



## UV Fuzziness in Particle Physics & Braneworlds

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# Introduction Part I – Why UV Nonlocality in Particle Physics?

- UV nonlocal QFT's  $\Rightarrow$  Better UV behavior than local QFT's  $\Rightarrow$  Quantum gravity?
- Usually: Quantum gravity/spacetime  $\Rightarrow$  Minimal length scale  $\Rightarrow$  UV nonlocality.
- String field theory (SFT) = QFT approach to string theory (strings = 1D objects).  
 $\Rightarrow$  UV nonlocality manifest.
- In this talk: Prototypes of UV nonlocal QFT's inspired by SFT.  
 $\Rightarrow$  Nonlocal scale  $\geq \mathcal{O}(1)$  TeV (not necessary  $\sim$  Planck scale  $\Lambda_P \sim 10^{18}$  GeV).  
 $\Rightarrow$  No notion of microcausality! But macrocausality seems OK...
- Difficulties: UV nonlocal field theories may have Ostrogradsky ghosts (= dof with wrong sign kinetic terms) at the classical and/or at the quantum level!  
 $\Rightarrow$  Instability + Nonunitarity?

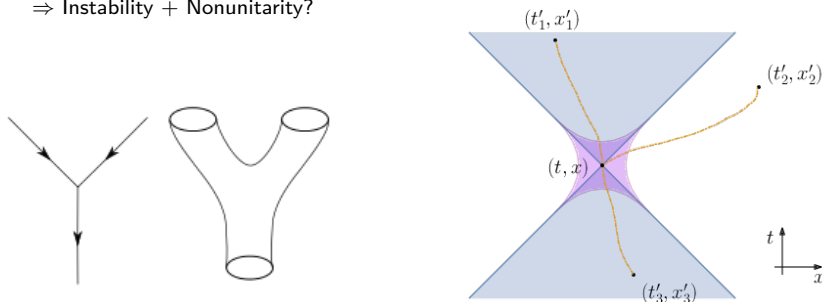
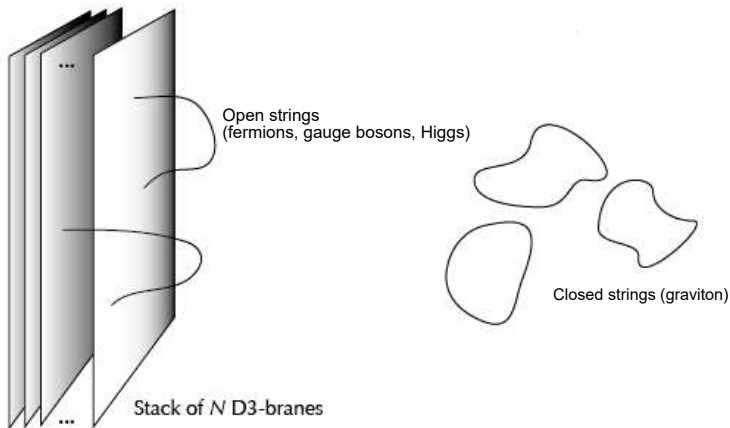


Figure: Interaction vertex & light cone: local QFT versus SFT

## String theory:

- Critical heterotic strings & superstrings I-II  $\Rightarrow$  6 extra dimensions of space.
- Stack of D-branes  $\Rightarrow$  Gauge theories.
- Strings = 1D extended objects  $\Rightarrow$  UV nonlocality in EFT's.



## 1 UV Nonlocality in Particle Physics

- String-Inspired Toy Model of Fuzzy Particles
- Stability of the Electroweak Scale
- Asymptotic Safety

## 2 UV Nonlocality in Braneworlds

- Effective Field Theories with an Extra Dimension of Space & Branes
- Warp Transmutation of Scales
- Split Fermions

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# String-Inspired Toy Model of Fuzzy Particles

L. Buoninfante, G. Lambiase, A. Mazumdar, Nucl. Phys. B 944 (2019) 114646

$\phi^n$ -theory with a real scalar  $\phi$  on a 4D Euclidean spacetime  $\mathbb{R}^4$  of signature  $(++++)$ :

$$\mathcal{L} = -\frac{1}{2} \phi(x) (\square - m^2) \phi(x) + \frac{\lambda}{n!} \tilde{\phi}^n(x), \quad \square = \partial_\mu \partial_\mu.$$

