Concluding remark

COMMENTS ON HIGGS, FLAVOR
PHYSICS, AND
DISCRETE SYMMETRY

Jihn E. Kim

Kyung Hee University &
Seoul National University

Summer Institute 2013
(Gurye, 22. 08. 2013)

1. Nakada on flavor

Baek, Cheng, Faisal, Kaneta, Kohda, Shimizu, Enomoto, Tatsuda

2. Low on Higgs boson

Taniguchi, Shindou, Yagyu, Yu, Ka

$$+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \frac{c_{ijkl}}{\Lambda^2_{UV}} \bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu}$$

Chang, Ohki, Hosotani, Moreau, I

3. Chun on neutrinos

Choi on dark matter

$$m_{DM} \approx \frac{5.7\ \text{GeV}}{Q_{DM}}, \text{ADM}$$

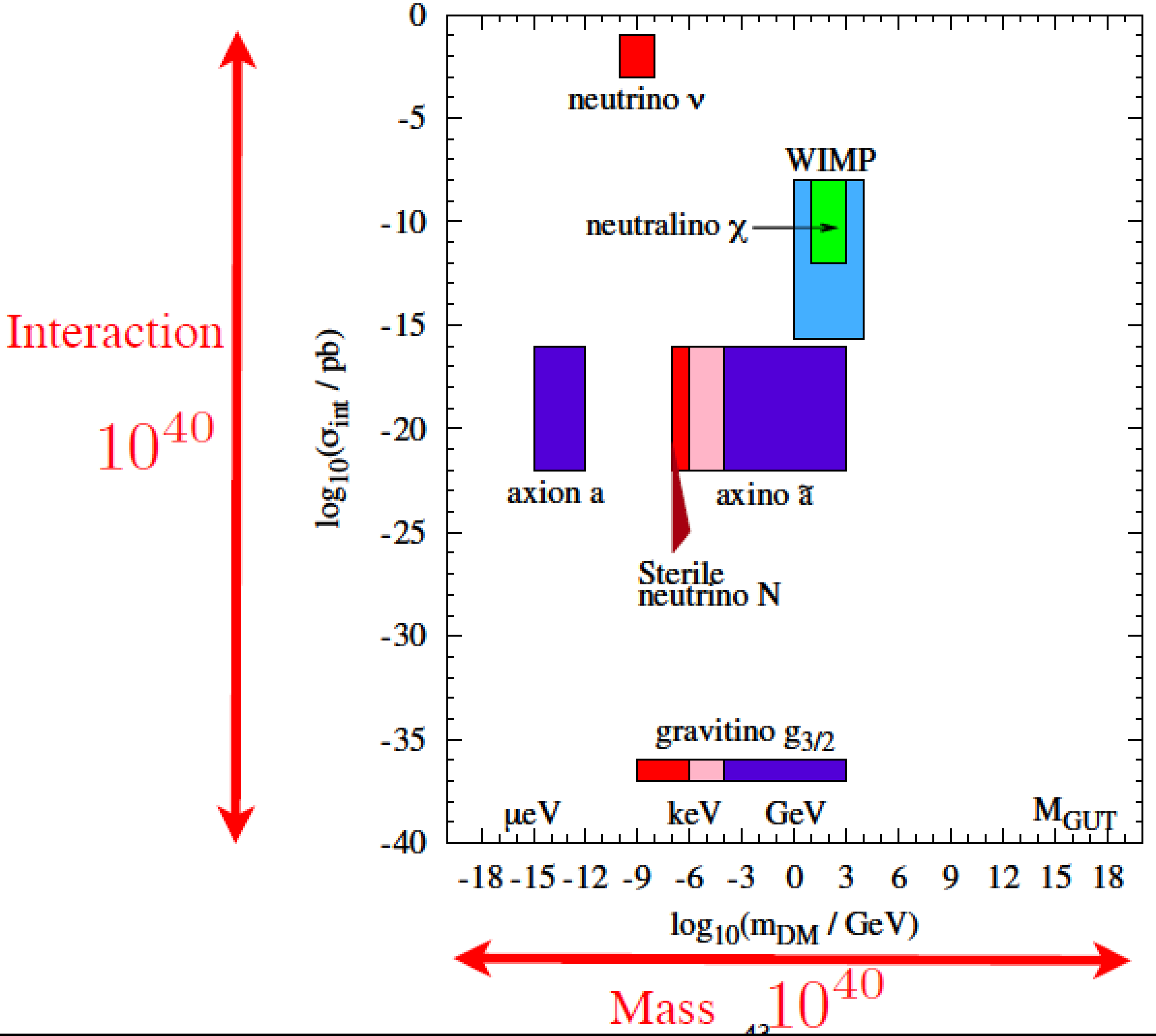
Yang, Chen on LHC ex

Eijima, Ishida, Araki, Matsumoto, Nomura, Toma, Wong, Machida, Matsui , Follin, Imai, Kashiwase, Ohta, Takano, Takeda, Terada, Nihei, Park

