Seventh Workshop on Theory, Phenomenology and Experiments in Flavour Physics - FPCapri2018
8-10 June 2018 *Villa Orlandi, Anacapri, Capri Island, Italy*
Europe/Rome timezone

Continuum Top Partners

Seung J. Lee

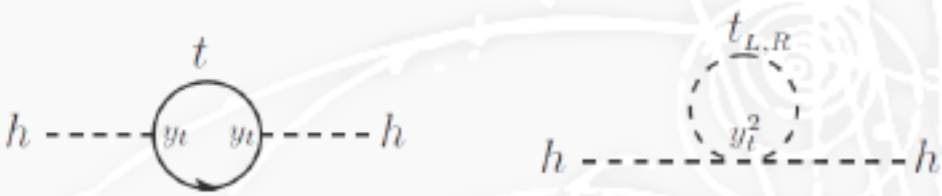
With B. Bellazzini, C. Csaki, J. Hubisz, J. Serra, J. Terning; PRX 2016
With C. Csaki, S. Lombardo; work in progress
With C. Csaki, S. Lombardo, G. Lee, O. Telem; work in progress
With J. Terning and amazing students; work in progress
With M. Park and Z. Qian; work in progress

KOREA UNIVERSITY

June 9, 2018

Naturalness Paradigm Under Pressure

Naturalness => new colored partners, potentially within the LHC reach.



$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

2 leading frameworks
of naturalness

AdS/CFT
warped extra dimension

Supersymmetry
top partners=stops

Composite Higgs
top partners = "T"

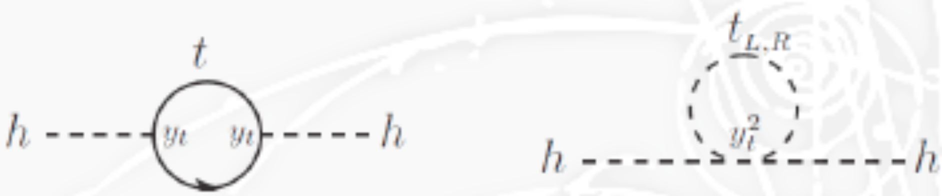
Well, Higgs is just another fundamental scalar bosons, and more is coming…!
m_{stop} > 1 TeV

No, Higgs is just another composite resonance we are familiar with …!

Naturalness Paradigm Under Pressure

Naturalness => new colored partners, potentially within the LHC reach.

*Neutral Naturalness is not discussed in this talk



$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

2 leading frameworks
of naturalness

AdS/CFT
warped extra dimension

Supersymmetry
top partners=stops

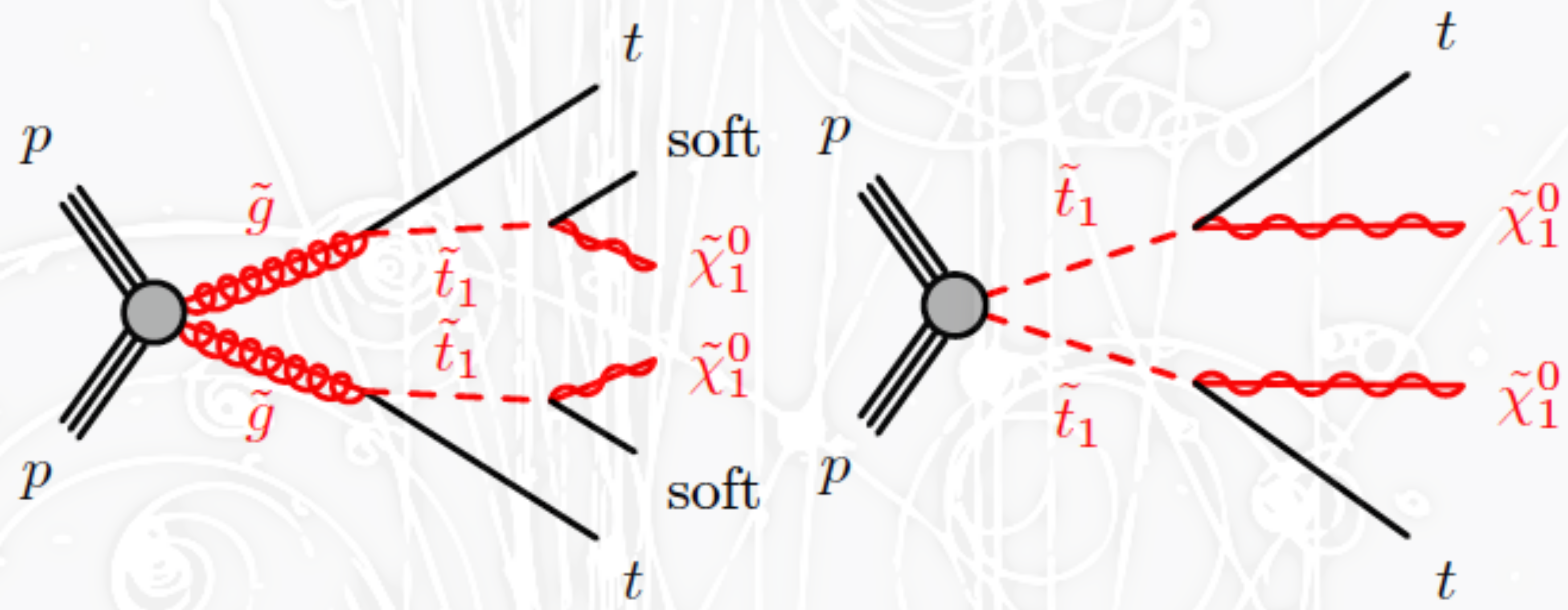
Composite Higgs
top partners = "T"

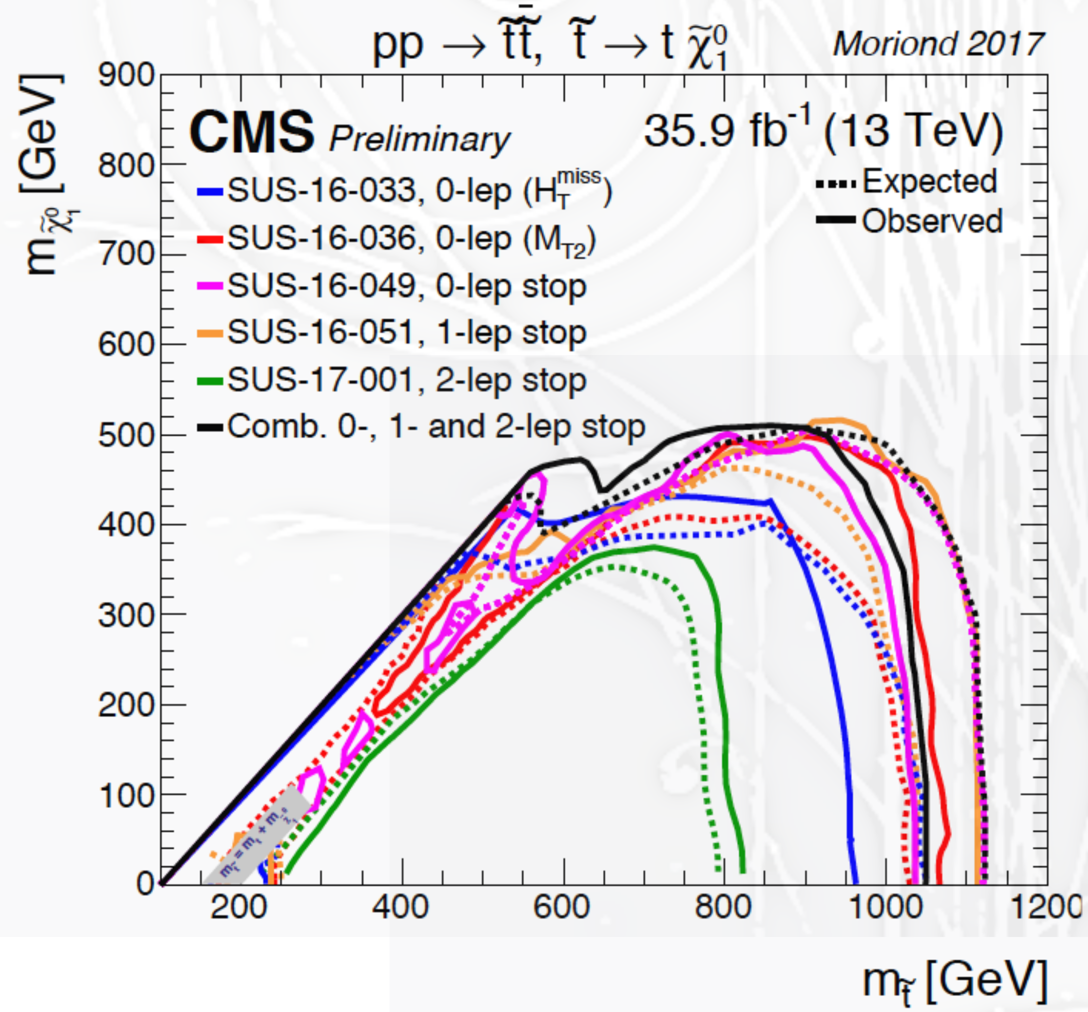
Well, Higgs is just another fundamental scalar bosons, and more is coming…!
m_{stop} > 1 TeV

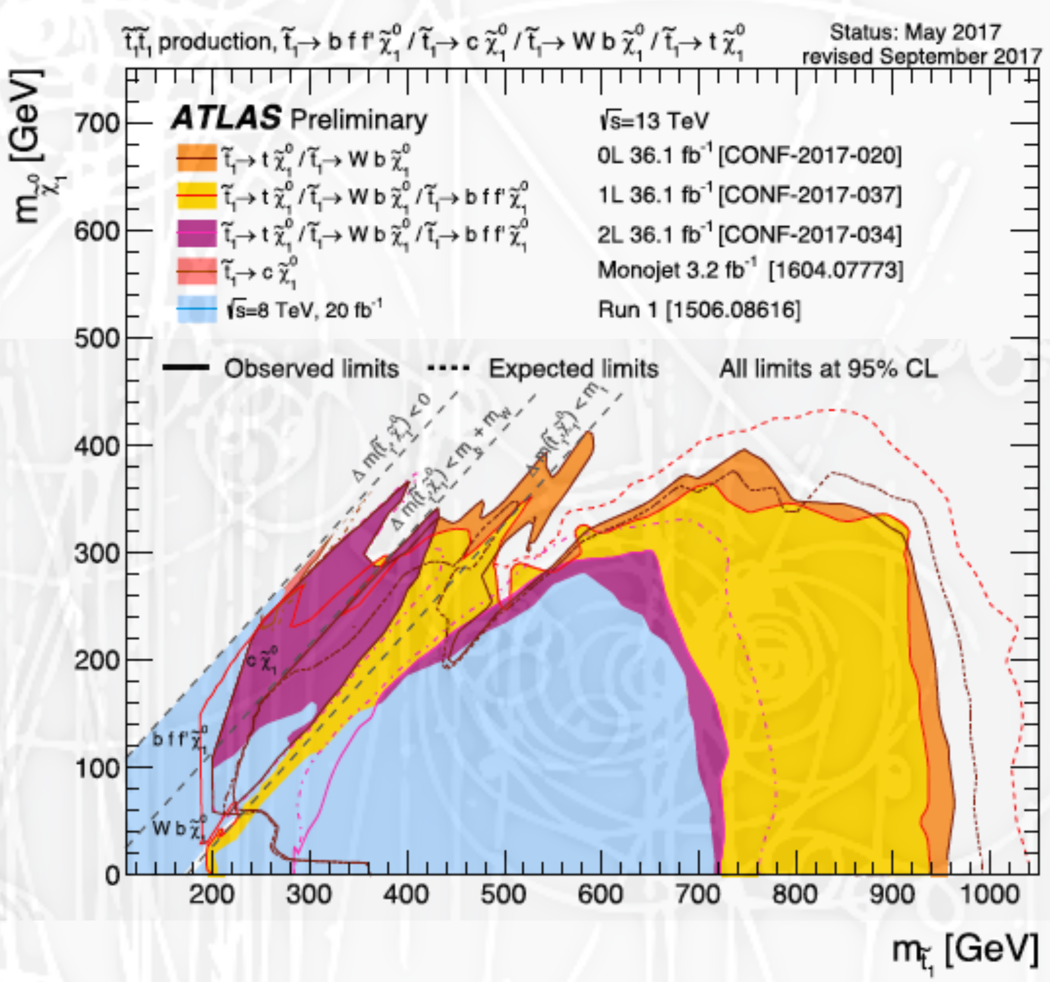
No, Higgs is just another composite resonance we are familiar with …!

SUSY top partner searches

see Greg Landsberg's and Lucia MASETTI's talk today



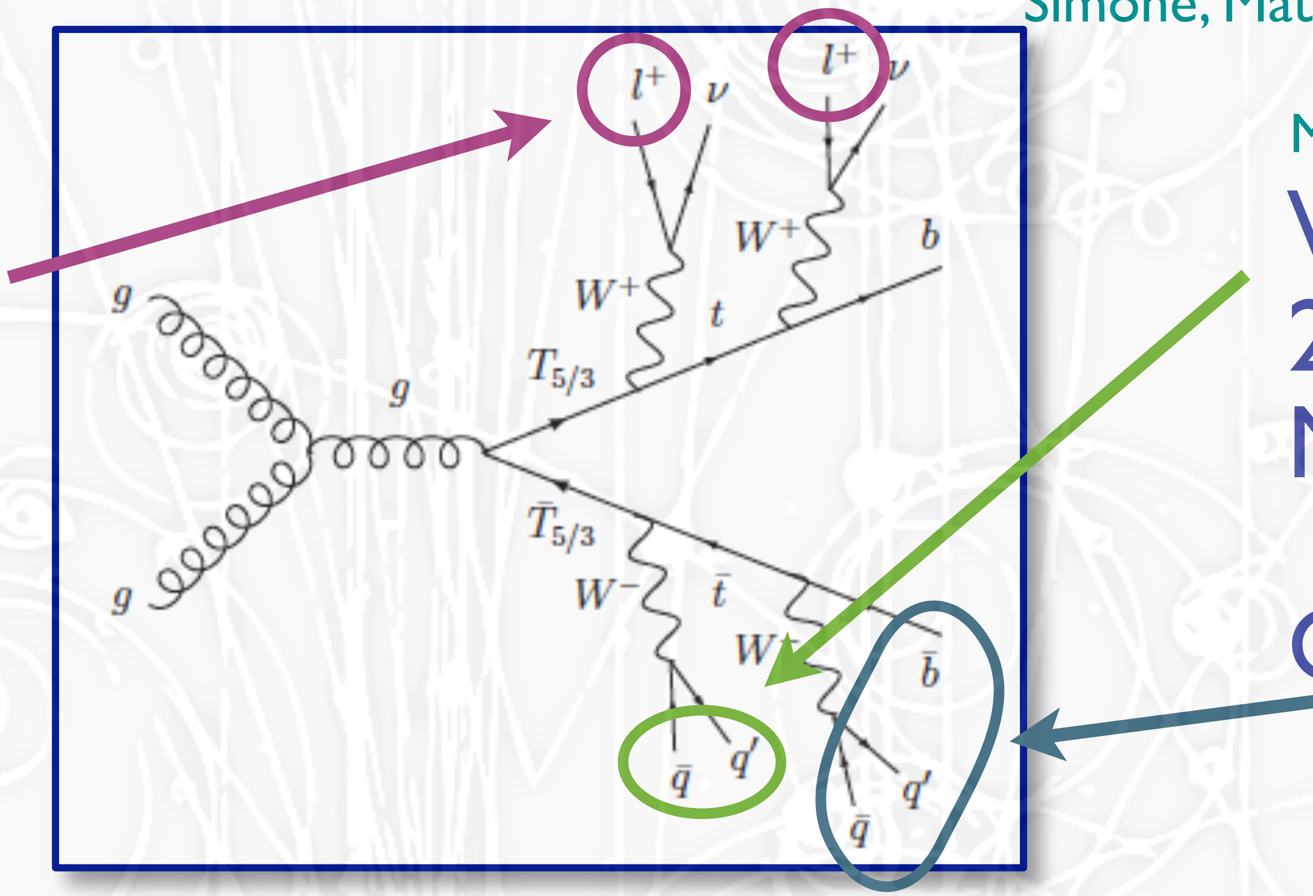




Composite Top Partner Searches

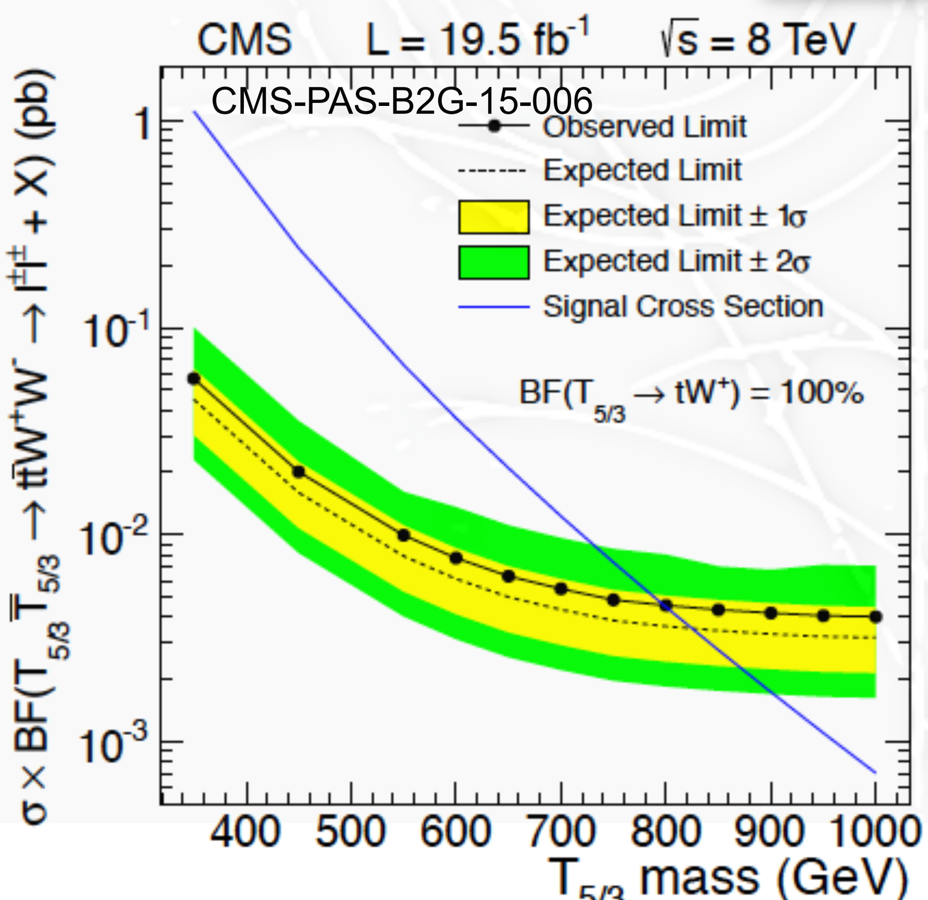
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



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

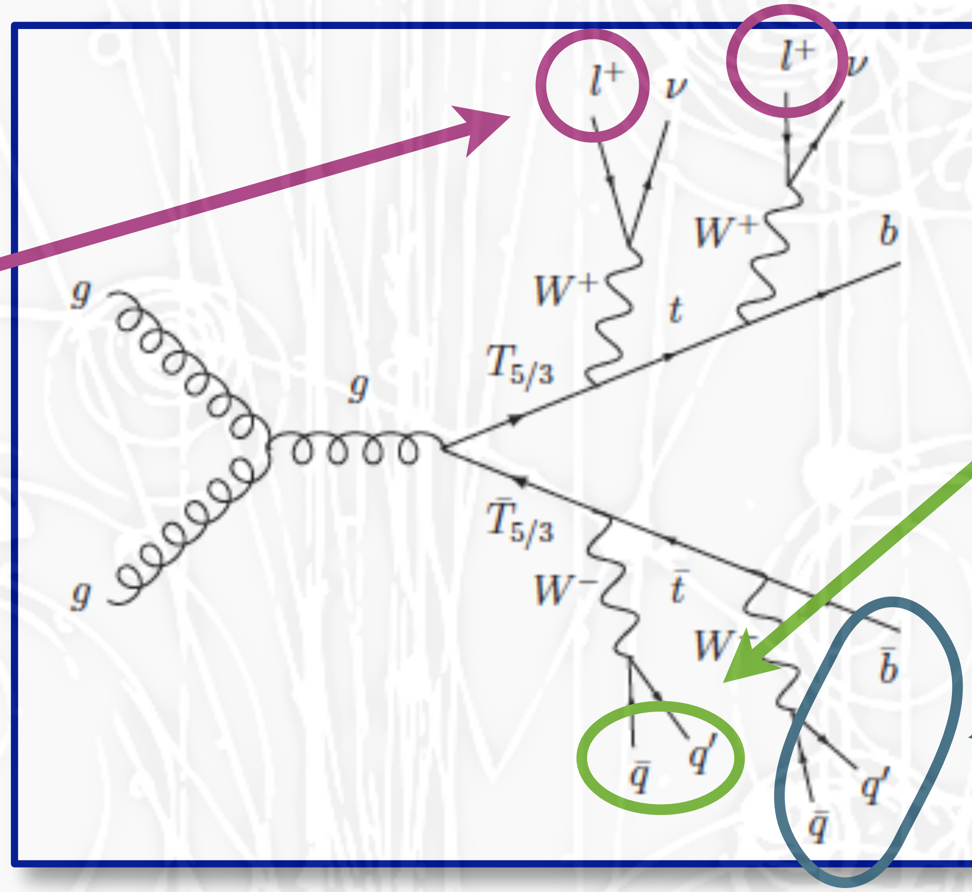
CMS top tag



Composite Top Partner Searches

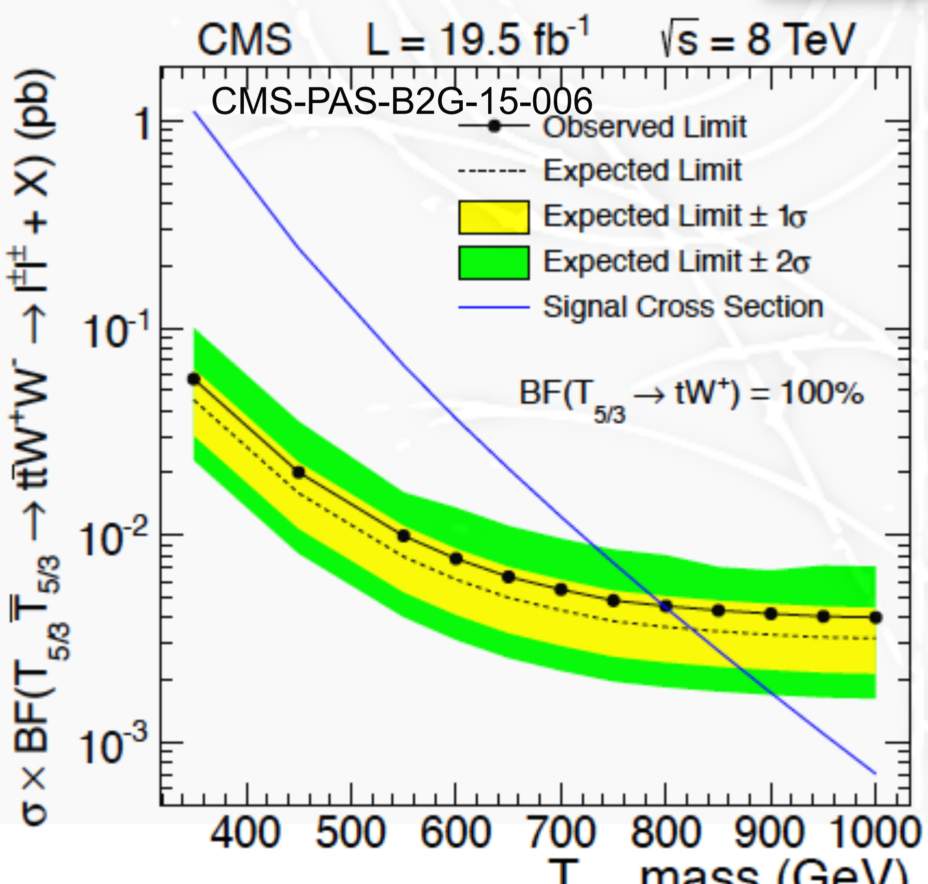
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



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

CMS top tag



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

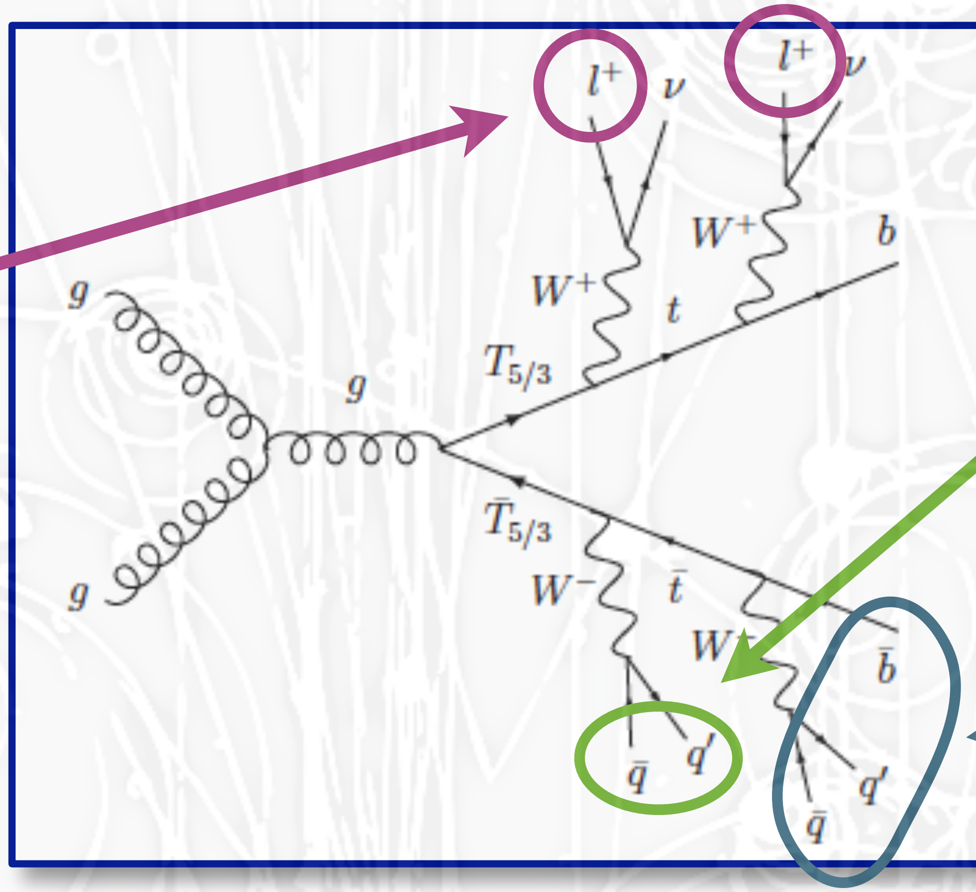
Grojean, Matsedonskyi, Panico `13

Ciuchini, Franco, Mishima, Silvestrini `13

Composite Top Partner Searches

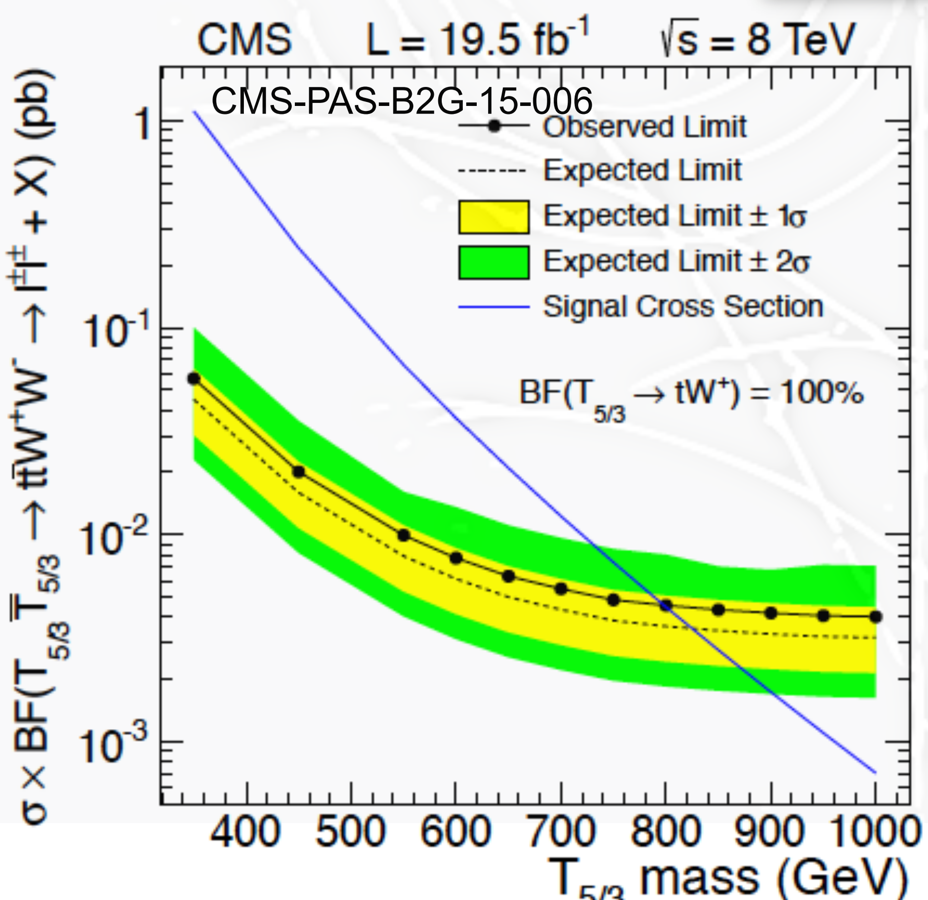
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



