CP Violation for the Heavens *and* on Earth

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National Taiwan University

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

0. Intro: Our Life & Times – Setting

I. General 2HDM

II. Electroweak Baryogenesis

III. eEDM 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

I. General 2HDM

Two Higgs Doublet Model

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: $\mathcal{O}(1)$ Higgs Quartics OK / CPV in V(Φ_1, Φ_2) problematic w/ d_n

Wise to keep V(Φ_1, Φ_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: $\mathcal{O}(1)$ Higgs Quartics OK / Extra Yukawa's w/o Z_2

$\mathcal{O}(1)$
ρ_{tt} the driver; ρ_{tc} the backup

EWBG

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

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

Extra Yukawa Couplings

General 2HDM w/o Z_2

General Yukawa interaction for up-type quarks

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

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

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

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

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

$$\rho = V_L^{u\dagger}\,(-Y_1\, s_\beta + Y_2\, c_\beta)\,V_R^u$$ FCNH (flavor changing neural H)

Neutral up-type Yukawa interaction

c_γ $c_{\beta-\alpha} \to 0$ alignment limit!

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

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

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

→ FCNH ρ_{ij}

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

Extra Higgs Quartic Couplings

Sub-TeV Spectrum & 1st EWPT

SM

V(Φ) ~ − $\mu^2|\Phi|^2 + \lambda|\Phi|^4$

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

Higgs basis

G2HDM

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

$$\mu_{12}^2 = \frac{1}{2}\eta_6 v^2$$

"min. cond."

w/o Z_2

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; μ_{22}^2/v^2 ⇨ H, A, H+

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

v.e.v.

Alignment argument →

unnatural

incredulous

GeV: 800, 700, 600, 500, 400, 300, 200, 100

tt̄, h, W Z

a Sakharov condition: 1st EWPT

N.B. $\mathcal{O}(1)$ η_i's needed for 1st order Phase Trans., prerequisite for ElectroWeak BaryoGenesis.

Kanemura,Okada,Senaha, PLB'05

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

II. EWBG

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

strongly 1st order EW phase transition (EWPT)

Extra Higgs Thermal Loops
w/ $\mathcal{O}(1)$ Higgs Quartics

2HDM OK

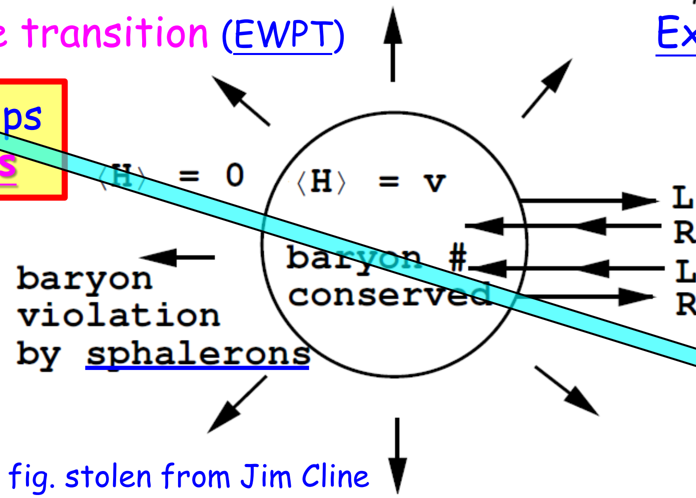


fig. stolen from Jim Cline

Expanding Bubble of Broken Phase

To avoid n_B washout:

Hubble const.

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

n_B changing rate (br)

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

vev @ T_C

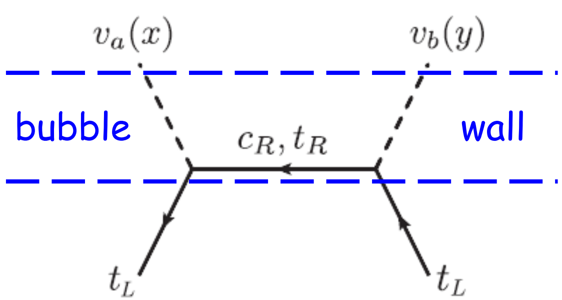
$\sqrt{v_1^2(T_C) + v_2^2(T_C)}$

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

$$Y_B^{\mathrm{obs}} = 8.59 \times 10^{-11}$$



$\Gamma_B^{(\mathrm{sym})} = 120\alpha_W^5 T$		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

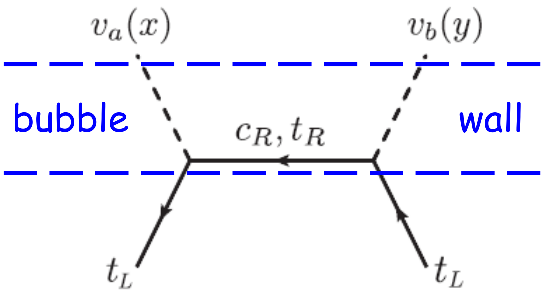
CPV source term

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

$Z = (t_Z, \boldsymbol{Z})$	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

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



BAU $\Leftarrow$ CPV Top interactions at Bubble Wall $\Rightarrow$ n_L

n_L left-handed Top density

z' coord. oppo. bubble exp. dir.

skip detail (Transport)

CPV Top interactions

CPV source term

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

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

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 $\sqrt{2}Y^{\rm SM} = Y_1 + Y_2$ diag. by just V_R^u

but $-Y_1 + Y_2$ not diag.

