CP Violation for the Heavens and the Earth

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Oct. 12 @ CFPP 2021, NCTS/NTU, Taipei

0. Intro: Our Life & Times

I. General 2HDM

II. Electroweak Baryogenesis

III. Under the Heavens on Earth: *e*EDM

IV. Phenomenological Consequences

V. Summary

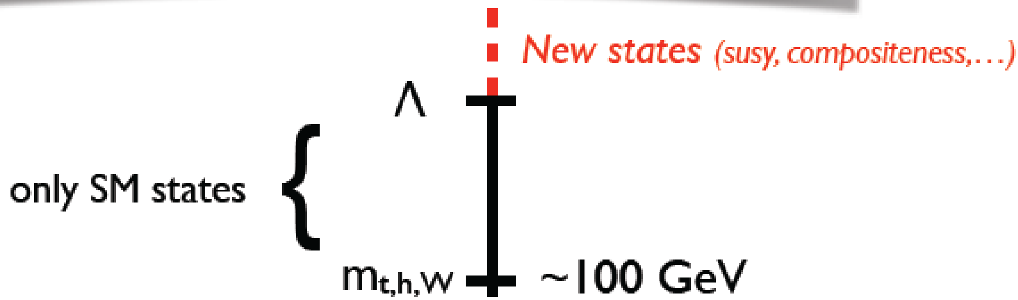
0. Intro: Our Life & Times

h(125) ✓ *New Physics* ✗

Where is SUSY?

Out-of-the-box Searches (XLPs) & EFTs ⟸ Where is Everybody?

Assuming only the SM states below some Λ:



We can then Taylor expand (SM fields and derivative over Λ):

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

dimension-4 terms: The SM

dimension-6 terms: Leading deviations from the SM

Alex Pomarol @ LHCP

0. Intro: Our Life & Times

h(125) ✓ *New Physics* ✗

Where is SUSY?

Out-of-the-box Searches (XLPs) & EFTs ⟸ Where is Everybody?

unconventional-Conventional

Assuming only the SM states below some Λ:

New states (susy, compositeness,…)

Λ

only SM states

$m_{t,h,W}$ ~100 GeV

We can then Taylor expand (SM fields and derivative over Λ):

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff}=\frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda},\frac{g_H H}{\Lambda},\frac{g_{f_{L,R}}f_{L,R}}{\Lambda^{3/2}},\frac{gF_{\mu\nu}}{\Lambda^2}\right)\simeq\mathcal{L}_4+\mathcal{L}_6+\cdots$$

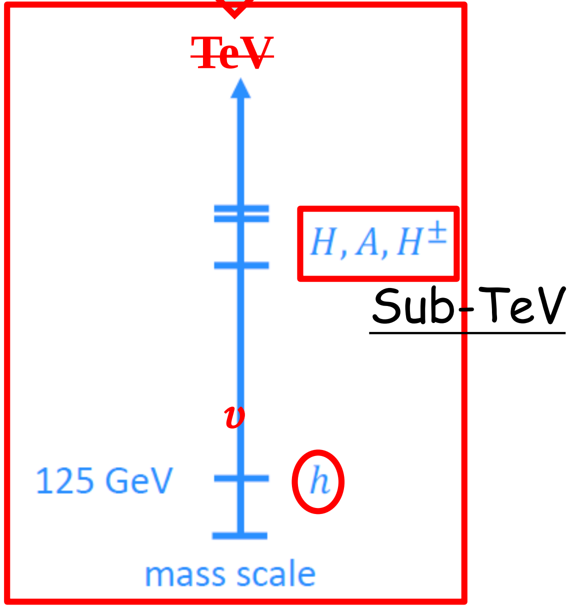
dimension-4 terms: The SM (G2HDM) *General* 2HDM

dimension-6 terms: Leading deviations from the SM

Alex Pomarol @ LHCP

Road Not Taken

Extra Higgs Doublet w/
Extra Yukawa Couplings
& Extra Quartic Couplings



0. Intro: Our *Life* & Times

h(125) ✓ *New Physics* ✗

However,

Where is SUSY?

Beyond CKM **CPV**

EW BaryoGenesis (EWBG)