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

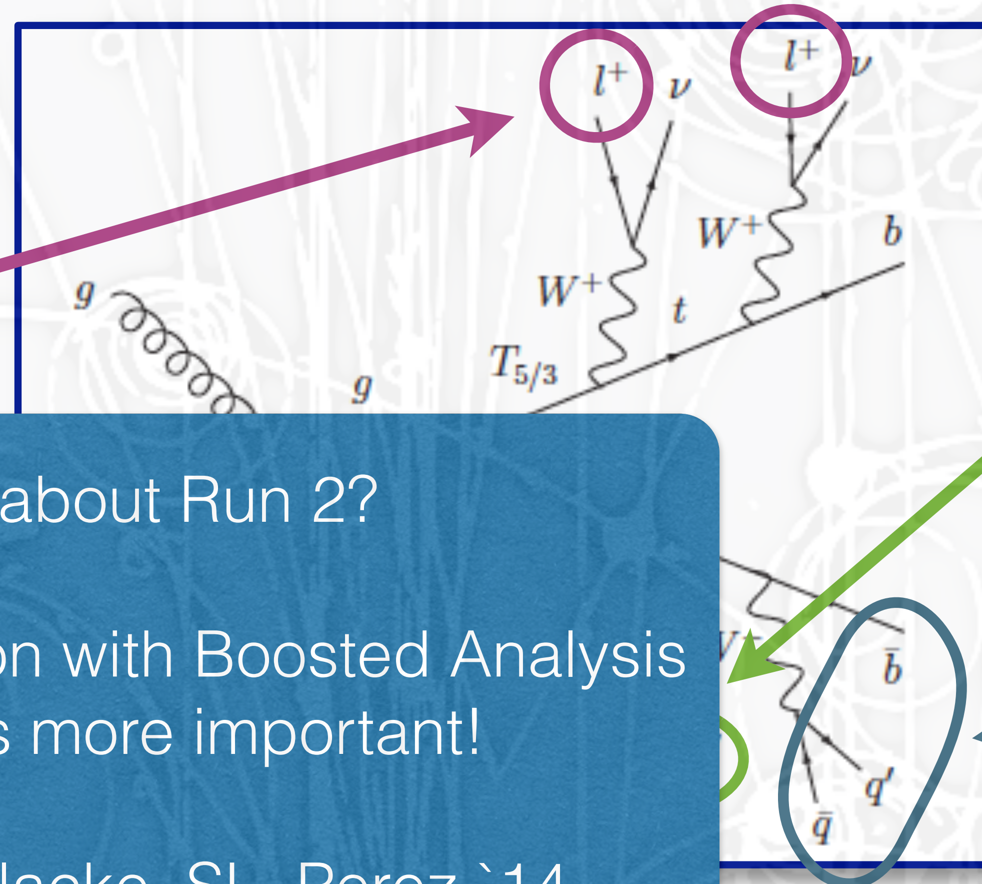
CMS top tag



Composite Top Partner Searches

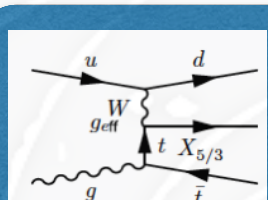
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



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

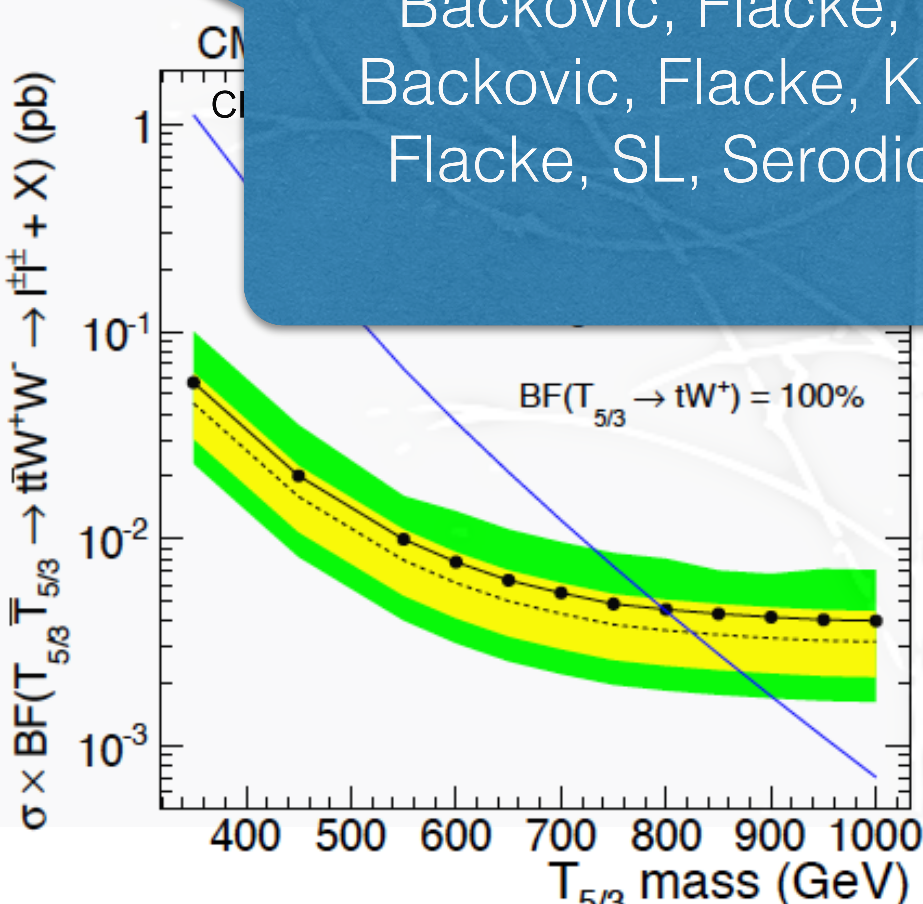
CMS top tag



How about Run 2?

Single production with Boosted Analysis becomes more important!

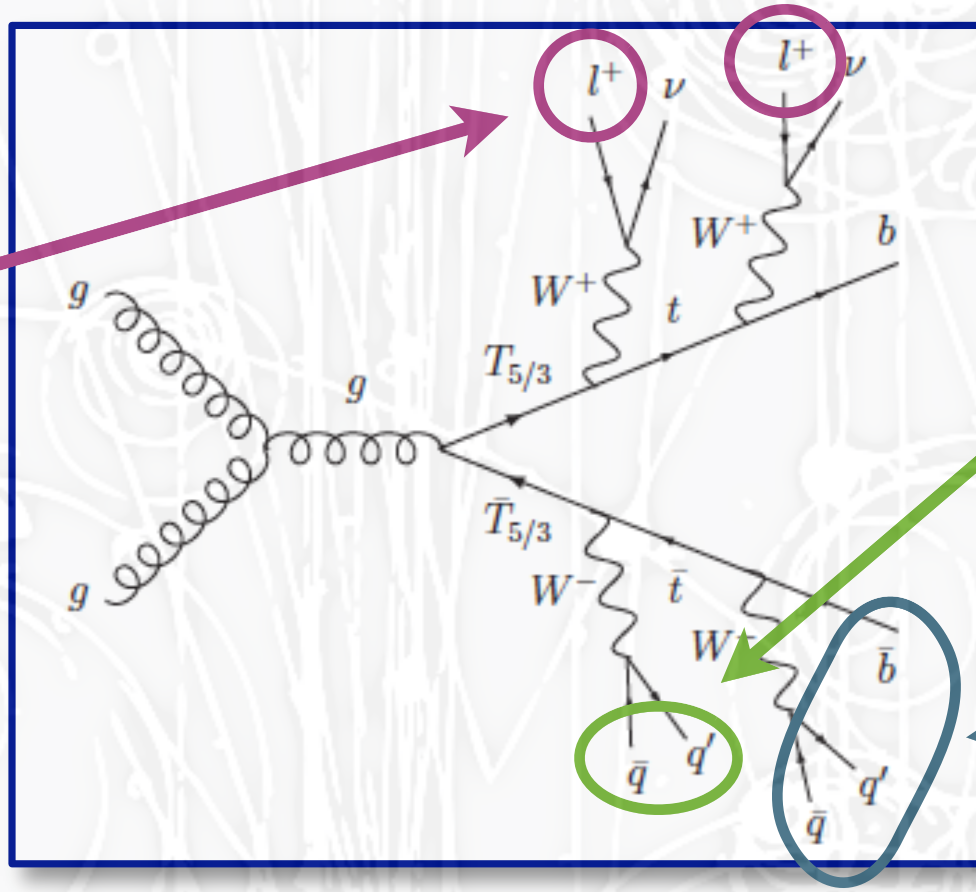
Backovic, Flacke, SL, Perez `14
Backovic, Flacke, Kim, SL (x2),`15
Flacke, SL, Serodio, Parolini, `16



Composite Top Partner Searches

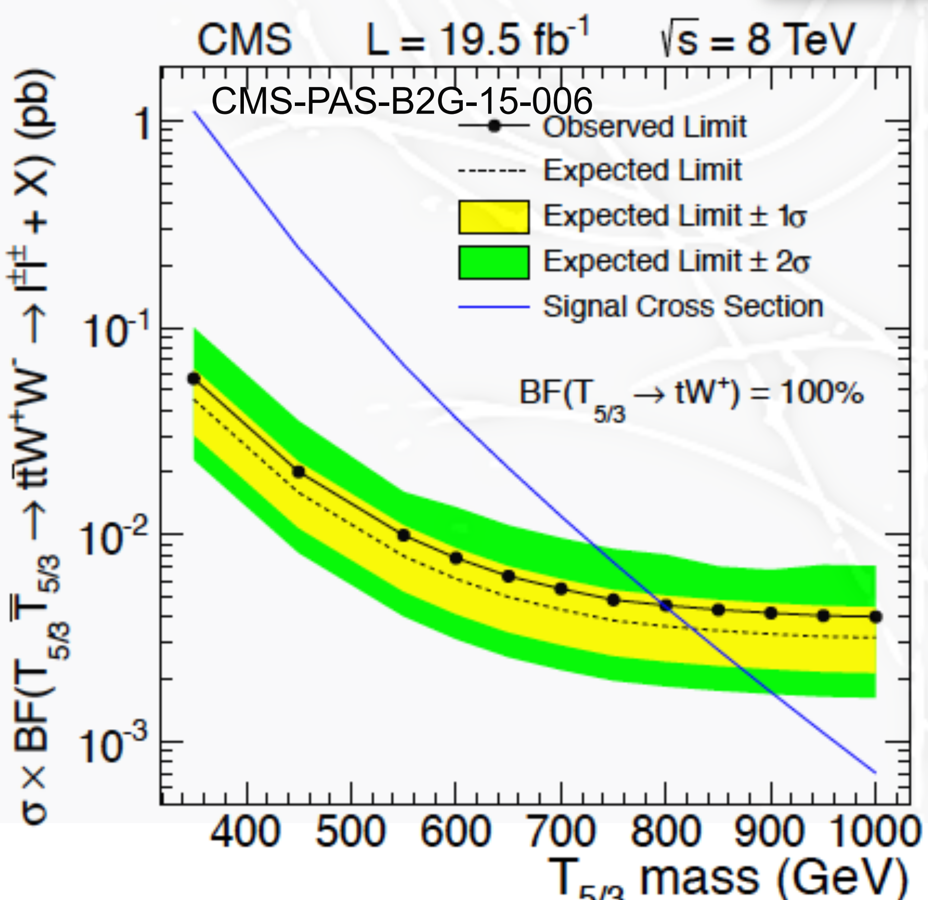
Simone, Matsedonski, Rattazzi, Wulzer `12
Azatov, Son, Spannowsky `13
Matsedonski, Panico, Wulzer `14

same-sign dileptons



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

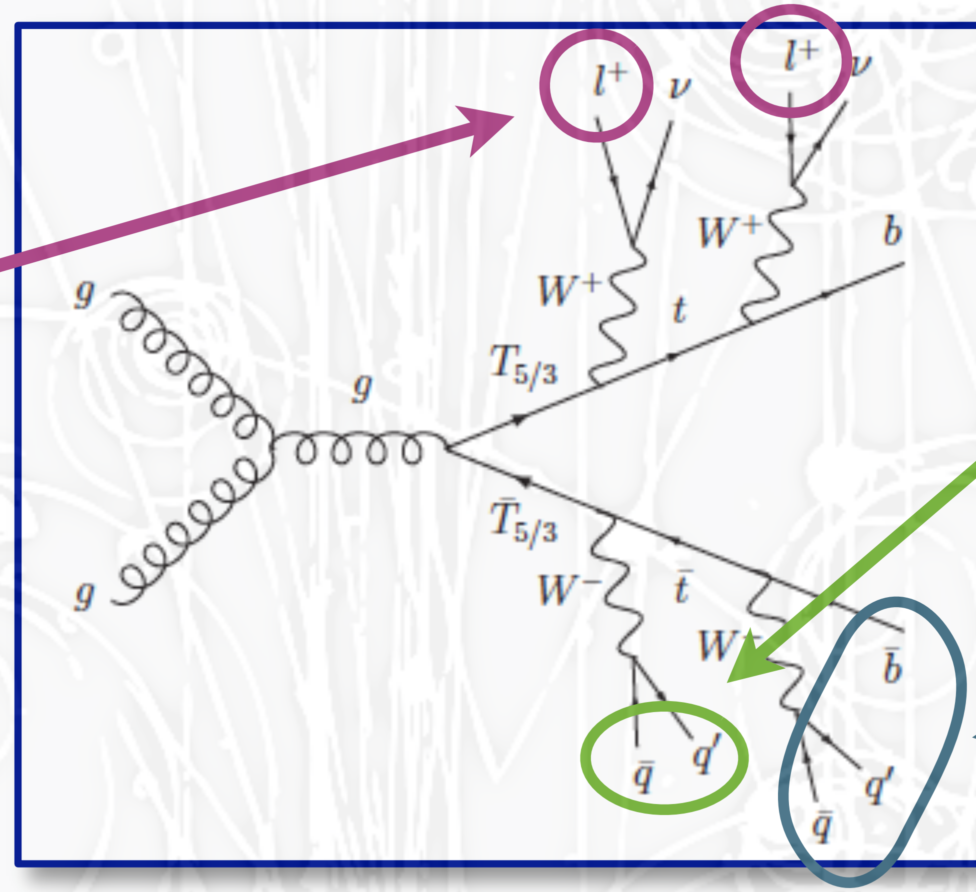
CMS top tag



Composite Top Partner Searches

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

same-sign dileptons

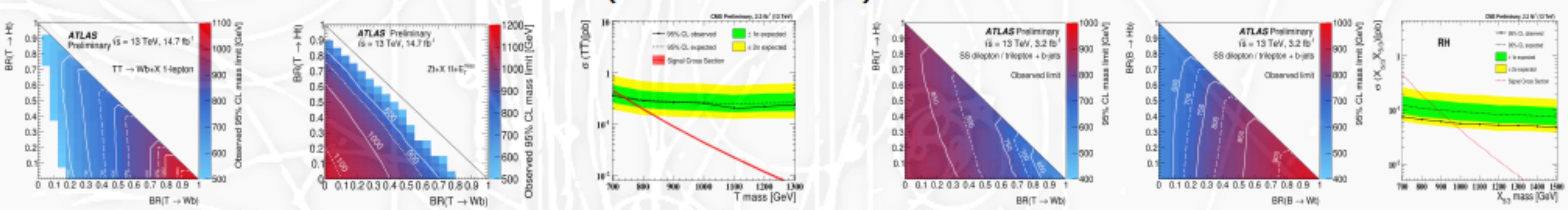


W tag:
2 subjets,
M_j[60,130]

CMS top tag

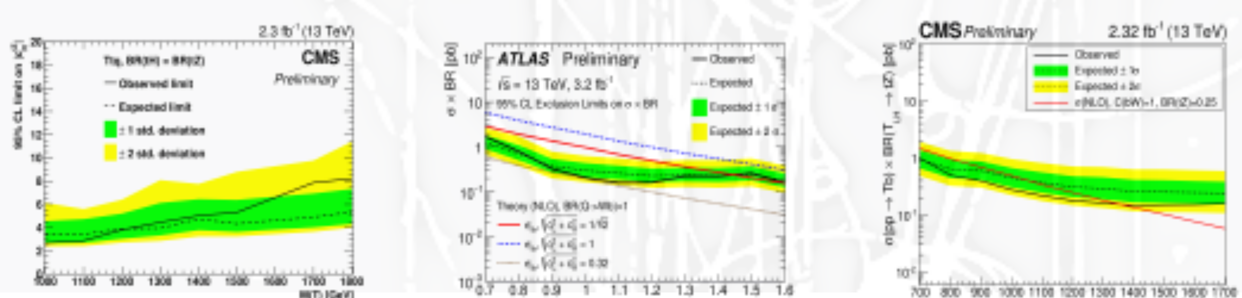
TT→bW+x | TT→tZ+x | TT (T→tW,bZ,bH) | TT→tH+x | BB→tH+x | XX→tWtW

pair VLQ



T→tH | T/Y→bW | T→tZ, B→bZ

single VLQ



Excluding masses $X_{5/3}^{RH}$ < 1.16 TeV

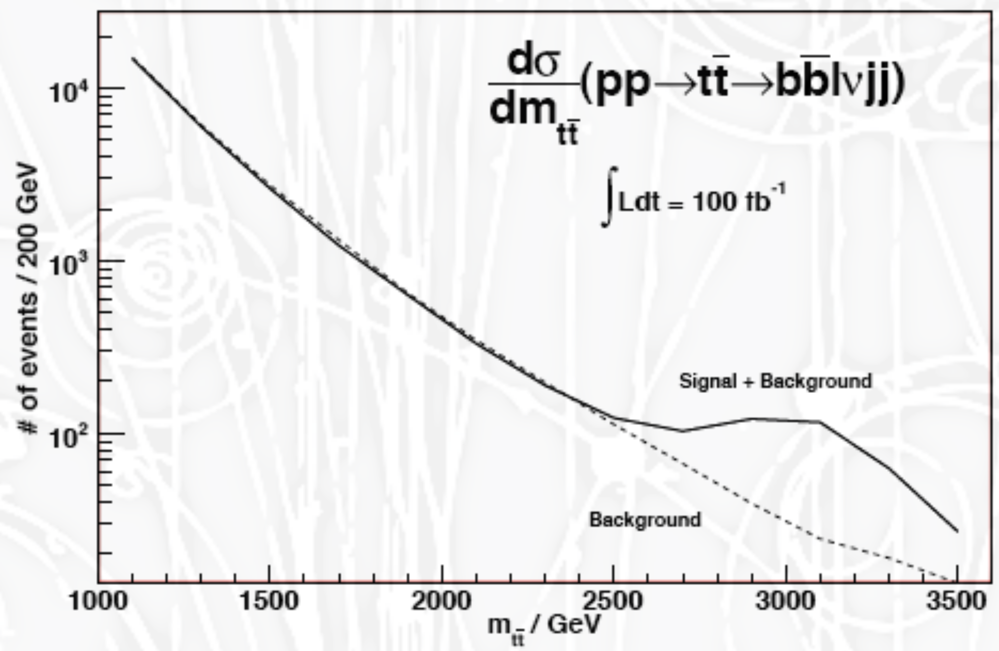
Excluding masses T/Y→bW (100%) < 1295 GeV

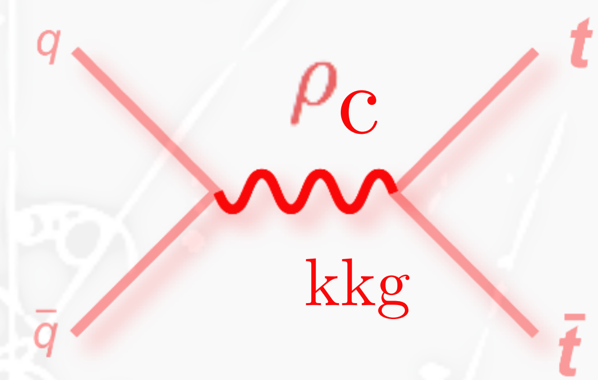
Excluding masses $X_{5/3}^{RH}$ < 1.32 TeV

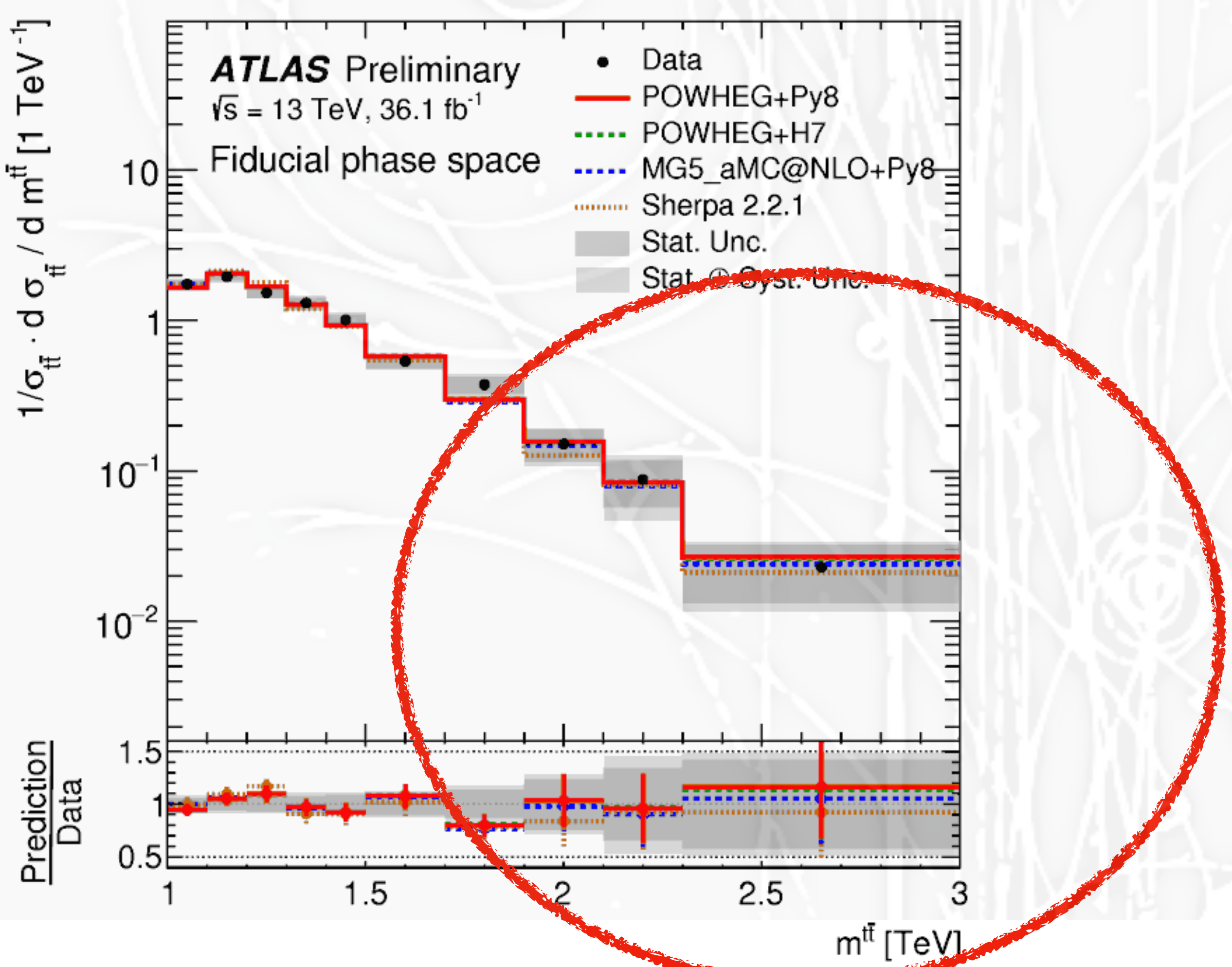
$T_{5/3}$ mass (GeV)

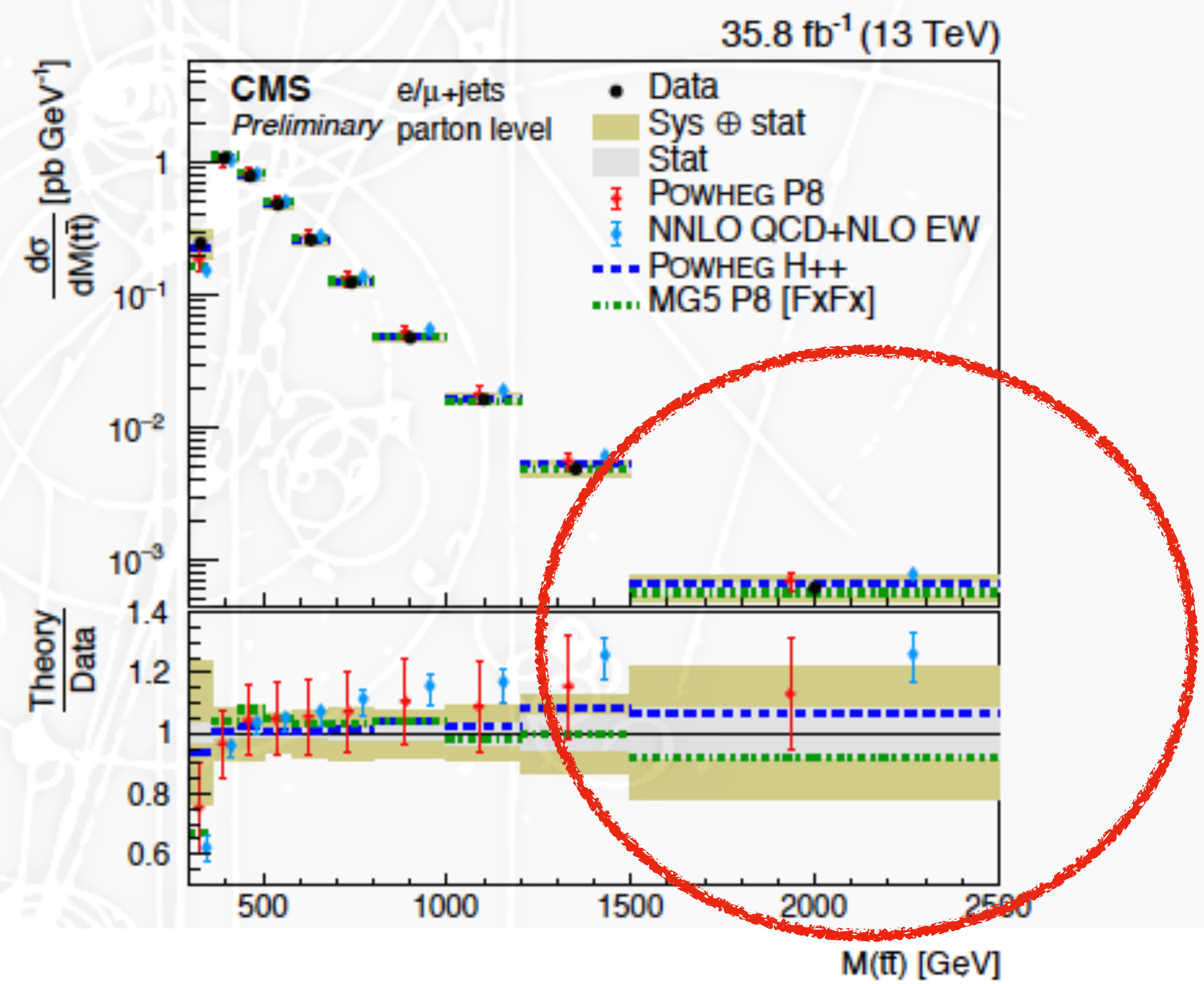
No Resonance, No New Physics? Naturalness?