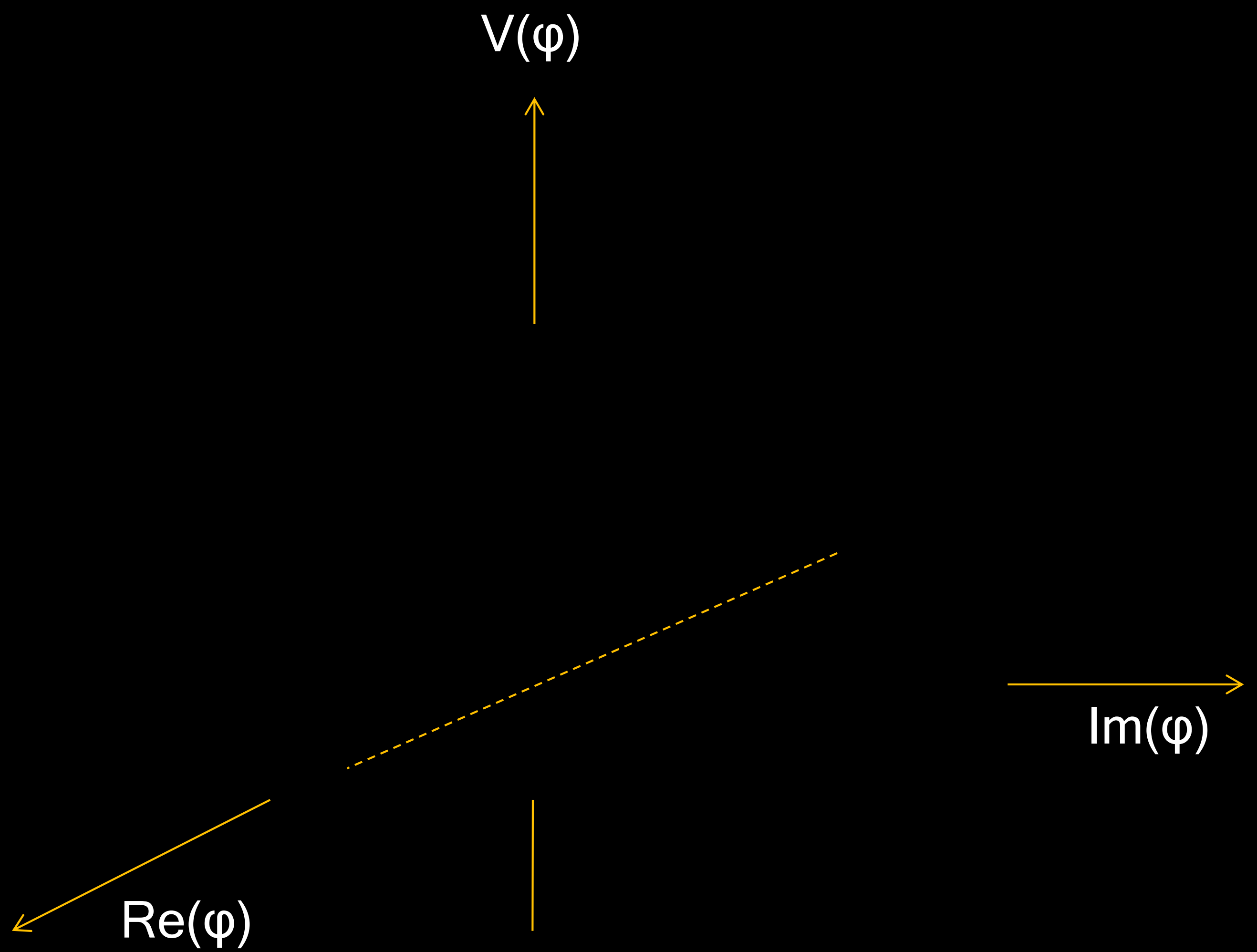
4. Rattazzi on EFT and CFT

Yokozaki on gaugino med

- Candidates of dark matter beyond Standard Model



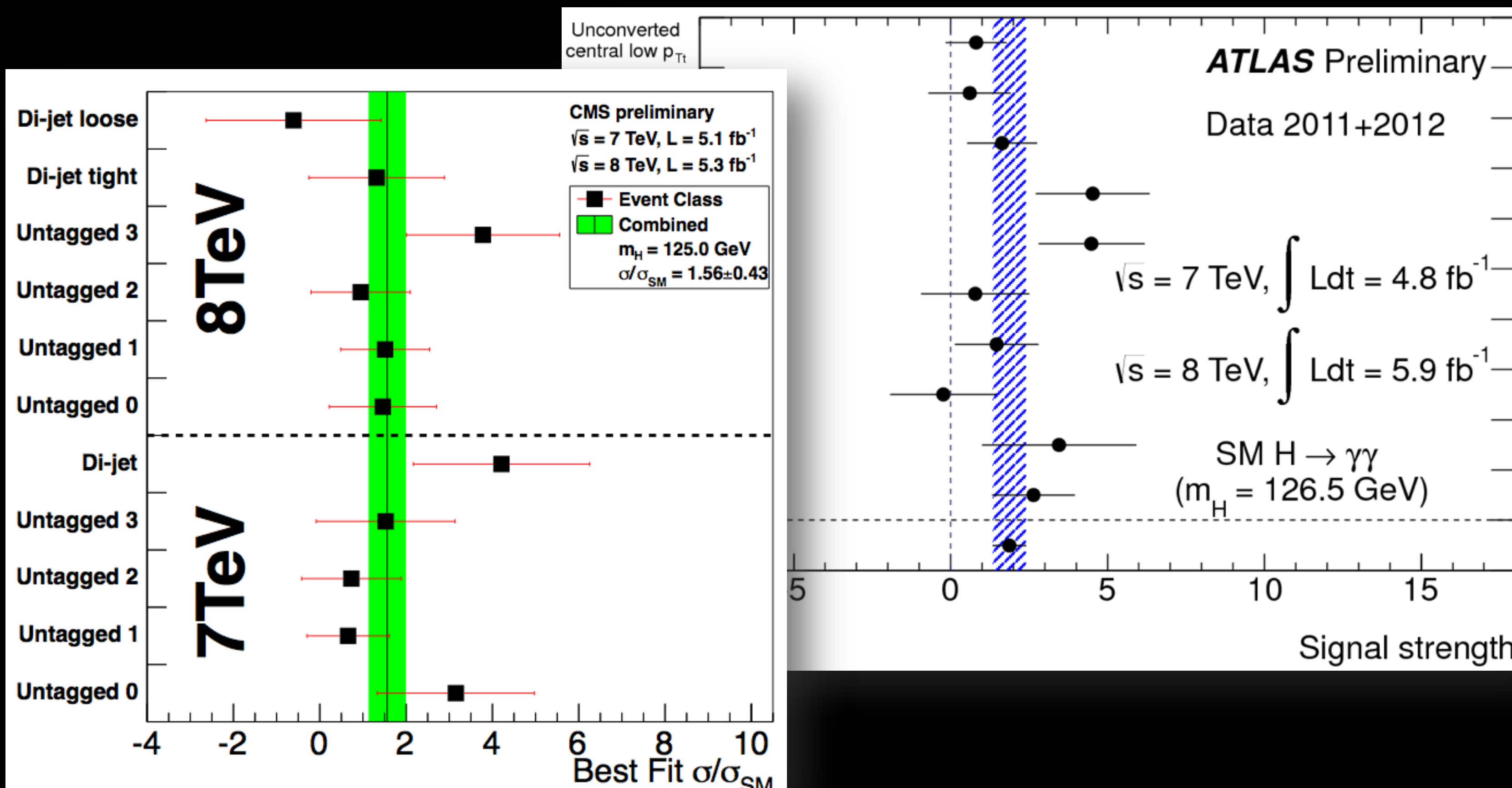
K.-Y. Choi

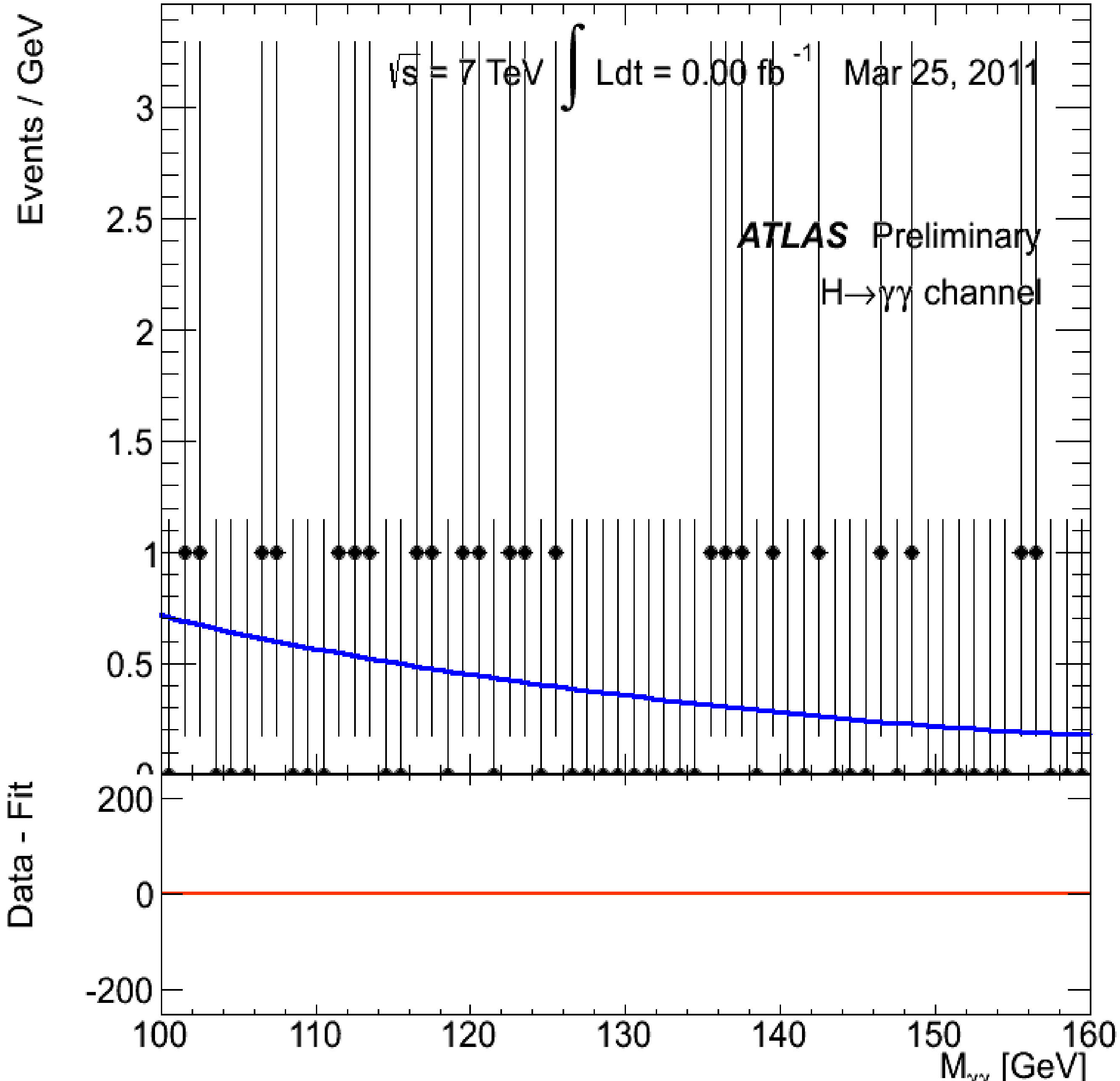

V(φ)
Im(φ)
Re(φ)

A case in point is the Higgs-to-diphoton signal strength.

On July 4th 2012 both ATLAS and CMS reported significantly enhanced signal strength in the diphoton channel:

Ian Low





ATLAS accumulation of data: Butterworth, presented at Planck 2013 May 20

The annoying thing about the mass:

Ian Low

We can't predict it!

There are two free parameters in the Higgs potential:

$$V = \frac{\lambda}{2}\left(H^+H - \frac{v^2}{2}\right)^2 \qquad \langle H\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

The Higgs mass is controlled by the quartic coupling:

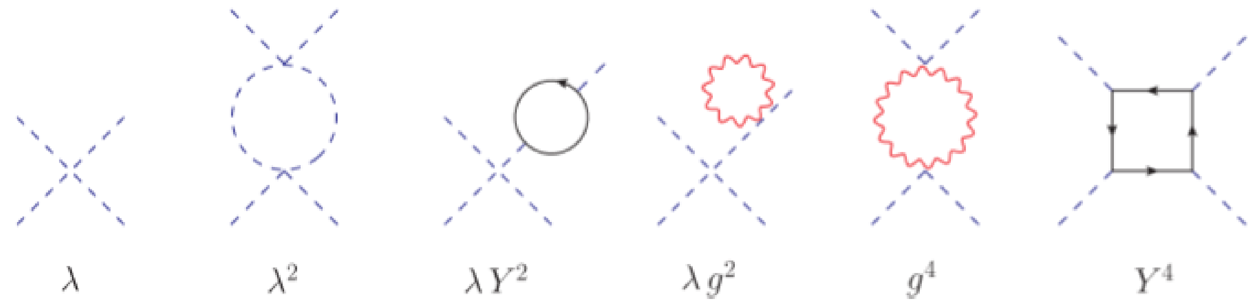
$$m_h^2 = \lambda v^2 \ , \qquad v \approx 246 \quad \mathrm{GeV}$$

$$\lambda \cong \frac{1}{4}$$

Ian Low

The renormalization group evolution of the quartic coupling can be studied in the SM and is known to two-loop.

