Signals from Flavor Trivial Warped Extra dimension

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based on hep-ph:1007.0243(V2!) , 1012.soon & work in progress

w/ O. Gedalia, S.J. Lee, G. Perez & E. Ponton

Disclaimer:

this is not about a N+1 flavor protection mechanism in << anarchic >> RS

Outline:

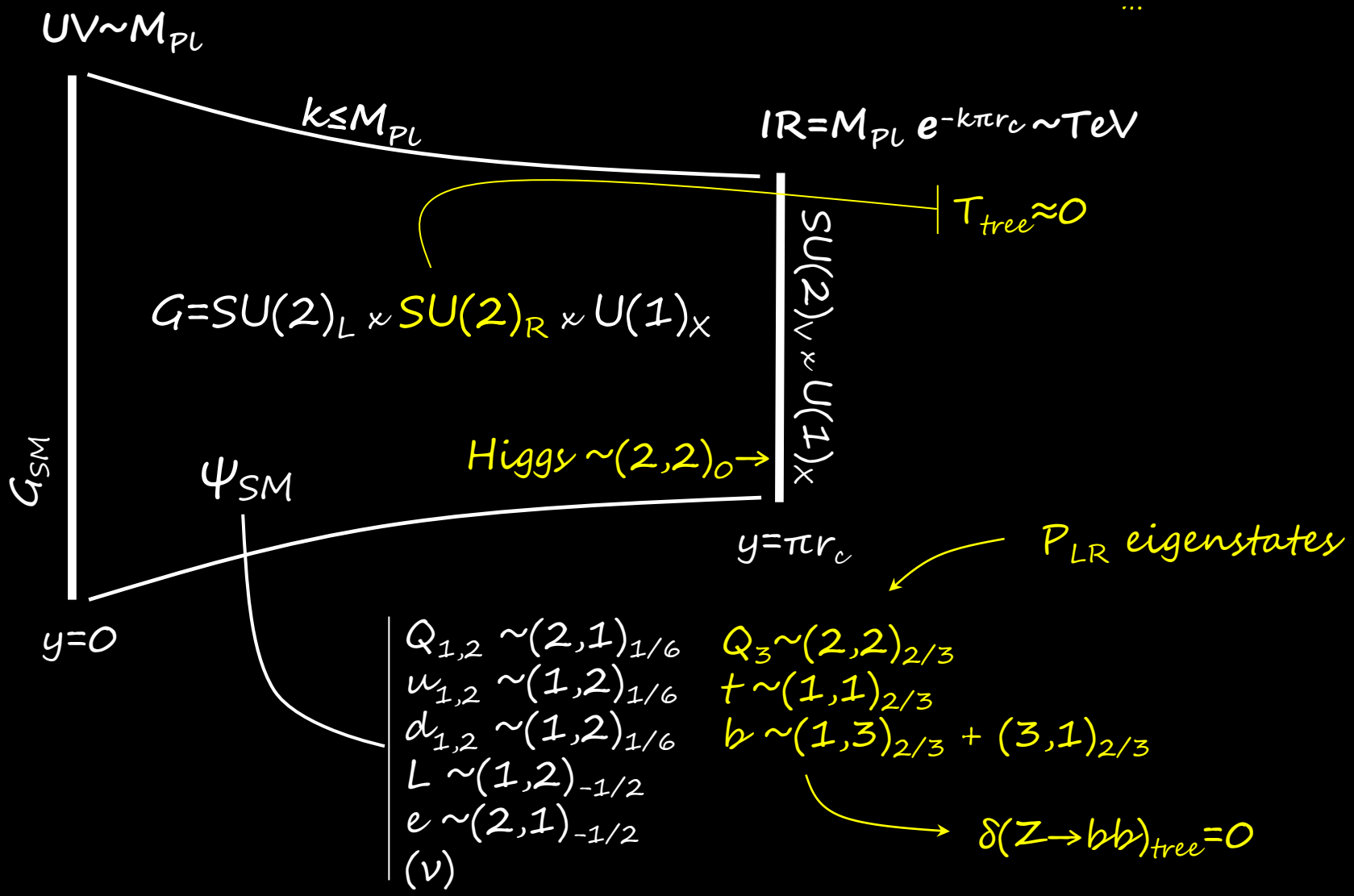
- what is Flavor Triviality?
- $m_{KK} \approx 2.1$TeV (1 d.o.f.) consistent w/EWPTs
- no <<little CP problem >> & no FCNCs
- exciting new collider(s!) phenomenology

Flavor Triviality in RS

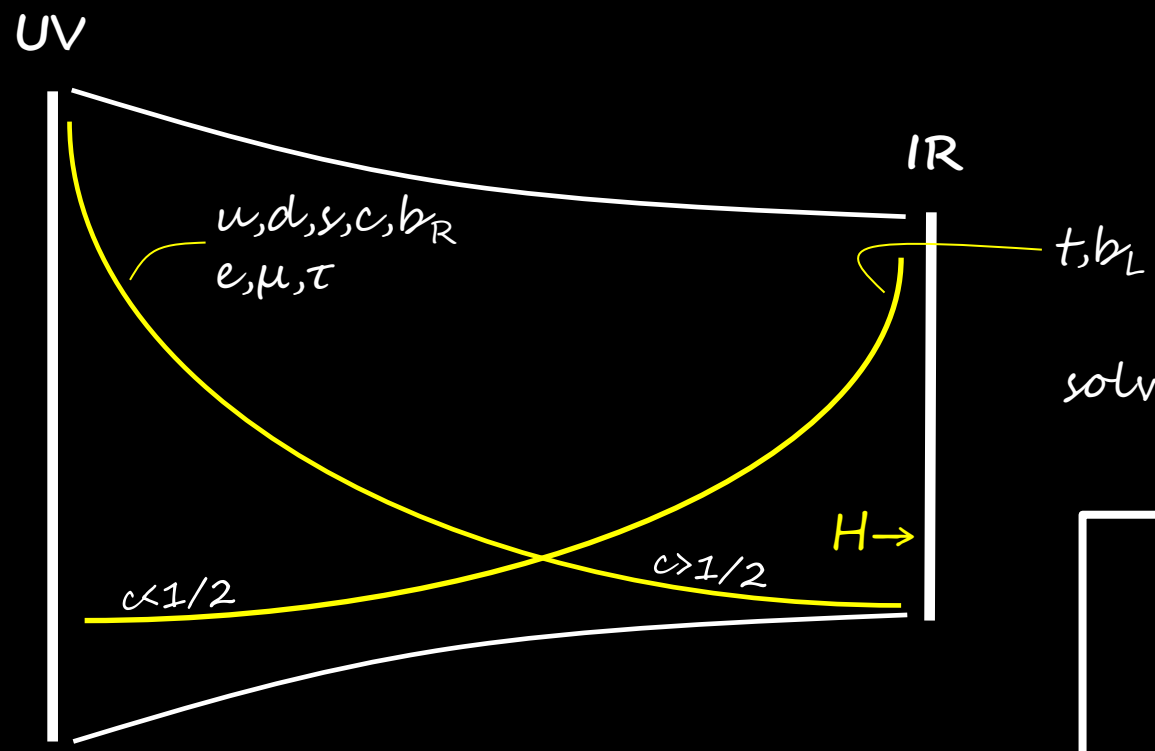
ie. RS w/out flavor

RS in a (chest)Nutshell

RS '99
May et al. '03
...



