Top Flavor Gauge Boson Physics (& Flavor Triviality)

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Based on works in collaboration with
Delaunay, Gedalia, Perez & Ponton (x2)
Csáki, Kagan, Perez & Weiler (in preparation)

Outline

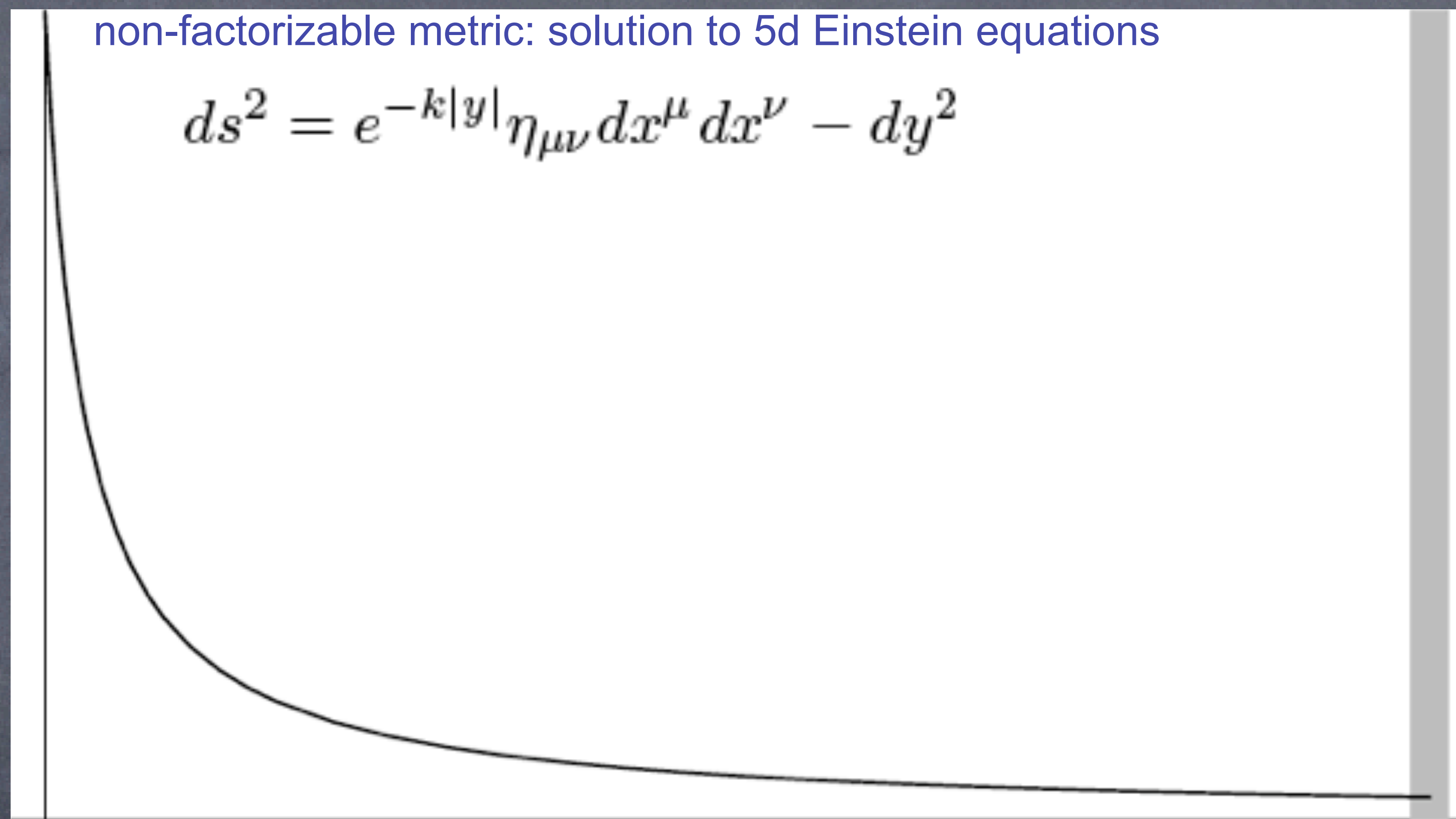
- Introduction: Warped XD & little CP problem
- Flavor symmetry (decoupling flavor and CP): "Flavor triviality" and flavor gauge boson
- Improved EW fit: Global fit to the EW observables
- Signals from Flavor Trivial Warped Extra Dimension: KK gluon and flavor gauge boson
  - top physics at LHC and Tevatron
- Summary

RS & the hierarchy problem

Randall-Sundrum, PRL (99)

- XD curved, but brane remains static and flat

SM+Higgs



UV (y=0) IR (y=b)

- address the hierarchy problem by providing concrete 5D realizations of various 4D EWSB scenarios: composite higgs, pseudo-Goldstone higgs, higgsless, etc.

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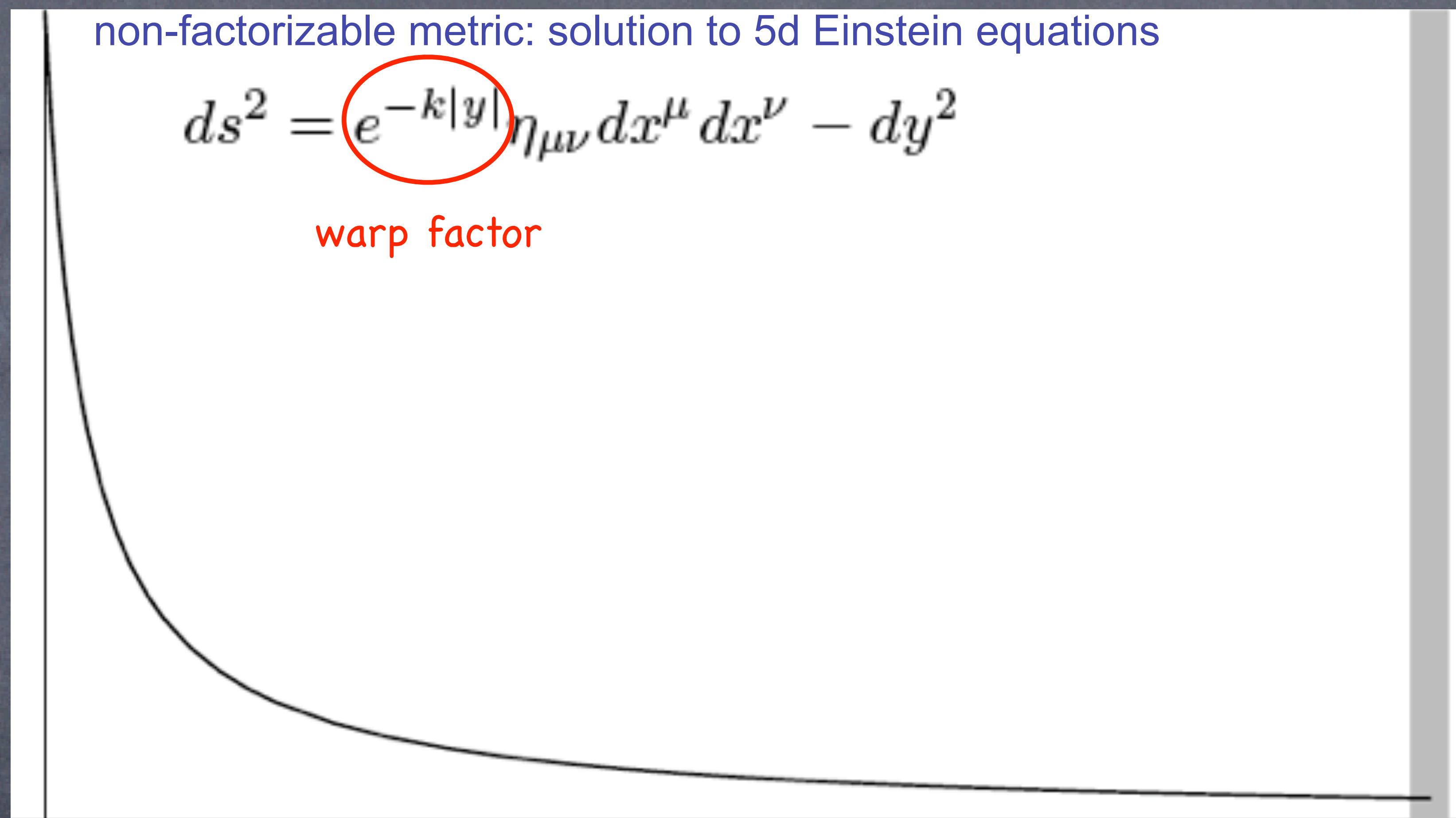

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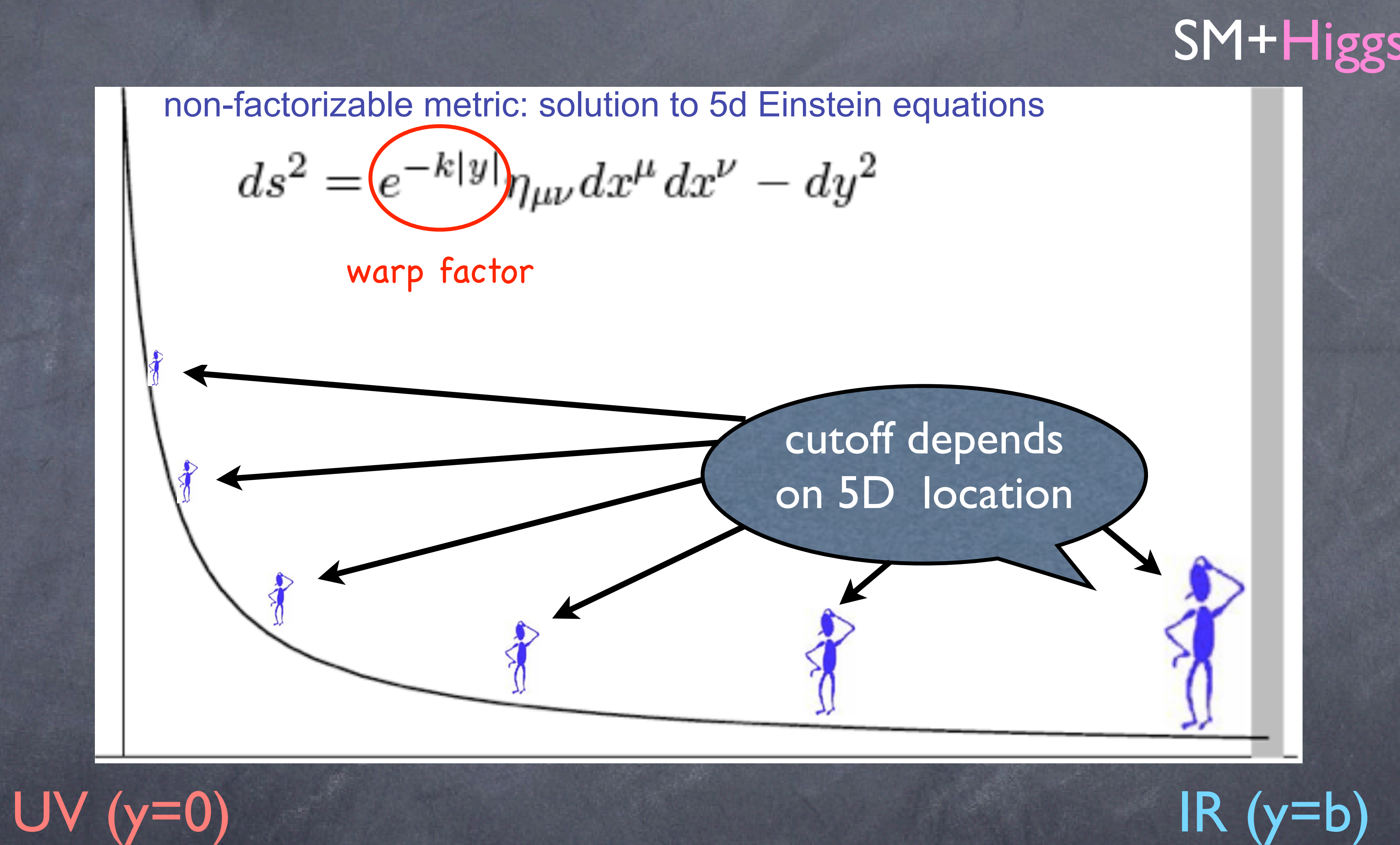

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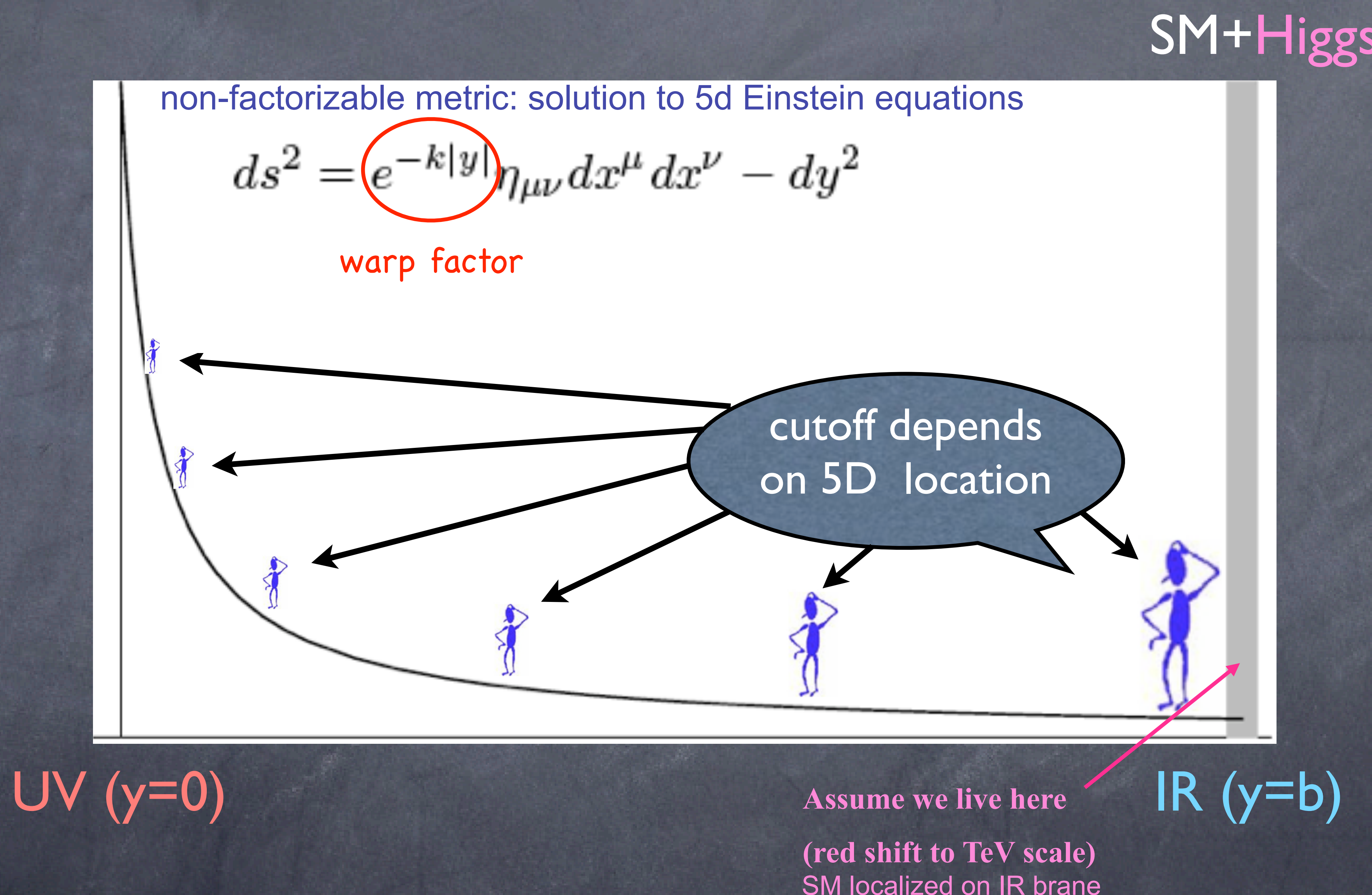