λ runs



$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left[+24\lambda^2 + \lambda\left(4N_cY_t - 9g^2 - 3g'^2\right) - 2N_cY_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2g'^2 + \dots\right]$$

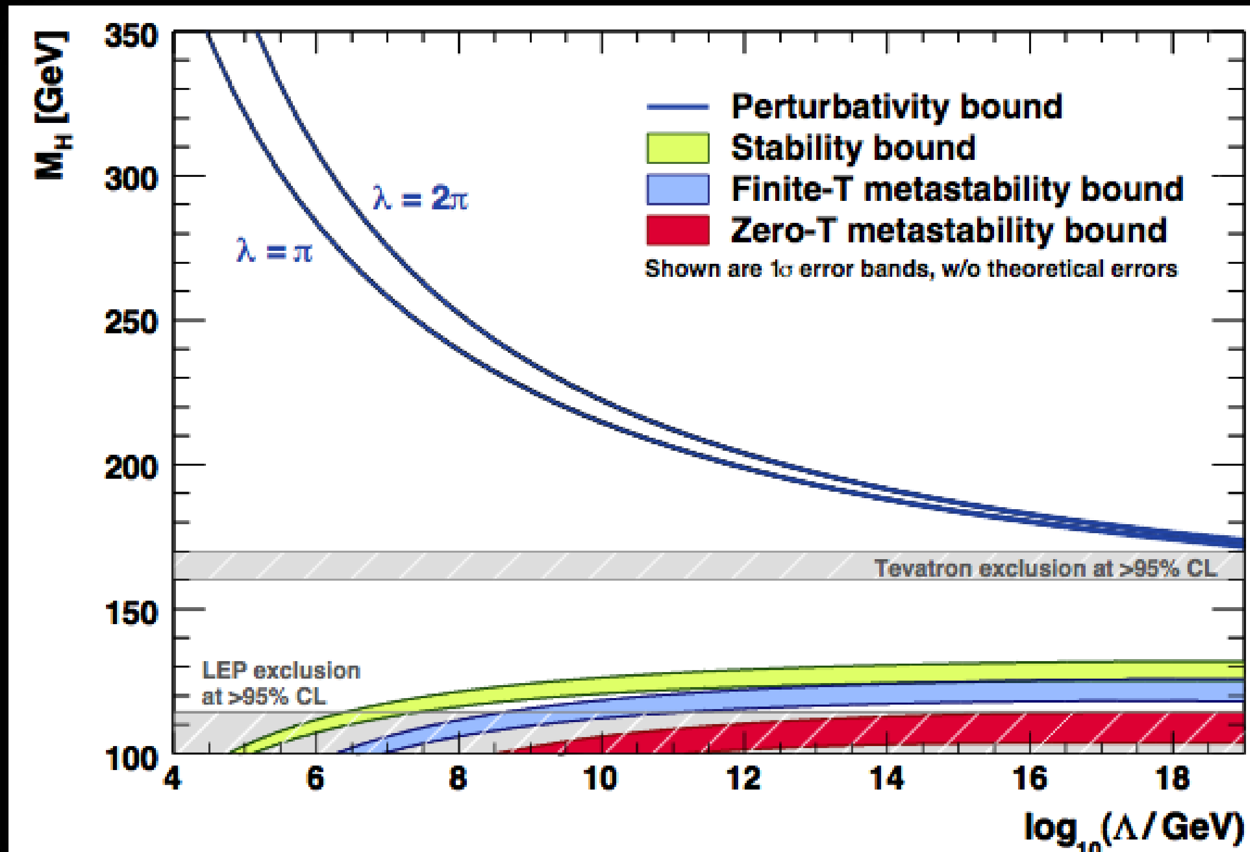
M_H large: λ^2 wins $\quad \lambda(M_t) \to \lambda(\mu) \gg 1$ $\quad$ non-perturbative regime, Landau pole

M_H small: $-Y_t^4$ wins $\quad \lambda(M_t) \to \lambda(\mu) \ll 1$

Slides from Degrassi, talk at KITP, July 2013

Ian Low
Ian Low
Ian Low

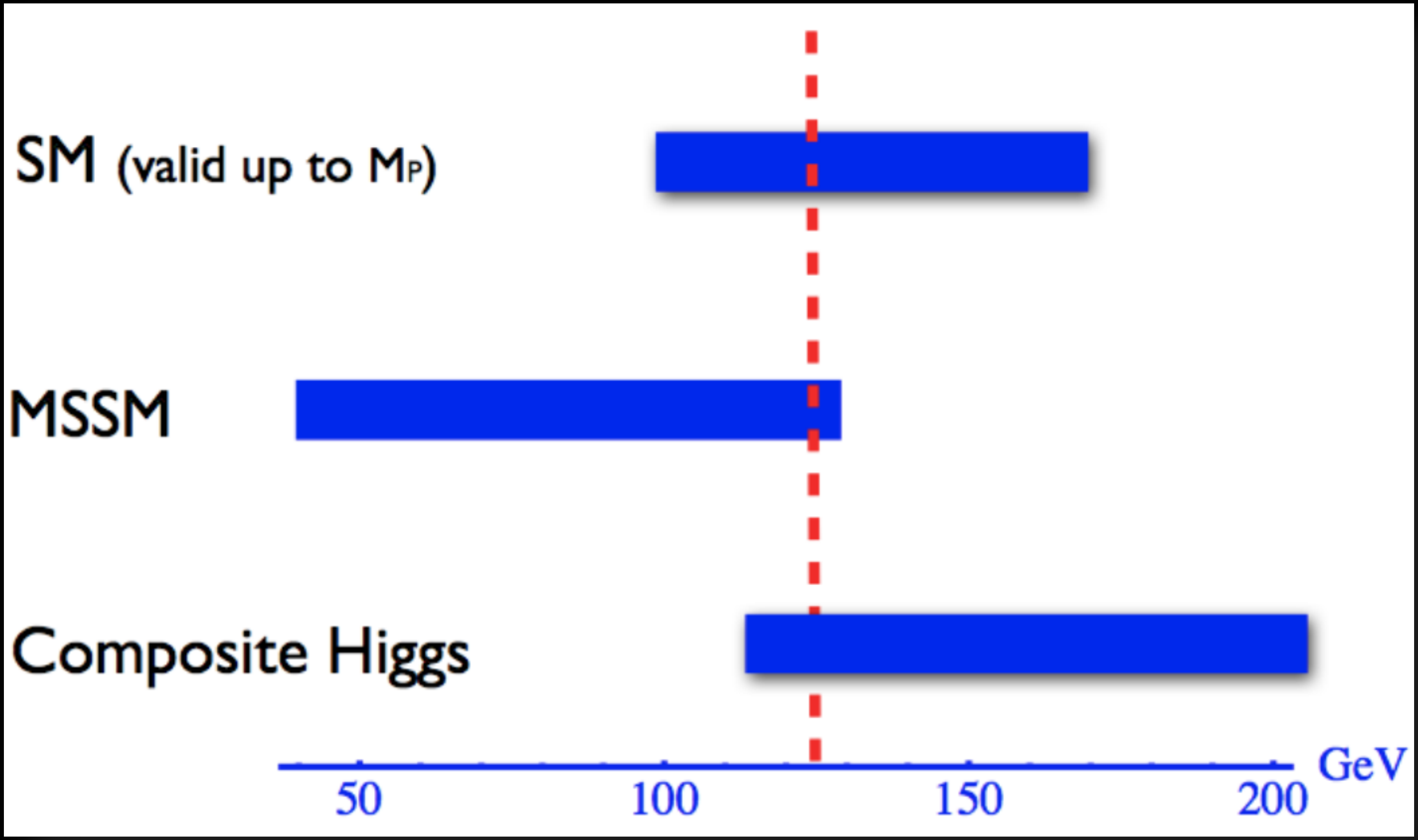
Whether we have a mexican hat or a dog bowl depends on the Higgs mass and other SM input parameters:



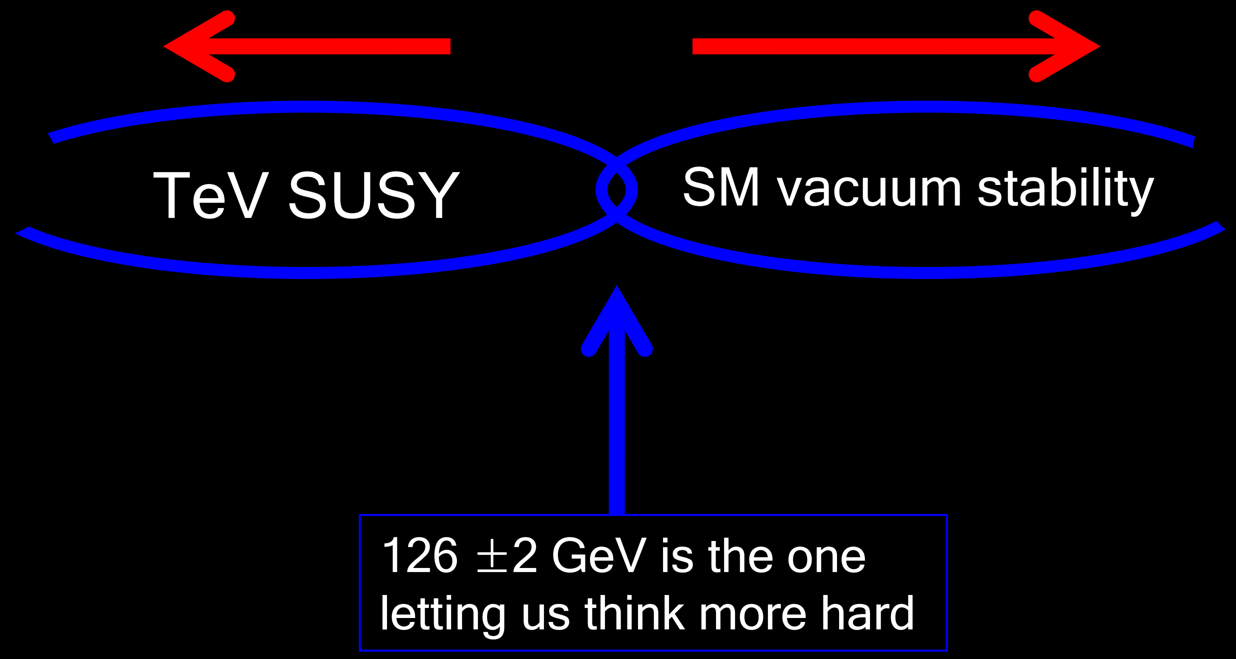
Ellis et. al.: 0906.0954

Ian Low

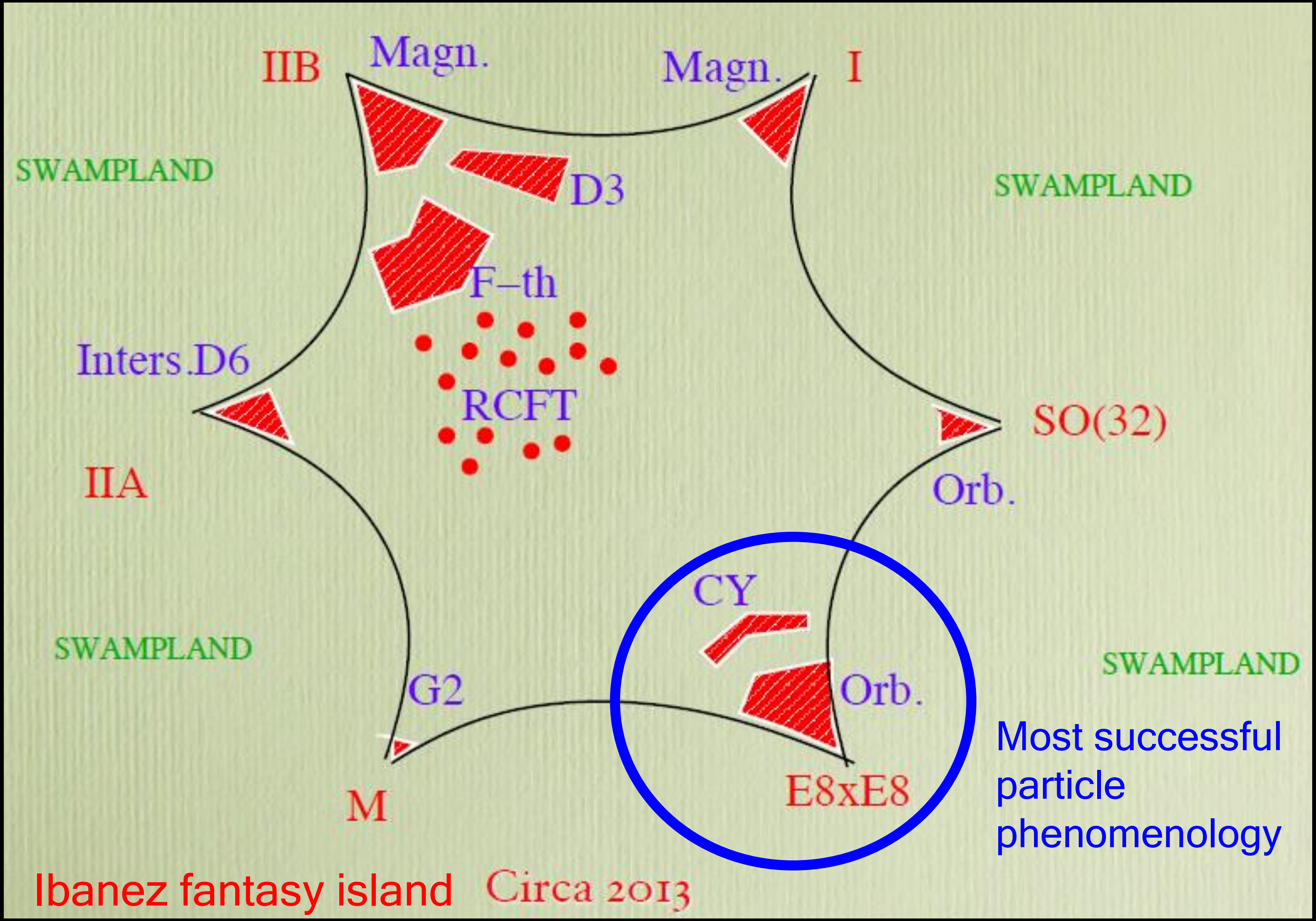
In the end, 125 GeV is in a sort of “no man’s land” for BSM theories:

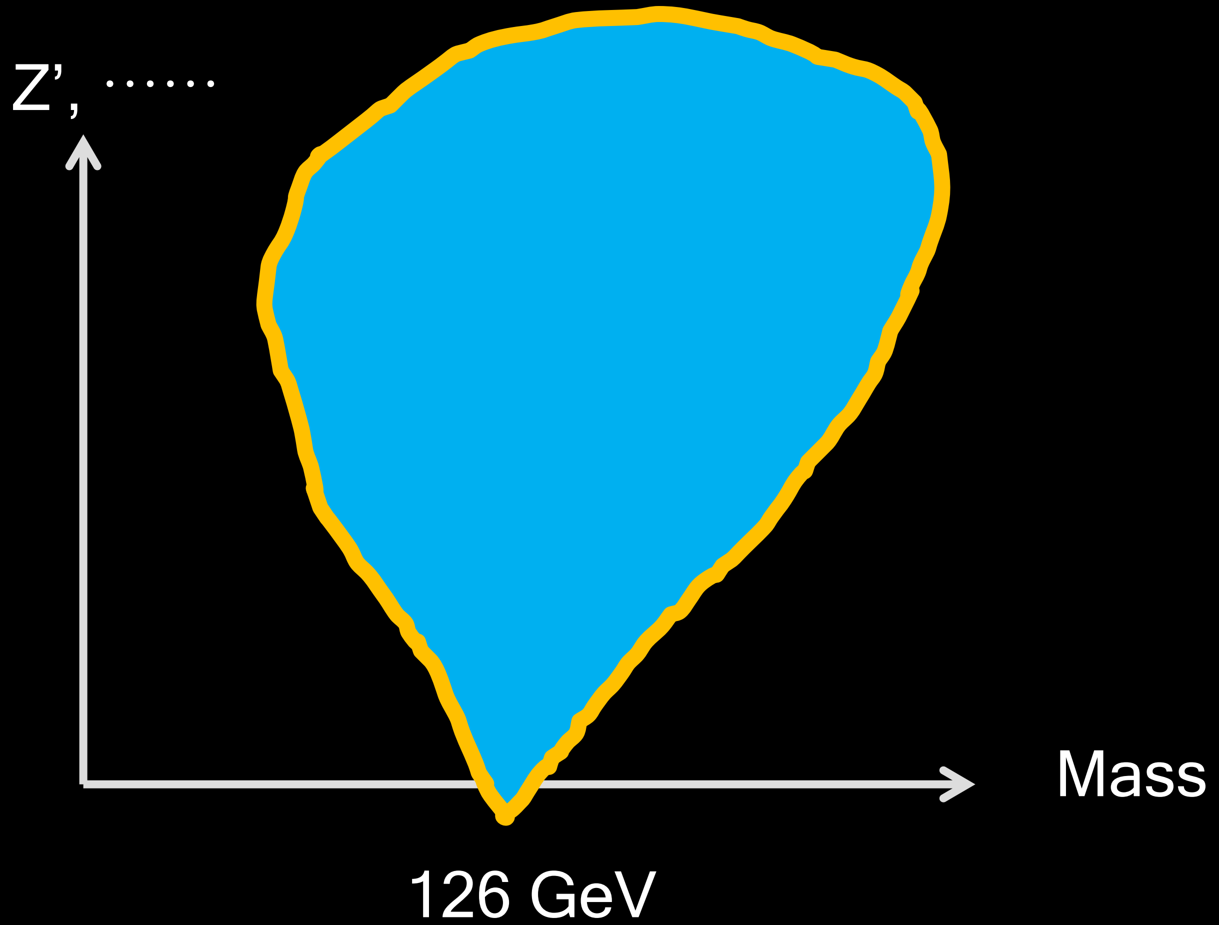


Pomarol, ICHEP ‘12


TeV SUSY
SM vacuum stability
126 ±2 GeV is the one
letting us think more hard

Outside this land: Mathematics IBS string




Z', ...
Mass
126 GeV

$$V_{\mathrm{Wolf}} = \begin{pmatrix} 1-\lambda^2/2, & \lambda, & A\lambda^3(\rho - i\eta) \\ -\lambda, & 1-\lambda^2/2, & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta), & -A\lambda^2, & 1 \end{pmatrix} + \mathcal{O}(\lambda^4), \qquad (1)$$