- more testable -

tension

LHC

- *N*o *N*ew *P*hysics -

tension

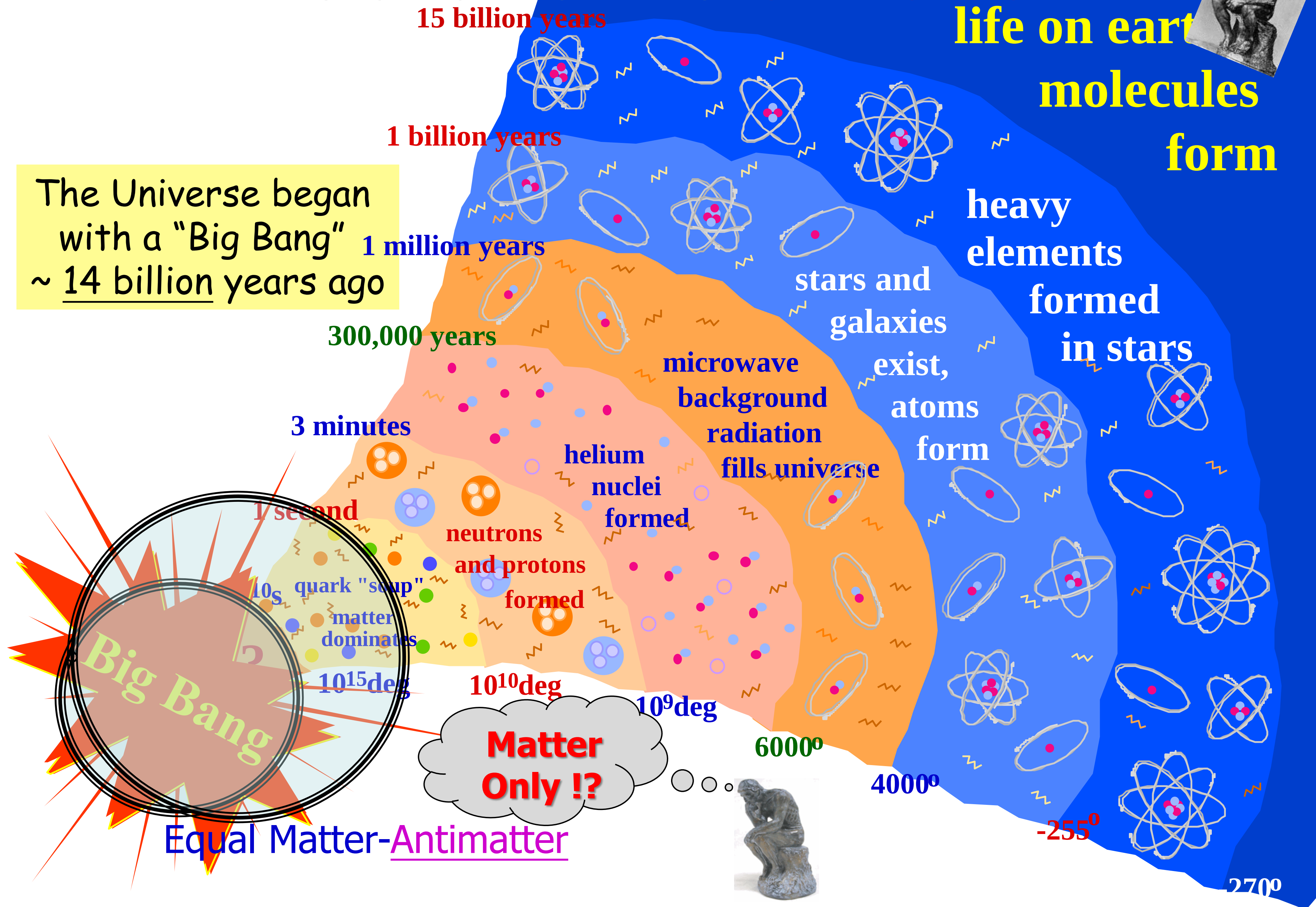
competition

*e*EDM: ACME14 → ACME18

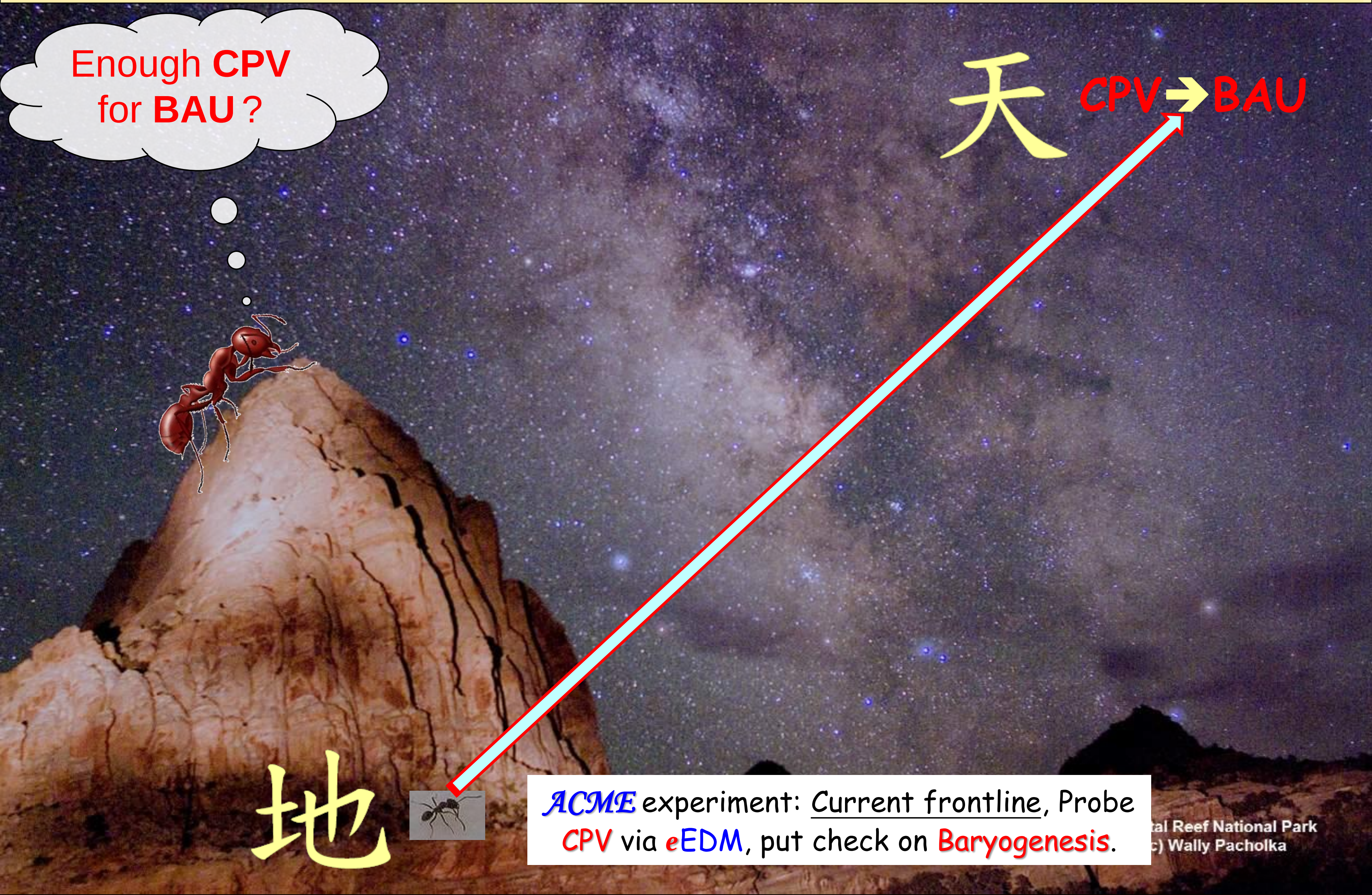
- L.E. Precision Frontier -

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

Evolution of the Universe



Soaring to the Starry Heavens



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 $V(\Phi_1, \Phi_2)$ 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) for 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

N.B. Data-driven ρ_{ij}: $t \to ch$; $h \to \mu\tau$ ...

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

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

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

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

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

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

$$-\mathcal{L}_Y = \bar{u}_{iL}\left[\frac{y_i\delta_{ij}}{\sqrt{2}} s_{\beta-\alpha} + \frac{\rho_{ij}}{\sqrt{2}} c_{\beta-\alpha}\right] u_{jR} h$$ → 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 & 1^{st}EWPT

SM

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

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

G2HDM

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

WSH&Kikuchi, EPL'18

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

"min. cond."

η_6: sole param. for h-H mixing (c_γ)

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

η_i with $i = 1$–7; μ_{22}^2/v^2 ⇨ H, A, H^+

Search Zone

v.e.v.

Alignment argument →

unnatural ⇧

incredulous ⇩

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

$t\bar{t}$, t, h, W Z

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

a Sakharov condition: 1^{st}EWPT

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

II. EWBG

strongly 1st order EW phase transition (EWPT)