Anarchic RS



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

solves the SM flavor puzzle:
(with $C_{Q,U,D} \sim O(1)$)

$$M_{U,D} \propto f_{cQ}\, Y_{U,D}\, f_{cU,D}$$

$$V^{CKM}_{ij} \approx f_{cQi}/f_{cQj}$$

where: $f_c^2 \approx$

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

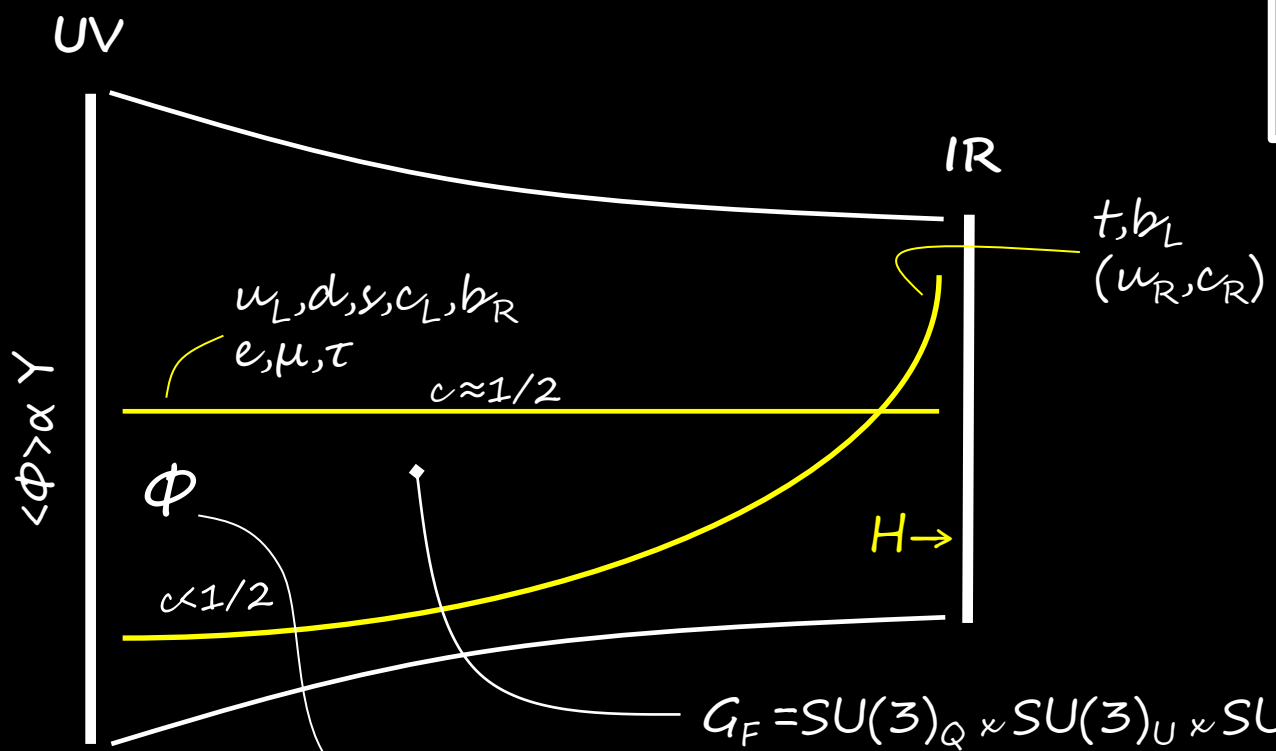
from flavor anarchy to triviality

flavor puzzles are not <u>necessarily</u> related to the TeV scale.

$$\epsilon_{ij}\frac{\bar{Q}_i Q_j \bar{Q}_i Q_j}{\Lambda_F^2}\,,\ |\epsilon_{ij}|\sim O(1) \rightarrow \Lambda_F > 10^{3\text{-}4}\ \text{TeV!}$$ (eg. from ϵ_K)

what if we give up on the split fermion + RS-GIM ideas in RS?

Flavor Trivial RS



$Y_{U,D}$ hierarchical

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

$G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$

«flavon» scalars : $\Phi_{U,D}\sim(3_Q,\bar{3}_{U,D})$ & $\Phi_E\sim(3_L,\bar{3}_E)$

- SM flavor puzzle solution **postponed to the UV**, where $G_F \rightarrow$ 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
- old idea, but w/ SM on the IR Rattazzi & Zaffaroni '00
  (note: flavor sym. force to embed all 3 q-gen. in custodial reps.)

EW Precision Tests (in RS)

Anarchy Vs. Hierarchy

EFT entr'acte

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

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

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

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

(+3rd gen. quark effects: $SU(3)^3 \rightarrow SU(2)^3 \times U(1)^3$)

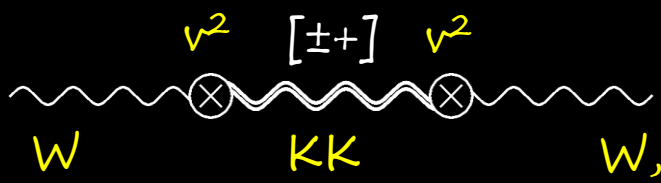
- EWPT fitting procedure:
  1) match your beloved UV physics to L_{eff}
  2) constrain its fundamental parameters (Λ_{NP},...) w/ χ^2-like analysis.

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

EWPOs in anarchic RS

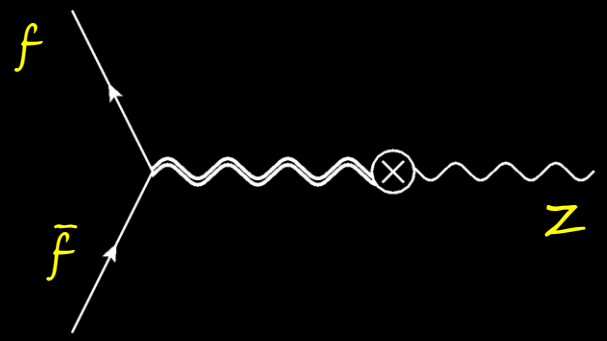
[++] KK = Z «cousins»
[−+] KK = non-SM broken gen.

(v<<mKK → <H>=perturbation) May et al. '03



→ no WBH²! only arises @O(v/m_KK)⁴

$T_{[++]} + T_{[-+]} \approx 0$ $SU(2)_V$ at work



→

$f = u,d,s,c,b_R;e,\mu,\tau$

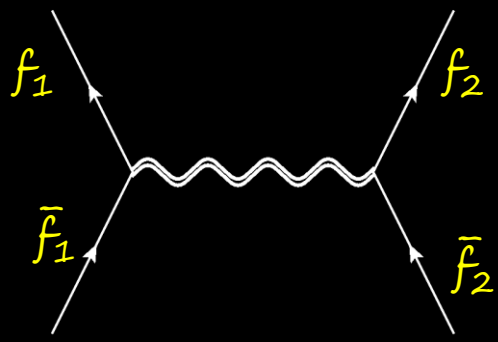
$[++]\ KK : Q_Z^f(f_{cf}^2 - k\pi r_c^{-1}) \approx \frac{-Q_Z^f}{k\pi r_c}$

$[-+]\ KK : Q_{[-+]}\, f_{cf}^2 \approx 0$

$f = b_L \quad (Q_Z = Q_{[-+]})$

$[++] + [-+] = \frac{-Q_Z^b}{k\pi r_c}$ P_{LR} at work

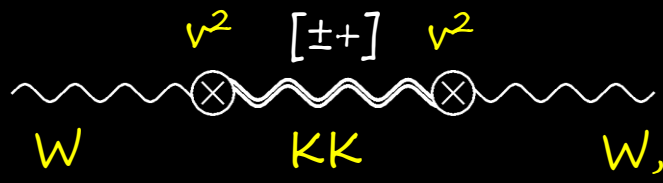
oblique vertex corr. ↔ S,T shift



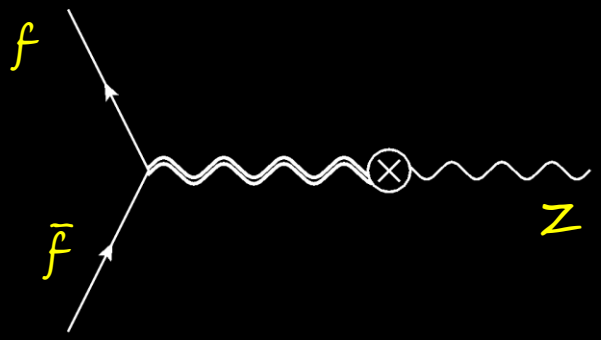
→ exp. suppressed, no 4ψ!

