New physics & flavor at high & low p_T

Andreas Weiler
DESY/CERN

The SM flavor puzzle

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

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

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	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) 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}	Δm_K; ϵ_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}	Δm_K; ϵ_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}	Δm_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}	Δm_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}	Δm_{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}	Δm_{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}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

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

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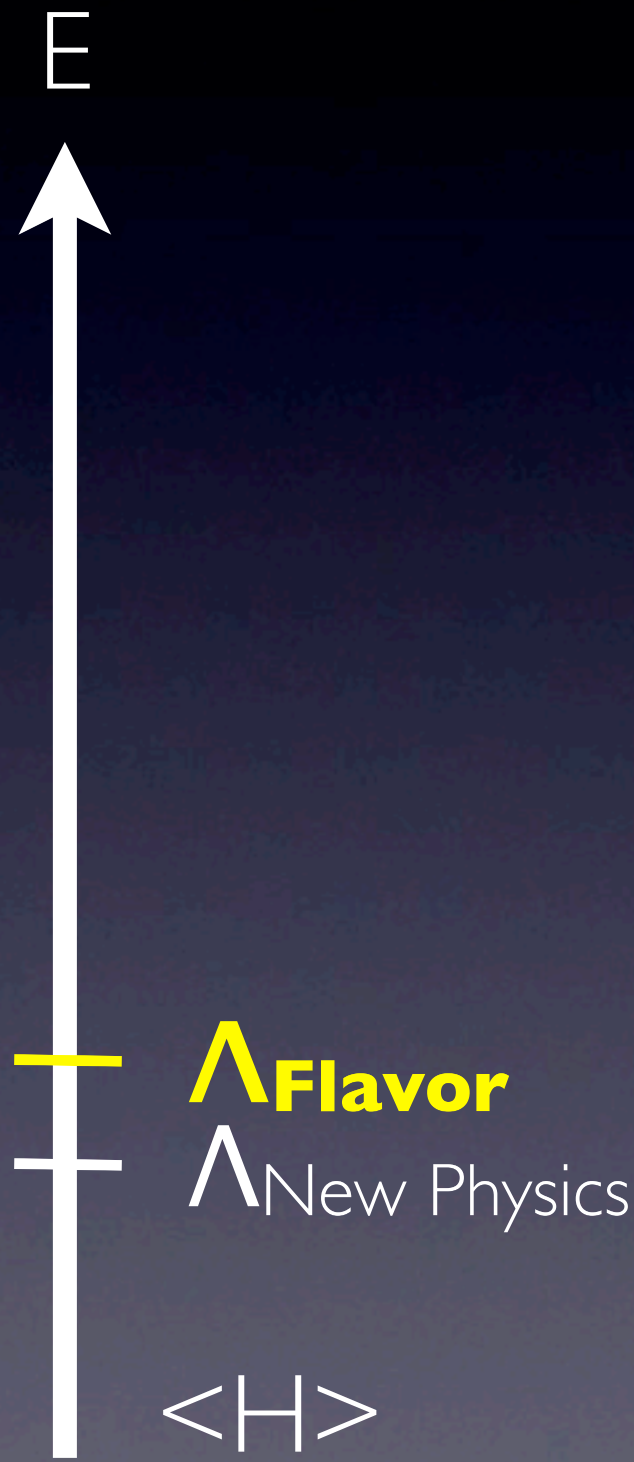
Very strong suppression! New flavor violation must either approximately (exactly?) follow SM pattern…

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

Flavorgenesis scale?

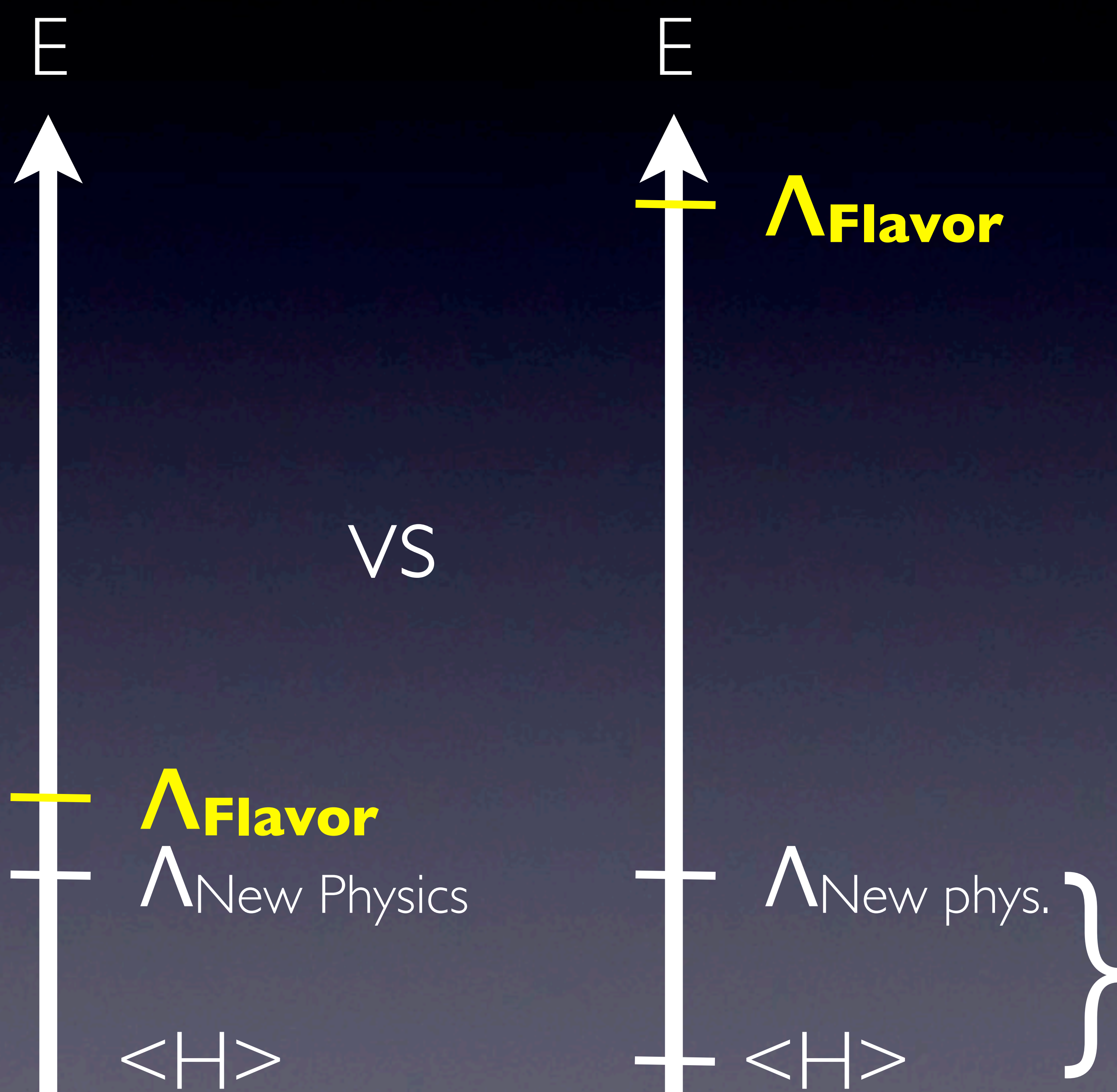


$$\frac{1}{\Lambda^2_{\mathrm{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

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

} naturalness

Flavorgenesis scale?



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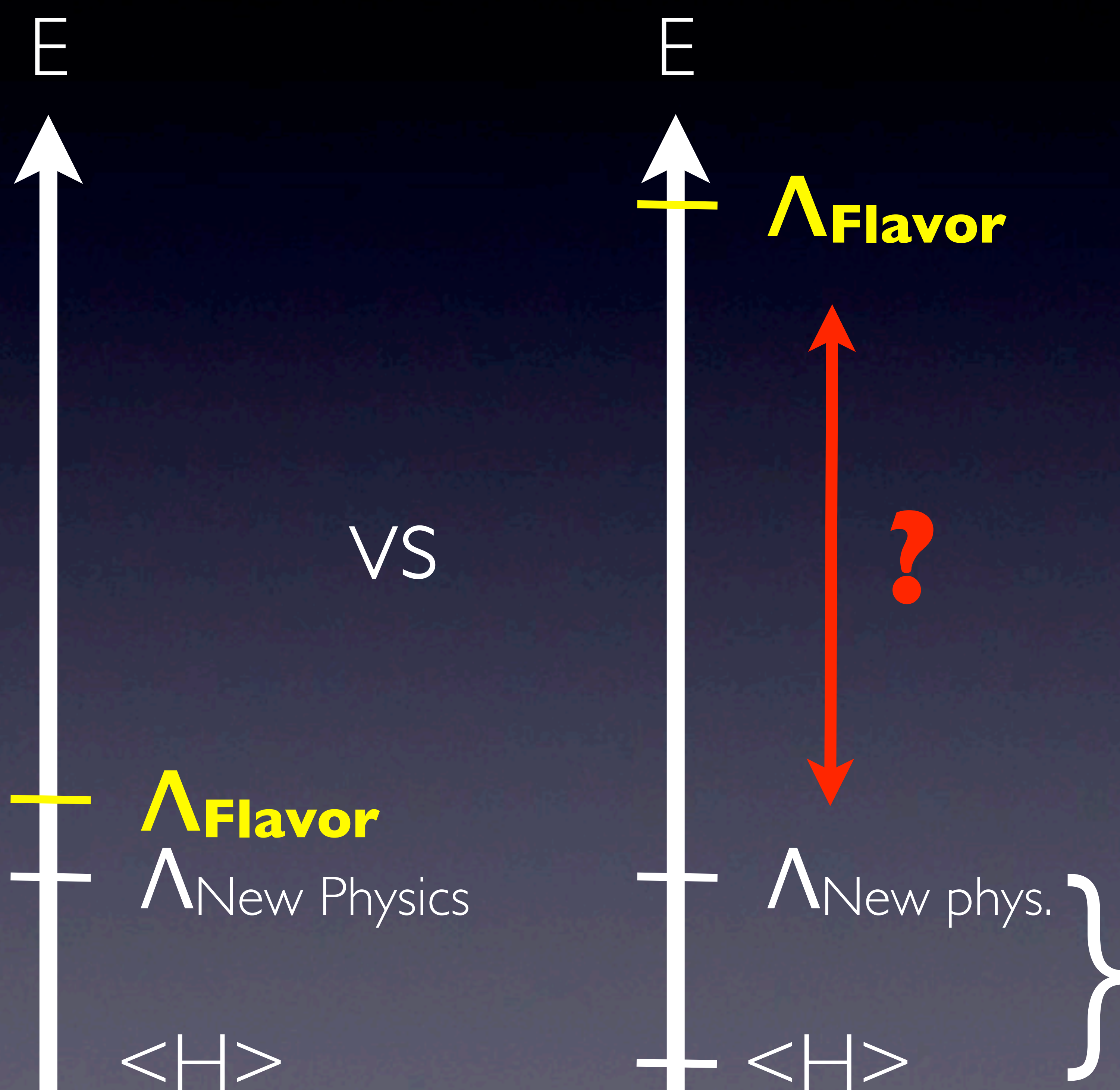

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Log(SM flavor puzzle)

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

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

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

anarchic ("structure-less")

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

split fermions/RS

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

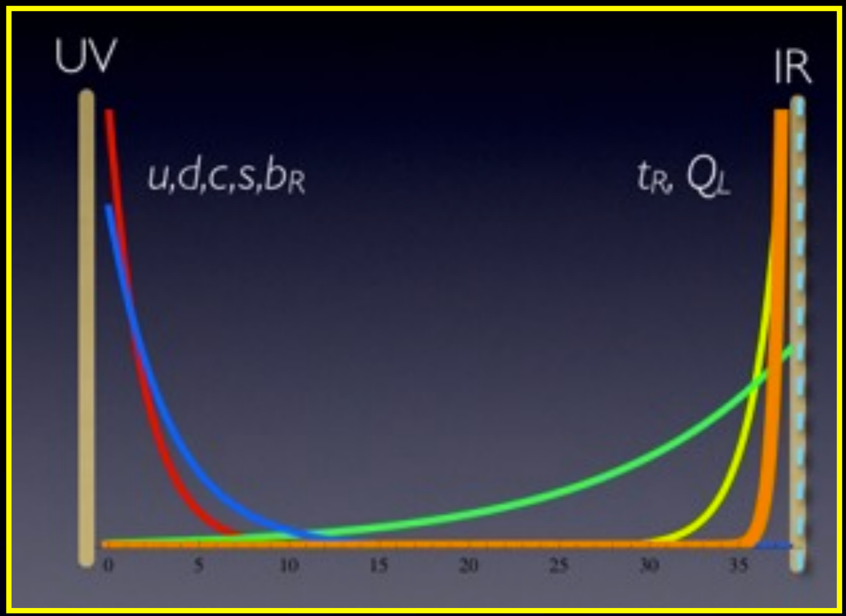
strong dynamics

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

Froggatt-Nielsen

Hierarchy { => hierarchical
masses & mixing angles

anarchic ("structure-less")



