CP Violation for the Heavens **and** *the Earth*

George W.S. Hou (侯維恕)
National Taiwan University

14 November @**L'Irfu, CEA-Saclay**

臺灣大學
National Taiwan University

Universe **8** (2022) 234 [2201.13245 [hep-ph]]

CP Violation for the Heavens and the Earth

0. *Intro: Our Life & Times* – Setting

I. *General 2HDM*

II. *ElectroWeak Baryogenesis*

III. *e**EDM** on Earth: Respect ACME*

[Nature's Flavor Design

IV. *Phenomenological Consequences*

[one-loop muon g - 2

V. Summary

0. Intro: Our Life & Times

h(125) ✔ New Physics ✘

Where is SUSY/WIMP?

Beyond CKM **CPV** (*Large*)

EW BaryoGenesis (EWBG)

- more testable -

tension

LHC

- No New Physics -

tension

competition

eEDM: ACME14 ACME18

- L.E. Precision Frontier -

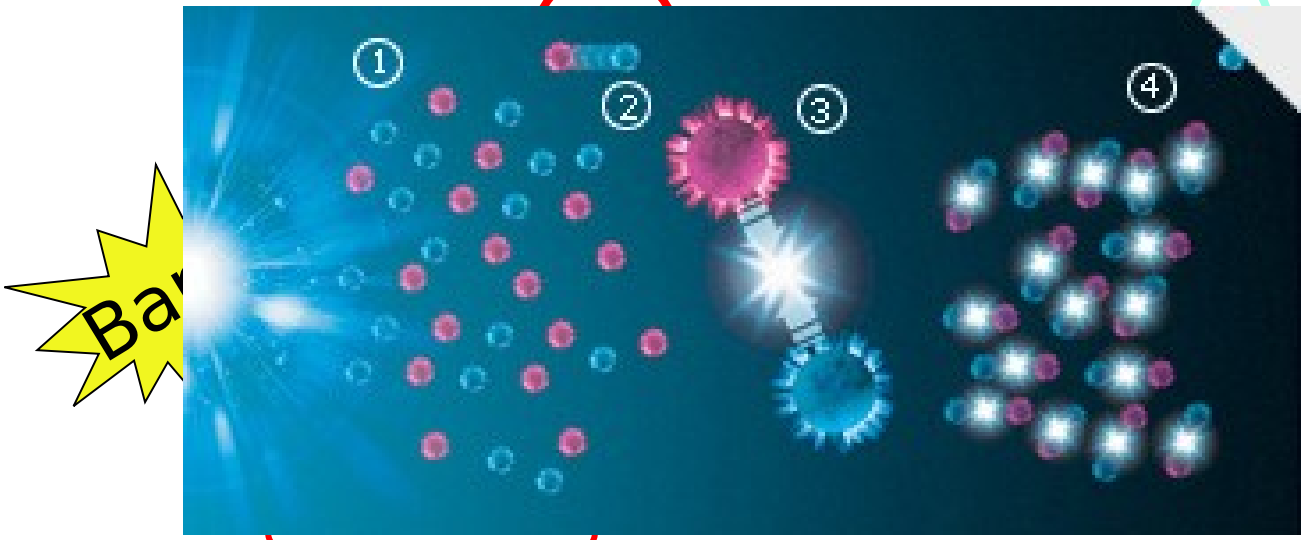
$|d_e| < 1.1 \times 10^{-29}\ e$ cm

CPV & B.A.U.: The Sakharov View (1967)

B.A.U. = Baryon Asymmetry Universe

- **Baryon Number Violation**
- *CP Violation*
- Deviation from Equilibrium

10^{-9} *Matter left !*



14Byr

Us

Equal Matter -Antimatter

Pair Annihilation

Soaring to the Starry Heavens

Enough **CPV** for **B.A.U. ?**

天

CPV ⇒ BAU

$|d_e| < 1.1 \times 10^{-29}\ e$ cm

地

ACME *experiment: Current frontline, Probe CPV via e EDM, put check on Baryogenesis.*

Capital Reef National Park
(c) Wally Pacholka

Whither 1st Order Phase Trans. / Sufficient CPV?

SM: Weak Int. too Weak / Jarlskog Invariant way too small !

All 3 gens. ⇒ Mass and CKM suppressed

2HDM: O(1) Higgs Quartics OK / CPV in $V(\Phi_1, \Phi_2)$ problematic w/ d_n

Wise to keep $V(\Phi_1, \Phi_2)$ ~~CP Conserving~~

Comment: Known CPV in CKM, i.e. Yukawa's. Extra Yukawa's ?

Killed by Z_2 (Glashow-Weinberg 1977)

"Natural Flavor Conservation".

ad hoc

General

2HDM: O(1) Higgs Quartics OK / Extra Yukawa's w/o Z_2

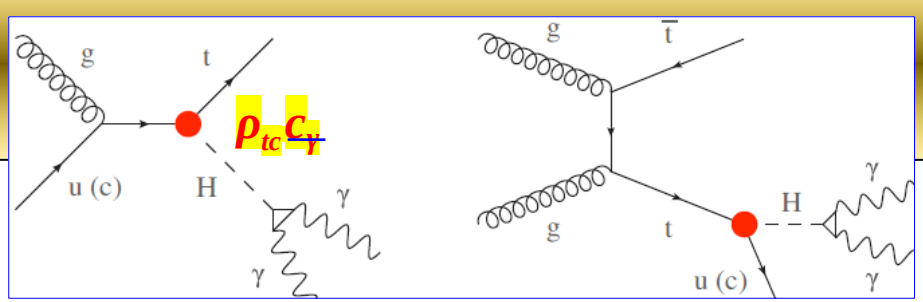
O(1)

ρ_{tt} the driver; ρ_{tc} the backup

EWBG

Fuyuto, WSH, Senaha, Phys. Lett. B 776 (2018) 402

N.B. Data-driven ρ_{ij}: $t \to ch$; $h \to \mu\tau$ ... WSH, PLB'92



alignment
c_γ small

h-H *mixing*

PHYSICAL REVIEW LETTERS **129,** 032001 (2022)

Search for Flavor-Changing Neutral Current Interactions of the Top Quark and Higgs Boson in Final States with Two Photons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.*[*]
(CMS Collaboration)

(Received 3 November 2021; accepted 13 June 2022; published 13 July 2022)

Proton-proton interactions resulting in final states with two photons are studied in a search for the signature of flavor-changing neutral current interactions of top quarks (t) and Higgs bosons (H). The analysis is based on data collected at a center-of-mass energy of 13 TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of 137 fb^{-1}. No significant excess above the background prediction is observed. Upper limits on the branching fractions ($\mathcal{B}$) of the top quark decaying to a Higgs boson and an up (u) or charm (c) quark are derived through a binned fit to the diphoton invariant mass spectrum. The observed (expected) 95% confidence level upper limits are found to be 0.019% (0.031%) for $\mathcal{B}(t \to Hu)$ and 0.073% (0.051%) for $\mathcal{B}(t \to Hc)$. These are the strictest upper limits yet determined.

WSH, PLB'92 (PSI-PR-91-34)
Chen, WSH, Kao, Kohda, PLB'13

Extra Yukawa Couplings

General ~~2HDM~~ w/o Z_2

General Yukawa interaction for up-type quarks

$$-\mathcal{L}_Y = \bar{q}_{iL}(Y^u_{1ij}\tilde{\Phi}_1 + Y^u_{2ij}\tilde{\Phi}_2)u_{jR} + \text{h.c.}$$

$\upsilon_1 = \upsilon\, c_\beta \qquad \upsilon_2 = \upsilon\, s_\beta$

$$Y^{\rm SM} = Y_1\, c_\beta + Y_2\, s_\beta$$

$$m_f = y_f\, v/\sqrt{2}$$

$$V_L^{u\dagger} Y^{\rm SM} V_R^u = \text{diag}(y_u,\ y_c,\ y_t) \equiv Y_D \qquad \textit{diagnonal}$$

$$\rho = V_L^{u\dagger}\left(-Y_1\, s_\beta + Y_2\, c_\beta\right) V_R^u$$

FCNH (flavor changing neural H)

Neutral up-type Yukawa interaction

c_γ

$$c_{\beta-\alpha} \to 0$$

alignment limit !