EWPOs in flavor trivial RS

[++] KK = Z «cousins» (v<<mKK → <H>=perturbation)
[−+] KK = non-SM broken gen.



→ **idem !** (≈0)



→

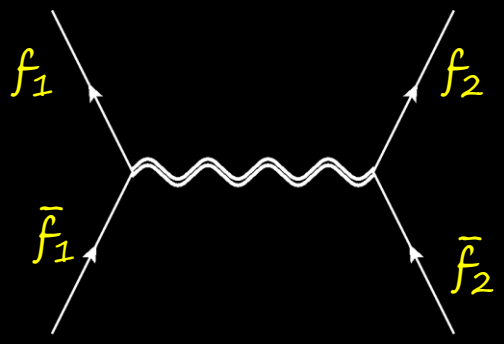
$f = u, d_R, s_R, c, b_R; e_R, \mu_R, \tau_R$

$[++]$ KK : $Q_Z^f (f_{cf}^2 - k\pi r_c^{-1}) \sim Q_Z^f f_{cf}^2$

$[-+]$ KK : $Q_{[-+]} f_{cf}^2 \sim O(1)$

$f = e_L, \mu_L, \tau_L, d_L, s_L, b_L$ $(Q_Z = Q_{[-+]})$

$[++] + [-+] = \dfrac{-Q_Z^b}{k\pi r_c}$ P_{LR} **also** at work



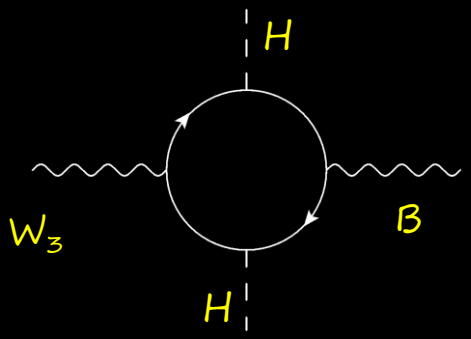
→ ~ O(1) no longer exp. suppressed

→ highly non-oblique corr.!

Loop corrections to EWPOs

radiative corr. are important! May et al. '03/Carena et al. '06

- $T\&Z_{bLbL}$ are finite to all orders (custodial $SU(2)_V \times P_{LR}$)
- S is 1-loop finite 5D for bulk H



(5D)NDA

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

$-1 + -1 + 5/2 + 5/2 + 3 = 6$

Loop corrections to EWPOs

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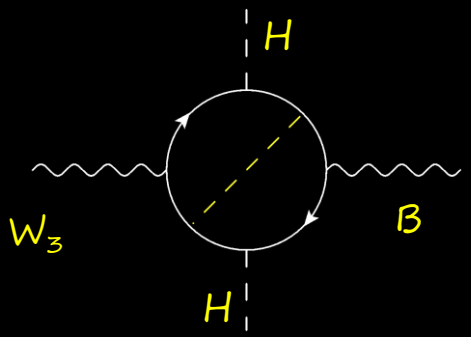


(5D)NDA

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

$-1 + -2 + 5/2 + 5/2 + 3 = 5$

suppressed (as it should!) for perturbative Y_t
(numerically ~< 20% correction)

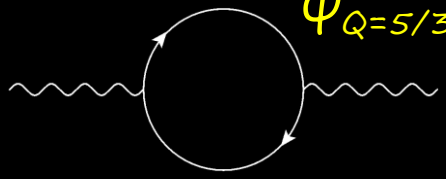
- other loop corr. are unimportant
  (supressed. by smaller Y's or gauge couplings)

we add rad. corr. from 2KK-levels @1loop

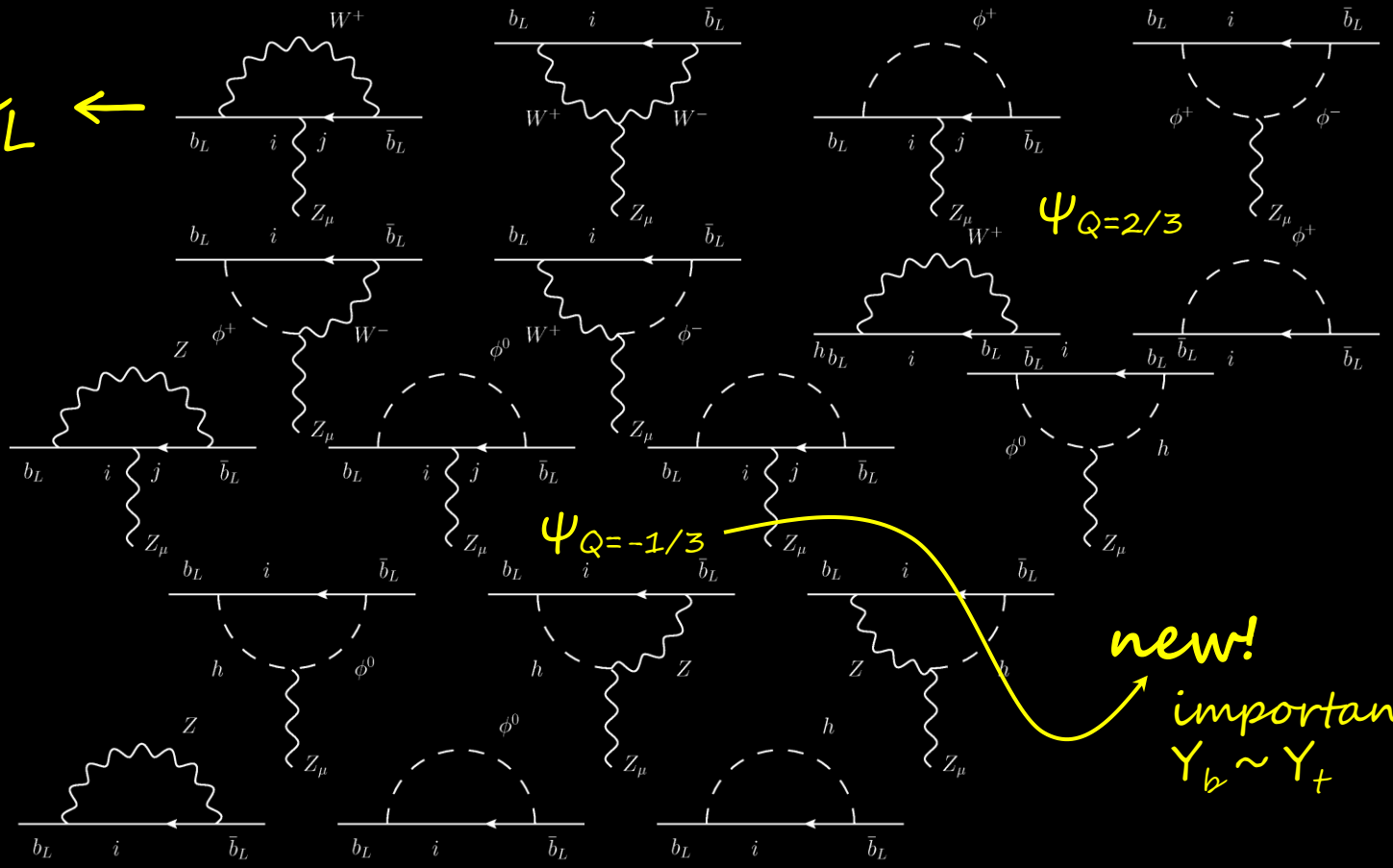
Loop corrections to EWPOs

S,T ←

$\Psi_{Q=5/3,2/3,-1/3}$



Zb_Lb_L ←



new!

important if $Y_b \sim Y_t$

χ^2 fit results

- we (re)did the EWPT fit for anachic RS (most precise to date):
  @26 : mKK > 4.6 (3.9) TeV for 1(3)dof
  → is the celebrated anarchic RS model visible at LHC?

