Extra-Dimensions & Flavor

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(CERN)

22/3/2010
GGI, Firenze

4D → 5D

Why?

4D → 5D

Why *not*?

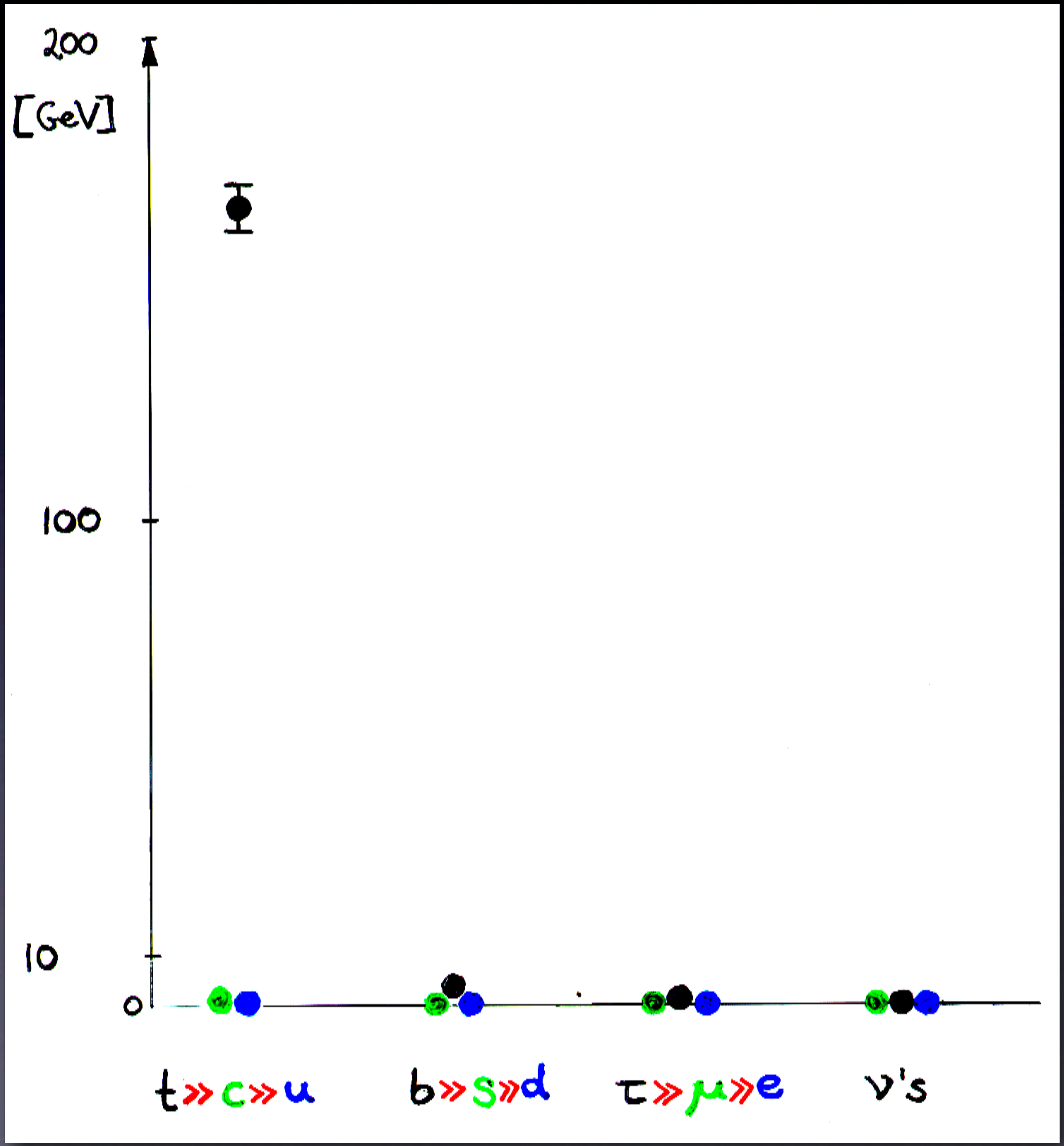
Crazier than a fermionic extra dimension?

4D → 5D

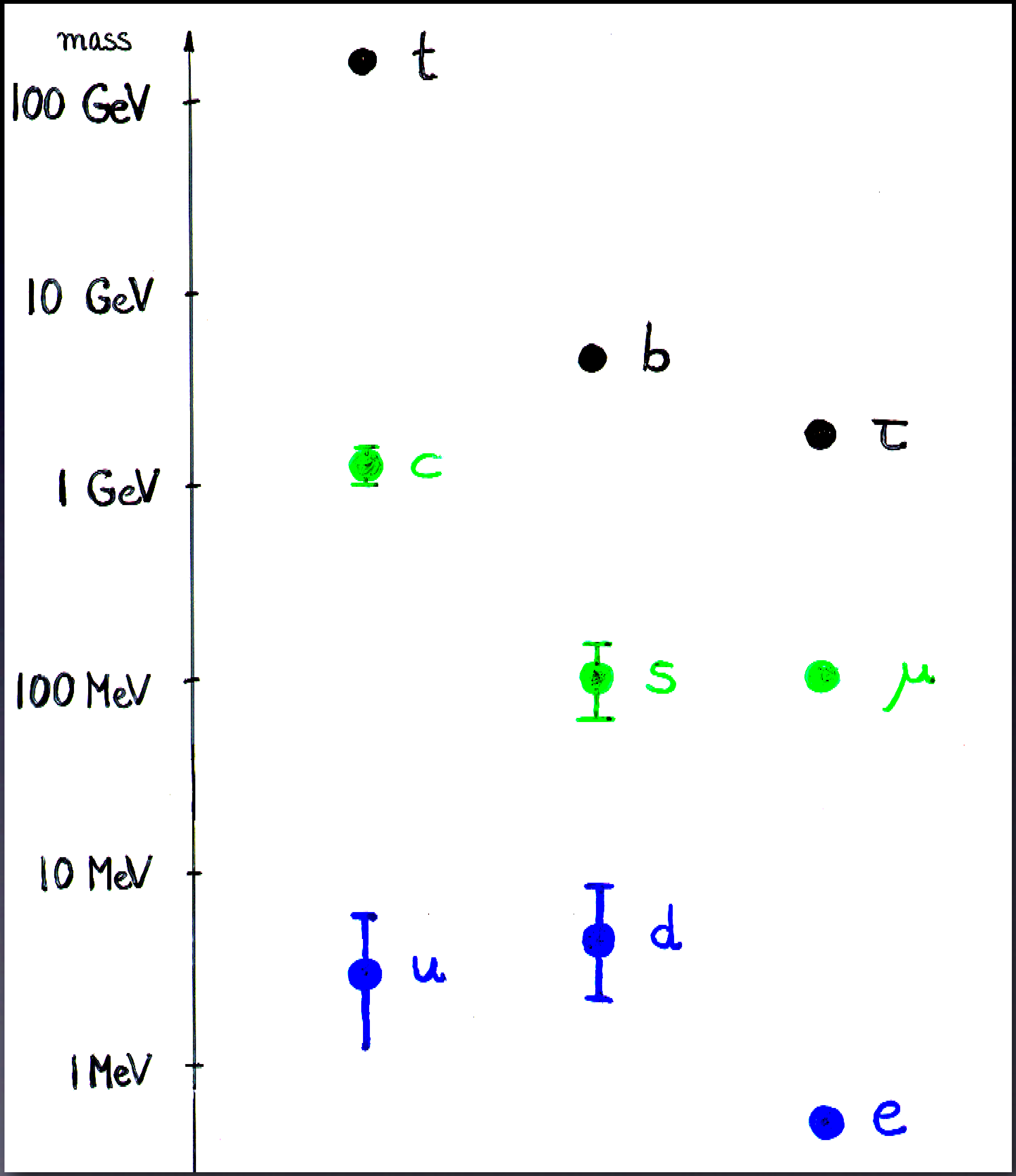
Why *4D*?

The flavor puzzle

Quark and Lepton mass hierarchy



Masses on a Log-scale



The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\begin{pmatrix} 2\cdot 10^{-5} & 0.0005 & 0.02 \end{pmatrix}$$

$$Y_U \approx \begin{pmatrix} 6\cdot 10^{-6} & -0.001 & 0.008+0.004i \\ 1\cdot 10^{-6} & 0.004 & -0.04+0.001 \\ 8\cdot 10^{-9}+2\cdot 10^{-8}i & 0.0002 & 0.98 \end{pmatrix}$$

Why this structure?

Other dimensionless parameters of the SM:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{Higgs} \sim 1$, $|\theta| < 10^{-9}$

Log(SM flavor puzzle)

$$-\log|Y_D| \approx \mathrm{diag}\begin{pmatrix}11 & 8 & 4\end{pmatrix}$$

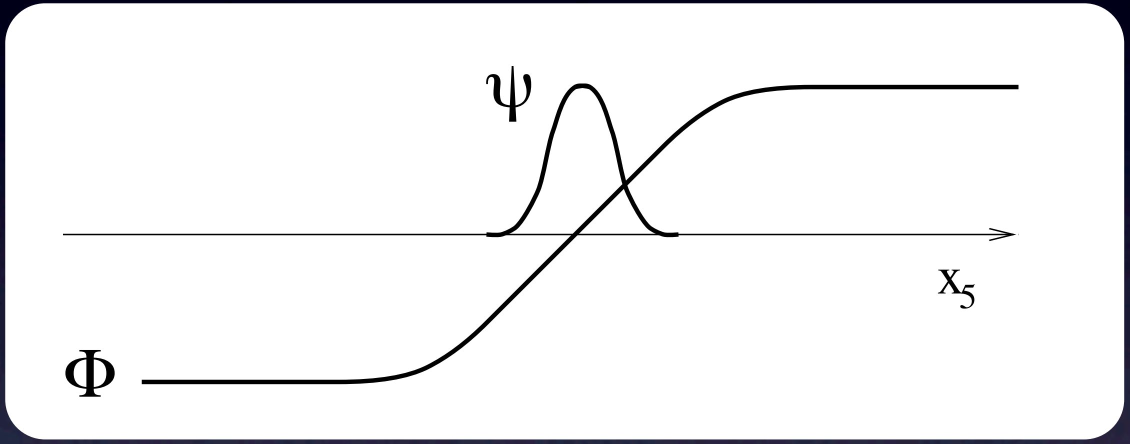
$$-\log|Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}$$

If $Y = e^{-\Delta}$, then the Δ don't look crazy.

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

SM on thick brane & domain wall ⇒ chiral localization



$$\mathcal{S} = \int \mathrm{d}^5x \sum_{i,j} \bar{\Psi}_i [i \, \partial\!\!\!/_5 + \lambda \Phi(x_5) - m]_{ij} \Psi_j$$

$$\Psi = \begin{pmatrix} \Psi_L \\ \Psi_R \end{pmatrix} = \begin{pmatrix} \psi_L^0 \\ 0 \end{pmatrix} + \text{KK modes}$$

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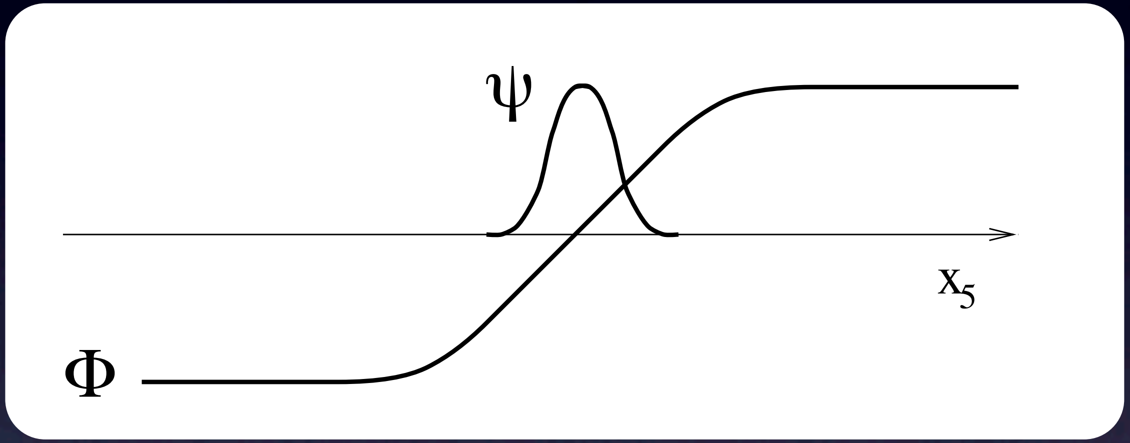

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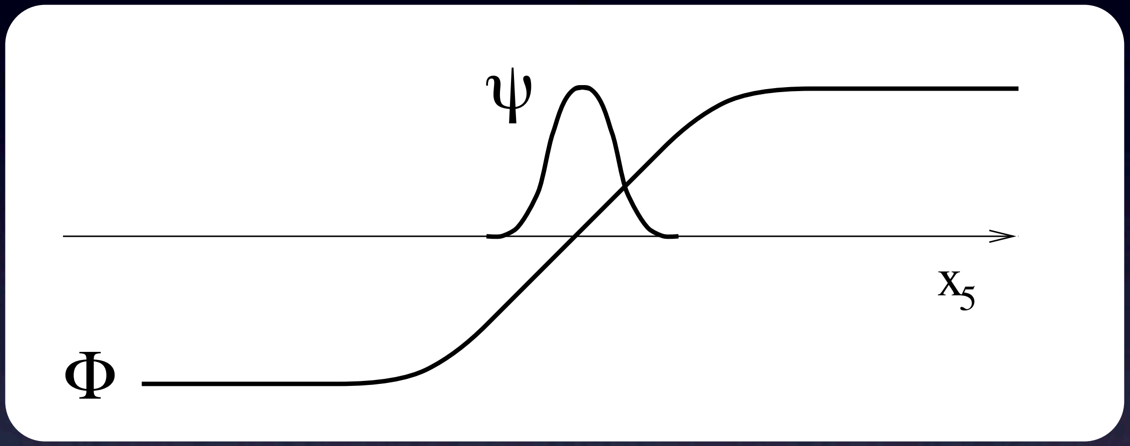