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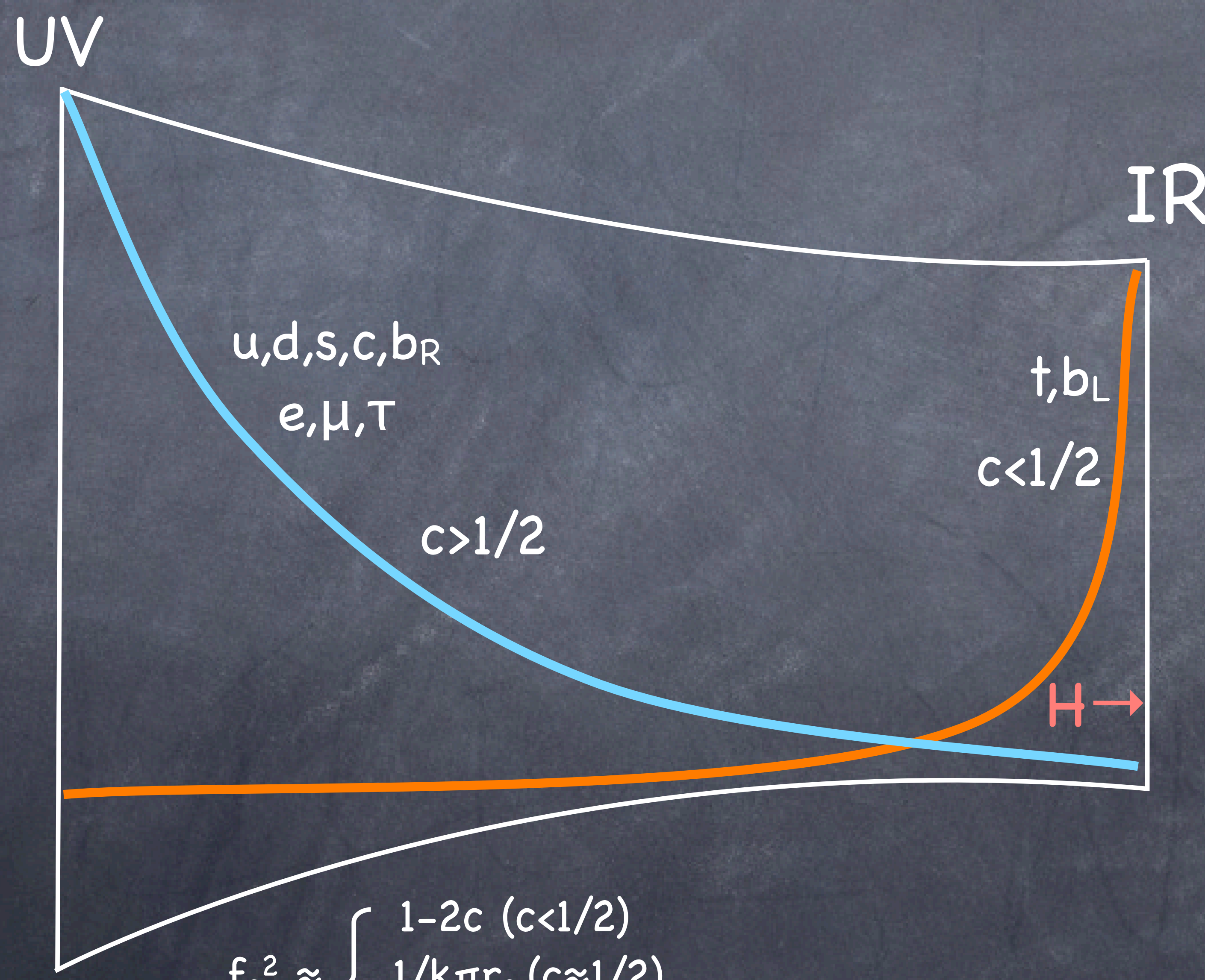
Anarchic RS

- Anarchic model: Localization address flavor hierarchy and also give protection against flavor & CPV (with $c_{Q,U,D} \sim O(1)$)



$$f_c^2 \approx \begin{cases} 1-2c \ (c<1/2) \\ 1/k\pi r_c \ (c\approx 1/2) \\ (2c-1)\exp[(1-2c)\ k\pi r_c] \ (c>1/2) \end{cases}$$

$Y_{U,D} \sim O(1)$

$M_{U,D} \sim v \ f_{c_Q} Y_{U,D} \ f_{c_{U,D}}$

$V^{CKM}{}_{ij} \approx f_{c_{Qi}} / f_{c_{Qj}}$

Anarchic RS: Little CP Problem

- Stringent bound from flavor physics:

$$\varepsilon_K = \frac{A(K_{\rm L} \to (\pi\pi)_{I=0})}{A(K_{\rm S} \to (\pi\pi)_{I=0})}$$

$$\epsilon' / \epsilon_K$$

Davidson, Isidori & Uhlig (07);
Gedalia, Isidori & Perez (09).

Csaki, Falkowski & Weiler;
Agashe, Azatov & Zhu (08)

$$\varepsilon_{ij} \frac{\bar{Q}_i Q_j \bar{Q}_i Q_j}{\Lambda_F}$$

$$|\varepsilon_{ij}| \sim O(1) \rightarrow \Lambda_F > O(6)\ \text{TeV!}$$

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New Physics > 5-6 TeV: out of reach from LHC for best case

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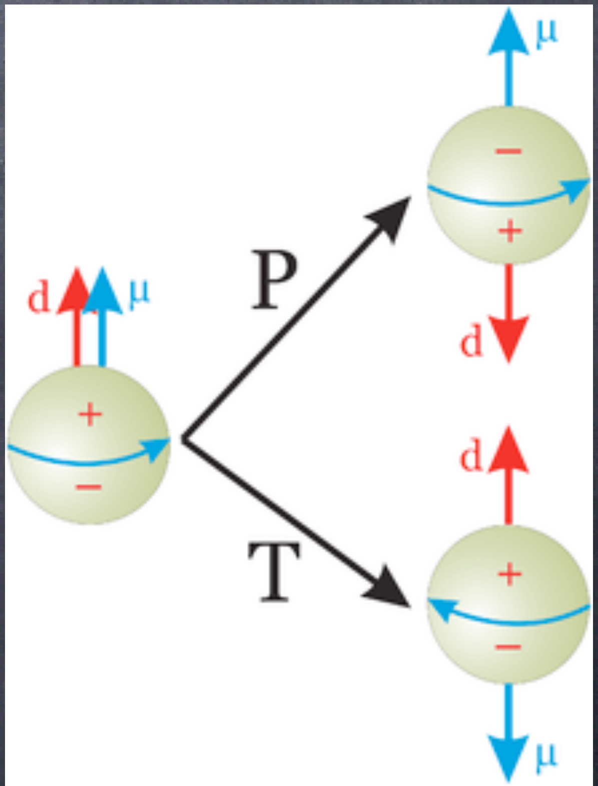
New Physics > 5-6 TeV: out of reach from LHC for best case

- neutron Electric Dipole Moment constraint: O(20) larger than bounds

measure for the distribution of positive and negative charge inside the neutron

Agashe, Perez & Soni (04)

Delaunay, Gedalia, SJL, Perez & Ponton (11)



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$\varepsilon_{ij}\frac{\bar{Q}_iQ_j\bar{Q}_iQ}{\Lambda_F}$ > O(6) TeV!

New Physics ach from LHC case

combining EDM and ε_K, m_{KK} > 8.4 TeV for anarchic RS

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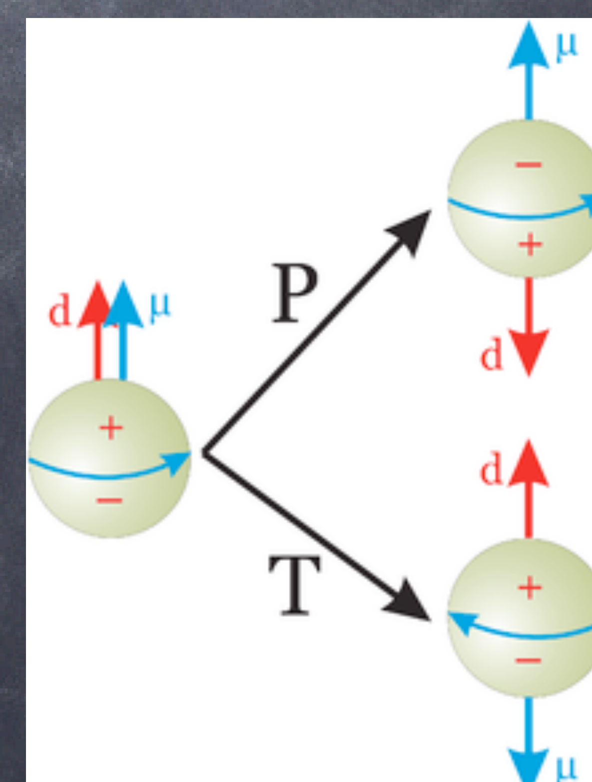
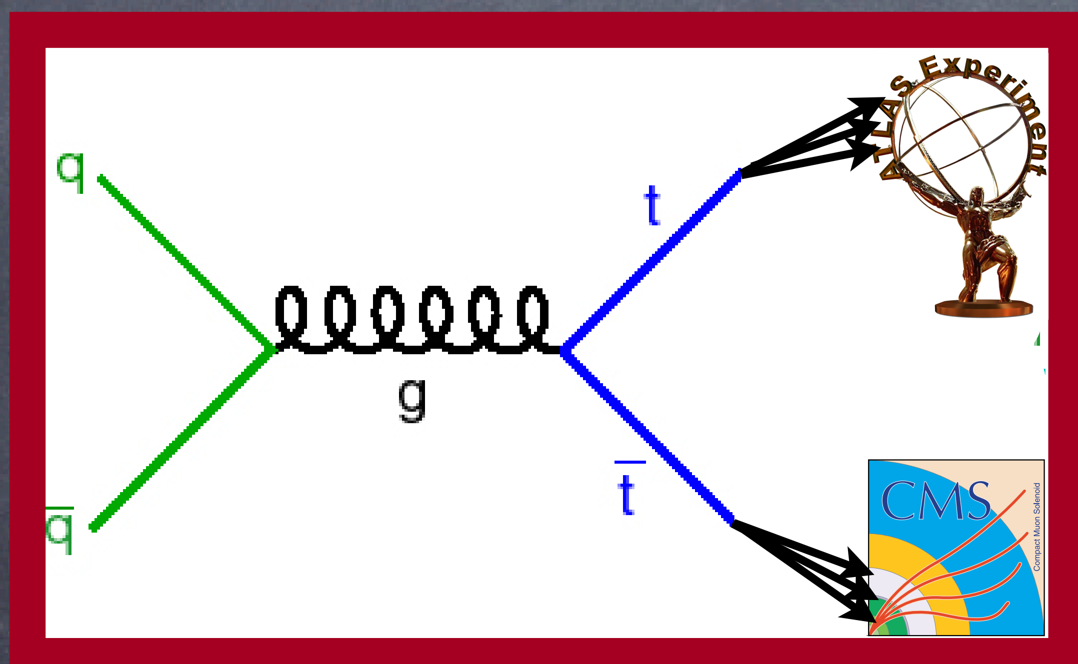
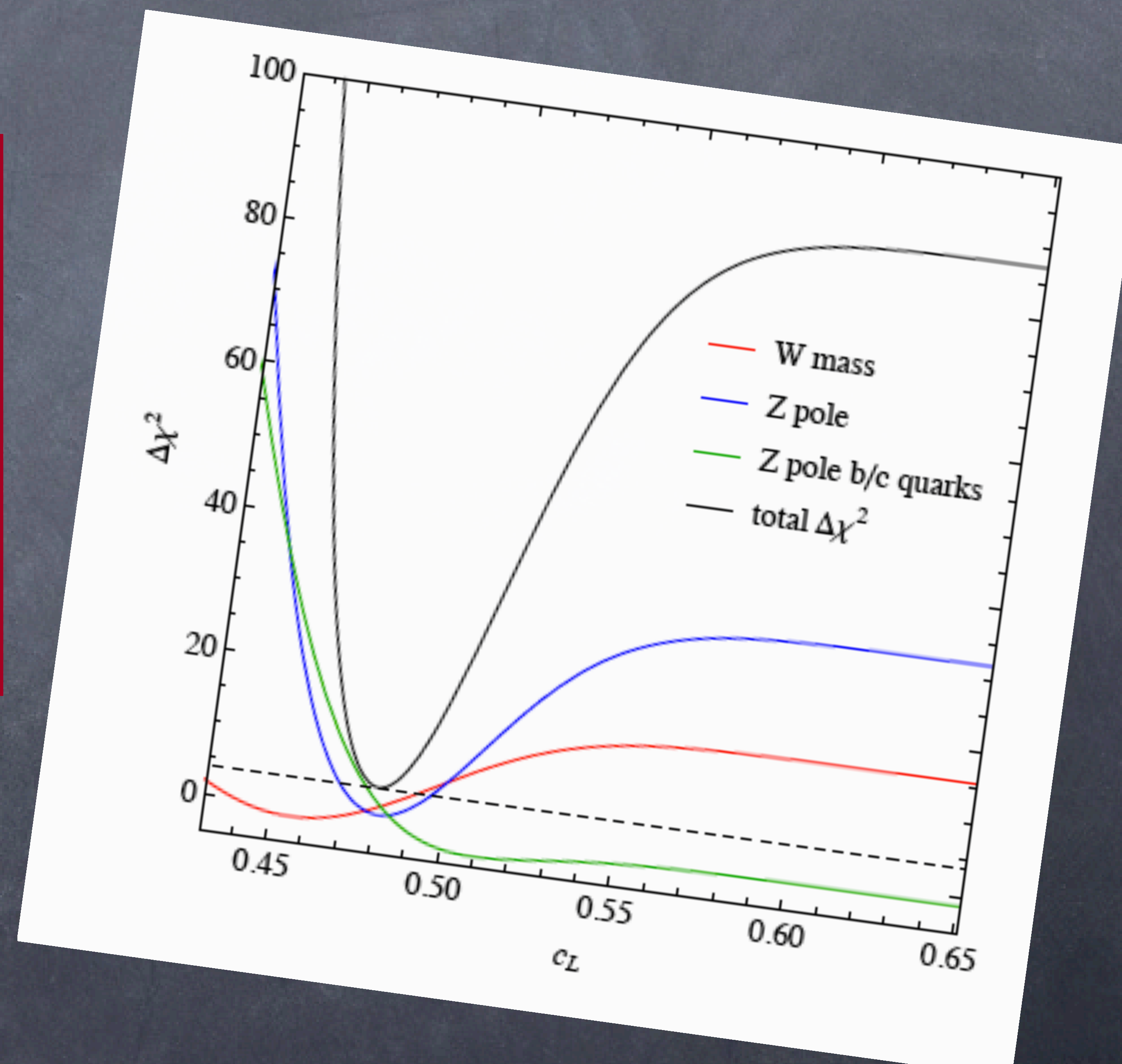


extraordinary pheno' from "flavor triviality" & Improved Naturalness

Delaunay, Gedalia, SJL, Perez & Ponton (10, 11)



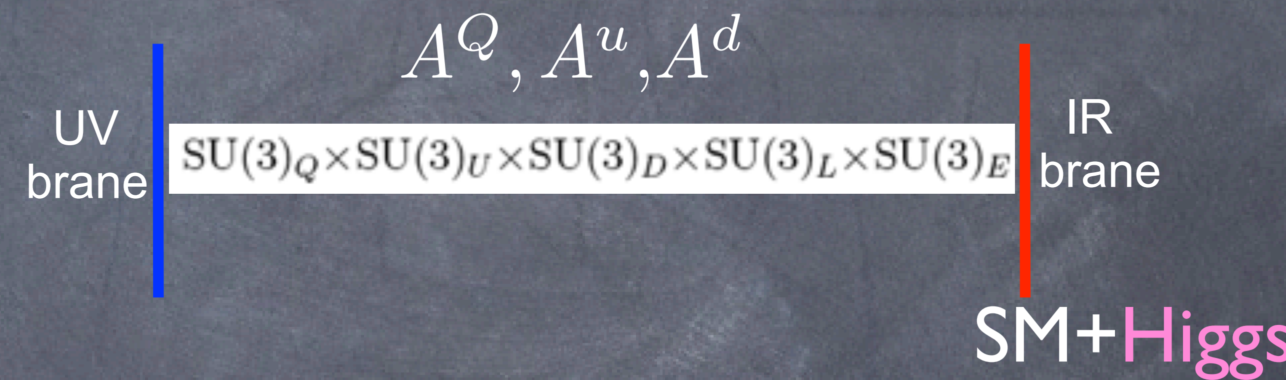


Rattazzi-Zaffaroni model w/ original RS1
(dynamical MFV)

Rattazzi & Zaffaroni (00)

- Basic idea: both the bulk and the IR are flavor conserving, while the UV is flavor violating: only two marginal, flavor violating operators (SM Yukawa couplings): <-> (5D picture) bulk scalars:

gauging flavor symmetries
in the bulk of ED
=> Flavor gauge boson!



