Tops Beyond the Asymmetry

Andreas Weiler
CERN&DESY

Planck 2011
Lisbon

3/6/2011

Naturalness vs. flavor triviality

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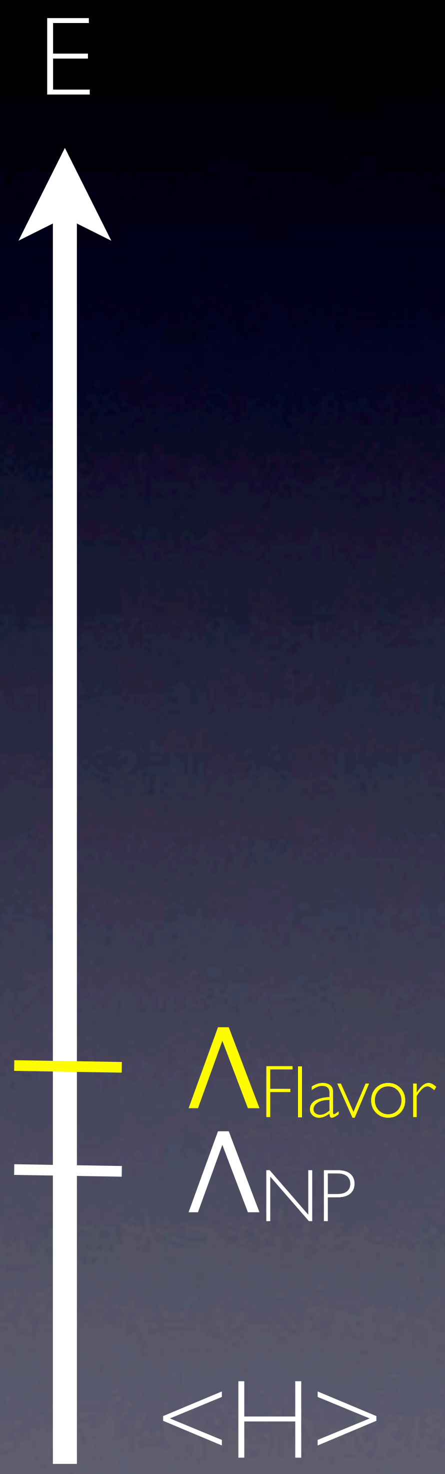
EWSB & Flavor

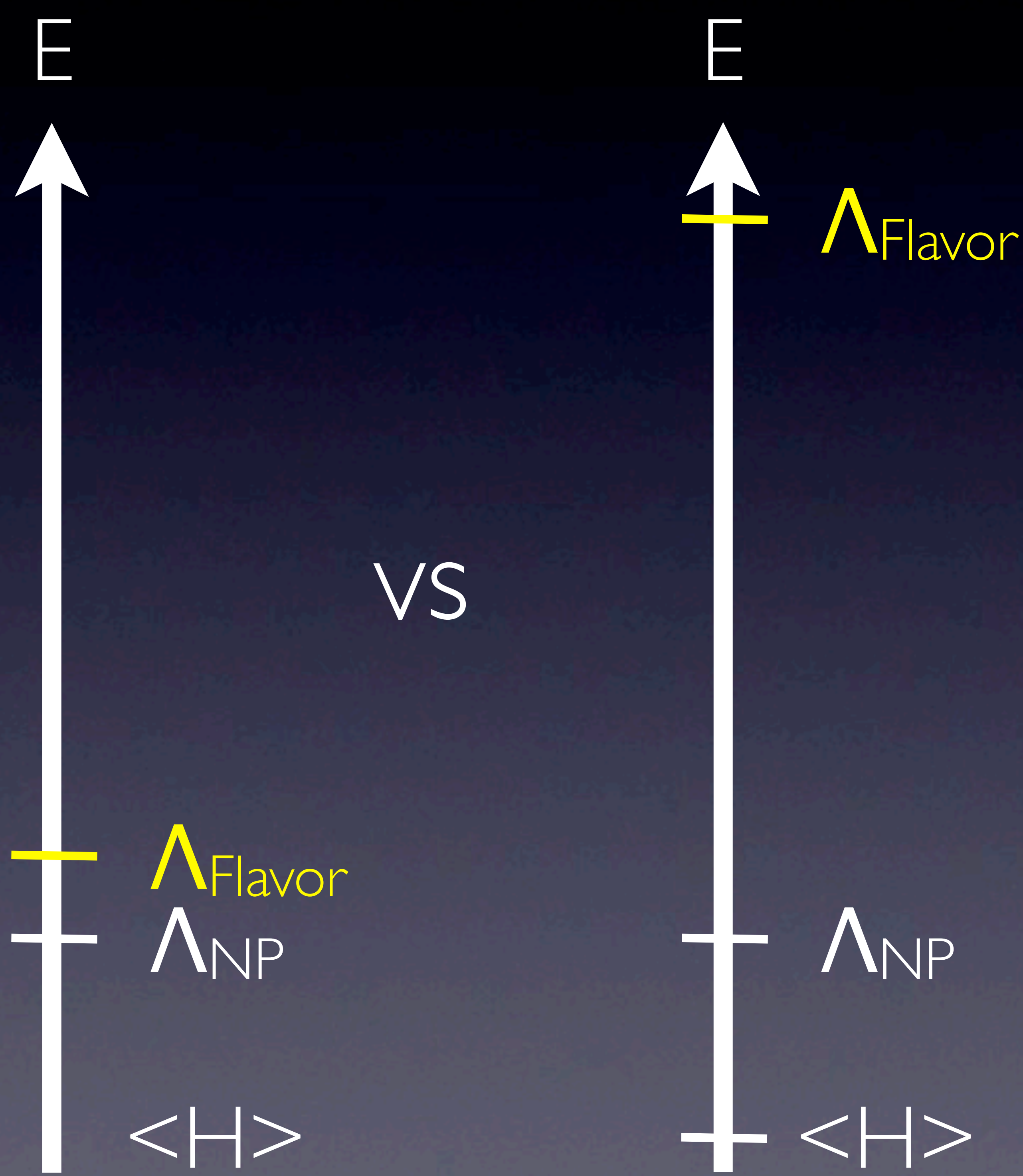


$$\frac{1}{\Lambda^2_{\mathrm{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

$$y_{ij}\,\bar{\psi}_i\mathcal{H}\psi_j$$

} naturalness

EWSB & Flavor



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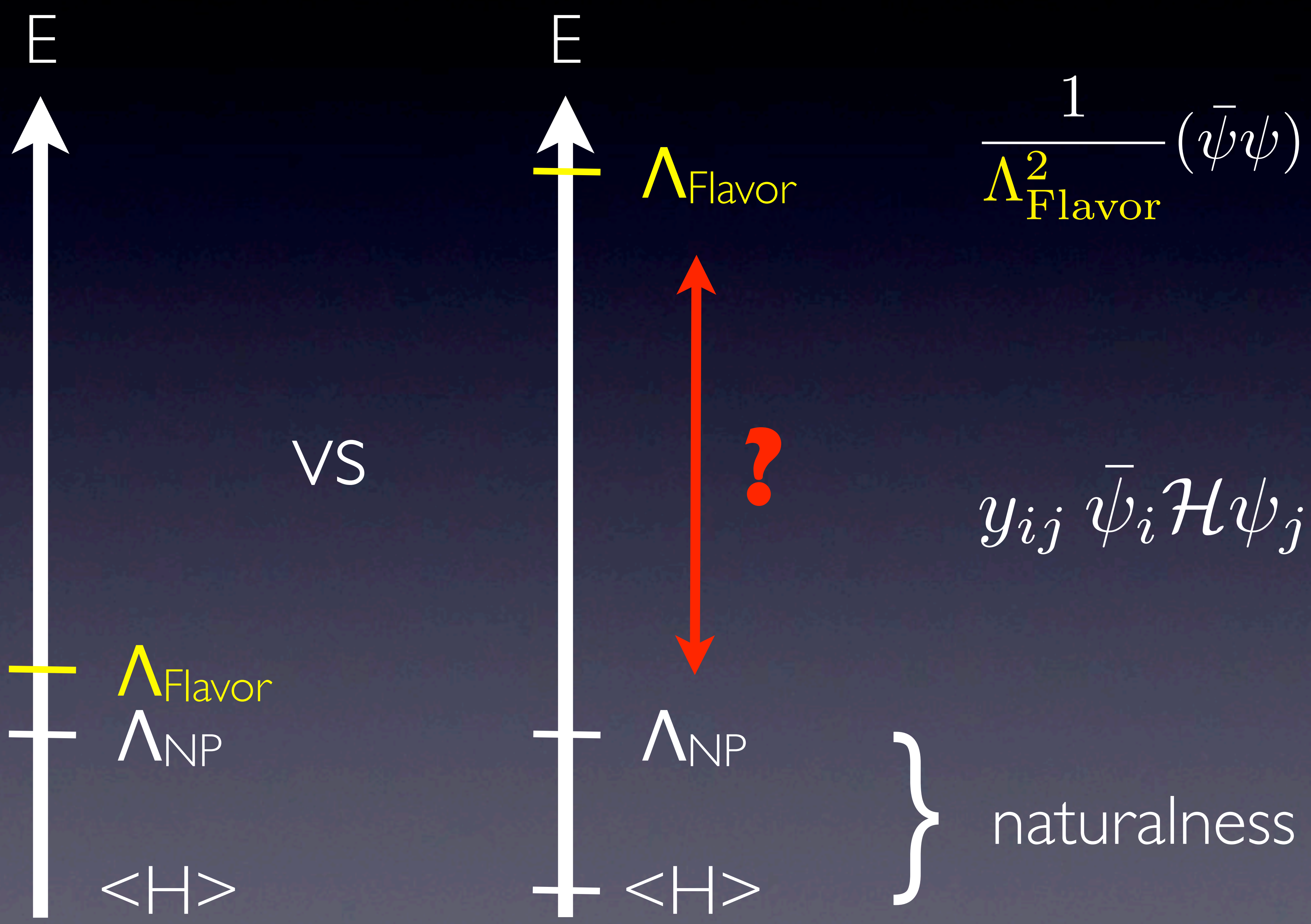

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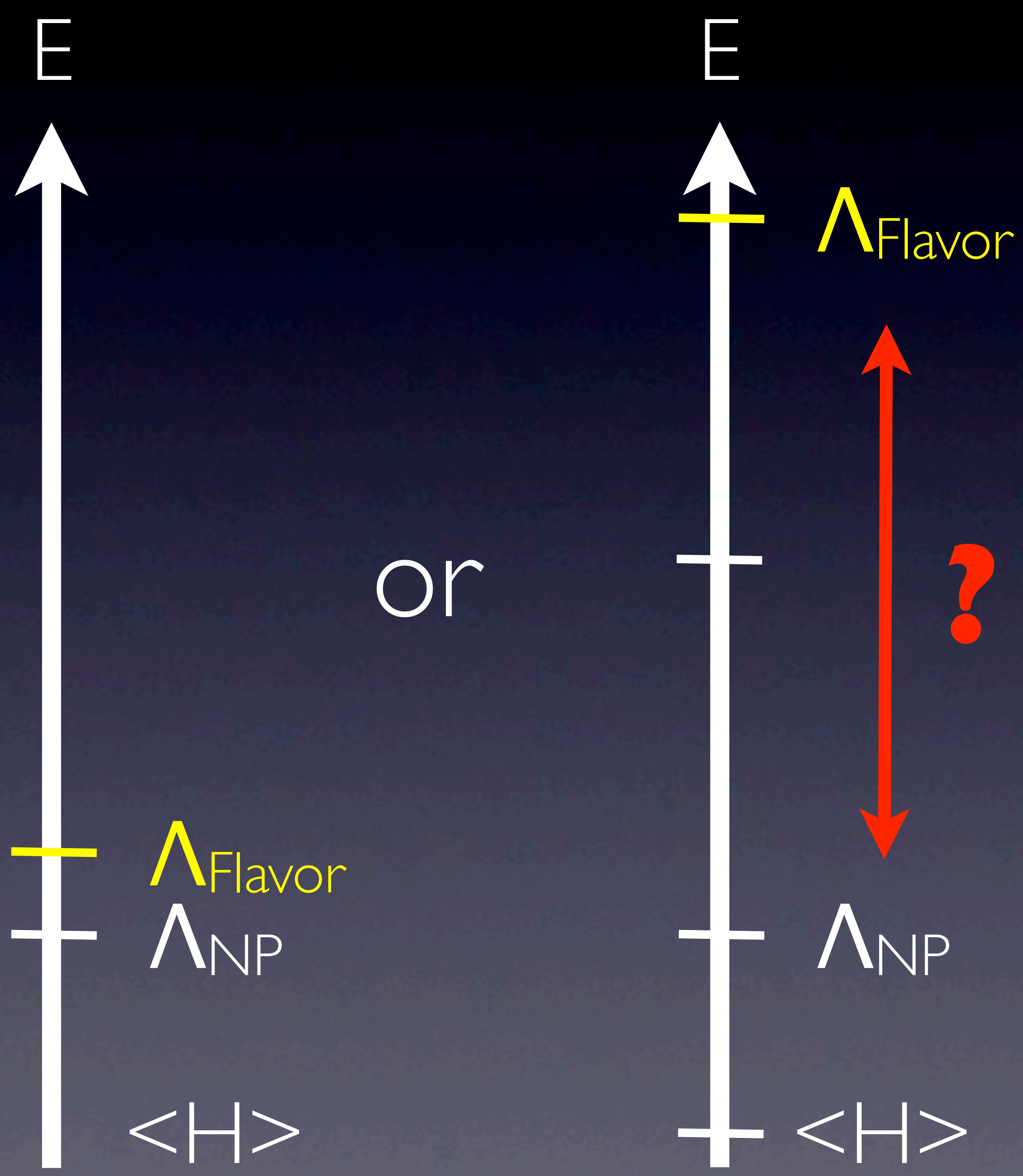

$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

only trace left: MFV

$$y_{ij}\,\bar{\psi}_i \mathcal{H} \psi_j$$

naturalness
top partners!

1) composite Higgs vs. MFV (EWPT, top mass, EDMs)

w/ Michele Redi (CERN/INFN) and ideas by R. Rattazzi

2) chromo-electric dipole moment of the top

w/ Jernej Kamenik (IJS, Ljubljana) Michele Papucci (CERN/LBL)

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3) Flavor & Naturalness & susy breaking

w/ Michele Papucci (CERN/LBL)

if time allows

Old Flavor problem of composite Higgs

Higgs as bound state, naively $D_{\mathcal{H}=\langle\bar{\psi}\psi\rangle} \approx 3$

$$\frac{1}{\Lambda^{D_{\mathcal{H}}-1}} y_{ij}\,\bar{\psi}_i \mathcal{H} \psi_j + \frac{1}{\Lambda^2} c_{ijkl}\,\bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$$

Λ can not be too large, because want top mass

$$\Lambda = \mathcal{O}(\text{TeV})$$

=> talk by Rychkov

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Λ can not be too large, because want top mass

Λ must be very large because this leads to FCNCs

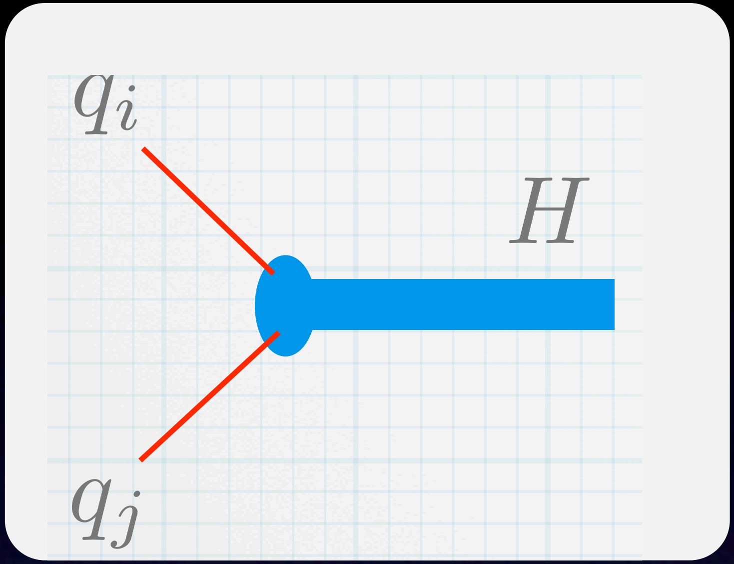
$K^0 - \bar{K}^0$

$$\Lambda = \mathcal{O}(\text{TeV})$$

$$\Lambda > 10^5\, \text{TeV}$$ ✗

=> talk by Rychkov

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

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

$\propto$

Two ways of giving mass to fermions…

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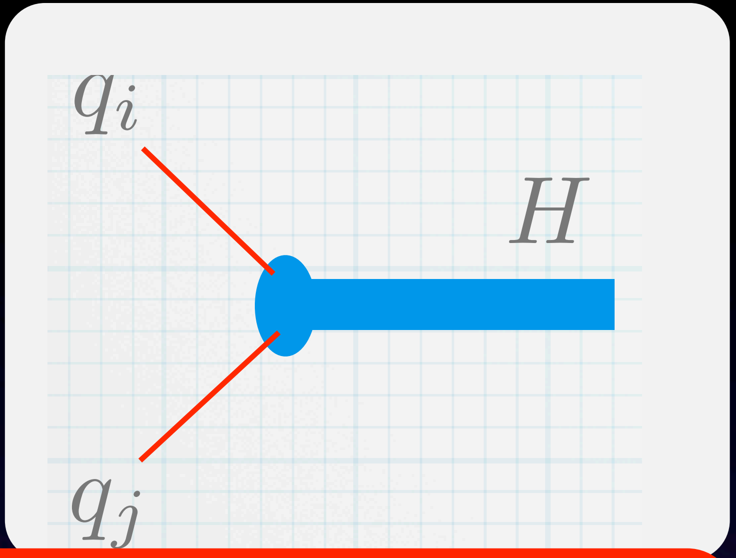

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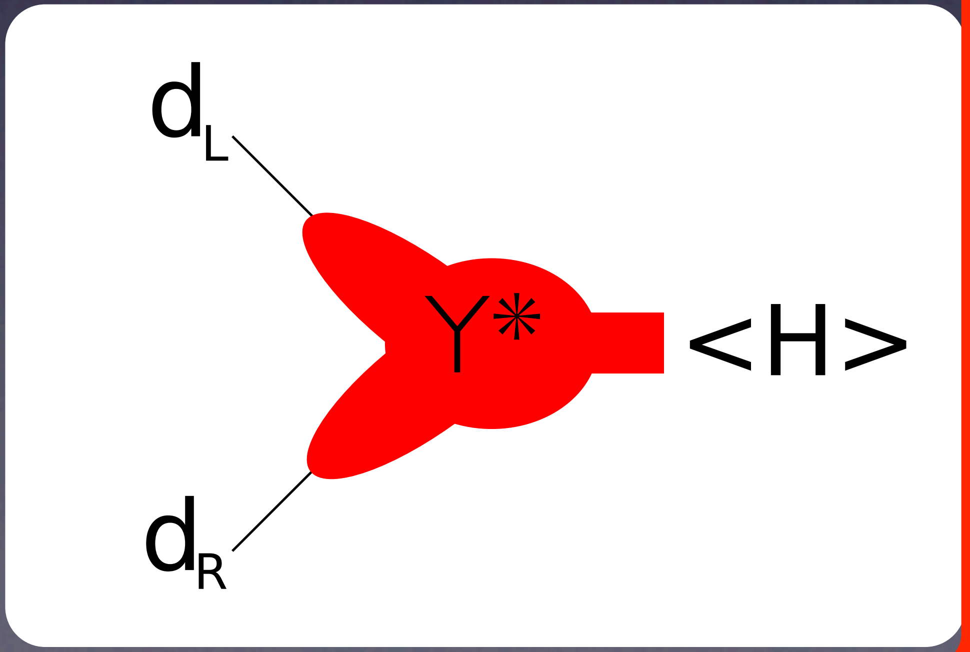
Quarks & Leptons mix with strong sector

mass $\propto$ compositeness



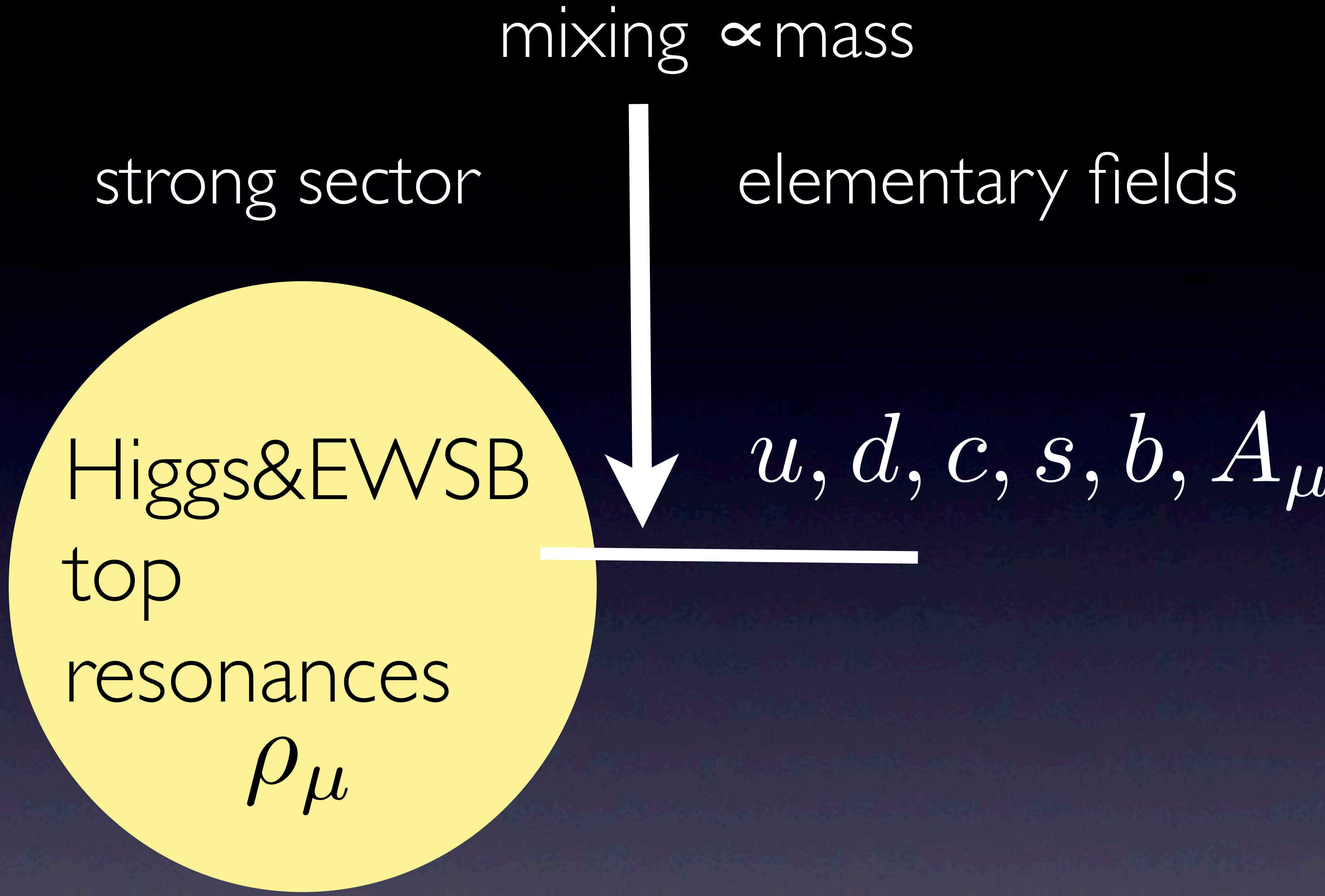
Partial compositeness

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

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

Composites are heavy ($m_\rho \approx \mathrm{TeV}$).

Light quarks have very little composite admixture.



