Unparticle Physics: a plunge into a Warped extra dimension

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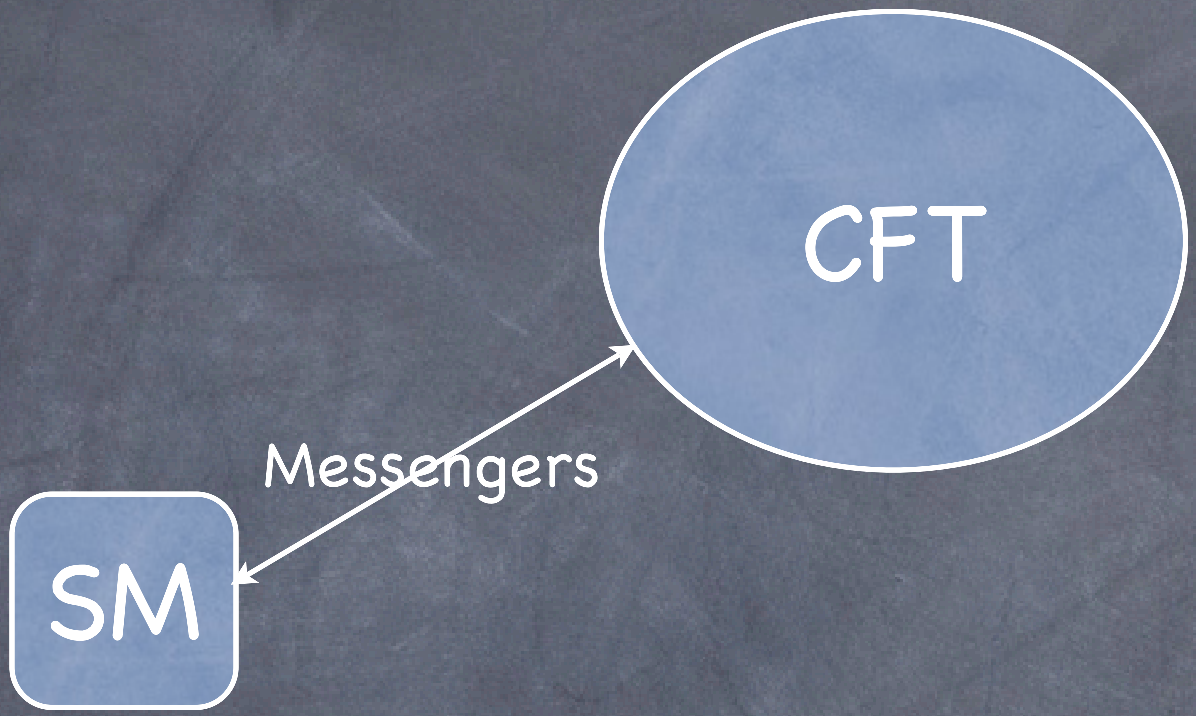
CERN TH Seminar

What are "Unparticles"?

An effective description of Conformal Field Theories.



Scale invariant theory:

p -> x p

$$\mathcal{O} \longleftrightarrow d_s$$

$$\mathcal{O}(\mathrm{x}p) = \mathrm{x}^{d_s}\mathcal{O}(p)$$

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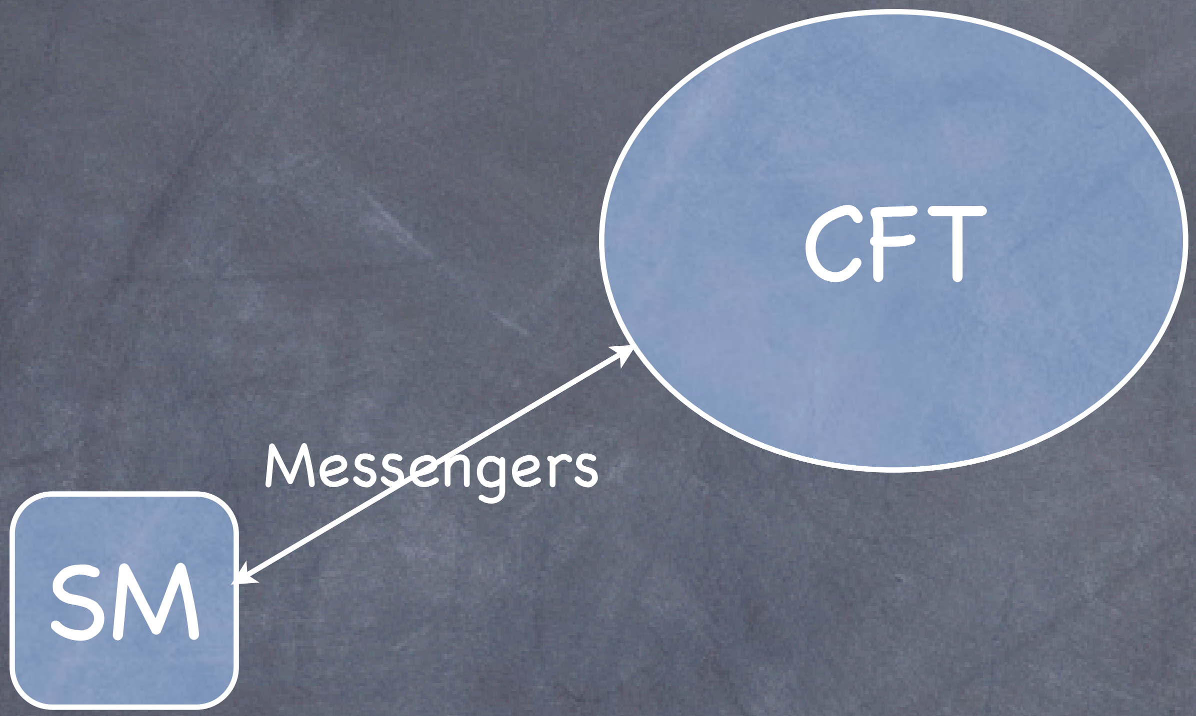