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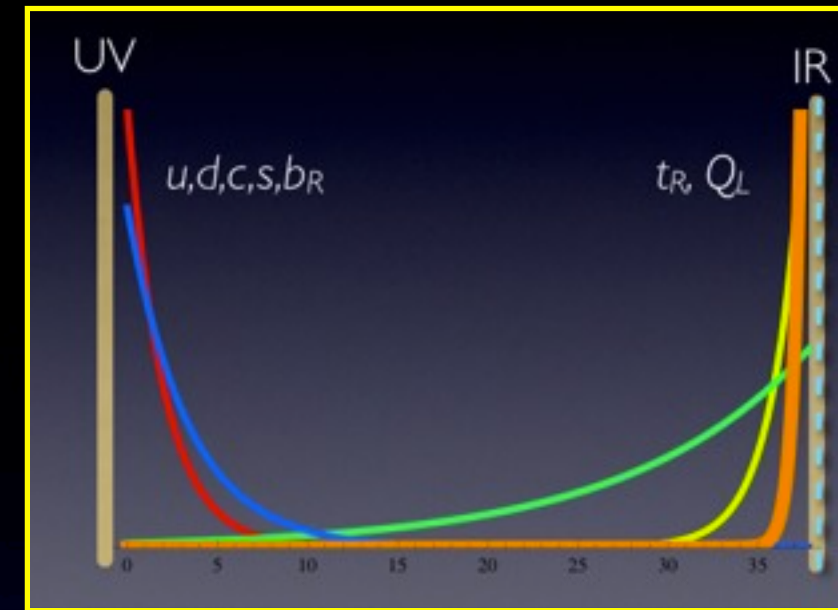
Hierarchy { => hierarchical masses & mixing angles

anarchic ("structure-less")



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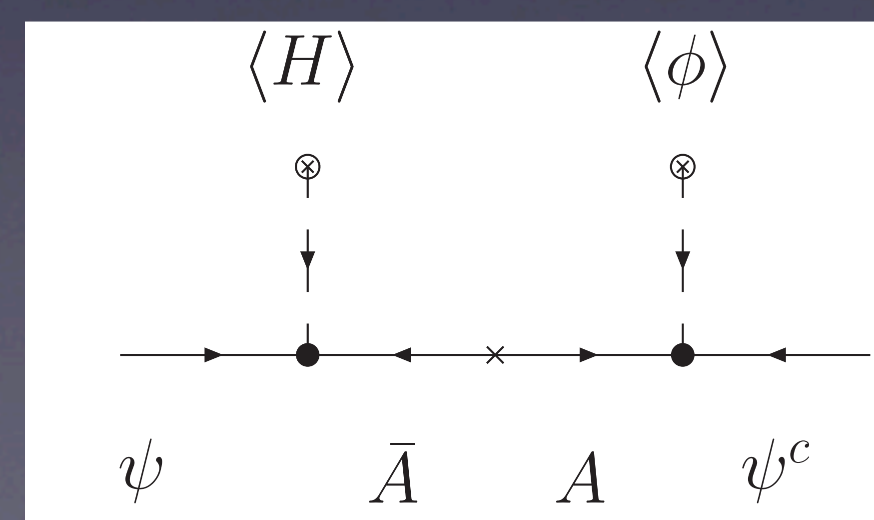

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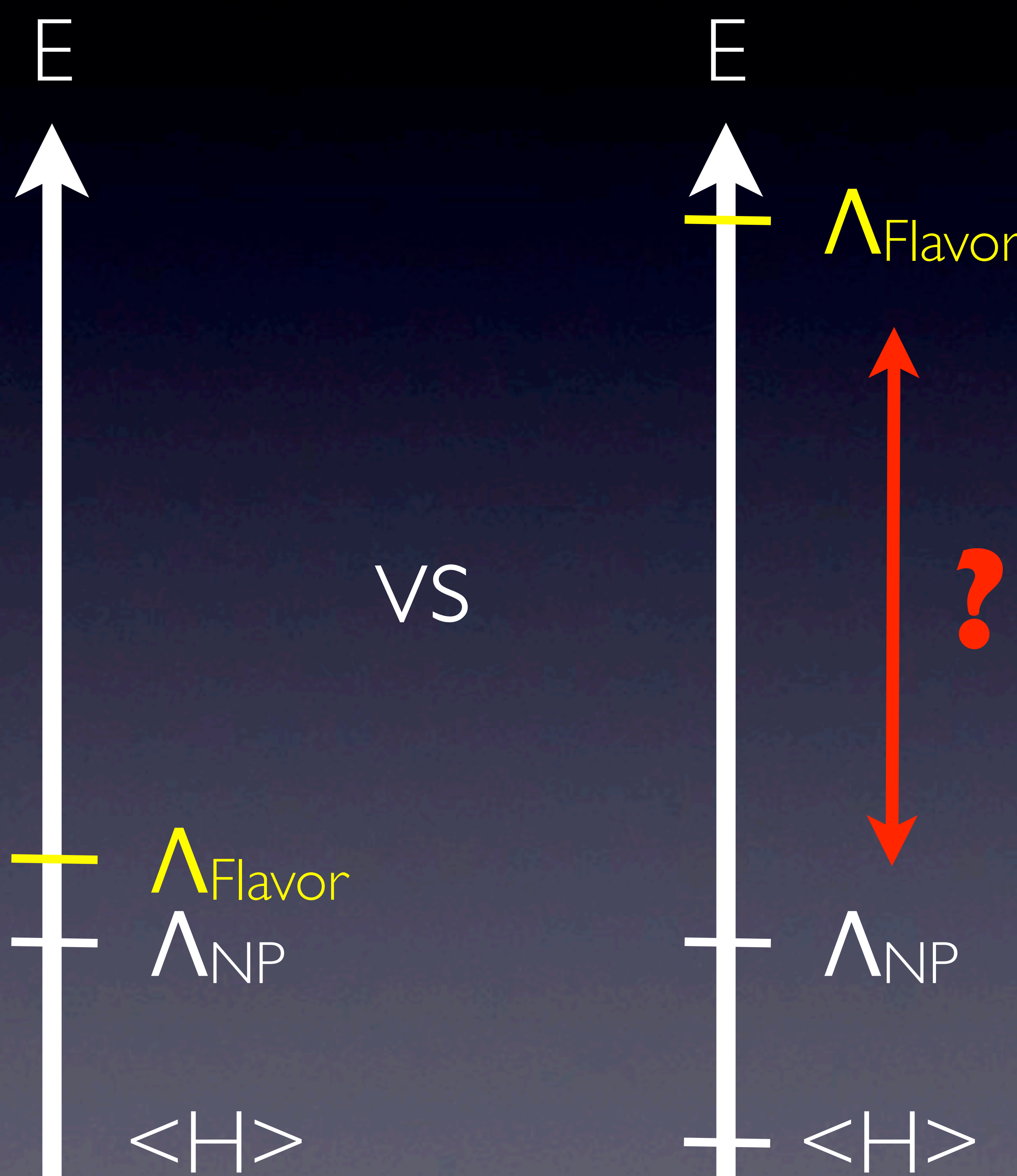
Flavorgenesis scale?



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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*).

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

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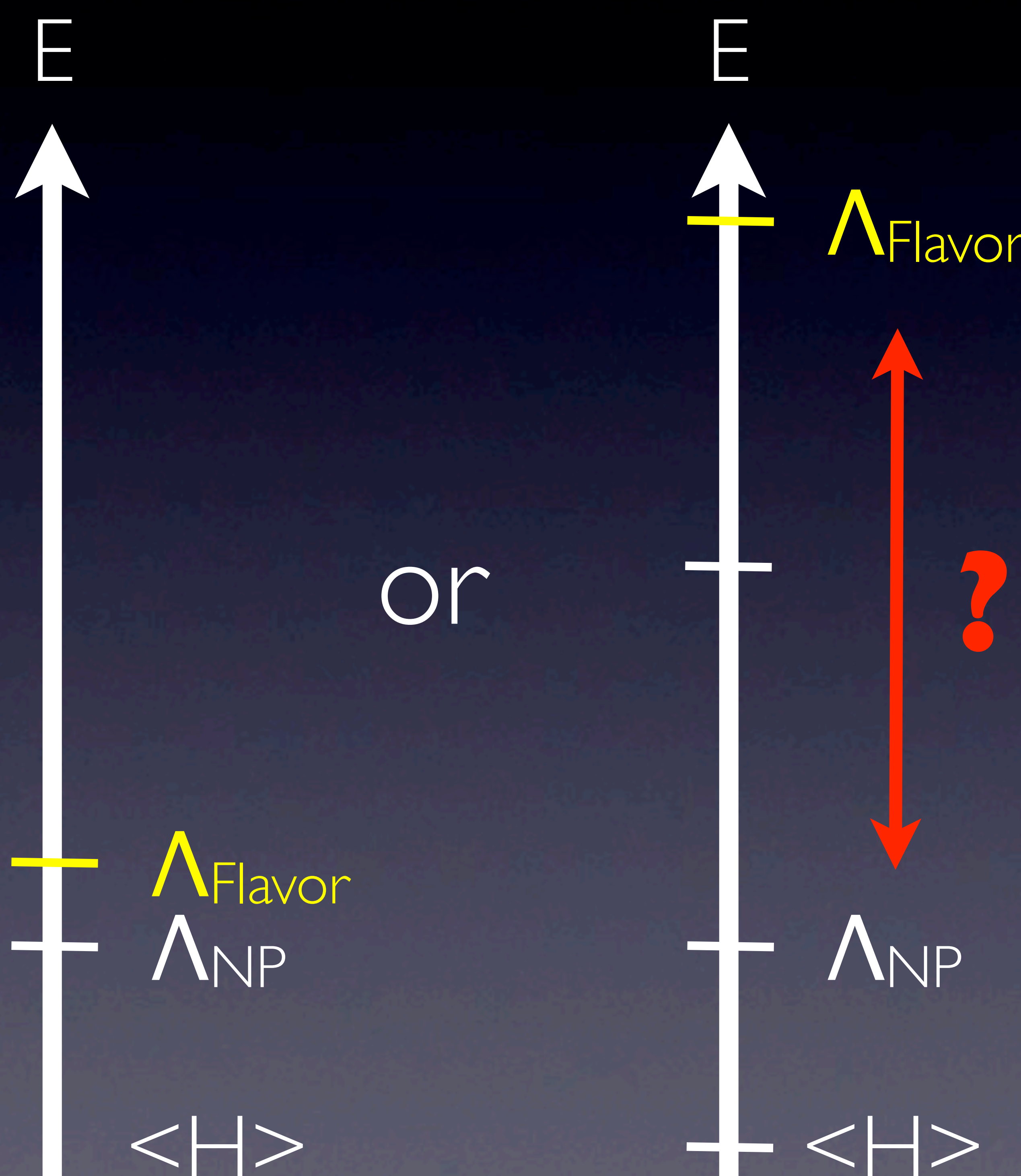
Flavorgenesis scale?