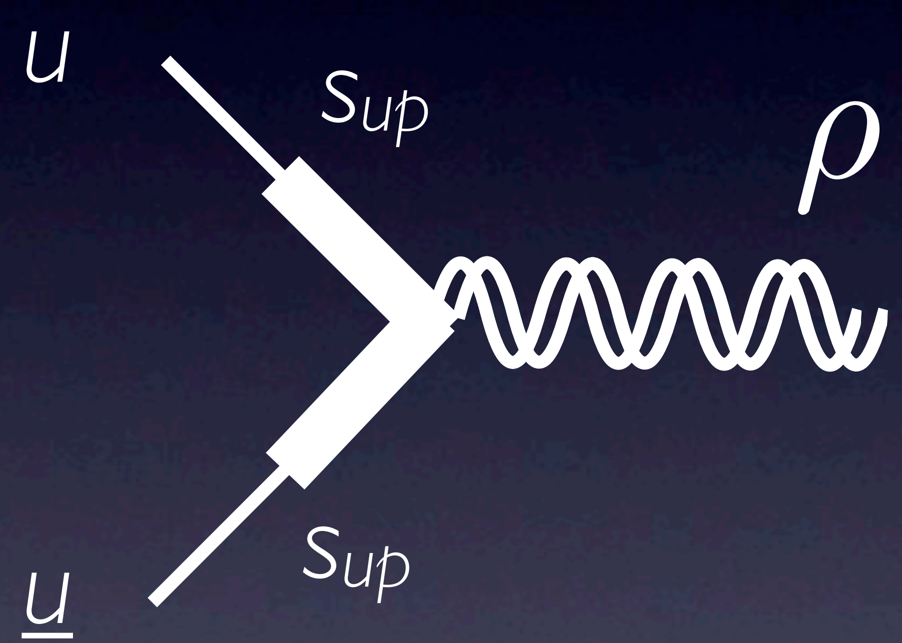
$g_*, \; m_\rho$

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

Kaplan; Contino, Kramer, Son, Sundrum

high pT

Resonance production (option 1)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

high p_T

Resonance production (option 2)

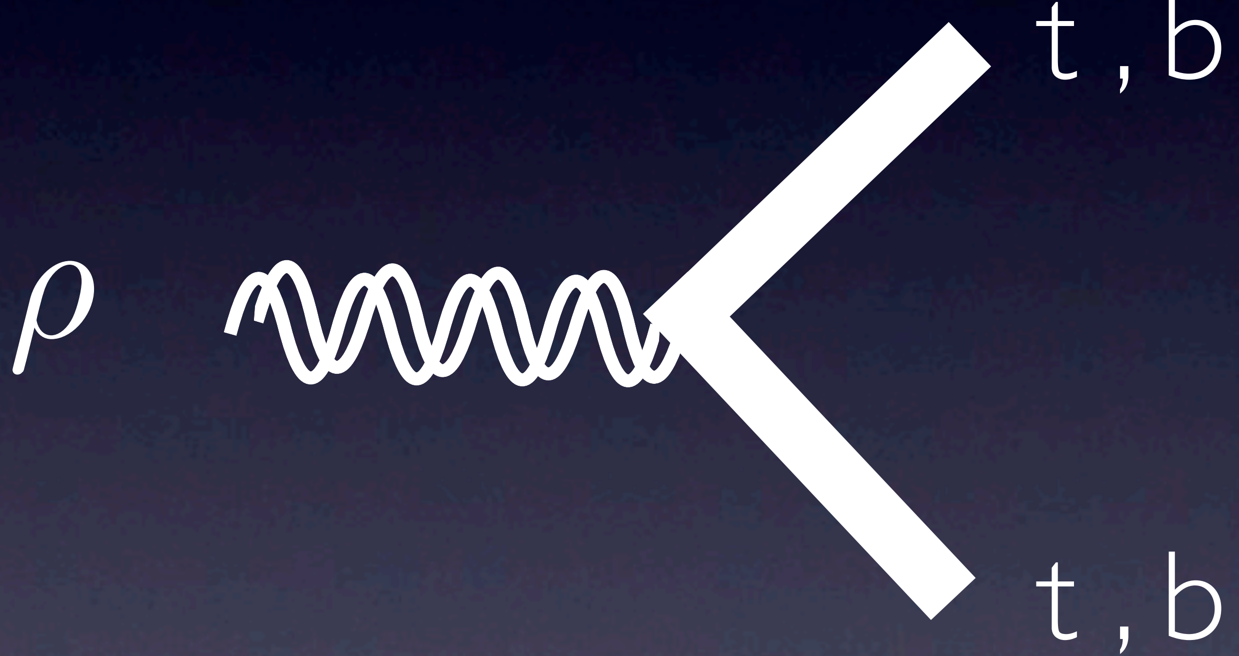
$$\sim \frac{g_s}{g*}$$

analog to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

high p_T

Resonance decay



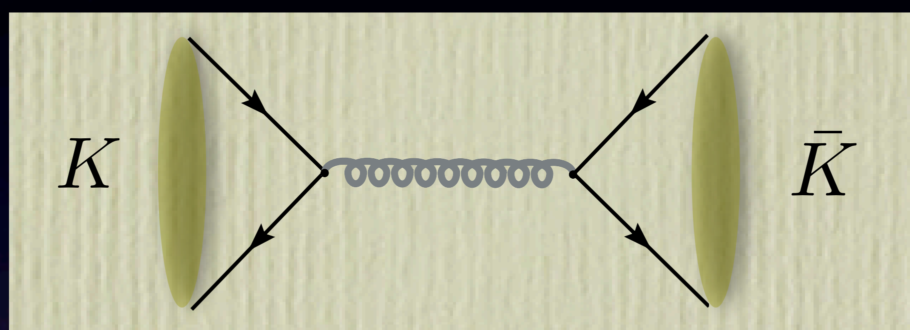
decays dominantly into 3rd generation! (tt, bt, bb)

CP problems

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

$\Delta F = 2$ (strongest from ϵ_K)

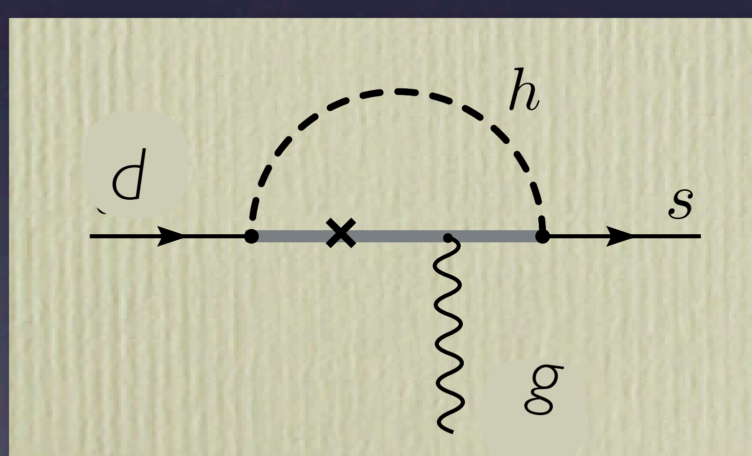
$$g_* \approx Y_* \approx 3 \ldots 6$$



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

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

Gedalia et. al



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

$\Delta F = 0$ neutron EDM

$$M_* \geq 2.5\, Y_* \text{ TeV}$$

Agashe et. al, Delaunay et. al, Redi, AW

=> talk by R. Ziegler

Flavor breaking external

Michele Redi, AW

Postulate flavor agnostic strong sector

Usually tension between large top mass & universal mixings and EWPT

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

→ either some flavor breaking or special flavor dynamics ("shining")

=> talk by C. Delaunay

Found a simpler, easily discoverable model that avoids these problems and doesn't require a flavorful strong sector!

MFV with split LH doublets

Michele Redi, AW

Main Idea: mixing w/ **split LH doublets***

$$Q_{Lu}\ (2,2)_{2/3} \quad Q_{Ld}\ (2,2)_{-1/3} \quad u_R\ (1,1)_{2/3} \quad d_R\ (1,1)_{-1/3}$$

Strong sector *SU(3)$_F$*

$$\lambda_{Lu} \propto y_u, \quad \lambda_{Ld} \propto y_d$$
$$\lambda_{Ru} \propto Id \quad \lambda_{Rd} \propto Id$$

In the limit that *y_u, y_d* → *0* => *$U(3)^3$* aka **GIM**

* *inspired by composite Higgs. NB, in anarchic scenario this is completely unsafe and leads generically to large FCNC's.*

EWPT&compositeness

Michele Redi, AW

$$\delta g \approx \frac{Y^2 v^2}{2\, m_\rho^2} \sin^2\varphi_{q_L}\, (T'_{3L}(Q) - T_{3L}(q_L)) + g_2^2 \frac{v^2}{4m_\rho^2} \sin^2\varphi_{q_L} (T_{3R} - T_{3L})$$

Hadronic width

$\frac{\delta R_h}{R_h}$ => $\frac{\delta g_{Lu}}{g_{Lu}} < .002$

correction=0 @tree-level ✔

Dijet search (by ATLAS/CMS)

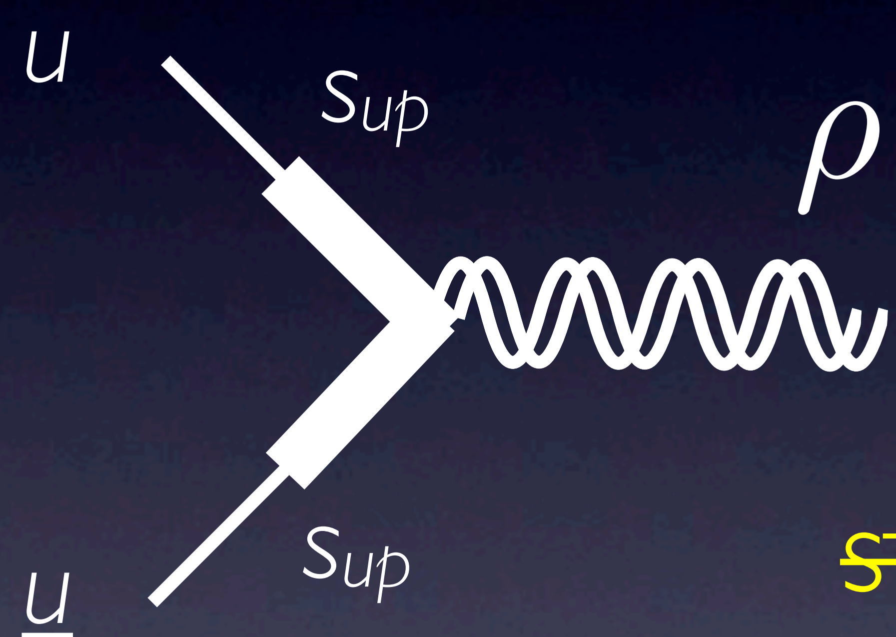
$$\sin^2\varphi_{q_{L,R}} \lesssim \frac{1}{g_\rho}\left(\frac{m_\rho}{3\,\text{TeV}}\right)$$

RH quarks can be easily fully composite!

✔

high p_T in MFV

Resonance production



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

~~strongly suppressed for light quarks!~~

=> O(1) coupling to light quarks!

“Ultra-visible”

Michele Redi, AW

production cross-section of color octet spin-1:

(similar conclusions for spin 1/2)

g_ρ	$\sin\varphi_{u_R}$	$\sin\varphi_{d_R}$	σ(pb)	Γ(GeV)	Br($u\bar{u}$)	Br($t_L\bar{t}_L$)	Br($t_R\bar{t}_R$)
3	RS	RS	3.3	425	0.05	0.045	0.76
5	RS	RS	2.7	1075	0.006	0.0005	0.97
3	0.7	0.7	41	825	0.17	0.0004	.16
5	0.5	0.5	24	645	0.17	0.01	0.15
2	1	.25	74	990	0.30	0.006	0.27
3	1	.25	375	2200	0.33	0.0008	0.032

> *10 x* anarchic (RS) model !

Flavor Gauge Boson @ Tevatron?

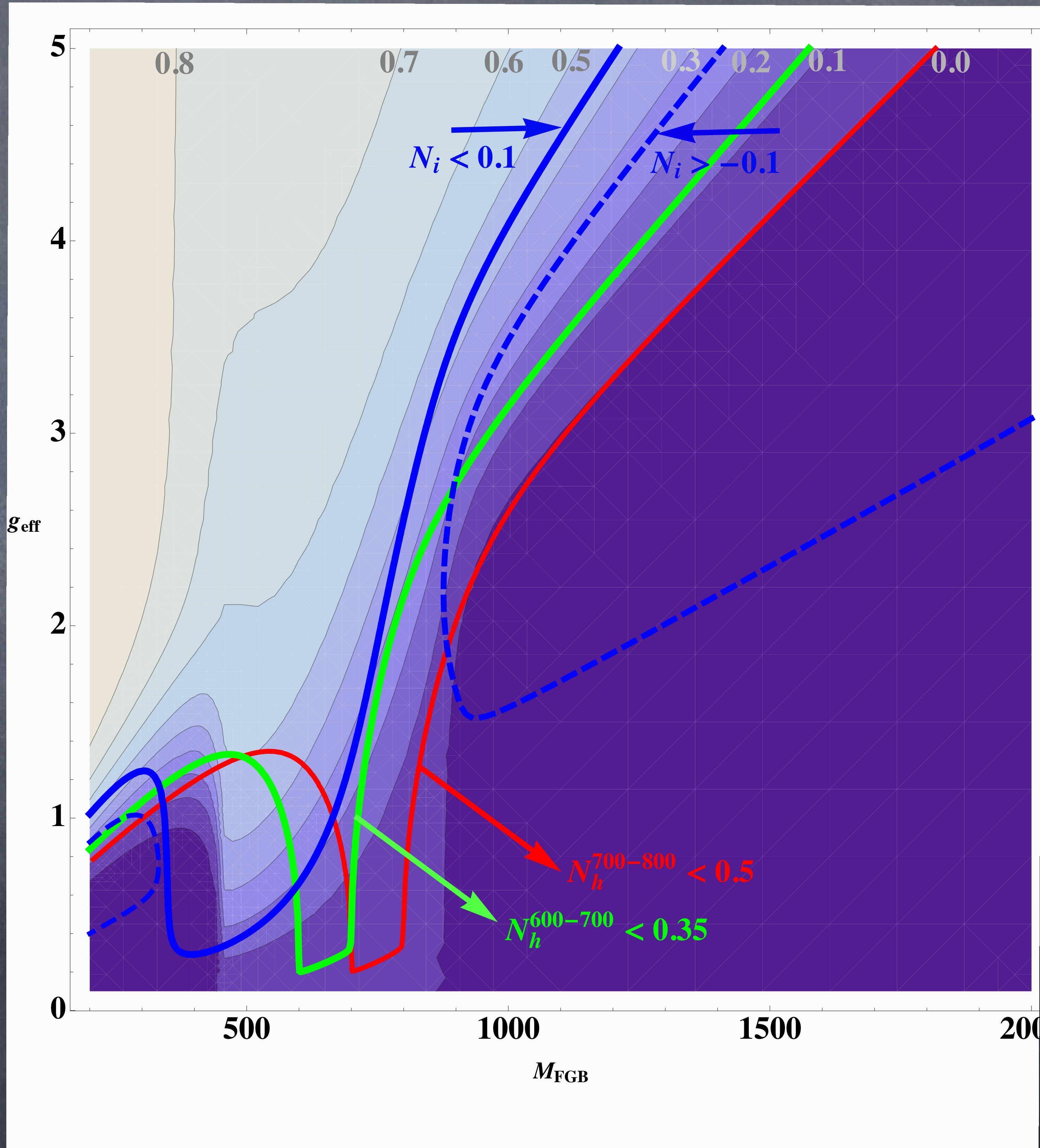
Csaki, Kagan, Lee, Perez, AW

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

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

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

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



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

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

- σ_{NP}/σ_{SM}(pT>400GeV): 2-3

2) chromo-magnetic EDM of the top

1106.xxxx with

Jernej Kamenik (IJS, Ljubljana) &

Michele Papucci (CERN/LBL)

Measure CPV of the top?

Chromo-electric and chromo-magnetic dipole

$$\mathcal{L}_{t\bar{t}G} = -g_s\,\bar{t}\gamma^\mu G_\mu t - i\frac{d'_t}{2}\,\bar{t}\sigma^{\mu\nu}\gamma_5 G_{\mu\nu}t - \frac{\mu'_t}{2}\,\bar{t}\sigma^{\mu\nu}G_{\mu\nu}t$$

CEDM CMDM

Can be sizable in partial compositeness, RS, susy
(light top partners required by naturalness)

ttbar cross-section

P. Haberl, O. Nachtmann, A. Wilch

qq → tt

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\left(\frac{1}{2} - v + z + 2\hat{\mu}_t' + (\hat{\mu}_t'^2 - \hat{d}_t'^2) + (\hat{\mu}_t'^2 + \hat{d}_t'^2)\frac{v}{z}\right)$$

and similar for gg initial state

see e.g. Hioki et al, Peskin et al, many more

Experimental constraints

Tevatron

$$\sigma_{obs}^{1.96\ \mathrm{TeV}} = 7.5 \pm 0.31(\mathrm{stat}) \pm 0.34(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\ \mathrm{pb}$$

$$\sigma_{700} \equiv \sigma^{t\bar{t}}(700\ \mathrm{GeV} < M_{t\bar{t}} < 800\ \mathrm{GeV}) = 80 \pm 37\ \mathrm{fb}\,,$$

ATLAS

five-channel combined	180 ± 9 (stat.) ± 15 (syst.) ± 6 (lumi.)

CMS

$158 \pm 10 \pm {}^{15}_{15} \pm 6$

($36\ pb^{-1}$)

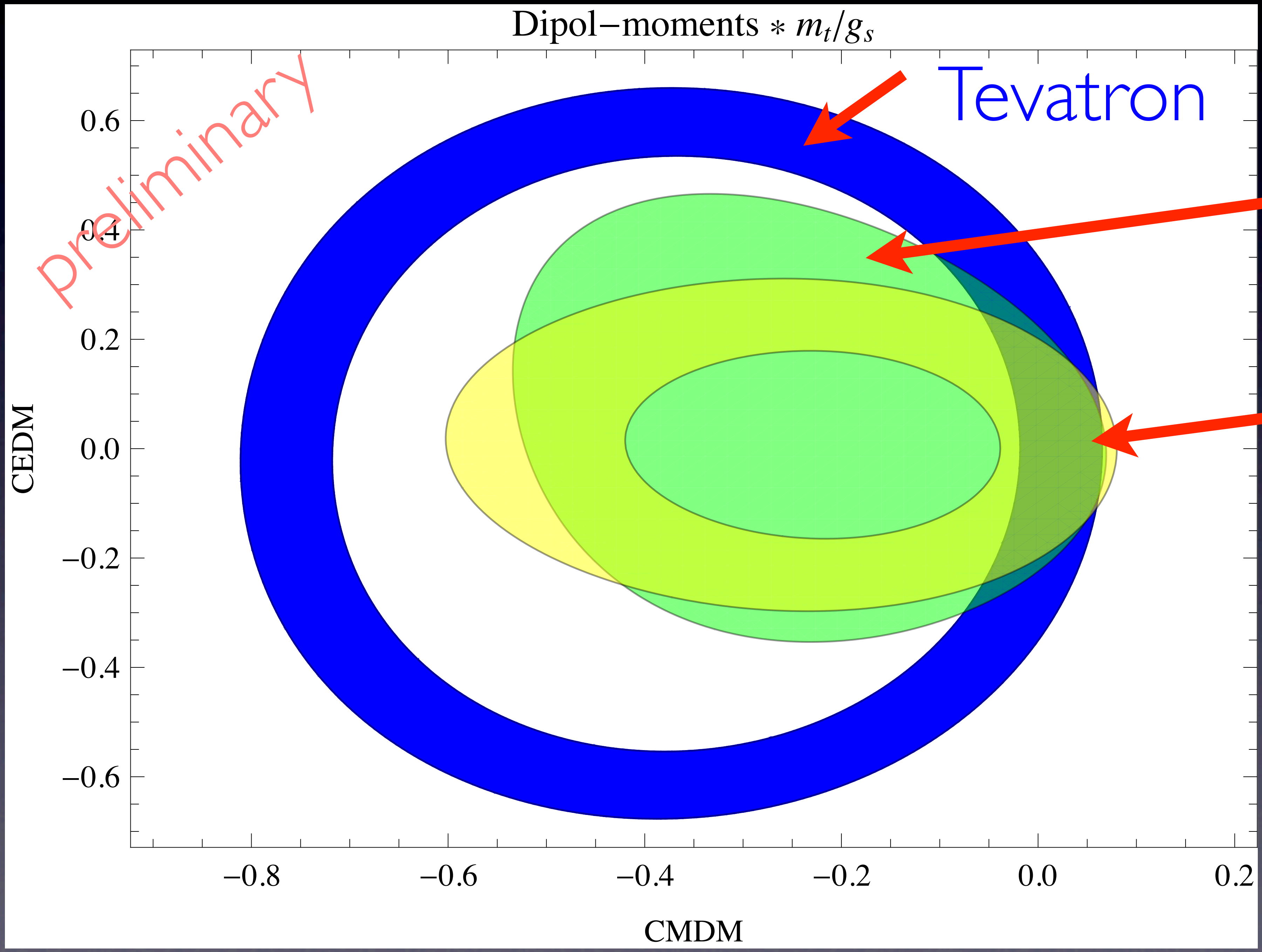
Ahrens et al. ,Kidonakis

vs. SM theory:

	Tevatron		LHC7	
	MSTW	CTEQ	MSTW	CTEQ
LO	$6.66^{+2.95+(0.34)}_{-1.87-(0.27)}$	$5.45^{+2.16+0.33(0.29)}_{-1.42-0.27(0.24)}$	$122^{+49+(6)}_{-32-(7)}$	$100^{+35+9(7)}_{-24-8(7)}$
NLO	$6.72^{+0.41+0.47(0.37)}_{-0.76-0.45(0.24)}$	$6.77^{+0.40+0.50(0.43)}_{-0.74-0.40(0.34)}$	$159^{+20+14(8)}_{-21-13(9)}$	$148^{+18+13(11)}_{-19-12(10)}$
NNLO approx.	$6.63^{+0.07+0.63(0.33)}_{-0.41-0.48(0.25)}$	$6.91^{+0.09+0.53(0.46)}_{-0.44-0.43(0.36)}$	$155^{+8+14(8)}_{-9-14(9)}$	$153^{+8+13(11)}_{-8-12(10)}$

Top Chromo-electric dipole

Kamenik, Papucci, W



CDF

700<m_{tt}<800 GeV

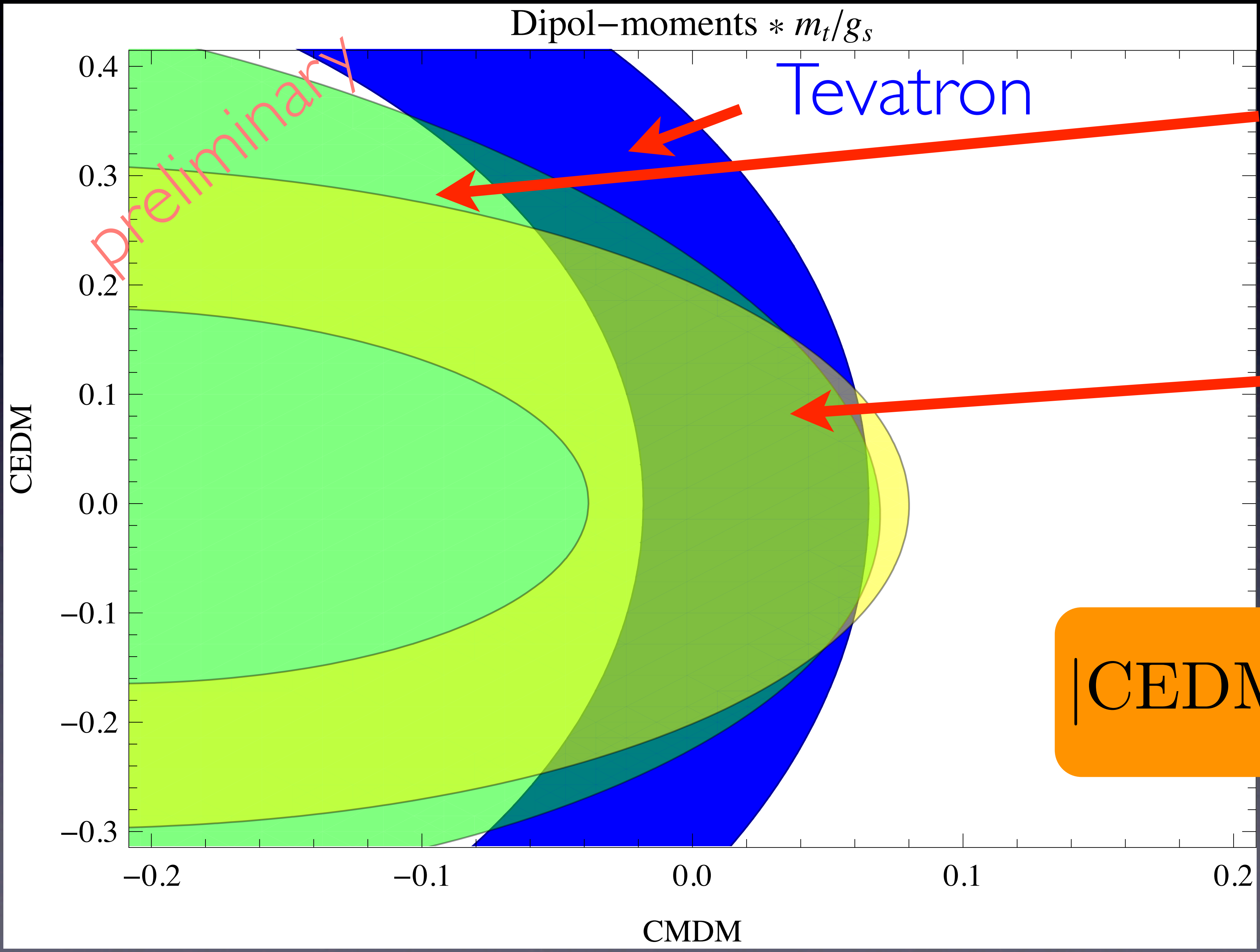
LHC (35 1/pb)

Ahrens et al.

mathematica + mstw08 pdf's, SM normalized to "N"NLO

Top Chromo-electric dipole

Kamenik, Papucci, W



CDF
700<m_{tt}<800 GeV

LHC *(35 1/pb)*

$$|\mathrm{CEDM}_{top}| < 0.25/m_{\mathrm{top}}$$

@ 95 % CL

Constraints from *neutron EDM?*

Weinberg op. mixes into chromo-magnetic top

But chromo-magnetic top does not mix into Weinberg operator (which would lead to neutron EDM)

QFT: no mixing of higher dim op.'s in lower dim.

$$
\begin{aligned}
O_e^q &= -\frac{i}{2} e\, Q_q m_q\, \bar{q} \sigma^{\mu\nu} \gamma_5 q\, F_{\mu\nu}, \\
O_c^q &= -\frac{i}{2} m_q \bar{q}\, \sigma^{\mu\nu} t^a \gamma_5 q\, G^a_{\mu\nu}, \\
O_G &= -\frac{1}{6} f^{abc} G^a_{\mu\rho} G^{b\rho}_{\nu} G^c_{\lambda\sigma} \epsilon^{\mu\nu\lambda\sigma}
\end{aligned}
$$

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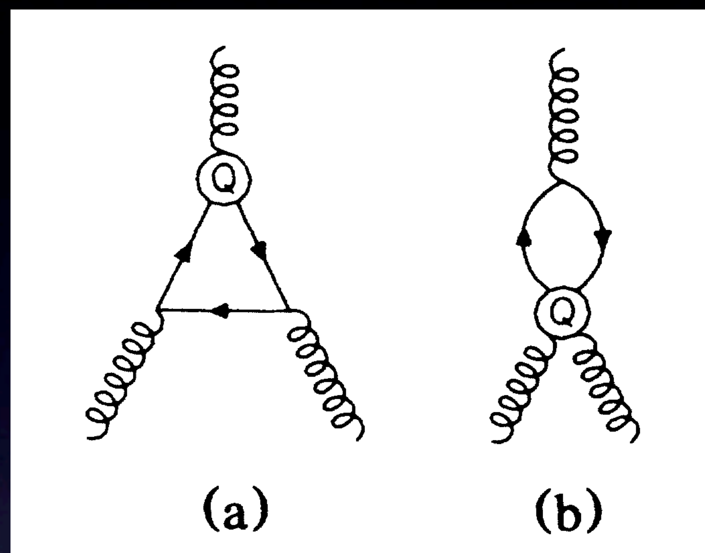
$$

But there's a finite part at 1 loop!