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}}s_{\beta-\alpha} + \frac{\rho_{ij}}{\sqrt{2}}c_{\beta-\alpha}\right]u_{jR}h \quad \rightarrow \textit{diag.}$$

$$+\bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}}c_{\beta-\alpha} - \frac{\rho_{ij}}{\sqrt{2}}s_{\beta-\alpha}\right]u_{jR}H$$

$$-\frac{i}{\sqrt{2}}\bar{u}_{iL}\rho_{ij}u_{jR}A + \text{h.c.}, \quad \rightarrow \textit{FCNH}\ \ \rho_{ij}$$

$$|\rho_{ij}|e^{i\phi_{ij}}$$

Data suggest approx. alignment !

$$\begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

Extra Higgs Quartic Couplings

Sub-TeV Spectrum & *1st EWPT*

SM

$V(\Phi) \sim -\mu^2|\Phi|^2 + \lambda|\Phi|^4$

$v^2 \sim \mu^2/\lambda$

G2HDM

$$V(\Phi,\Phi') = \mu_{11}^2|\Phi|^2 + \mu_{22}^2|\Phi'|^2 - (\mu_{12}^2\Phi^\dagger\Phi' + \text{h.c.}) + \frac{\eta_1}{2}|\Phi|^4 + \frac{\eta_2}{2}|\Phi'|^4 + \eta_3|\Phi|^2|\Phi'|^2 + \eta_4|\Phi^\dagger\Phi'|^2 + \left\{\frac{\eta_5}{2}(\Phi^\dagger\Phi')^2 + [\eta_6|\Phi|^2 + \eta_7|\Phi'|^2]\,\Phi^\dagger\Phi' + \text{h.c.}\right\}$$

$\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$ "min. cond."

w/o Z_2

Higgs basis *CP Conserving* WSH&Kikuchi, EPL'18

η_6: sole param. for h-H mixing (c_γ)

Search Zone

Dim'less params. $\mathcal{O}(1)$ ("Common" Naturalness):

η_i with $i = 1$–7; $\mu_{22}^2/v^2 \gtrsim 0$ ⇒ H, A, H+

$$c_\gamma \simeq \frac{-\eta_6 v^2}{m_H^2 - m_h^2} \quad \text{(near alignment)}$$

Alignment argument

a Sakharov condition: 1st EWPT

N.B. **O** *(1)* η_i**'s** *needed for 1st order Phase Trans., prerequisite for ElectroWeak BaryoGenesis.*

Kanemura,Okada,Senaha, PLB'05

GeV: 800, 700, unnatural, 600, 500, 400, $t\bar{t}$, 300, incredulous, 200, h, 100

neutrino ν | lepton eμτ | down-type dsb | up-type uc | vector γ g | scalar

Fuyuto, WSH, Senaha, Phys. Lett. B 776 (2018) 402

strongly 1st order EW phase transition (EWPT)

Expanding Bubble of Broken Phase

Extra Higgs Thermal Loops w/ O(1) Higgs Quartics

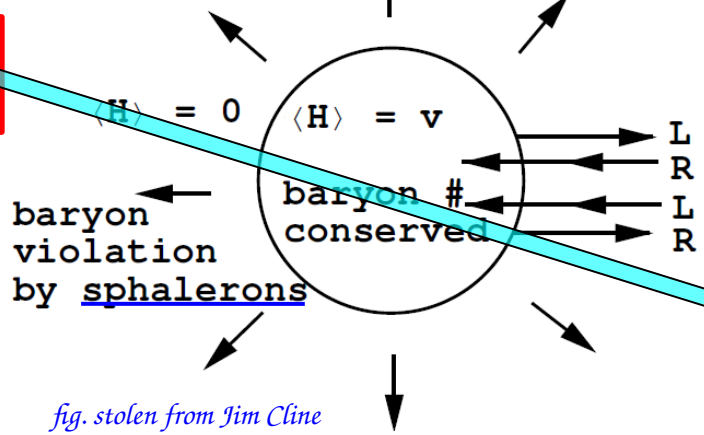


fig. stolen from Jim Cline

2HDM OK

To avoid n_B washout:

Hubble const.

$$\Gamma_B^{(\mathrm{br})}(T_C) < H(T_C)$$

n_B changing rate (br)

$$v_C/T_C > \zeta_{\mathrm{sph}}(T_C) \sim \mathrm{O}(1)$$

vev @ T_C

$$\sqrt{v_1^2(T_C)+v_2^2(T_C)}$$

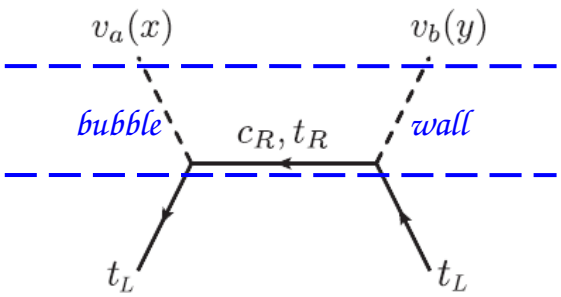
Baryon Asymm. of Universe (BAU)

n_B/s

$$Y_B = \frac{-3\Gamma_B^{(\mathrm{sym})}}{2D_q\lambda_+ s}\int_{-\infty}^{0} dz'\, n_L(z')e^{-\lambda_- z'}$$

Planck 2014

$$Y_B^{\mathrm{obs}} = 8.59\times10^{-11}$$



$\Gamma_B^{(\mathrm{sym})} = 120\alpha_W^5 T$ — n_B changing rate (sym)

$D_q \simeq 8.9/T$ — quark diffusion const

s — entropy density

$\lambda_\pm \simeq v_w$ — bubble wall velocity

n_L — l.h. fermion density (l.h. top density)

z' — coord. oppo. bubble exp. dir.

CPV Top interactions

CPV source term

$$S_{i_L j_R}(Z) = N_C F \left[\mathrm{Im}\left[(Y_1)_{ij} (Y_2)^*_{ij} \right] \right] v^2(Z)\, \partial_{t_Z} \beta(Z)$$

$Z = (t_Z, \boldsymbol{Z})$ — *position in heat bath (Very Early Univ.)*

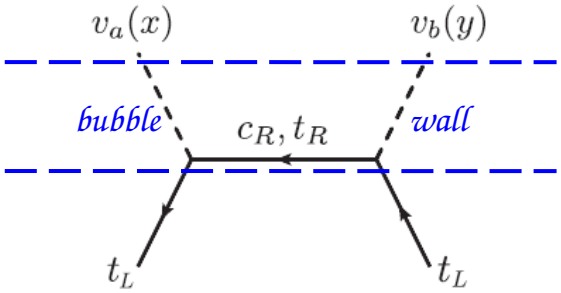
$N_C = 3$ — *# of color*

F — *function of complex energies for i_L, j_R*

$\partial_{t_Z} \beta(Z)$ — *physical variation* $\Delta\beta = 0.015$

Baryon Asymm. of Universe (BAU) n_B/s

$$Y_B = \frac{-3\Gamma_B^{(\mathrm{sym})}}{2 D_q \lambda_+ s} \int_{-\infty}^{0} dz'\, n_L(z') e^{-\lambda_- z'}$$



z'

ρ_{tt}, ρ_{tc}

BAU ⇐ *CPV Top interactions at Bubble Wall*

left-handed Top density n_L

coord. oppo. bubble exp. dir.

skip detail (*Transport*)

CPV Top interactions

CPV source term

$$S_{i_L j_R}(Z) = N_C F \left[\mathrm{Im}\left[(Y_1)_{ij} (Y_2)^*_{ij} \right] \right] v^2(Z)\, \partial_{t_Z} \beta(Z)$$

$$\mathrm{Im}\left[(Y_1)_{ij} (Y_2)^*_{ij} \right] = \mathrm{Im}\left[(V^u_L Y_D V^{u\dagger}_R)_{ij} (V^u_L \rho V^{u\dagger}_R)^*_{ij} \right]$$

lifted from Guo,Li,Liu,Ramsey-Musolf,Shu PRD'17

To understand the plot of next page, suppose (exercise)

$(Y_1)_{tc} \neq 0$, $(Y_2)_{tc} \neq 0$, $(Y_1)_{tt} = (Y_2)_{tt} \neq 0$ *(3 params.)*

all else vanish, and take $t_\beta = 1$ *for convenience*

then $\sqrt{2} Y^{\rm SM} = Y_1 + Y_2$

but $-Y_1 + Y_2$

solve V^u_R

$$\mathrm{Im}\left[(Y_1)_{tc} (Y_2)^*_{tc} \right] = -y_t \mathrm{Im}(\rho_{tt}), \quad \rho_{ct} = 0$$

