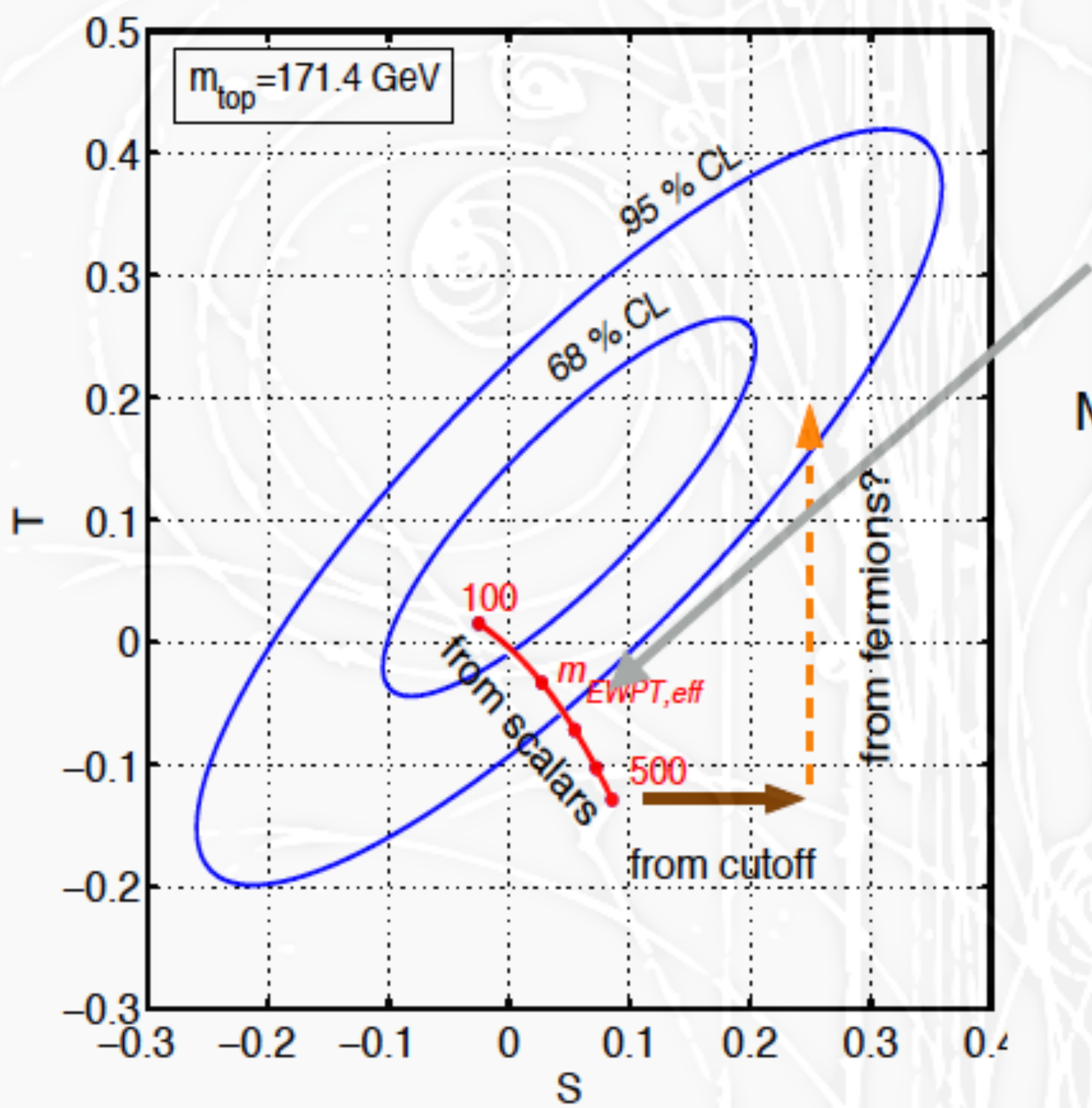
$T_{5/3}$ mass (GeV)

VLQ masses excluded up to:

- 1.4 TeV (100% BR T→Ht)
- 1.3 TeV (doublet)

$M(T_{5/3})$>1.2 TeV (95% CL)

EWPT and Top Partners



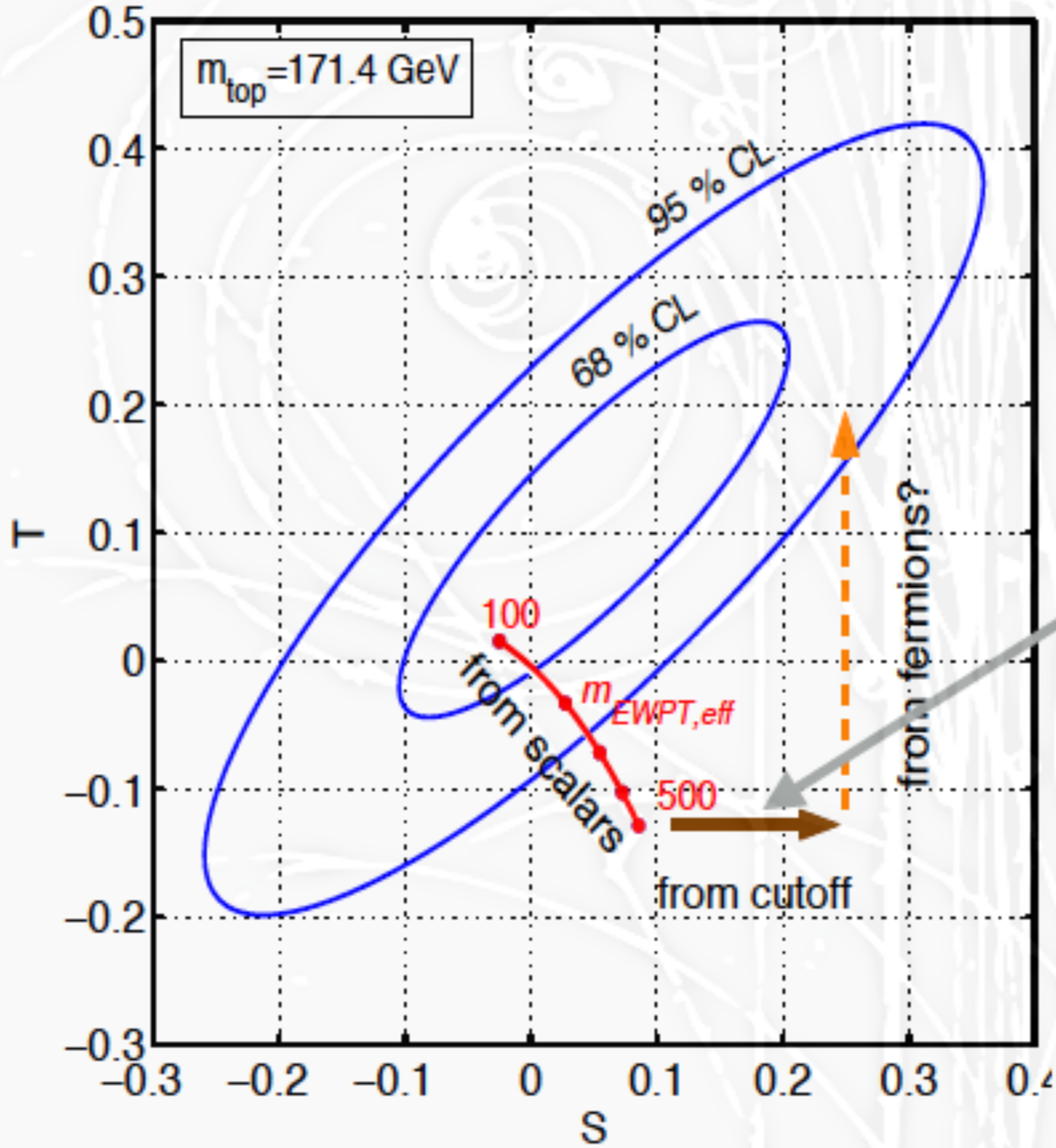
$$\Delta \hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

$$\Delta \hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right)$$

Modified Higgs couplings go in bad direction.

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

EWPT and Top Partners



$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2}$$

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Resonance exchange as well

Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

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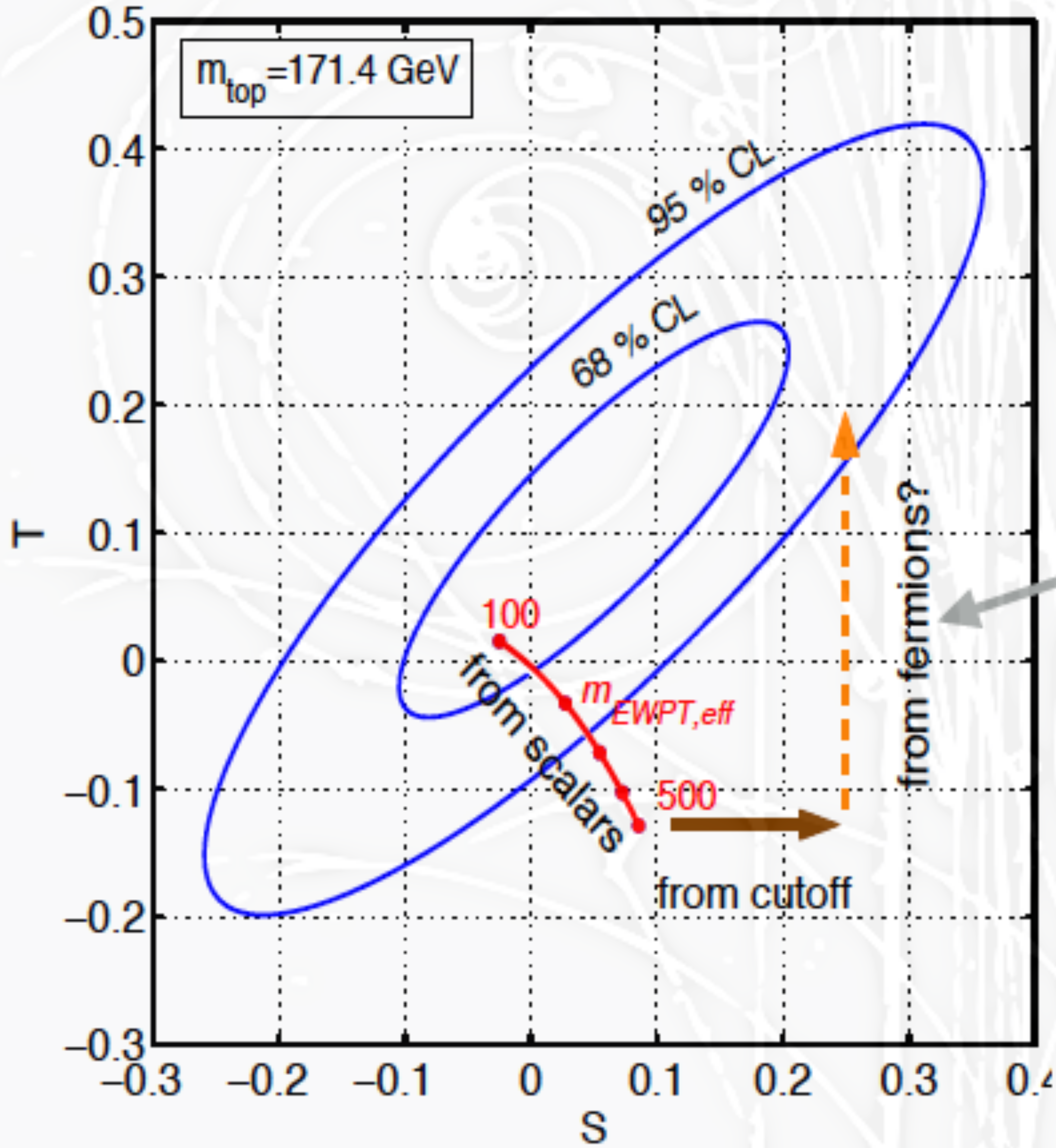


$$\Delta\hat{S} = \frac{g^2}{96\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \frac{m_W^2}{m_\rho^2} + \alpha \frac{g^2}{16\pi^2}\xi\,,$$

$$\Delta\hat{T} = -\frac{3g'^2}{32\pi^2}\xi \log\left(\frac{8\pi m_W}{g m_h \sqrt{\xi}}\right) + \beta \frac{3y_t}{16\pi^2}\xi\,,$$

Modified Higgs couplings go in bad direction.

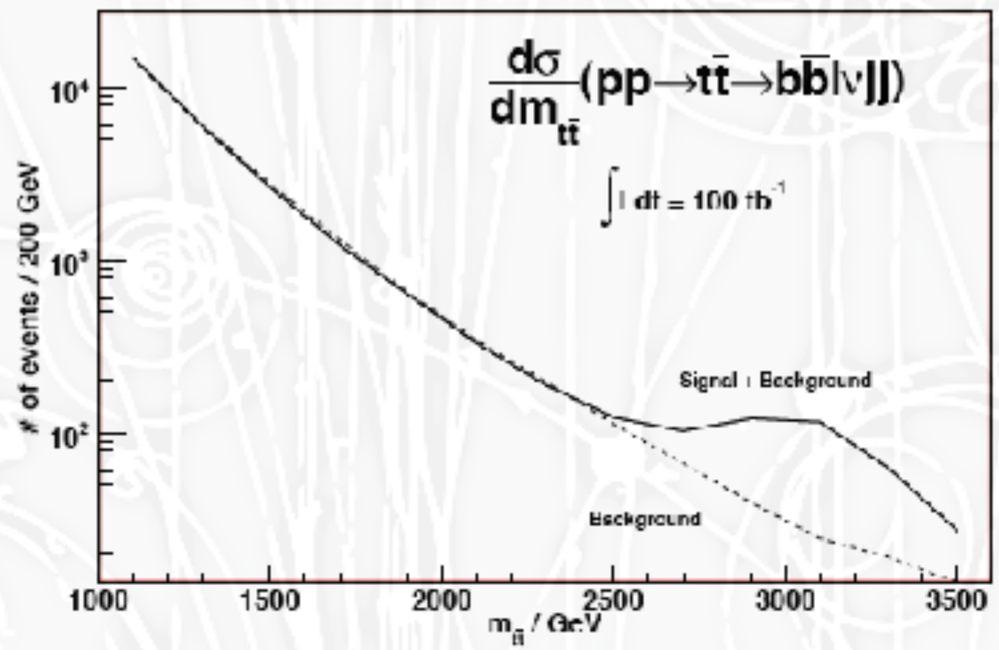
Resonance exchange as well

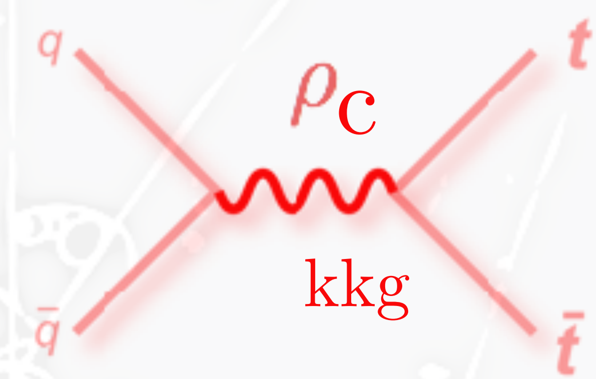
Light Top Partners come to rescue.

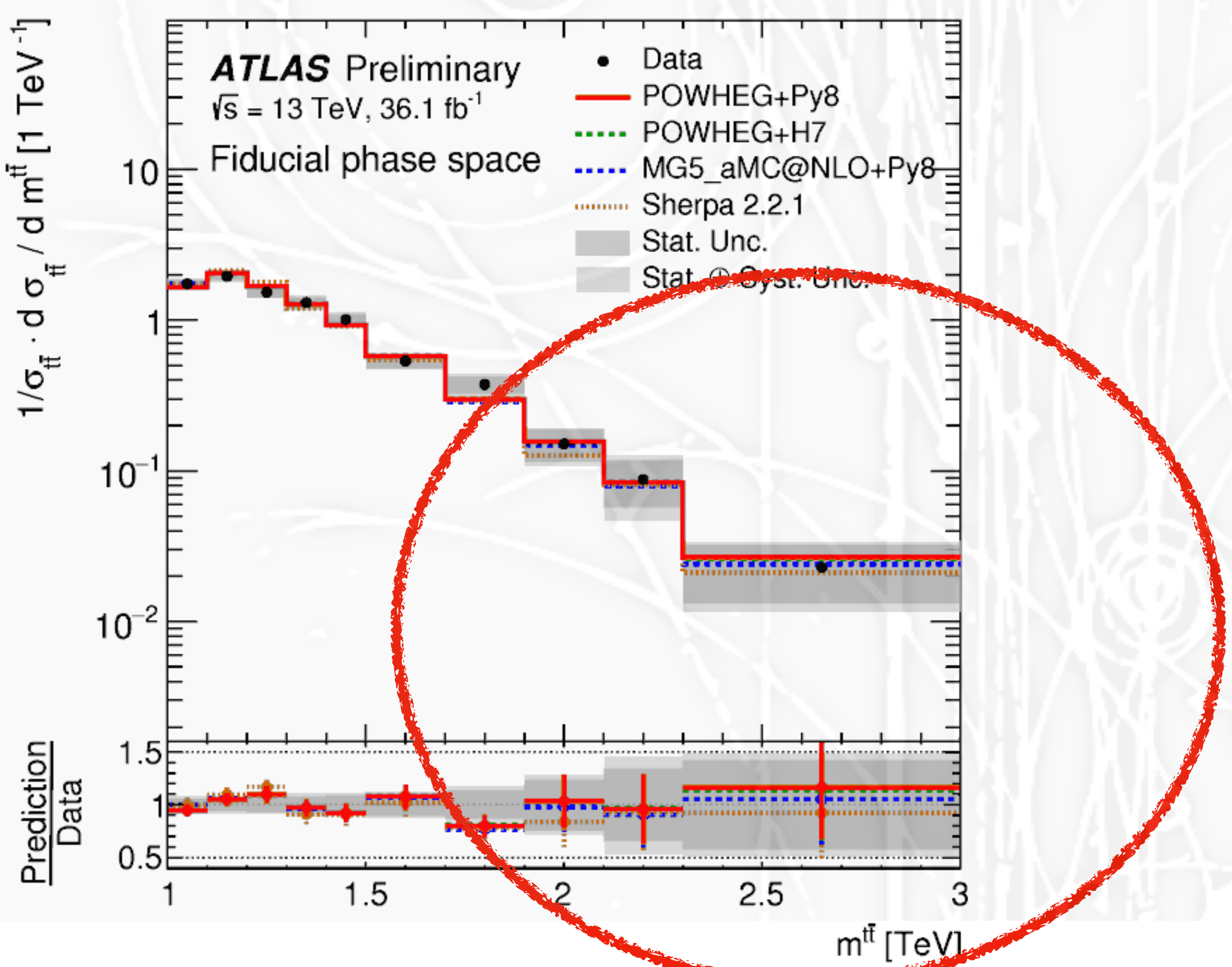
Barbieri, Bellazzini, Rychkov, Varagnolo ,`07

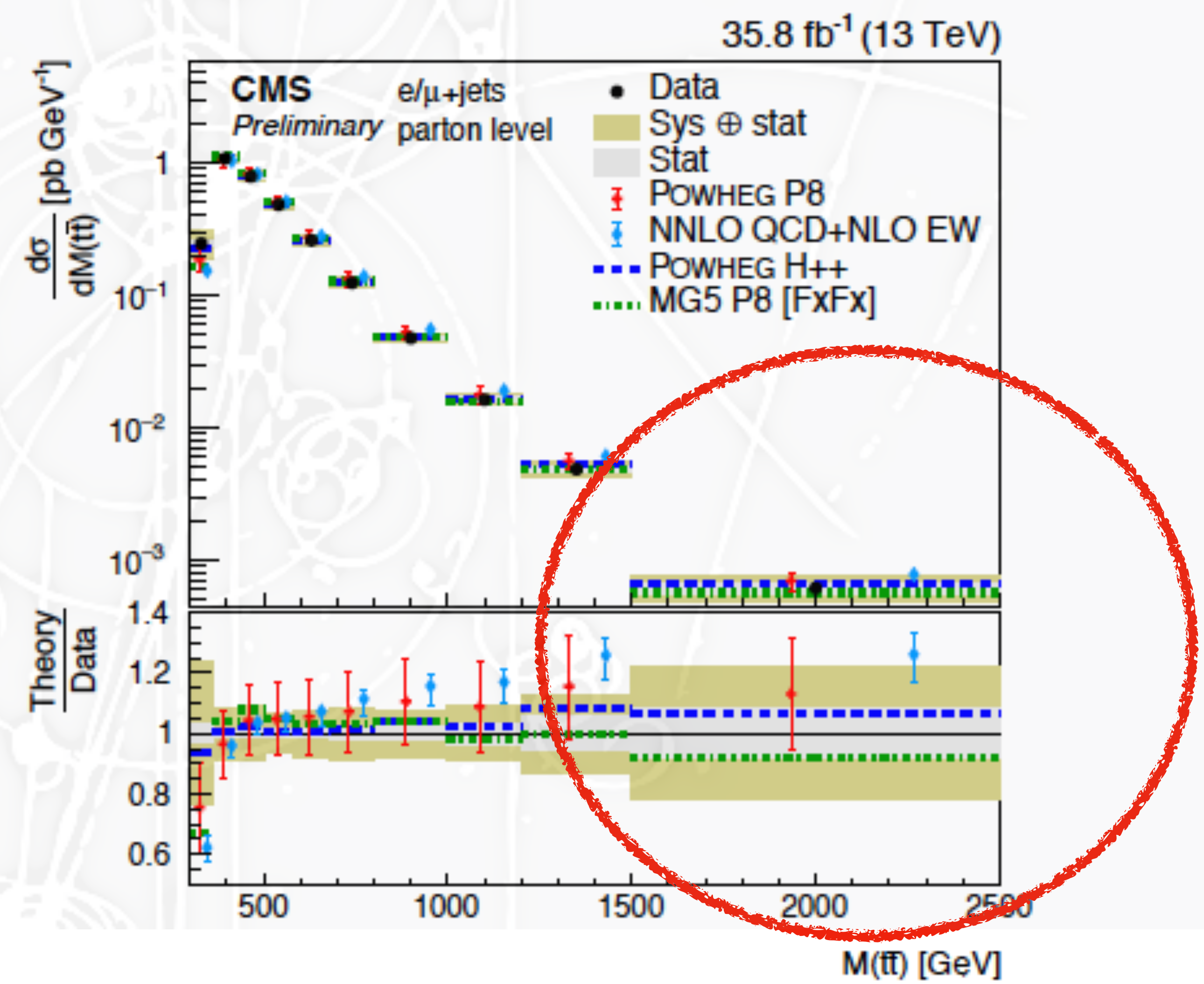
No Resonance, No New Physics? Naturalness?

$M_{KKG} = 3\,\text{TeV}$



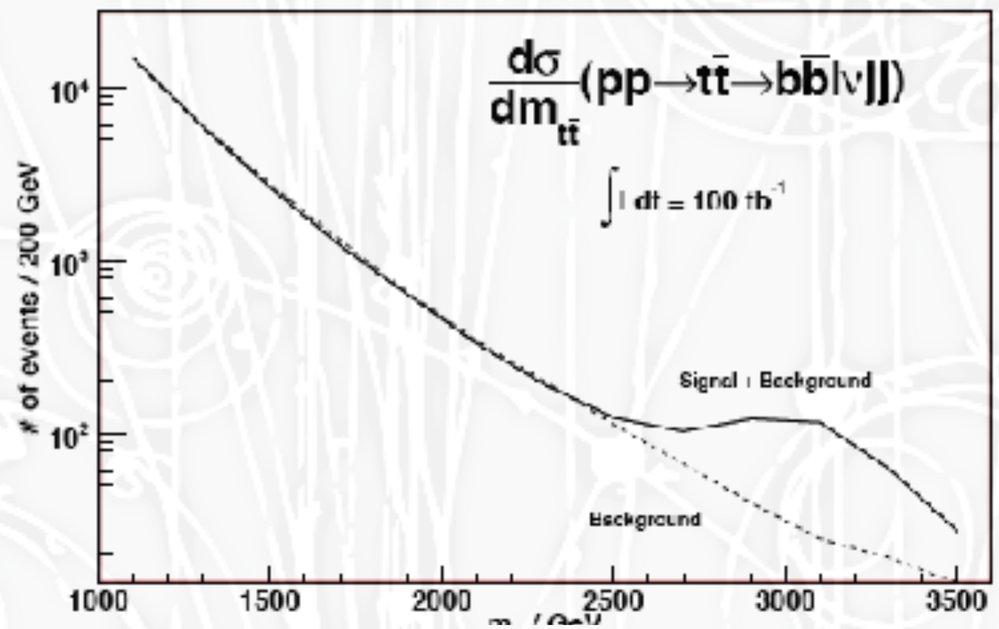


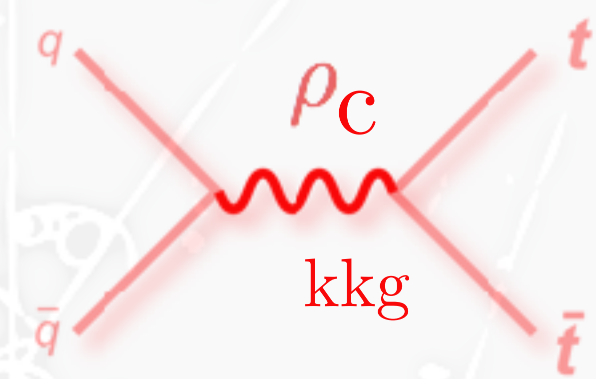


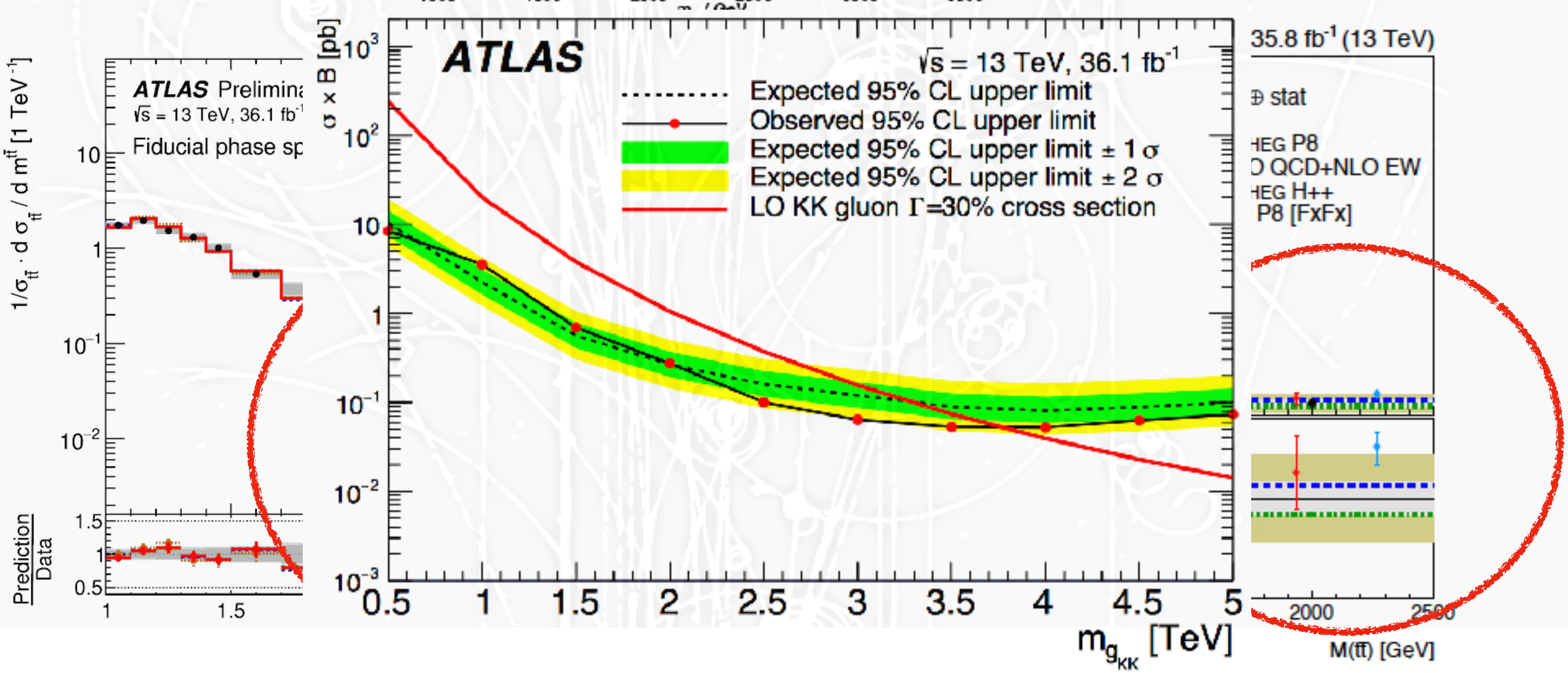


No Resonance, No New Physics? Naturalness?

$M_{KKG} = 3$ TeV







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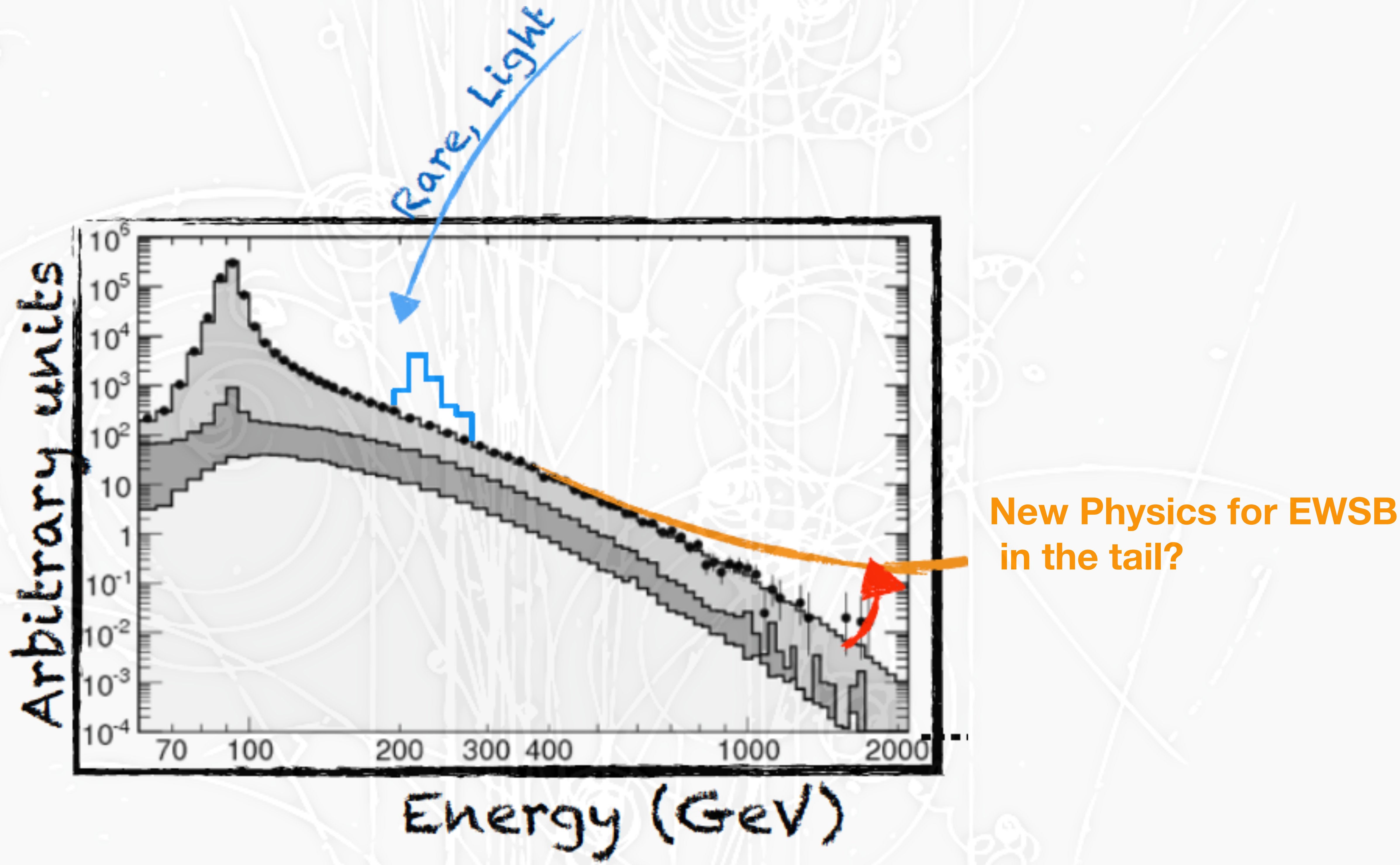

picture adapted from Francesco Riva

No Resonance, No New Physics? Naturalness?

- New Physics may appear solely as a continuum

  -approximately conformal sector (i.e. CFT broken by IR cutoff)

  -multi-particle states with strong dynamics (branch cut at $4m_\pi^2$ in $\pi\pi\rightarrow\pi\pi$ scattering)

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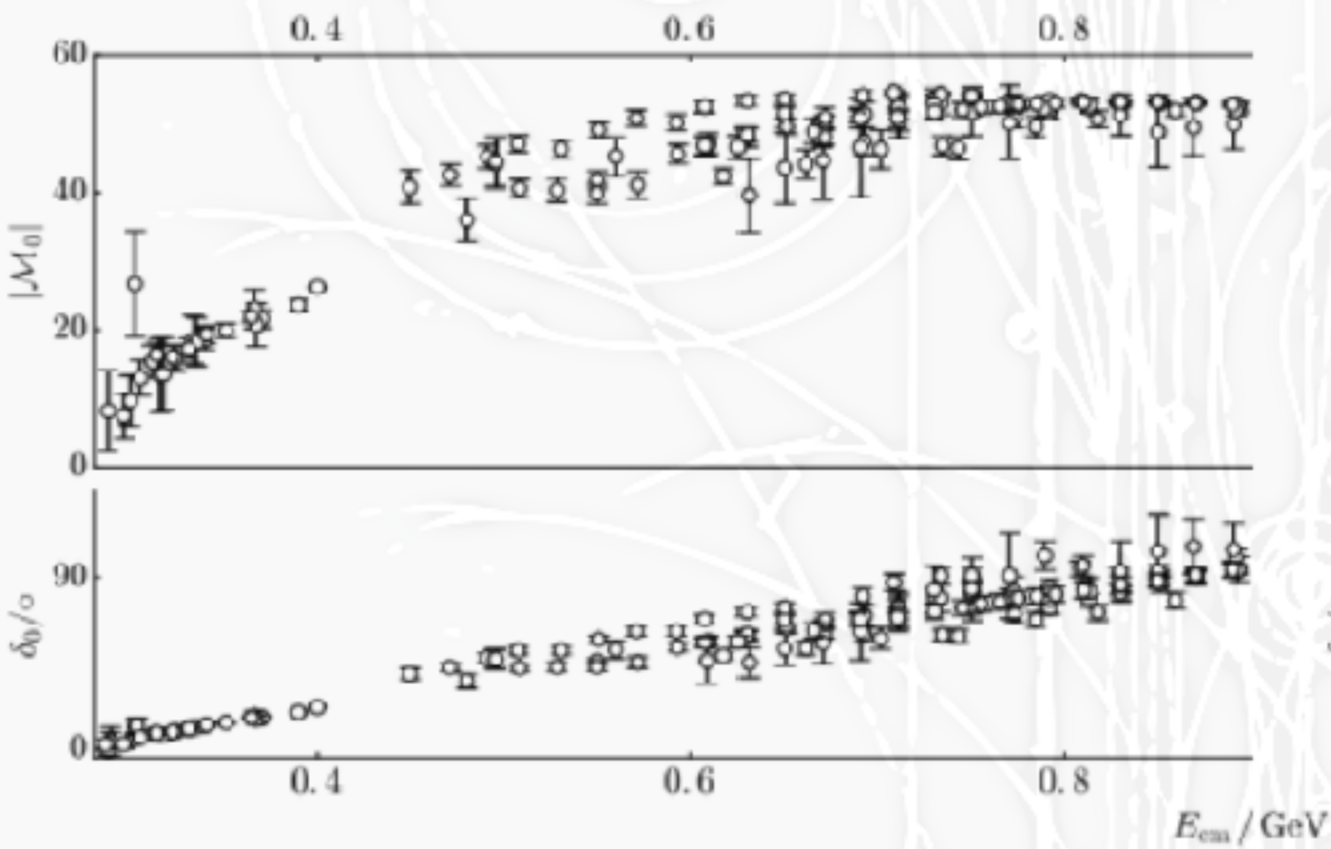
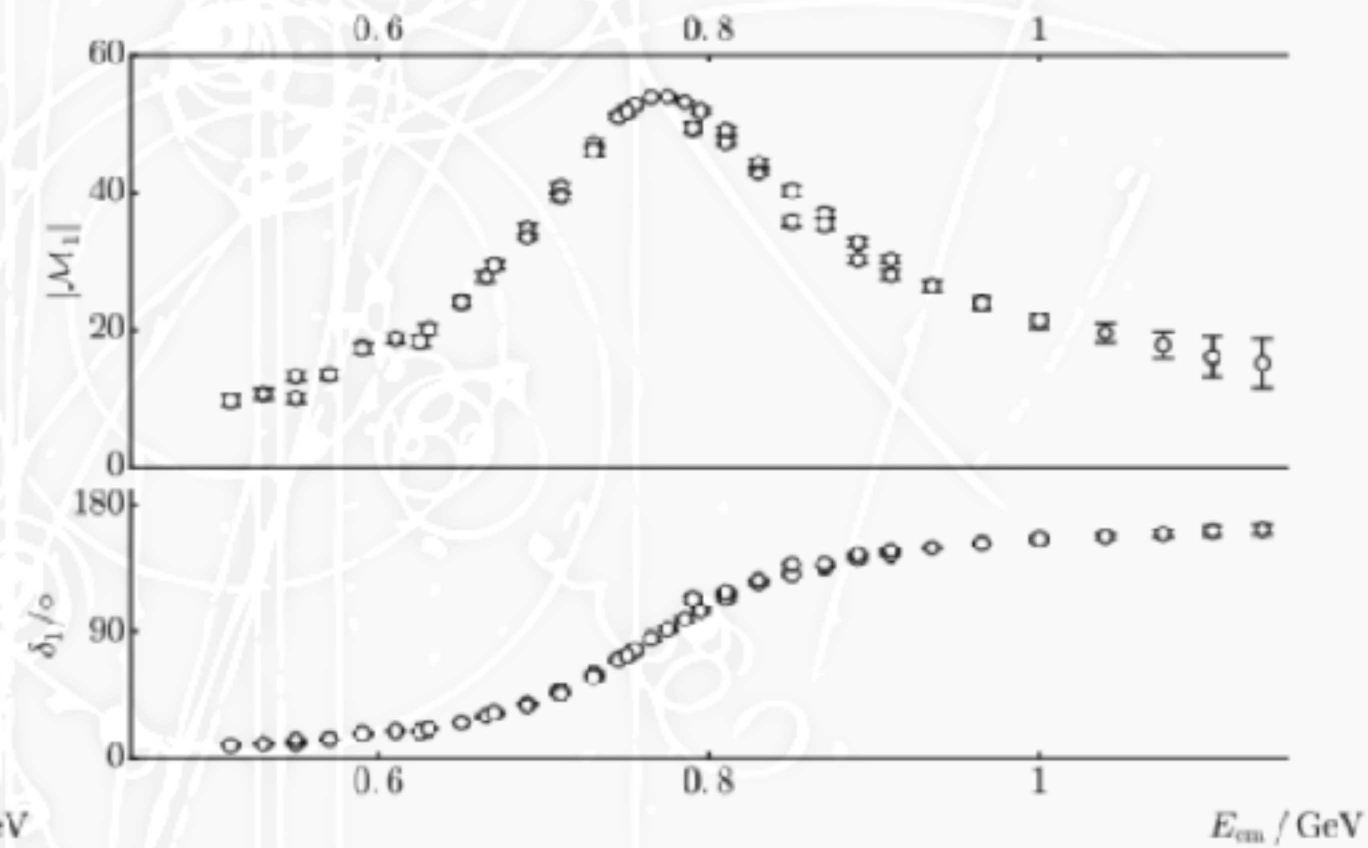
QCD

σ / $f_0(500)$



M_σ=450 MeV Γ_σ=550 MeV

ρ



M_ρ=770 MeV Γ_ρ=145 MeV

No Resonance, No New Physics? Naturalness?