Constraints from *neutron EDM*?



$$C_G(m_Q^-) = C_G(m_Q^+) + C_Q(M)\left(\frac{g_s(m_Q)}{g_s(M)}\right)^{\gamma_{qq}/\beta}\frac{1}{8\pi}\frac{\alpha_s(m_Q)}{m_Q}$$

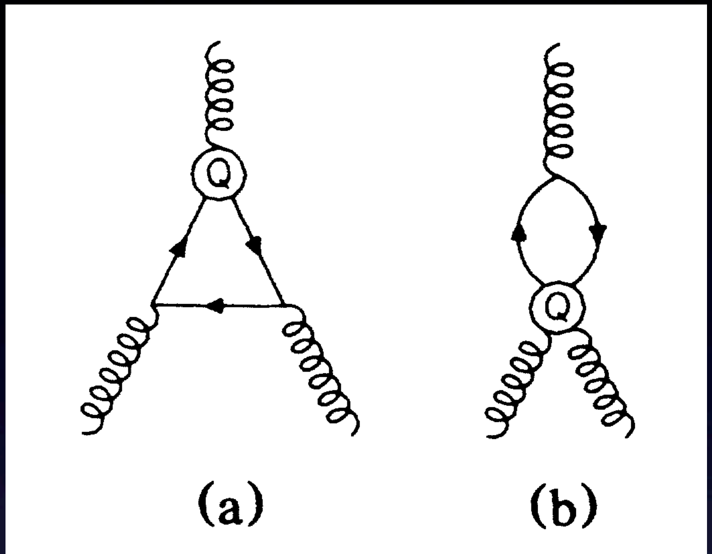
Chang et. al, Braaten et. al 90's

Finite threshold correction

@ m_{top} $$C_{\rm Weinberg} = \frac{g_s^2}{32\pi^2}\,{\rm CEDM}_{\rm top}$$

Weinberg 89, Pospelov et. al

Constraints from *neutron EDM*?



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Finite threshold correction

@ m_{top} $$C_{\text{Weinberg}} = \frac{g_s^2}{32\pi^2}\,\text{CEDM}_{\text{top}}$$

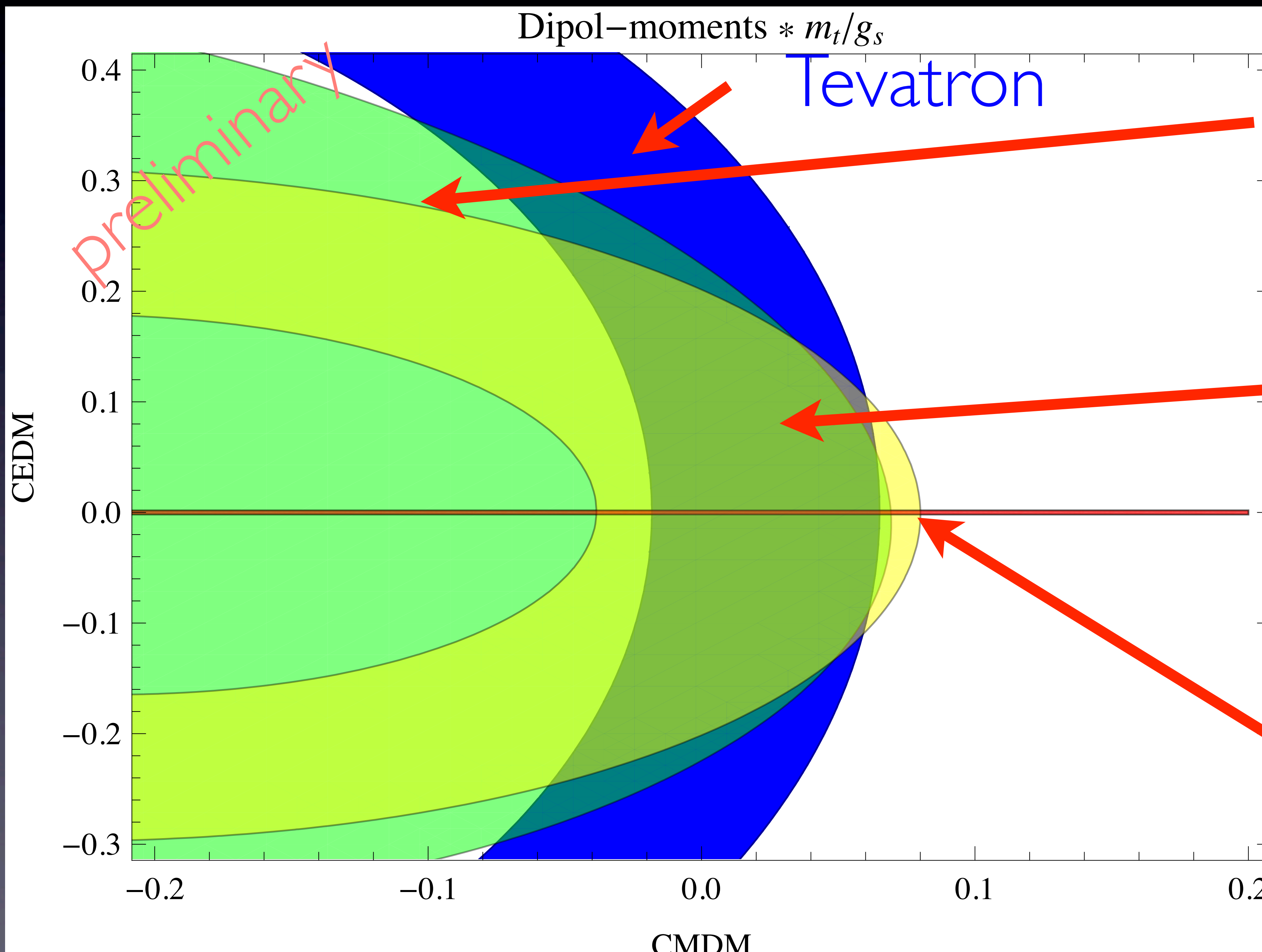
Weinberg 89, Pospelov et. al

→ Weinberg op contributes to neutron EDM!

$$d_n(w) = e\,(10 - 30)\ \text{MeV}\, w(1\,\text{GeV})$$

Top Chromo-electric dipole

Kamenik, Papucci, W



CDF

700<m_{tt}<800 GeV

LHC (35 1/pb)

New constraint!

***EDM**$_{neutron}$*

Top Chromo-electric dipole

Kamenik, Papucci, W

Our new constraint is ~ 100x stronger than direct collider constraints and somehow has been missed.

Cross-section limits are now not sensitive any more, but CPV observables (a.(b x c)) might be stronger.

Interesting to study in any non CPV-conserving scenarios with light top partners (any natural model…)!

3) Naturalness vs. flavor blind susy breaking

Fast forward to Fall 2011 (or even 2012?) and nothing new yet

in progress w/ Michele Papucci (CERN/LBL) susy is the prime example for flavor triviality, use flavor blind susy breaking (GMSB) and decouple flavor genesis.

Still natural after 5 1/fb LHC7?

Susy & naturalness

- Susy stabilizes the weak scale $M_Z << M_{Planck}$

$$\frac{m_Z^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2 \simeq -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{M}{m_{\tilde{t}}}\right)$$

- Natural iff higgsinos and stops not too heavy < O(few 100 GeV), unavoidable!

$$m_{\tilde{t}}^2 \lesssim (500\mathrm{GeV})^2\left(\frac{10}{\ln\left(M/m_{\tilde{t}}\right)}\right)$$

Susy & naturalness

- Gluinos enter the higgs potential @ 2loop, mass is bounded too

$$\delta m_{\tilde{t}}^2 \simeq \frac{8\alpha_s}{3\pi} M_3^2 \ln\left(\frac{M}{m_{\tilde{t}}}\right)$$

- The MSSM is tuned, tension from LEP Higgs bound O(1 in 100)

=> talk by Djouadi

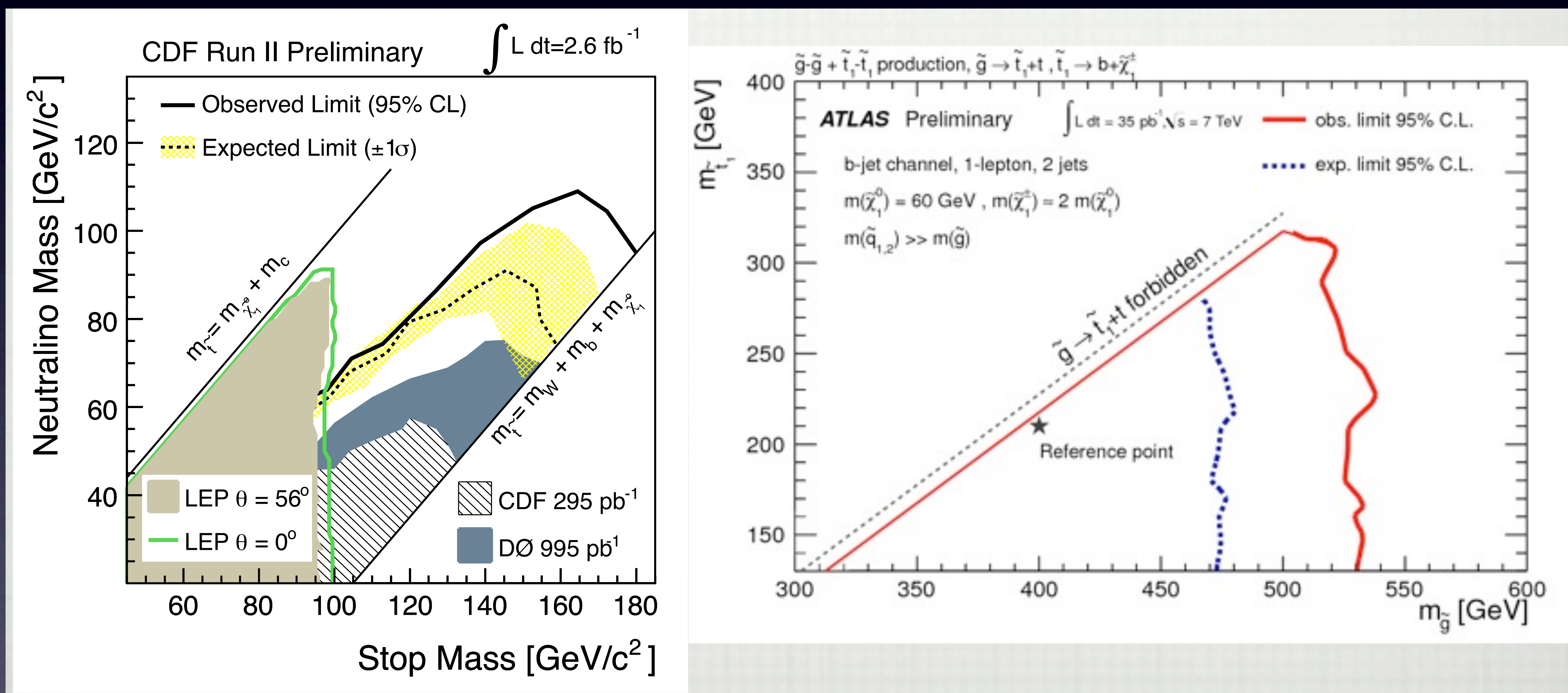
$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right] \qquad X_t = A_t - \mu\cot\beta$$

Higgs tuning may be reduced by extending the MSSM

A natural (light) 3rd gen?

talks by Hoecker, Boccali

- Present searches do not exclude light stops/sbottoms, susy can still be natural



- Limits well below 250-350 GeV if gluinos, squarks$_{1,2}$, … are decoupled

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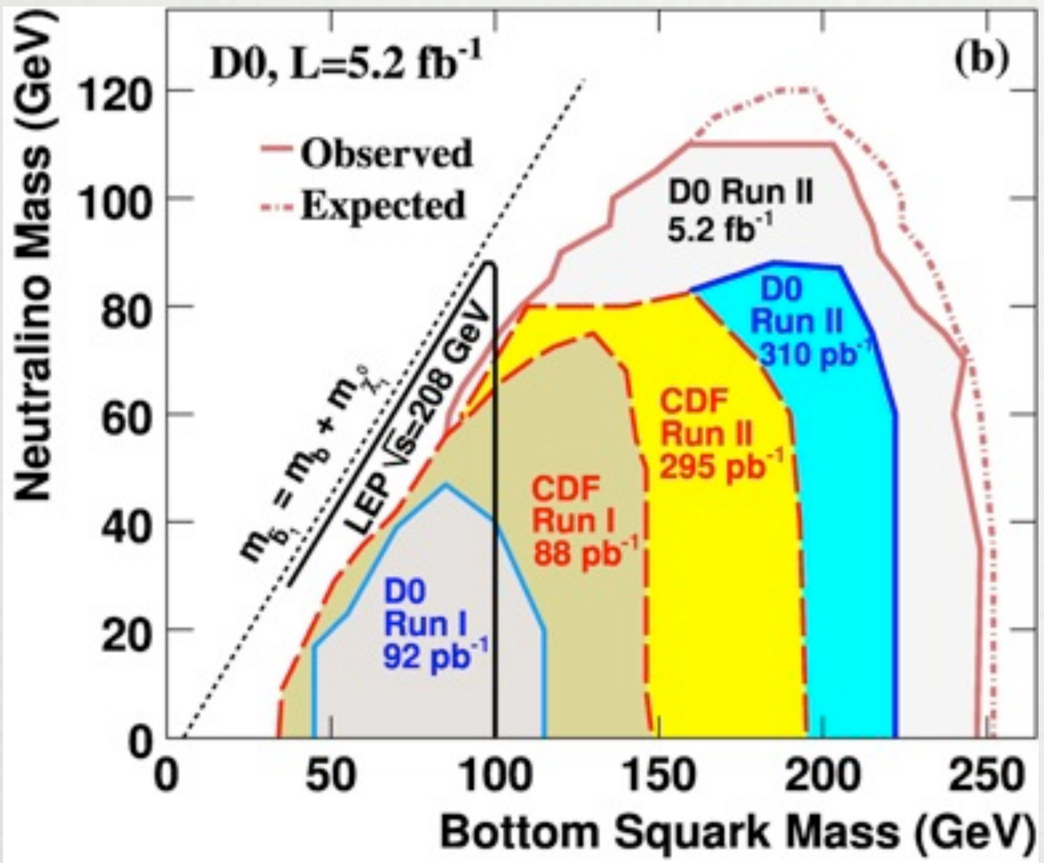
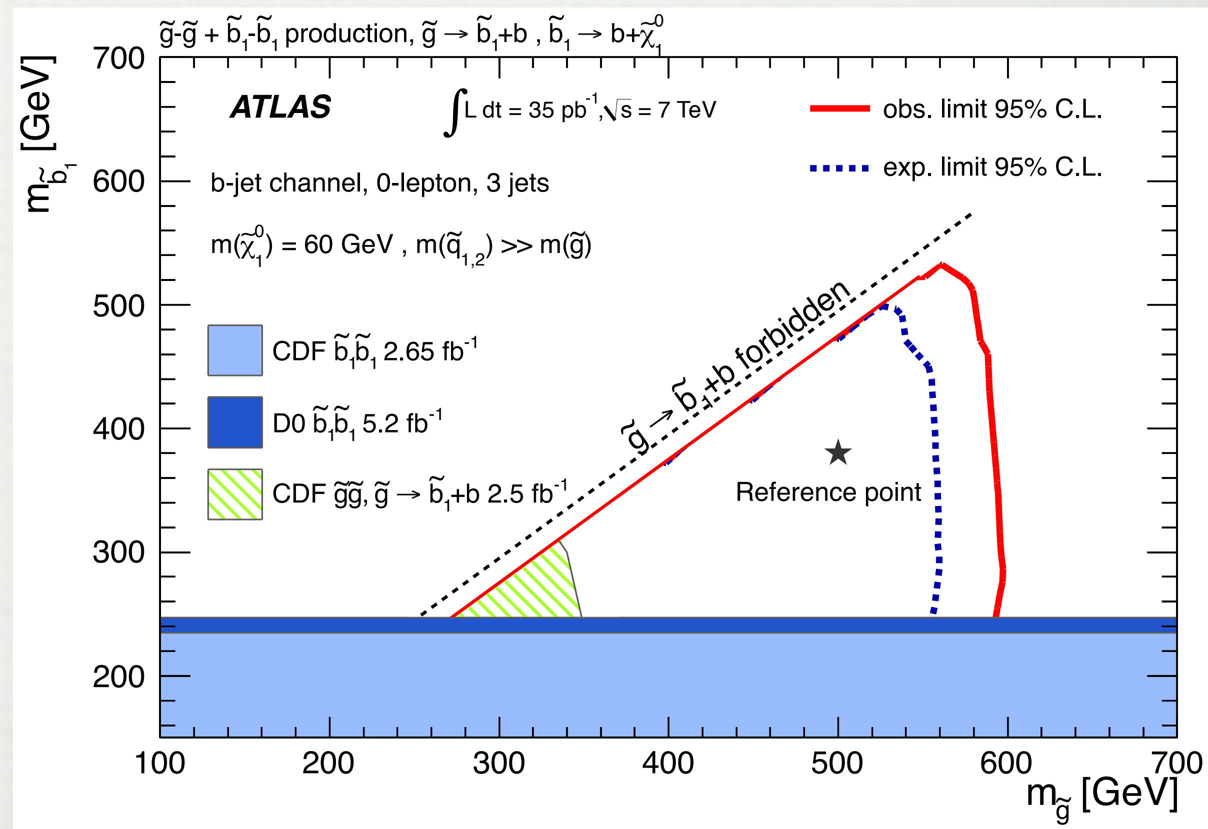


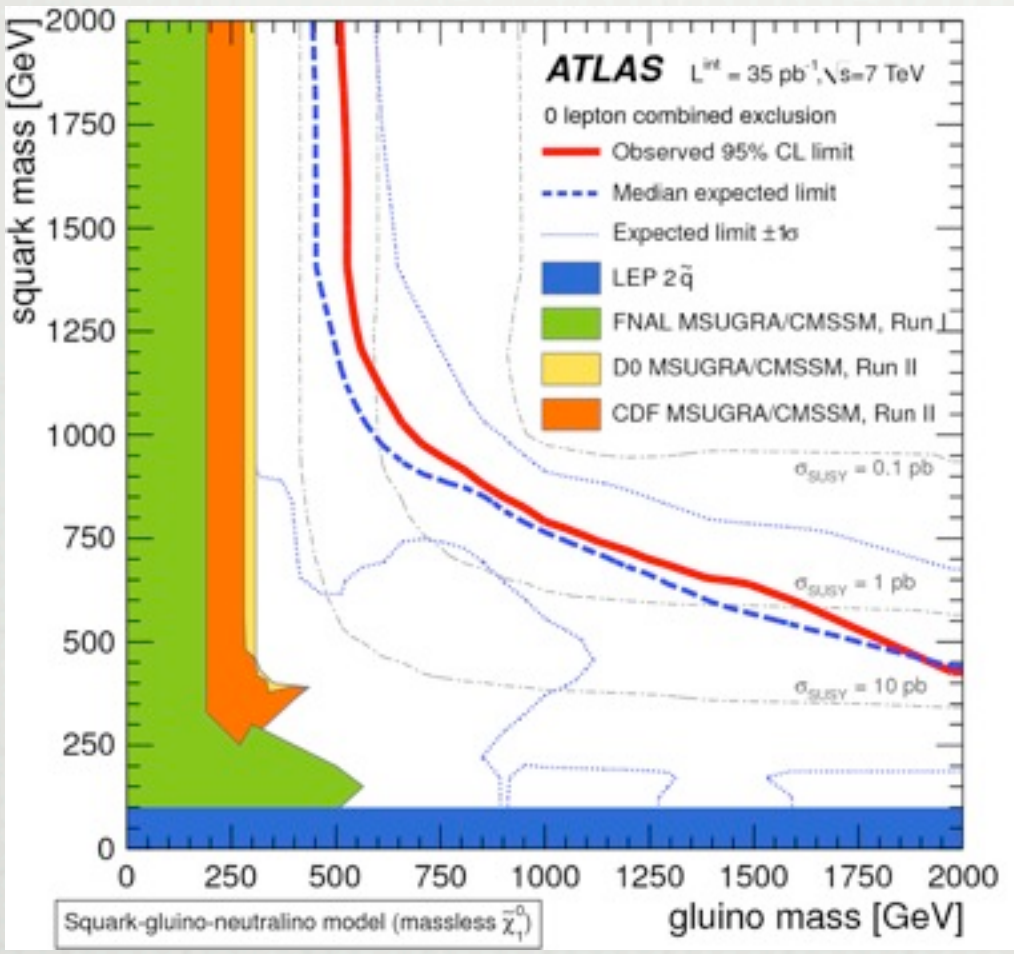


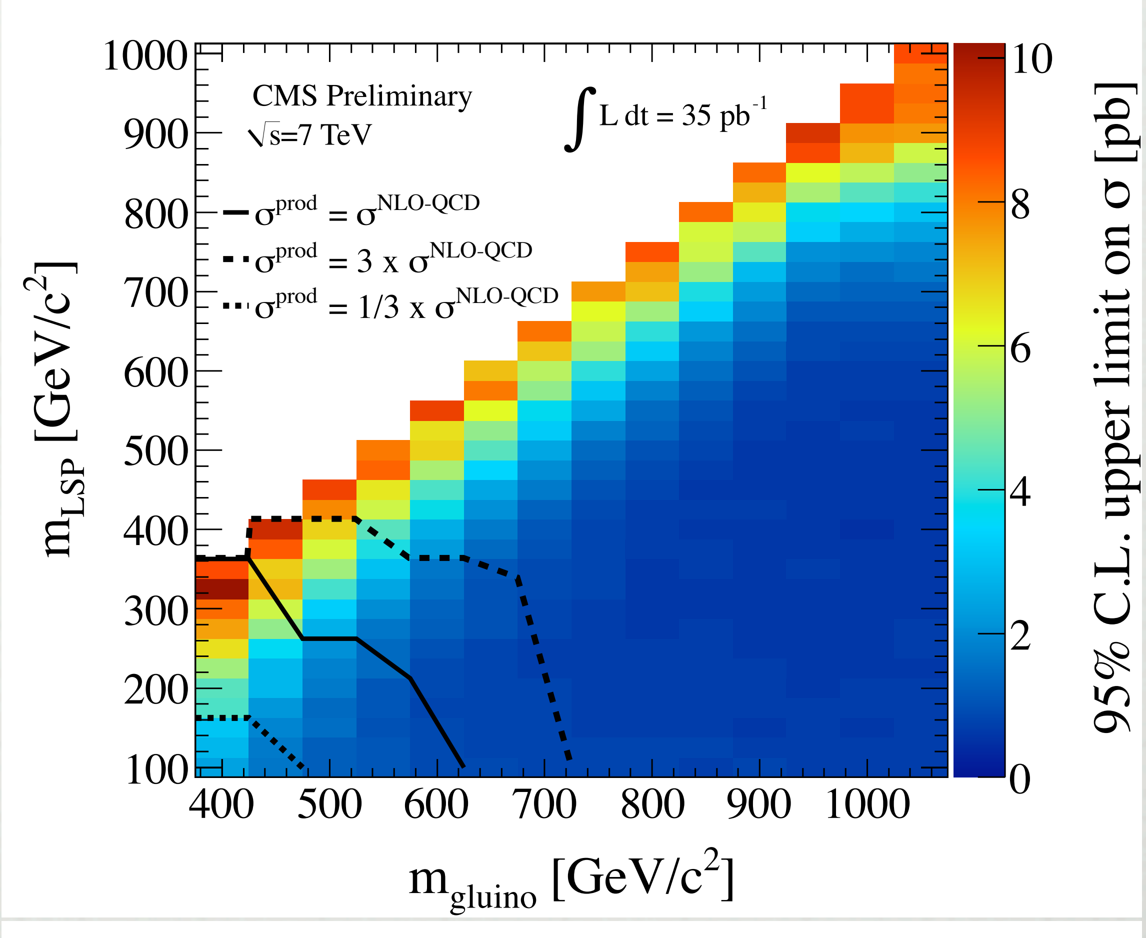
- Limits well below 250-350 GeV if gluinos, squarks$_{1,2}$, … are decoupled

Limits on Squarks & Gluinos

talks by Hoecker, Boccali

Early (Jets+MET+(0,1) lepton) searches put strong limits on gluinos first two generations of squarks





Already have to be > 500-600 GeV!