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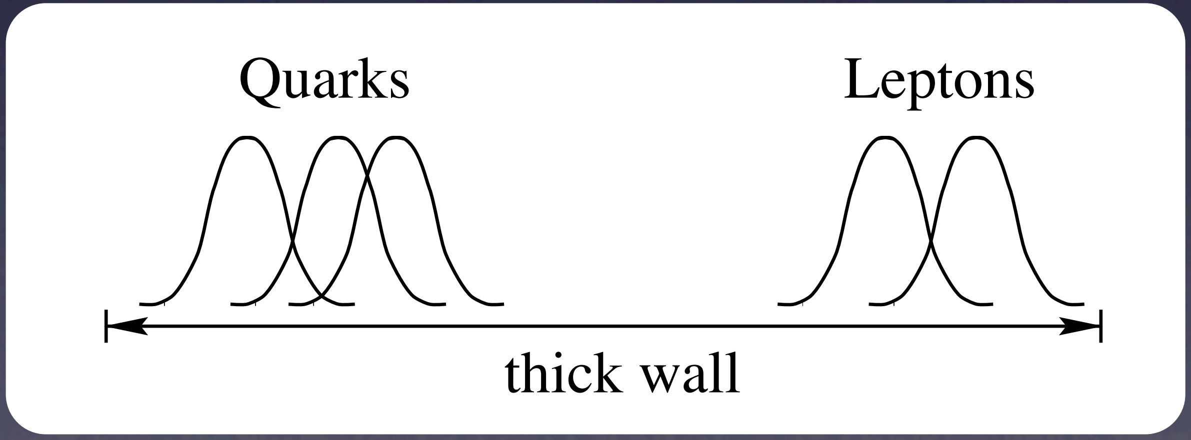

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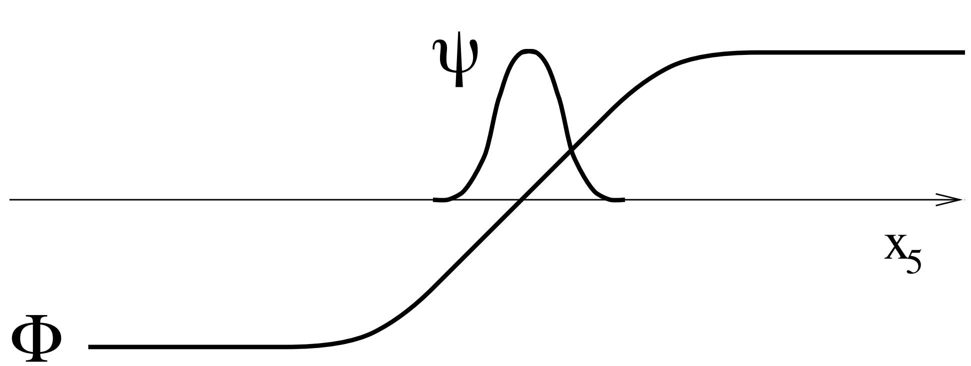

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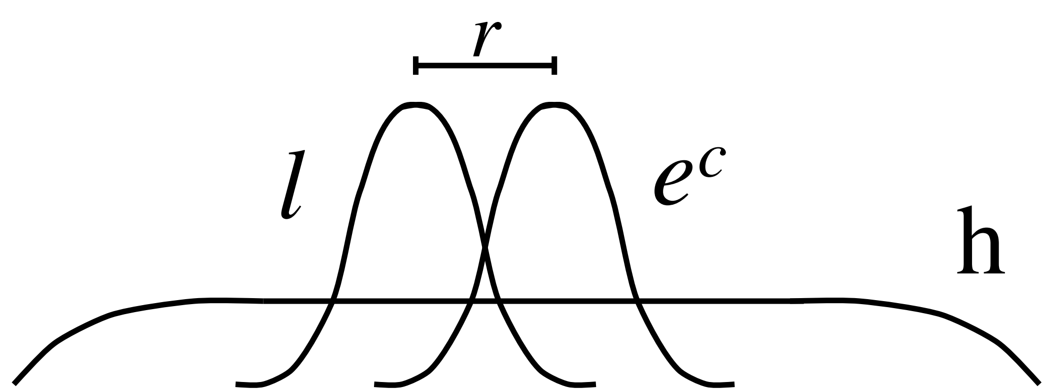

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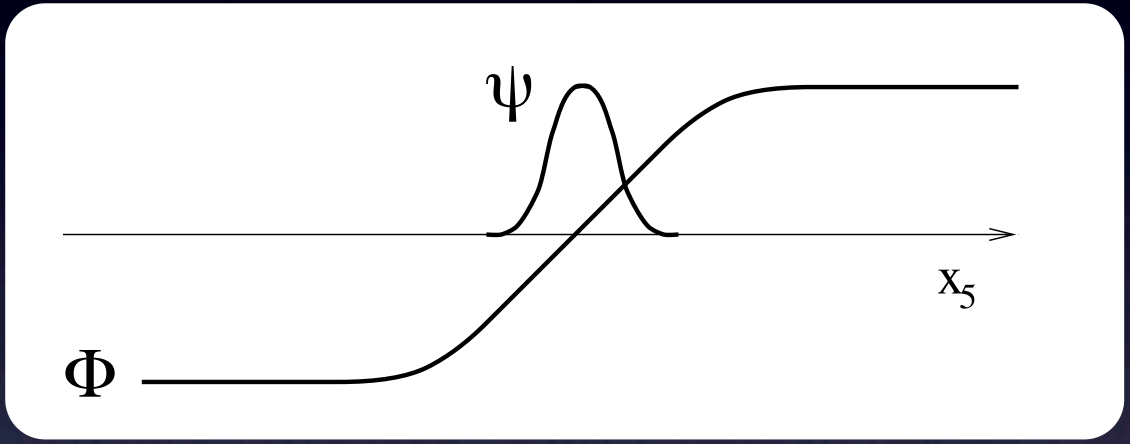

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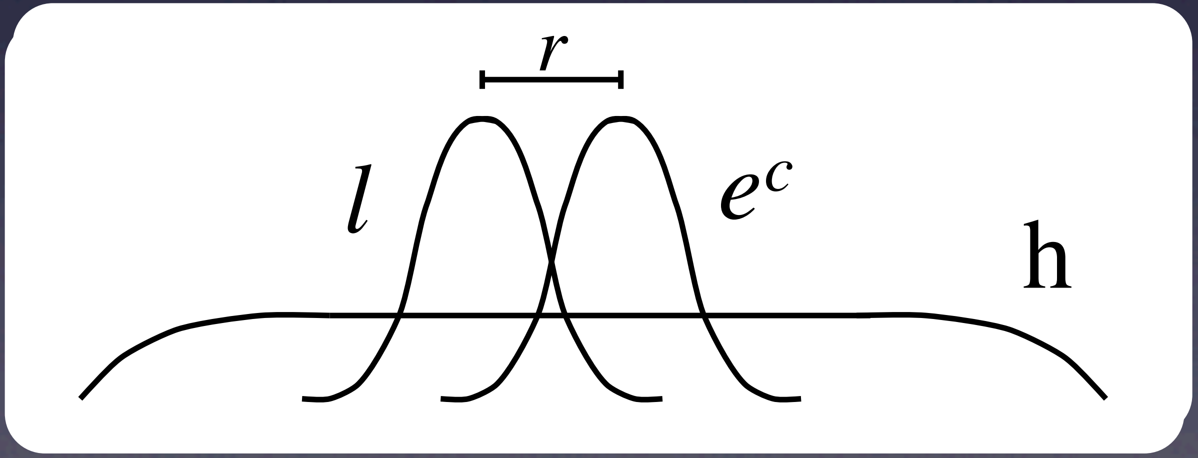

$$\int \mathrm{d}x_5 \; \phi_l(x_5) \; \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int \mathrm{d}x_5 \; e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} = e^{-\mu^2 r^2/2}$$

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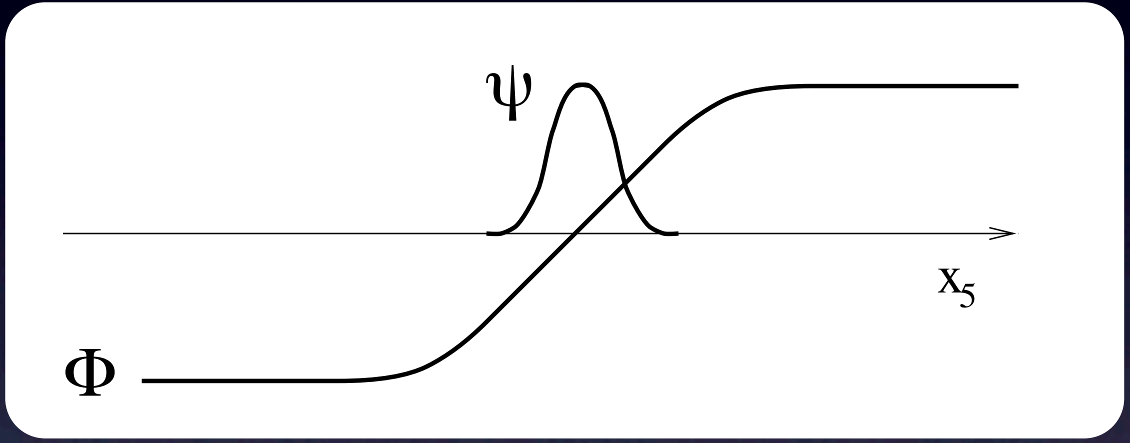

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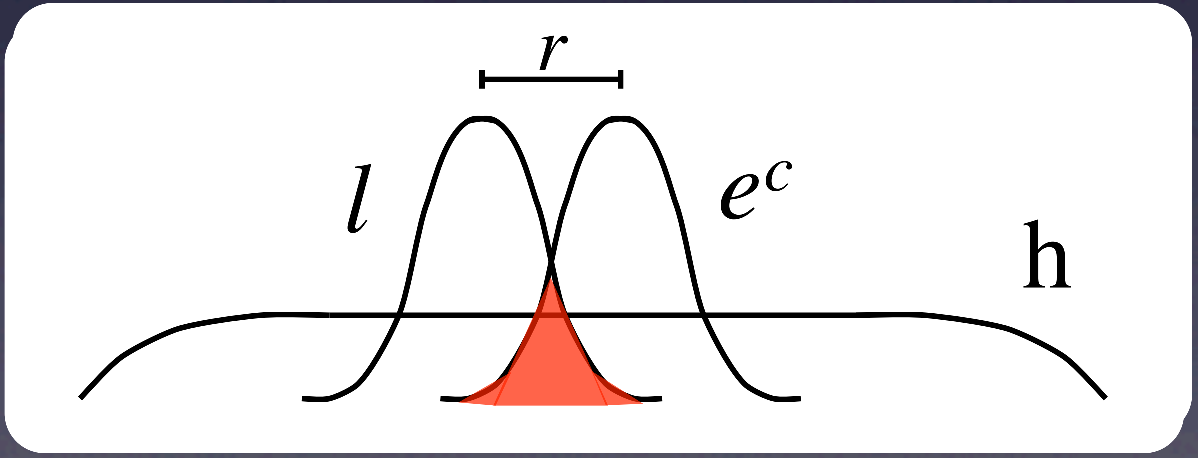

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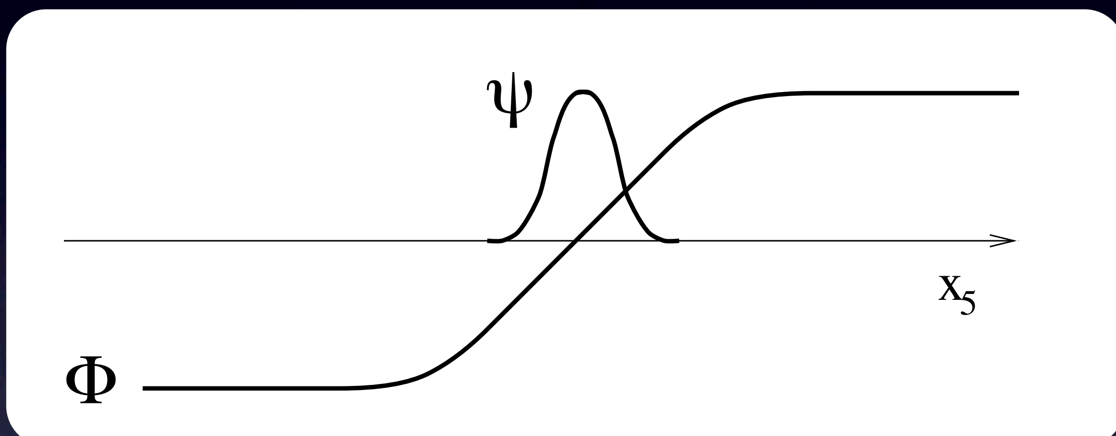