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

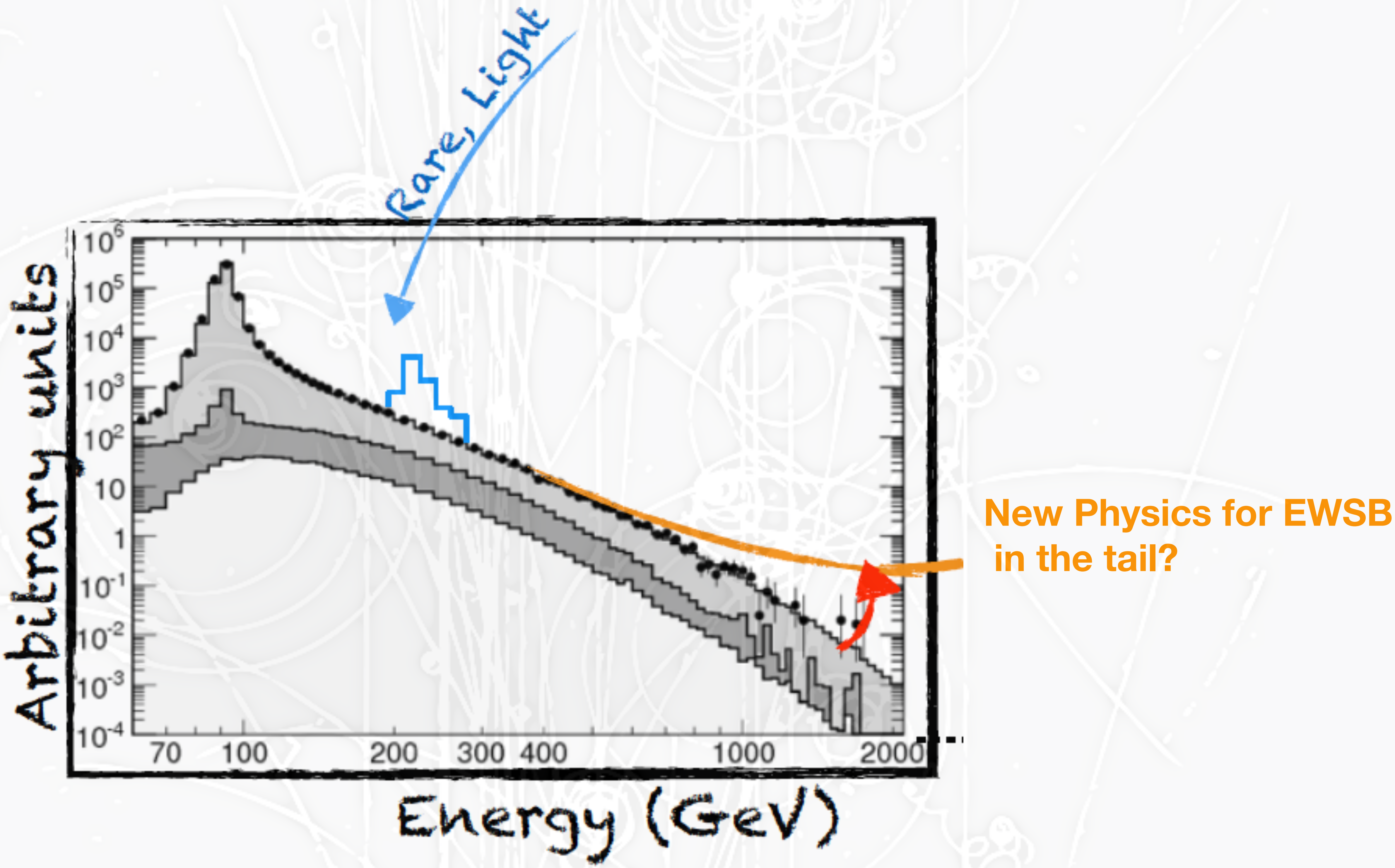








No Resonance, No New Physics? Naturalness?



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 $\pi\pi \to \pi\pi$ scattering)

No Resonance, No New Physics? Naturalness?

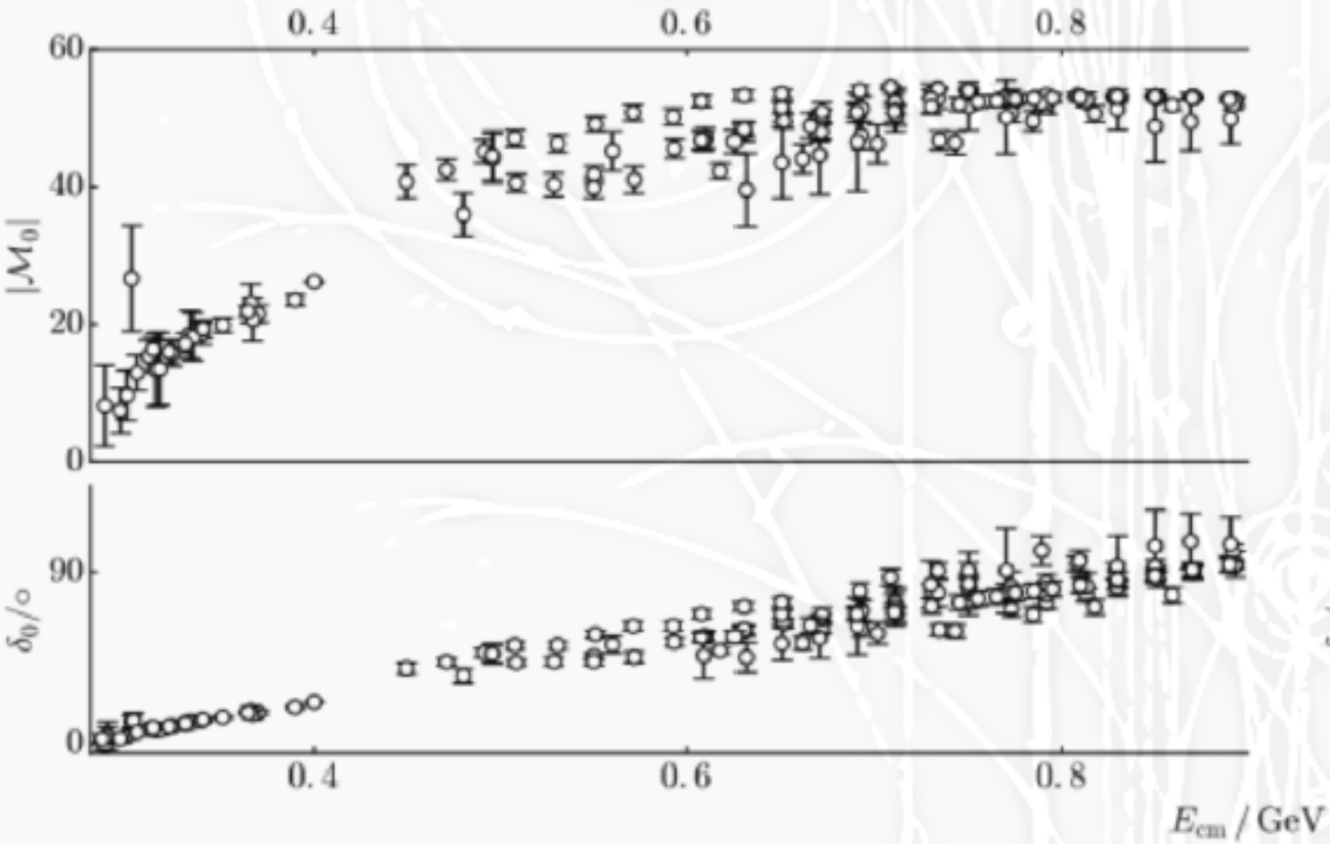
- New Physics may appear solely as a continuum

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

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

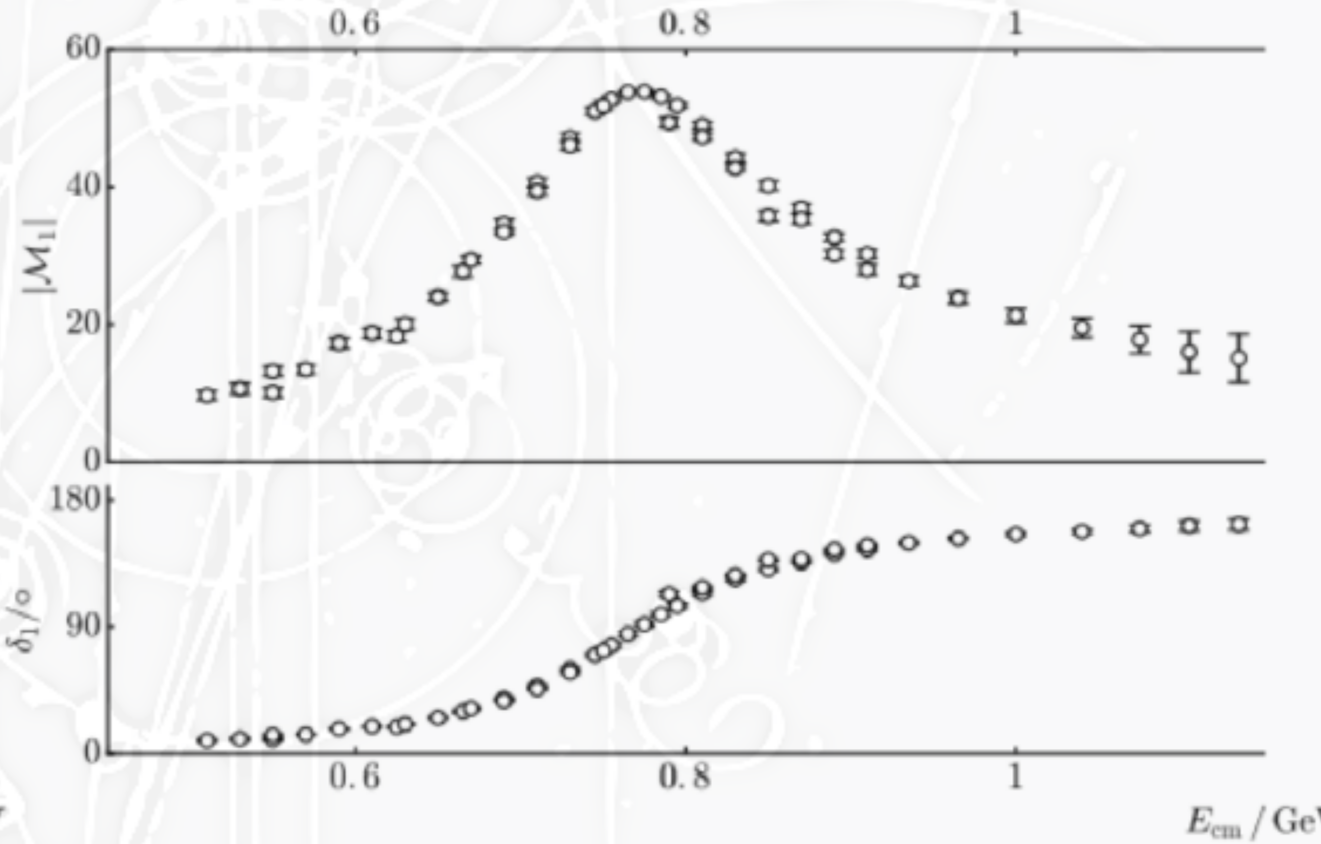
QCD

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.

Ising Model

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

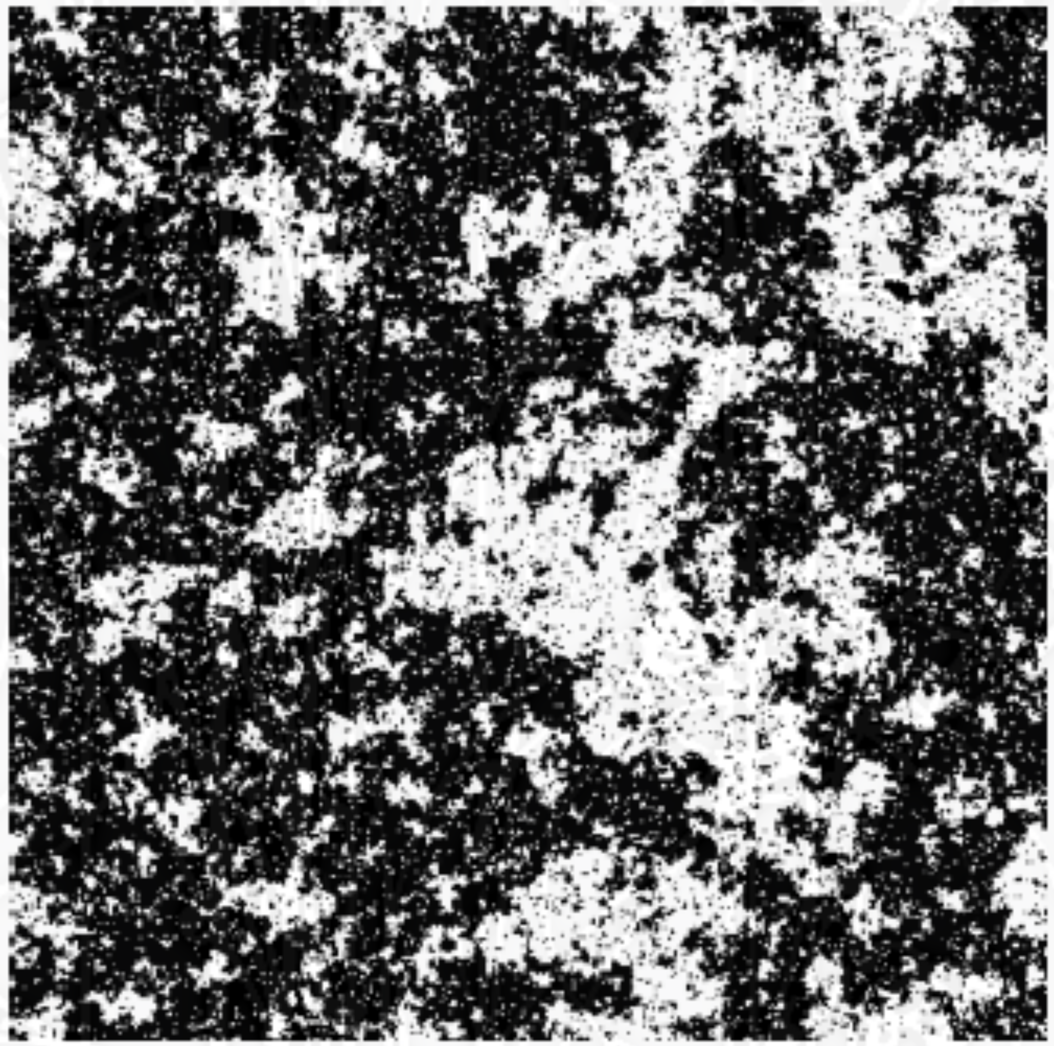
$$s(x) = \pm 1$$

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

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

Courtesy of J. Terning

Critical Ising Model is Scale Invariant

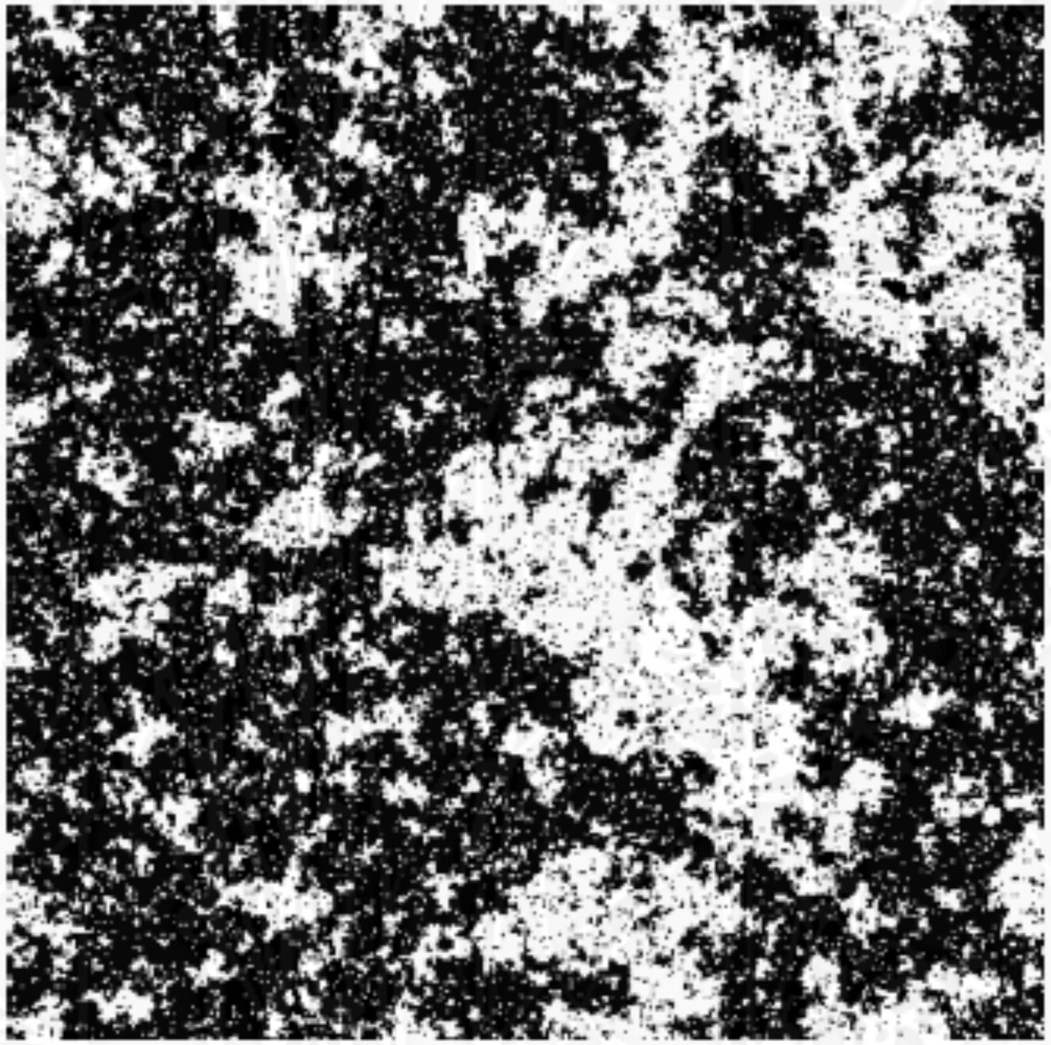


http://bit.ly/2Dcrit

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

Courtesy of J. Terning

Critical Ising Model is Scale Invariant



http://bit.ly/2Dcrit

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

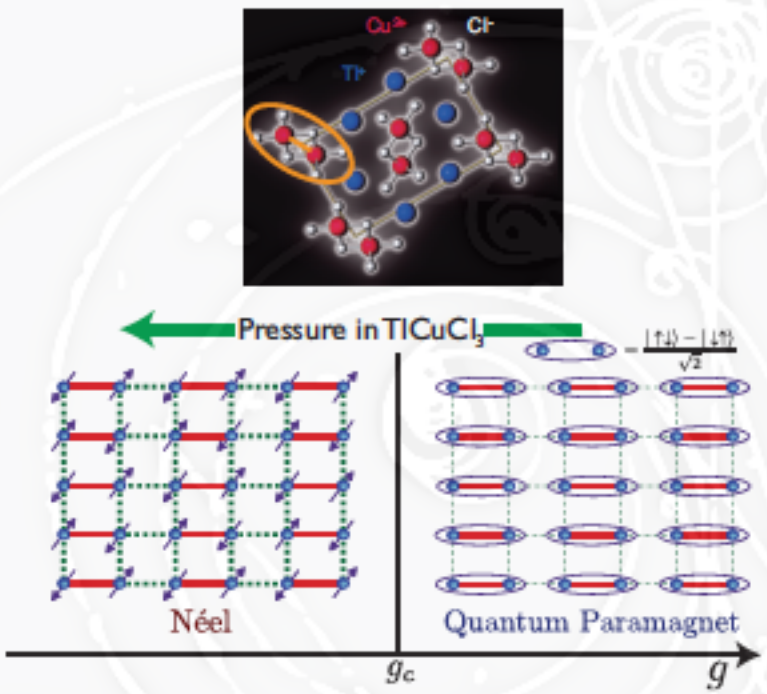
critical exponent

Courtesy of J. Terning

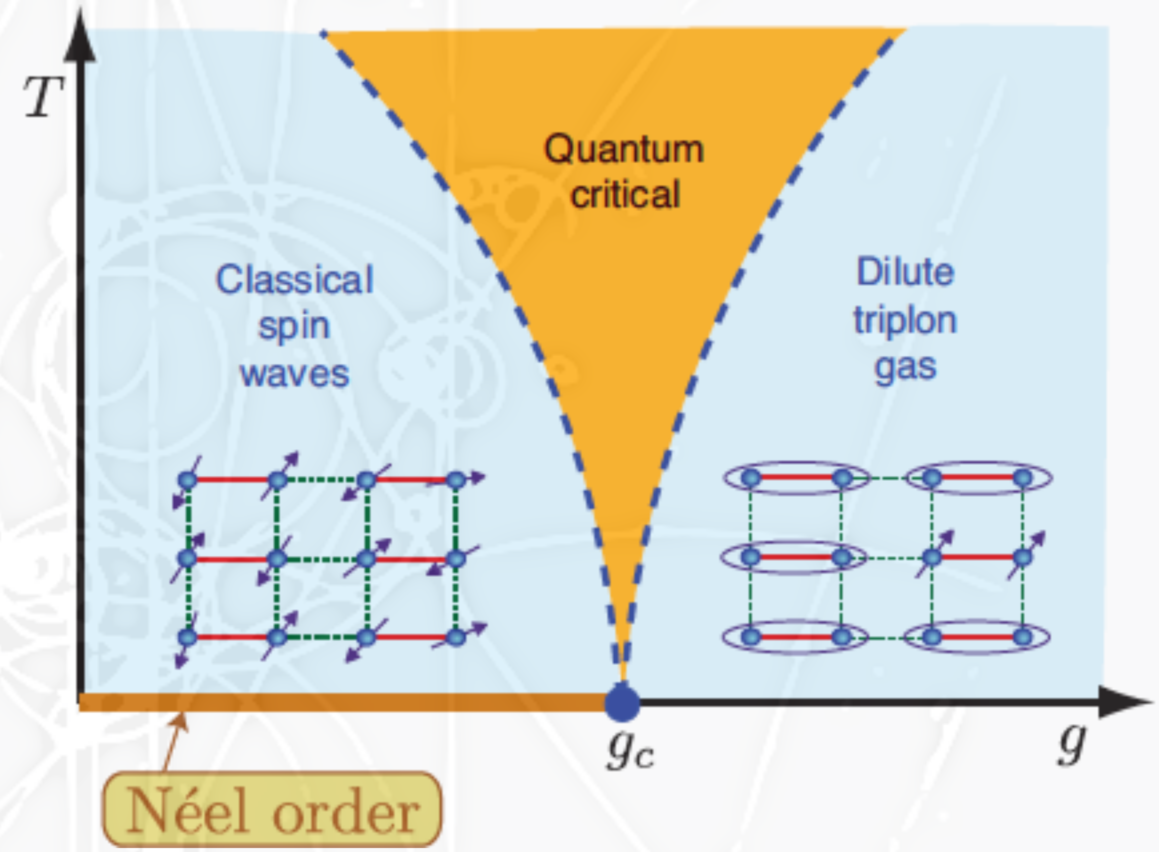
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

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

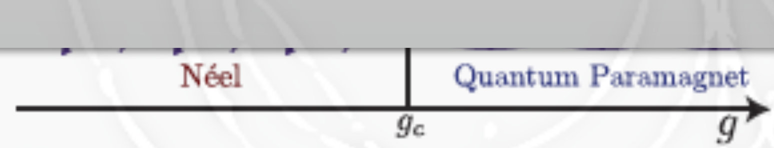
Higgs & Quantum Phase Transition

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

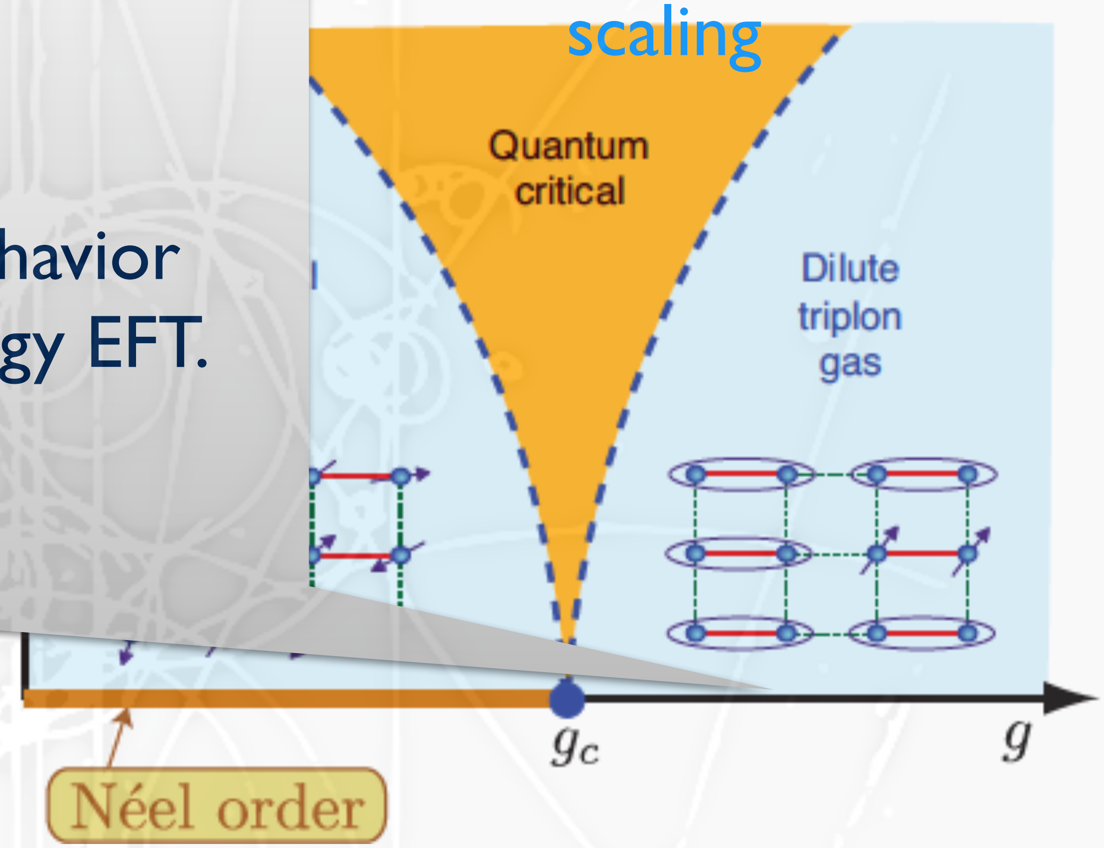
rs.