Splitting the generations

perturbatively

stop mass

$$M^2_{\tilde{t}} \simeq \begin{pmatrix} m^2_{Q_3} + \Delta/6 + m_t^2 + D_{u_L} & m_t\,(A_t - \mu/\tan\beta) \\ m_t\,(A_t - \mu/\tan\beta) & m^2_{U_3} + \Delta/3 + m_t^2 + D_{u_R} \end{pmatrix}$$

1st and 2nd generation: $(A_t \to 0, \Delta \to 0, m_t \to 0)$

$$\Delta \simeq \frac{3y_t^2}{4\pi^2}\left(f_{33}(t)M_3^2 + f_{3t}(t)M_3A_t + f_{tt}(t)A_t^2 + f(t)(m^2_{H_u} + m^2_{Q_3} + m^2_{U_3}) + \ldots\right) \qquad t = \ln\left(M_{mess}/m_{\tilde{t}}\right)$$

Flavor universal boundary conditions:

$M_3, A_t, m_{H_u}, M_{Q_3}, M_{u_3}$ bounded from above →

splitting between 1,2 vs. 3 is bounded from above

Fall 2011 (2012?)

Difficult to extrapolate experimental constraints, (analysis in final stages), **BUT**

Stop/Bottom: most holes closed this summer, increased limit (350~400 GeV)

Gluinos & light squarks limits well above 1 TeV, likely around 1.5 TeV.

Already some tension but still not high tuning!

Split spectrum necessary for naturalness

Fall 2011 (2012?)

Difficult to extrapolate experimental constraints, (analysis in final stages), BUT

Stop/Bottom: most hole ... her, increased limit (350 ...

Gluinos & li... well above 1 TeV, likely a...

Already so... tension but still not high tuning!

Split spectrum necessary for naturalness

Flavor non-universal susy breaking!

General message

Natural Susy surviving this fall (w/ no observed signal) likely involves flavor non-universal susy breaking ("flavorful susy").

=> talk by Isidori, Lalak

Caveats:

o squeezing the spectrum (tuning?)
o engineer small missing E_T (not looking for it)
o R-parity violation …

Conclusions

MFV with split doublets solves flavor and EWPT problems of partial compositeness, early discovery at LHC.

A new & very strong bound on the CEDM tough to see at LHC. BUT: Very important to test models with large CPV in the top sector!

Supersymmetry can still be natural but if nothing is seen until 2011 ('12?), flavor blind susy breaking is tuned.

The SM flavor puzzle

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

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

Origin of this structure?

Other dimensionless parameters of the SM:

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

UTfit 08, Isidori, Perez, Nir '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	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}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM pattern…

UTfit 08, Isidori, Perez, Nir '10

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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM pattern…

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

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

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

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")

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

split fermions/RS

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

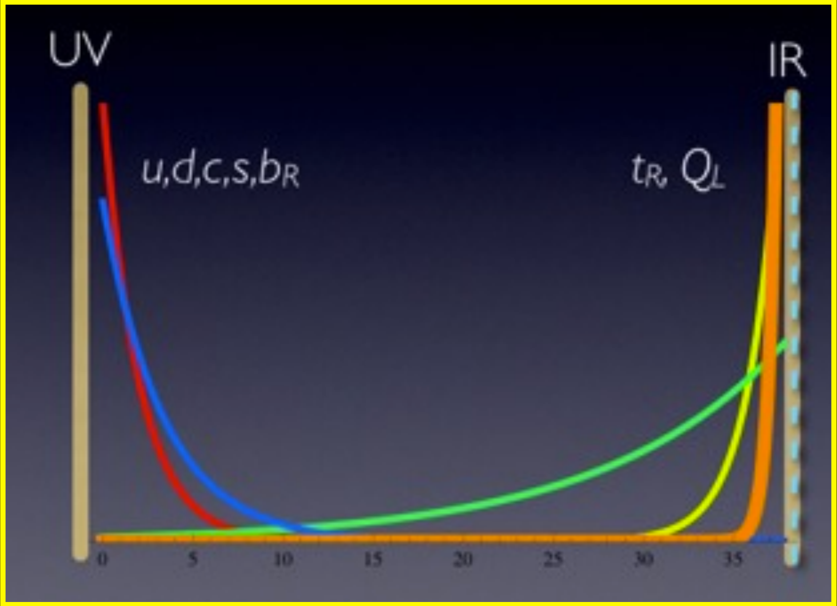
strong dynamics

$$\propto \quad Y_{ij} \left(\frac{\langle \Phi \rangle}{M_{\mathrm{mess}}} \right)^{Q^i-Q^j}$$

Froggatt-Nielsen

Hierarchy { => hierarchical masses & mixing angles

anarchic ("structure-less")



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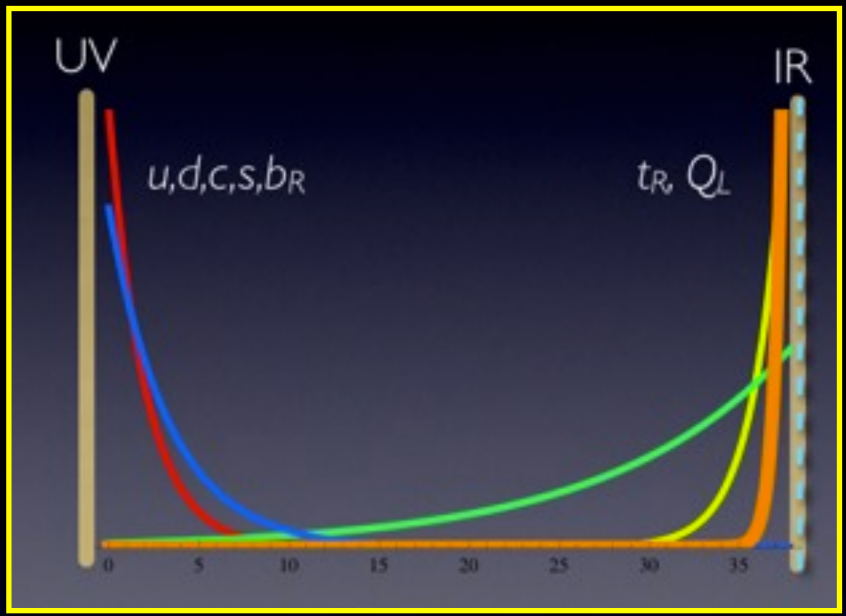

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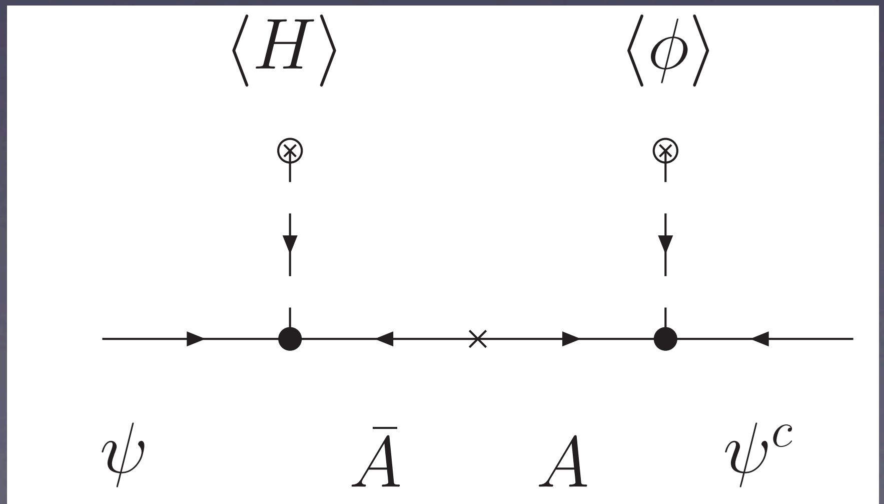
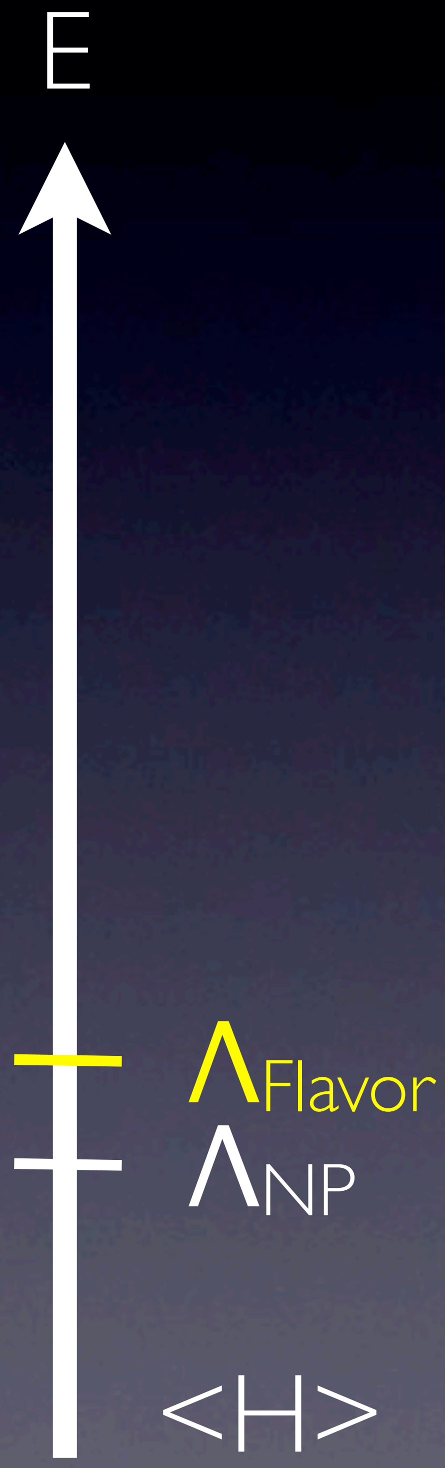


Hierarchy { => hierarchical masses & mixing angles

Flavorgenesis scale?

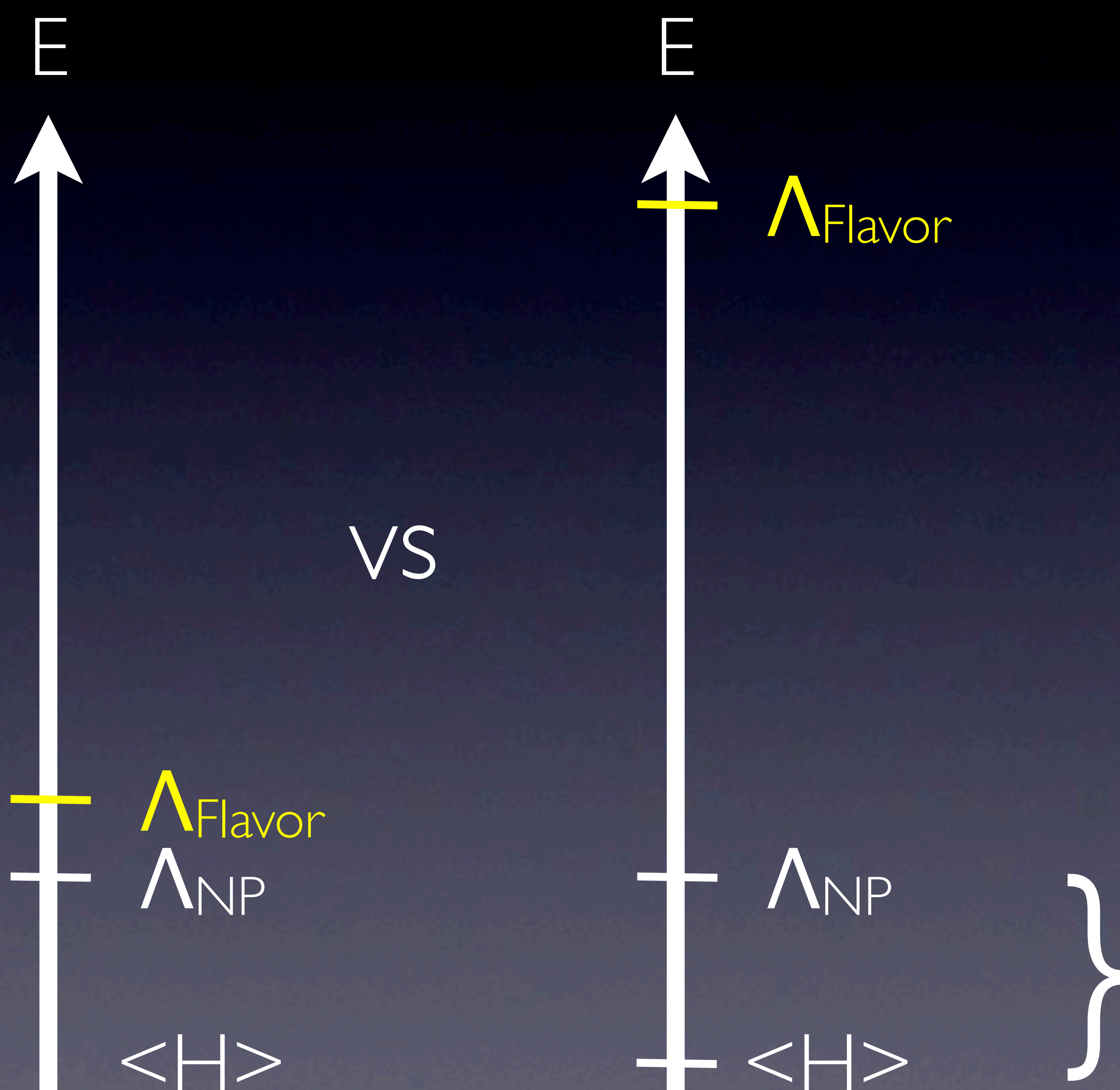


$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

$$y_{ij}\,\bar{\psi}_i\mathcal{H}\psi_j$$

} naturalness

Flavorgenesis scale?



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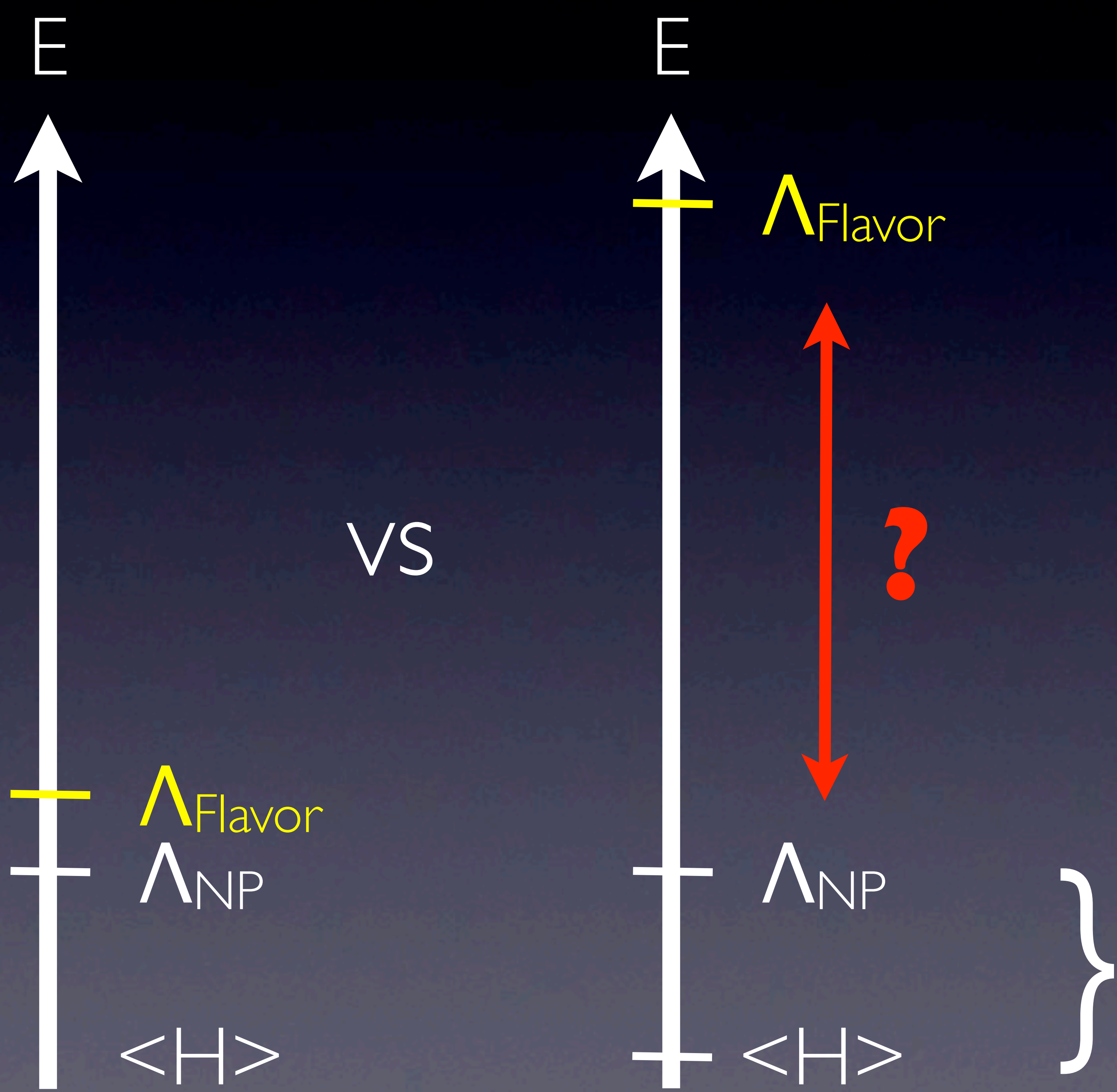

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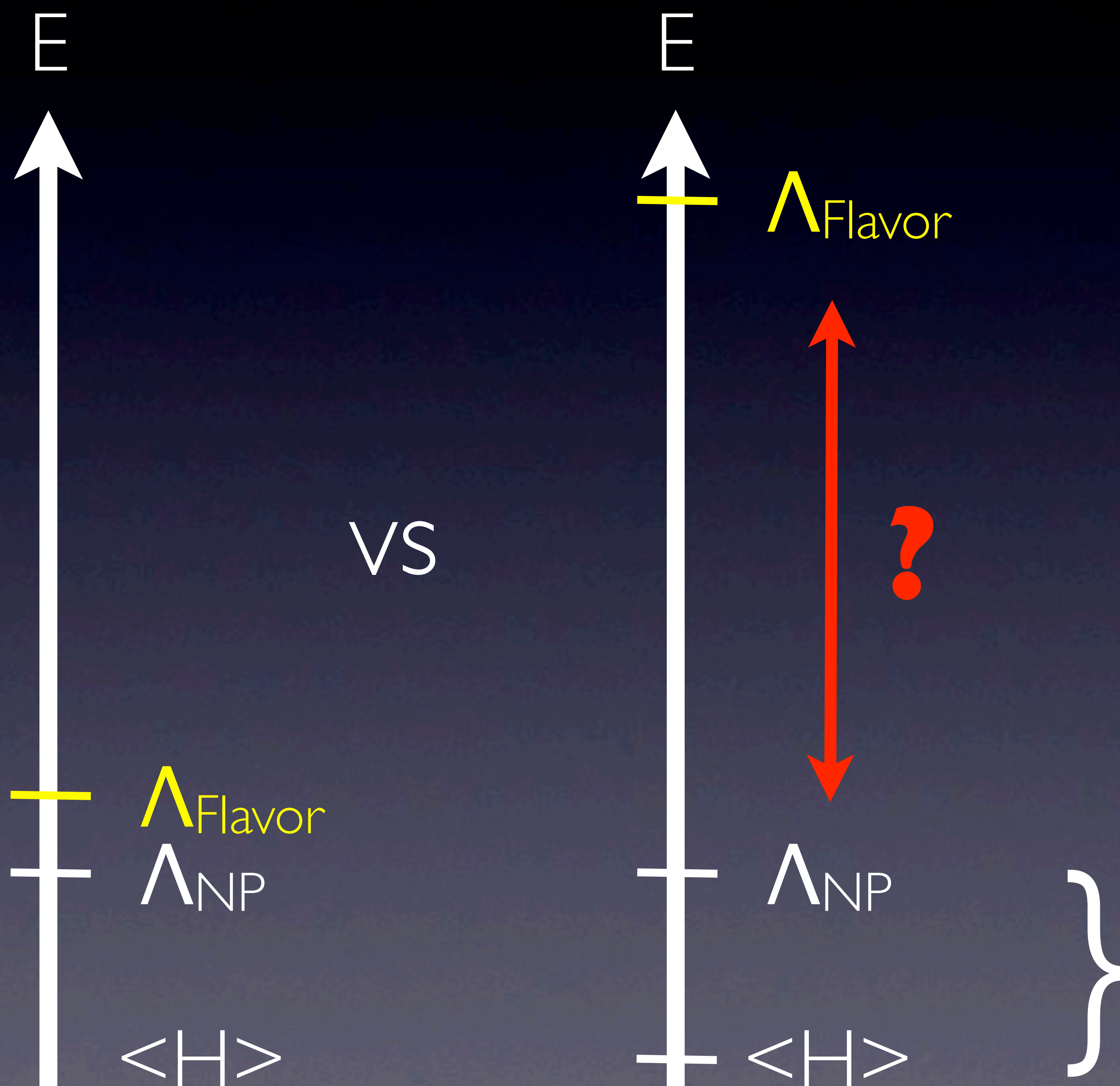

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$$y_{ij}\,\bar{\psi}_i\mathcal{H}\psi_j$$

naturalness

Flavorgenesis scale?