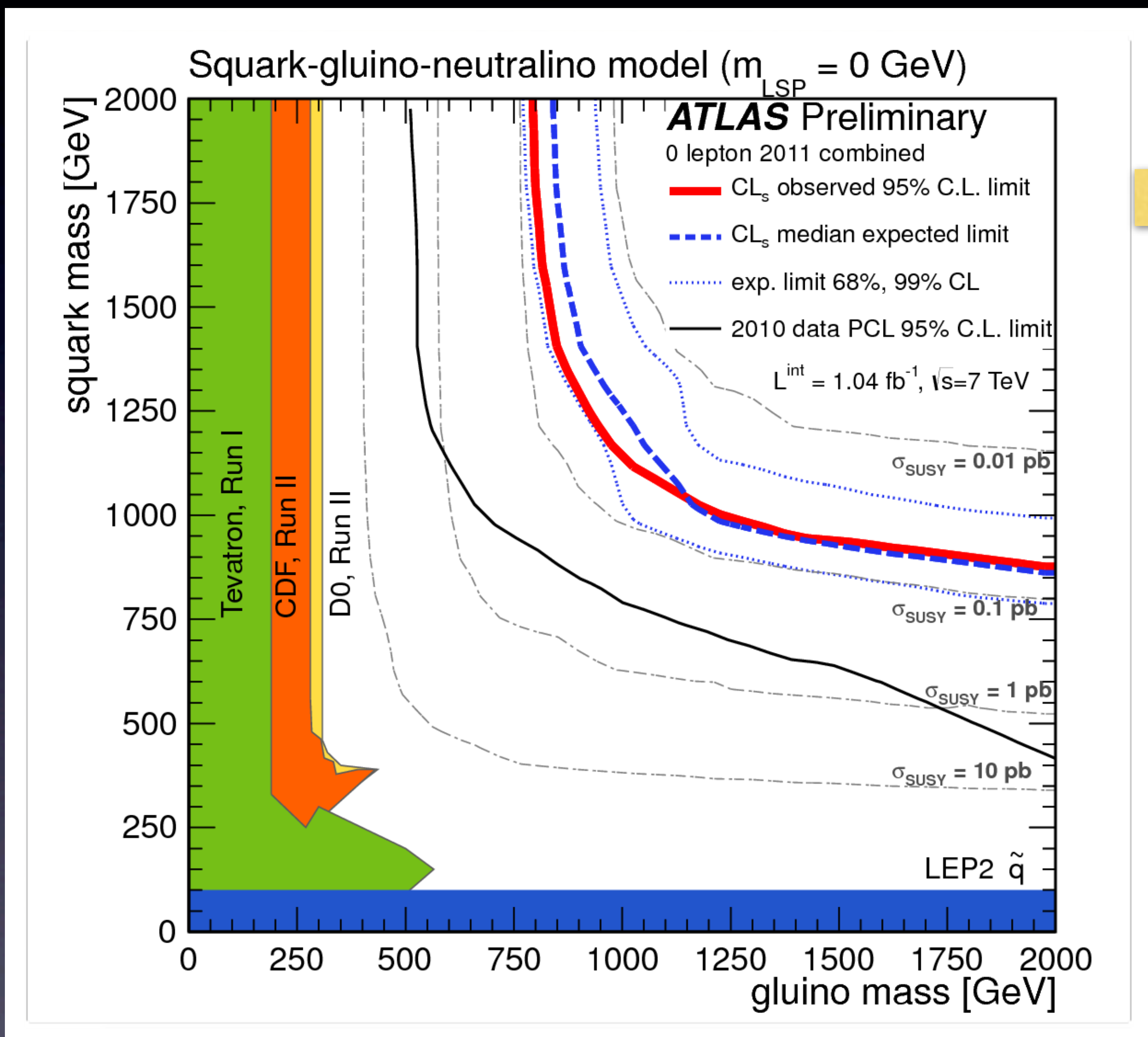
$$\frac{1}{\Lambda^2_{\rm Flavor}}(\bar\psi\psi)(\bar\psi\psi)$$

only trace left: MFV

$$\boxed{y_{ij}\,\bar\psi_i\mathcal{H}\psi_j}$$

naturalness

Remark on Supersymmetry



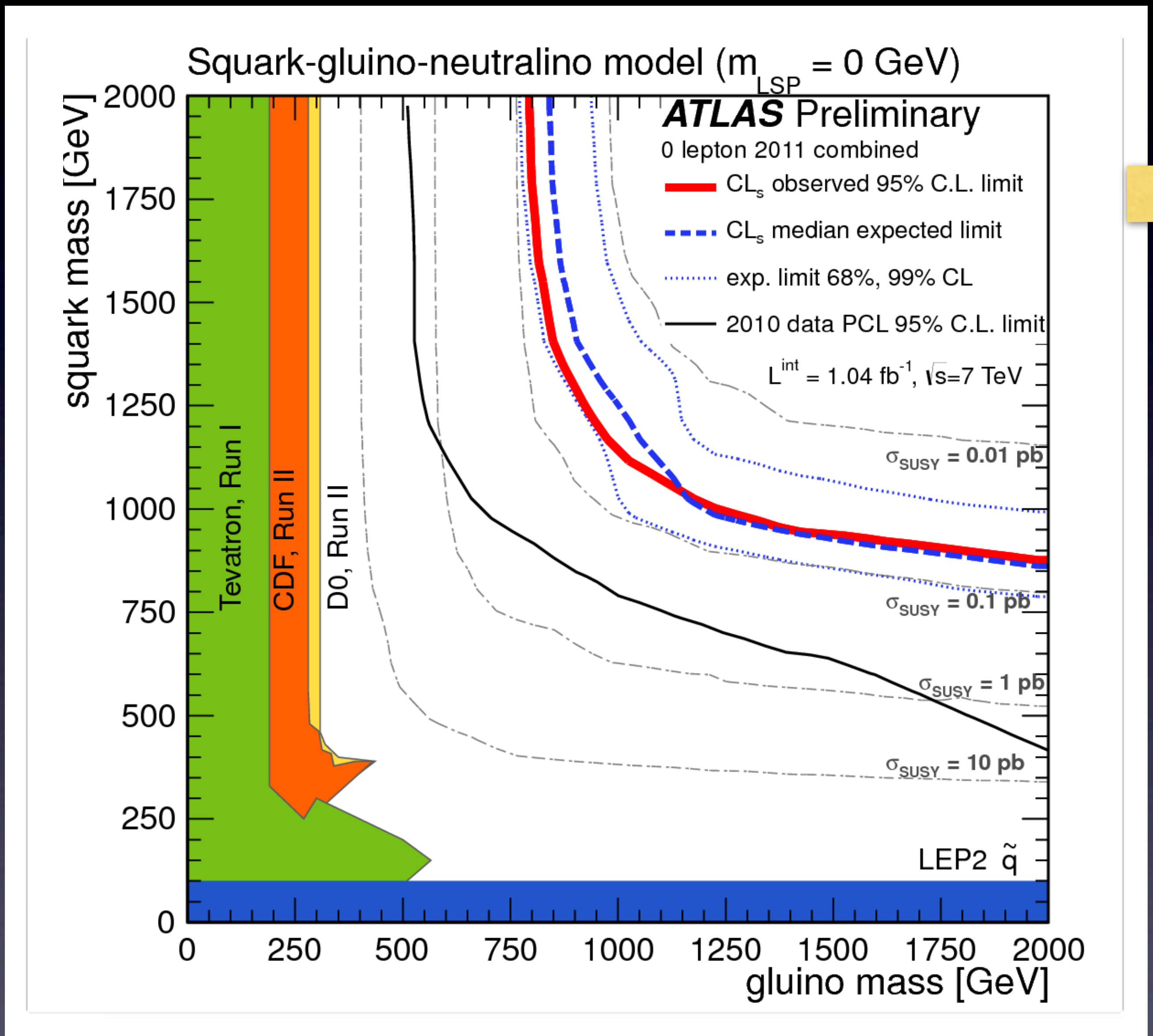
Taffard's talk

1st & 2nd gen. squark and gluino must be heavy

still want natural Susy: light stops

Papucci&AW, in progress

Remark on Supersymmetry



Taffard's talk

1st & 2nd gen. squark and gluino must be heavy

still want natural Susy: light stops

Squark spectrum split: not MFV & expect effects in 3rd gen. flavor!

$\tilde{q}_{1,2}$ $\tilde{g}$

$\tilde{t}$

Papucci&AW, in progress

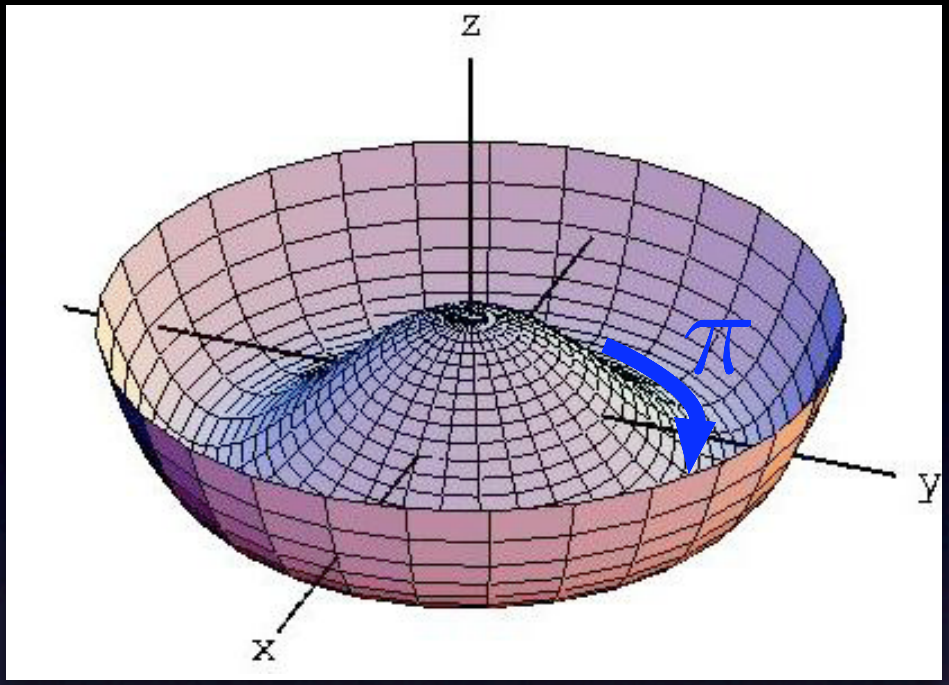
A particular class of models: partial compositeness (geometric alignment vs. MFV)

Weak scale is unstable

elementary scalar Higgs

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

Inspiration by QCD



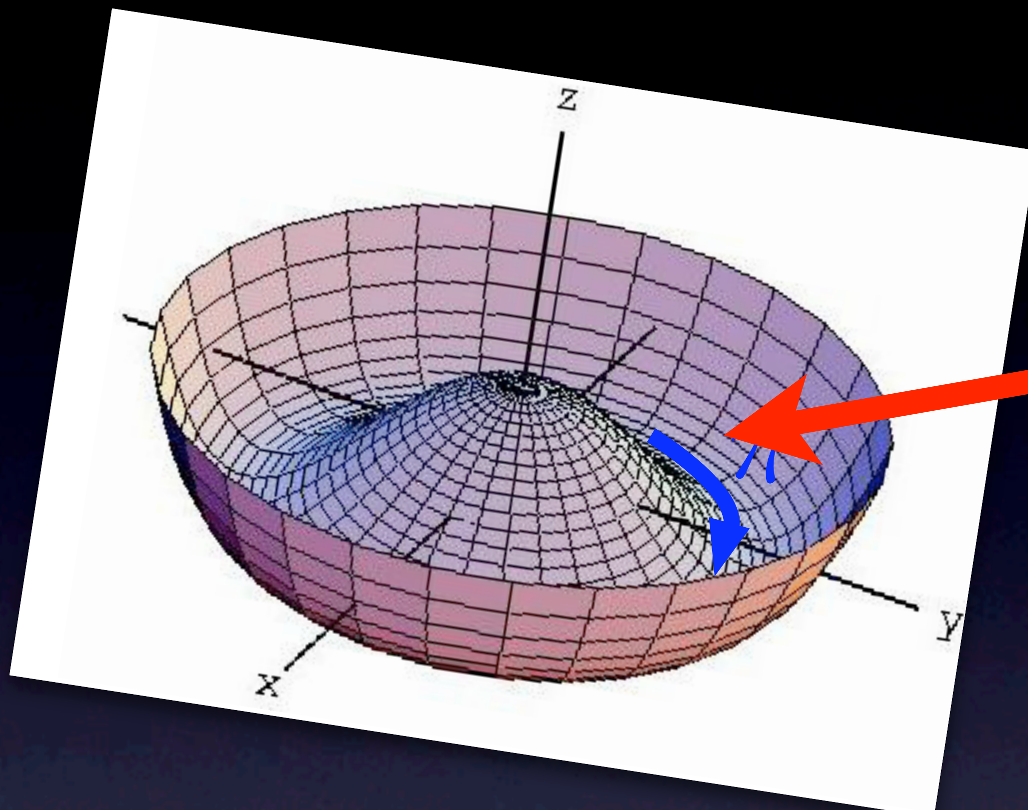
$\rho, \ldots$

π

mass protected by global symmetry

$$\pi \rightarrow \pi + \alpha$$

Inspired by QCD



Potential tilted:
due to quark masses
and gauging of EM

GB → pGB

$$m^2_{\pi^\pm} \approx \frac{\alpha_{em}}{4\pi}\Lambda^2_{QCD}$$

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

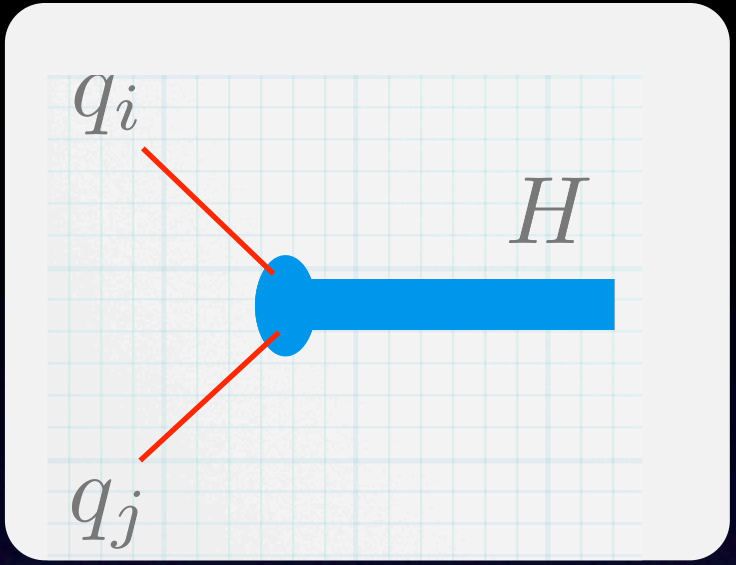
Λ must be very large because this leads to FCNCs