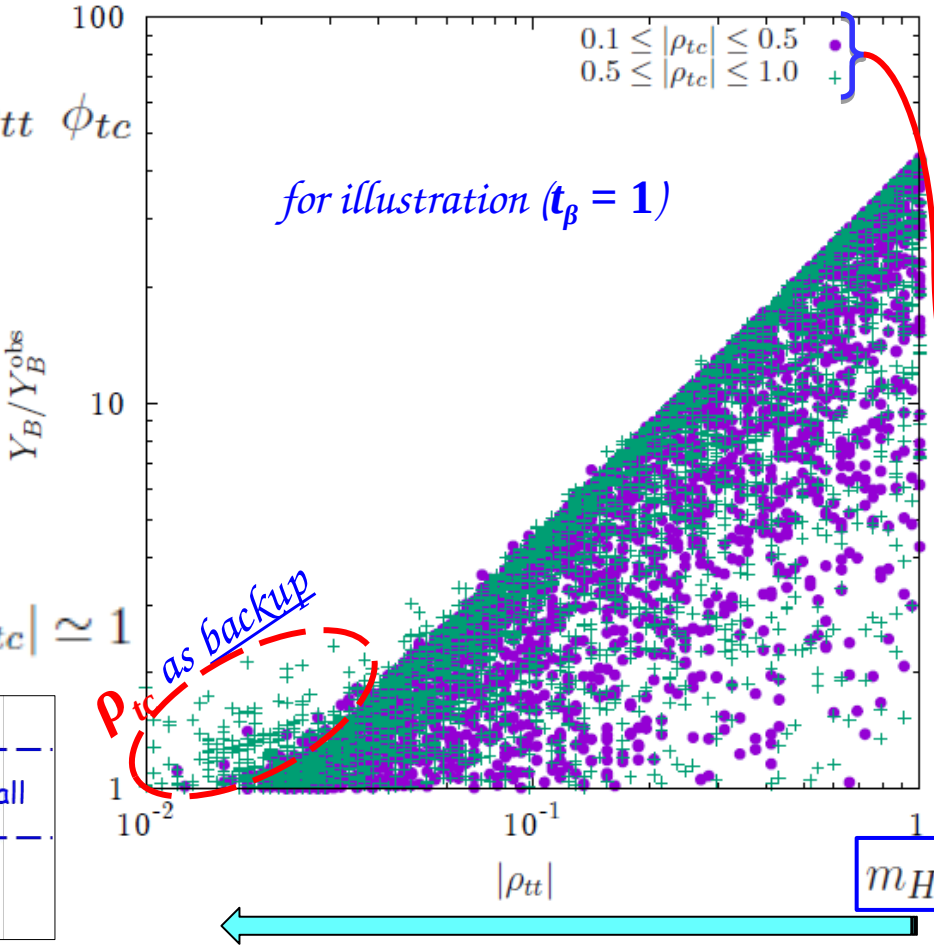
ρ_{tc} *still basically free param.*

Fuyuto, WSH, Senaha, Phys. Lett. B 776 (2018) 402

Robust: *Large Parameter Space for EWBG*

scan over $|\rho_{tc}|\ \phi_{tt}\ \phi_{tc}$

$|\sin\phi_{tc}| \simeq 1$

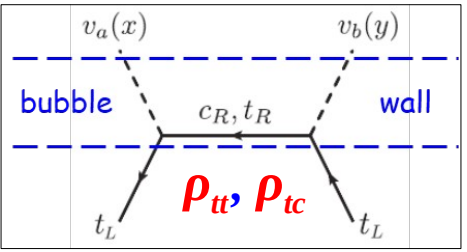


for illustration ($t_\beta = 1$)

ρ_{tc}, ρ_{tt} *satisfy* $B_{d,s}$ *mixing,* $b \to s\gamma$

no obvious diff.

⇒ ρ_{tt} driven!



small ρ_{tt}

the charm of EWBG

$$m_H = m_A = m_{H^\pm} = 500\ \text{GeV}$$

$$-y_t \mathrm{Im}(\rho_{tt})$$

$v_C/T_C >$ O(1)

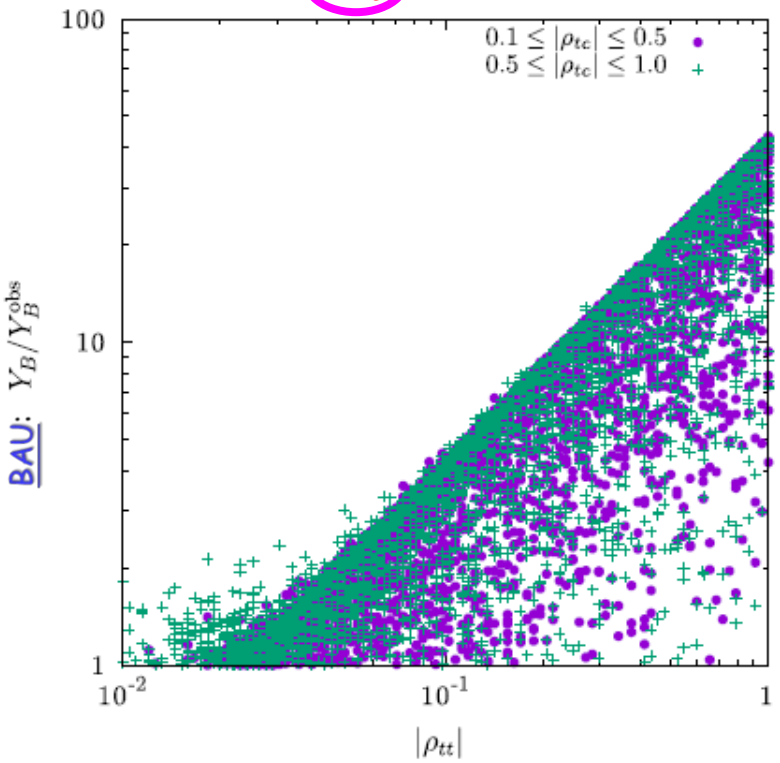
$T_C = 119.2\ \text{GeV}$ $v_C = 176.7\ \text{GeV}$ $v_w = 0.4$ $\Delta\beta = 0.015$ $D_q = 8.9/T$ $D_H = 101.9/T$

$m_{t_L} = 0.59T$ $m_{t_R} = 0.62T$ $m_{c_R} = 0.50T$ $\Gamma_{q_{L,R}} = 0.22T$ $\Gamma_B^{(s)} = 120\alpha_W^5 T$ $\Gamma_{ss} = 16\alpha_s^4 T$

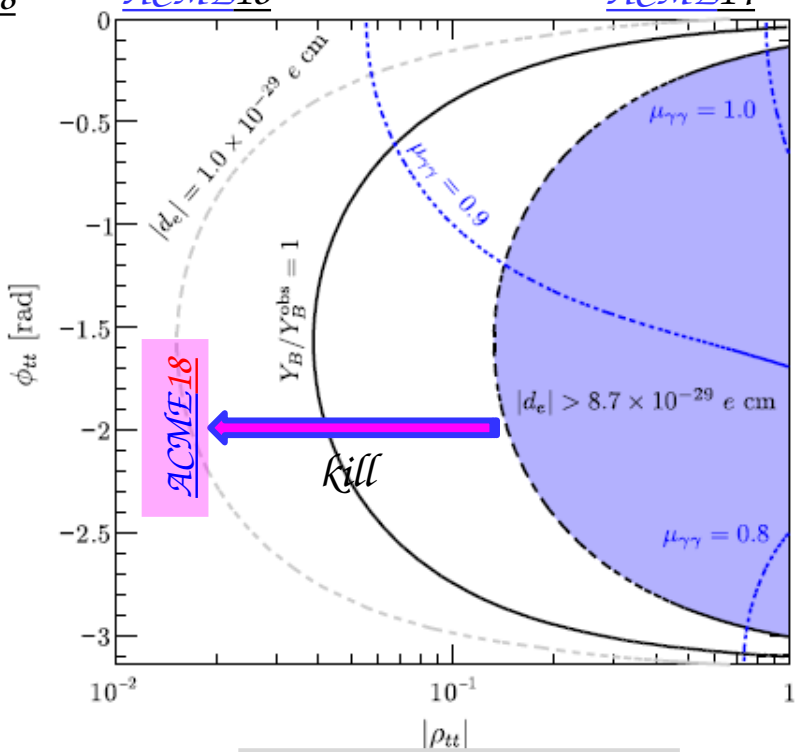
III. Under the Heavens on Earth: eEDM

complex ρ_{tt}

K. Fuyuto et al. / Physics Letters B 776 (2018) 402–406



FHS' 18



Oversimplified: $\rho_{ee} = 0$

EWBG ⇐ $\lambda_t \mathrm{Im}\,\rho_{tt}$ *robust driver* ⊕ *eEDM:* $\lambda_e \mathrm{Im}\,\rho_{tt}$

$O(\lambda_t) \approx 1$

$[\rho_{tc}$ *as backup*

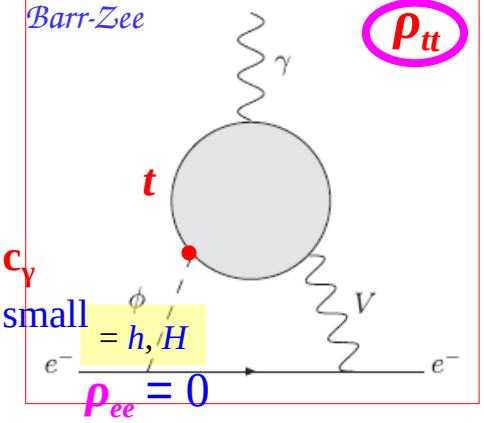
Ruled Out by ACME18!