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

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



Sachdev, arXiv:1102.4268



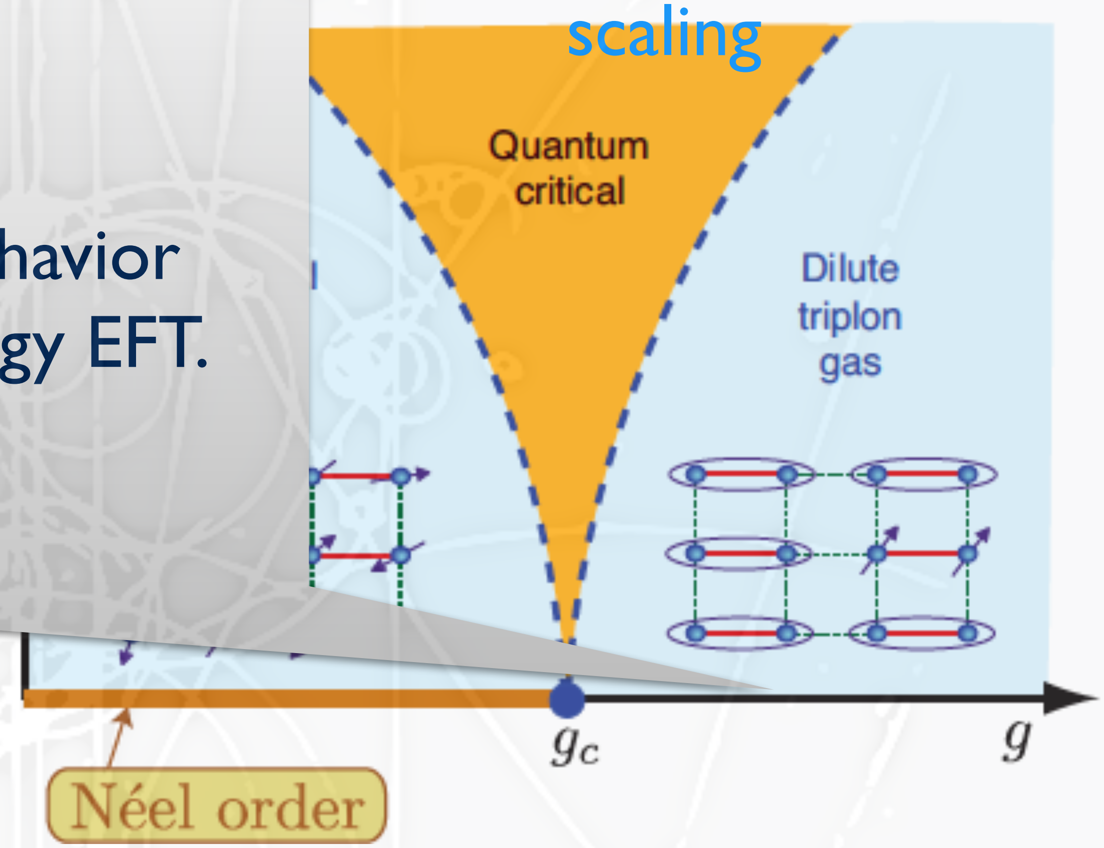
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

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 scaling dimensions of the field,

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



Sachdev, arXiv:1102.4268

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

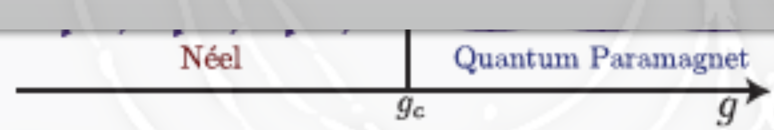
Higgs & Quantum Phase Transition

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

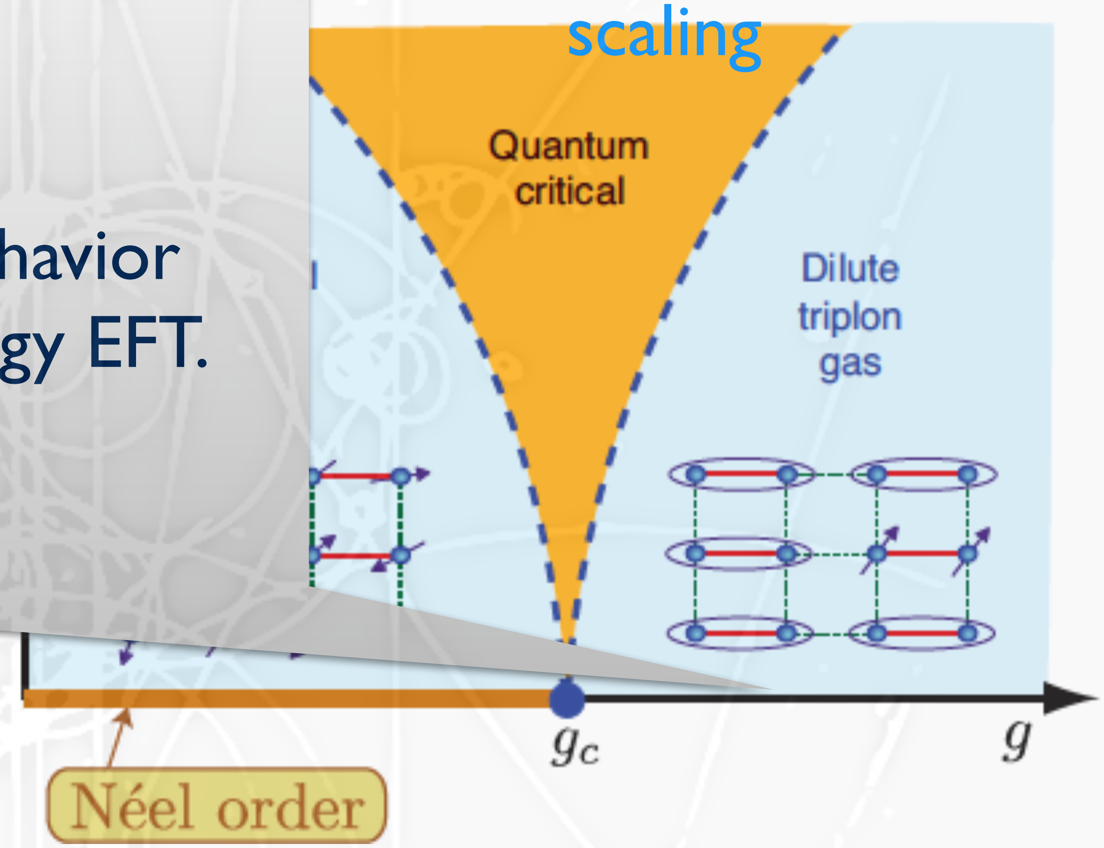
rs.

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

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



Sachdev, arXiv:1102.4268



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?

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

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

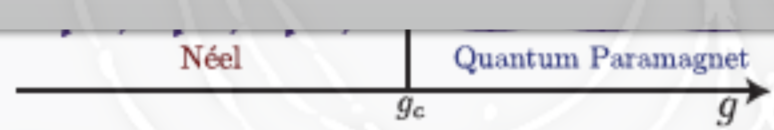
Higgs & Quantum Phase Transition

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

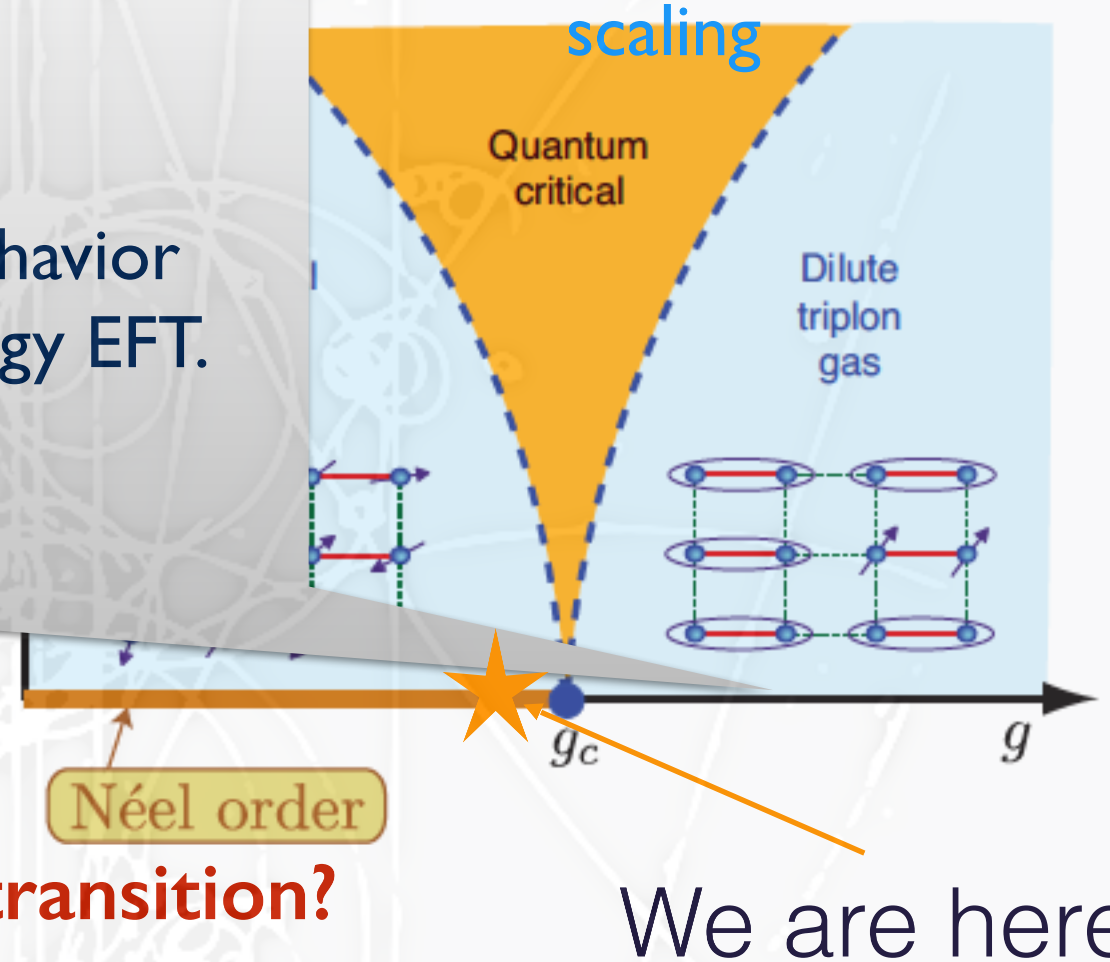
rs.

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

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



Sachdev, arXiv:1102.4268



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?

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

AdS/CFT

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

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

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

AdS/CFT

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

$$z > \epsilon$$

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

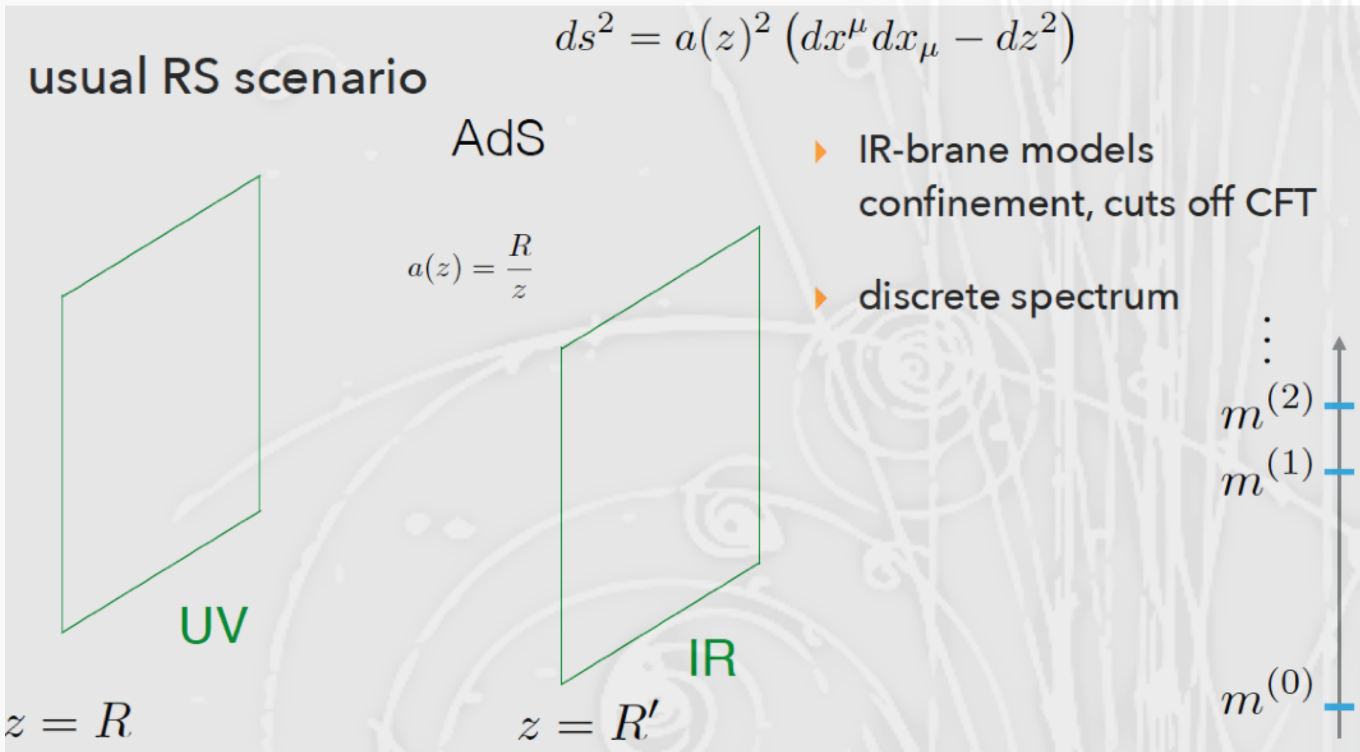
$$\phi(p,z) = az^2 J_\nu(pz) + bz^2 J_{-\nu}(pz)$$

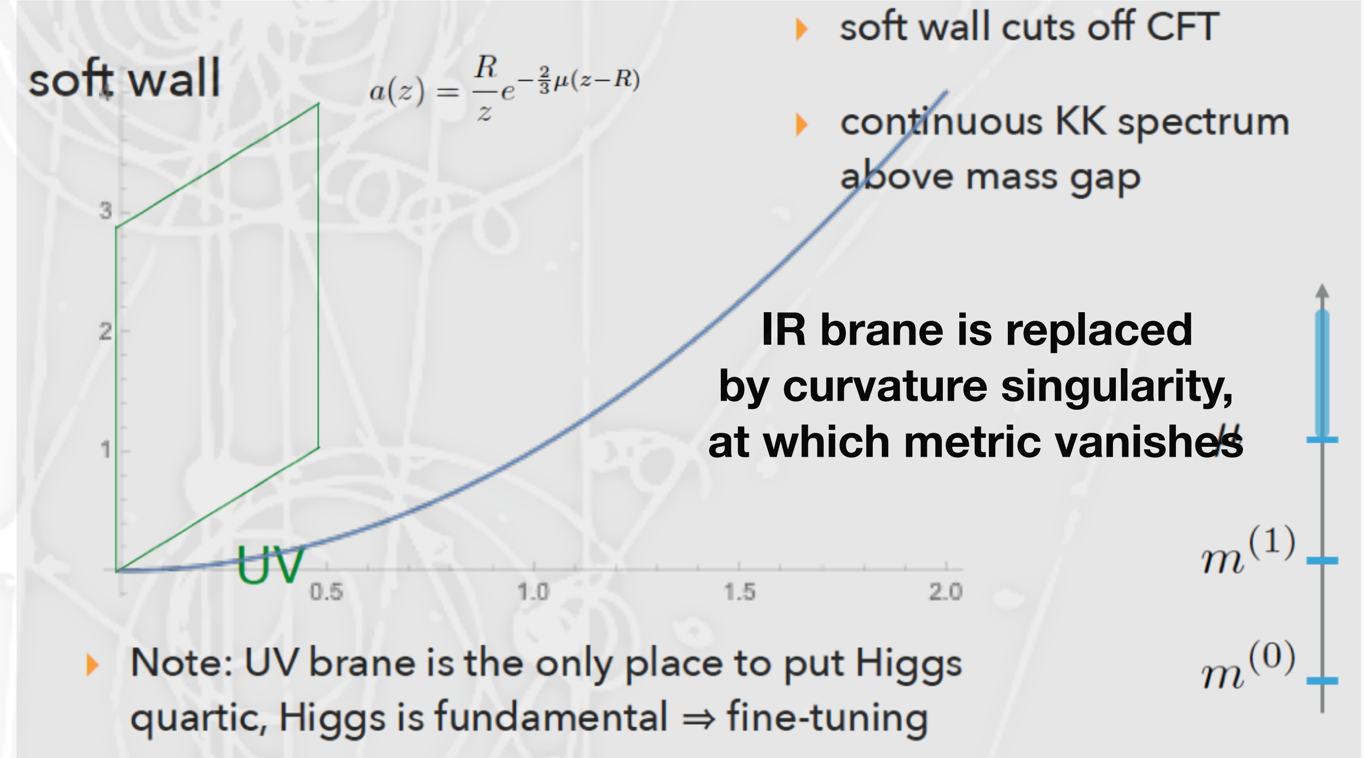
$$\Delta[\mathcal{O}] = 2 \pm \nu = 2 \pm \sqrt{4 + m^2 R^2}$$

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

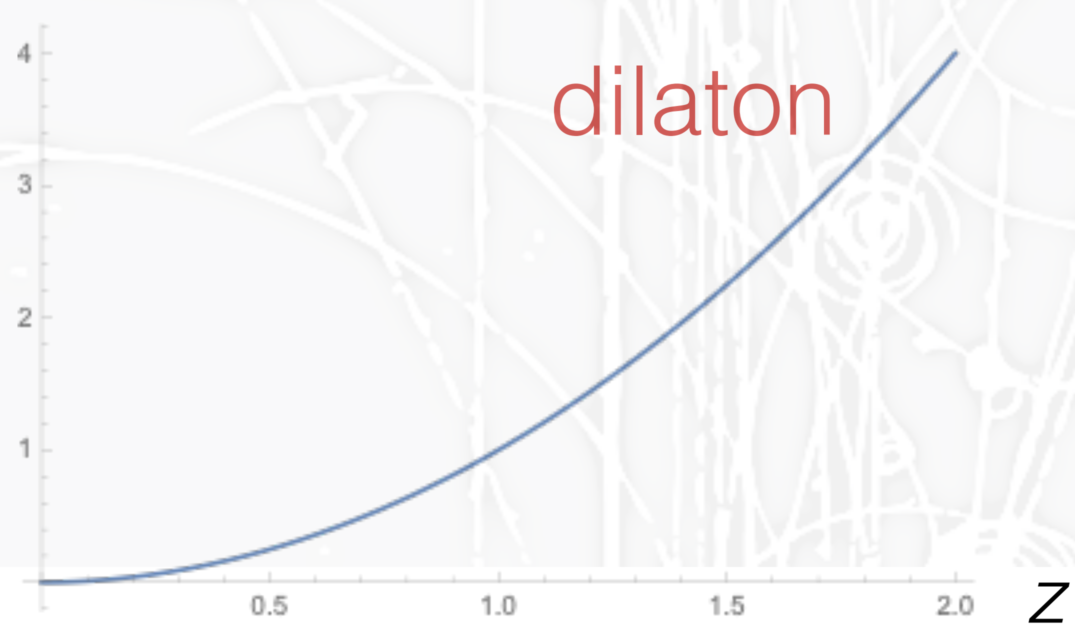
Witten, Klebanov 99'

broken CFT



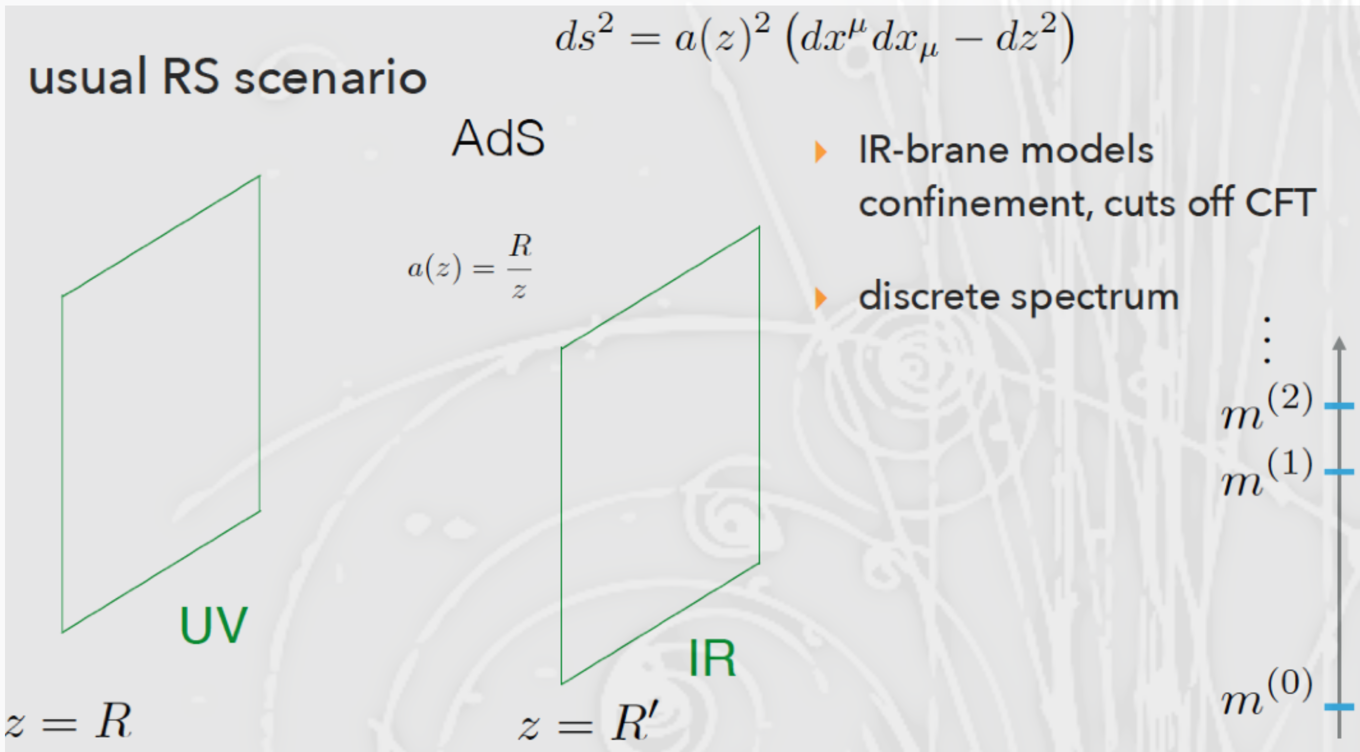


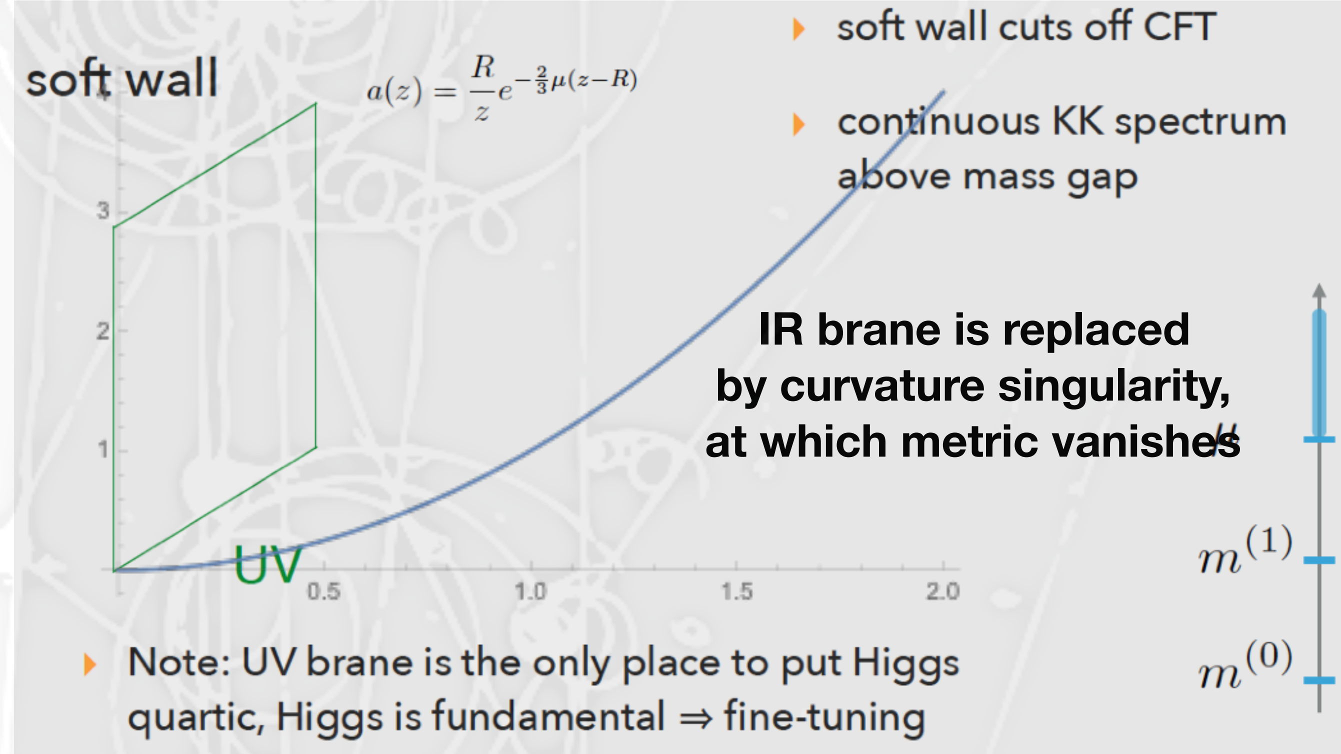
- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology



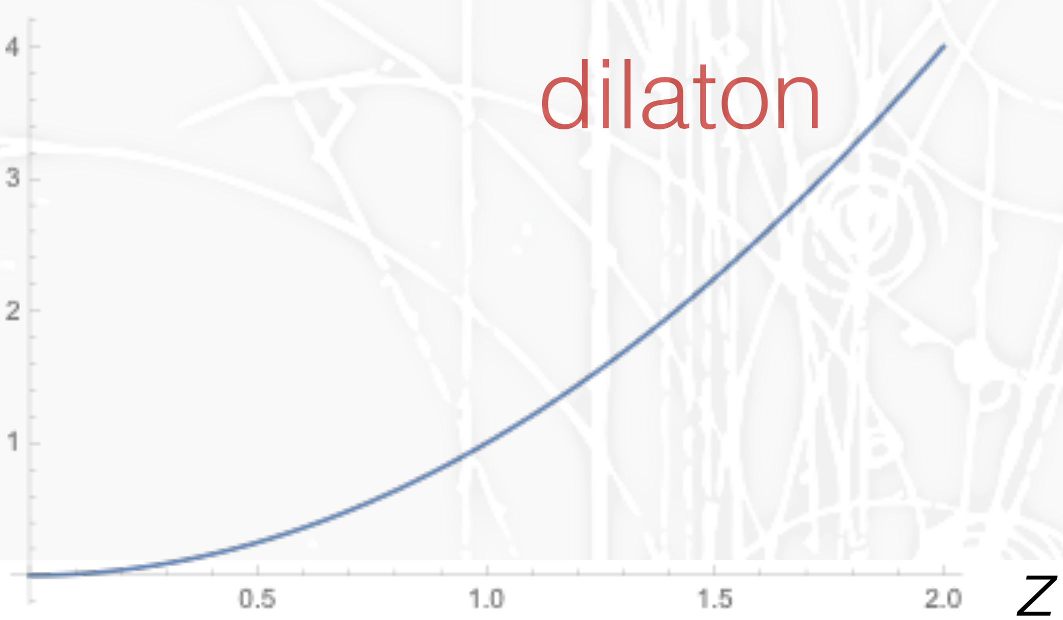
Karch, Katz, Son, Stephaniv 06`

broken CFT





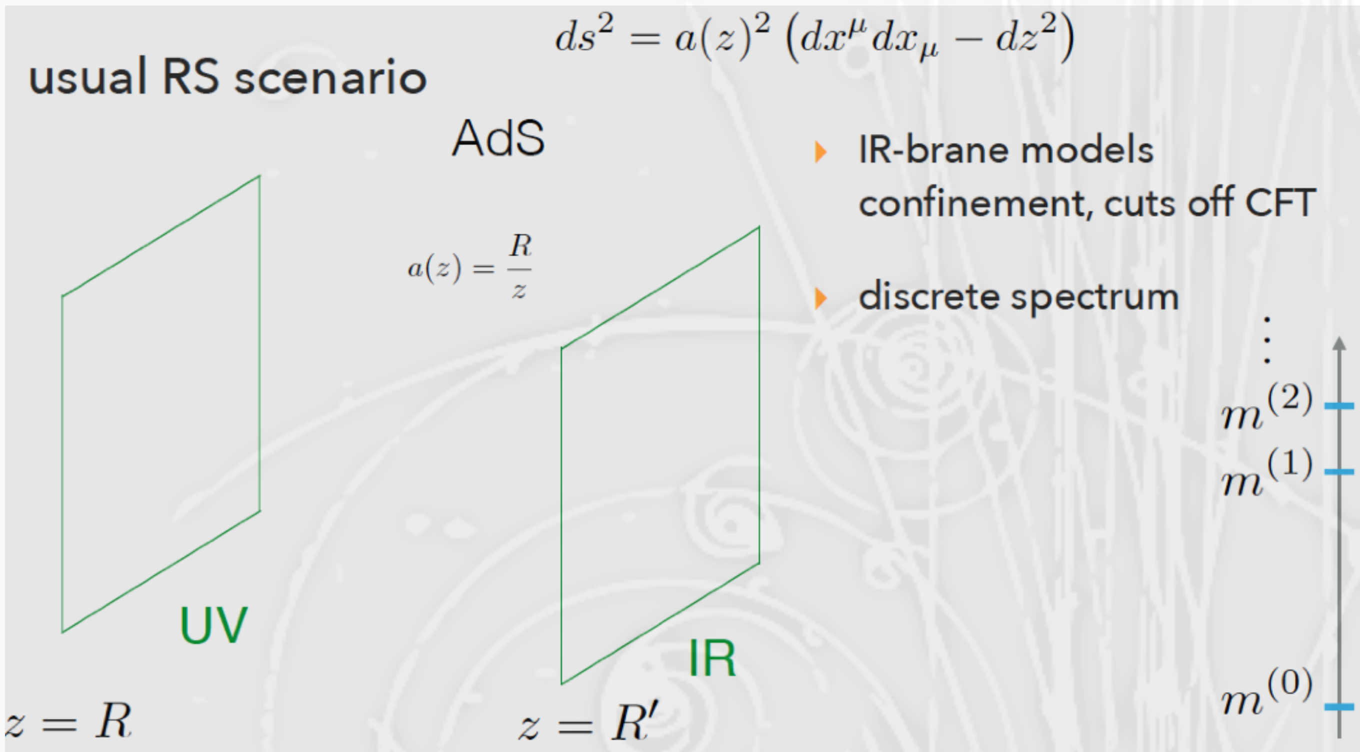
- Randall Sundrum 2 (only UV brane and bulk): cuts from 0 (CFT)
- RS1: putting IR cutoff at TeV
- New type of IR cutoff (soft wall) gives rise to a different phenomenology