Flavor physics on maximal CP

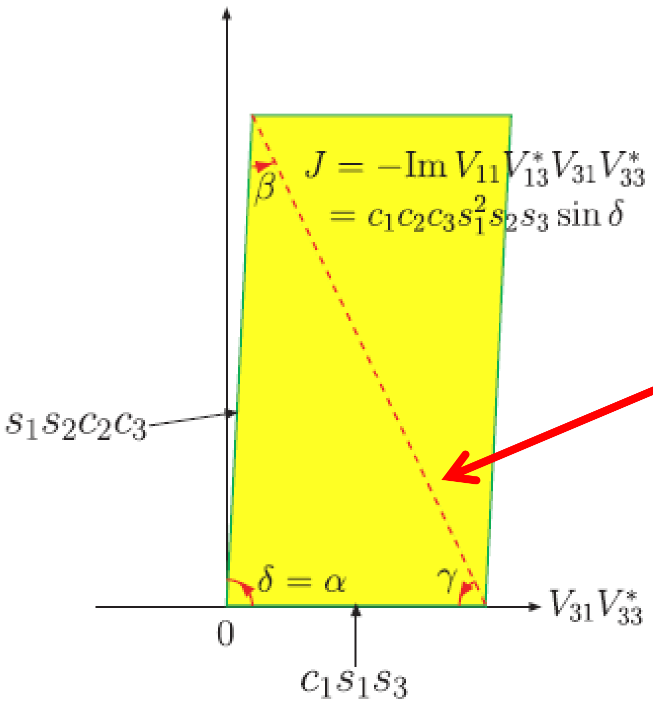
$$V_{\mathrm{KS}} = \begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -c_2s_1 & e^{-i\delta}s_2s_3 + c_1c_2c_3 & -e^{-i\delta}s_2c_3 + c_1c_2s_3 \\ -e^{i\delta}s_1s_2 & -c_2s_3 + c_1s_2c_3e^{i\delta} & c_2c_3 + c_1s_2s_3e^{i\delta} \end{pmatrix},$$

JEK-Seo, PRD84, 037303 (2011) [arXiv:1105.3304[hep-ph]]

$$\begin{aligned}
V_{11}V_{22}V_{33} &= c_1^2c_2^2c_3^2 + c_1^2s_2^2s_3^2 + 2c_1c_2c_3s_2s_3\cos\delta \\
&\quad - c_1c_2c_3s_1^2s_2s_3e^{i\delta}, \\
-V_{11}V_{23}V_{32} &= c_1^2c_2^2s_3^2 + c_1^2s_2^2c_3^2 - 2c_1c_2c_3s_2s_3\cos\delta \\
&\quad + c_1c_2c_3s_1^2s_2s_3e^{i\delta}, \\
V_{12}V_{23}V_{31} &= s_1^2s_2^2c_3^2 - c_1c_2c_3s_1^2s_2s_3e^{i\delta}, \\
-V_{12}V_{21}V_{33} &= s_1^2c_2^2c_3^2 + c_1c_2c_3s_1^2s_2s_3e^{i\delta}, \\
V_{13}V_{21}V_{32} &= s_1^2c_2^2s_3^2 - c_1c_2c_3s_1^2s_2s_3e^{i\delta}, \\
-V_{13}V_{22}V_{31} &= s_1^2s_2^2s_3^2 + c_1c_2c_3s_1^2s_2s_3e^{i\delta}.
\end{aligned}$$

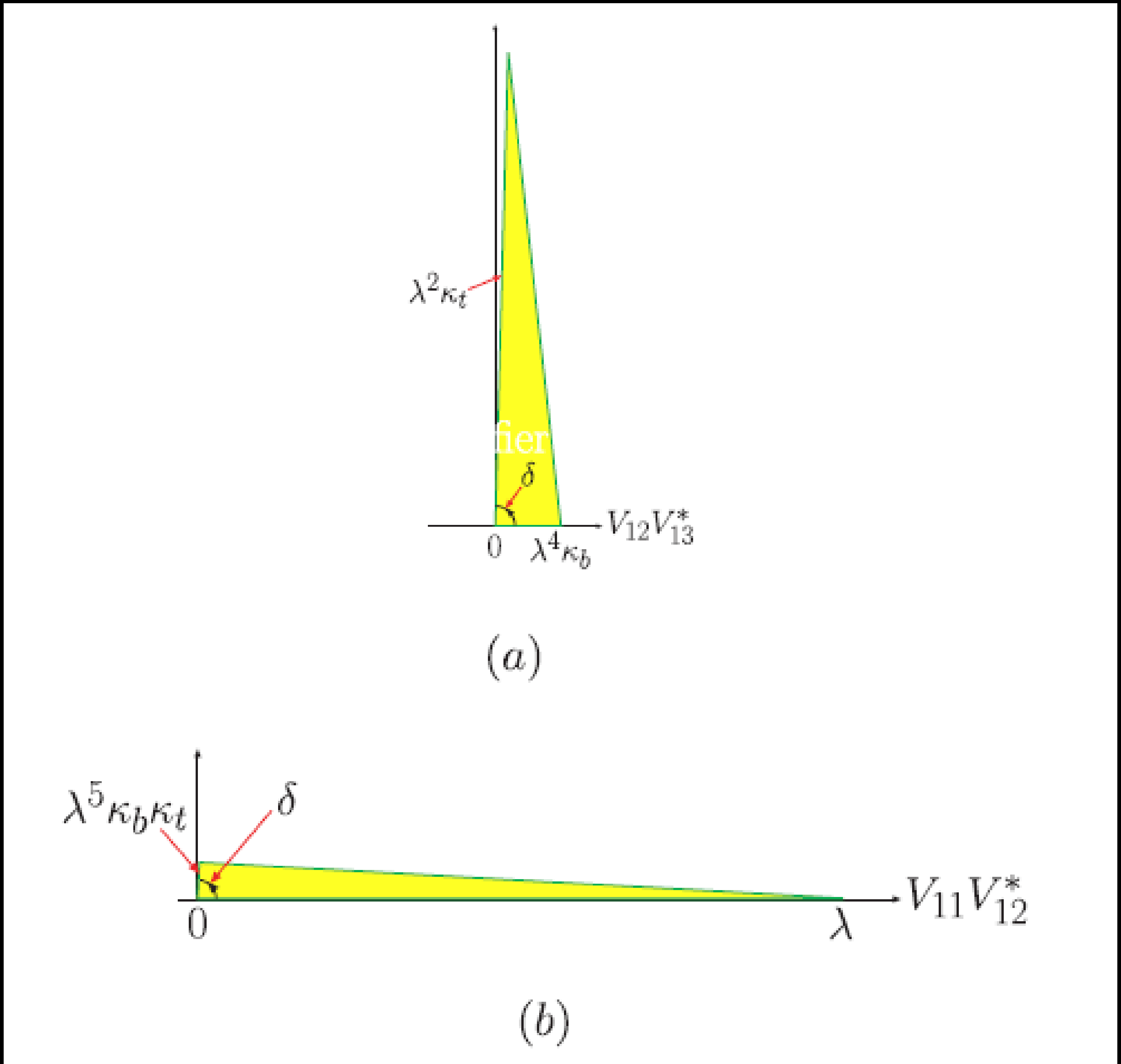
$$V_{\rm KS} = \begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -c_2s_1 & e^{-i\delta}s_2s_3 + c_1c_2c_3 & -e^{-i\delta}s_2c_3 + c_1c_2s_3 \\ -e^{i\delta}s_1s_2 & -c_2s_3 + c_1s_2c_3e^{i\delta} & c_2c_3 + c_1s_2s_3e^{i\delta} \end{pmatrix},$$

PHYSICAL REVIEW D **84,** 037303 (2011)



Jarlskog determinant

Maximal CP violation



Jarlskog Determinant

Area the same

Maximal CP violation

JEK+Seo proved it recently. J det consists of two lelements of V and two elements of V*. But det consists of three elements of V. It is not obvious at the outset.