Mech. to render small? Yes!

Cancellation Mechanism for d_{ThO} to survive

complex ρ_{tt}

Barr-Zee



c_γ small

$\phi = h, H$

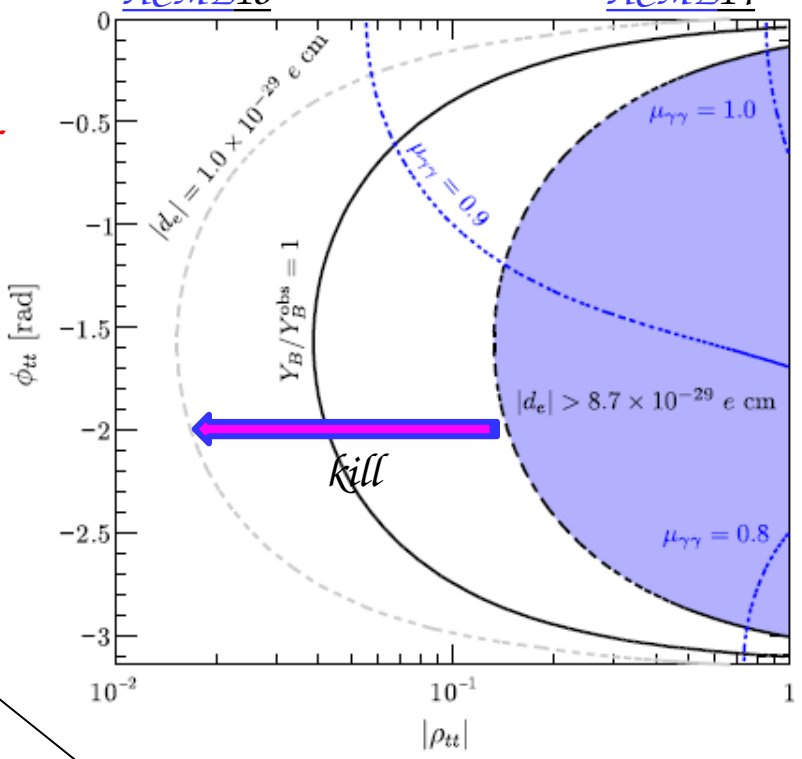
$\rho_{ee} = 0$

dom.

$$d_e = d_e^{\phi\gamma} + d_e^{\phi Z} + d_e^{\phi W}$$

Need to cancel

ACME18 ACME14



λ_e/λ_t FHS'18

$$\frac{(d_e^{\phi\gamma})_t}{e} = \frac{\alpha_{em} s_{2\gamma}}{12\sqrt{2}\pi^3 v}\frac{m_e}{m_t}\mathrm{Im}\rho_{tt}\Delta g,$$

$$= -6.6\times 10^{-29}\left(\frac{s_{2\gamma}}{0.2}\right)\left(\frac{\mathrm{Im}\rho_{tt}}{-0.1}\right)\left(\frac{\Delta g}{0.94}\right)$$

Ruled Out

EWBG ⟸ $\lambda_t \mathrm{Im}\rho_{tt}$ robust driver

$O(\lambda_t) \approx 1$

$$g(m_t^2/m_h^2) - g(m_t^2/m_H^2)$$

$$g(z) \equiv \tfrac{1}{2} z \int_0^1 dx \frac{1}{x(1-x)-z} \ln\frac{x(1-x)}{z}$$

FHS' 20 Fuyuto, WSH, Senaha, Phys. Rev. D **101**, 011901(R) (2020)

Barr, Zee, PRL'90

Cancellation Mechanism for d_{ThO}

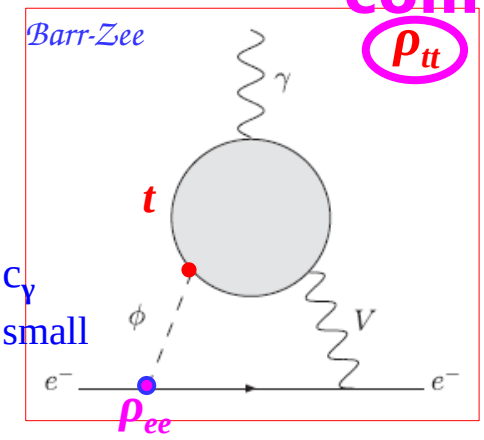
to survive ACME18:

turn on ρ_{ee}

complex ρ_{tt}

FHS' 20

Barr-Zee



c_γ small

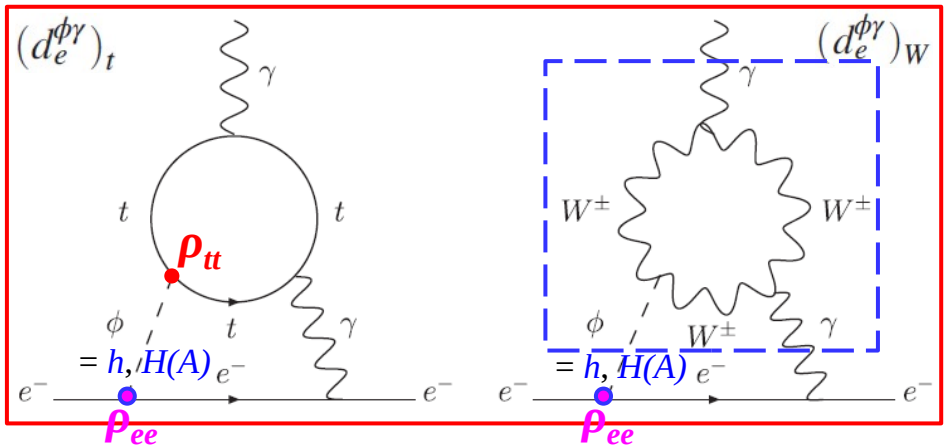
dom.

$$d_e = d_e^{\phi\gamma} + d_e^{\phi Z} + d_e^{\phi W}$$

Recall

$h \to \gamma\gamma$: W-loop > t-loop

Need to cancel



Abe,Hisano,Kitahara,Tobioka, JHEP' 14

h-H mixing

$$\frac{(d_e^{\phi\gamma})_t^{\rm mix}}{e} = \frac{\alpha_{\rm em} s_{2\gamma}}{12\sqrt{2}\pi^3 v}\left[{\rm Im}\rho_{ee}\Delta f + \frac{m_e}{m_t}{\rm Im}\rho_{tt}\Delta g\right]$$

$$\frac{(d_e^{\phi\gamma})_W^{\rm mix}}{e} = -\frac{\alpha_{\rm em} s_{2\gamma}}{64\sqrt{2}\pi^3 v}{\rm Im}\rho_{ee}\Delta\mathcal{J}_W^\gamma$$

Cancel

$$\frac{{\rm Im}\rho_{ee}}{{\rm Im}\rho_{tt}} = c\times\frac{\lambda_e}{\lambda_t}$$

$$c = (16/3)\Delta g/(\Delta\mathcal{J}_W^\gamma - (16/3)\Delta f)$$

purely extr. Yuk.

$$\frac{(d_e^{\phi\gamma})_t^{\rm extr}}{e} \simeq \frac{\alpha_{\rm em}}{12\pi^3 m_t}{\rm Im}(\rho_{ee}\rho_{tt})[f(\tau_{tA}) + g(\tau_{tA})]$$