Delocalized scalar field defined via a smearing heat kernel  $K$  (nonlocal scale:  $\Lambda = 1/\ell$ ):

$$\tilde{\phi}(x) = \int d^4x' K(x - x') \phi(x'), \quad K(x - x') = \left(\frac{1}{4\pi\ell^2}\right)^2 \exp\left[-\left(\frac{|x - x'|}{2\ell}\right)^2\right],$$

related to a smearing infinite derivative operator:

$$K(x - x') = e^{f(\square)} \delta(x - x'), \quad f(\square) = \frac{\square - m^2}{\Lambda^2}.$$

Move nonlocality: *interaction*  $\rightarrow$  *kinetic* terms  $\Rightarrow$  SFT-like form factor:

$$\mathcal{L} = -\frac{1}{2} \tilde{\phi}(x) e^{-2f(\square)} (\square - m^2) \tilde{\phi}(x) + \frac{\lambda}{n!} \tilde{\phi}^n(x) \quad \Rightarrow \quad \Pi(p^2) = \frac{-ie^{-2f(p^2)}}{p^2 + m^2}.$$

Exponential = Entire function on the complex plane  $\Rightarrow$  No ghost at tree level!

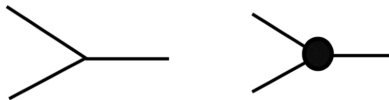


Figure: Local versus nonlocal vertex ( $\phi^3$ -theory)

# Stability of the Electroweak Scale

T. Biswas, N. Okada, Nucl. Phys. B 898 (2015) 113-131

- 1-loop radiative correction to the scalar mass  $m$  in  $\phi^4$ -theory:

$$\Lambda \gg m \Rightarrow \delta m^2 \simeq \frac{\lambda}{64\pi^2} \Lambda^2 \Rightarrow \Lambda = \text{smooth cutoff } (\sim \text{Lee-Wick SM}).$$

$\Rightarrow$  Stabilized against radiative corrections if  $\Lambda \sim 1 \text{ TeV}$ ! But why  $\Lambda \ll \Lambda_P$ ?

- Nonlocal Yang-Mills theory, with  $\nabla_\mu = \partial_\mu - igA_\mu^a T_a$  and  $F_{\mu\nu}^a = \partial_{[\mu} A_{\nu]}^a + g f^{abc} A_\mu^b A_\nu^c$ :

$$\mathcal{L}_{YM} = \frac{1}{4} F_{\mu\nu}^a e^{-2\nabla^2/\Lambda^2} F_{\mu\nu}^a - i\bar{\psi} e^{-2\nabla^2/\Lambda^2} \gamma_\mu \nabla_\mu \psi.$$

- UV nonlocality signatures at LHC?  $\Rightarrow$  ex: Drell-Yan dilepton cross section:

$$q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^- \Rightarrow \sigma_{NLSM} = e^{-2s/\Lambda^2} \sigma_{SM}, \quad \text{dev.} = \left( \frac{d\sigma_{NLSM}}{dM_{ee}} / \frac{d\sigma_{SM}}{dM_{ee}} \right) - 1.$$

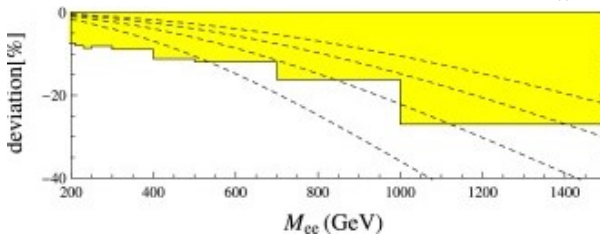


Figure: LHC Run 1; ATLAS uncertainties;  $\sqrt{s} = 8 \text{ TeV}$ ;  $\Lambda/\sqrt{2} = 1.5, 2, 2.5 \text{ and } 3 \text{ TeV}$  (bottom  $\rightarrow$  top)