solve

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

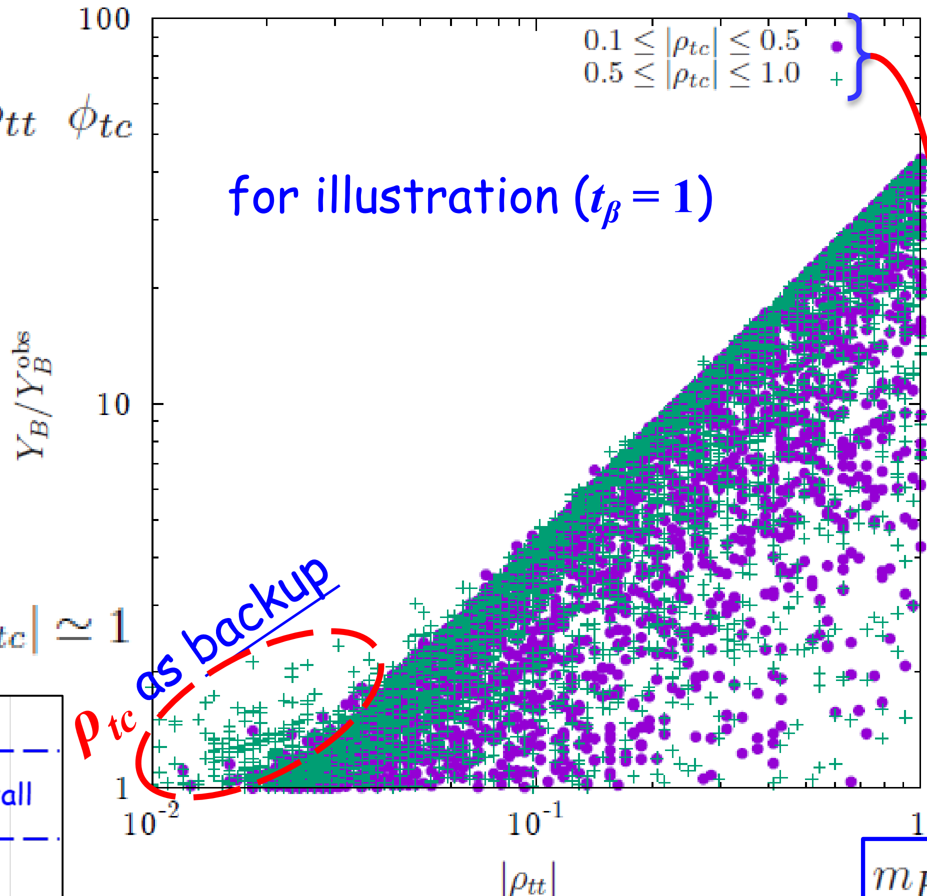
ρ_{tc} still basically free param.

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

Robust: Large Parameter Space for EWBG

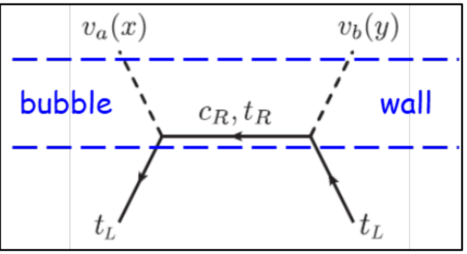
scan over $|\rho_{tc}|\ \ \phi_{tt}\ \ \phi_{tc}$

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



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

no obvious diff.
$\Rightarrow \rho_{tt}$ driven!



the charm of EWBG

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

small ρ_{tt}

$v_C/T_C > \mathcal{O}(1)$

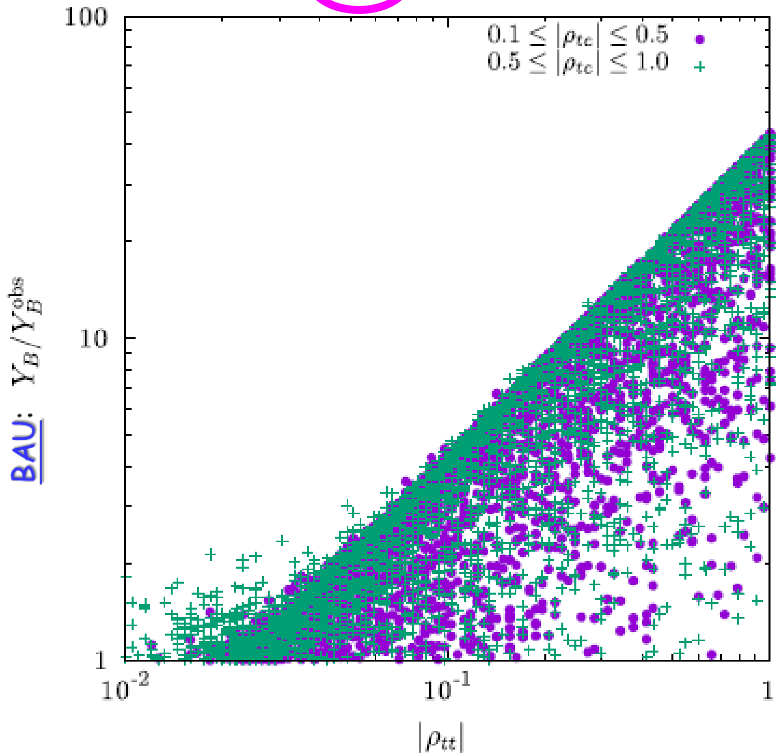
$T_C = 119.2$ GeV	$v_C = 176.7$ GeV	$v_w = 0.4$	$\Delta\beta = 0.015$	$D_q = 8.9/T$	$D_H = 101.9/T$
$m_{t_L} = 0.59T$	$m_{t_R} = 0.62T$	$m_{c_R} = 0.50T$	$\Gamma_{q_{L,R}} = 0.22T$	$\Gamma_B^{(s)} = 120\alpha_W^5 T$	$\Gamma_{ss} = 16\alpha_s^4 T$