- Flavor Triviality fit: $m_{KK}, c_t, c_b, c_{Q3}, c_{Qi}, c_{ui}, c_{di}, c_L, c_e$ (6 important dofs)

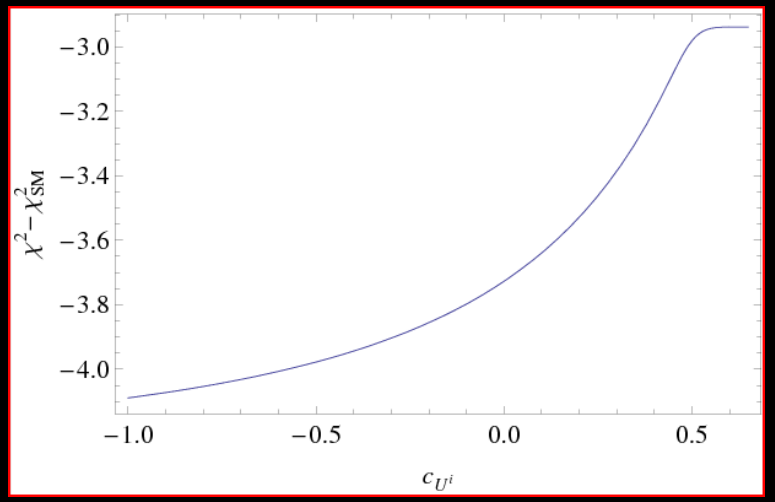
  We find :
  - FTRS provides a better fit than the SM (w/ m_{KK}=3.9TeV)

$(\chi^2/dof)_{SM} = 219.9/232 \sim 0.95 \quad \sim< \quad (\chi^2/dof)_{FTRS} = 217.3/223 \sim 0.97$

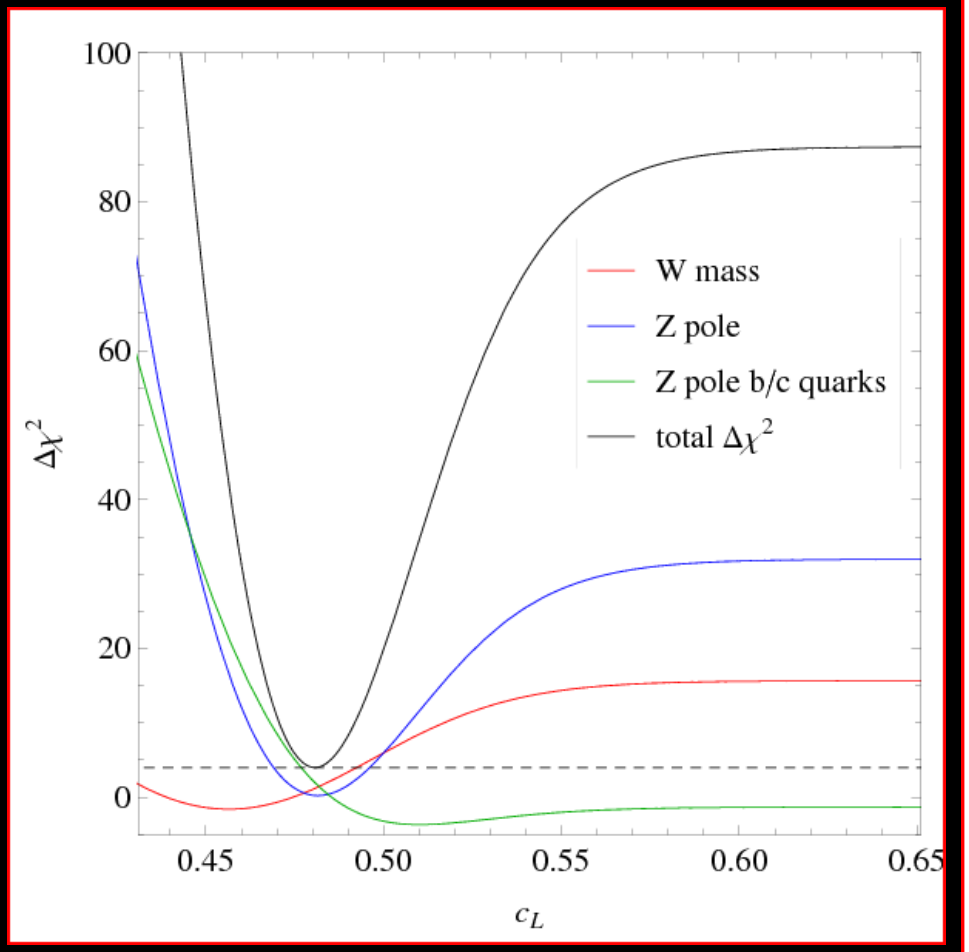
  - 2σ lower-bound on $m_{KK} > 2.1\ (1.7)$TeV for 1(6)d.o.f.

w/ sweet-spot parameters:
$c_{Q3} \approx 0$, $c_t \approx 0.47$, $c_b \approx 0.6$, $c_{Qi} \approx 0.51$,
$c_L \approx 0.48$, $c_e \approx 0.5$, $c_{ui} \approx -0.5$, $c_{di} \approx 0.7$

u_i slightly prefers compositeness



χ^2 fit results



	$\chi^2 - \chi^2_{\rm SM}$	$\chi^2_{\rm min} - \chi^2_{\rm SM}$	$\Delta\chi^2$
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	3.44	1.86
s^2_W hadronic charge asymmetry	0.20	0.23	−0.03
Leptonic polarization asymmetries	−1.95	−2.18	0.23
Deep inelastic scattering	−0.13	−0.12	−0.01
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	−1.47
LEP2 ee→cc	−0.18	−0.08	−0.10
Total	0.02	−3.98	4

...quite sensible to the c's

Improved naturalness?

- need to lift the model to a PGB Higgs ~ SO(5)/SO(4)
  → no little hierarchy problem
- here $m_h \alpha \log\Lambda$, but can estimate m_h fine-tuning by:
  $FT_{KK} \approx (v/m_{KK})^2$ (assuming m_h cut off by mKK, not Λ)

FT_{KK} ~ 10% (2%) for flavor trivial (anarchic) case

- but low m_{KK} has a price = sensitivity to c's:
  $FT_c \approx |\partial \log m_{KK}/\partial \log c|^{-1} (=0!) \rightarrow |\Delta \log m_{KK}/\Delta \log c|^{-1} (\Delta c \sim g^2/16\pi^2)$

$FTc_{L,E\,(c_t)}$ ~ 5% (20%) for flavor trivial (anarchic)

- how to combine them?? let's take the product!

→ FTRS «seems» as unnatural as anarchic RS, but $m_{KK} \approx 2$TeV!!!

Flavor & CPV Physics

FCNCs+EDMs

RS flavor structure

Agashe et al. '04

- $G_F = SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$
- Spurions : $Y_{U,D} \sim (3_Q, \bar{3}_{U,D})$ & $C_{Q,U,D} \sim (3 \times \bar{3})_{Q,U,D}$
- FT leads to ~ 5DMFV expansion (Randall & Perez '07):

leading order: $\bar{\Psi}_i \Psi_i$ + higher order corr. $\frac{1}{\Lambda_{5D}^2}(\Psi \Phi \Phi \Psi) + \ldots$

(flavor universal, $i = Q,U,D$)

$$C_Q = \alpha_Q \mathbf{1}_3 + \beta_Q{}^U\, Y_U Y_U^\dagger + \beta_Q{}^D\, Y_D Y_D^\dagger + O(Y^4)$$
$$C_{U,D} = \alpha_{U,D} \mathbf{1}_3 + \beta_{U,D}\, Y_{U,D}^\dagger Y_{U,D} + O(Y^4)$$

- $Y_t \sim O(1)$ so higher powers of Y_U are important → G(eneral)MFV!
  (likewise for the down sector if $Y_b \sim O(1)$ (↔large tanβ in SUSY)
- GMFV in d-sector comes w/ a new CPV phase (dimuon anomaly?)