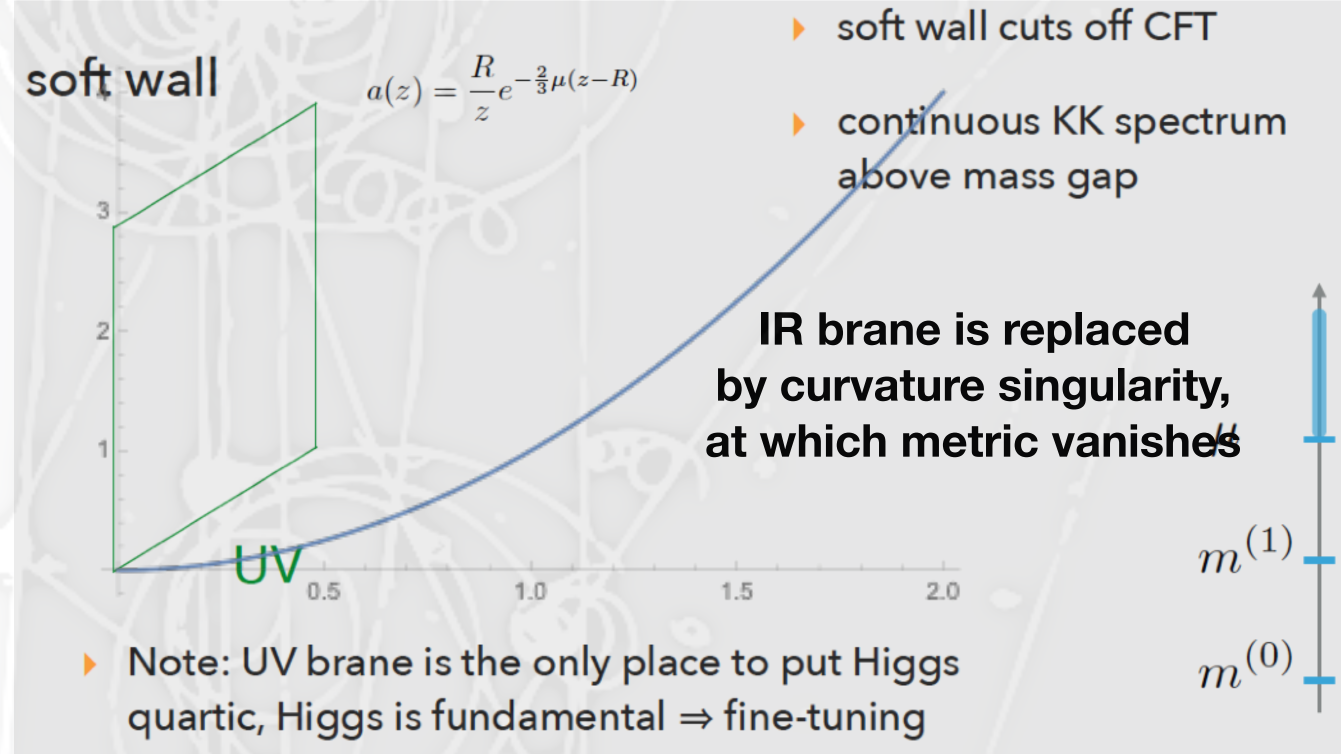


scalar getting VEV => marginal deformation of CFT

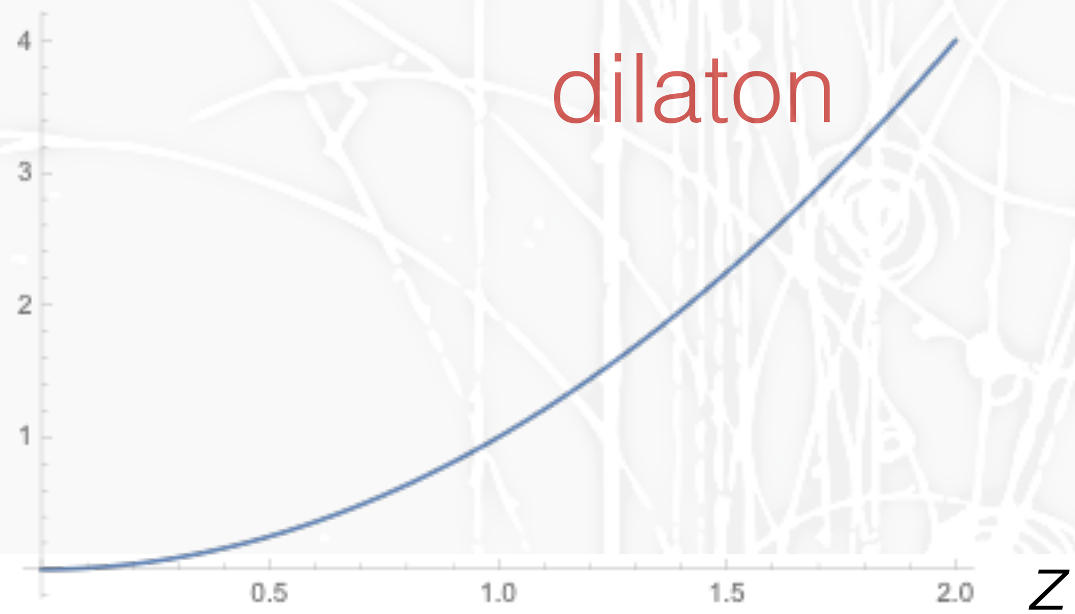
Karch, Katz, Son, Stephaniv 06`

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`

broken CFT by IR cutoff

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

$$\phi = \mu z^2$$

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

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

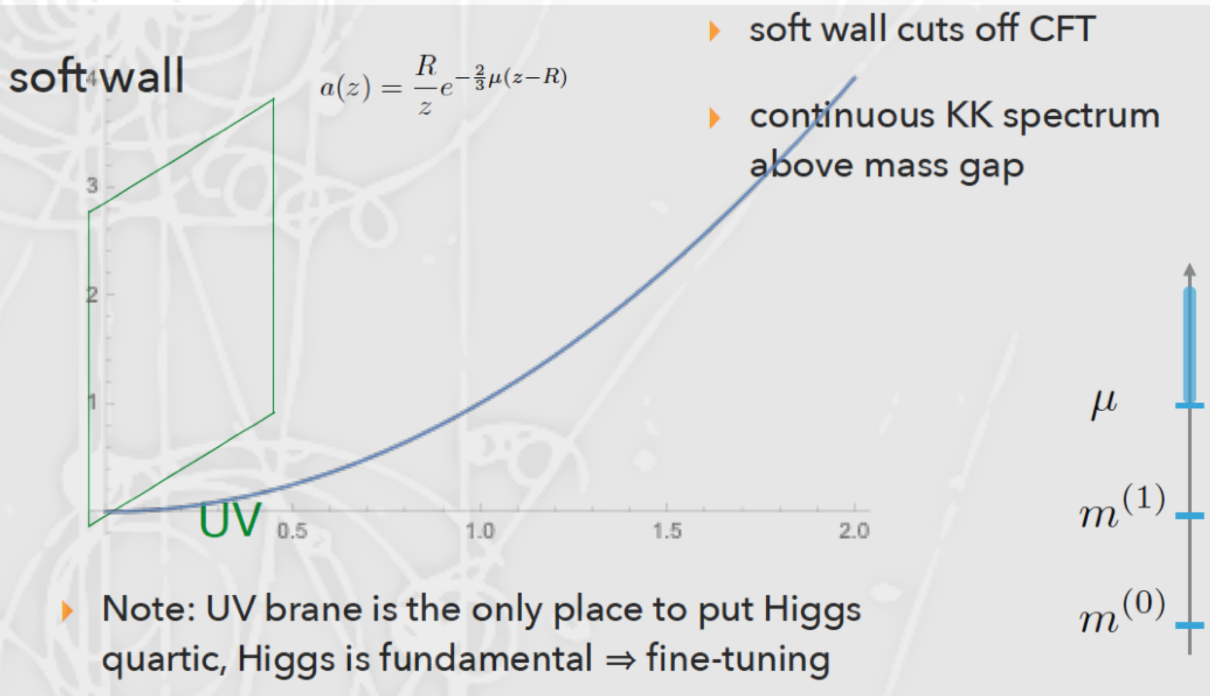
$$[\partial^2-\mu^2]^{2-\Delta}\delta(x-y)$$

soft wall (AdS/QCD)

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

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

$$S_{\rm gauge} = \int d^5x \, -\frac{1}{4} a(z) F^{a2}_{MN}$$

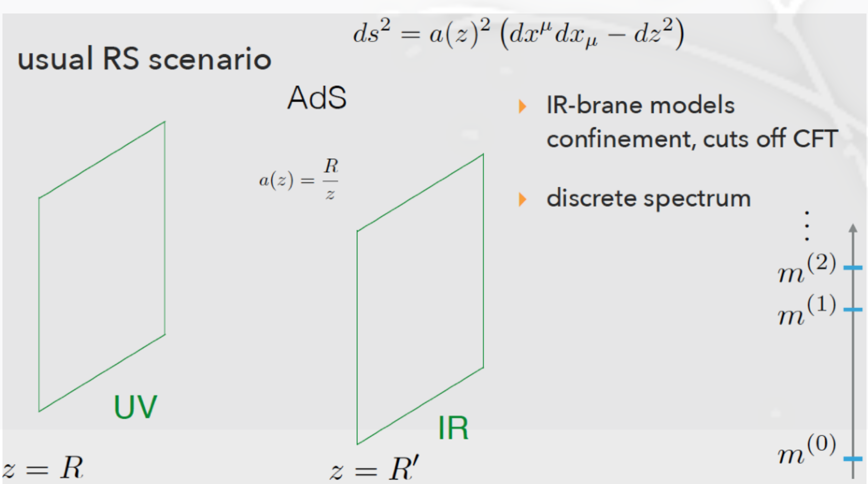


EOM: $\left(a^{-1}\partial_z(a\partial_z) + p^2\right) f = 0$ $\qquad f = a^{-\frac{1}{2}}\Psi$

"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: $p^2 = (\mu/3)^2$



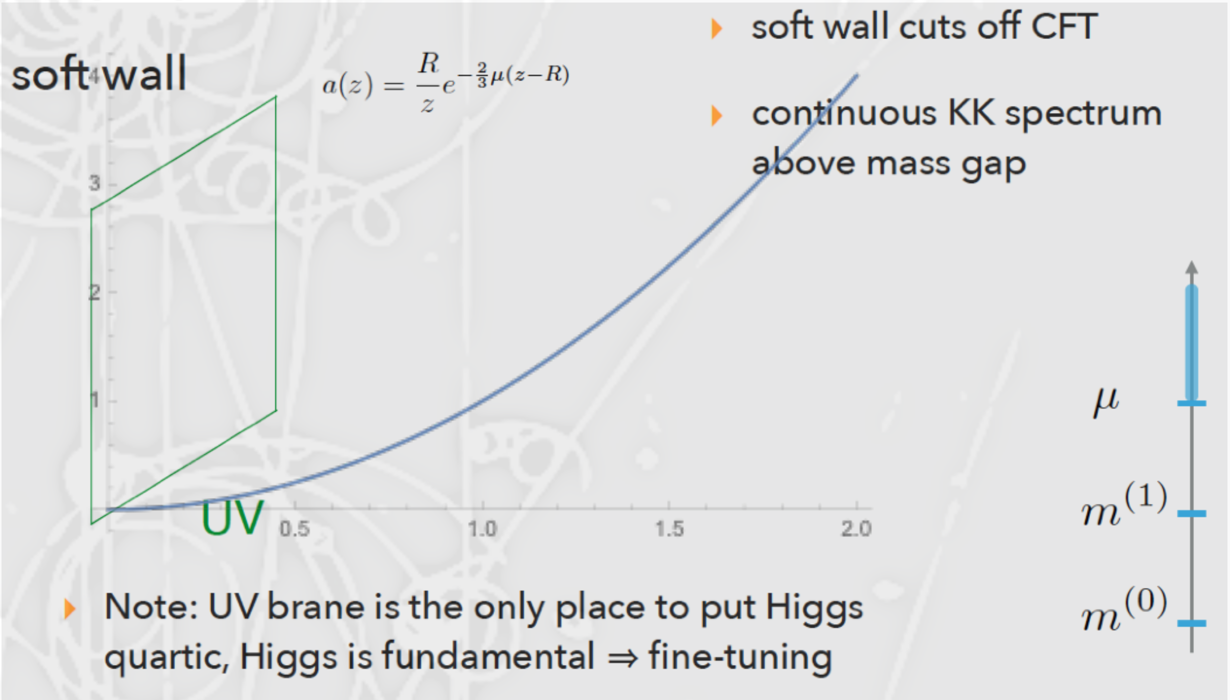
$\to \infty$ (infinite well) => just like IR brane: KK towers

soft wall (AdS/QCD)

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

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

$$S_{\text{gauge}} = \int d^5x \, -\frac{1}{4} a(z) F^{a2}_{MN}$$

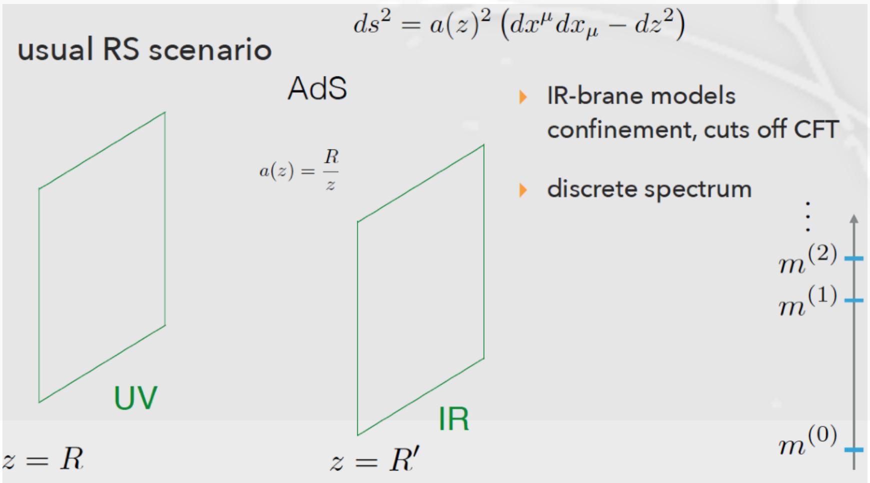


EOM: $\left(a^{-1}\partial_z(a\partial_z) + p^2\right) f = 0$ $\qquad f = a^{-\frac{1}{2}}\Psi$

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

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

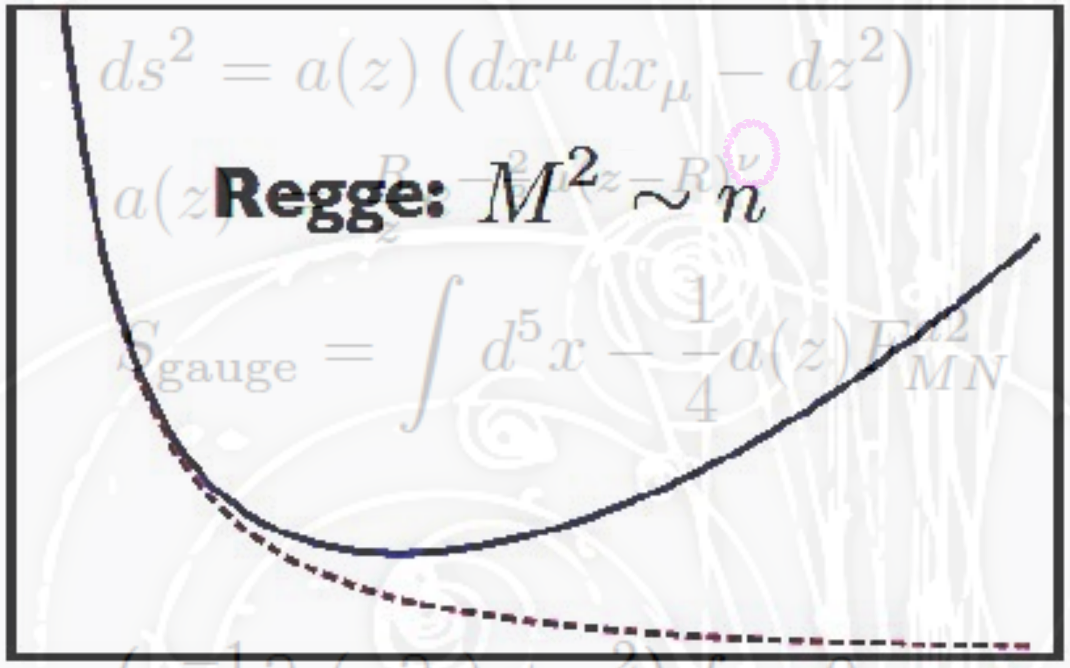
=> continuum begins at: $p^2 = (\mu/3)^2$

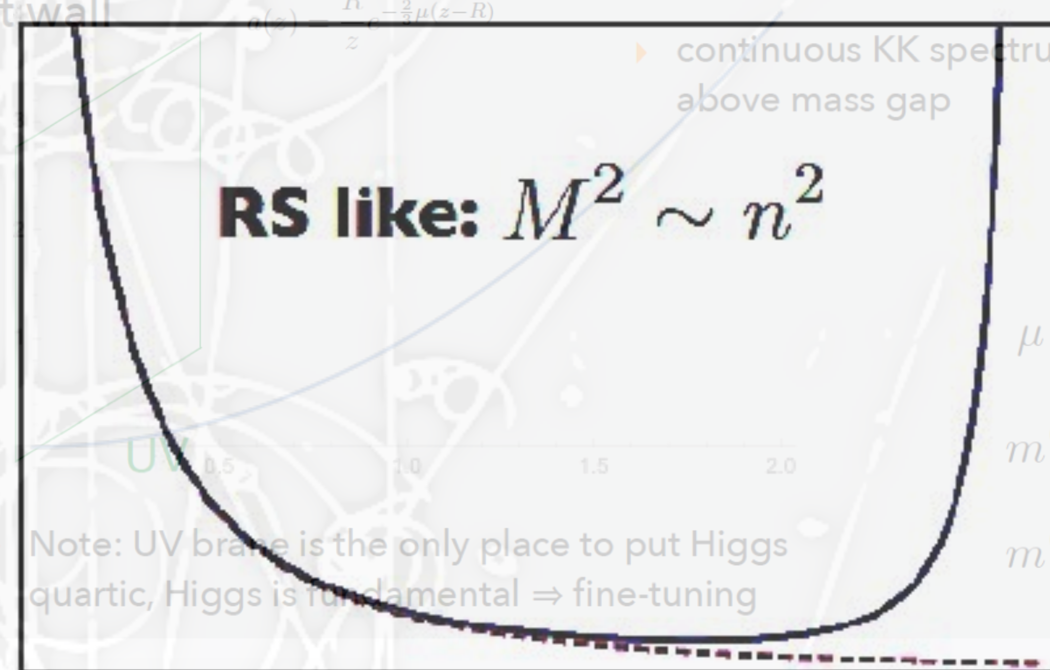


$\to \infty$ (infinite well) => just like IR brane: KK towers

soft wall (AdS/QCD)

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





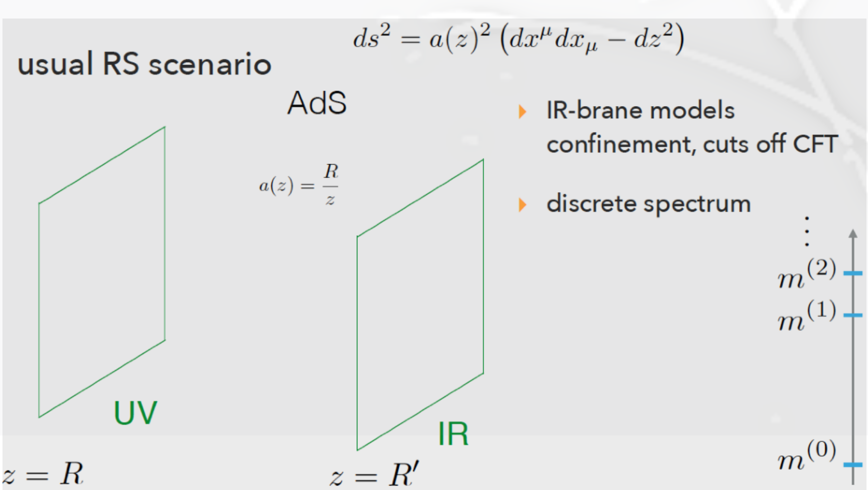
Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental ⇒ fine-tuning

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

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

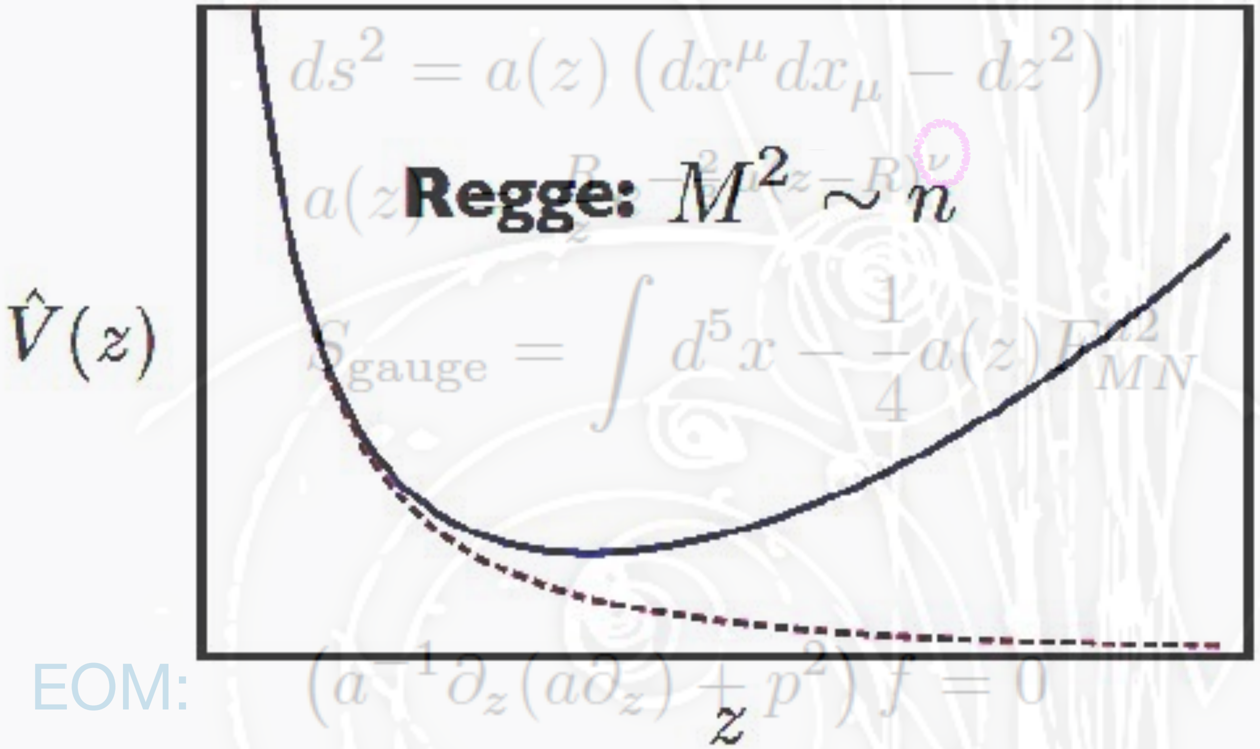
$$V(z)\big|_{z\to\infty} \to \left(\frac{\mu}{3}\right)^2$$

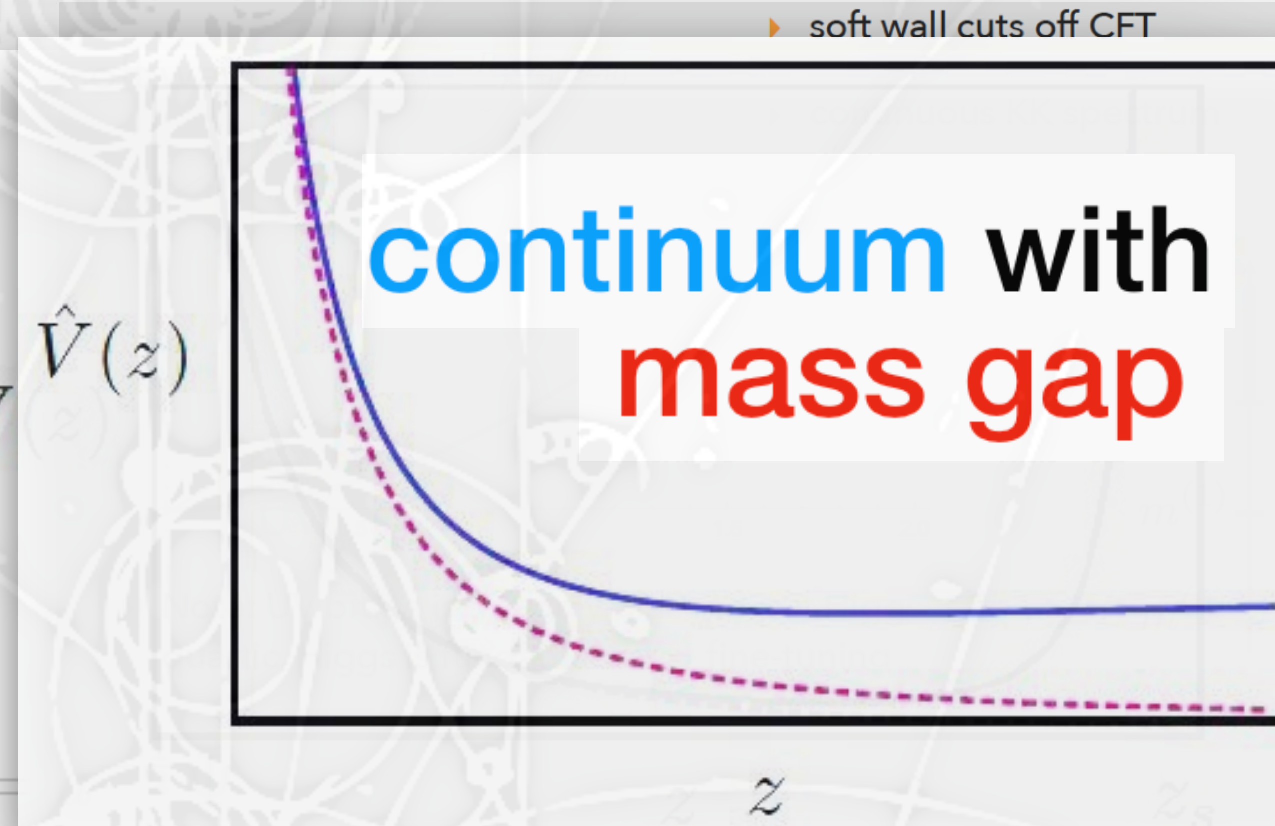
=> continuum begins at: $p^2 = (\mu/3)^2$



$\to \infty$ (infinite well) => just like IR brane: KK towers

soft wall (AdS/QCD)



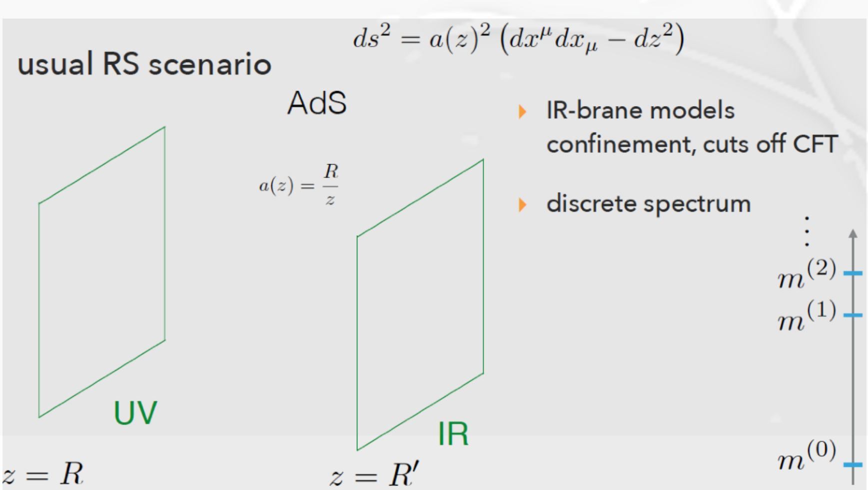


EOM:

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

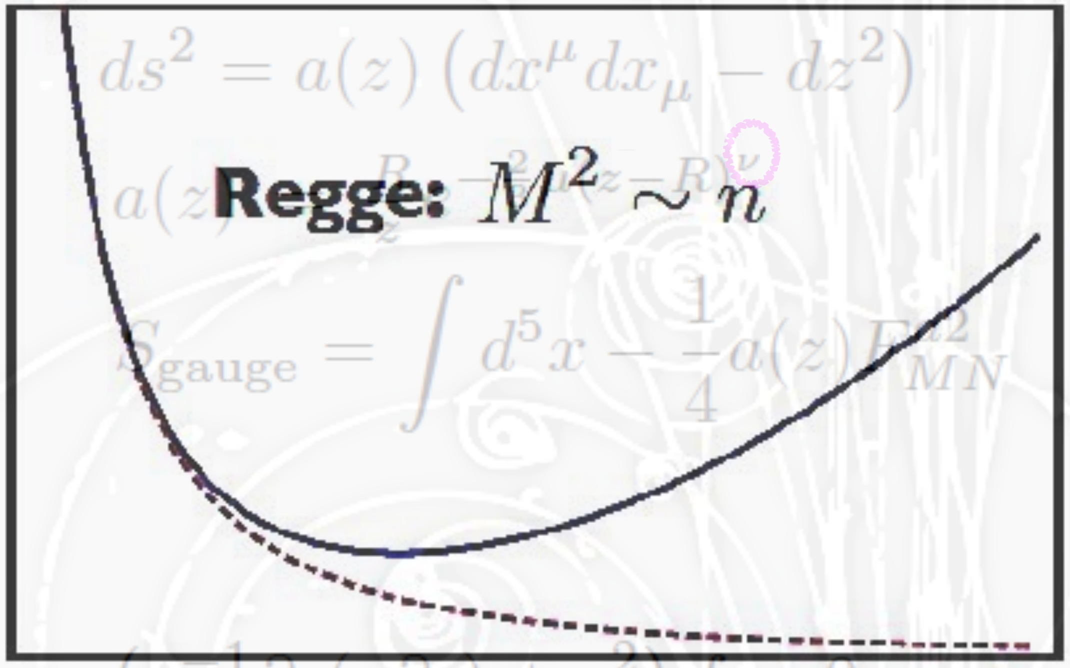
$$V(z)\big|_{z\to\infty} \to \left(\frac{\mu}{3}\right)^2$$

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

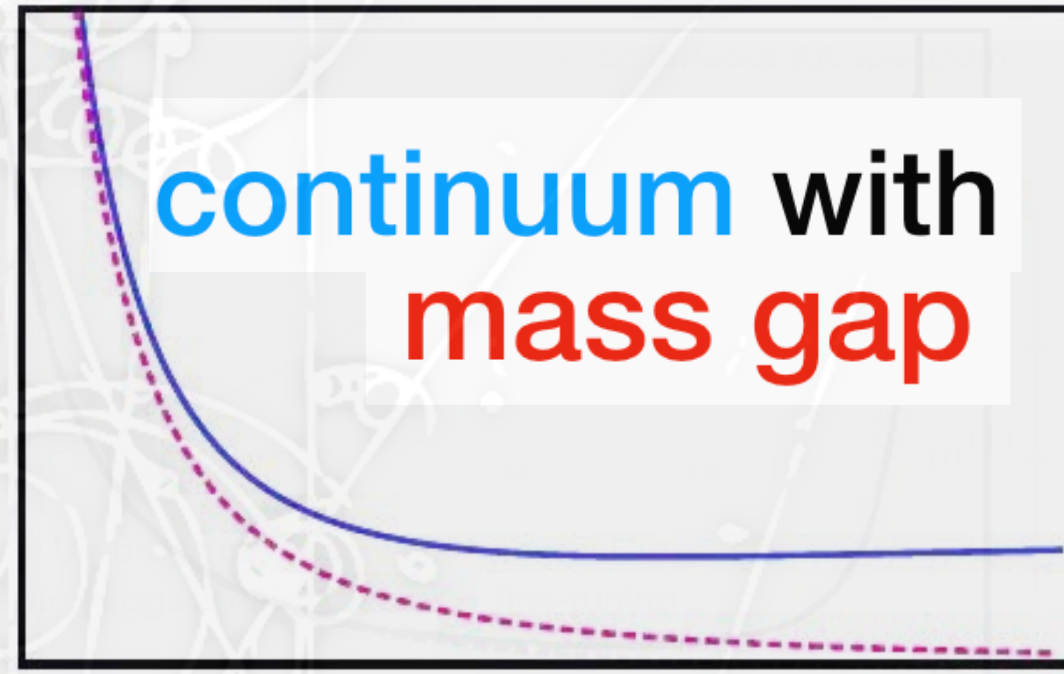


$\to \infty$ (infinite well) => just like IR brane: KK towers

soft wall (AdS/QCD)



▸ soft wall cuts off CFT



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

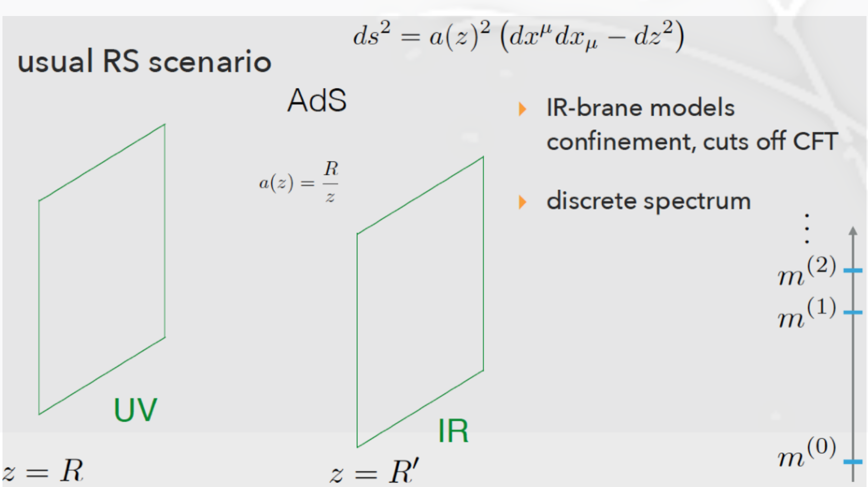
"Schrödinger Eqn".: $\left(-\partial_z^2 + V(z)\right)\Psi = p^2\Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2}$

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

=>

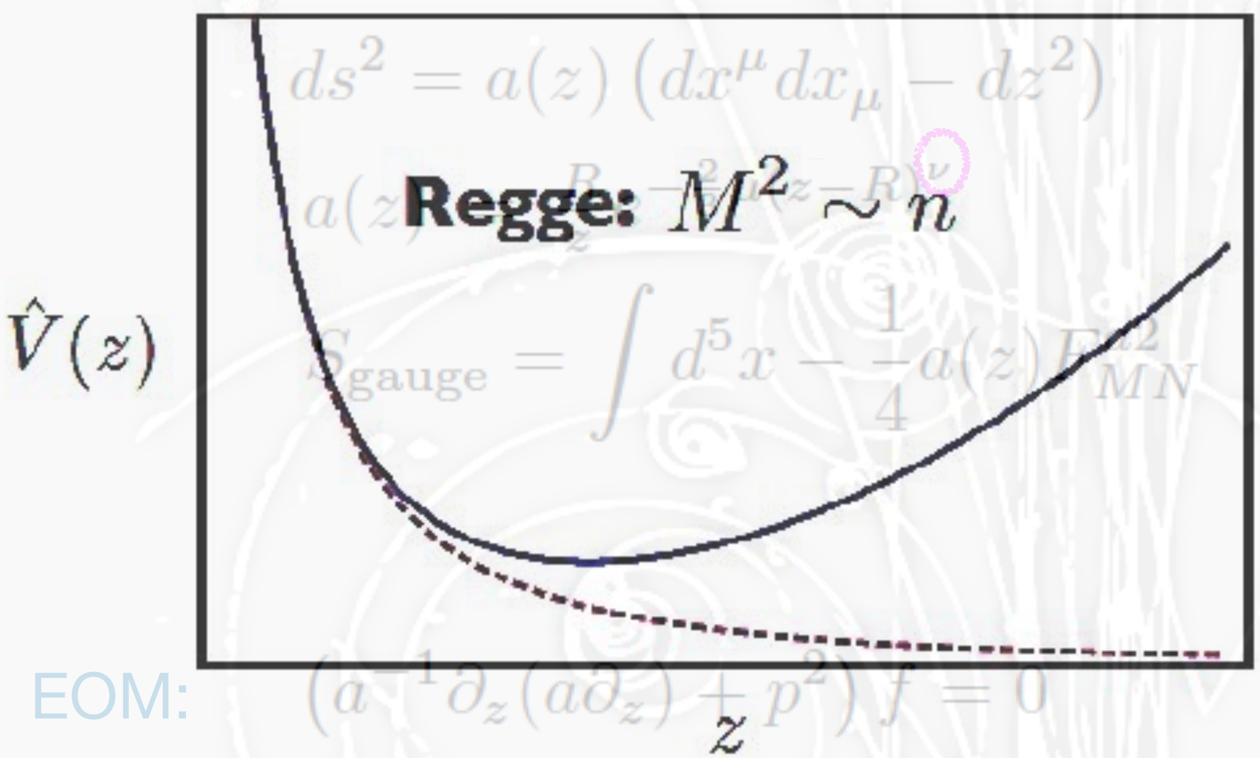
Stabilization of this setting:

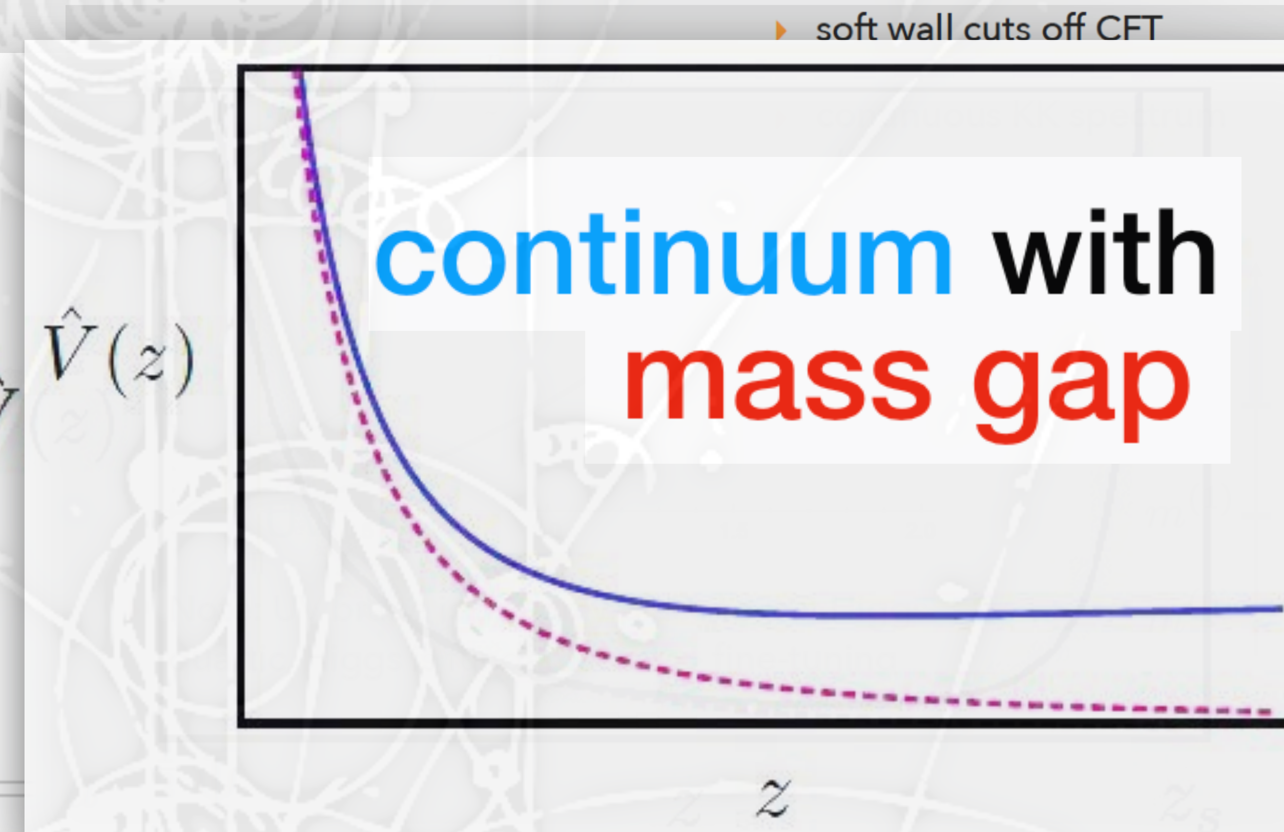
Batell, Gherghetta, Sword '08
Cabrer, Gersdorff , Quiros '09



$\to \infty$ (infinite

soft wall (AdS/QCD)

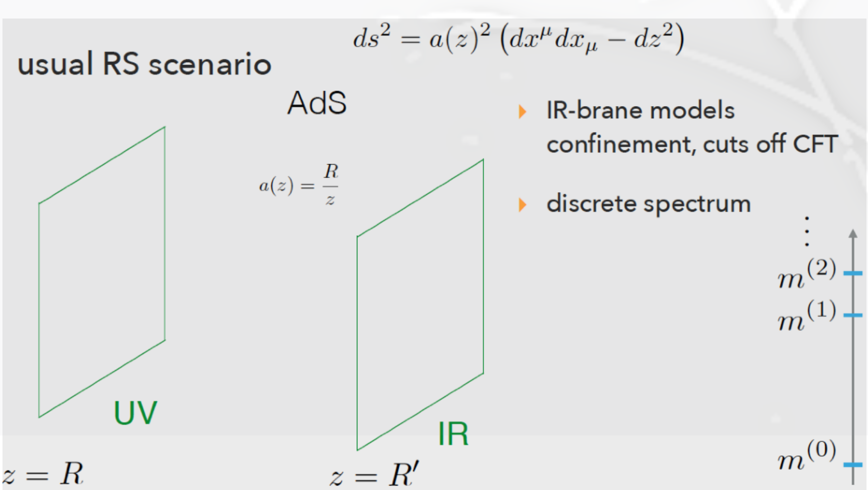




"Schrödinger Eqn".: $\left(-\partial_z^2 + V(z)\right)\Psi = p^2\Psi, \quad V(z) = \frac{a''}{2a} - \frac{a'^2}{4a^2}$

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

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



$\to \infty$ (infinite well) => just like IR brane: KK towers

Modeling the QCH: generalized free fields

Generalized Free Fields

Polyakov, early ‘70s- skeleton expansions

CFT completely specified by 2-point function - rest vanish

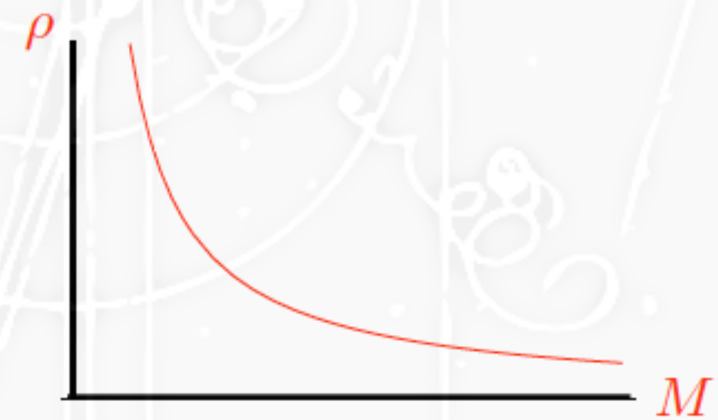
Scaling - 2-point function: $G(p^2) = -\frac{i}{(-p^2 + i\epsilon)^{2-\Delta}}$

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

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)

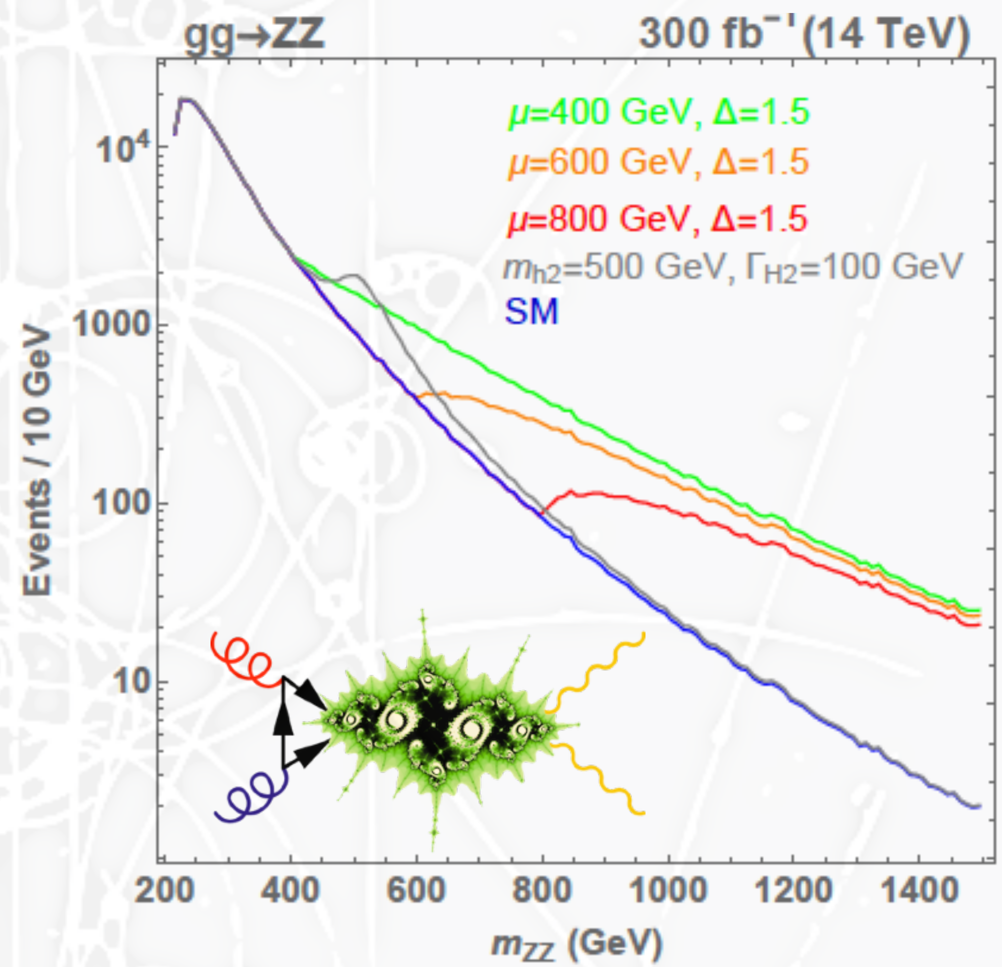
Bellazzini, Csaki, Hubisz, SL, Serra, Terning

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

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

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

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

Quantum Critical Higgs (Generalized Free Fields)

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

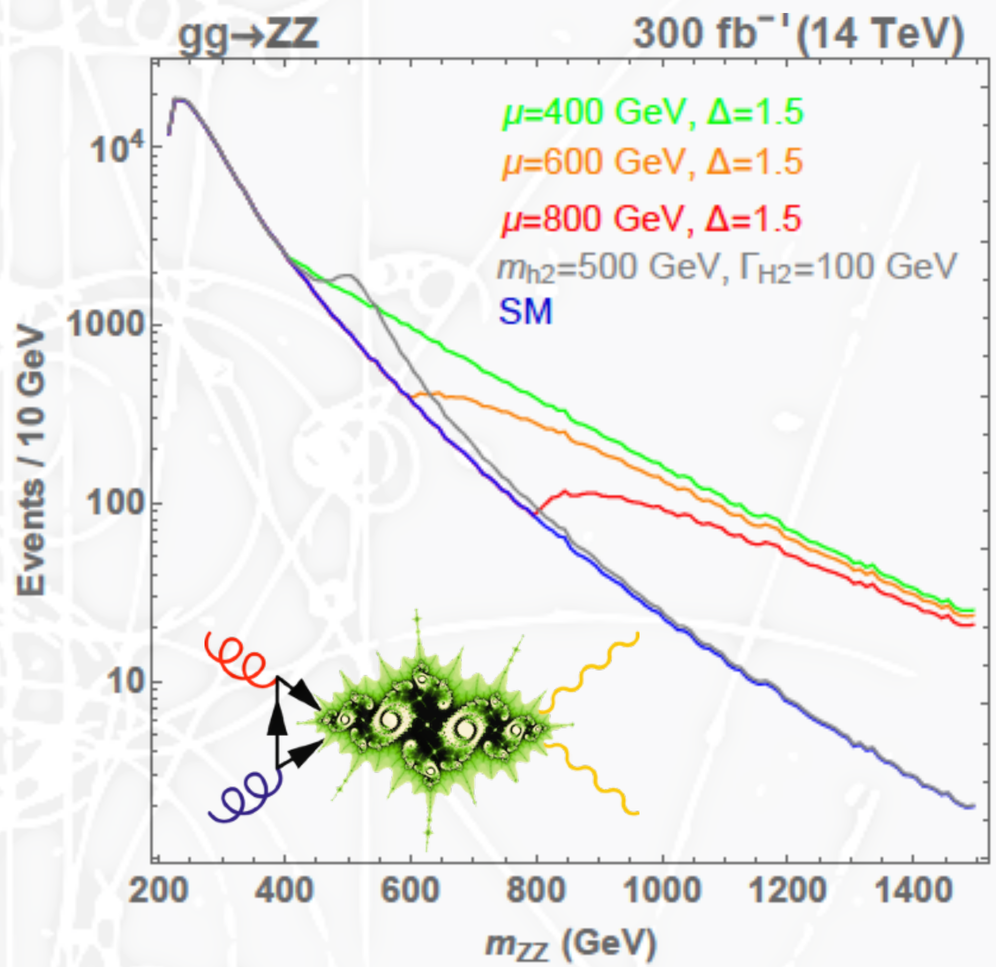
- 5D model: $S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W^{a\,2}_{MN} - \phi(z)\,|H|^2 + \mathcal{L}_{\rm int}(H) \right] + \int d^4x\, \mathcal{L}_{\rm perturbative}.$

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

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

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



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

Quantum Critical Higgs (Generalized Free Fields)

Bellazzini, Csaki, Hubisz, SL, Serra, Terning

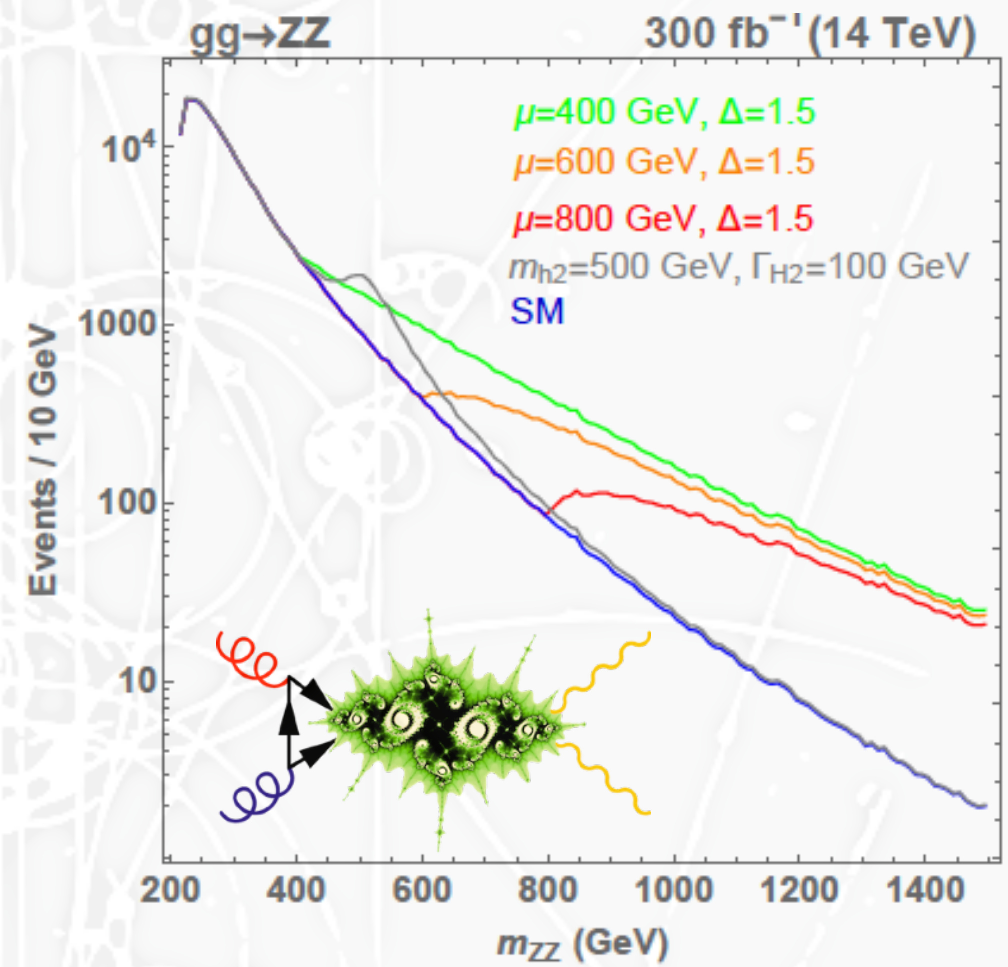
- 5D model: $$S = \int d^4x dz \sqrt{g} \left[|D_M H|^2 - \frac{1}{4g_4^2} W^{a\,2}_{MN} - \phi(z) |H|^2 + \mathcal{L}_{\rm int}(H) \right] + \int d^4x \, \mathcal{L}_{\rm perturbative}.$$

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

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

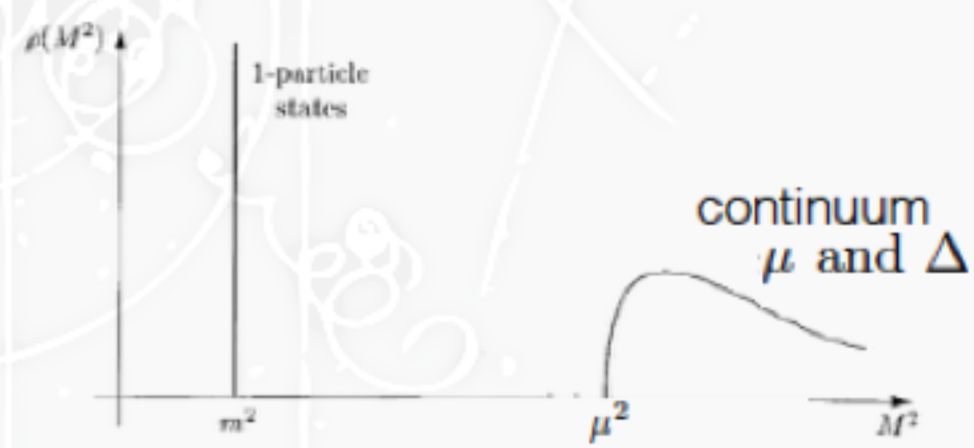
With the discovery of Higgs, we need a pole (125 GeV) and a gap to BSM continuum

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



Generally:

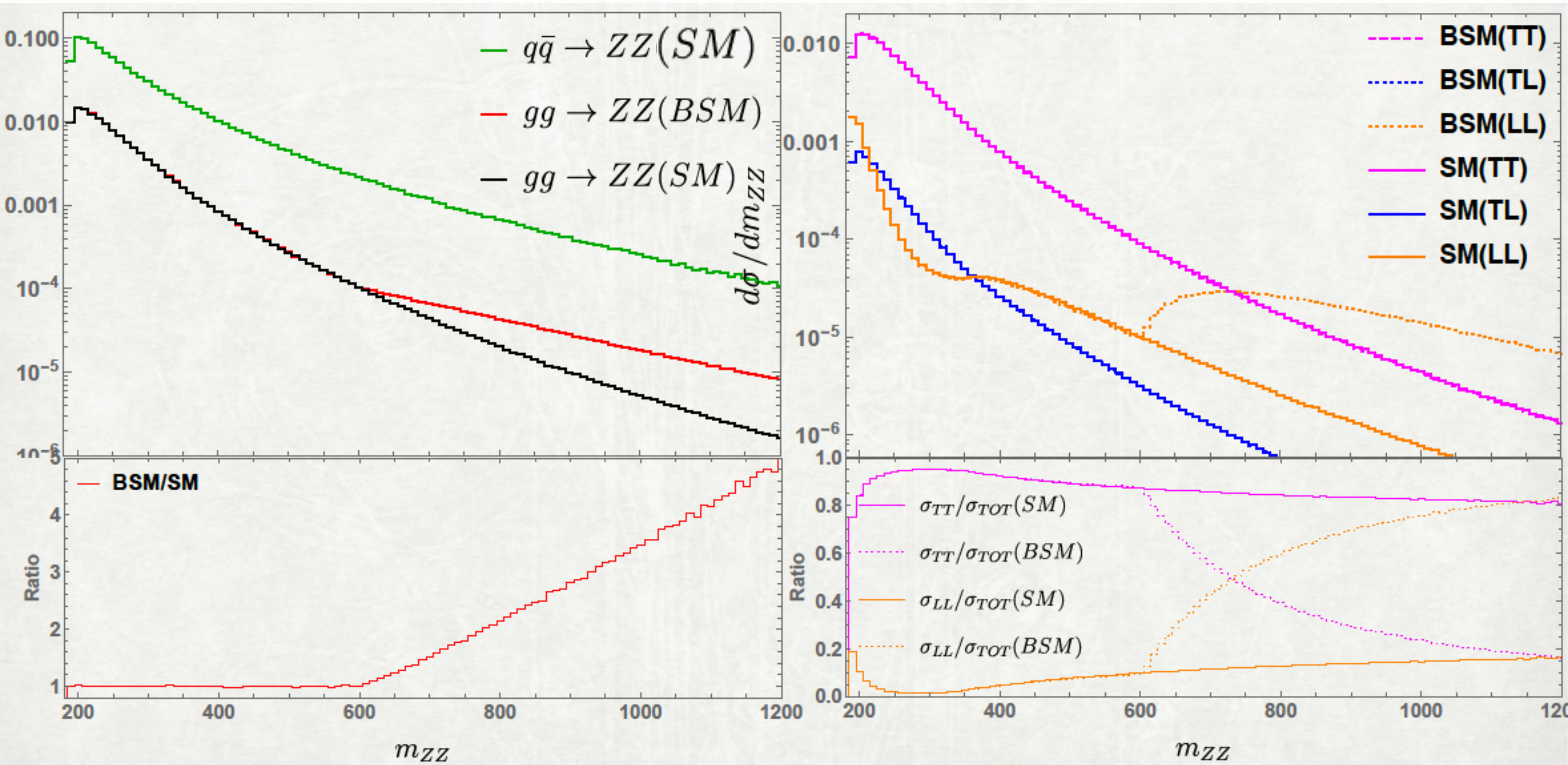
$$G_h(p^2) = \frac{i}{p^2 - m_h^2} + \int_{\mu^2}^{\infty} dM^2 \frac{\rho(M^2)}{p^2 - M^2}$$