III. Under the Heavens on Earth: eEDM

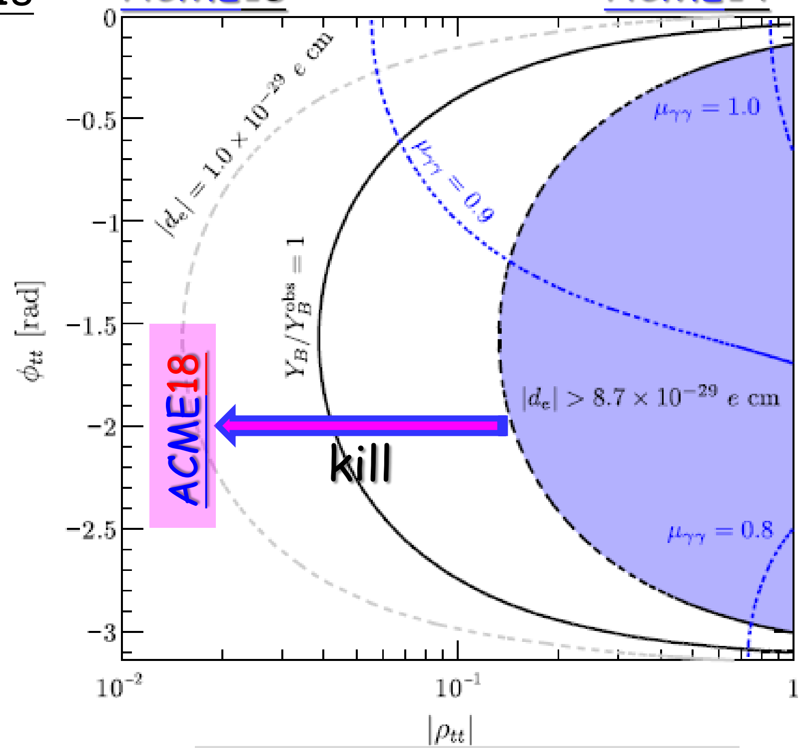
complex ρ_{tt}

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

FHS'18



ACME18 ACME14



Oversimplified: $\rho_{ee} = 0$

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

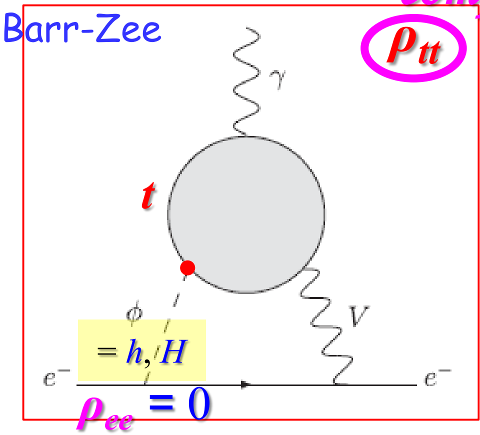
$\mathcal{O}(\lambda_t) \approx 1$

[ρ_{tc} as backup

Ruled Out by ACME18!

Mech. to render small? Yes!

Barr-Zee



dom.

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

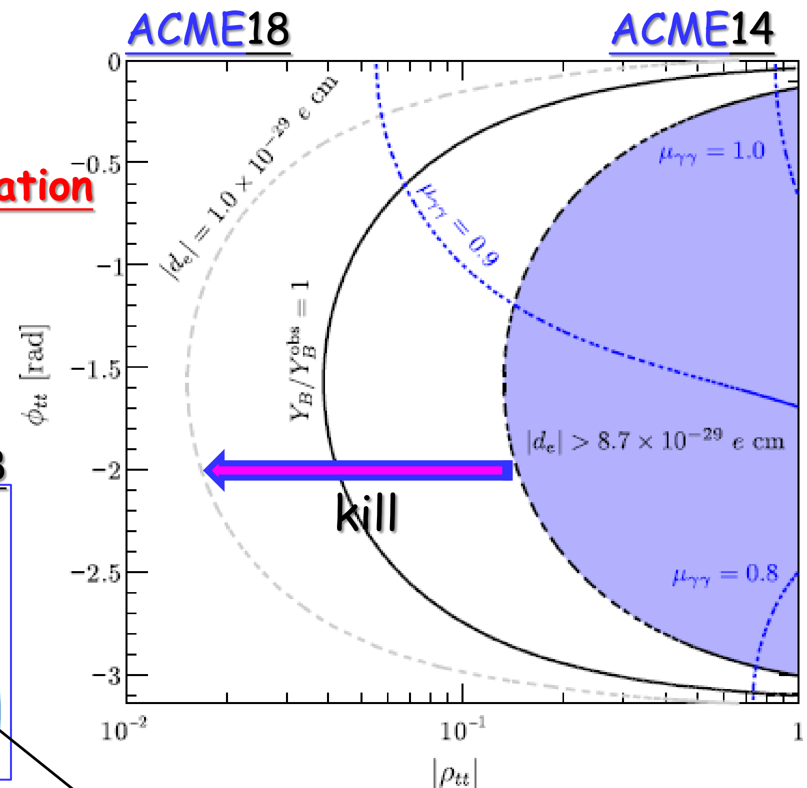
need cancellation

FHS'18

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

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

Ruled Out



EWBG ⇐ $\lambda_t {\rm Im}\rho_{tt}$ robust driver

$\mathcal{O}(\lambda_t) \approx 1$

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

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

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

Barr, Zee, PRL'90

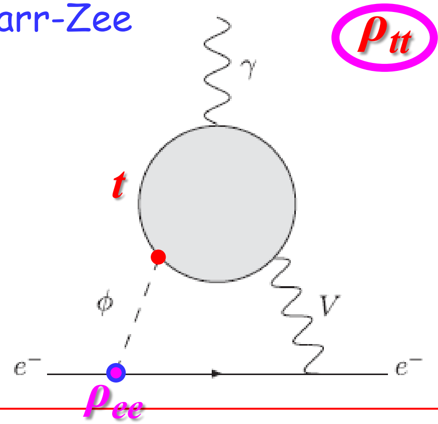
Cancellation Mechanism for $d_{\rm ThO}$ to survive ACME18:

turn on ρ_{ee}

FHS'20

Barr-Zee

complex ρ_{tt}



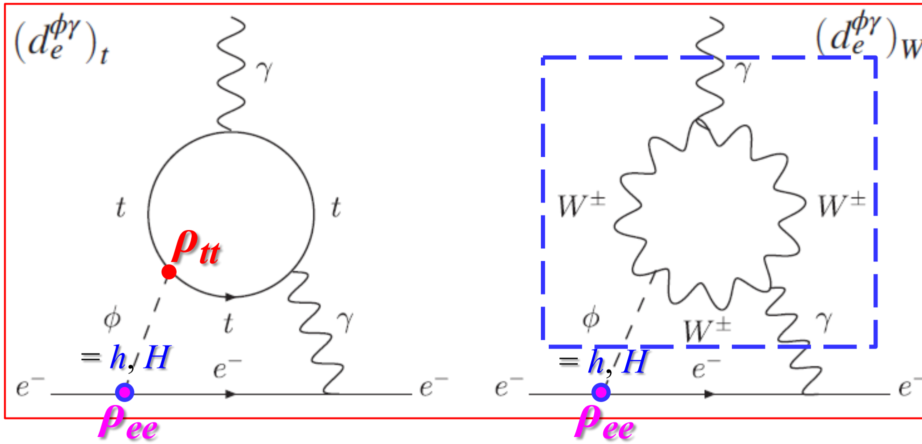
dom.

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

need cancellation

N.B.

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



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

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

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

ACME18

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

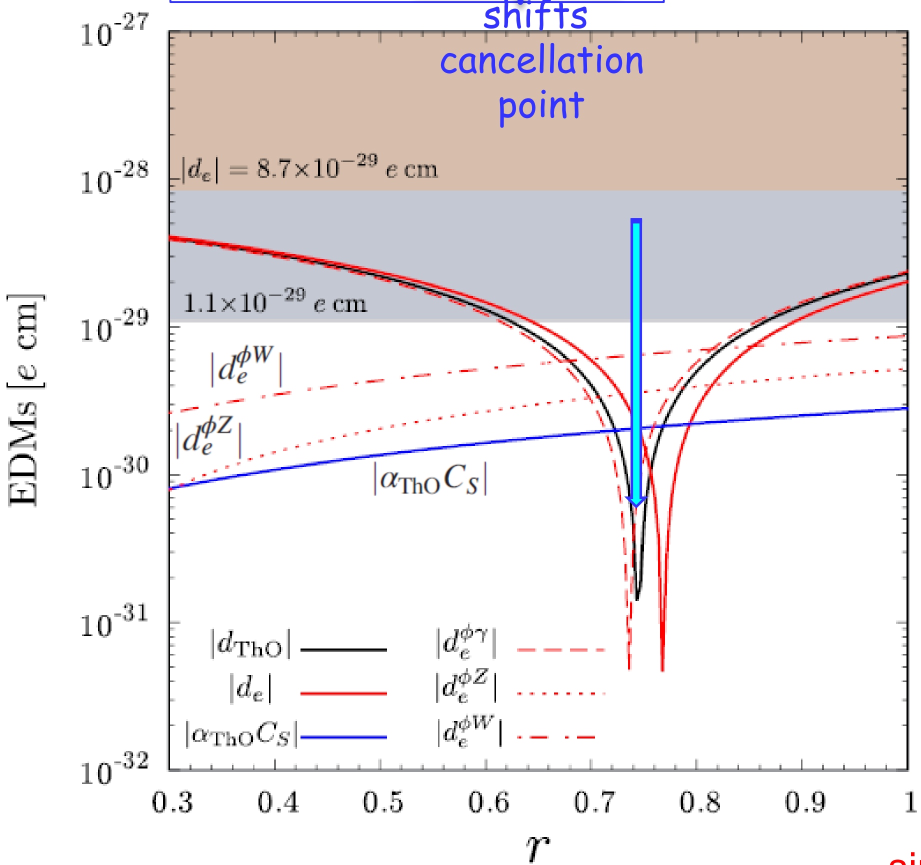
cancel. mech.

