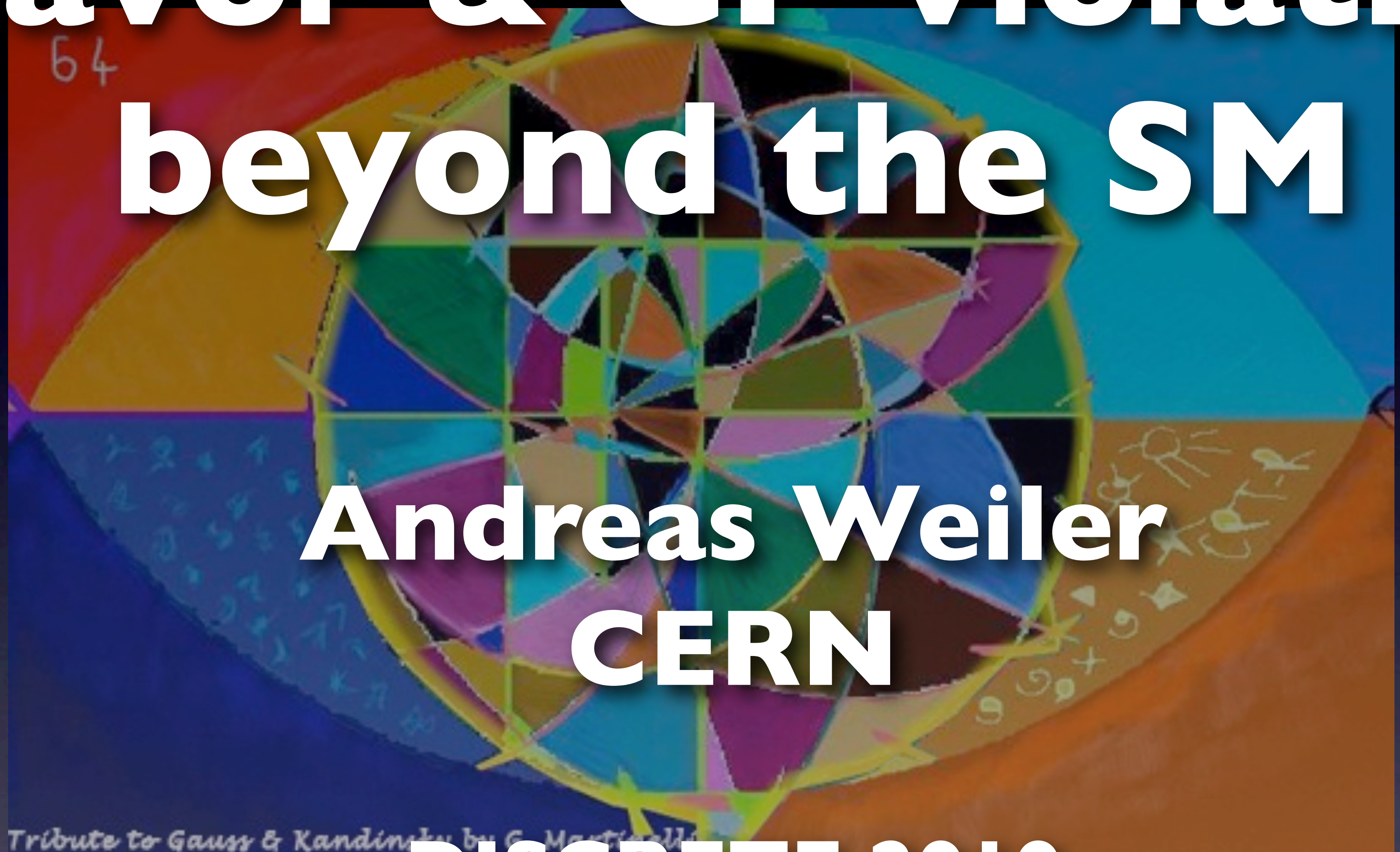
Flavor & CP violation beyond the SM



Andreas Weiler
CERN

DISCRETE 2010

6/12/2010

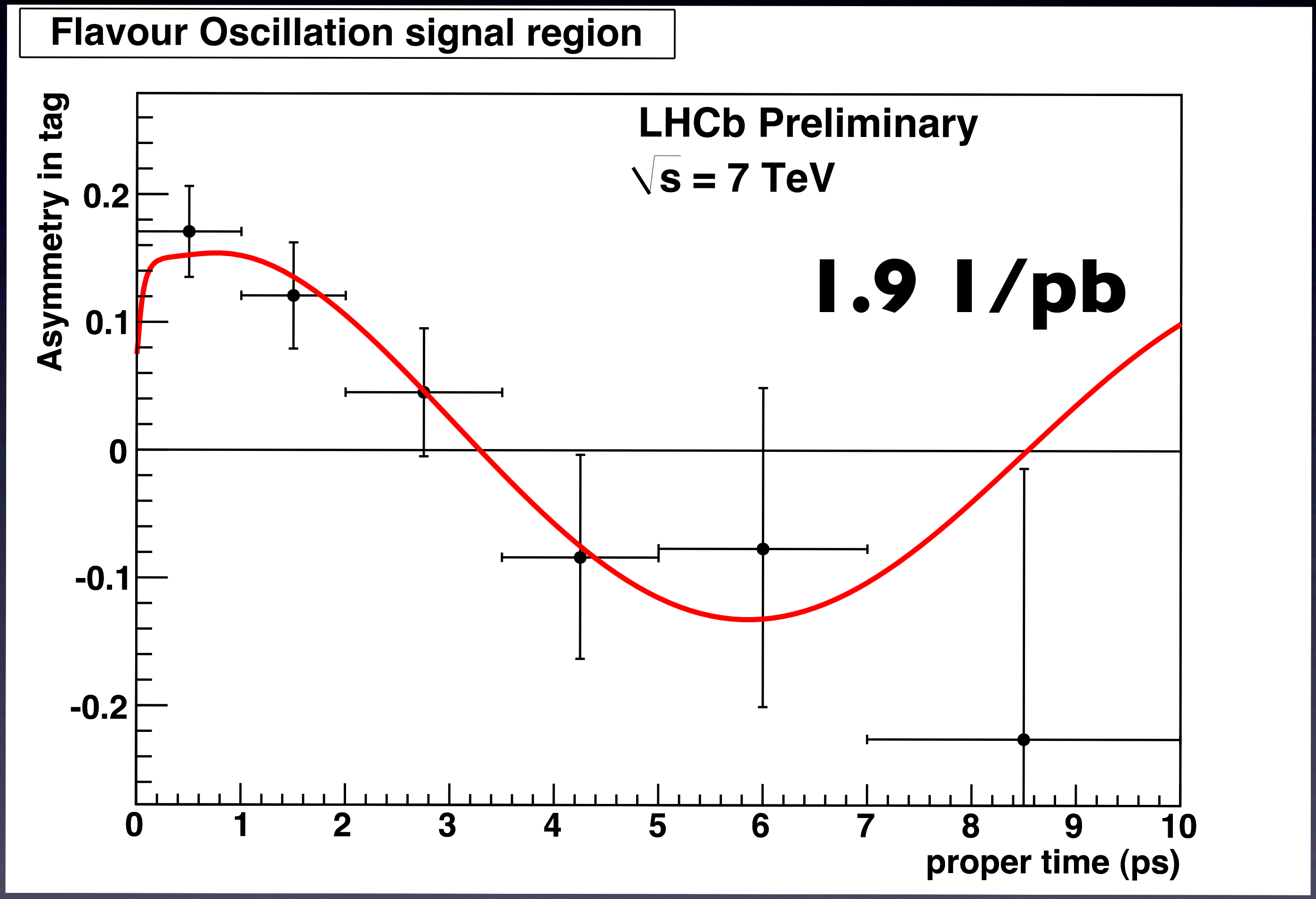
1) We are entering the TeV era. Why is ~5 GeV precision physics still interesting?

2) Any theory of the weak scale (susy, technicolor, extra-dimensions,…) has to have flavor structure. Can it be non-minimal?

3) Will we be able to learn about the origin of flavor at the LHC?

LHCb reaches adolescence

S. Stone @ LPCC

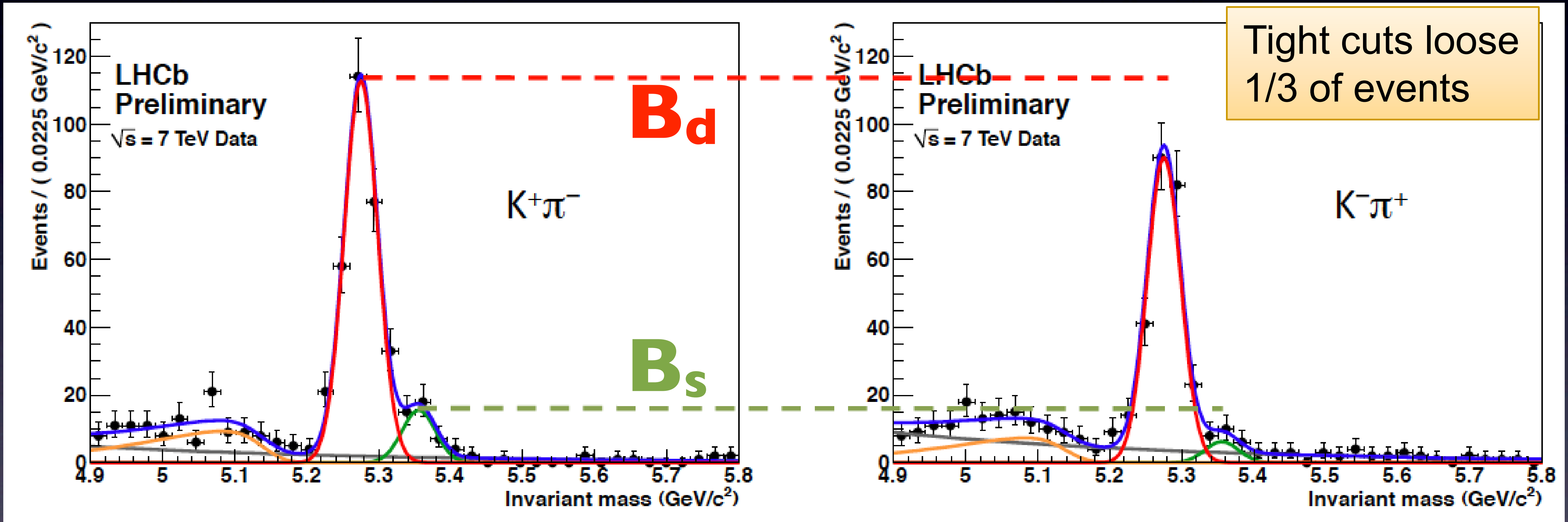


First
B^0 oscillations
seen at LHCb!

$$B \to D^* \mu\nu$$

CPV in $B \to \pi K$

first 37 1/pb !



$A_{CP}(B_0)$ = - 0.134 ± 0.041

$A_{CP}(B_s)$ = - 0.43 ± 0.17

Raw asymmetries, stat. error only, have to be calibrated & corrected

1)

We are entering the TeV era.

Why is ~5 GeV high precision physics still interesting?

Indirect tests: new physics C.S.I.

SM has accidental symmetries (B, L), e.g.

$$\mathcal{L}_{SM} + \frac{C_{\not B}}{\Lambda^2}(\bar{u}^c u)(\bar{e}^+ d)$$

$p \to e^+ \pi^0$

⇒ ***absence*** of violation probes very high scales

Flavor symmetries are only weakly broken (except top) & no tree-level FCNCs

$$\mathcal{L}_{SM} + \frac{C_{\not{\text{flavor}}}}{\Lambda^2}(\bar{b}d)(\bar{b}d)$$

$\bar{B}^0 \leftrightarrow B^0$

⇒ ***smallness*** of violation probes high scales

The SM flavor puzzle

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

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

Why this structure? Small & hierarchical.

Other dimensionless parameters of the SM:

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

UTfit 08, Isidori et. al '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert,\phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
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Very strong suppression! New flavor violation must either approximately follow SM pattern…

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Very strong suppression! New flavor violation must either approximately follow SM pattern…

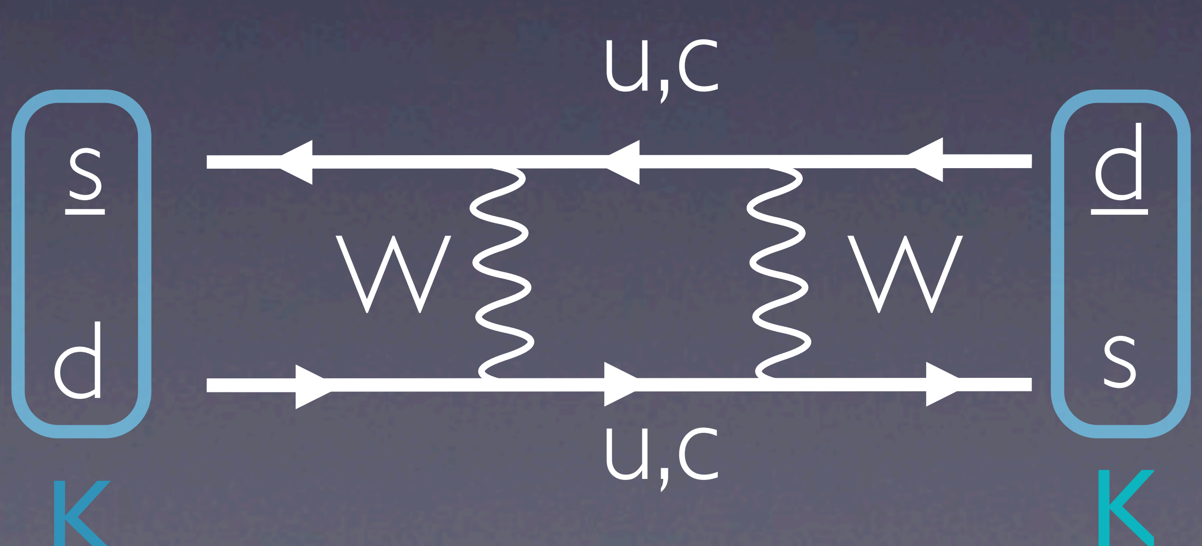
… or exist only at very high scales (10^2 - 10^5 TeV)

Why are FCNCs so suppressed in the SM?

no tree FCNCs: $g^4/(4\pi)^2$ $\sim (1/30)^2$

mixing & GIM: $\dfrac{m_c^2 - m_u^2}{m_W^2} \sin^2\theta_C$ $\sim (1/400)^2$

$$\Rightarrow \quad \frac{1}{(30\cdot 400)^2}\frac{1}{m_W^2} \sim \frac{1}{(10^3\ \mathrm{TeV})^2}$$



Flavor and CP in the SM

Experimental picture

+ spectrum, *BR*, A_{CP}, particle-antiparticle oscillations
+ determine masses, mixing angles and phases

Theorist's view

+ In the absence of Yukawas, SM globally $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ symmetric

$$v\,Y_u = U_u \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} V_u \qquad v\,Y_d = U_d \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} V_d$$

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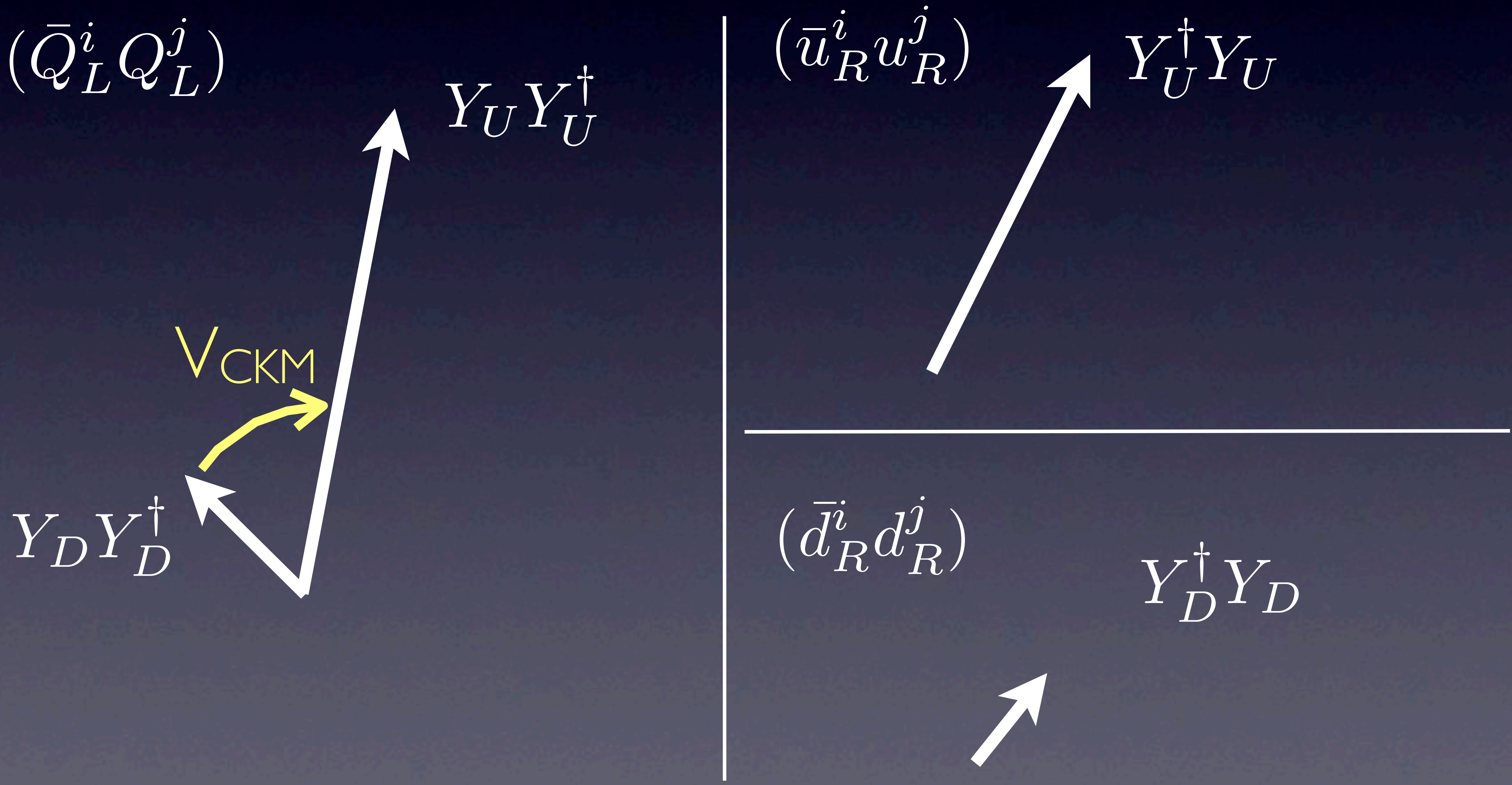
$\Downarrow$

V_{ckm}

unphysical due to SU(3)^3 !

Flavor and CP in the SM

Yukawa matrices Y_U & Y_D encode flavor violation



+ LR, RL

Charged currents:

measure only **LH misalignment**

$$v\,Y_u = \cancel{U_u} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cancel{V_u}$$

$$v\,Y_d = \boxed{V_{\mathrm{CKM}}} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cancel{V_d}$$

Charged currents:

measure only **LH misalignment**

Neutral currents:

enhanced flavor symmetry

$SU(3)_Q \rightarrow SU(3)_{u_L} \times SU(3)_{d_L}$

Yukawas diagonal, **no (tree-level) flavor violation**

$$v\,Y_u = \cancel{U_u} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cancel{V_u}$$

$$v\,Y_d = \cancel{V_{\rm CKM}} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cancel{V_d}$$

CP violation in the quark sector

Two 3x3 Yukawa matrices: 2 × (9 real, 9 phases)

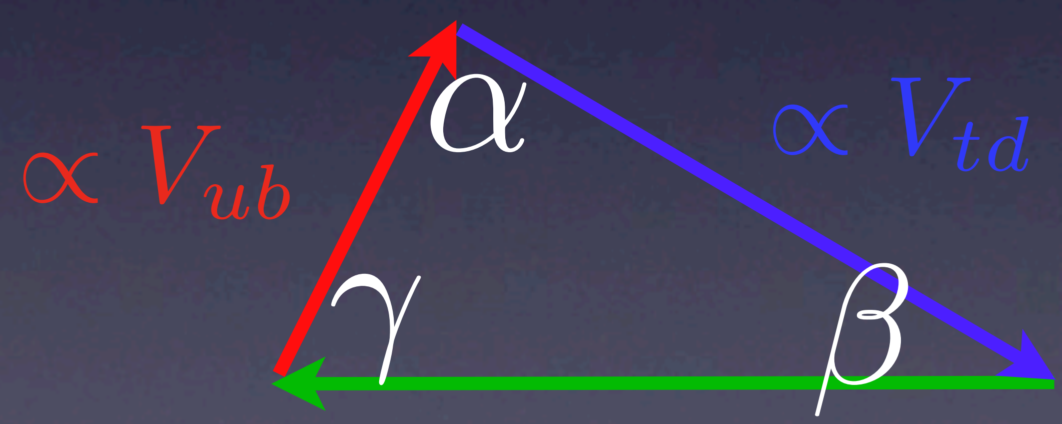
Flavor symmetry $U(3)_Q \times U(3)_u \times U(3)_d \,/\, U(1)_B$

rotates away $3 \times (3, 6)_{U(3)}$ - $(0,1)_B$ = (9 real, 17 phases)

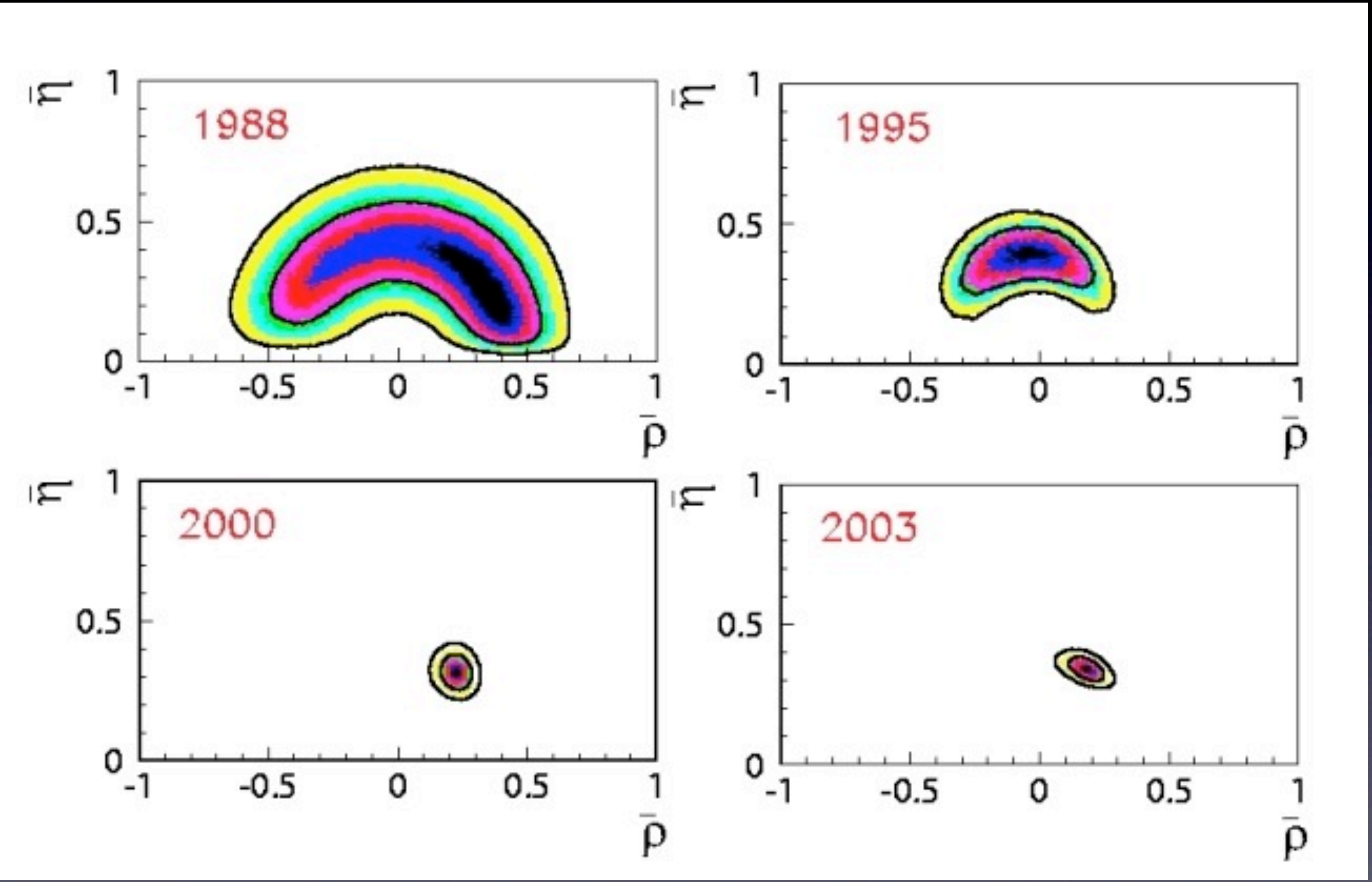
Physical parameters: $\Rightarrow$ (6_{masses} + 3_{angles} , $\mathbf{1}_{\mathbf{CP}}$)

$$(V_{\mathrm{CKM}})^{\dagger} V_{\mathrm{CKM}} = \mathbf{1}$$

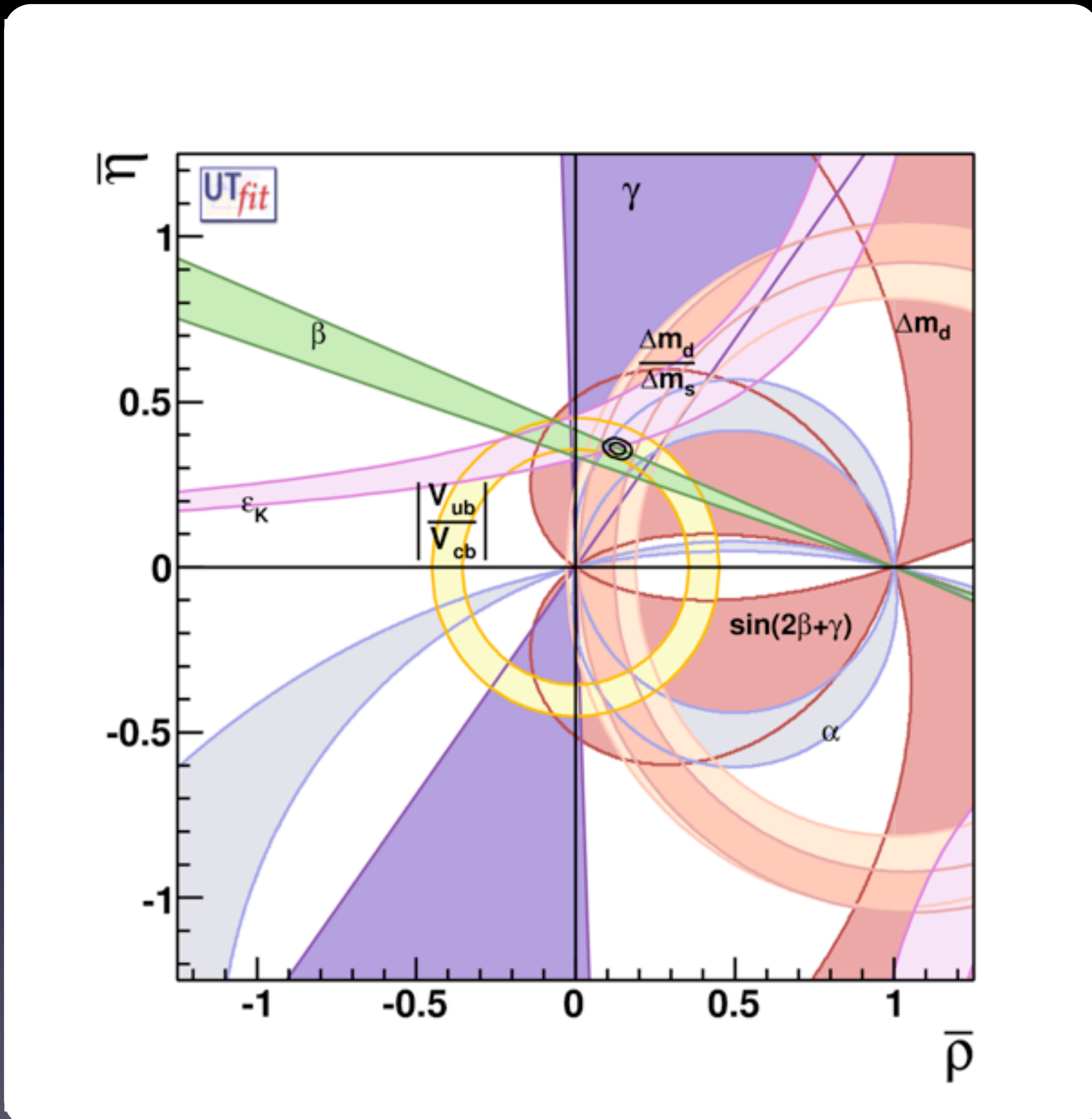
$$V_{ub}^{*} V_{ud} + V_{cb}^{*} V_{cd} + V_{tb}^{*} V_{td} = 0$$



We have come a long way…



source: utfit.org



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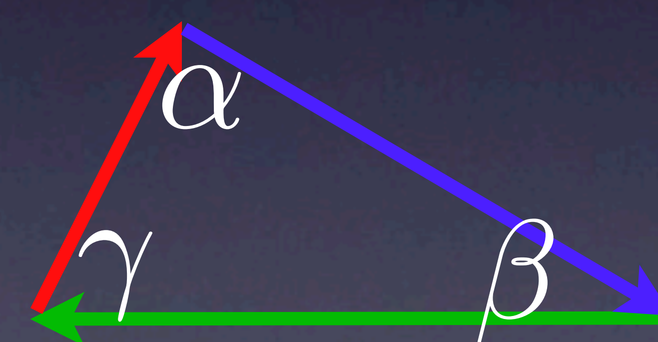
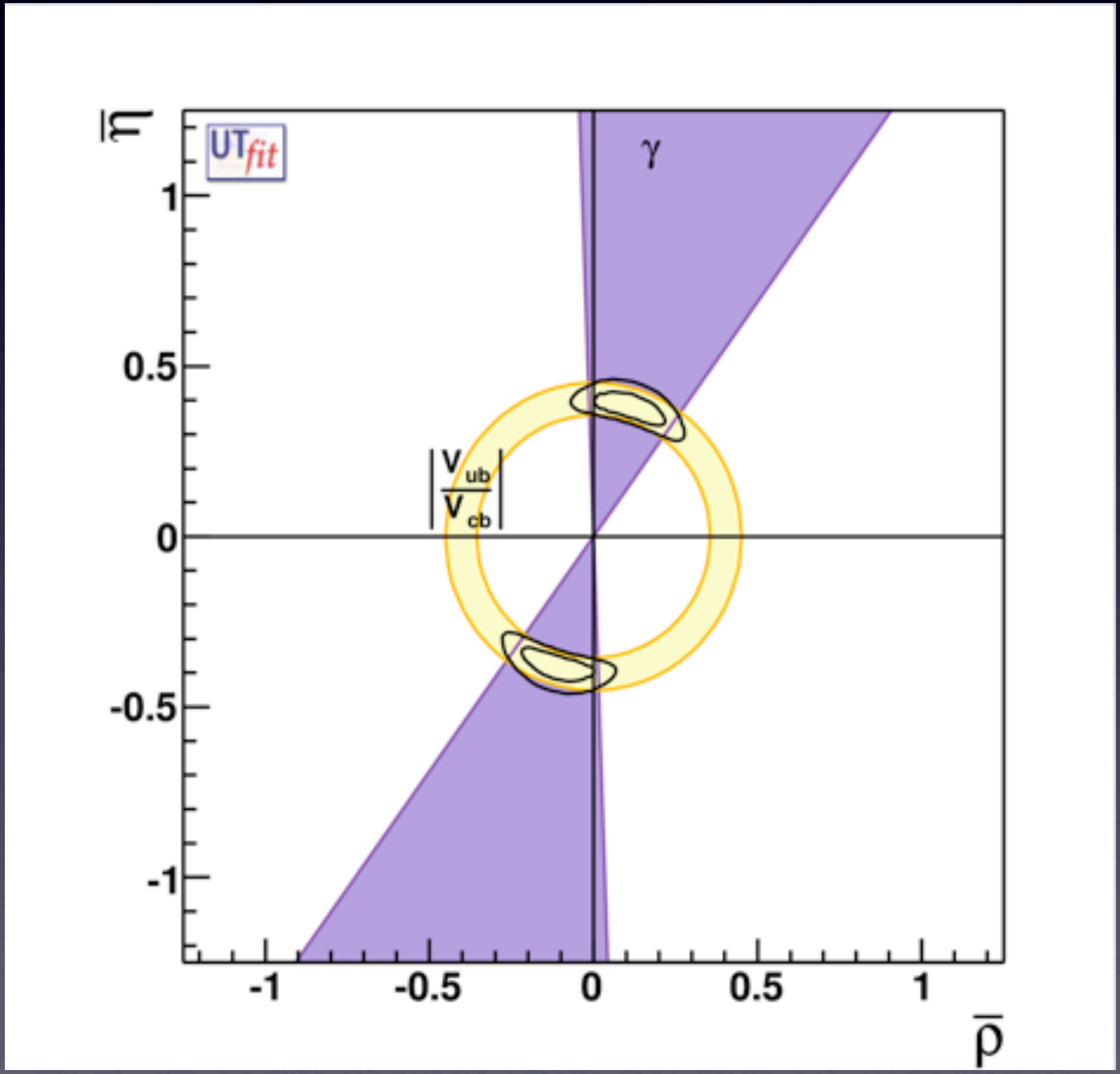


Only a subset of all constraints, other precision tests also consistent…

Tree level CKM

not affected by new physics, crucial to constrain NP



$$\gamma[^\circ] = -106 \pm 11$$
$$\text{and } \ 74 \pm 11$$

Need better precision in gamma to resolve tensions in CKM!