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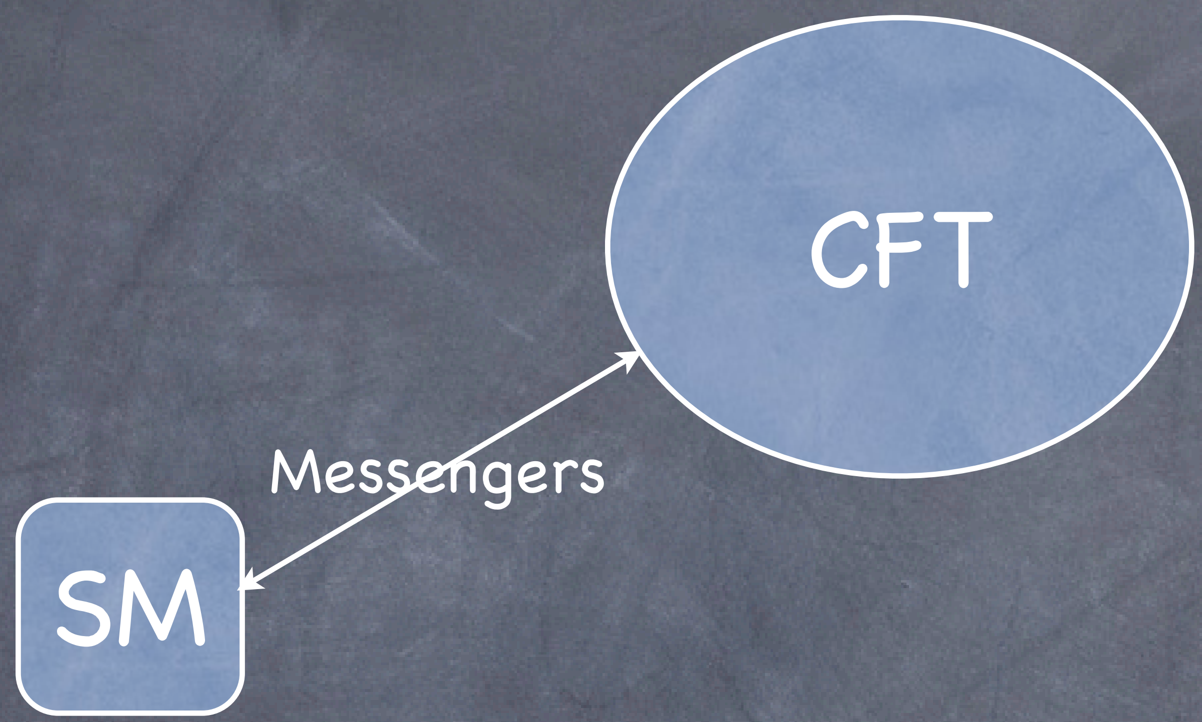
Trivial example: a massless particle d=1!

$$S = \int d^4x\, \partial_\mu \phi^\dagger \partial^\mu \phi \qquad \phi(\mathrm{x}p) = \mathrm{x}\phi(p)$$

$$E^2 - p^2 = 0$$

What are "Unparticles"?

An effective description of Conformal Field Theories.



Scale invariant theory:

p -> x p

$$\mathcal{O} \longleftrightarrow d_s$$

$$\mathcal{O}(\mathrm{x}p) = \mathrm{x}^{d_s}\mathcal{O}(p)$$

The conformal sector couples to the Standard Model via:

$$S_{\mathrm{int}} = \int d^4x \, \frac{c}{\Lambda^{d_{SM}+d_s-4}} \mathcal{O}_{SM}\mathcal{O}$$

H.Georgi proposed... unparticles:

Georgi, hep-ph/0703260 & 0704.2457

- Consider a massless particle (d=1):

$$\Delta_s(p) = \frac{i}{p^2 + i\epsilon}$$

$$= \int_0^\infty \delta(M^2) \frac{i}{p^2 - M^2 + i\epsilon} dM^2$$

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Scales like: $$\frac{1}{M^{(2=4-2d)}}$$

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- Consider an operator $\mathcal{O}$ with scaling dimension $d_s > 1$

$$\Delta_s(p, d_s) \equiv \int d^4x\, e^{ipx} \langle 0|\mathcal{O}(x)\mathcal{O}^\dagger(0)|0\rangle$$

$$= \frac{A_{d_s}}{2\pi} \int_0^\infty (M^2)^{d_s - 2} \frac{i}{p^2 - M^2 + i\epsilon} dM^2$$

$$= \frac{A_{d_s}}{2 \sin d_s \pi} \frac{i}{(-p^2 - i\epsilon)^{2 - d_s}} + \ldots$$

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Phase space: $$d\Phi(p, d_s) = A_{d_s}\, \theta\left(p^0\right)\, \theta\left(p^2\right)\, (p^2)^{d_s-2}$$

Phase space of d-particles: un-particles!

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Phase space: $d\Phi(p, d_s) = A_{d_s}\, \theta\left(p^0\right)\, \theta\left(p^2\right)\, \left(p^2\right)^{d_s - 2}$

Normalization fixed, recover particle for d->1.

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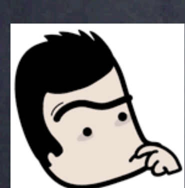


The integral diverges for $d_s > 2$

but the phase space is well behaved!

However, quite boring at the LHC: signatures are

- Interactions with the SM via contact terms (higher order)

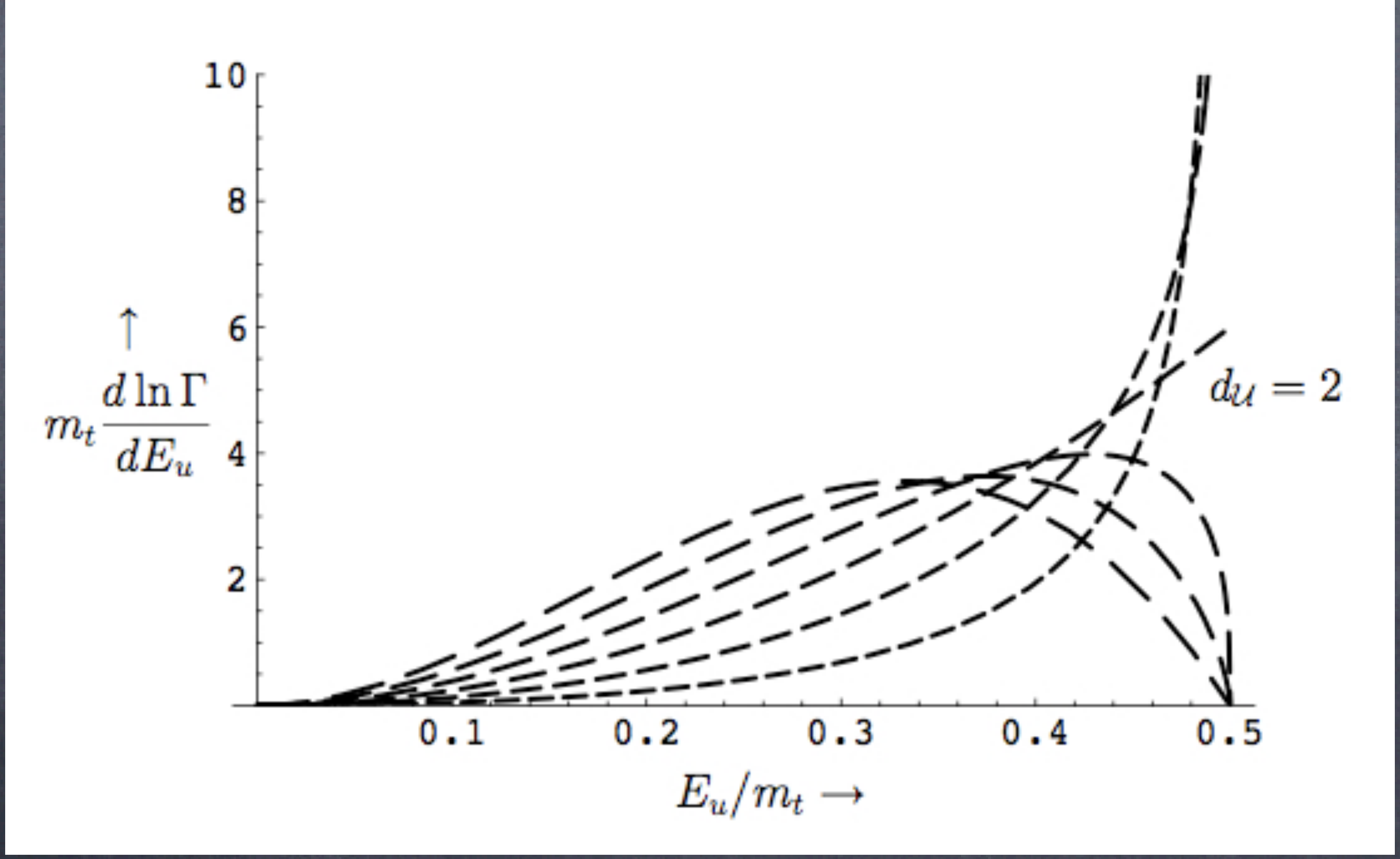
$$\frac{c}{\Lambda^{d_{SM}+d_s-4}}\mathcal{O}_{SM}\mathcal{O}$$