Flavor trivial flavor physics

$$C_Q = \alpha_Q \mathbf{1}_3 + \beta_Q{}^U\, Y_U Y_U^\dagger + \beta_Q{}^D\, Y_D Y_D^\dagger + O(Y^4)$$

$$C_{U,D} = \alpha_{U,D} \mathbf{1}_3 + \beta_{U,D}\, Y_{U,D}^\dagger Y_{U,D} + O(Y^4)$$

$$M_{U,D} \approx v/\sqrt{2}\; F_Q^\dagger Y_{U,D} F_{U,D}$$

- NDA → $\alpha,\beta \sim O(1)$ but carry different «PQ-like» charges under various U(1)'s → hierarchies among them are natural!

- <u>low tanβ:</u> $Y_D \ll Y_U$ → up alignment : $[M_U, Y_U]=0$

  → $Y_U = \lambda_U$, $Y_D = V^5 \lambda_D$ w/ $V^5_{12} \sim V_{us}$, $V^5_{13;23} \sim r_Q V_{td;ts}$

  $(r_Q \equiv f_{Q3}/f_{Q1} \sim 2\text{-}3)$

(+ RH current rotation $\sim m_{d,s}/m_b$)

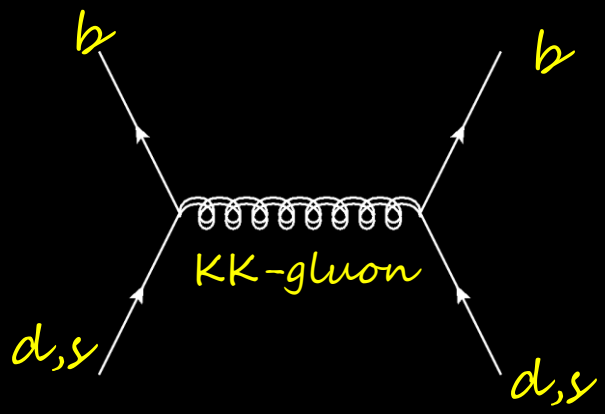
- <u>large tanβ:</u> $Y_D \sim O(1)$ → more involved , but qualitatively the same + new CPV phase!

FCNCs

- approx. $SU(2)_{Q,U,D}$ → no $i=1,2$ FCNCs → no ϵ_K problem!

  (ϵ_K suppressed by $r_Q^4 m_d m_s / m_b^2$)

- flavor changing through 3rd gen. only → $B_{d,s}$ mixings



→

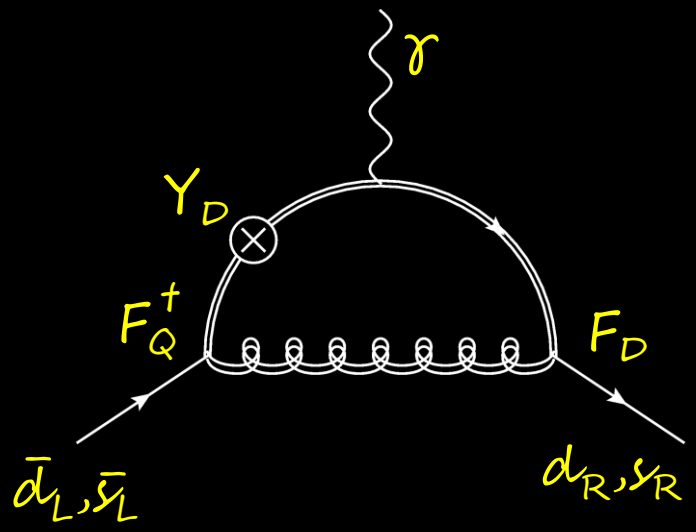
$$O_1 = (\bar{b}_L \gamma^\mu d_L)(\bar{b}_L \gamma_\mu d_L)$$
$$O_4 = (\bar{b}_L d_R)(\bar{b}_R d_L)$$

$C_1 \approx g^{*2}/(6 m_{KK}^2)(V_{td}V_{td,s})^2 [f_{cQ3}^2 - f_{cQi}^2]^2$

$C_4 \approx g^{*2}/m_{KK}^2 (V_{td}V_{td,s})^2 (m_{d,s}/m_b)(r_Q^2 - 1)[f_{cQ3}^2 - f_{cQi}^2]\,[f_{cb}^2 - f_{cdi}^2]$

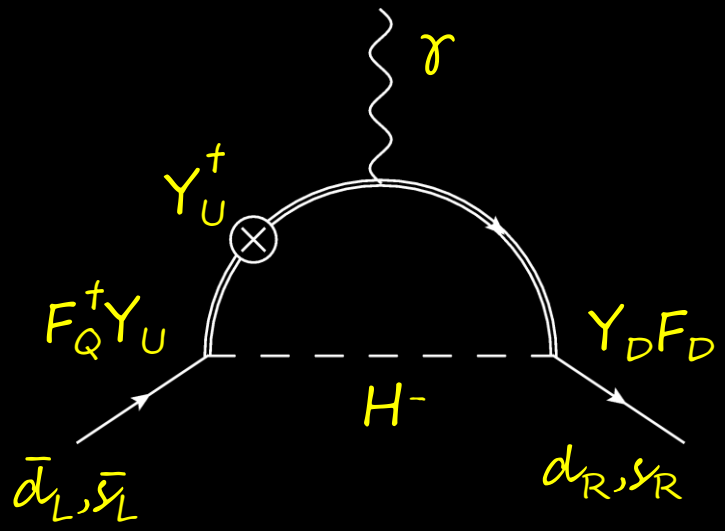
@low tanβ: C_1 dominates → flavor+EWPT: $m_{KK} > 2.4$TeV (1dof)

EDMs



~ aligned w/ M_D → real !

(similarly, no Weinberg op.)



$$\rightarrow d_n \approx \frac{e\, m_s}{16\pi^2 m_{KK}^2}\, Y_t^2 r_Q^2 V_{ts}^2$$

$\approx 0.47\, d_n^{EXP}$ fine!

(Hg and Tl are even smaller)

combining EDM+ε_K in anarchic RS

- n-EDM bound : $m_{KK} > (3.6\text{TeV})Y$ (from s-EDM) NEW!
- ϵK bound : $m_{KK} > (8.5\text{TeV})\, g_*/Y$ (bulk higgs, β=0)

Gedalia et al. '09

- combining them + optimizing the overall Y scale yield:

$$m_{KK} > 9.6\text{TeV} \quad (\text{for } Y\approx 2.2)$$

there is a big «little CP problem» in anarchic RS!

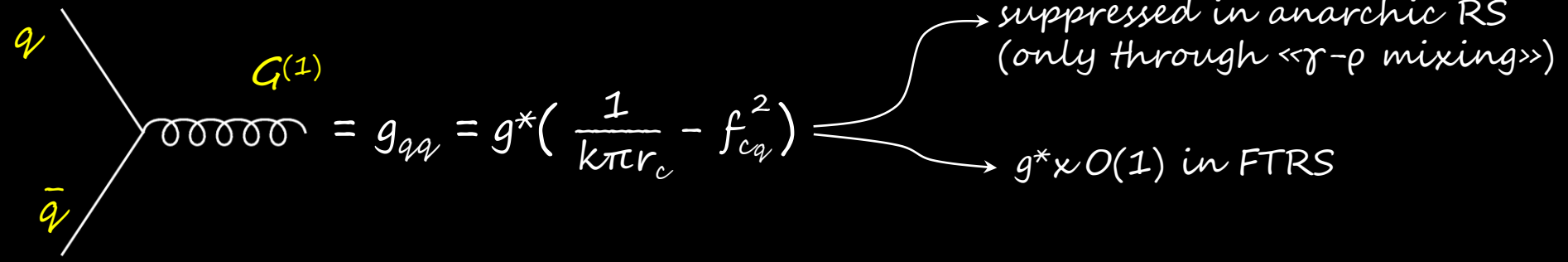
(Extraordinary!)