- New Physics may appear solely as a continuum

  - If the new strong dynamics responsible for furnishing a composite Higgs is near a quantum critical point, the composite spectrum may effectively consist of a continuum with a mass gap.

  - In this scenario, poles corresponding to the composite top partner (and vector meson) excitations have merged into a branch cut in the scattering amplitude.

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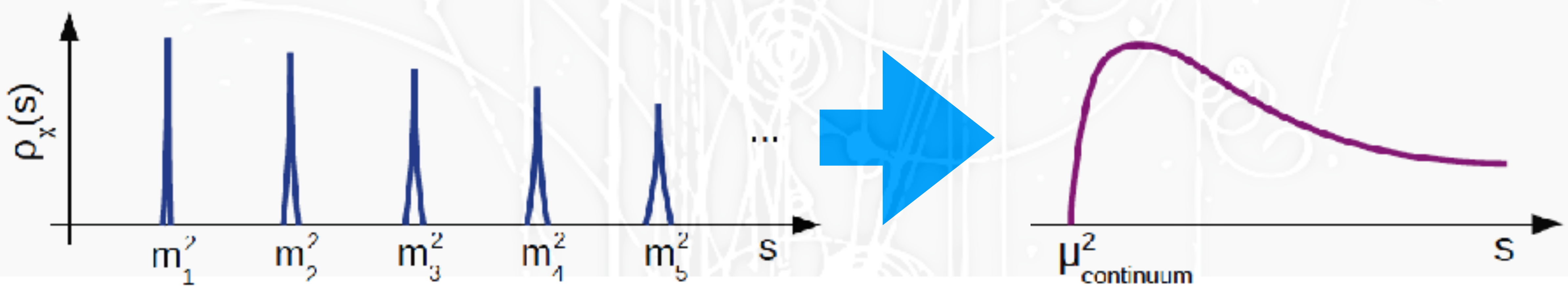
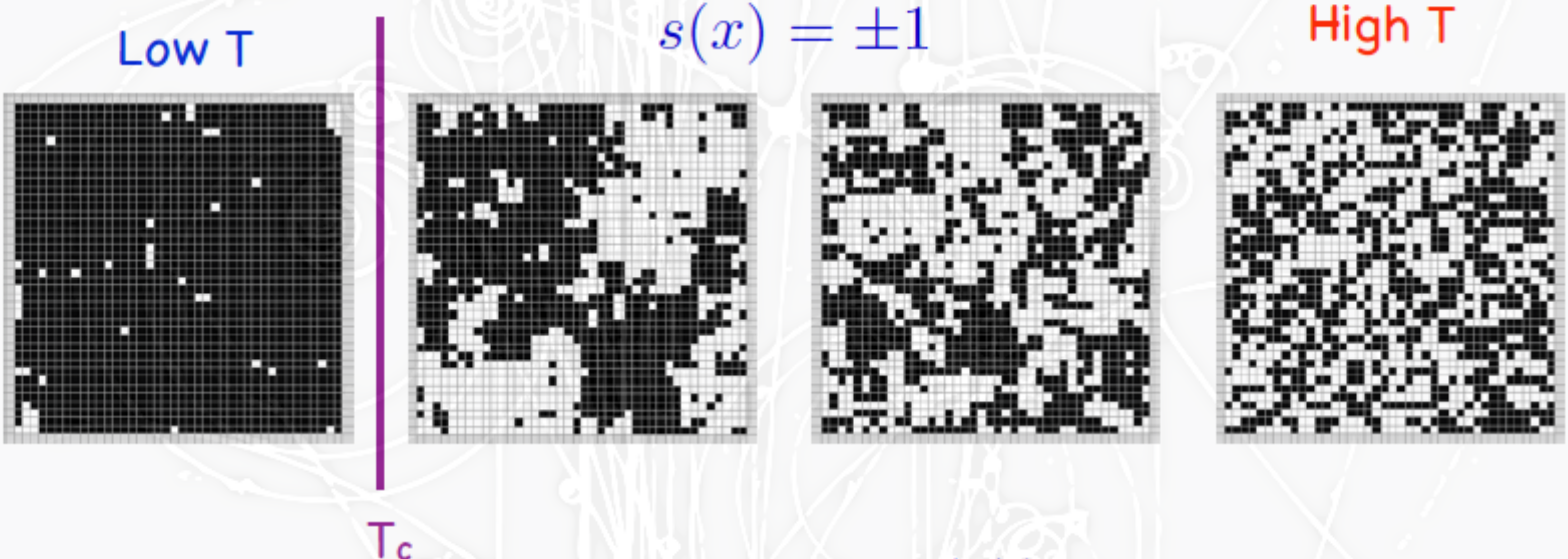


Ising Model

$$H = -J \sum s(x) s(x+n)$$

$$s(x) = \pm 1$$

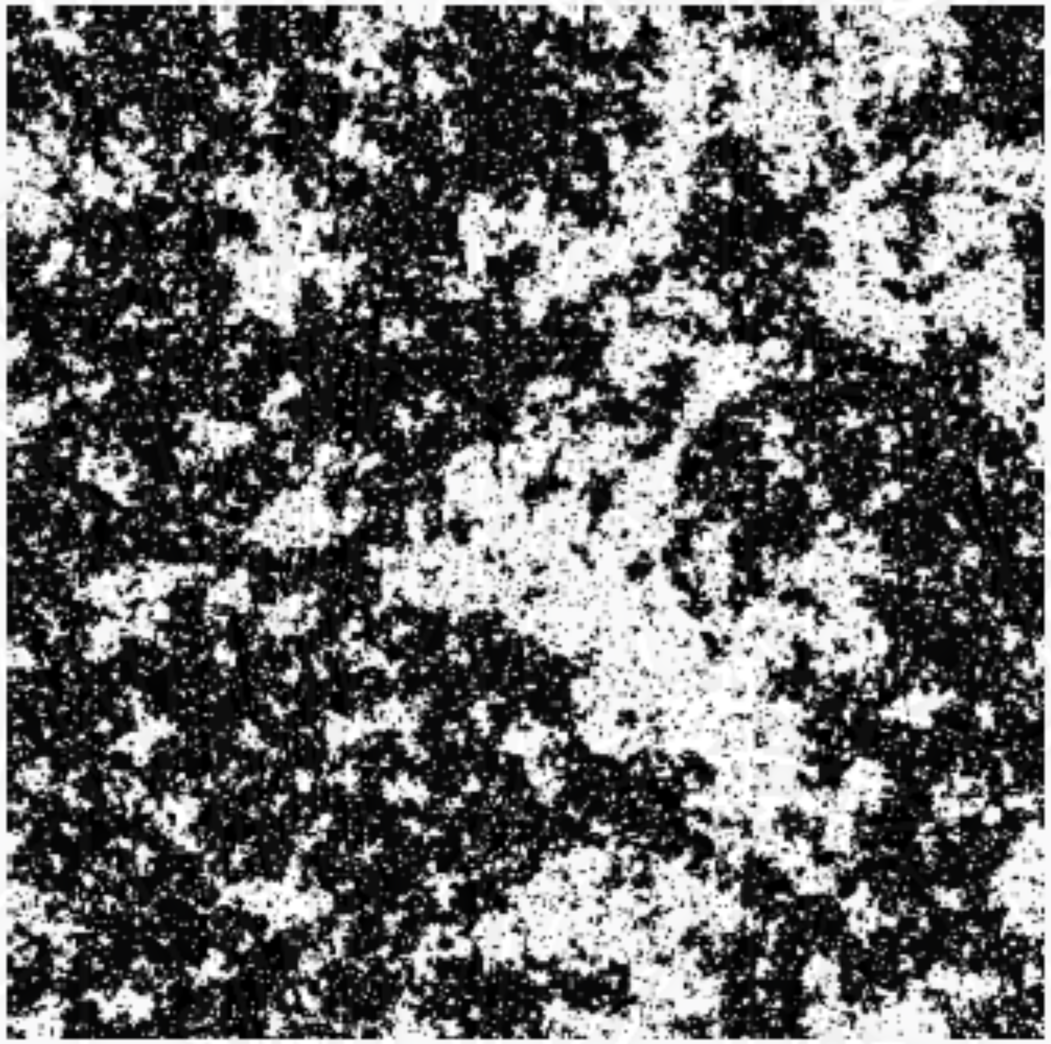


$$\langle s(0) s(x) \rangle = e^{-|x|/\xi}$$

at T=T_c $\quad \xi \to \infty$

Courtesy of J. Terning

Critical Ising Model is Scale Invariant



http://bit.ly/2Dcrit

at T=T_c $\quad \langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}}$

Courtesy of J. Terning

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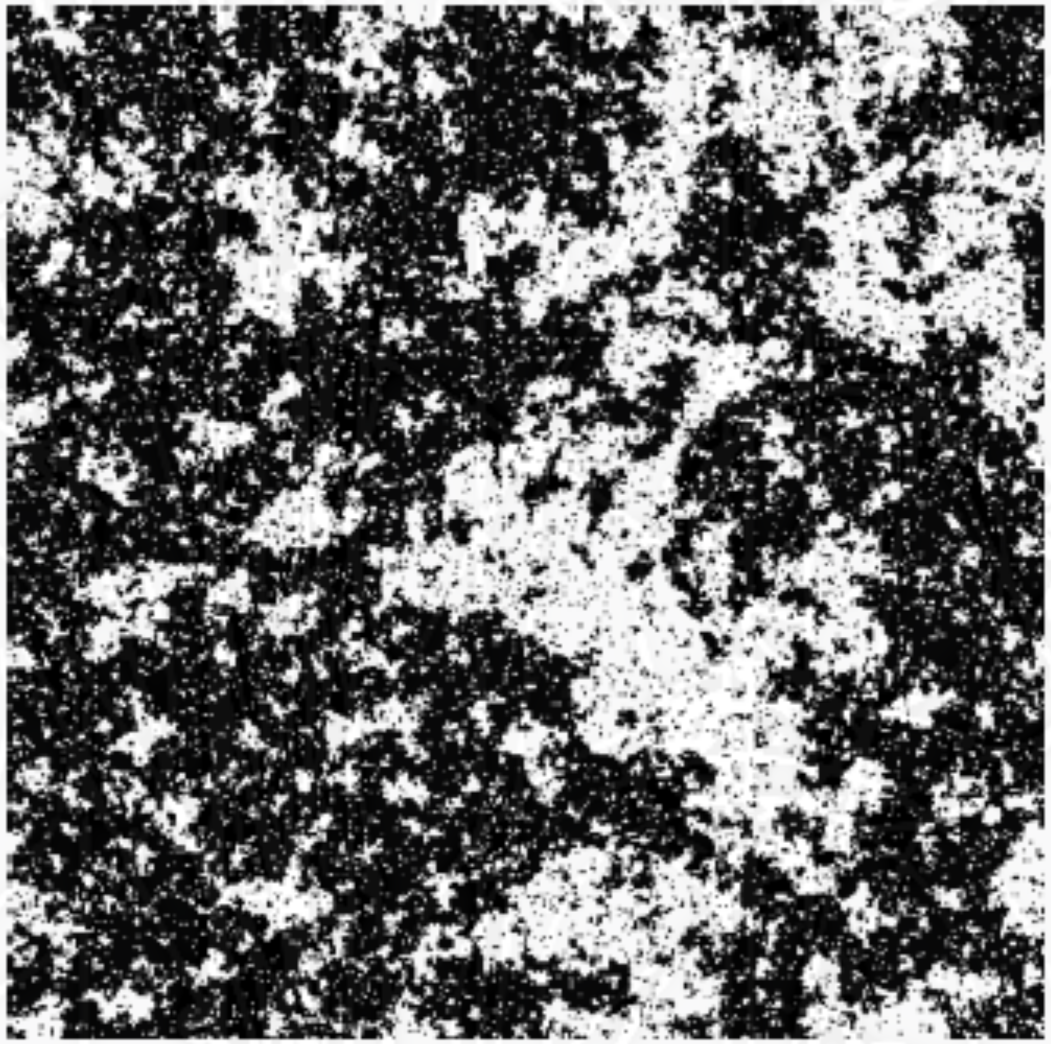

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at $T=T_c$ $$\langle s(0)s(x)\rangle \propto \frac{1}{|x|^{2\Delta-1}} = \int d^3p \, \frac{e^{ip\cdot x}}{|p|^{4-2\Delta}}$$

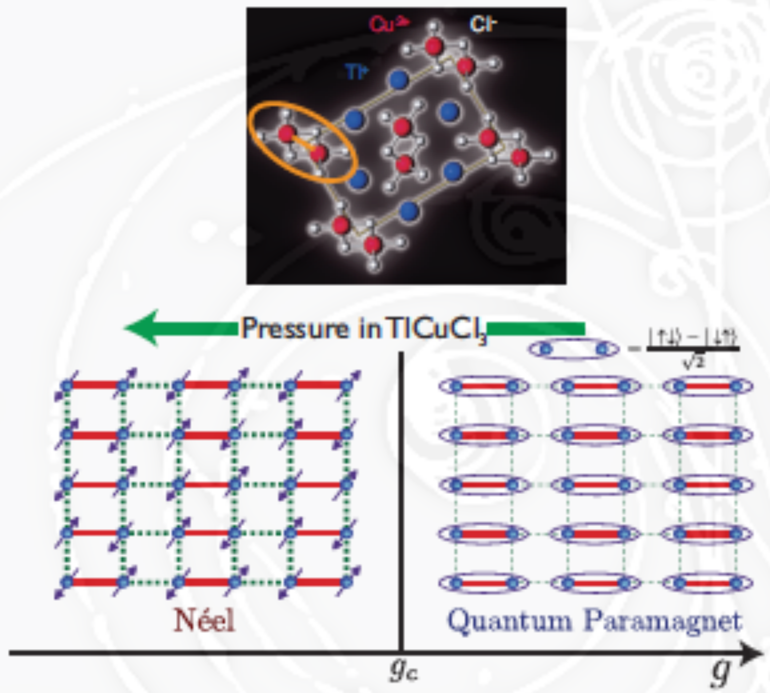
critical exponent

Courtesy of J. Terning

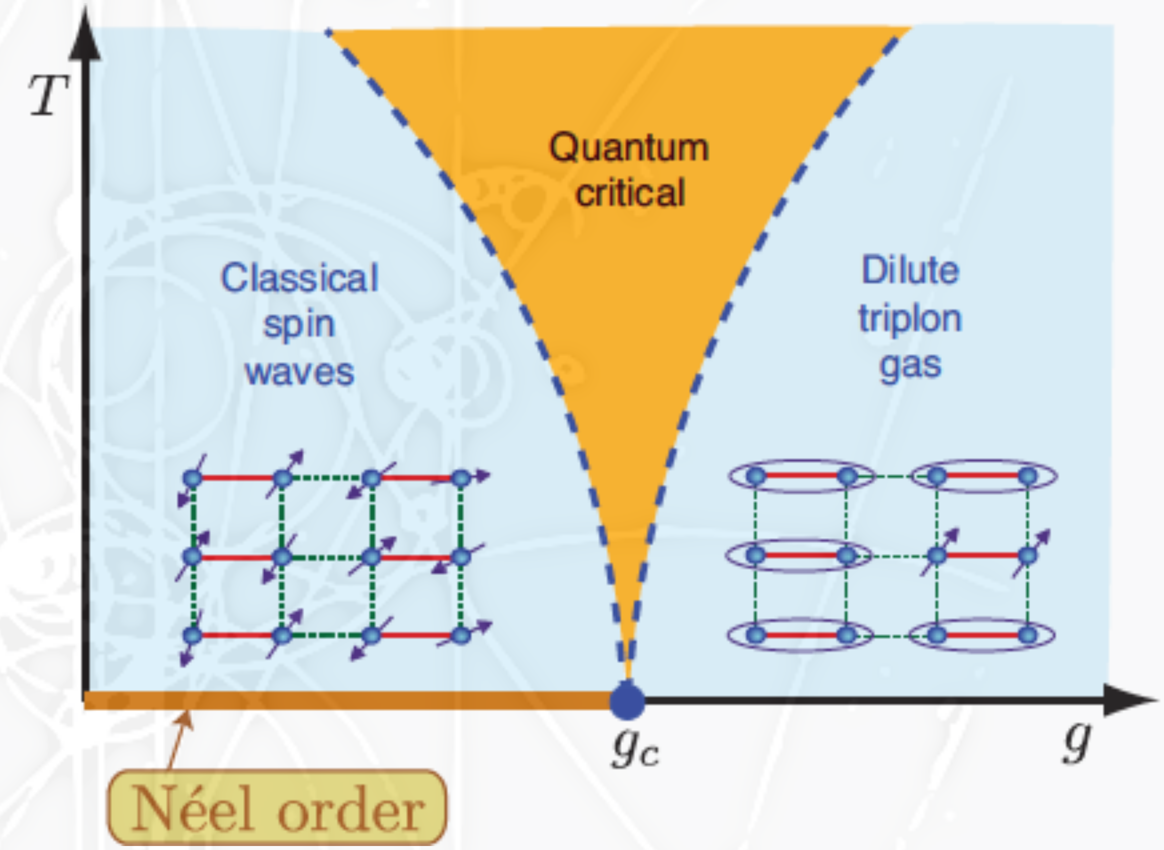
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

Higgs & Quantum Phase Transition

Condensed matter systems can produce a light scalar by tuning the parameters close to a critical value where a continuous phase transition occurs.



Sachdev, arXiv:1102.4268



Bellazzini, Csaki, Hubisz, SL, Serra, Terning

Higgs & Quantum Phase Transition

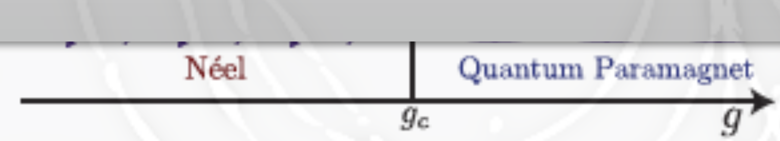
Condensed matter systems can produce a light scalar by tuning the parameters close

rs.

@2nd order QPT, @ critical point, all masses vanish & the theory is scale invariant, characterized by the dimensions of the field,

and at low energies we will see the universal behavior of some fixed point that constitutes the low-energy EFT.

scaling



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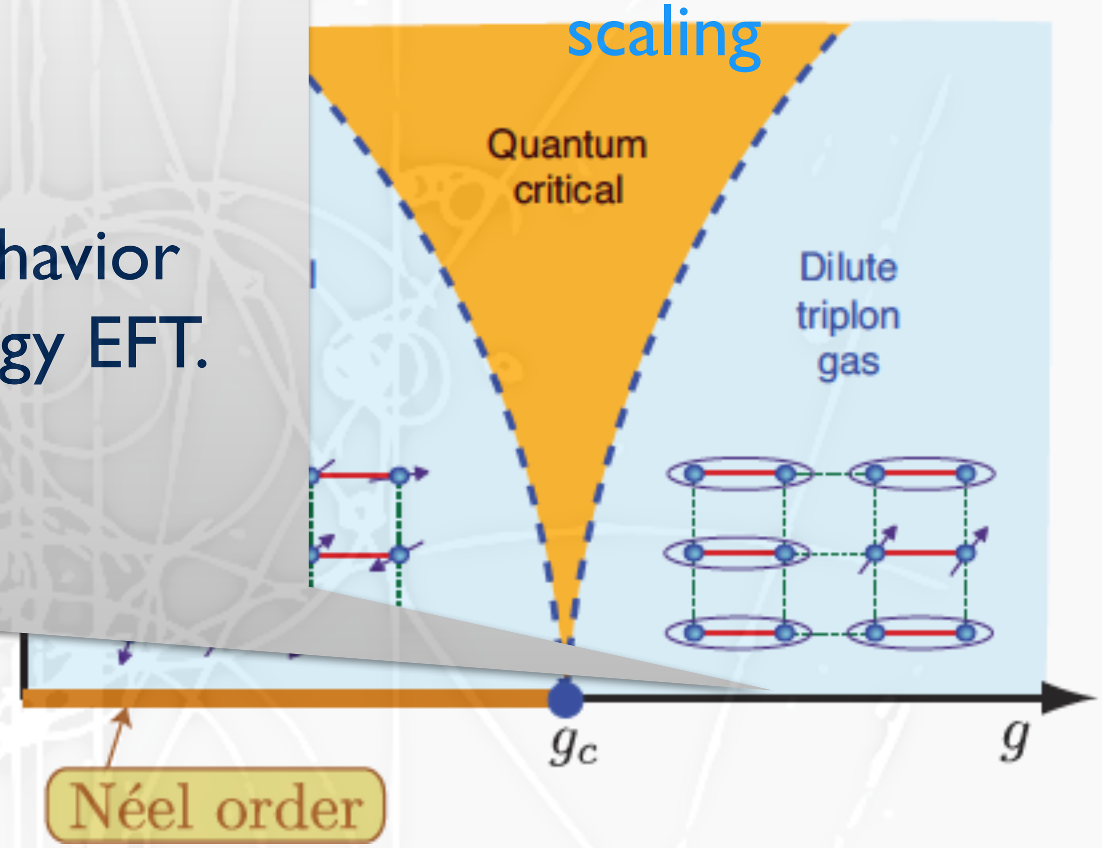

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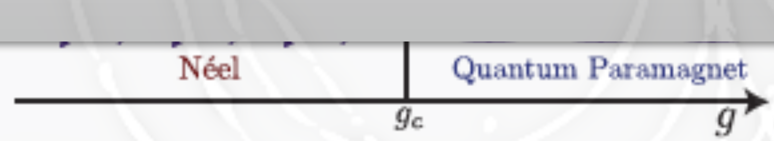

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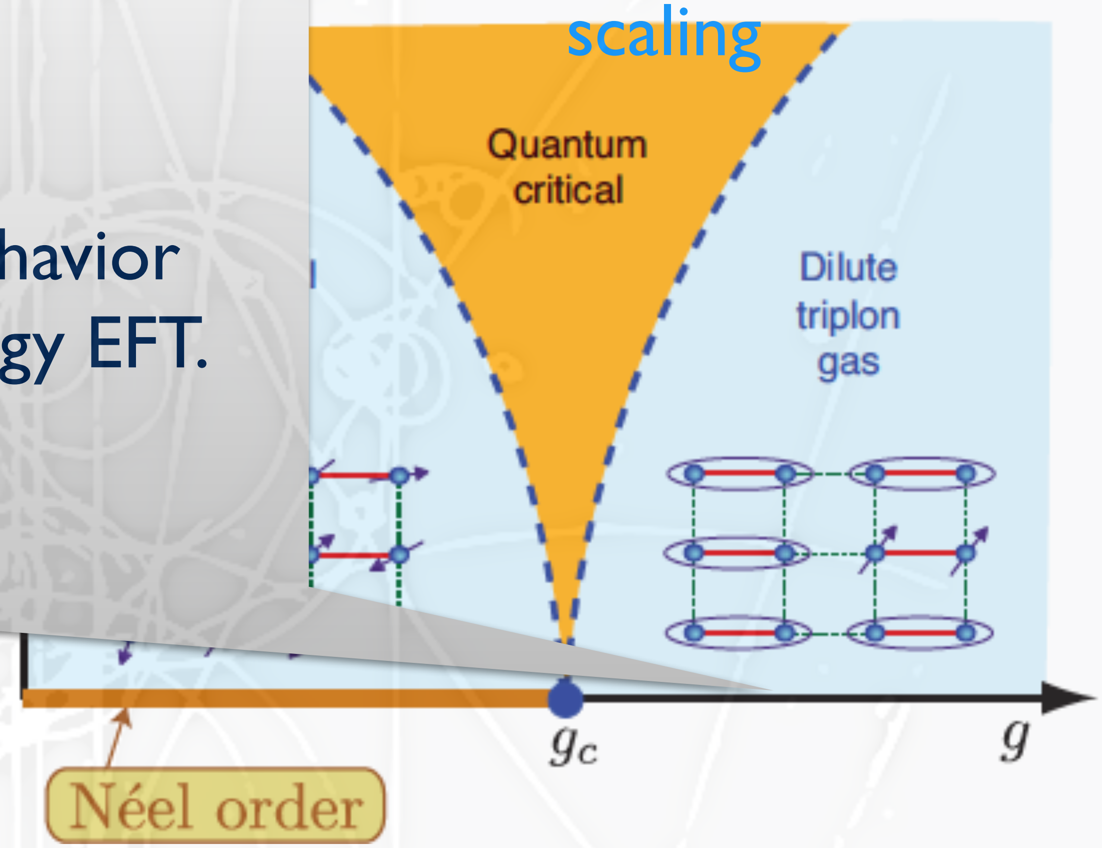

What is the nature of electroweak phase transition?

Does the underlying theory also have a QPT?

If so, is it more interesting than mean-field theory?

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

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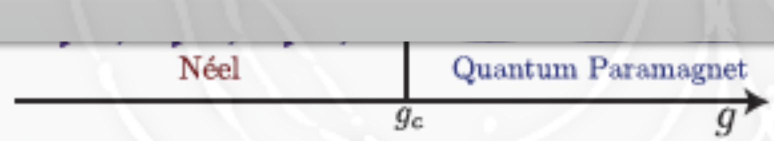

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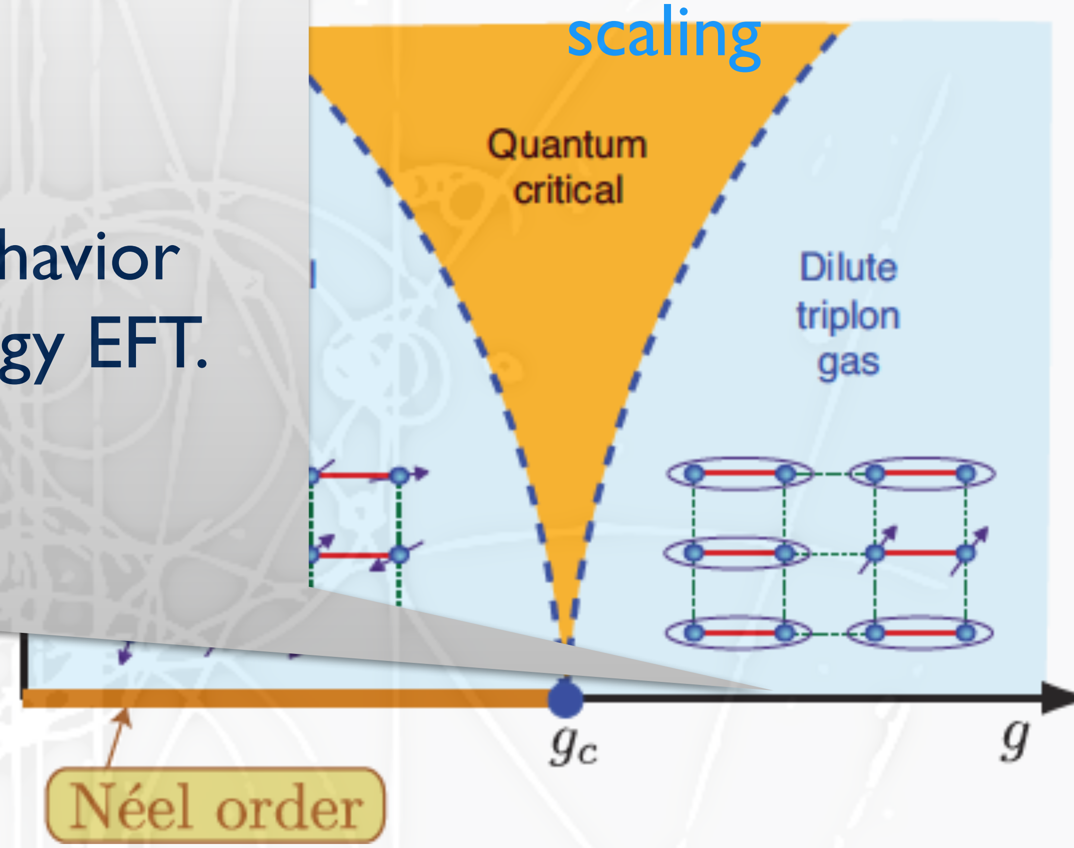

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$$G(p) \sim \frac{i}{p^2} \quad \text{vs.} \quad G(p) \sim \frac{i}{(p^2)^{2-\Delta}} \quad \text{or} \quad G(p) \sim \frac{i}{(p^2-\mu^2)^{2-\Delta}}$$

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

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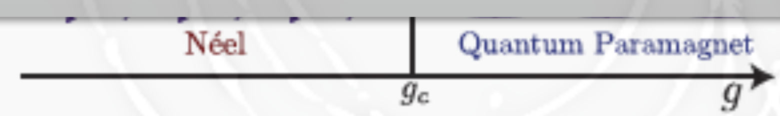

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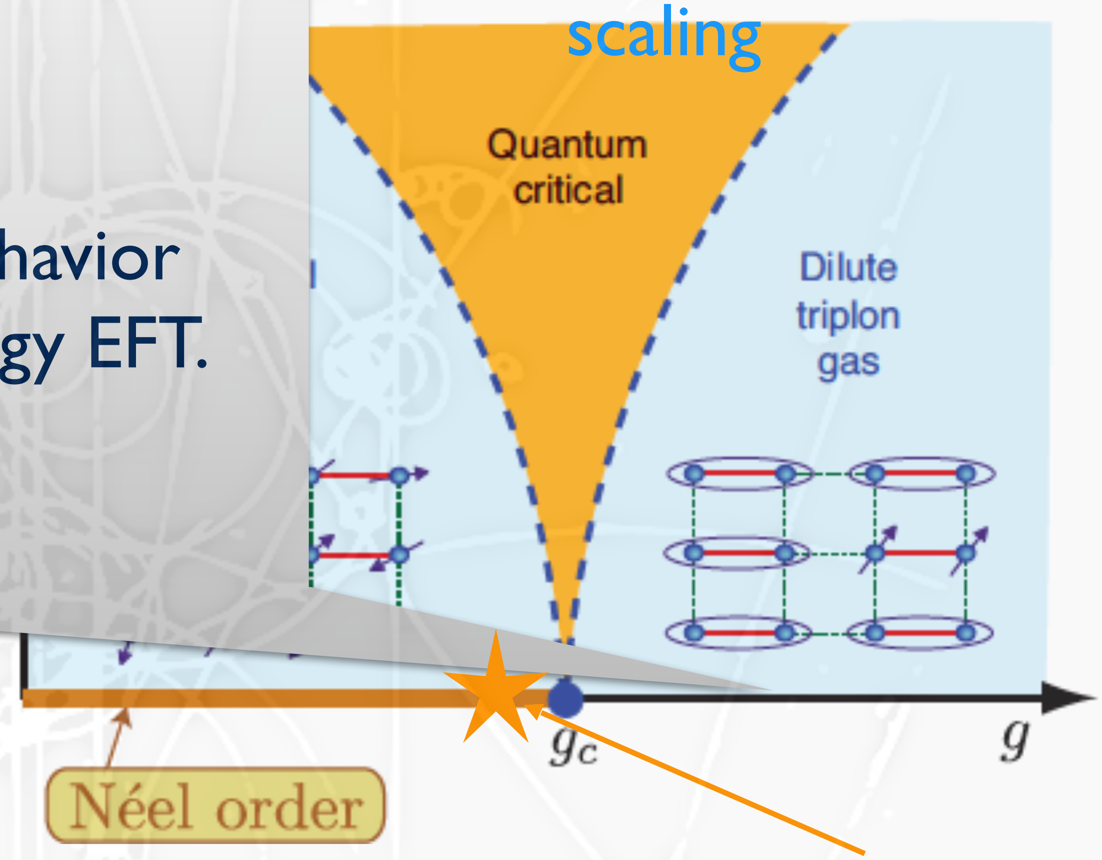

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$G(p) \sim \frac{i}{p^2}$ vs. $G(p) \sim \frac{i}{(p^2)^{2-\Delta}}$ or $G(p) \sim \frac{i}{(p^2-\mu^2)^{2-\Delta}}$

AdS/CFT

$$\left\langle e^{\int d^4x \phi_0(x) \mathcal{O}(x)} \right\rangle_{\mathrm{CFT}} \approx e^{S_{5\mathrm{Dgravity}}[\phi(x,z)|_{z=0}=\phi_0(x)]}$$

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

$\mathcal{O} \subset \mathrm{CFT} \leftrightarrow \phi$ AdS_5 field

AdS/CFT

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

$$z > \epsilon$$

$$S_{bulk} = \frac{1}{2}\int d^4x dz \sqrt{g}(g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi + m^2\phi^2)$$

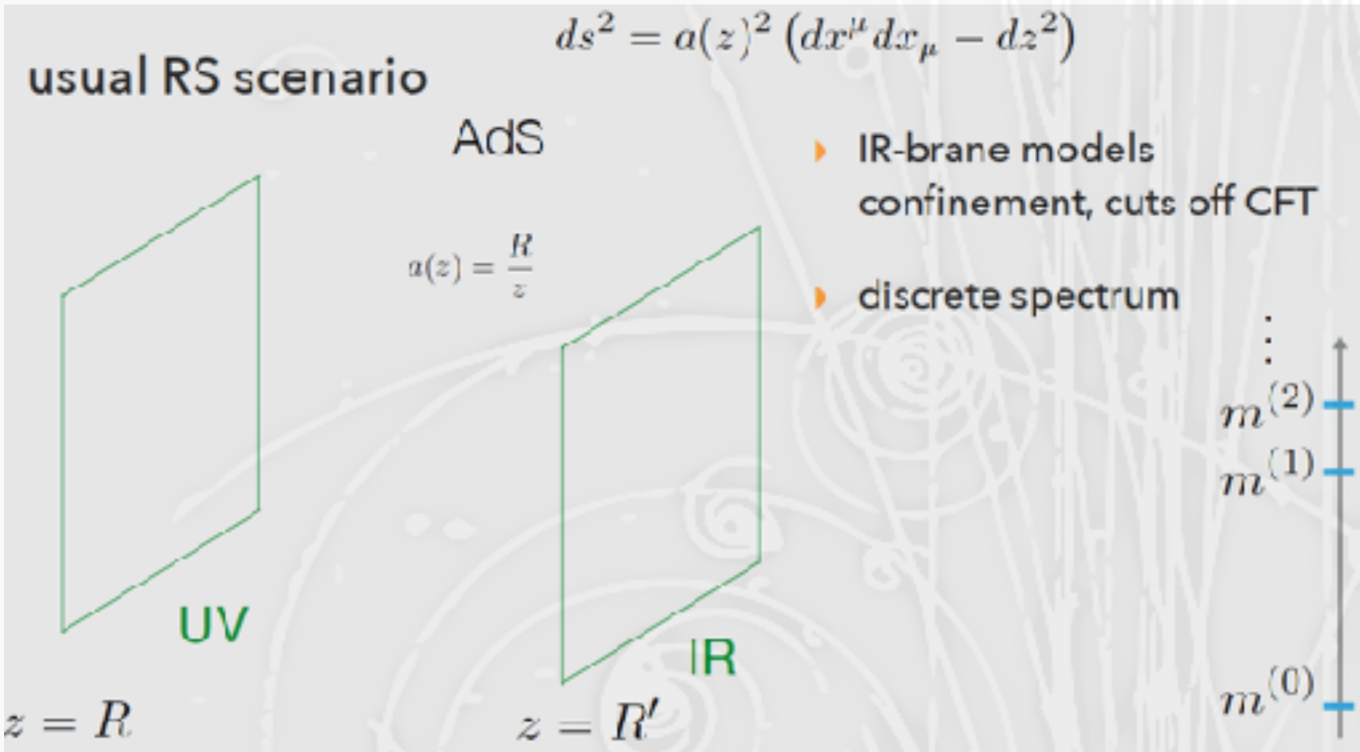
$$\phi(p,z) = az^2 J_\nu(pz) + bz^2 J_{-\nu}(pz)$$