- Missing ET (transverse energy): non-integer number of invisible particles
- Virtual effects: interference with SM processes

Example 1:
top decay

top -> up + unparticle

$$i \frac{\lambda}{\Lambda^{d_\mathcal{U}}} \overline{u}\, \gamma_\mu (1-\gamma_5)\, t\, \partial^\mu O_\mathcal{U} + \text{h.c.}$$



Georgi, hep-ph/0703260

Example 2:

interference in e+e- -> μ+μ-

Total cross section ->

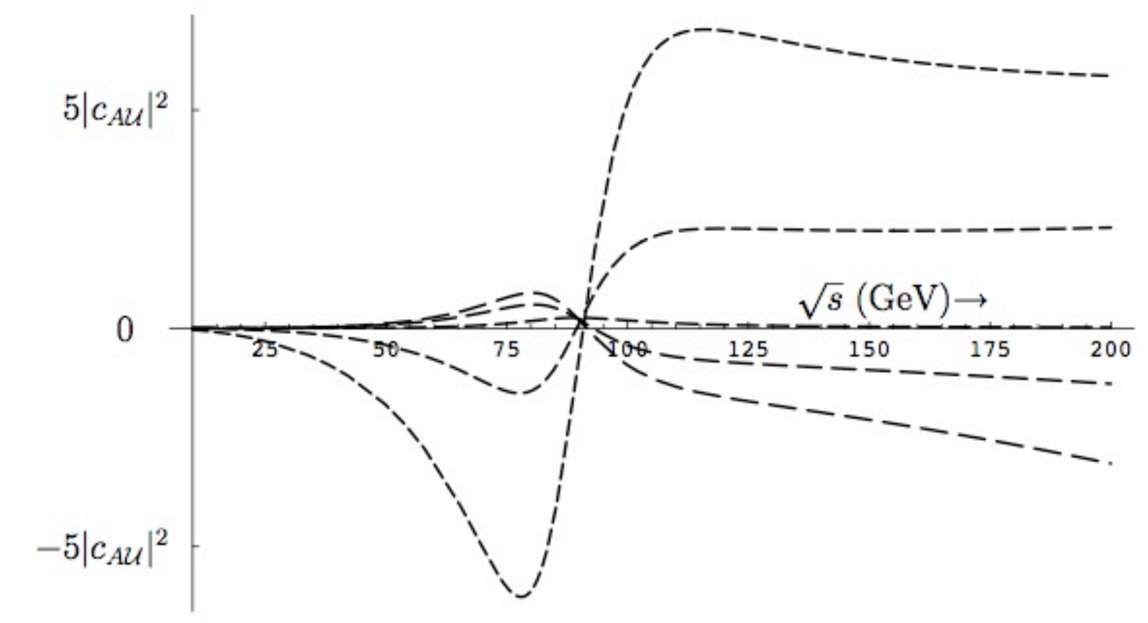


Figure 1: The fractional change in total cross-section for $e^+e^- \to \mu^+\mu^-$ versus $\sqrt{s}$ for $d_{\mathcal{U}} = 1.1$, 1.3, 1.5, 1.7 and 1.9 for non-zero $c_{A\mathcal{U}}$ and $c_{V\mathcal{U}} = 0$. The dash-length increases with $d_{\mathcal{U}}$.

$$\frac{C_{V\mathcal{U}}\,\Lambda_{\mathcal{U}}^{k+1-d_{\mathcal{U}}}}{M_{\mathcal{U}}^k}\,\bar{e}\,\gamma_\mu\,e\,O_{\mathcal{U}}^\mu + \frac{C_{A\mathcal{U}}\,\Lambda_{\mathcal{U}}^{k+1-d_{\mathcal{U}}}}{M_{\mathcal{U}}^k}\,\bar{e}\,\gamma_\mu\gamma_5\,e\,O_{\mathcal{U}}^\mu$$

Georgi, 0704.2457

Forward-Backward Asymmetry ->

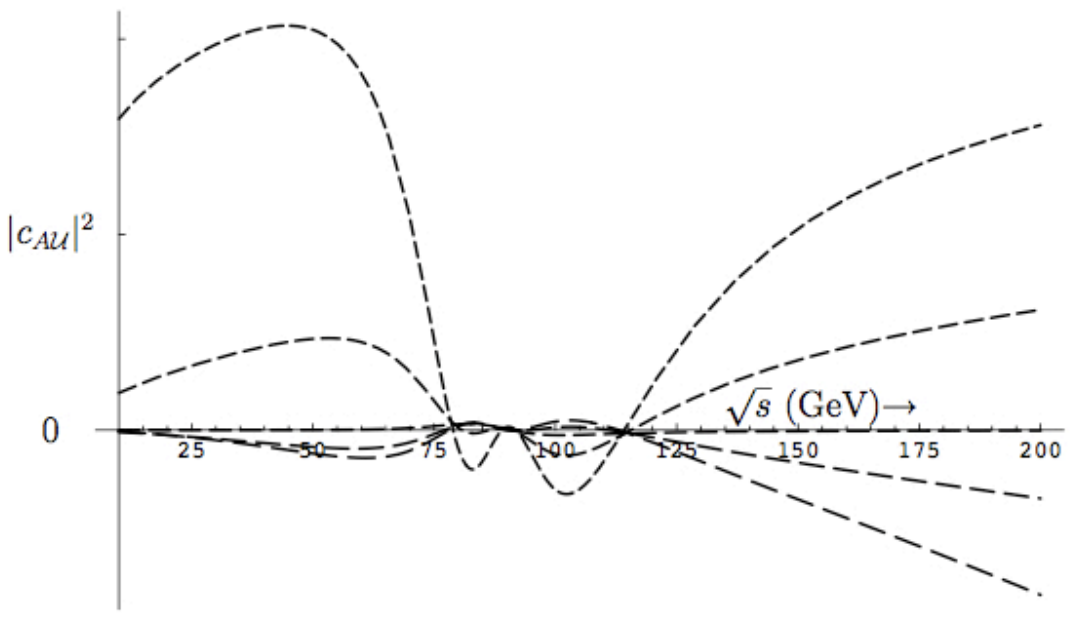


Figure 5: The change in the front-back asymmetry for $e^+e^- \to \mu^+\mu^-$ versus $\sqrt{s}$ for $d_{\mathcal{U}} = 1.1$, 1.3, 1.5, 1.7 and 1.9 for non-zero $c_{A\mathcal{U}}$ and $c_{V\mathcal{U}} = 0$. The dash-length increases with $d_{\mathcal{U}}$.