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

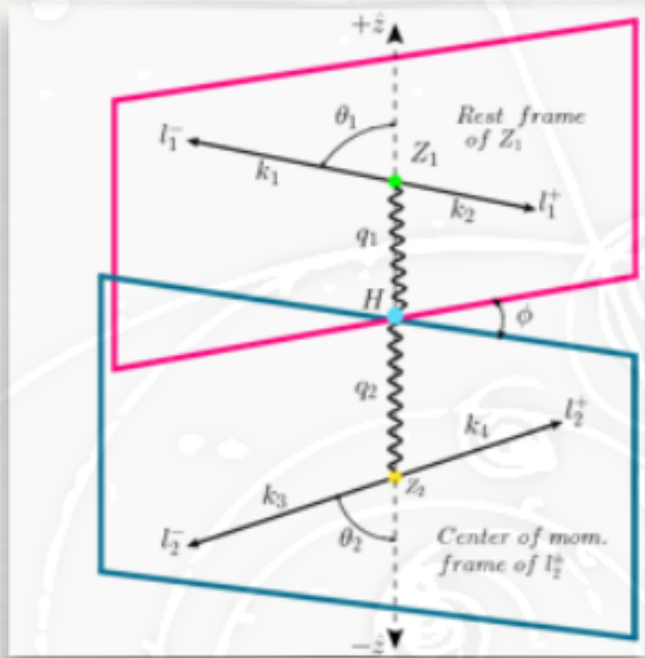
Probing Naturalness by the Tail of the Off-shell Higgs via Polarization Tagging

SL, Park, Qian; to appear soon



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

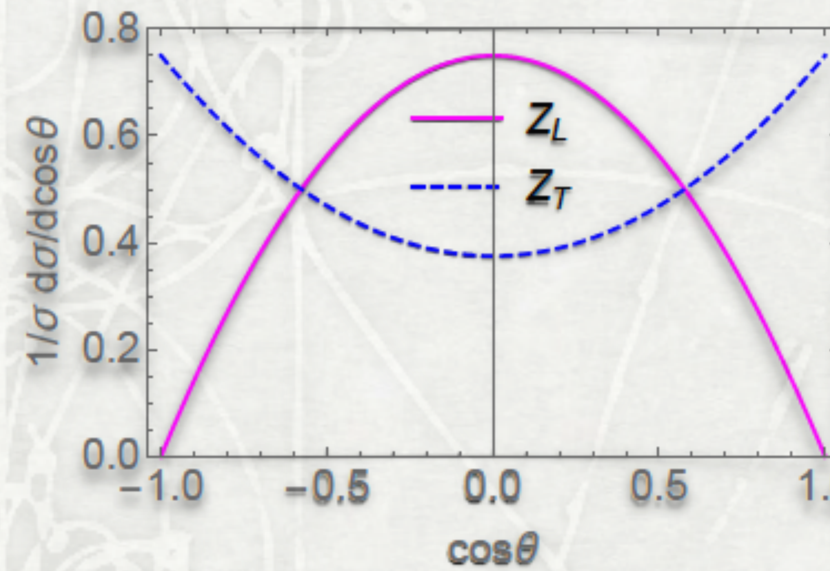
SL, Park, Qian; to appear soon



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

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

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

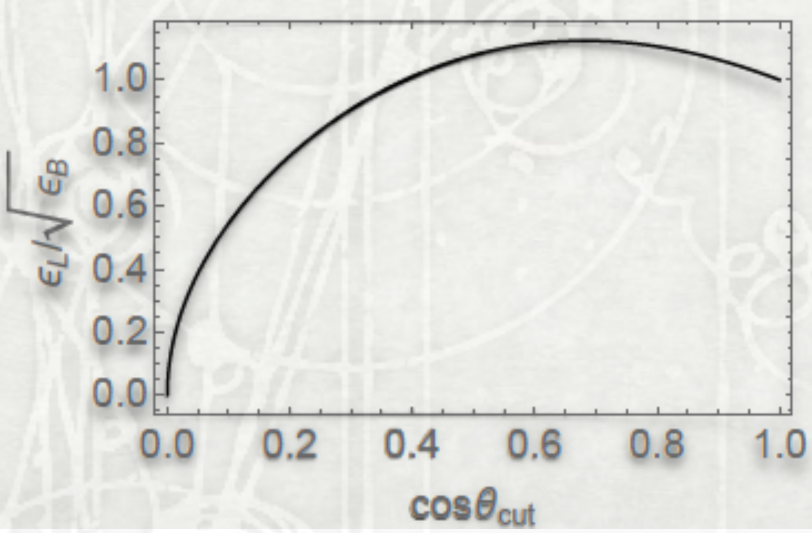


To optimize the longitudinal over transverse mode significance:

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

$$\cos\theta_C = 0.68$$

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



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

SL, Park, Qian; to appear soon

1. Theoretical discriminant: σ_{LL}/σ_{TT}

2. Experimental observable: $$\frac{\sigma_{|\cos\theta|<\cos\theta_C}}{\sigma_{|\cos\theta|>\cos\theta_C}}$$

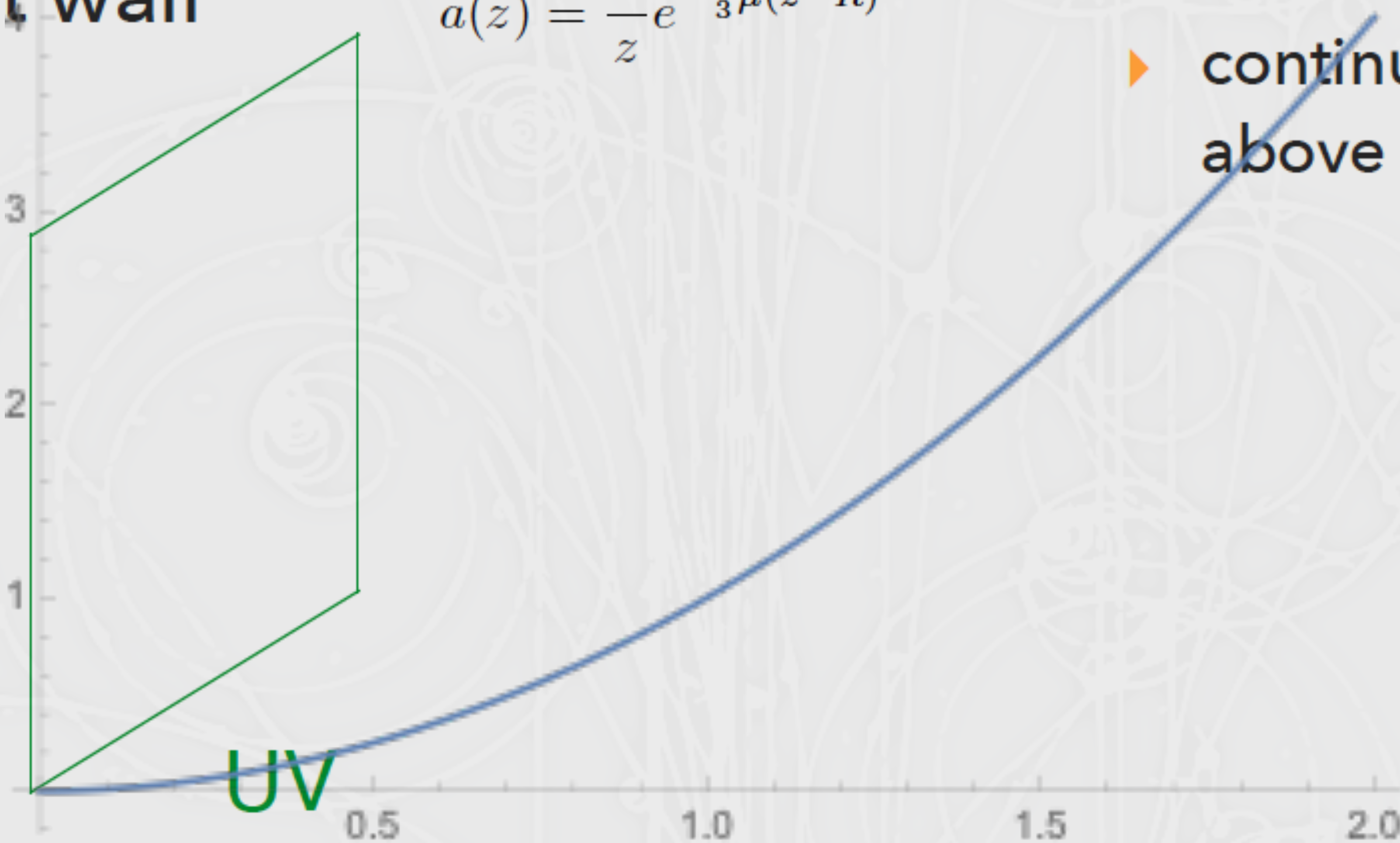
MZZ>800	Theory Cross Section (fb)					Observable (# events)		14 TeV 3000 fb-1	ZZ>4l
CASE C									
	TOT	LL	TT	TL	Ratio		Icthl<C	Icthl>C	RATIO
SM	2.91	0.40	2.43	0.08	0.17		15.81	9.34	1.69
BSM	8.58	6.10	2.40	0.08	2.54		59.17	16.32	3.63
SMQQ	122.07	0.02	120.89	1.16	0.00		633.39	440.07	1.44
SMTOT	124.98	0.43	123.32	1.24	0.00		649.20	449.41	1.44
BSMTOT	130.65	6.12	123.29	1.24	0.05		692.56	456.39	1.52
						err%	0.039	0.047	0.086
			Pol-tag	<	>				2.51
Signif_tot	1.51		L	0.86	0.14		lepton-eff	tot-eff	
Sig_cut	1.70		T	0.59	0.41		0.8	8.87808	

3. Pseudo experiment that make use of the whole polarization angle spectra in real analysis.

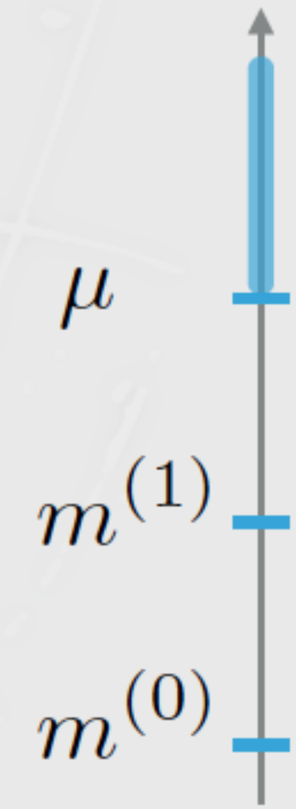
Quantum Critical Higgs

soft wall

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



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

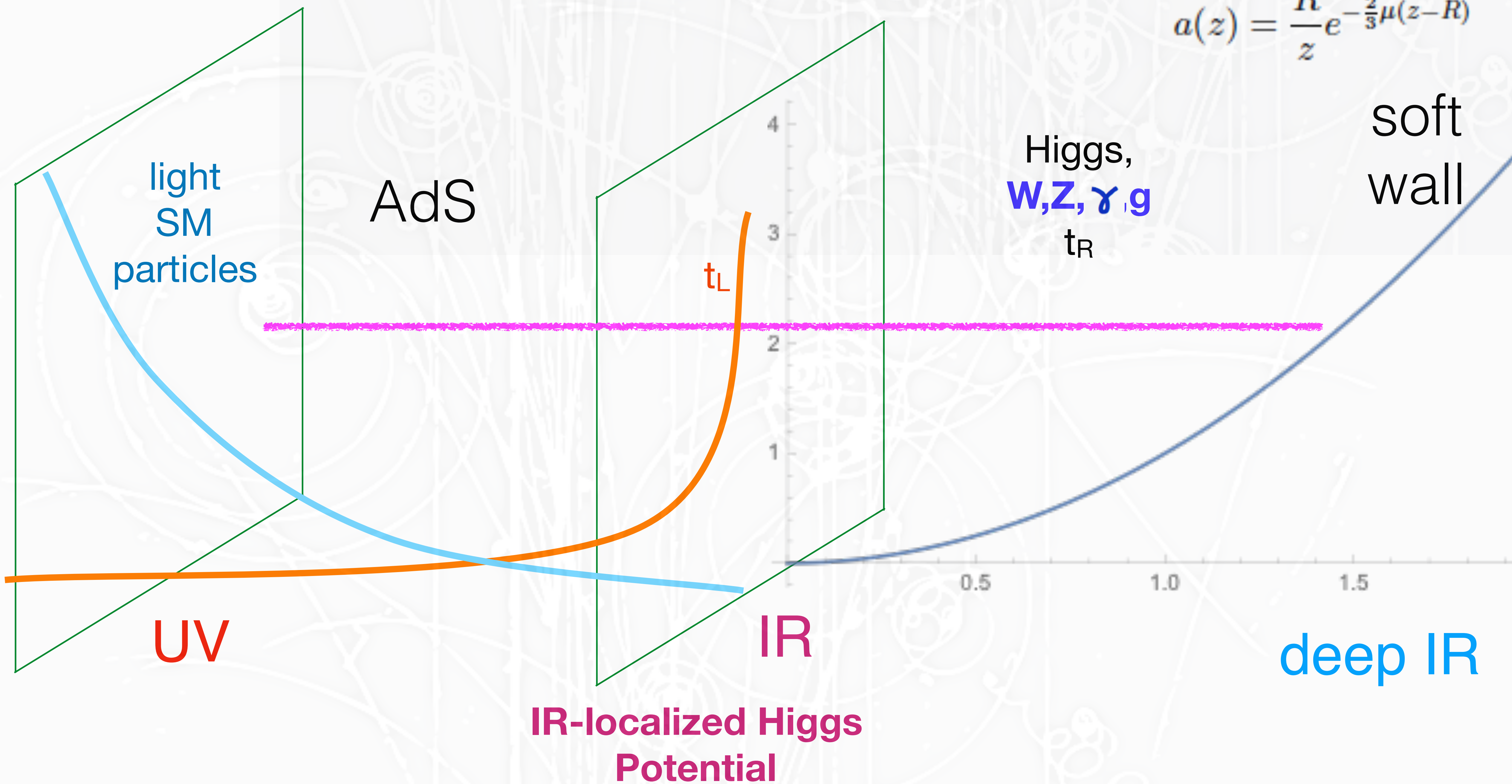


- Note: UV brane is the only place to put Higgs quartic, Higgs is fundamental ⇒ fine-tuning

Csaki, SL, Lombardo, work in progress

A Natural Quantum Critical Higgs: 5D model

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

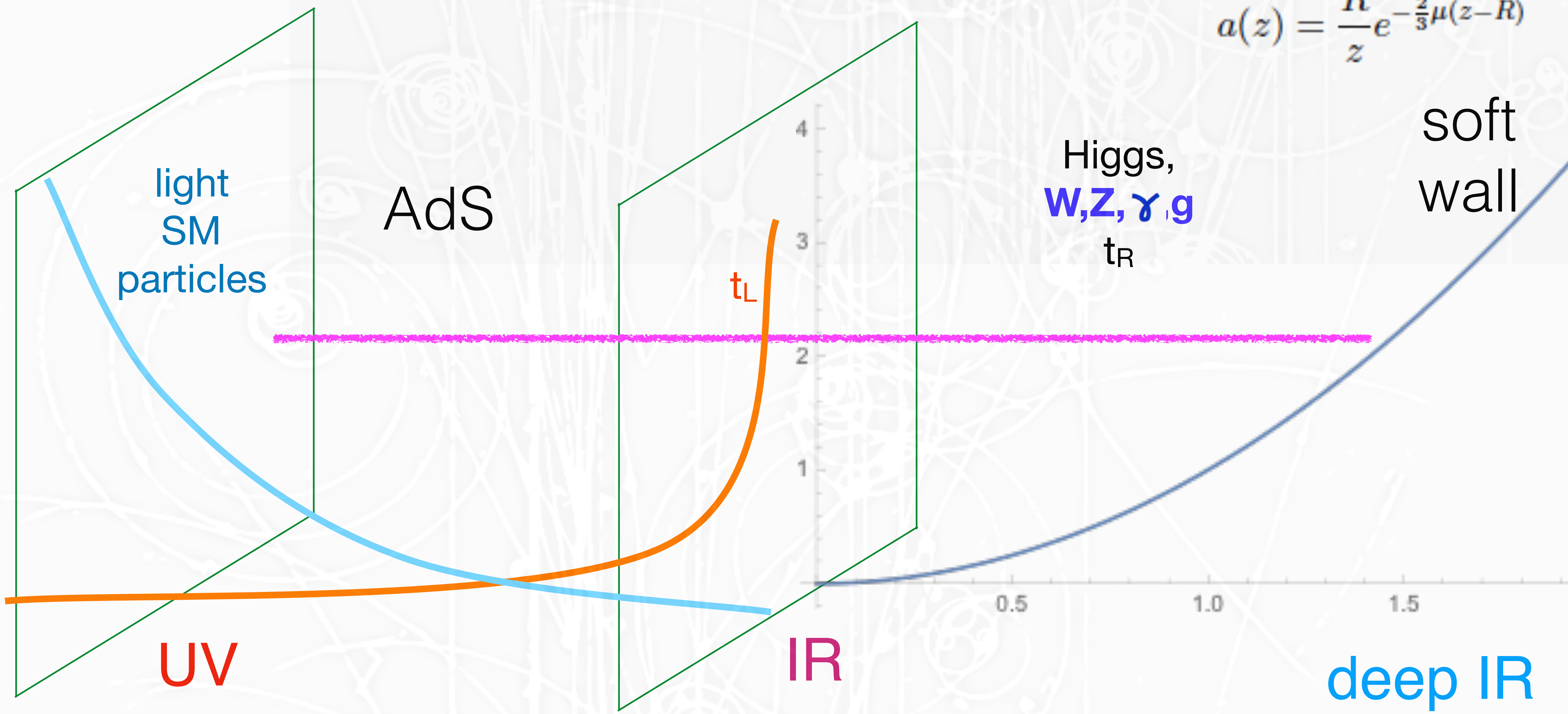


Csaki, SL, Lombardo, work in progress

A Natural Quantum Critical Higgs: 5D model

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

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



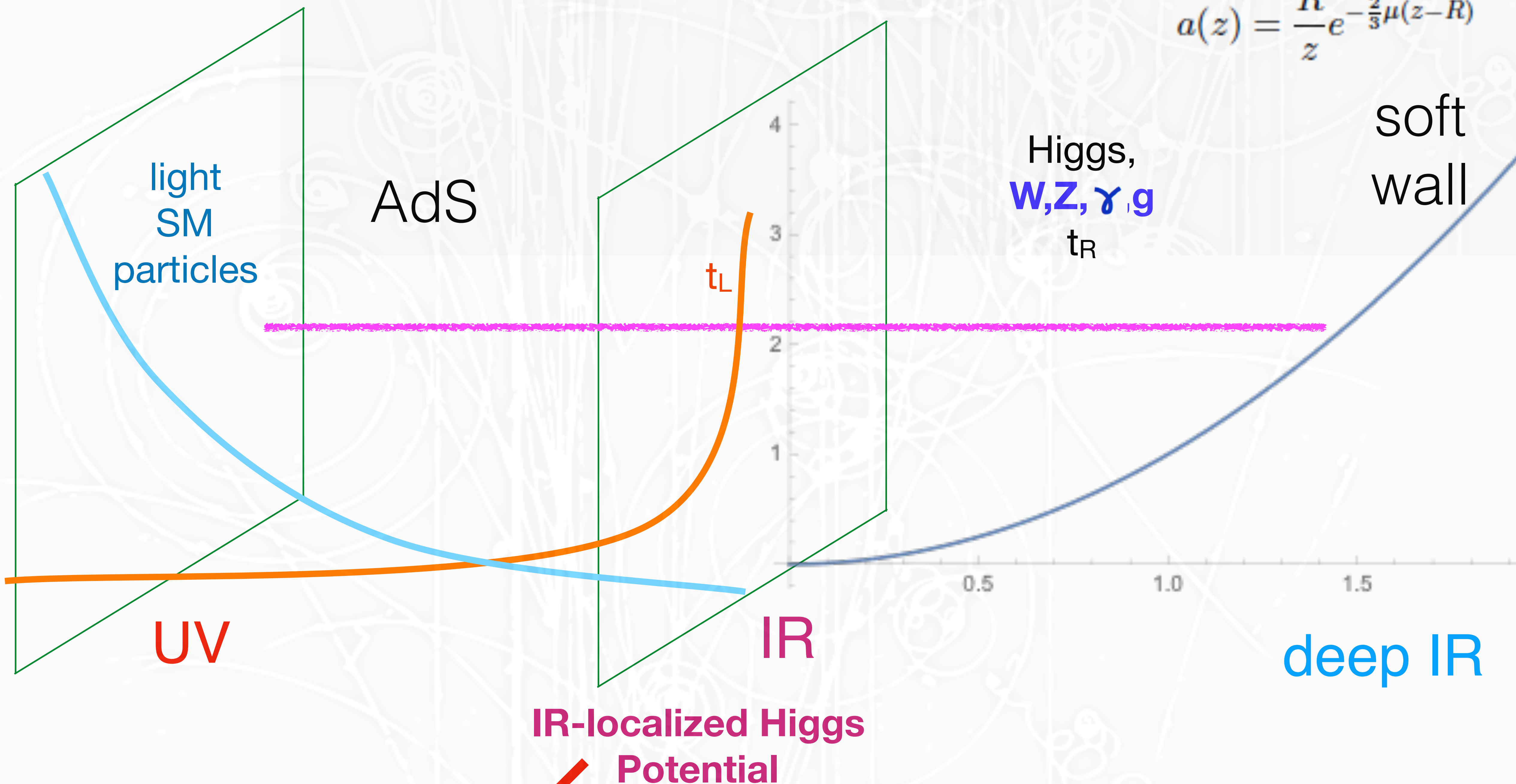
IR-localized Higgs Potential

Csaki, SL, Lombardo, work in progress

A Natural Quantum Critical Higgs: 5D model

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

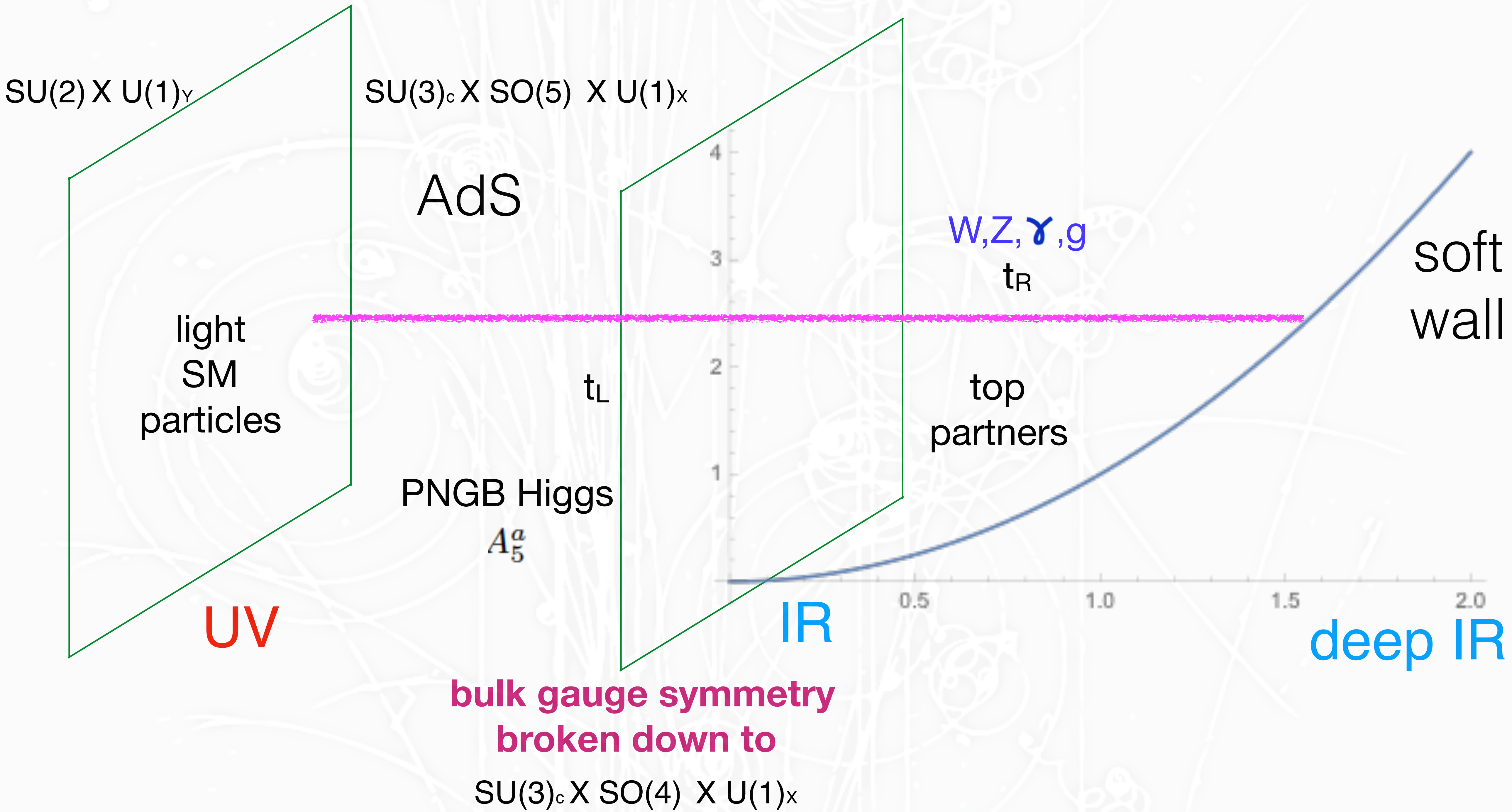
$$a(z) = \frac{R}{z} e^{-\frac{2}{3}\mu(z-R)}$$