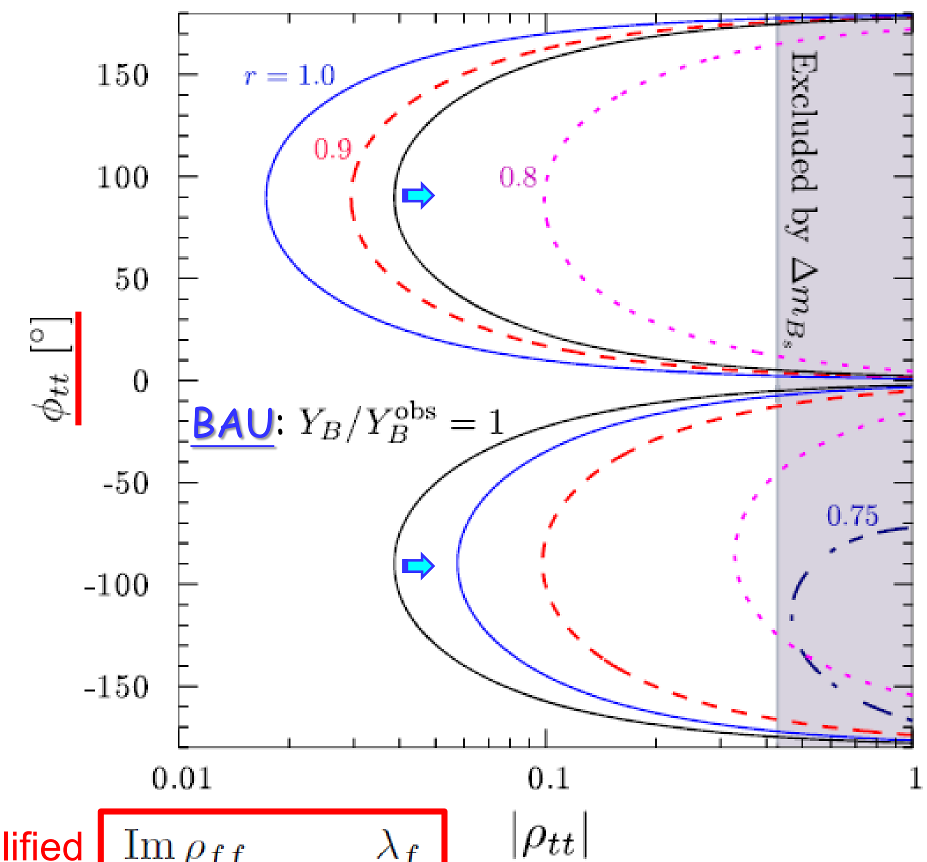
$$d_e = d_e^{\phi\gamma} + d_e^{\phi Z} + d_e^{\phi W}$$

$$-\frac{i}{2} d_e (\bar{e}\sigma^{\mu\nu}\gamma_5 e) F_{\mu\nu} \quad - \frac{G_F}{\sqrt{2}} C_S (\bar{N}N)(\bar{e} i\gamma_5 e)$$

FHS'20

shifts cancellation point





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

(GeV)

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

simplified "Ansatz"

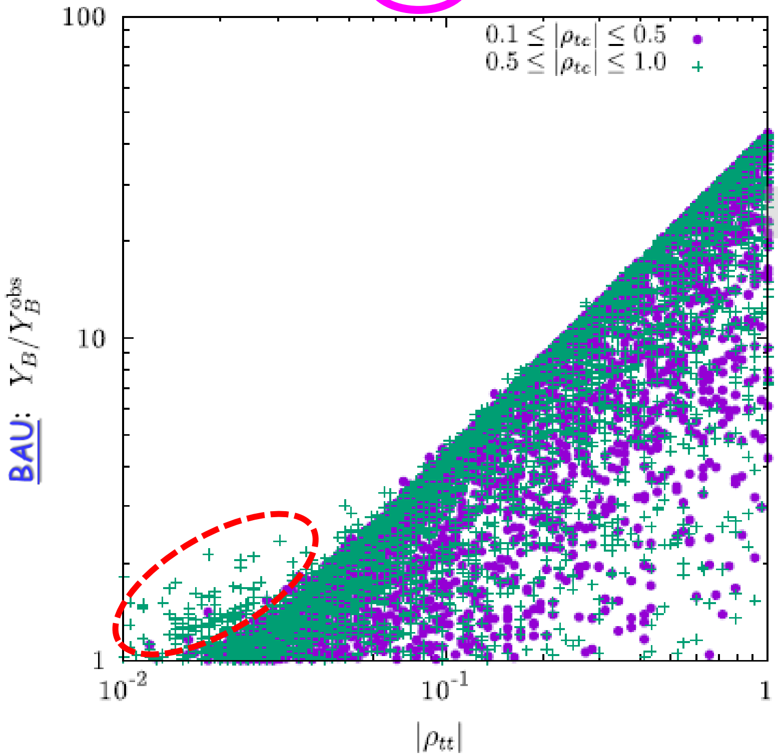
$$\frac{\mathrm{Im}\,\rho_{ff}}{\mathrm{Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t} \qquad \frac{\mathrm{Re}\,\rho_{ff}}{\mathrm{Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

Follow SM Hierarchy

N.B. r can be f-dep.