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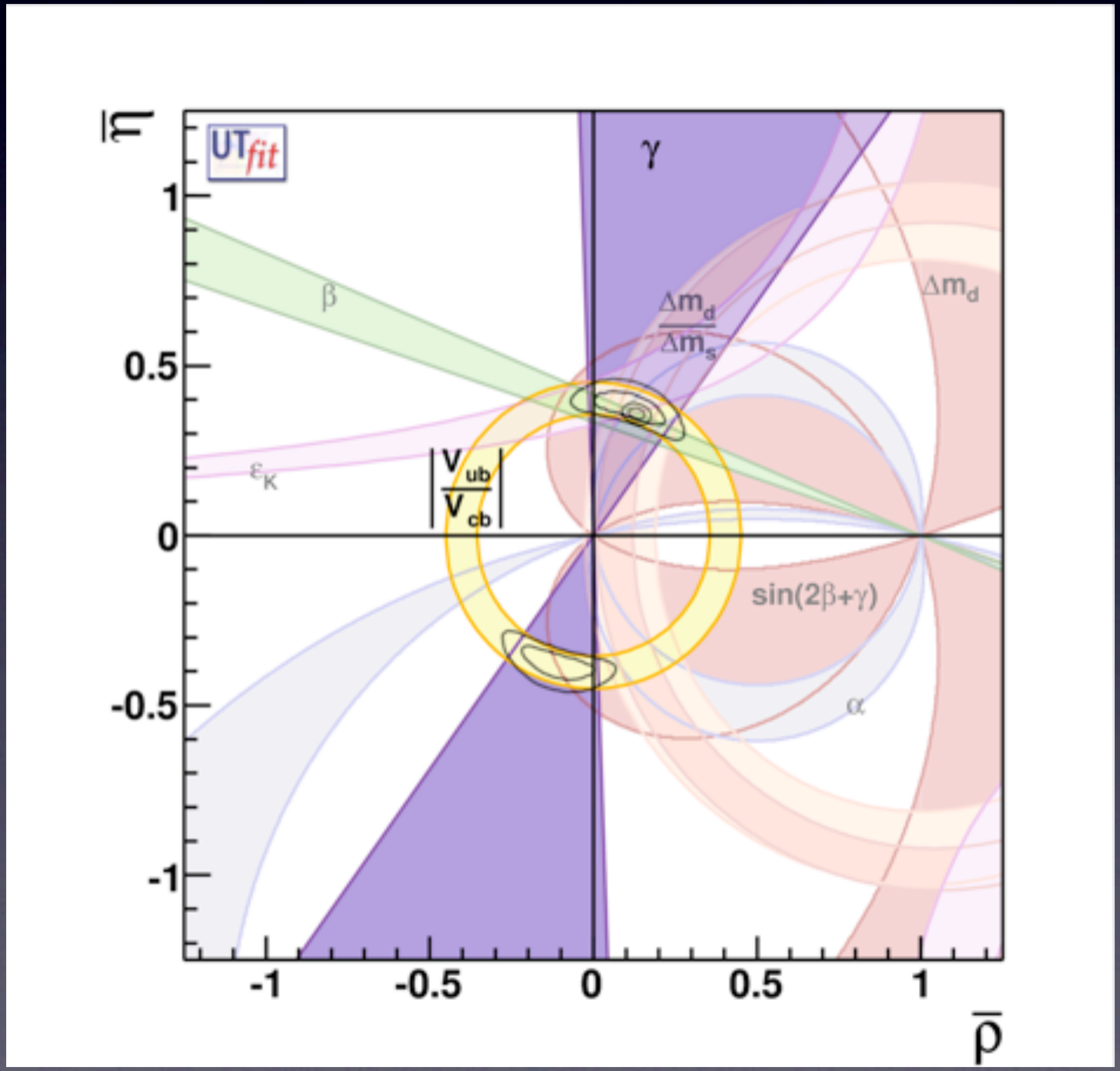

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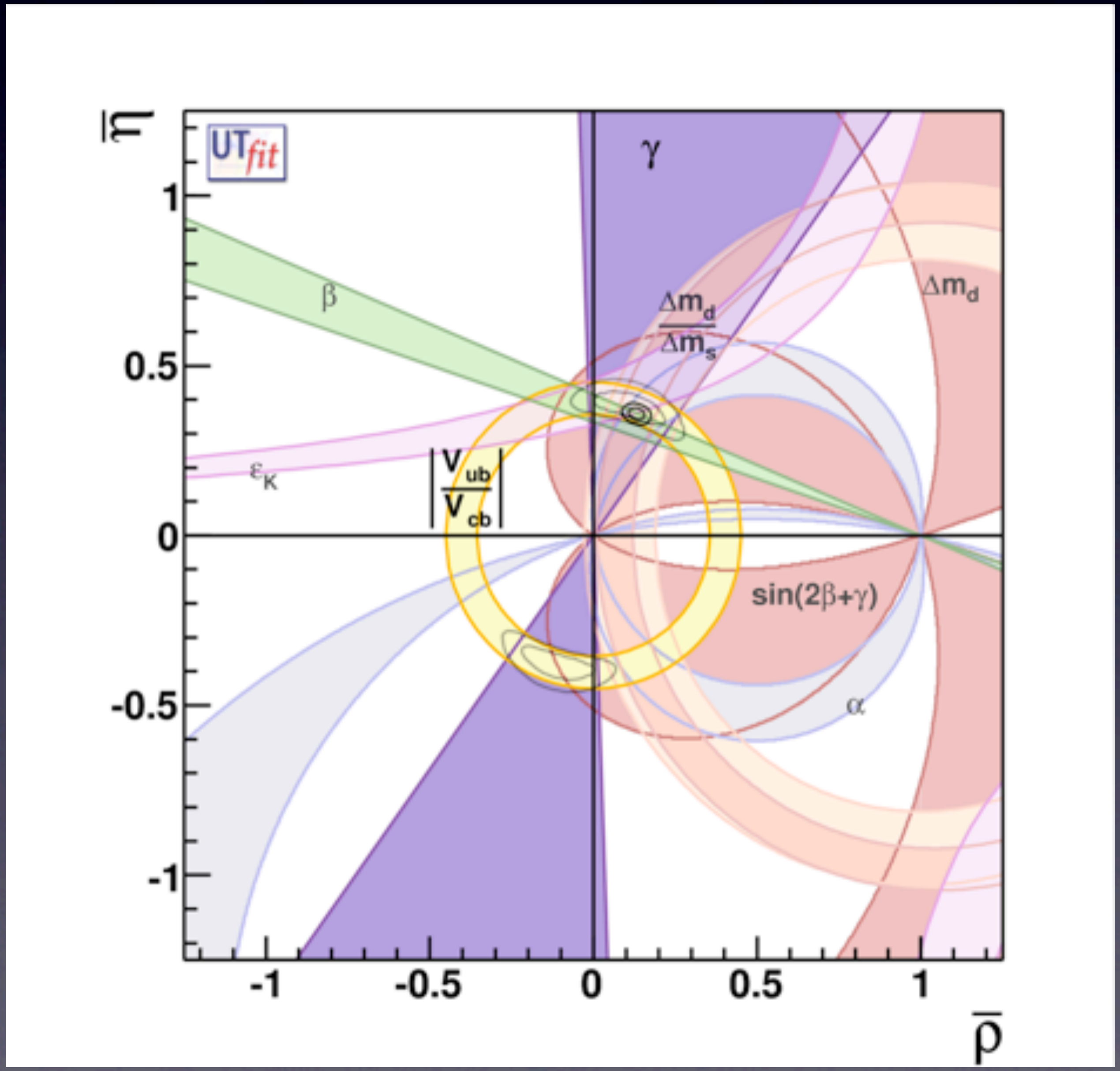

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CKM assumption self-consistent?

"*Most likely, CP violation in flavor violating processes is dominated by the KM-phase.*"

Various 2~3 σ tensions: first signs of NP or flukes?

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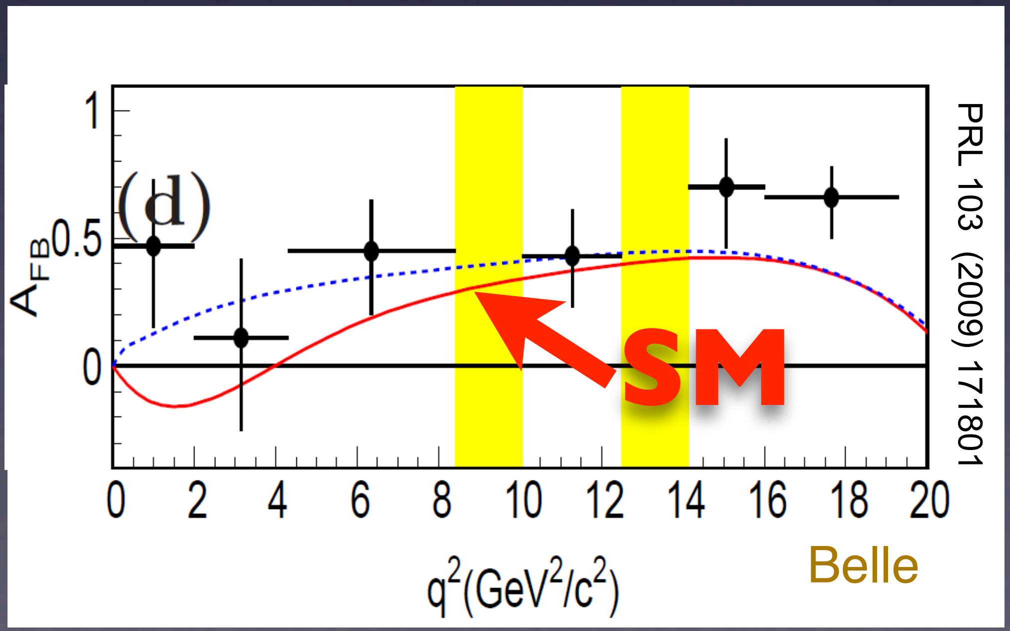
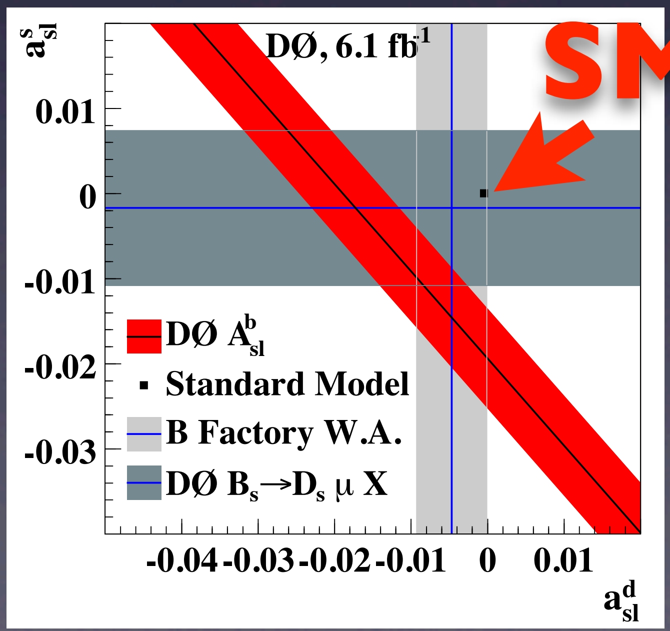
Various 2~3 σ tensions: first signs of NP or flukes?

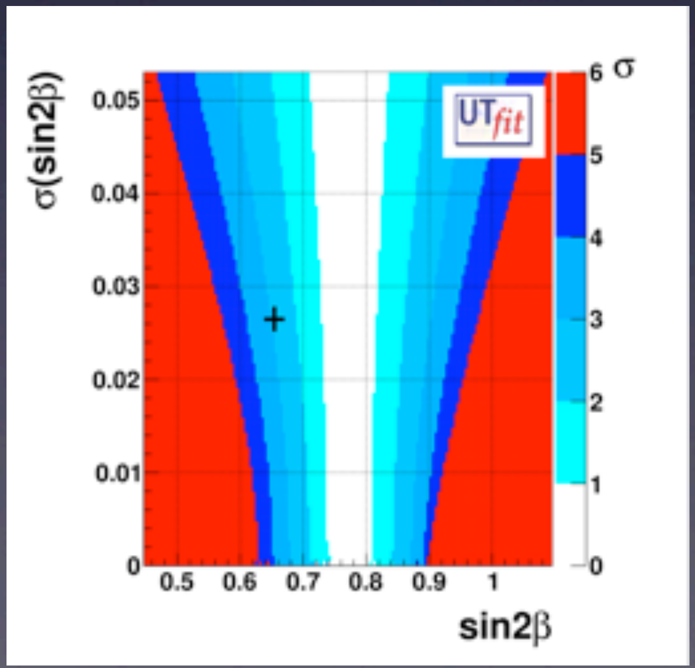
~2.7 σ



~3.2 σ



~2.6 σ



+ CDF & BaBar results

NB: CDF in $A_{\psi\phi}$ in agreement with SM at 1 σ

Future experimental challenges

These tensions might all go away with higher statistics.

Want high precision determination of theoretically clean observables.

Preferably 1) SM "Null tests" (CP phase in B_s-$\underline{B}_s$)
2) SM FCNC + additionally suppressed (helicity suppression of $B_q \to \mu^+ \mu^-$)
3) tree-level CKM (γ)
4) FB Asymmetries $B \to K^* \mu\mu$
5) Golden Kaon modes $K \to \pi\nu\nu$

Future ... ges

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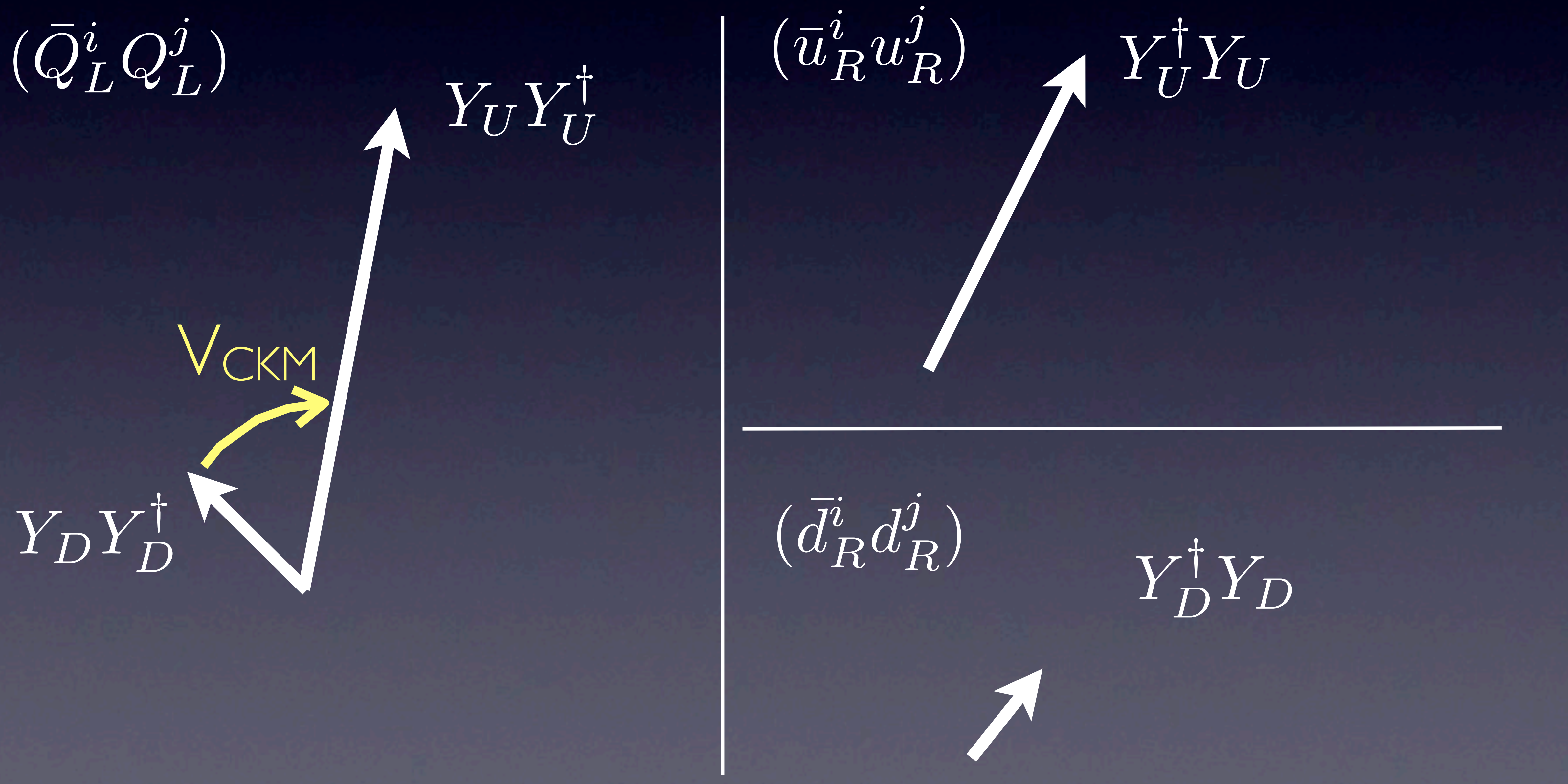
Flavor and CP in the SM

Yukawa matrices Y_U & Y_D encode flavor violation



+ LR, RL

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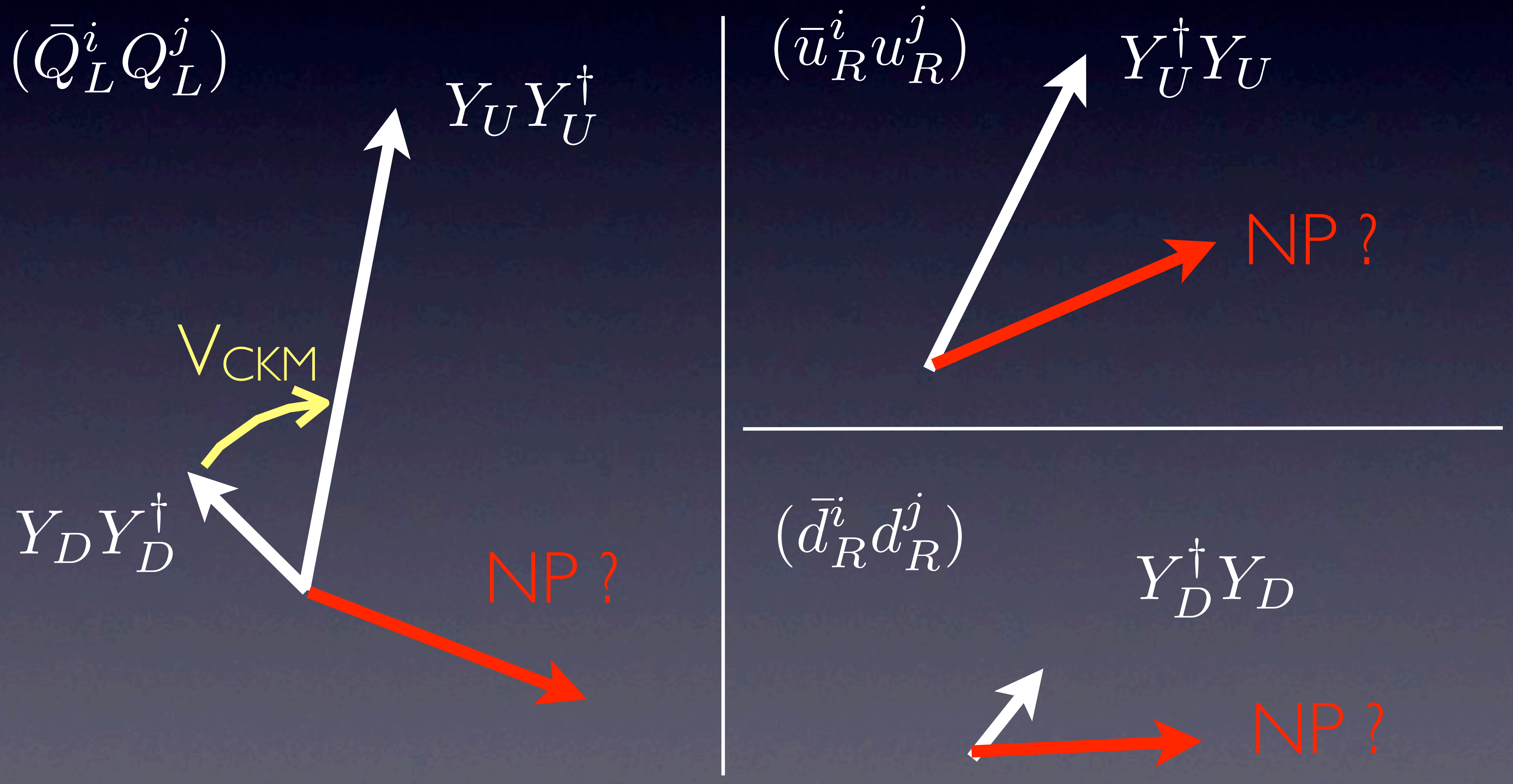


+ LR, RL

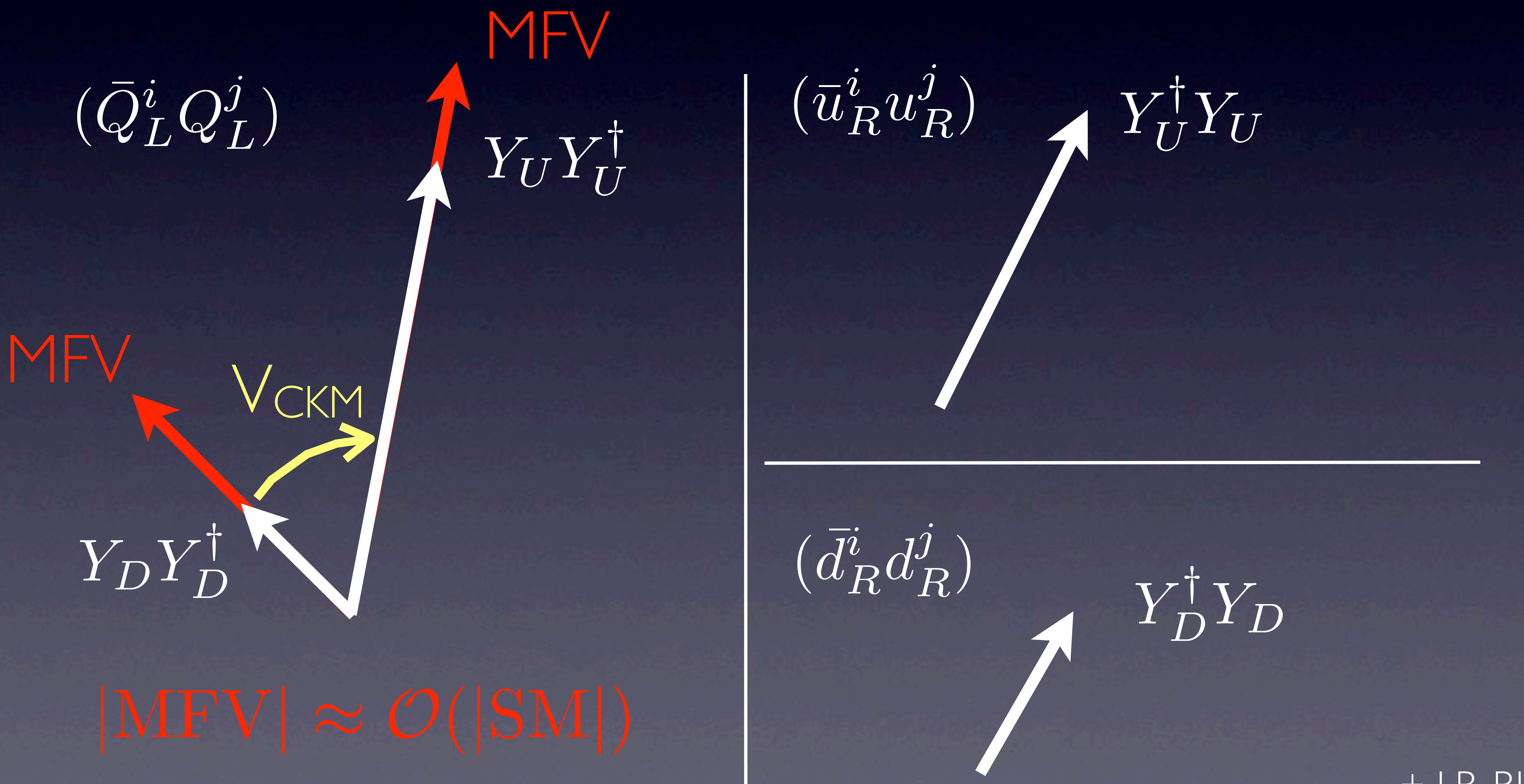
2)

Any theory of the weak scale (susy, technicolor, extra-dimensions,…) has some flavor breaking. Can it be non-minimal?

Minimal flavor violation

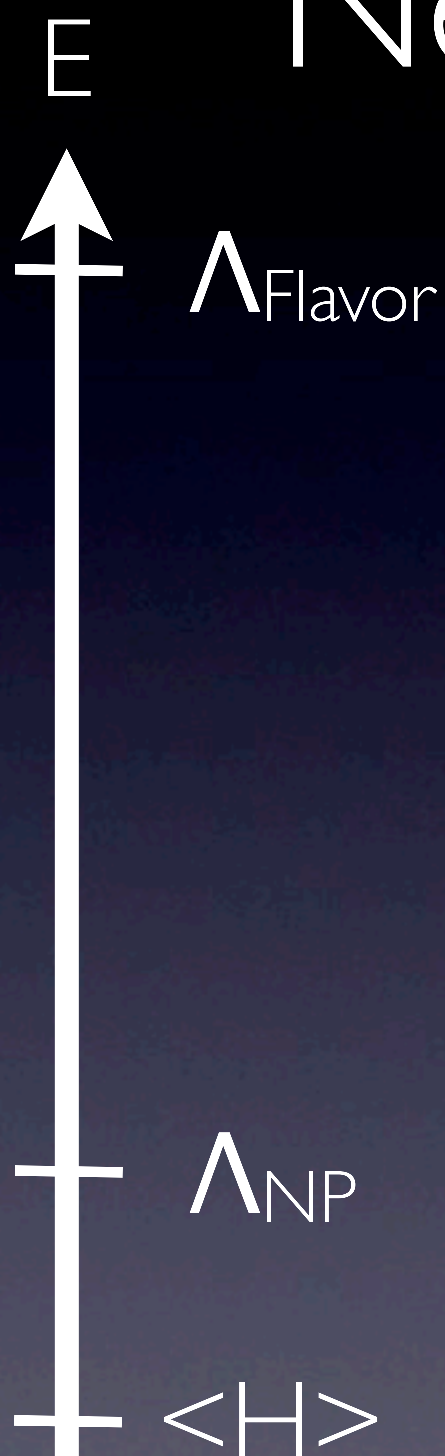
Chivukula Georgi; Buras et. al; D'Ambrosio et. al

New particles/interactions, but flavor structure ~V_{CKM}



condition: moderate tanß or small $U(1)_{PQ}$ breaking

New physics is MFV, if...



Origin of flavor structure decoupled

$\Lambda_{Flavor} >> \Lambda_{NP}$

NP below Λ_{Flavor} is flavor degenerate (or flavor like in SM)

But : little learned about the origin of flavor ☹

MFV example: SUSY

MSSM with unbroken SUSY is already MFV!

=> MSSM is MFV if ~~SUSY~~ is flavor blind

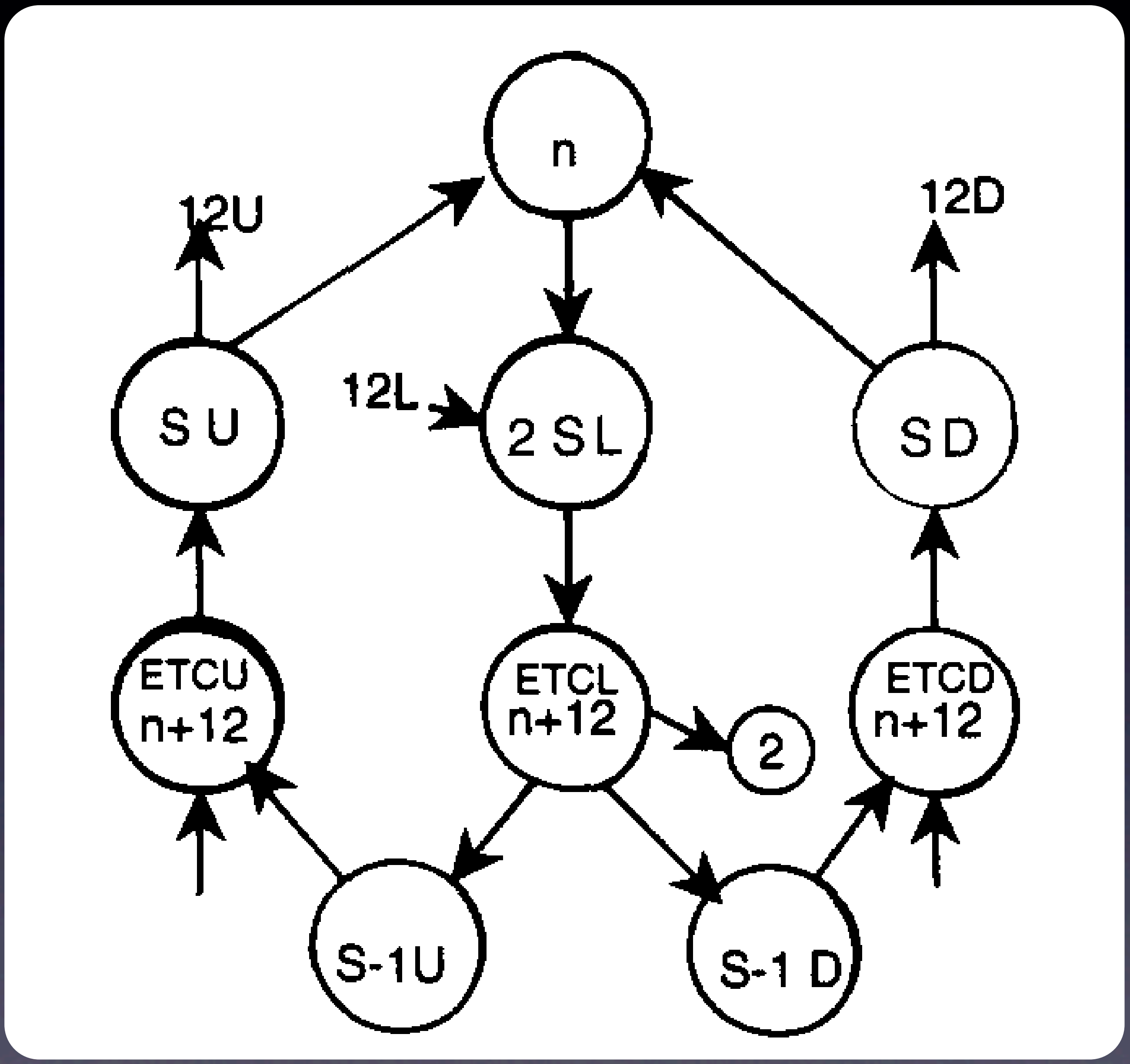
Example: Gauge mediation with $M_{mess} << \Lambda_{flavor}$

(Gravity mediation in general not MFV)

MFV non-SUSY alternatives: UED and the Littlest Higgs with appropriate UV completions.

MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi,Randall '87; Randall '93; Georgi '94, Skiba '96



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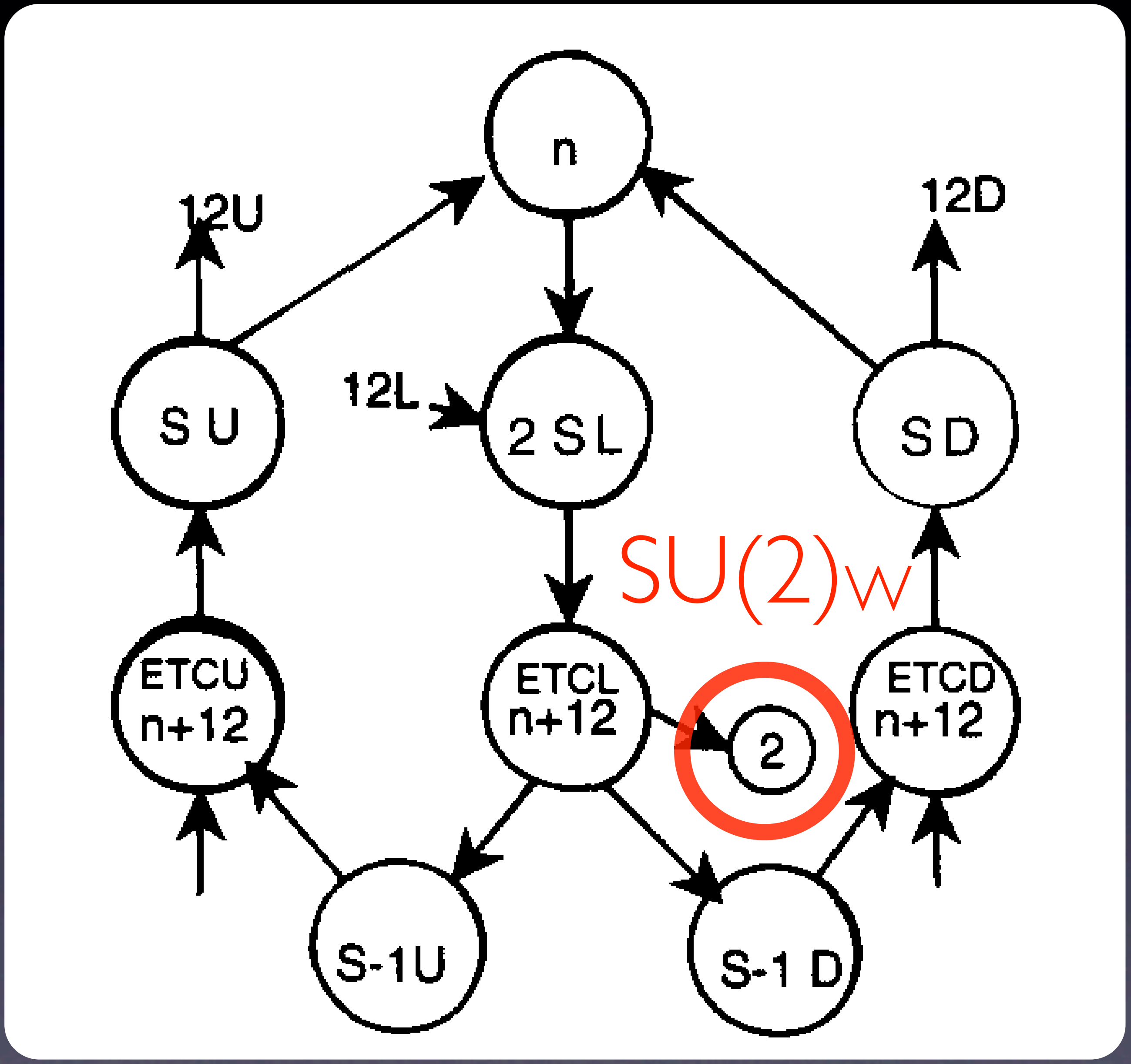

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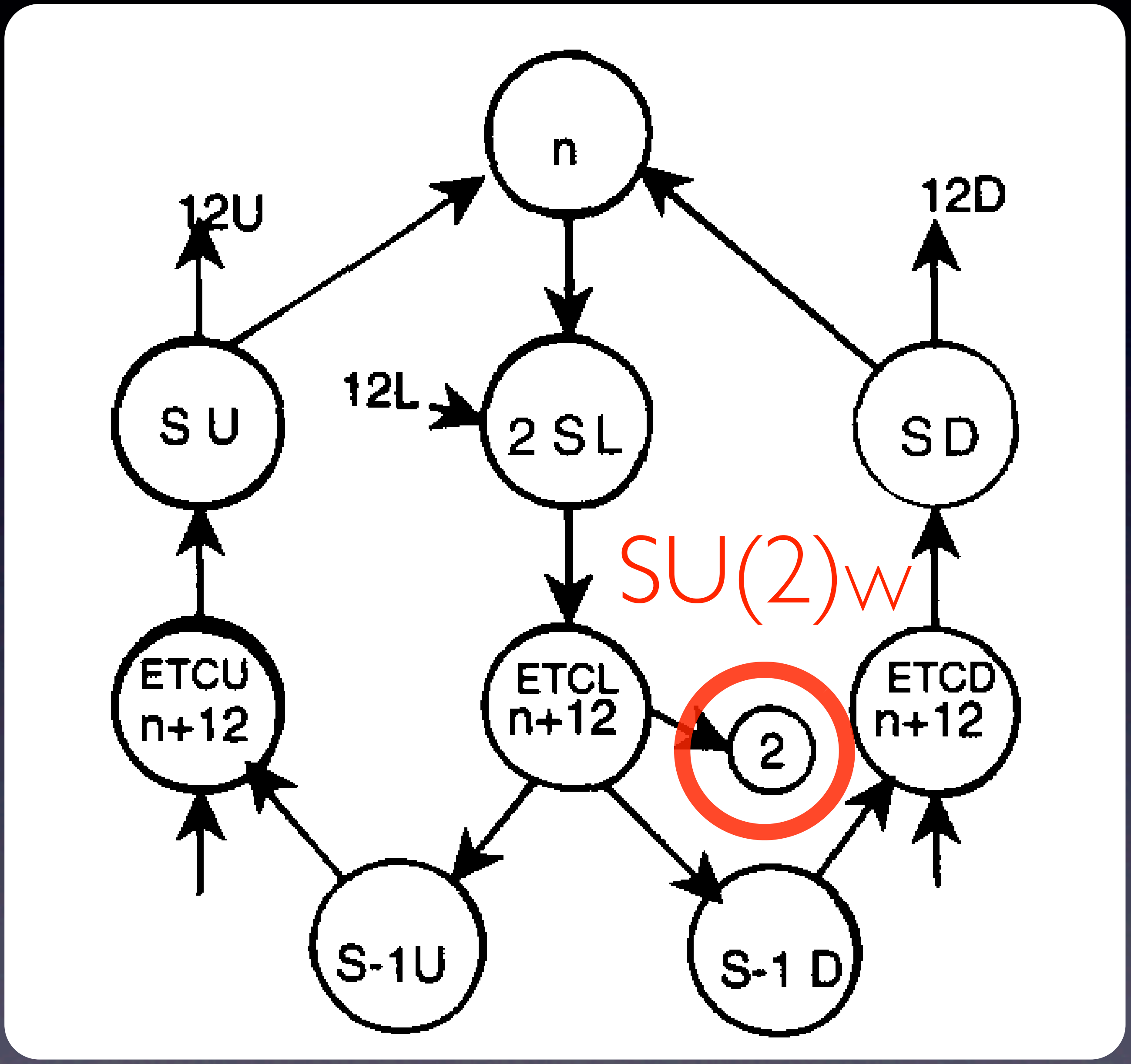


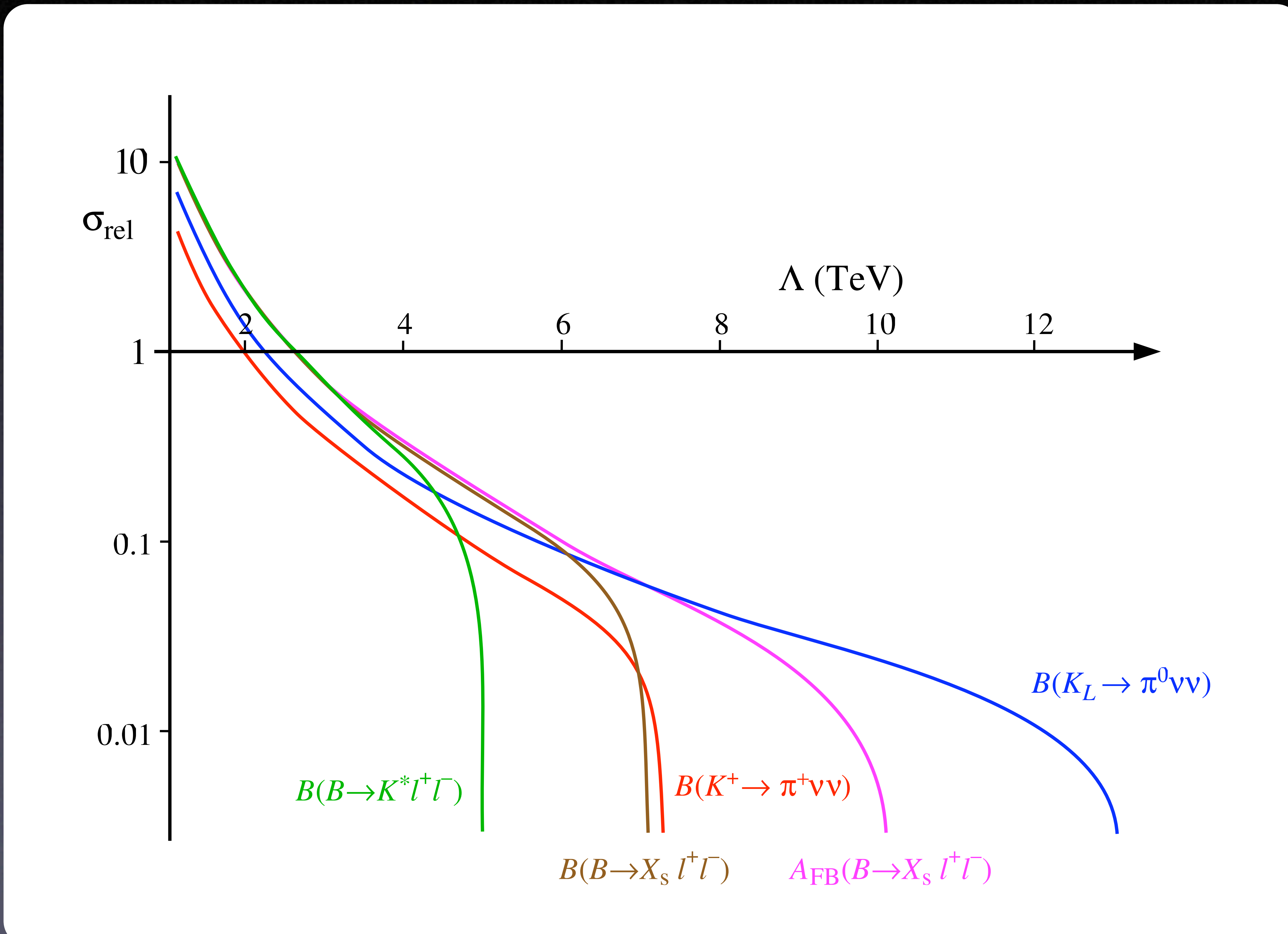
Simpler proposal:

AdS/CFT construction : 5D GIM mechanism

Cacciapaglia, Csaki, Galloway, Marandella,Terning, A.W., '08

Distinguishing MFV & SM is hard

D'Ambrosio, et al; Buras et al '05



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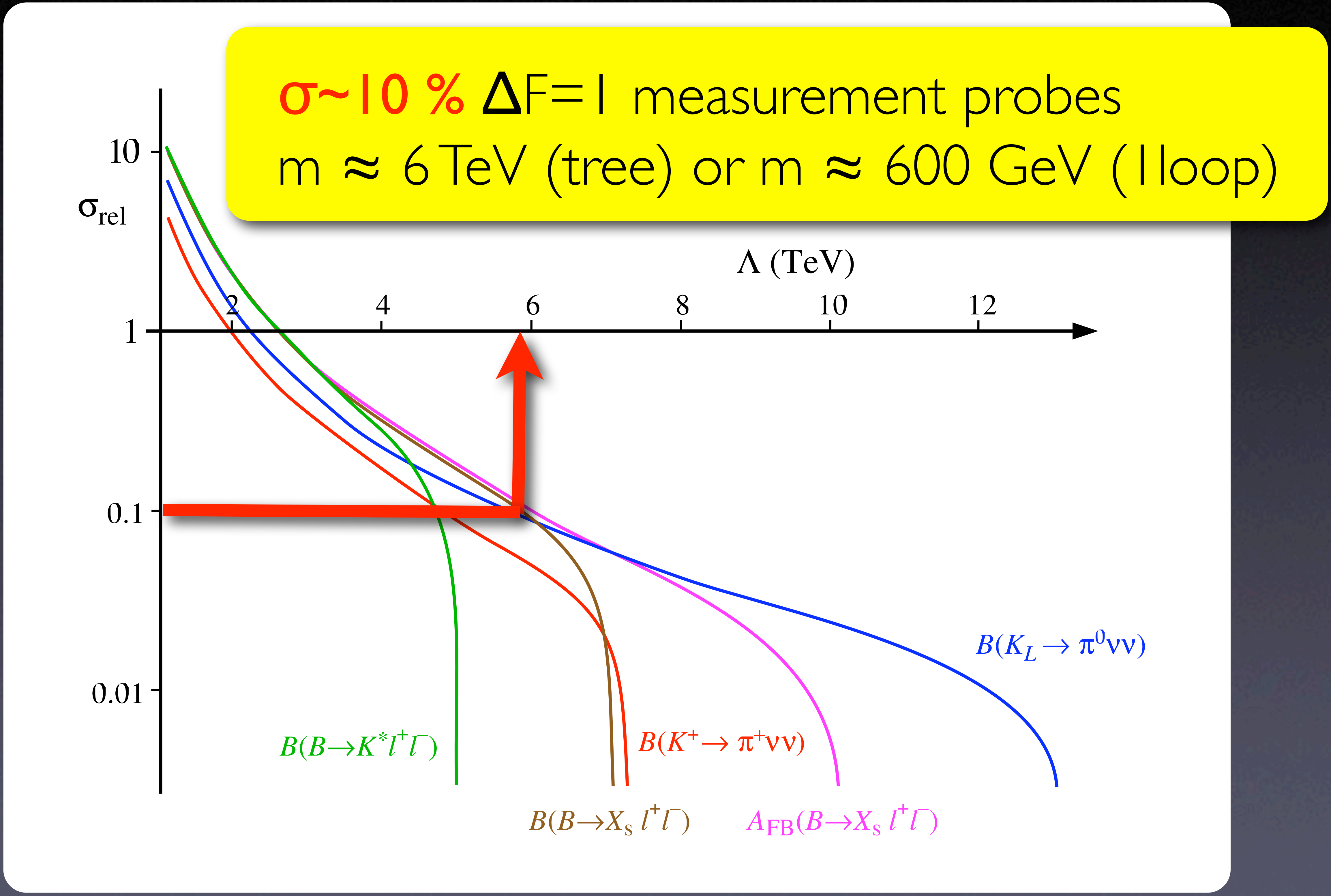
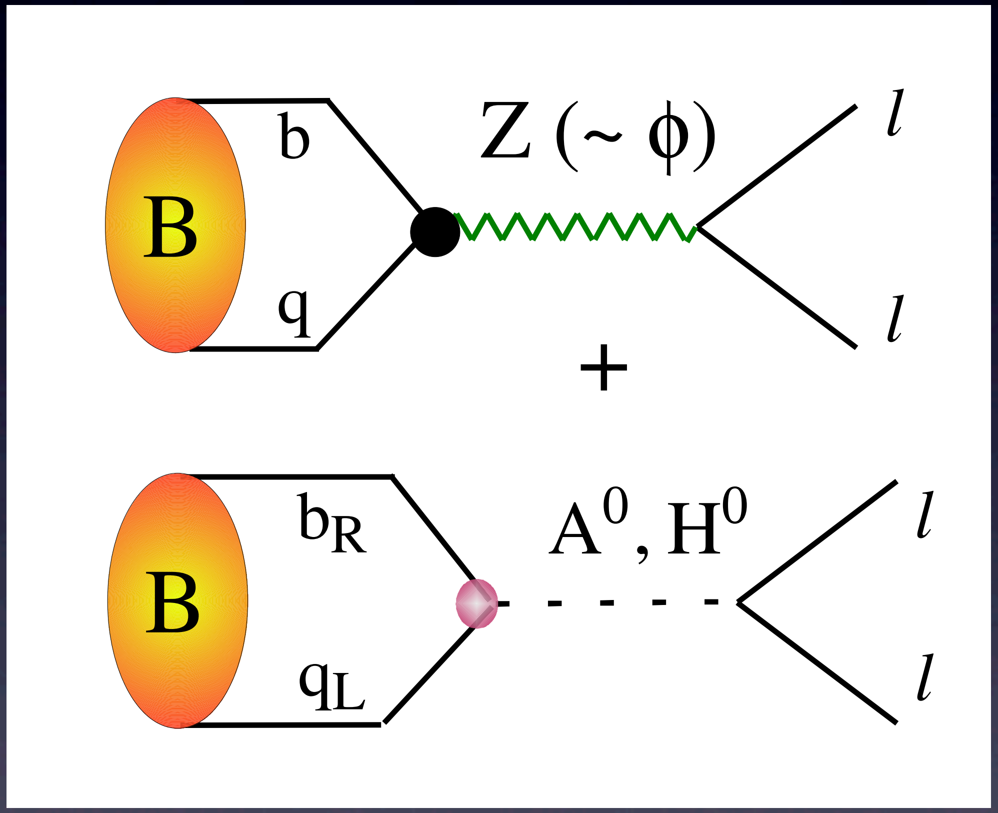


$\mathrm{Br}(\mathrm{B}_{\mathrm{d,s}} \to \mu^+\mu^-)$



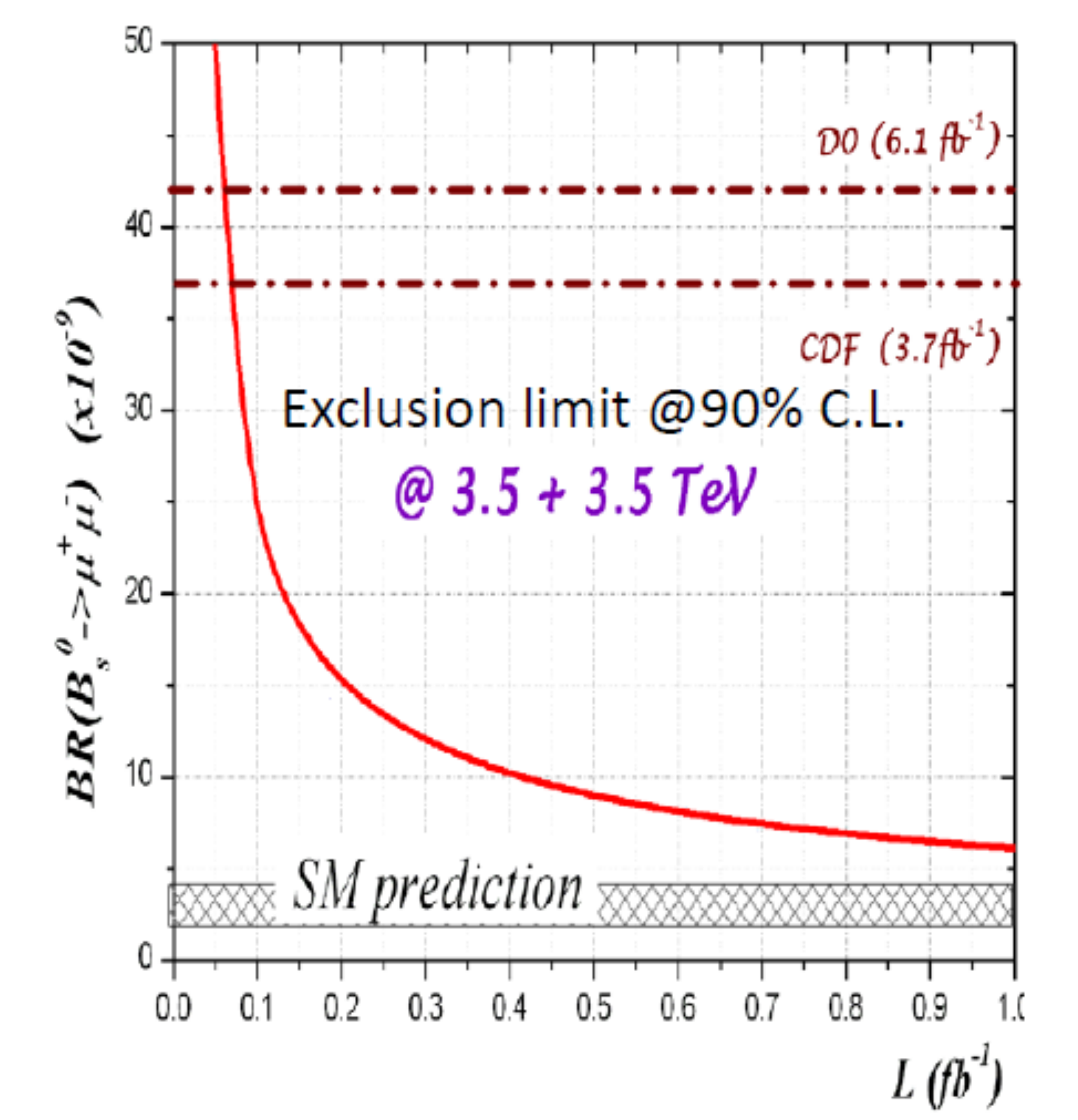
In the SM both GIM and helicity suppressed

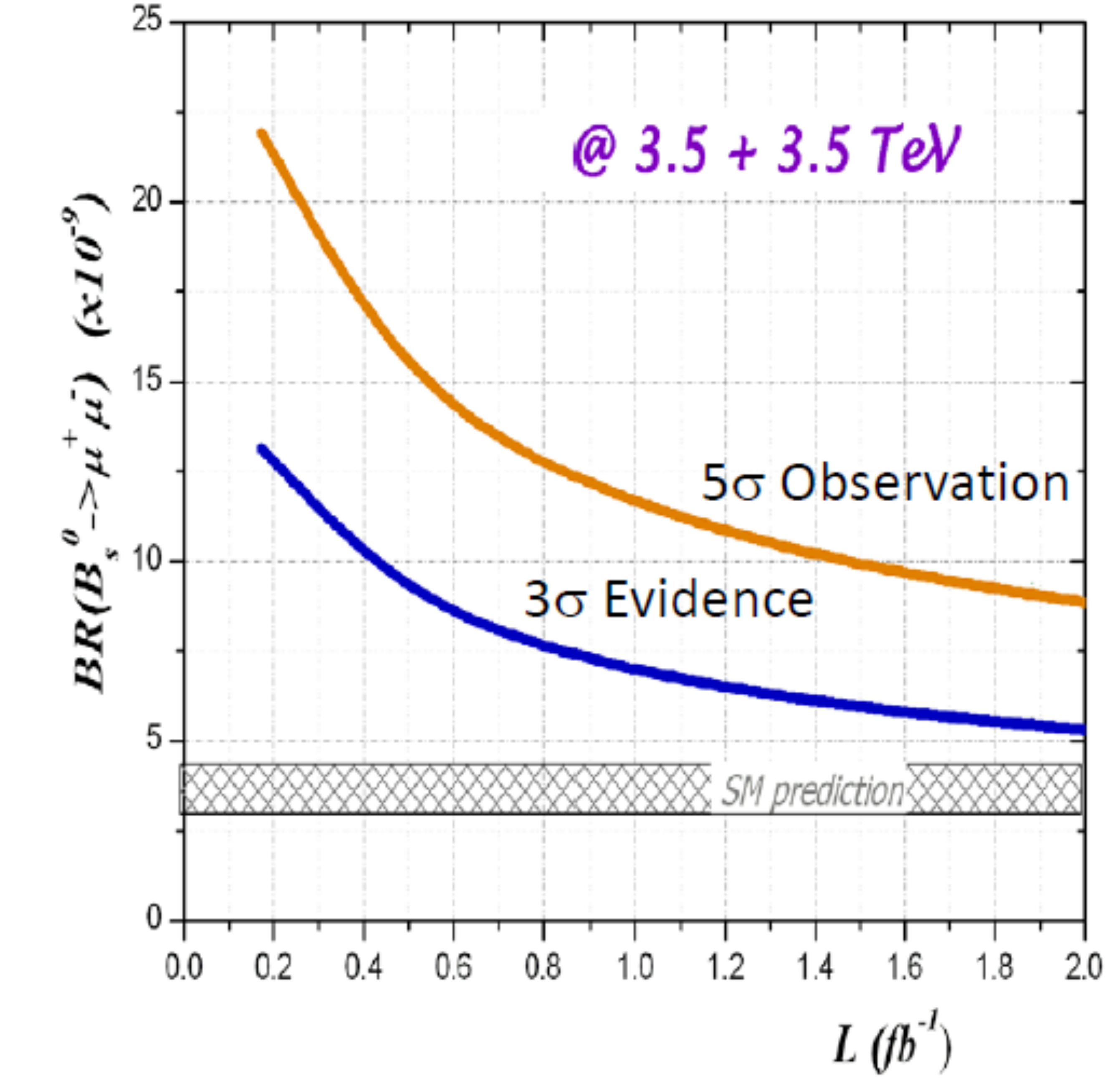
$$Br \propto \frac{m_\mu^2}{M_B^2}|V_{tb}V_{ts}|^2$$

Can be magnitudes larger in multi-Higgs models even in MFV. In the MSSM:

$$Br \propto (\tan\beta)^6$$

$Br(B_s \to \mu^+\mu^-)$ LHCb sensitivity for 1/fb

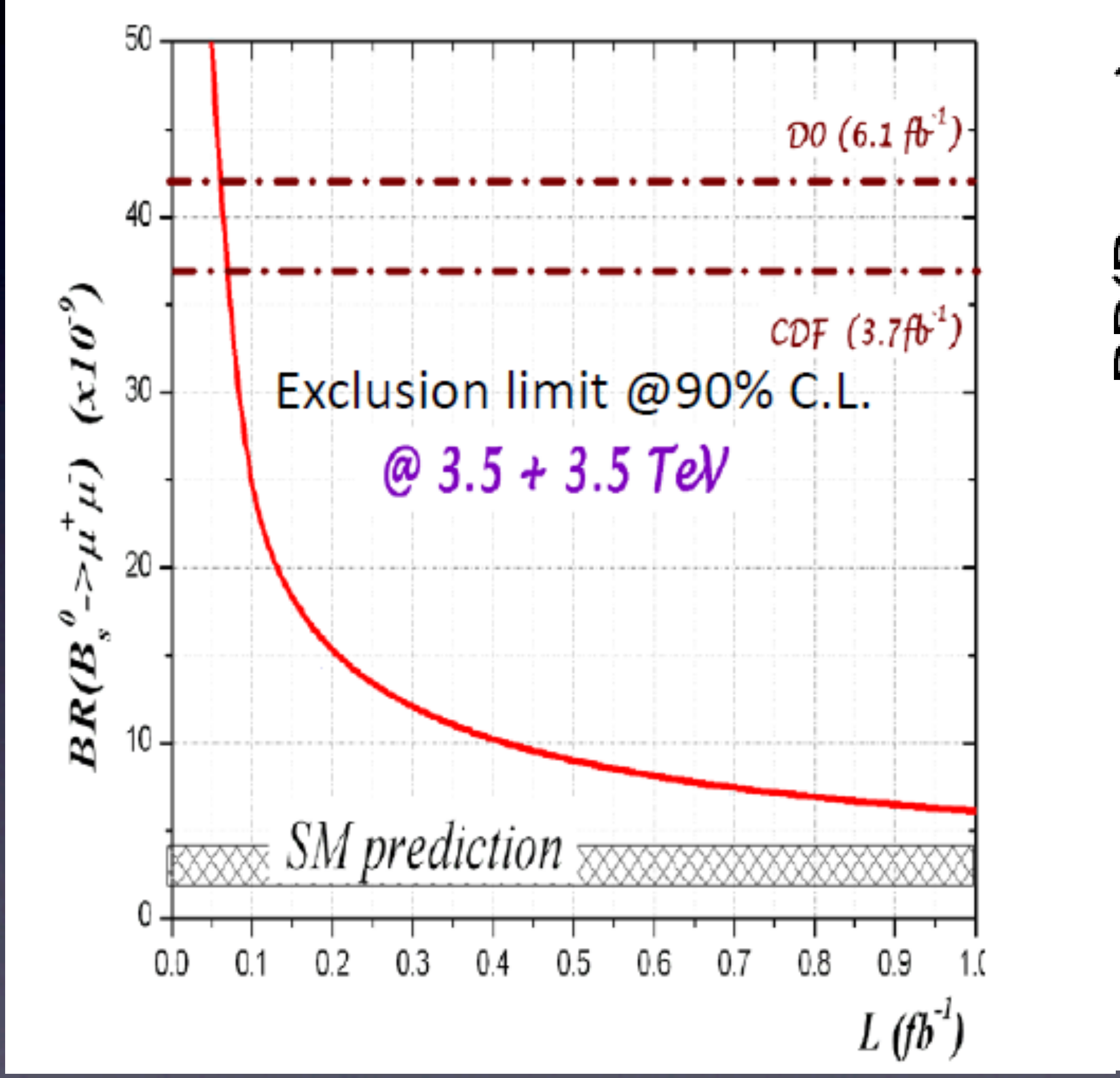


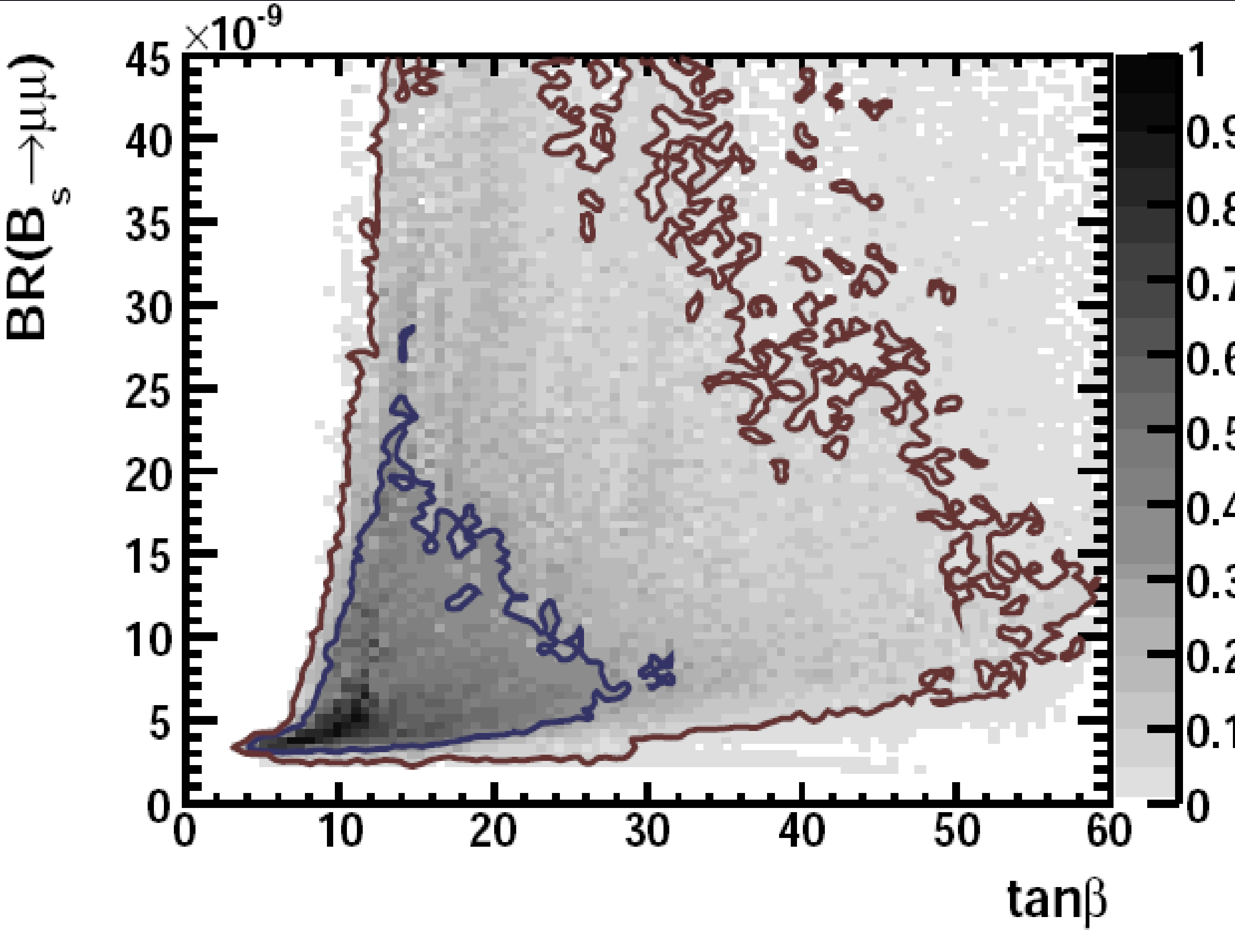


searches also by ATLAS EXPERIMENT & CMS

$B_s \to \mu^+\mu^-$

MSSM: $Br \propto (\tan\beta)^6$





Buchmuller et al. arXiv: 0907.5568
Constrained – MSSM with
non-universal Higgs masses (NUHM)

Falsifying MFV is easy...