E

E

Λ_{Flavor}

$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

Example: MSSM is MFV before susy breaking. If flavor is generated well above messenger scale, TeV theory flavor trivial (= *MFV*).

$$S = \int \mathrm{d}^4x \left(\mathrm{d}^2\theta \mathrm{d}^2\bar{\theta}\, \Phi_i^* \exp\left(2g_A T_A^a V_A^a\right) \Phi_i + \left\{ \mathrm{d}^2\theta \left[\mathcal{W}(\{\Phi_i\}) + \frac{1}{4} W_A^a W_A^a \right] + \text{h.c.} \right\} \right)$$

<H>

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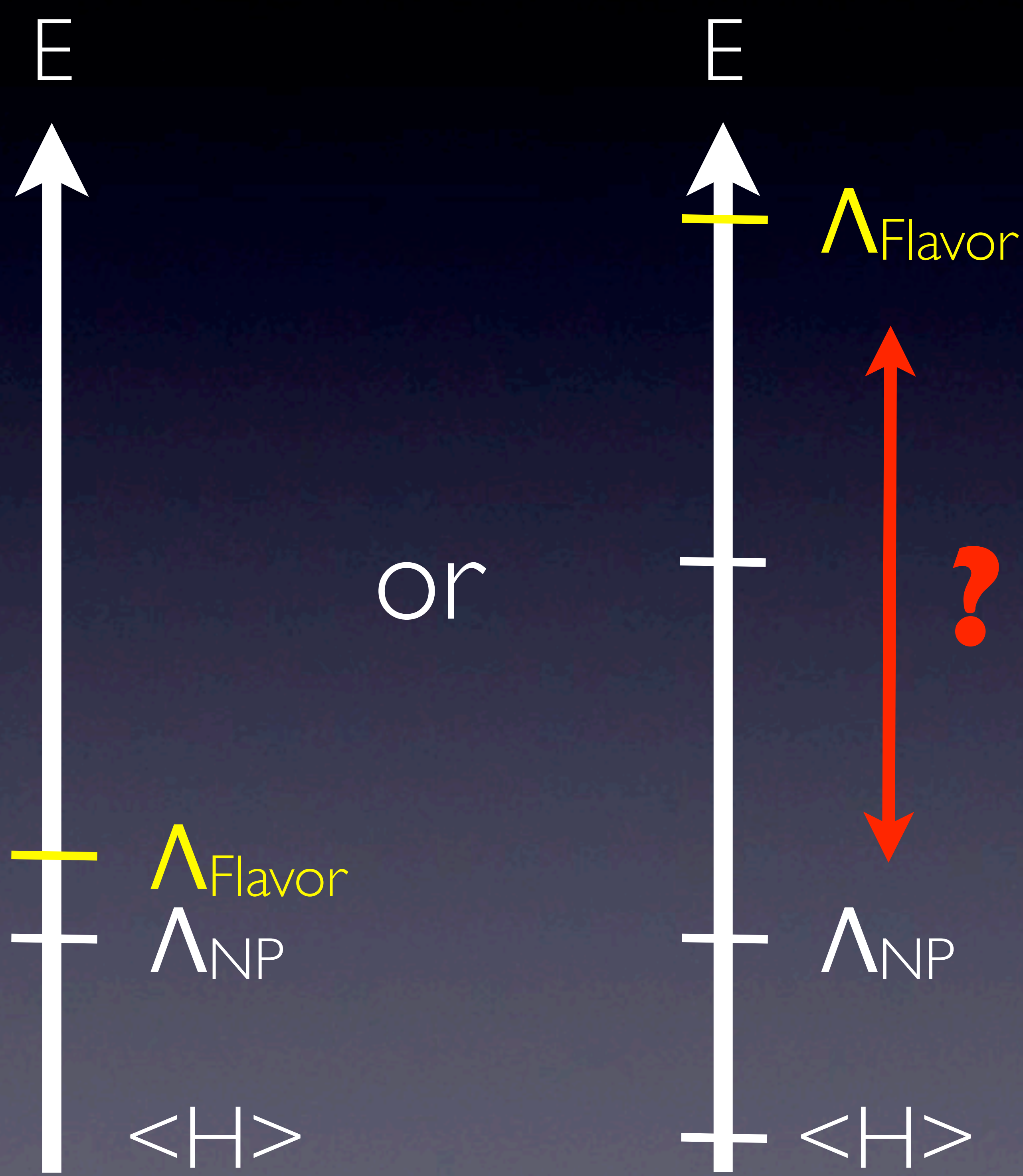
Flavorgenesis scale?



$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

only trace left: MFV

$$y_{ij}\,\bar{\psi}_i\mathcal{H}\psi_j$$

} naturalness

Model independent constraints

Minimal flavor violation

UTfit, Buras et. al, Hurth et al

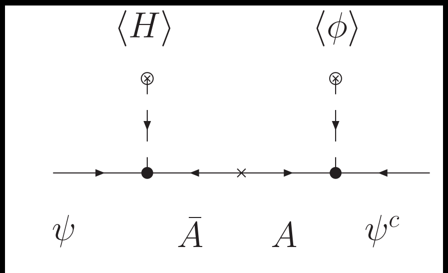
Tree

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)(\overline{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)(\overline{L}_L \gamma_\mu L_L)$	1.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s \ell^+\ell^-$

If 1-loop suppressed like in MSSM < *TeV* !

$$\Lambda_{\rm loop} \approx \left(\frac{\alpha}{4\pi}\right)^{\frac{1}{2}} \Lambda_{\rm tree} \approx \frac{1}{10}\Lambda_{\rm tree}$$

Alignment vs. MFV



Lalak et al

Flavour violating dimension six operator		Λ/Λ_{MFV} Ex. 1	Ex. 2	Ex. 3	$U(1)^2$	N-A	F
$\mathcal{O}_0 =$	$\frac{1}{2}(\bar{Q}_L X^Q_{LL} Q_L)^2$	ϵ^{-4}	ϵ^{-4}	1	1	ϵ^{-2}	1
$\mathcal{O}_{F1} =$	$H^\dagger \left(\bar{D}_R X^{D\dagger}_{LR} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{G1} =$	$H^\dagger \left(\bar{D}_R X^{D\dagger}_{LR} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{\ell 1} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{\ell 2} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{H1} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{q5} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1

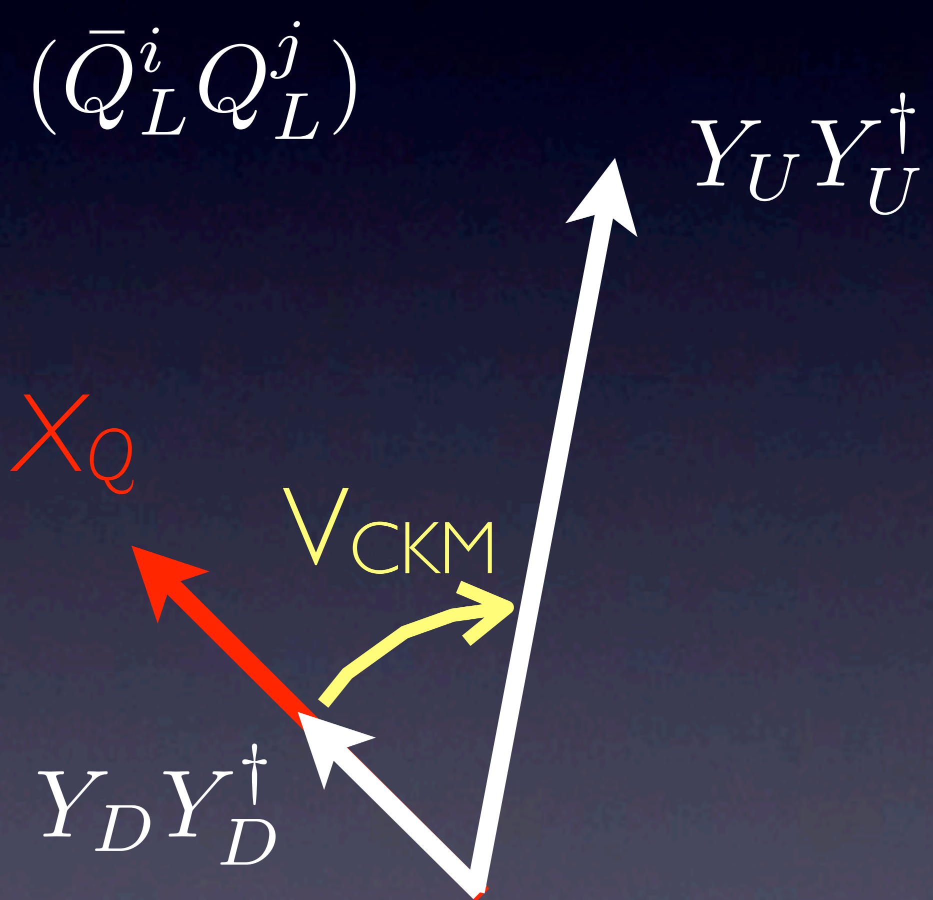
$$\epsilon = \frac{\text{flavon vev}}{\text{messenger mass}} \ll 1 \qquad\qquad x = (m_t/m_b)^{\frac{1}{2}}$$

Here only MFV operators, flavorgenesis scale from first two generations

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

Nir 07; Blum et. al '09

Can not simultaneously evade constraints from D$\bar{D}$ & K$\bar{K}$



D-$\bar{D}$ mixing !

no effect in K-$\bar{K}$ mixing

$$\frac{1}{\Lambda^2_{\rm NP}}(\overline{Q}_{Li}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q}_{Li}(X_Q)_{ij}\gamma^\mu Q_{Lj})$$

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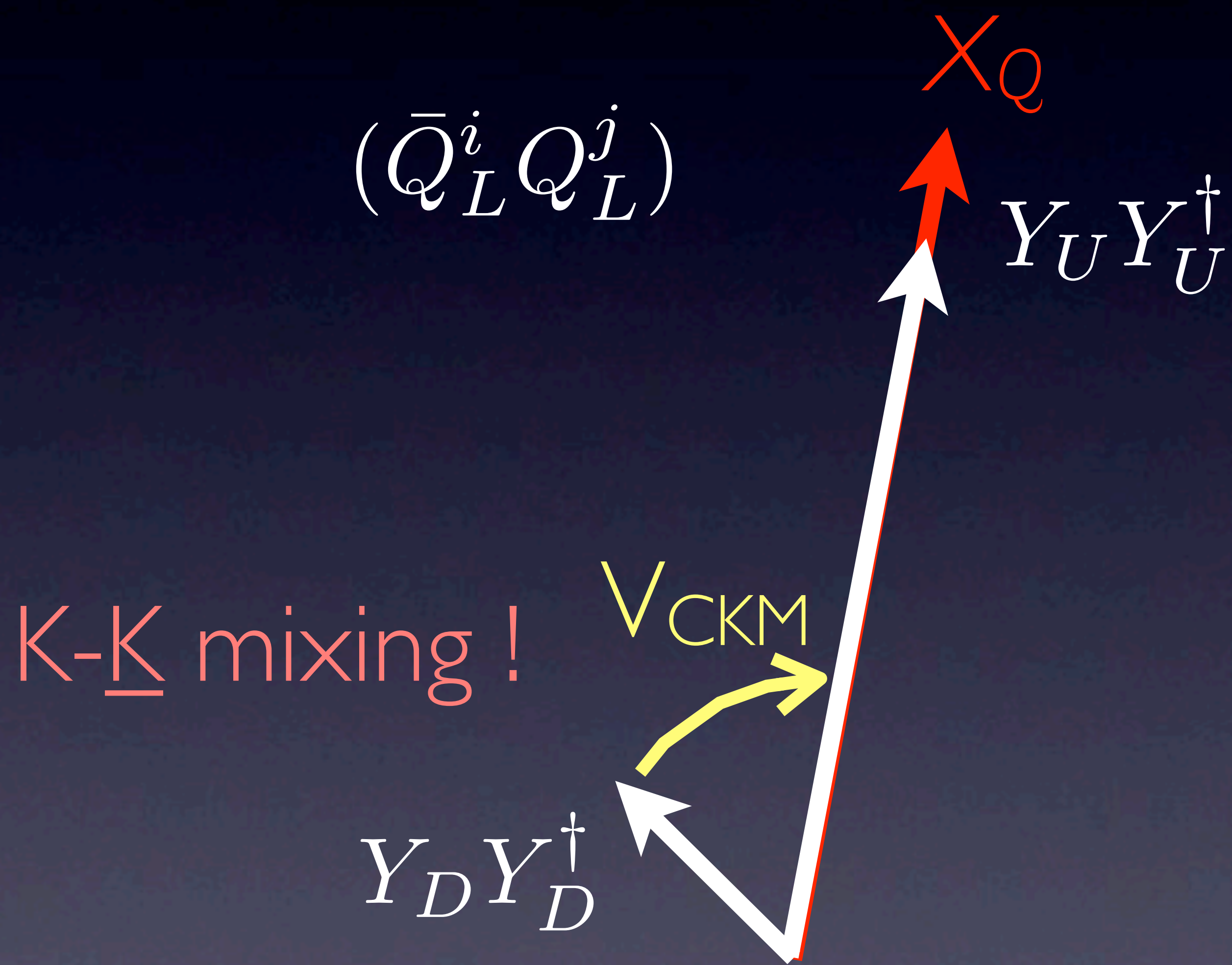

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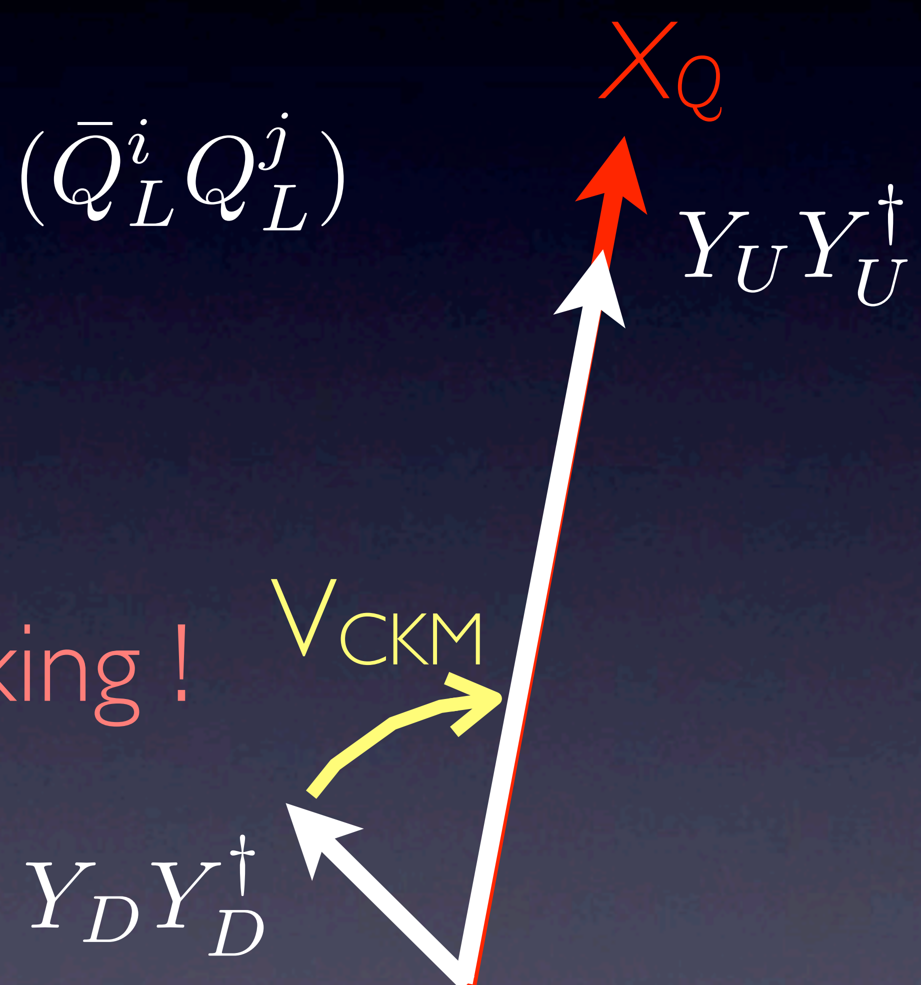


K-$\overline{K}$ mixing !

=> *squarks*$_{1,2}$ ≈ degenerate

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

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

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

$$\frac{1}{\Lambda^2_{\rm NP}}(\overline{Q}_{Li}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q}_{Li}(X_Q)_{ij}\gamma^\mu Q_{Lj})$$

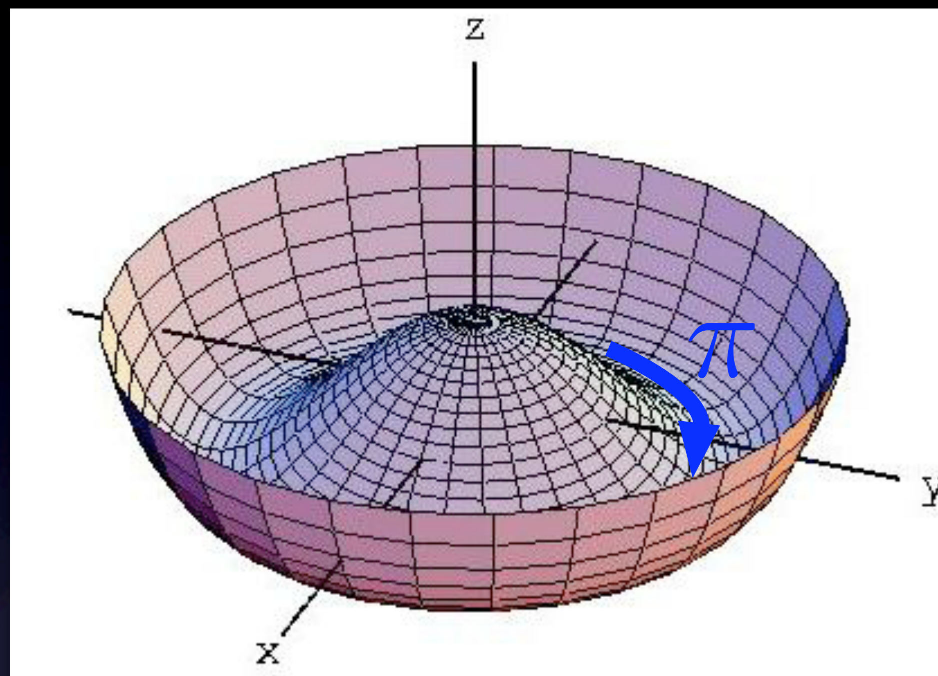
A particular class of models: partial compositeness (geometric alignment vs. MFV)

Weak scale is unstable

elementary scalar Higgs

$$\mathcal{L}_{Higgs} = \Lambda^2 H^2 + \ldots$$ ✗

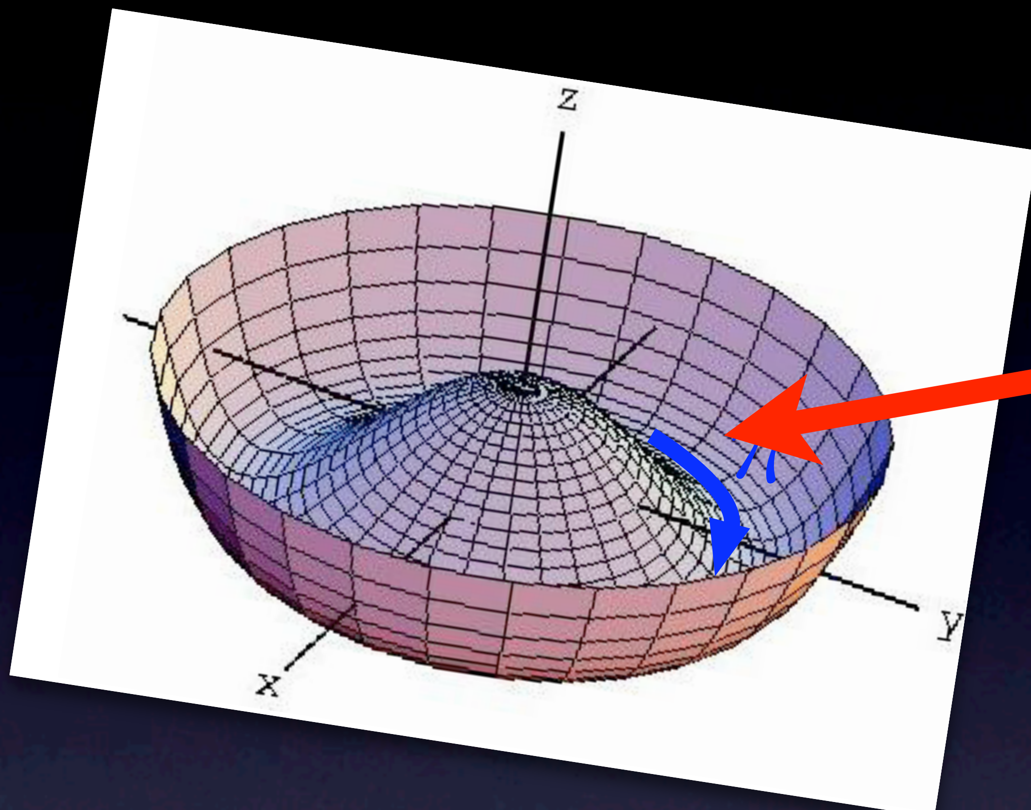
Inspiration by QCD



mass protected by global symmetry

$$\pi \to \pi + \alpha$$

Inspired by QCD



Potential tilted:
due to quark masses
and gauging of EM

GB → pGB

$$m_{\pi^\pm}^2 \approx \frac{\alpha_{em}}{4\pi}\Lambda_{QCD}^2$$

Fermions get masses by coupling to this new sector

MFV or not MFV?