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

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

$\Lambda > 10^5\,\mathrm{TeV}$

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

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

$\propto$

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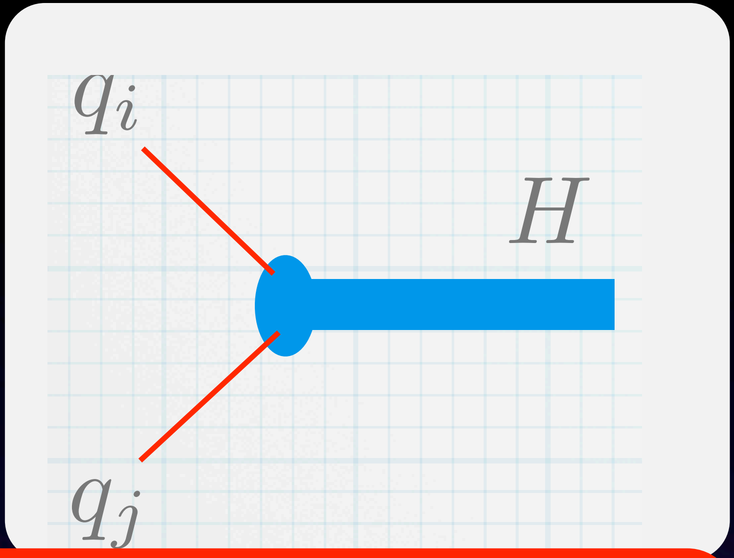

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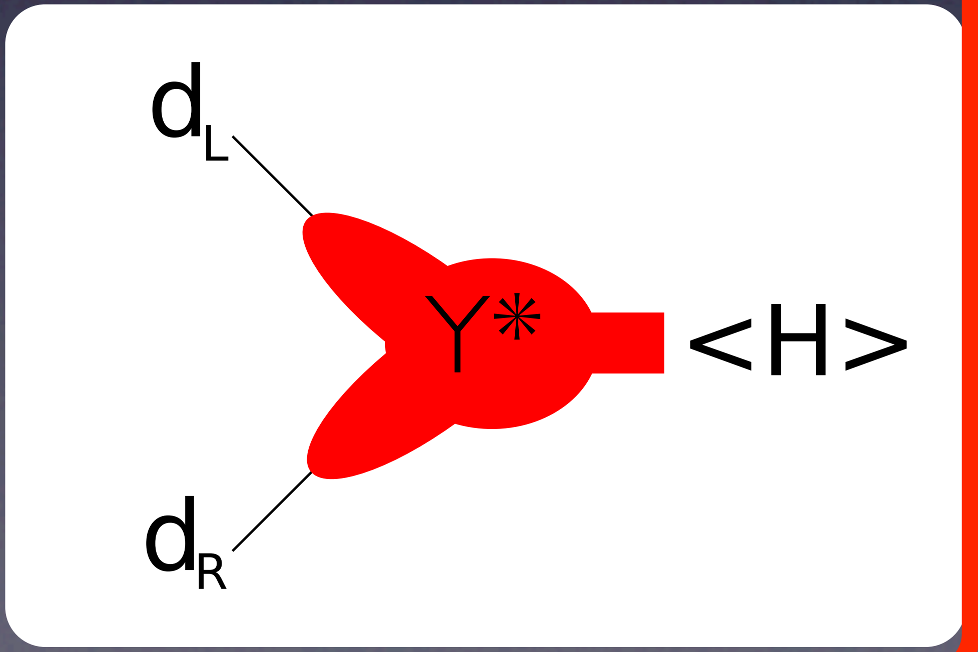
Quarks & Leptons mix with strong sector

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.