...once you have shown that the SM is dead

e.g. Bobeth, Bona, Buras, Ewerth, Pierini, Silvestrini, A.W.

MFV falsified by violating "sum rules"

New CP phases e.g. CPV in Bs mixing $A_{\psi\phi}$

At the LHC: Br(q_3)~ Br($q_{1,2}$)

Top FCNCs

...

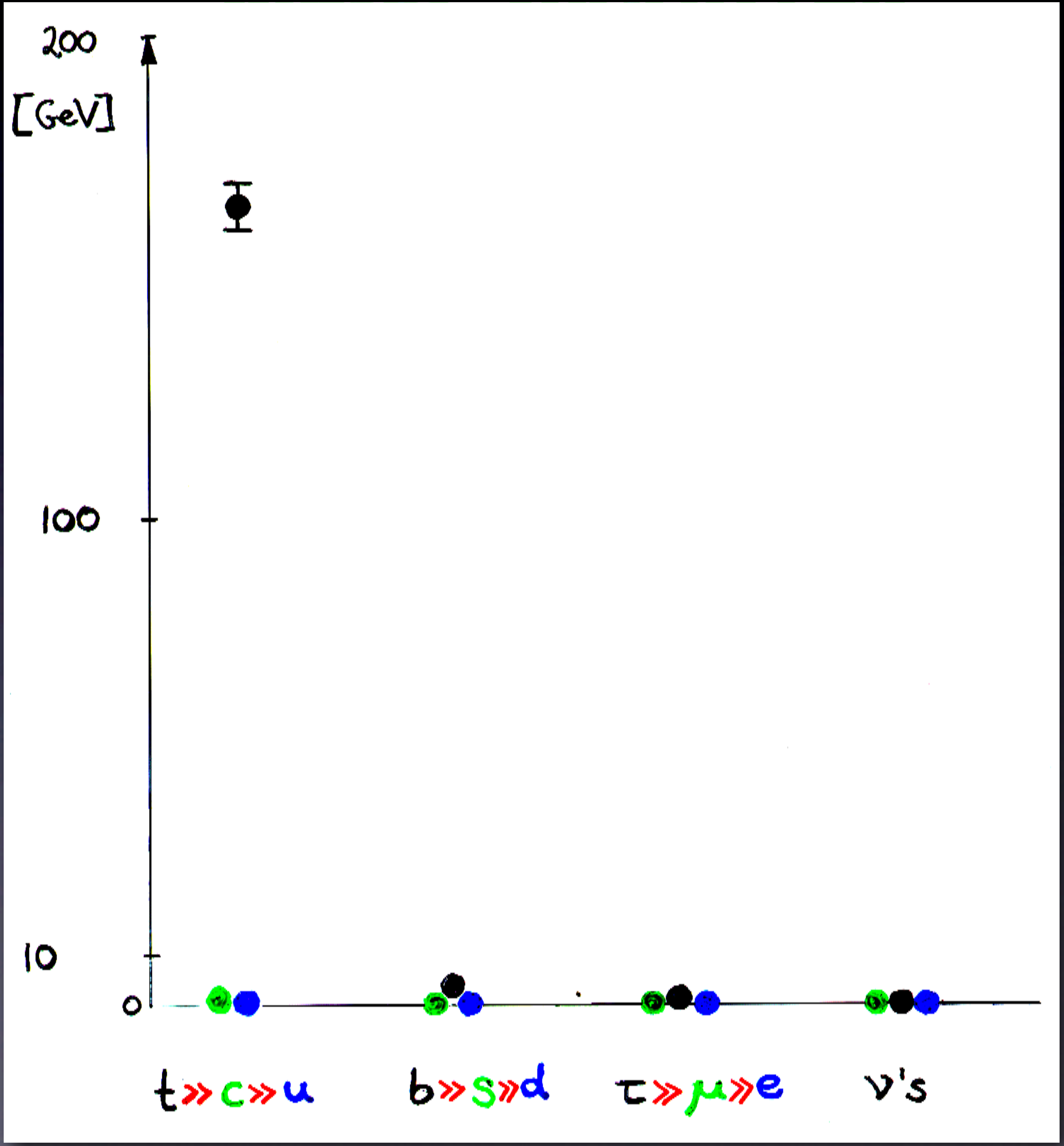
Is there anything else beside the SM Yukawa couplings?

→ main goal of flavor physics in the early LHC phase

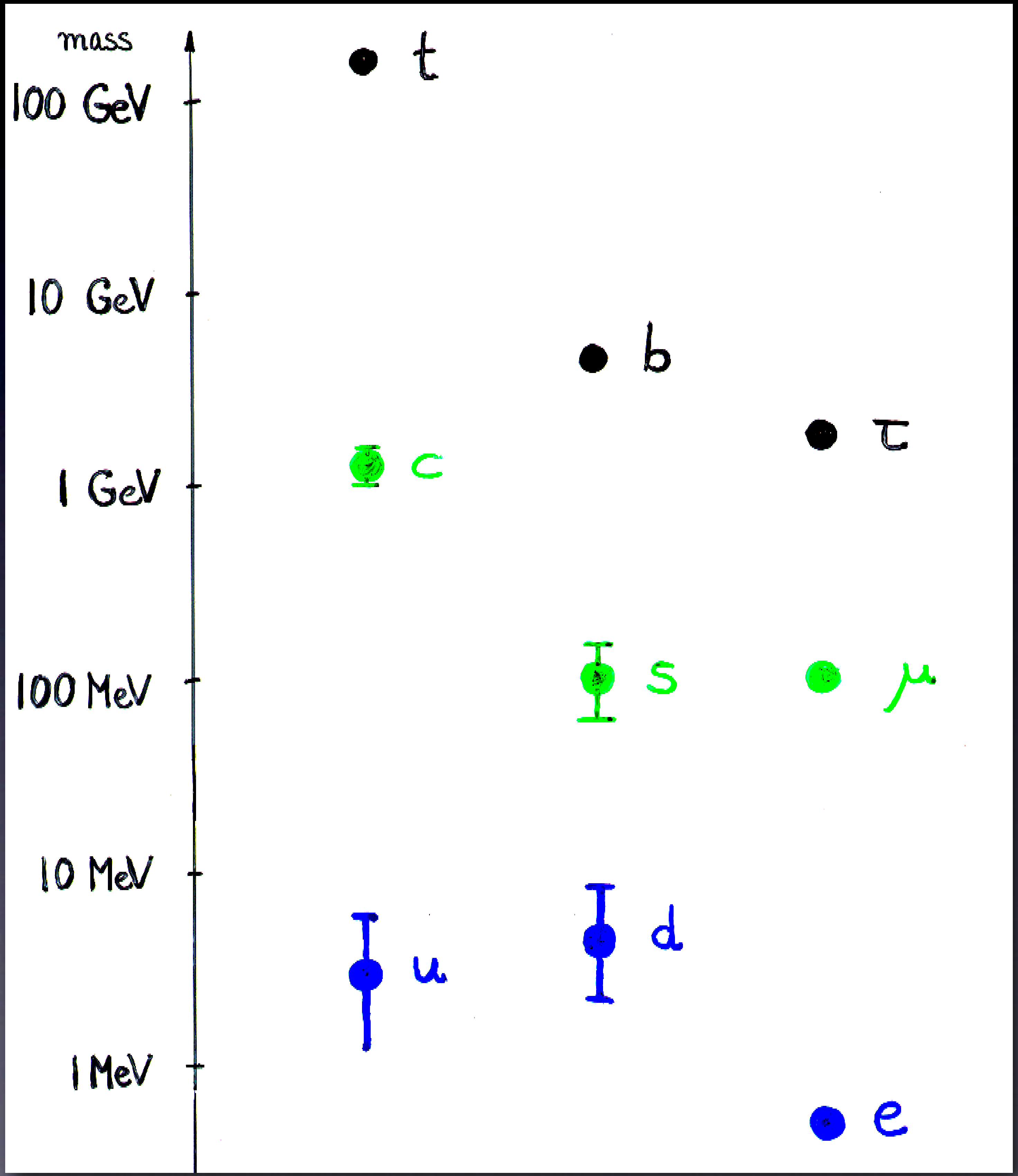
3)

Will we be able to learn something about the origin of flavor at the LHC?

Quark and Lepton mass hierarchy



Masses on a Log-scale



The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2\cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

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

Why this structure?

Other dimensionless parameters of the SM:

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

Log(SM flavor puzzle)

$$-\log|Y_D| \approx \mathrm{diag}\,(11 \quad 8 \quad 4)$$

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

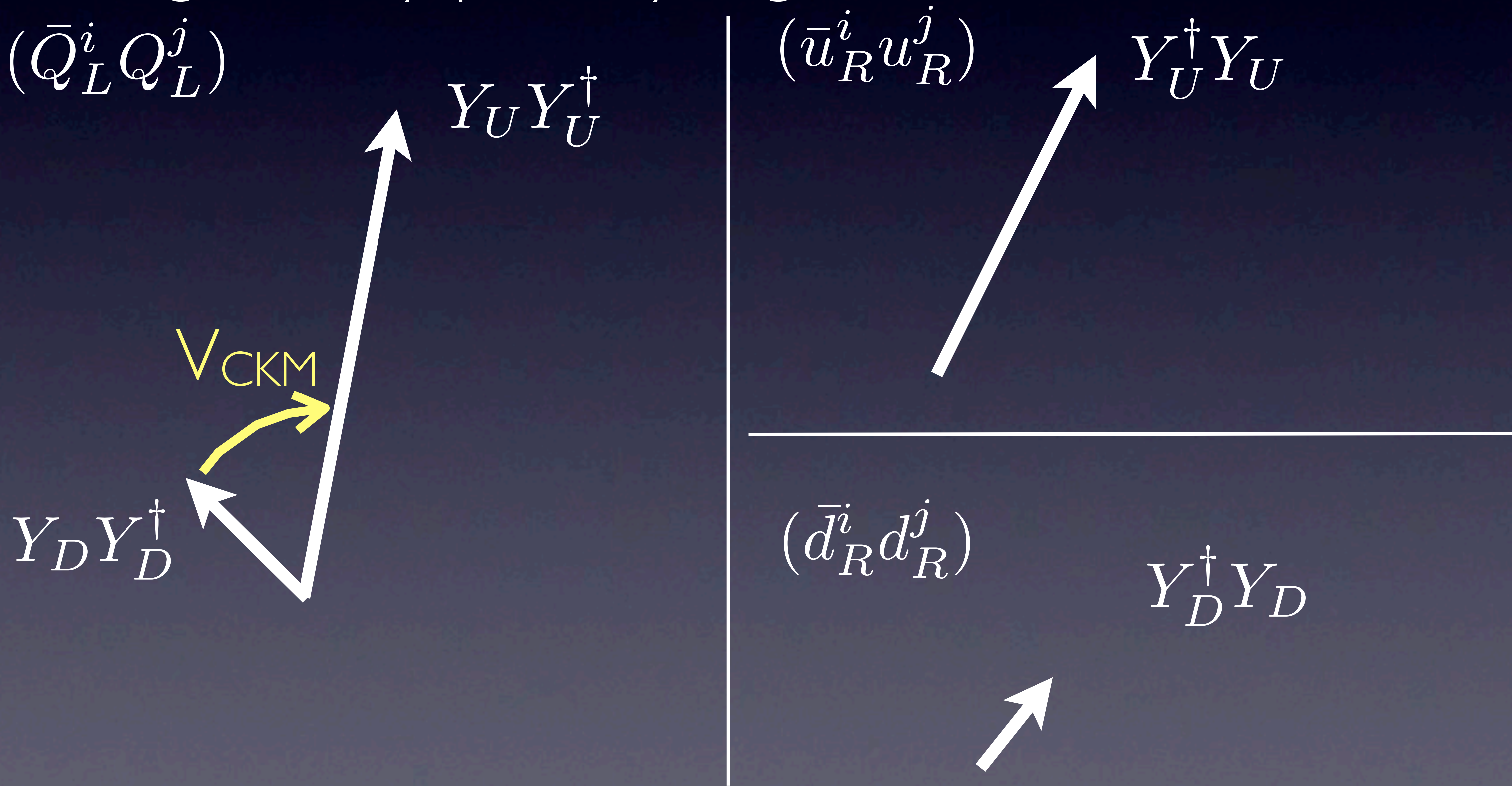
If $Y = e^{-\Delta}$, then the Δ don't look crazy.

anarchic ("structure-less")

$$\begin{aligned}
\mathrm{Mass}_{ij} &\propto Y_{ij} e^{-MR(c_i+c_j)} && \text{split fermions/RS} \\
&\propto Y_{ij} \left(\frac{\mu_{\mathrm{low}}}{\mu_{\mathrm{high}}}\right)^{\gamma^i+\gamma^j} && \text{strong dynamics} \\
&\propto Y_{ij} \left(\frac{\langle\Phi\rangle}{M_{\mathrm{mess}}}\right)^{Q^i-Q^j} && \text{Froggatt-Nielsen}
\end{aligned}$$

NP Flavor dynamics

Dynamics that generates hierarchies in masses & mixings usually partially aligned with SM



+ LR, RL

NP Flavor dynamics

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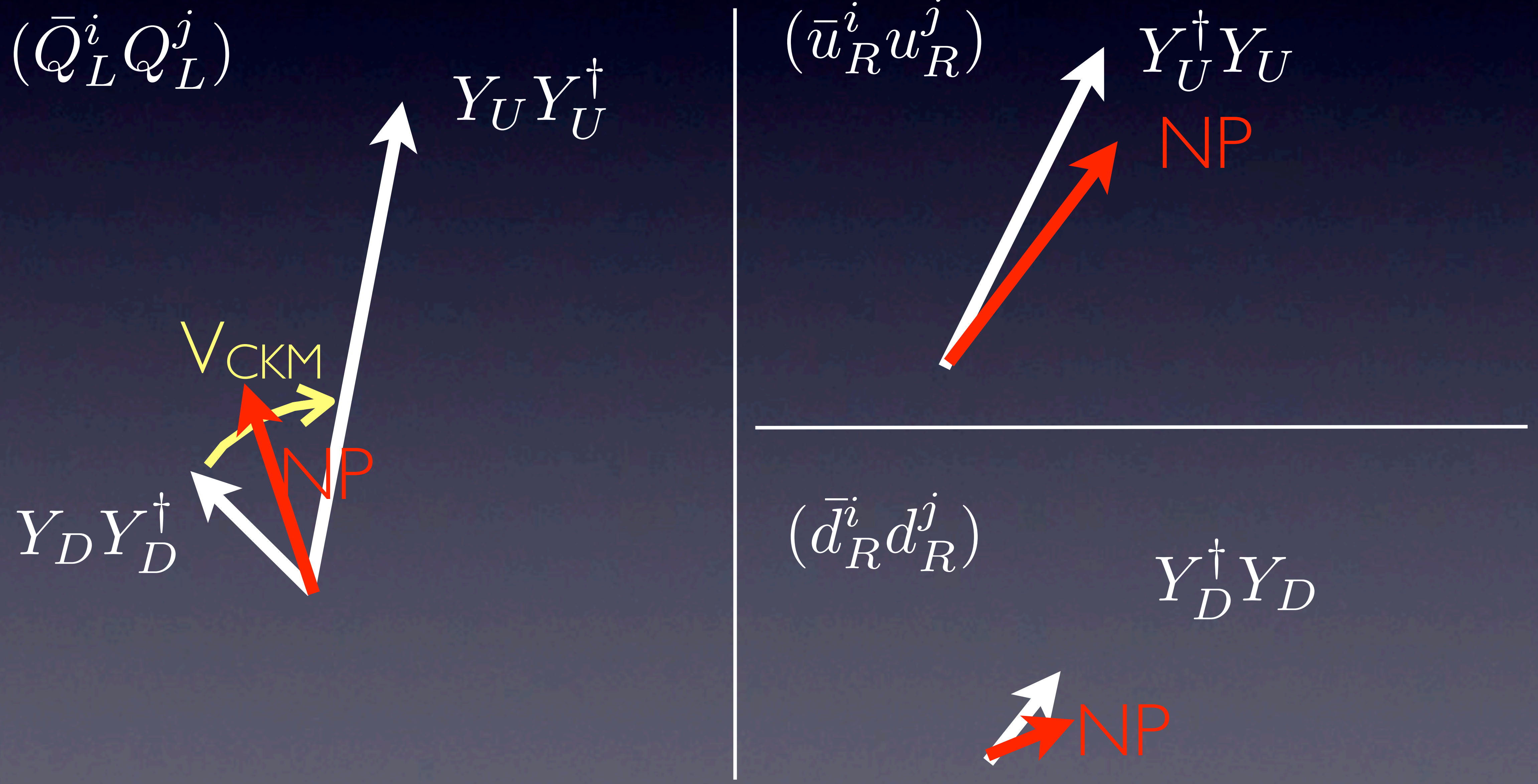

+ LR, RL

NP Flavor dynamics

Dynamics that generates hierarchies in masses & mixings usually partially aligned with SM

$(\bar{Q}^i_L Q^j_L)$ $Y_U Y_U^\dagger$

$(\bar{u}^i_R u^j_R)$ $Y_U^\dagger Y_U$

NP

Effects are O(SM) but not MFV, still possible for M ~ TeV: expect signatures also in direct tests!

NP

+ LR, RL

How low can we go?

Although the mechanism to generate the hierarchies looks similar, constraints are different.

$$(\bar{Q}_L^I X^{IJ} Q_L^J)$$

MFV: $X^{IJ} = (Y_U Y_U^\dagger)^{IJ} \approx \lambda_t^2 V_{3I}^* V_{3J}$

wave-function/RS $X^{IJ} \sim F_Q^I F_Q^J \sim (F_Q^3)^2 \, V_{3I} V_{3J}$

$U(1)_{\text{horizontal}}$ $X^{IJ} \sim \left(\frac{\theta}{M}\right)^{-Q_I + Q_J} \approx \lambda^1 \text{ or } \lambda^5 \ldots$

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depending on model & charge assignments

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	U(1)	U(1)′
$\bar{Q}_1$	-3	0
$\bar{Q}_2$	0	-1
$\bar{Q}_3$	0	0
D_1	1	-2
D_2	-4	1
D_3	0	-1
U_1	1	-2
U_2	-1	0
U_3	0	0

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Leurer Nir Seiberg

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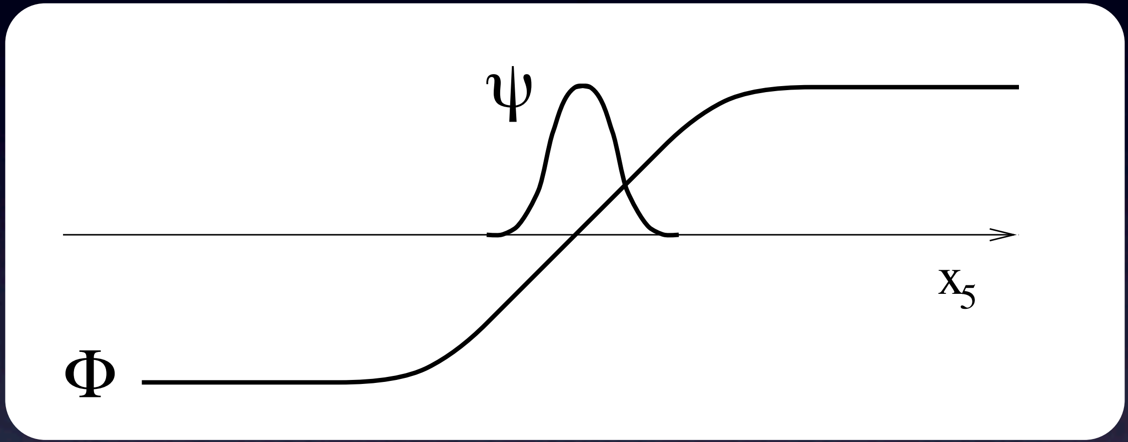
Hierarchies w/o Symmetries

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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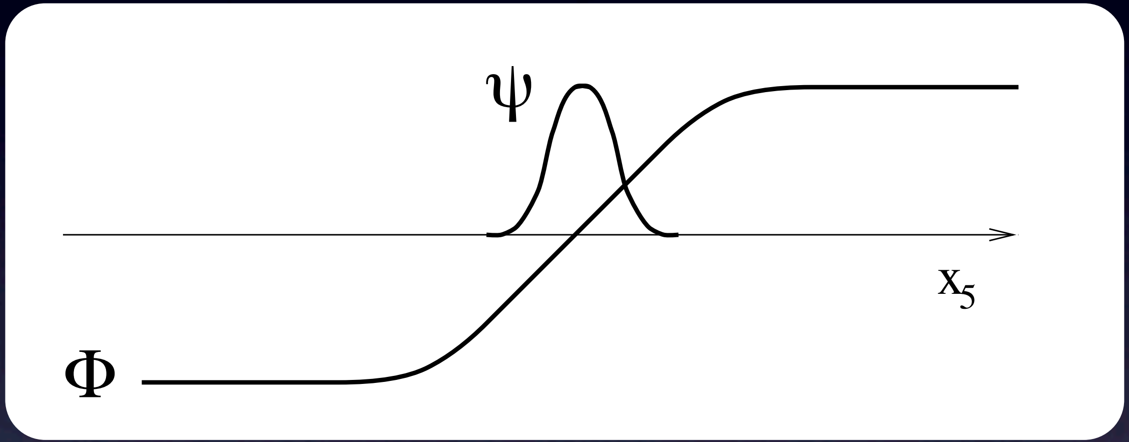

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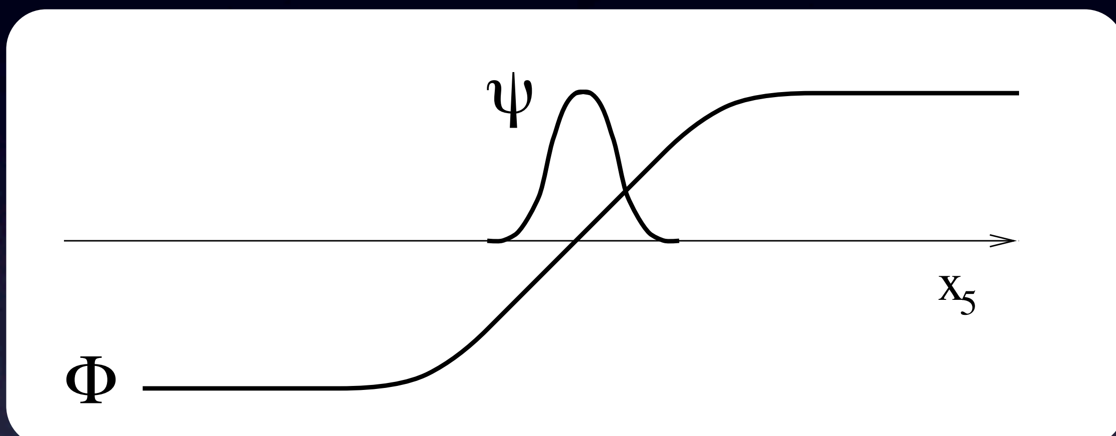

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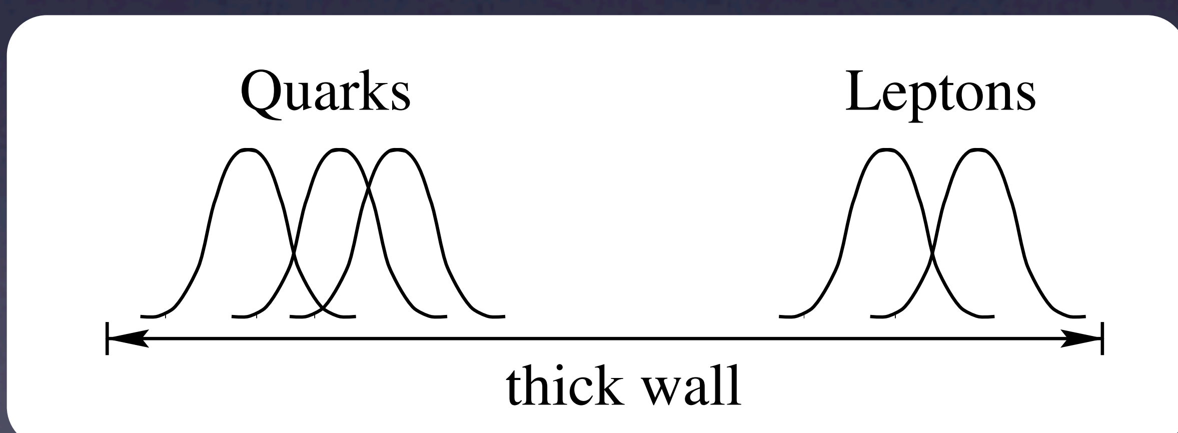

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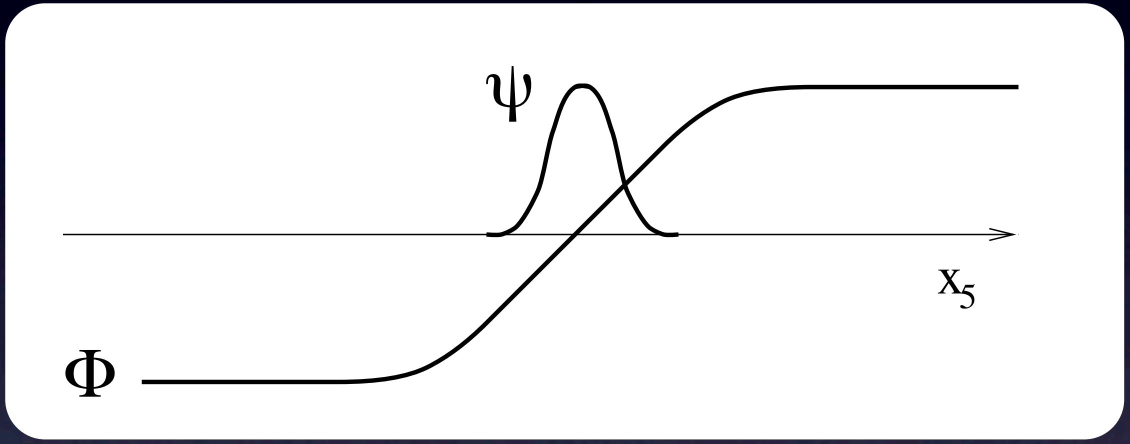

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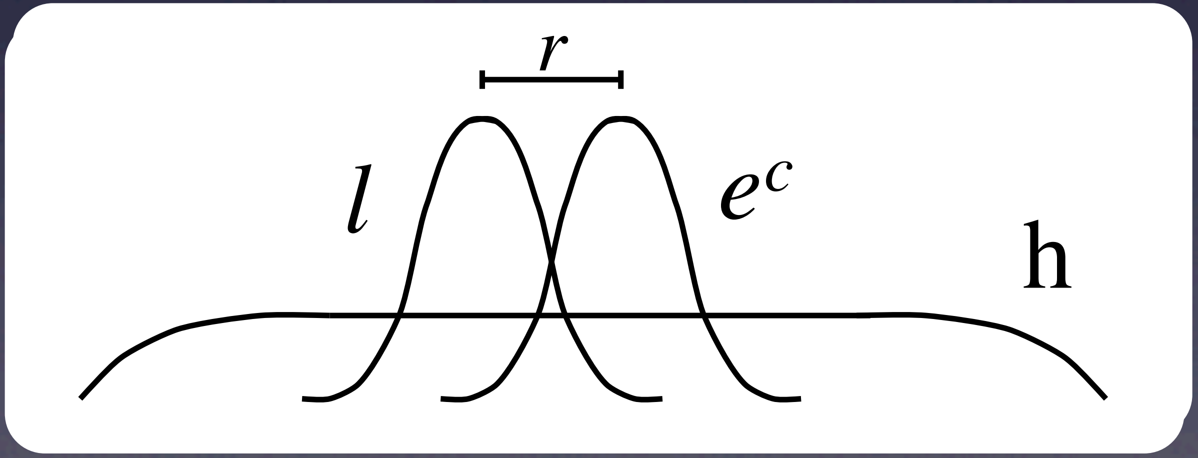

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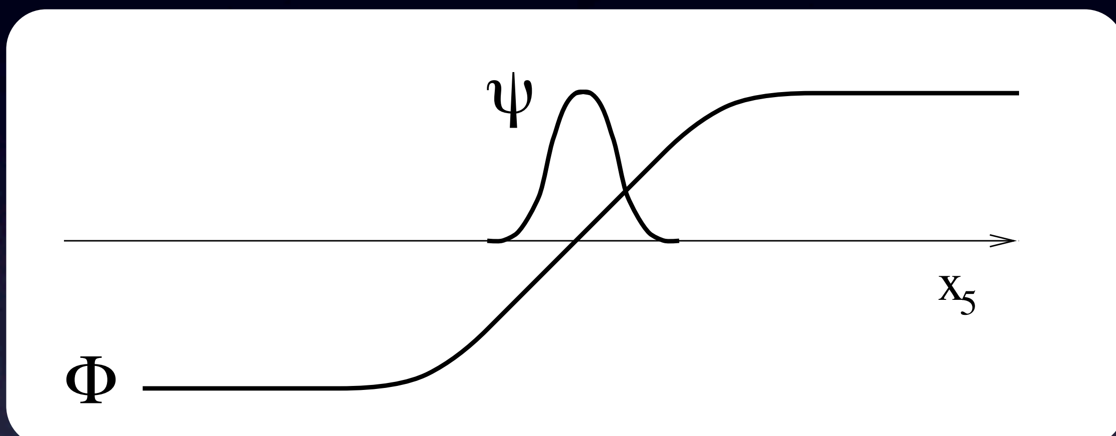

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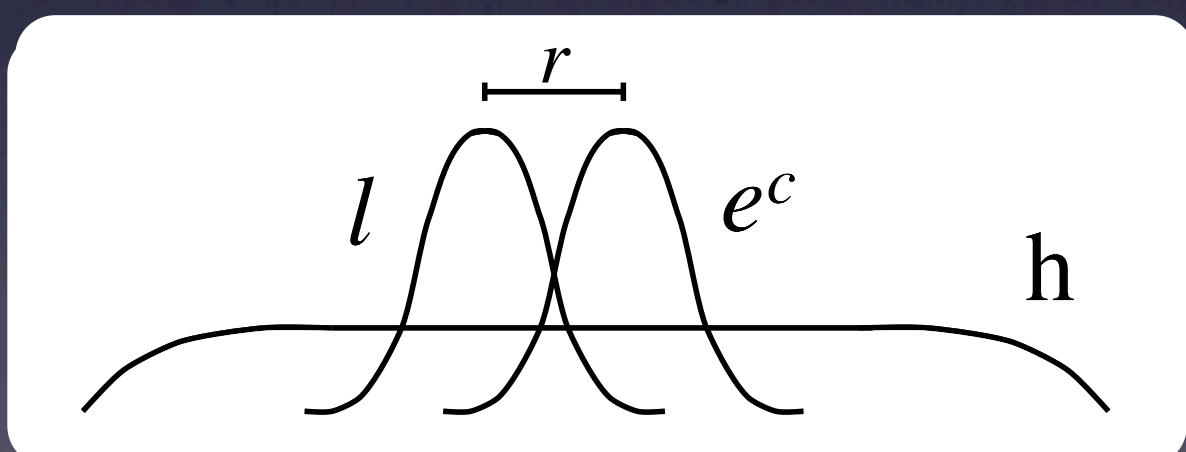

$$\int dx_5\ \phi_l(x_5)\ \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5\ e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} = e^{-\mu^2 r^2/2}$$

Hierarchies w/o Symmetries

Arkani-Hamed, Schmaltz

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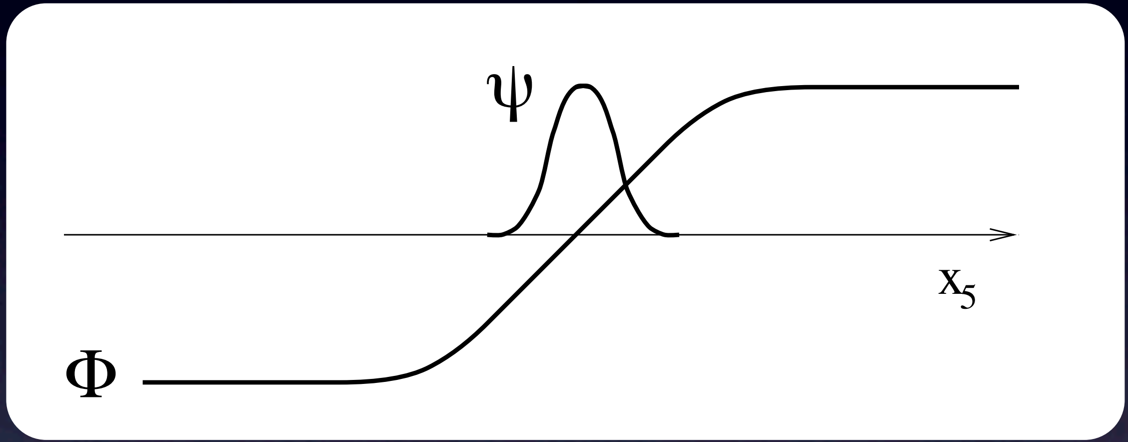