- The scalar VEVs give rise to the Yukawa couplings on the IR brane:

$$\phi_u = (3, \bar{3}, 1) \text{ and } \phi_d = (\bar{3}, 1, 3) \quad \text{of } \mathrm{SU(3)}_Q \times \mathrm{SU(3)}_u \times \mathrm{SU(3)}_d$$

$$\bar{Q} H \phi_u u + (u \leftrightarrow d) \qquad \phi_u \sim Y_u, \quad \phi_d \sim Y_d$$

Rattazzi-Zaffaroni model w/ original RS1

(dynamical MFV)

Rattazzi & Zaffaroni (00)

- Basic idea: ... rving,
while the ...
violating ... e)
bulk sca...

gauging ...
in the ... ne

=> Flavor ... SM+Higgs

Simplest setup w/ SM on IR brane
(all of the SM being composite)

No explanation
for the absence of EWP corrections
(why S-parameter is small)
& little hierarchy

- The scalar VEVs give ... plings on the IR brane:

$\phi_u = (3, \bar{3}, 1)$ and $\phi_d = (\bar{3}, 1, 3)$ of $\mathrm{SU}(3)_Q \times \mathrm{SU}(3)_u \times \mathrm{SU}(3)_d$

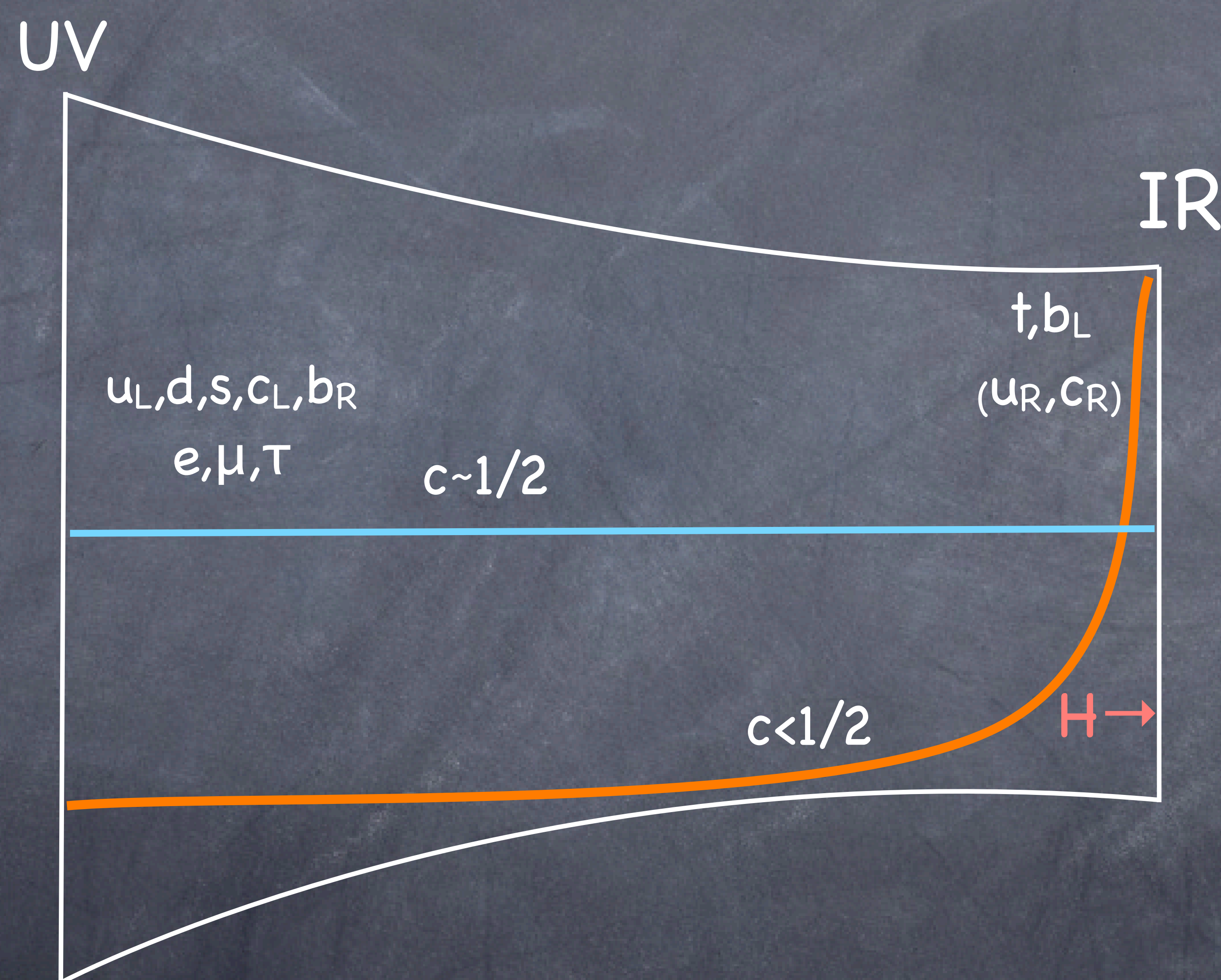
$\bar{Q} H \phi_u u + (u \leftrightarrow d)$

$\phi_u \sim Y_u, \quad \phi_d \sim Y_d$

Flavor Triviality

Delaunay, Gedalia, SJL, Perez & Ponton (10,11)

- giving-up on flavor puzzle solution:
  Generalization of RZ model w/ SM into 5D bulk
  (anomaly mediation, gauge mediation)



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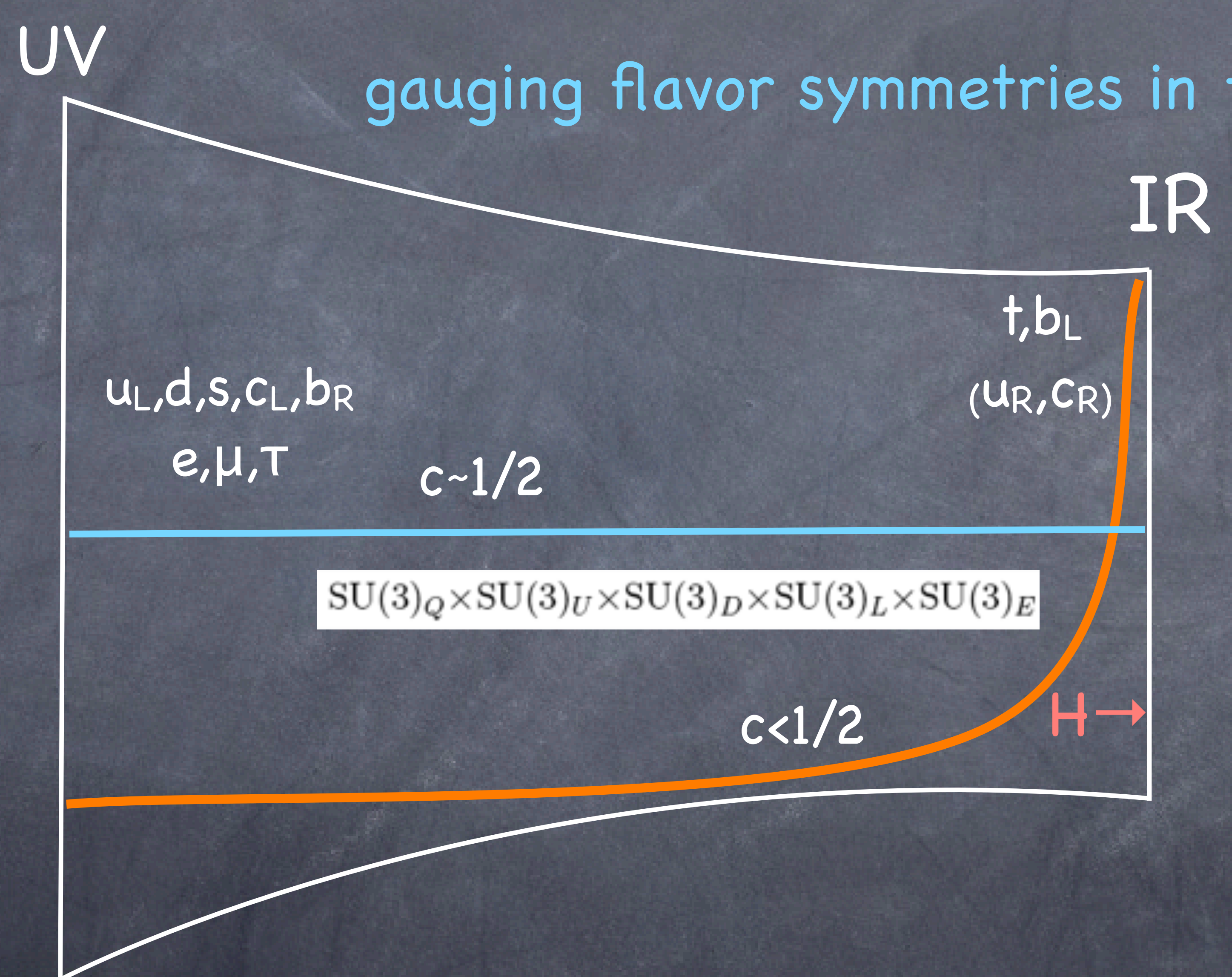

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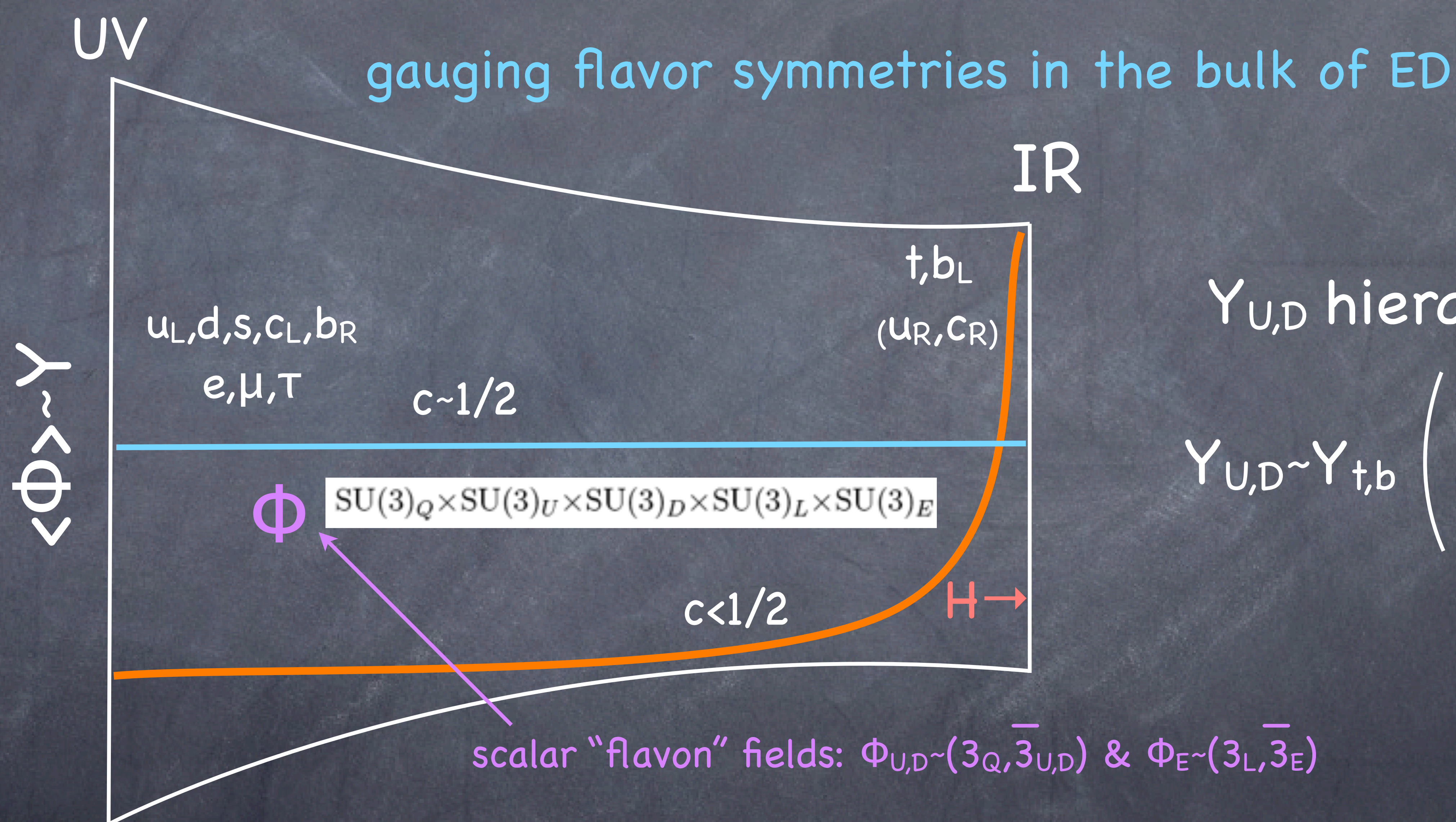