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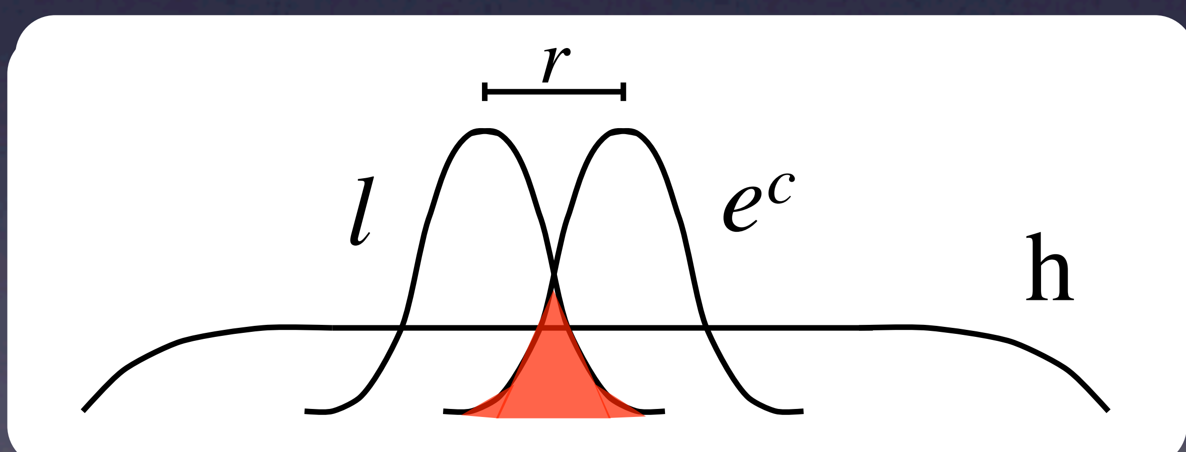
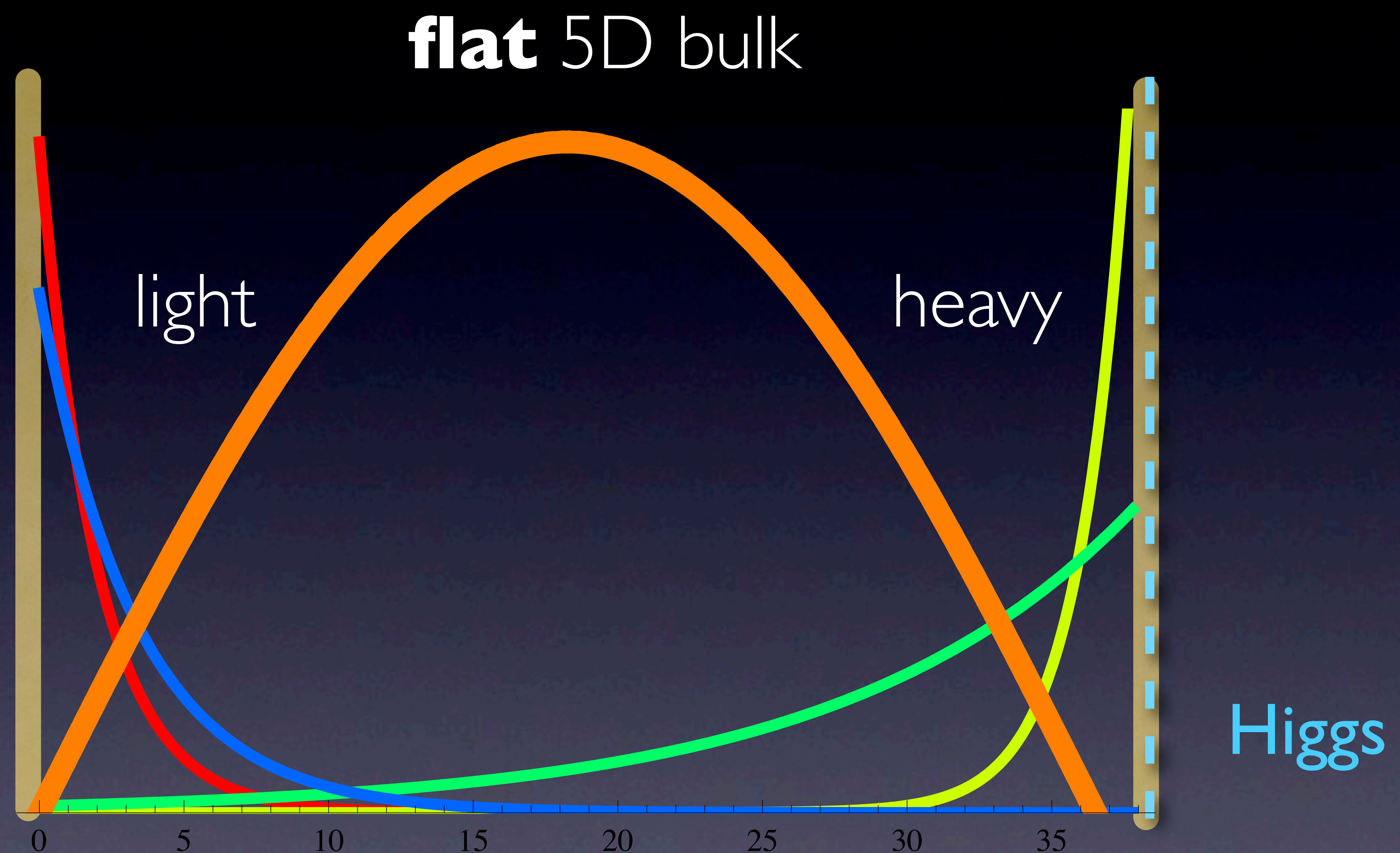


Log(flavor hierarchy)!

$$\int \mathrm{d}x_5\ \phi_l(x_5)\ \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int \mathrm{d}x_5\ e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} \underline{= e^{-\mu^2 r^2/2}}$$

New sources for FCNCs

Delgado, Pomarol, Quiros '99



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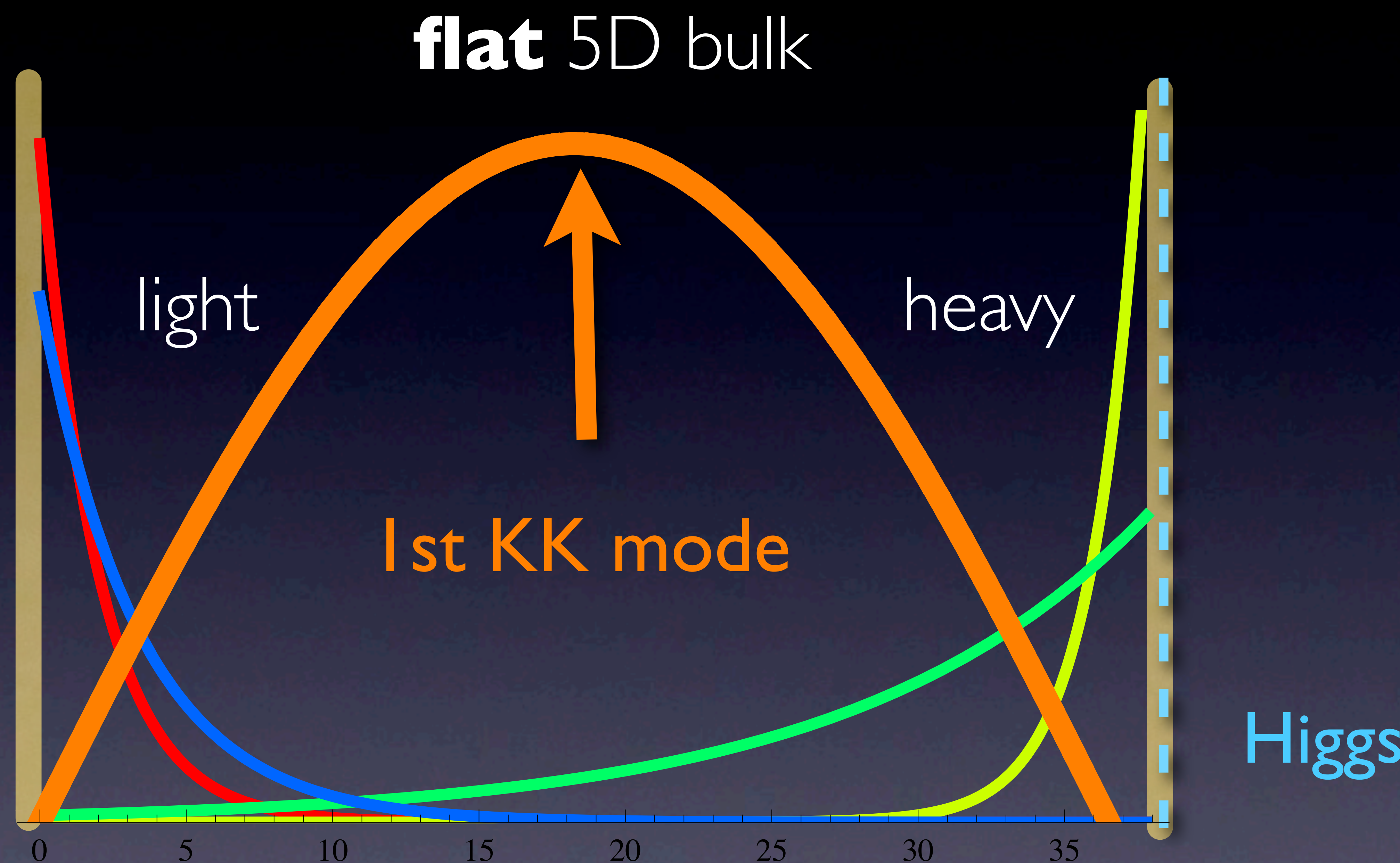

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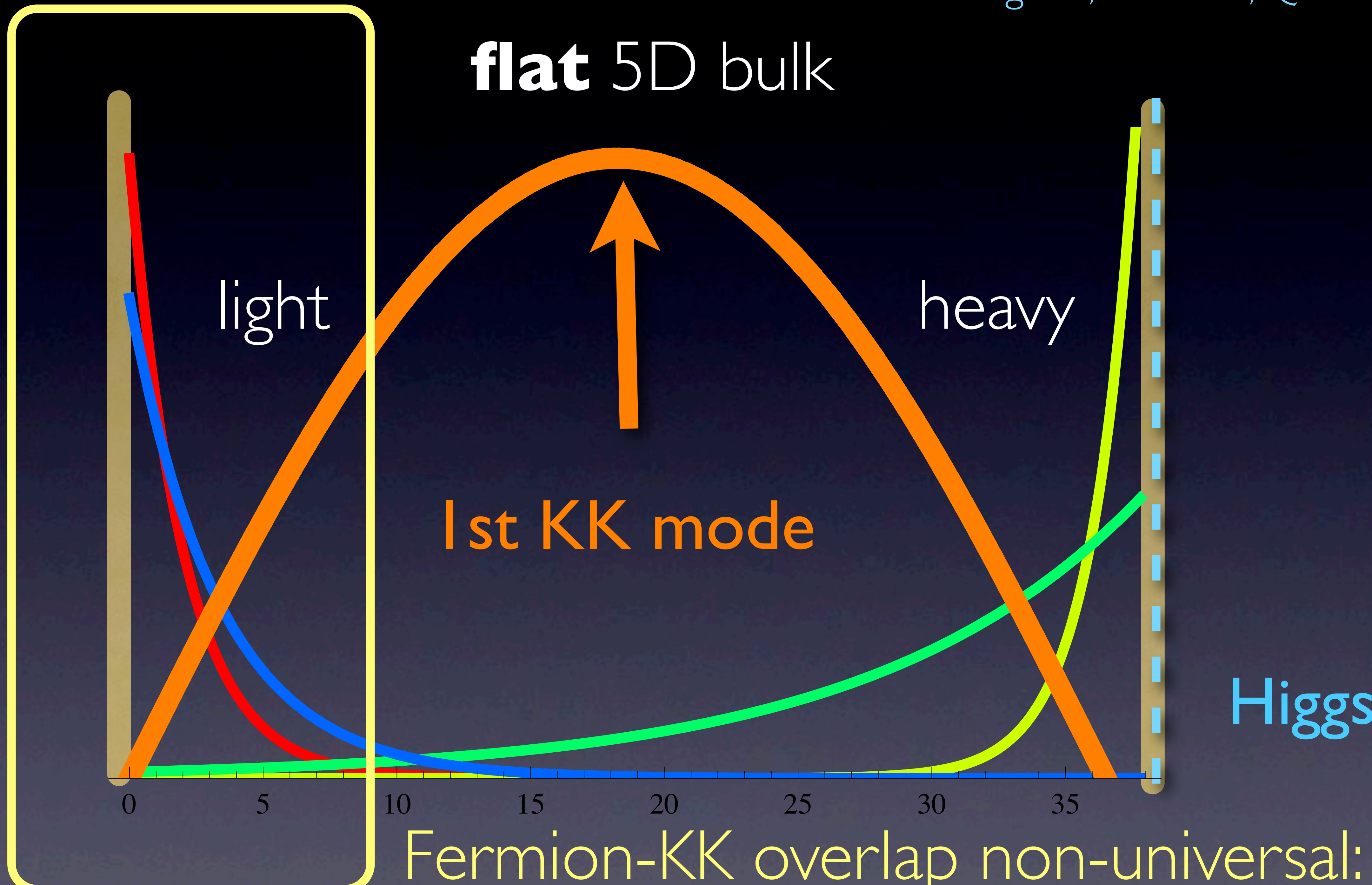