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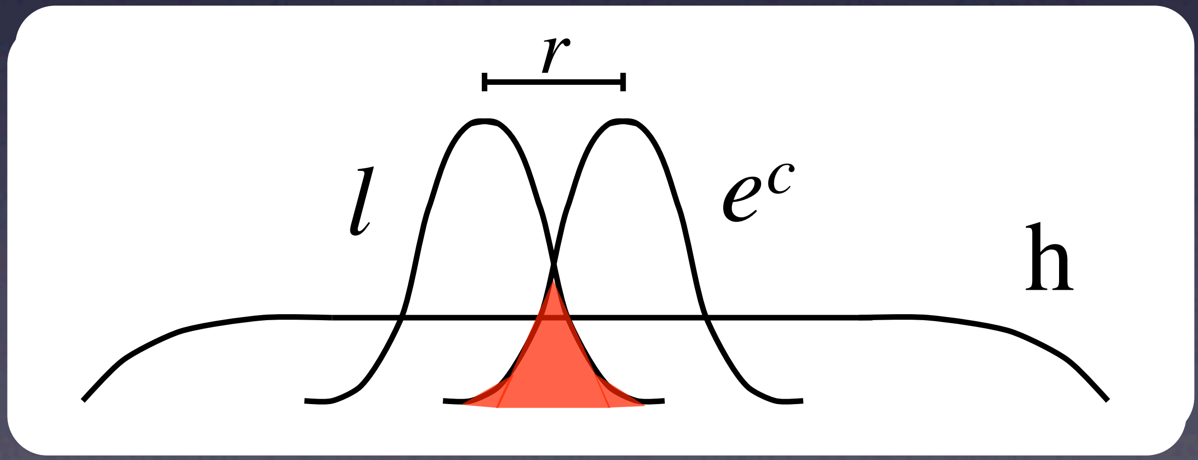

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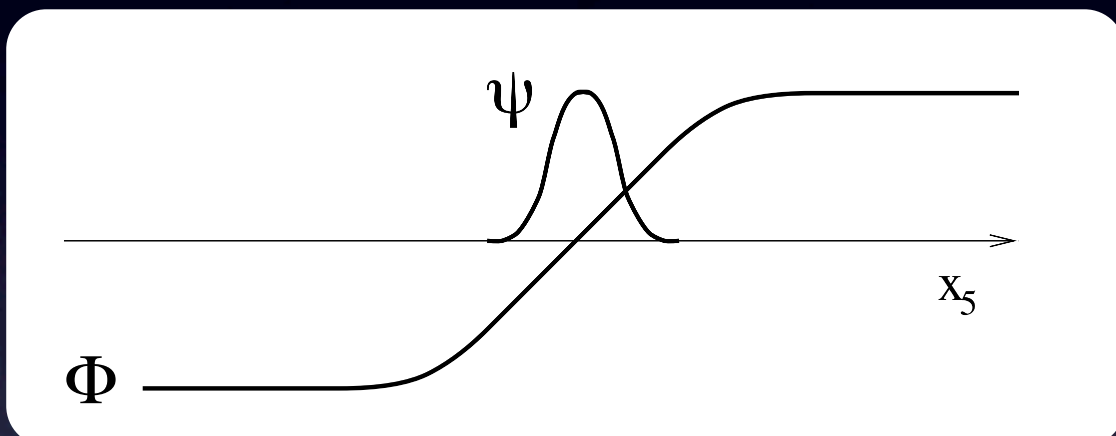

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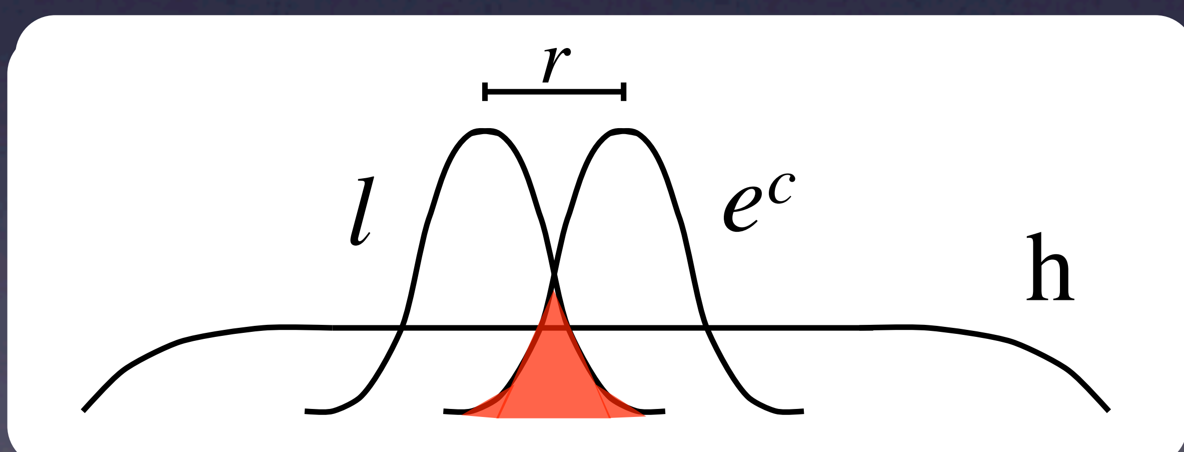


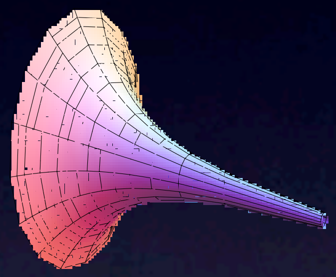
Log(flavor hierarchy)!

$$\int dx_5\ \phi_l(x_5)\ \phi_{e^c}(x_5) = \frac{\sqrt{2}\mu}{\sqrt{\pi}} \int dx_5\ e^{-\mu^2 x_5^2} e^{-\mu^2 (x_5 - r)^2} = e^{-\mu^2 r^2/2}$$

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

$$\downarrow$$

Randall, Sundrum

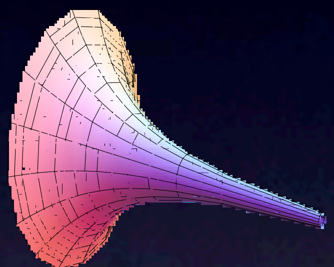


$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2) \; .$$

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

$$\downarrow$$

Randall, Sundrum

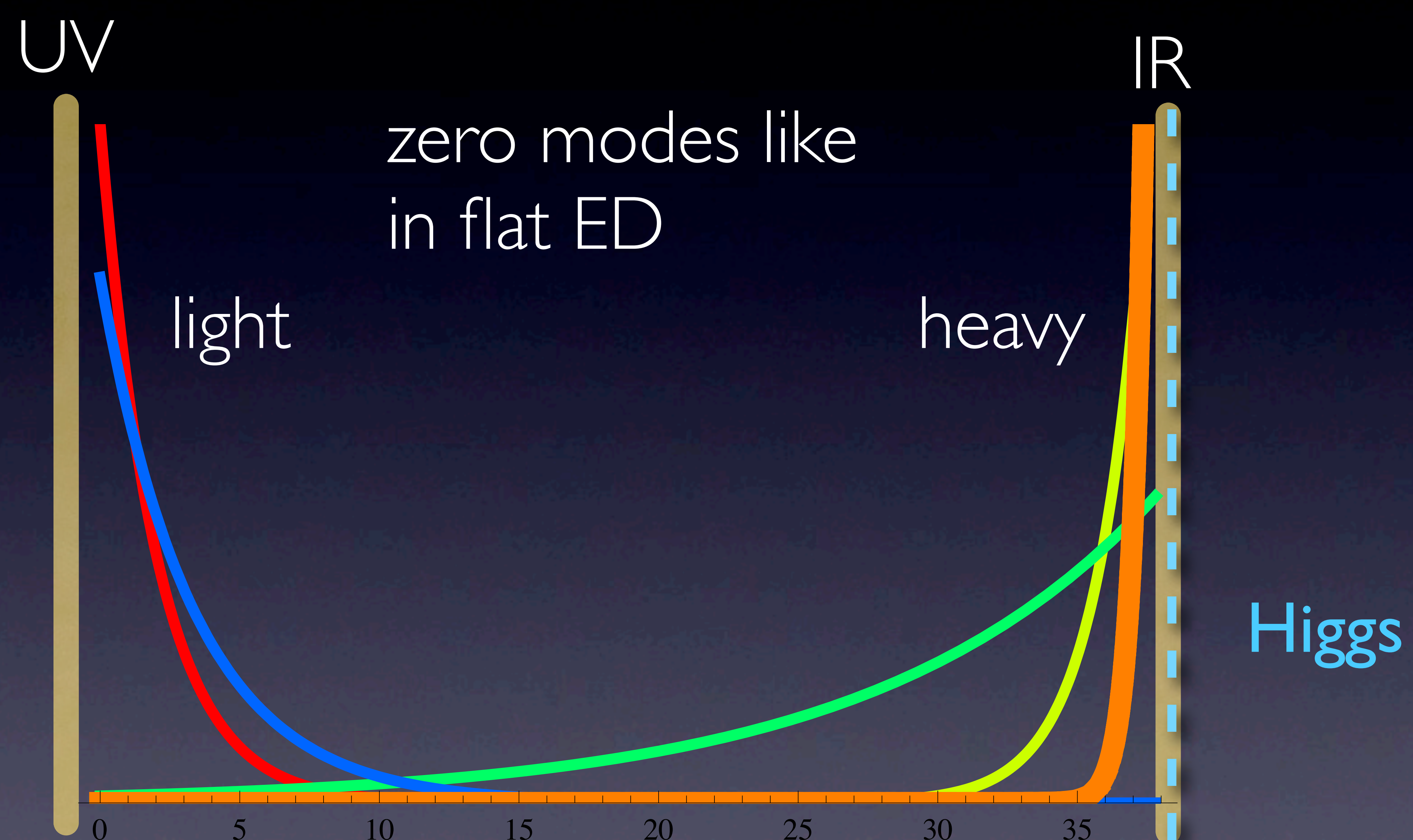


$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2) \, .$$

✓ 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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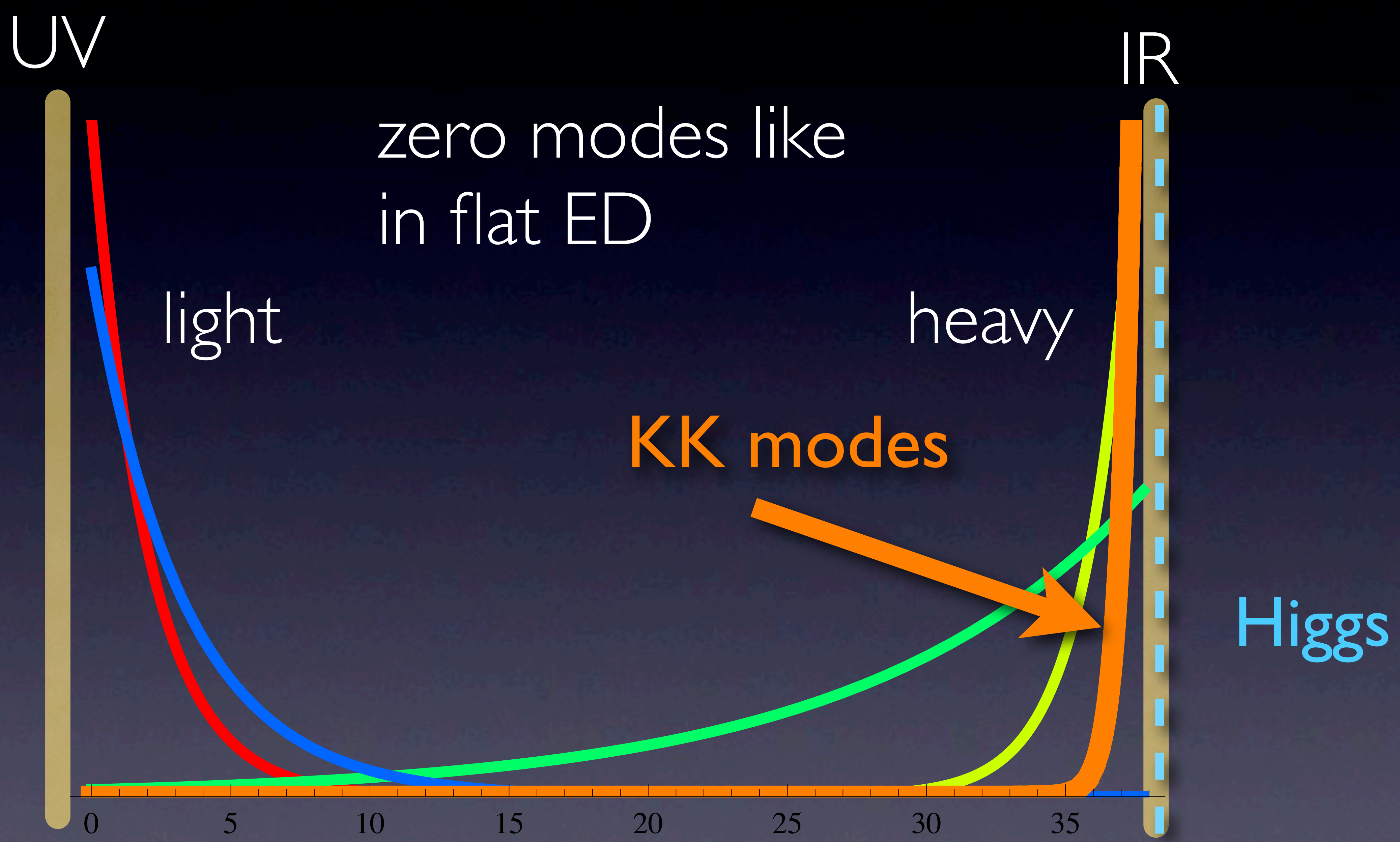

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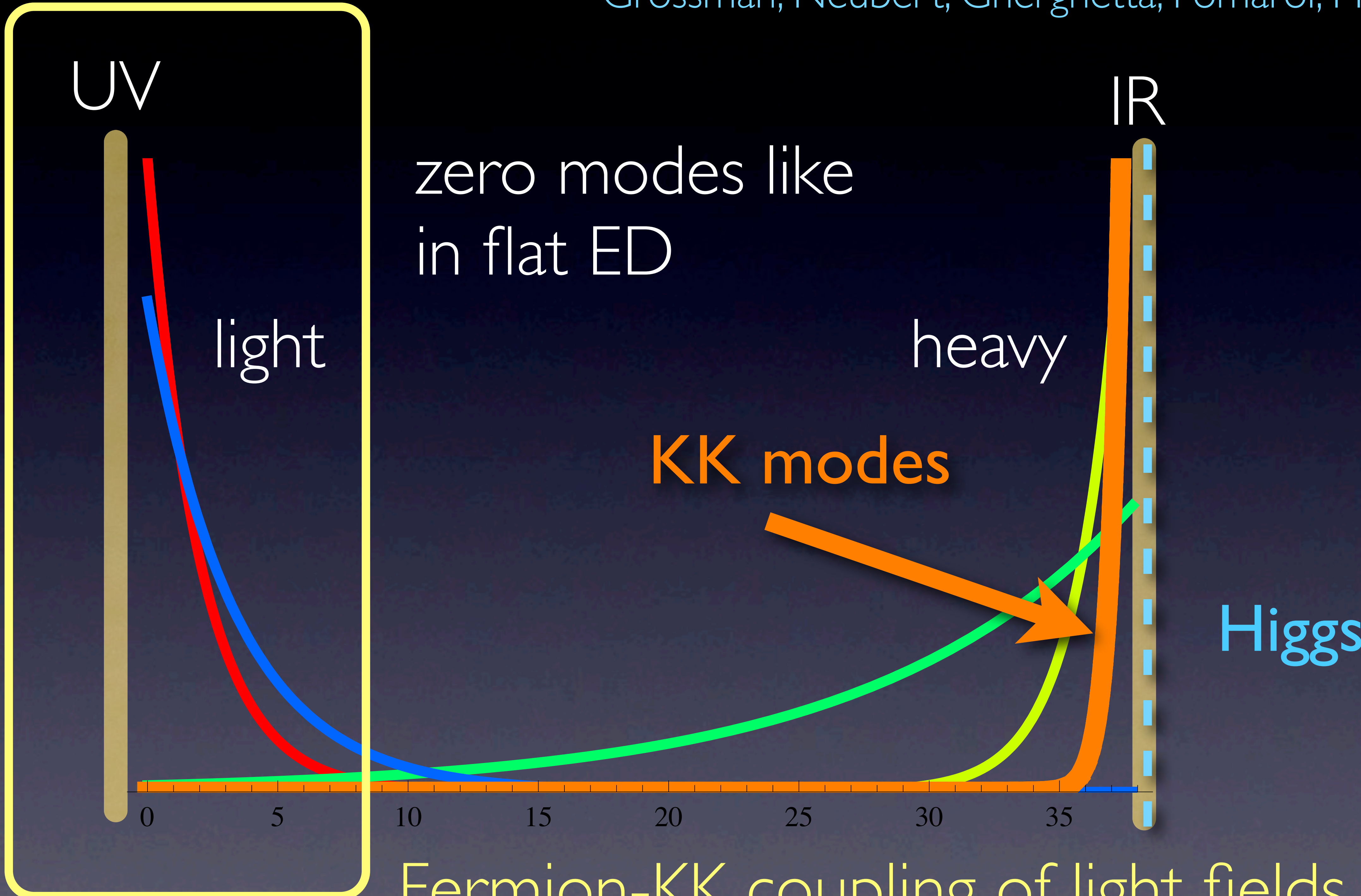

Fermion-KK coupling of light fields
almost universal!

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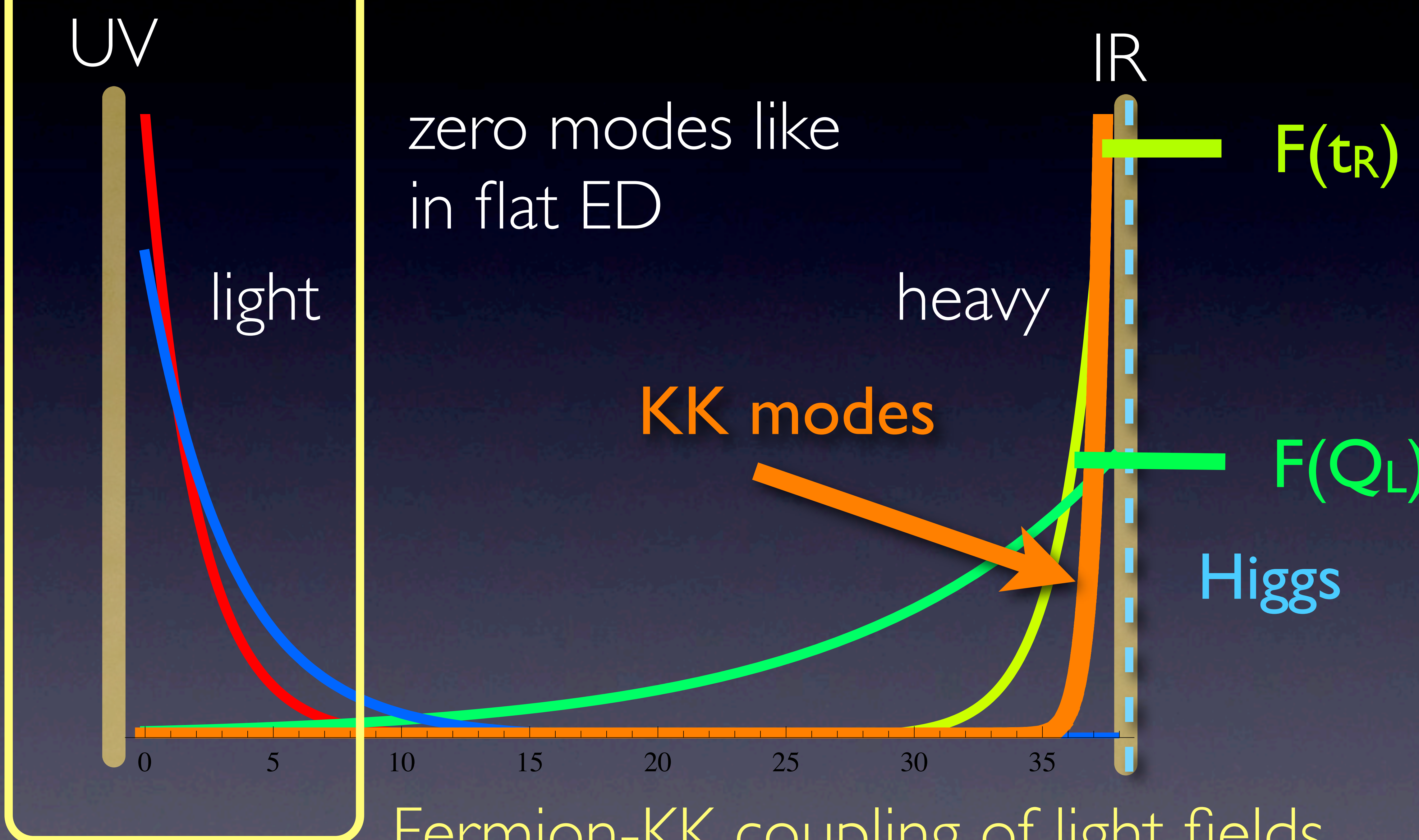


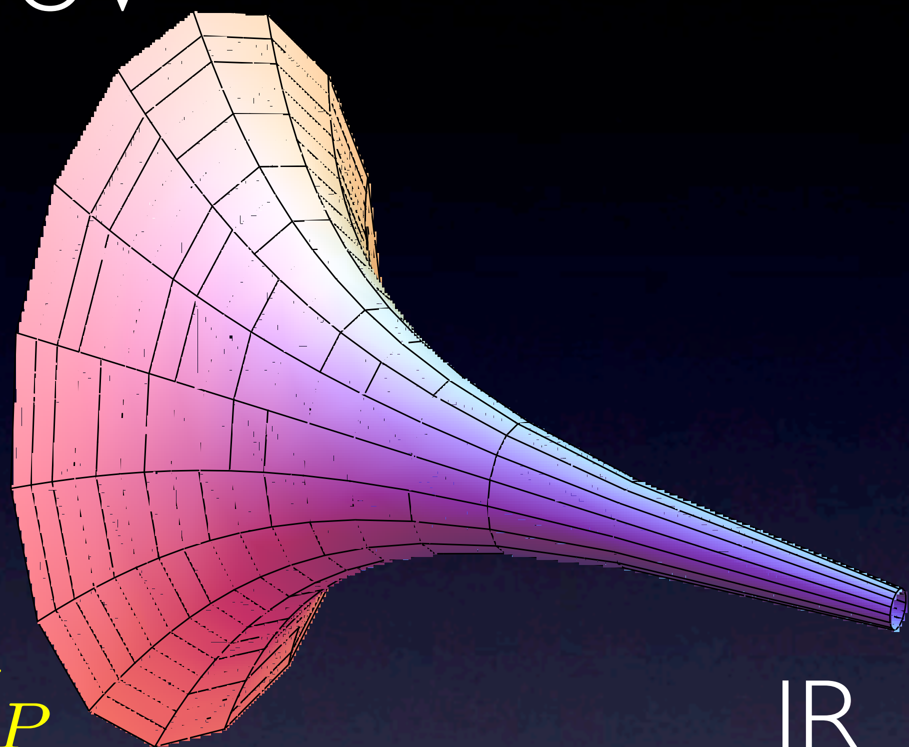
Fermion-KK coupling of light fields almost universal!

Why are FCNCs protected?

Excursion into AdS/CFT

AdS/CFT (popular science realization)

Randall, Sundrum



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

Anti-de-Sitter (AdS) ⟺ Conformal (CFT)

Compactification ⟺ Mass gap

Red-shifting of scales ⟺ Dimensional trans-mutation

$$m_W = \sqrt{\frac{g(IR)}{g(UV)}}\, M_P \ll M_P \qquad m_W \sim e^{-4\pi/\alpha} M_P$$

Two ways of giving mass to fermions…

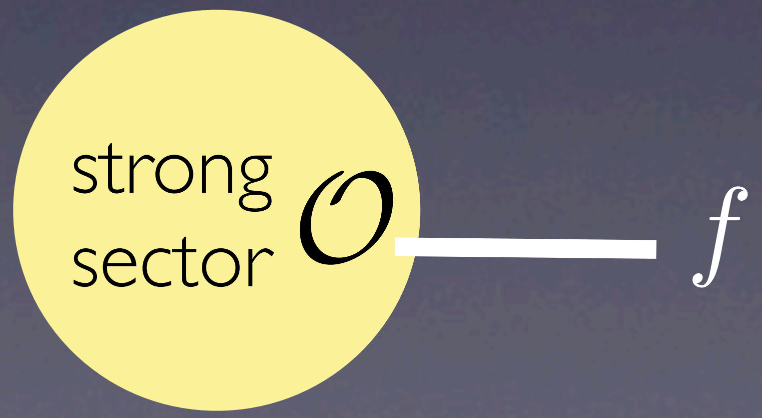
Bi-linear (like SM):

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

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

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

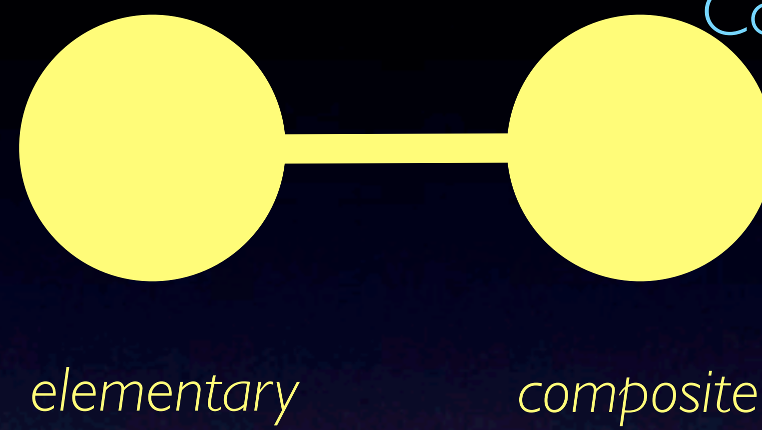
$$1 \lesssim g_* \lesssim 4\pi$$

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

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

Two-site description

Contino, Kramer, Son, Sundrum



$$\mathcal{L}_{elementary} = -\frac{1}{4}F_{\mu\nu}^2 + \bar{\psi}_L i\not{D}\psi_L + \bar{\tilde{\psi}}_R i\not{D}\tilde{\psi}_R$$

$$\mathcal{L}_{composite} = -\frac{1}{4}\rho_{\mu\nu}^2 + \frac{M_*^2}{2}\rho_\mu^2 + |D_\mu H|^2 - V(H)$$
$$+ \bar{\chi}(i\not{D} - m)\chi + \bar{\tilde{\chi}}(i\not{D} - \tilde{m})\tilde{\chi} - \bar{\chi}\left(Y_{*u}\tilde{H}\tilde{\chi}^u + Y_{*d}H\tilde{\chi}^d\right) + \text{h.c.}$$

$$\mathcal{L}_{mixing} = -M_*^2 \frac{g_{el}}{g_*} A_\mu \rho_\mu^* + \frac{M_*^2}{2}\left(\frac{g_{el}}{g_*}A_\mu\right)^2 + (\bar{\psi}_L \Delta \chi_R + \bar{\tilde{\psi}}_R \tilde{\Delta}\tilde{\chi}_L + \text{h.c.})$$

Partial compositeness

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

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heavy ~ TeV, *up,down ~ MeV :*

Rationale for *sin(*$\mathbf{\Phi}$*)* << *1* ?

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

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

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

Partial compositeness

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

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

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

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

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

anarchic (“structure-less”)

$$\text{Mass}_{ij} \quad \propto \quad Y_{ij} e^{-MR(c_i+c_j)}$$

split fermions/RS

$$\propto \quad Y_{ij} \left(\frac{\mu_{\text{low}}}{\mu_{\text{high}}} \right)^{\gamma^i+\gamma^j}$$

strong dynamics

anarchic ("structure-less")

$$\mathrm{Mass}_{ij} \propto Y_{ij} e^{-MR(c_i+c_j)}$$

$$\propto Y_{ij} \left(\frac{\mu_{\mathrm{low}}}{\mu_{\mathrm{high}}}\right)^{\gamma^i+\gamma^j}$$

split fermions/RS

Duality!

strong dynamics

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

$$\begin{aligned} m_u^{SM} &= \frac{v}{\sqrt{2}} F_q \mathbf{Y_u} F_u, \\ m_d^{SM} &= \frac{v}{\sqrt{2}} F_q \mathbf{Y_d} F_d \end{aligned}$$

$\mathbf{Y_u}$, $\mathbf{Y_d}$ ~ 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)

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

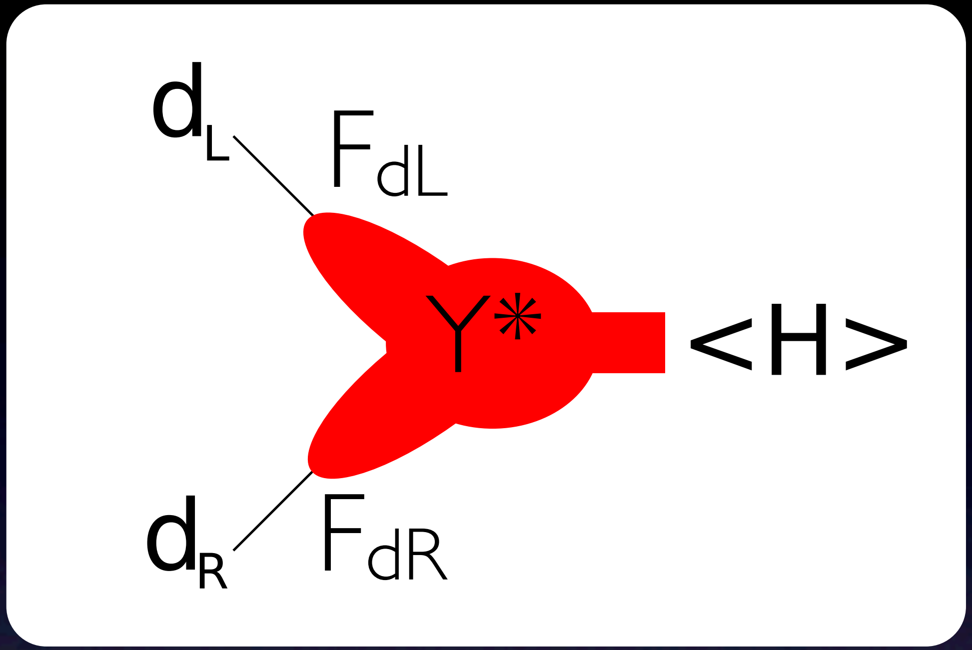
$$F_{Q_2}/F_{Q_3} \sim \theta_{23} \sim \lambda^2$$

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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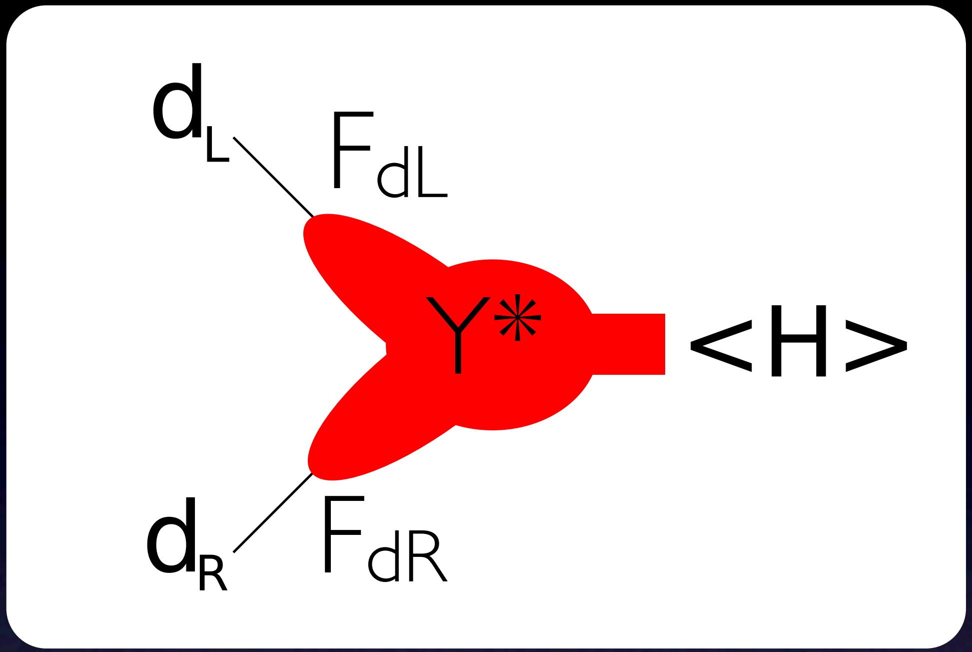