Expanding Bubble of Broken Phase

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

2HDM OK

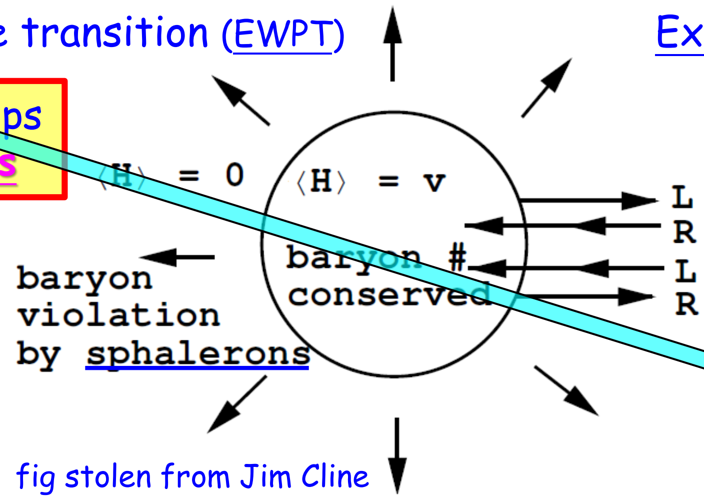


fig stolen from Jim Cline

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

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

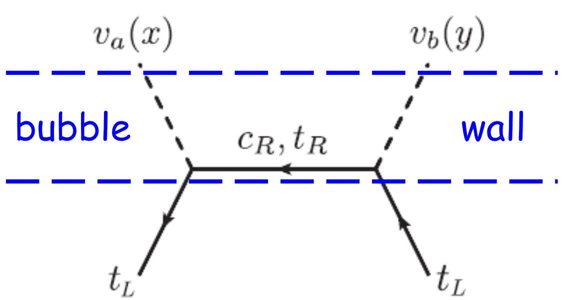
Baryon Asymm. of Universe (BAU)

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

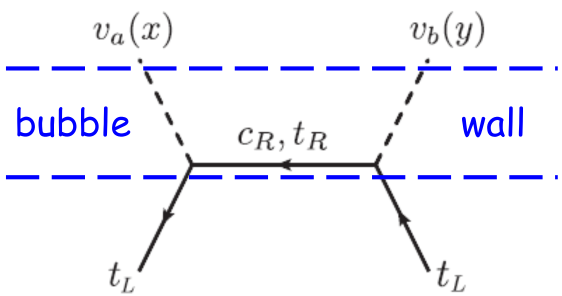
CPV source term

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

$Z = (t_Z, \boldsymbol{Z})$	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 ⇐ CPV Top interactions at Bubble Wall ⇒ n_L

left-handed Top density

z' coord. oppo. bubble exp. dir.

skip detail (Transport)

CPV Top interactions

CPV source term

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

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

To understand the plot to follow, 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

solve

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

but $-Y_1 + Y_2$ not diag.

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

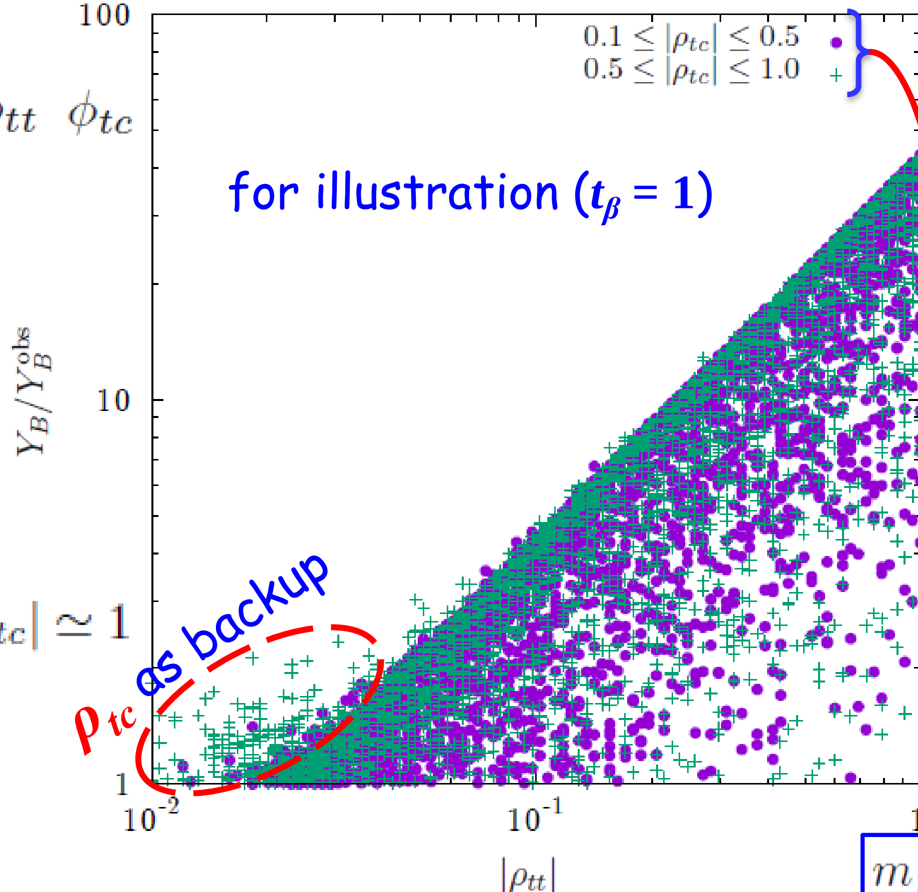
ρ_{tc} still basically free param.

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

Robust: Large Parameter Space for EWBG

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

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



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

no obvious diff.

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

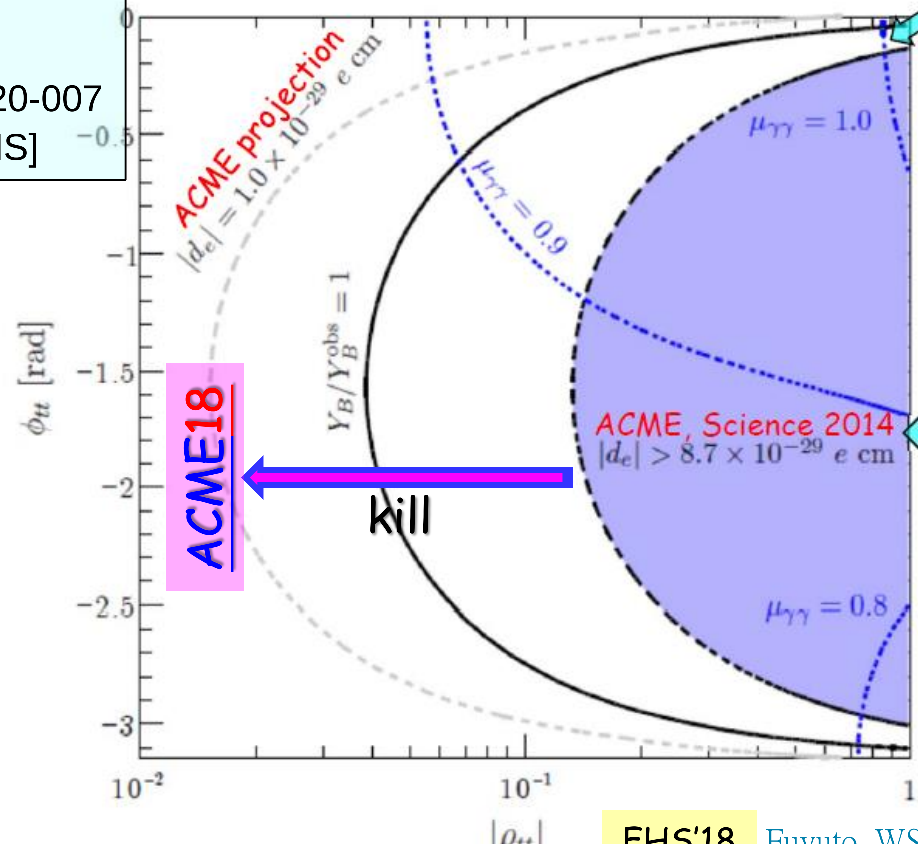
Simplified <u>flop</u>: *e*EDM "Prediction"

for illustration: $t_\beta = 1$, $c_{\beta-\alpha} = 0.1$

$\mathcal{B}(t \to ch) \simeq 0.15\%$ for $|\rho_{tc}| = 1$

vs $<$ 0.46% (0.40%) ATLAS (CMS)