mixing $\propto$ mass

strong sector

elementary fields

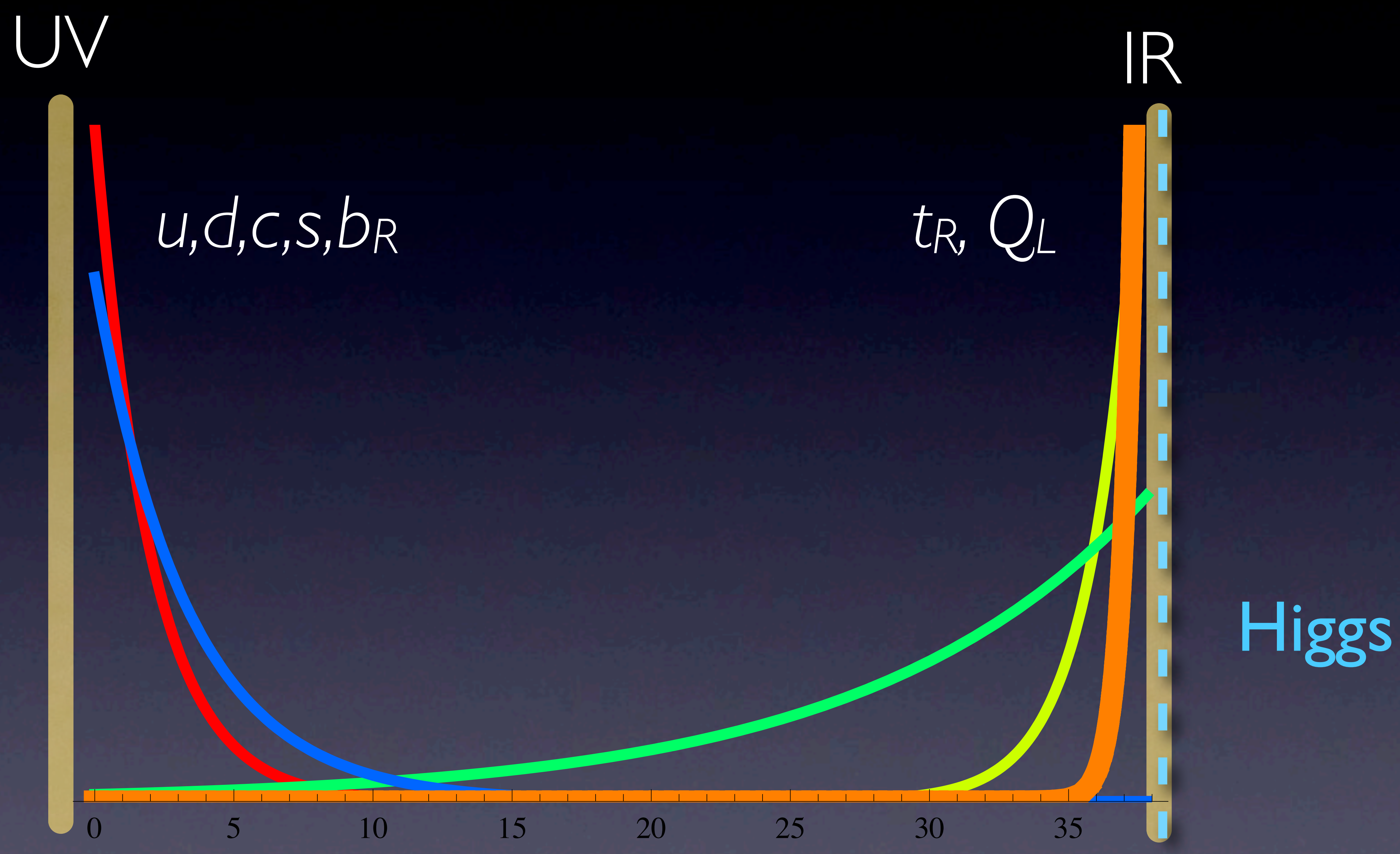
Higgs&EWSB
top
resonances
ρ_μ

u, d, c, s, b, A_μ

$g_*,\ m_\rho$

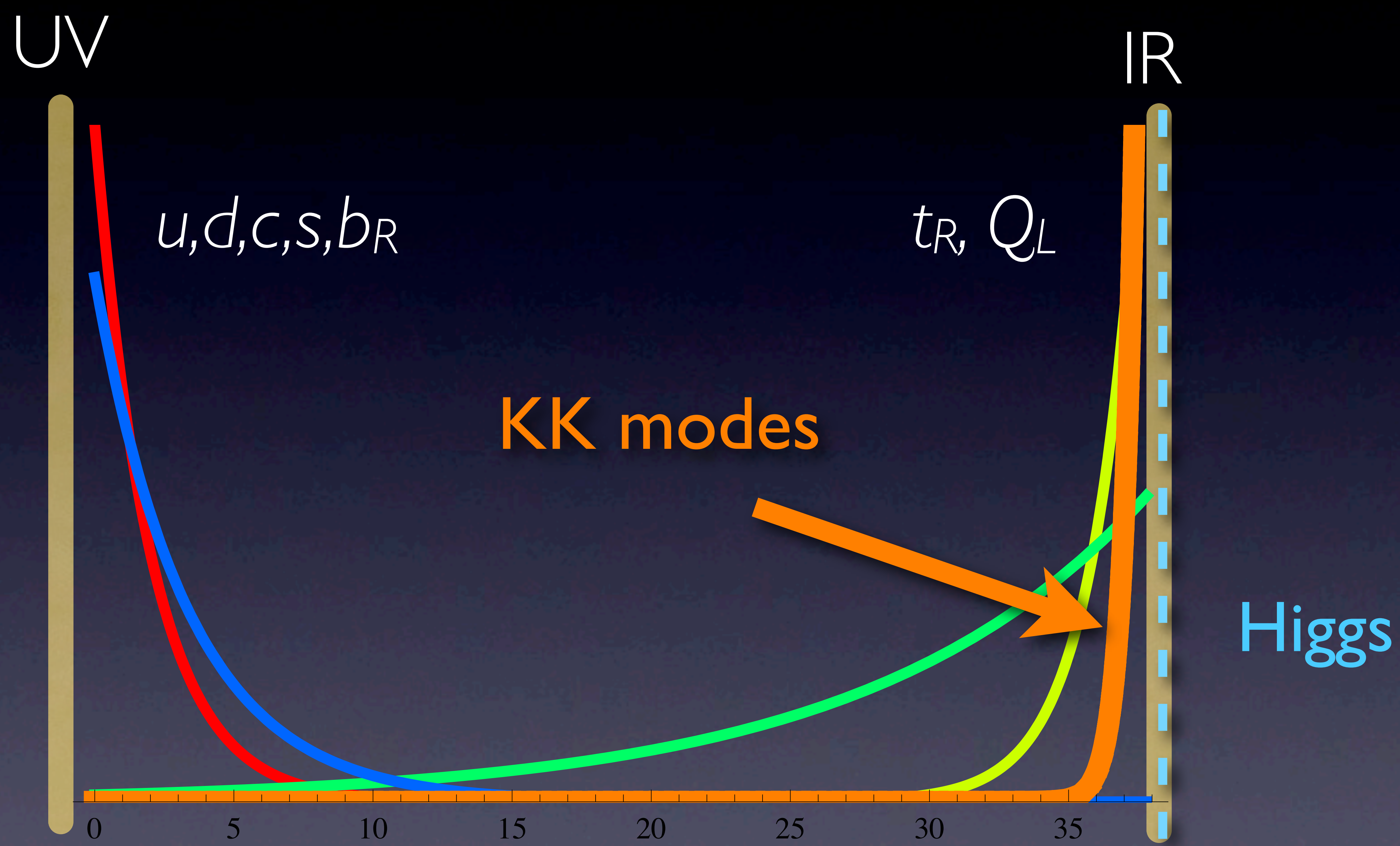
$1 \lesssim g_* \lesssim 4\pi$

Kaplan; Contino, Kramer, Son, Sundrum



RGE of the mixing UV → IR

Contino, Pomarol;
Contino, et al



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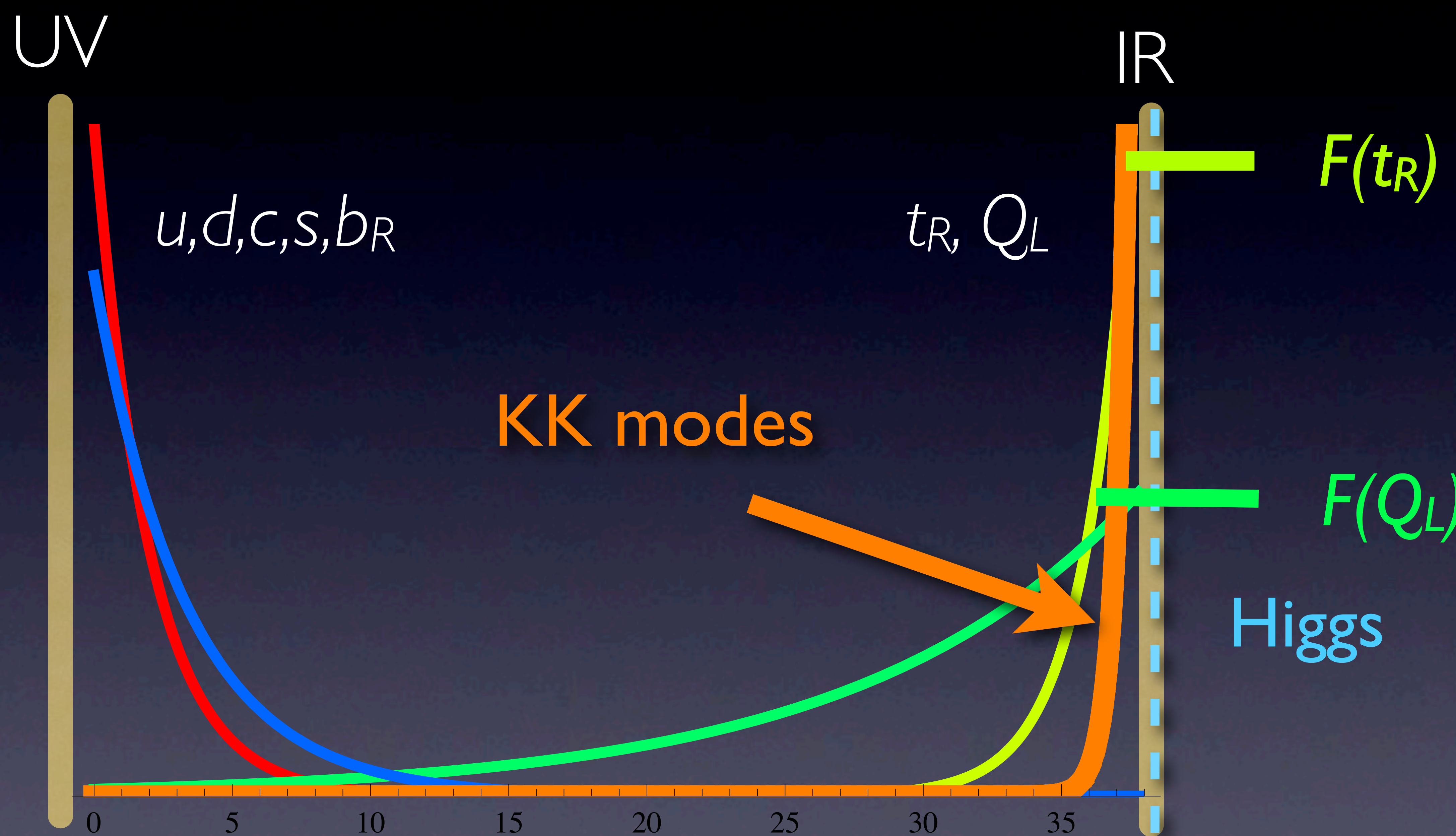
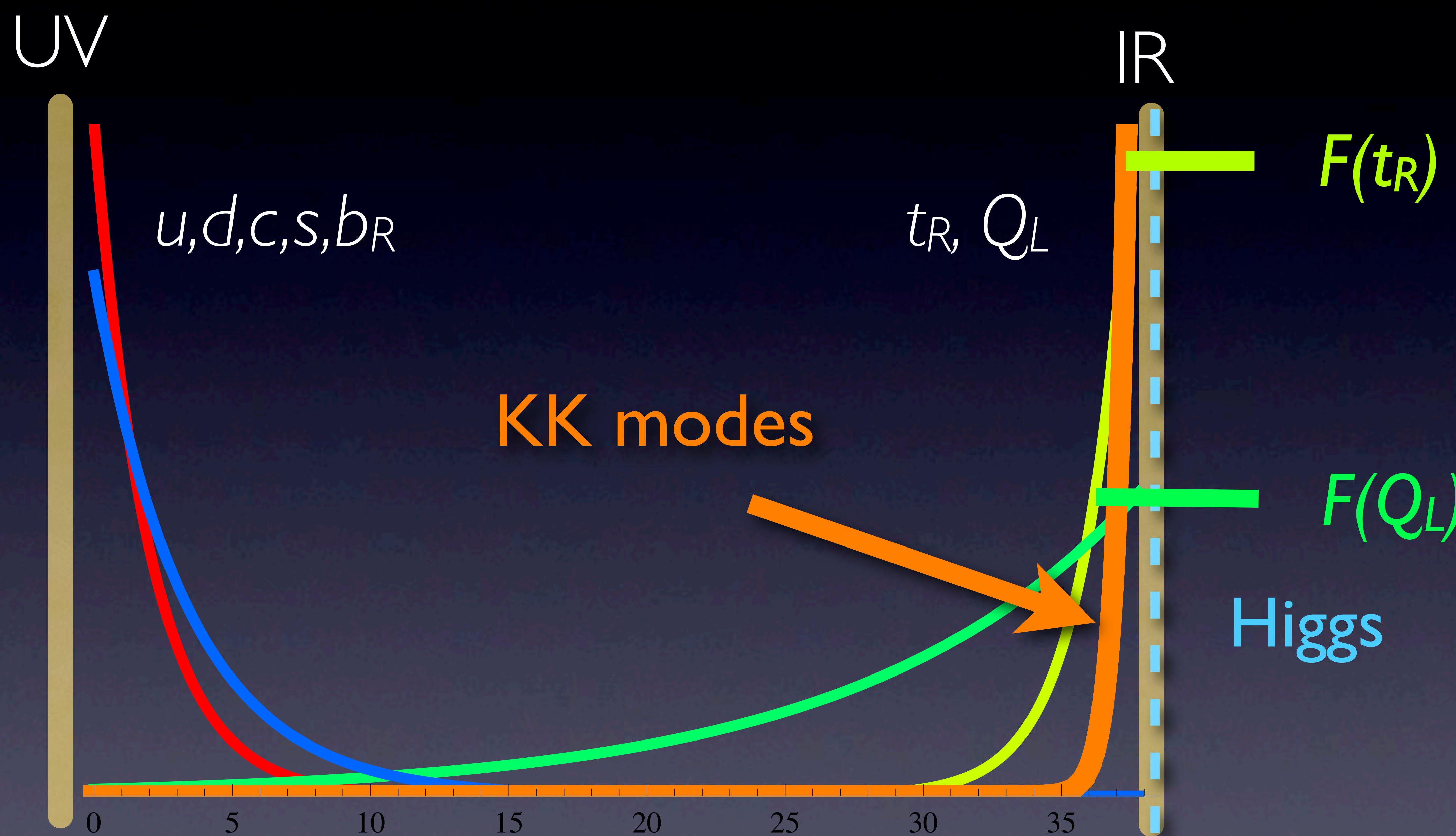


Contino, Pomarol;
Contino, et al

RGE of the mixing UV → IR

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



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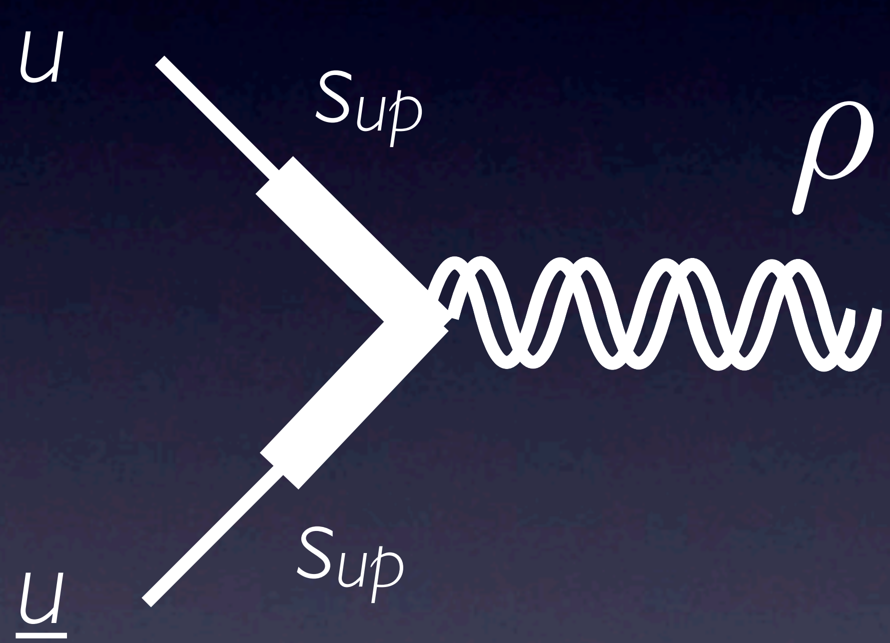
high p_T

Resonance production (option 1)



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

strongly suppressed for light quarks!

high p_T

Resonance production (option 2)

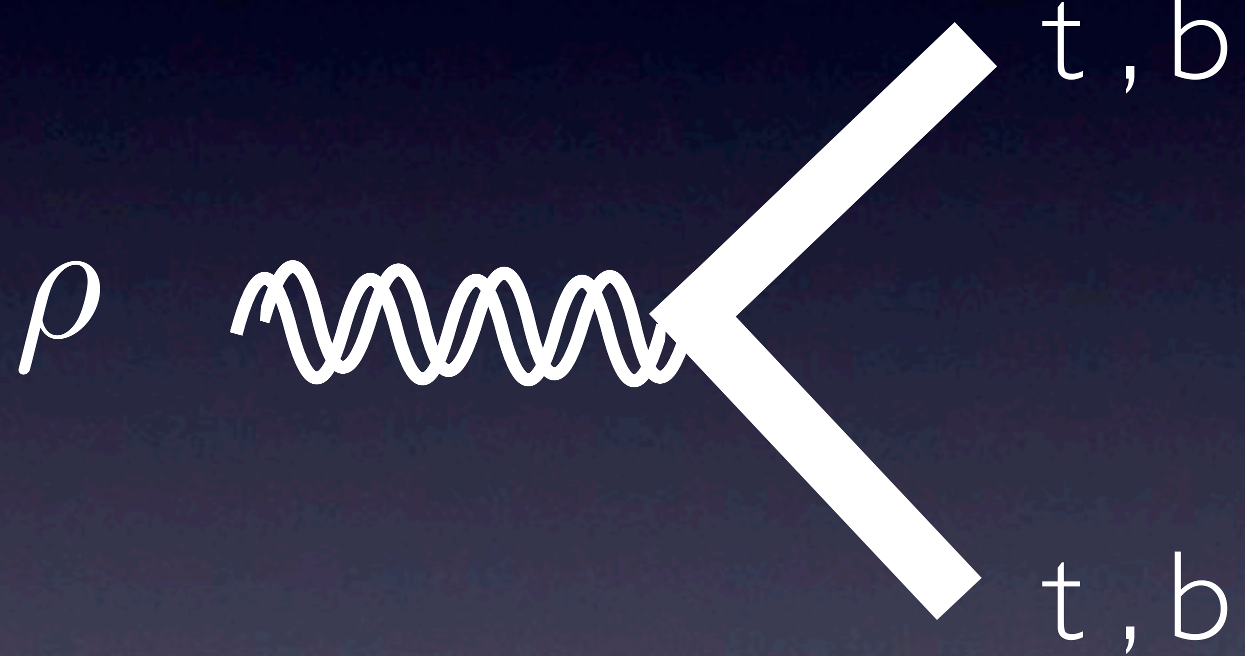
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