$Y_{U,D}$ hierarchical

$$Y_{U,D} \sim Y_{t,b} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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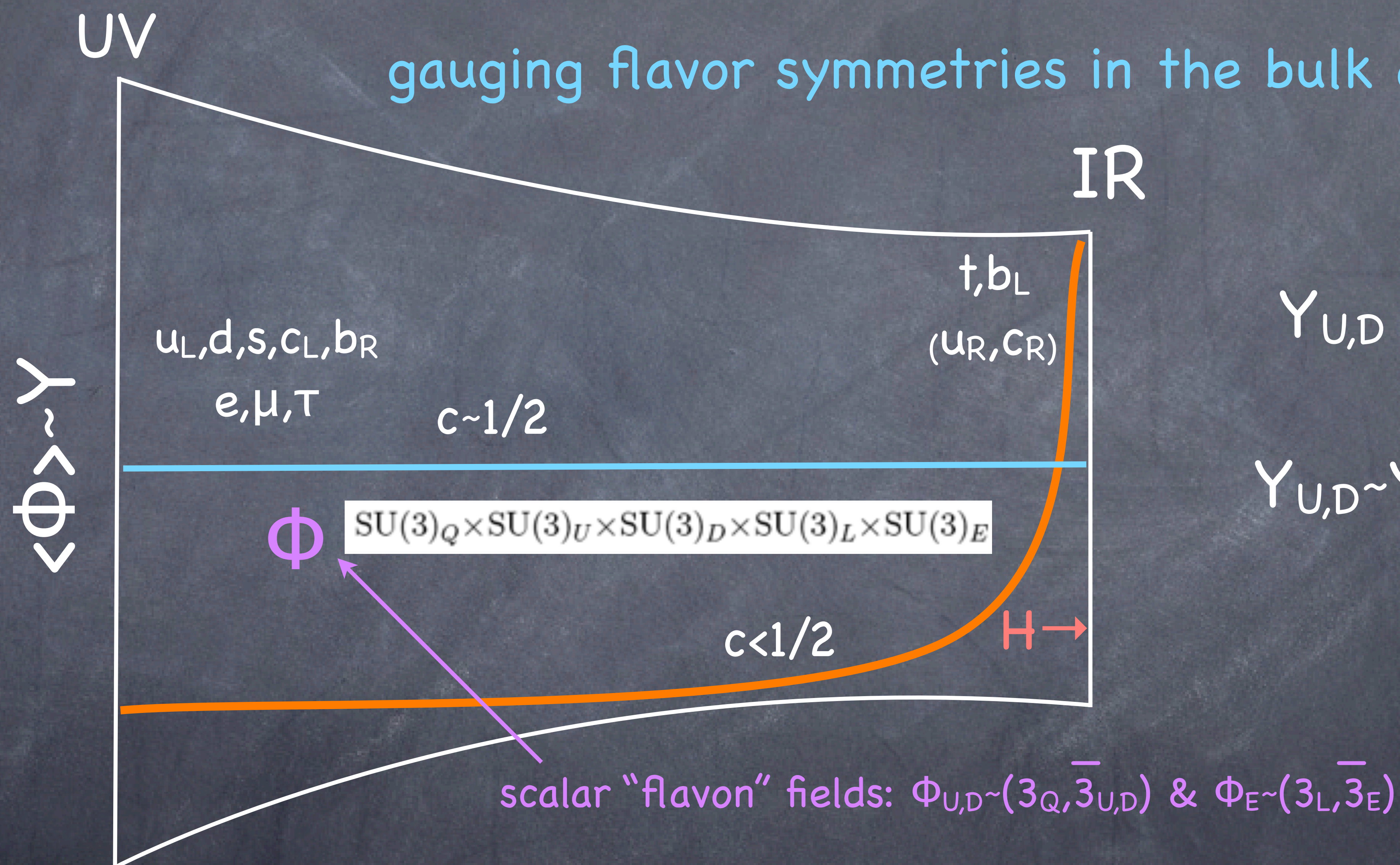

$Y_{U,D}$ hierarchical

$$Y_{U,D} \sim Y_{t,b} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- SM flavor puzzle solution postponed to the UV:
  $G_F \to$ approx. $SU(2)_Q \times SU(2)_U \times SU(2)_D \times SU(3)_L \times SU(3)_E$

- hierarchical Y "shined" to the IR by the Φ's

Flavor Triviality

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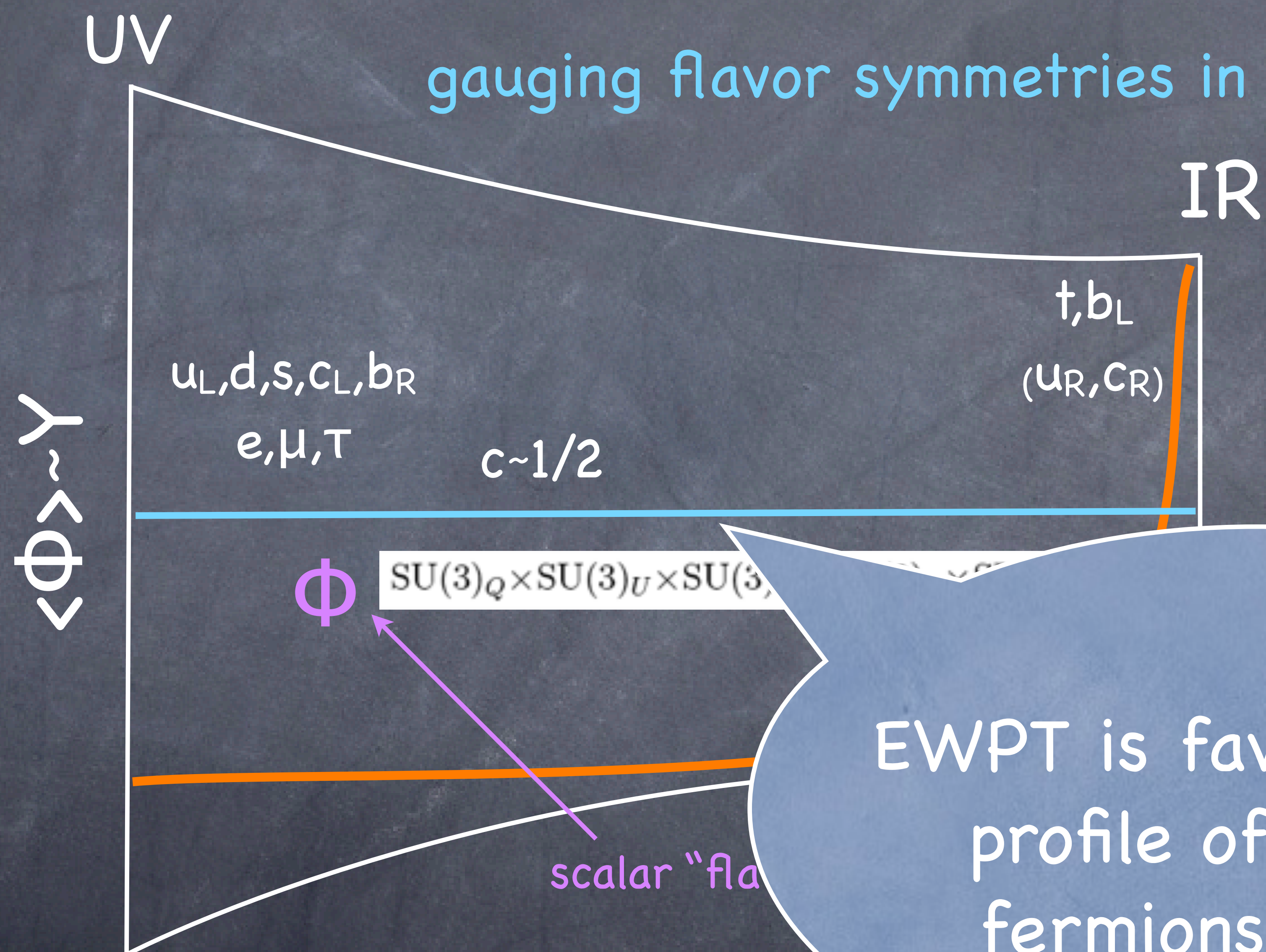

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EWPT is favored by flat profile of the light fermions (S_{tree} ~0)

- SM flavor puzzle solution postpo…
  $G_F \to$ approx. $SU(2)_Q \times SU(2)_U \times SU(2)_D$ […] $(3)_E$

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Electroweak Precision Test

- $O_{LEP} \approx \langle O \rangle_{SM} (1+\delta_{NP}) \to |\delta_{NP}| < 10^{-3}$ (precision tests!)
- Naturalness: $\Lambda_{NP} \sim$ TeV → EFT
- 20 (D=6) operators "measured" @LEP1+2:

(i) gauge prop. : $B_{\mu\nu} H^{\dagger} W_{\mu\nu} H$, $|H^{\dagger} D_{\mu} H|$ (→ S,T)

(ii) vertex corr. : $(\bar{f}\gamma^{\mu} f) H^{\dagger} D_{\mu} H$, $(\bar{f}\sigma^{a}\gamma^{\mu} f) H^{\dagger}\sigma^{a} D_{\mu} H$ ($Z \to ff$)

(iii) 4ψ: $(\bar{f}_1 \gamma^{\mu} f_1)(\bar{f}_2 \gamma^{\mu} f_2)$, $(\bar{f}_1 \sigma^{a}\gamma^{\mu} f_1)(\bar{f}_2 \sigma^{a}\gamma_{\mu} f_2)$ ($ee \to ff$)

(+3rd gen. quark effects: $U(3)_3 \to U(2)_3 \times U(1)_3$)

Electroweak Precision Test

- EWPT fitting procedure:

i) matching UV physics to L_{eff}

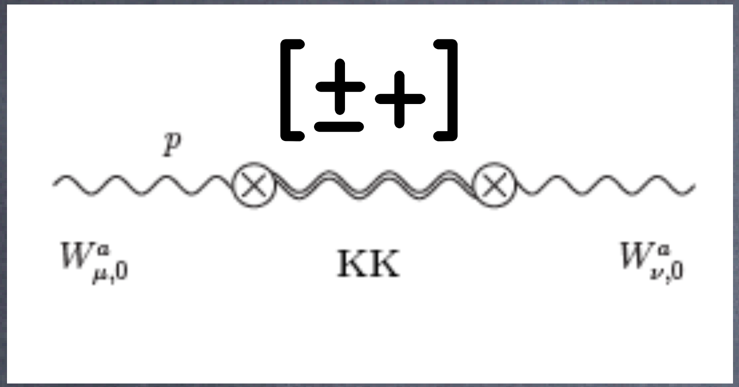
ii) constraints fundamental parameters (Λ_{NP},...) with χ^2-like analysis

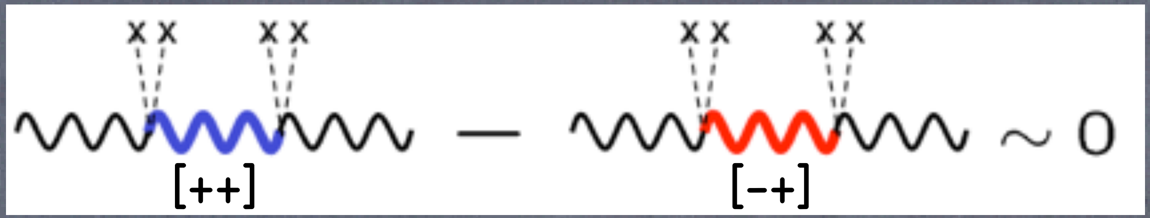
$$\chi^2=\Sigma_{ij}\,(<O>-O_{LEP})_i\,(\sigma^2)^{-1}_{ij}\,(<O>-O_{LEP})_j$$

Tree level EWPOs

Agashe, Delgado, May, Sundrum

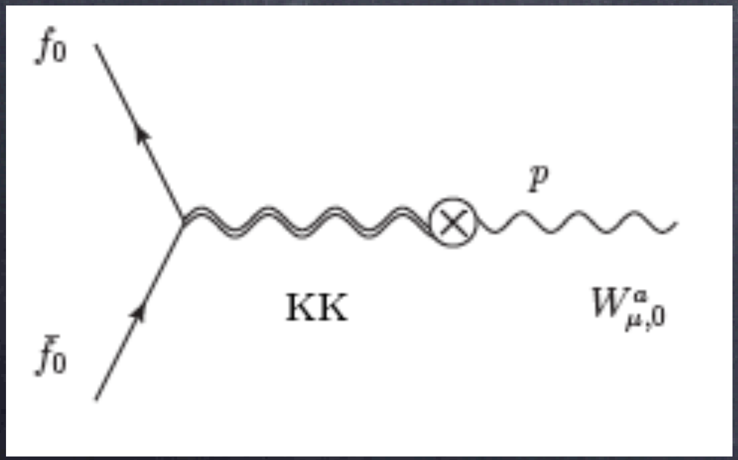
- Custodial symmetry: Avoid large corrections to the Mz/Mw ratio (T parameter): $SU(2)_L$ X $SU(2)_R$

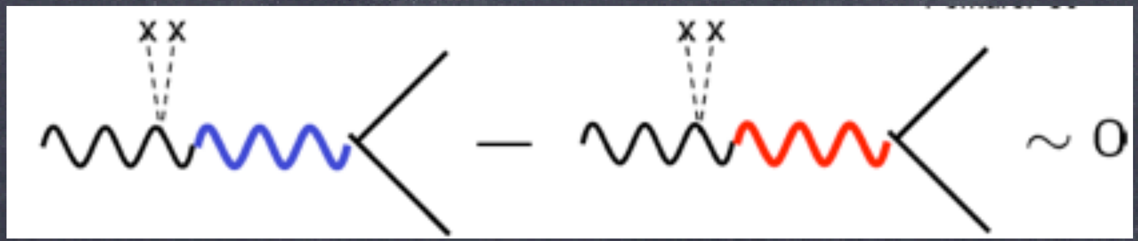




Agashe, Contino, DaRold, Pomarol

- To avoid Large corrections to Zbb coupling, δg_{bL}: impose discrete LR symmetry with $SU(2)_L$ X $SU(2)_R$





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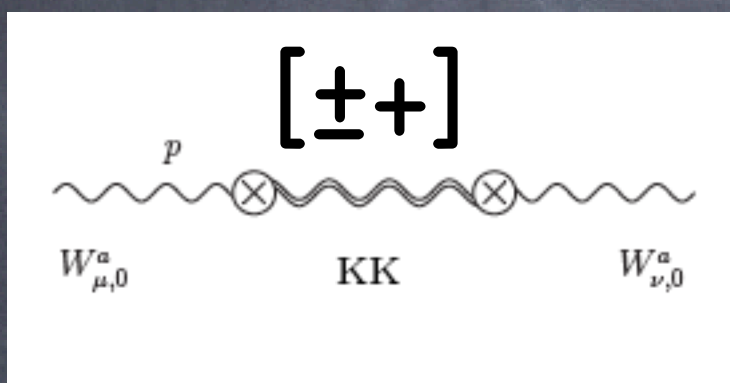