$< 0.073\%$
CMS TOP-20-007
[NTUCMS]



charged Higgs H^+

$h \to \gamma\gamma$ width reduction
(ρ_{tt} compensate)

Barr-Zee
e-EDM (2-loop)

but: $c_{\beta-\alpha} \to 0$, $|\rho_{ee}| \sim y_e$

FHS'18 [Fuyuto, WSH, Senaha, Phys. Lett. B **776** (2018) 402]

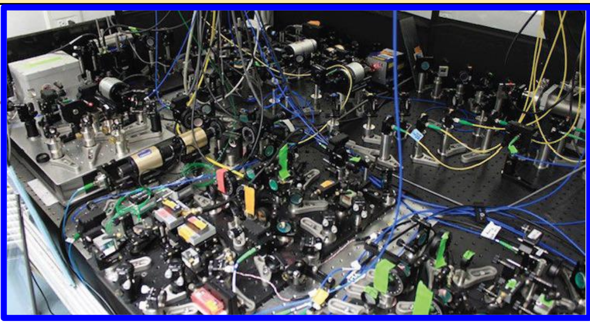
the Advanced Cold Molecule Electron EDM Experiment

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

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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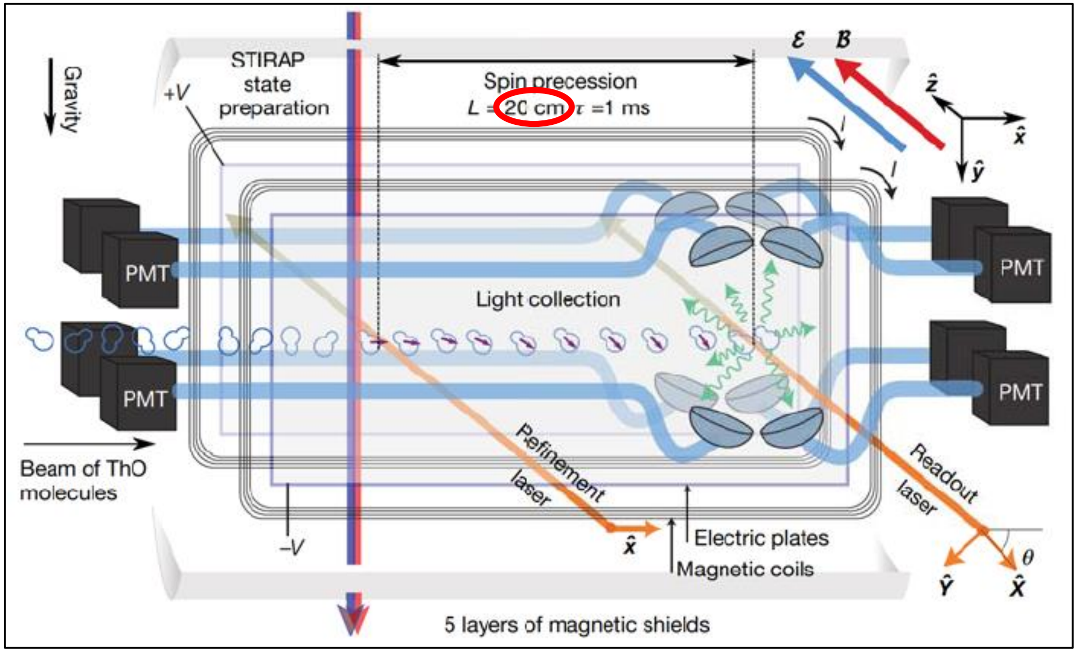
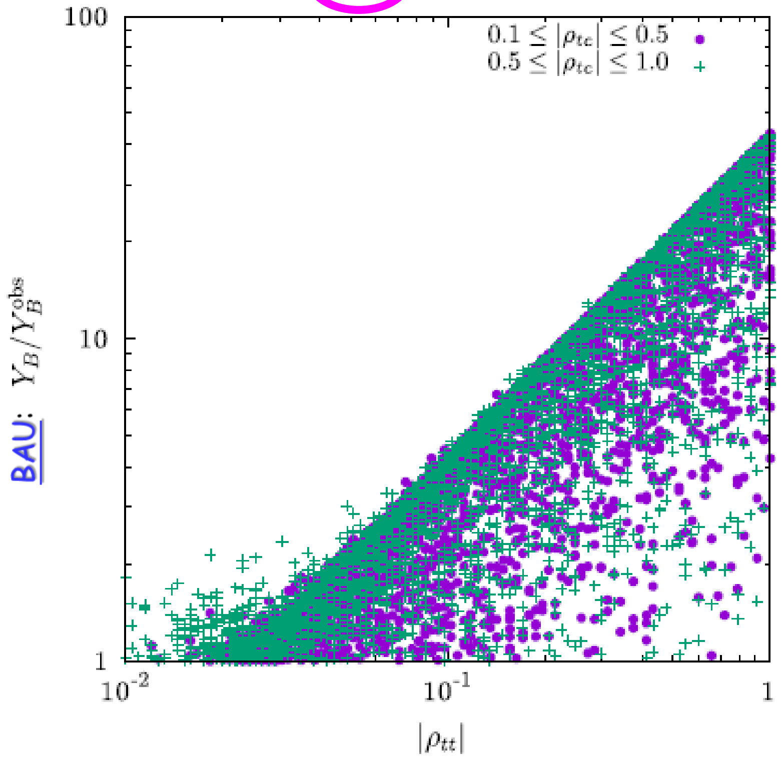