$$J = \frac{-\mathrm{Det.}\, C}{2F(m_{t,c,u})F(m_{b,s,d})} \tag{1}$$

where $F(m_{t,c,u}) = (m_t - m_c)(m_t - m_u)(m_c - m_u)$ and $F(m_{b,s,d}) = (m_b - m_s)(m_b - m_d)(m_s - m_d)$, and C is

$$iC = [M_u, M_d], \tag{2}$$

The Jarlskog det is

$$J = V_{11}\, V_{33}\, V^*_{13}\, V^*_{31}$$

The determinant is real. If it is not real, we can change the quark phases to make it real. This process changes the coefficint of the gluon anomaly term, i.e. the θ term. So, it is reasonable to work in this basis.

$$1 = V_{11}V_{22}V_{33} - V_{11}V_{23}V_{32} + V_{12}V_{23}V_{31} - V_{12}V_{21}V_{33} + V_{13}V_{21}V_{32} - V_{13}V_{22}V_{31}.$$

Multiplying $V^*_{13}\, V^*_{22}\, V^*_{31}$, we have

$$V^*_{13}V^*_{22}V^*_{31} = |V_{22}|^2 V_{11}V_{33}V^*_{13}V^*_{31} - V_{11}V_{23}V_{32}V^*_{13}V^*_{31}V^*_{22} + |V_{31}|^2 V_{12}V_{23}V^*_{13}V^*_{22} - V_{12}V_{21}V_{33}V^*_{13}V^*_{31}V^*_{22} + |V_{13}|^2 V_{21}V_{32}V^*_{31}V^*_{22} - |V_{13}V_{22}V_{31}|^2.$$

In the same way, the 4th term can be written with two terms
And one of them combine with the 3rd term to make
$(1-|V^*_{11}|^2)\, V_{12}\, V_{23}\, V^*_{13}\, V^*_{22}$.
So we have

The Jarlskog det
$J= V_{11}\, V_{33}\, V^*_{13}\, V^*_{31}$

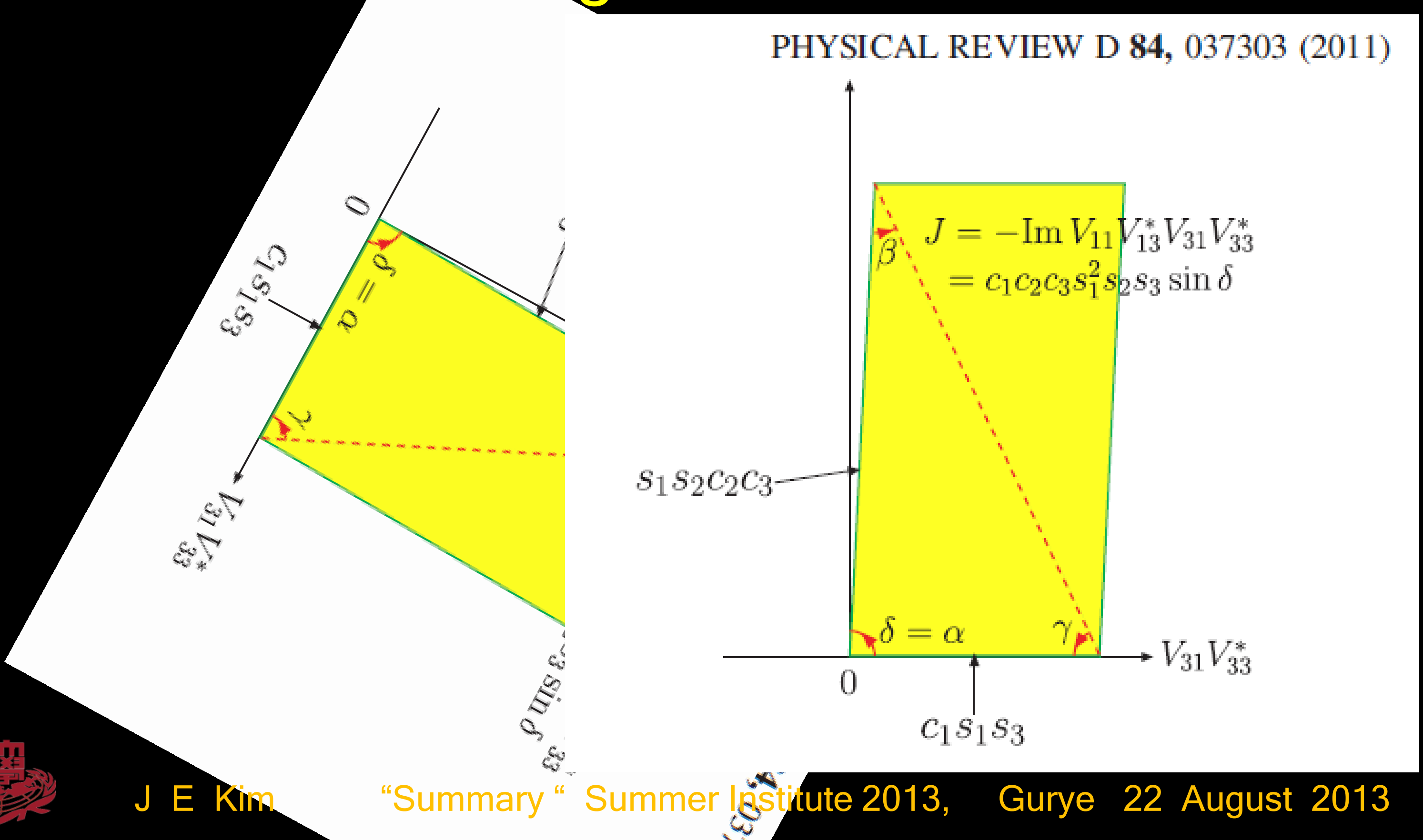
$$
\begin{aligned}
V_{13}^* V_{22}^* V_{31}^* &= (1-|V_{21}|^2) V_{11} V_{33} V_{13}^* V_{31}^* \\
&+ V_{11} V_{23} V_{13}^* V_{21}^* |V_{31}|^2 + (1-|V_{11}|^2) V_{12} V_{23} V_{13}^* V_{22}^* \\
&+ |V_{13}|^2 (V_{12} V_{21} V_{11}^* V_{22}^* + V_{21} V_{32} V_{31}^* V_{22}^*) \\
&- |V_{13} V_{22} V_{31}|^2 .
\end{aligned}
$$

$\mathrm{Im} V^*_{31} V^*_{22} V^*_{13} =$

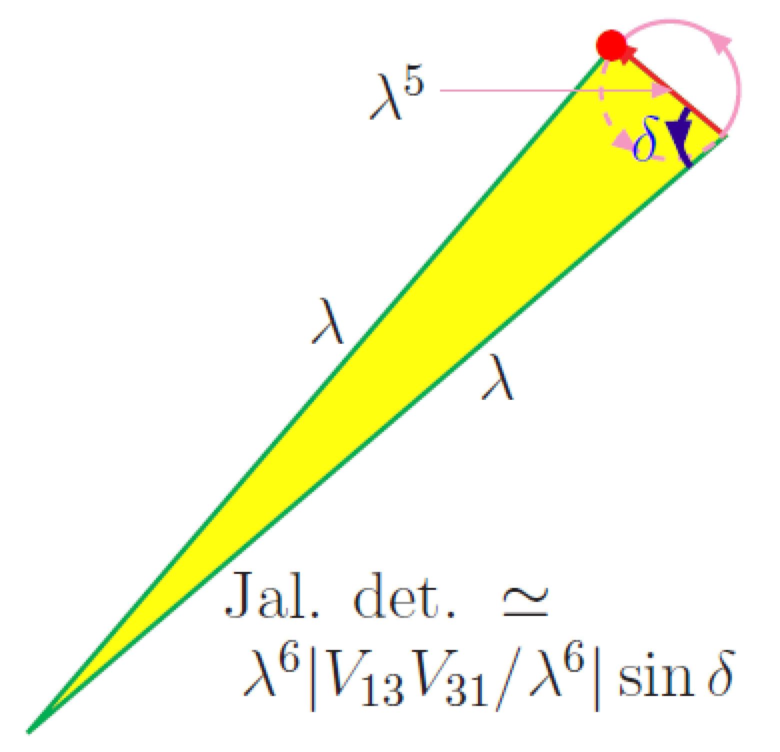
$$
\begin{pmatrix}
c_1 & s_1 c_3 & s_1 s_3 \\
-c_2 s_1 & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\
-e^{i\delta} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta}
\end{pmatrix}
$$

So the essence of the weak CP violation can be looked upon by scrutinizing the CKM matrix.

We can also say that the weak CP violation is maximal. PDG gives



Since the area of the J det is the same, we look for two long sides triangles. For example,



$$\begin{pmatrix} 1-\lambda^2/2, & \lambda, & A\lambda^3(\rho - i\eta) \\ -\lambda, & 1-\lambda^2/2, & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta), & -A\lambda^2, & 1 \end{pmatrix}$$

The area is maximum when $\delta=\pi/2$. So, we observed the maximal CP violation.