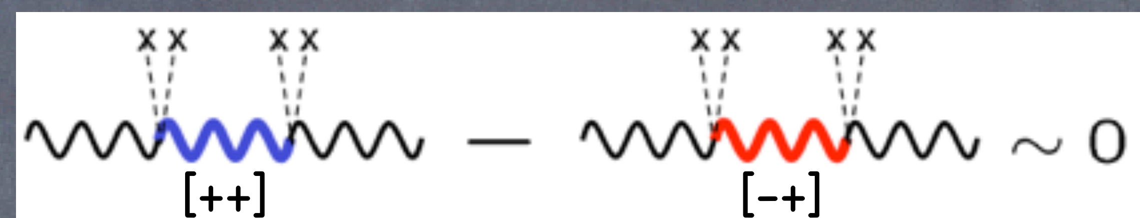

symmetry works for both anarchic and flavor trivial models

Agashe, Contino, DaRold, Pomarol

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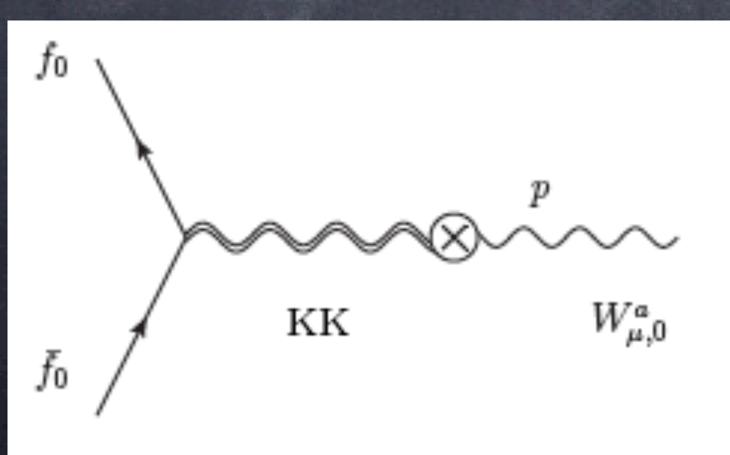
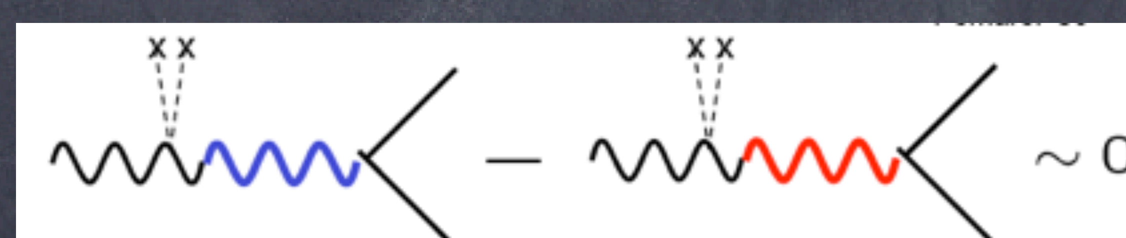
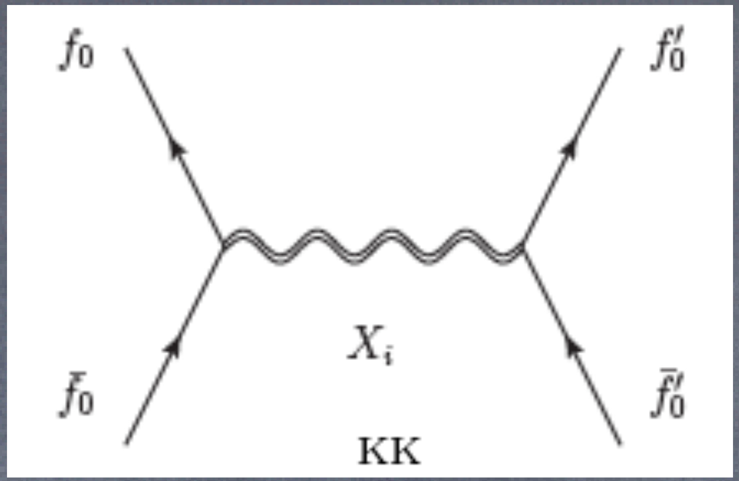




Tree level EWPOs

- 4-fermion operators involving light fermions

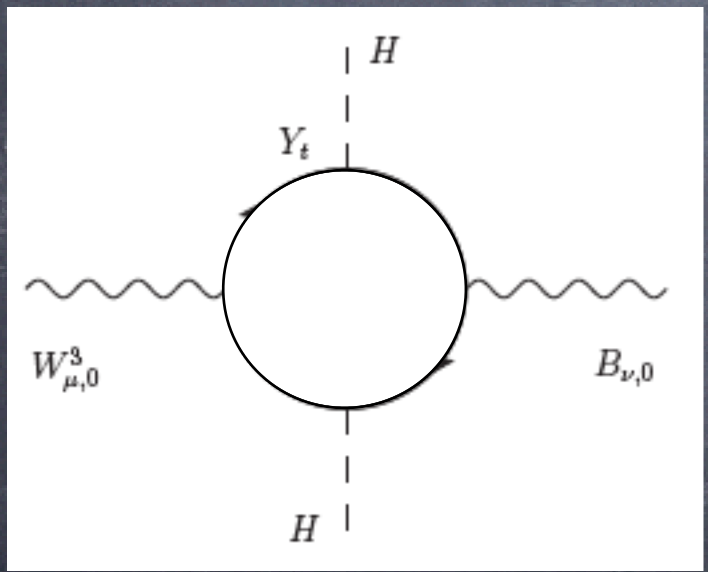


- Anarchic RS: negligible due to small wave function overlap between KK GB and light elementary fermions => fit for "oblique parameters" (S,T,U) + δg_{bL}

- FT RS: 4-fermion operators become important (large non-oblique corrections) => one must look at more than O(35) EWPOs in order to assess whether EWPTs are passed

Radiative corrections to EWPOs

- Loop corrections are important:
  - T & δg_{bL} are finite to all orders (custodial $SU(2)_V \times P_{LR}$)
  - S is finite at 1-loop in 5D for bulk Higgs



5D NDA

$$g_5^2 \quad Y_5^2 \quad B_{\mu\nu} \quad W^{\mu\nu} \quad H^2 \sim \quad \text{finite}$$

(-1)+ (-1)+ 5/2 + 5/2 + 3 = 6

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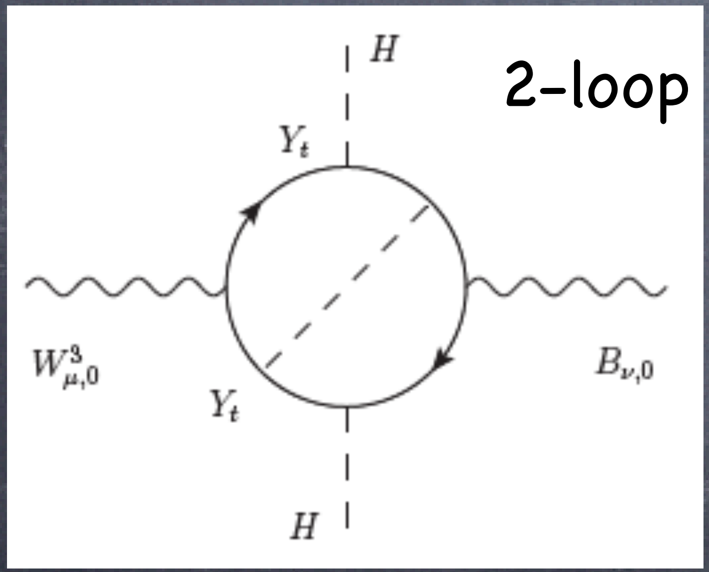

5D NDA

$$g_5^2 \quad Y_5^4 \quad B_{\mu\nu} \quad W^{\mu\nu} \quad H^2 \sim \quad Log \Lambda_5$$

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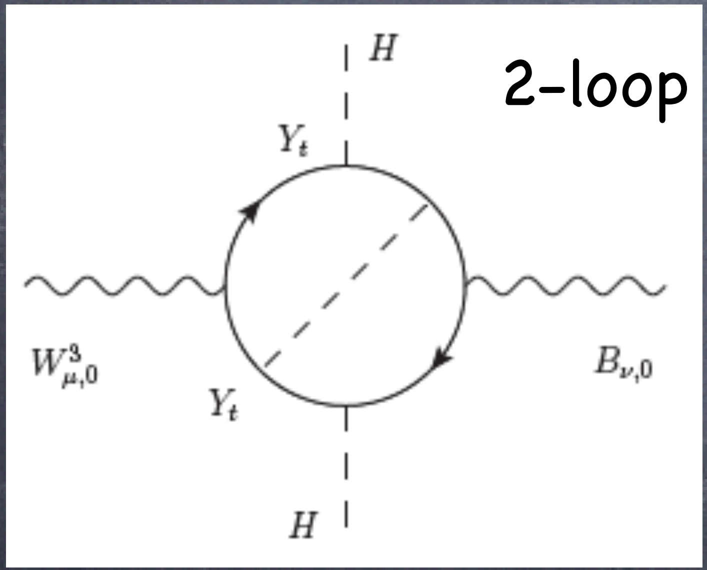

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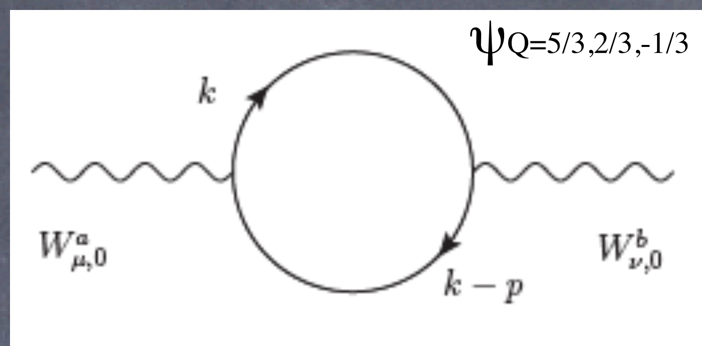
- 2-loop corrections are suppressed for purtabative Y_t and Y_b (less than 20%)
- Higher-loop corrections are more suppresed by NDA expansion $(Y^2\Lambda_5/16Pi^2)<1$

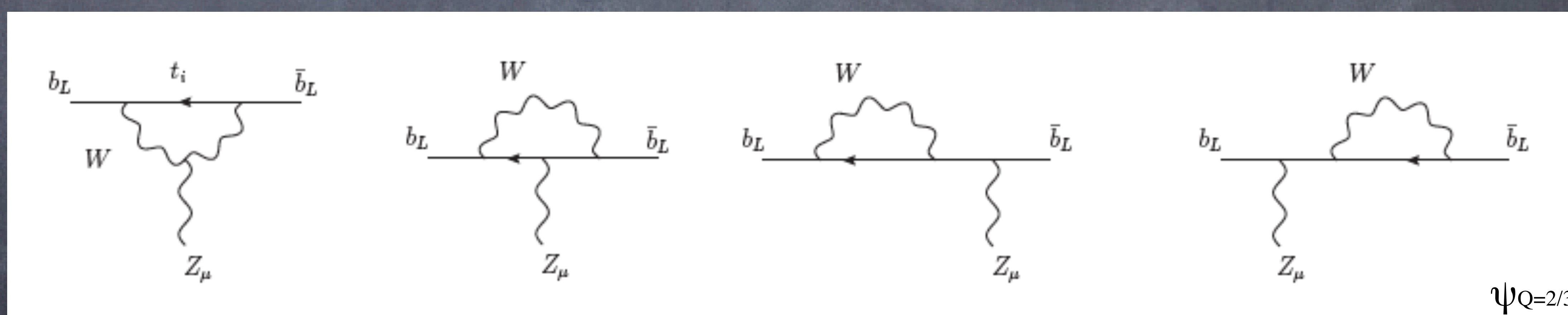
Wednesday, April 13, 2011

Radiative corrections to EWPOs

(i) S,T



(ii) $Z \to b_L b_L$



χ^2 global fit results

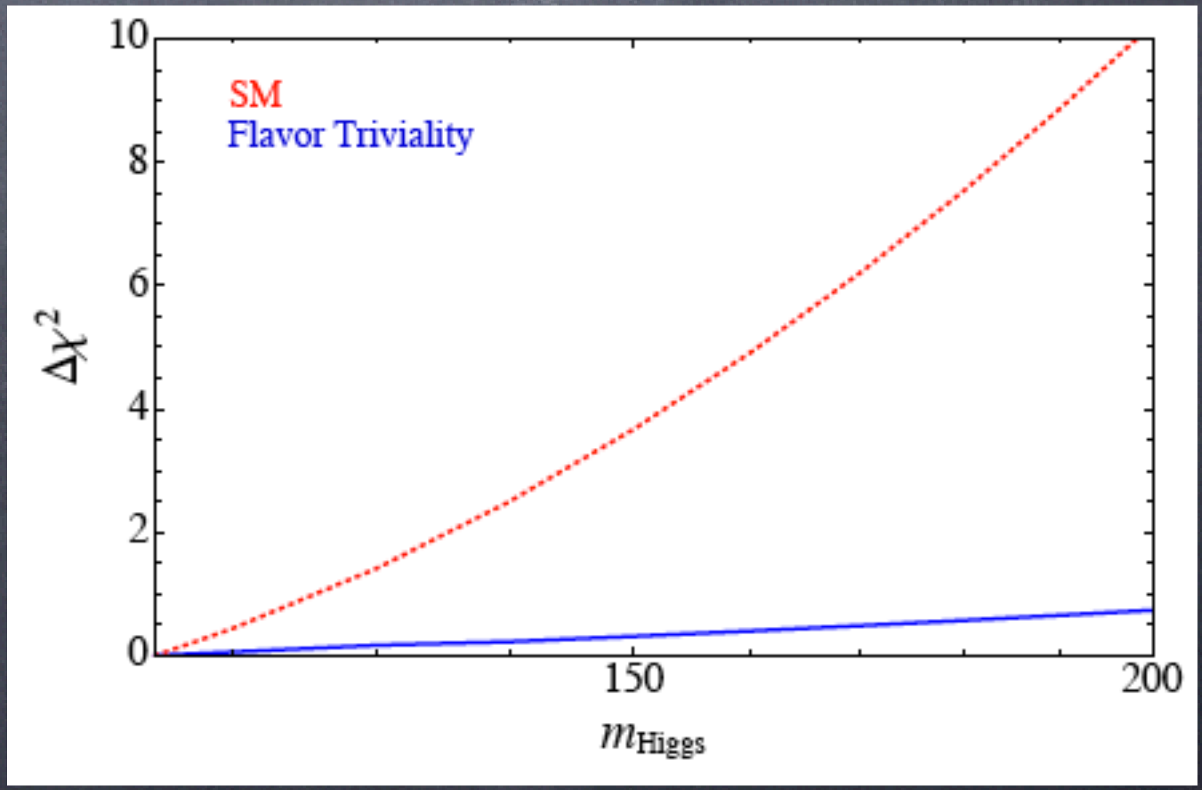
- we (re)did the EWPT fit for anarchic RS (most precise to date): @2σ: m_{KK} >4.6 (3.9) TeV for 1(3) d.o.f.

is the celebrated anarchic RS model visible @ LHC?

- Flavor Triviality fit: m_{KK}, c_t, c_b, c_{Q3}, c_{Qi}, c_{ui}, c_{di}, c_L, c_e : @2σ: m_{KK} >2.1 (1.7) TeV for 1(6 important d.o.f.s) d.o.f.