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interference in e+e- -> μ+μ-

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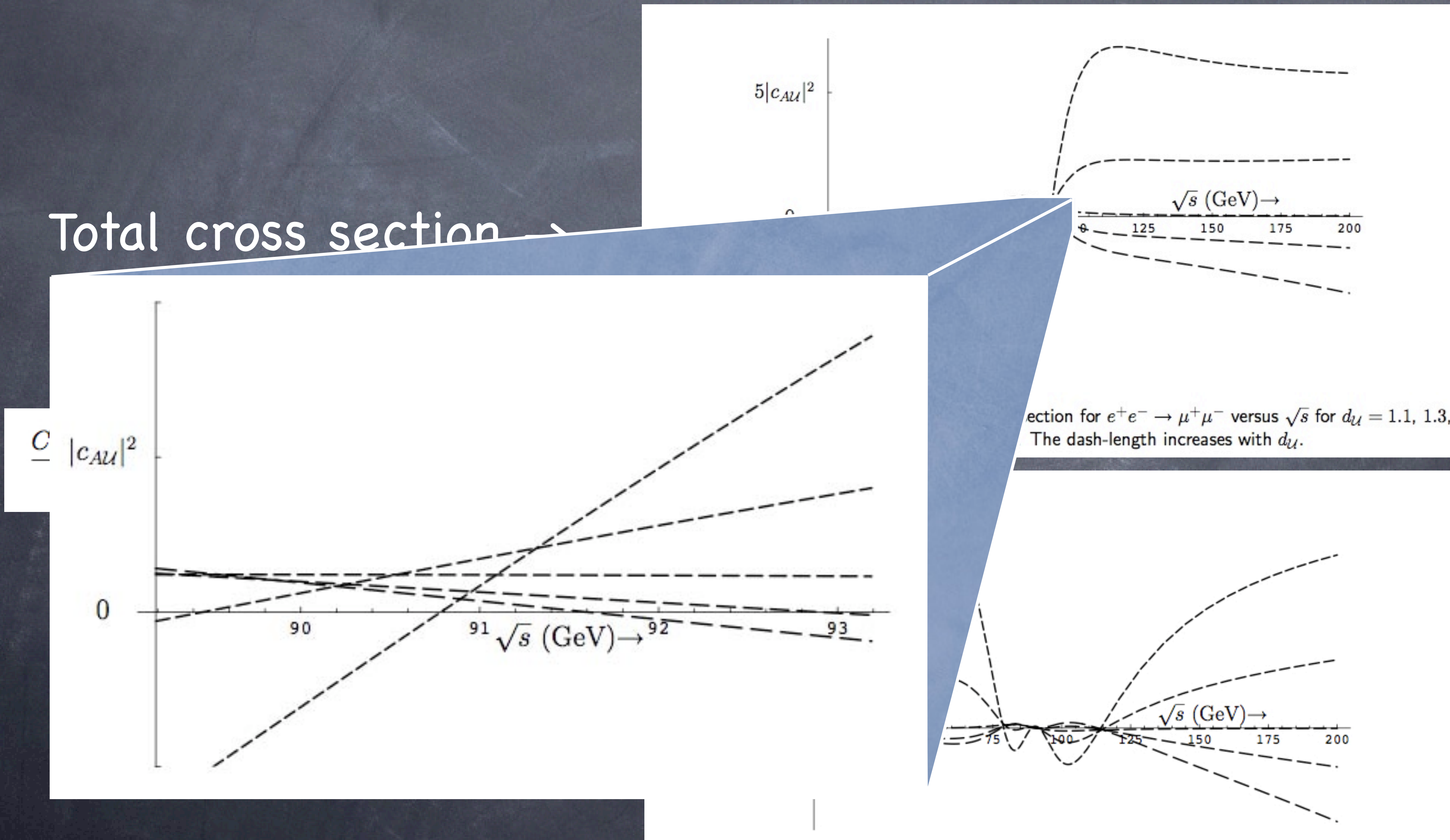


ection for $e^+e^- \to \mu^+\mu^-$ versus $\sqrt{s}$ for $d_{\mathcal{U}} = 1.1,\ 1.3,$ The dash-length increases with $d_{\mathcal{U}}$.

Figure 5: The change in the front-back asymmetry for $e^+e^- \to \mu^+\mu^-$ versus $\sqrt{s}$ for $d_{\mathcal{U}} = 1.1,\ 1.3,\ 1.5,\ 1.7$ and 1.9 for non-zero $c_{A\mathcal{U}}$ and $c_{V\mathcal{U}} = 0$. The dash-length increases with $d_{\mathcal{U}}$.

Colored Unparticles

Cacciapaglia, Marandella, Terning
0708.0005

- Can unparticles carry SM charges? Pourquoi pas?
- Derive a non-local action from Georgi's propagator:

$$S \sim \int \frac{d^4p}{(2\pi)^4}\, \phi(p)\, (p^2)^{2-d_s}\, \phi(p)$$

- Gauge it! (minimal gauging)
- Vertices with arbitrary number of gauge bosons, non trivial p-dependence...

One gluon:

$$ig\,\Gamma_s^{a\nu}(p,q) = ig\,T^a(2p^\nu + q^\nu)\,\mathcal{F}_s(p,q)\ ,$$

Two gluons:

$$\begin{aligned}\Gamma_s^{a\mu,b\nu} &= (T^aT^b + T^bT^a)\,g^{\mu\nu}\mathcal{F}_f(p,q_1+q_2) + \\ &\quad T^aT^b\,\frac{(2p^\nu + q_2^\nu)(2p^\mu + q_1^\mu + 2q_2^\mu)}{q_1^2 + 2p\cdot q_1 + 2q_1\cdot q_2}\,(\mathcal{F}_f(p,q_1+q_2) - \mathcal{F}_f(p,q_2)) + \\ &\quad T^bT^a\,\frac{(2p^\mu + q_1^\mu)(2p^\nu + q_2^\nu + 2q_1^\nu)}{q_2^2 + 2p\cdot q_2 + 2q_1\cdot q_2}\,(\mathcal{F}_f(p,q_1+q_2) - \mathcal{F}_f(p,q_1))\ .\end{aligned}$$