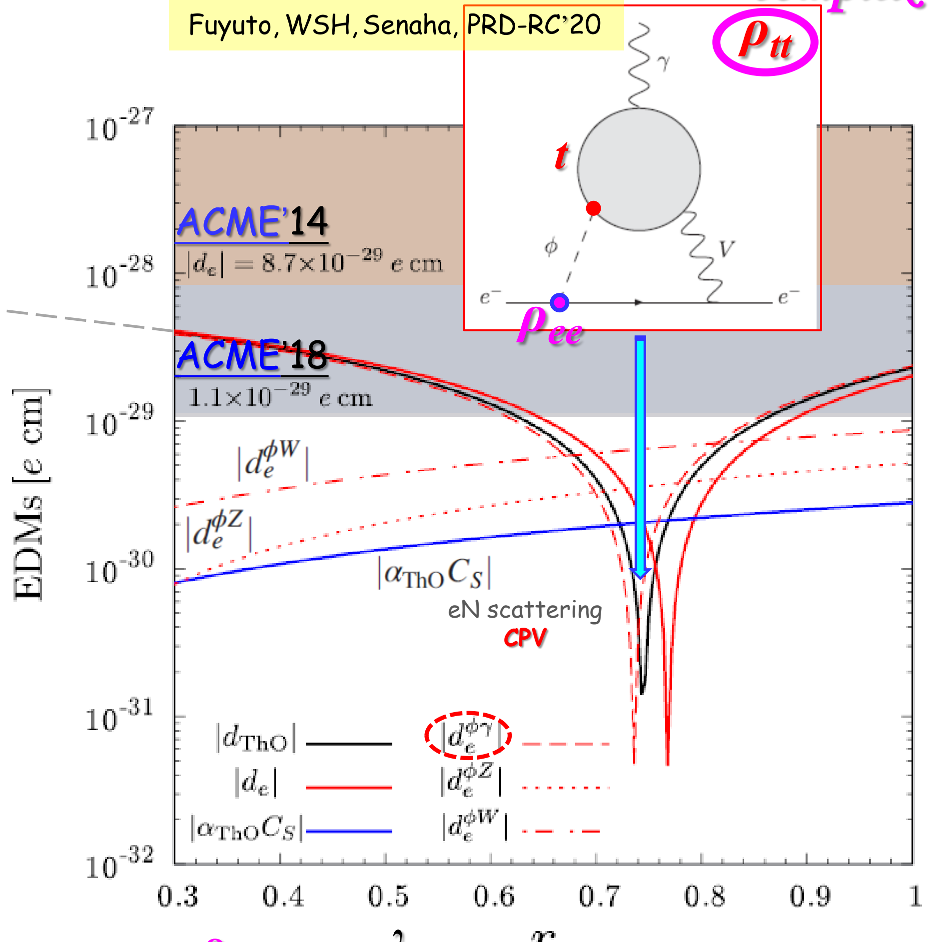
Fuyuto, WSH, Senaha, PLB'18

complex ρ_{tt}



Fuyuto, WSH, Senaha, PRD-RC'20

complex ρ_{tt}



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

$\mathcal{O}(\lambda_t) \approx 1$

[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)

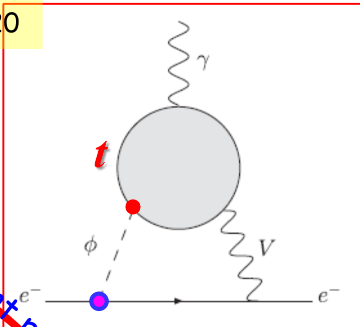
Follow SM Hierarchy!

N.B. r depend on loop functions

III′. Emergent: Nature's Flavor *Design*

Fuyuto, WSH, Senaha, PLB'18

Fuyuto, WSH, Senaha, PRD-RC'20



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

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

$^* c_\gamma$

Alignment protection: c_γ small (Emergent)

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

Glas.-Wein. Knew:

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

Did not expect:

$$m_t/m_b \gg 1,$$

1986⁺

Totally Out of Whack: ca. 1983

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

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

$\mathcal{O}(\lambda_t) \approx 1$

[ρ_{tc} as backup

simplified "Ansatz"

ρ_{ee} λ_e

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

Follow SM Hierarchy!

N.B. r depend on loop functions

On "the Heavens and the Earth"

ρ_{tt}

ρ_{ee}

In context of **EWBG** driven by an *extra* ***top*** Yukawa coupling, the impressive **ACME18** bound suggests an *extra* ***electron*** Yukawa coupling that works in concert to give *exquisite* **cancellation** among dangerous diagrams. The cancellation mechanism calls for the *extra* Yukawas to *echo* the *hierarchical pattern* of SM Yukawa couplings.

known

- ACME14 was confirmed by JILA17 using HfF^+, i.e. good that "JILA is chasing Harvard/Yale(/Northwestern)."

- 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!

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

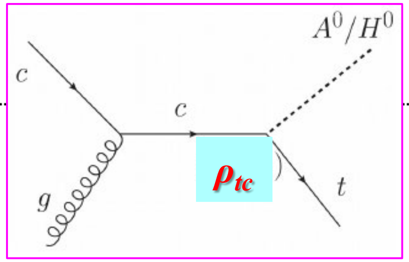
H/A/H^+ Search & *Flavor* Frontier

Leading Search Modes at the LHC

*G*2HDM

Sub-TeV Spectrum

WSH, Kikuchi, EPL'18



Search at ATLAS/CMS started

Search Zone

Kohda, Modak, WSH, PLB'18

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)

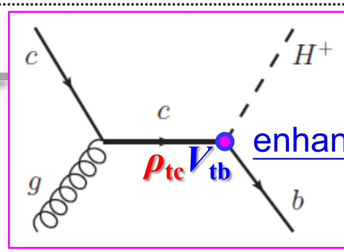
cg → bH⁺ → btb(bar) Top w/ two p_T b-jets (H⁺)

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

H, A, H⁺

√ HKM, PLB'18

v.e.v.