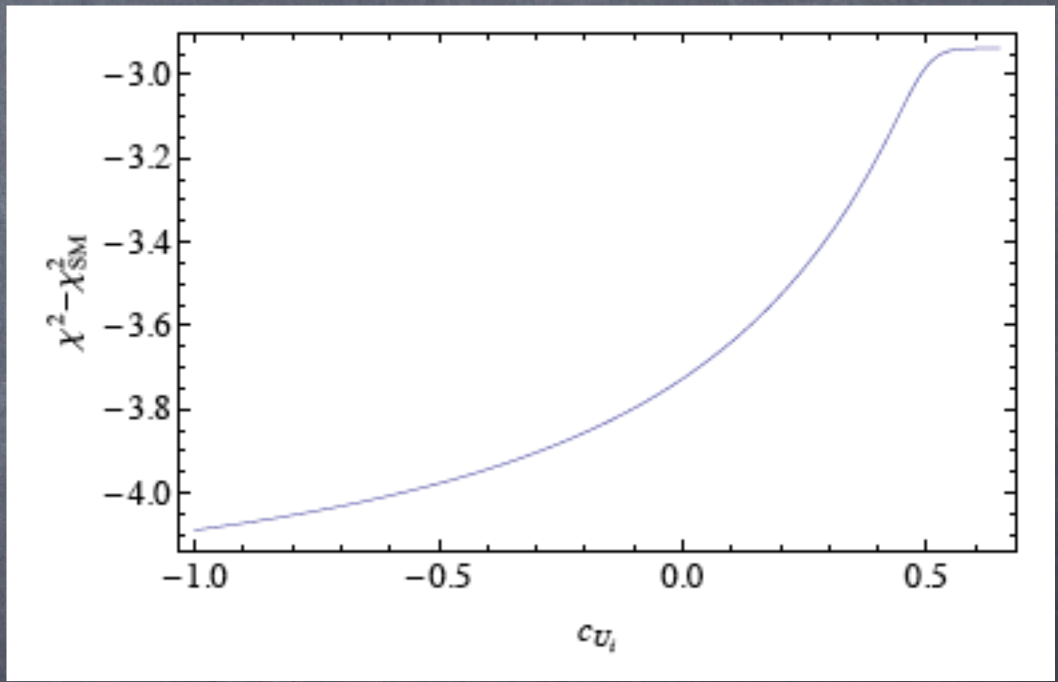
$(\chi^2/\text{dof})\text{SM} = 219.9/232 \sim 0.95 < (\chi^2/\text{dof})\text{FT RS} = 217.3/223 \sim 0.97$

- We find FTRS provides a better fit than SM (with m_{KK}=3.9TeV)
- We find fit depends only mildly on the Higgs mass => large Higgs mass values are still compatible with the model, without spoiling the EW fit



χ^2 global fit results

- slight preference of u_R being composite (localize towards IR brane)
- w/ sweet-spot parameters:
  - $CQ \simeq (0.50, 0.50, 0.02)$
  - $CD \simeq (0.63, 0.63, 0.57)$
  - $CU \simeq (0.15, 0.15, 0.48)$
  - $\alpha_U Y_U \simeq (4.3\times10^{-5}, 0.021, 4.2)$
  - $\alpha_D Y_D \simeq (0.01, 0.19, 0.45)$.



with $\alpha_{U,D} \simeq 4, 0.12$,

$Y_b^2 >> Y_t^2$

down alignment: $[m_D, Y_D] \simeq 0$

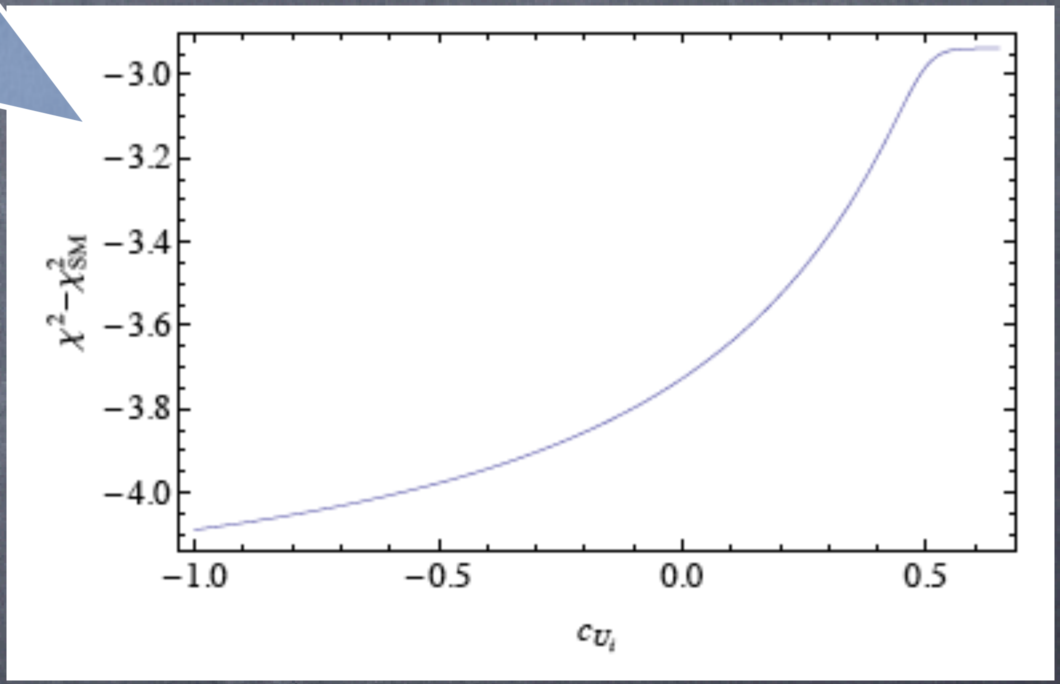
Flavor physics is decoupled!

χ^2 global fit results

- slight … composite (localize
  towa…

composite u_R => exciting
collider phenomenology,
with no flavor constraint

- w/ sweet-sp… …ers:
  - CQ ≃ (0.50, 0.50, 0.02)
  - CD ≃ (0.63, 0.63, 0.57)
  - CU ≃ (0.15, 0.15, 0.48)
  - $\alpha_U Y_U$ ≃(4.3x10^{-5}, 0.021, 4.2)
  - $\alpha_D Y_D$≃(0.01, 0.19, 0.45).



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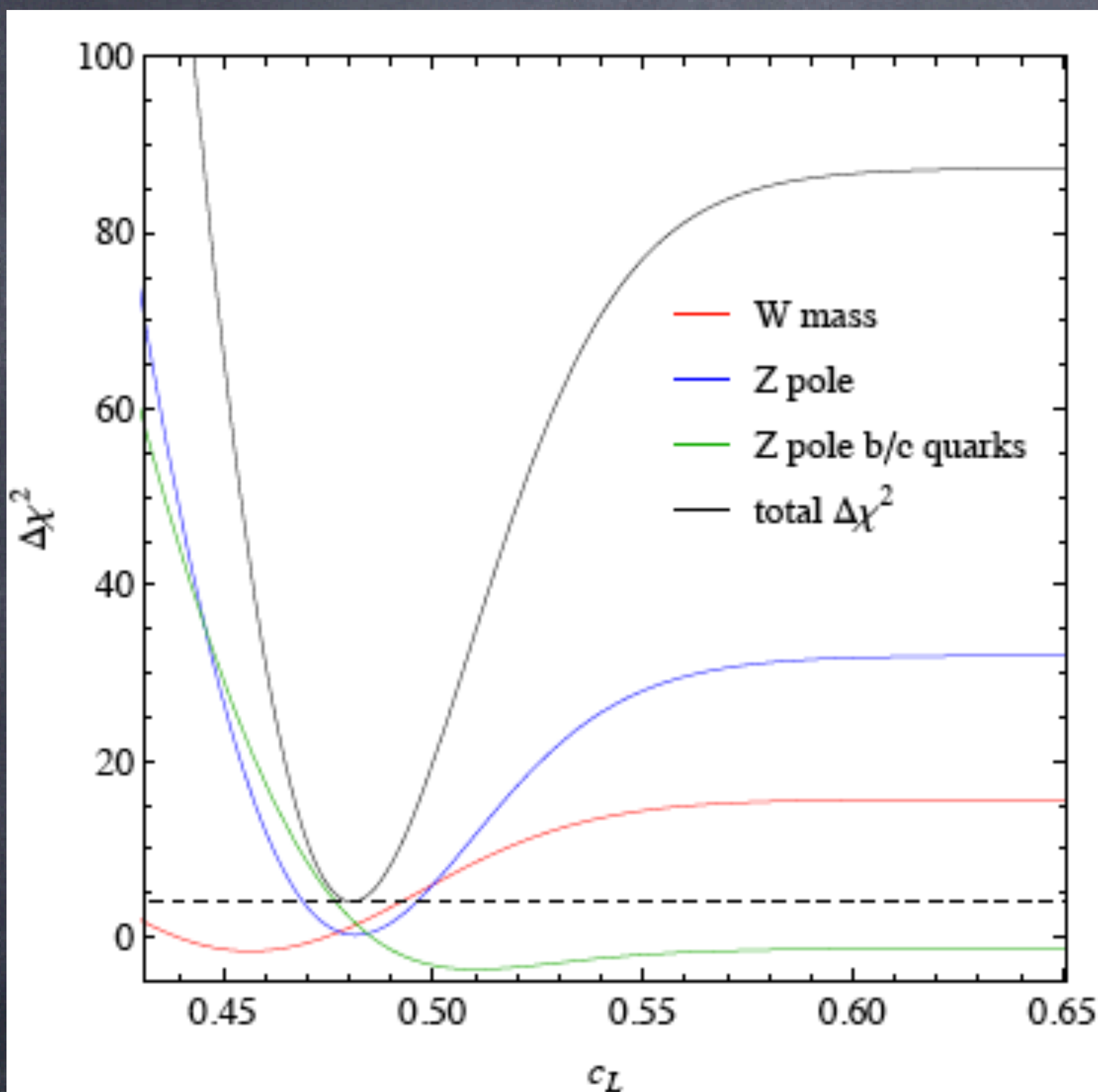
$Y_b^2 \gg Y_t^2$
down alignment: $[m_D, Y_D] \simeq 0$
Flavor physics is decoupled!

χ^2 global fit results

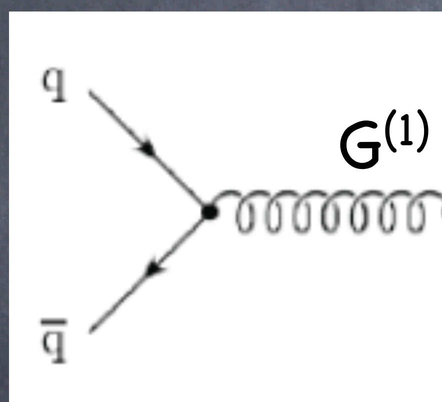


	$\chi^2 - \chi^2_{\mathrm{SM}}$	$\chi^2_{\mathrm{min}} - \chi^2_{\mathrm{SM}}$	$\Delta\chi^2$
W mass	1.37	0.12	1.25
Z line shape & lepton A_{FB}	−2.47	−2.74	0.27
Z pole b&c quarks	5.30	3.45	1.85
Leptonic polarization asymmetries	0.20	0.23	−0.04
s^2_W hadronic charge asymmetry	−1.95	−2.18	0.23
Deep Inelastic Scattering	−0.13	−0.12	$< 10^{-2}$
Atomic Parity Violation	3.23	0.11	3.12
LEP2 hadronic cross-section	−1.97	−0.97	−1.00
LEP2 muon pair	$< 10^{-2}$	0.03	−0.03
LEP2 tau pair	−0.04	−0.03	−0.01
OPAL electron pair	−0.02	−0.02	$< 10^{-2}$
L3 W pair	−0.17	−0.11	−0.06
Z pole s quark	0.07	0.09	−0.02
LEP2 ee→bb	−3.22	−1.75	−1.48
LEP2 ee→cc	−0.18	−0.08	−0.10
total	0.02	−3.98	4

Interplay between Flavor Physics & Collider (top) Physics

FT RS is ultra visible

- generic RS signature: KK gluon production (& FGB for FT model)



$$= g^* \left(\frac{1}{k\pi r_c} - f_{c_q}^2 \right)$$

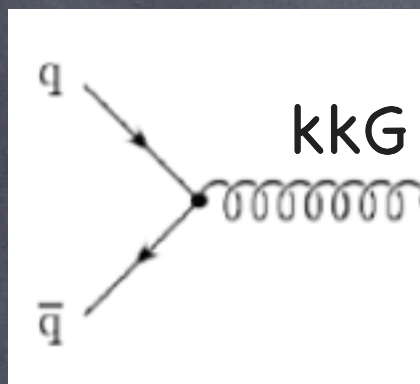
→ suppressed in anarchic RS (only through "γ-ρ mixing")

→ O(1) x g^* for FT RS

$$f_c^2 \approx \begin{cases} 1-2c \ (c<1/2) \\ 1/k\pi r_c \ (c\approx 1/2) \\ (2c-1)\exp[-(2c-1)\, k\pi r_c] \ (c>1/2) \end{cases}$$

- 7(14)TeV LHC : $\sigma_{KK} \approx$ 0.04(6)fb in anarchic RS w/ m_{KK}=4.6TeV
- 7(14)TeVLHC : $\sigma_{KK} \approx$ 3(500)pb in FT RS w/ m_{KK}=2.1 TeV (mainly due to composite u_R, and also due to low m_{KK})

RS KKG and forward-backward asymmetry



$$g^*\gamma^\mu(v_q + \gamma_5 a_q)$$

→ $a_{u,d} \approx 0$ in anarchic RS

→ $a_u \approx O(1)$ in FT RS

Agashe, Belyaev, Krupovnickas, Peres & Virzi (06); Bauer, Goertz, Haisch, Pfoh & Westhoff (10).

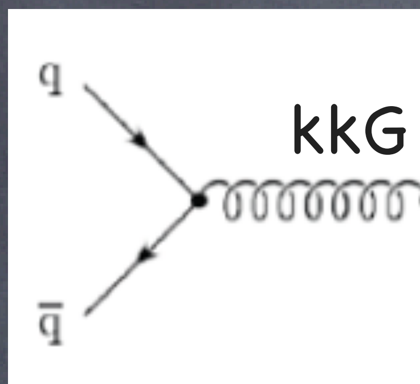
- Anarchic models => tiny effect (vectorial & suppressed production couplings).

$\sigma^{NP}/\sigma^{SM}(p_T>400\mathrm{GeV})$: 2~3

$$v_q \equiv -\frac{1}{\xi} + \frac{1}{2}(f_{qL}^2 + f_{qR}^2)\,, \quad a_q \equiv \frac{1}{2}(f_{qL}^2 - f_{qR}^2)$$

ξ ↘ $k\pi R \sim \log(M_{Pl}/\mathrm{TeV})$

RS KKG and forward-backward asymmetry



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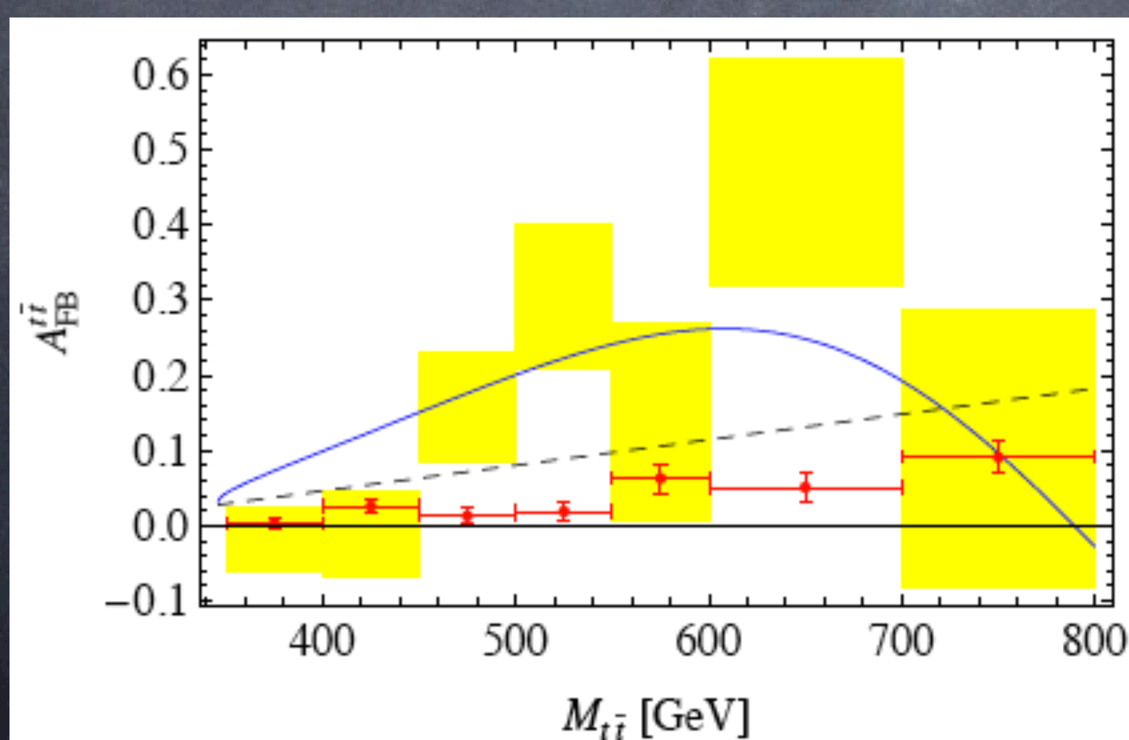
- Anarchic models => tiny effect (vectorial & suppressed production couplings).
- FT models: **Delaunay, Gedalia, SJL, Perez & Ponton (11)**



$$\beta_t \equiv \sqrt{1 - 4m_t^2/\hat{s}}$$

$$\hat{A} \propto \beta_t \hat{s} \left|\mathcal{D}\right|^2 a_t a_q g_{s*}^2 \left[g_s^2(\hat{s} - m_{\rm KK}^2) + 2g_{s*}^2 \hat{s} v_t v_q\right]$$

$$A^{t\bar{t}}(M_{t\bar{t}} > 450GeV) = 0.19$$ ~2σ

$$A^{t\bar{t}}(|\Delta y| > 1) = 0.24$$

$$A^{t\bar{t}} = 0.118$$

$\sigma^{NP}/\sigma^{SM}(p_T{>}400GeV)$: 2~3

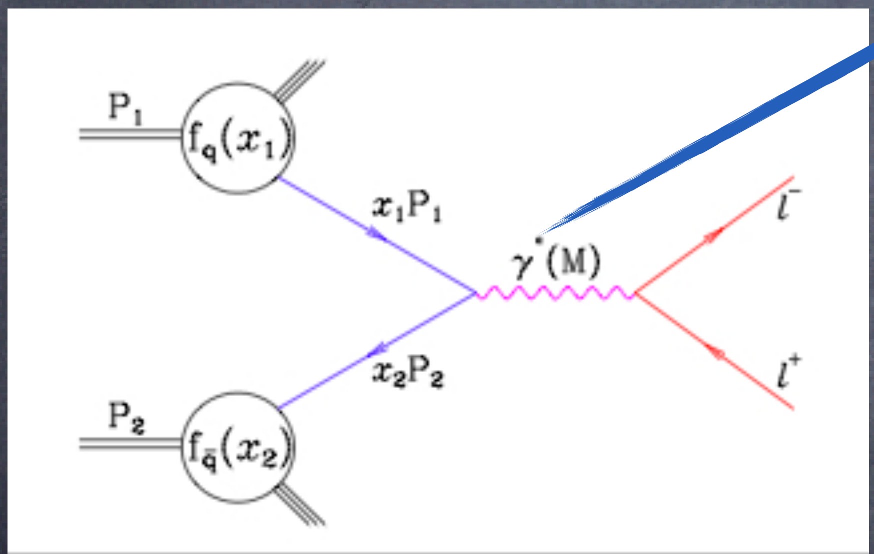
$$v_q \equiv -\frac{1}{\xi} + \frac{1}{2}(f_{qL}^2 + f_{qR}^2), \quad a_q \equiv \frac{1}{2}(f_{qL}^2 - f_{qR}^2)$$