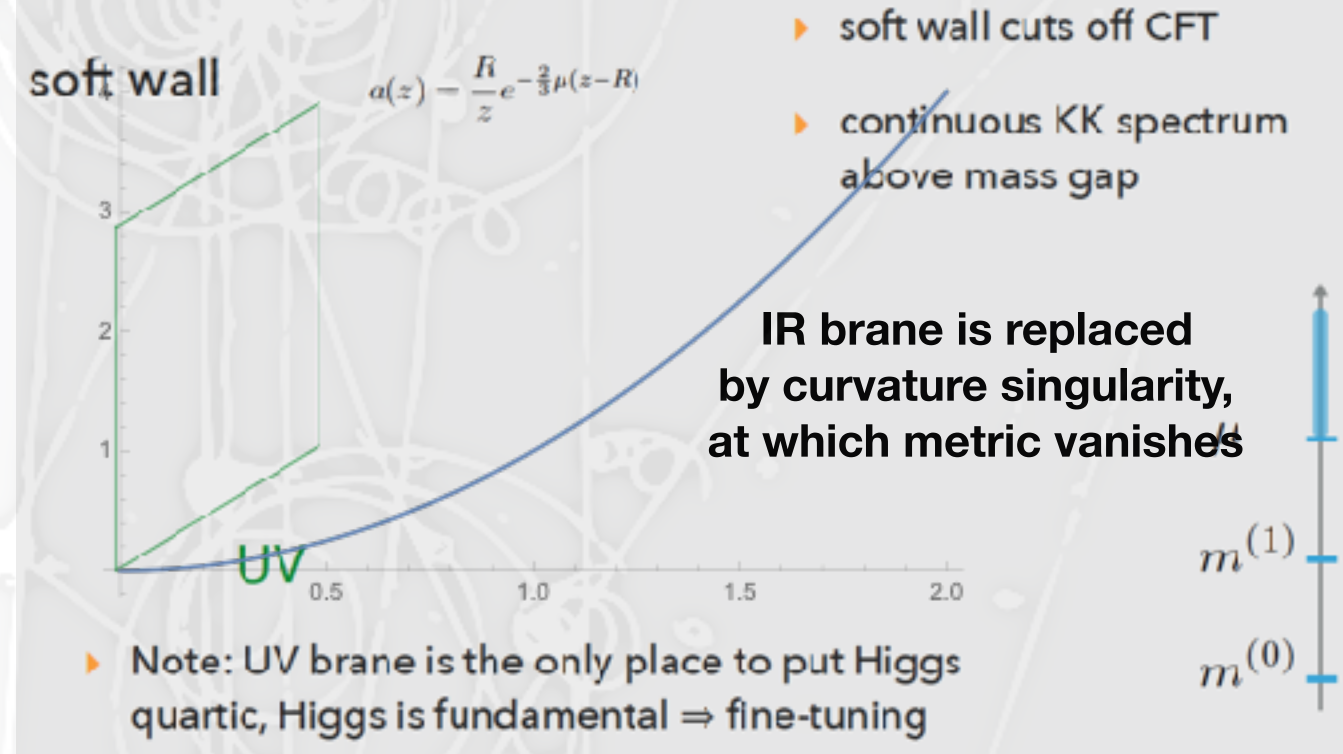
$$\Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2R^2}$$

$$< \mathcal{O}(p)\mathcal{O}(p) > \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2}(p^2)^{\Delta-2}$$

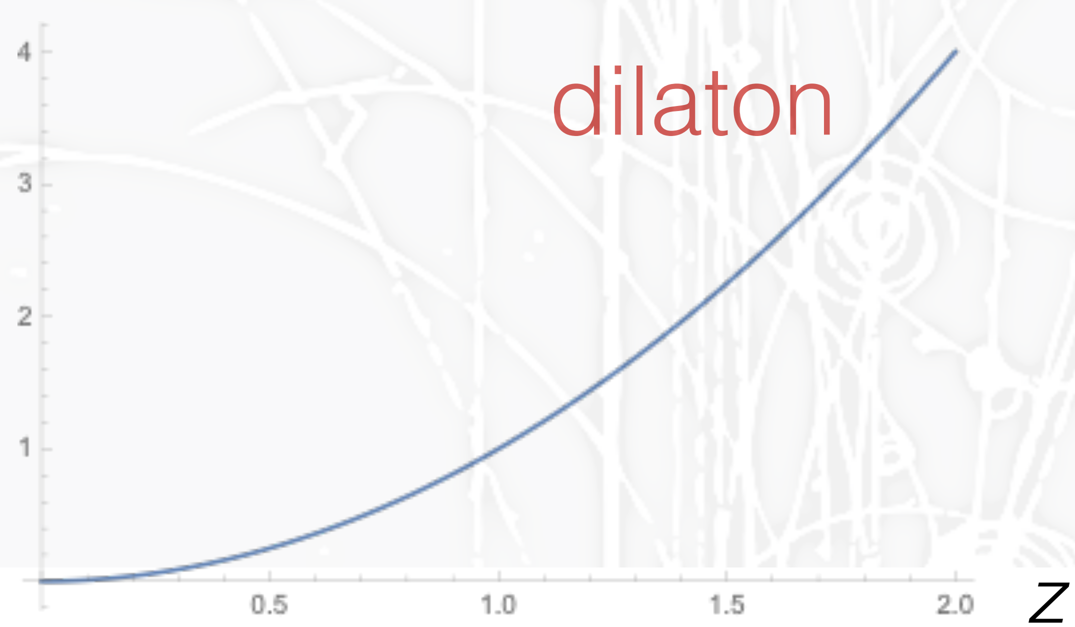
Witten, Klebanov 99'

broken CFT





- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology



Karch, Katz, Son, Stephaniv 06`

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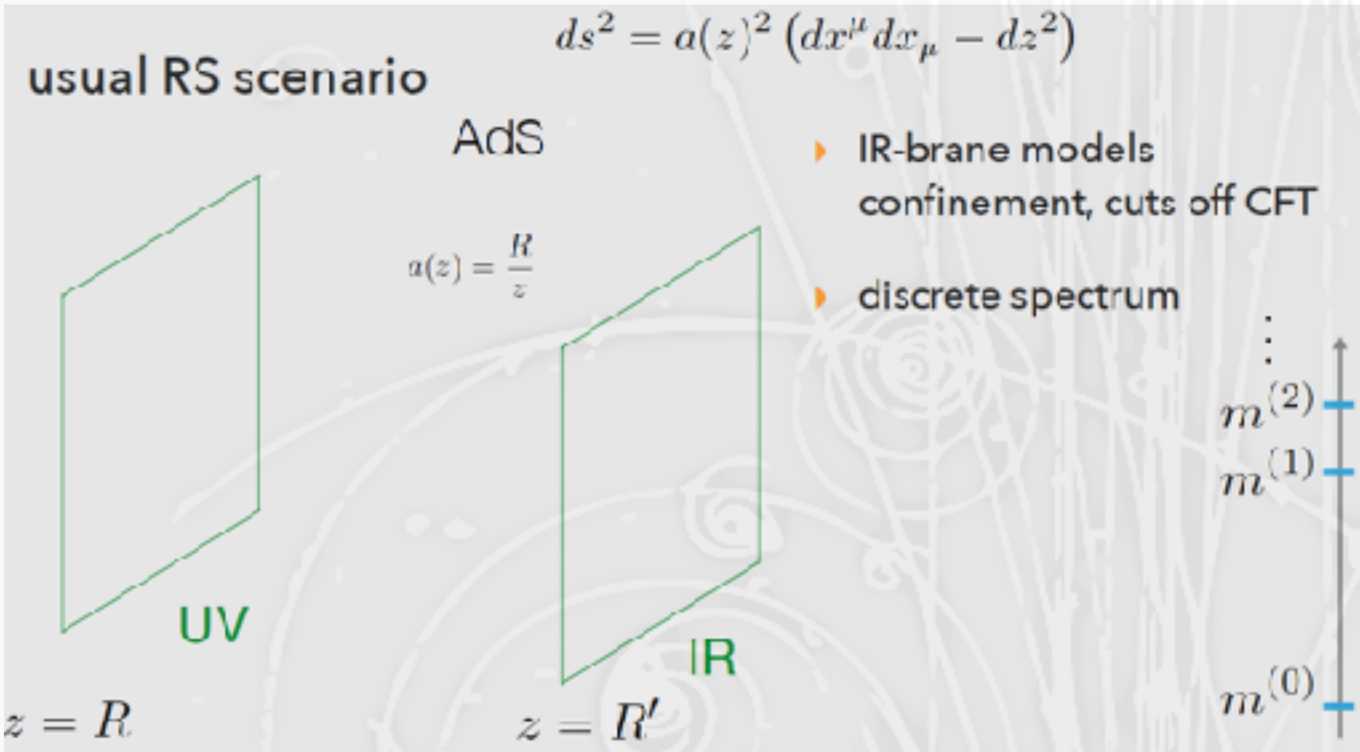

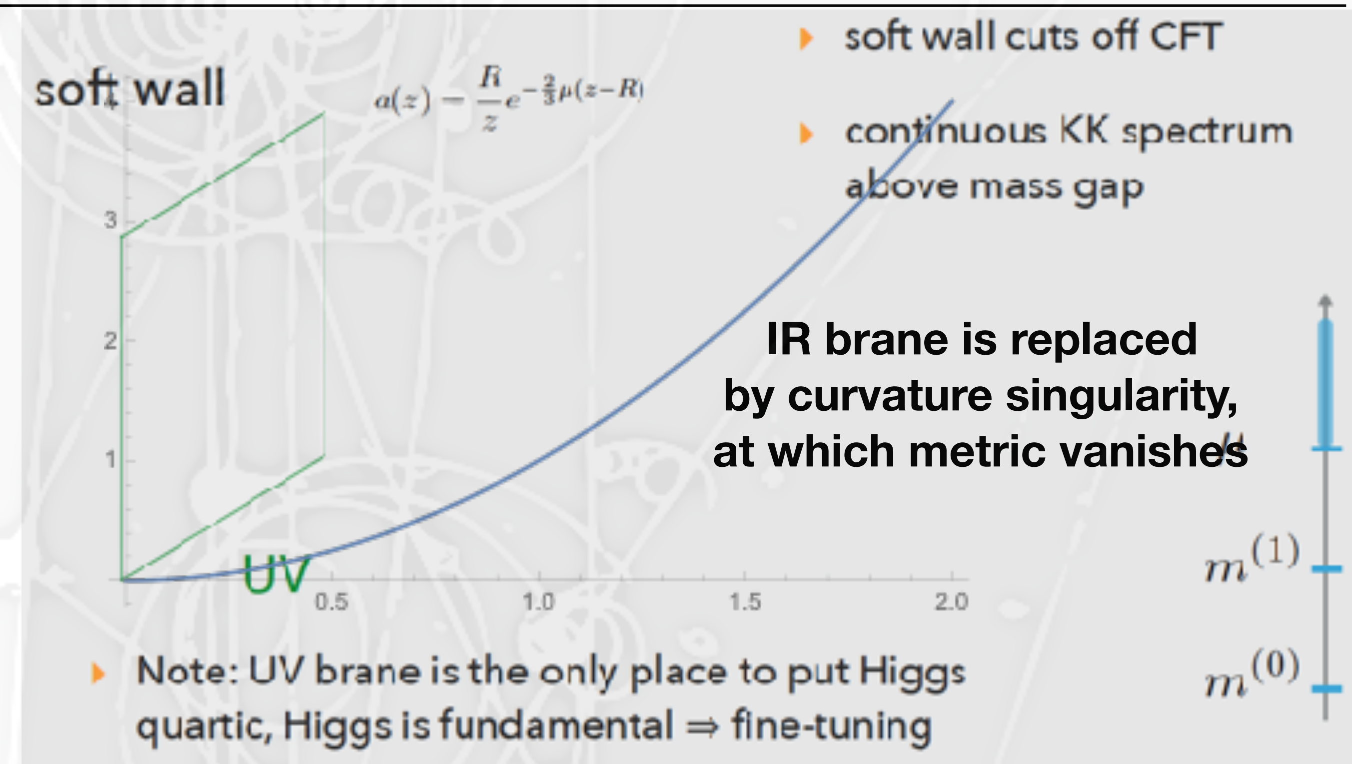

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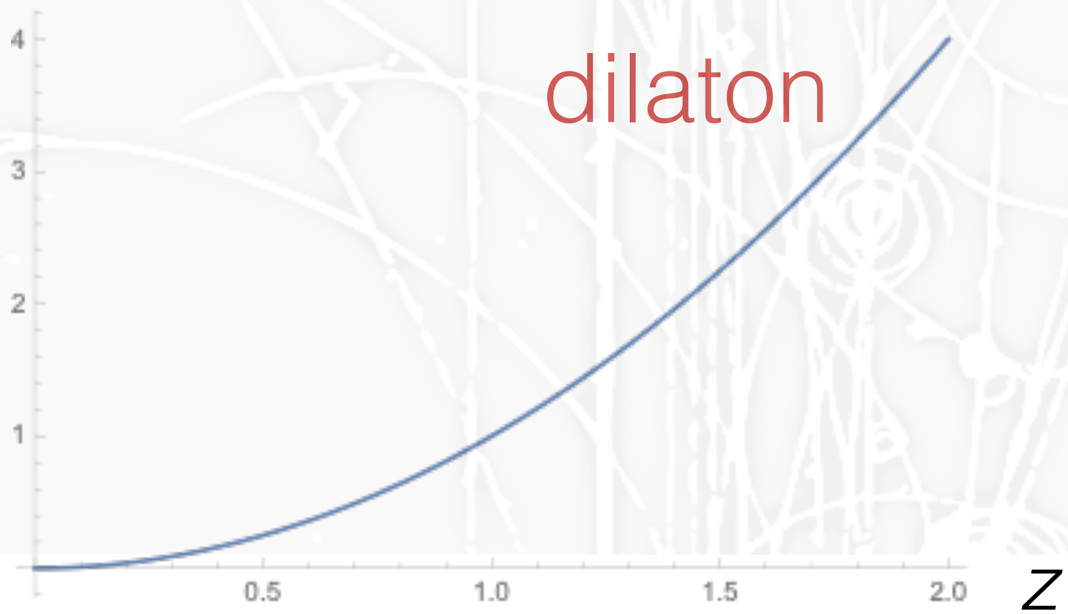

scalar getting VEV => marginal deformation of CFT

Karch, Katz, Son, Stephaniv 06`

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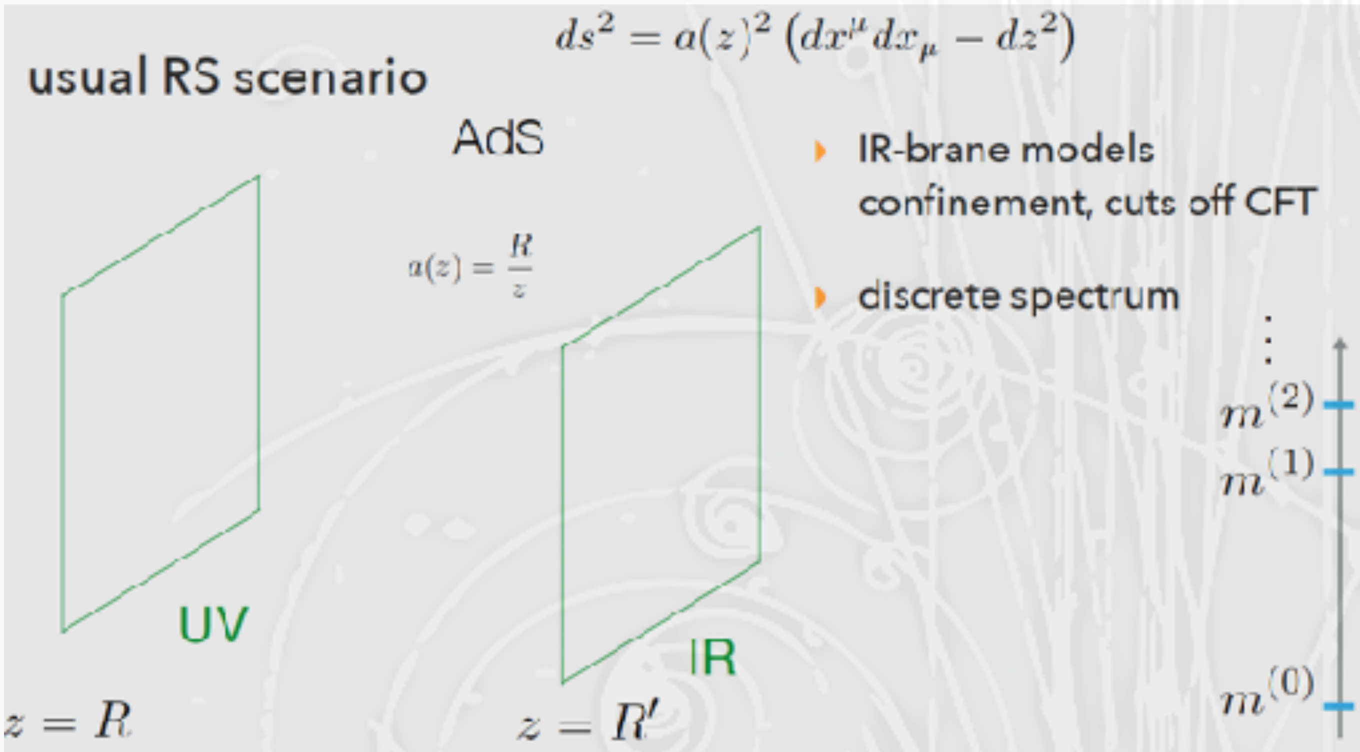

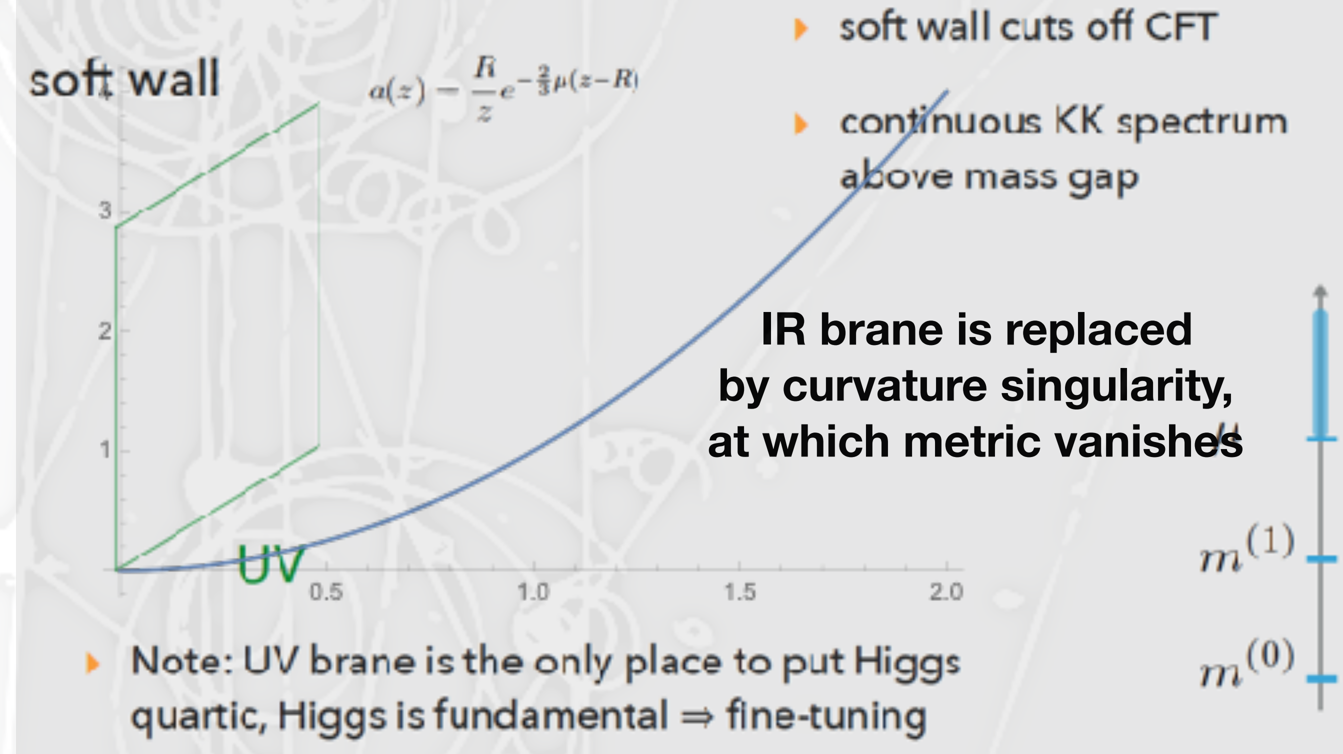

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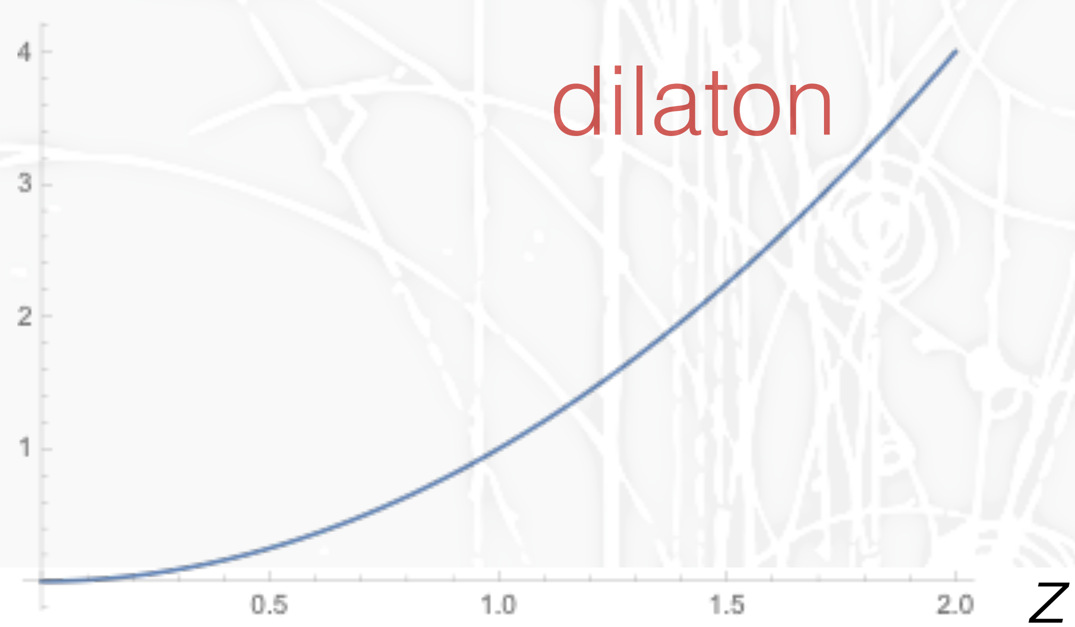


Karch, Katz, Son, Stephaniv 06`

broken CFT by IR cutoff

$$S_{\rm int} = \frac{1}{2}\int d^4x dz \sqrt{g}\phi \mathcal{H}^\dagger \mathcal{H}$$

$$\phi = \left(\frac{\mu z}{R}\right)^2$$

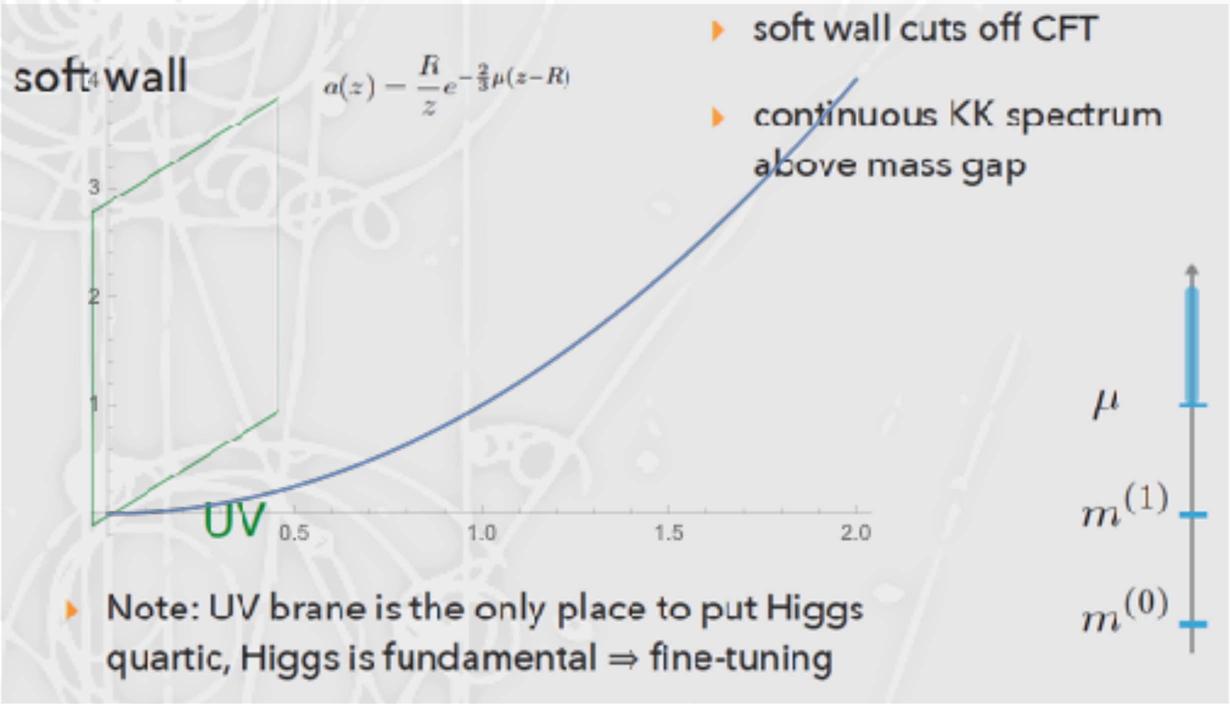
$$z^5 \partial_z \left(\frac{1}{z^3}\partial_z \mathcal{H}\right) - z^2(p^2 - \mu^2)\mathcal{H} - m^2 R^2 \mathcal{H} = 0$$

$$< \mathcal{O}(p)\mathcal{O}(p) > \propto \frac{\delta^{(4)}(p+p')}{(2\pi)^2}(p^2 - \mu^2)^{\Delta - 2}$$

$$[\partial^2 - \mu^2]^{2-\Delta}\delta(x-y)$$

soft wall (AdS/QCD)

$$ds^2 = a(z)\left(dx^\mu dx_\mu - dz^2\right)$$
$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)^\nu}$$
$$S_{\rm gauge} = \int d^5x\, -\frac{1}{4} a(z) F^{a2}_{MN}$$

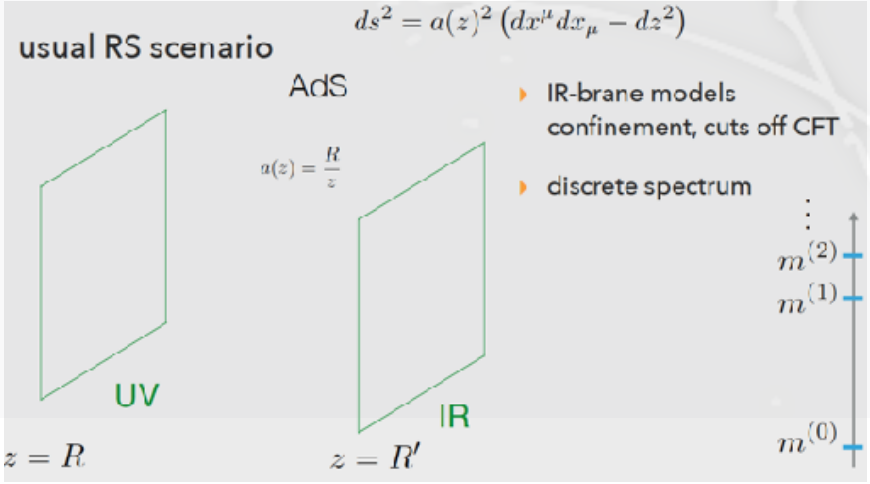


EOM: $\left(a^{-1}\partial_z(a\partial_z) + p^2\right) f = 0$ $\quad f = a^{-\frac{1}{2}}\Psi$

"Schrödinger Eqn".: $\left(-\partial_z^2 + V(z)\right)\Psi = p^2\Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2}$

$$V(z)\big|_{z\to\infty} \to \left(\frac{\mu}{3}\right)^2$$

=> continuum begins at: $p^2 = (\mu/3)^2$



$\to \infty$ (infinite well) => KK towers

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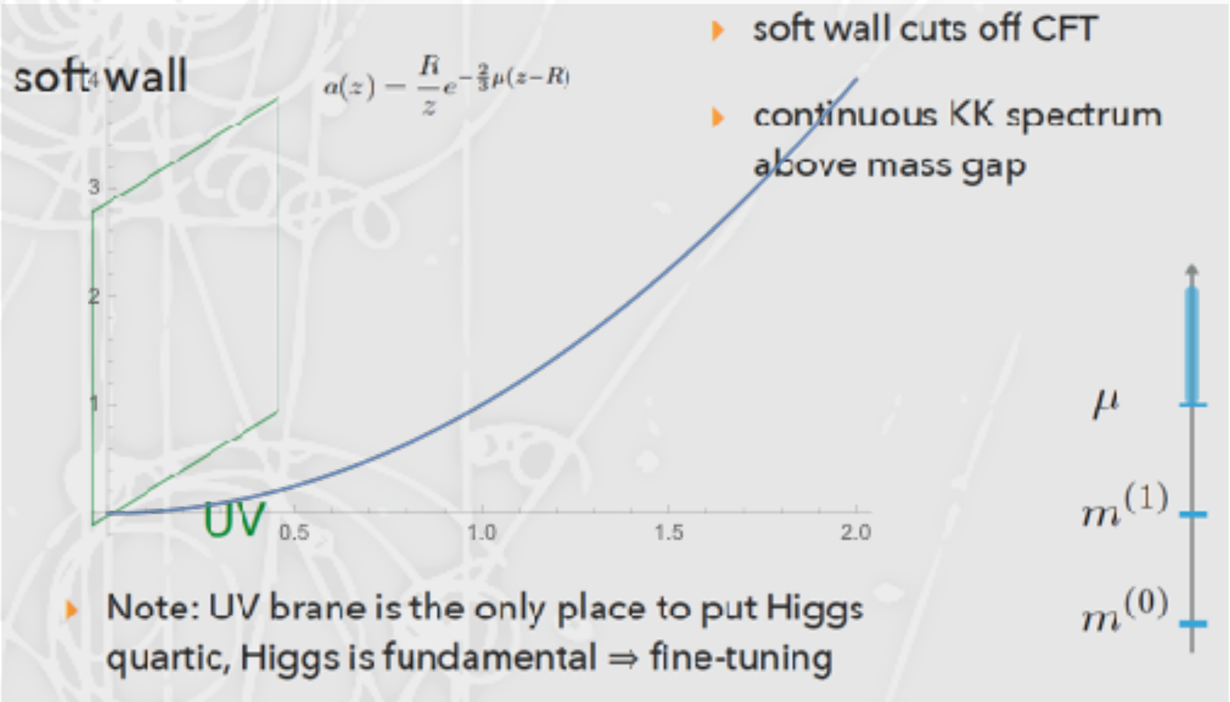

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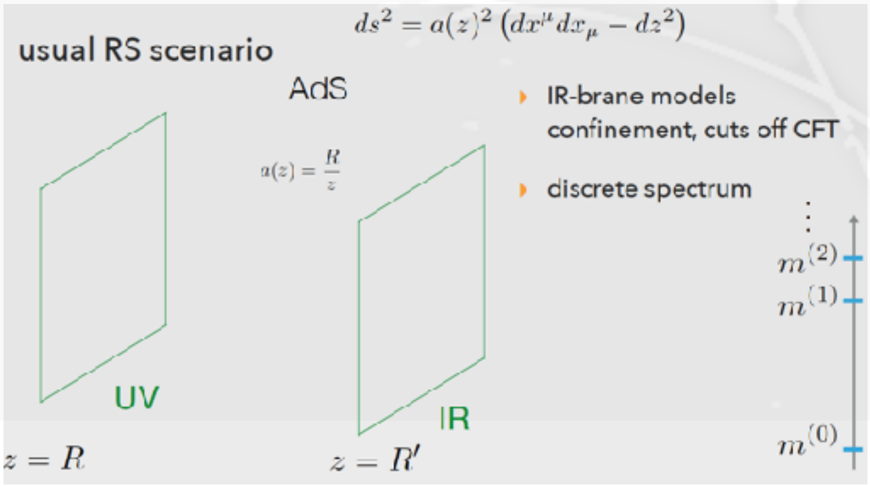

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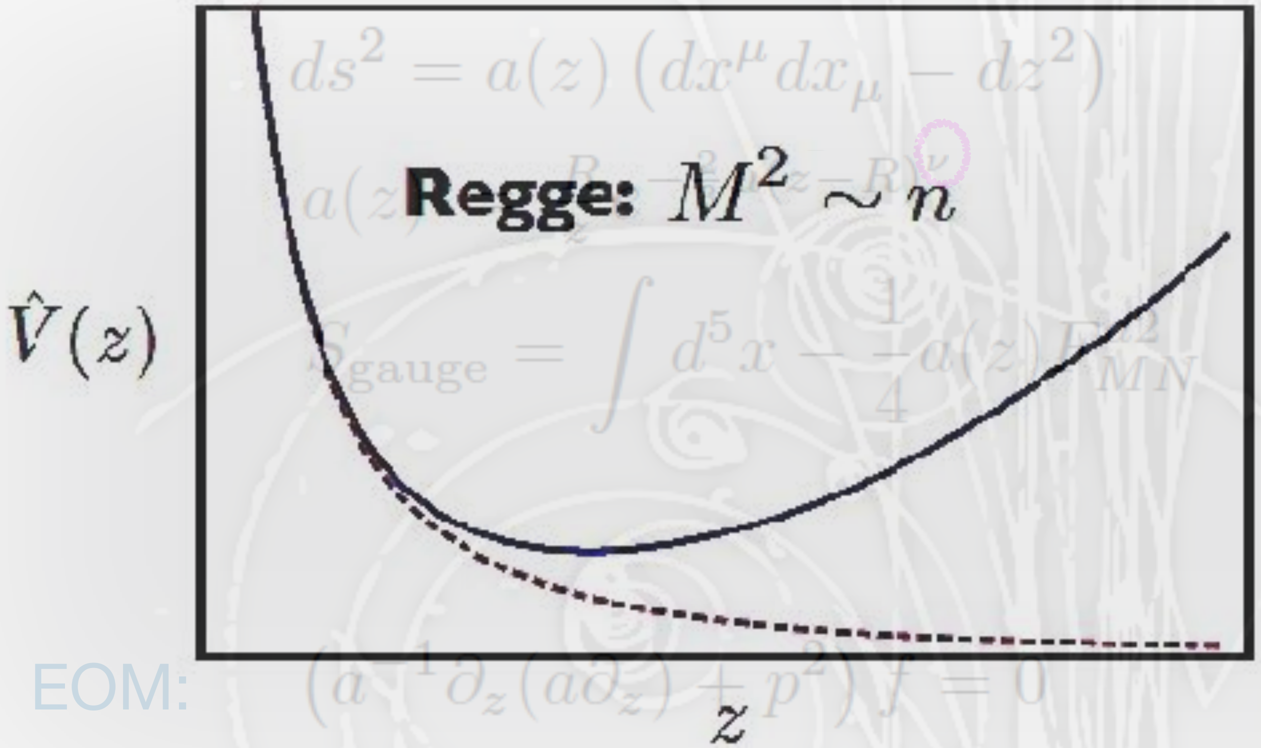
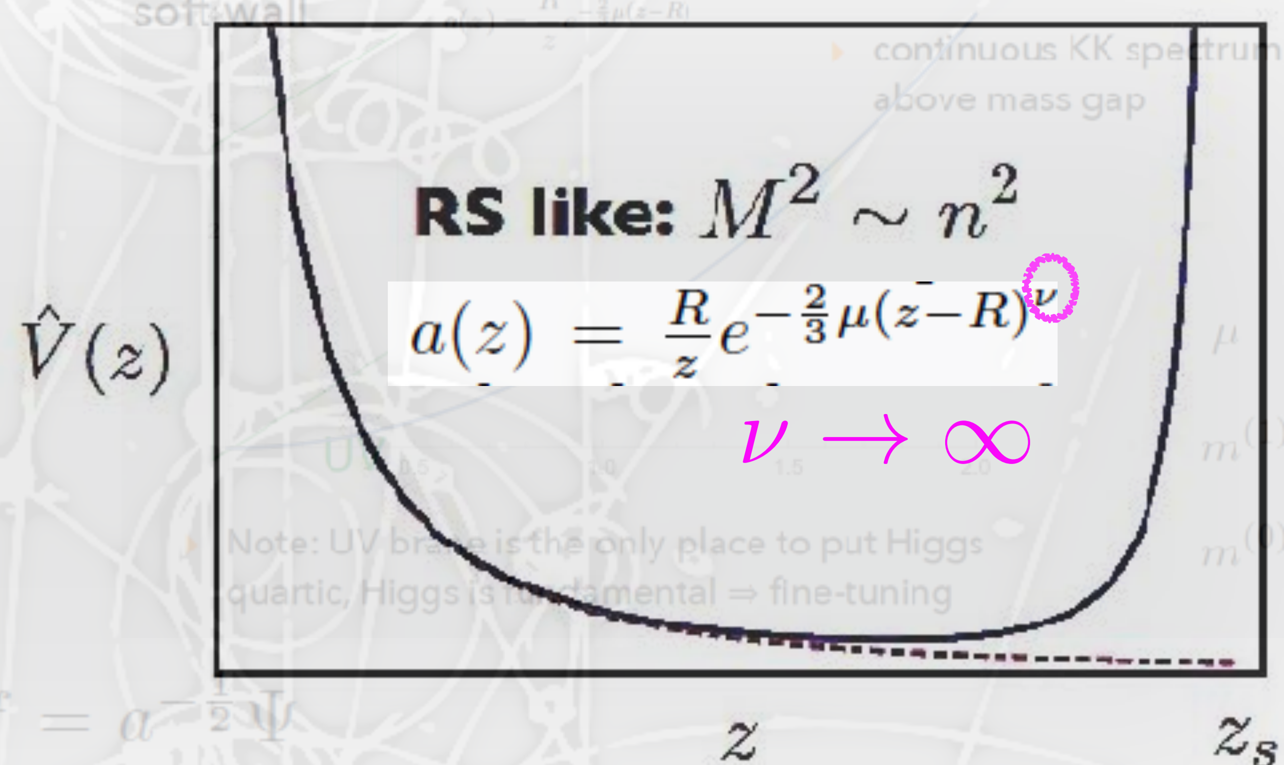
soft wall (AdS/QCD)