Fermion-KK overlap non-universal: induces FCNCs among light fermions

$\Rightarrow M_{KK} \sim 1/R > 5000$ TeV

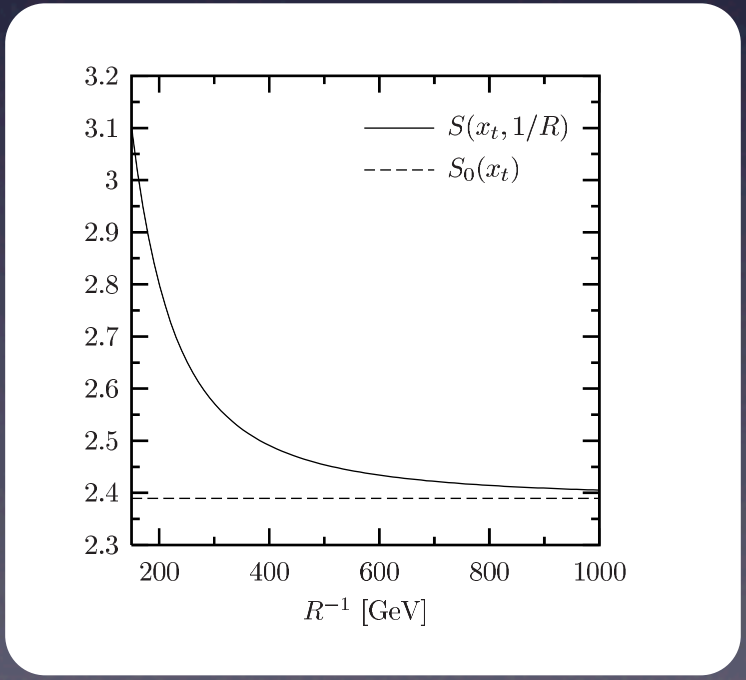
Universal extra dimensions

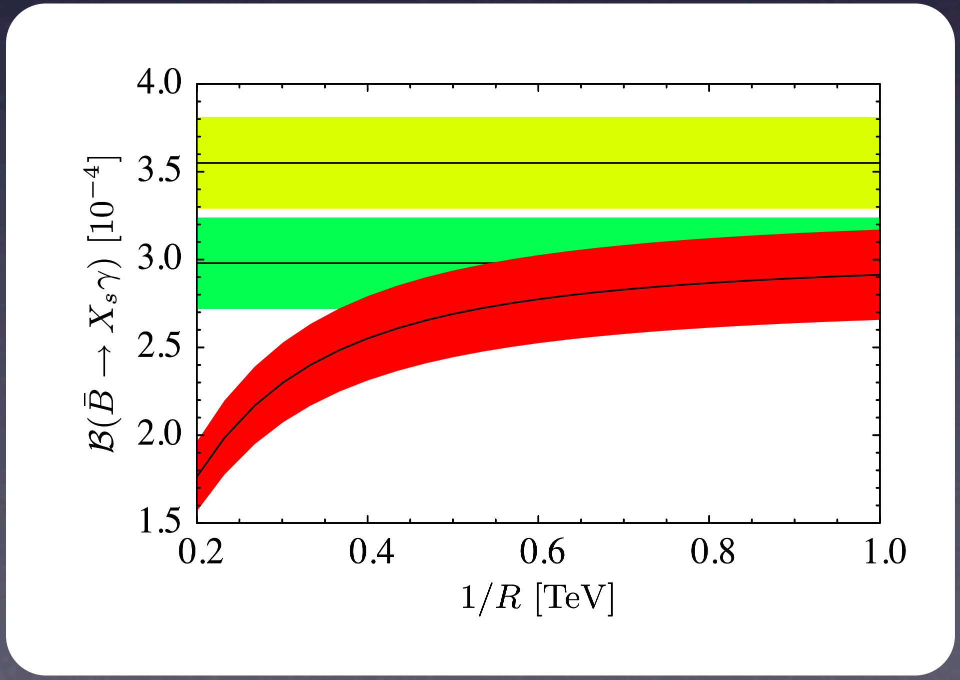
Cheng, Matchev, Schmaltz

Even with flat wave-functions for all fermions (and the higgs) remains a conceptual problem.

Agashe, Deshpande; Buras, Spranger, W

Calculable contributions are MFV, but…





4D → 5D EFT

$$\int d^4x \, \lambda_4 \, \bar{\psi} h \psi \longrightarrow \int d^4x \int_0^R dy \, \lambda_5 \, \bar{\Psi} H \Psi$$

$$[\lambda_4] = 0 \longrightarrow [\lambda_5] = -1/2 \qquad \lambda_5 = \sqrt{2\pi R} \, \lambda_4$$

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NDA: $$\Lambda \simeq \frac{8\pi}{\lambda_4^2}\frac{1}{R}$$

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$$\int d^4x \int_0^R dy \, \lambda_5 \, \bar{\Psi} H \Psi + \ldots \simeq \int d^4x \, \lambda_4 \, \bar{\psi} h \psi + \frac{1}{\Lambda^2} \bar{\psi}\psi\bar{\psi}\psi + \ldots$$

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NDA: $\Lambda \simeq \dfrac{8\pi}{\lambda_4^2} \dfrac{1}{R}$ vs. $\underline{\Lambda_{\epsilon_K} > 10^5 \text{ TeV}}$

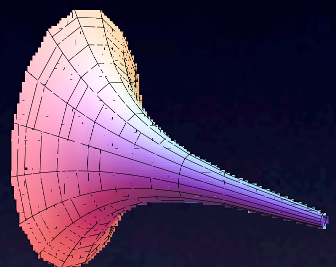
$$\int d^4x \int_0^R dy\, \lambda_5\, \bar{\Psi} H \Psi + \ldots \simeq \int d^4x\, \lambda_4\, \bar{\psi} h \psi \boxed{+ \frac{1}{\Lambda^2} \bar{\psi}\psi\bar{\psi}\psi} + \ldots$$

From flat to warped ED

$$ds^2 = dx_\mu dx_\nu - dy^2$$

$$\downarrow$$

Randall, Sundrum



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

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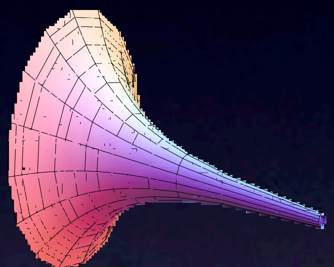
$$\downarrow$$

Randall, Sundrum



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

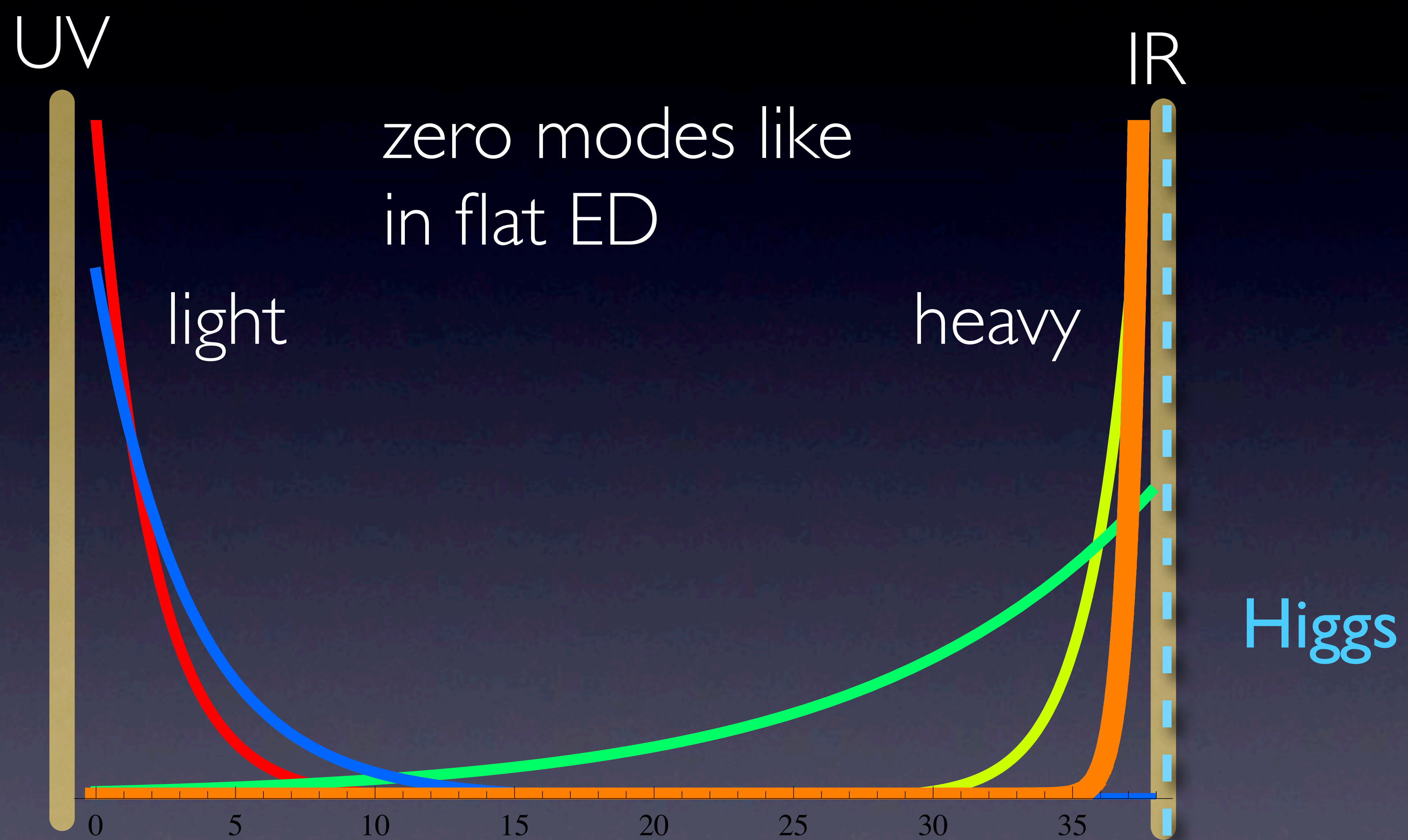
✓ solution to the hierarchy problem

✓ AdS/CFT description: reappraisal of strong EW symmetry breaking (composite Higgs, technicolor,…)

✓ high scale unification, log running of gauge couplings

Flavor in RS

Grossman, Neubert; Gherghetta, Pomarol; Huber;



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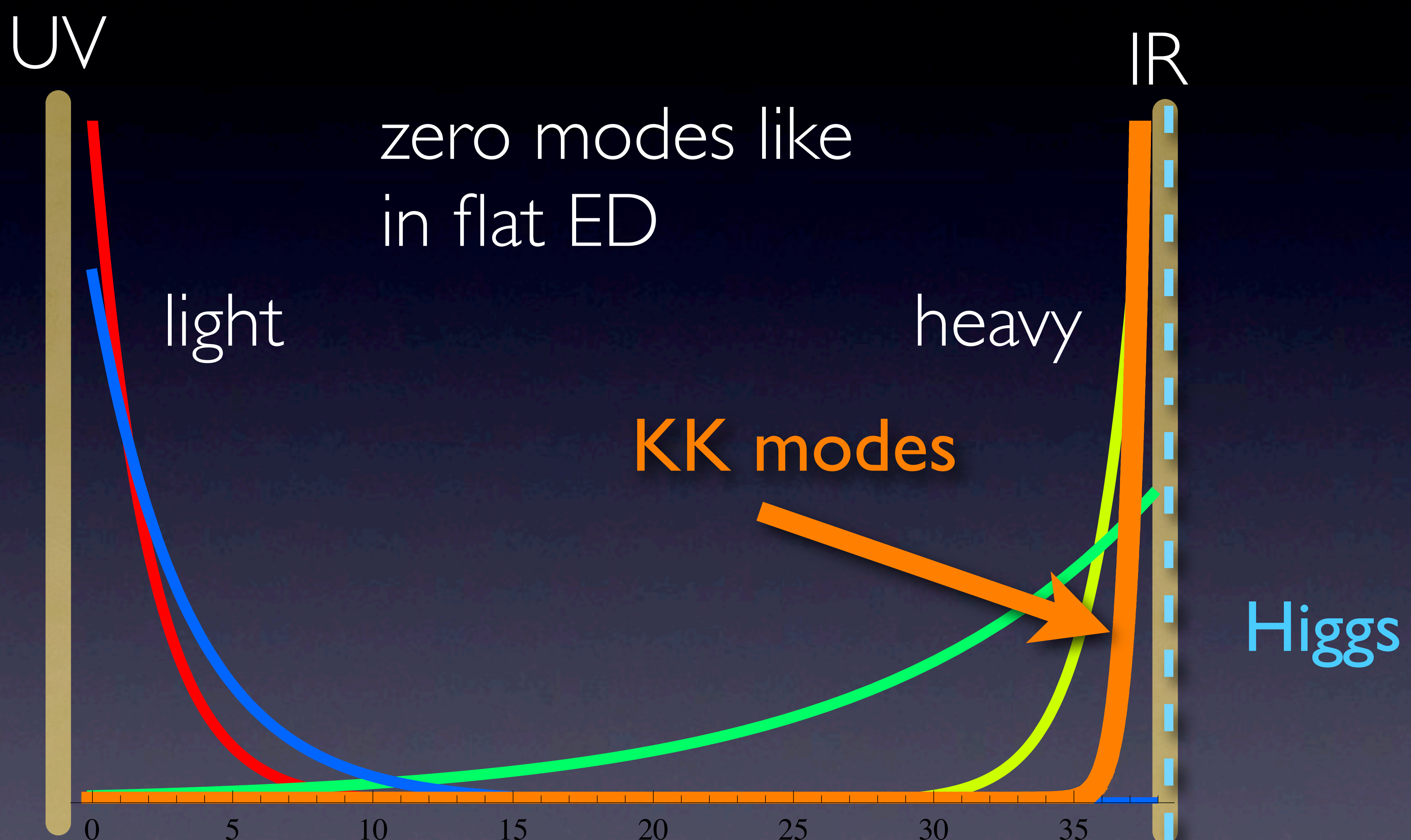