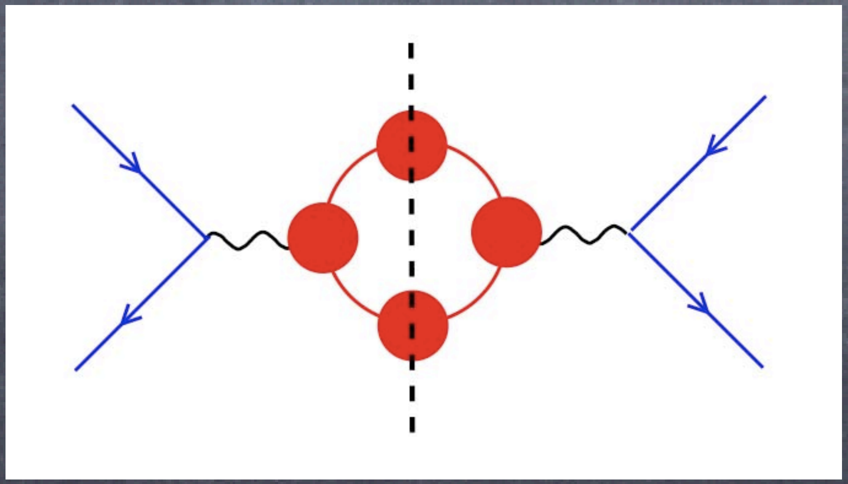
$$\mathcal{F}(p,q) = \frac{2\sin d_s\pi}{A_{d_S}}\,\frac{(-(p+q)^2)^{2-d_s} - (-p^2)^{2-d_s}}{2\,p\cdot q + q^2}$$

- Is the gauging we proposed unique? Consistent?

- Can we calculate cross sections?

Naive answer using phase space:

$$\sigma(q\bar{q} \to unparticles) = \infty$$



Smells like IR divergencies in QCD
reg. by emission of real soft gluon.

- Is the gauging we proposed unique? Consistent?

- Can we calculate cross sections?

$$\sigma(q\bar{q} \to unparticles) = (2 - d_s)\,\sigma(particles)$$

Negative for d_s > 2???

The vertices also contribute to the Im part!
Non trivial cancellation between the two diagrams

IR threshold

- To be consistent with low energy data, we need an IR threshold:

Fox, Rajaraman, Shirman

$$\Delta_s(p,\mu,d_s) = i\frac{A_{d_s}}{2\pi}\int_{\mu^2}^{\infty}(M^2-\mu^2)^{d_s-2}\frac{1}{p^2-M^2+i\epsilon}dM^2$$

$$= i\frac{A_{d_s}}{2\sin d_s\pi}\left(\mu^2-p^2-i\epsilon\right)^{d_s-2}+\ldots$$

- Is it consistent? Does the mass gap generate confinement or light resonances, thus destroying the unparticles?

List of open issues:

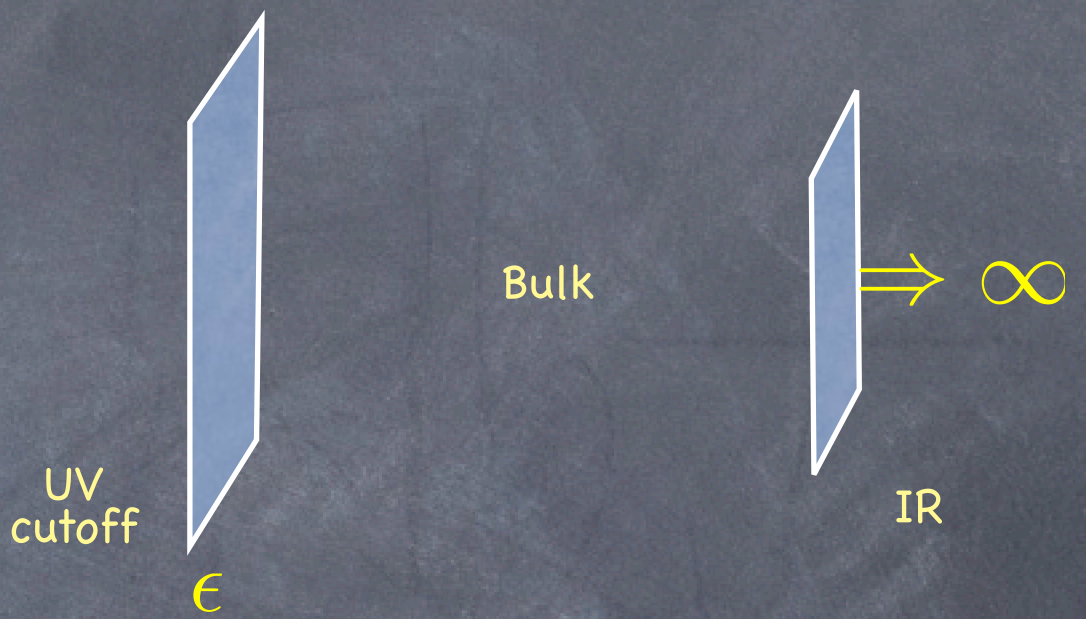
- Propagator sick for d > 2
- Gauge interactions - effective actions
- Negative cross sections for d > 2
- IR threshold
- …

Can the AdS/CFT correspondence help?

Why warping?

Randall, Sundrum...

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



- Conformal when $\epsilon \to 0$
- AdS/CFT: it is dual to strongly coupled conformal sector
- Continuum when IR brane is removed

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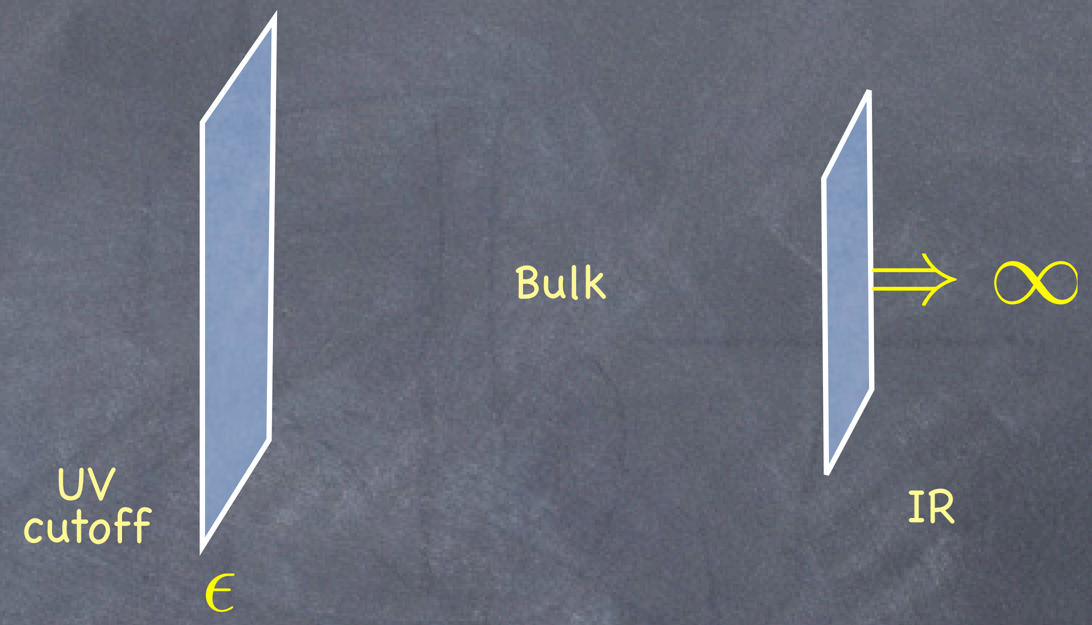


Goal: build a model of unparticles in warped space!

