Decadal Mission: Extra Higgs Boson Effects in General 2HDM

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

June 9, 2025, Pic of Cosmo Hall@NTU

臺灣大學
National Taiwan University

Searching for Extra Higgs Boson Effects in General 2HDM

Outline

But: EWBG!?

0. Our current *impasse:* *No New Physics* (*NNP*) — *beyond* **h(125)**
   Our predicament

5 Merits

I. General (w/o Z_2) Two-Higgs Doublet Model (G2HDM)
   Take Home Msg
   More Dim-4's (two extra sets of couplings) ➔ Don't EFT yet!!

II. *Decadal Mission* of the *New Higgs/Flavor* Era
   Midterm Report "my view for *BSM*": $pp \to ttc(bar)$ ATLAS & CMS

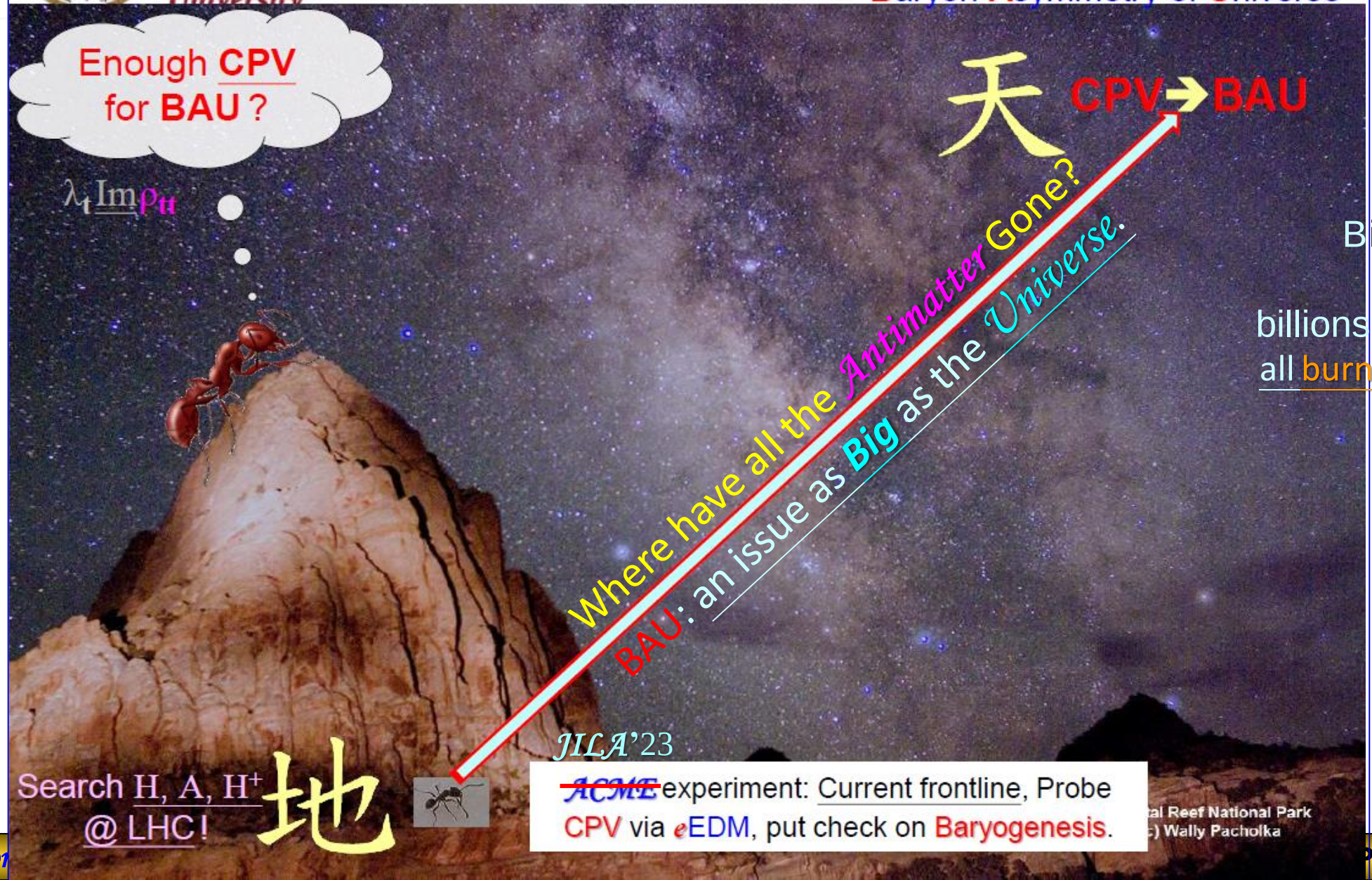
III. Post-Midterm: $pp \to bH^+ \to btb(bar)$; $ttt(bar)$ @ NTUCMS
   [$t \to ch$ & $ttc(bar)$ redux