‣ soft wall cuts off CFT





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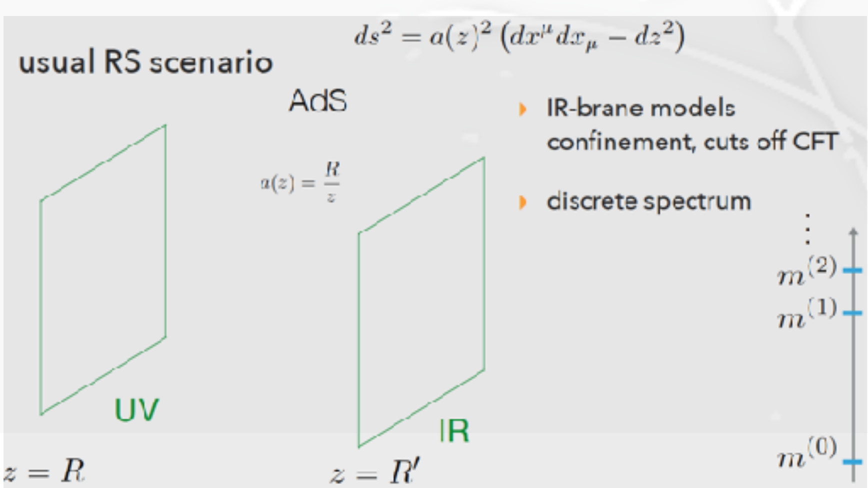
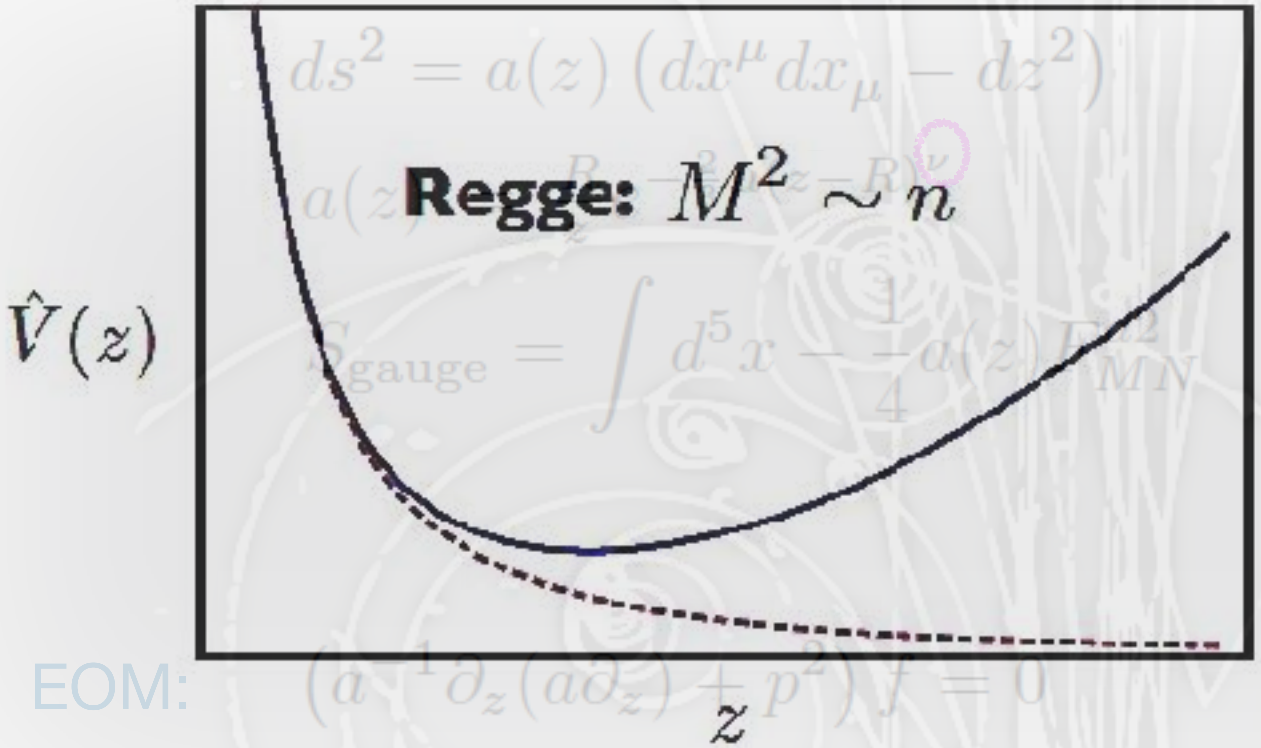
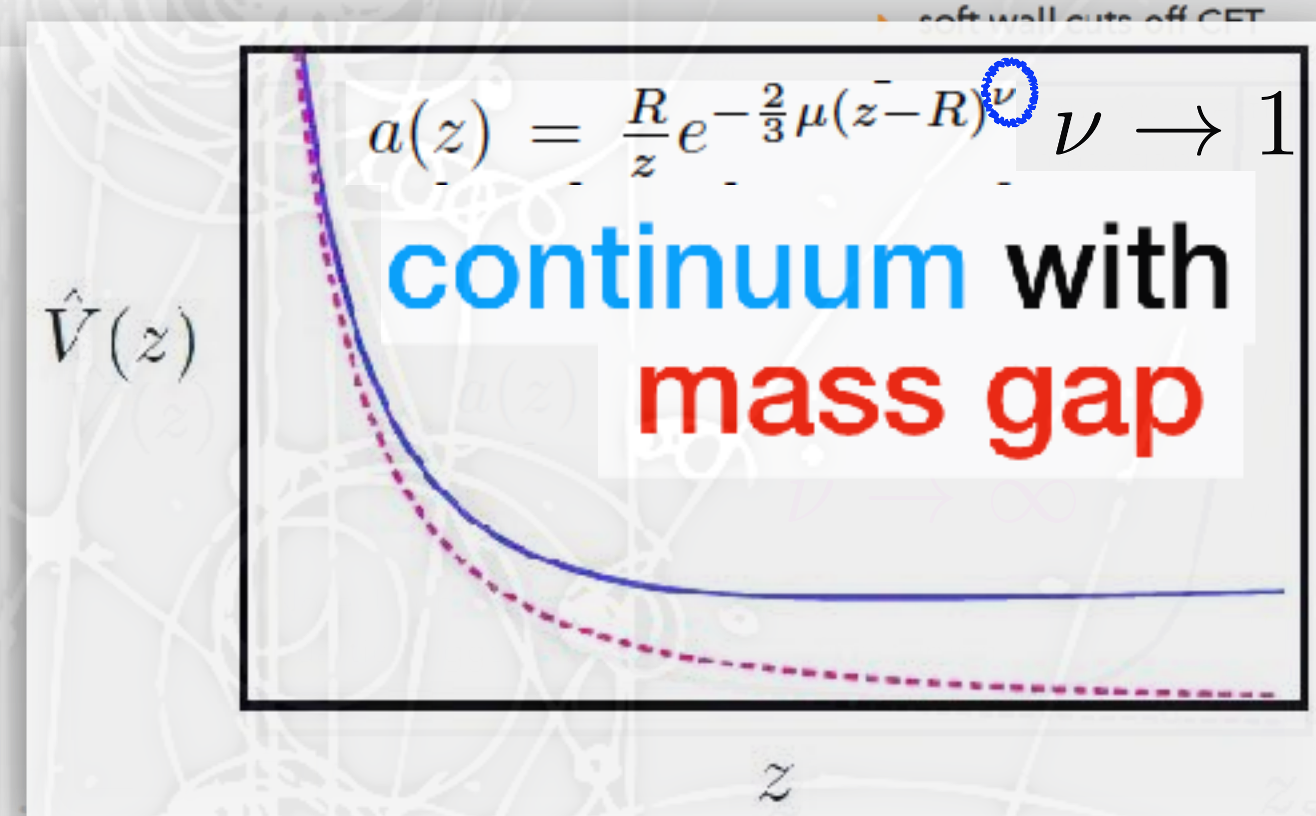


$\to \infty$ (infinite well) => KK towers

5D UnHiggs: Falkowski, Perez-Victoria

soft wall (AdS/QCD)





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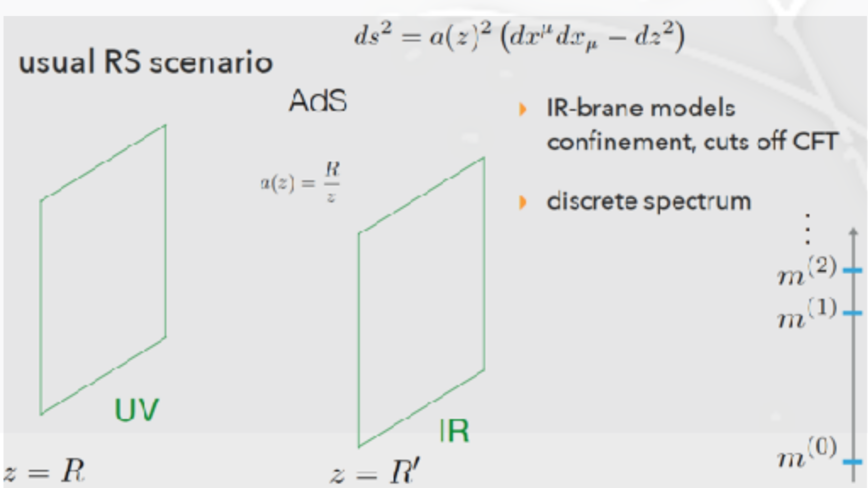

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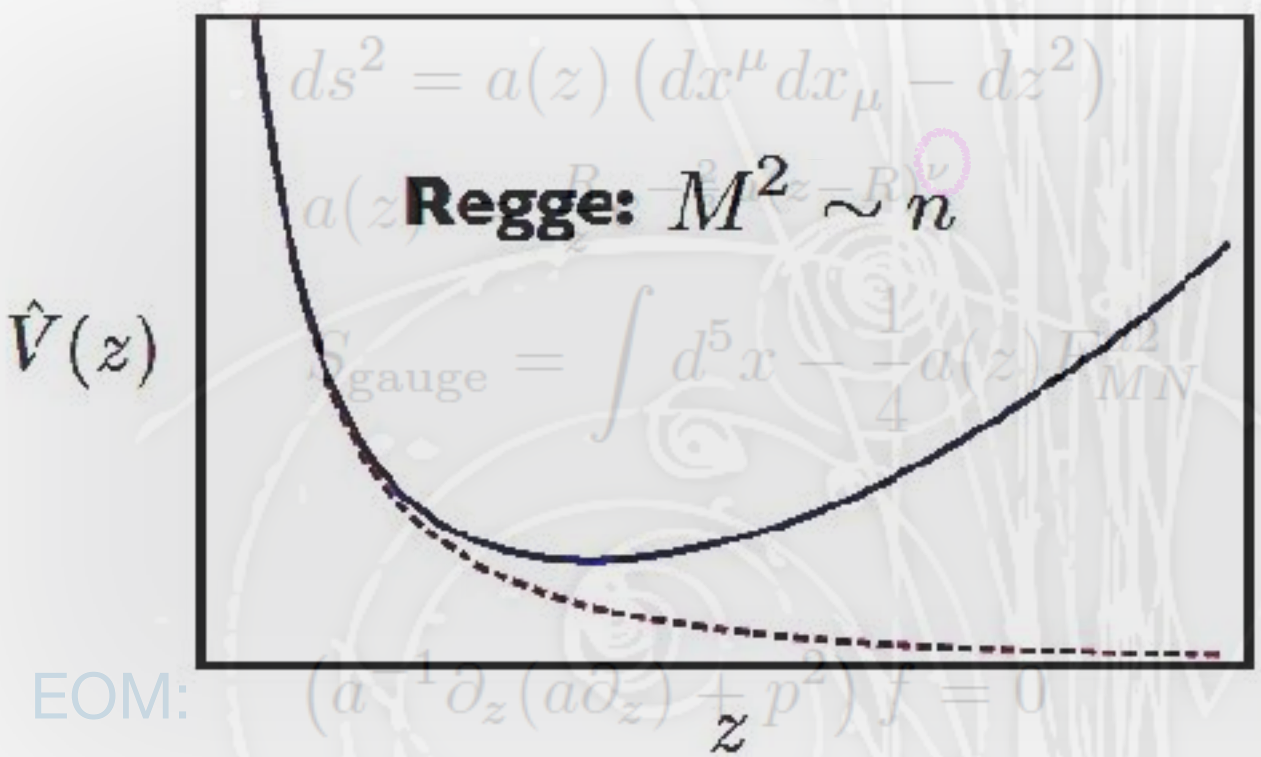

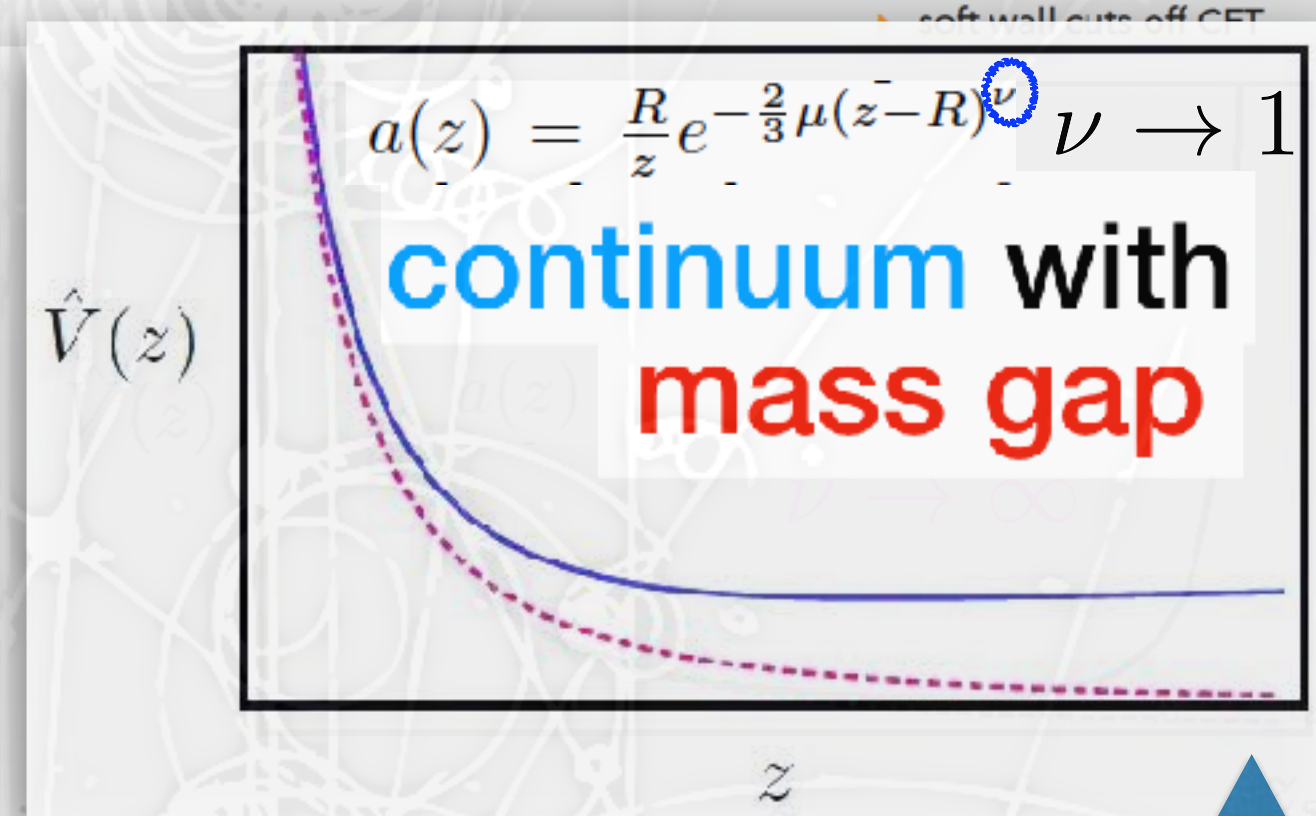

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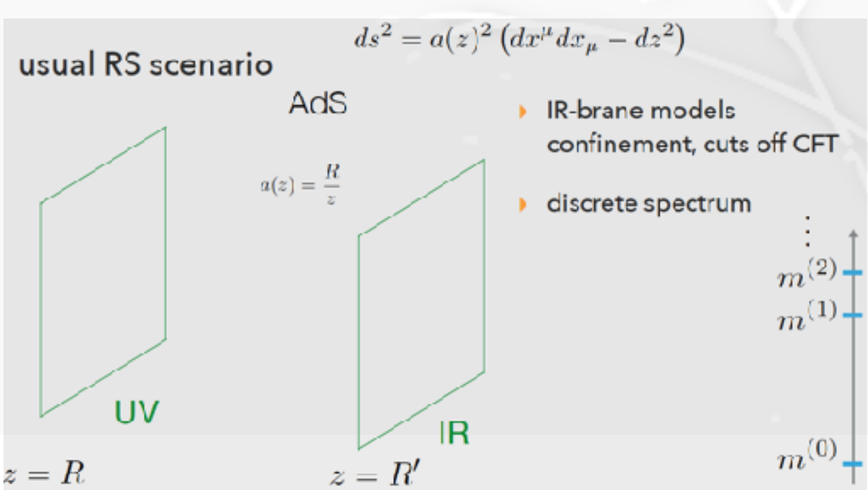
Stabilization of this setting:

Batell, Gherghetta, Sword '08
Cabrer, Gersdorff , Quiros '09



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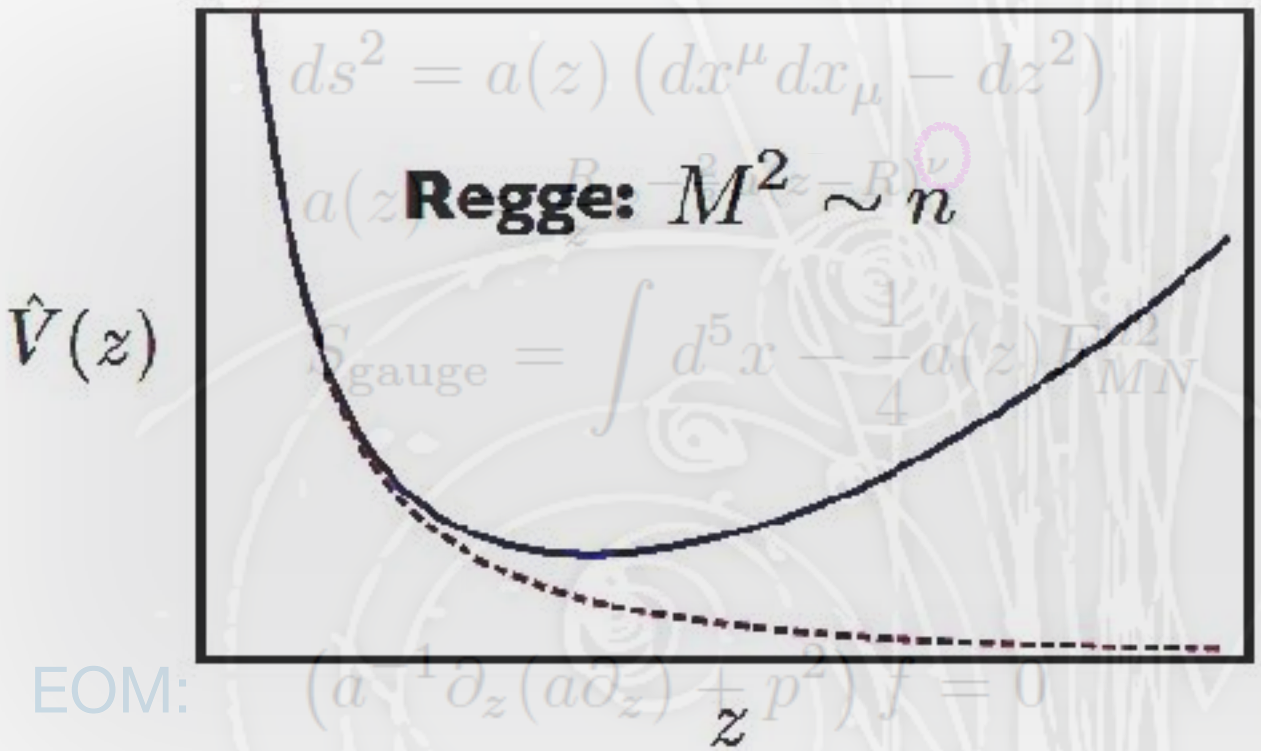

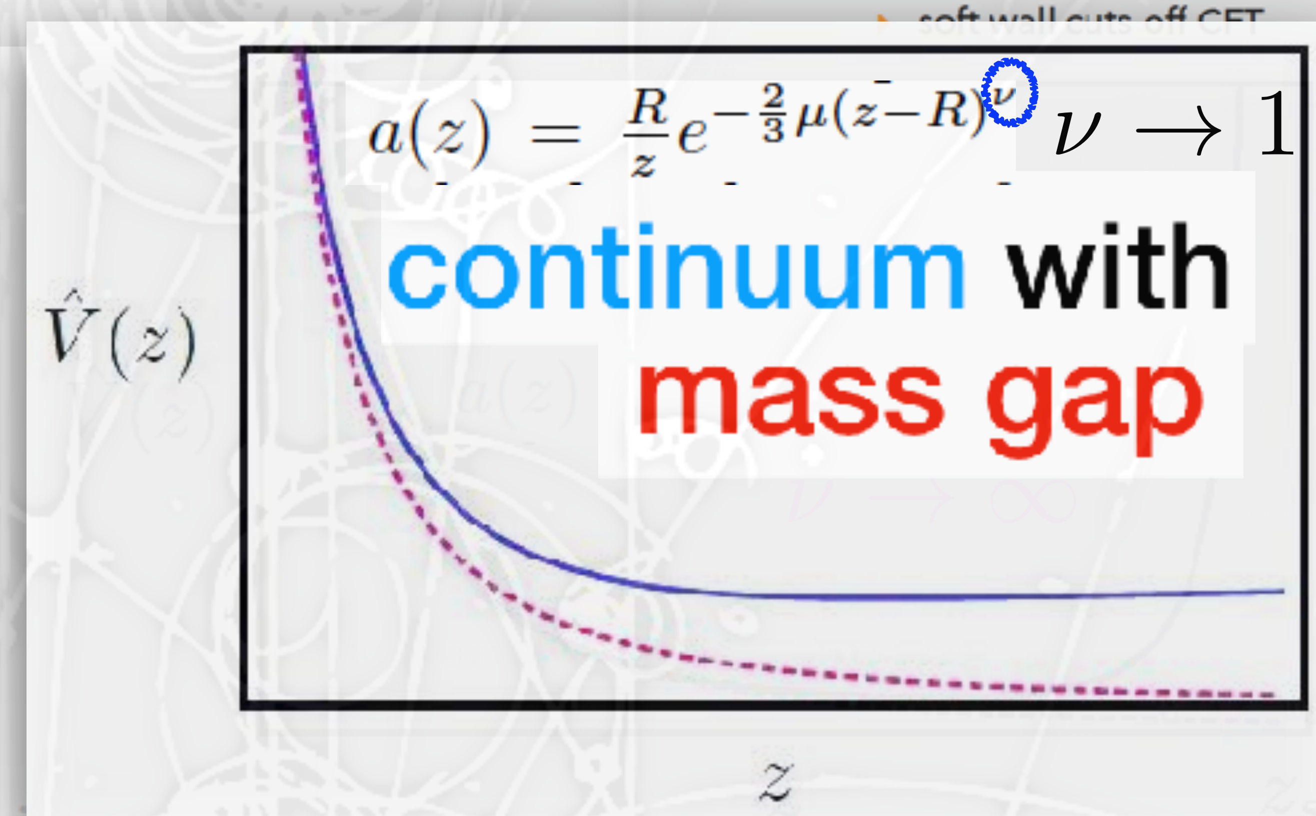

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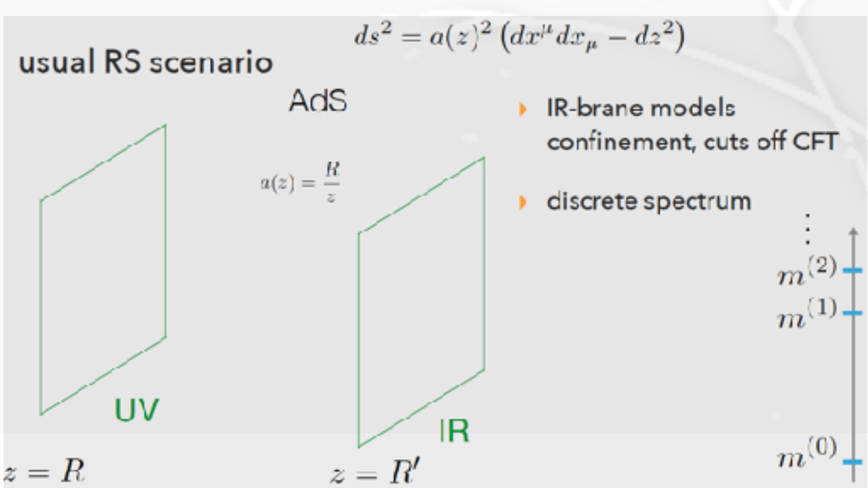

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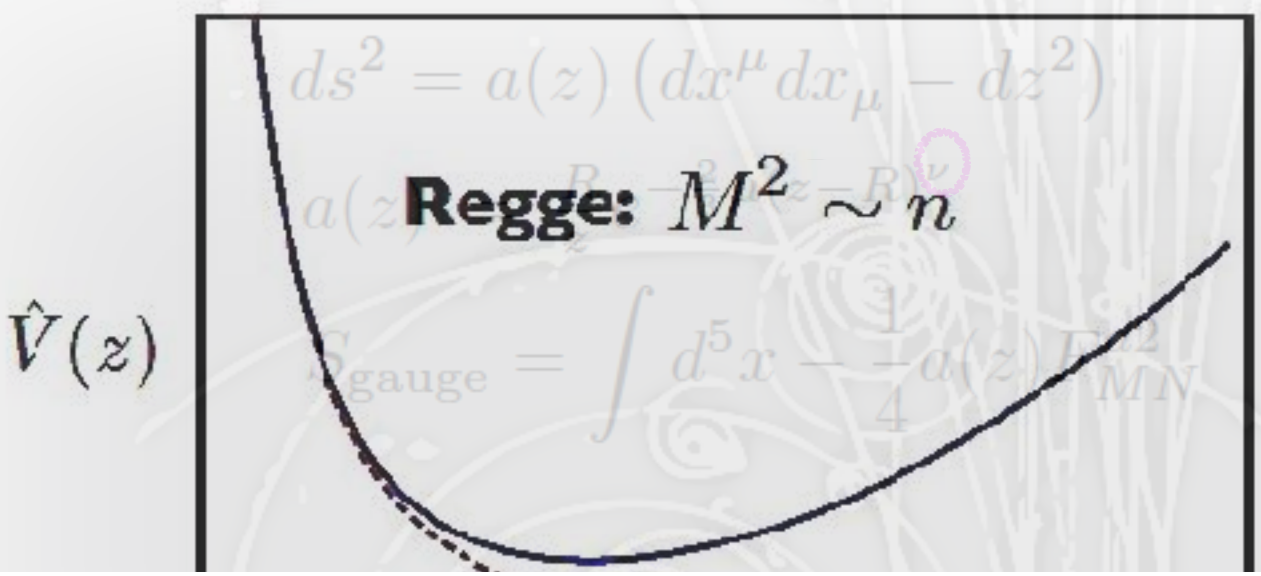
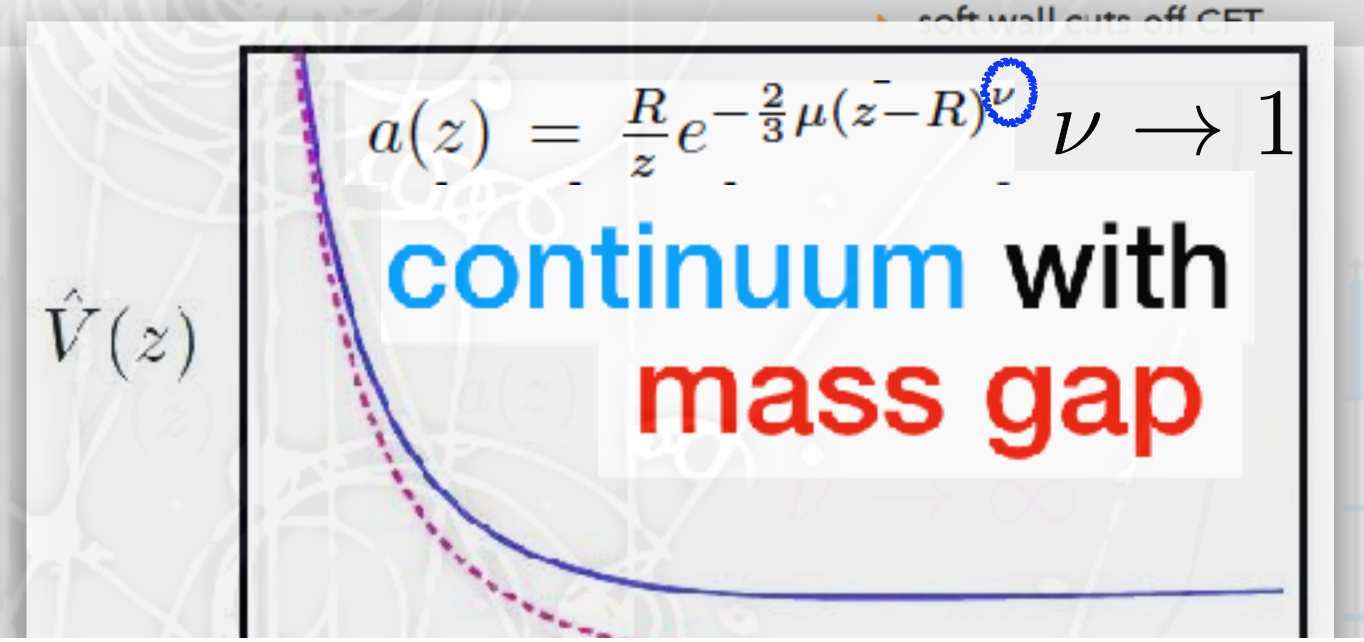
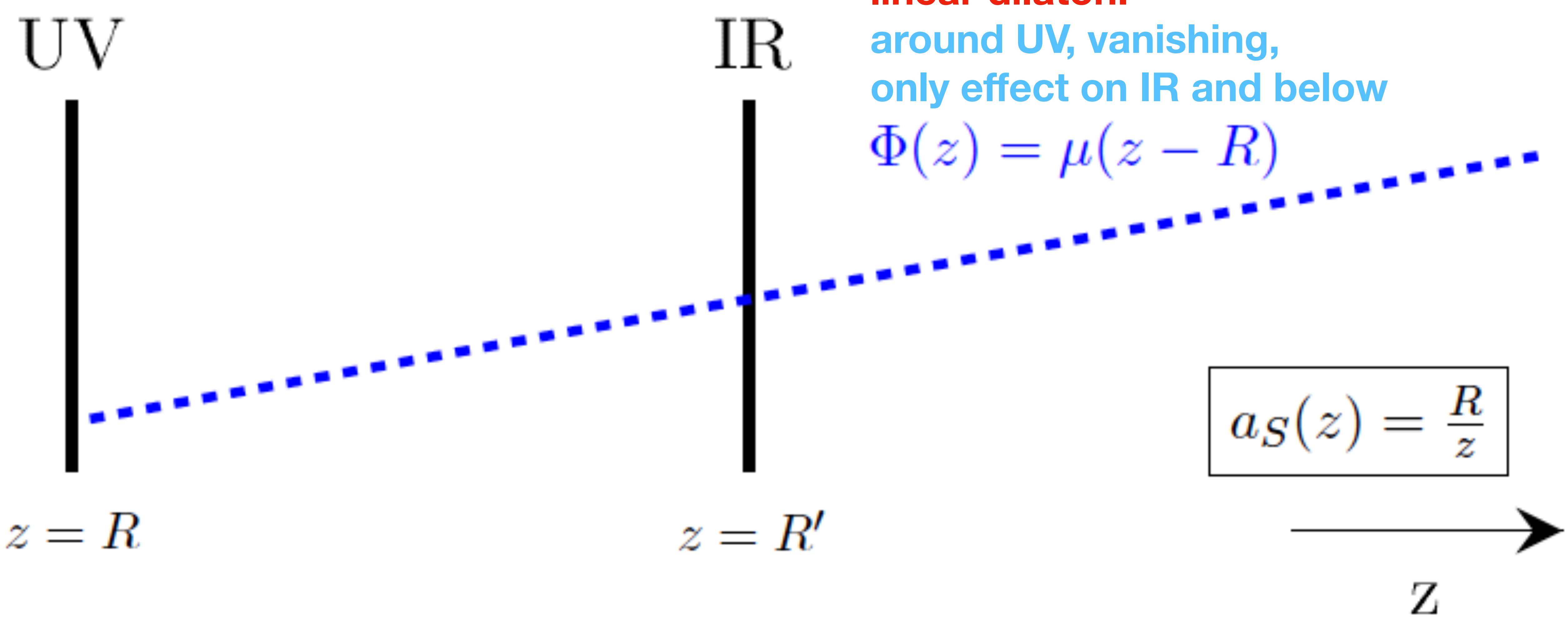




linear dilaton:

around UV, vanishing,
only effect on IR and below

$$\Phi(z) = \mu(z - R)$$



The Quantum Critical higgs

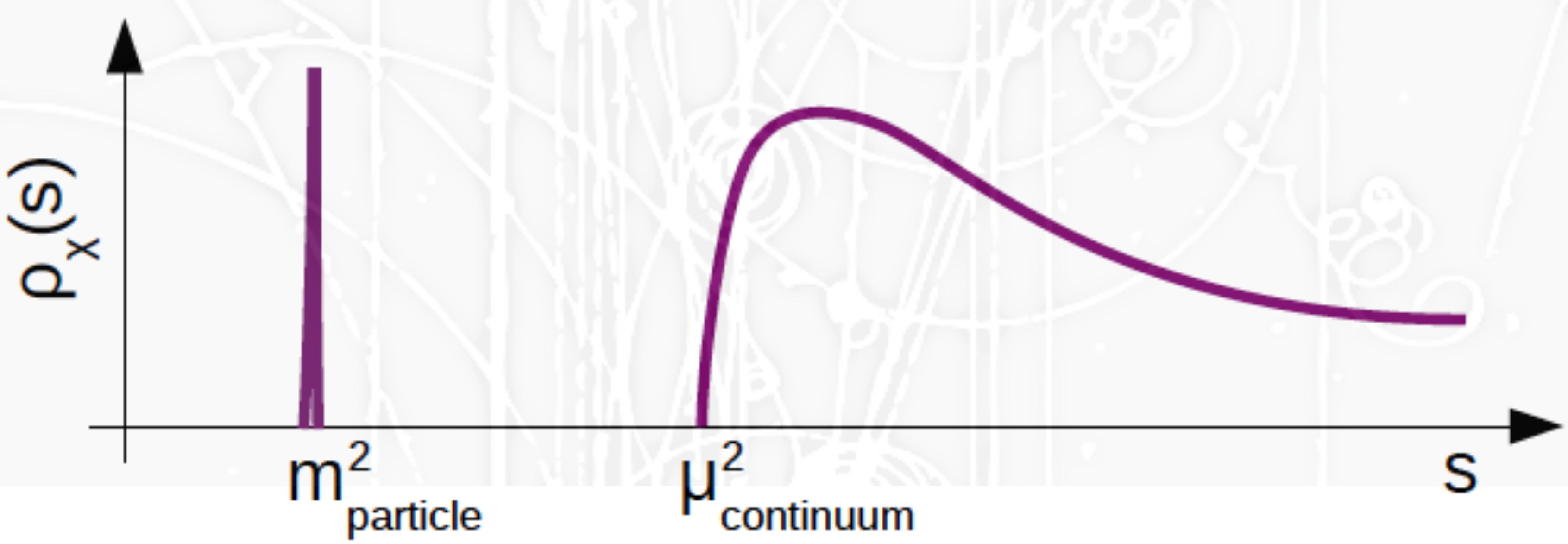
- At a QPT the approximate scale invariant theory is characterized by the scaling dimension Δ of the gauge invariant operators.