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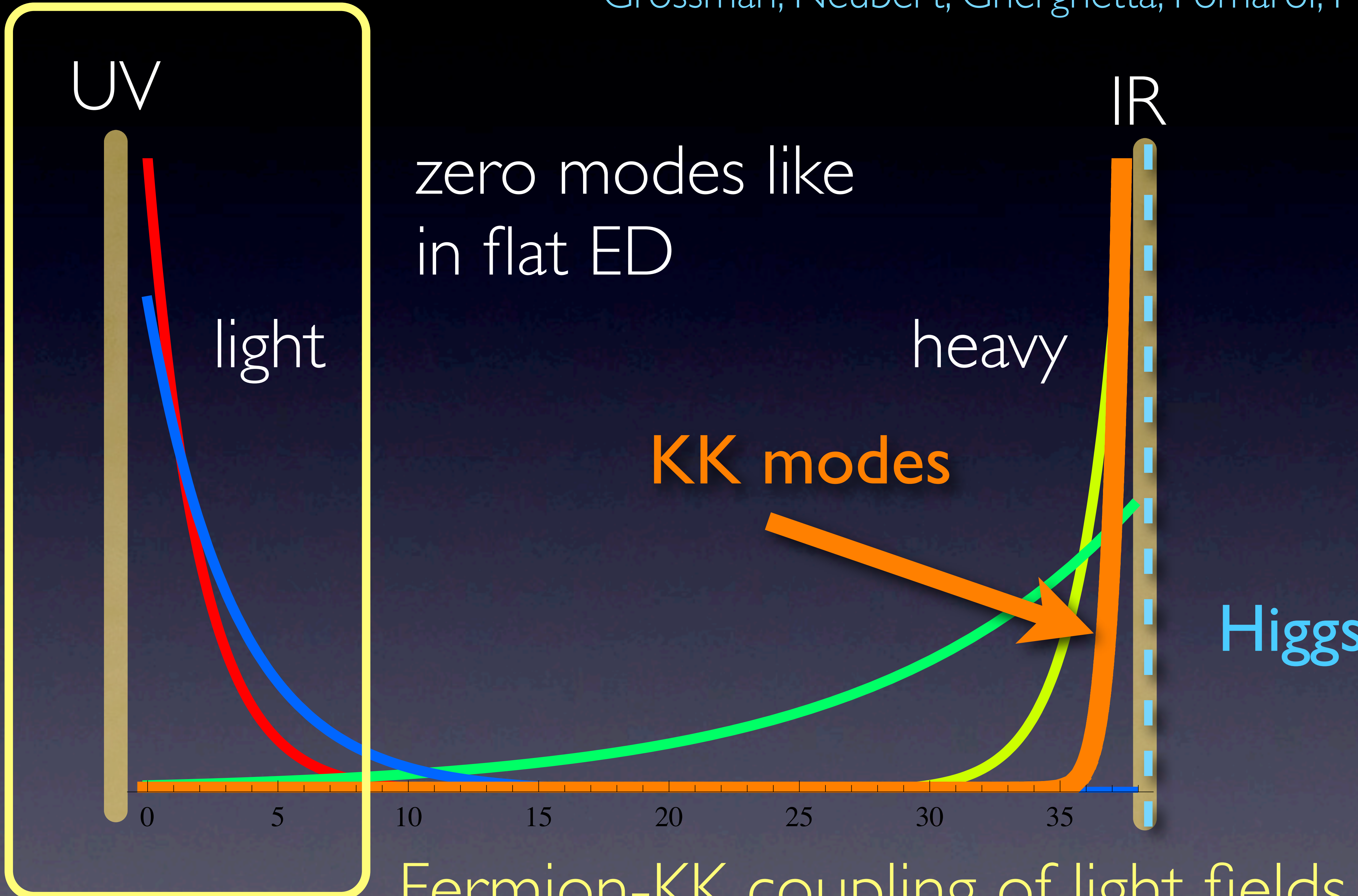

Fermion-KK coupling of light fields almost universal!

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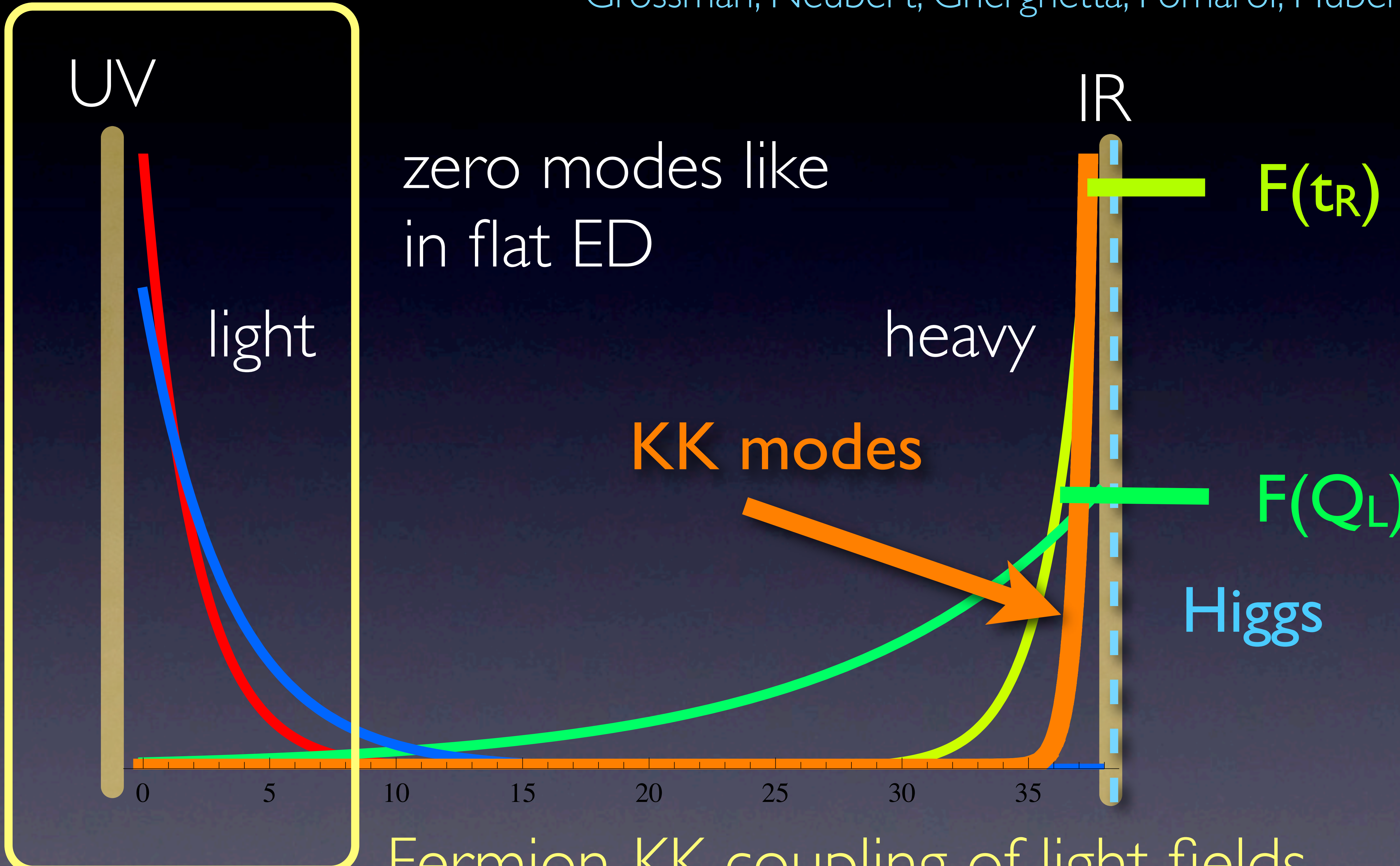


Fermion-KK coupling of light fields almost universal!

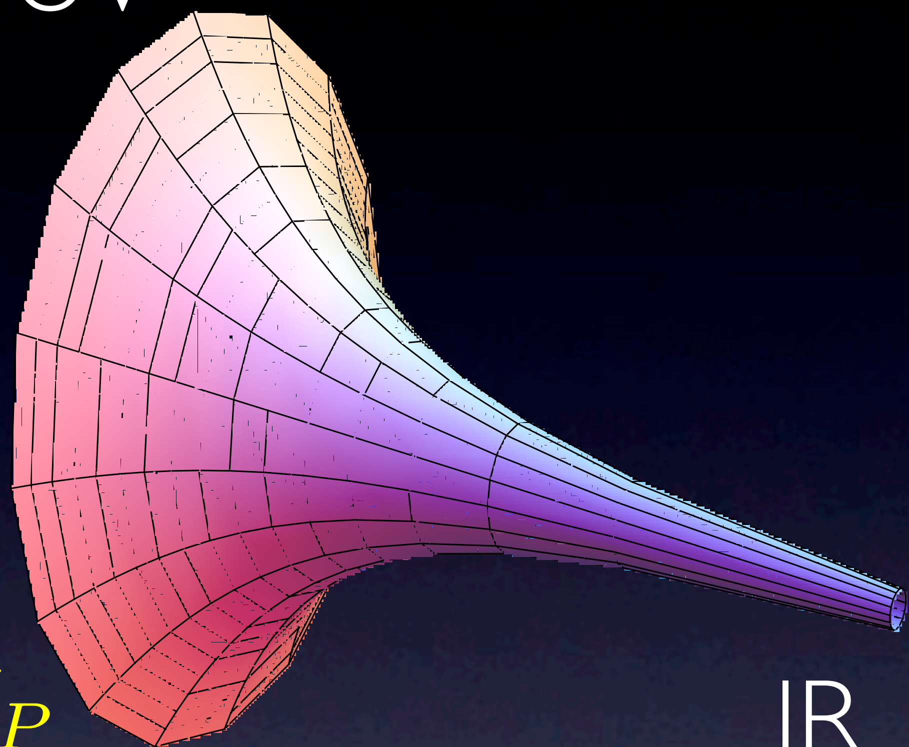
Why are FCNCs protected?

Excursion into AdS/CFT

AdS/CFT (popular science realization)

Randall, Sundrum

UV



M_P IR m_W

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

Anti-de-Sitter (AdS)	$\Longleftrightarrow$	Conformal (CFT)
Compactification	$\Longleftrightarrow$	Mass gap
Red-shifting of scales	$\Longleftrightarrow$	Dimensional trans-mutation

$$m_W = \sqrt{\frac{g(IR)}{g(UV)}}\, M_P \ll M_P$$

$$m_W \sim e^{-4\pi/\alpha} M_P$$

Two ways of giving mass to fermions…

Bi-linear:

$$\mathcal{L} = y f_L \mathcal{O}_H f_R, \quad \mathcal{O}_H \sim (1,2)_{\frac{1}{2}}$$

Linear:

D.B. Kaplan '91

$$\mathcal{L} = y f_L \mathcal{O}_R + y_R f_R \mathcal{O}_L + m \mathcal{O}_L \mathcal{O}_R, \quad \mathcal{O}_R \sim (3,2)_{\frac{1}{6}}$$

Partial compositeness

$$\mathcal{L} = \mathcal{L}_{elem}(g_{elem}) + \mathcal{L}_{comp}(g_*) + \mathcal{L}_{mix}$$

$$1 \lesssim g_* \lesssim 4\pi$$

Contino,Kramer, Son, Sundrum

$$|SM\rangle = \cos\phi|elem.\rangle + \sin\phi|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

1) Linear coupling of SM fields to composites

$$\mathcal{L}_{\mathrm{UV}} \supset \lambda \bar{\mathcal{O}}_R \psi_L$$

Contino, Pomarol

2) Strong sector conformal over large energy range

$$\mu \frac{d\lambda}{d\mu} = \gamma\lambda \qquad \gamma = \dim[\mathcal{O}_{\mathcal{R}}] + 3/2 - 4$$

$$\lambda \sim \left(\frac{\mathrm{TeV}}{M_{Pl}}\right)^{\gamma}$$

AdS/CFT translation:

$$\gamma = c - \frac{1}{2}$$

Partial compositeness

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$$|SM\rangle = \cos\phi|elem.\rangle + \boxed{\sin\phi}|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

Degree of compositeness: $\boxed{\sin\phi = F(c) \sim \left(\frac{\mathrm{TeV}}{\mathrm{M_{pl}}}\right)^{c-\frac{1}{2}}}$

Meanwhile in the Extra-Dimension

Fermion zero mode on the IR brane

$$F(c) \quad \sim \quad \begin{cases} (\mathrm{TeV}/\mathrm{Planck})^{c-\frac{1}{2}} & c > 1/2 \\ \sqrt{1-2c} & c < 1/2 \end{cases}$$

Structure of the mass matrix

$$m_u^{SM} \quad = \quad \frac{v}{\sqrt{2}} F_q \mathbf{Y_u} F_u,$$

$$m_d^{SM} \quad = \quad \frac{v}{\sqrt{2}} F_q \mathbf{Y_d} F_d$$

$\mathbf{Y_u}$, $\mathbf{Y_d}$ ~ O(1) & anarchic and $F_i \ll F_j$ for i < j.