enhanced

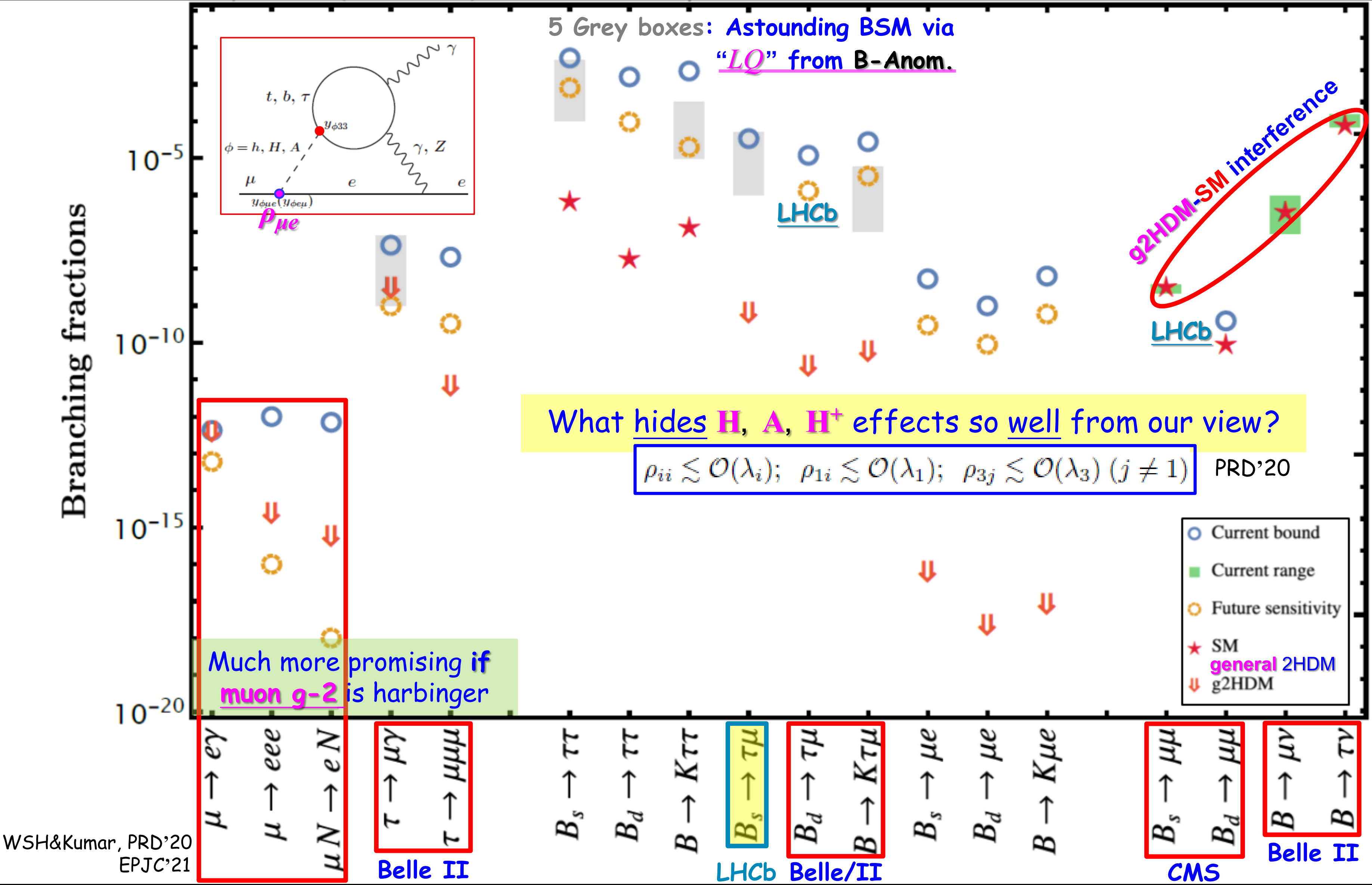
GeV: 800, 700, 600, 500, 400, $t\bar{t}$, 300, 200, 100

t, h, W Z

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

Glimpse of coming New *Flavor* Era

μ & τFV (Flav.Viol.) in B decay



Our Life & Times

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

1^{st}EWPT

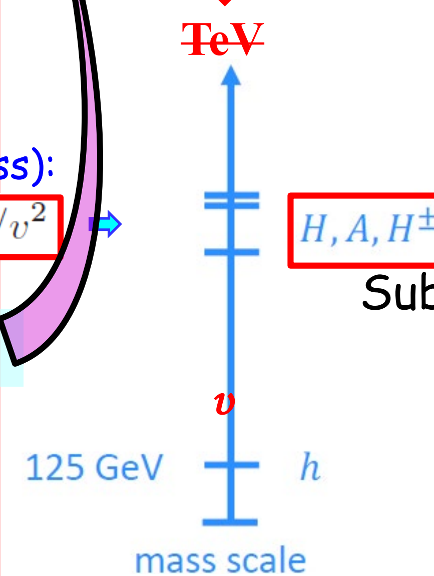
Dim'less Quartics $\mathcal{O}(1)$ (Naturalness):

η_i with $i = 1$–7; μ_{22}^2/v^2

100 TeV pp collider

➔ Landau Pole ~ 10-20 TeV

WSH, Kikuchi, EPL'18

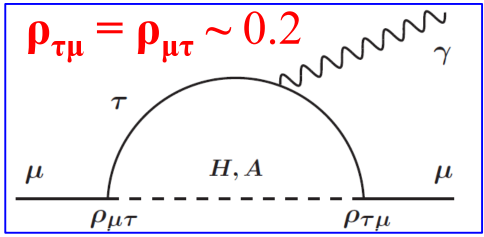


Sub-TeV

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

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

  ρ_{tt} > 0.1 can still drive EWBG.



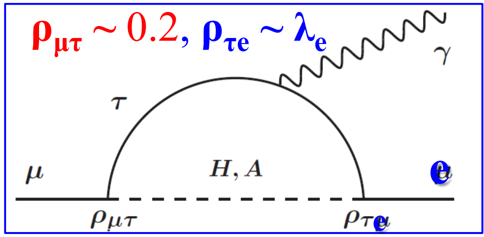
- gg $\xrightarrow{\rho_{tt}}$ H, A $\xrightarrow{\rho_{tc}}$ tc: ρ_{tc} can dilute the above

  → $cg \to bH^+ \to \mu\tau bW^+,\ tcbW^+$ 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)

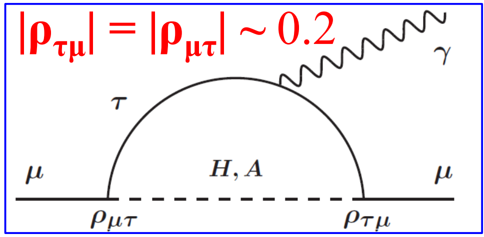


- μEDM: Same one-loop diagram, complex $\rho_{\tau\mu}\rho_{\mu\tau}$

  CPV

  → Possibly discoverable at PSI with planned sensitivity!