SM: $\Delta = 1 + \mathcal{O}(\alpha/4\pi)$.

- We want to present a general class of theories describing a higgs field near a non-mean-field QPT.

- In such theories, in addition to the pole (Higgs), there can also be a higgs continuum, representing additional states associated with the dynamics underlying the QPT

$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



Modeling the QCH: generalized free fields

Generalized Free Fields

Polyakov, early '70s- skeleton expansions

CFT completely specified by 2-point function - rest vanish

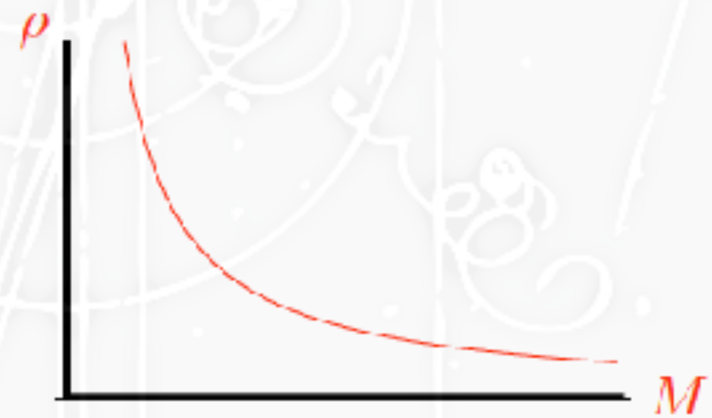
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

Can be generated from: $\mathcal{L}_{\rm GFF} = -h^\dagger \left(\partial^2\right)^{2-\Delta} h$

Georgi
hep-ph/0703260

Branch cut starting at origin - spectral density purely a continuum:

$$G(p) \sim \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



Quantum Critical Higgs (Generalized Free Fields)

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

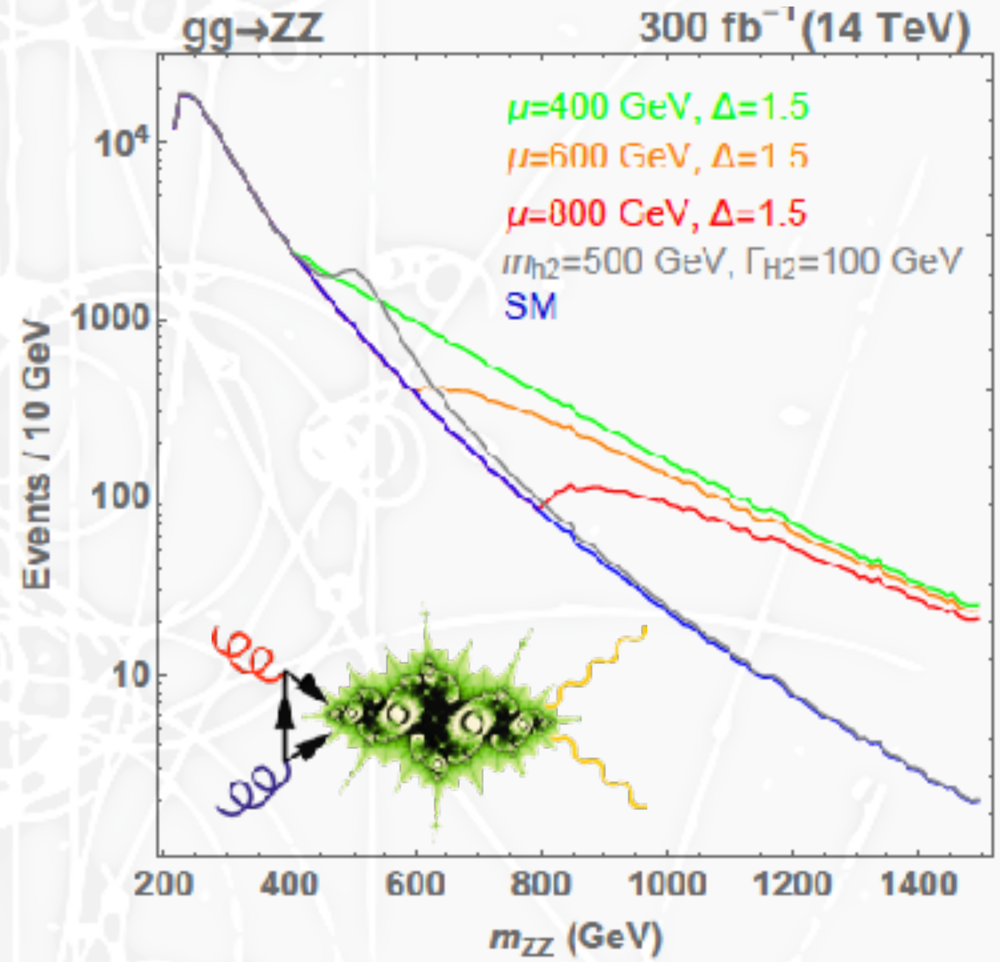
- 5D model: $$S=\int d^4x dz\sqrt{g}\left[|D_M H|^2-\frac{1}{4g_4^2}W_{MN}^{a\,2}-\phi(z)\,|H|^2+\mathcal{L}_{\rm int}(H)\right]+\int d^4x\,\mathcal{L}_{\rm perturbative}.$$

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

$$a(z)=\frac{R}{z}e^{-\frac{2}{3}\mu(z-R)}$$

With the discovery of Higgs,
we need a pole (125 GeV)
and a gap to BSM continuum

Soft wall terminates CFT with continuum, not set of KK modes



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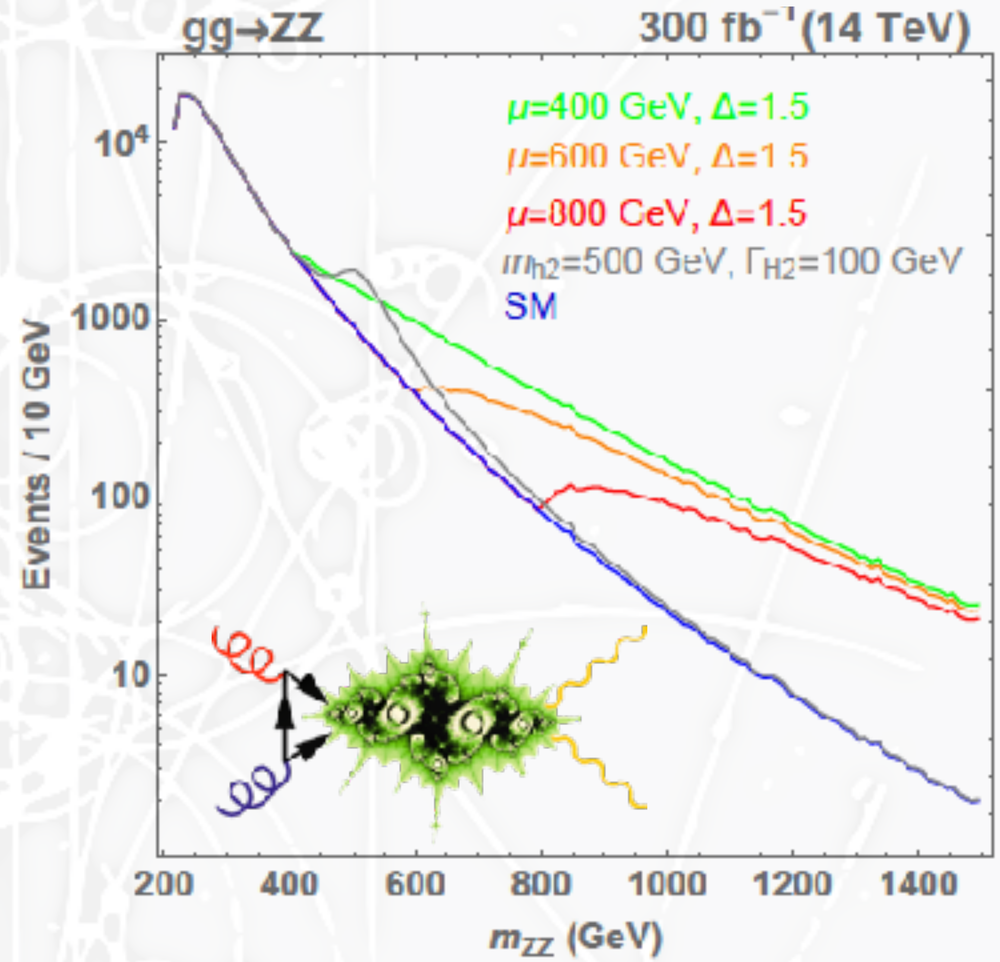

The momentum space propagator for the physical Higgs scalar can be written as

$$G_h(p) = -\frac{i\, Z_h}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}}, \qquad Z_h = \frac{(2-\Delta)}{(\mu^2 - m_h^2)^{\Delta-1}}$$

c.f. unparticle propagator

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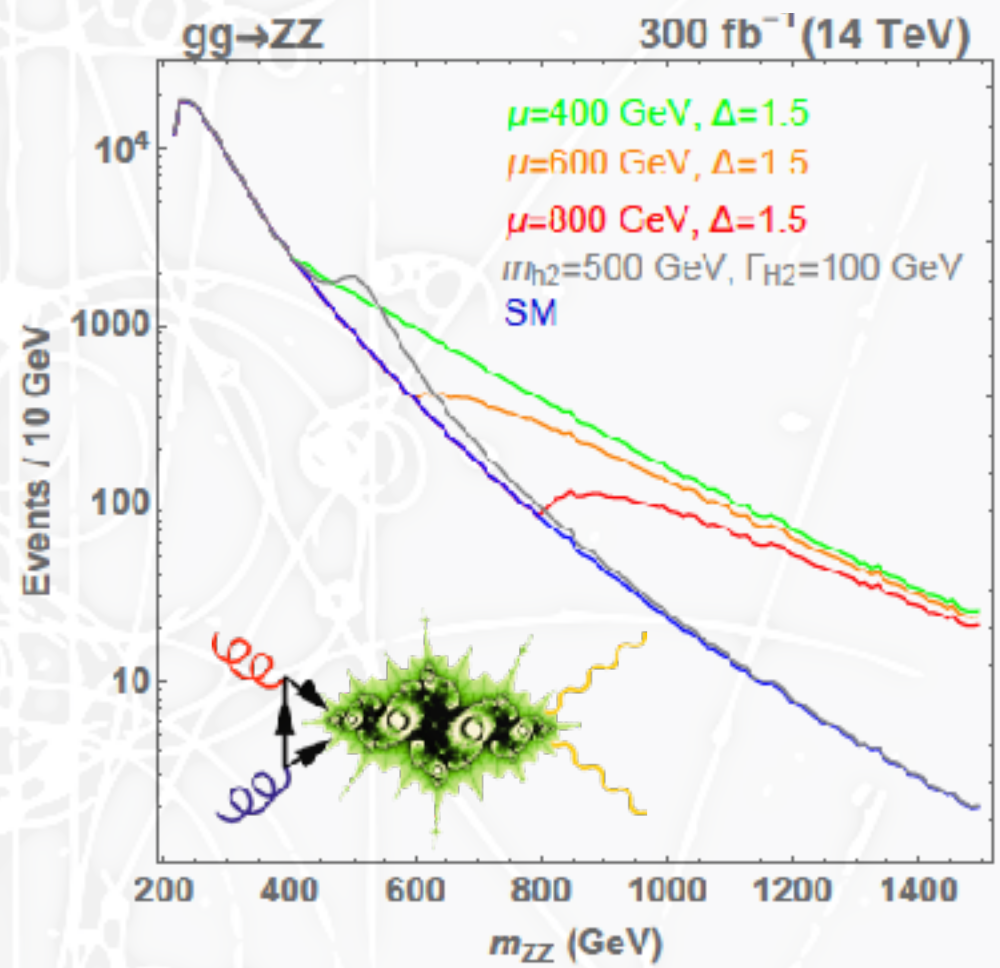

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Generally:

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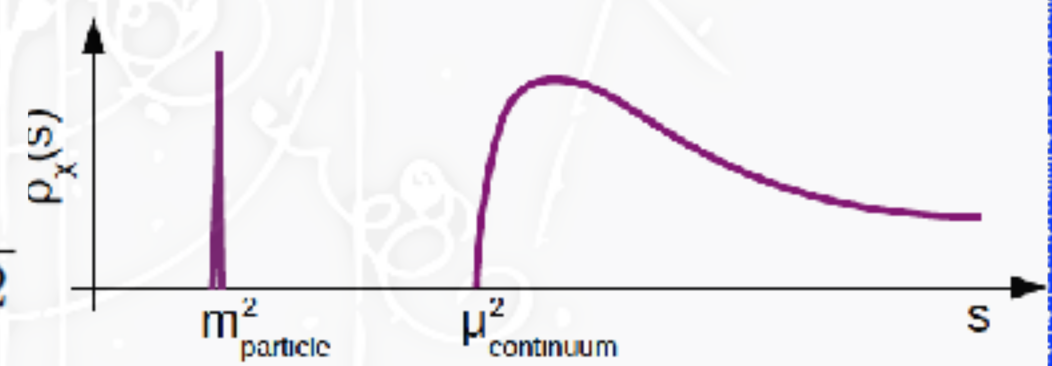


SM recovered in limits $\mu\to\infty$ and/or $\Delta\to 1$

short detour

What Kind of New Physics could be nearby (near the EWSB scale), which is not described by usual EFT?

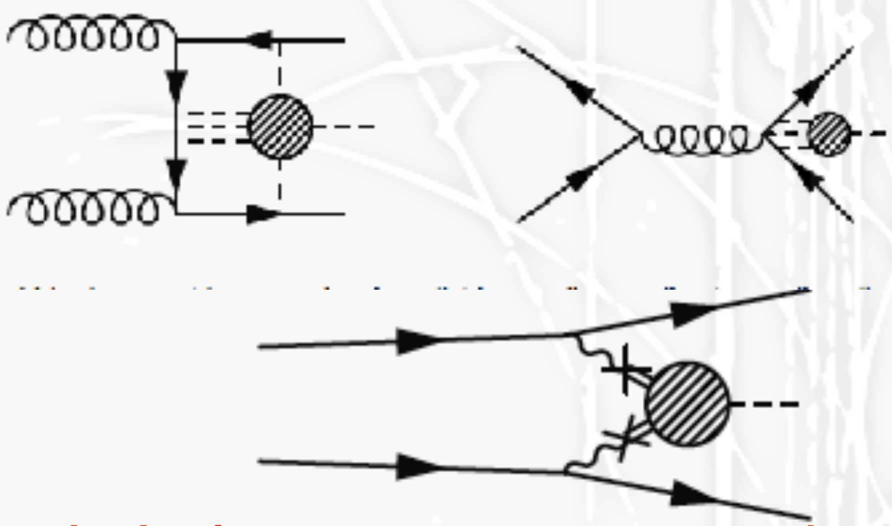
short detour

What Kind of New Physics could be nearby (near the EWSB scale), which is not described by usual EFT?

- Not super-weakly coupled,
- yet not inconsistent with the data?

Form Factors for the Quantum Critical higgs

- When looking at observables, we need to use form factors to characterize the strong sector in generality, since there is no separation of scales.



nontrivial momentum dependent off-shell form factors

Form Factors for the Quantum Critical higgs

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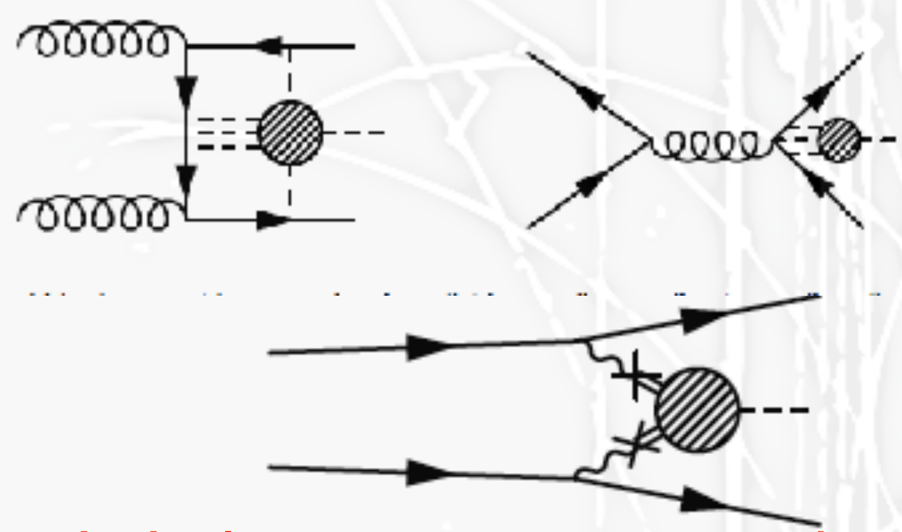
This is not an EFT expansion, but rather an expansion in weak couplings that perturb the generalized free field theory.



nontrivial momentum dependent off-shell form factors

Generalized Free Fields via AdS/CFT

Cacciapaglia, Marandella and Terning 08'
Falkowski and Perez-Victoria 08'
Bellazzini, Csaki, Hubisz, SL, Serra, Terning 15'

- SO(4) global symmetry is gauged in the 5D bulk

$$S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W^{a\,2}_{MN} - \phi(z)\,|H|^2 + \mathcal{L}_{\rm int}(H) \right] + \int d^4x\, \mathcal{L}_{\rm perturbative}.$$

$$ds^2 = a(z)^2 \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right) \qquad a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$

$$G_h(R,R,p^2) = i\tilde{Z}_h \left[\frac{\mu K_{1-\nu}(\mu R)}{R K_\nu(\mu R)} - \frac{\sqrt{\mu^2-p^2} K_{1-\nu}(\sqrt{\mu^2-p^2} R)}{R K_\nu(\sqrt{\mu^2-p^2} R)} - M_0^2 \right]^{-1}$$

Soft wall terminates CFT with continuum, not set of KK modes

The bulk to brane propagator is then given by $G_h(R,z,p^2) = a^{-\frac{3}{2}}(z)(z/R)^{\frac{1}{2}} \frac{K_\nu(\sqrt{\mu^2-p^2} z)}{K_\nu(\sqrt{\mu^2-p^2} R)}$

=> reduce to the previous propagator in the limit pR <<1 :

$$G_{\mathcal{h}}(p) = -\frac{i\, Z_{\mathcal{h}}}{(\mu^2 - p^2 + i\epsilon)^{2-\Delta} - (\mu^2 - m_h^2)^{2-\Delta}} \qquad Z_{\mathcal{h}} = \frac{(2-\Delta)}{(\mu^2 - m_h^2)^{\Delta-1}}$$

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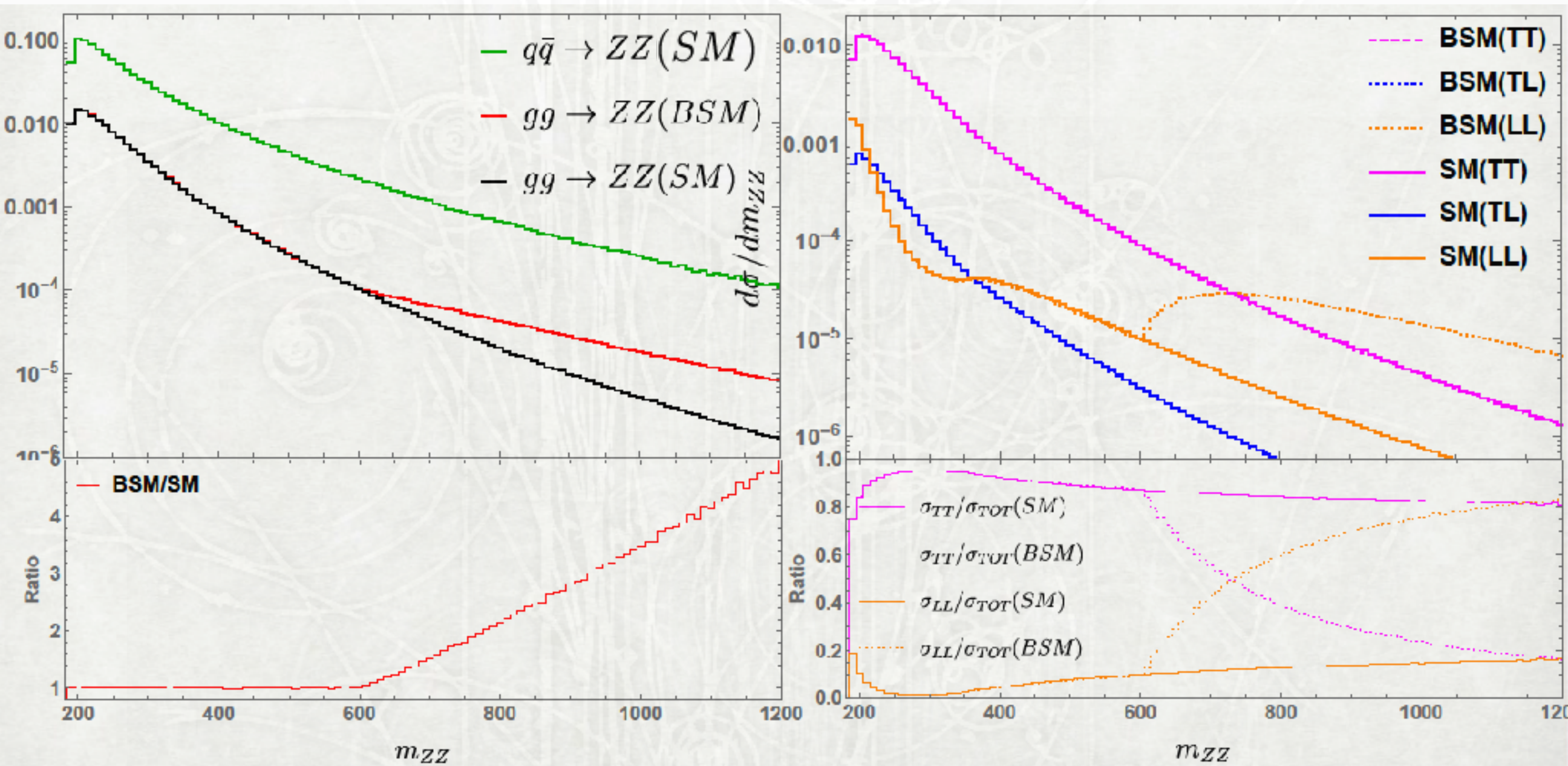
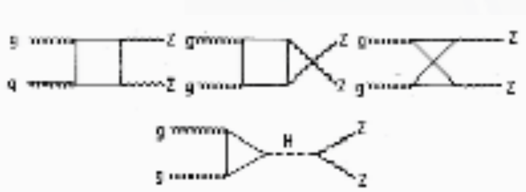
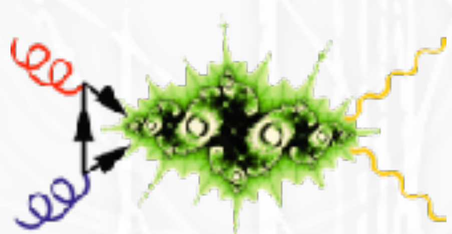
obtain such propagator from a calculable model of this sort based on a Banks-Zaks fixed point in a supersymmetric QCD theory: Csaki, SL, Shirmanm, Parolini (in preparation)

Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

SL, Park, Qian



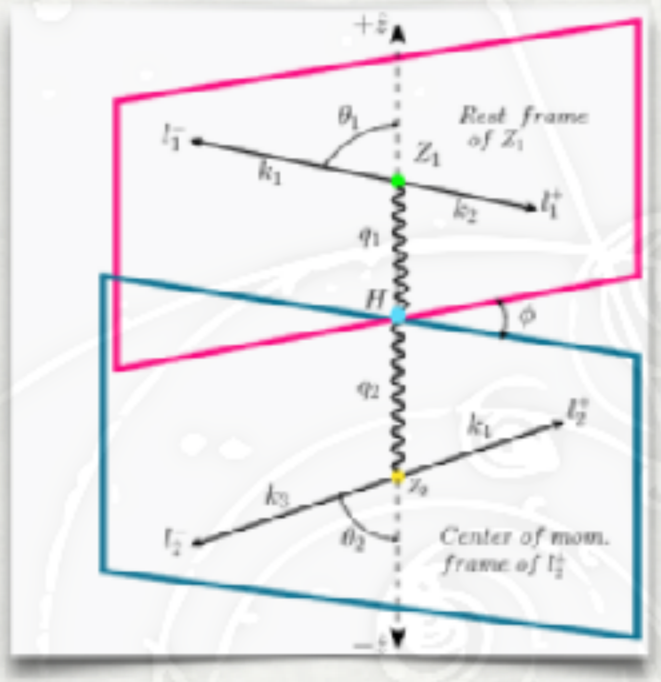




c.f. $$\frac{1}{2\Lambda^4}\left(i\bar{\psi}\gamma^{\{\mu}\partial^{\nu\}}\psi + \text{h.c.}\right) D_\mu H^\dagger D_\nu H$$

Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

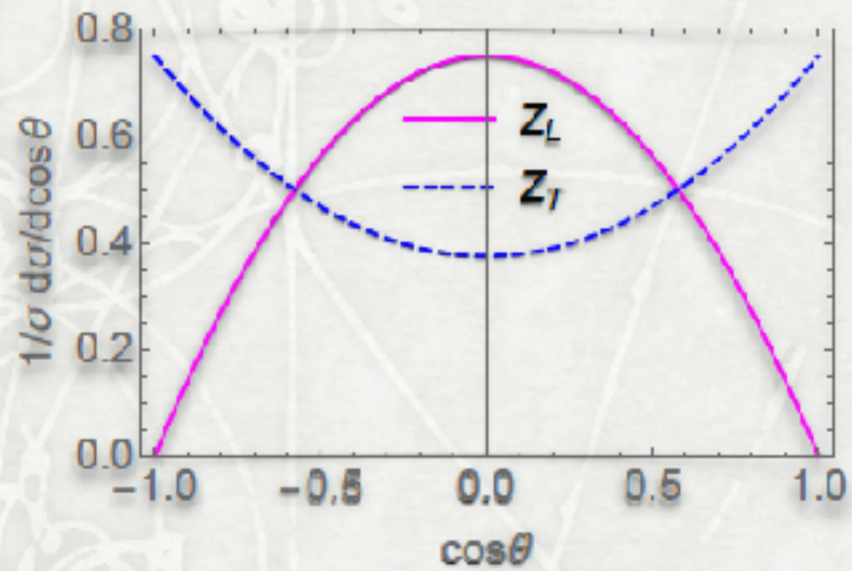
SL, Park, Qian



Z Polarization ⟷ Angle $\cos\theta$ dist. from decay

$$\text{Transverse}: \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta)$$

$$\text{Longitudinal}: \frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{3}{4}(1-\cos^2\theta)$$

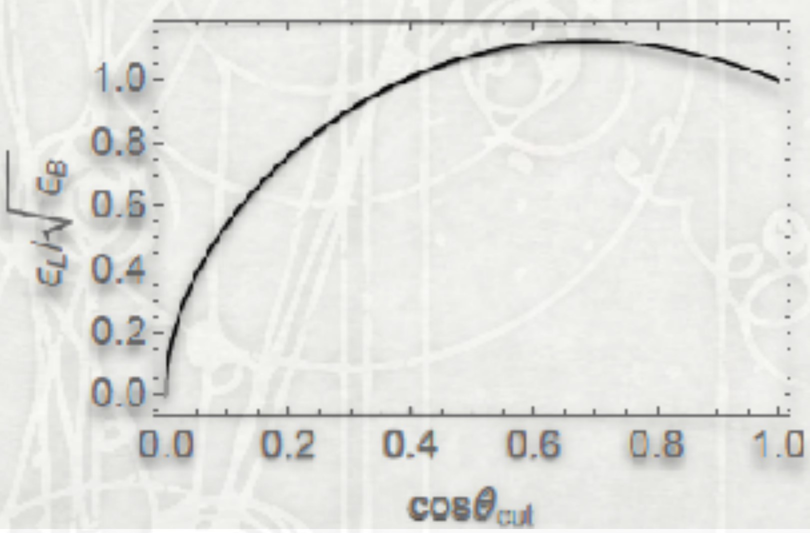


To optimize the longitudinal over transverse mode significance:

$$-0.68 < \cos\theta < 0.68$$

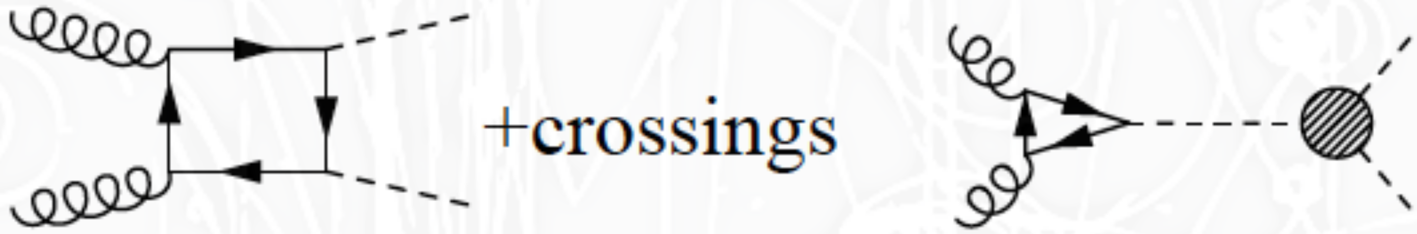
$$\cos\theta_C = 0.68$$

$$\{\epsilon_L,\ \epsilon_T\} = 86\%,\ 59\%$$



Direct Signals (double Higgs)

- Double Higgs production



$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15}\pi M_W^4 \hat{s}^2}\left(|\text{gauge1}|^2 + |\text{gauge2}|^2\right)$$

gauge1 = box + triangle (negative interference)

gauge2 = box (largest contribution)

Direct Signals (double Higgs)

- Double Higgs production

probe the higher n-point correlators of the CFT.

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\alpha_w^2 \alpha_s^2}{2^{15}\pi M_W^4 \hat{s}^2}\left(|\text{gauge1}|^2 + |\text{gauge2}|^2\right)$$

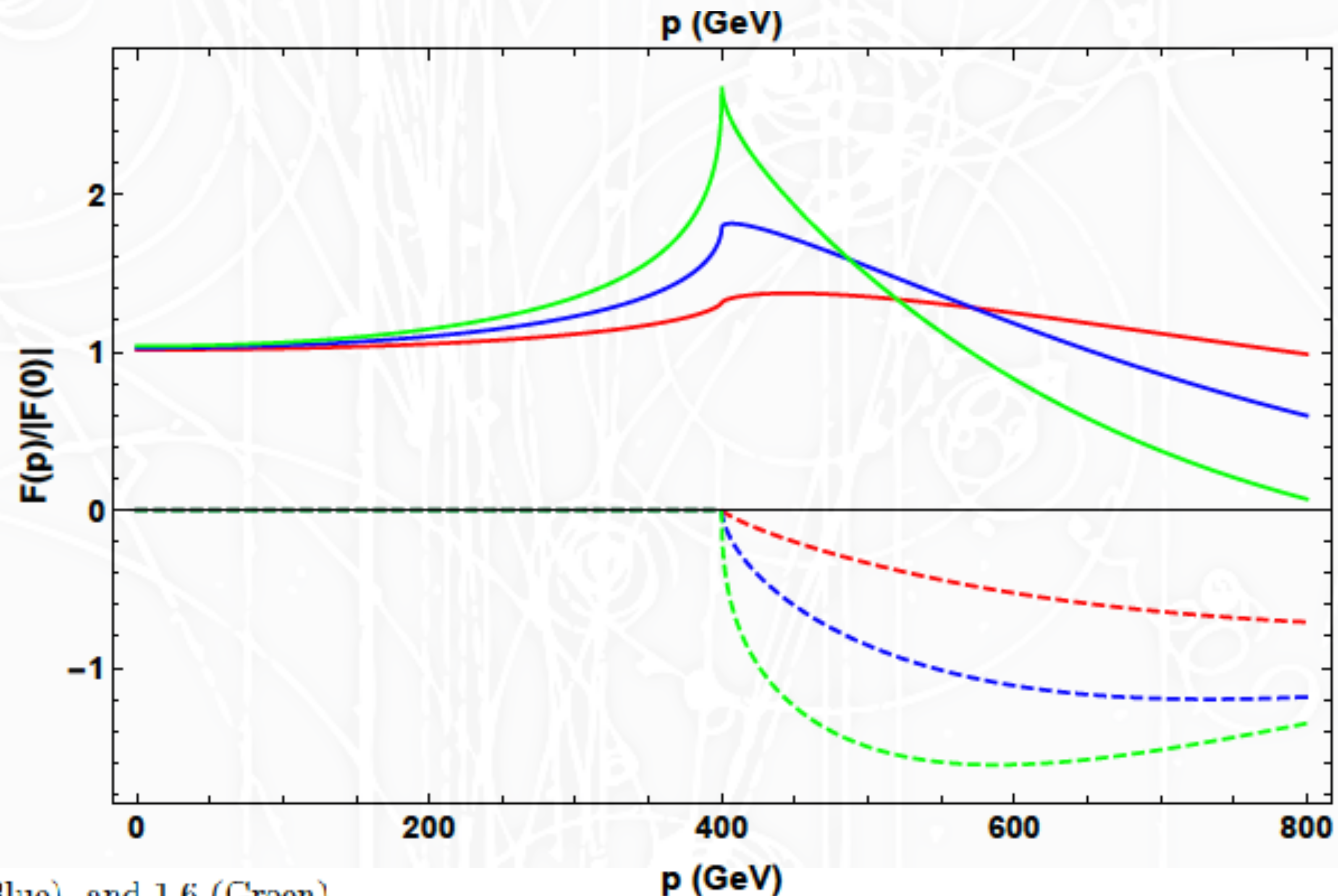
gauge1 = box + triangle (negative interference)

gauge2 = box (largest contribution)

Direct Signals (double Higgs)

- Form factors for trilinear Higgs self coupling $\lambda_5 (H^\dagger H)^2$

$$F_{hhh} = \frac{\lambda_5}{L^2} \mathcal{V} \int_R^\infty dz \, \frac{1}{a} \left(\frac{z}{R}\right)^2 \frac{K_{2-\Delta}(\mu\, z)}{K_{2-\Delta}(\mu\, R)} \prod_{i=1}^{3} \frac{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2}\, z)}{K_{2-\Delta}(\sqrt{\mu^2 - p_i^2} R)}$$

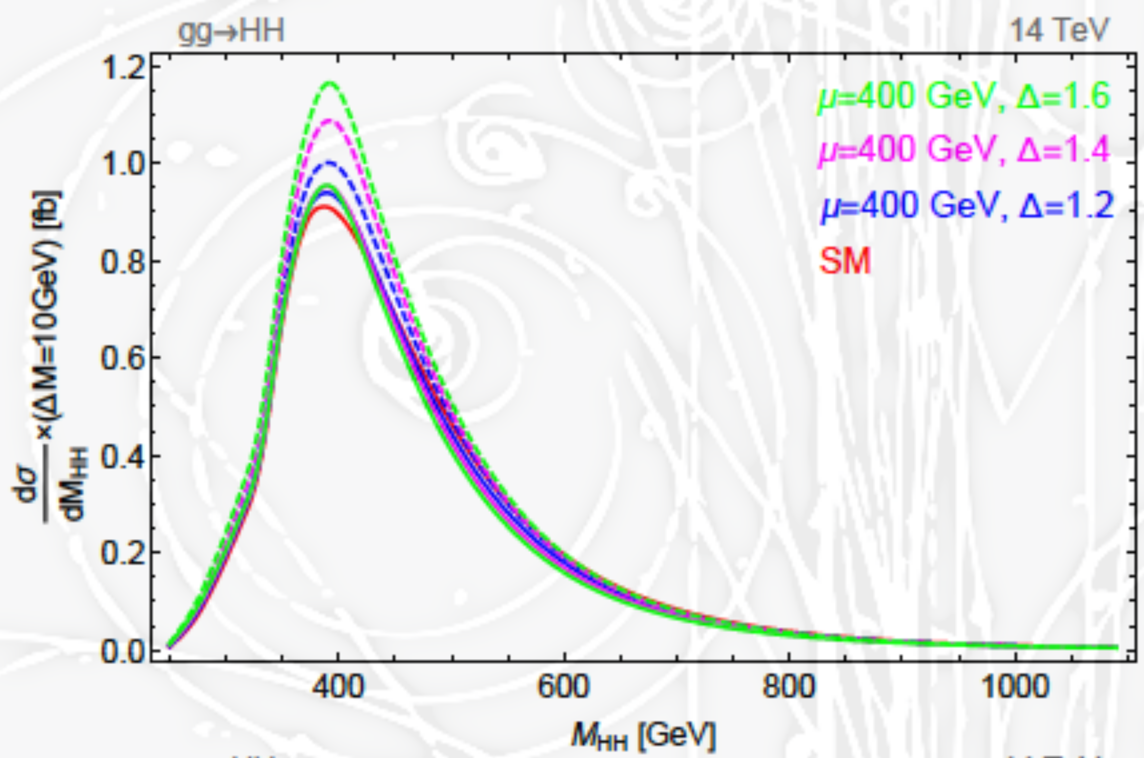


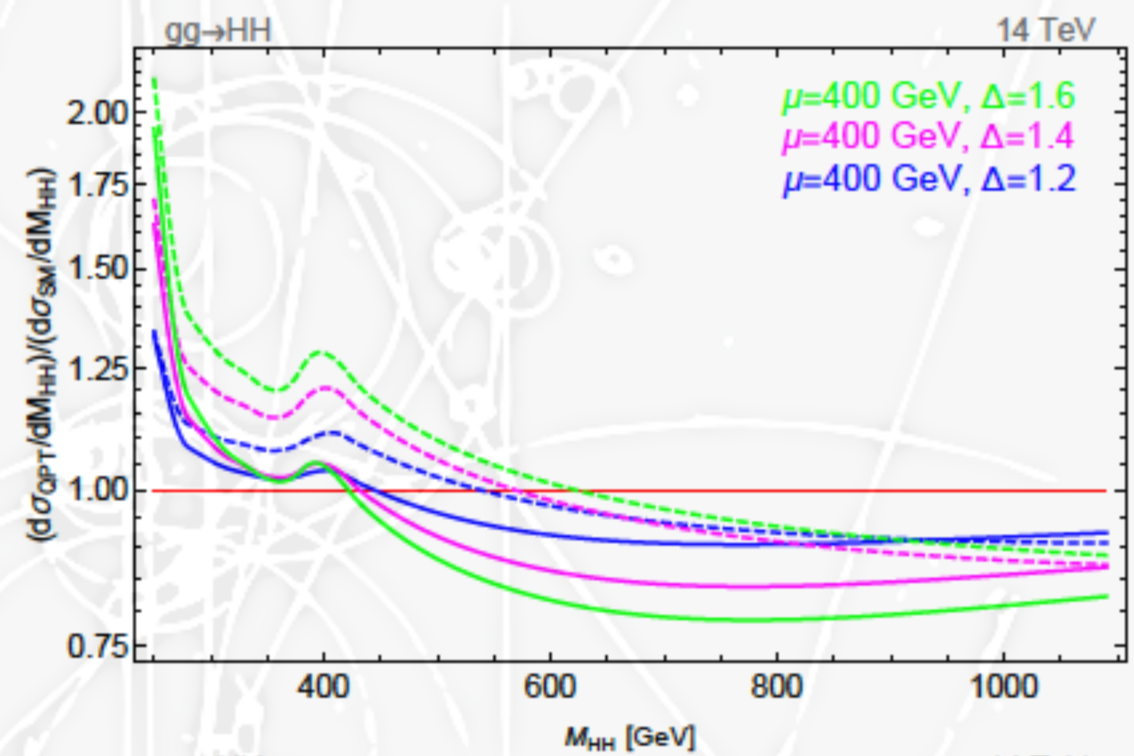
$\mu = 400$.
$\Delta = 1.2$ (Red) 1.4 (Blue), and 1.6 (Green).