Old Flavor problem of composite Higgs

Higgs as bound state, naively $D_{\mathcal{H}=\langle\bar{\psi}\psi\rangle} \approx 3$

$$\frac{1}{\Lambda^{D_{\mathcal{H}}-1}} y_{ij}\, \bar{\psi}_i \mathcal{H} \psi_j + \frac{1}{\Lambda^2} c_{ijkl}\, \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$$

Λ can not be too large, because want top mass

$$\Lambda = \mathcal{O}(\mathrm{TeV})$$

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Λ can not be too large, because want top mass

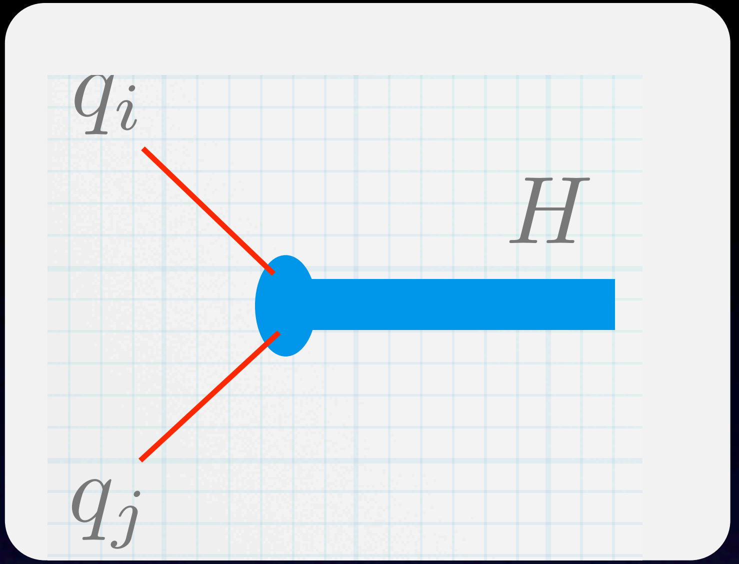
Λ must be very large because this leads to FCNCs

$K^0 - \bar{K}^0$

$$\Lambda = \mathcal{O}(\mathrm{TeV})$$

$$\Lambda > 10^5\,\mathrm{TeV}$$ ✗

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:

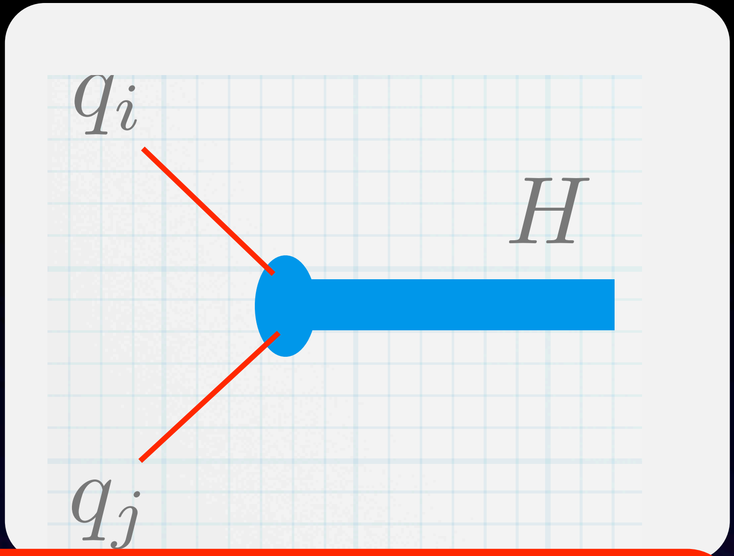
D.B. Kaplan '91

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

$\propto$

Two ways of giving mass to fermions…

Bi-linear (like SM):



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

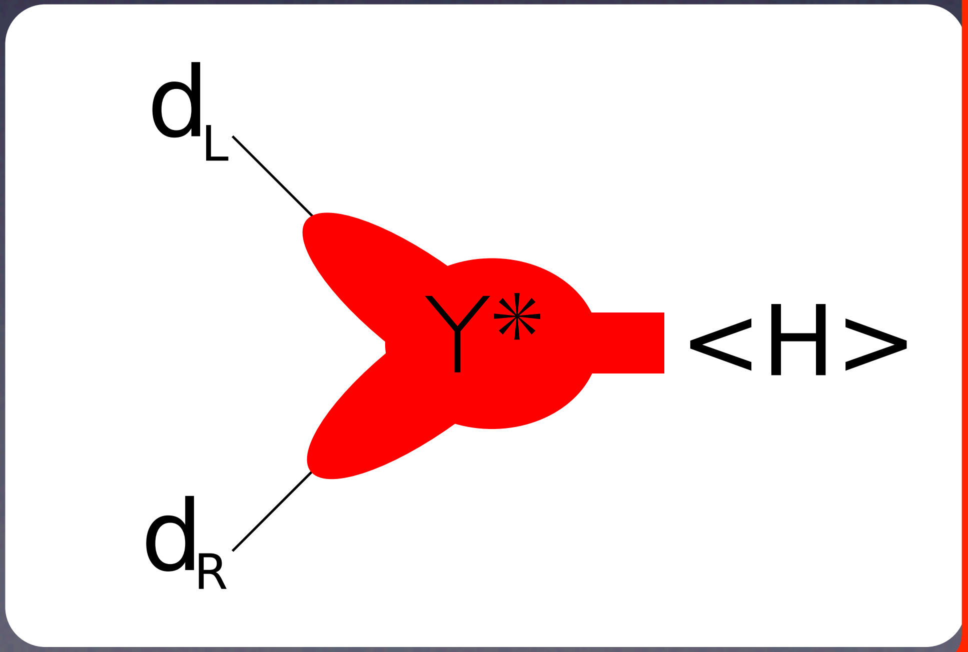
Linear:

D.B. Kaplan '91

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

Quarks & Leptons mix with strong sector

mass $\propto$ compositeness



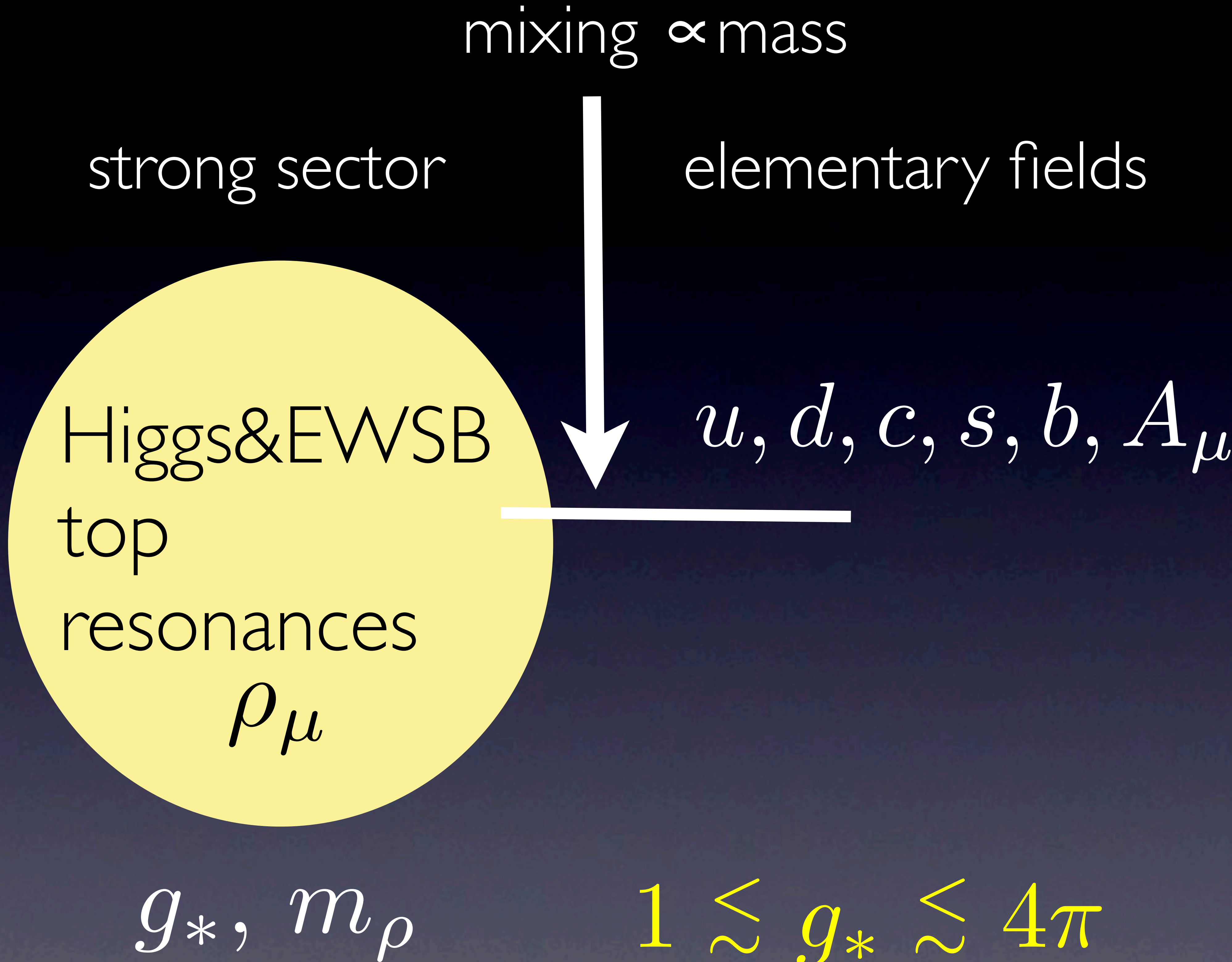
Partial compositeness

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

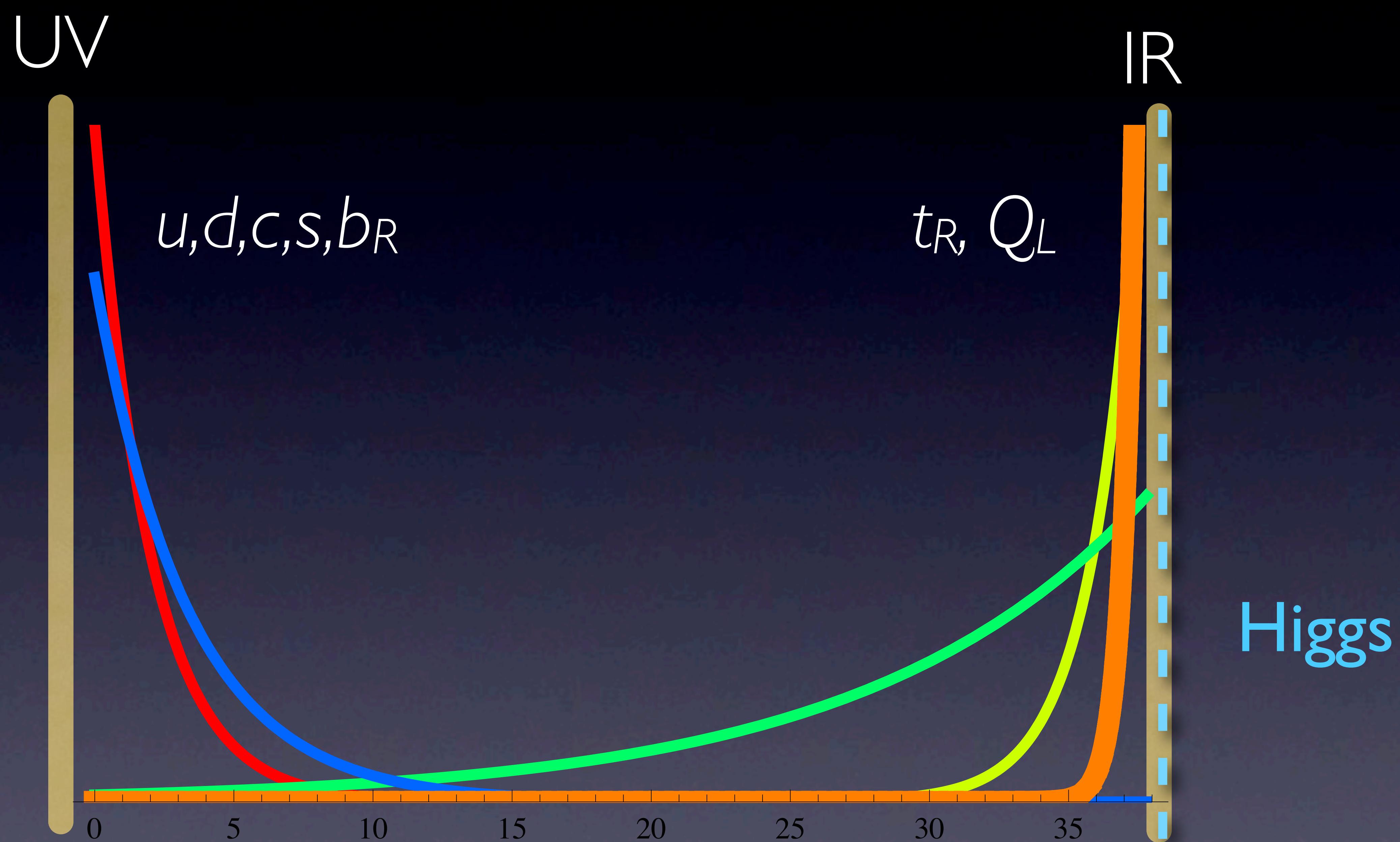
$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

Composites are heavy ($m_\rho \approx \mathrm{TeV}$).

Light quarks have very little composite admixture.

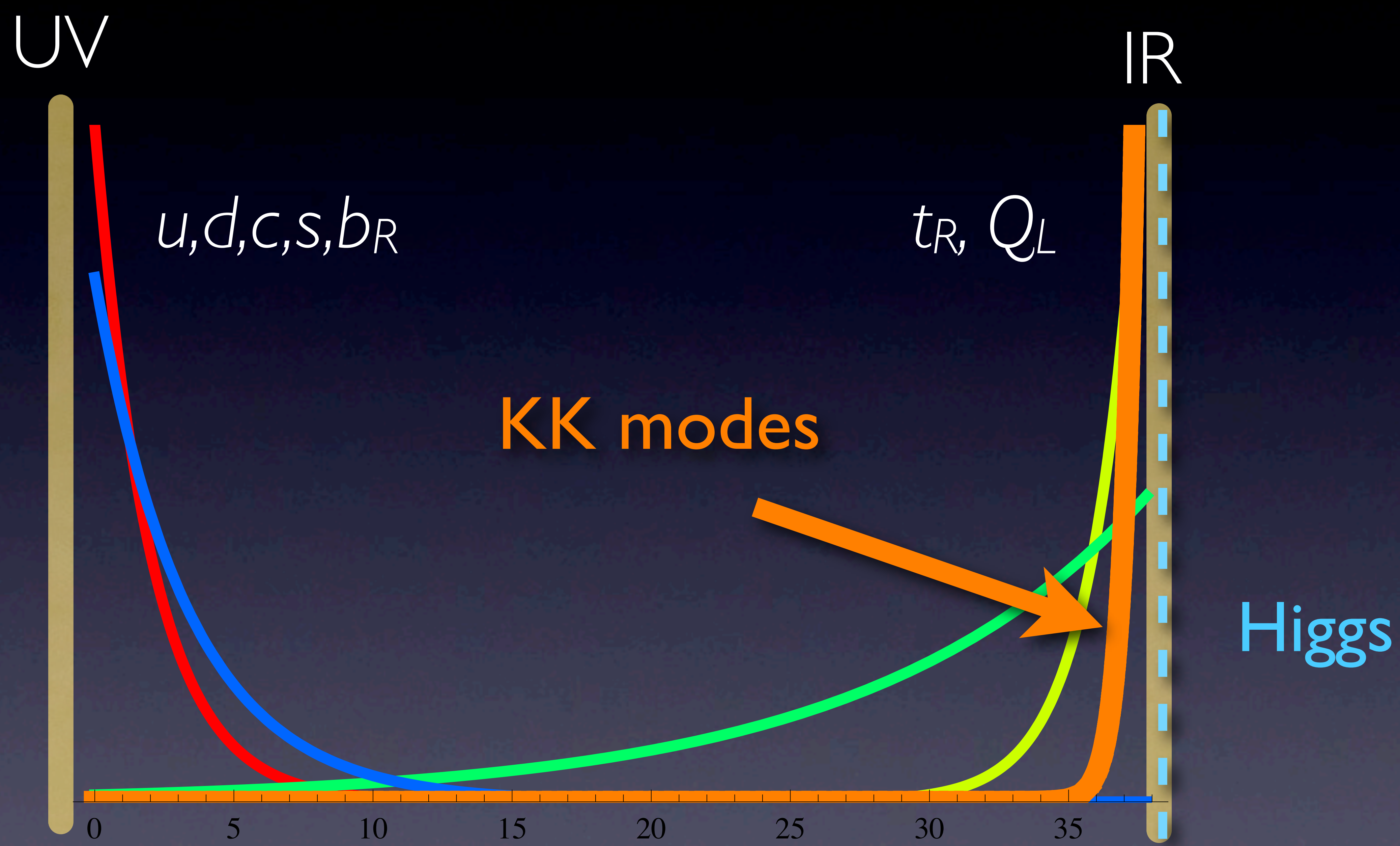


Kaplan; Contino,
Kramer, Son, Sundrum



RGE of the mixing UV → IR

Contino, Pomarol;
Contino, et al



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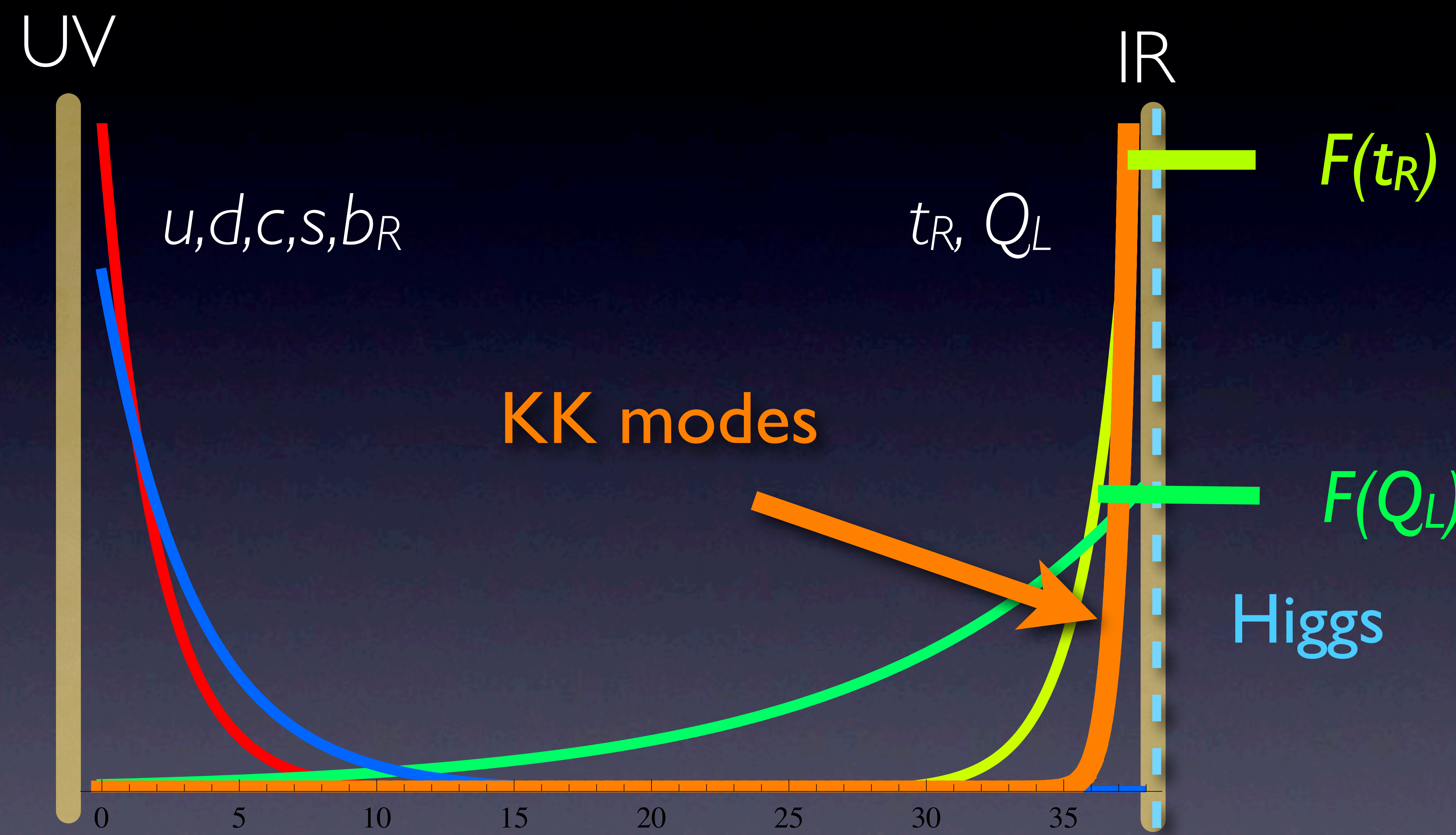
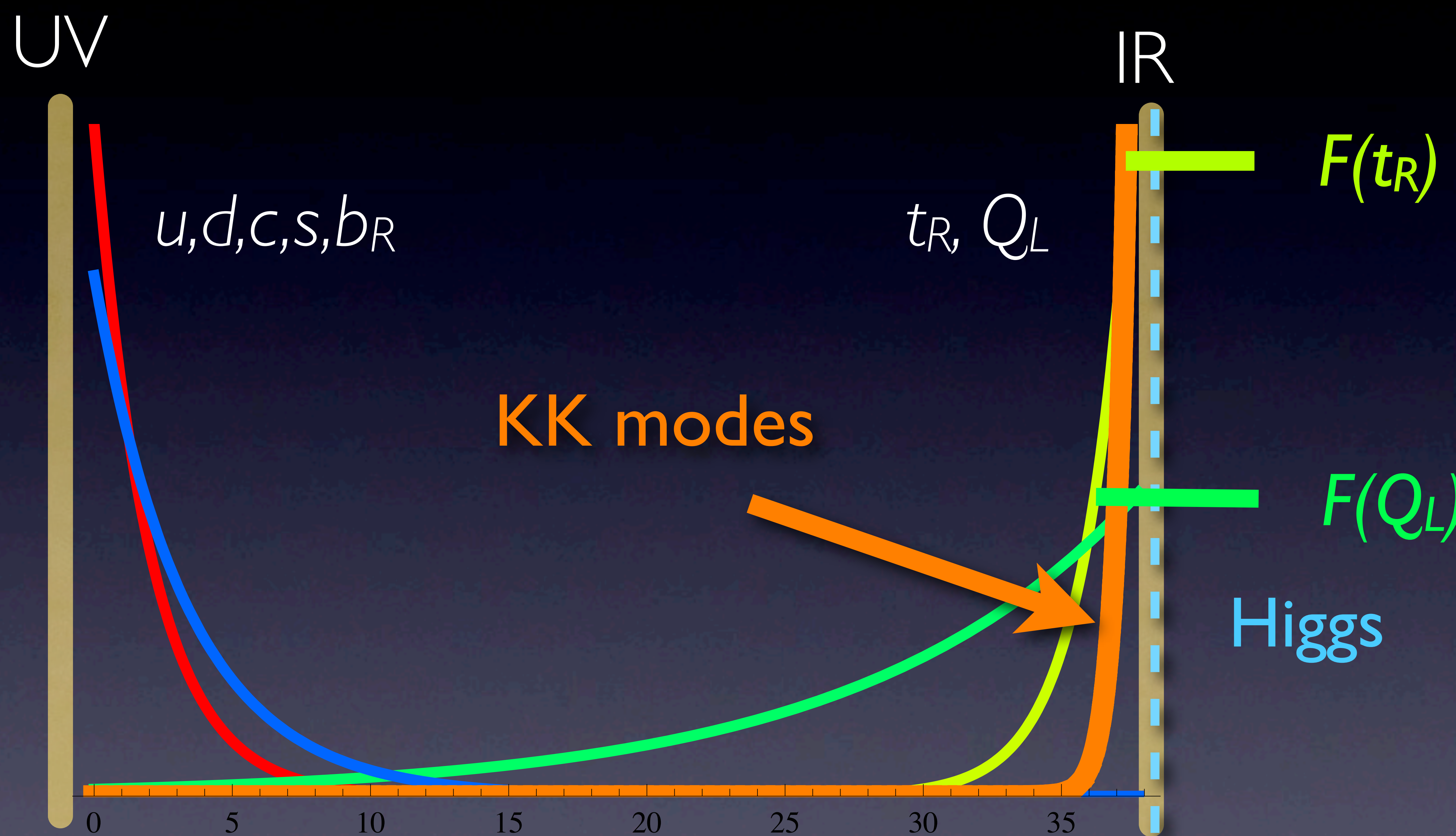


RGE of the mixing UV → IR

Contino, Pomarol;
Contino, et al

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

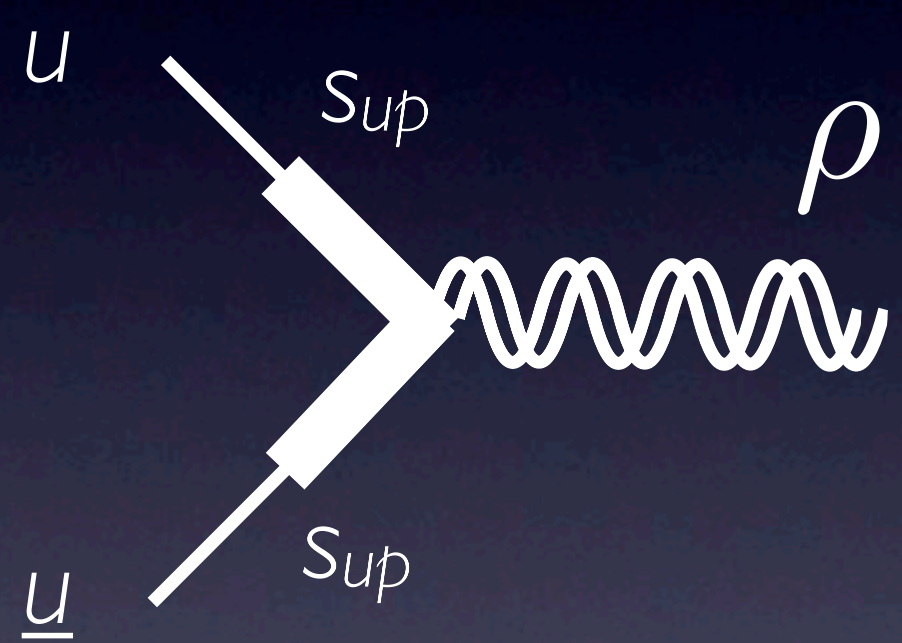


RGE of the mixing UV ⇒ IR

Contino, Pomarol;
Contino, et al

high p_T

Resonance production (option 1)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

high pT

Resonance production (option 2)