Match SM spectrum and V_{CKM}

Hierarchical mass eigenvalues (6 conditions)

$$(m_{u,d})_{ii} \sim \frac{v}{\sqrt{2}} F_{Q_i} Y_{u,d} F_{u_i,d_i} \qquad F_q = \left(\frac{F}{\Lambda}\right)^q$$

and hierarchical mixing angles (2 conditions)

$$F_{Q_1}/F_{Q_3} \sim \theta_{13} \sim \lambda^3$$

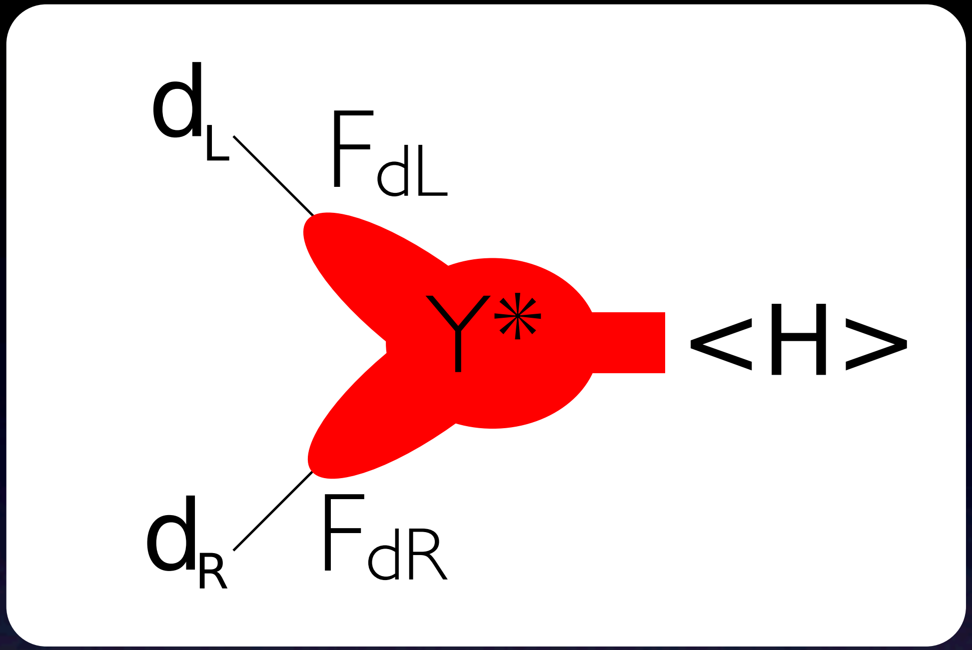
$$F_{Q_2}/F_{Q_3} \sim \theta_{23} \sim \lambda^2$$

check Cabibbo:

$$\theta_{12} \sim F_{Q_1}/F_{Q_2} \sim F_{Q_1}/F_{Q_3} \cdot F_{Q_3}/F_{Q_2} \sim \lambda \quad ✔$$

RS GIM - partial compositeness

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



Flavor hierarchy from hierarchy in F_i

$$m_d \sim v\, F_{d_L} Y^* F_{d_R}$$

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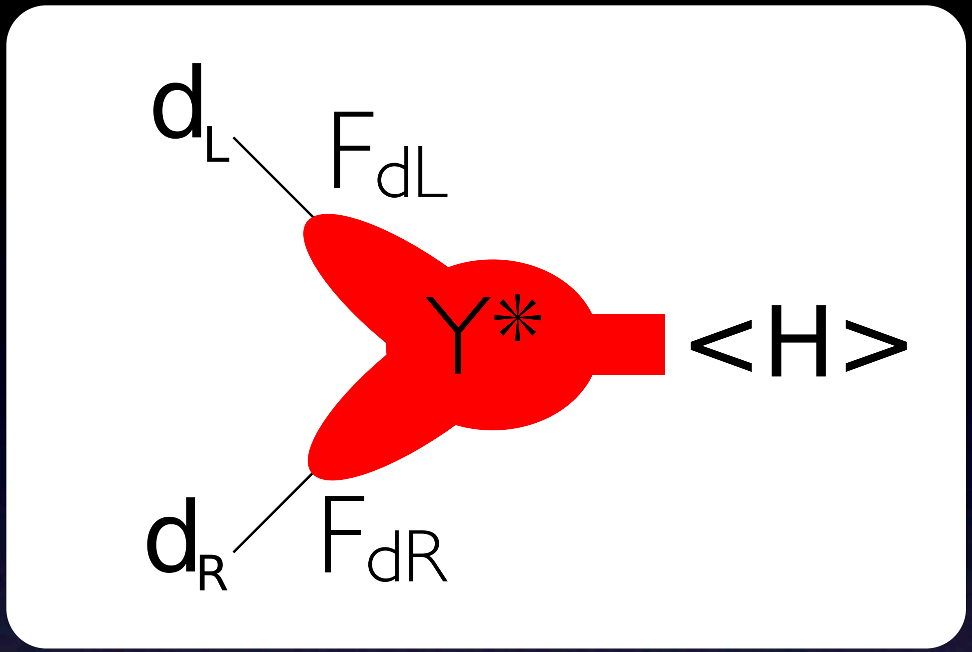

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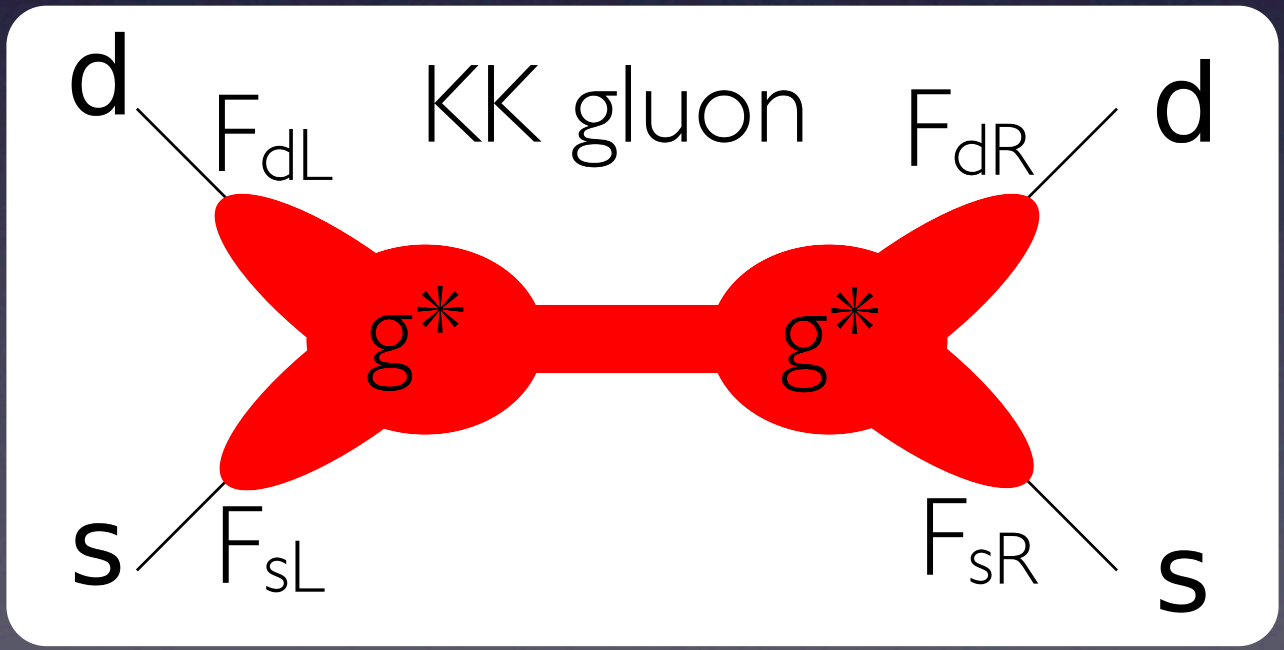


KK gluon FCNCs proportional to the same small F_i :

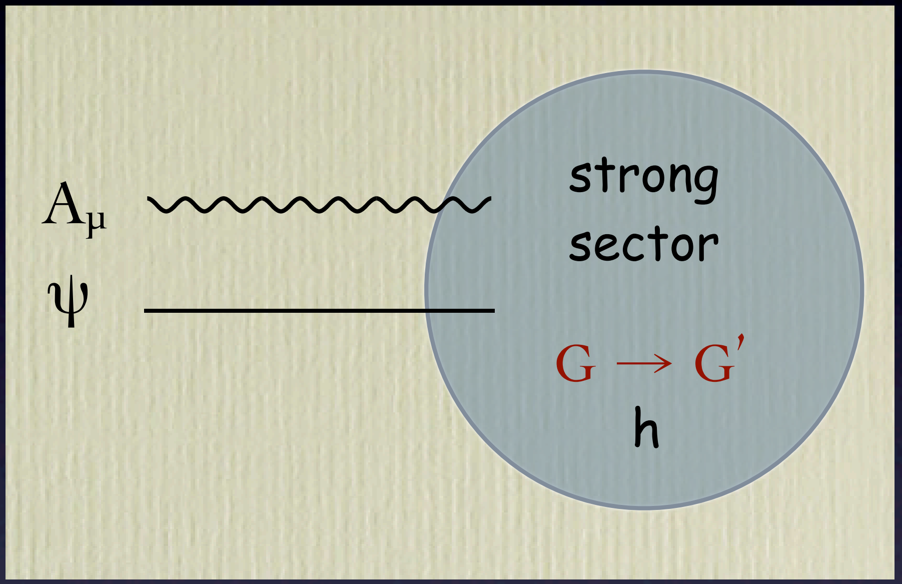
$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}$$

$$\sim \frac{(g^*)^2}{M_{KK}^2} \frac{m_d\, m_s}{(vY^*)^2}$$

RS vs. Composite Higgs

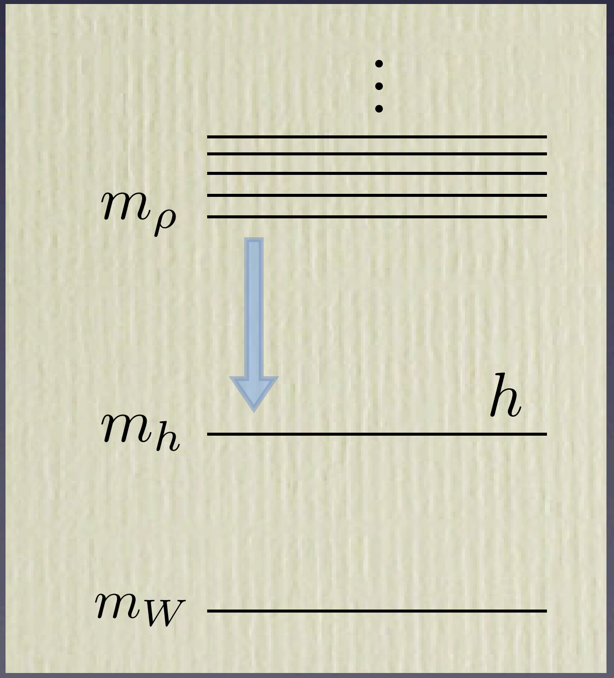
Georgi, Kaplan

Light Higgs-like scalar arises as a bound state from a strongly-interacting EWSB sector



Motivations:

- A composite Higgs solves the hierarchy problem
- A light Higgs is preferred by the electroweak fit



A light composite Higgs can naturally arise as a (pseudo) Goldstone boson

Brane/bulk scalar in RS ≡ 4Dcomposite Higgs.