0

$[m_H \to m_A$

$$\frac{{\rm Re}\rho_{ee}}{{\rm Re}\rho_{tt}} = -\frac{{\rm Im}\rho_{ee}}{{\rm Im}\rho_{tt}}$$

$$\left|\frac{\rho_{ee}}{\rho_{tt}}\right| = c\frac{\lambda_e}{\lambda_t}$$

w/ correlated phase

$$d_{\rm ThO} = d_e + \alpha_{\rm ThO} C_S$$

$\alpha_{\rm ThO} = 1.5 \times 10^{-20}$

ACME18

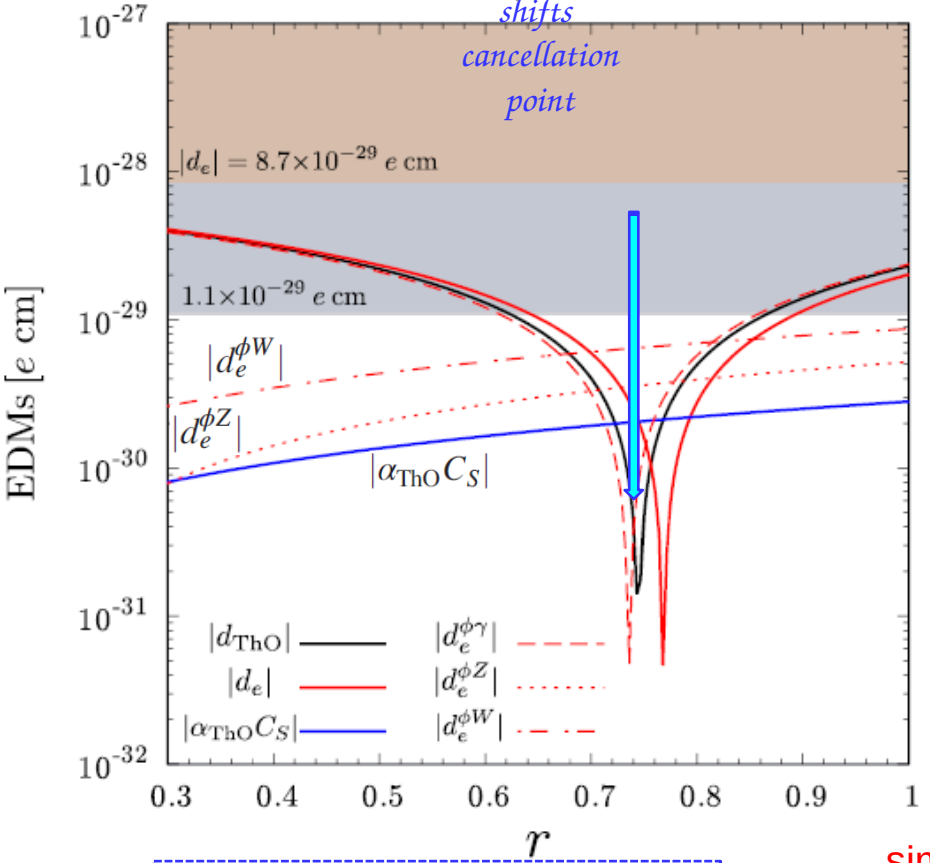
$(4.3 \pm 4.0) \times 10^{-30}\ e\,{\rm cm}$

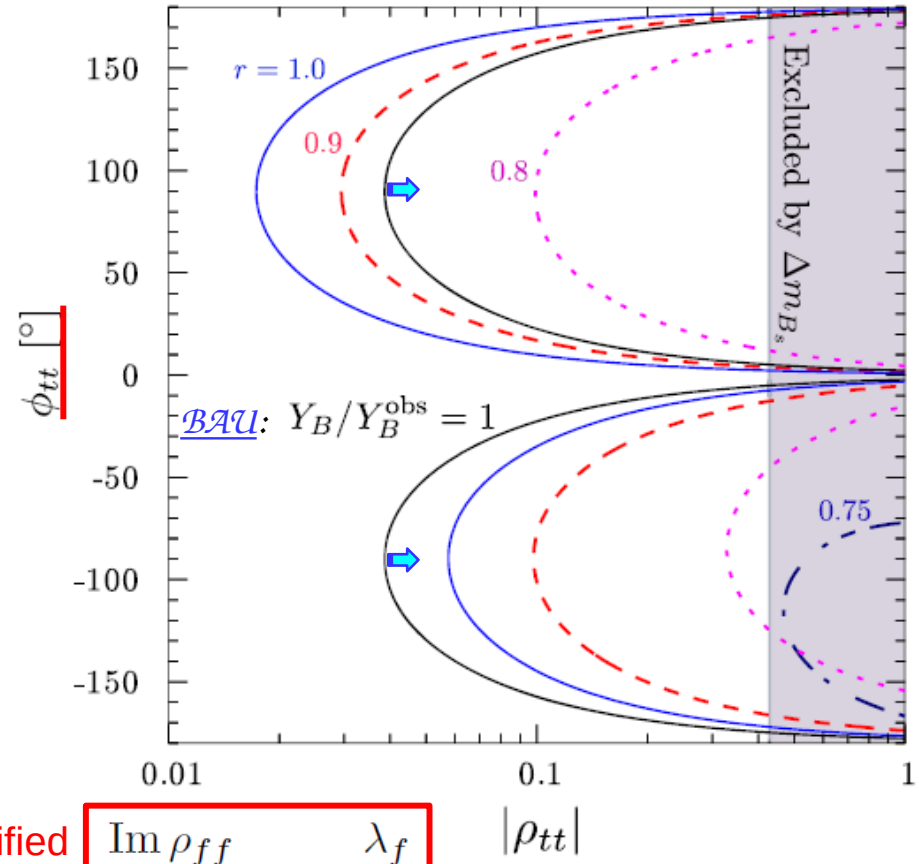
cancel. mech.

$$d_e = d_e^{\phi\gamma} + d_e^{\phi Z} + d_e^{\phi W} \qquad -\frac{i}{2} d_e (\bar{e}\sigma^{\mu\nu}\gamma_5 e) F_{\mu\nu} \qquad -\frac{G_F}{\sqrt{2}} C_S (\bar{N}N)(\bar{e} i\gamma_5 e)$$

shifts cancellation point

FHS' 20





$$C_S = -2v^2\left[6.3(C_{ue}+C_{de}) + C_{se}\frac{41\ {\rm MeV}}{m_s} + C_{ce}\frac{79\ {\rm MeV}}{m_c} + 0.062\ ({\rm GeV})\left(\frac{C_{be}}{m_b}+\frac{C_{te}}{m_t}\right)\right]$$

consistent w/ Cesarotti, Lu, Nakai, Parikh, Reece, JHEP' 18

simplified "Ansatz"

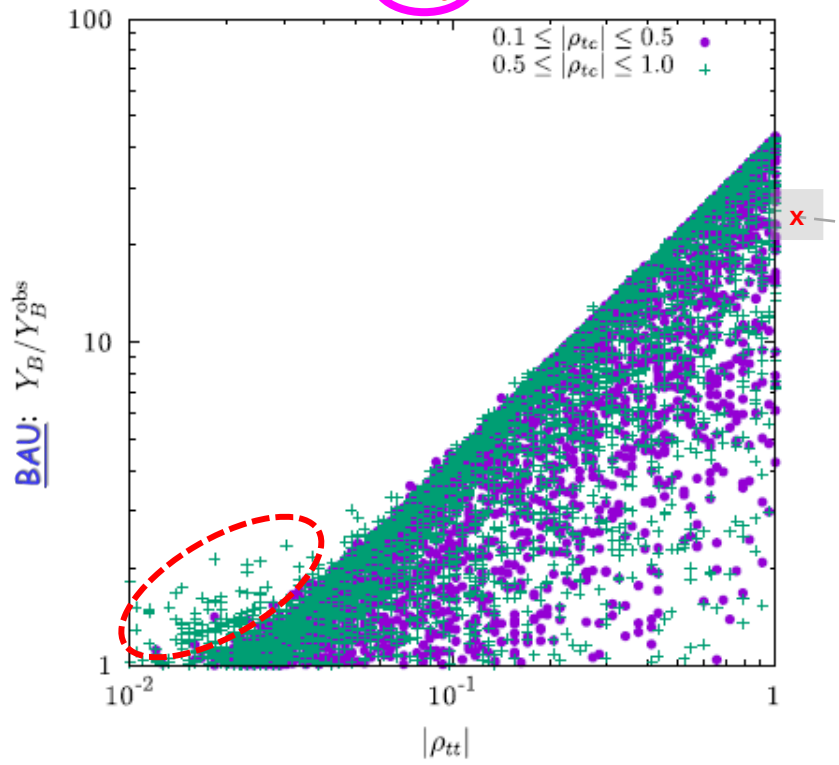
$$\frac{{\rm Im}\,\rho_{ff}}{{\rm Im}\,\rho_{tt}} = r\frac{\lambda_f}{\lambda_t} \qquad \frac{{\rm Re}\,\rho_{ff}}{{\rm Re}\,\rho_{tt}} = -r\frac{\lambda_f}{\lambda_t}$$