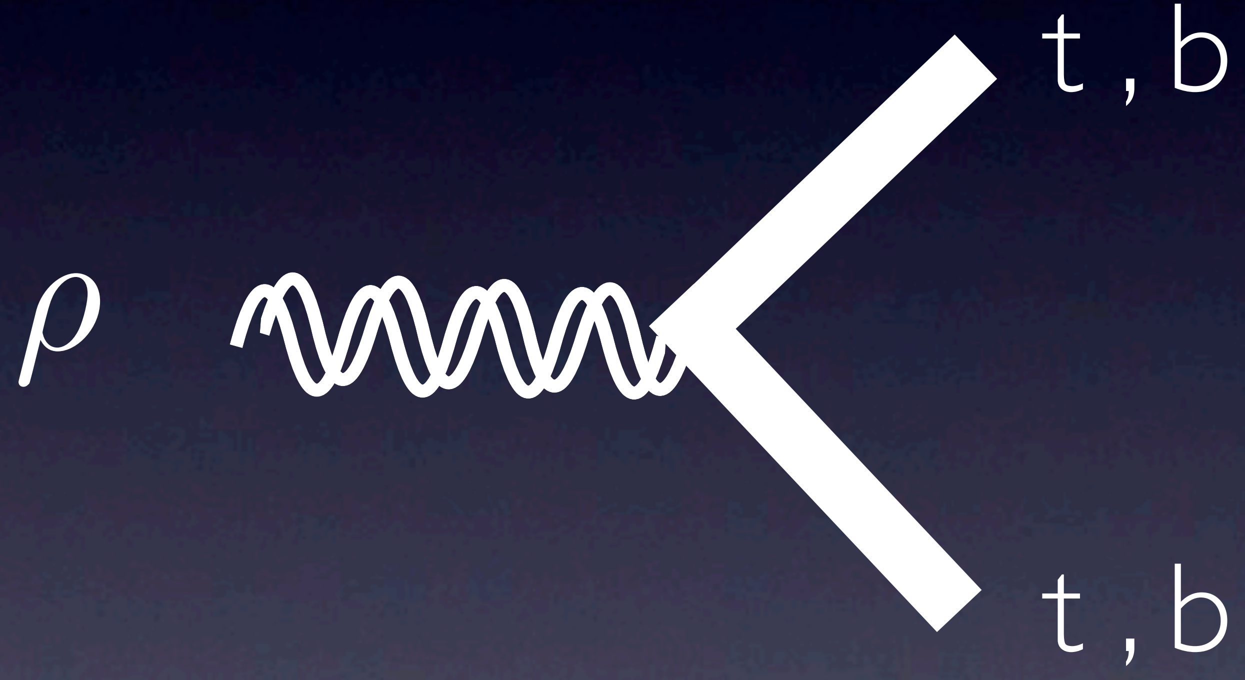
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

high p_T

Resonance decay



decays dominantly into 3rd generation! (tt, bt, bb)

Top FCNCs

SM $$Br(t \to q(Z, \gamma, G)) \sim 10^{-12}$$

partial compositeness/ warped flavor

$$Br(t \to c_R Z) \propto |U_R|_{23} \times \delta g_Z \sim 10^{-5}$$

LHC (100 1/fb)

$$Br(t \to (Z, \gamma)) \geq 10^{-5}$$

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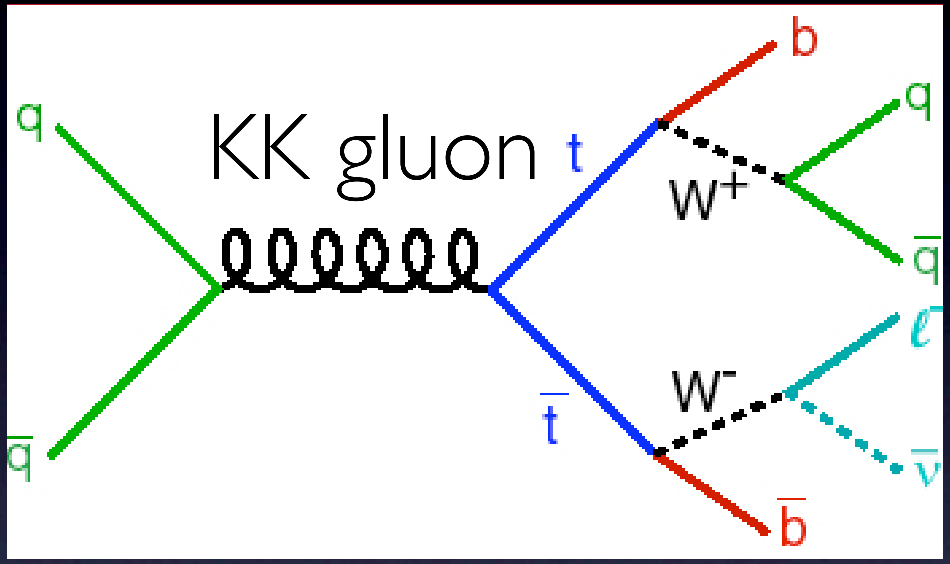
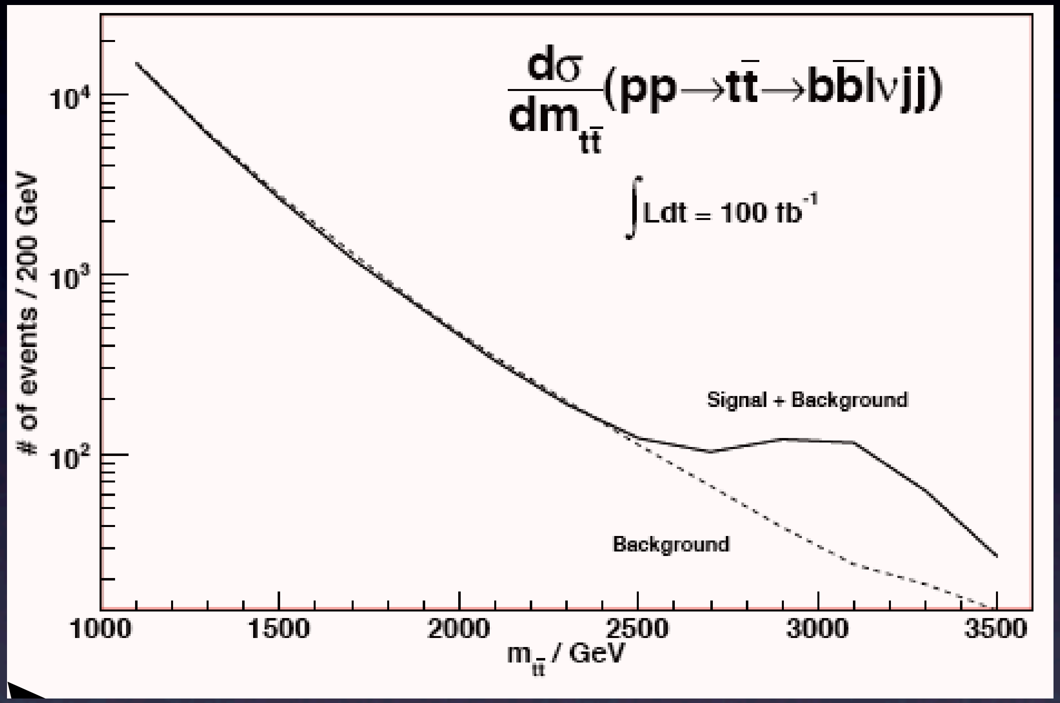
Resonances decay to Tops

Agashe et al, Lillie et al



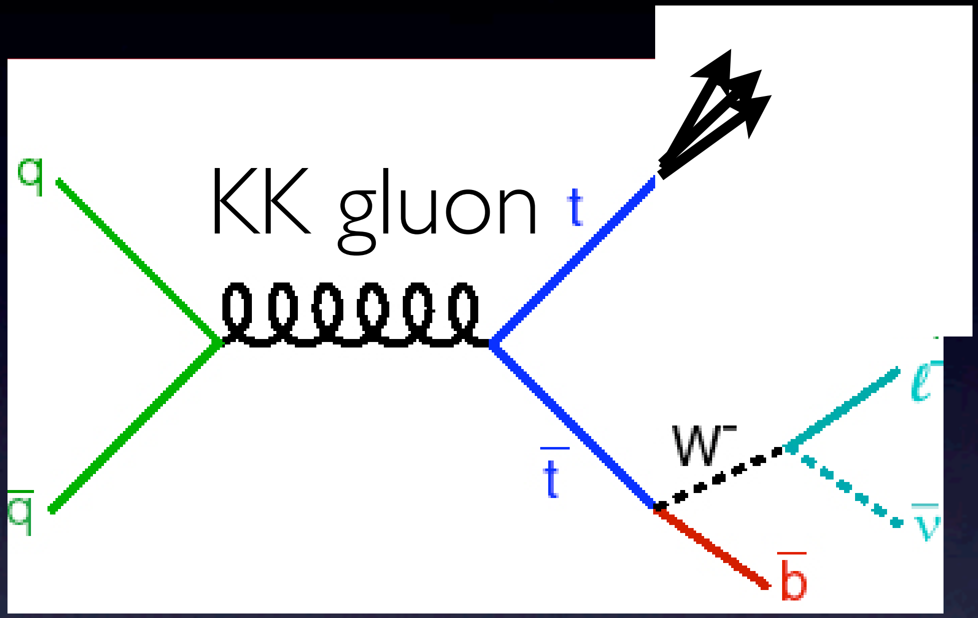


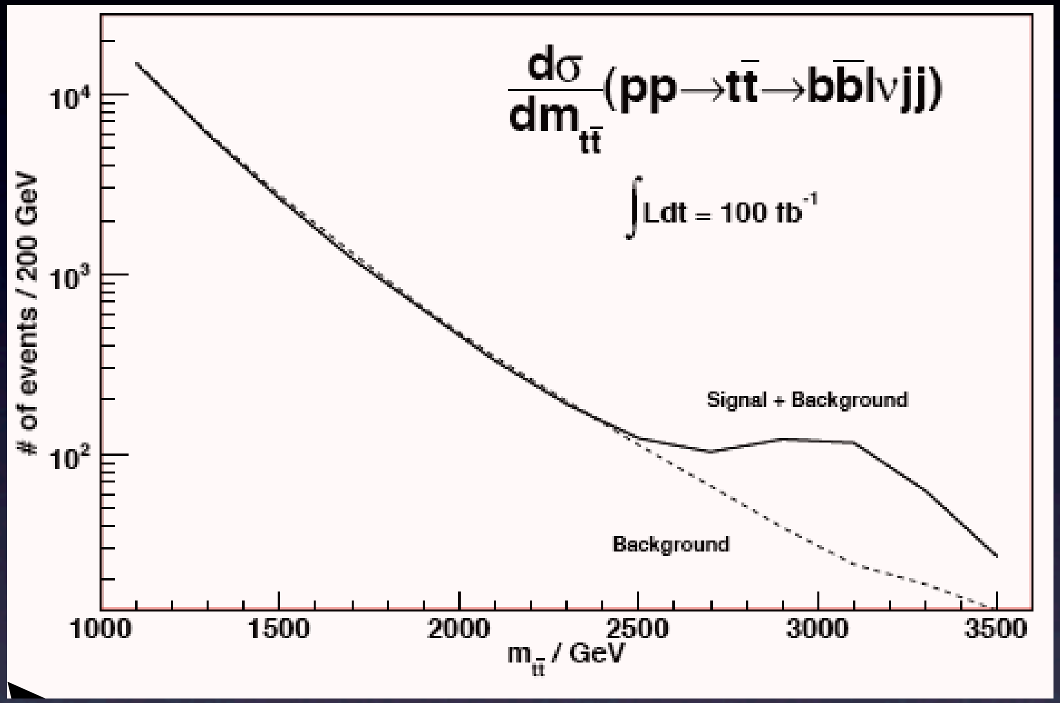
Collimation poses challenge
($m_{KK} \sim 3$ TeV vs. m_{top})

high p_T - flavor interplay!

Resonances decay to Tops

Agashe et al, Lillie et al





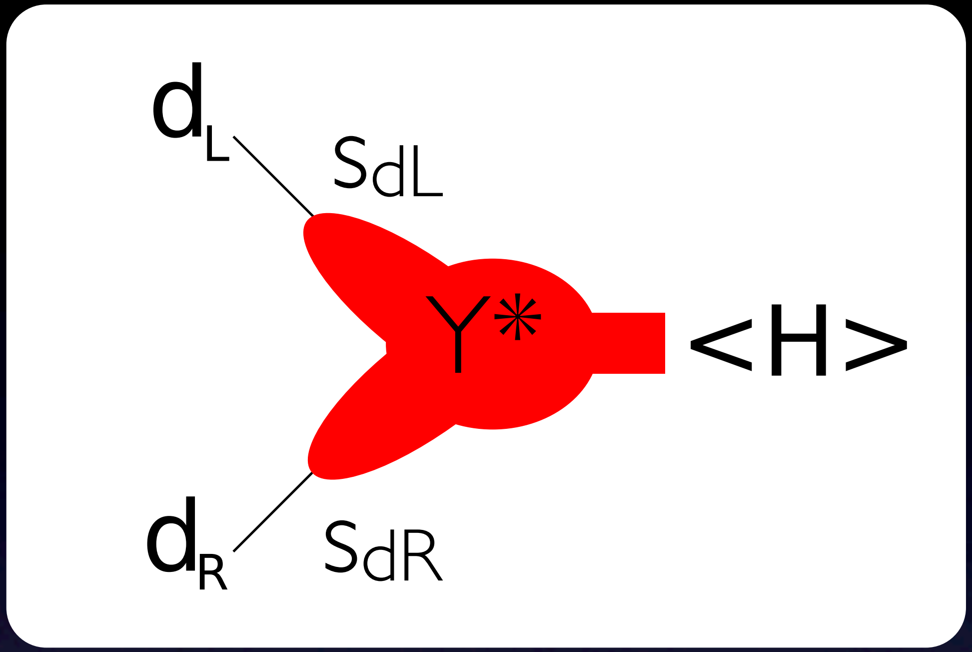
Collimation poses challenge ($m_{KK} \sim 3$ TeV vs. m_{top})

high p_T - flavor interplay!

FCNCs

FCNC protection

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



masses from mixing in composites

$$m_d \sim v \sin\theta_{d_L} Y^* \sin\theta_{d_R}$$

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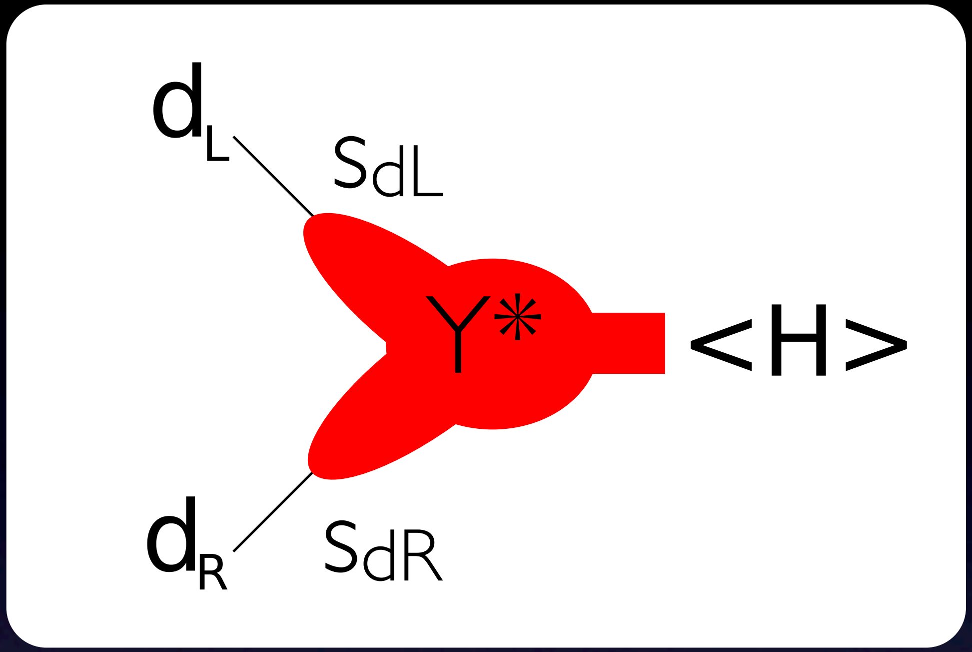

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RS-GIM

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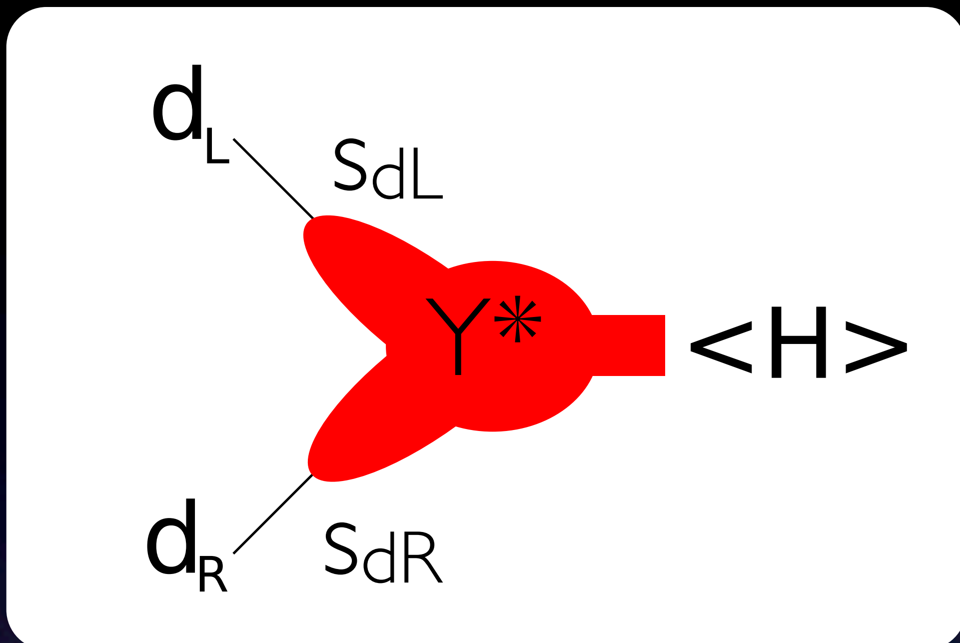

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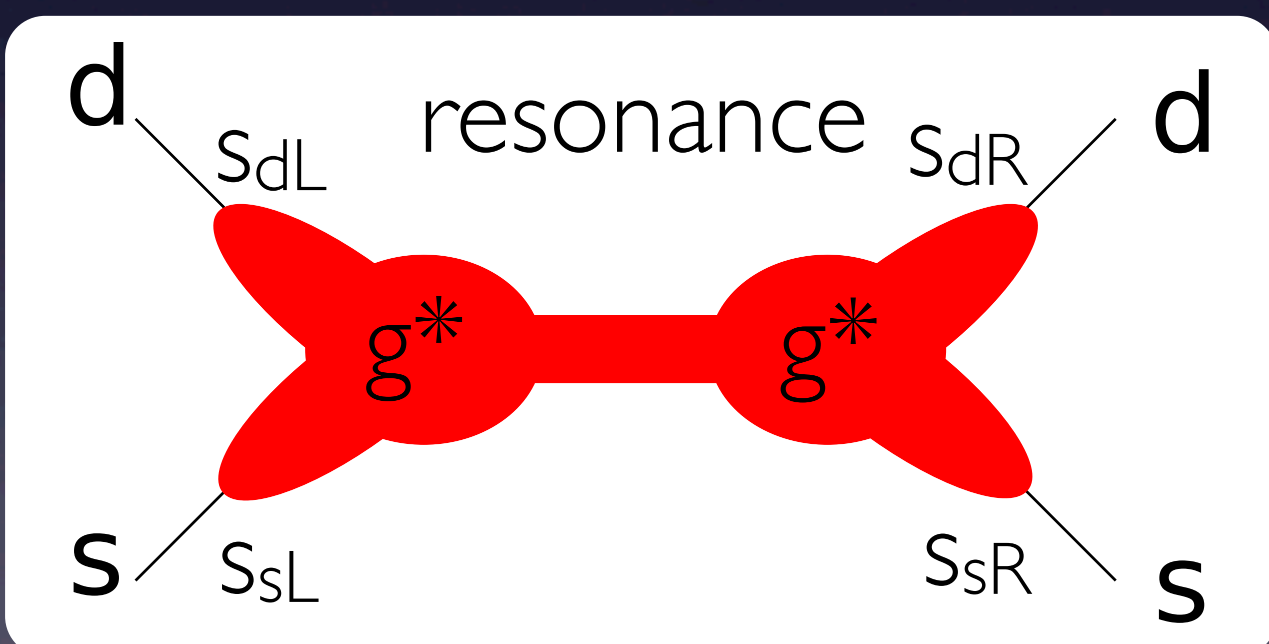


$$K^0 - \bar{K}^0$$

FCNCs suppressed by the same mixings

$$\sim \frac{g_*^2}{M_\rho^2} s_{d_L} s_{d_R} s_{s_L} s_{s_R}$$

$$\sim \frac{g_*^2}{M_\rho^2} \frac{m_d m_s}{v Y_*^2}$$

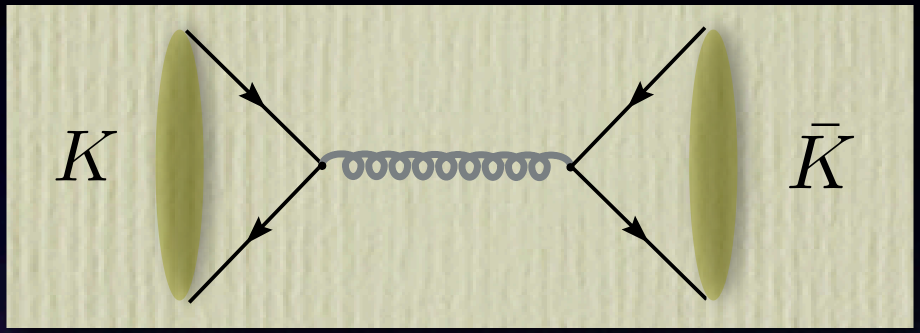
RS-GIM

Little CP problem

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

$\Delta F = 2$ (strongest from ϵ_K)