$k\pi R \sim \log(M_{Pl}/\text{TeV})$

Flavor Gauge Bosons @ LHC

Csáki, Kagan, SJL, Perez & Weiler (in preparation)

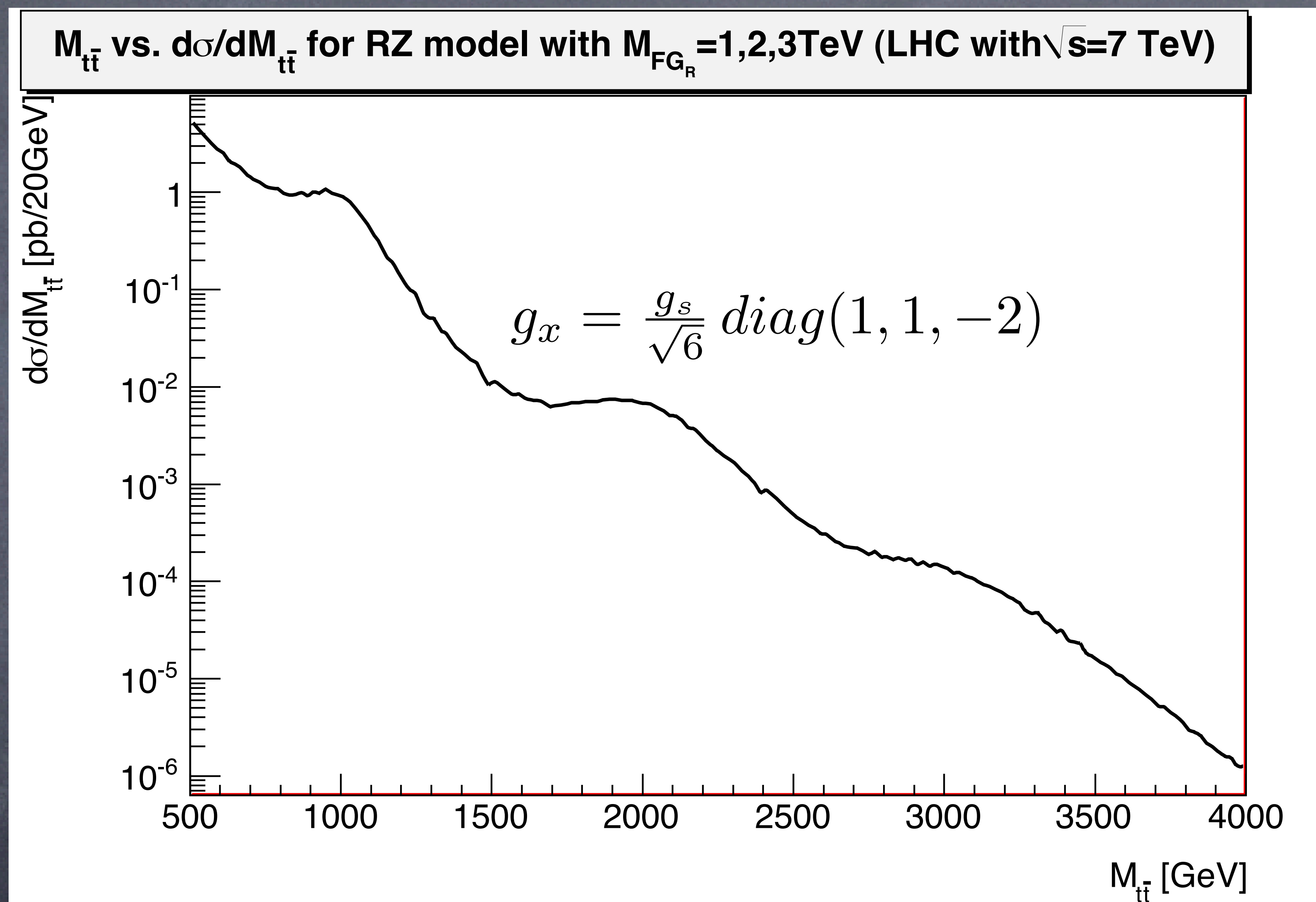
$$g_{eff} G_\mu^{(1)KK} \bar{\psi}\psi$$



- Flavor gauge bosons do not have massless modes (flavor is broken)
- no γ – ρ mixing !
- But quark composite mixing can be flavor universal & large
- with BKT, it is possible to have $m_{FGB} < M_{KK}$

FGBs at the LHC (preliminary)

- The flavor gauge bosons & scalars might be observable.



$$\begin{aligned}\mathcal{L} &= \frac{\lambda}{2} V_\mu^8 \left(\frac{1}{\sqrt{3}} \bar{u}_R \gamma^\mu u_R + \frac{1}{\sqrt{3}} \bar{c}_R \gamma^\mu c_R - \frac{2}{\sqrt{3}} \bar{t}_R \gamma^\mu t_R \right) \\ &+ \frac{\lambda}{2} \left((V_\mu^4 - i V_\mu^5) \bar{u}_R \gamma^\mu t_R + (V_\mu^6 - i V_\mu^7) \bar{c}_R \gamma^\mu t_R + h.c. \right)\end{aligned}$$

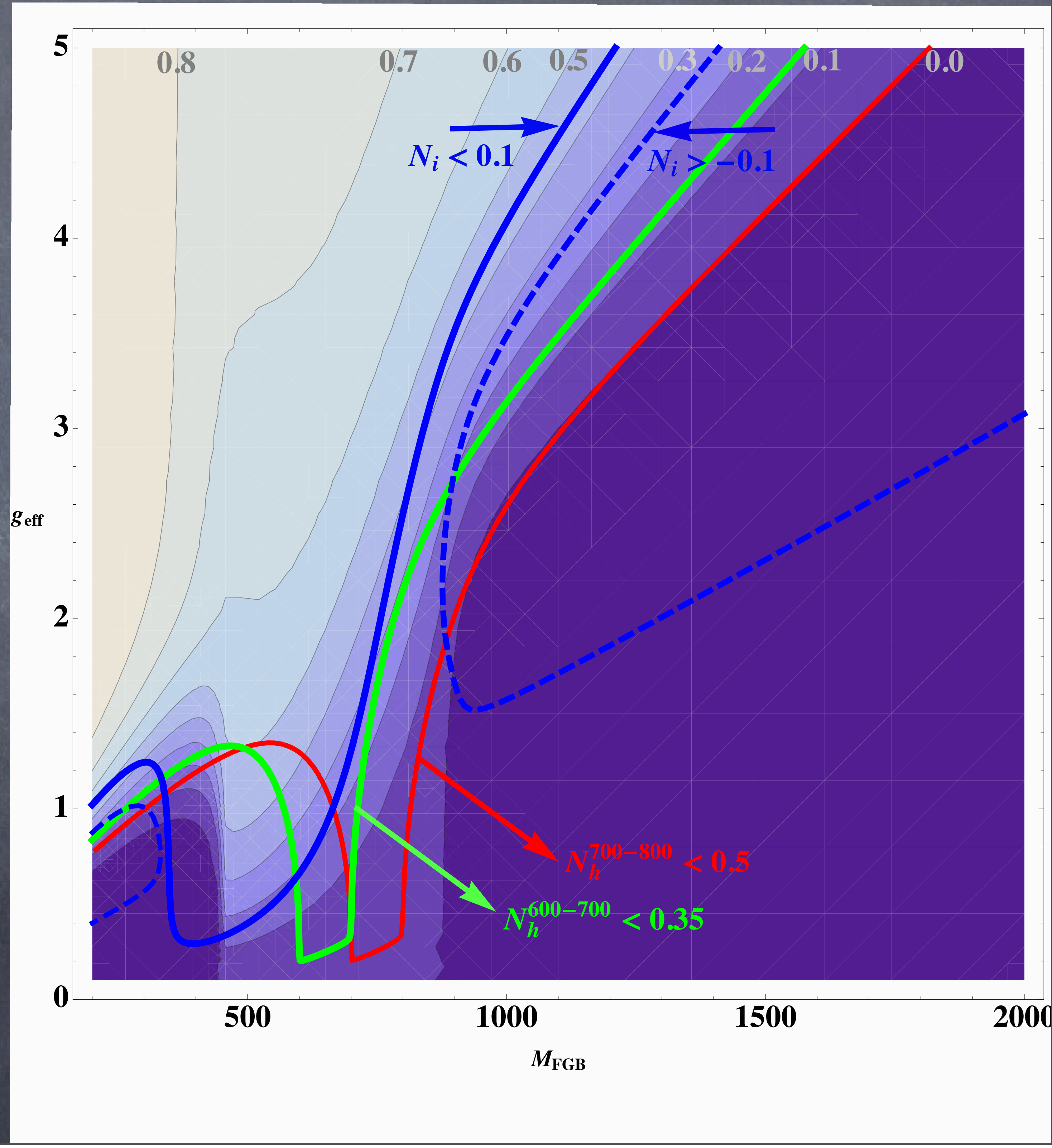
Flavor Gauge Boson @ Tevatron?

$$\mathcal{L} = g_{eff}\bar{u}_R V_\mu^A \frac{T^A}{2}\gamma_\mu u_R + h.c.$$

- Can partially explain A_{FB} with the usual constraints:

i) $\delta\sigma^{\rm NP}_{700-800\,{\rm GeV}}/\sigma^{\rm SM}_{700-800\,{\rm GeV}} \lesssim 47\%$

ii) $\delta\sigma^{\rm NP}_{t\bar{t}}/\sigma^{\rm SM}_{t\bar{t}} \lesssim 10\%$



- M_{FGB} <900 GeV, g_{eff} ~O(1)

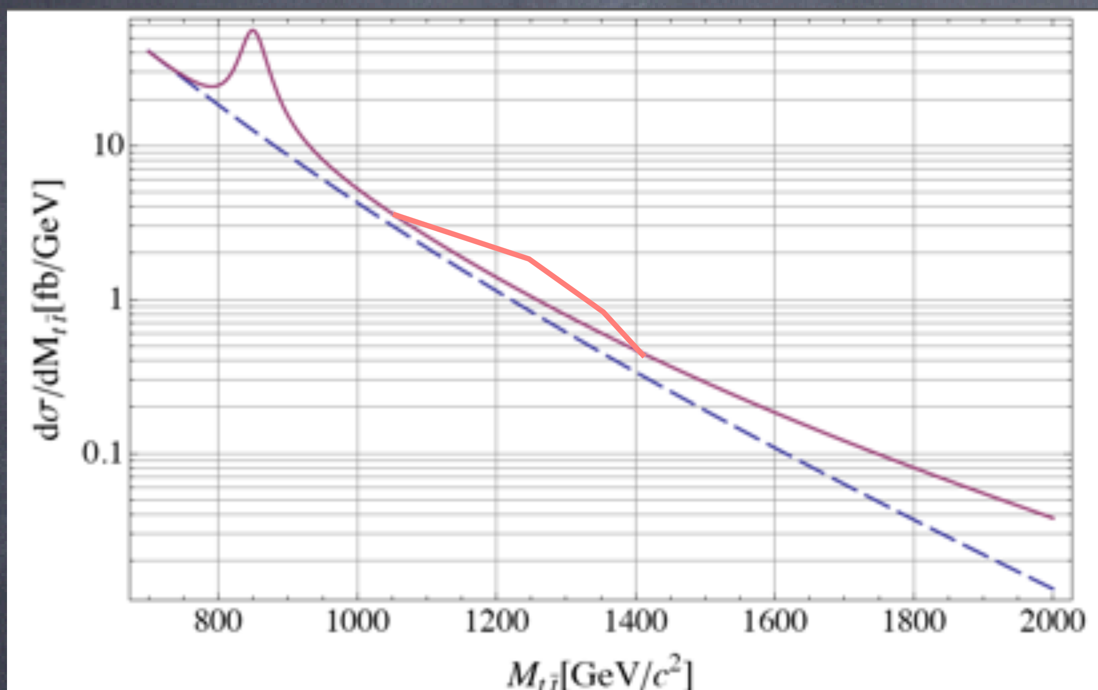
$A_{FB}^{t\bar{t}}(M_{inv} > 450GeV) \lesssim 10\%$

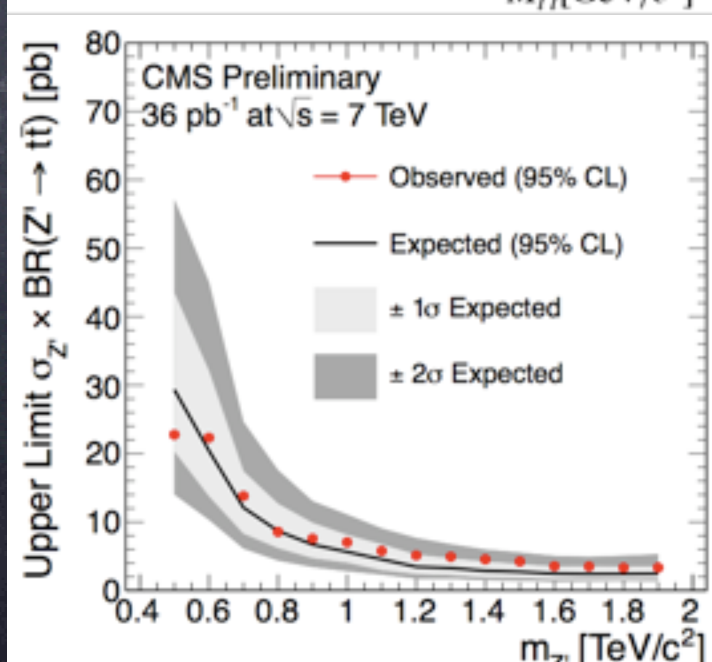
- σ_{NP}/σ_{SM}(pT>400GeV): 2-3

Signals and Constraint for A_{FB} sweet spot (Preliminary)