Follow SM Hierarchy

N.B. **r** can be **f**-dep.

complex ρ_{tt}

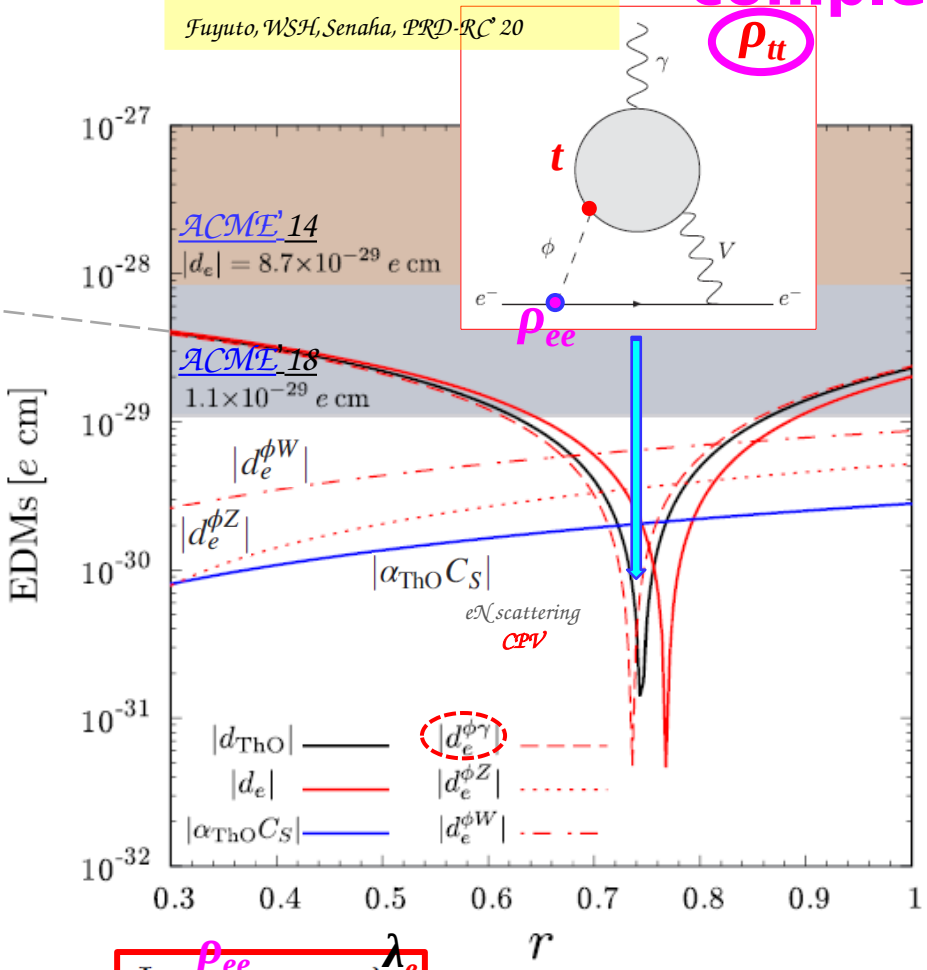
Fuyuto, WSH, Senaha, PLB' 18



x

Fuyuto, WSH, Senaha, PRD-RC' 20

complex ρ_{tt}



EWBG ⟸ $\lambda_t \,\mathrm{Im}\,\rho_{tt}$ *robust driver*

$O(\lambda_t) \approx 1$

[ρ_{tc} as backup

simplified "Ansatz"

$$\frac{\mathrm{Im}\,\rho_{ff}}{\mathrm{Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t}$$
$$\frac{\mathrm{Re}\,\rho_{ff}}{\mathrm{Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

(ρ_{ee}, λ_e)

"Know" SM Hierarchy!

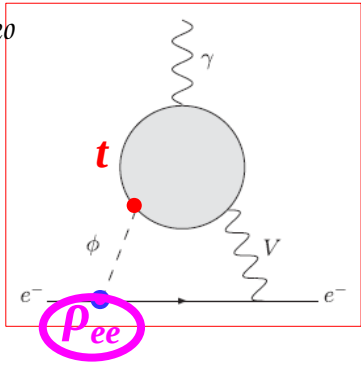
N.B. **r** *depend on loop functions*

Extra Weinberg* Couplings

Baryogenesis & electron EDM

complex ρ_{tt}

Fuyuto, WSH, Senaha, PRD-RC'20



O Lord, our Lord,
How Majestic is Thy Name
in all the Earth,
Who have set Thy Splendor
above the Heavens !

Psalm 8:1 (of David)

EWBG ⟸ $\lambda_t \mathrm{Im}\,\rho_{tt}$ *robust driver*

$O(\lambda_t) \approx 1$

[ρ_{tc} *as backup*

Fuyuto, WSH, Senaha, PLB'18

simplified "Ansatz"

ρ_{ee} λ_e

$$\frac{\mathrm{Im}\,\rho_{ff}}{\mathrm{Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t}$$
$$\frac{\mathrm{Re}\,\rho_{ff}}{\mathrm{Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

"Know" SM Hierarchy!

N.B. **r** *depend on loop functions*

On "the Heavens and the Earth"

- *Amusing:* *Largest* *diagonal* **extra** *Yukawa* ρ_{tt} *drives* B.A.U.,
  in concert w/smallest diagonal **extra** *Yukawa* ρ_{ee} *for* *e*EDM;

  could be revealed soon by very-L.E. ultraprecision probes.

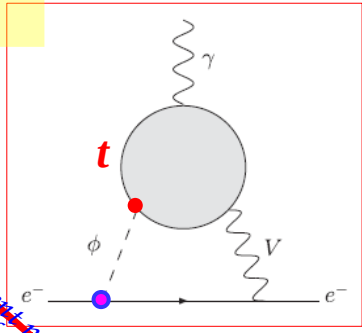
  10^{-29} ~~-10^{-30}~~ *e*cm looks **fabulous**. *Godspeed success!*

Only one expt has reached 10^{-29} *so far …*

III Emergent: Nature's Flavor Enigma Design

Fuyuto, WSH, Senaha, PLB' 18

Fuyuto, WSH, Senaha, PRD-RC' 20



We are Probing Extra Yukawa Couplings: ρ_{tc}; $\rho_{\mu\tau}$

$t \to ch$; $h \to \mu\tau$

$* c_\gamma$

c_γ small (Emergent) Alignment protection:

Glashow-Weinberg'77: Absence of 2nd "Yukawa"!

Glas.-Wein. Knew:

$$m_e \ll m_\mu \ll m_\tau,$$
$$m_d \ll m_s \ll m_b,$$
$$m_u \ll m_c \ll m_t,$$

Did not expect:

$$m_t/m_b \gg 1,$$

1986± [B^0 mixing]

Totally Out of Whack: ca. 1983

$$|V_{ub}|^2 \ll |V_{cb}|^2 \ll |V_{us}|^2 \ll |V_{tb}|^2 \cong 1,$$

10^{-5} 10^{-3} 1/20

Mass-Mixing Hierarchy

Nature's Design

WSH, Kikuchi, EPL' 18: Mass-Mixing Hier. + Alignment Retire Glas.-Wein. NFC

EWBG ⟸

$\lambda_t \mathrm{Im}\,\rho_{tt}$ robust driver

$O(\lambda_t) \approx 1$

[ρ_{tc} as backup

simplified "Ansatz"

$$\frac{\mathrm{Im}\,\rho_{ff}}{\mathrm{Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t}$$
$$\frac{\mathrm{Re}\,\rho_{ff}}{\mathrm{Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

(ρ_{ee}, λ_e)

"Know" SM Hierarchy!