# Asymptotic Safety – Stability of the Higgs Potential

A. Ghoshal, A. Mazumdar, N. Okada, D. Villalba, Phys. Rev. D 97 (2018), 076011

Nonlocal Yukawa theory:

$$\mathcal{L}_\varphi = -\frac{1}{2} \varphi e^{-2\Box/\Lambda^2} \Box \varphi - i\bar{\psi} e^{-2\Box/\Lambda^2} \gamma_\mu \partial_\mu \psi + \frac{\lambda}{4!} \varphi^4 + y \varphi \bar{\psi} \psi.$$

$\beta$ -function for  $\lambda \Rightarrow$  Conformal behavior above  $\Lambda \Rightarrow$  Stability of the scalar potential!

$$\beta_\lambda^{(1)}(\mu^2 \gg \Lambda^2) \sim \frac{3\lambda^2 + 8\lambda y^2}{16\pi^2} e^{-4\mu^2/\Lambda^2}$$

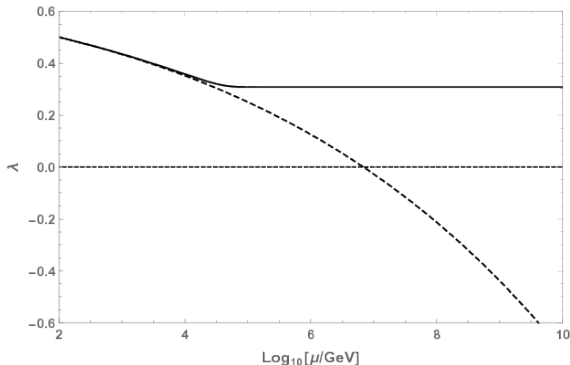


Figure:  $\Lambda/\sqrt{2} = 10^5$  GeV; initial conditions:  $\lambda = 0.5$  &  $y = 0.6$  at  $\mu = 100$  GeV

# Asymptotic Safety – No UV Landau Pole for the Weak Hypercharge

A. Ghoshal, A. Mazumdar, N. Okada, D. Villalba, Phys. Rev. D 97 (2018), 076011

Nonlocal QED, with  $\nabla_\mu = \partial_\mu - igA_\mu$  and  $F_{\mu\nu} = \partial_{[\mu}A_{\nu]}$ :

$$\mathcal{L}_{QED} = \frac{1}{4}F_{\mu\nu}e^{-2\Box/\Lambda^2}F_{\mu\nu} - i\bar{\psi}e^{-2\nabla^2/\Lambda^2}\gamma_\mu\nabla_\mu\psi,$$

$\beta$ -function for  $g \Rightarrow$  Conformal behavior above  $\Lambda \Rightarrow$  No UV Landau pole!

$$\beta_g^{(1)}(\mu^2 \gg \Lambda^2) \sim \frac{1}{16\pi^2} \left(\frac{4}{3}\right) e^{-4\mu^2/\Lambda^2}$$

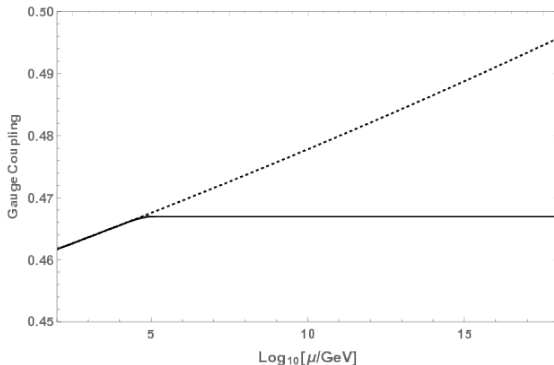


Figure:  $\Lambda/\sqrt{2} = 10^5$  GeV

# Conclusion Part I – UV Nonlocality in Particle Physics

## Summary:

- Motivated to include gravity in a UV complete quantum theory of Nature.
  - Has a smearing effect on interaction vertices & pointlike sources.
  - Potential new path to stabilize the electroweak scale?
  - Potential path towards asymptotic safety?
    - ⇒ Stability of the Higgs potential? + No Landau pole for the weak hypercharge?
- ⇒ New model building issues for the energy frontier!