high p_T

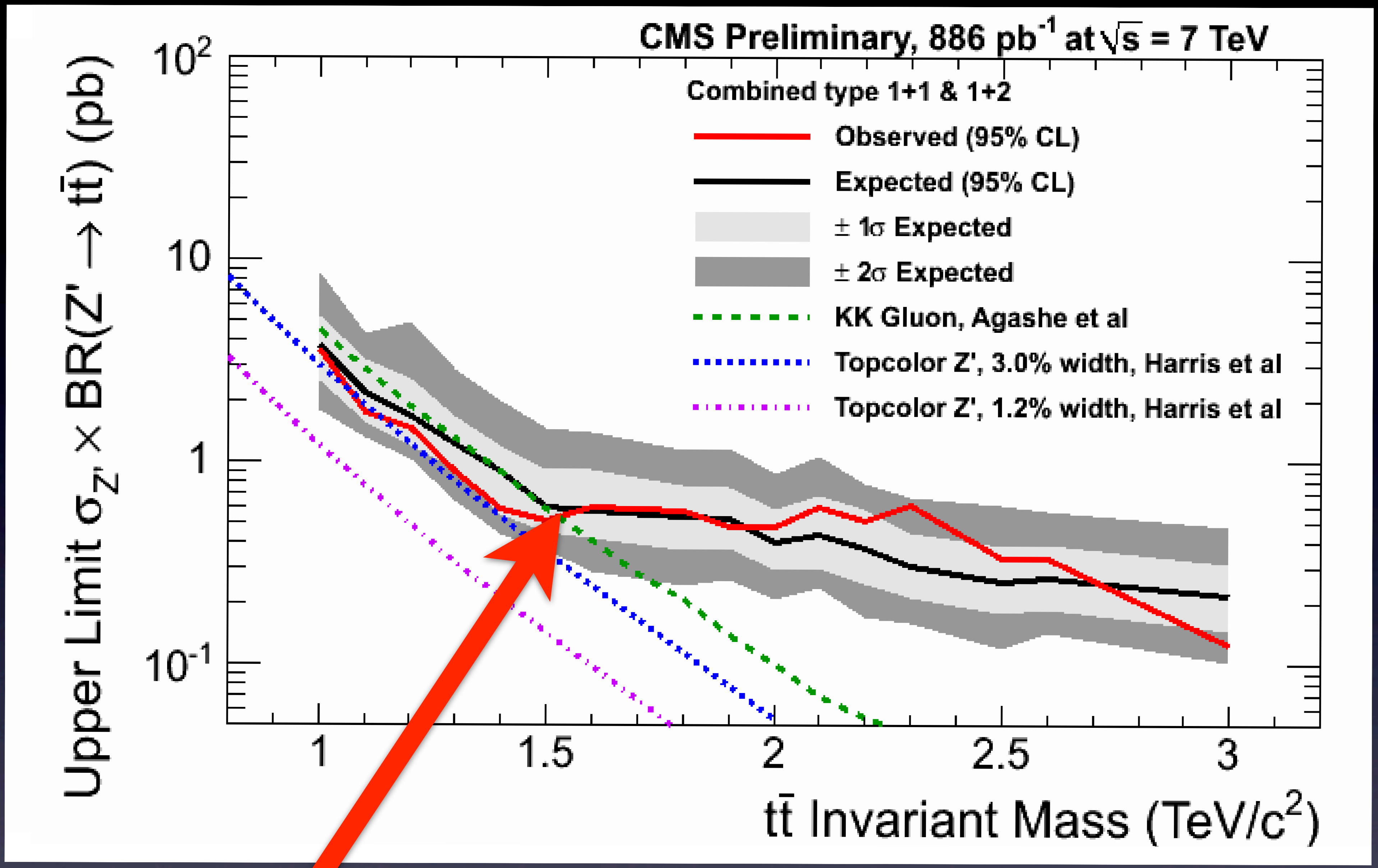
Resonance decay



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

Agashe et al, Lillie et al

Mulder's talk



M > 1.5 TeV @ 95CL

Remark on top properties

(beyond mass, charge & spin)

If 3rd generation composite or if e.g. stops light
=> top precision properties change <=

Leading effect at $1/\Lambda^2$: top Dipole moments

anomalous top couplings to

$$\left(c_{LR,c}\ g_s \bar{Q} H\, \sigma^{\mu\nu} T^a U + \mathrm{h.c.}\right) G^a_{\mu\nu}\,,$$

gluon

$$\left(c_{LR,w}\ g\, \bar{Q}\, \tau^a H \sigma^{\mu\nu} U + \mathrm{h.c.}\right) W^a_{\mu\nu}\,,$$

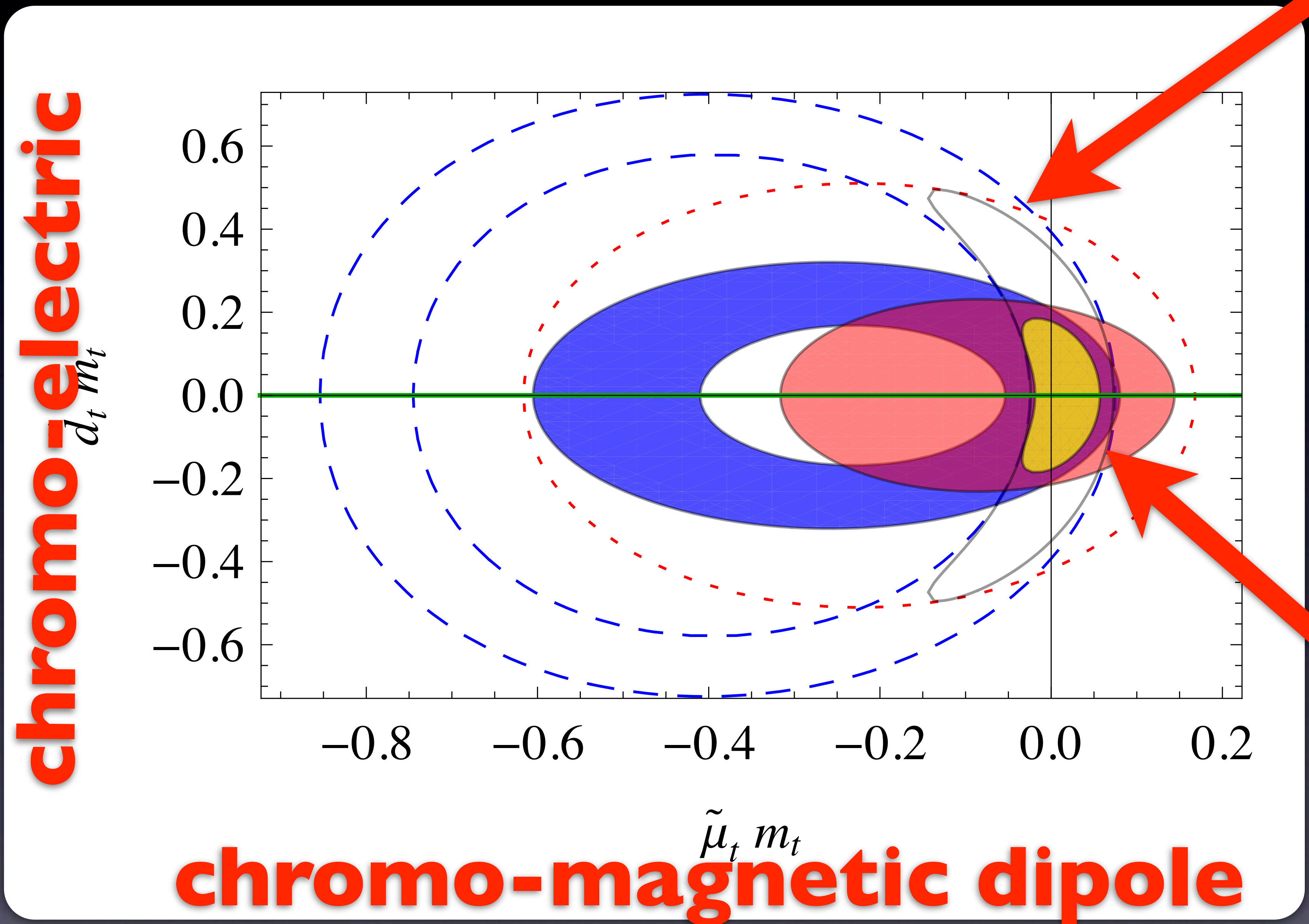
$$\left(c_{LR,y}\ g' \bar{Q} H\, \sigma^{\mu\nu} U + \mathrm{h.c.}\right) B_{\mu\nu}\,,$$

W, Z, photon

Kamenik, Papucci, AW

Direct constraint: $t\bar{t}$ - spectrum

dashed: Tevatron

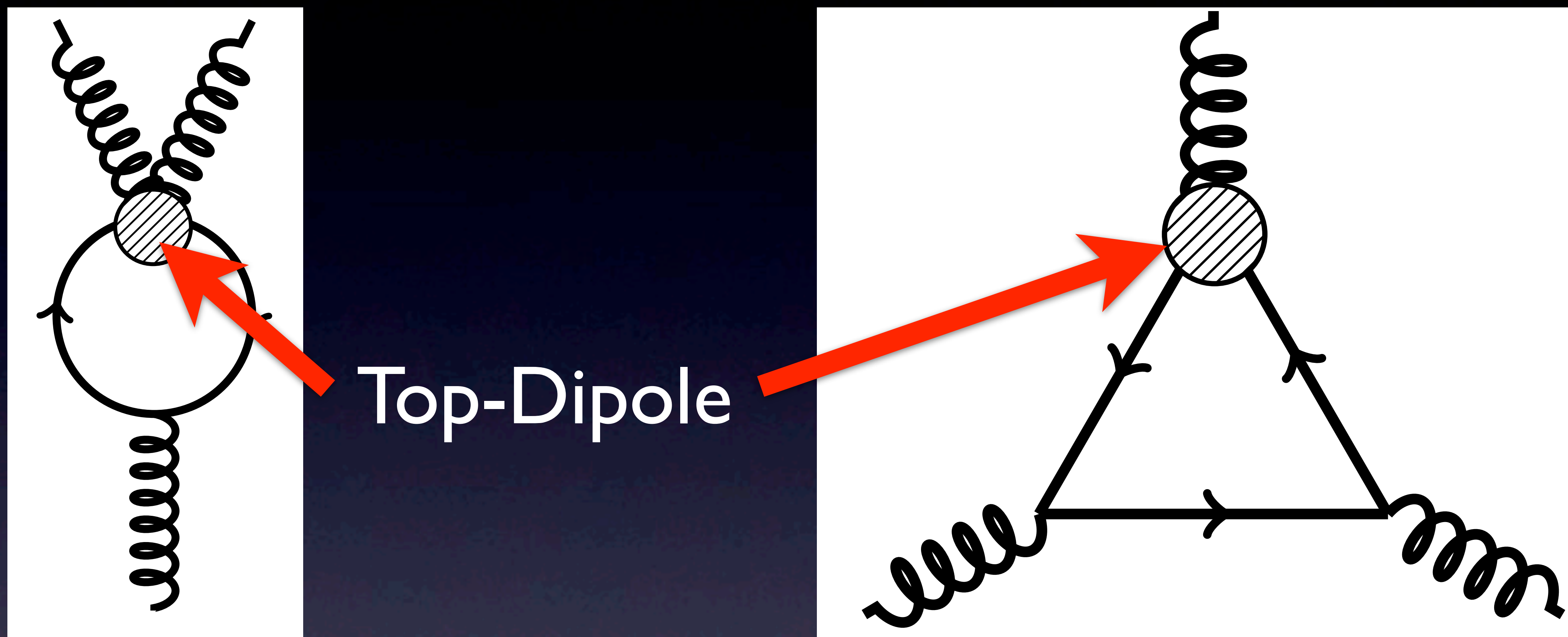


LHC7 *200 1/pb*

(ATLAS-CONF-2011-087)

Kamenik, Papucci, AW

The neutron also knows about the top



Kamenik, Papucci, AW

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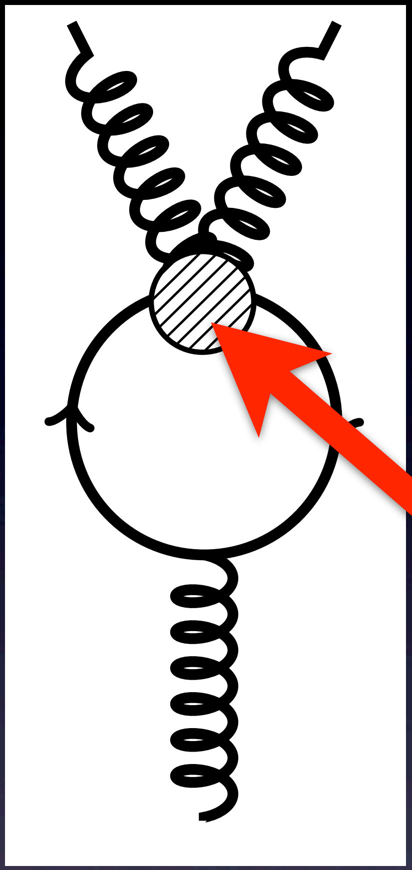