Collider Phenomenology

@ Tevatron & LHC

FTRS ultra-visible @hardron colliders

- BEST RS signature = KK-gluon production



roughly speaking:

@7(14)TeV LHC : $\sigma_{KK} \approx$ 0.04(6)fb in <u>anarchic RS</u> w/ m_{KK}=4.6TeV

However, thanks to PDFs : $\sigma_{KK} \propto g_{qq}^2/m_{KK}^{5.3}$

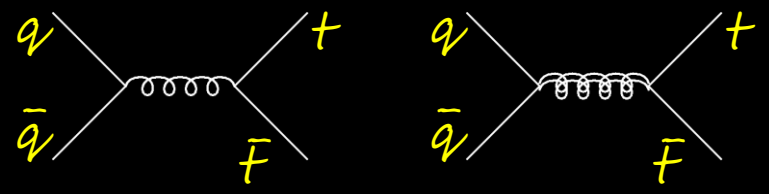
@7(14)TeV LHC : $\sigma_{KK} \approx$ 3(500)pb! <u>in FTRS</u> w/ m_{KK}=2.1TeV

→ FTRS could give a ~10^3 events by the end of 2011!!

- FTRS other signature = flavor gauge bosons @~TeV

top forward-backward asymmetry @tevatron

- $A_{FB|@CDF} = (15.8 \pm 7.2(stat) \pm 1.7(syst))\%$ ($t\bar{t}$ rest frame)
  while $A_{FB|SM@NLO} = (5.8 \pm 0.9)\%$ → ~2σ deviation
  → ISR/FSR interference
- impossible to generate A_{FB} in anarchic RS:



gluon/KK-gluon interference

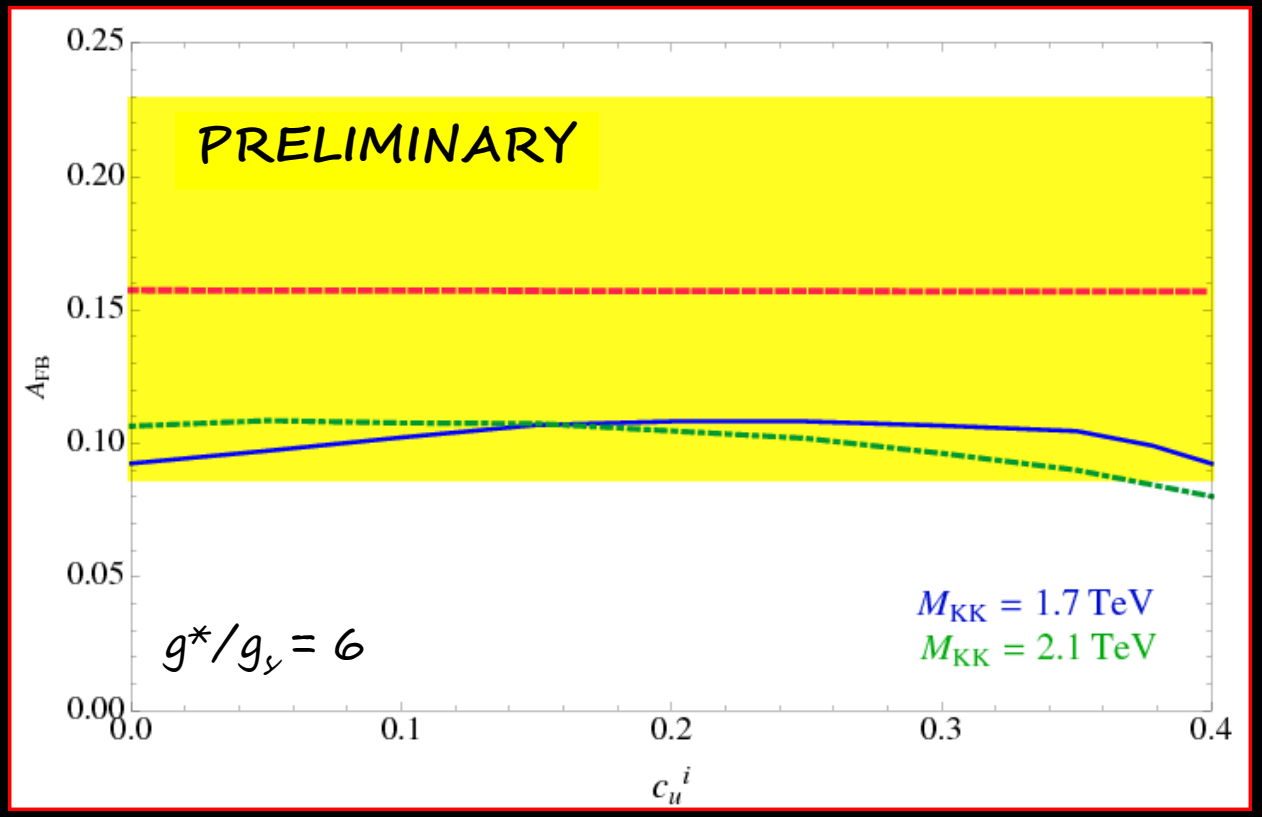
$q\text{-}q\text{-}G^{(1)} = g^*\gamma(v_q + \gamma_5 a_q) \rightarrow A_{FB|RS} \propto a_{u,d}\, a_t$

$a_q = (f_{cqL}^2 - f_{cqR}^2)/2$

→ $a_{u,d} \approx 0$ in anarchic RS ($f^2_{c>0.5} \sim 0$)

→ $a_u \approx O(1)$ in FTRS ($f^2_{c<0} \sim 2c-1$)

top forward-backward asymmetry @tevatron



... but FCNCs enhanced by $(g^*/3)^2 \sim 4$ and mKK>>2TeV

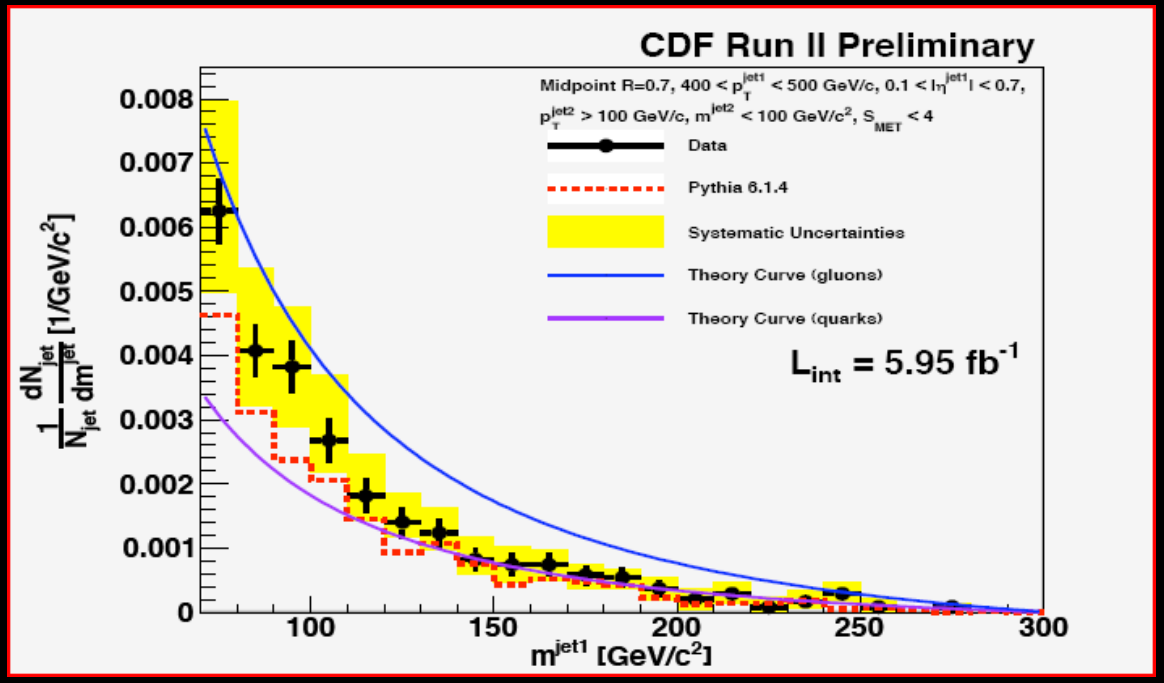
solution: make YD>>YU → down alignment $[M_D, Y_D]=0$ → no FCNCs
(but no 2μ anomaly)

An excess of high-p_T jets @CDF?