FCNCs from composite Higgs

Agashe, Contino; Azatov, Toharia, Zhu

Further constraints from compositeness of Higgs

$$Y_d \bar{Q}_L H d_R + \frac{\tilde{Y}^d}{\Lambda^2} \bar{Q}_L H d_R (H^\dagger H) + \frac{\tilde{Z}}{\Lambda^2} \bar{Q}_L \, i \not{D} \, Q_L (H^\dagger H) + \ldots$$

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$$M^d = v Y^d - \left(\tilde{Y}^d + \tilde{Z} Y^d + \ldots \right) \frac{v^3}{\Lambda^2} ,$$

$H = v + h(x)$

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$$M^d = v Y^d - \left(\tilde{Y}^d + \tilde{Z} Y^d + \ldots\right) \frac{v^3}{\Lambda^2} \,,$$

$H = v + h(x)$

$$h \, \bar{d}_L d_R \left[Y^d - 3 \left(\tilde{Y}^d + \tilde{Z} Y^d + \ldots\right) \frac{v^2}{\Lambda^2} \right] ,$$

FCNCs from composite Higgs

Agashe, Contino; Azatov, Toharia, Zhu

Further constraints from compositeness of Higgs

$$Y_d \bar{Q}_L H d_R + \frac{\tilde{Y}^d}{\Lambda^2} \bar{Q}_L H d_R (H^\dagger H) + \frac{\tilde{Z}}{\Lambda^2} \bar{Q}_L \, i \not{D} \, Q_L (H^\dagger H) + \ldots$$

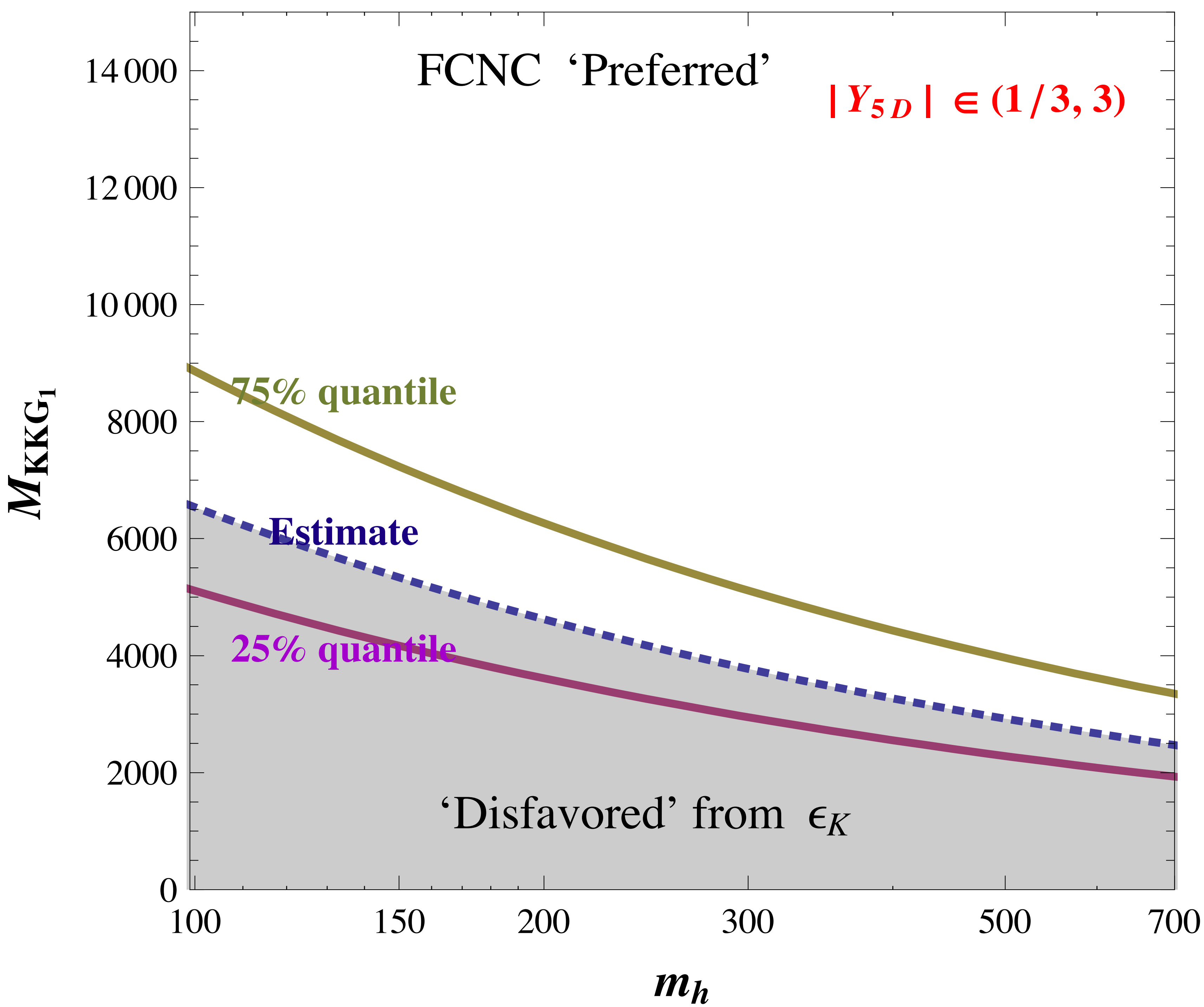
$$M^d = vY^d - \left(\tilde{Y}^d + \tilde{Z}Y^d + \ldots\right)\frac{v^3}{\Lambda^2} \,,$$

$H = v + h(x)$

FCNCs

$$h \, \bar{d}_L d_R \left[Y^d - 3 \left(\tilde{Y}^d + \tilde{Z}Y^d + \ldots\right)\frac{v^2}{\Lambda^2} \right] ,$$

Toharia, Zhu



FCNC 'Preferred'
$|Y_{5D}| \in (1/3, 3)$
75% quantile
Estimate
25% quantile
'Disfavored' from ϵ_K
M_{KKG_1}
14 000
12 000
10 000
8000
6000
4000
2000
0
100
150
200
300
500
700
m_h

Agashe, Contino

If composite Higgs is not just ordinary bound state but pGB associated with G→H in strong sector

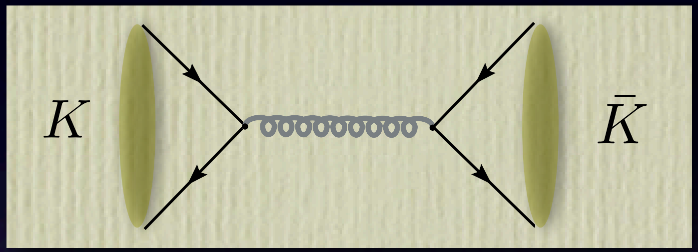
$$\bar{Q}_L H \left(Y^d + \tilde{Y}^d \frac{H^\dagger H}{\Lambda^2} + \cdots \right) d_R \longrightarrow \bar{\psi}^i_L P_{ij}(\Sigma) \psi^j_R$$

Constraints are less severe (only from kinetic terms, suppressed by small quark masses).

FCNCs assuming anarchy

Csaki, Falkowski, W; Buras et al; Casagrande et al

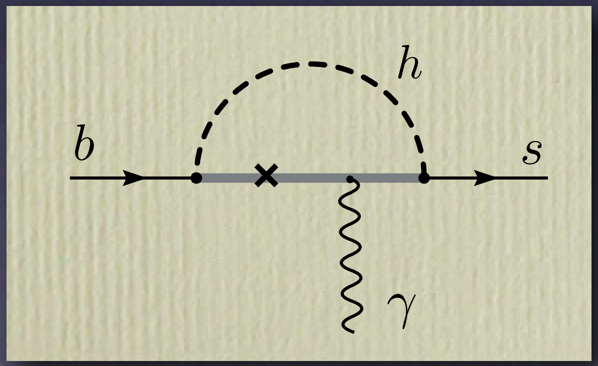
$\Delta F = 2$ (strongest constraint from ϵ_K)



$$C^4(M_*) \sim \frac{1}{M_*^2} \frac{2m_d m_s}{v^2} \left(\frac{g_*}{Y_*}\right)^2$$

$$M_* \gtrsim 10 \left(\frac{g_*}{Y_*}\right) \text{TeV}$$

$\Delta F = 1$ (strongest constraint from ϵ'/ϵ)



$$M_* \gtrsim 1.3\, Y_* \,\text{TeV}$$

Combined constraints strong ⇒ flavor problem w/ anarchy

Spurion analysis

Without the Yukawas SM has

$$SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$$

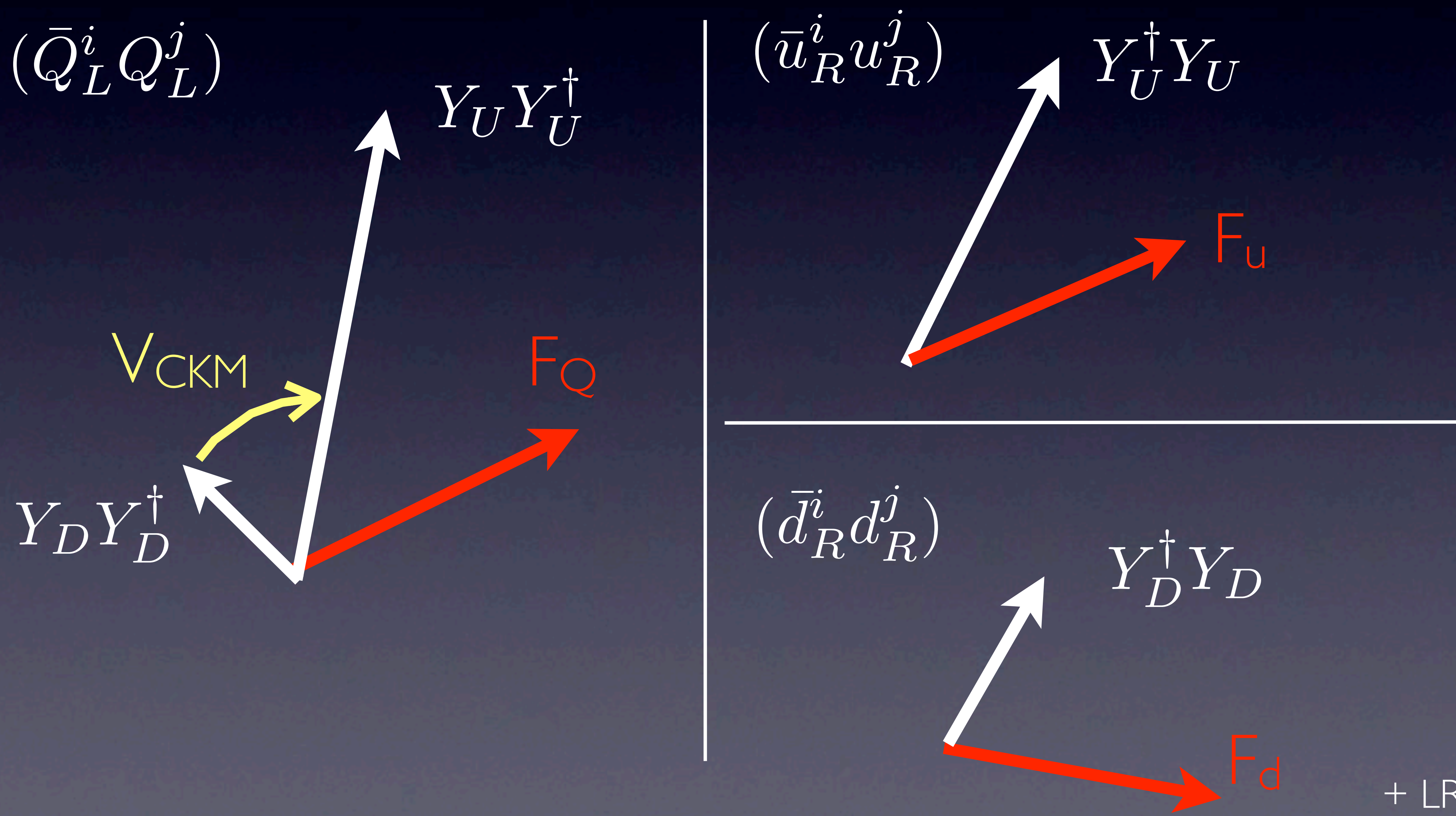
global flavor symmetry.

In RS broken by $\quad Y_u^*, Y_d^* \;+\; F_Q, F_d, F_u$

No dangerous FCNCs in the down sector if

$Y_d^* \;+\; F_Q, F_d$ aligned (diagonal in the same basis)