## Potential problems:

- UV nonlocal QFT's usually defined on Euclidean spacetime (Wick rotation not defined: essential singularity at  $\infty$  on the complex plane):
  - ⇒ Artificial analytic continuation ( $S$ -matrix: only real momenta of asymptotic states).
  - ⇒ Lorentzian starting point? UV change of signature? (ex: LQG)
- Simplest nonlocal theories ⇒ Ghosts may reappear in dressed propagators or at tree level with a shift of vacuum (Higgs mechanism)...

## Outlook:

- Building a consistent nonlocal UV completion of the SM ⇒ Collider phenomenology?
- Interplay with quantum spacetime constructions?
  - ex: stochastic spacetimes,  $\kappa$ -Minkowski spacetime, ...
- Interplay with noncommutative QFT's?
  - ⇒ Other UV nonlocal features (Lorentz symmetry breaking, UV/IR mixing, ...).
  - ⇒ Constraining gauge groups: only  $U(N)$  in  $\theta$ -Poincaré noncommutative QFT's.

## 1 UV Nonlocality in Particle Physics

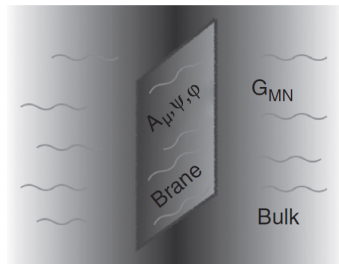
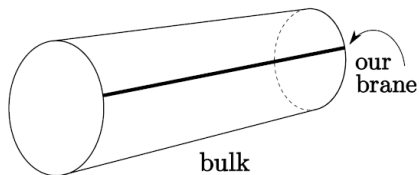
- String-Inspired Toy Model of Fuzzy Particles
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## 2 UV Nonlocality in Braneworlds

- Effective Field Theories with an Extra Dimension of Space & Branes
- Warp Transmutation of Scales
- Split Fermions

Local EFT's with an extra dimension of space &  $\delta$ -like branes.

- $\delta$ -like brane = Hypersurface where fields and/or interactions can be localized.
- Bulk = Whole spacetime outside the branes.



5D action with multibranes:

$$S_{5D} = \int d^4x \, dy \left[ \mathcal{L}_{bulk} + \sum_{i=1}^N \delta(y - y_i) \mathcal{L}_{brane}^{(i)} \right].$$

Kaluza-Klein (KK) dimensional reduction (5D  $\rightarrow$  4D).

$\Rightarrow$  4D KK-modes  $\phi_n$  & bulk wave functions  $f_n$ :

$$\Phi(x, y) = \sum_n^{\infty} f_n(y) \phi_n(x).$$

# Warp Transmutation of Scales – Electroweak Scale

L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370-3373

RS model:

- Spacetime = **Slice of AdS<sub>5</sub>** (proper length  $\rho$ ), signature  $(+ - - -)$ :

$$ds^2 = g_{MN} dx^M dx^N = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2.$$

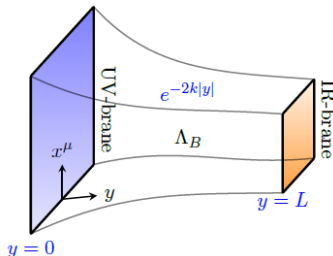
- 4D **electroweak Higgs field  $H$**  localized on the **IR-brane**:

$$S_{IR} = \int d^4x \int_0^\rho dy \sqrt{g_5} \delta(y - \rho) \left[ g^{\mu\nu} (\partial_\mu H)^\dagger \partial_\nu H - \lambda (H^\dagger H - v_5^2)^2 + \dots \right]$$

- 4D Higgs field canonically normalized  $\Rightarrow$  Redshifted Higgs VEV on the IR-brane:

$$v_4 \sim e^{-k\rho} v_5 \sim 100 \text{ GeV} \Rightarrow \text{Warp transmutation of the electroweak scale!}$$

+ Stability against radiative corrections.