The CP violation is modeled in JEK, PLB704 (2011) 360 [1109.0995].

the three problems

$$+\Lambda_{UV}^4 \sqrt{g}$$ d=0

$$+c\Lambda_{UV}^2\, H^\dagger H$$ d=2

$$+\theta\, \tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$$ d=4

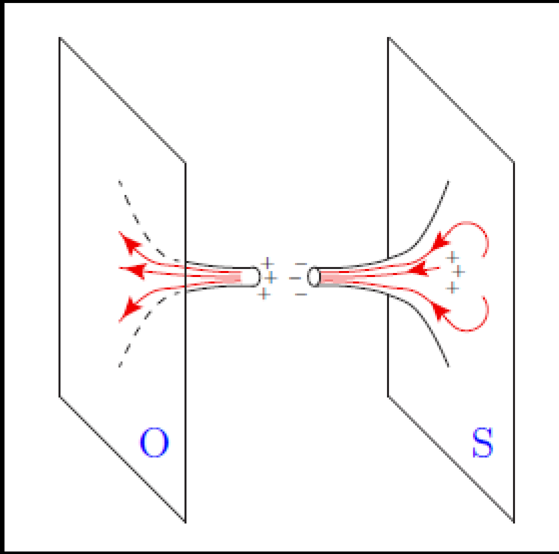
$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$ d=4

$$+ \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$
$$+ \frac{c_{ijkl}}{\Lambda_{UV}^2}\bar{F}_i F_j \bar{F}_k F_\ell + \frac{c_{ij}}{\Lambda_{UV}}\bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \dots$$
$$+ \quad \dots$$ d>4

$\Lambda_{UV} \gg$ TeV (pointlike limit) nicely accounts for 'what we see'

Rattazzi

DISCRETE SYMMETRY



Giddings-Strominger,

Krauss-Wilczek,

Barr-Seckel, Kamionkowski-March-Russell, Holman et al.

Problem with flavor models with global U(1)'s

for Froggart-Nielsen;

Problem on p-decay in SUSY models.

JEK[PLB to appear. 1308.0344]

S$_2$(L) x S$_2$(R) symmetric fermion masses can arise from

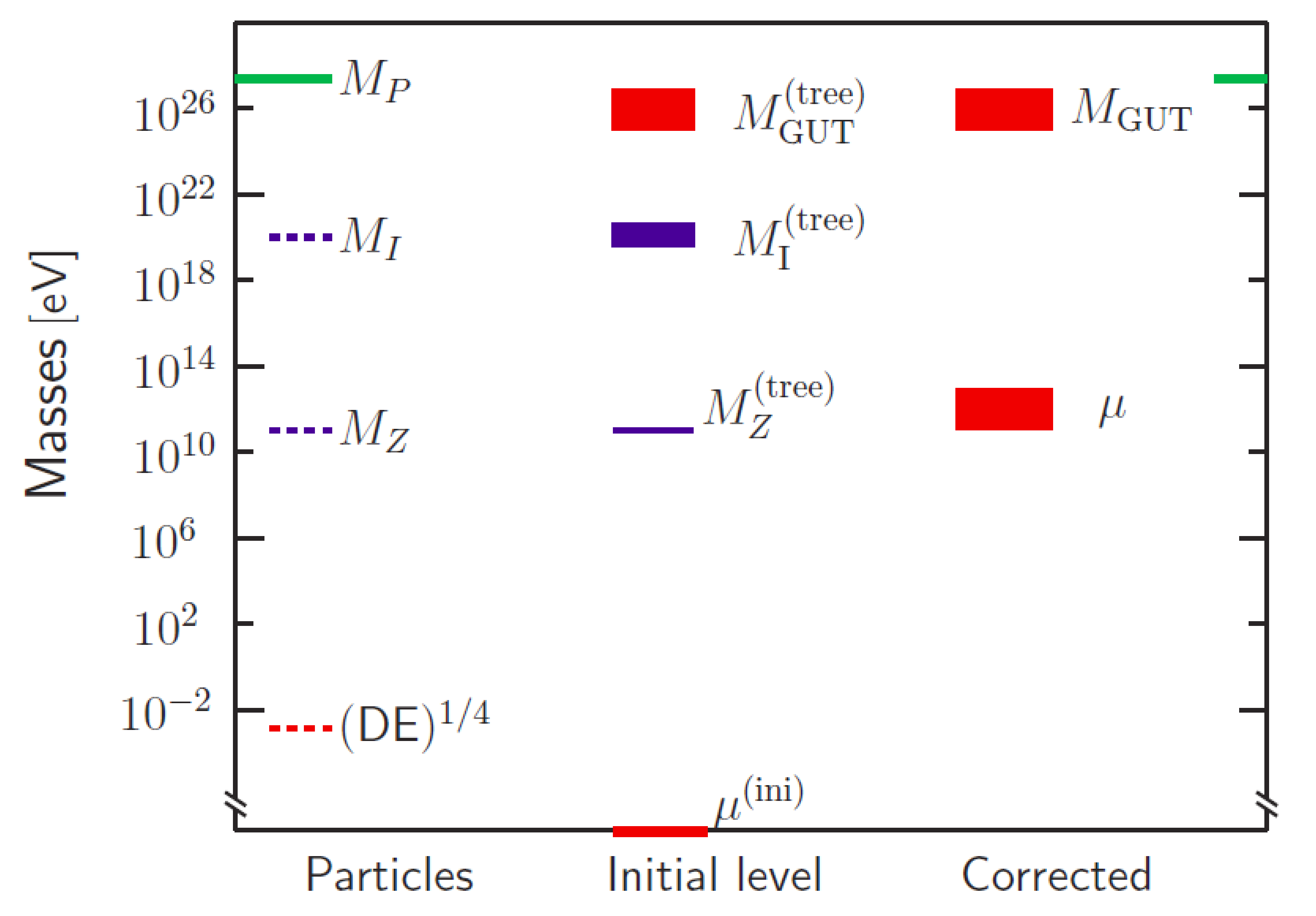
$$\mathcal{L} = -\frac{m}{2}\left(\overline{\Psi}_L^{(1)}\overline{\Psi}_R^{(1)} + \overline{\Psi}_L^{(1)}\overline{\Psi}_R^{(2)} + \overline{\Psi}_L^{(2)}\overline{\Psi}_R^{(1)} + \overline{\Psi}_L^{(2)}\overline{\Psi}_R^{(2)}\right) + h.c.$$

The fermion mass matrix will be

$$M_0 = \begin{pmatrix} m/2 & m/2 \\ m/2 & m/2 \end{pmatrix}$$

$$M = \begin{pmatrix} 0 & 0 \\ 0 & m \end{pmatrix}$$

The first step for the solution of the μ-problem.
[JEK, PRL 111, 031801 [arXiv:1303.1822]].



[JEK, PRL 111, 031801, arXiv:1303.1822].

In string theory, matter fields are from
$E_8 \times E_8$ representations. Not from B_{MN} .

Kim-Nilles μ-term arises from

$$W = \frac{\lambda X_u X_d}{2M_P} H_u H_d$$

Accidental PQ symmetry
JEK, PRL 111, 031801

How can we break $S_2(L) \times S_2(R)$ symmetry ?

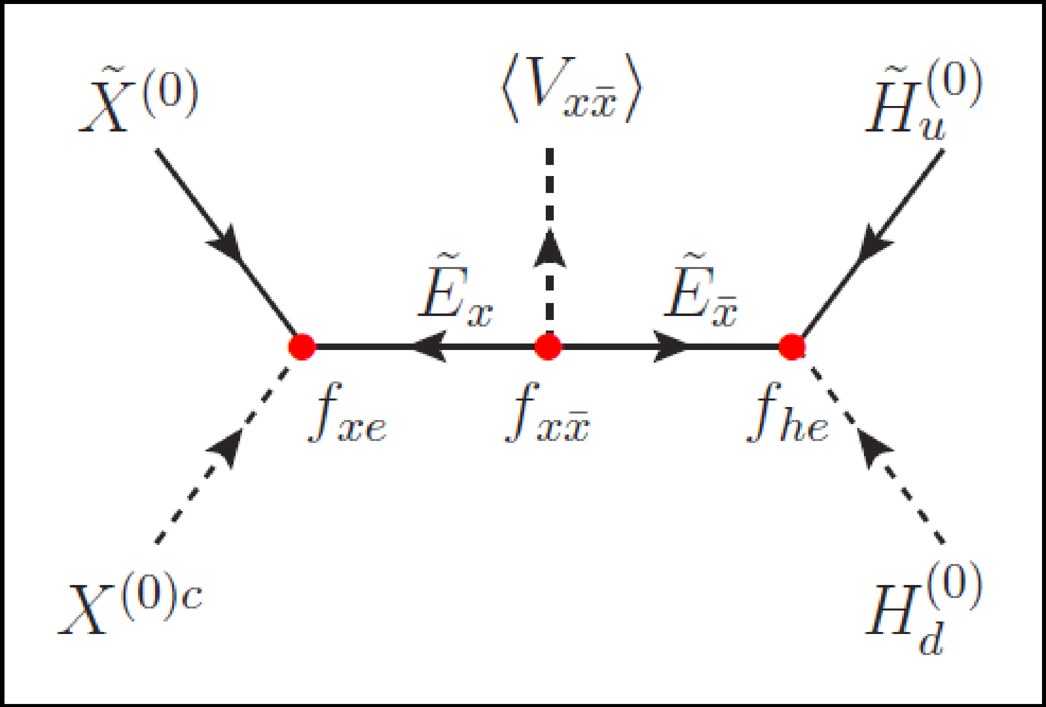
Spontaneously by

$$\langle X^{(1)} \rangle = \langle \overline{X}^{(1)} \rangle = F_a \,, \quad \langle X^{(2)} \rangle = \langle \overline{X}^{(2)} \rangle = 0$$