Cacciapaglia, Marandella, Terning
0804.0424

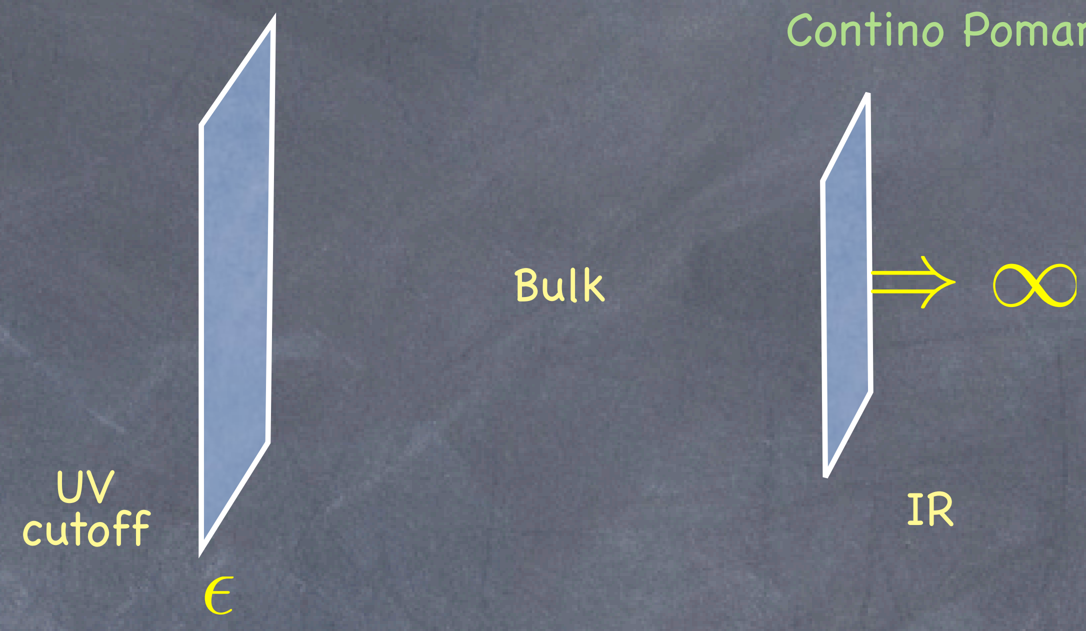
Fermionic unparticles

$$
\begin{aligned}
\Delta_f(p, d_f) &\equiv \int d^4x\, e^{ipx} \langle 0|\Theta(x)\Theta^\dagger(0)|0\rangle \\
&= \frac{A_{d_f-1/2}}{2\pi i} \int_0^\infty (M^2)^{d_f-5/2} \frac{\sigma^\mu p_\mu}{p^2 - M^2 + i\epsilon} dM^2 \\
&= \frac{A_{d_f-1/2}}{2i \cos d_f \pi} (\sigma^\mu p_\mu) \left(-p^2 - i\epsilon\right)^{d_f-5/2} + \dots
\end{aligned}
$$

- Left-handed operator Θ with dimension d_f
- Propagator sick for $d_f > 5/2$
- Recover particle limit for $d_f \to 3/2$

AdS/CFT for fermions

Contino Pomarol, 0802.2946



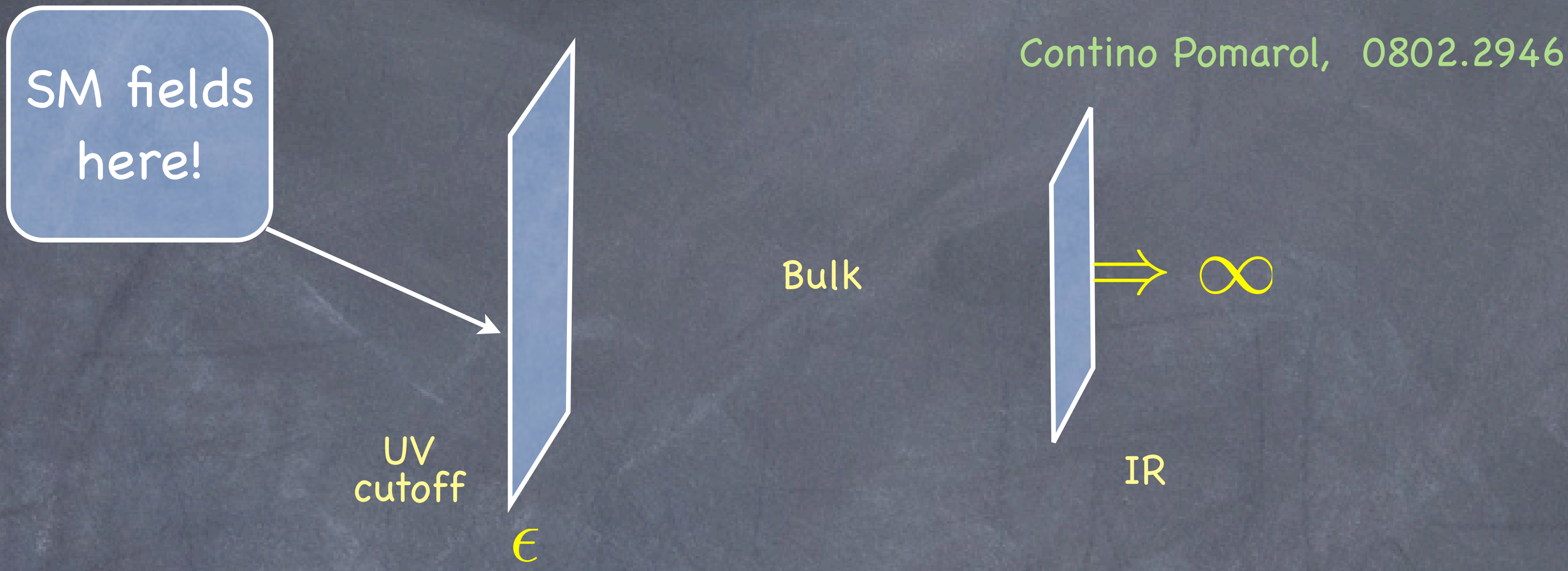
- Consider a fermion with bulk mass c

$$\chi(p,z) = A\, z^{\frac{5}{2}} \left(c_\alpha J_{c+\frac{1}{2}}(pz) + s_\alpha J_{-c-\frac{1}{2}}(pz) \right)$$

$$\psi(p,z) = A\, z^{\frac{5}{2}} \left(c_\alpha J_{c-\frac{1}{2}}(pz) - s_\alpha J_{-c+\frac{1}{2}}(pz) \right)$$