WSH, Kumar, 2109.08936 (JHEP'22) $6 \times 10^{-23}\ e\,\mathrm{cm}$



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

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**$^+$ bosons and crack the *Flavor* code!

Go CMS & Belle II (and others) !

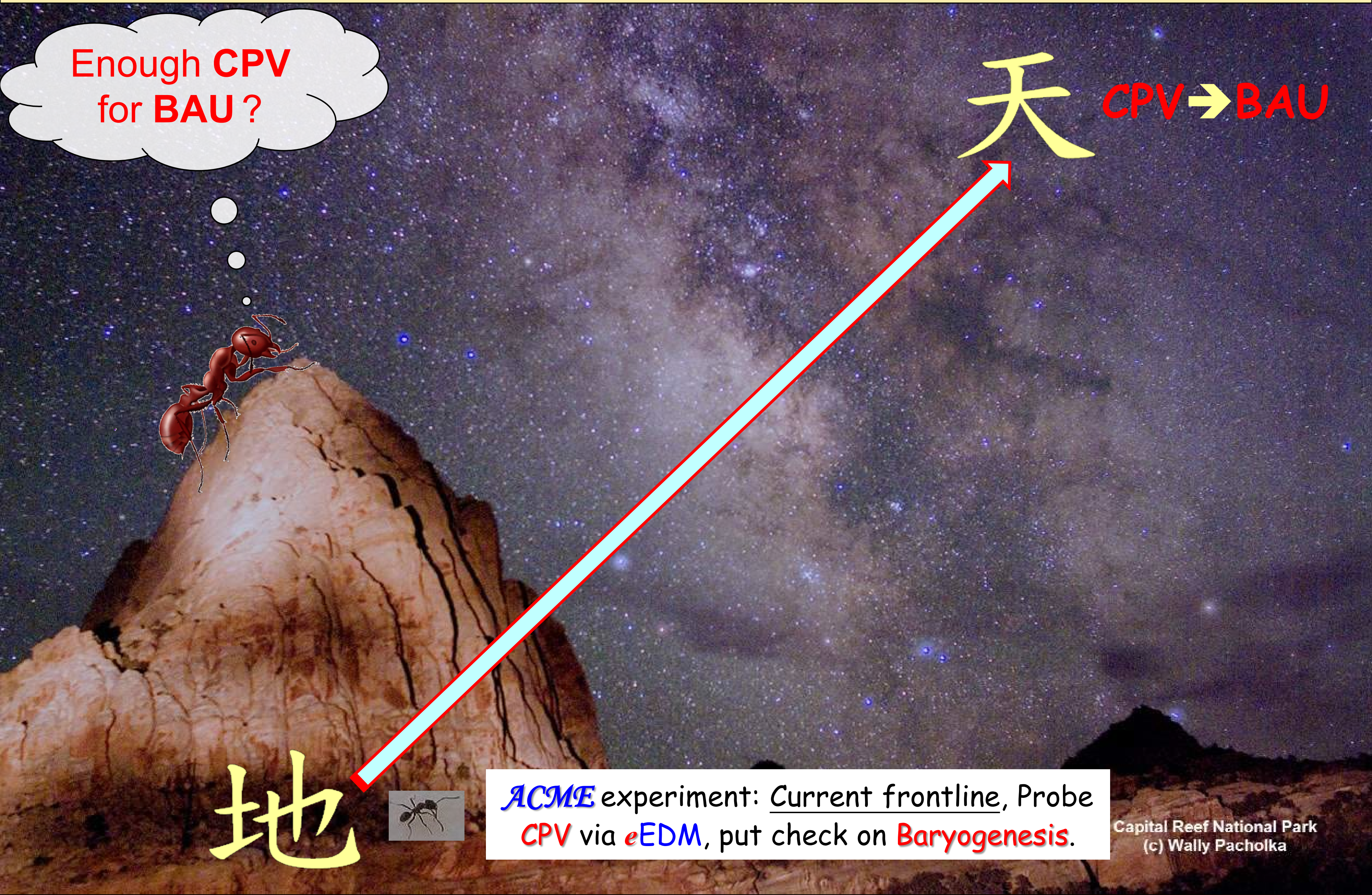
& Lattice

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

Thank you!

Join the Mission

Soaring to the Starry Heavens



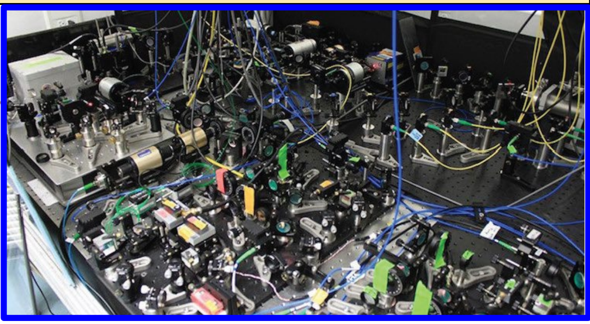
Enter the Advanced Cold Molecule Electron EDM Experiment

Science AAAS

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



Editor's Summary

Stubbornly Spherical

ThO

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

JILA'17 (Cornell): $< 13 \times 10^{-29}$ e cm

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

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[34], our measurement can be more generally interpreted as $\hbar\omega^{\mathcal{NE}} = -d_e\mathcal{E}_{\text{eff}} + W_S C_S$, 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_T, that can lead to measurable EDMs. Within typical extensions of the standard model, an EDM arising from new particles

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