# Warp Transmutation of Scales – Nonlocal Scale

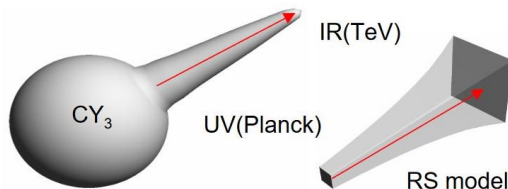
F. Nortier, Working paper, DOI: 10.5281/zenodo.4898023

- **String-inspired nonlocality**  $\Rightarrow$  Delocalized Higgs field with a nonlocal form factor, signature  $(++++)$ :

$$\tilde{H}(x) = e^{f(g^{\mu\nu}\partial_\mu\partial_\nu)} H(x), \quad f(g^{\mu\nu}\partial_\mu\partial_\nu) = \frac{g^{\mu\nu}\partial_\mu\partial_\nu + \mu^2}{\Lambda_5}.$$

$\Rightarrow \Lambda_4 = e^{-k\rho}\Lambda_5 \quad \Rightarrow \quad$  **Warp transmutation of the nonlocal scale!** (smooth cutoff)

- If  $\Lambda_5 \sim \Lambda_s$ , the **string scale**  $\Rightarrow$  Recover the redshift of  $\Lambda_s$  in **warped throat models**.  
ex: Klebanov-Strassler (KS) throat (Superstring IIB).



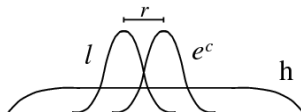
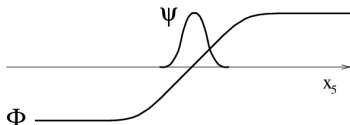
**Figure:** KS throat versus RS model

# Split Fermions – Domain Wall

N. Arkani-Hamed, M. Schmaltz, Phys. Rev. D 61 (2000) 033005

## AS model:

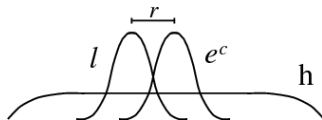
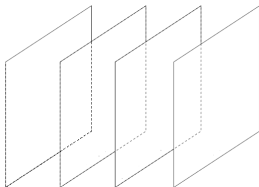
- **Goal:** Generate **natural small interaction couplings**.  
⇒ flavor physics, neutrino physics, dark matter, suppressing proton decay, ...
- **Domain wall** from a **bulk scalar field  $\Phi$**  in a flat extra dimension of space.
- Bulk **Yukawa coupling  $\mathcal{O}(1)$**  between  **$\Phi$**  & a **bulk fermion field  $\Psi$** .  
⇒ 1 zero mode: 4D **chiral fermion** trapped in the **domain wall** with a **Gaussian bulk wave function**.
- 2 bulk fermions  $\Psi^{(1)}$  &  $\Psi^{(2)}$  with  $\neq$  bulk masses  $\mathcal{O}(1)$ .  
⇒ 4D chiral zero modes: left-handed  $\psi_L^{(1)}$  & right-handed  $\psi_R^{(2)}$ .  
⇒ Gaussian wave functions **peaked at  $\neq$  positions** along the extra dimension.
- **Bulk Higgs field:** 4D zero mode  $h$  with a **flat bulk wave function**.  
+ **Bulk Yukawa coupling  $\mathcal{O}(1)$**  to  $\Psi^{(1)}$  &  $\Psi^{(2)}$ .  
⇒ **4D Yukawa coupling** between the zero modes  $h$ ,  $\psi_L^{(1)}$  &  $\psi_R^{(2)}$  **naturally  $\ll 1$** .