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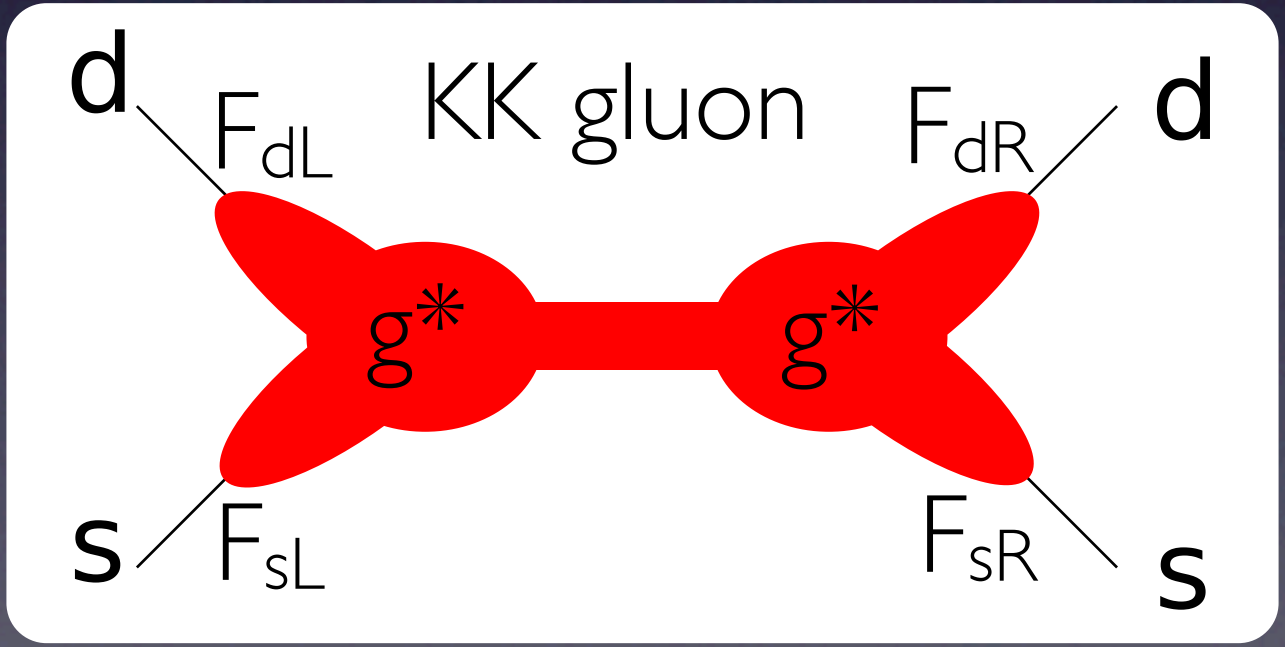


KK gluon FCNCs proportional to the same small F_i :

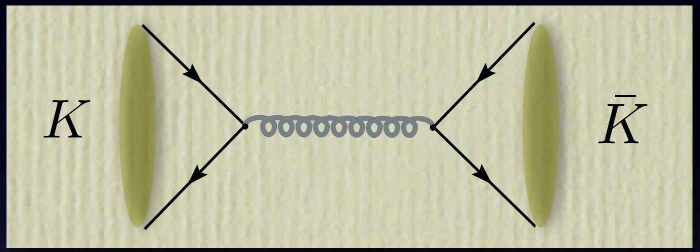
$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}$$

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

FCNCs assuming anarchy

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

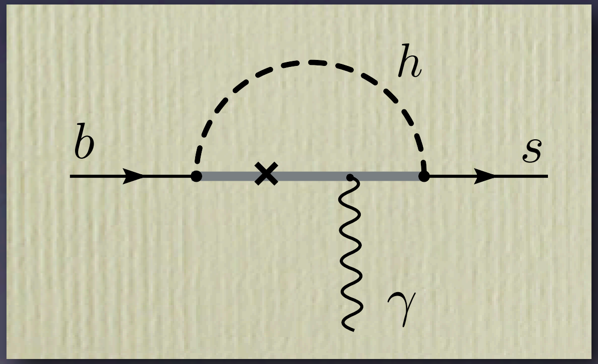
$\Delta F = 2$ (strongest constraint from ϵ_K)



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

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

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



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

Combined constraints ⇒ 'little' flavor problem w/ anarchy

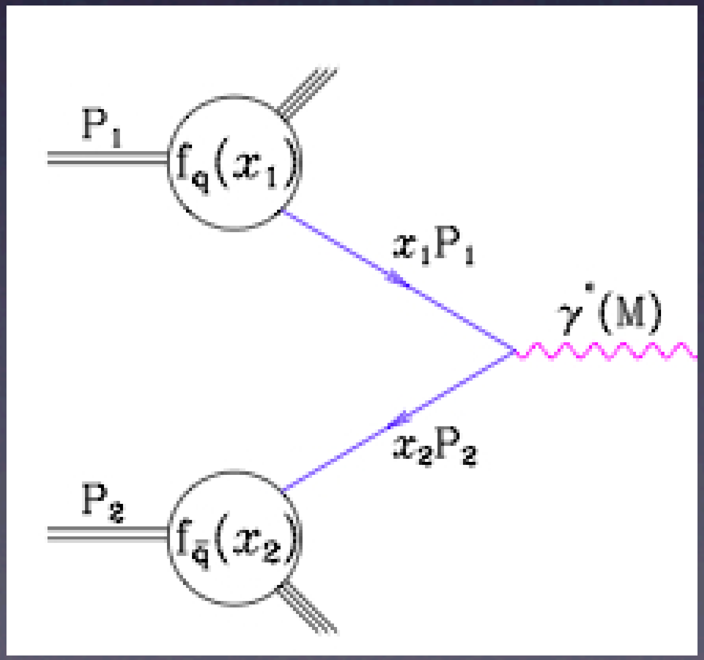
Adding flavor symmetries:
flavor gauge bosons

o tension with $\Delta F=2$ bounds require some alignment & additional flavor symmetries
o global symmetries of the strong sector are dual to local gauge symmetries (consequence of AdS/CFT)

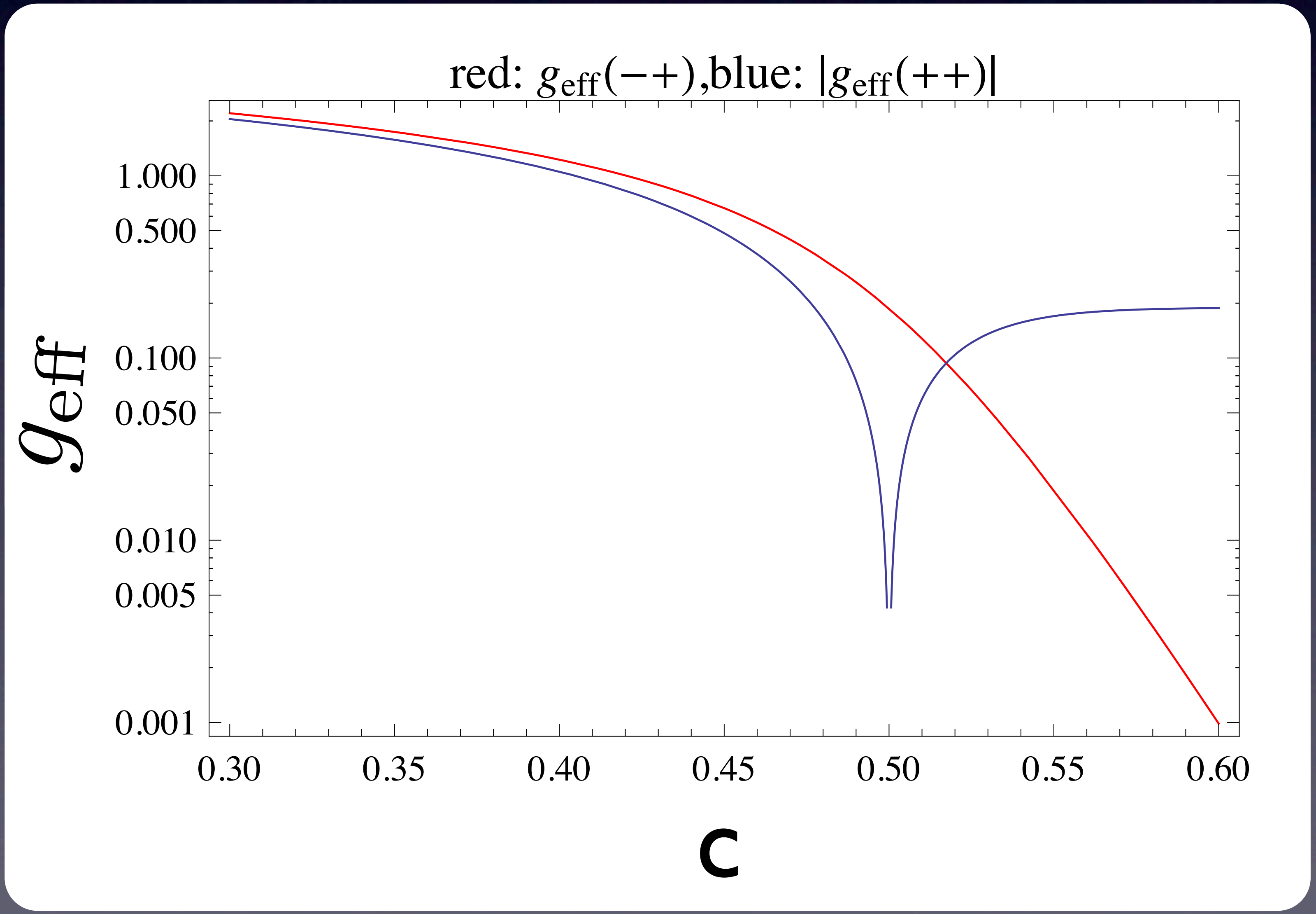
(to avoid arbitrary cutoff-flavor breaking, need to gauge SM approximate flavor currents)

Flavor gauge bosons at the LHC

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



$\sigma_{bb} \sim 0.1\,(1)\mathrm{pb}$



Flavor gauge bosons at the LHC

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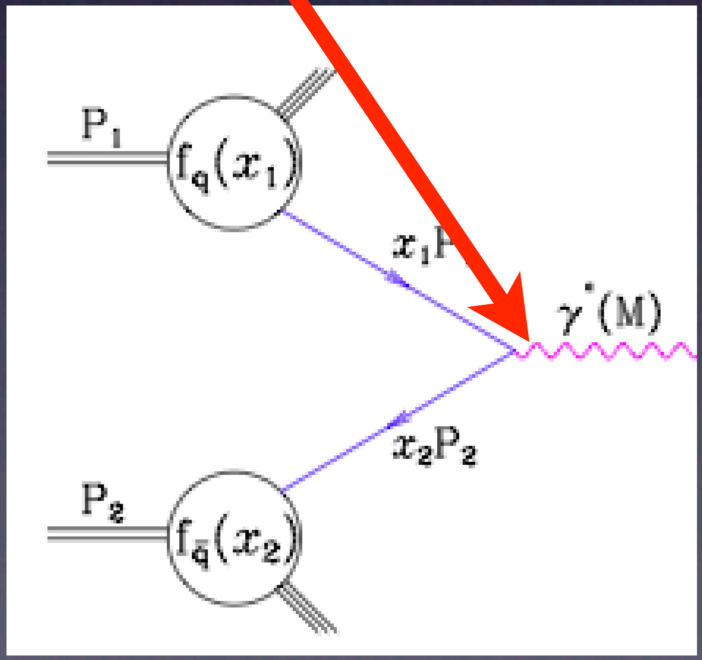
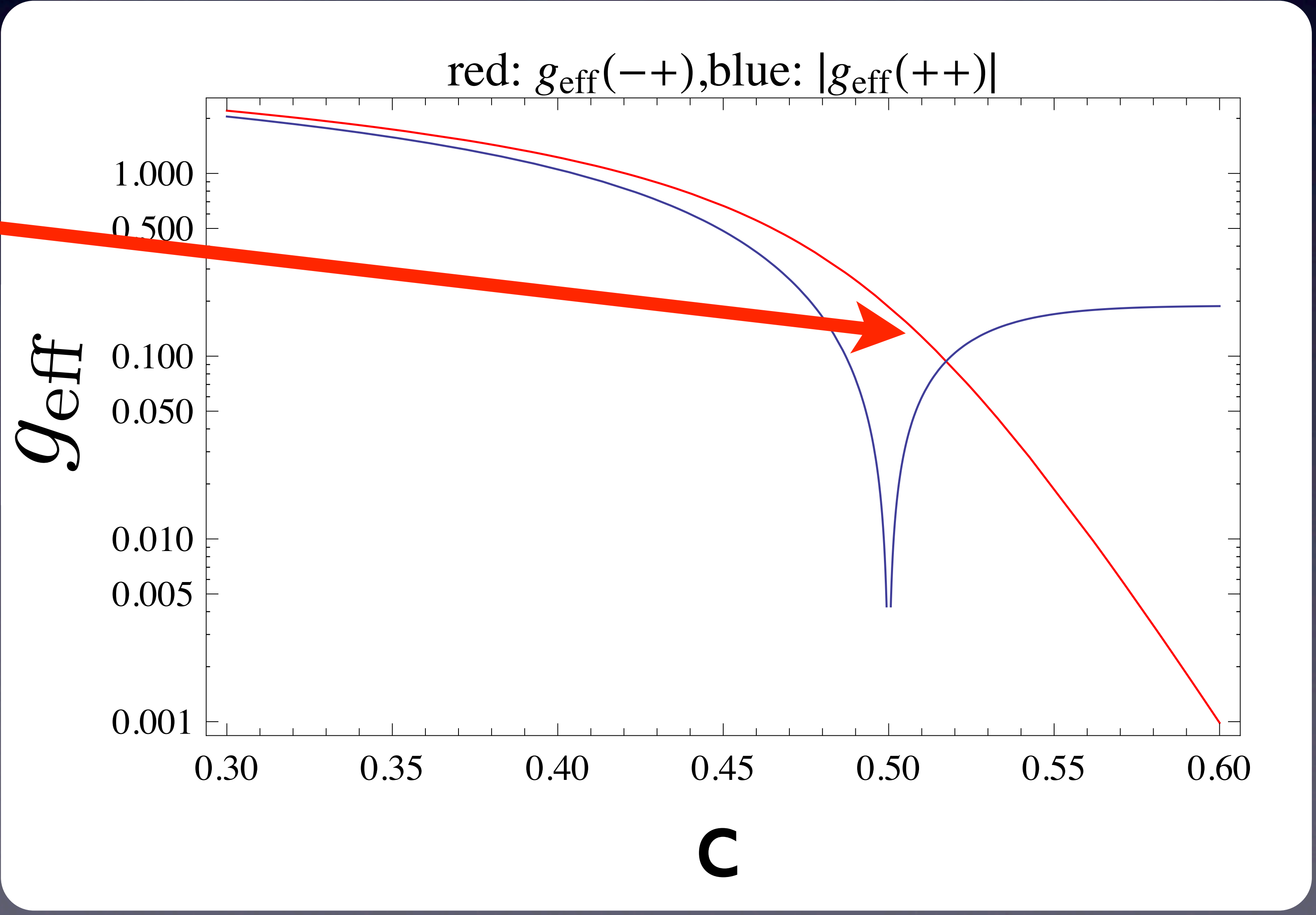
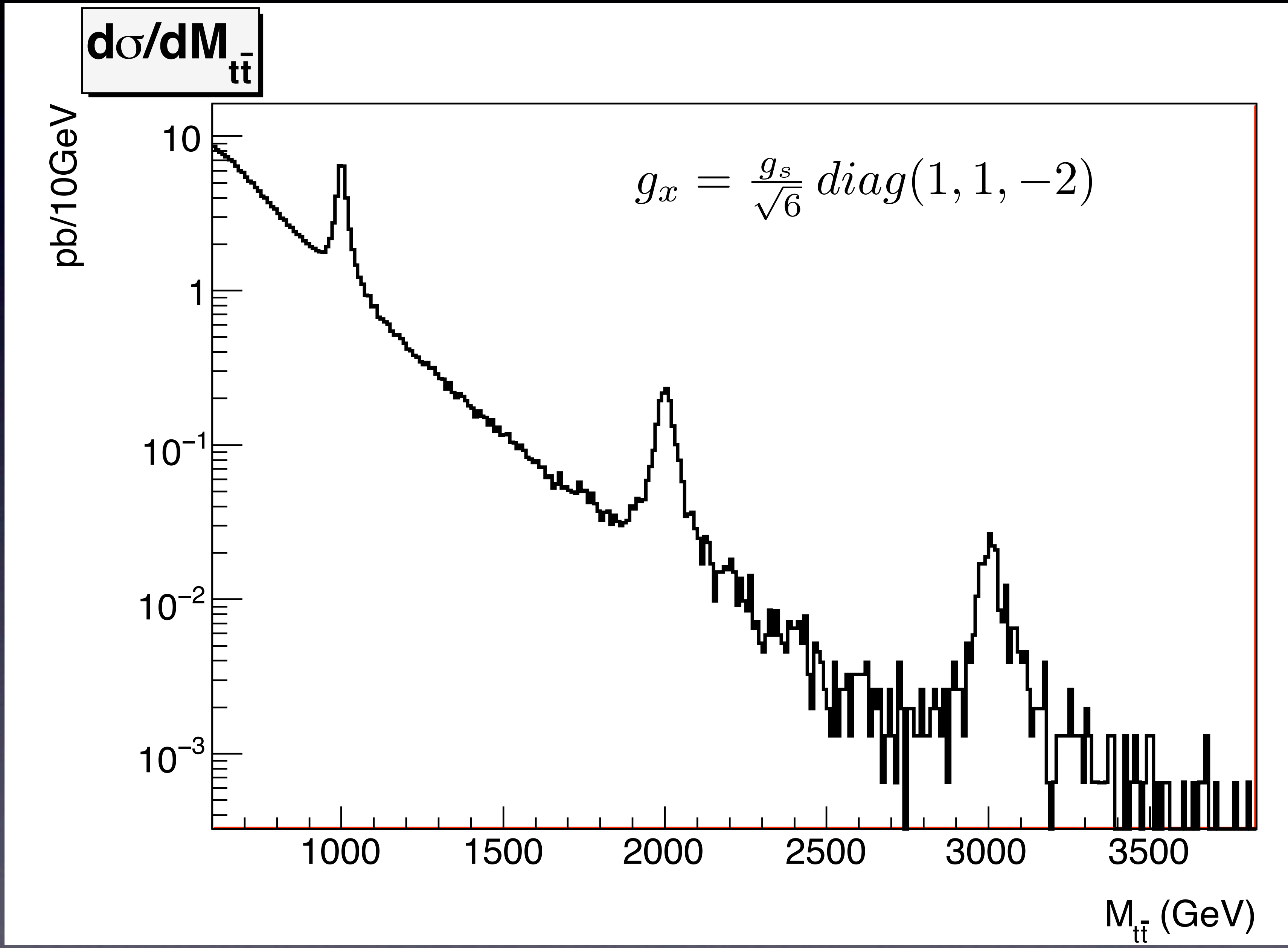


$\sigma_{bb} \sim 0.1\ (1)\rm pb$



Flavor scalars & gauge bosons

Csaki, Lee, Perez, AW in preparation



Interplay between ATLAS/CMS & LHCb

Outlook

By Moriond 2011, LHCb will be competitive.
In the summer/end of 2011, LHCb will perform worlds best measurements of NP sensitive observables

$A_{\psi\phi}$ $B_s \to \mu^+\mu^-$ γ

FB asymmetry in $B \to K^*\mu\mu$

CPV in charm ?

FCNCs from composite Higgs

Agashe, Contino; Azatov, Toharia, Zhu

Further constraints from compositeness of Higgs

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

FCNCs from composite Higgs

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

$H = v + h(x)$

FCNCs from composite Higgs

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

$H = v + h(x)$

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

FCNCs from composite Higgs

Agashe, Contino; Azatov, Toharia, Zhu

Further constraints from compositeness of Higgs

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

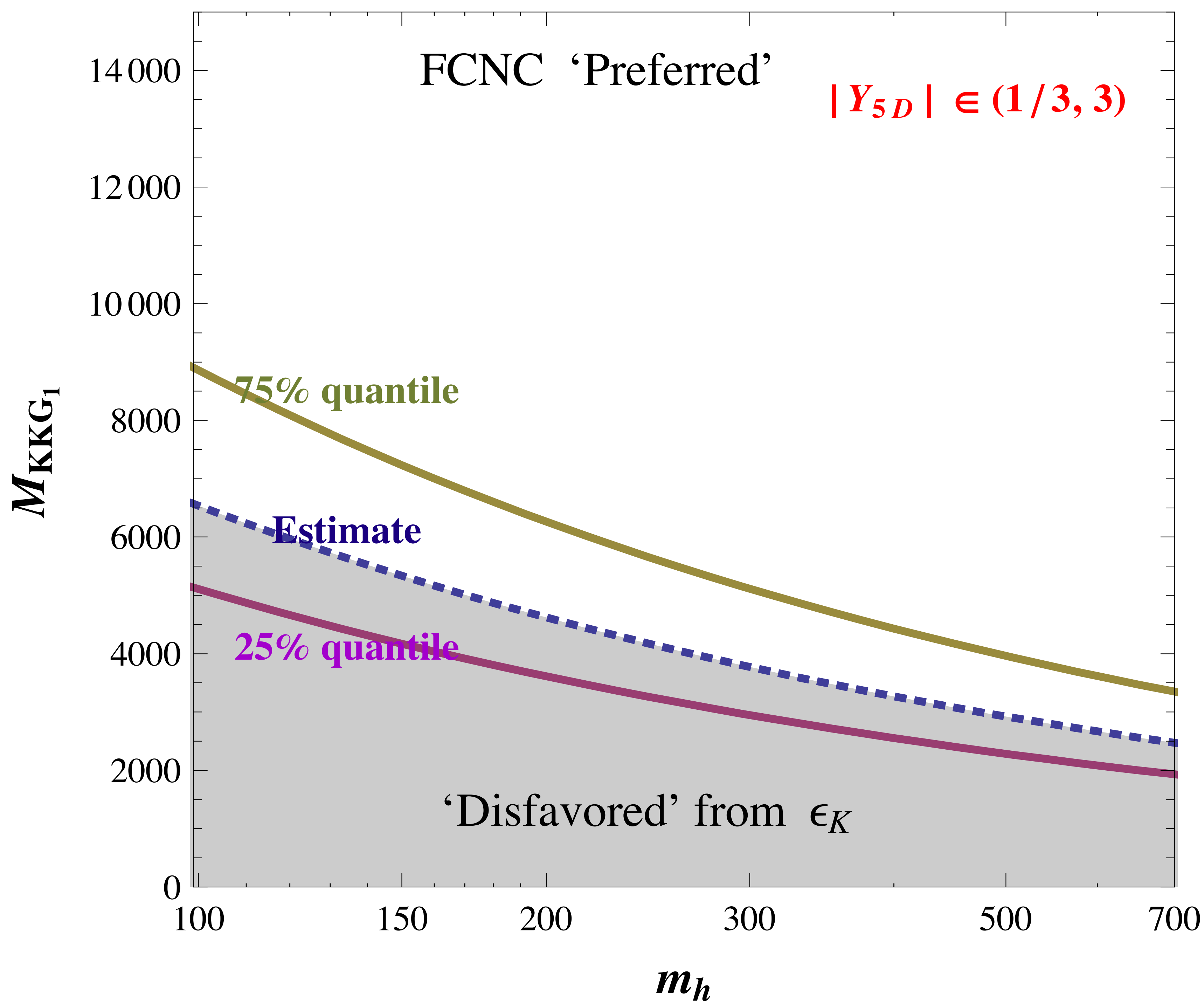
$$M^d = vY^d - \left(\tilde{Y}^d + \tilde{Z} Y^d + \dots\right) \frac{v^3}{\Lambda^2} \, ,$$

$H = v + h(x)$

$\Downarrow$ FCNCs

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

Toharia, Zhu



FCNC 'Preferred'
$|Y_{5D}| \in (1/3, 3)$
75% quantile
Estimate
25% quantile
'Disfavored' from ϵ_K
M_{KKG_1}
14000
12000
10000
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).

Anarchy alone does not seem to work

Agashe et al., Buras et al., Casagrande et al., Gedalia et al.

- o Finetuned scales? Raise the KK scale to $M_{KK} \sim$ 10-20 TeV

- o Finetuned Yukawas? Yukawas might allow accidental cancellations

- o No tuning, more structure: Alignment and flavor symmetries

Fitzpatrick, Randall, Perez; Santiago; Csaki Falkowski, A.W; Csaki, Grossman, Perez, Surujon, A.W. ; Agashe;

Spurion analysis

Without the Yukawas SM has

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

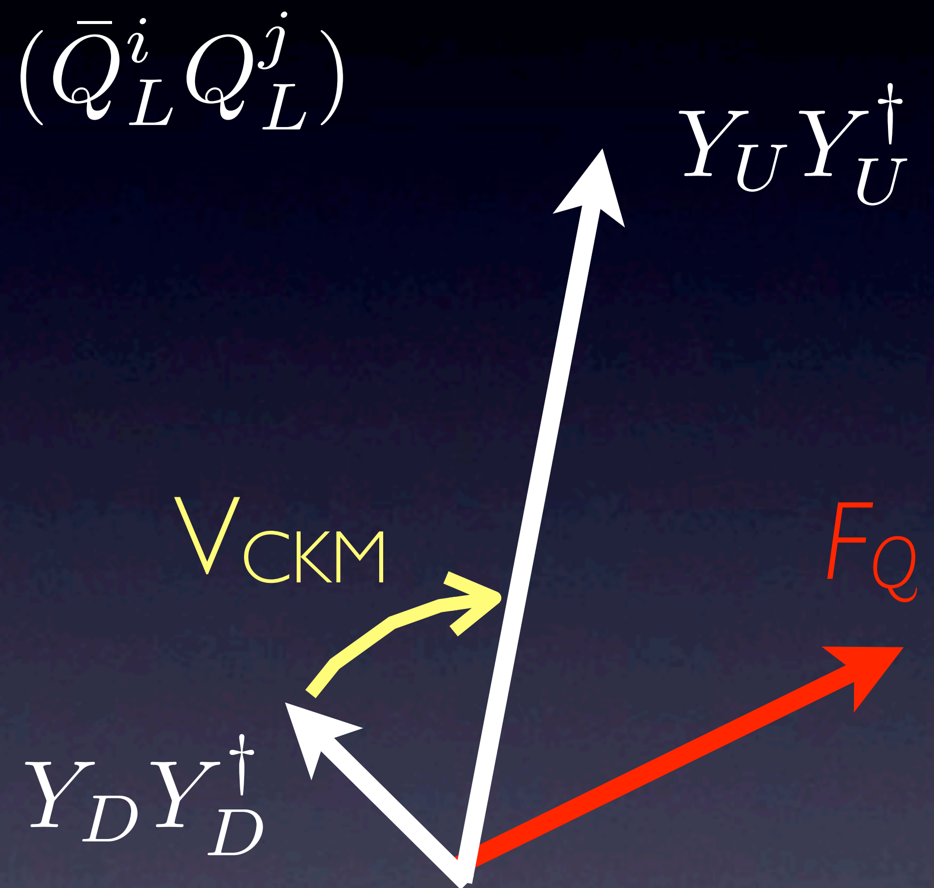
global flavor symmetry.

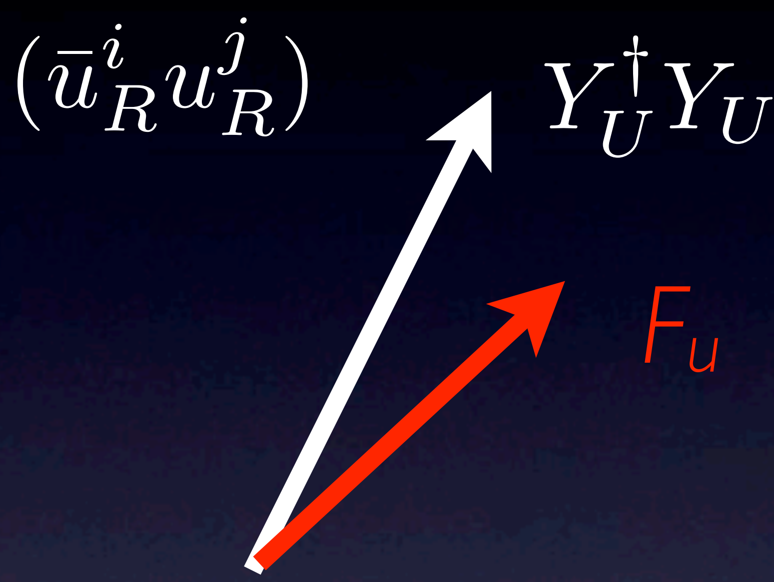
In RS broken by Y_u^*, Y_d^* + F_Q, F_d, F_u

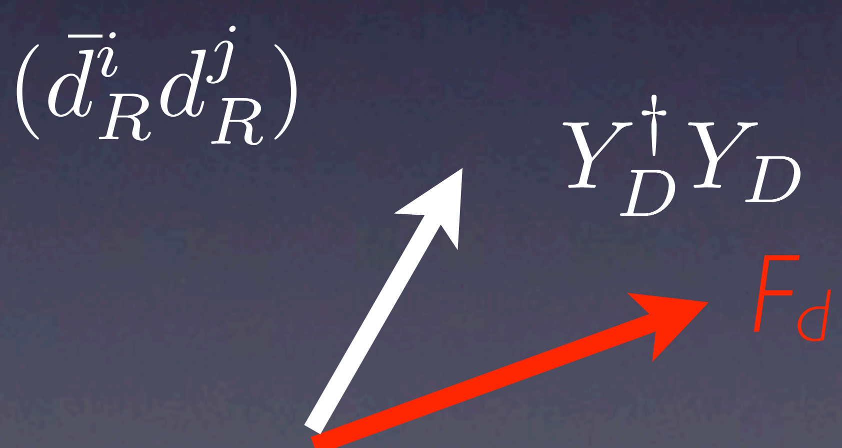
No dangerous FCNCs in the down sector if