N.B. r depend on loop functions

extra Yukawas reflect SM Yukawa pattern

$$\rho_{ii} \lesssim \mathcal{O}(\lambda_i);\quad \rho_{1i} \lesssim \mathcal{O}(\lambda_1);\quad \rho_{3j} \lesssim \mathcal{O}(\lambda_3)\ (j \neq 1)$$

WSH & Kumar, PRD' 20

IV. Phenomenological Consequences

H/A/$H^{\pm}$ *Search &* Flavor *Frontier*

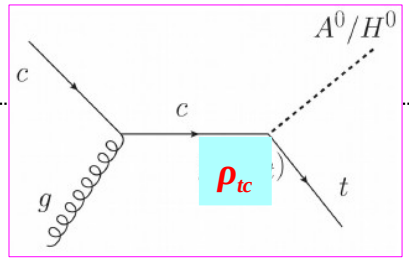
Leading Search Modes at the LHC

G2HDM

Sub-TeV Spectrum

WSH, Kikuchi, EPL'18

H/A/H± Search



Search at ATLAS/CMS started

ATLAS-CONF-2022-039 (ICHEP)

Kohda, Modak, WSH, PLB'18

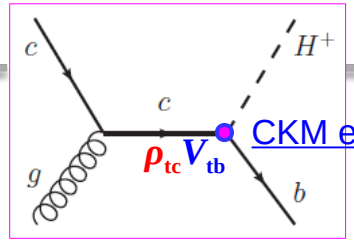
Search Zone

cg → tH/A $\xrightarrow{\rho_{tc}}$ ttc(bar) Same-Sign Top + jet

$\xrightarrow{\rho_{tt}}$ ttt(bar) Triple-Top (High Lumi LHC; higher mass, more exquisite, tiny SM)

cg → bH⁺ → btb(bar) Top w/ two p_T b-jets (H⁺)

Ghosh, WSH, Modak, 1912.10613 (PRL'20)



CKM enhanced

v.e.v.

HKM, PLB'18

GeV

800

700

600

500

400

300

200

100

H, A, H^+

$t\bar{t}$

t

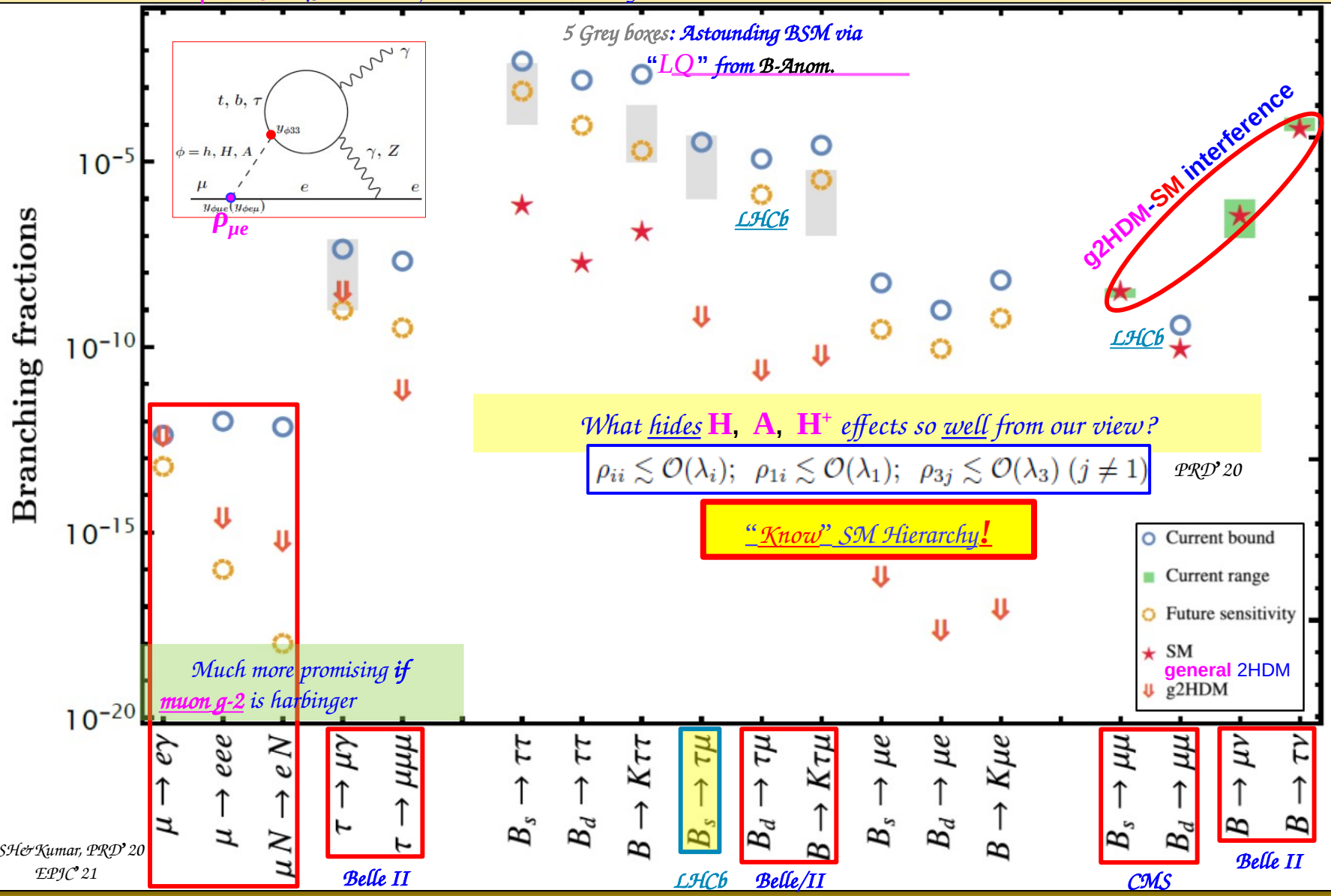
h

W Z

ν	eμτ	dsb	uc	γ g	
neutrino	lepton	down-type	up-type	vector	scalar

Glimpse of coming New Flavor *Era*

μ & τ FV (Flav.Viol.) *in* B *decay*



WSHou&Kumar, PRD' 20
EPJC' 21

h(125) ✔ New Physics ✘

High Scale SUSY?!

Where is SUSY?

Space to be

Filled in the

Future…

unconventional-Conventional

Road Not Taken

Extra Higgs Doublet w/

Extra Weinberg Couplings

& Extra Quartic Couplings

1st EWPT Lattice

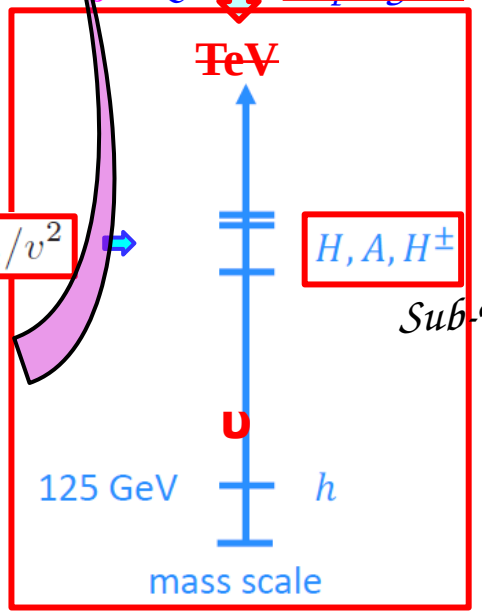
Dim'less Quartics O(1) (Naturalness):

η_i with $i = 1$–7; μ_{22}^2/v^2

100 TeV pp collider

Landau Pole ~ 10-20 TeV

WSH, Kikuchi, EPL'18



V. Summary

the Alpha and the Ω

I could have told you up front:

H^0, A^0, $H^\pm$ ~ *500 GeV*

can generate ***B.A.U.***

accommodate ***e*** *EDM*

CAN

Verify at LHC.

⇒ *Fantastic!!*

and **FPCP** *Probes* !

Decadal Mission:

Find the extra **H**, **A**, **$H^\pm$** *bosons and Crack the* **Flavor** *code*!

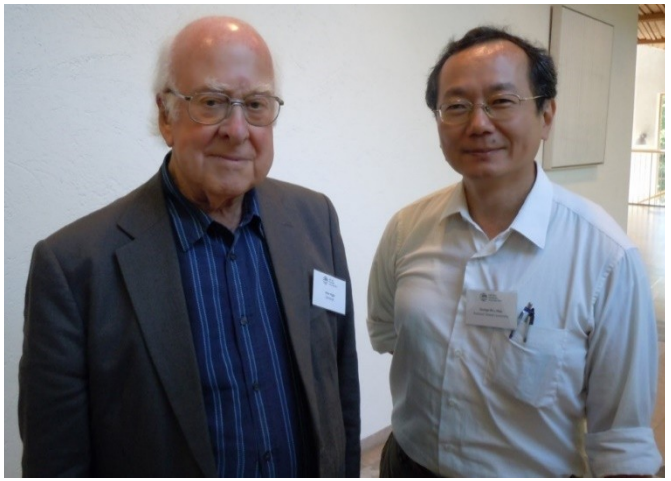
Go CMS *&* Belle II *(and others)*!