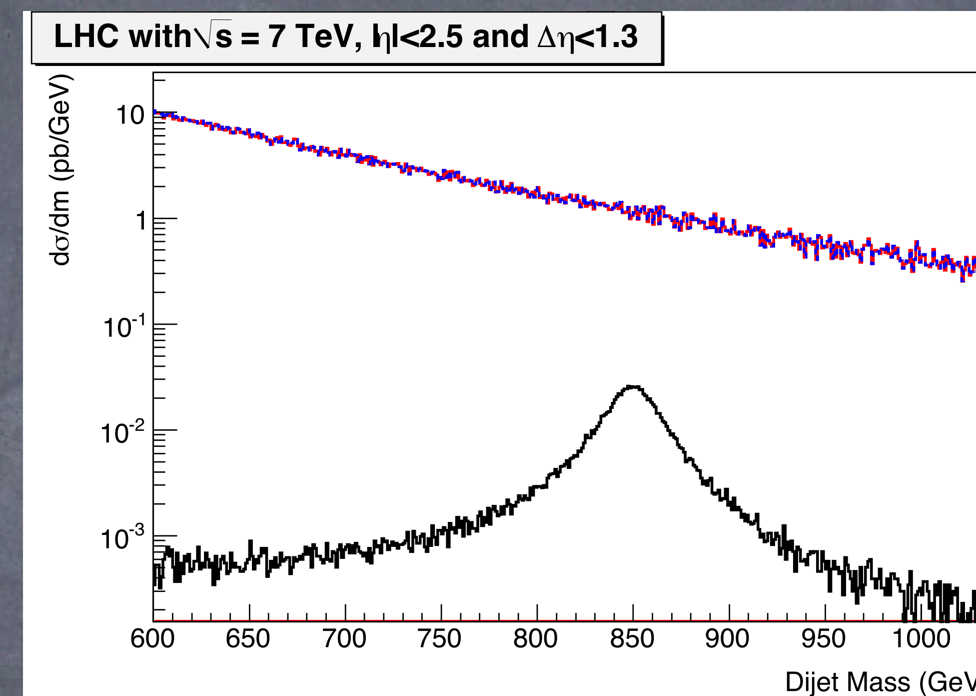
M_{FGB} <900 GeV, geff ~O(1)

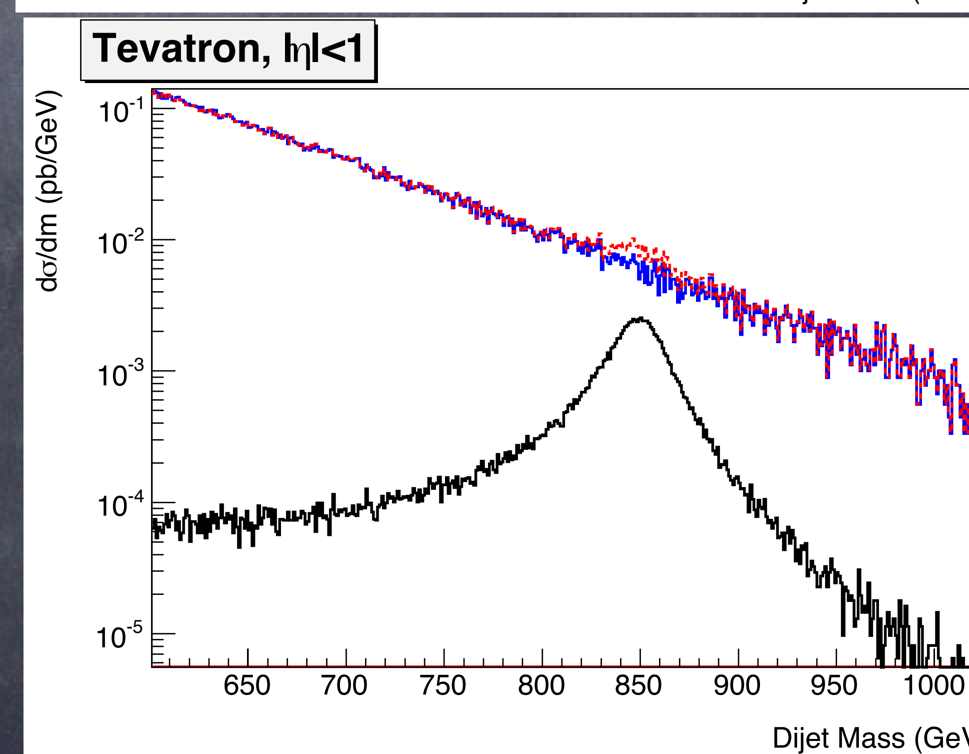
- ttbar





- Dijet





Summary

- Warped XD provide an effective theory frame work for probing strong dynamics via AdS/CFT @ LHC
- Little CP Problem => flavor symmetry for NP scale relevant for EWSB and LHC => presence of flavor gauge boson
- Flavor trivial Warped Extra Dimension model can be tested @ LHC by 2012 (unlike popular anarchic RS, which we shows that m_{kk} > 4.6 TeV); it can't explain Tevatron hints entirely, but improvement is in the right direction
- The flavor gauge boson production cross section can be sizable and lead to observable effects at the Tevatron and at the LHC
- Top physics might be crucial for NP discovery @ LHC

hvala

Backup Slide

Q(2,2)$_{2/3}$ SU(2)$_R$ U(1)$_Q$

SU(2)$_L$

$$\begin{pmatrix} X_L(-,+) & t_L(+,+) \\ T_L(-,+) & b_L(+,+) \end{pmatrix}_X \sim (2,2)_{2/3} \sim \begin{pmatrix} 5/3 & 2/3 \\ 2/3 & -1/3 \end{pmatrix}.$$

U(+,+)~$(1,1)_{2/3}$

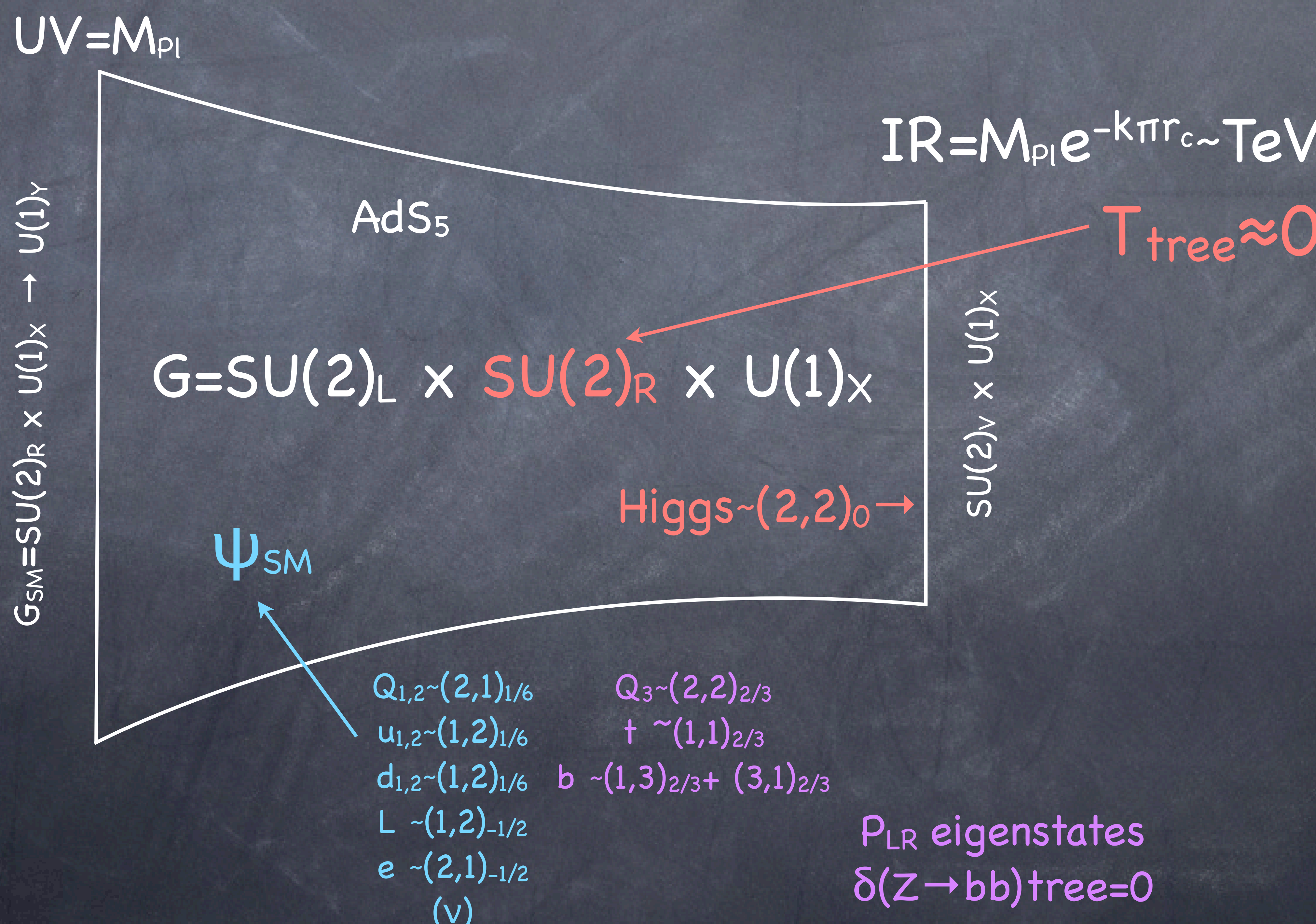
D ~$(1,3)_{2/3}$ + $(3,1)_{2/3}$

L(+,+)~$(2,2)_{-1}$

E ~$(1,3)_0$ + $(3,1)_0$

Realistic Warped Extra dimension (RS)

Randall, Sundrum
Agashe, Delgado, May, Sundrum
Agashe, Contino, DaRold, Pomarol
...



FCNC's from FGB

- When diagonalizing the Yukawa interaction, we can also diagonalize some of the GB interactions by redefining a basis of the gauge fields.

$$\phi_d = U_d \phi_d^{(diag)} V_d^\dagger$$
$$\phi_u = U_u \phi_u^{(diag)} V_u^\dagger$$

- However, there are four rotations needed, one has only three sets of flavor gauge bosons, thus the effect of one combination of these rotation matrices can not be eliminated.

$$A^u \to V_u A^u V_u^\dagger, \quad A^d \to V_d A^d V_d^\dagger, \quad A^Q \to U_d A^Q U_d^\dagger.$$

couplings of the u_R, d_R, d_L

$$g_* \bar{q}_i T^a_{ij} A^a_\mu \gamma^\mu q_j$$

couplings of u_L

$$g_* \bar{u}_L V A^Q_\mu V^\dagger \gamma^\mu u_L$$

- Similarly, the effect of the flavor rotations on the scalar VEVs will yield the following set of GB mass matrices

$$M^2_{KK}\left(\alpha_u \mathrm{Tr}[Y_u A_u A_u Y_u] + \beta_u \mathrm{Tr}[A_Q V Y_u Y_u V^\dagger A_Q] + \gamma_u \mathrm{Tr}[V^\dagger A_Q V Y_u A_u Y_u]\right.$$
$$\left.\alpha_d \mathrm{Tr}[Y_d A_d A_d Y_d] + \beta_d \mathrm{Tr}[A_Q Y_d Y_d A_Q] + \gamma_d \mathrm{Tr}[A_Q Y_d A_d Y_d]\right)$$

diagonal real Yukawa coupings

FCNC's from FGB

- When diagonalizing the Yukawa interaction, we can also diagonalize some of the GB interactions by redefining a basis of the gauge fields.

$$\phi_d = U_d \phi_d^{(diag)} V_d^\dagger$$
$$\phi_u = U_u \phi_u^{(diag)} V_u^\dagger$$

- However, there are four rotations needed, one has only three sets of flavor gauge bosons, thu ... tion of these rotation matrices can

$$A^u \to V_u A^u V_u^\dagger, \quad A^d \to V_d A^d V_d^\dagger,$$

couplings of the u_R, d_R, d_L

$$g_* \bar{q}_i T^a_{ij} A^a_\mu \gamma^\mu q_j$$

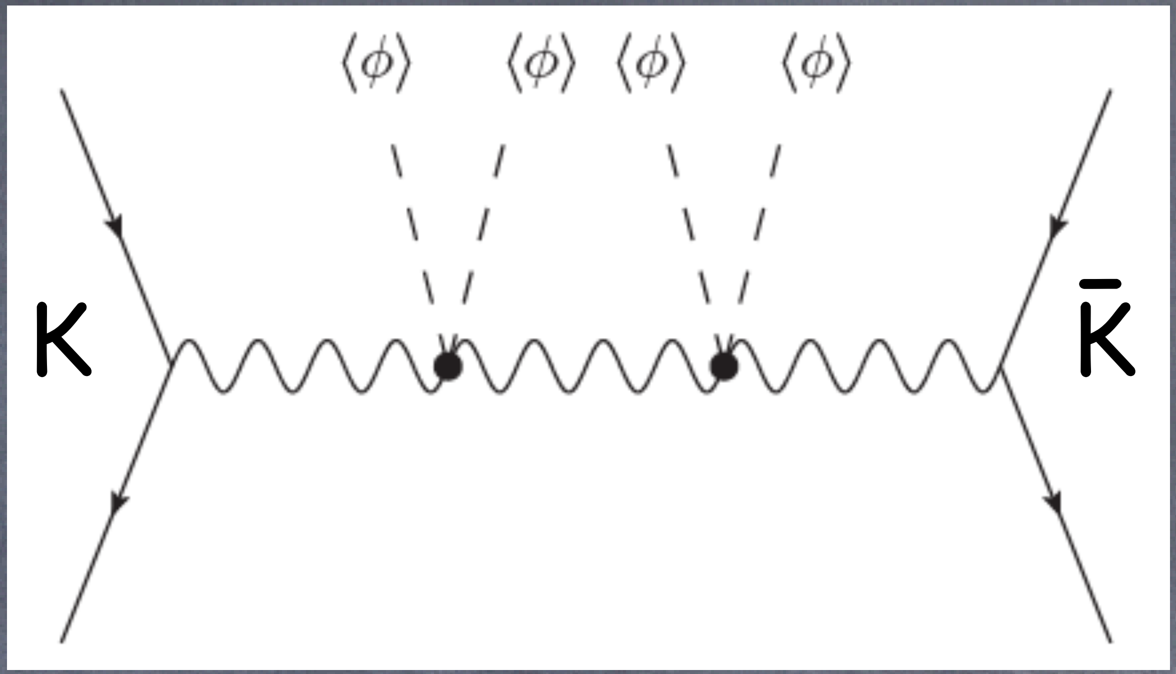
Clearly the only sources of flavor violation in this basis are explicitly proportional to V_{CKM} => MFV

- Similarly, the effect of the flav... VEVs will yield the following set of GB mass matrices

$$M^2_{KK}\left(\alpha_u \mathrm{Tr}[Y_u A_u A_u Y_u] + \beta_u \mathrm{Tr}[A_Q V Y_u Y_u V^\dagger A_Q] + \gamma_u \mathrm{Tr}[V^\dagger A_Q V Y_u A_u Y_u]\right.$$
$$\left.\alpha_d \mathrm{Tr}[Y_d A_d A_d Y_d] + \beta_d \mathrm{Tr}[A_Q Y_d Y_d A_Q] + \gamma_d \mathrm{Tr}[A_Q Y_d A_d Y_d]\right)$$

diagonal real Yukawa coupings

FCNC's from FGB



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

g∗~4 allowed

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