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

Anarchy and hierarchical F's



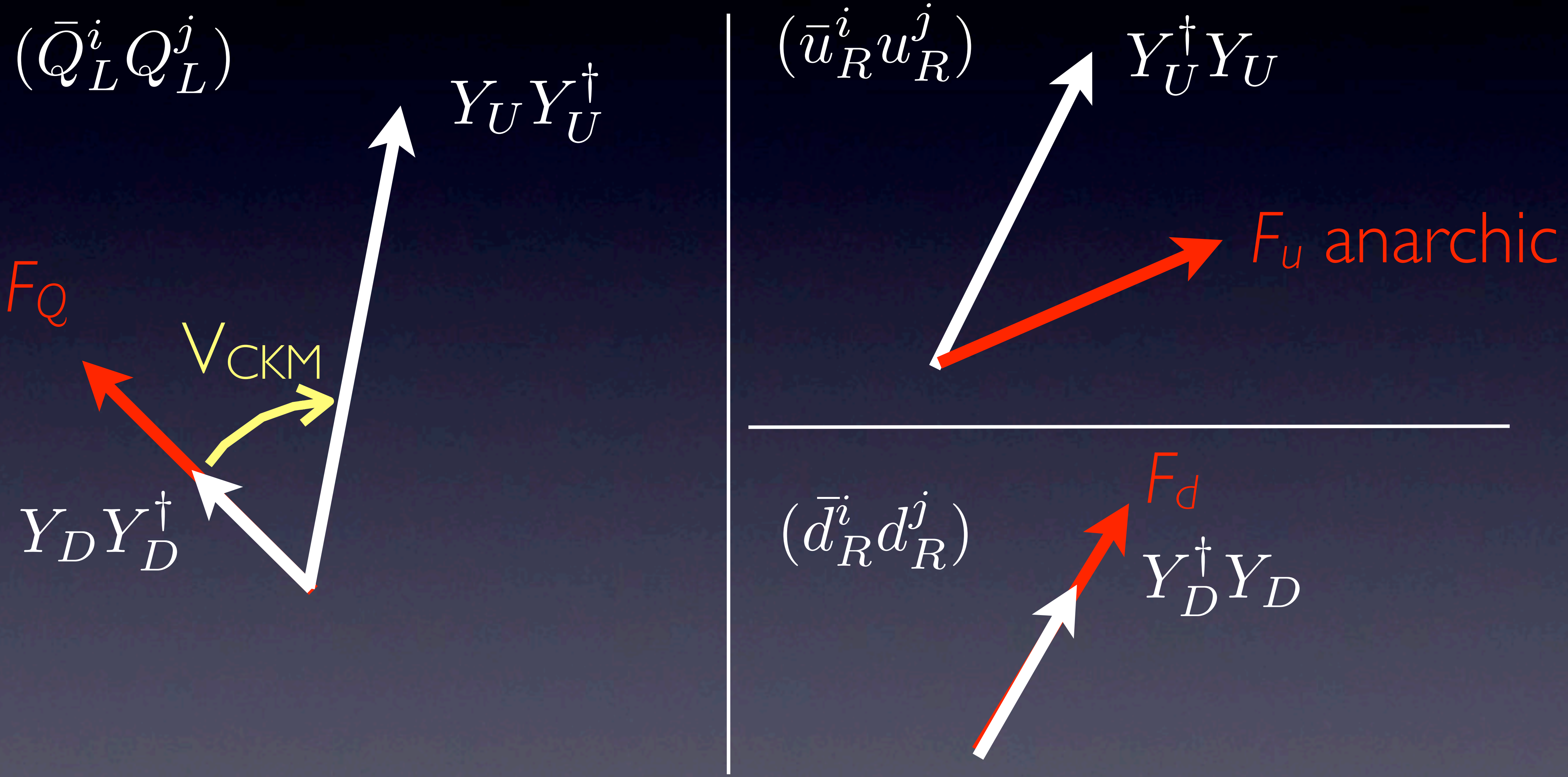




+ LR, RL

Align down sector

similar to Nir, Seiberg '93 for MSSM



+ LR, RL

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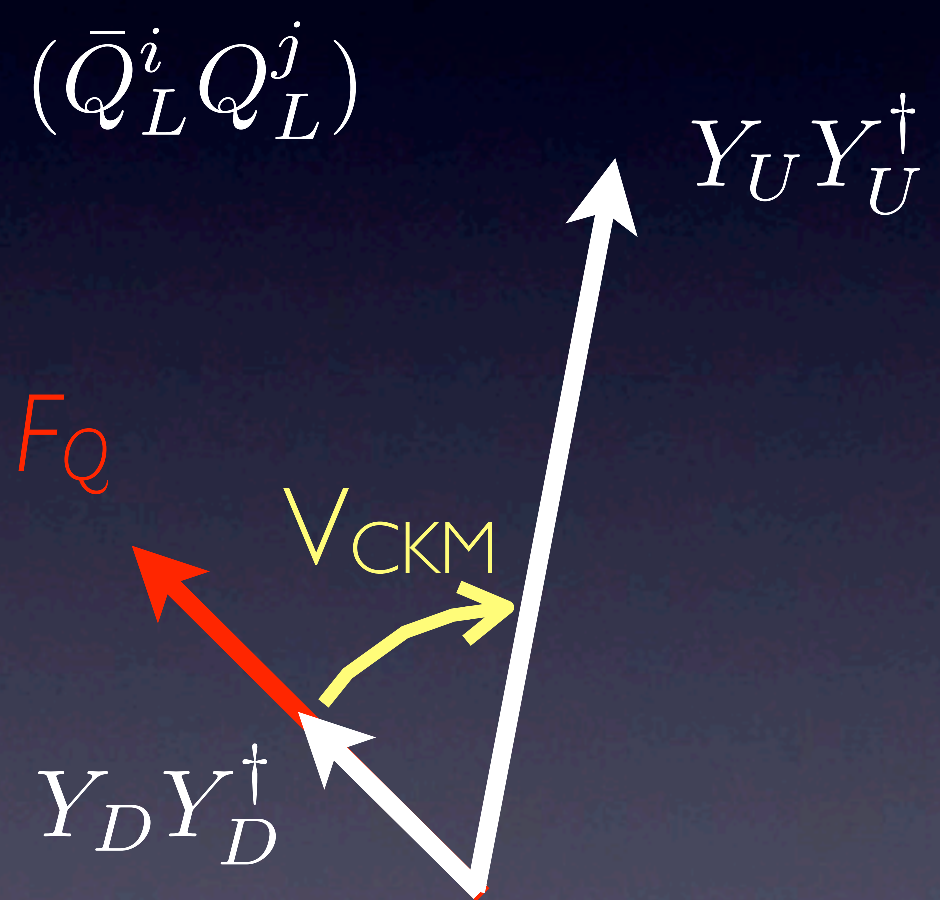
Combination of K-K and D-D

Nir 07; Blum et. al '09

Cannot simultaneously eliminate constraints from D & K



contribution to D-D mixing

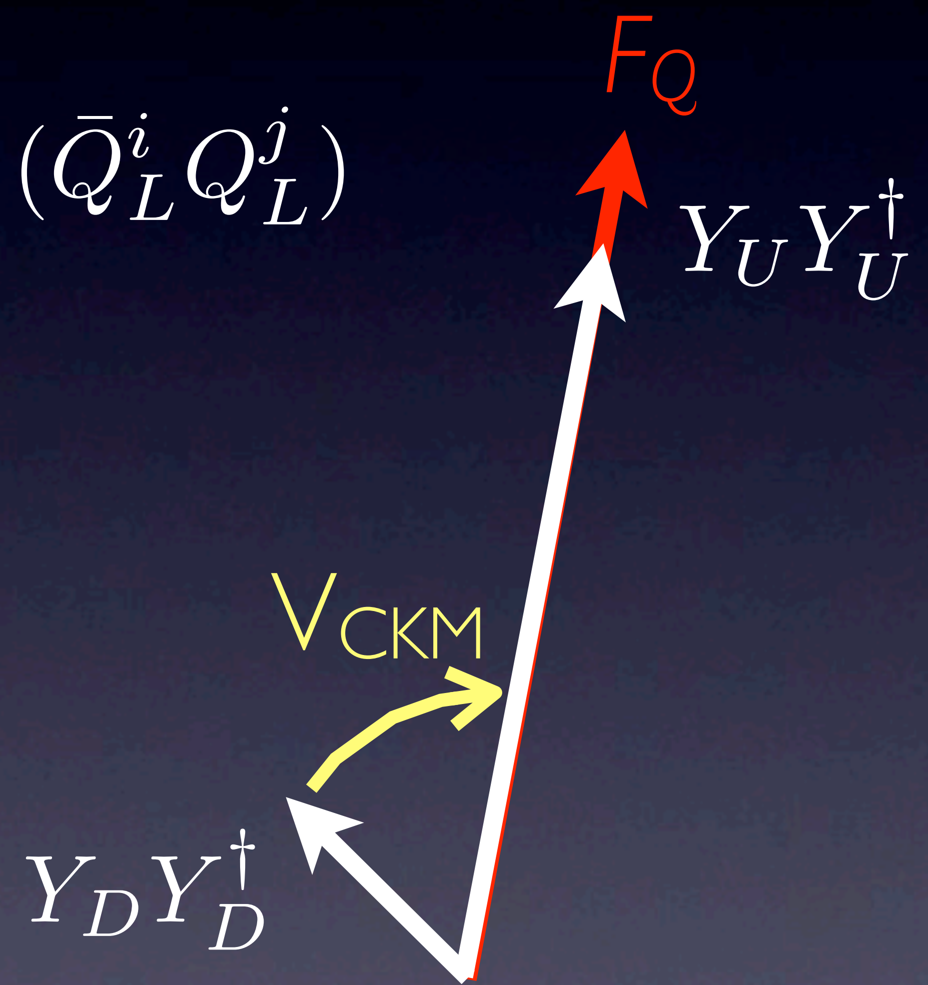
no effect in K-K mixing

Combination of K-K̲ and D-D̲

Nir 07; Blum et. al '09

Cannot simultaneously eliminate constraints from D & K

$(\bar{Q}^i_L Q^j_L)$



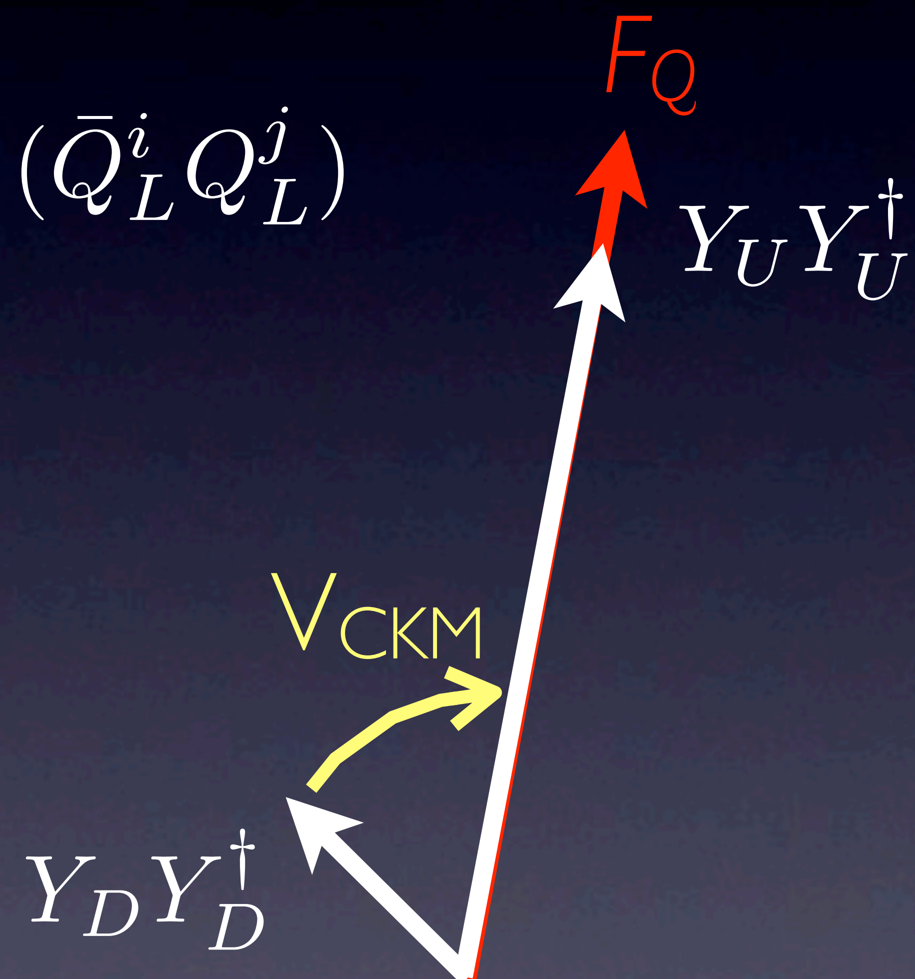
contribution to K-K̲ mixing

no effect in D-D̲ mixing

Combination of K-$\underline{K}$ and D-$\underline{D}$

Nir 07; Blum et. al '09

Cannot simultaneously eliminate constraints from D & K



alignment Susy models:

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \lesssim 0.05 - 0.14,$$
$$\frac{m_{\tilde{u}_2} - m_{\tilde{u}_1}}{m_{\tilde{u}_2} + m_{\tilde{u}_1}} \lesssim 0.02 - 0.04.$$

contribution to K-$\underline{K}$ mixing

no effect in D-$\underline{D}$ mixing

}

Aligning 5D MFV

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

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

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

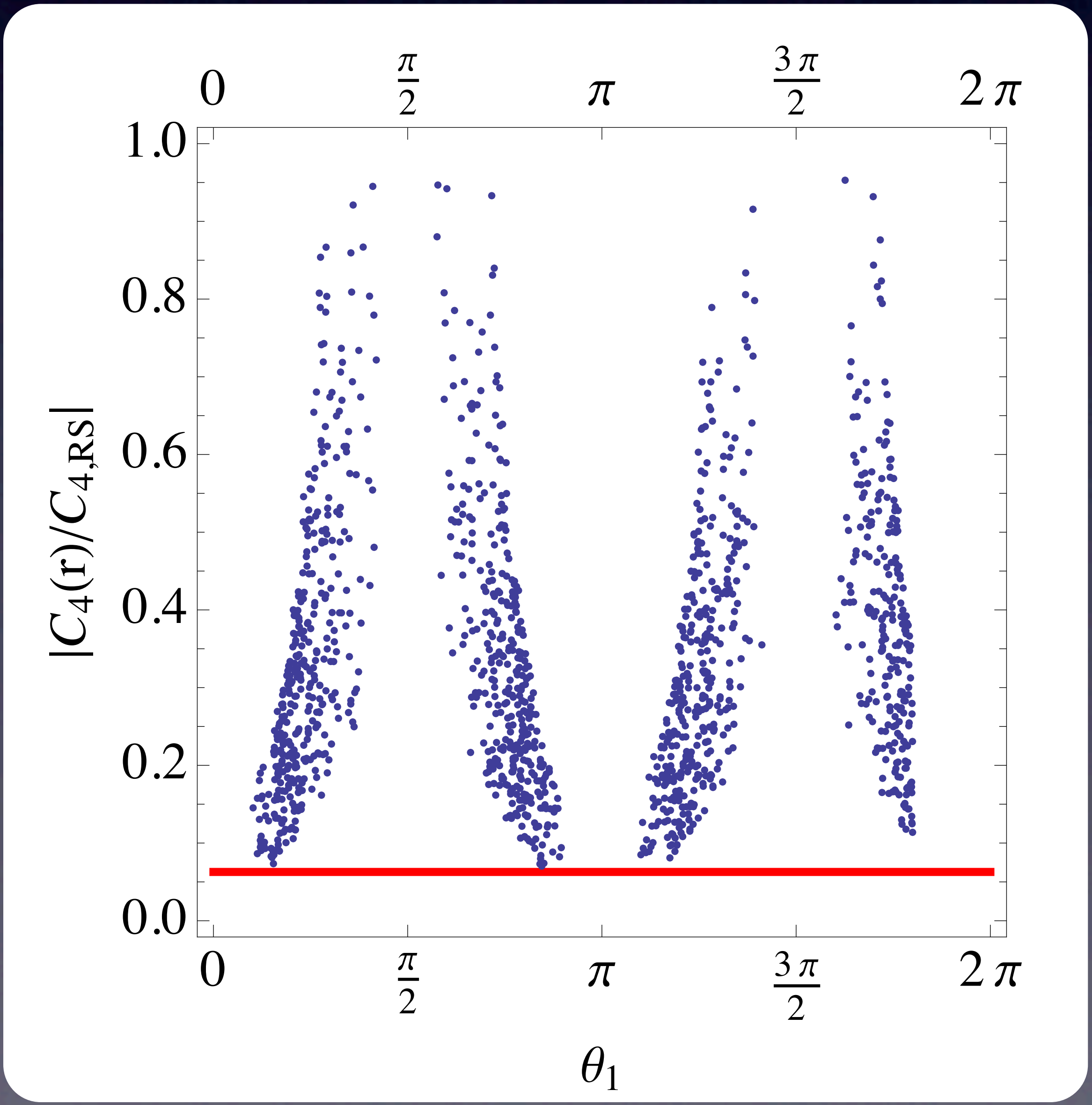
Need $\epsilon \ll 1$ to align F_Q, F_d, and Y_d

Aligning 5D MFV

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

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

Keep $\boldsymbol{\varepsilon} = 0.2$ fixed.



Need $\epsilon \to 0$

$\Rightarrow$ symmetry ?

Alignment due to shining

Csaki, Grossman, Perez, Surujon, A.W., in progress

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

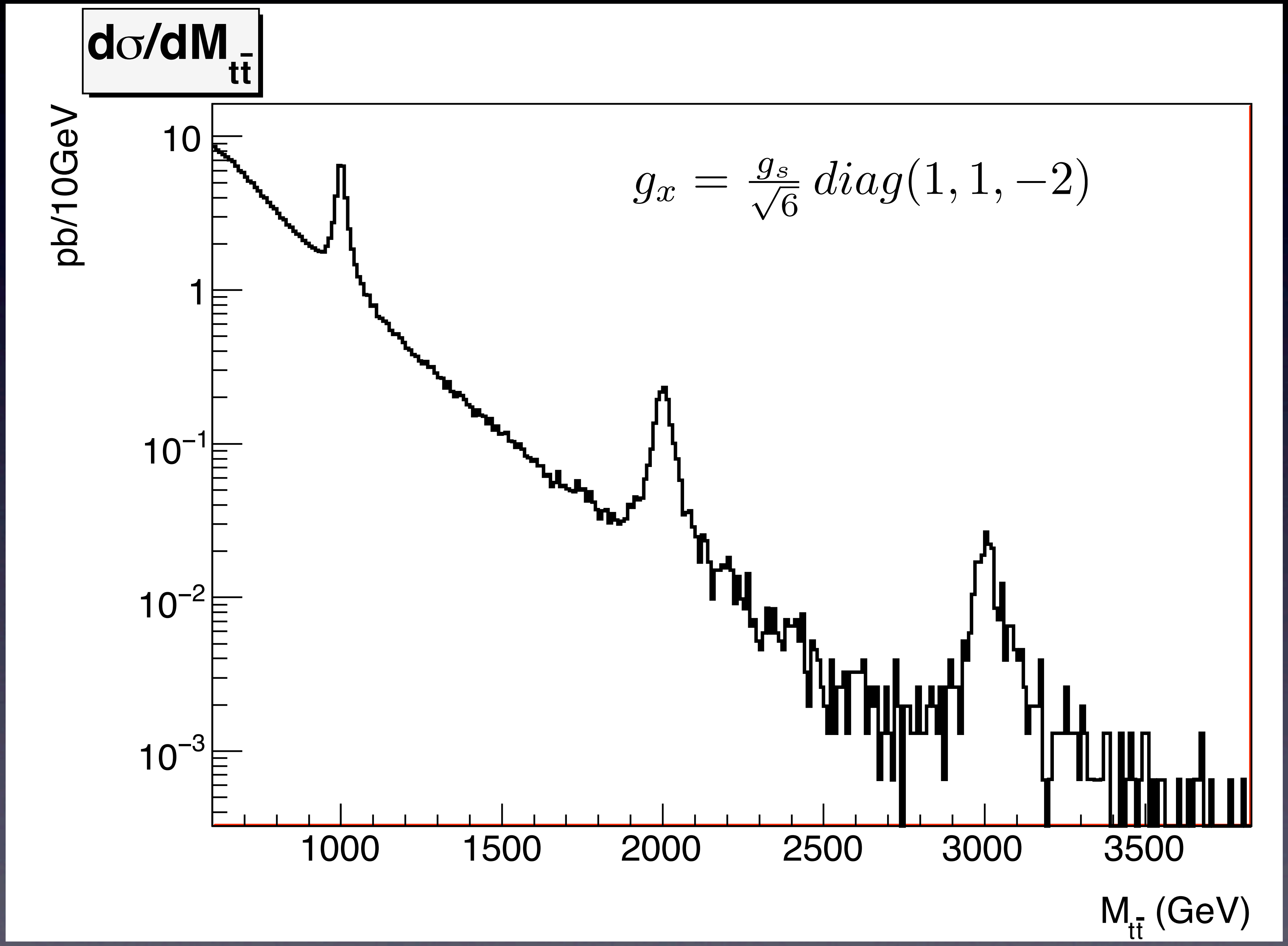
$\Phi_d : (\mathbf{3}, \mathbf{1}, \underline{\mathbf{3}})$, $\quad \langle \Phi_d \rangle = Y_{*d}\ (z/R)^{-\varepsilon}$

Large effects in up-FCNCs expected.

A theory of flavor at the LHC?

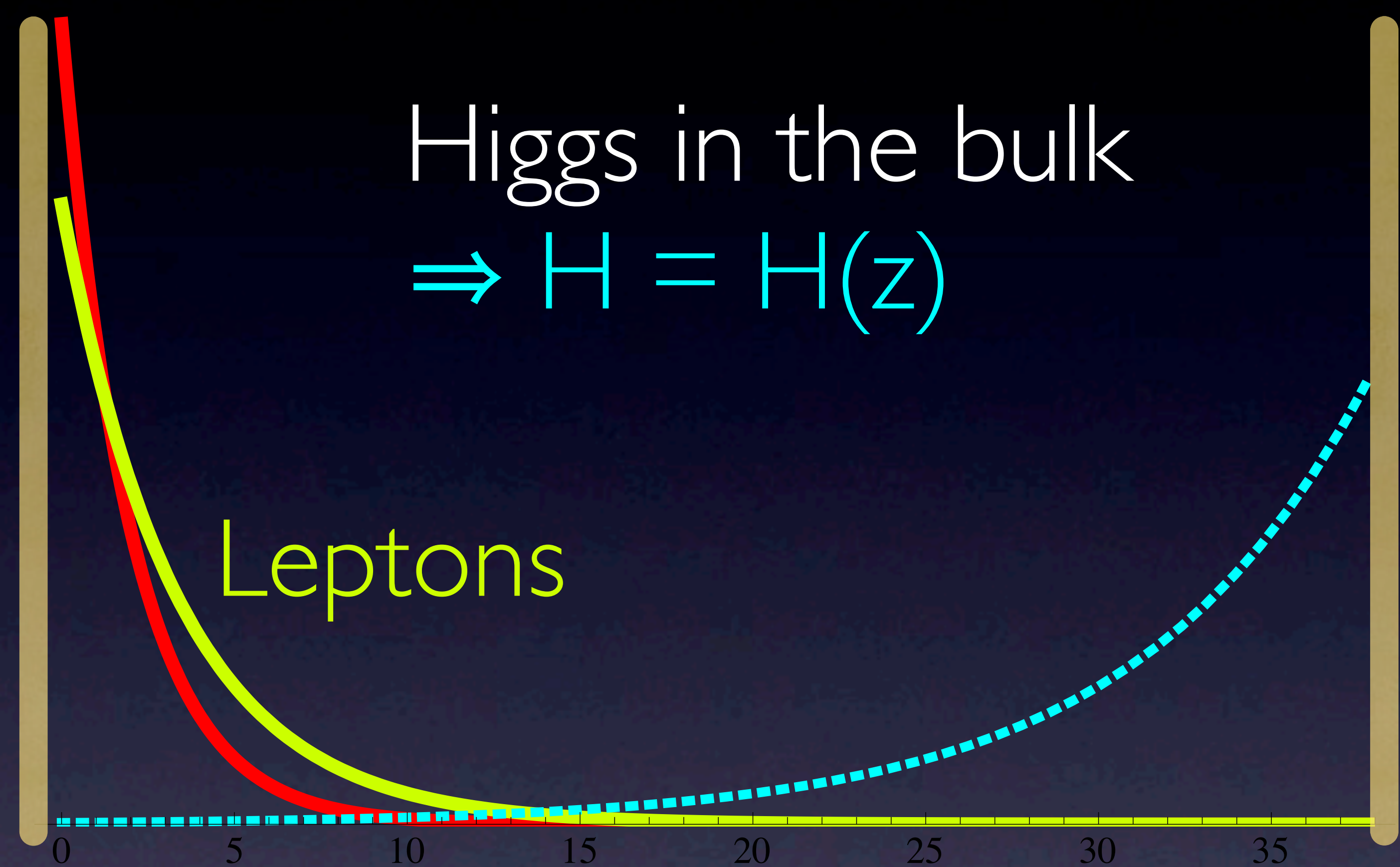
Flavor scalars & gauge bosons

Csaki, Lee, Perez, AW in preparation



thanks to Seung Lee for the plot

Remark on lepton flavor



Neutrino wave function picks up UV tail of Higgs

Agashe, Sundrum, Okui

Exponential suppression of overall mass scale
but O(1) **ν** mixing angles.

Flavor symmetries alternative: Perez, Randall; Delaunay,

Remark on lepton flavor

$$Y_{4\mathrm{D},ij} \sim \int_0^a dy\, Y_{5\mathrm{D},ij}(y)\, e^{-(M_{L_i}+M_{R_j})y+M_H(y-a)}$$

$(M_{L_i}+M_{R_j}>M_H)$ $\quad\quad$ $(M_{L_i}+M_{R_j}<M_H)$

$$\sim \widetilde{Y}_{0,ij}\, e^{-M_H a} \quad \lll \quad \sim \widetilde{Y}_{a,ij}\, e^{-(M_{L_i}+M_{R_j})a}$$

$M_i = c_i$

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$$(M_{L_i}+M_{R_j}>M_H) \qquad\qquad (M_{L_i}+M_{R_j}<M_H)$$

$$\boxed{\sim \widetilde{Y}_{0,ij}\, e^{-M_H a}} \quad \ll \quad \sim \widetilde{Y}_{a,ij}\, e^{-(M_{L_i}+M_{R_j})a}$$

$M_i = c_i$

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Mass terms from gauge interactions

Possible fermion embedding: **4** of SO(5)

$$\Psi_q = \begin{pmatrix} \boxed{q_q[+,+]} \\ u^c_q[-,+] \\ d^c_q[-,+] \end{pmatrix} \qquad \Psi_u = \begin{pmatrix} q_u[+,-] \\ \boxed{u^c_u[-,-]} \\ d^c_u[+,-] \end{pmatrix} \qquad \Psi_d = \begin{pmatrix} q_d[+,-] \\ u^c_d[+,-] \\ \boxed{d^c_d[-,-]} \end{pmatrix}$$

1) $\boxed{\qquad}$ = chiral zero modes

Mass terms from gauge interactions

Possible fermion embedding: **4** of SO(5)

A_5

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1) = chiral zero modes

2) <A_5> marries fields in same multiplet

Mass terms from gauge interactions

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$\tilde{M}_u$

1) = chiral zero modes

2) $\langle A_5 \rangle$ marries fields in same multiplet

3) SO(4) invariant brane masses mix multiplets

$$\mathcal{L}_{IR} = -\left(\frac{R}{R'}\right)^4 \left[\tilde{m}_u \chi_{q_q}\psi_{q_u} + \tilde{m}_d \chi_{q_q}\psi_{q_d} + \tilde{M}_u(\chi_{u^c_q}\psi_{u^c_u} + \chi_{d^c_q}\psi_{d^c_u}) + \tilde{M}_d(\chi_{u^c_q}\psi_{u^c_d} + \chi_{d^c_q}\psi_{d^c_d})\right]$$

Mass terms from gauge interactions

Possible fermion embedding: **4** of SO(5)

A5

$$\Psi_q = \begin{pmatrix} q_q[+,+] \\ u^c_q[-,+] \\ d^c_q[-,+] \end{pmatrix} \qquad \Psi_u = \begin{pmatrix} q_u[+,-] \\ u^c_u[-,-] \\ d^c_u[+,-] \end{pmatrix} \qquad \Psi_d = \begin{pmatrix} q_d[+,-] \\ u^c_d[+,-] \\ d^c_d[-,-] \end{pmatrix}$$

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4D CFT explanation

Contino, Pomarol

Quasi conformal sector between TeV … $M_{\rm pl}$

Linear coupling of SM fields to composites

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

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

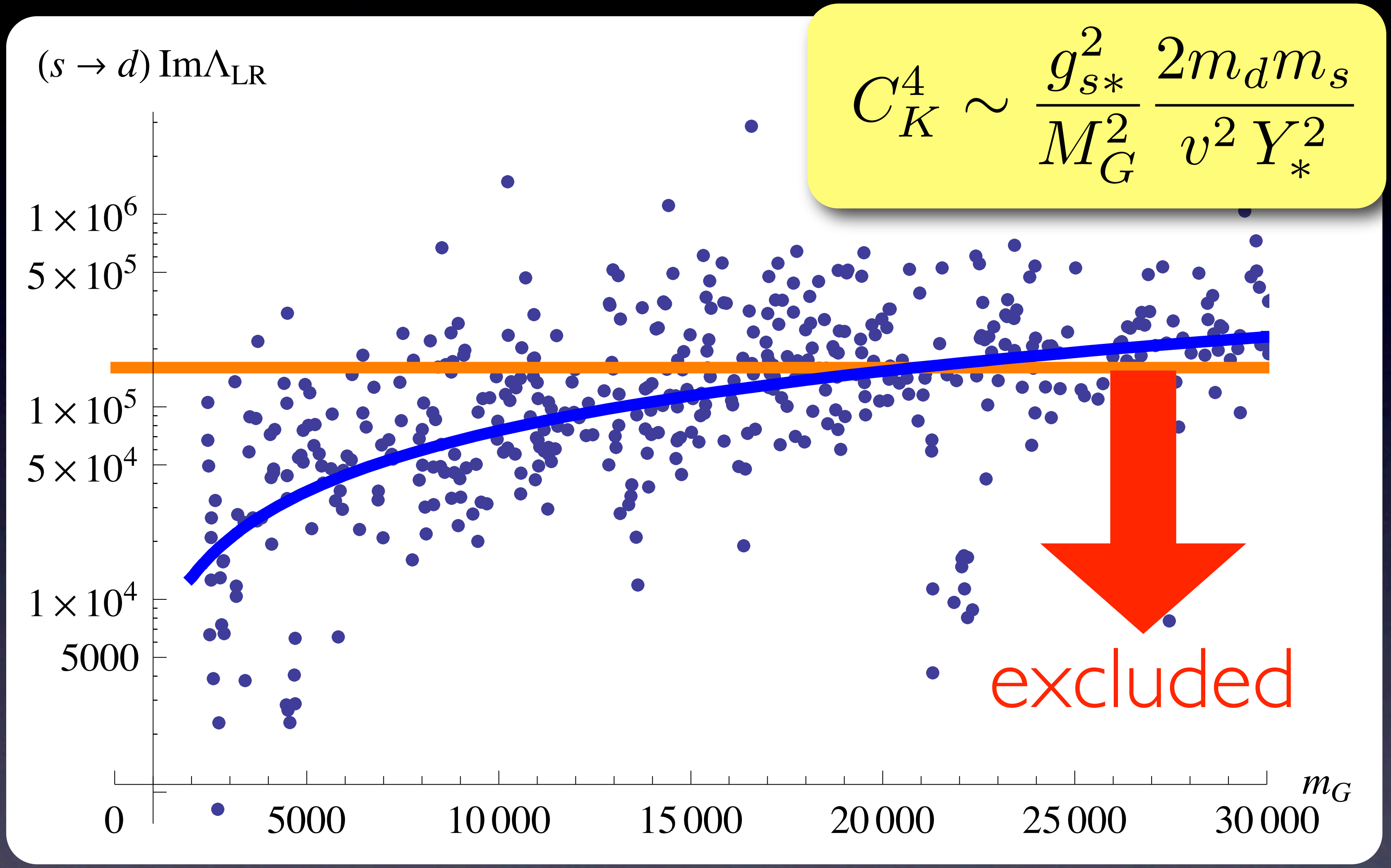
$$\lambda \sim \left(\frac{\rm TeV}{M_{Pl}}\right)^{\gamma}$$

AdS/CFT translation:

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

KK gluon mass bound in RS

Csaki, Falkowski, A.W.; Buras et. al.



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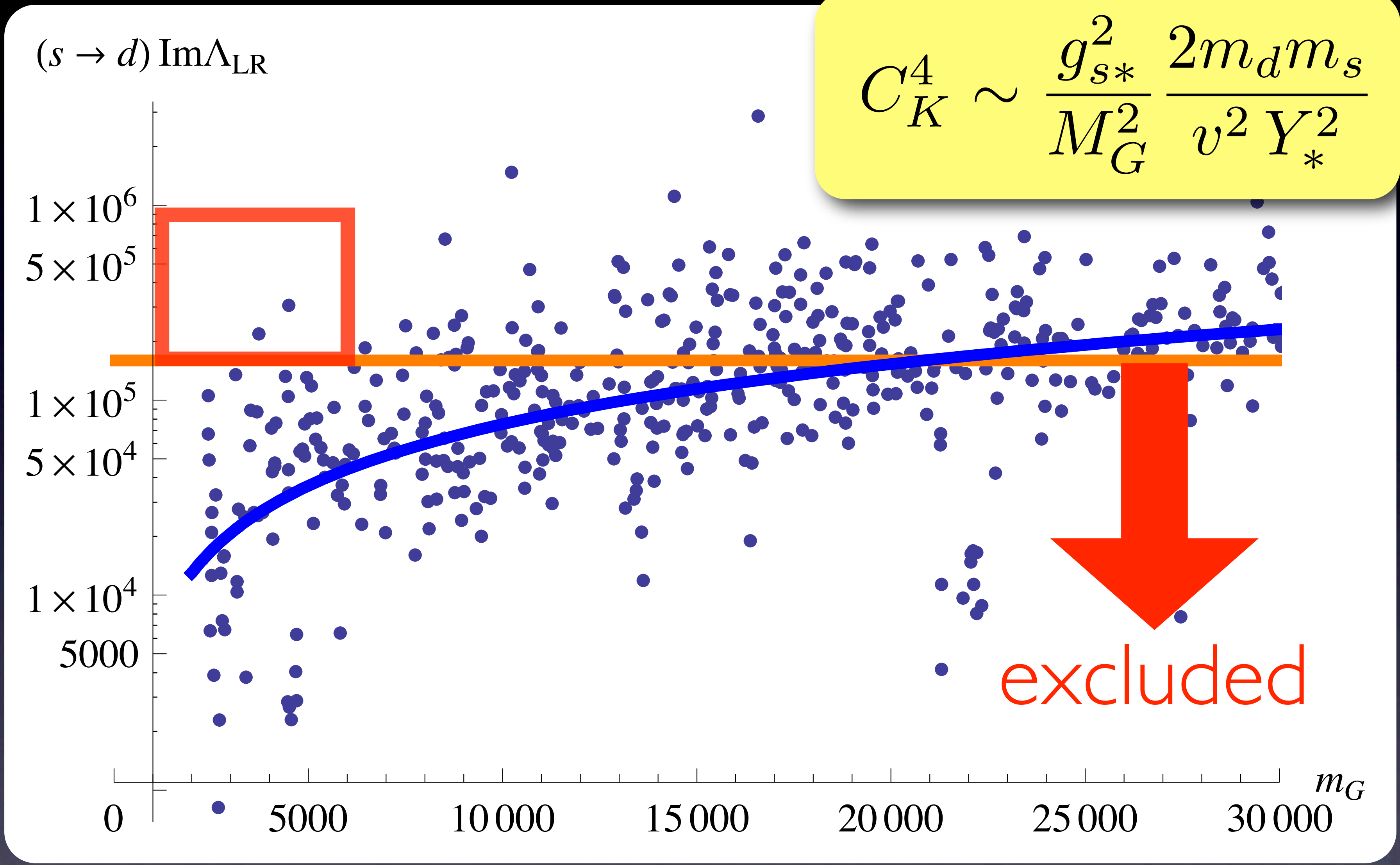


$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2}\,\frac{2 m_d m_s}{v^2\, Y_*^2}$$

Some points are ok: any rationale to live here?