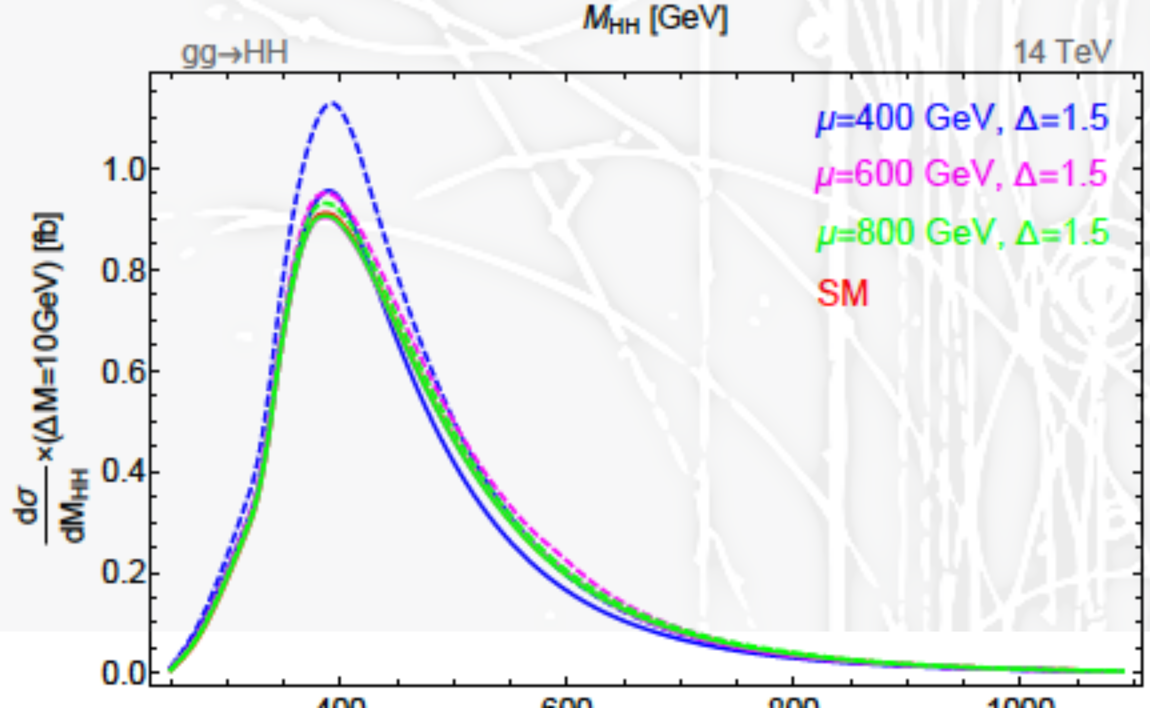
Direct Signals (double Higgs)

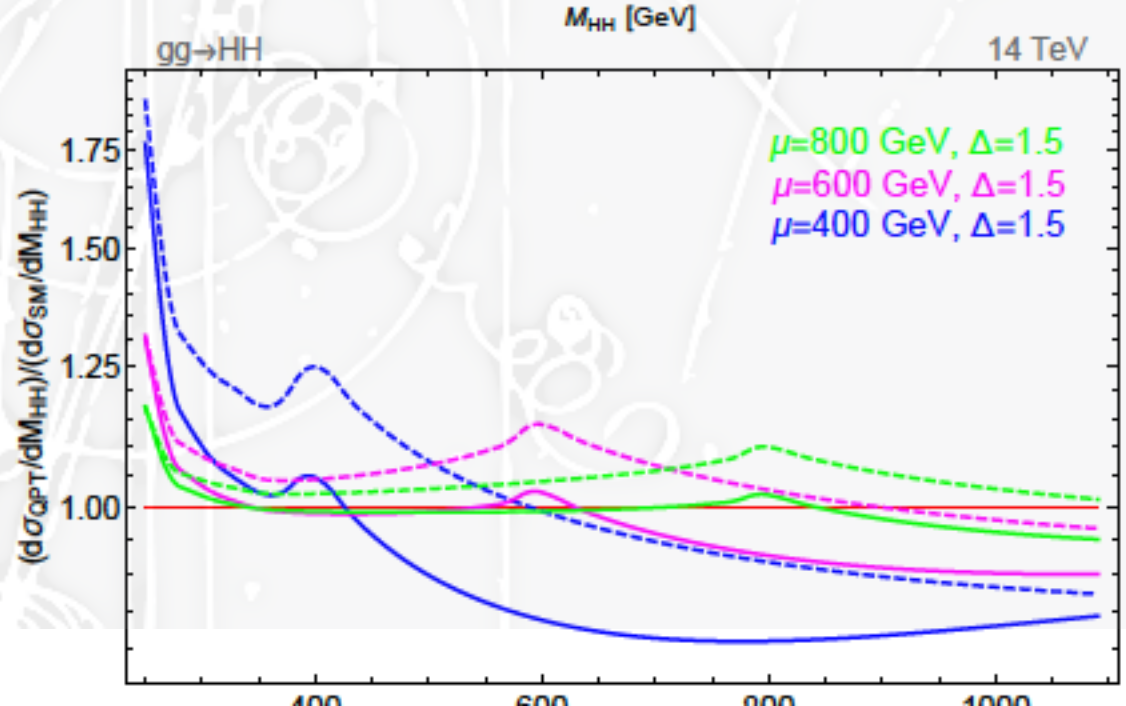
- Double Higgs production

dashed lines correspond to the case where only the Higgs two-point function has non-trivial behavior inherited from a sector with strong dynamics.

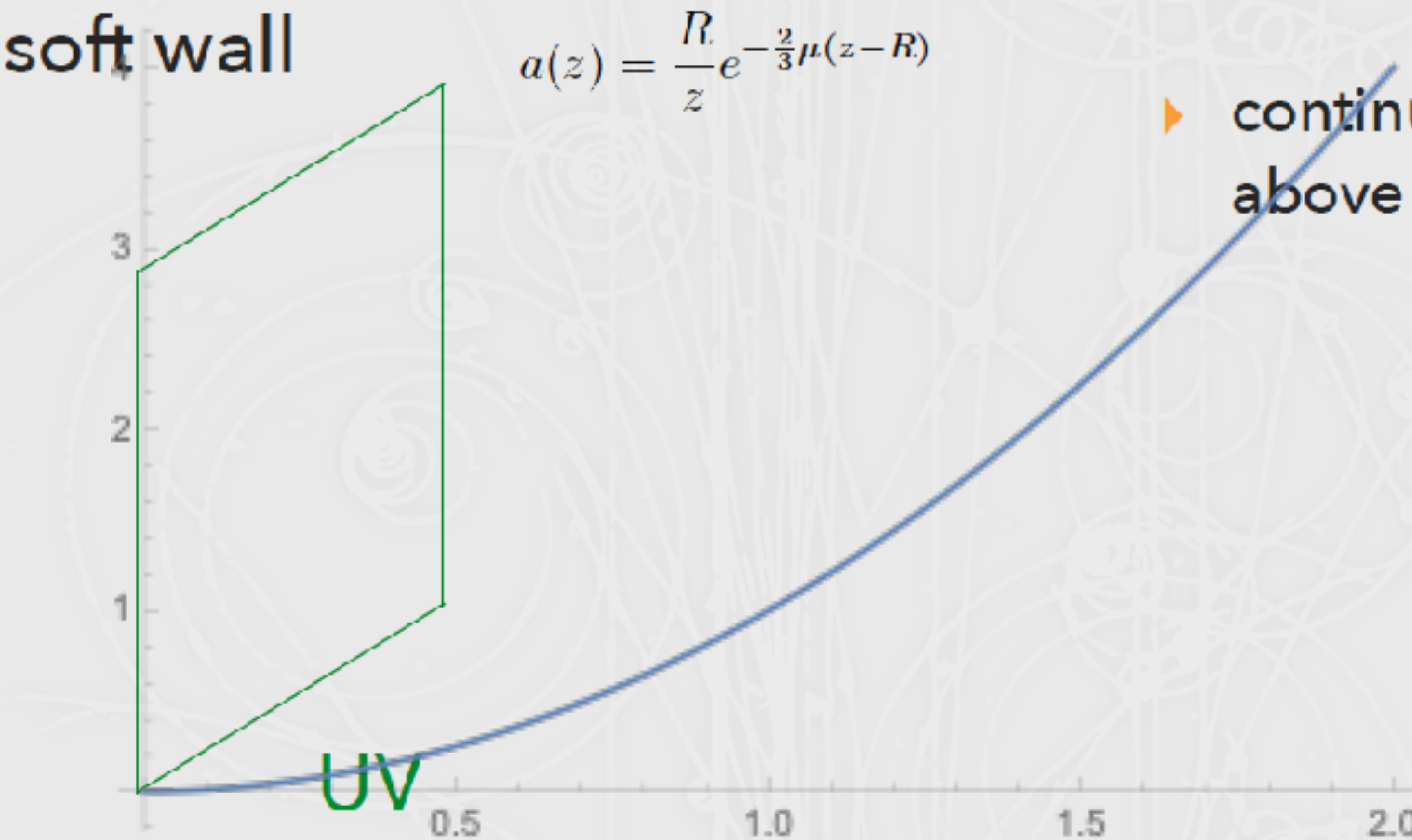






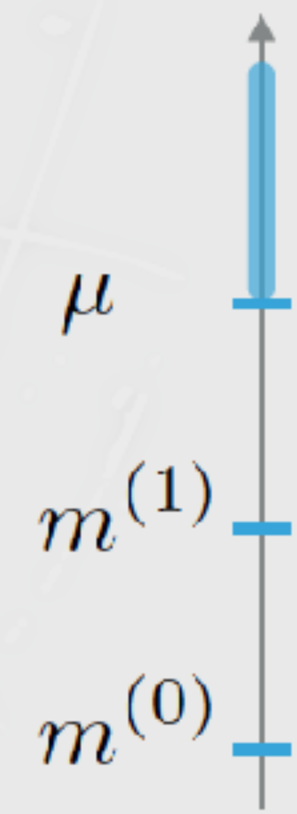


Quantum Critical Higgs



$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$

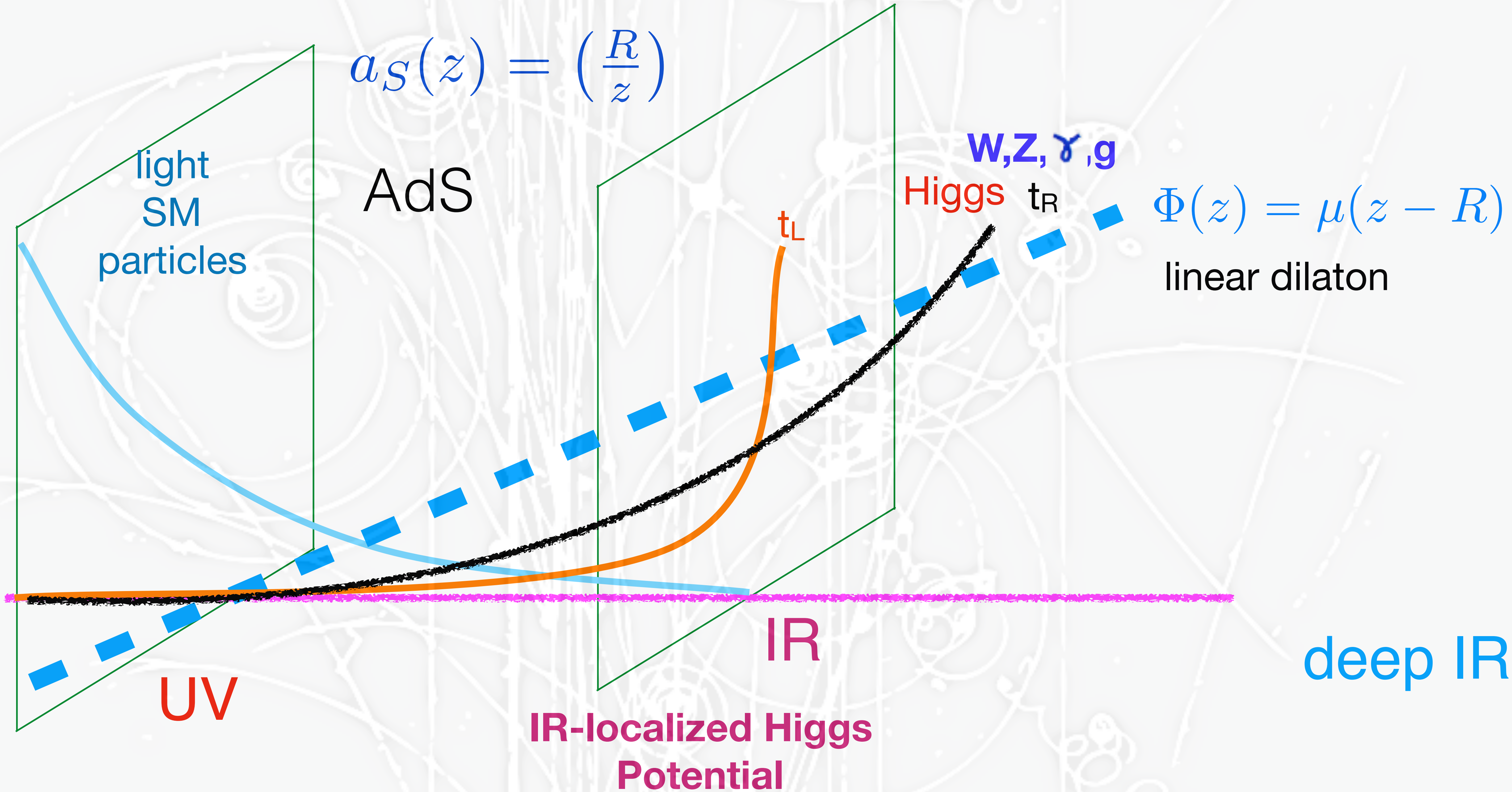
- soft wall cuts off CFT
- continuous KK spectrum above mass gap



- Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental ⇒ fine-tuning

Csaki, SL, Lombardo, work in progress

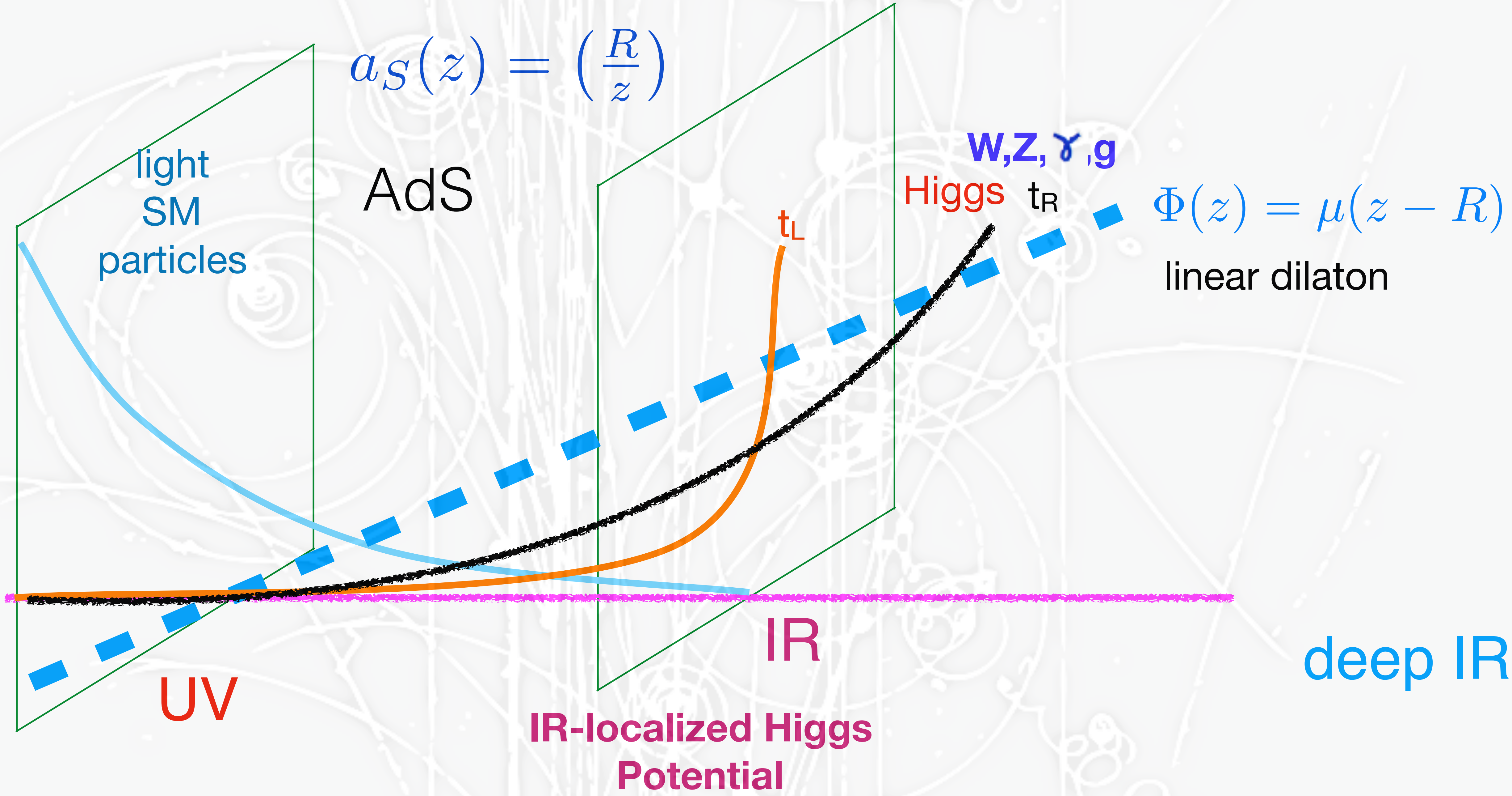
A Natural Quantum Critical Higgs: 5D linear dilaton



Csaki, SL, Lombardo, work in progress

A Natural Quantum Critical Higgs: 5D linear dilaton

Higgs arises from CFT with a domain wall (IR brane)



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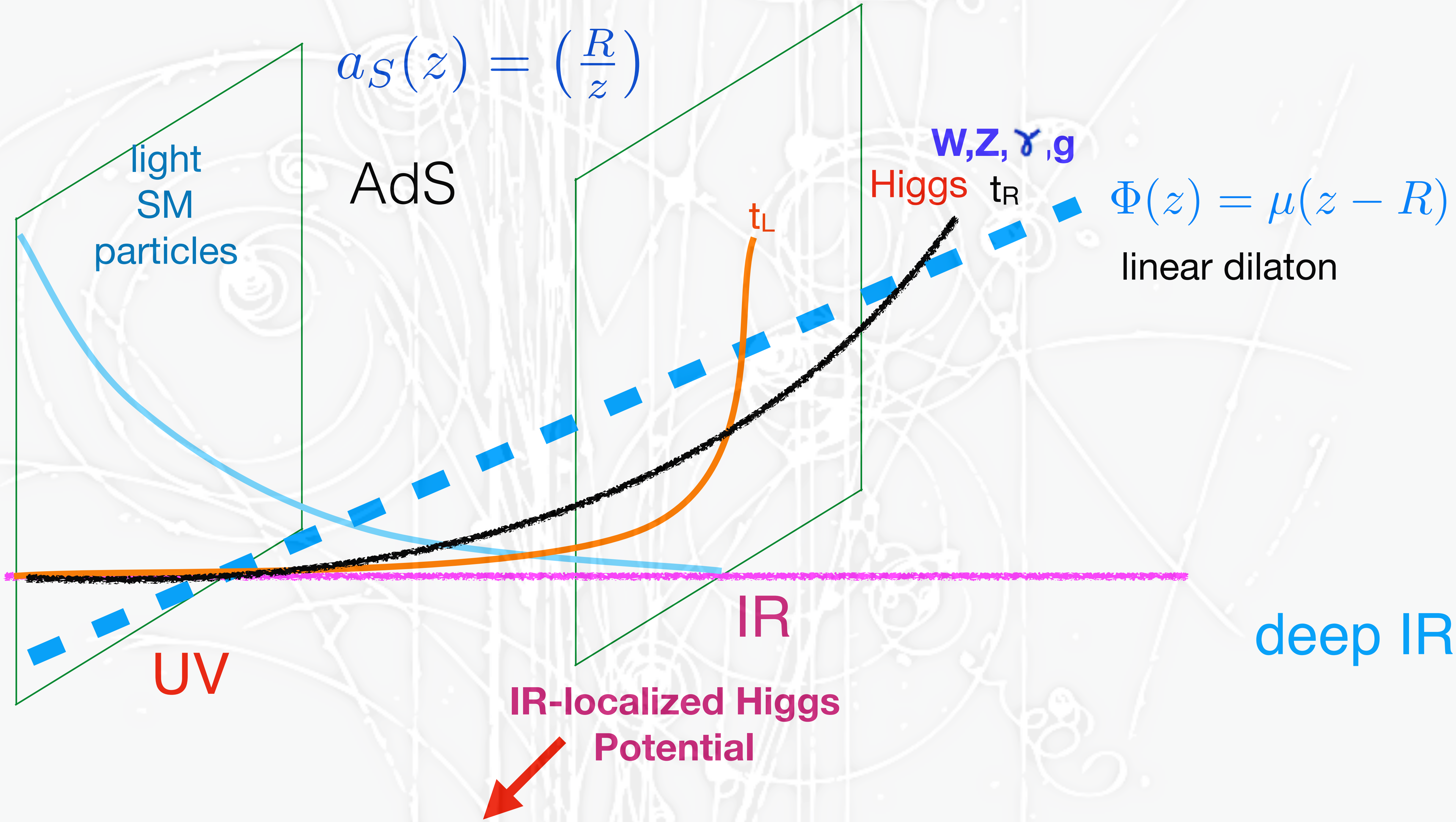
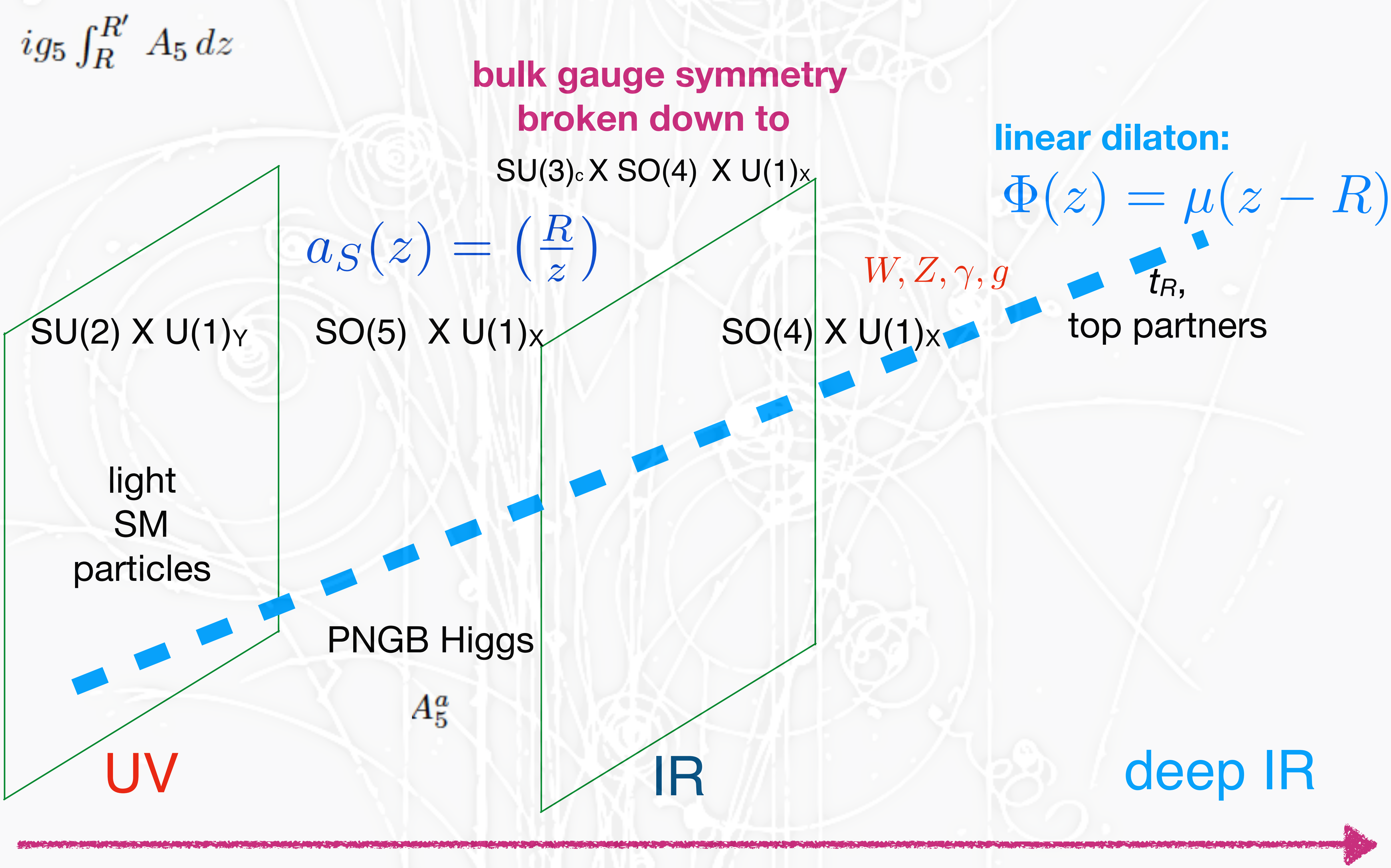


taking a pole (physical Higgs) out of CFT
=> arises as a composite bound state of CFT

Csaki, Lombardo, Lee, SL, Telem

A “more” Natural model: Linear Dilaton



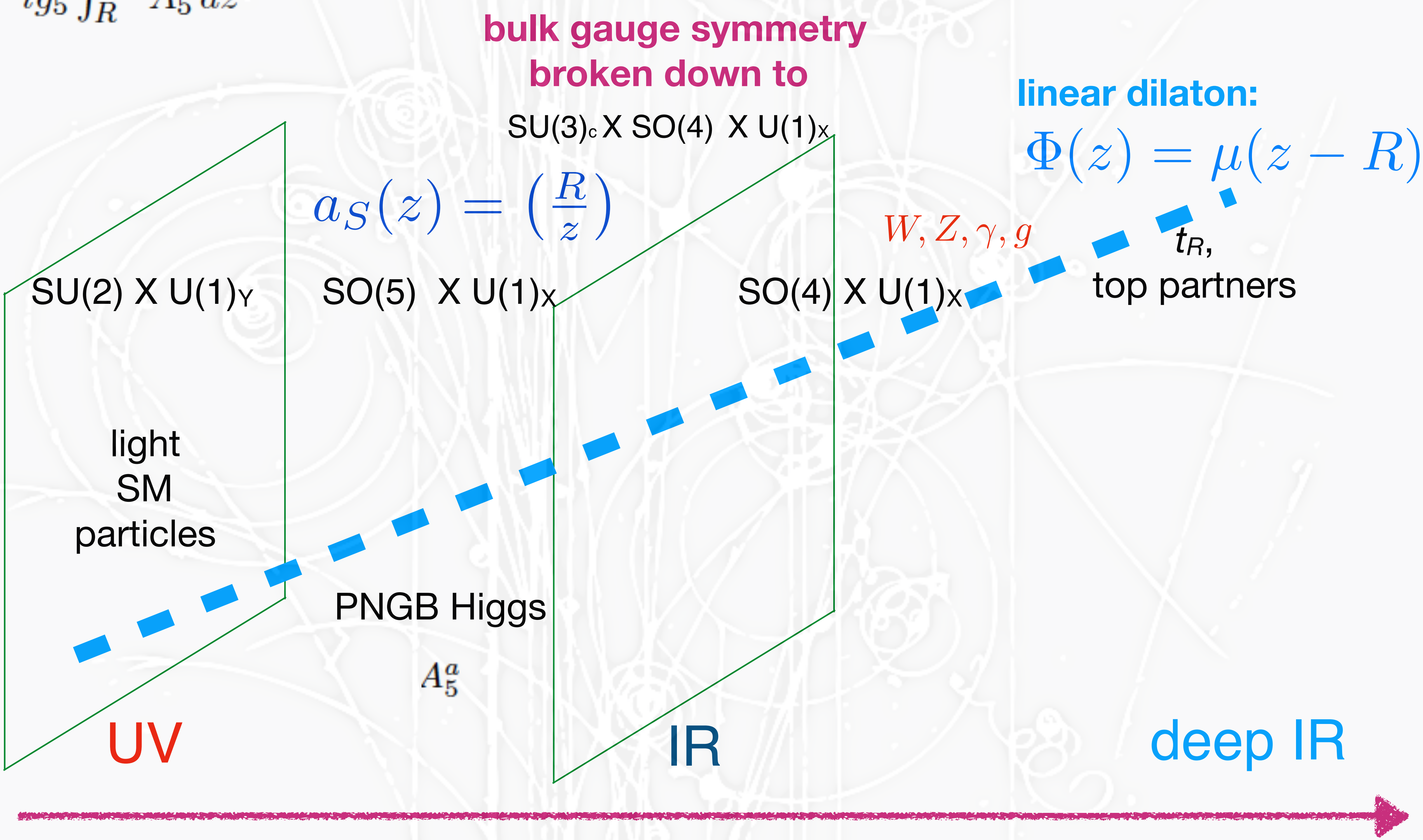
theory gets closed to a fixed point, but then gets a mass gap

Csaki, Lombardo, Lee, SL, Telem

A “more” Natural model: Linear Dilaton

PNGB Higgs: Wilson line with A_5 (BC on IR brane)

$i g_5 \int_R^{R'} A_5\, dz$



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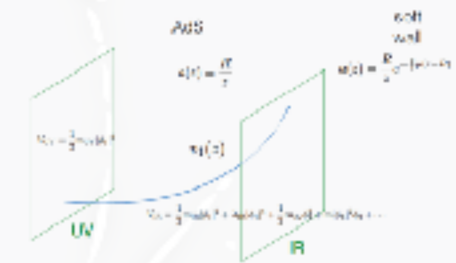
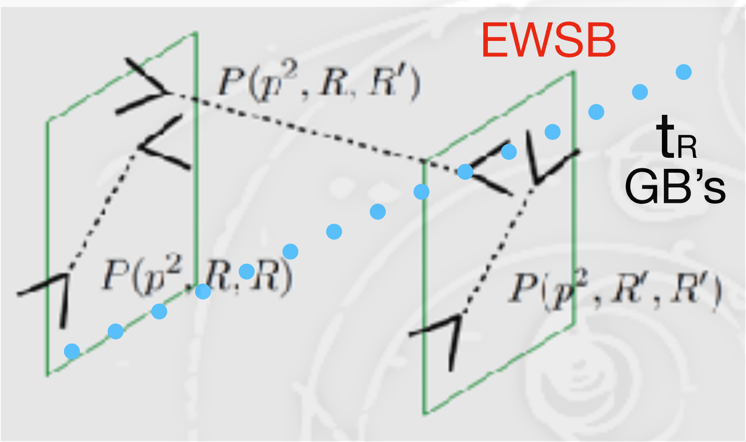
Continuum Naturalness?