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

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

A "more" Natural Quantum Critical Higgs: 5D model

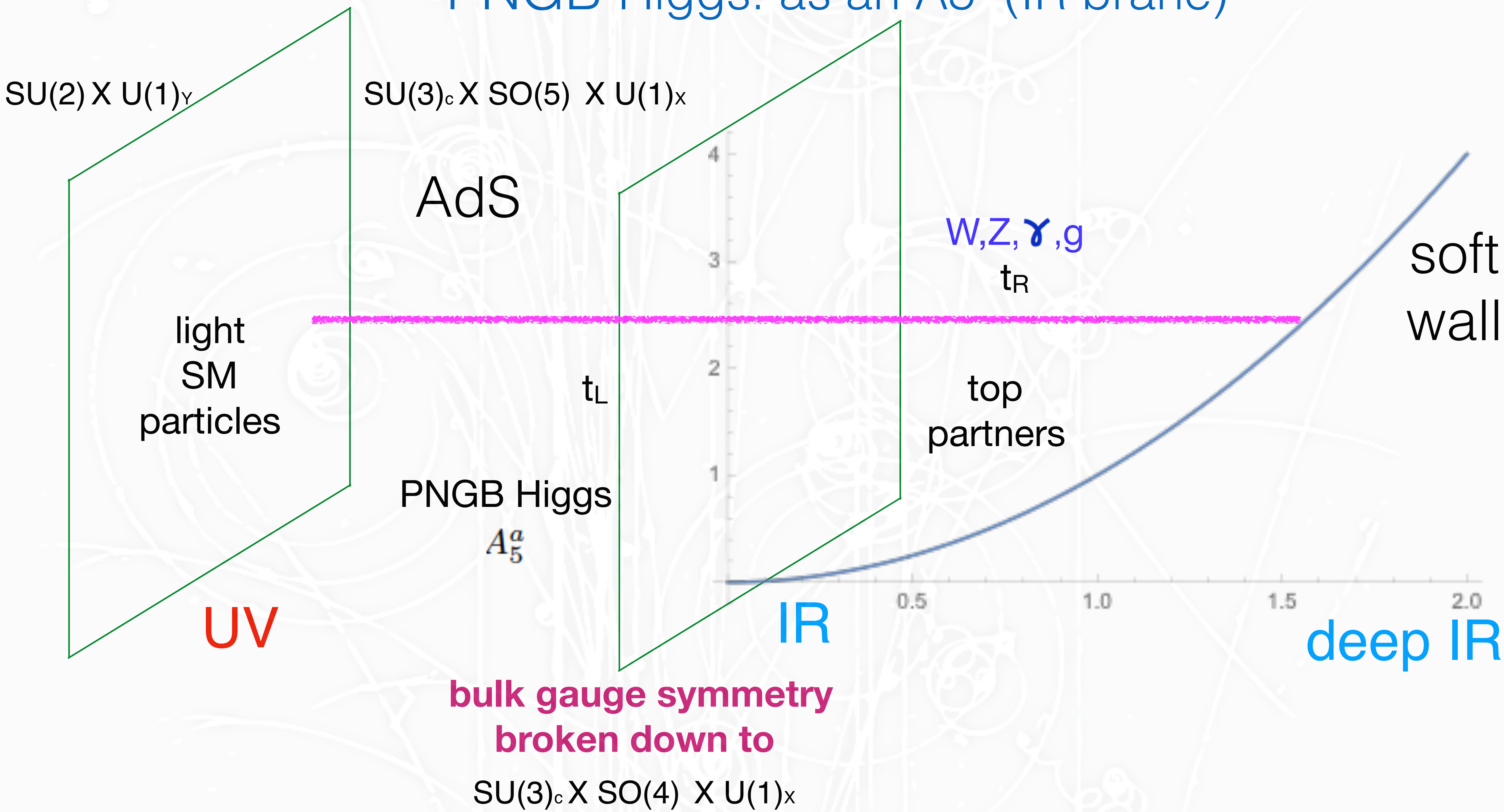


position of IR brane controls whether KK poles or continuum begins first

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

A “more” Natural Quantum Critical Higgs: 5D model

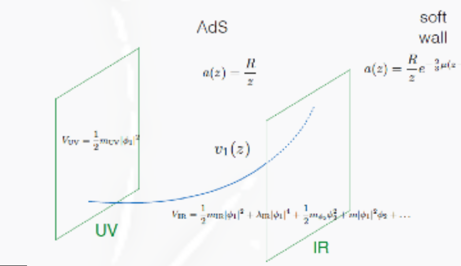
PNGB Higgs: as an A5 (IR brane)



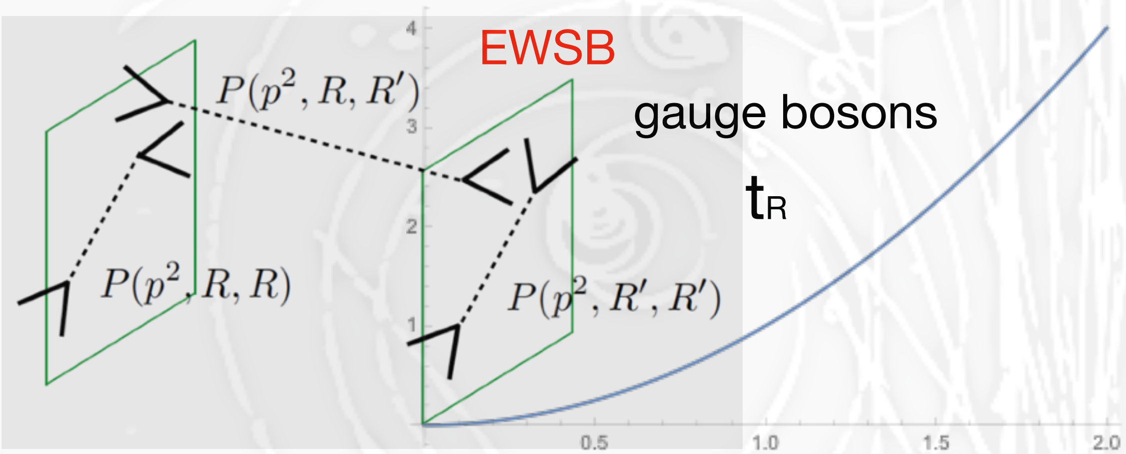
position of IR brane controls whether KK poles or continuum begins first

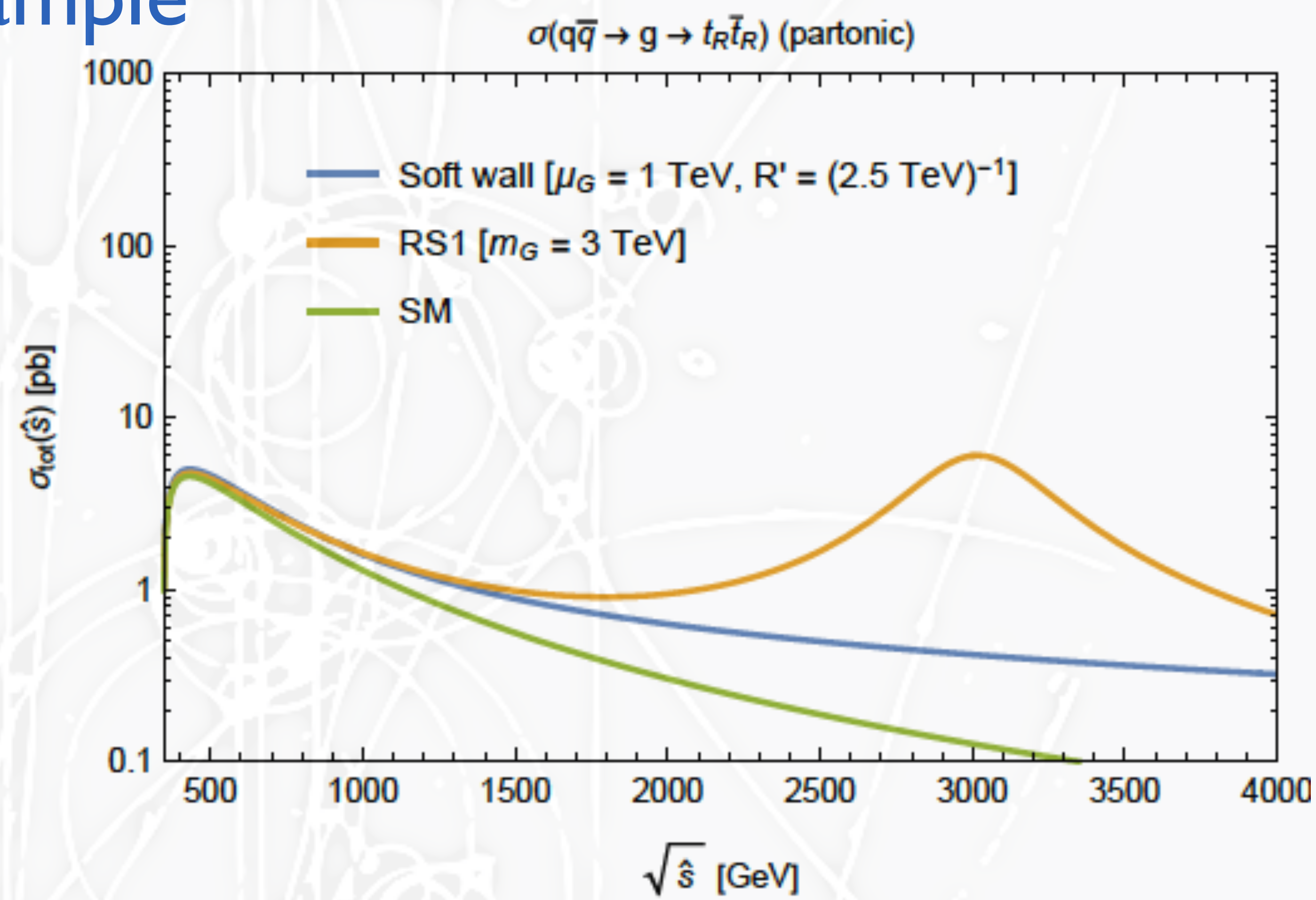
Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem (appear soon)



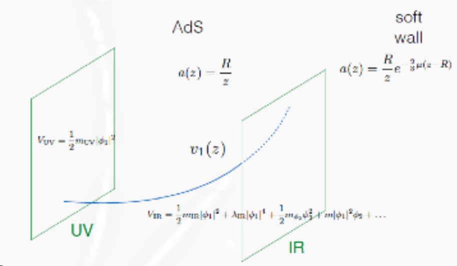
- New Physics (e.g. Top partner) appear solely as a continuum
  - KK gluon / colored octet example



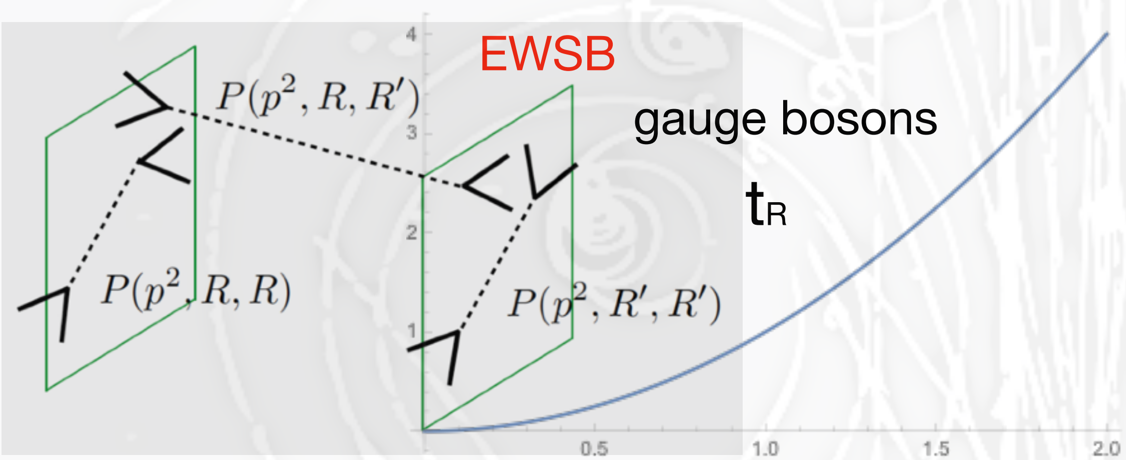


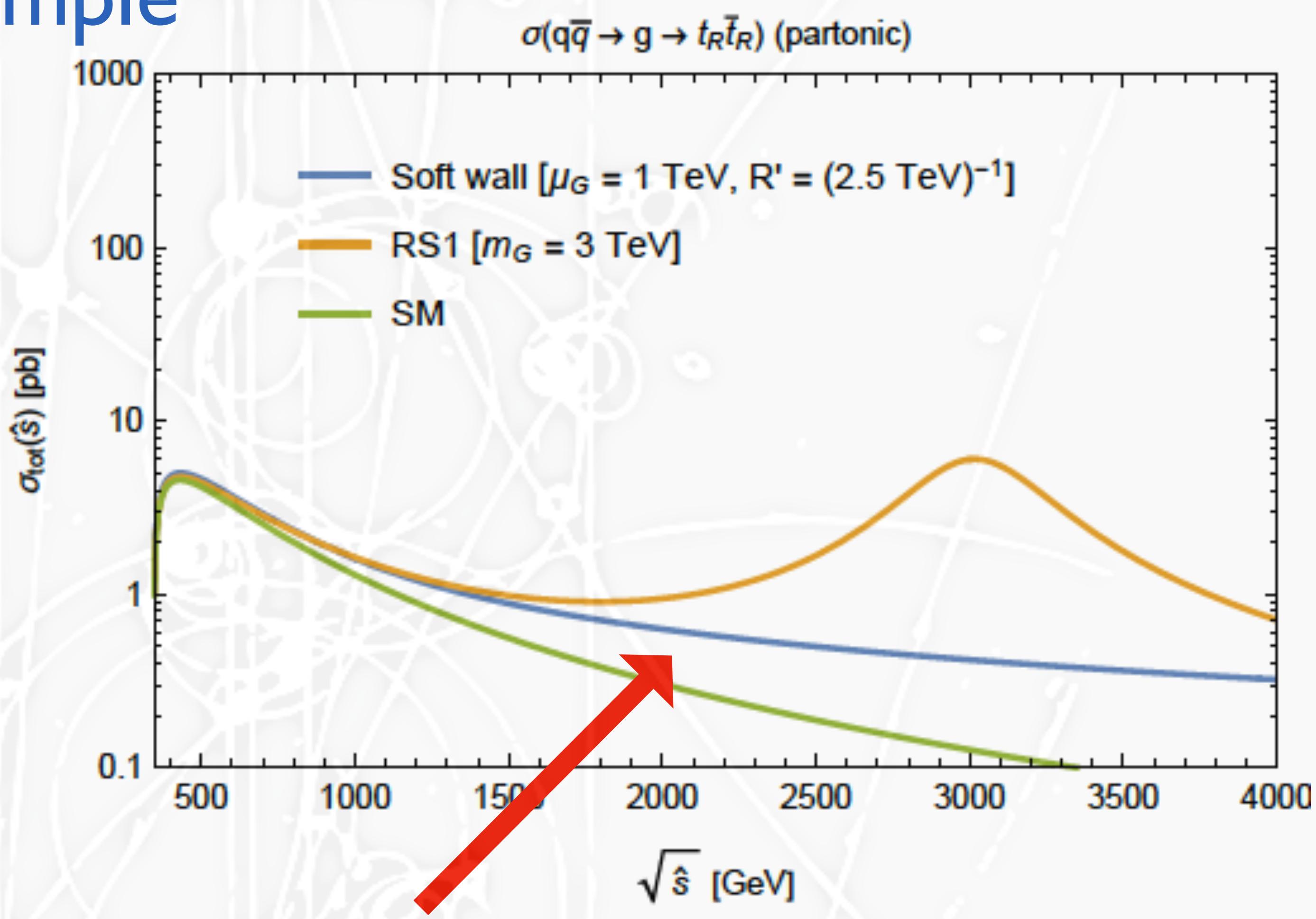
Continuum Naturalness?

Csaki, Lombardo, Lee, SL, Telem (appear soon)



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

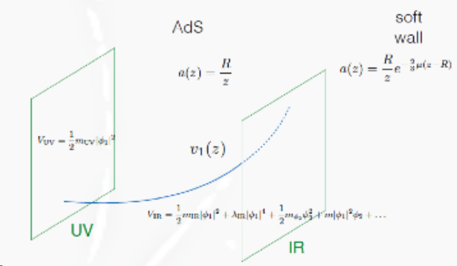




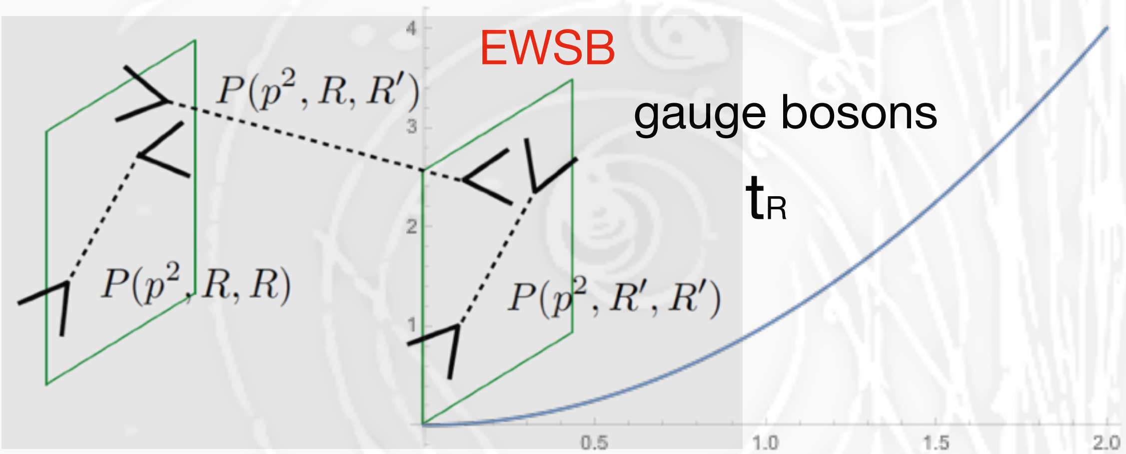
New Physics is hidden in the tail region!!

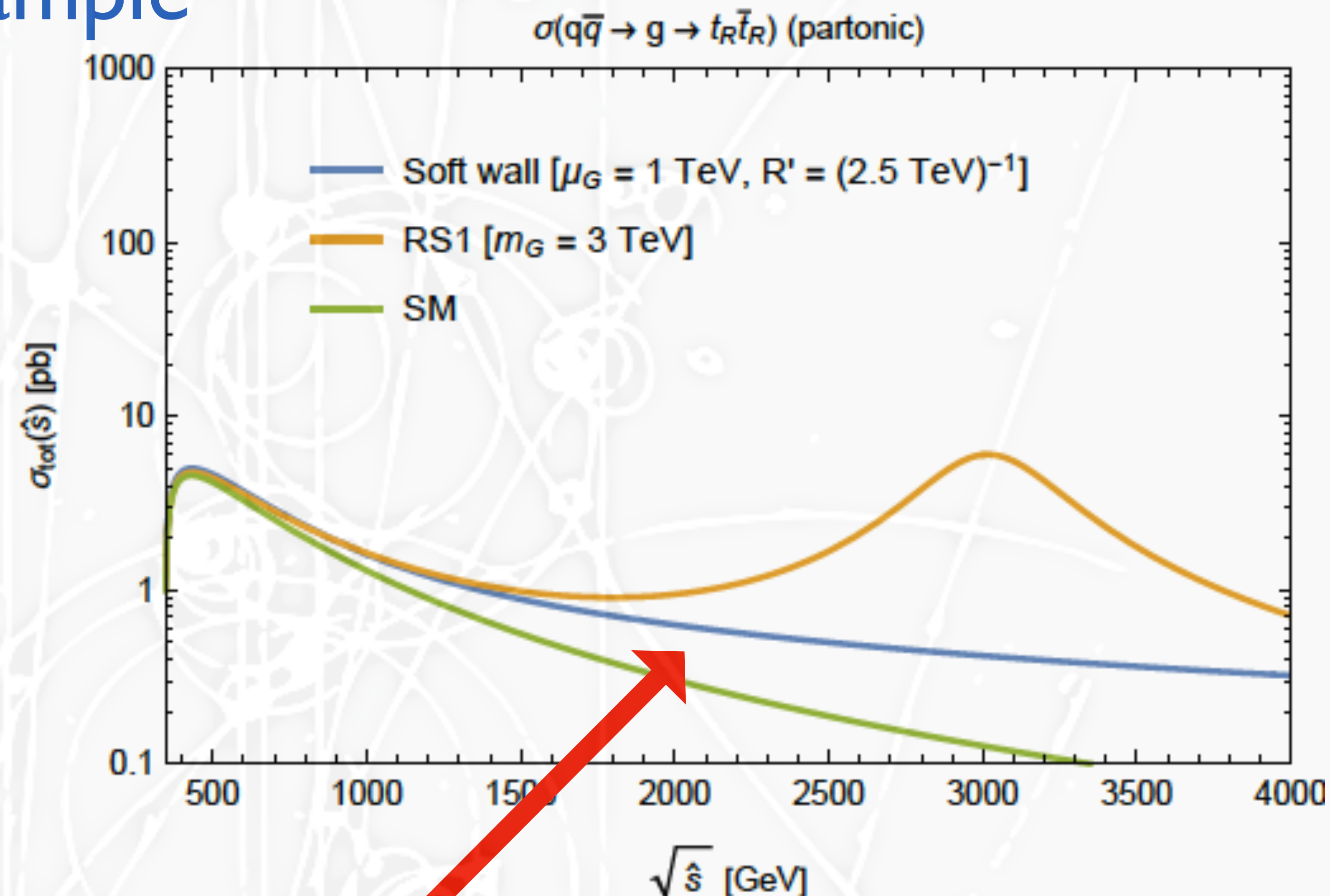
Continuum Naturalness?

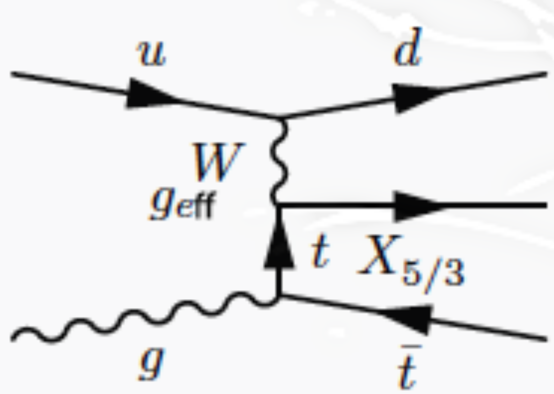
Csaki, Lombardo, Lee, SL, Telem (appear soon)



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







New Physics is hidden in the tail region!!

-Similar stories for continuum top partners

-Set of EFT operators searches

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

$$-iP_t(p) = \frac{1}{\not{p} - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} \overset{\text{Källén-Lehmann}}{=} \int dm^2\, \frac{\not{p}+m}{p^2-m^2}\rho_t(m^2)$$

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

$$-iP_t(p) = \frac{1}{\not{p} - \frac{M(p)}{\sqrt{\Pi_L(p)\Pi_R(p)}}} \overset{\text{Källén-Lehmann}}{=} \int dm^2 \frac{\not{p} + m}{p^2 - m^2} \rho_t(m^2)$$

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

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: $\mathcal{L}_{\text{top}} = \bar{t}_L \not{p}\, \Pi_L(p)\, t_L + \bar{t}_R \not{p}\, \Pi_R(p)\, t_R + \bar{t}_L\, M(p)\, t_R + h.c.$
  - 2-point function <tt> is given by

Källén-Lehmann

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

  - non-local effective action: $S_{\text{eff}} = \int d^4x\, d^4y\, \bar{\psi}(x)(i\not{\partial}_y - m)\Sigma(x-y)\psi(y)$
  - gauge invariant way: $S_{\text{eff}} = \int \frac{d^4p\, d^4k}{(2\pi)^8}\, \bar{\psi}(k)(\not{p}-m)\Sigma(p^2)F(k-p,p)$

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

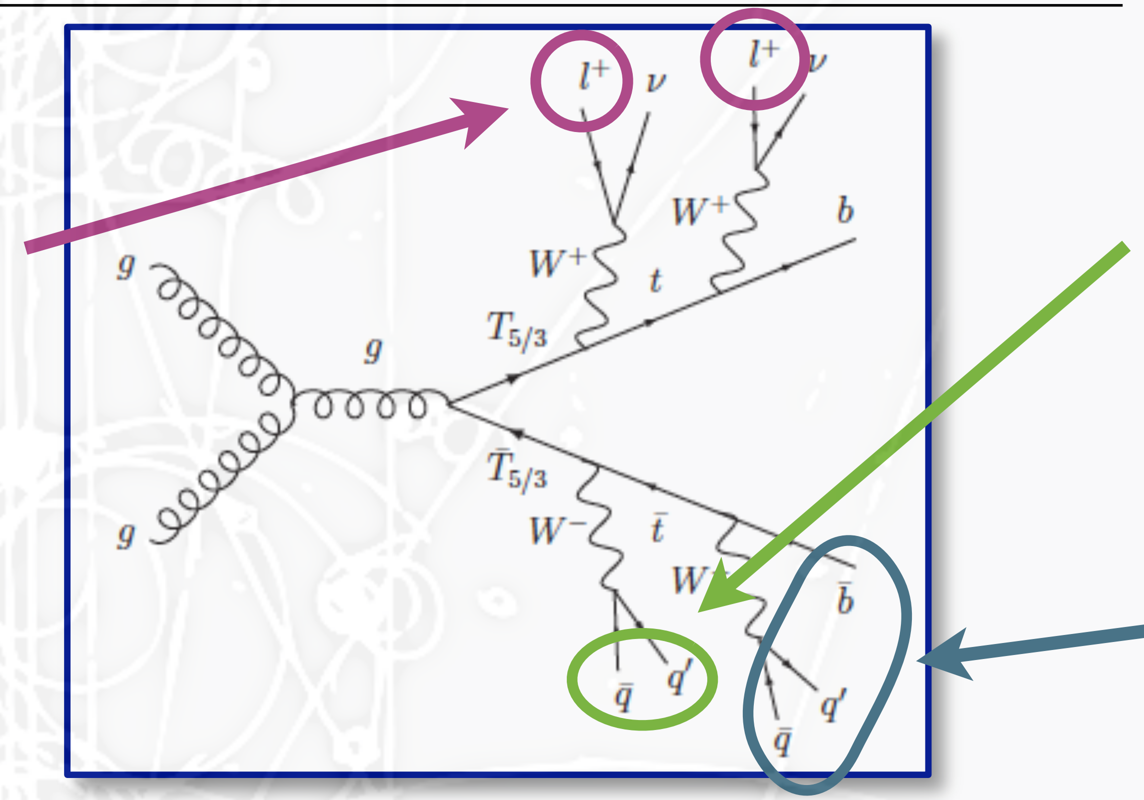
$$F(x,y) = \mathcal{P}\exp\left(-igT^a \int_x^y A^a \cdot dw\right)\psi(y)$$

Continuum Top Partners

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

- Can we hide top partners at the LHC?

same-sign dileptons



- depending on profile of the spectral density
- calculate top partner production for a given $\rho_h = \frac{1}{\pi}\mathrm{Im}\Sigma^{-1}$

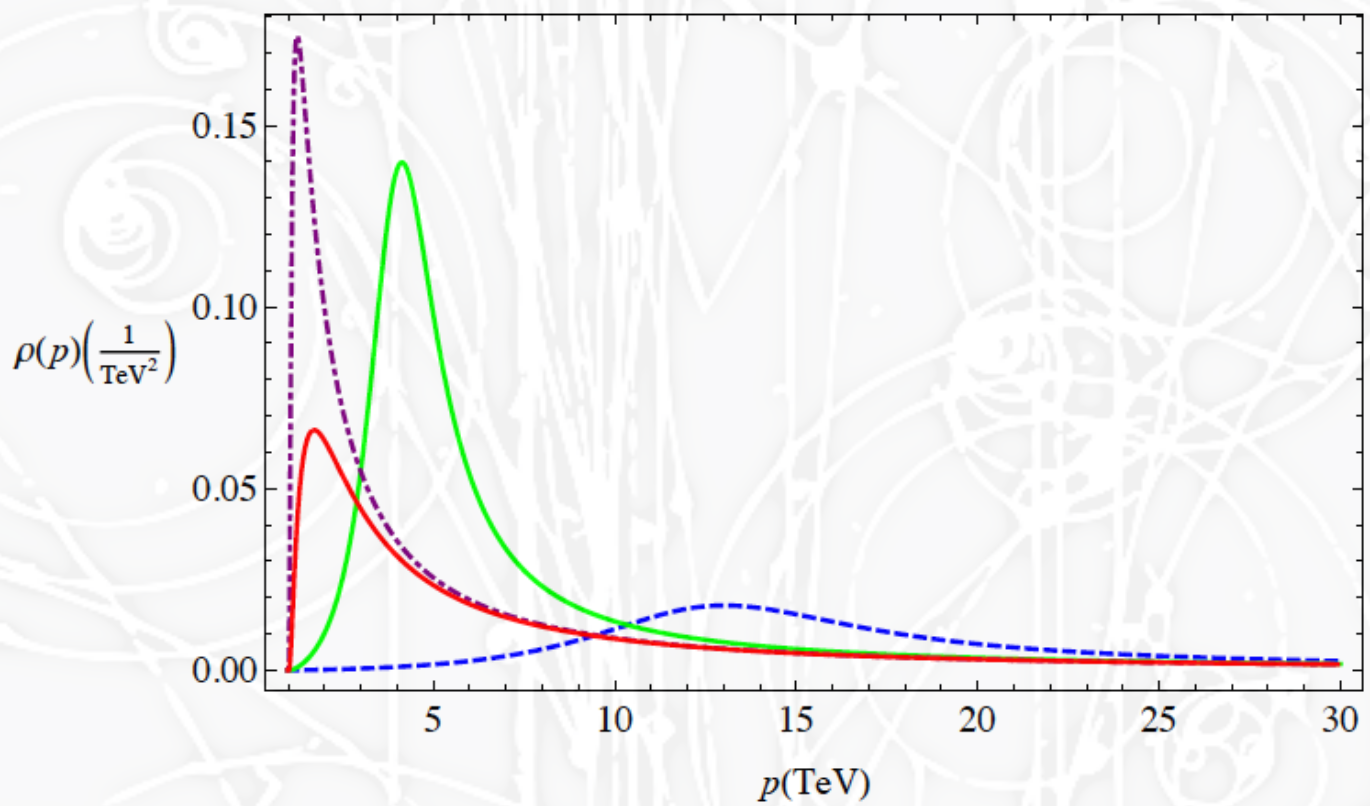
- quadratic divergence cancellation: the discrete sum rule turns into a continuous integral over the top partners

Continuum Super-partners

SL, Terning, (and amazing phD students); 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!