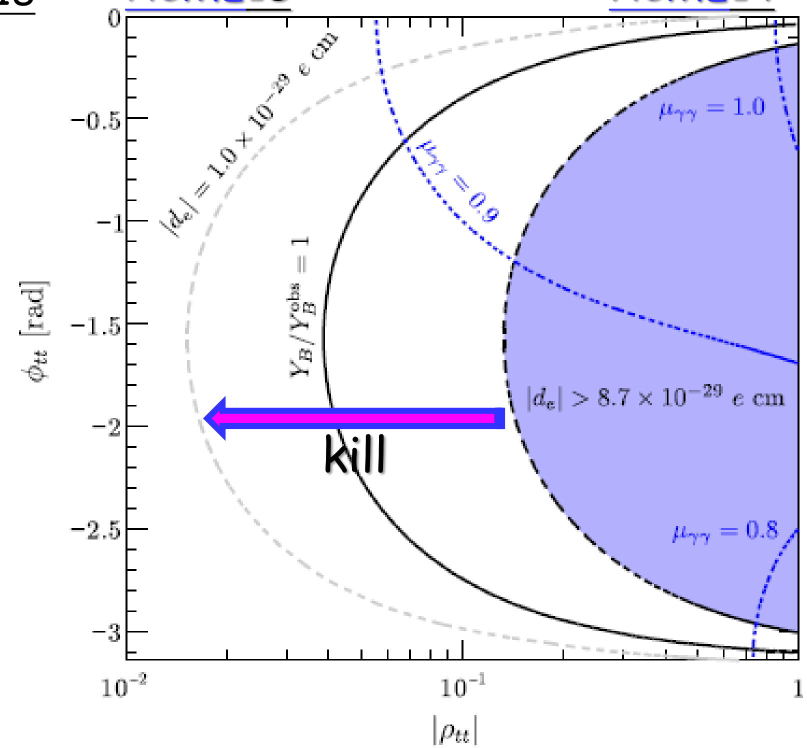
III. Under the Heavens on Earth: *e*EDM

complex ρ_{tt}

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

FHS'18





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

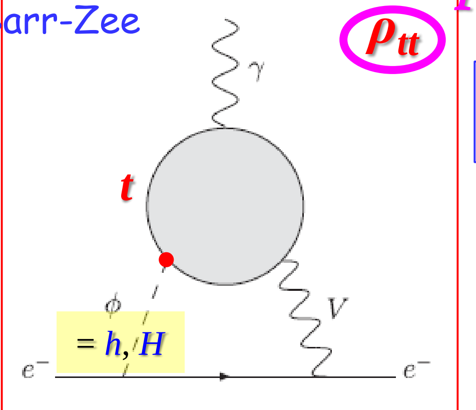
Ruled Out by ACME18!

Mech. to render small? *Yes!*

Cancellation Mechanism for d_{ThO} to survive

Barr-Zee

complex ρ_{tt}



dom.

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

need cancellation

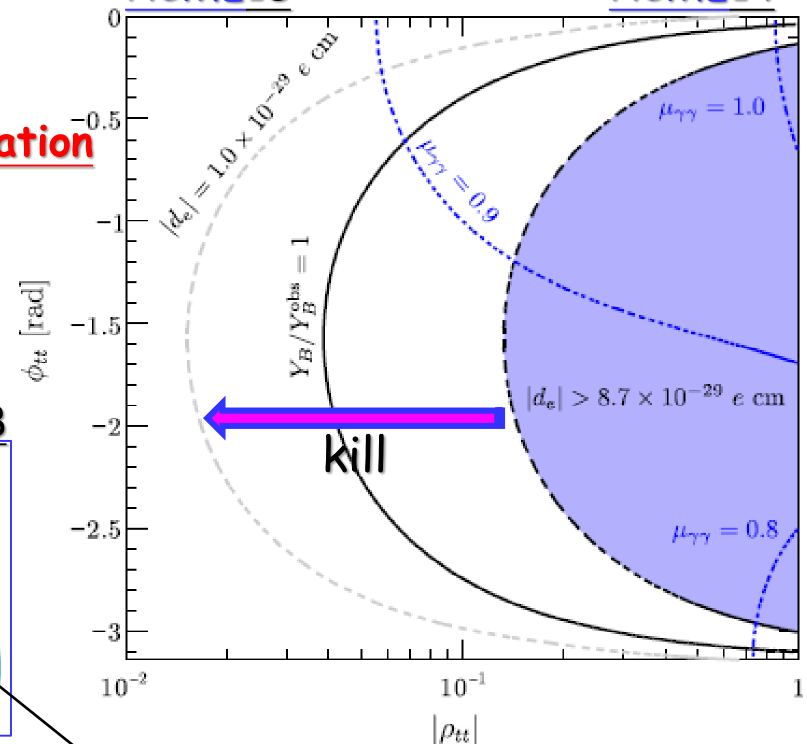
FHS'18

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

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

Ruled Out

ACME18 ACME14



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

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

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

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

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

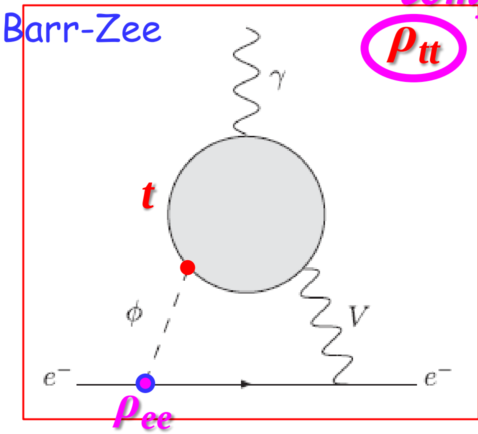
Barr, Zee, PRL'90

Cancellation Mechanism for d_{ThO}

to survive ACME18: turn on ρ_{ee}

FHS'20

complex



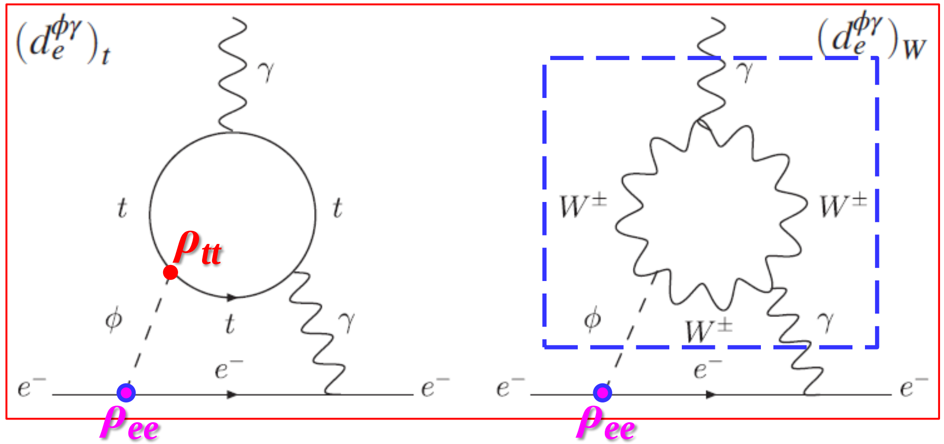
dom.

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

need cancellation

N.B.

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



h-*H* mixing

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

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

Cancel

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

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

purely extr. Yuk.