- α is determined by boundary conditions in the IR, A by the BCs in the UV: $\chi(p,\epsilon) = \chi_0$

AdS/CFT for fermions



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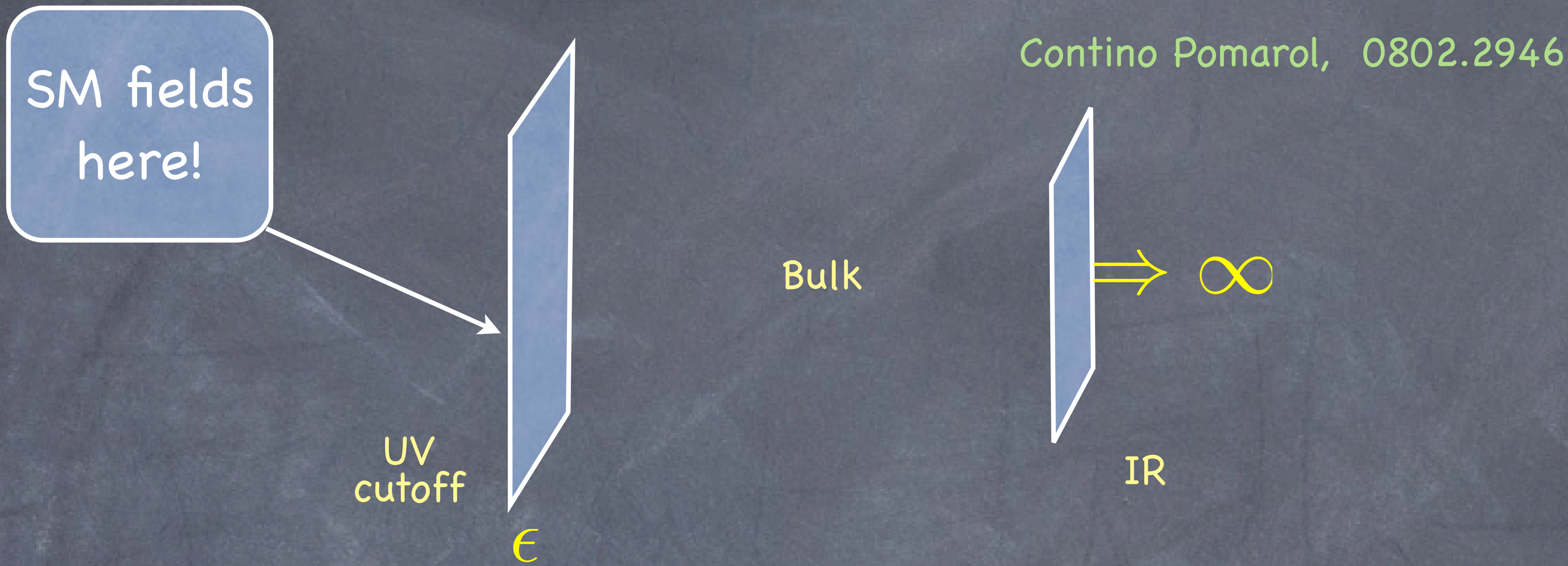

- After integrating out the bulk, we are left with a UV-brane action:

$$\mathcal{L} = \left(\frac{R}{\epsilon}\right)^4 \frac{c_\alpha J_{c-\frac{1}{2}}(p\epsilon) - s_\alpha J_{-c+\frac{1}{2}}(p\epsilon)}{c_\alpha J_{c+\frac{1}{2}}(p\epsilon) + s_\alpha J_{-c-\frac{1}{2}}(p\epsilon)} \frac{\bar{\chi}_0 \bar{\sigma}^\mu p_\mu \chi_0}{p}$$

$\Rightarrow$ Propagator of a r.h. operator Θ_R

$$\langle \Theta_R \Theta_R \rangle = \Delta_R(p,c) \sim \left(\frac{R}{\epsilon}\right)^4 \frac{c_\alpha J_{c-\frac{1}{2}}(p\epsilon) - s_\alpha J_{-c+\frac{1}{2}}(p\epsilon)}{c_\alpha J_{c+\frac{1}{2}}(p\epsilon) + s_\alpha J_{-c-\frac{1}{2}}(p\epsilon)} \frac{\bar{\sigma}^\mu p_\mu}{p}$$

$$J_\nu(p\epsilon) \sim (p\epsilon)^\nu \left(1 + \mathcal{O}(p)^2\right)$$

For $c < -1/2$ (zero mode localized at UV)

$$\Delta_R \sim \frac{\bar{\sigma} \cdot p}{p^2} \left(1 + \dots\right)$$

Massless fermion!

$$\langle \Theta_R \Theta_R \rangle = \Delta_R(p,c) \sim \left(\frac{R}{\epsilon}\right)^4 \frac{c_\alpha J_{c-\frac{1}{2}}(p\epsilon) - s_\alpha J_{-c+\frac{1}{2}}(p\epsilon)}{c_\alpha J_{c+\frac{1}{2}}(p\epsilon) + s_\alpha J_{-c-\frac{1}{2}}(p\epsilon)} \frac{\bar{\sigma}^\mu p_\mu}{p}$$

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$$\Delta_R \sim \frac{c_\alpha}{s_\alpha} \frac{\bar{\sigma} \cdot p}{p^{1-2c}} \left(1 + \dots\right) - \epsilon^{1-2c} \bar{\sigma} \cdot p \left(1 + \dots\right)$$

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Unparticle propagator with $d_f = 2 + c$

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$$\Delta_R \sim \frac{c_\alpha}{s_\alpha} \frac{\bar{\sigma} \cdot p}{p^{1-2c}} (1 + \dots) - \epsilon^{1-2c} \bar{\sigma} \cdot p \, (1 + \dots)$$

Unparticle propagator with $d_f = 2 + c$

Local terms: dominate for c>1/2 ($d_f > 5/2$)

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$$J_\nu(p\epsilon) \sim (p\epsilon)^\nu \left(1 + \mathcal{O}(p)^2\right)$$

For $c > -1/2$

$$\Delta_R \sim \frac{c_\alpha}{s_\alpha} \frac{\bar{\sigma} \cdot p}{p^{1-2c}} (1 + \dots) - \epsilon^{1-2c} \bar{\sigma} \cdot p (1 + \dots)$$

Unparticle propagator with $d_f = 2 + c$

Local terms: dominate for c>1/2 ($d_f > 5/2$)

For a l.h. operator, c -> -c

For $d_f > 5/2$, the local terms cannot be neglected:

- They are the counter-terms that make the unparticle propagator finite!
- They do not contribute to the phase space.
- They do contribute to the propagator, generating effective contact interactions.
- The qq cross section is suppressed by the UV cutoff for $d_f > 5/2$ ($d_s > 2$)