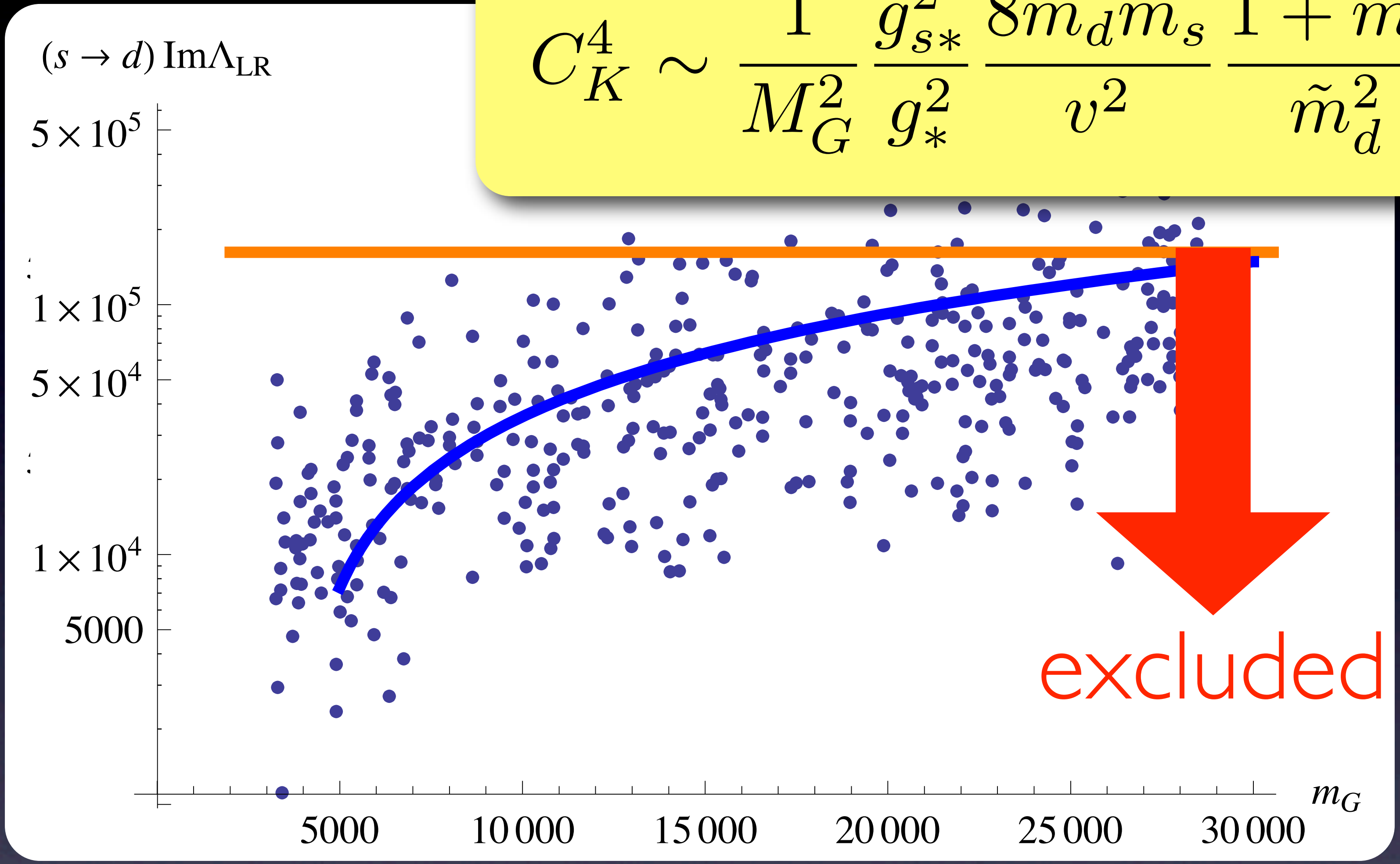
Radiative stability?

Bound depends on bulk QCD coupling $\mathbf{g_{s*}}$ and $\mathbf{Y_*}$

Bound for pGB Higgs

Csaki, Falkowski, A.W.;

$$C_K^4 \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+m^2}{\tilde{m}_d^2}$$



M_{KK} > 30 TeV

FCNC constraint more severe in composite pGB!

Why? $Y^* \rightarrow g_* / 2$ & fermionic kinetic mixings

Bound for pGB Higgs

Csaki, Falkowski, A.W.;

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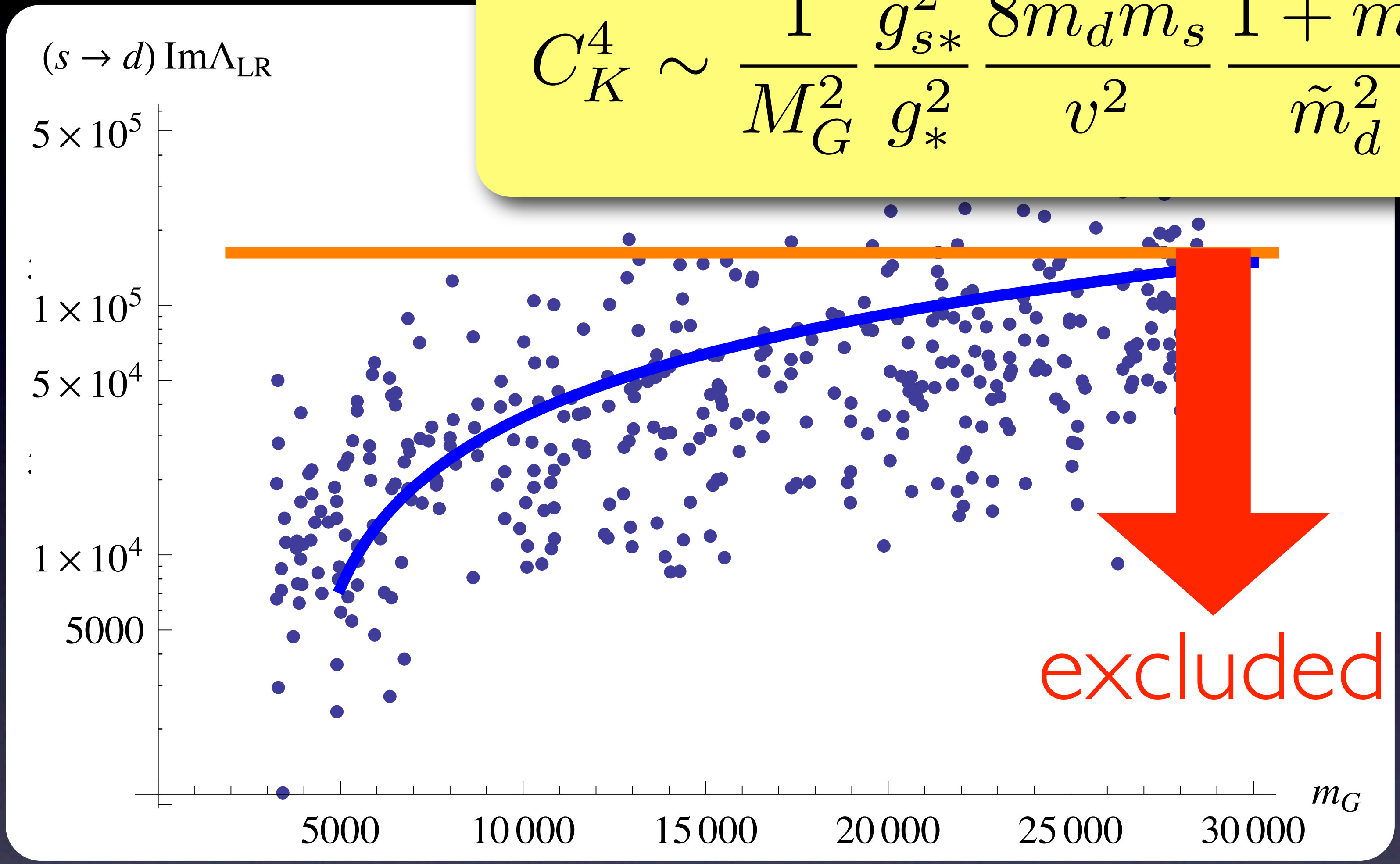
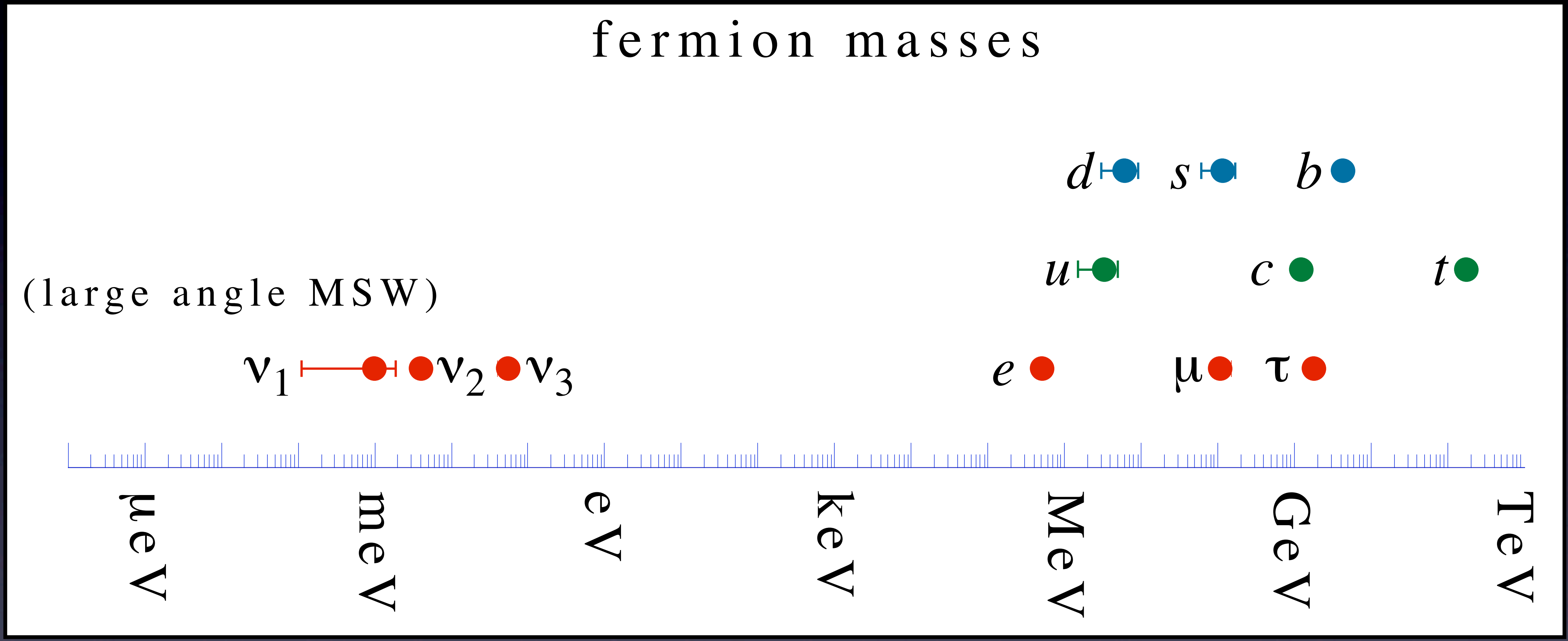


M_{KK} > 30 TeV

FCNC constraint more severe in composite pGB!

Why? Y^* → g_* / 2 & fermionic kinetic mixings

Fermion masses & mixings



$$V_{CKM} \sim \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 \\ \lambda & 1-\frac{\lambda^2}{2} & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda \approx 0.23$$

Higgs as flavon

Babu, Nandi ’99; Giudice, Lebedev ’08

“Higgs dependent Yukawas”
Yukawas effective interaction after integrating out heavy physics. Postulate leading terms are absent

$$\mathcal{L}_Y = Y^u_{ij}(H)\ \bar{q}_{Li} u_{Rj} H^c + Y^d_{ij}(H)\ \bar{q}_{Li} d_{Rj} H$$

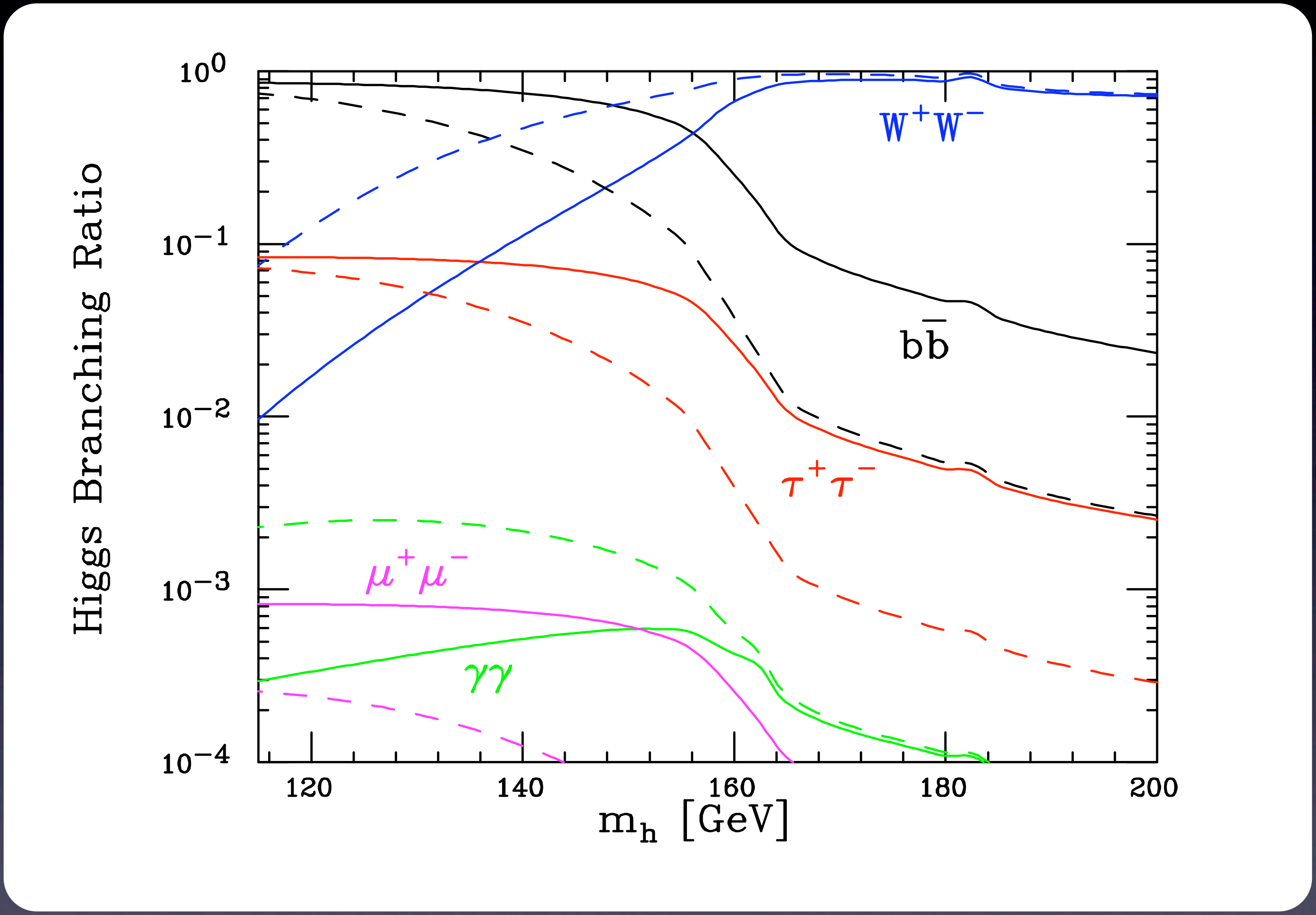
$$Y^{u,d}_{ij}(H) = c^{u,d}_{ij} \left(\frac{H^\dagger H}{M^2} \right)^{n^{u,d}_{ij}}$$

n_{ij} generation dependent integer, determines mass hierarchy

$v^2/M^2 \approx m_b^2/m_t^2$ => $M \approx 1 - 2\,\mathrm{TeV}$

Higgs as flavon: signals

Giudice, Lebedev '08



Higgs dependent Yukawas

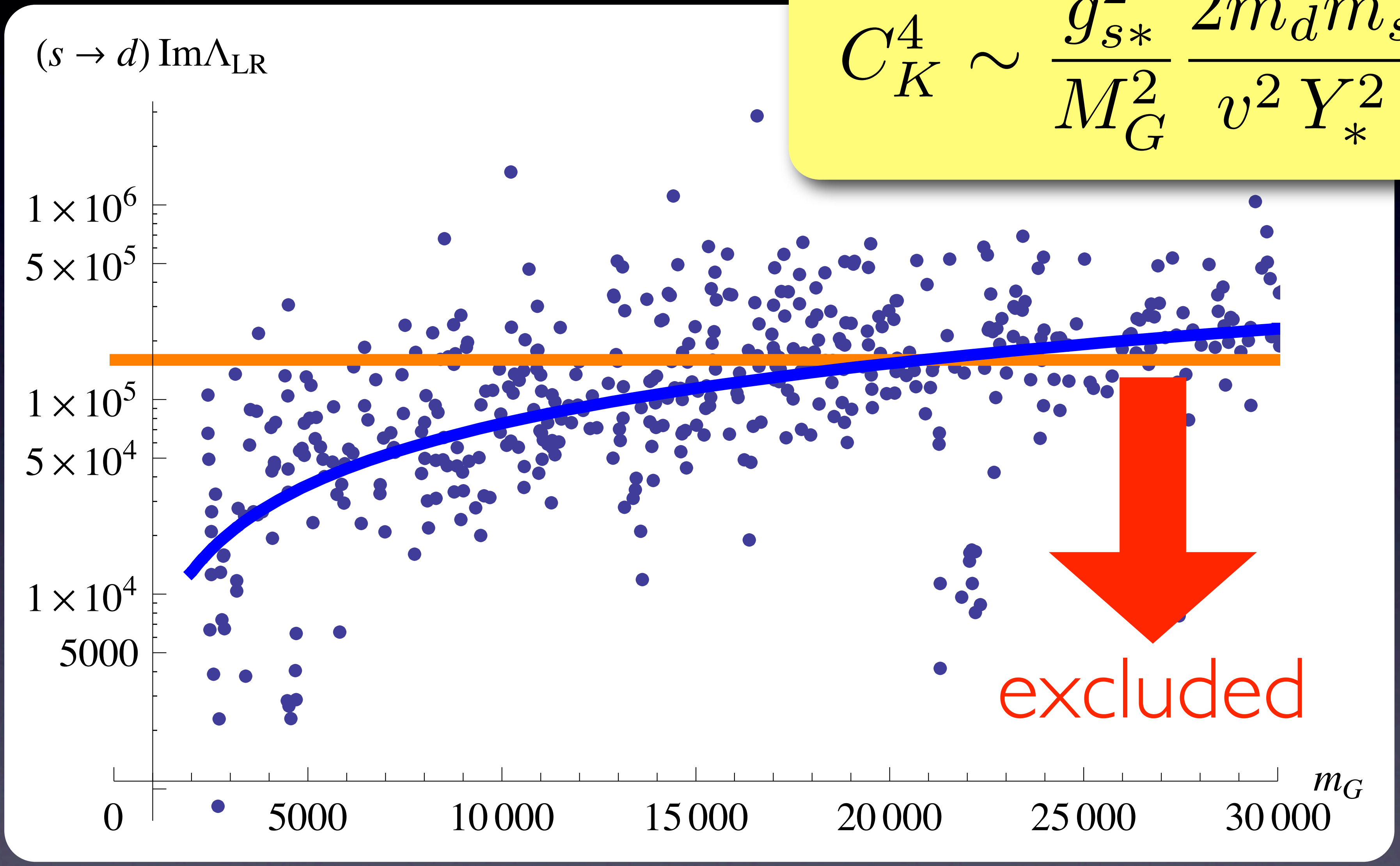
SM

$$\frac{\Gamma\left(h\to b\bar{b}\right)}{\Gamma\left(h\to b\bar{b}\right)_{SM}}=\frac{\Gamma\left(h\to c\bar{c}\right)}{\Gamma\left(h\to c\bar{c}\right)_{SM}}=\frac{\Gamma\left(h\to \tau^+\tau^-\right)}{\Gamma\left(h\to \tau^+\tau^-\right)_{SM}}=9 \qquad \frac{\Gamma\left(h\to \mu^+\mu^-\right)}{\Gamma\left(h\to \mu^+\mu^-\right)_{SM}}=25$$

Bound on the KK gluon mass

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

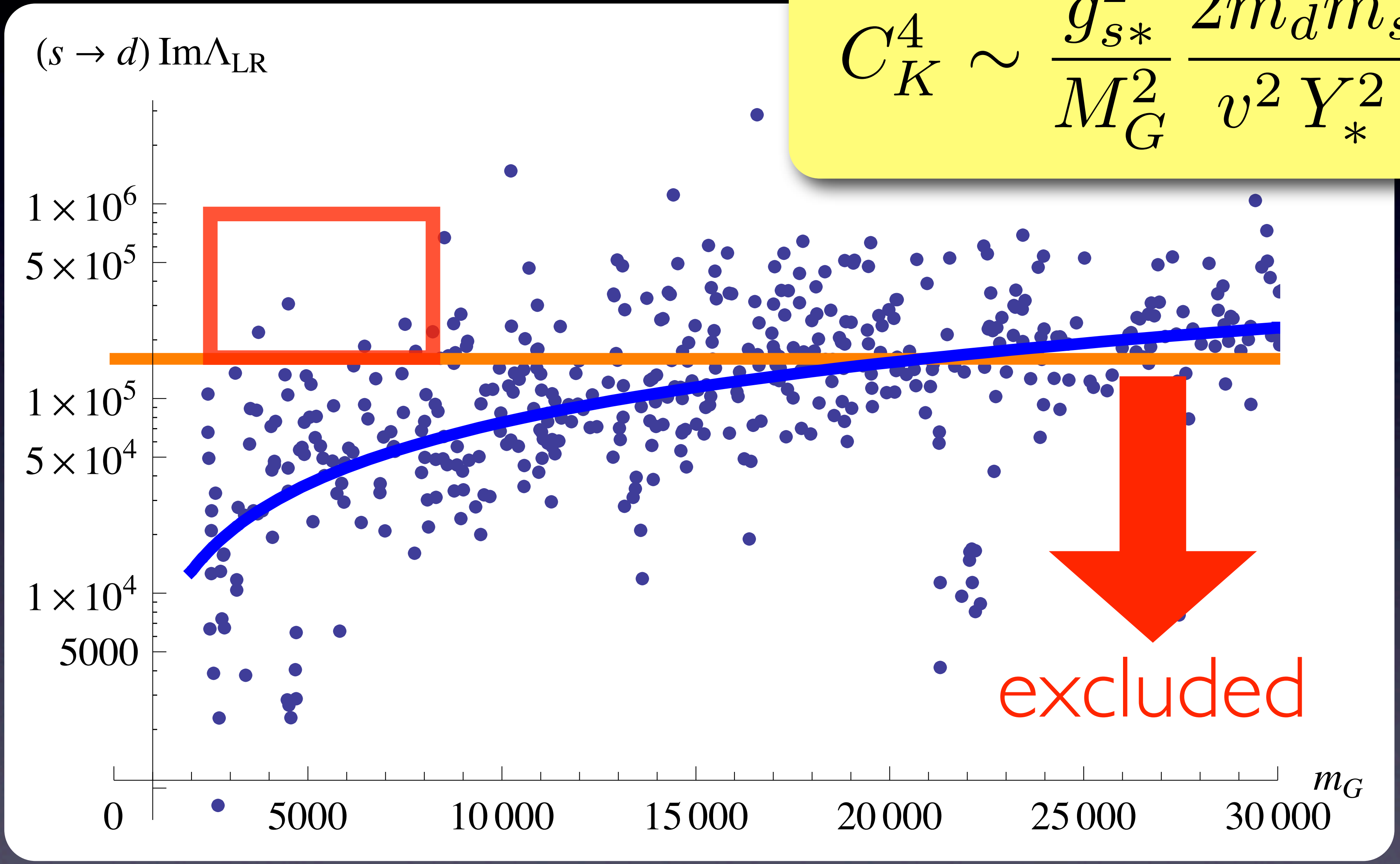
$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2}\,\frac{2 m_d m_s}{v^2\,Y_*^2}$$



☞ more in M. Neubert's talk

Bound on the KK gluon mass

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



$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2}\,\frac{2m_d m_s}{v^2\,Y_*^2}$$

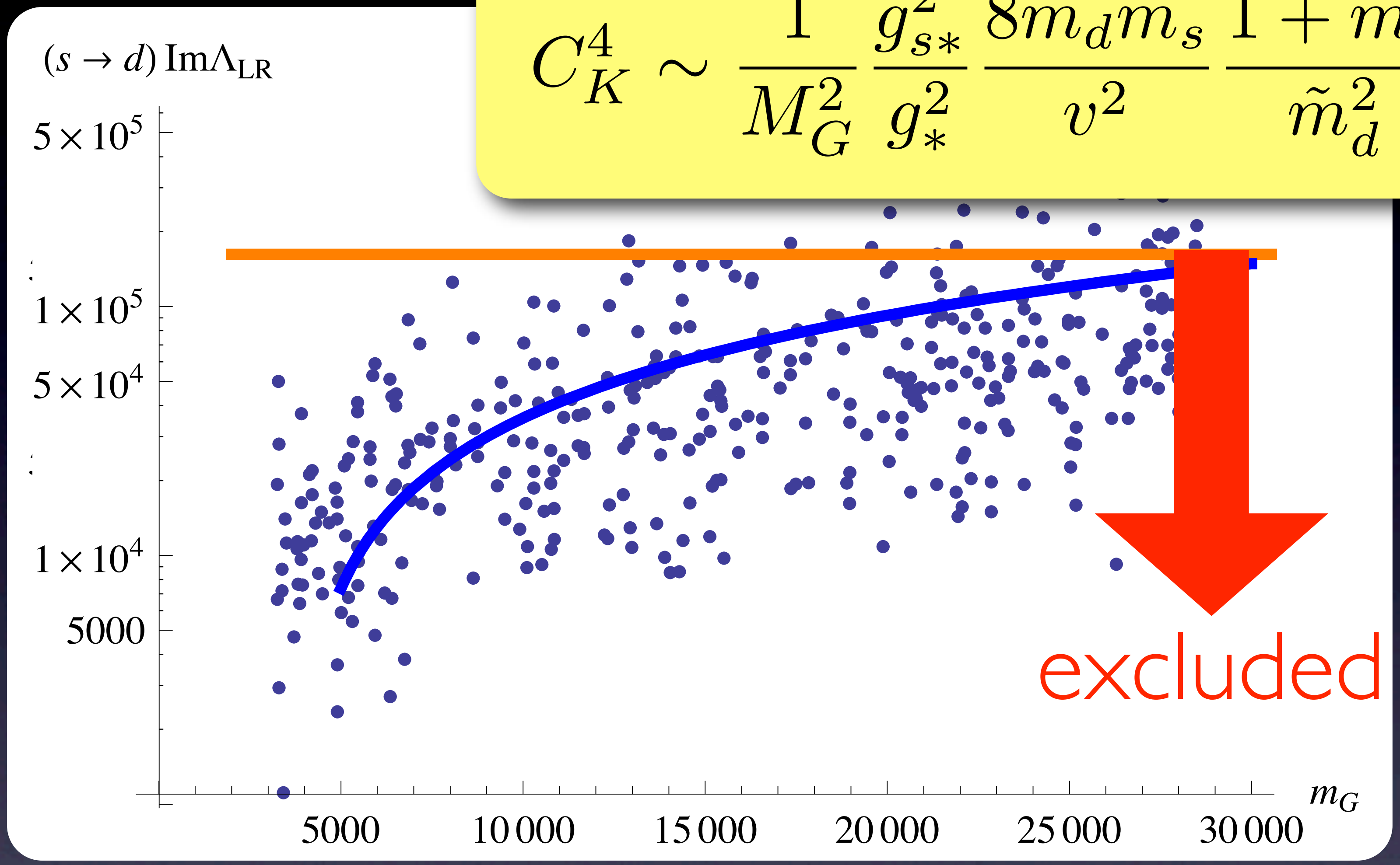
Some points above the bound: any rationale to live here? Radiative stability?

☞ more in M. Neubert's talk

Bound in the composite pGB

Csaki, Falkowski, A.W.;

$$C_K^4 \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+m^2}{\tilde{m}_d^2}$$



more flavor violation in composite pGB:

$Y^* \to g_* / 2$ & fermionic kinetic mixings

$M_{KK} > 30$ TeV

Bound in the composite pGB

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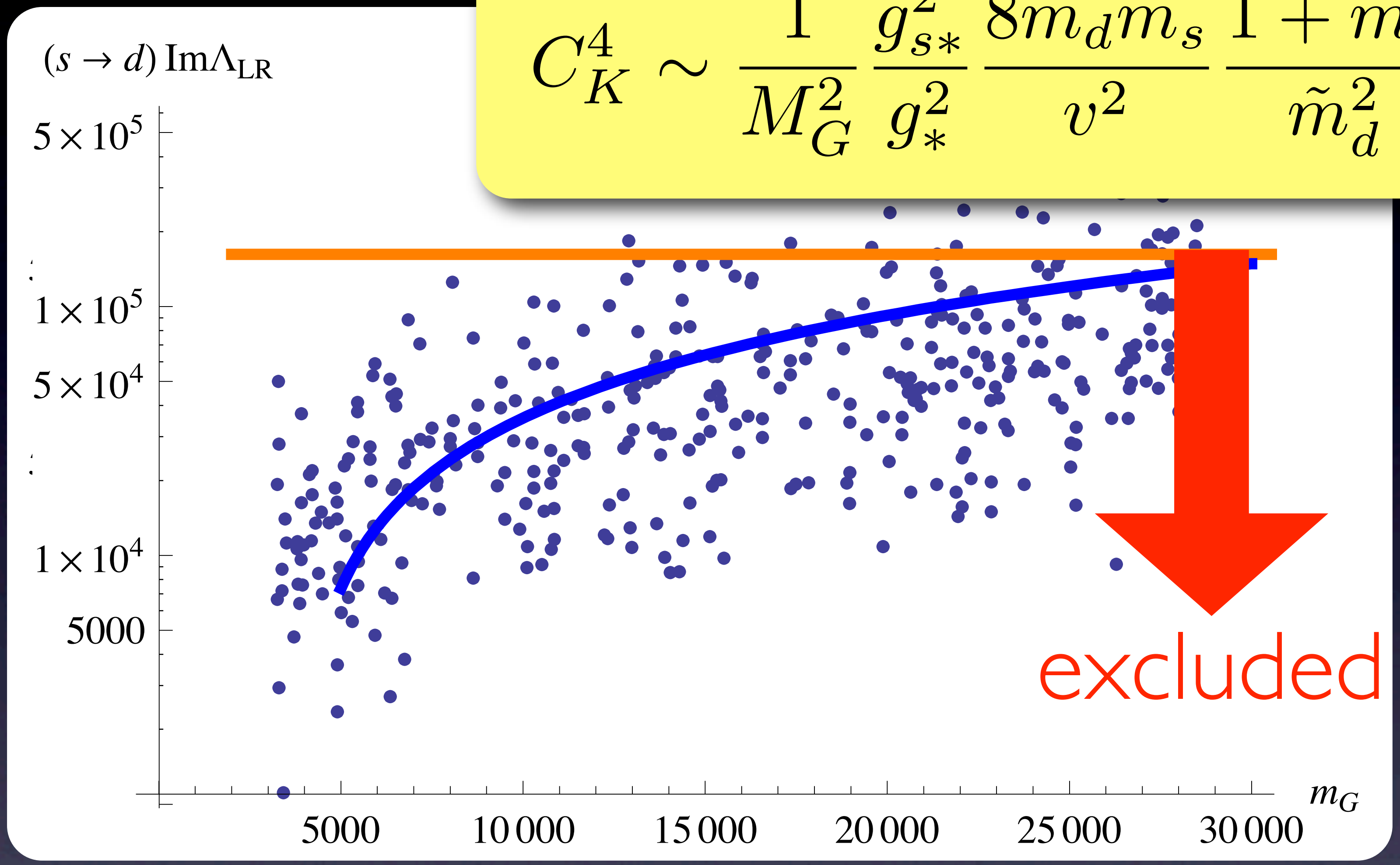

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