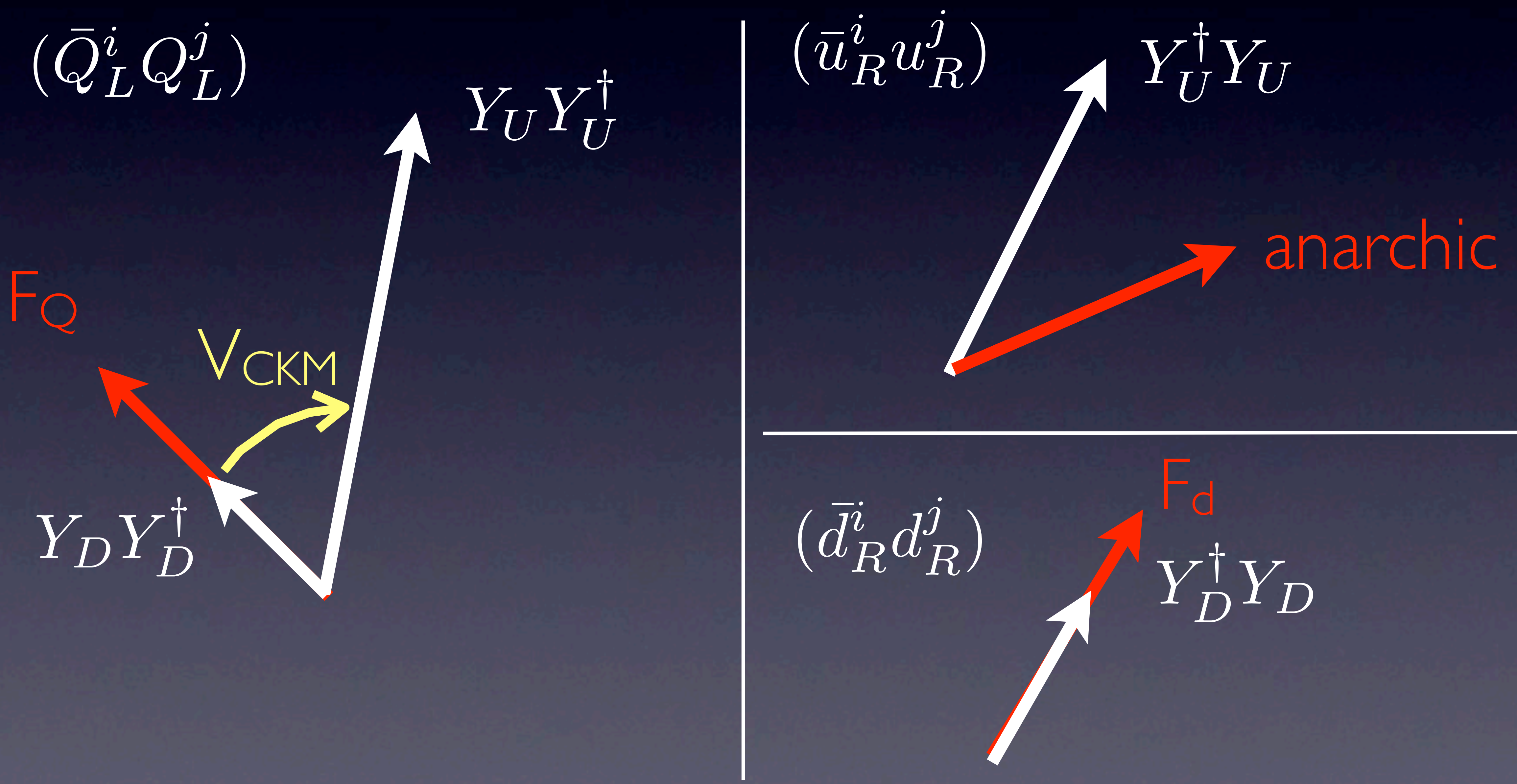
Anarchy



+ LR, RL

Align down sector

similar to Nir, Seiberg '93 for MSSM



+ LR, RL

Aligning 5D MFV

Fitzpatrick, Randall, Perez; Csaki, Perez, Surujon, A.W.,

$SU(3)^3$ flavor symmetry broken by Yukawas only

$$c_Q \sim Y_d Y_d^\dagger + \epsilon Y_u Y_u^\dagger \qquad c_d \sim Y_d^\dagger Y_d \qquad c_u \sim Y_u^\dagger Y_u$$

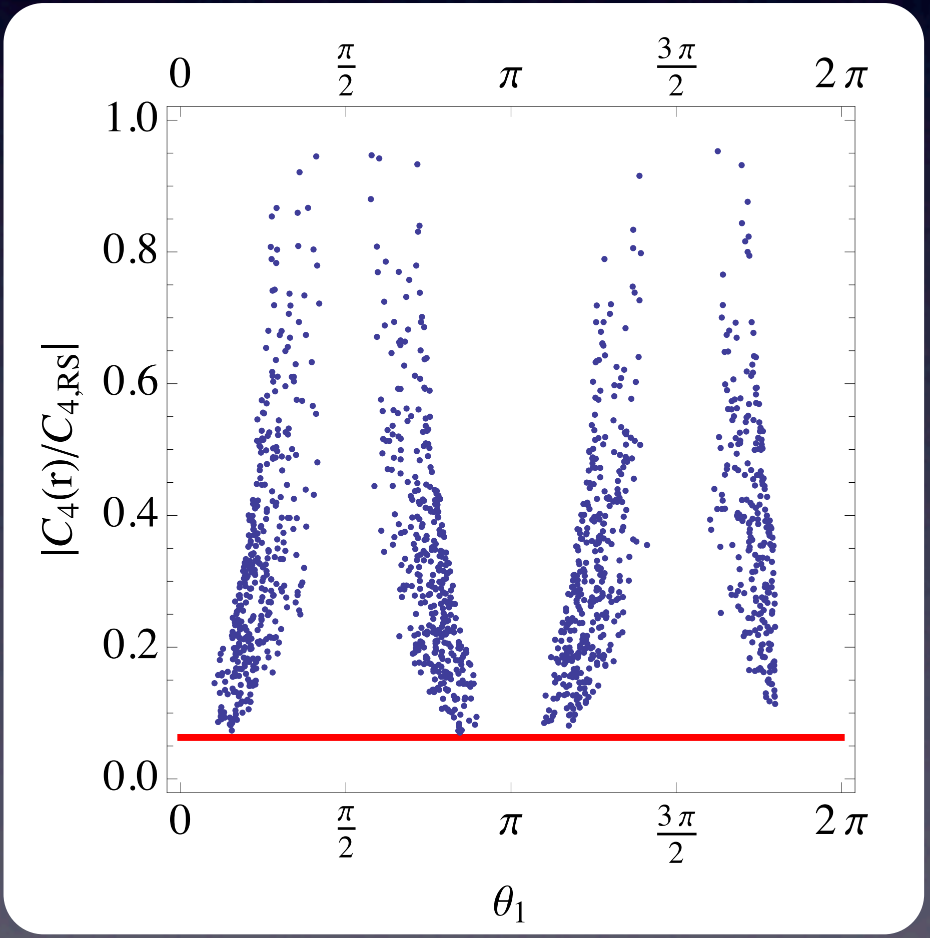
Need **ε** ≪ 1 to align F_Q , F_d , and Y_d

Aligning 5D MFV

Fitzpatrick, Randall, Perez; Csaki, Perez, Surujon,A.W.,

Scan 5D CKM and test suppression C_{4MFV} / $C_{4,RS}$

Keep **ε** = 0.2 fixed.



Need $\epsilon \longrightarrow 0$

$\Rightarrow$ symmetry ?

Alignment due to shining

Csaki, Perez, Surujon, A.W.

In the bulk: gauged $SU(3)_Q \times SU(3)_d$ flavor

$$F(c_Q) = F(Y_{*d} Y_{*d}{}^\dagger), \qquad F(c_d) = F(Y_{*d}{}^\dagger Y_{*d})$$

Flavor broken by vev of Yukawa field Y_{*d} only

UV breaking 'shines' into the bulk via marginal operator

Rattazzi, Zafaroni

Φ_d : (**3**,**1**,<u>**3**</u>), $\langle \Phi_d \rangle = Y_{*d}\,(z/R)^{-\varepsilon}$

Big effects in up-FCNCs expected.

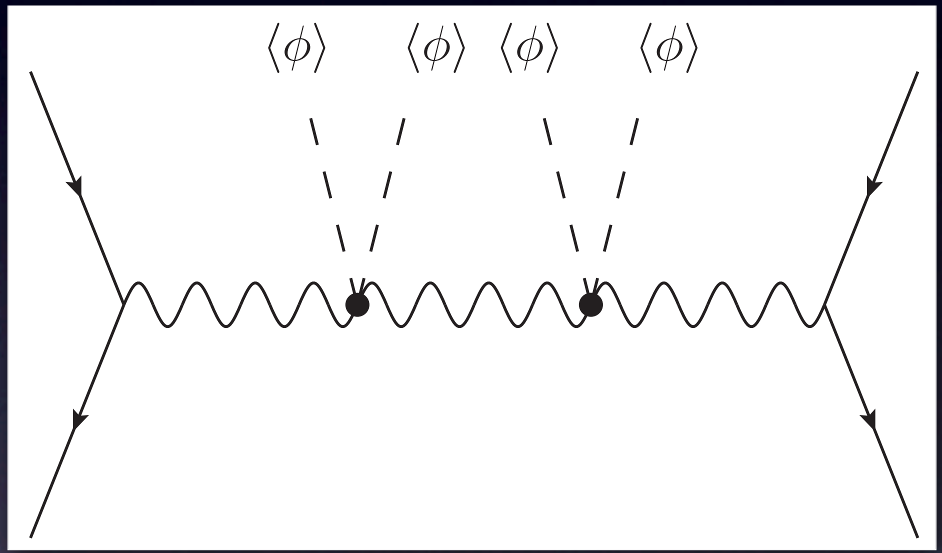
A theory of flavor at the LHC?

Flavor gauge boson FCNCs

Csaki, Lee, Perez, AW in preparation

In Rattazzi-Zaffaroni model: dynamical MFV

K



$\underline{\text{K}}$

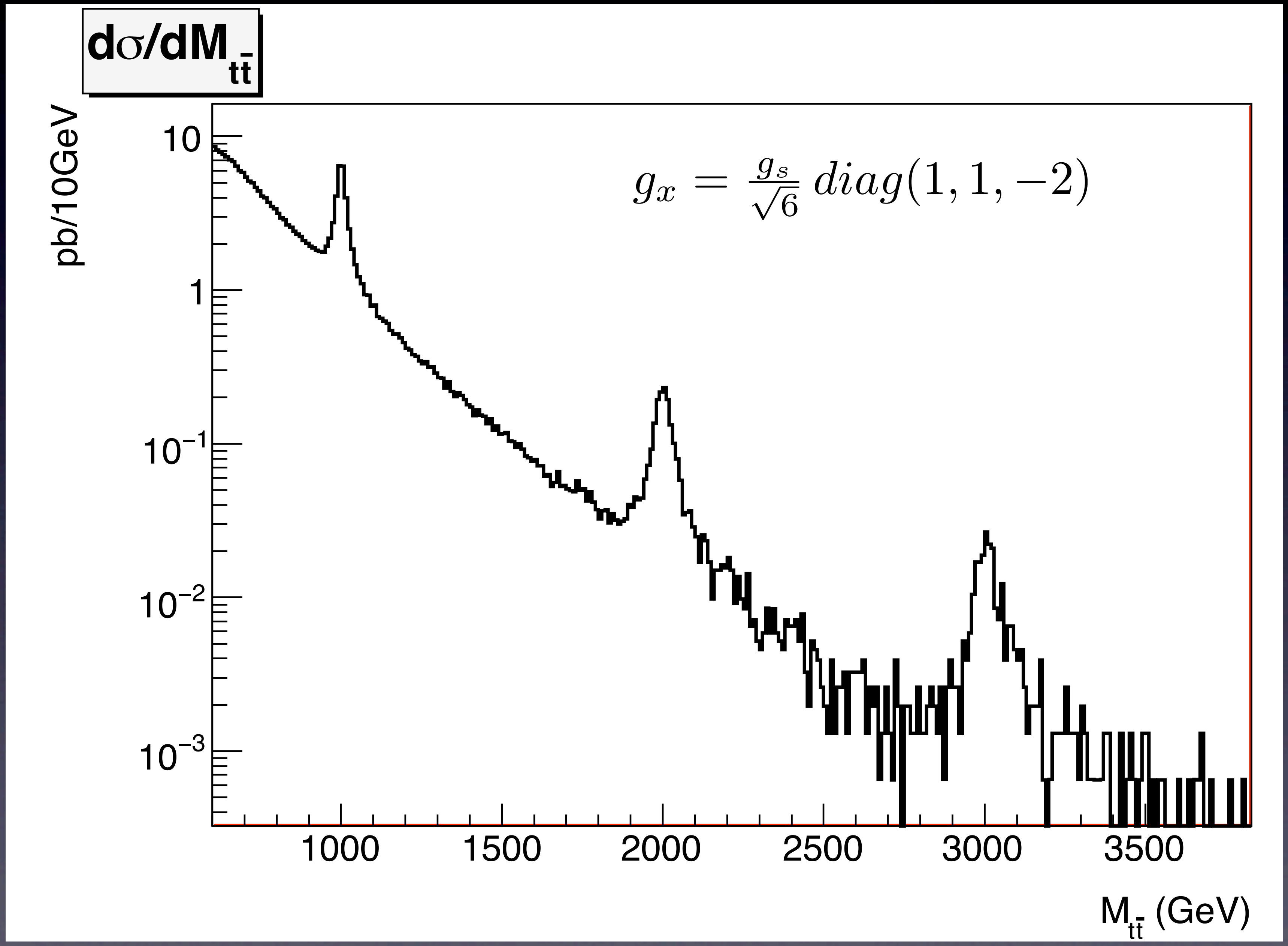
$$\mathcal{L}_{mass} = M_{KK}^2 \mathrm{Tr}[A_Q A_Q] + \frac{4 g_{Q*}^2 R^3}{3 R'^2} \mathrm{Tr}[\phi_u A_Q A_Q \phi_u]$$

g* ~ 4 allowed

$$\frac{1}{M_{KK}^2} \frac{2\, g_{Q*}^6 y_t^4}{27\,(M_{KK}R')^4 + 42\,(g_{Q*}y_t)^2\,(M_{KK}R')^2 + 16\,(g_{Q*}y_t)^4} \left((V^\dagger Y_u^2 V)_{ij}\right)^2 (\bar{d}_i \gamma_L^\mu d_j)(\bar{d}_i \gamma_L^\mu d_j)$$

Flavor scalars & gauge bosons

Csaki, Lee, Perez, AW in preparation



thanks to Seung Lee for the plot

Conclusions

Extra dimensions allow new approaches to the flavor puzzle.

Warped flavor is a calculable realization of partial compositeness, a linear mixing with the composite sector.

RS-GIM suppresses dangerous FCNCs, tension with CPV in Kaon sector. Can decouple problems but decouple from LHC.

Anarchy alone needs tuning to survive, additional flavor structure indicated.
Signal: large FCNCs in the up-sector (top FCNCs, D-$\underline{\text{D}}$),
Flavor gauge bosons?