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

0

$[m_H \to m_A$

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

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

w/ correlated phase

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

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

ACME18 $(4.3 \pm 4.0) \times 10^{-30}\ e\,{\rm cm}$

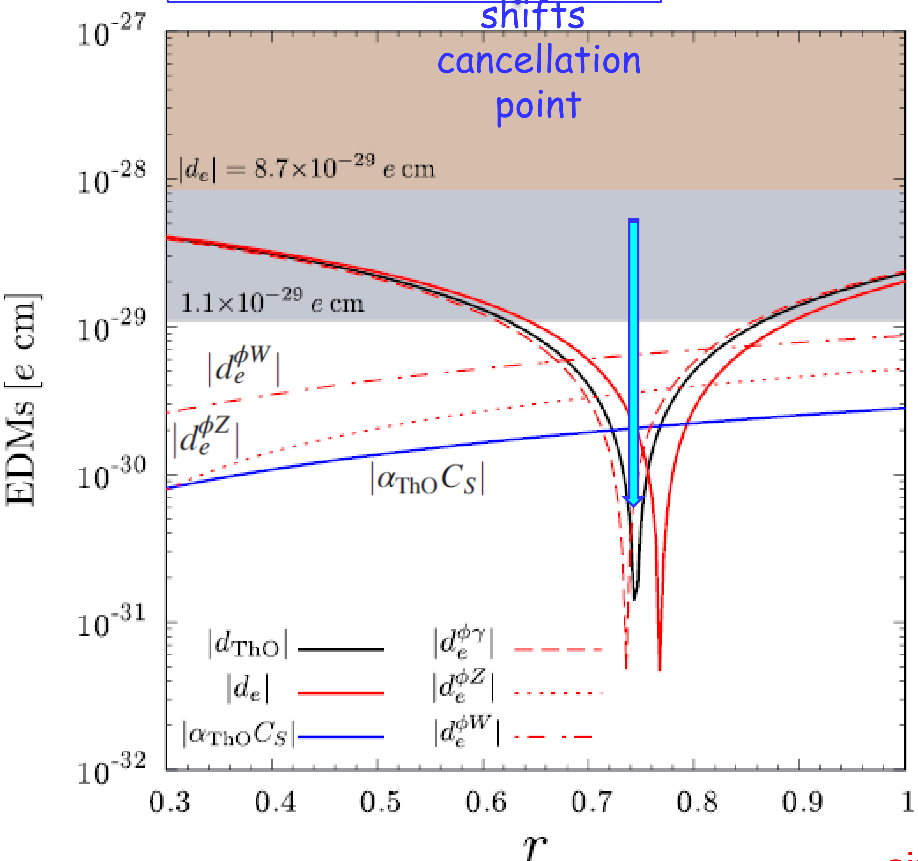
cancel. mech.

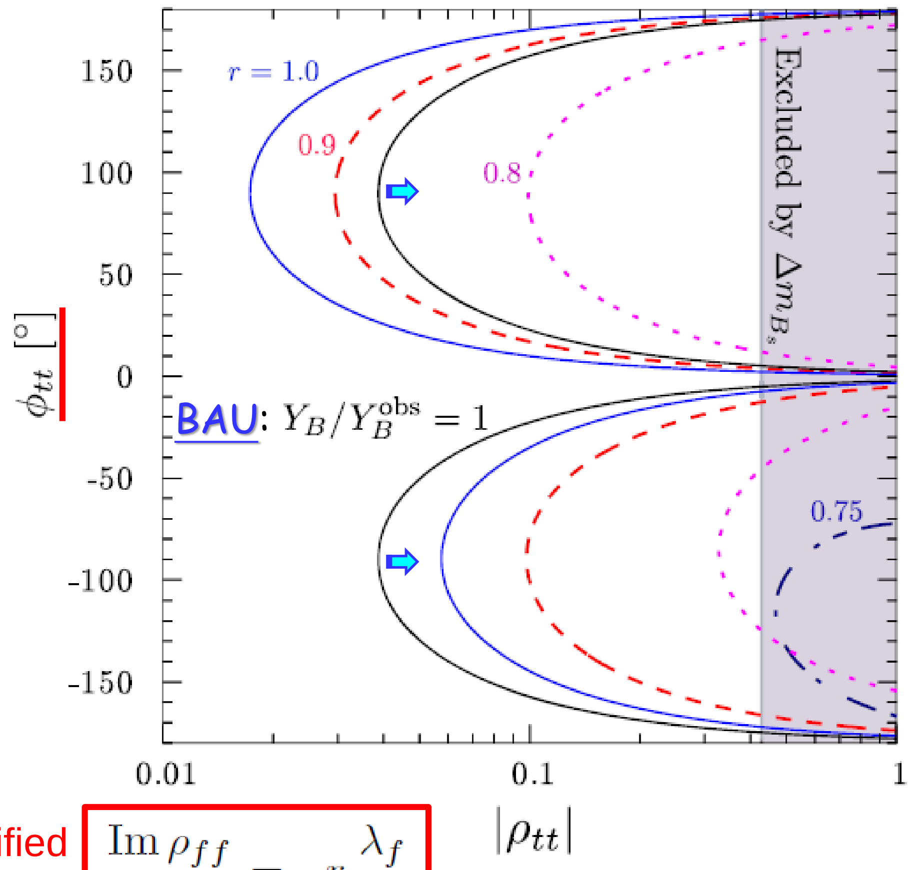
FHS'20

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

shifts cancellation point

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





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

(GeV)

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

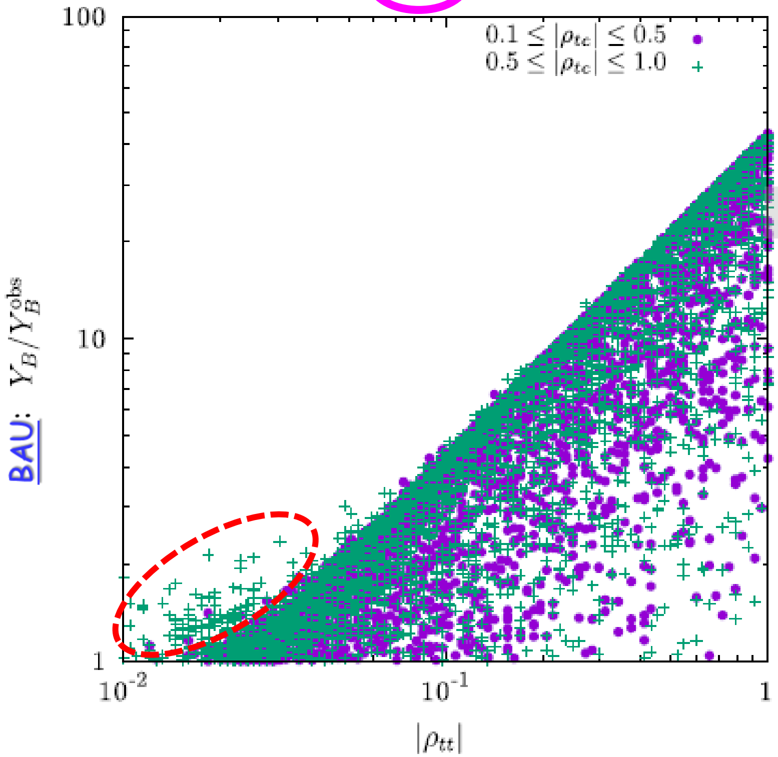
simplified "Ansatz"