# Split Fermions – Multiple Fuzzy Branes (1/2)

F. Nortier, Working paper, DOI: 10.5281/zenodo.4898023

**Goal:** Reproduce AS model of split fermions: domain wall  $\rightarrow$  multiple fuzzy branes.



**Model:**

- 1 flat extra dimension of space: interval of length  $\rho \Rightarrow M_{KK} = 1/\rho$  (KK-scale).
- 1 bulk Higgs field  $H$  + 4D Weyl fermions  $\psi_L^{(1)}$  &  $\psi_R^{(2)}$  on 2 different  $\delta$ -like branes.
- 2 nonlocal scales:  $\Lambda_H = 1/\ell_H$  &  $\Lambda_\Psi = 1/\ell_\Psi$  + hierarchy:  $\Lambda_H \rightarrow \infty \gg \Lambda_\Psi \gg M_{KK}$ .  
 $\Rightarrow$  5D EFT: local bulk Higgs field ( $\ell_H \rightarrow 0$ ) + delocalized brane-fermions  $\psi_L^{(1)}$  &  $\psi_R^{(2)}$ .
- Delocalized fields  $\tilde{\Psi}_L^{(1)}(x, y)$  &  $\tilde{\Psi}_R^{(2)}(x, y)$  associated to  $\psi_L^{(1)}(x)$  &  $\psi_R^{(2)}(x)$  respectively.
- 5D action with Yukawa interaction between  $H$ ,  $\tilde{\Psi}_L^{(1)}$  &  $\tilde{\Psi}_R^{(2)}$ .

$$S_{5D} = \int d^4x \int_0^\rho dy \left[ \mathcal{L}_H - \sum_{i=1}^2 \delta(y - y_i) \psi_{L/R}^{(i)\dagger} (i \not{\partial}) \psi_{L/R}^{(i)} + Y \tilde{\Psi}_L^{(1)\dagger} H \tilde{\Psi}_R^{(2)} + \text{H.c.} \right].$$

# Split Fermions – Multiple Fuzzy Branes (2/2)

F. Nortier, Working paper, DOI: 10.5281/zenodo.4898023

Delocalized brane-fermion fields:

$$\begin{aligned}\widetilde{\Psi}_{L/R}^{(1/2)}(x, y) &= e^{\square_5/\Lambda_\Psi^2} \psi_{L/R}^{(1/2)}(x) \delta(y - y_{1/2}), \quad \square_5 = \partial_\mu \partial_\mu + \partial_y^2, \\ &= e^{\square_4/\Lambda_\Psi^2} \psi_{L/R}^{(1/2)}(x) g(y - y_{1/2}), \quad \square_4 = \partial_\mu \partial_\mu.\end{aligned}$$

Transverse smearing function (Gaussian):

$$g(y - y_{1/2}) = \sqrt{\frac{1}{4\pi\ell_\Psi^2}} \exp\left[-\left(\frac{y - y_{1/2}}{2\ell_\Psi}\right)^2\right].$$

KK decomposition of the 5D Higgs field with a VEV:

$$H(x, y) = \frac{v}{\sqrt{\rho}} + \sum_{n=0}^{+\infty} f_n(y) h_n(x), \quad f_0(y) = \sqrt{\frac{1}{\rho}}.$$

Natural 5D Yukawa coupling  $Y \sim \ell_\Psi^{3/2} + \text{interbrane distance } r = |y_2 - y_1| \gg \ell_\Psi$ .

$\Rightarrow$  Effective 4D Yukawa coupling:

$$y_0 = Y \int_0^\rho dy g(y - y_1) f_0(y) g(y - y_2) \sim \sqrt{\frac{\ell_\Psi}{8\pi\rho}} \exp\left(-\frac{r^2}{8\ell_\Psi^2}\right) \ll 1!$$

$\Rightarrow$  Nonlocal length scale  $\ell_\Psi$  plays the same role as the domain wall width in AS model.

## Summary:

- Motivated by **string theory**.
- Warped extra dimension  $\Rightarrow$  **Warp transmutation** of both **electroweak** & **nonlocal** scales.
- **Fuzzy branes**  $\Rightarrow$  Brane-fields can interact with **naturally suppressed effective 4D couplings**.

$\Rightarrow$  New model building issues for both **energy** & **intensity frontiers**!

## Outlook:

- Reinvestigate well known braneworld models with these new ingredients.
- Interplay with noncommutative QFT's?  
ex: New results on  **$\kappa$ -Minkowski spacetime** (J.-C. Wallet).  
 $\Rightarrow U(N)$  gauge theories consistent only in 5D  $\Rightarrow$  **extra dimension of space**!

You have enjoyed the MSSM, the MCHM, the MUED, ..., the M(thingummy)... Sorry, I am not sure I have any consistent MNLSM (Minimal NonLocal Standard Model) for you today, but wait... maybe it is not a so long way off...

Thank you for your attention!