Effective action: for -1/2 < c < 1/2

$$S_{\rm holo} \sim \int \frac{d^4p}{(2\pi)^4}\,\bar{\chi}_0\,\frac{\bar{\sigma}\cdot p}{(p^2)^{1/2-c}}\,\chi_0$$

- source coupled to rh operator of dim 2+c
- it is also action for a lh unparticle of dimension 2-c (Legendre transform)

$S_{\rm holo}$ can be used as an effective unparticle action

caveat: for large d ($d_f > 5/2, d_s > 2$),
UV-dependent local counterterms should be included

Gauge interactions

$$-\frac{1}{4g_5^2}\int_\epsilon^\infty d^4x\,dz\left(\frac{R}{z}\right) \qquad F^{aMN}F^a_{MN}$$

- The flat zero mode is non-normalizable:

$$\frac{1}{g_4^2}=\frac{R}{g_5^2}\int_\epsilon^{z_{IR}}\frac{1}{z}=\frac{R}{g_5^2}\ln\frac{z_{IR}}{\epsilon}\to\infty$$

g4 runs to zero in the IR...

- Can we stop the running? Dilaton function...

Gauge interactions

$$-\frac{1}{4g_5^2}\int_\epsilon^\infty d^4x\,dz\left(\frac{R}{z}\right)\Phi(z)\,F^{aMN}F^a_{MN}$$

$$\Phi(z) = e^{-mz}$$

- The flat zero mode is normalizable:

$$\frac{1}{g_4^2} = \frac{R}{g_5^2}\int_\epsilon^\infty \frac{e^{-mz}}{z} \sim \frac{R}{g_5^2}\ln\frac{1}{m\epsilon}$$

g4 runs from the UV cutoff to m...

- Spectrum: continuum? Isolated pole(s)?

$$f''(z) - \left(\frac{1}{z} + m\right) f'(z) + p^2 f(z) = 0$$

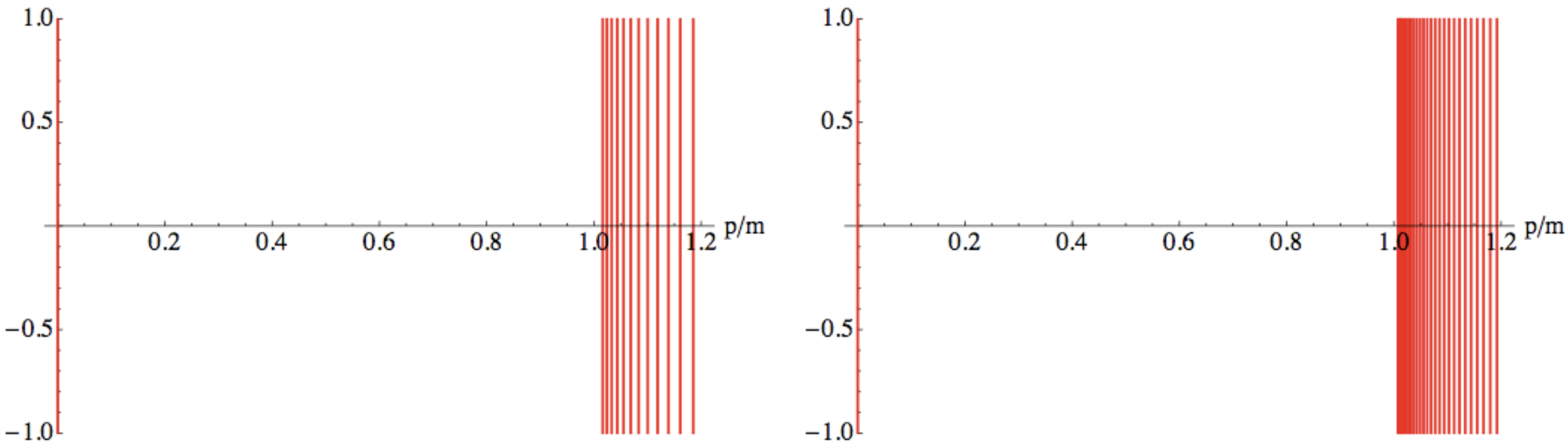
$$\Phi(z) = e^{-mz}$$

$$f(z) = z^2 \, e^{\frac{z}{2}\left(m - \sqrt{m^2 - 4p^2}\right)} \, g(z)$$

- p < m/2 : only the zero mode is present
- p > m/2 : the exponentials become oscillatory -> continuum!

The continuum only appears above the IR threshold m/2

spectrum



$z_{IR} = 100/m$ $z_{IR} = 200/m$

- Gauge interactions of the zero mode can be computed in AdS.
- They do coincide with our proposal of minimal-coupling of the effective action!

IR threshold: soft breaking of conformal inv.

$$\Delta_s(p,\mu,d_s) = i\frac{A_{d_s}}{2\pi}\int_{\mu^2}^{\infty}(M^2-\mu^2)^{d_s-2}\frac{1}{p^2-M^2+i\epsilon}dM^2$$
$$= i\frac{A_{d_s}}{2\sin d_s\pi}\left(\mu^2-p^2-i\epsilon\right)^{d_s-2}+\dots$$

- An IR brane will generate KK resonances, confinement.
- However, we can break conformal invariance with a bulk scalar VEV.
- Take a scalar H with dimension d_H that couple with the unparticle field: $H\phi\phi$

IR threshold:
soft breaking of conformal inv.

$$\Delta_s(p,\mu,d_s) = i\frac{A_{d_s}}{2\pi}\int_{\mu^2}^{\infty}(M^2-\mu^2)^{d_s-2}\frac{1}{p^2-M^2+i\epsilon}dM^2$$
$$= i\frac{A_{d_s}}{2\sin d_s\pi}\left(\mu^2-p^2-i\epsilon\right)^{d_s-2}+\ldots$$

If d_H = 2, the coupling scales like a kinetic term:

If $\langle H\rangle = \mu^2 z^2$,

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

In the solutions: $p \Rightarrow \sqrt{(p^2-\mu^2)}$

Similarly for fermions:

If d_H = 1 (scaling like a fermion kinetic term)

$$\Delta_f(p,\mu,d_f) = \frac{A_{d_f-1/2}}{2\pi i}\int_{\mu^2}^{\infty}(M^2-\mu^2)^{d_f-5/2}\frac{\not{p}+\mu}{p^2-M^2+i\epsilon}dM^2$$

$$= \frac{A_{d_f-1/2}}{2i\cos d_f\pi}\left(\not{p}+\mu\right)\left(\mu^2-p^2-i\epsilon\right)^{d_f-5/2}+\ldots$$

Conclusions

- Unparticles describe new signatures for experiments
- AdS provides a model of unparticles, with gauge interactions and IR threshold
- Many unparticle issues can be understood in this language
- Unparticles can provide new model-building ideas in AdS: soft breaking of conformal invariance, un-Higgs...