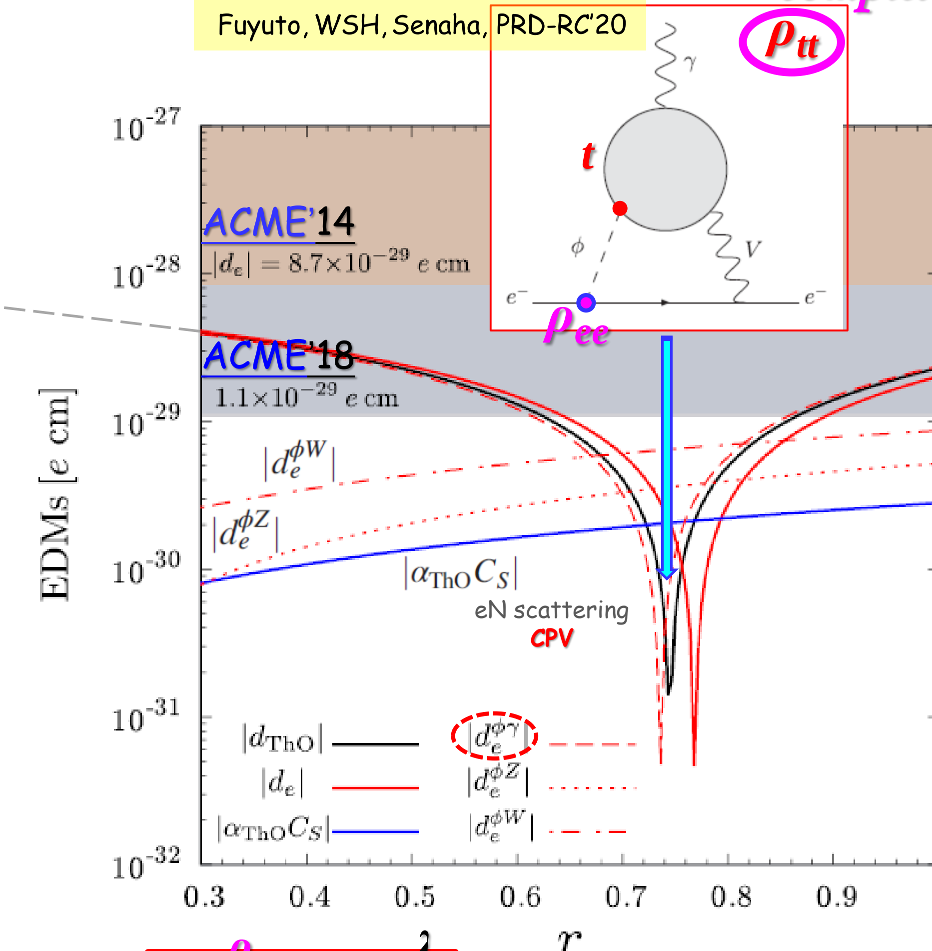
$$\frac{{\rm Im}\,\rho_{ff}}{{\rm Im}\,\rho_{tt}} = r\,\frac{\lambda_f}{\lambda_t} \qquad \frac{{\rm Re}\,\rho_{ff}}{{\rm Re}\,\rho_{tt}} = -r\,\frac{\lambda_f}{\lambda_t}$$

Follow SM Hierarchy

N.B. r can be f-dep.

Baryogenesis & electron EDM





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

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[ρ_{tc} as backup

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

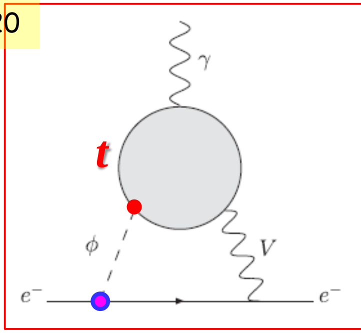
(ρ_{ee}, λ_e)

Follow SM Hierarchy!

N.B. r depend on loop functions

Fuyuto, WSH, Senaha, PLB'18

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

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

[ρ_{tc} as backup

simplified "Ansatz"

ρ_{ee} λ_e

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

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

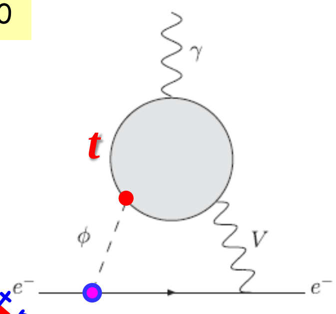
Follow SM Hierarchy !

N.B. r depend on loop functions

complex ρ_{tt} Baryogenesis & electron EDM ρ_{ee} complex

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"!

G-W 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⁺

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*

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

On "the Heavens and the Earth"

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.

ρ_{tt}

- ACME14 was confirmed by JILA17 using HfF^+, i.e. different approach. It is good that "JILA is chasing Harvard/Yale(/Northwestern)." Personally, **I don't think 10^{-29} $e\,$cm is finished business**.
- Amusing: The *largest* diagonal *extra* Yukawa ρ_{tt} drives B.A.U., in concert w/ *smallest* diagonal *extra* Yukawa ρ_{ee} to generate *e*EDM, that might be revealed soon by very-low-energy ultraprecision probes. For me, **I think 10^{-29} – 10^{-30} $e\,$cm is just *fabulous***. **Godspeed success!**

extra Yukawas reflect SM Yukawa pattern

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

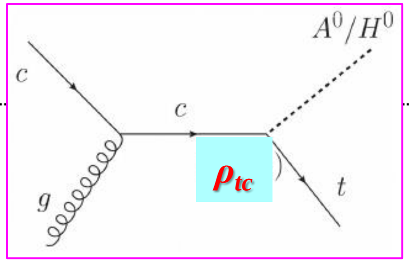
IV. Phenomenological Consequences

H/A/H^+ Search & Flavor Frontier

Leading Search Modes at the LHC

*G*2HDM

Sub-TeV Spectrum



Search at ATLAS/CMS started

Search Zone

Kohda, Modak, WSH, PLB'18

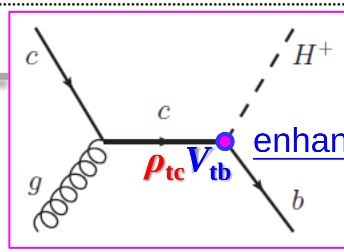
$cg \to tH/A \xrightarrow{\rho_{tc}} tt\bar{c}$ — ttc(bar) Same-Sign Top

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

$cg \to bH^+ \to bt\bar{b}$ — btb(bar) Top w/ two p_T b-jets (H^+)

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

v.e.v.