#jets around m_{top}

observed : 103
SM expected : 75
+/- ??(syst)

→ ~3σ deviation
blessed last night !



what if NP hint?

upper bound on NP cross section
σ_{tt}(pT>400GeV) < 54 fb @95%CL

FTRS @1.7(2.1)TeV → σ_{tt}(pT>400GeV) ≈ 24 (9) fb! (w/ $c_{ui} = 0$, $g^* = 6g_s$)

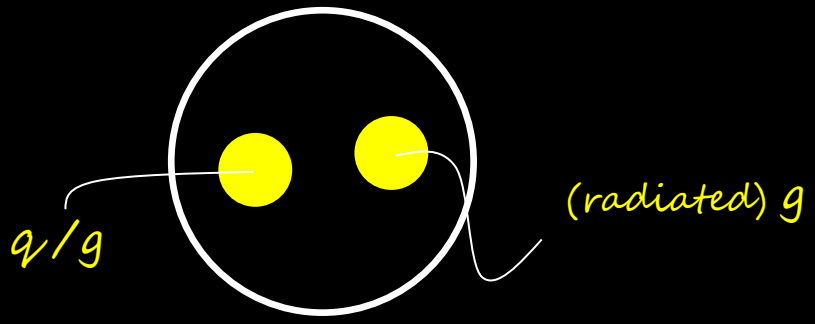
no hope in anarchic RS, m_{KK} too high !

Planar Flow

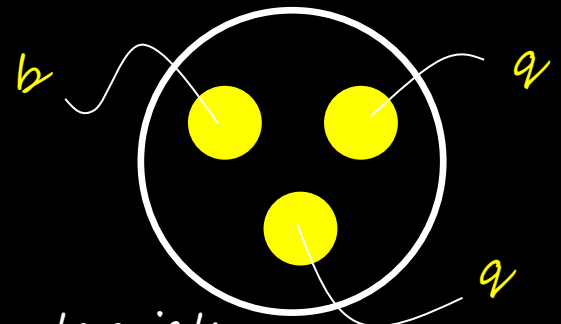
how to separate NP from QCD events w/ hard jets?

→ look at energy distrib. w/in the high-p_T jets: planar flow

($m_j \sim m_{top}$)

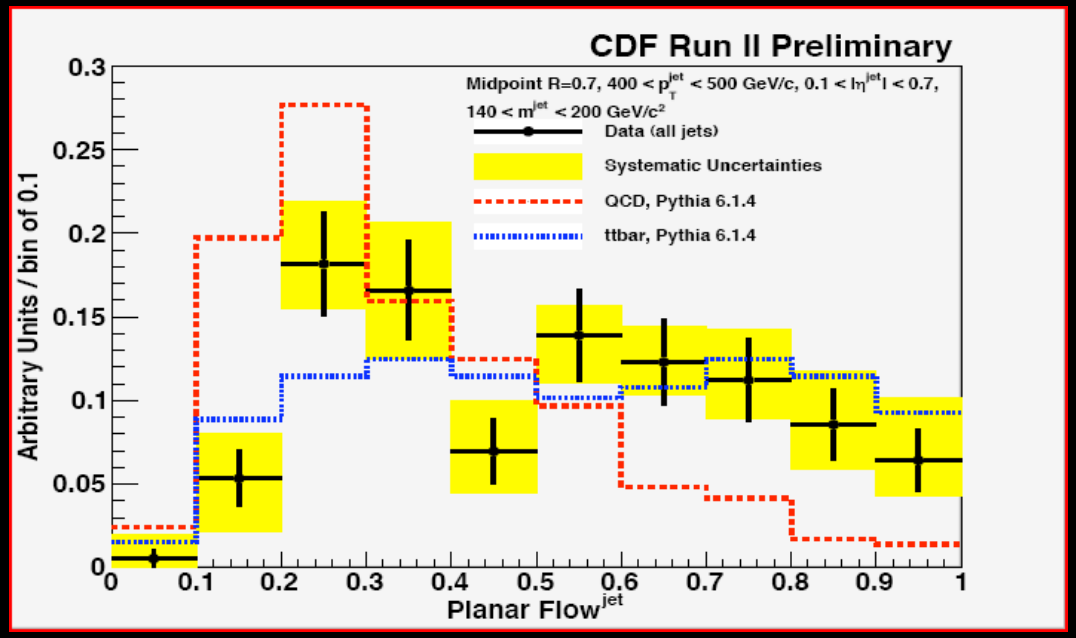


LO QCD jets
(PF << 1)



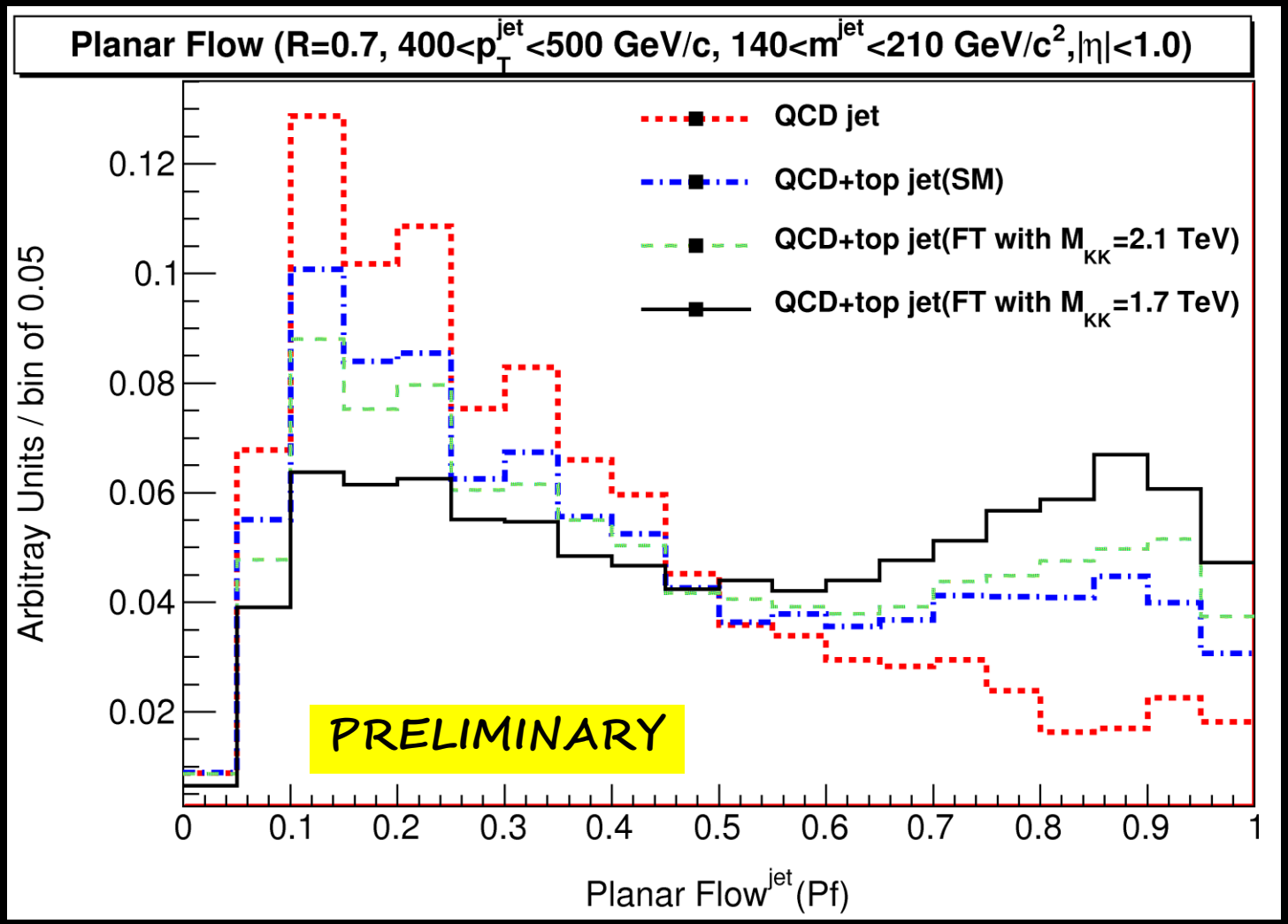
top jets
(PF ~ 1)