The massless (0) fields, and superheavy (G) fields

$$X^{(0),(G)} = \frac{1}{\sqrt{2}} (X^{(1)} \mp X^{(2)})$$

$$H_{u,d}^{(0),(G)} = \frac{1}{\sqrt{2}} (H_{u,d}^{(1)} \mp H_{u,d}^{(2)})$$



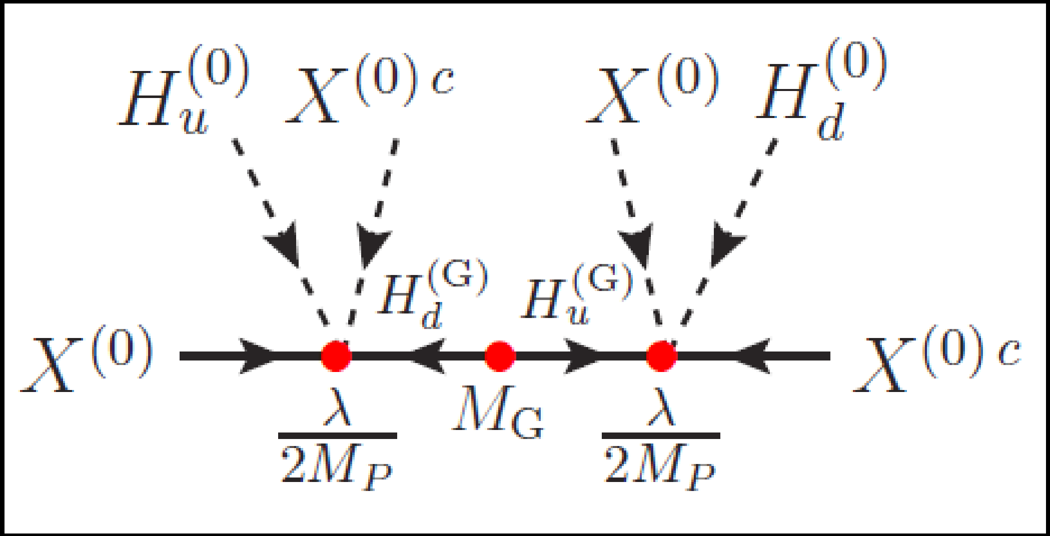
This defines the PQ charges of X and H.

$$\frac{\lambda}{2M_{\rm P}} X^{(0)} X^{(0)c} H_u{}^{(0)} H_d{}^{(0)}, \qquad \lambda = f_{xe} f_{he} \frac{\mathrm{M}_{\rm P}}{\mathrm{M}_{\rm E}}$$

$$\langle X^{(0)} \rangle = 10^{12}\ \mathrm{GeV}, \quad f = O(10^{-2}), \frac{\mathrm{M}_{\rm P}}{\mathrm{M}_{\rm E}} = 10, \text{gives}\ \lambda = 10^{-3}$$

Then, $\mu = 200$ GeV

The PQ breaking diagram is



The A-term

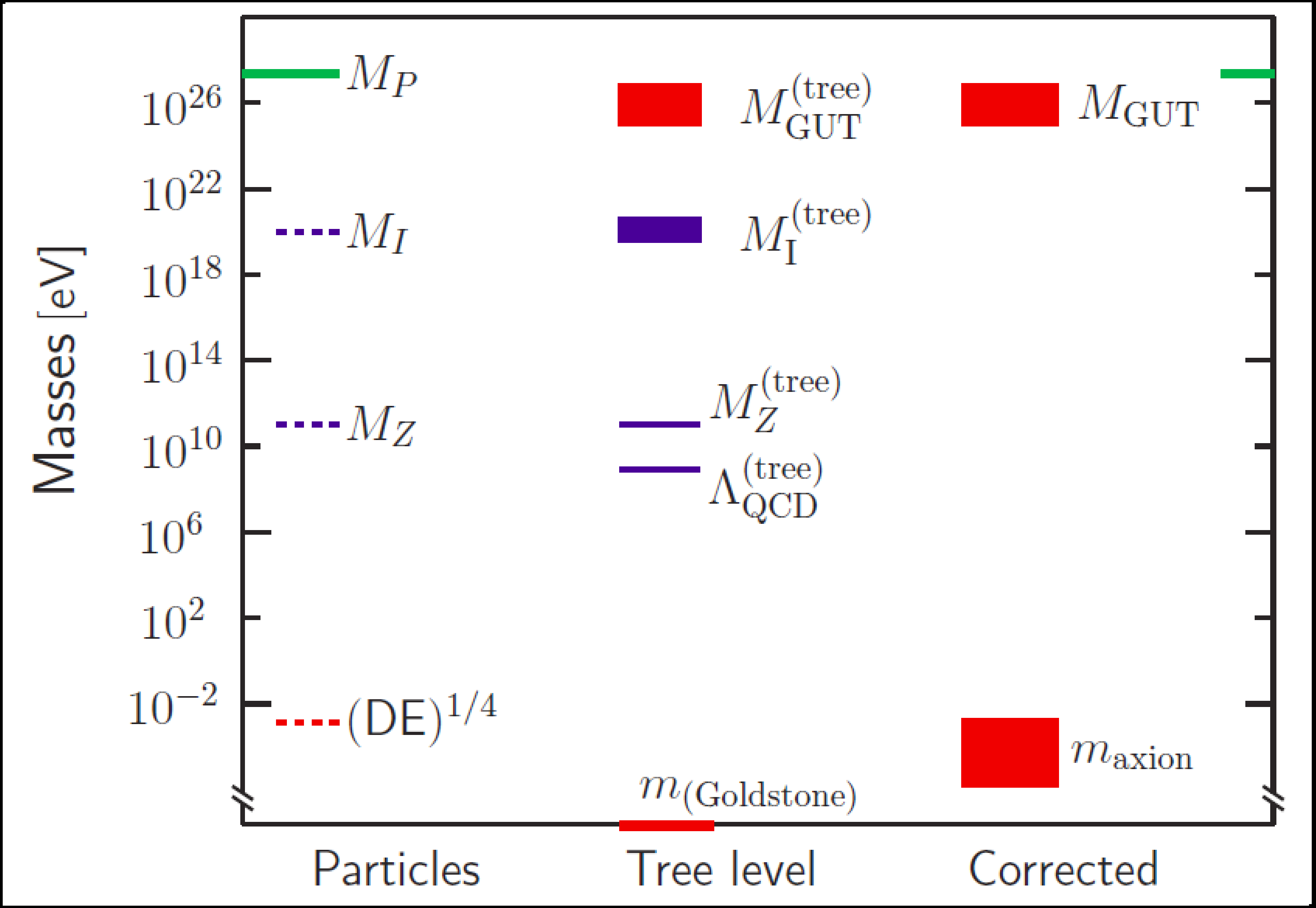
$$m_{3/2}\frac{\lambda^2}{4M_P^2}\left(\frac{1}{M_G}H_uH_d\right)(XX^c)^2=\frac{\lambda^2 m_{3/2}v_uv_dF_a^4}{8M_P^2M_G}\approx\left(\frac{\lambda^2\sin\beta\cos\beta}{8}\right)\frac{v_{\rm ew}^2}{M_G}m_{3/2}\mu^2$$
$$\approx\left(\frac{\lambda^2}{\tan\beta}\right)3\times10^{-6}\left(\frac{m_{3/2}}{\rm TeV}\right)\left(\frac{\mu}{\rm TeV}\right)^2\,[\mathrm{GeV}^4].$$

This can be compared with the main axion potential

$$V=\frac{Z\,f_\pi^2\,m_\pi^2}{(1+Z)^2}\left(1-\cos\frac{a}{F_a}\right)+10^{-13}\sin\frac{a}{F_a}[GeV^4]\rightarrow|\bar\theta|\approx10^{-9}$$

For gravity mediation, |θ| may be of order

$$\lambda=10^{-3}\rightarrow\qquad|\bar\theta|\approx10^{-9}$$


M_P
10^{26}
$M_{\rm GUT}^{\rm (tree)}$
$M_{\rm GUT}$
10^{22}
M_I
$M_{\rm I}^{\rm (tree)}$
10^{18}
Masses [eV]
10^{14}
M_Z
$M_Z^{\rm (tree)}$
10^{10}
$\Lambda_{\rm QCD}^{\rm (tree)}$
10^{6}
10^{2}
10^{-2}
$({\rm DE})^{1/4}$
$m_{\rm axion}$
$m_{\rm (Goldstone)}$
Particles
Tree level
Corrected

Thanks for coming this region.

END

Gold Stone boson settles down

the truth

金 鎮 義

愛新覺羅