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

H, A, H^+

$t\bar{t}$

√

HKM, PLB'18

t

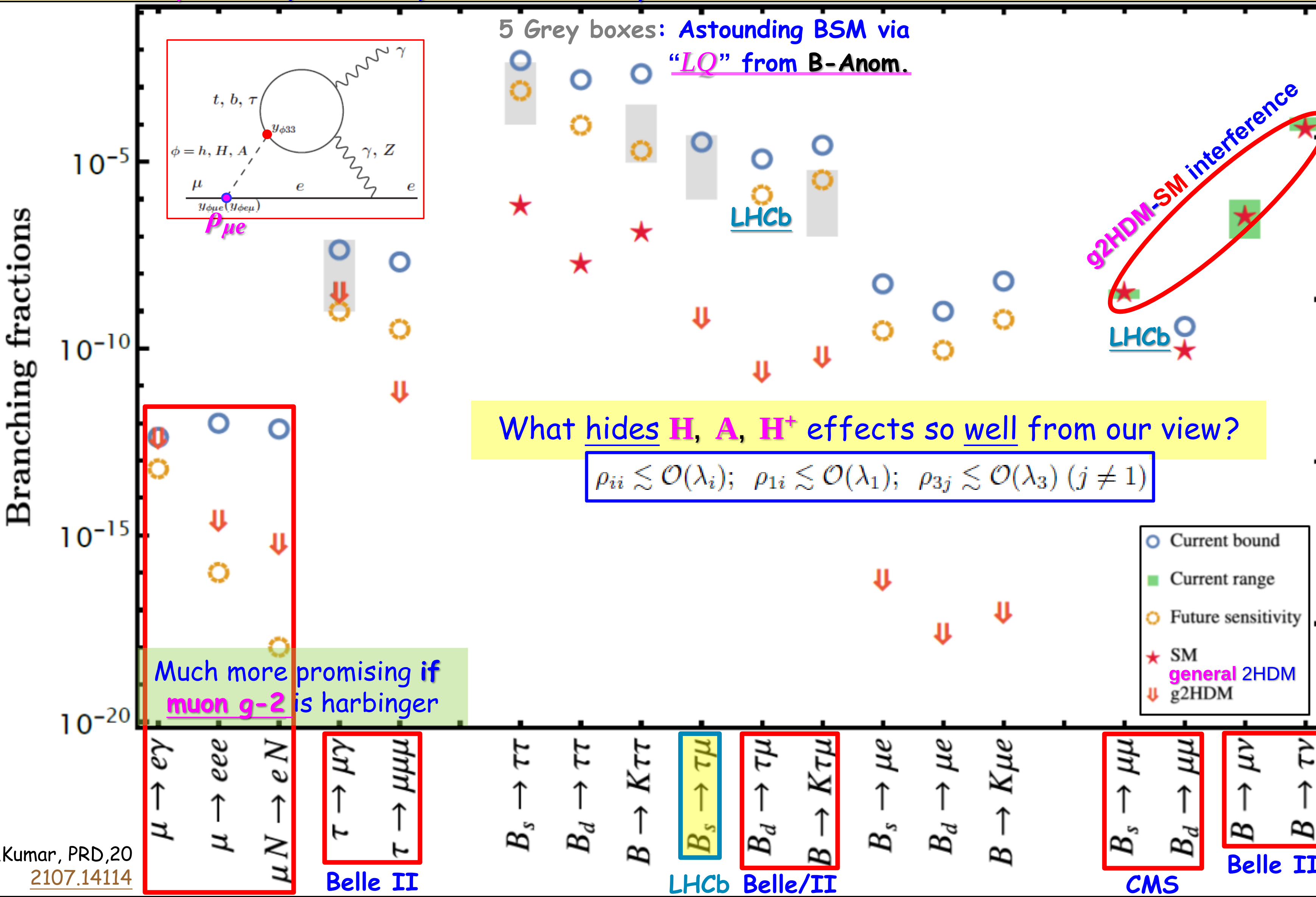
h

W Z

ν — neutrino
e μ τ — lepton
d s b — down-type
u c — up-type
γ g — vector
scalar

Glimpse of coming New *Flavor* Era

μ & τFV (Flav.Viol.) in B decay



WSH&Kumar, PRD,20
2107.14114

Our Life & Times

h(125) ✓ *New Physics* ✗

High Scale SUSY?!

Where is SUSY?

unconventional-Conventional

Road Not Taken

Extra Higgs Doublet w/
Extra Weinberg Couplings
& Extra Quartic Couplings

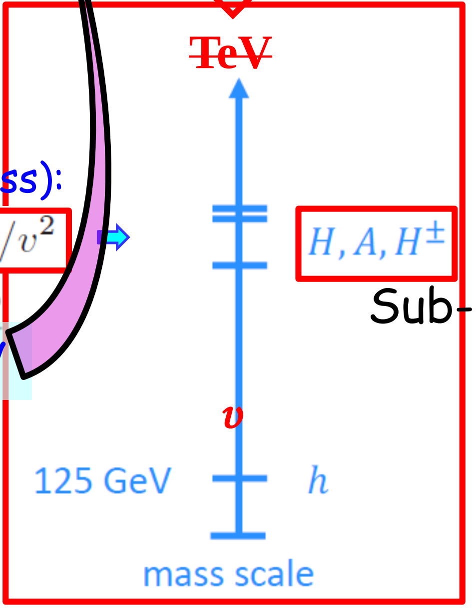
$1^{\rm st}$EWPT

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

η_i with $i = 1$–7; μ_{22}^2/v^2

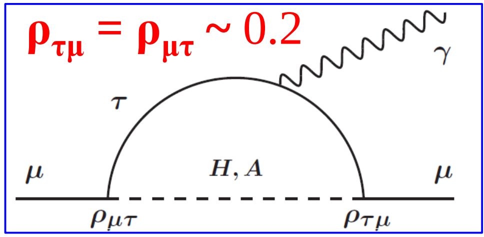
100 TeV pp collider

➔ Landau Pole ~ 10-20 TeV



- 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.



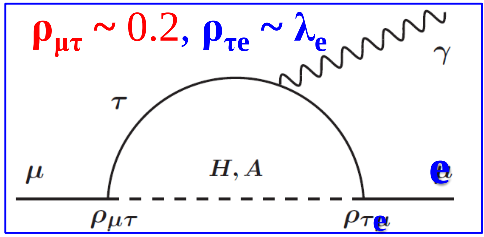
- gg $\xrightarrow{\rho_{tt}}$ H, A $\xrightarrow{\rho_{tc}}$ tc: ρ_{tc} can dilute the above

  → $cg \to bH^+ \to \mu\tau bW^+,\ tcbW^+$ fancy sigantures.

  WSH, Jain, Kao, Kumar, Modak, 2105.11315

- Revival of muon 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

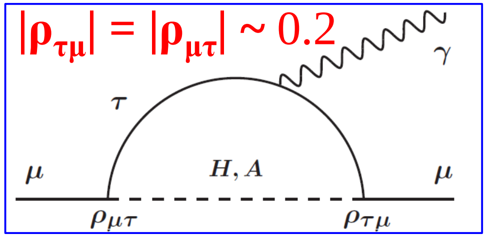


- μEDM: Same one-loop diagram, complex $\rho_{\tau\mu}\rho_{\mu\tau}$

  CPV

  → Possibly discoverable at PSI with planned sensitivity!

  WSH, Kumar, 2109.08936 $6 \times 10^{-23}\ e\,\mathrm{cm}$



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

the Alpha and the Ω

I 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

Thank you!

Soaring to the Starry Heavens