& Lattice

Chin. J. Phys. **77** (2022) 432-451 [2109.02557 [hep-ph]]

Thank you!

Join the Mission



Caution: Good reasoning does not mean Nature has to oblige …

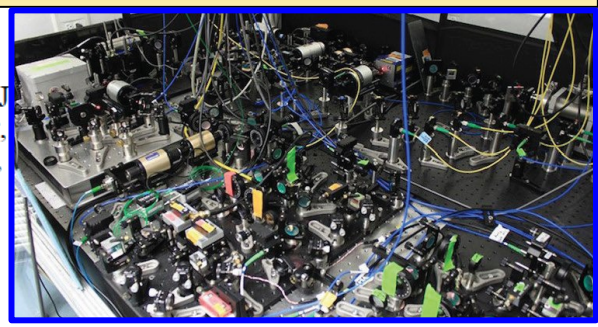
a Higgs; and a 2nd Higgs …

Enter the Advanced Cold Molecule Electron EDM Experiment

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration, J. Baron, W. C. Campbell, D. DeMille, J. M. Doyle, G. Gabrielse, Y. V. Gurevich, P. W. Hess, N. R. Hutzler, E. Kirilov, I. Kozyryev, B. R. O'Leary, C. D. Panda, M. F. Parsons, E. S. Petrik, B. Spaun, A. C. Vutha and A. D. West (December 19, 2013)

Science **343** (6168), 269-272. [doi: 10.1126/science.1248213] originally published online December 19, 2013



ACME14

ThO

Editor's Summary

Stubbornly Spherical

polar molecule thorium monoxide, we measured $d_e = (-2.1 \pm 3.7_{stat} \pm 2.5_{syst}) \times 10^{-29}$ e·cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ e·cm with 90% confidence, an order of magnitude

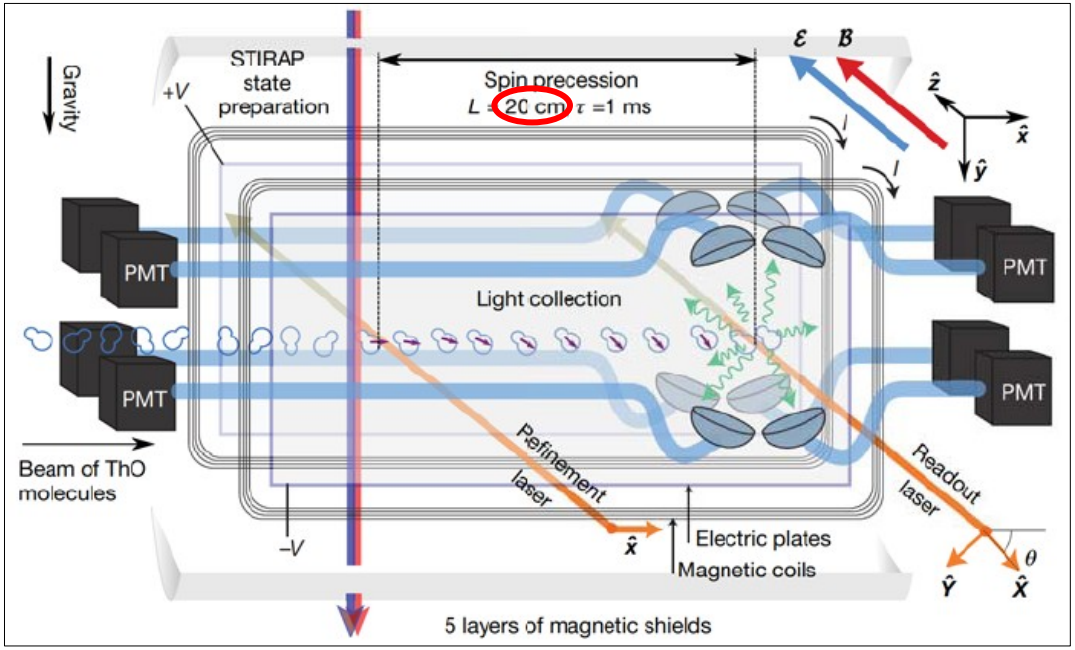
JILA'17 (E. Cornell): < 13 x 10^{-29} $e$cm

$$|d_e| < 1.1 \times 10^{-29} e\,\mathrm{cm} \quad (5)$$

at 90% confidence level. This is 8.6 times smaller than the best previous limit, from ACME I[1,9]. Because paramagnetic molecules are sensitive to multiple time-reversal-symmetry-violating effects[3,4], our measurement can be more generally interpreted as $\hbar\omega^{\mathcal{NL}} = -d_e\mathcal{E}_{\mathrm{eff}} + W_S C_S$, where C_S is a dimensionless time-reversal-symmetry-violating electron–nucleon coupling parameter and $W_S = -2\pi\hbar \times 282$ kHz is a molecule-specific constant[16,17,35]. For the d_e limit given above, we assume $C_S = 0$. Assuming $d_e = 0$ instead gives $|C_S| < 7.3 \times 10^{-10}$ (90% confidence level).

Because the values of d_e and C_S predicted by the standard model are many orders of magnitude below our sensitivity[2,3], this measurement is a background-free probe for new physics beyond the standard model. Nearly every extension of the standard model[4–6] introduces the possibility for new particles and new time-reversal-symmetry-violating phases, ϕ_P, that can lead to measurable EDMs. Within typical extensions of the standard model, an EDM arising from new particles

ACME18



IV′. Pheno Consequences: one-loop muon g - 2

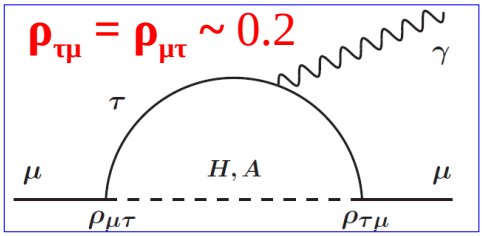
- $gg \xrightarrow{\rho_{tt}} H, A \xrightarrow{\rho_{\mu\tau}} \mu\tau$: stringent bound on $\rho_{tt}\,\rho_{\mu\tau}$, so could appear soon!

  $\rho_{tt} > 0.1$ can still drive EWBG.

- $gg \xrightarrow{\rho_{tt}} H, A \xrightarrow{\rho_{tc}} tc$: ρ_{tc} can dilute the above

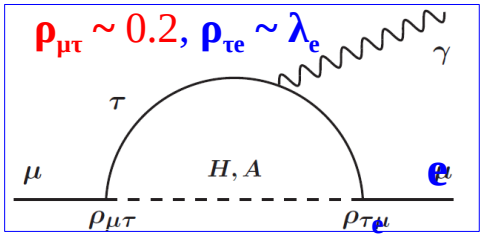
  ⇒ $cg \to bH^+ \to \mu\tau bW^+, tcbW^+$ fancy LHC signatures.

WSH, Jain, Kao, Kumar, Modak, 2105.11315 (PRD'21)



- *Revival* of muon-related physics:
  - MEG II discovery plausible (with $\rho_{\tau e} \sim \lambda_e$)
  - follow-up by $\mu N \to eN$, can even probe ρ_{qq}!
  - $\tau \to \mu\gamma$: probe $\rho_{\tau\tau} \sim \lambda_\tau$! / $\tau \to 3\mu$: probe $\rho_{\mu\mu} \sim \lambda_\mu$!

WSH, Kumar, 2107.14114 (EPJC'21)

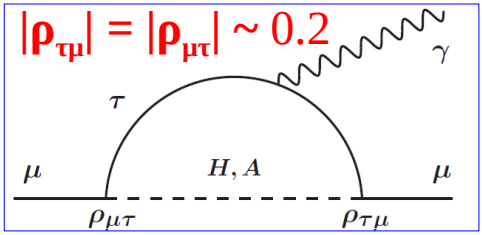


- μEDM: Same one-loop diagram, complex $\rho_{\tau\mu}\rho_{\mu\tau}$ ⇒ CPV

  ⇒ Possibly discoverable at PSI with planned sensitivity!

$6 \times 10^{-23}\ e\,\mathrm{cm}$

WSH, Kumar, 2109.08936 (JHEP'22)



N.B. This one-loop muon g - 2 would make Nature appear "whimsical"!