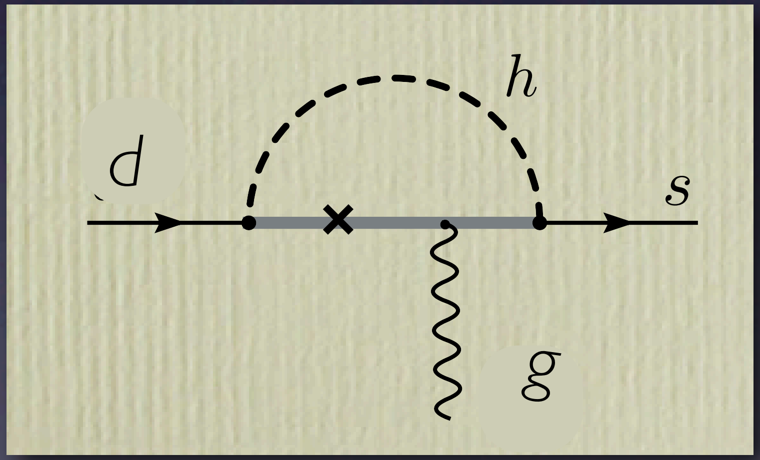
$$g_* \approx Y_* \approx 3 \ldots 6$$



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

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

Gedalia et. al

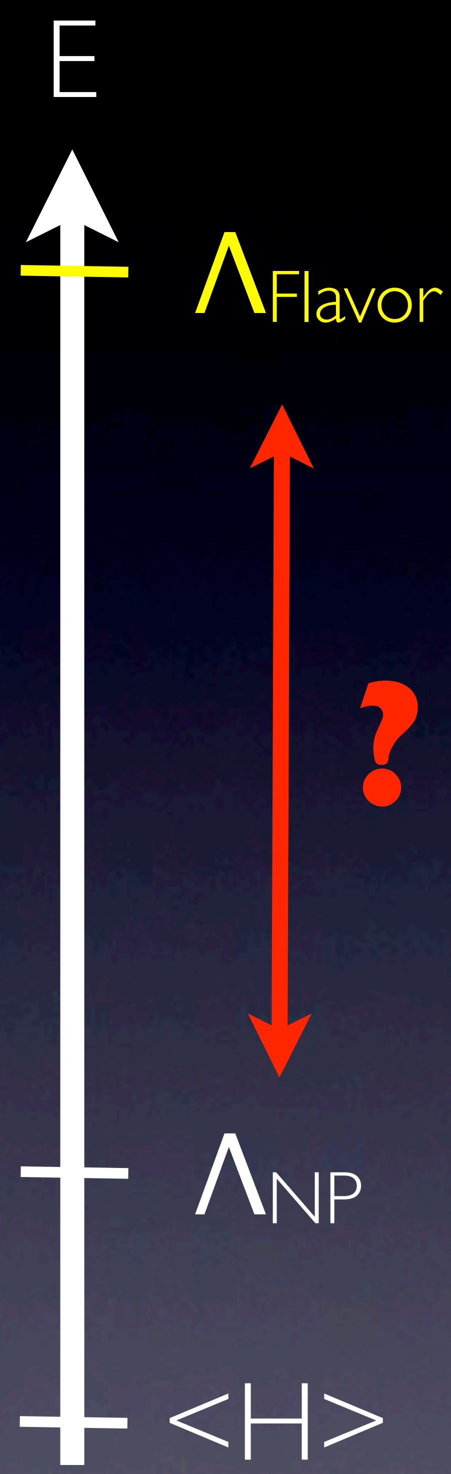


$$M_* \gtrsim 1.3\, Y_* \text{ TeV}$$

$\Delta F = 0$ neutron EDM

$$M_* \geq 2.5\, Y_* \text{ TeV}$$

Agashe et. al, Delaunay et. al, Redi, AW



generate $Y_{U,D}$ at high scale

new physics dynamics can depend non-trivially on $Y_{U,D}$

Flavor triviality: dynamical MFV

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

strong sector $SU(3)_Q \times SU(3)_u \times SU(3)_d$

mixing ~ Yukawas

$s_u, s_d \sim Y_u, Y_d$

Delaunay et al

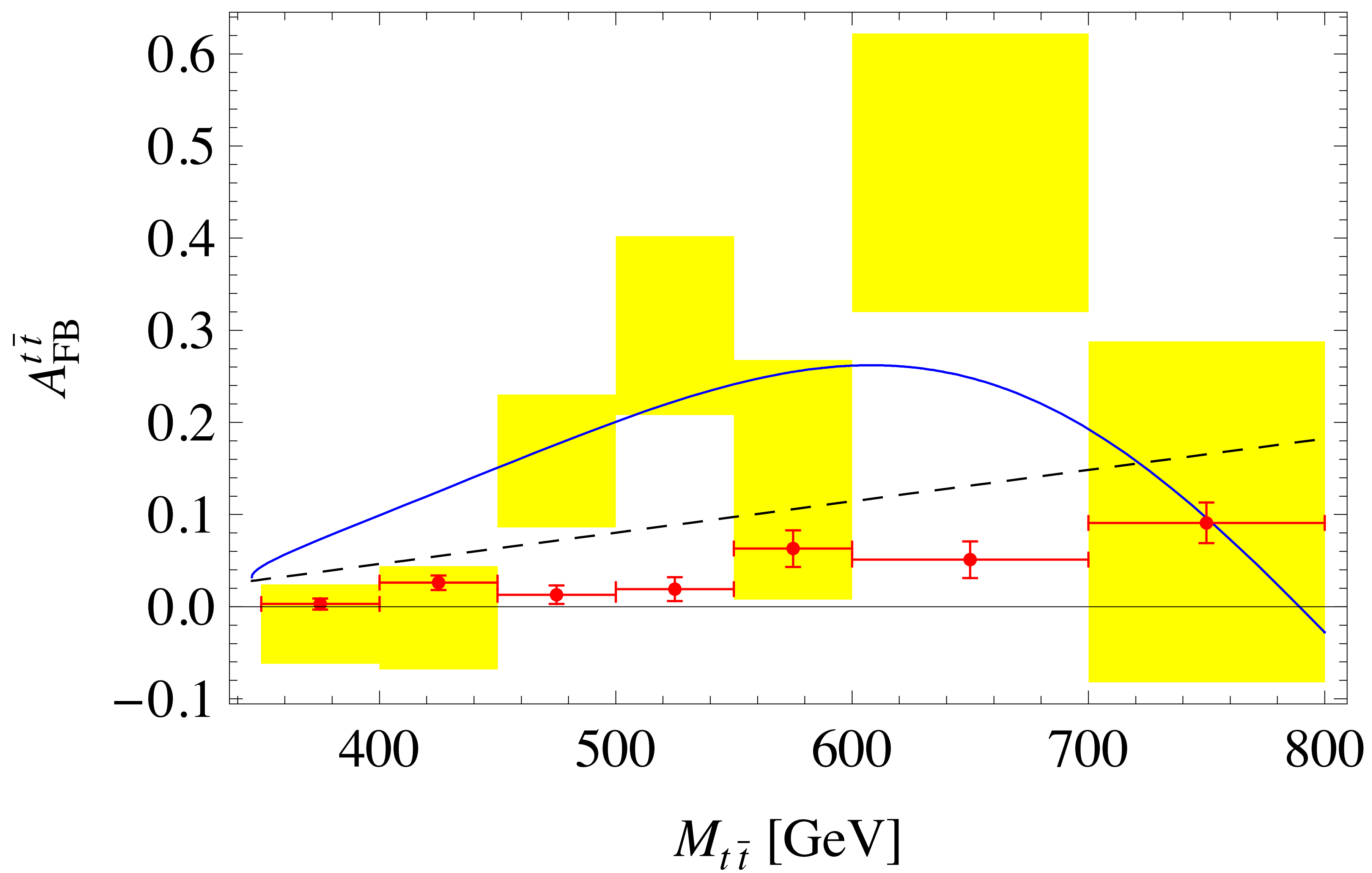
sweet spot if *Y*'s "shine" into the bulk, $m_\rho \approx 2\,\mathrm{TeV}$

=> flavor gauge bosons predicted (in 2 slides)

mixing can be large & universal

MFV-RS allows for sizable A_{FB}
(Small asymmetry in anarchic warped flavor: Bauer et al)

plot from Blum et al



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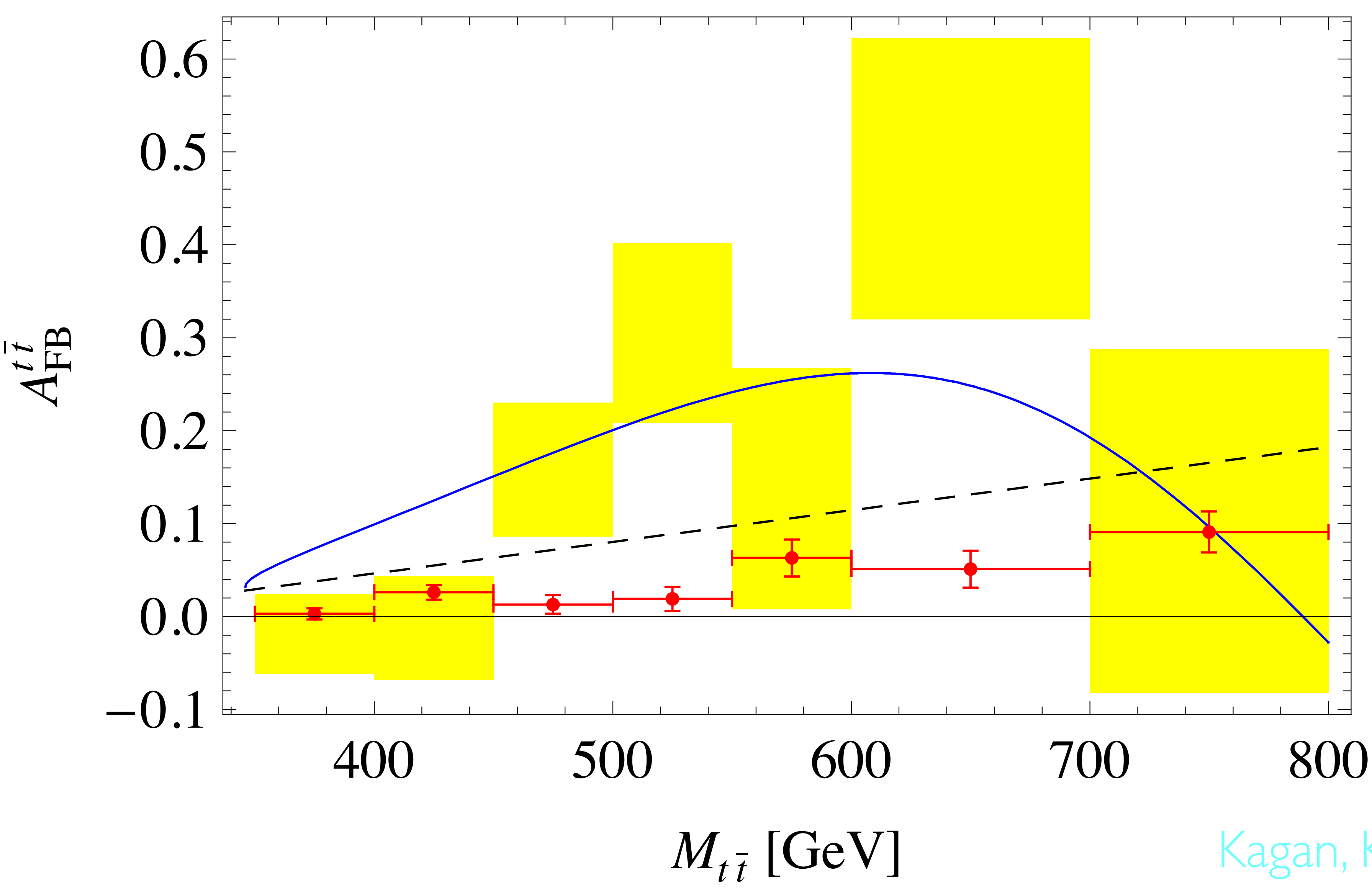


Kagan, Kamenik, Perez, Stone

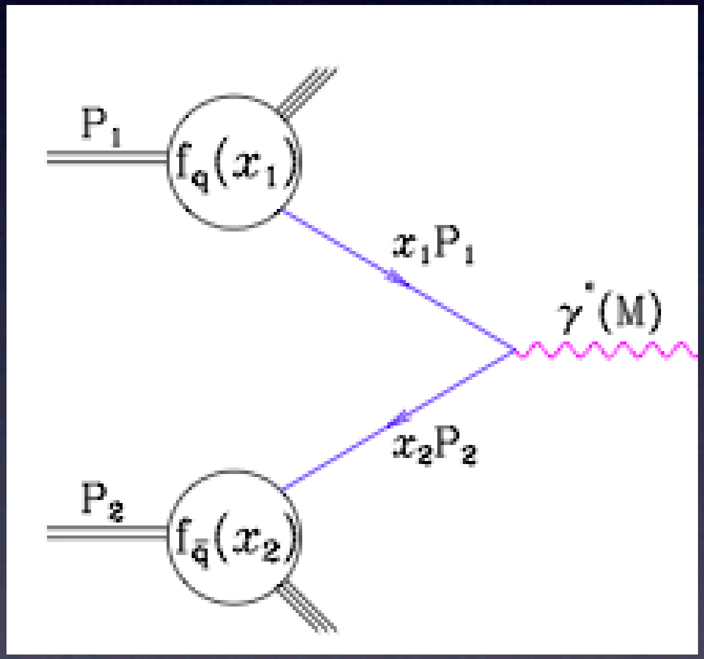
measurement at LHCb?

Flavor gauge bosons at LHC

Csaki, Kagan, Lee, Perez, AW

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

Flavor gauge bosons do not have massless modes (flavor is broken)



no $\gamma - \rho$ mixing !

But quark composite mixing can be flavor universal & large

$$\sim g_*^2 \sin^2 \theta_{u_R}$$

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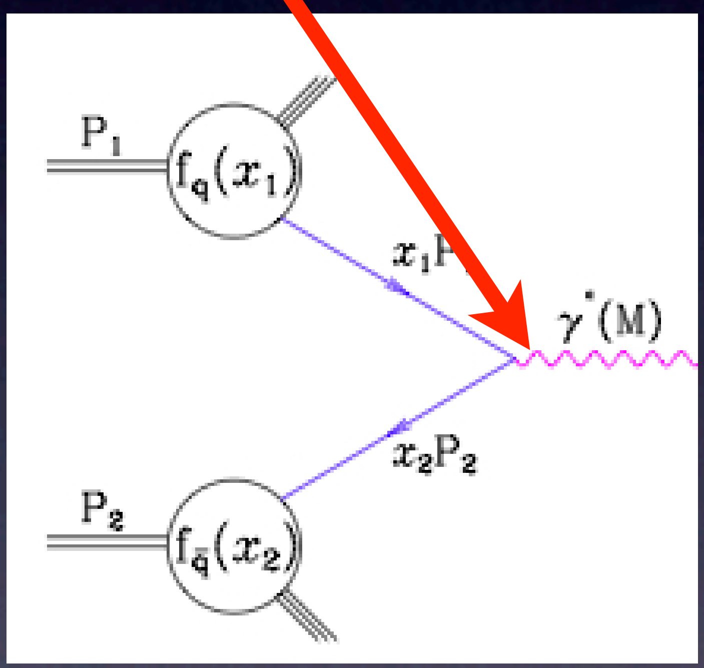

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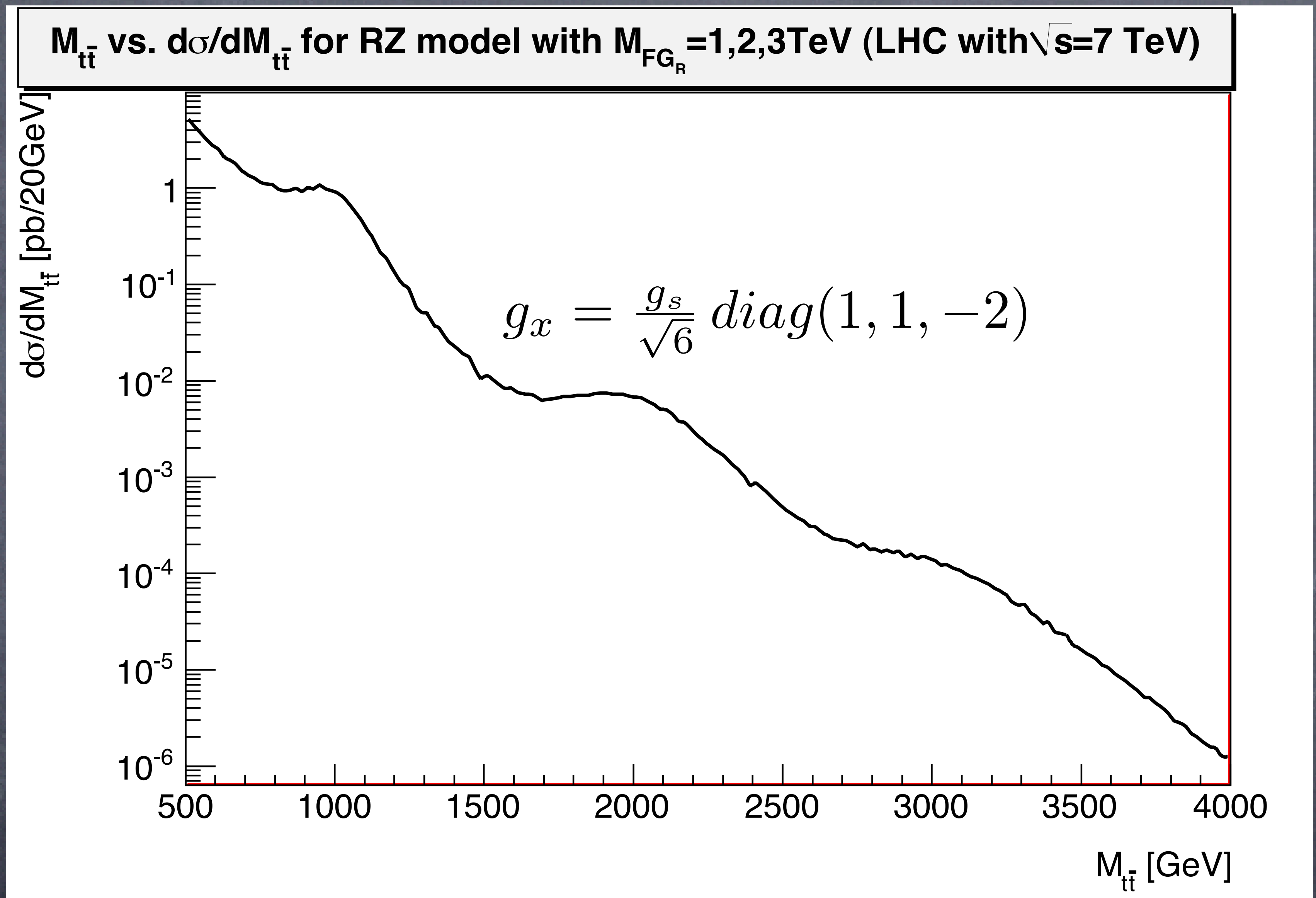
FGBs at the LHC (preliminary)

- The flavor gauge bosons & scalars might be observable.



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

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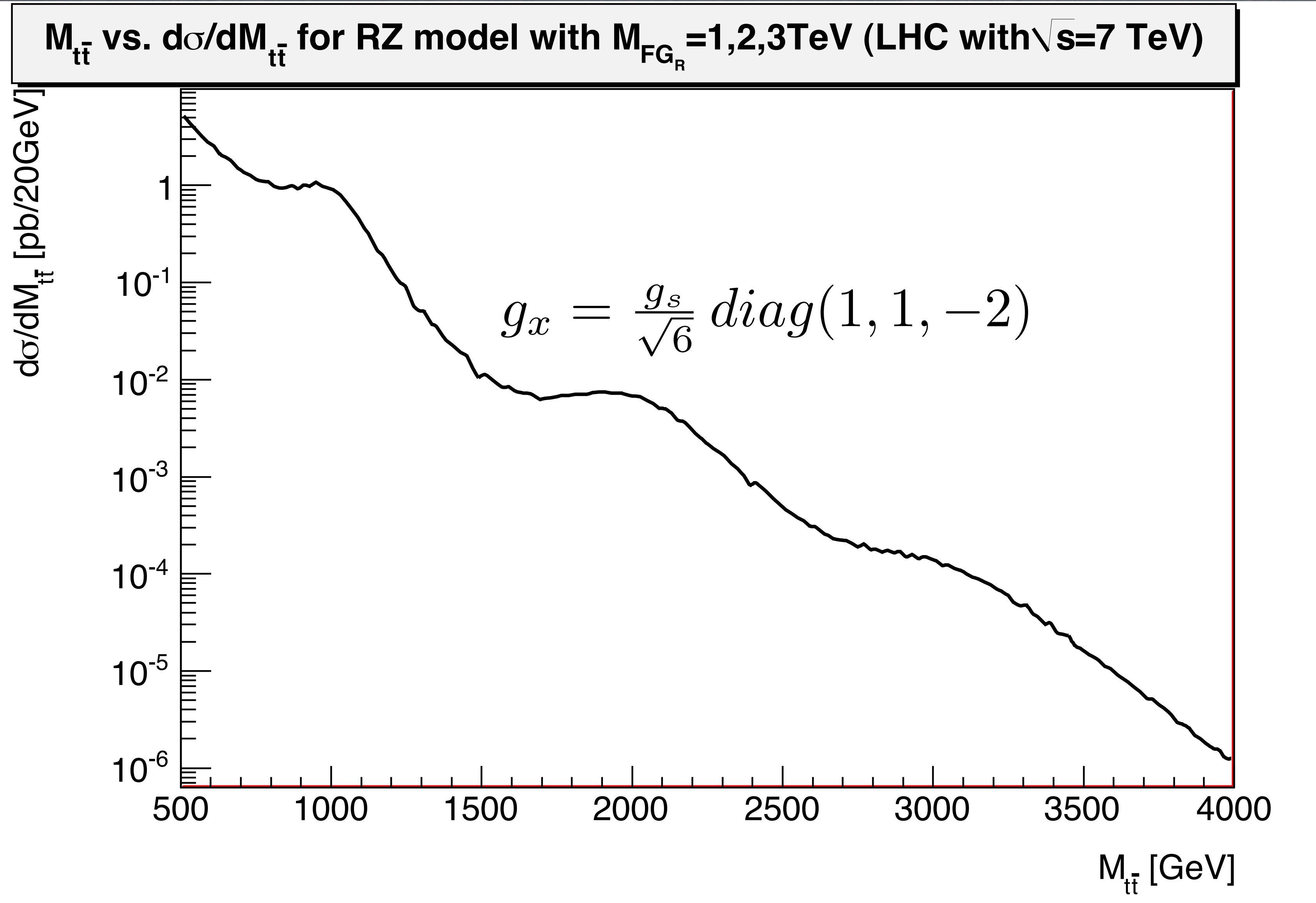


$$\mathcal{L} = \frac{\lambda}{2} V^8_\mu \left(\frac{1}{\sqrt{3}} \bar{u}_R \gamma^\mu u_R + \frac{1}{\sqrt{3}} \bar{c}_R \gamma^\mu c_R - \frac{2}{\sqrt{3}} \bar{t}_R \gamma^\mu t_R \right) + \frac{\lambda}{2} \left((V^4_\mu - i V^5_\mu) \bar{u}_R \gamma^\mu t_R + (V^6_\mu - i V^7_\mu) \bar{c}_R \gamma^\mu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

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:

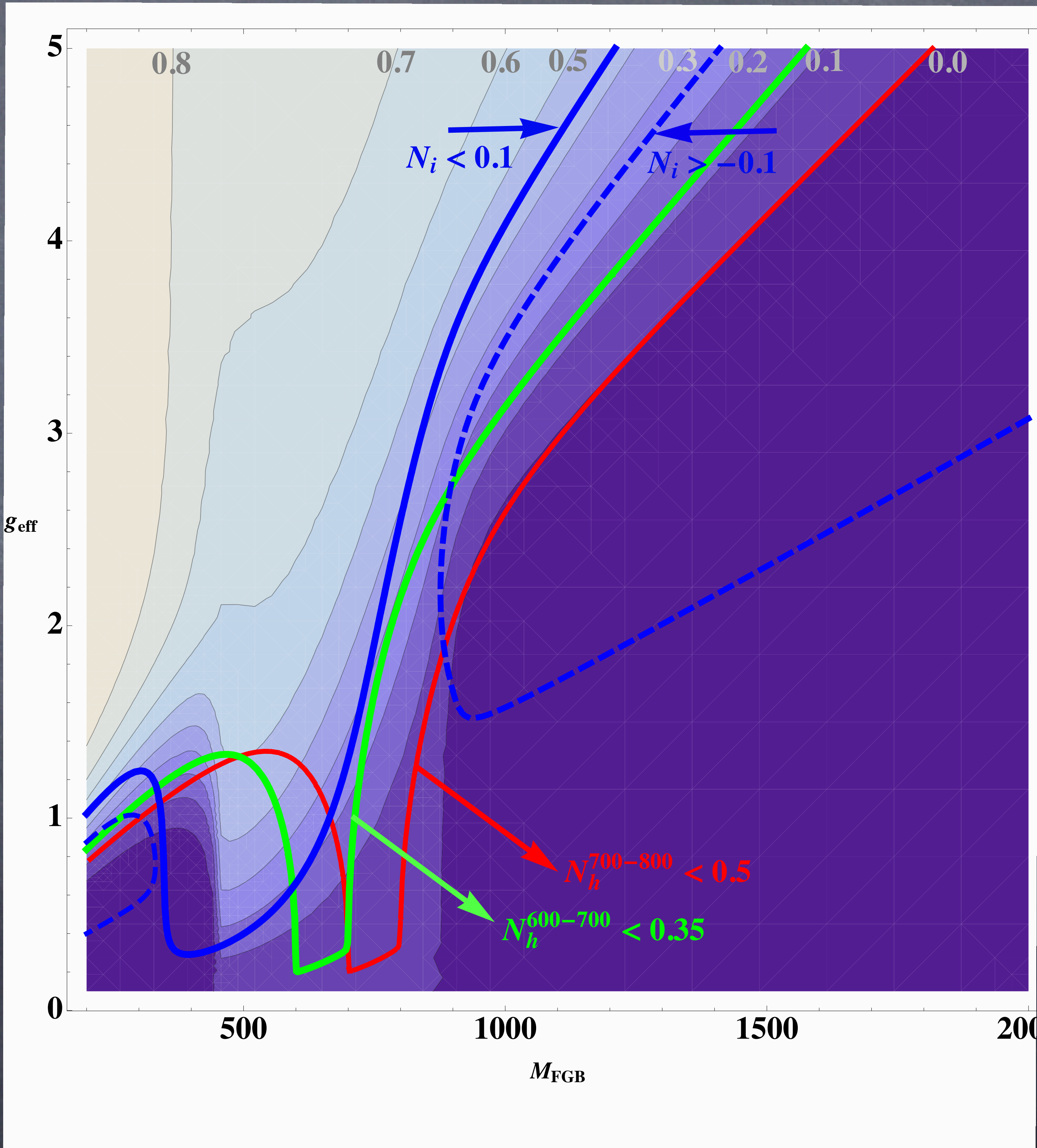
i) $\delta\sigma^{\rm NP}_{700-800\,{\rm GeV}}/\sigma^{\rm SM}_{700-800\,{\rm GeV}} \lesssim 47\%$

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

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

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

- σ_{NP}/σ_{SM}(pT>400GeV): 2-3



Conclusions

Most well-motivated models of NP at the TeV predict experimentally resolvable deviations from the SM

Discovery of non-MFV new physics might give insight in origin of Yukawas

high p_T can also offer window into flavor (see explanations of the top FB anomaly)