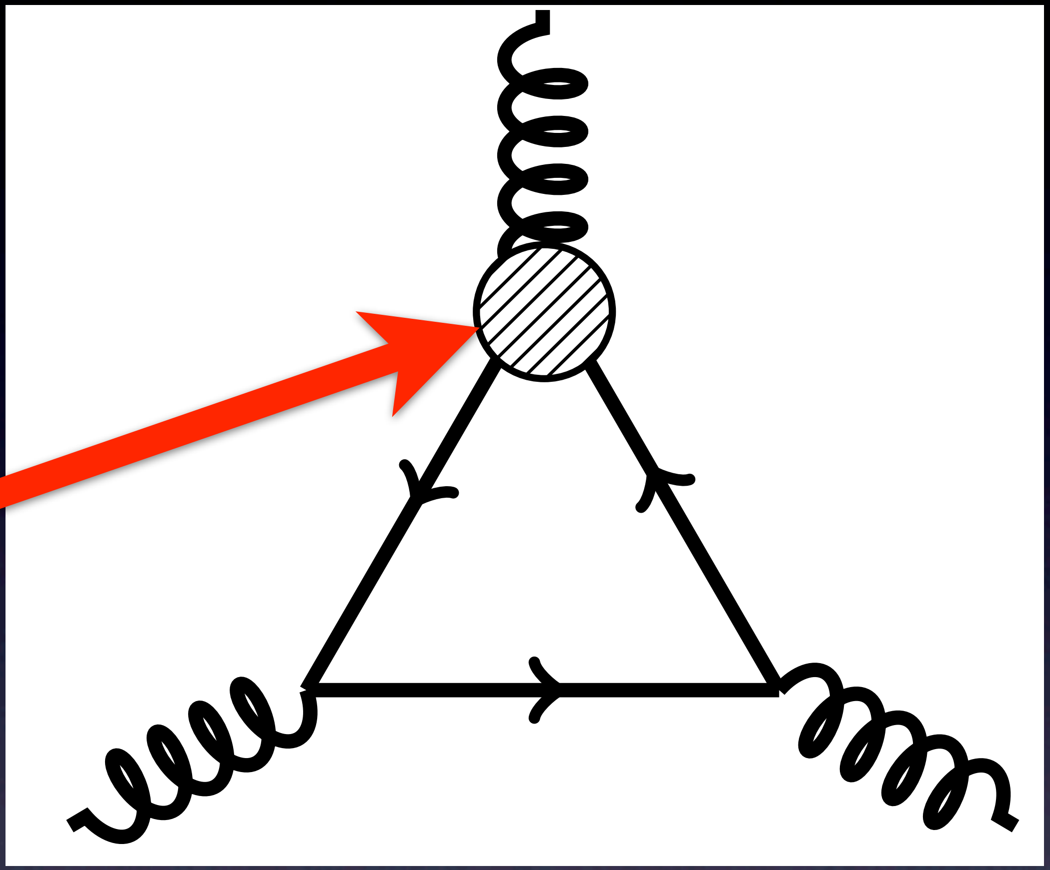

Top-Dipole

$$\mathrm{Re}\,\Lambda^{\mathrm{direct}}_{LR,c} > 1.1\ \mathrm{TeV}$$
$$\mathrm{Im}\,\Lambda^{\mathrm{direct}}_{LR,c} > 0.62\ \mathrm{TeV}$$
$$\mathrm{Im}\,\Lambda^{\mathrm{neutron}}_{LR,c} > 5.5\ \mathrm{TeV}$$

neutron EDM:
x100 stronger constraint than LHC (for CPV)

Kamenik, Papucci, AW

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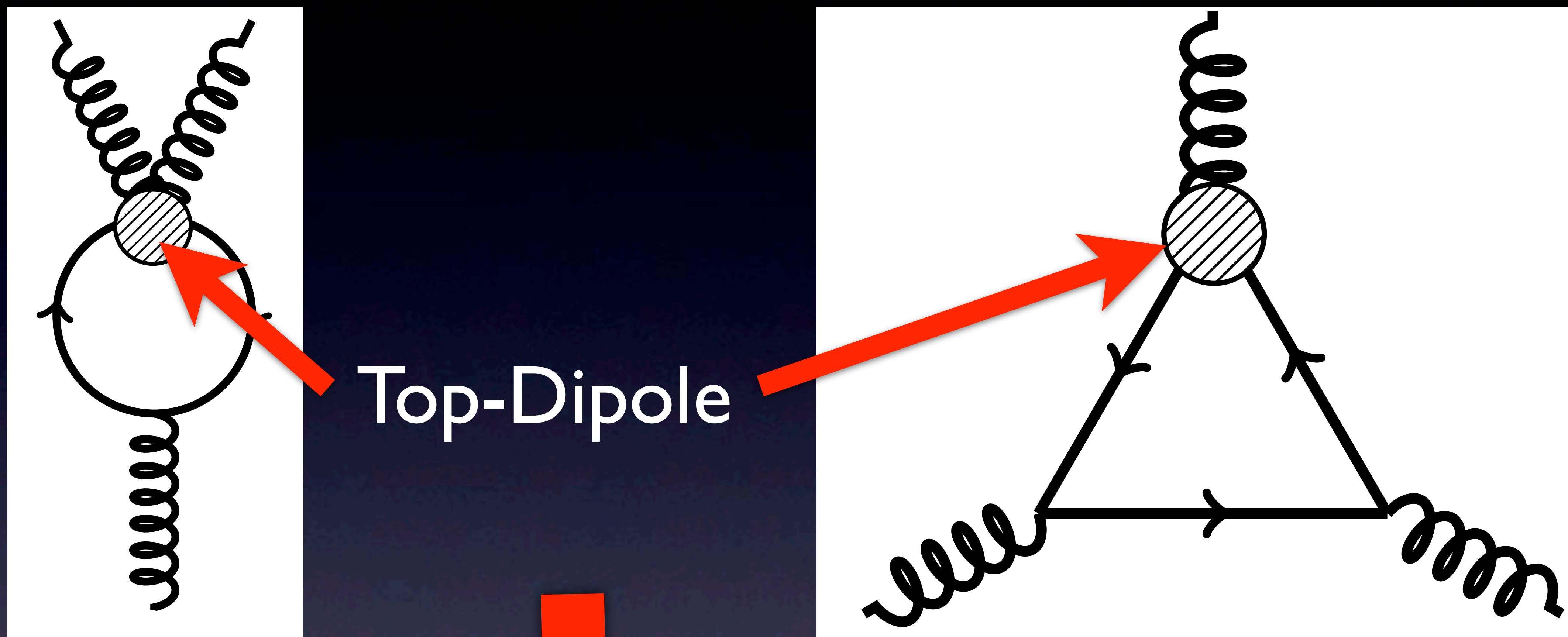

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Back to composite models

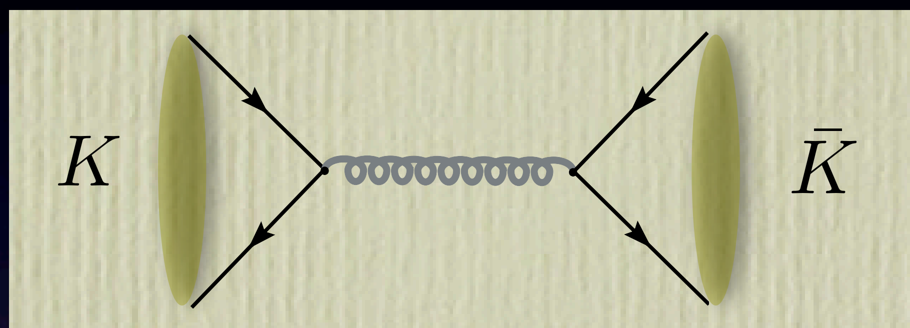
tension with CP observables

Little CP problem

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

$\Delta F = 2$ (strongest from ϵ_K)

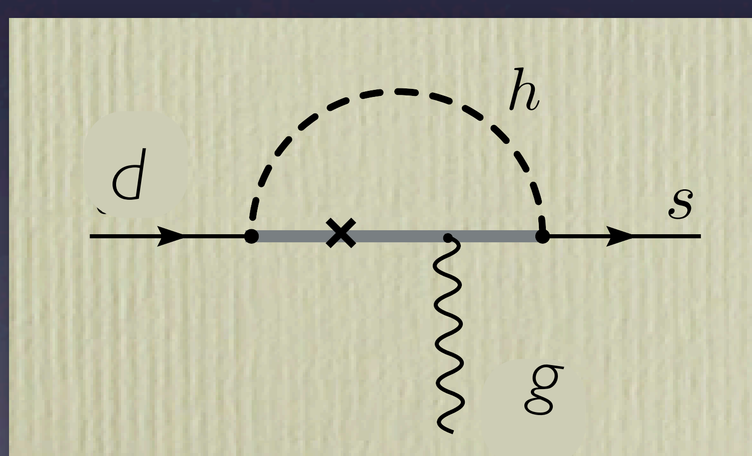
$$g_* \approx Y_* \approx 3 \ldots 6$$



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

$\Delta F = 1$ (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

strong sector has flavor invariant dynamics

Flavor triviality: dynamical MFV

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

mixing ~ SM Yukawas

Strong sector *SU(3)$_F$*

Flavor breaking external

Postulate flavor agnostic strong sector (like QCD)

Tension between large top mass & universal mixings and EWPT

Found a simple, easily discoverable model that avoids these problems

Michele Redi, AW

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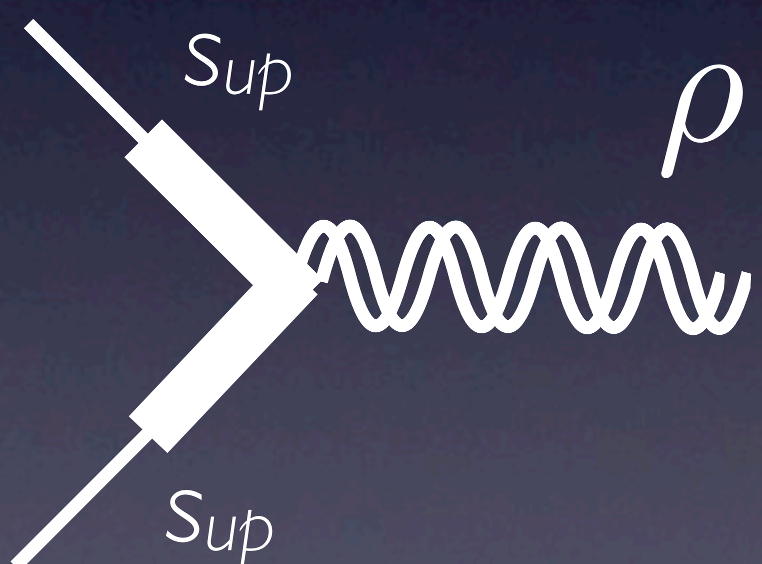
Strong sector $SU(3)_F$