CDF looked @jets
w/ 400 < p_T <500 GeV

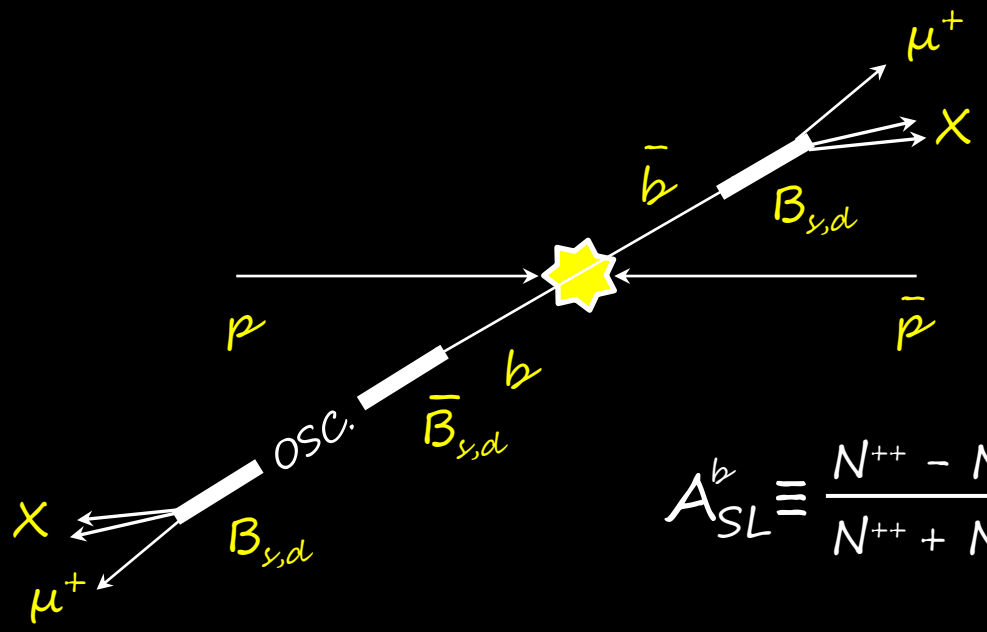


Planar Flow from FTRS

KK contribution : m_{KK}=2.1/1.7, TeV $g^*/g_s = 6$, c_{ui}=0)



Like-sign dimuon anomaly

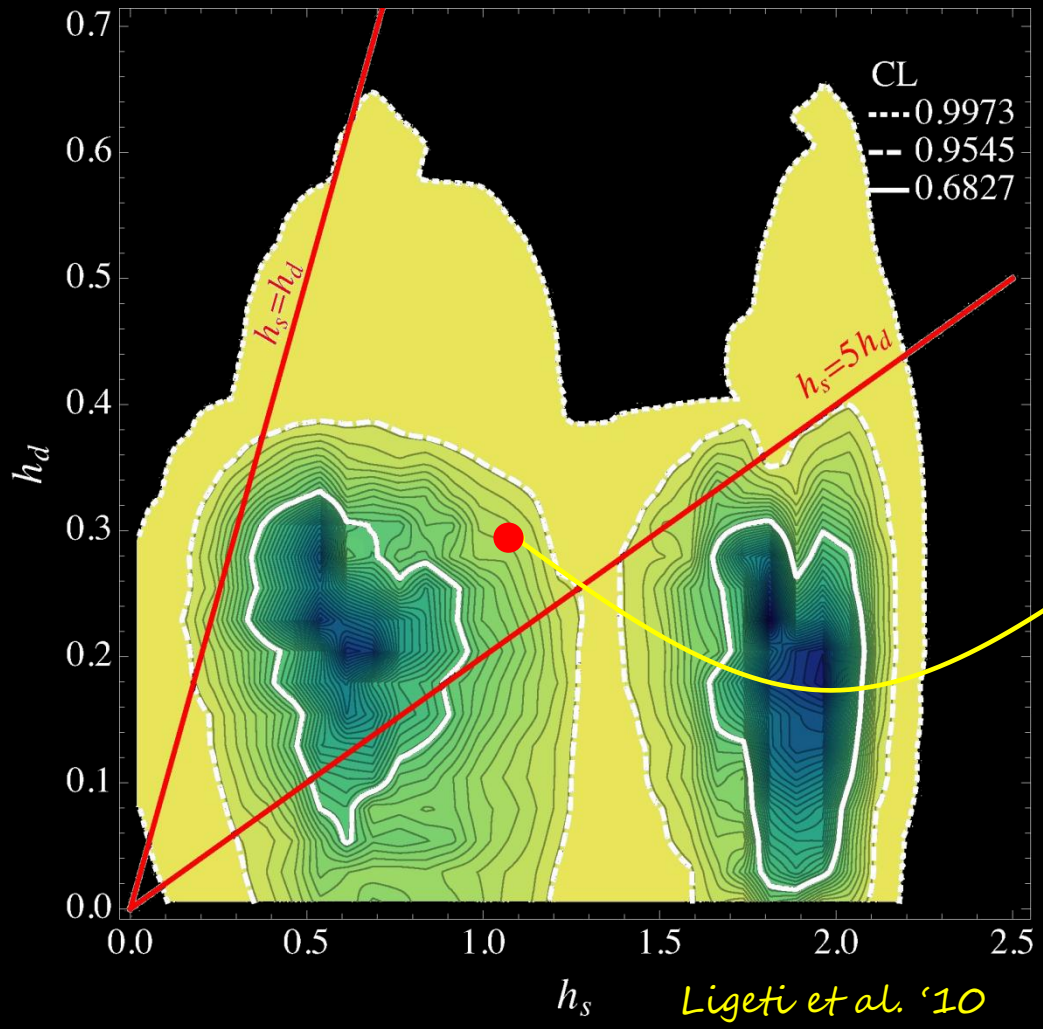


$$A_{SL}^b \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \neq 0 \text{ iff CPV!}$$

- $A_{SL|@D\emptyset}^b = (-9.57 \pm 2.51(\text{stat}) \pm 1.46(\text{syst})) \times 10^{-3}$
  while $A_{SL|SM} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4} \rightarrow 3.2\sigma$ deviation
- if confirmed → need new CPV source beyond KM phase!

Like-sign dimuon anomaly

NP contribution to $B_{s,d}$ mixing: $M_{12}^{s,d} = M_{12|SM}^{s,d} [1 + h_{s,d} \exp(i\sigma_{s,d})]$



Ligeti et al. '10

data favors CPV in B_s!

need O_4 to dominate over O_1

w/ $c_b = 0.49$, $c_{Q3} = 0.35$
$m_{KK} = 2.6$TeV
OK within 2σ!

Conclusions

Summary

- updates on anarchic RS:
  - most precise bound from EWPTs : $m_{KK}>4.6$TeV (in)visible @LHC?
  - bigger «little CP problem» : from nEDM+ϵ_K $m_{KK}>9.6$TeV
- decoupling flavor from TeV scale provides:
  - ≈2TeV KK-gluon ultra visible @LHC (possibly by '12)
  - improved naturalness? (need to look at pGB-higgs, but promissing)
  - no FCNCs, no little CP problem
  - some explanation for dimuon anomaly, top A_{FB} asymmetry, planar flow, #high-pT jets @Tevatron

are we already seeing RS?

Thank you !

miscellaneous