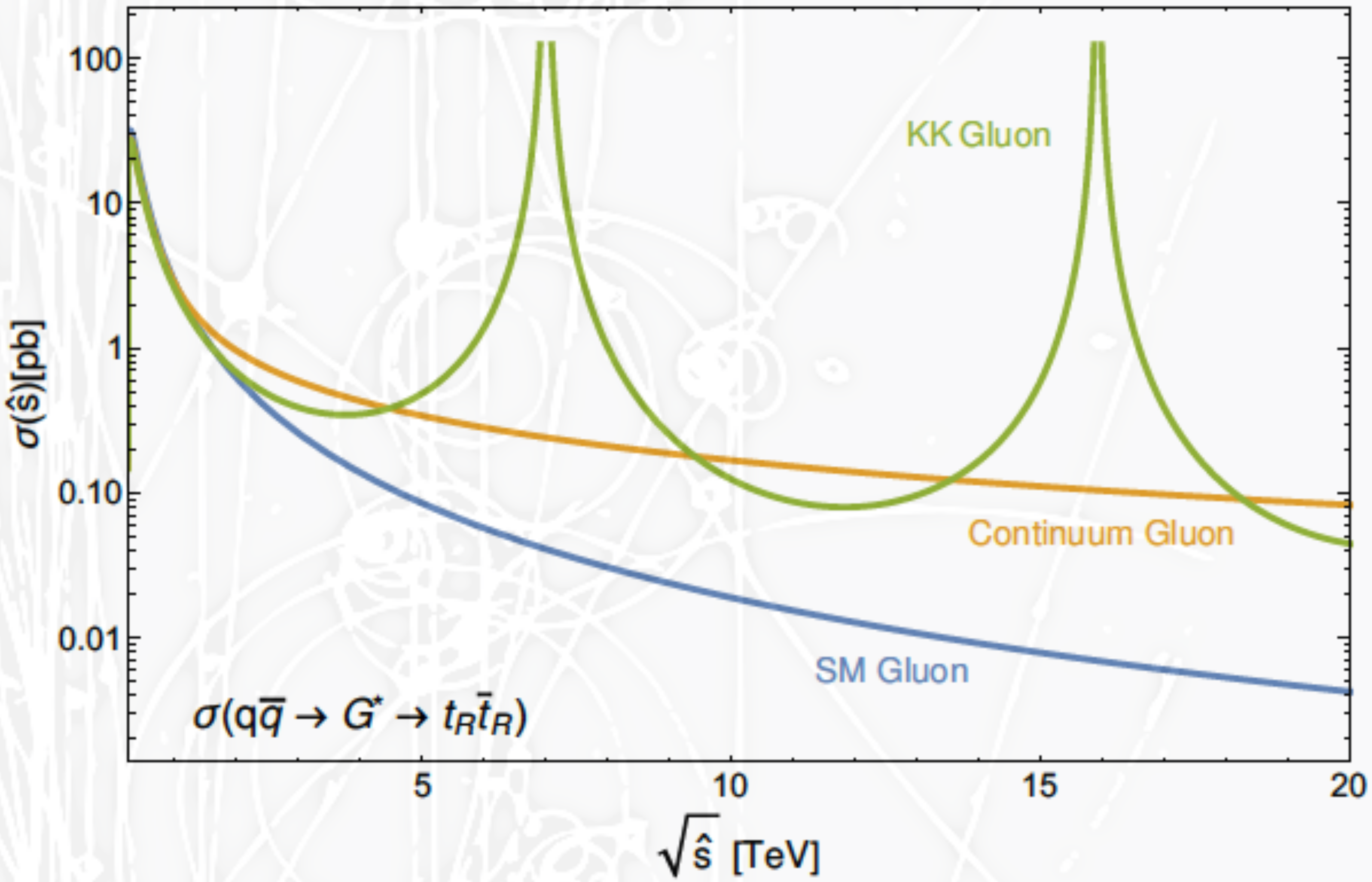


Csaki, Lombardo, Lee, SL, Telem

- New Physics (e.g. Top partner) appear solely as a continuum
  - KK gluon / colored ρ_c



$$\mathcal{L}_E = a(z)\, e^{-\frac{4}{3}\mu(z-R)} \left[\frac{1}{4} F^{MN} F_{MN}\right]$$



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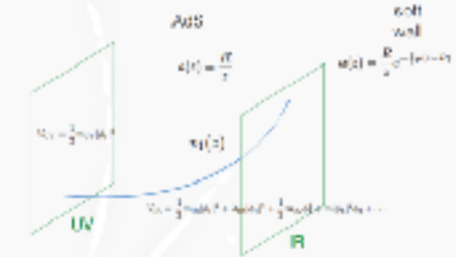

Csaki, Lombardo, Lee, SL, Telem

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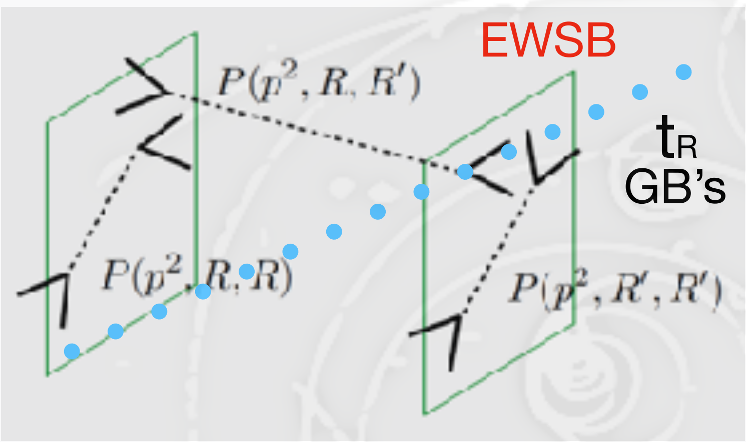
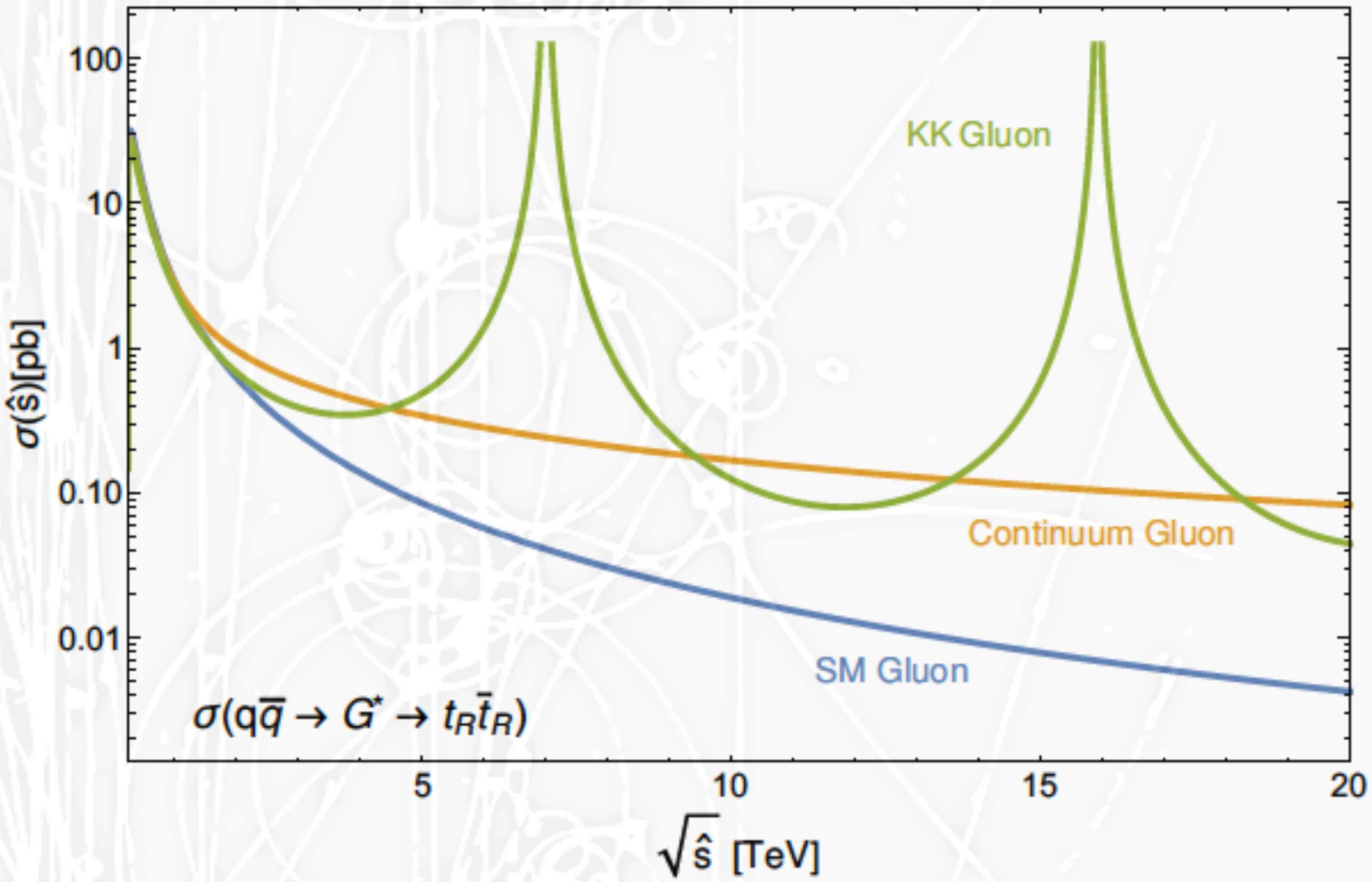




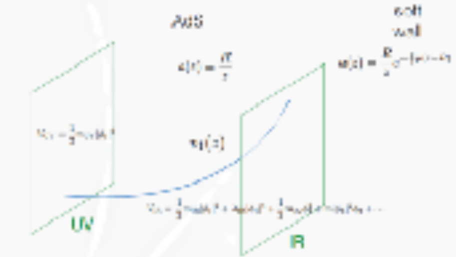
$$\mathcal{L}_E = a(z)\, e^{-\frac{4}{3}\mu(z-R)} \left[\frac{1}{4} F^{MN} F_{MN}\right]$$

$$-\hat{A}''(z) + V_{\text{eff}}(z)\hat{A}(z) \;=\; p^2 \hat{A}(z)$$

$$\hat{A}(z) = \sqrt{\frac{R}{z}}\, e^{-\mu(z-R)}\, A(z)$$

$$V_{\text{eff}}(z) = \mu^2 + \frac{\mu}{z} + \frac{3}{4z^2}$$

Continuum Naturalness?



Csaki, Lombardo, Lee, SL, Telem

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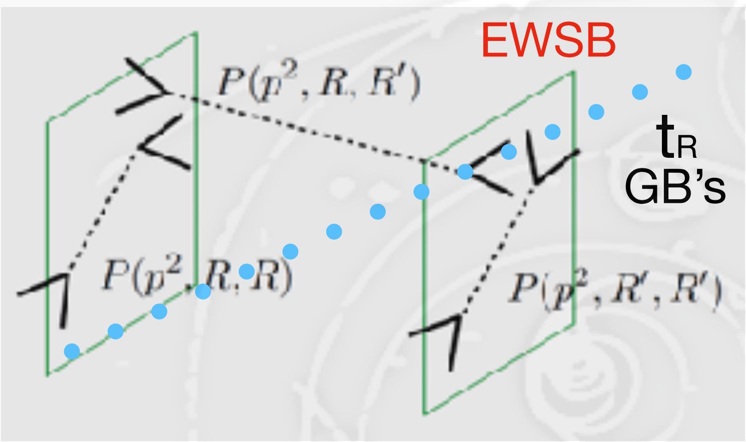

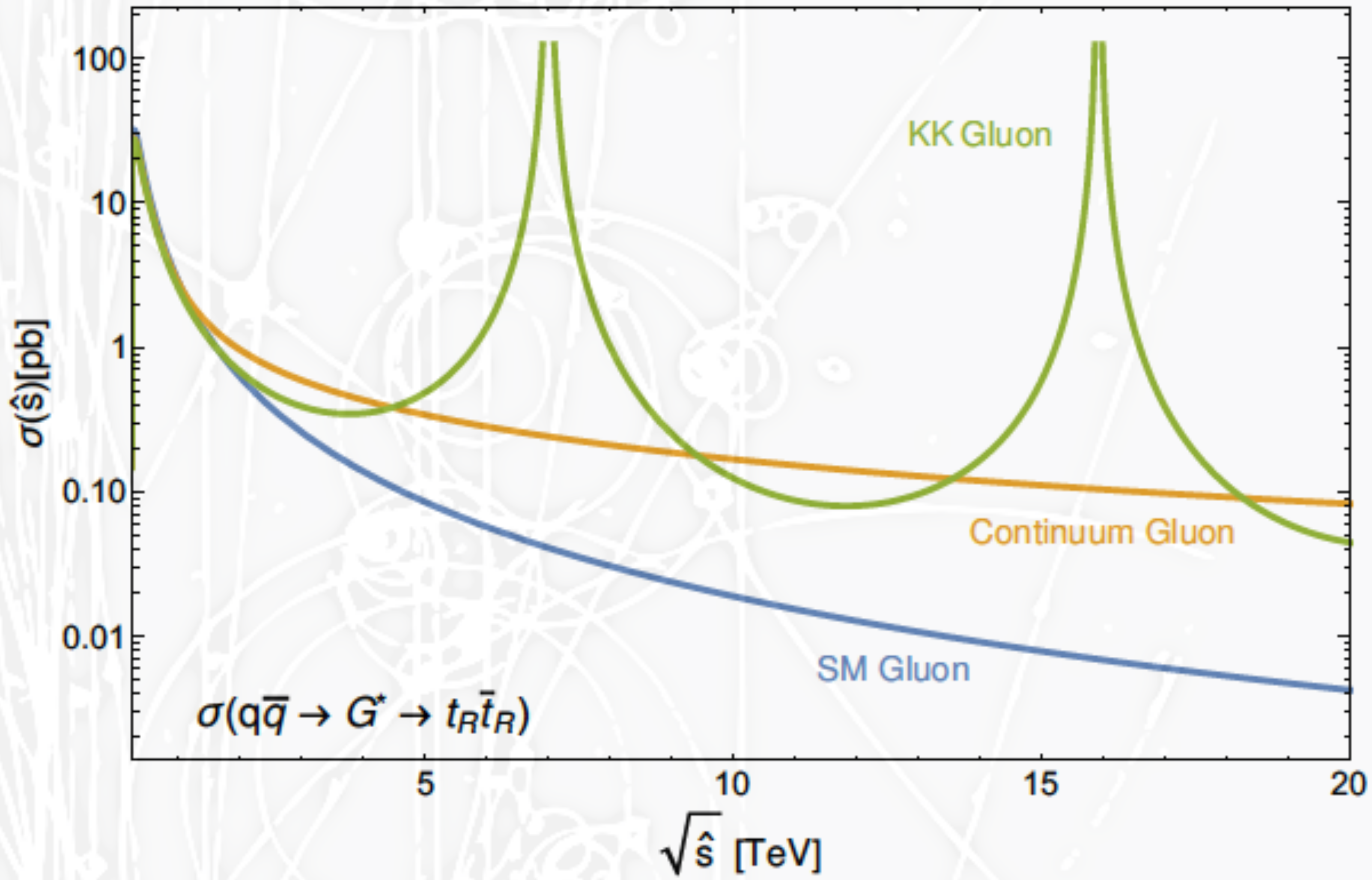

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Continuum Naturalness?

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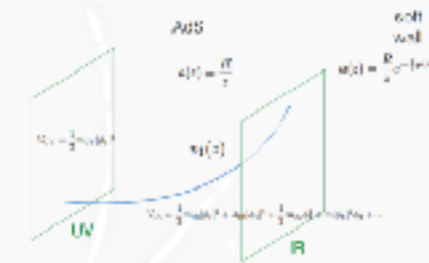

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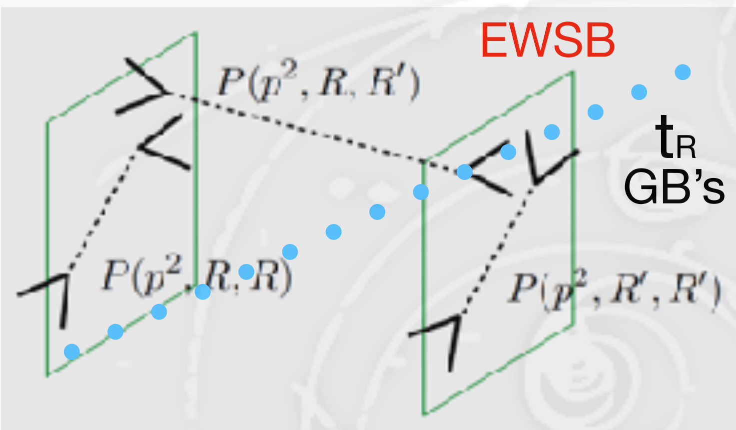

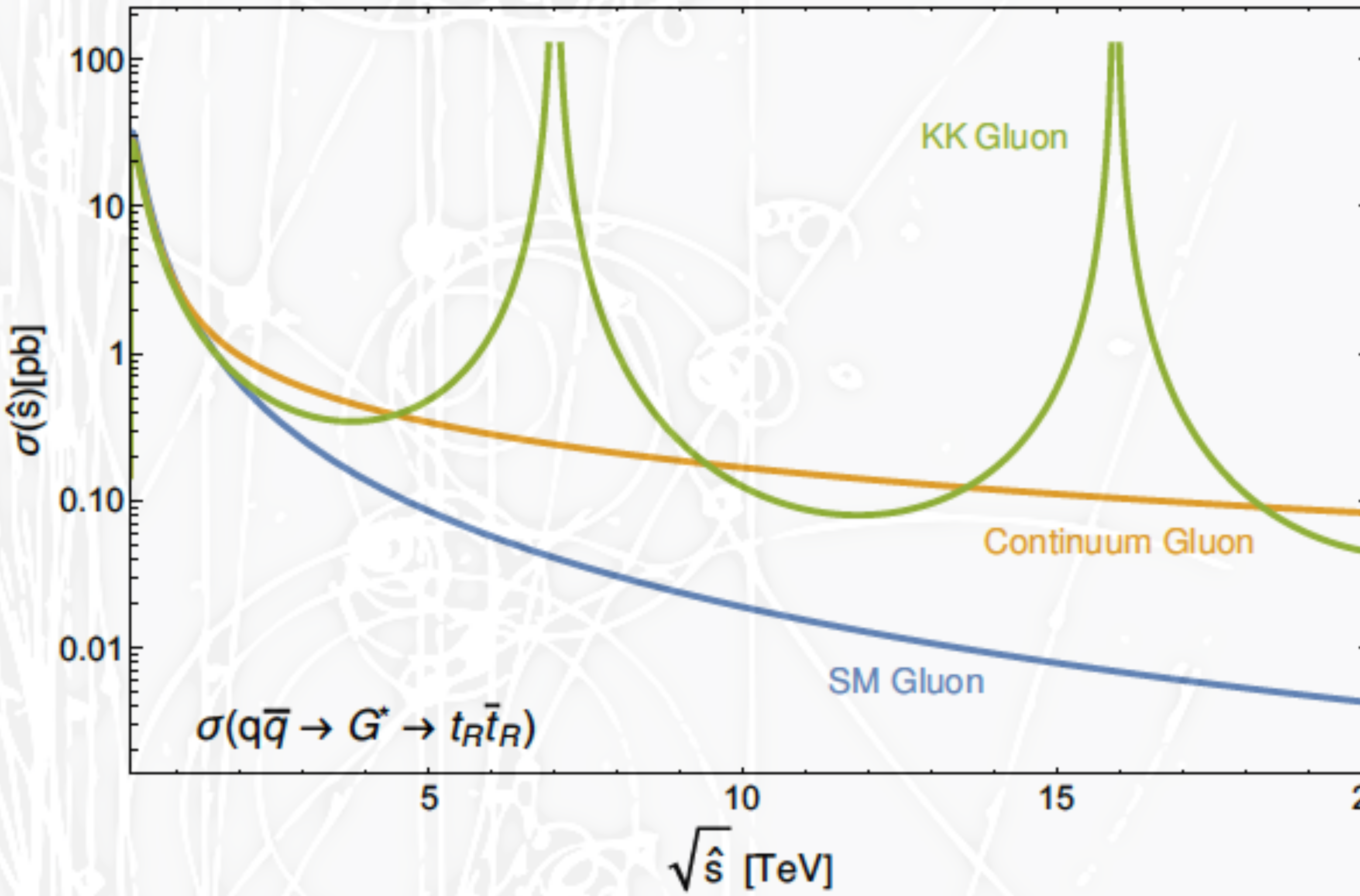

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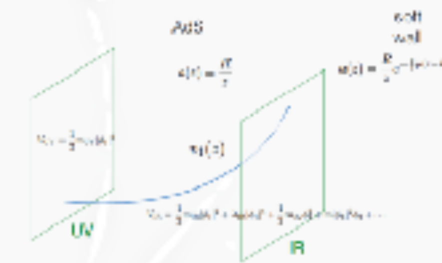
$$A(z) \;=\; A\sqrt{\frac{z}{R}}\, e^{\mu(z-R)}\, W\left(-\frac{\mu}{2\Delta}, 1; 2\Delta z\right) \qquad \Delta = \sqrt{\mu^2 - p^2}$$

$$\rho(s) \;=\; \frac{1}{\pi} \lim_{z\to 0} {\rm Im}\, \frac{A(z)}{A'(z)} \;=\; \frac{1}{2\pi s}\left[1 + i\psi\left(\frac{1}{2} + \frac{\mu}{2\Delta}\right) - i\psi\left(\frac{1}{2} - \frac{\mu}{2\Delta}\right)\right]$$

Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem



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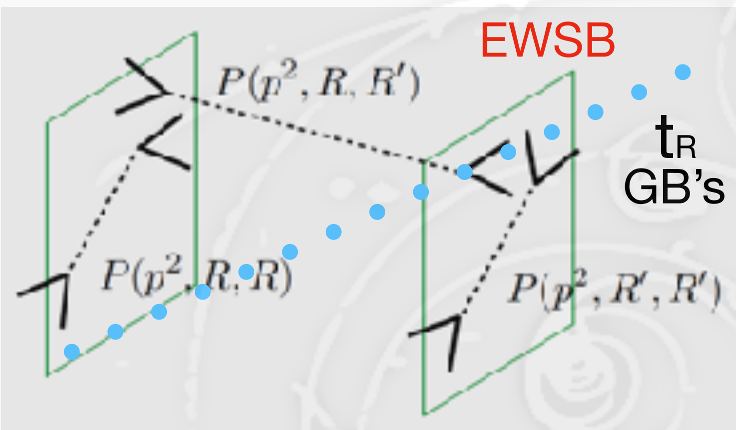

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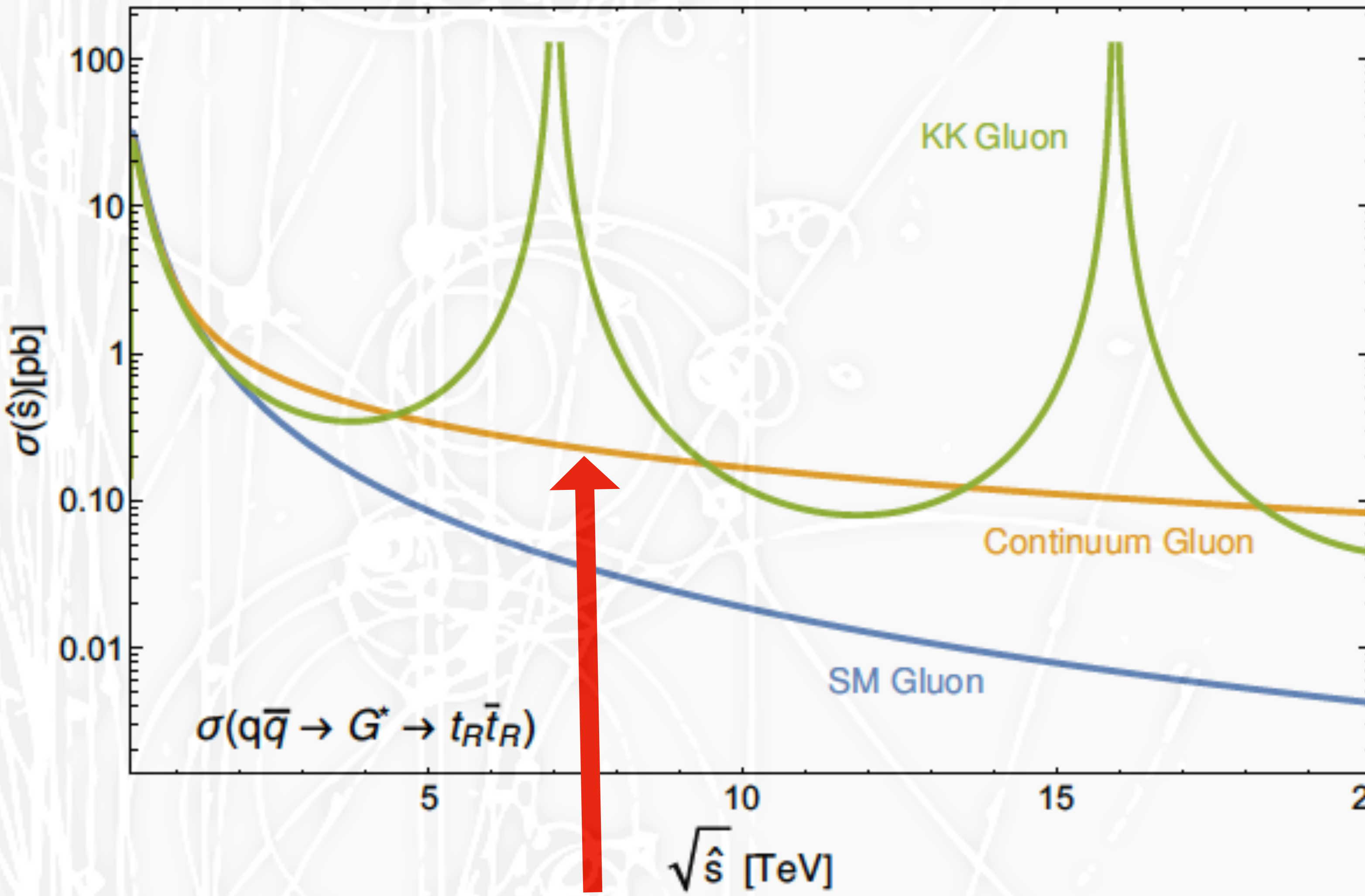

New Physics is hidden in the tail region!!

$$A(z) \;=\; A\sqrt{\frac{z}{R}}\, e^{\mu(z-R)}\, W\left(-\frac{\mu}{2\Delta}, 1; 2\Delta z\right) \qquad \Delta = \sqrt{\mu^2 - p^2}$$

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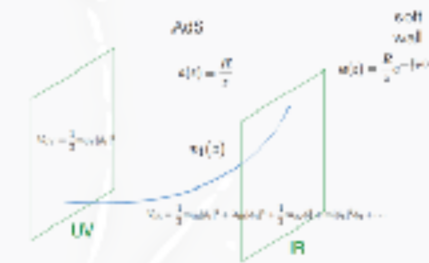
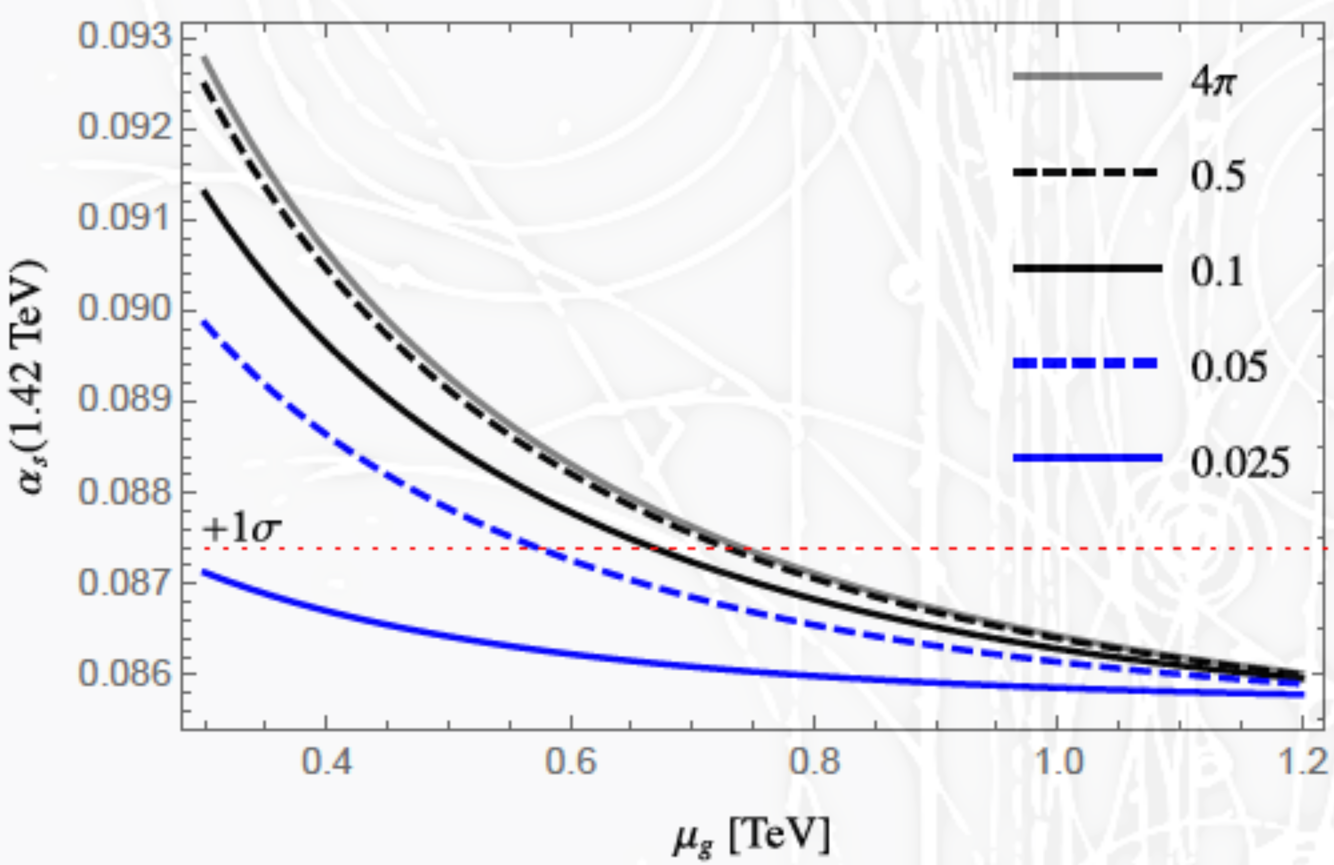


Csaki, Lombardo, Lee, SL, Telem

- New Physics (e.g. Top partner) appear solely as a continuum
  - KK gluon / colored octet example: running of strong coupling

e.g. CMS bound: α_s up to $Q \sim 1.42$ TeV

$$\frac{1}{g^2(Q)} = \frac{1}{g_5^2}\int_R^{1/Q} dz\, a(z) + \frac{1}{g_{\rm UV}^2} - \frac{b_{\rm UV}}{8\pi^2}\log\left(\frac{1}{RQ}\right)$$



$$\mu_g > 600 - 700 \text{ GeV}$$

Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem; to appear soon

- ♦ MCHM (Agashe, Contino, Pomarol) => continuum version
  - elementary fields which mix with the composite operators and the form factors: $\mathcal{L}_{\rm top} = \bar{t}_L\, \not{p}\, \Pi_L(p)\, t_L + \bar{t}_R\, \not{p}\, \Pi_R(p)\, t_R + \bar{t}_L\, M(p)\, t_R + h.c.$
  - 2-point function <tt> is given by

Källén-Lehmann

$$-i\Pi_t(p) = \frac{1}{\not{p} - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} = \int dm^2\, \frac{\not{p} + m}{p^2 - m^2}\rho_t(m^2)$$

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  - non-local effective action: $S_{\rm eff} = \int d^4x\, d^4y\, \bar{\psi}(x)(i\not{\partial}_y - m)\Sigma(x-y)\psi(y)$

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  - non-local effective action: $S_{\rm eff} = \int d^4x\, d^4y\, \bar{\psi}(x)(i\not{\partial}_y - m)\Sigma(x-y)\psi(y)$

  - gauge invariant way: $S_{\rm eff} = \int \frac{d^4p\, d^4k}{(2\pi)^8}\, \bar{\psi}(k)(\not{p}-m)\Sigma(p^2)F(k-p,p)$

$\rho_h = \frac{1}{\pi}{\rm Im}\Sigma^{-1}$

$F(x,y) = \mathcal{P}\exp\left(-igT^a \int_x^y A^a \cdot dw\right)\psi(y)$

Continuum States

Csaki, Lombardo, Lee, SL, Telem

- To describe the continuum (for example Weyl fermions)

$$\mathcal{L}_\chi = -i\bar{\chi}\bar{\sigma}^\mu p_\mu \chi \quad \rightarrow \quad \mathcal{L}_\chi^{\text{cont.}} = -i\bar{\chi}\frac{\bar{\sigma}^\mu p_\mu}{p^2 G(p^2)}\chi$$

- G proportional to the 2-point function

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

- Poles correspond to particles, branch cuts to continuum.

Characterized information written in terms of spectral density

$$G(p^2) = \int_0^\infty \frac{\rho(s)}{s - p^2 + i\epsilon} ds \quad , \quad \rho(s) = \frac{1}{\pi}\text{Im}G(s)$$

Spectral densities from 5D models

- In principle could just input the $\boldsymbol{\rho}$(s) spectral density, but don't know if it provides unitary, causal QFT

- To make sure we don't use inconsistent $\boldsymbol{\rho}$'s get them from 5D

- Old story: RS2 gives a model of continuum fermions without a gap (Cacciapaglia, Marandella, Terning)

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

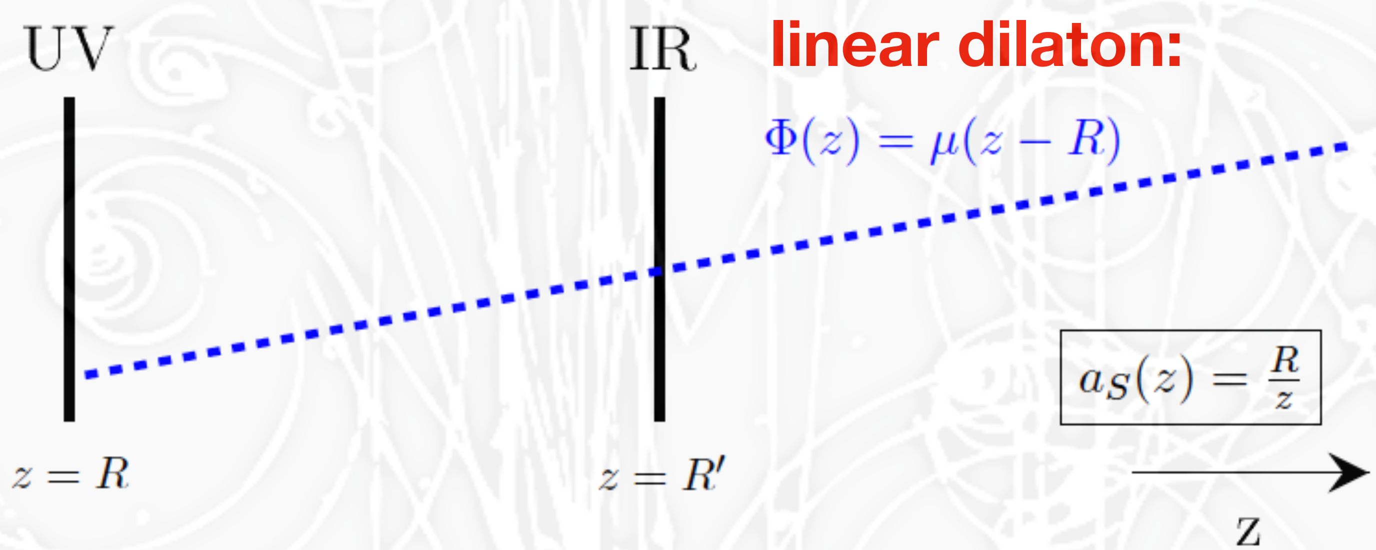
- Boundary RS2 Green's fn = 4D ungapped continuum fermion (``unparticle")

Continuum with mass gap

Csaki, Lombardo, Lee, SL, Telem

- To introduce mass gap, we need to modify the 5D background

- Introduce linear dilaton into AdS



- ***Φ***(z) linear dilaton - around the UV brane vanishing

→ won't have effect until IR (z~1/**μ**)

- Linear dilaton models the details of the IR dynamics

- theory gets close to fixed point but then gets gap

Continuum with mass gap

Csaki, Lombardo, Lee, SL, Telem

- Fermion EOM's in this background can be solved exactly
- Fermion Lagrangian in "string frame" $a_S(z) = \frac{R}{z}$

$$\mathcal{L}_S = e^{-2\Phi(z)} a_S^5(z) \left[a_S^{-1}(z)\mathcal{L}_{\rm kin} + \frac{1}{R}\left(c + y\,\Phi(z)\right)\left(\psi\chi + \bar\chi\bar\psi\right)\right]$$

bulk Yukawa coupling between the dilaton and the bulk fermion

- Kinetic term conventional

$$\mathcal{L}_{\rm kin} = -i\bar\chi\bar\sigma^\mu p_\mu \chi - i\psi\sigma^\mu p_\mu\bar\psi + \frac{1}{2}\left(\psi\overleftrightarrow{\partial}_5\chi - \bar\chi\overleftrightarrow{\partial}_5\bar\psi\right)$$

- Go to Einstein frame to see physics best $a(z) = a_S(z)\, e^{-\frac{2}{3}\Phi(z)}$

$$\mathcal{L}_E = a^4(z)\mathcal{L}_{\rm kin} + a^5(z)\frac{\hat c(z)}{R}\left(\psi\chi + \bar\chi\bar\psi\right)$$

- Effective mass parameter $\hat c(z) \equiv (c + y\Phi(z))e^{\frac{2}{3}\Phi(z)}$

Solutions to the bulk equations

Csaki, Lombardo, Lee, SL, Telem

- Schrödinger form for the EOM

$$-\hat{\chi}''(z) + V_{\rm eff}(z)\,\hat{\chi}(z) \;=\; p^2\hat{\chi}(z)\,, \qquad \hat{\chi}(z) = \left(\tfrac{R}{z}\right)^2\chi(z)$$

- Effective potential

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

- Gapped continuum if $V_{\rm eff}(z\to\infty) = \text{const} > 0$

- To achieve that, need a linear dilaton

$$\Phi(z) \;=\; \mu(z-R) \;\text{with}\; \mu \sim 1\,\text{TeV}$$

- will give: $V_{\rm eff}(z\to\infty) = y^2\mu^2$

→ **gap will show at** $y\mu$

Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem

- 5D holographic model with a linear dilaton

$$S_f = \int d^5x\, a(z)^4 \bar{\Psi} \left(i\gamma^M \partial_M + 2i \frac{a'(z)}{a(z)} \gamma^5 - \frac{a(z)c(z)}{R} \right)$$

$$c(z) = (c + \mu(z - R))\, e^{\frac{2}{3}\mu(z-R)}$$

$$-i\bar{\sigma}^\mu \partial_\mu \chi - \partial_5 \bar{\psi} - 2\frac{a'}{a}\bar{\psi} + \frac{ac}{R}\bar{\psi} = 0$$