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

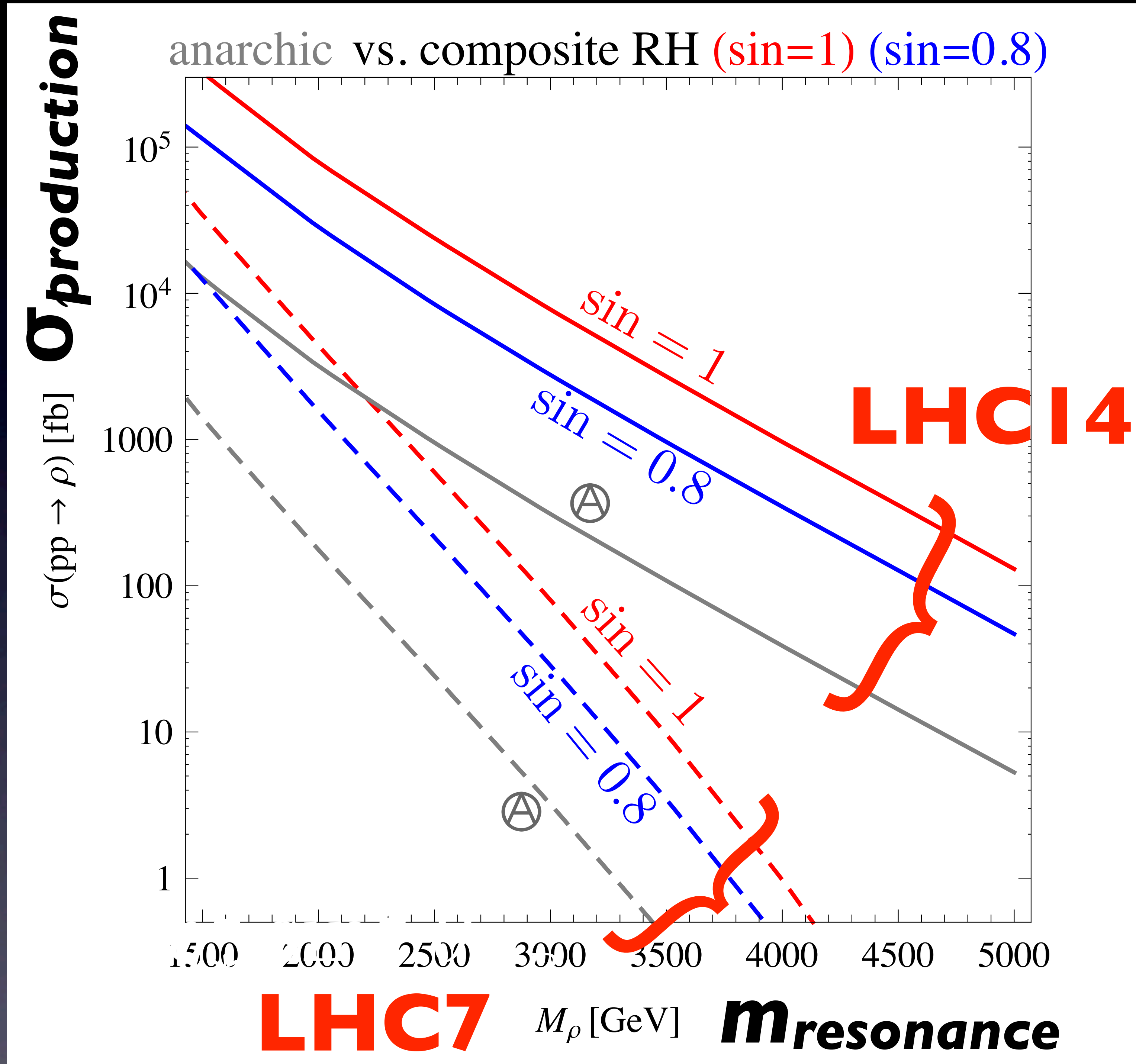
Production cross-section

Redi, AW

Due to top mass all RH-quarks have big composite admixture:



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



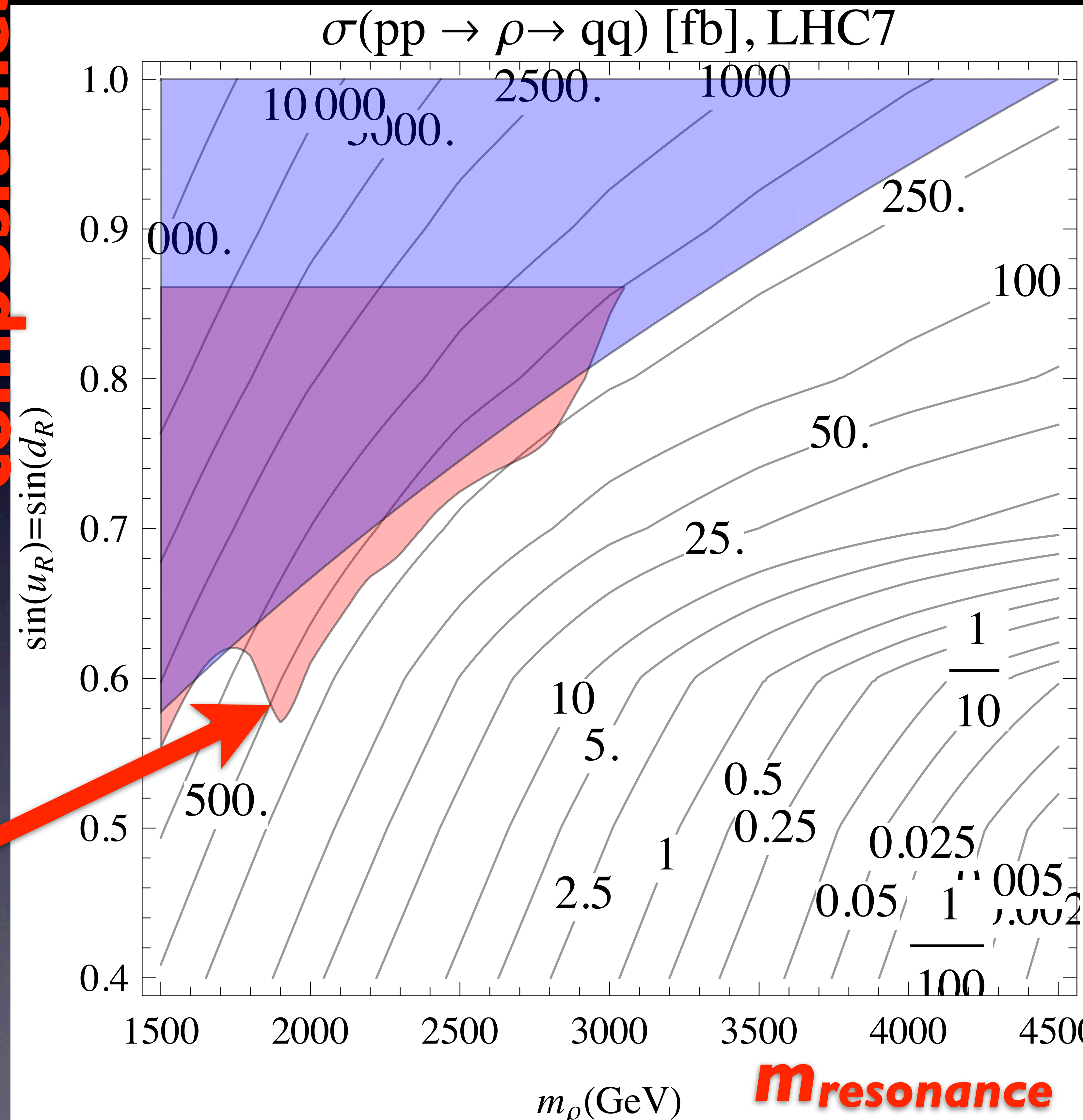
$10 - 50\times$ larger cross-section

LHC dijets (compositeness & bump search)

Redi, AW

x

compositeness

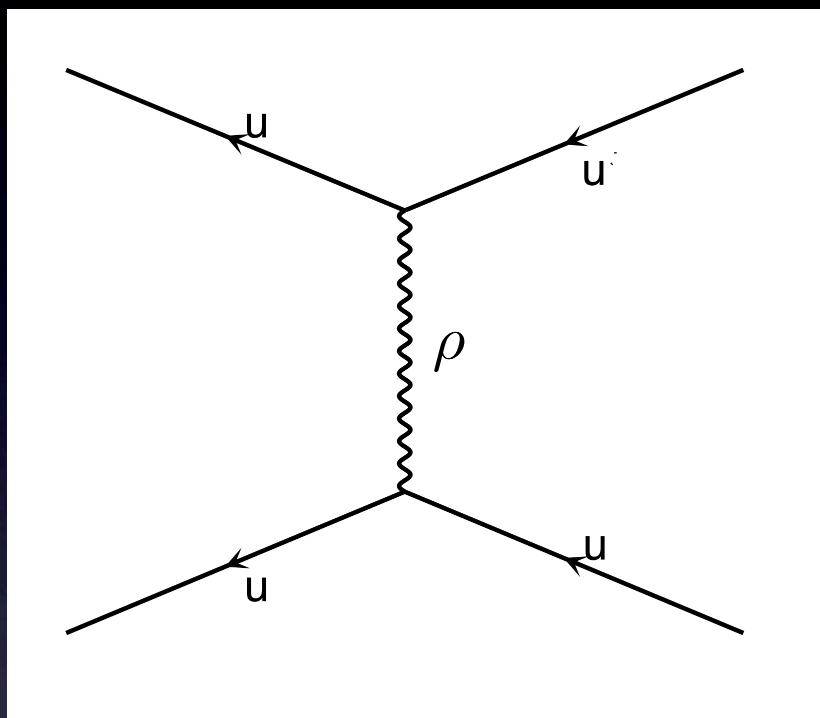


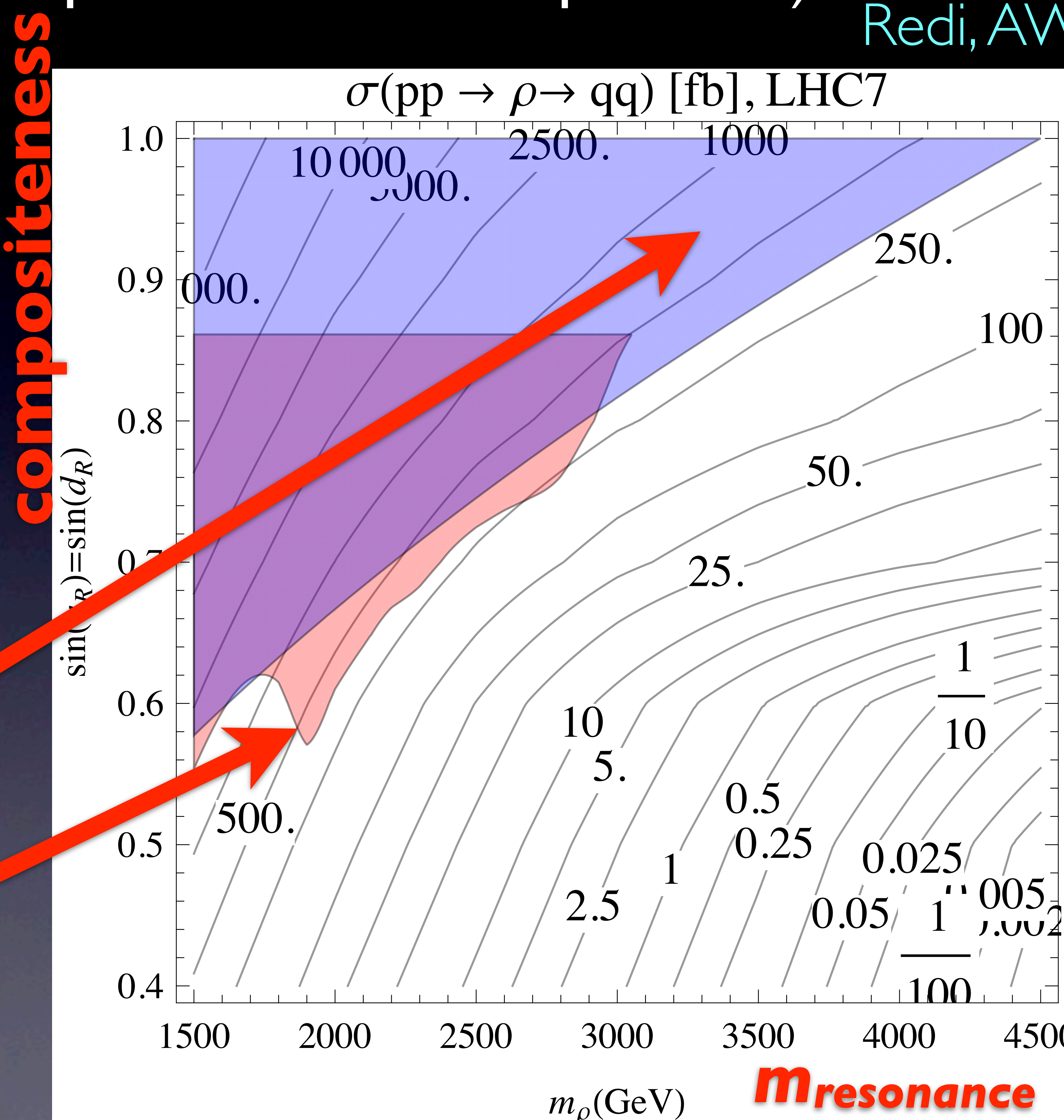
bump hunt

using *163 1/pb*:
ATLAS-CONF-2011-081

LHC dijets (compositeness & bump search)

Redi, AW





compositeness

bump hunt

using *163 1/pb*:
ATLAS-CONF-2011-081

Conclusions & Outlook

High p_T offers window into flavor

Flavor&CP know about TeV physics
(3rd gen special: measure $S_{\psi\phi}$ at LHCb!)

Natural susy should have non-MFV squarks
(find the light stop! see previous point)

Composite/Strongly coupled models are very visible if flavor invariant
(discover it at LHC14!)