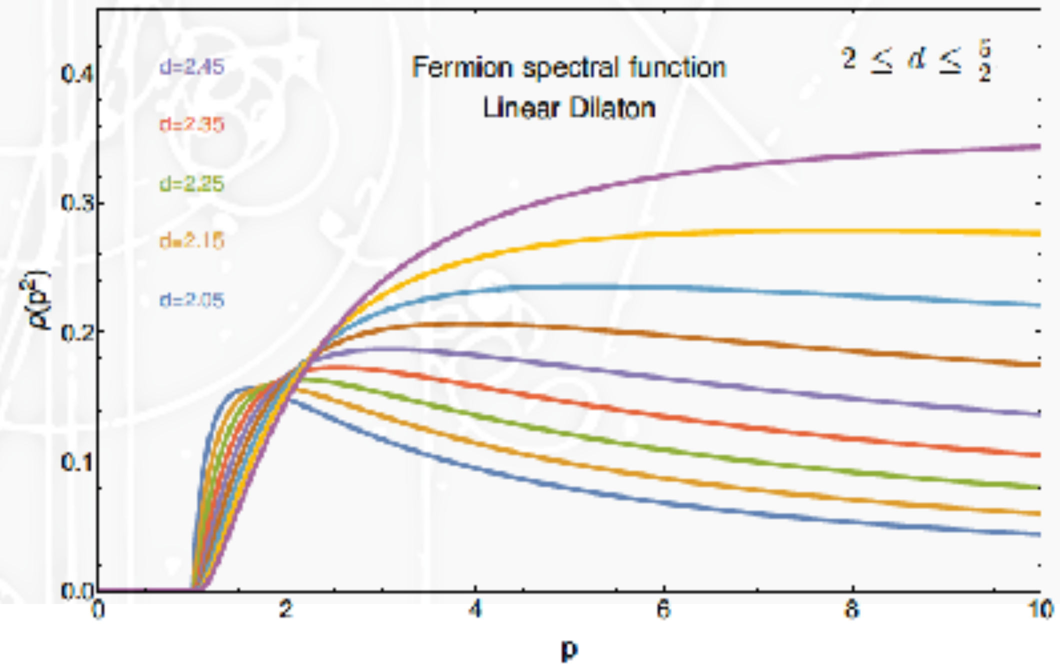
$$-i\sigma^\mu \partial_\mu \bar{\psi} + \partial_5 \chi + 2\frac{a'}{a}\chi + \frac{ac}{R}\chi = 0.$$

$$\chi = g(z)\chi(z)$$

$$\bar{\psi}(z) = f(z)\bar{\psi}(x)$$

$$g(z) = a^{-2}\Big[A\, M\left(\kappa, 1/2 + c - R\mu, 2z\sqrt{\mu^2 - m^2}\right) + B\, W\left(\kappa, 1/2 + c - R\mu, 2z\sqrt{\mu^2 - m^2}\right)\Big],$$

$$f(z) = a^{-2}\Big[C\, M\left(\kappa, 1/2 - c + R\mu, 2z\sqrt{\mu^2 - m^2}\right) + D\, W\left(\kappa, 1/2 - c + R\mu, 2z\sqrt{\mu^2 - m^2}\right)\Big],$$



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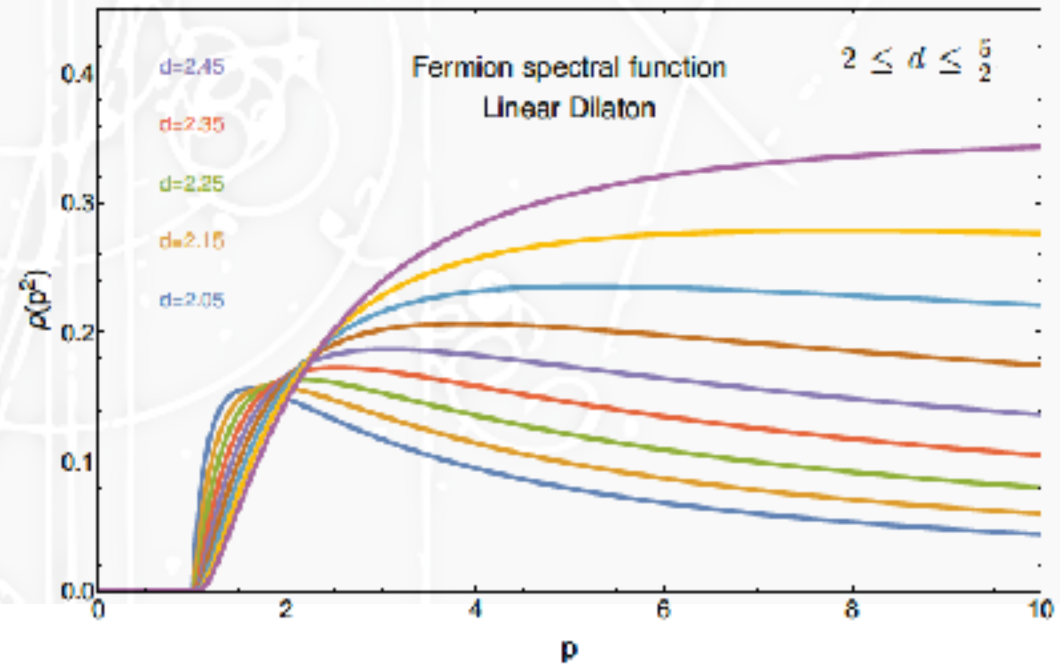
– profile of continuum depends on the scaling dimension of the fields



A Realistic Model

- Need the usual Composite Higgs setup in addition

- Bulk gauge group $G = SO(5) \times U(1)_X$ → $SO(4) \times U(1)_X$
  breaking on IR brane via BCs

- On UV brane, $G = SO(5) \times U(1)_X$ → $SU(2)_L \times U(1)_Y$

  $Y = T_R^3 + X$

- Wilson line for Higgs: $i g_5 \int_R^{R'} A_5 \, dz$

  (No other physical Wilson line beyond IR brane)

- Bulk fermions

$$Q_L(\mathbf{5})_{\frac{2}{3}} \to q_L(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_L(\mathbf{2})_{\frac{7}{6}} + y_L(\mathbf{1})_{\frac{2}{3}},$$

$$T_R(\mathbf{5})_{\frac{2}{3}} \to q_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}_R(\mathbf{2})_{\frac{7}{6}} + t_R(\mathbf{1})_{\frac{2}{3}},$$

$$B_R(\mathbf{10})_{\frac{2}{3}} \to q'_R(\mathbf{2})_{\frac{1}{6}} + \tilde{q}'_R(\mathbf{2})_{\frac{7}{6}} + x_R(\mathbf{3})_{\frac{2}{3}} + y_R(\mathbf{1})_{\frac{7}{6}} + \tilde{y}_R(\mathbf{1})_{\frac{1}{6}} + b_R(\mathbf{1})_{-\frac{1}{3}}$$

A Realistic Model

- To generate Yukawa couplings, need localized mass terms

$$S_{\rm IR} = \int d^4x \sqrt{g_{\rm ind}} \left[M_1 \bar{z}_L t_R + M_4 \left(\bar{q}_L q_R + \bar{\tilde{q}}_L \tilde{q}_R \right) + M_b \left(\bar{q}_L q'_R + \bar{\tilde{q}}_L \tilde{q}'_R \right) \right]$$

- A realistic benchmark point

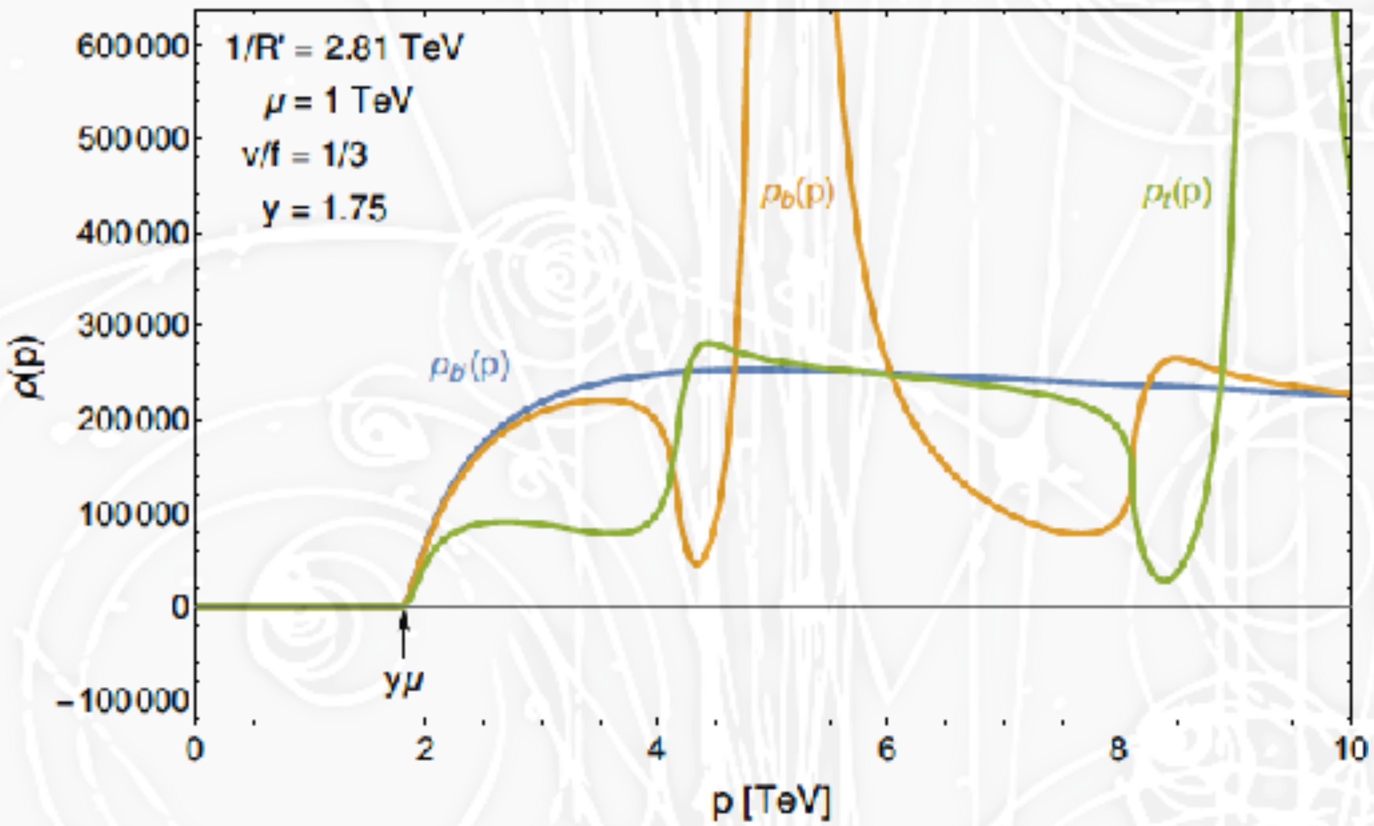
$$R/R' = 10^{-16},\ 1/R' = 2.81\ \text{TeV},\ \mu = 1\ \text{TeV},\ y = 1.75,$$
$$r = 0.975,\ \sin\theta = 0.39,$$
$$c_Q = 0.2,\ c_T = -\,0.22,\ c_B = -0.03,$$
$$M_1 = 1.2,\ M_4 = 0,\ M_b = 0.017\,.$$

- All SM parameters correctly reproduced with top slightly a bit light

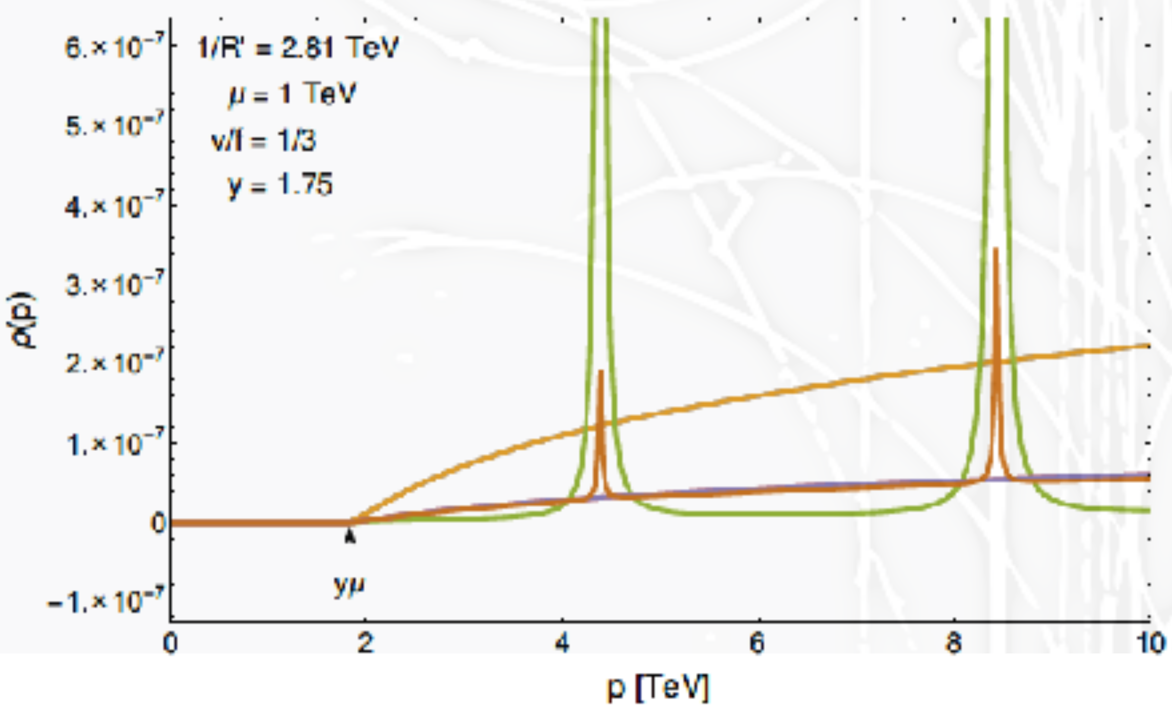
- Choose safe point where gauge cont. at 1 TeV, fermion at 1.75 TeV

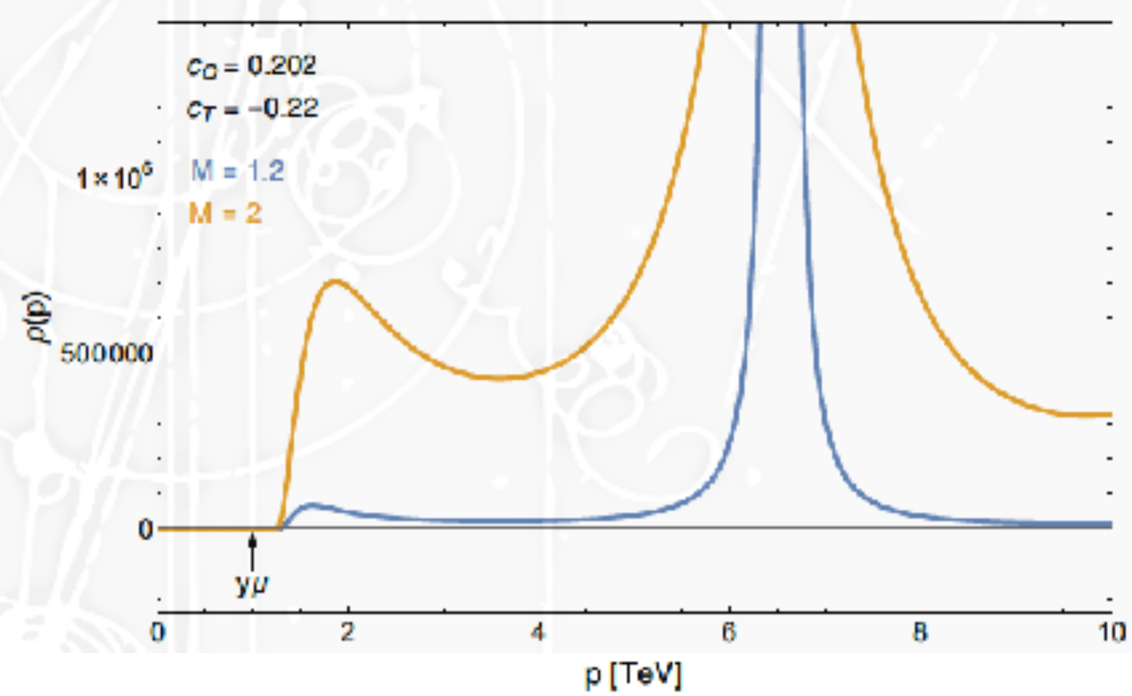
Fermionic Spectrum

- Fermion spectral densities. 3rd generation all very broad



- Exotic top partners- model dependent, could be probed as resonance at 100TeV collider



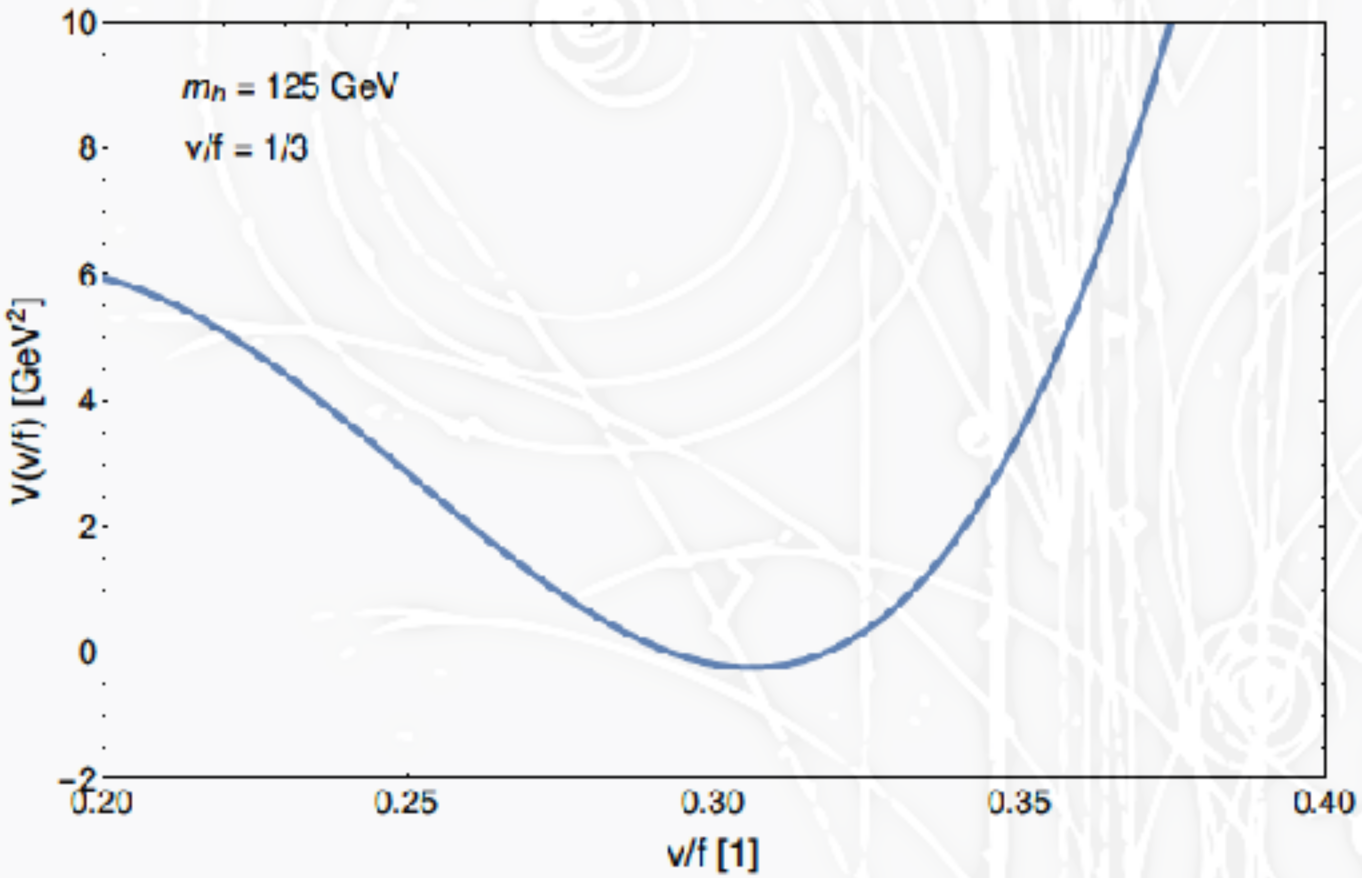


Continuum Top Partners

Csaki, Lombardo, Lee, SL, Telem; to appear soon

- Higgs Potential: $V(h) = \frac{3}{16\pi^2}\int dp\, p^3 \left[-4\sum_{j=1}^{20}\log G_{f_j}(ip) + \sum_{k=1}^{4}\log G_{g_k}(ip)\right]$

$$\text{tuning} = \left[\max_i \frac{d\log v}{d\log p_i}\right]^{-1} \qquad p_i \in \{R, R', \mu, r, \theta, y, c_Q, c_T, c_B, M_1, m_4, M_d\}$$



$$R/R' = 10^{-16},\ 1/R' = 2.81\text{ TeV},\ \mu = 1\text{ TeV},\ y = 1.75,$$
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fermion continuum starts at $y\mu = 1.75$ TeV

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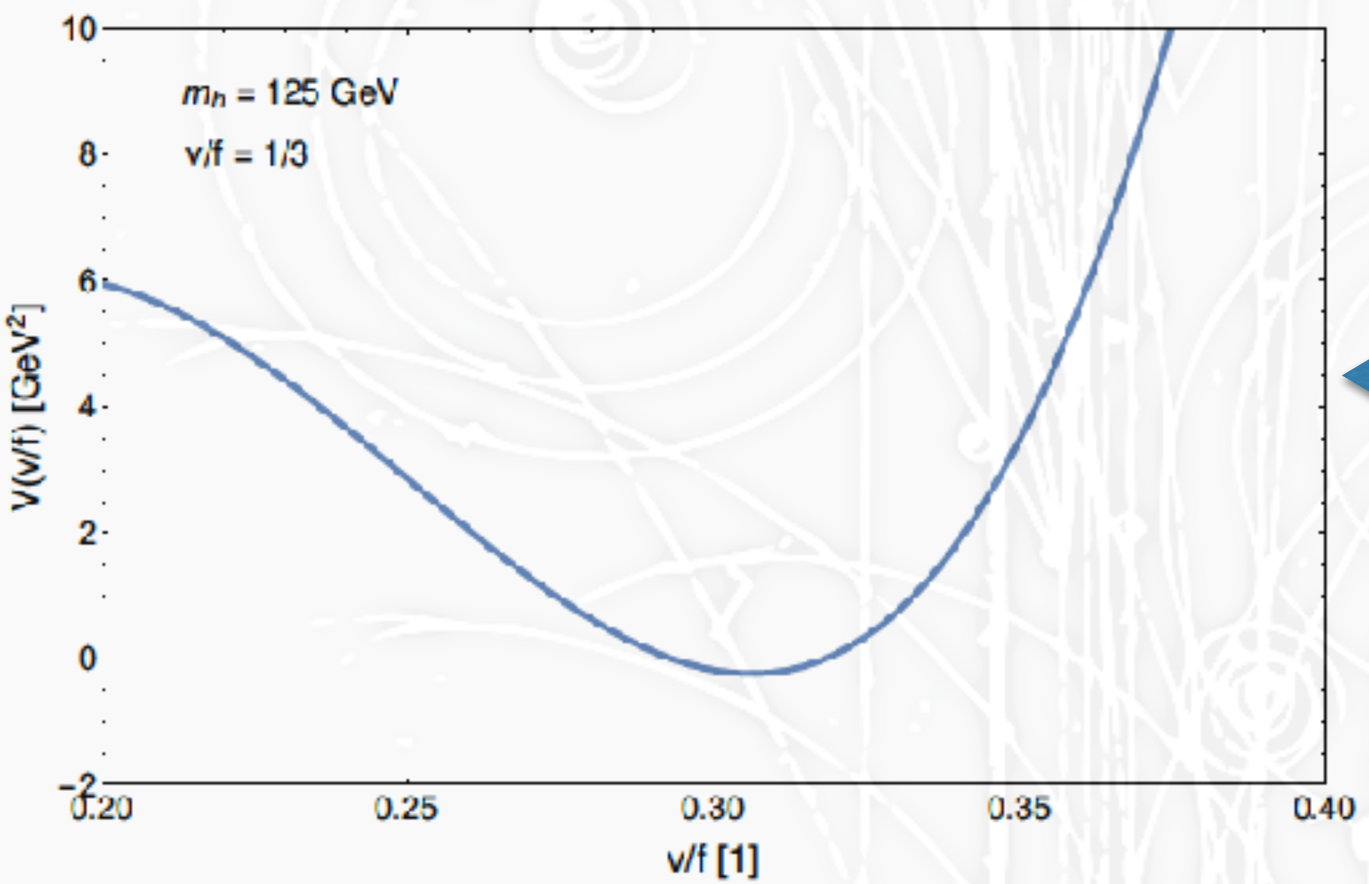

fermion continuum starts at $y\mu = 1.75$ TeV

➜ 1% tuning

c.f.: with the same set up, usual composite Higgs model has 0.1% tuning

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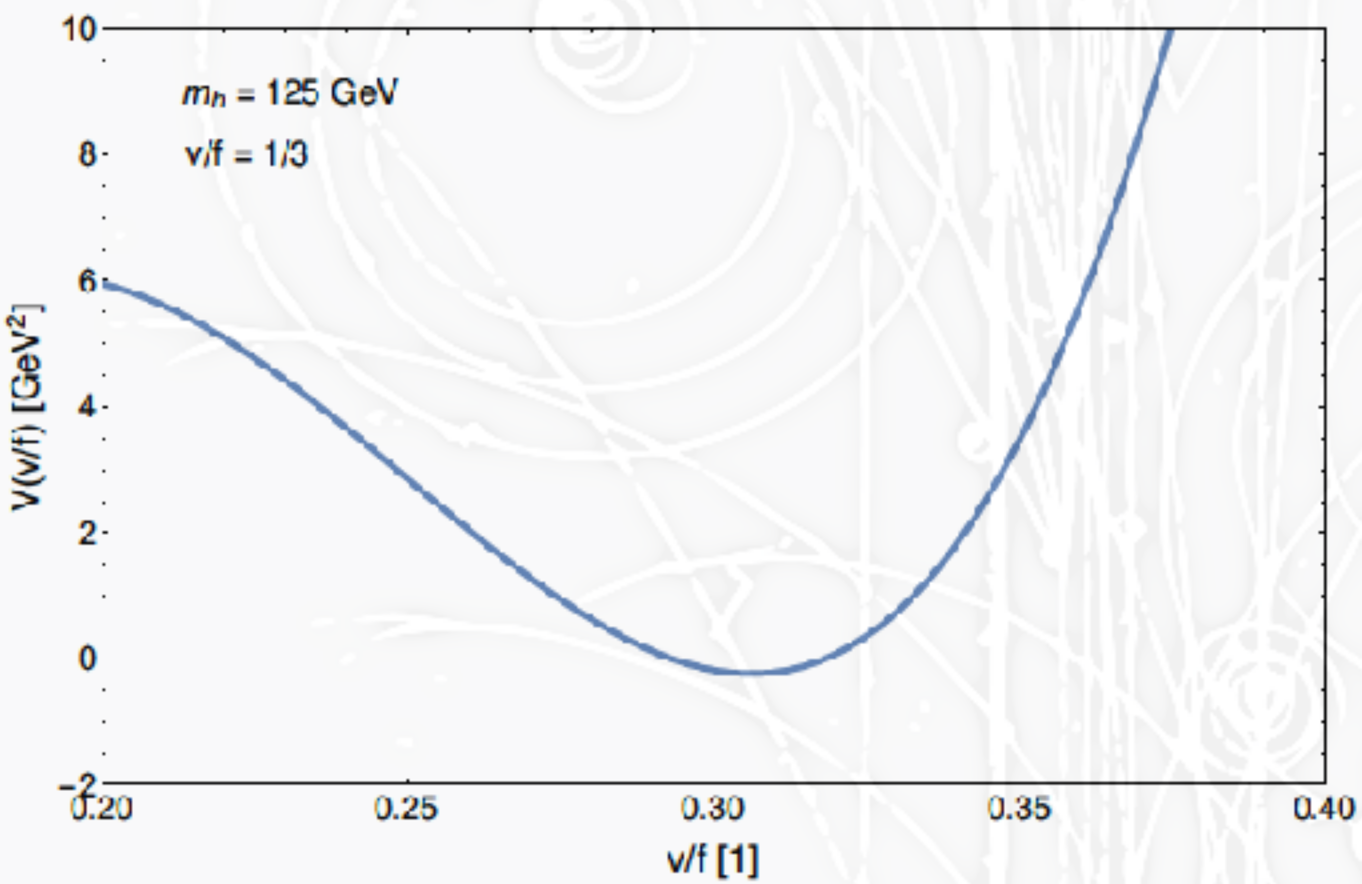

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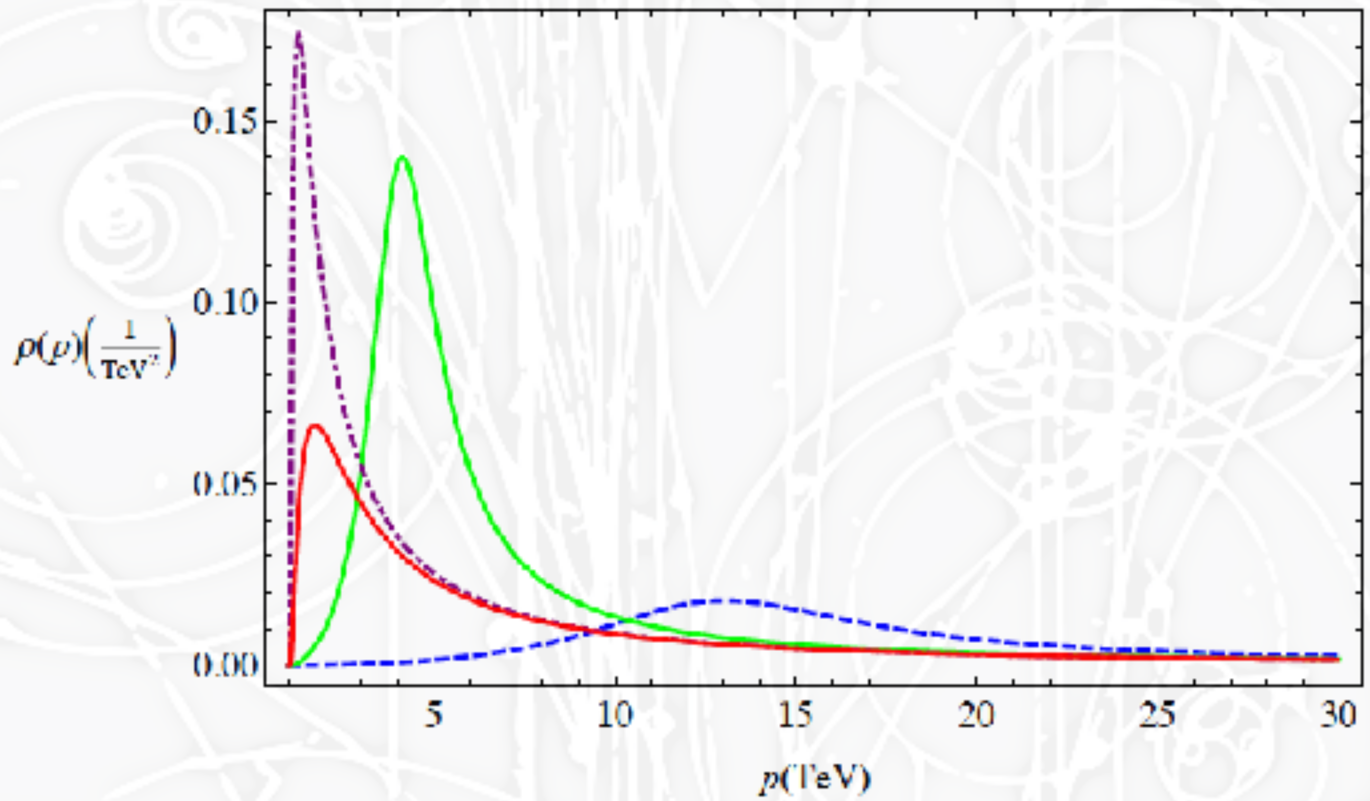
fermion continuum starts at $y\mu = 1.75$ TeV

Continuum Super-Partners

[amazing phD students: Ali Shayegan, Christina Gao, Jun Seok Lee], SL, Terning, work in progress

- New Physics (e.g. Top partner) appear solely as a continuum

  -SUSY + soft-wall (CFT with IR cutoff):



Cai, Cheng, Medina, Terning (09')

-combined to give gaugino mediation (solving flavor problem): hiding gaugino decaying into multiple leptons and missing ET

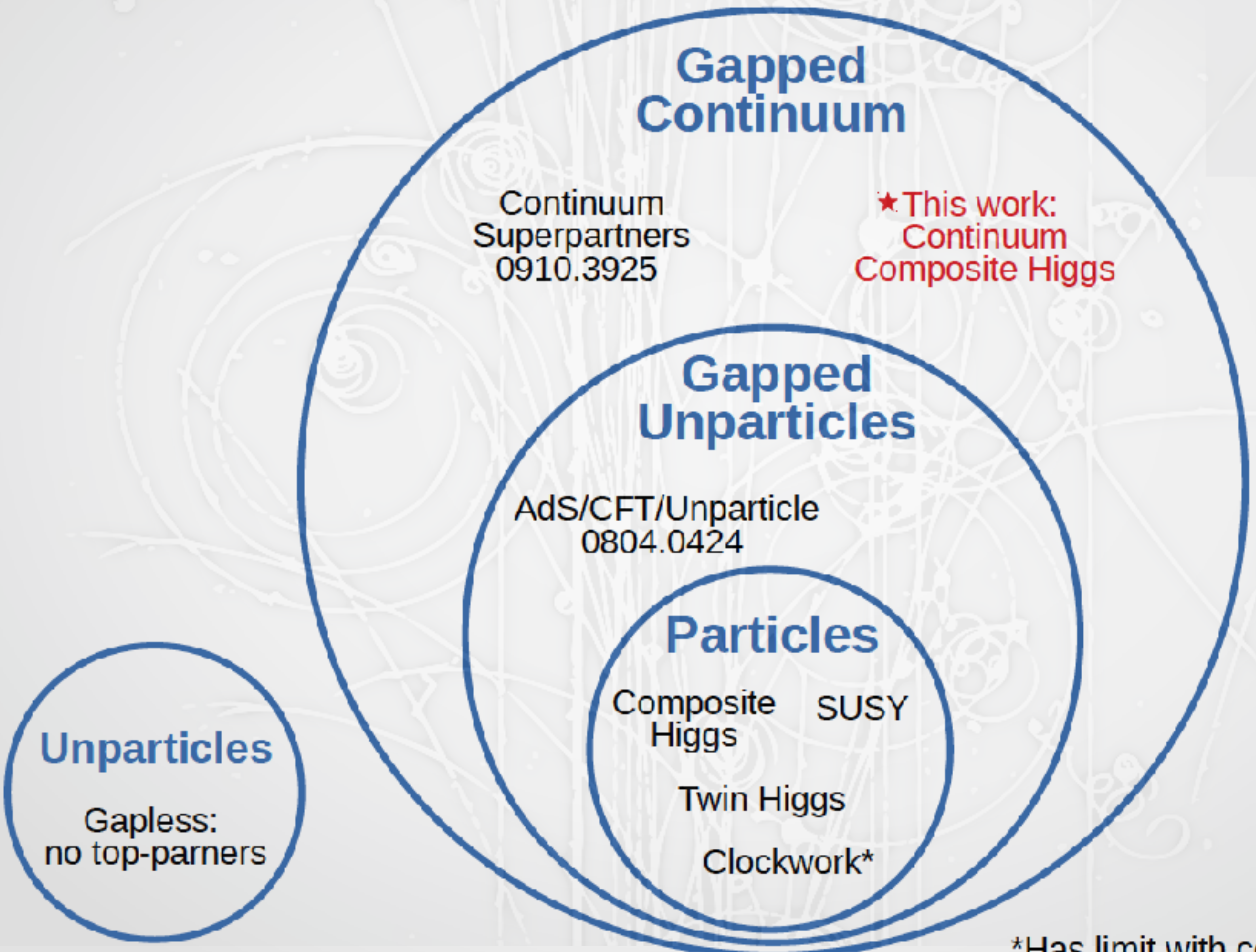
Summary

- The presence of a continuum can drastically change the LHC phenomenology of new BSM resonances

- we provided a model where the strong dynamics of confinement furnishes a continuum and bound states which mix together

- new signals:
  - enhancements to off-shell behavior of SM DOFs from mixing with continuum
  - top partners and New Physics may be hidden in the tail!

Summary



*Has limit with continuum partners

Merci beaucoup