IV. G2HDM as *Next NP*?!

V. Discussion & Conclusion

Soaring to the Starry Heavens

Baryon Asymmetry of Universe



le Raison d'être

Billions
&
billions of stars …
all burning protons

G2HDM

I. G2HDM

w/o Z_2 → ∃ extra

two identical weak doublets

- Yukawas: ρ^f
- Quartics: η_i

CPV

Merit

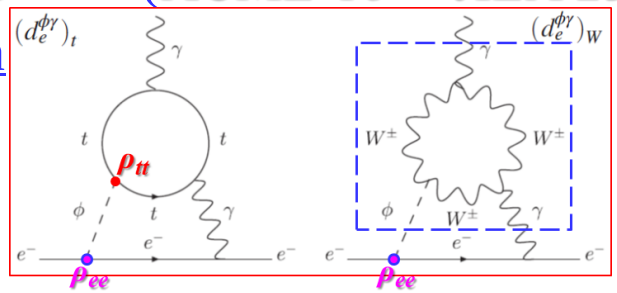
$\lambda_t \mathrm{Im}\,\rho_{tt}$

M①: extra top Yukawas ρ_{tt} and ρ_{tc} ~ 1 and complex, can drive EWBG, Fuyuto, WSH, Senaha PLB'18

Higgs quartic self-couplings η_i at $\mathcal{O}(1)$, i = 1–7, provide 1stOPhTr (→ primordial GW!)
Kanemura, Okada, Senaha, PLB'05

M②: CPV @ $\mathcal{O}(1)$ needed for EWBG → vulnerable to *e*EDM (ACME'18 & JILA'23)

➔ Spectacular 2-loop *diagrammatic* cancellation



Fuyuto, WSH, Senaha PRD'20 (R)

Higgs-γ-γ* insertions

→ $|\rho_{ee}/\rho_{tt}| \sim \lambda_e/\lambda_t$

the flavor code?

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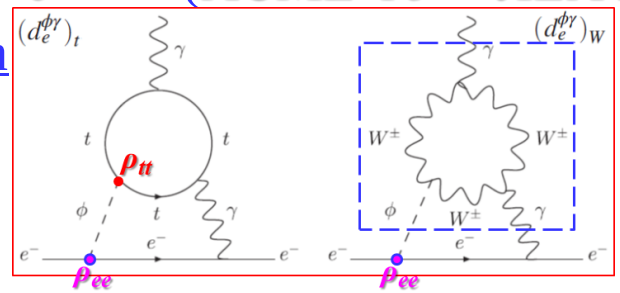

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Glashow-Weinberg PRD'77

M③: Glashow worried about FCNCs, such as t → ch;

WSH, PLB'92
flavor-protected

but with h < t, it is a "PDG" duty to search!

Curiously, t → ch remains elusive

— Nature threw in *alignment* (c_γ) (*small* h-H mixing)

to hide it so far! *Who* would have thought!?

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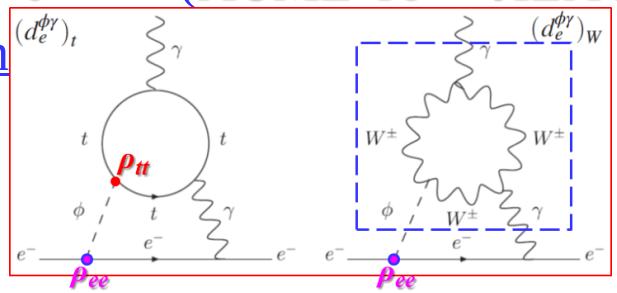

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sub-TeV H, A, H^+

M④: Small c_γ does *Not* contradict $\mathcal{O}(1)$ quartics:

→ Can argue that H, A, H^+ populate 300–600 GeV.

$$c_\gamma \sim \frac{\eta_6 v^2}{m_H^2 - m_h^2}$$

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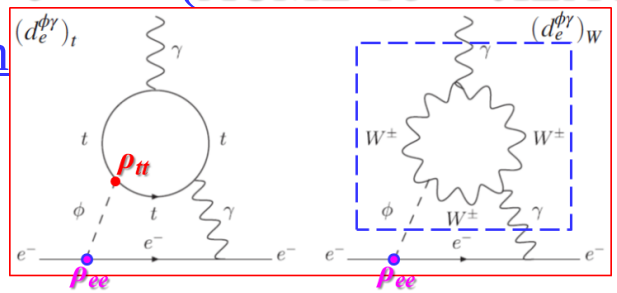

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WSH, Kikuchi EPL'18

M⑤: With t → ch c_γ-suppressed → Natural to pursue cg → tH/tA → ttc(bar) ($s_\gamma \to 1$) Kohda, Modak, WSH PLB'18

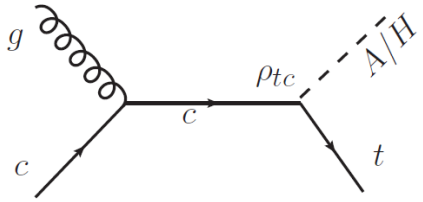
→ Better: cg → bH⁺ → btb(bar) [recoil b, not t] Ghosh, WSH, Modak PRL'20

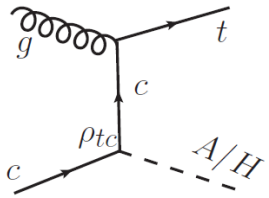
II. *Decadal Mission* of the *New Higgs/Flavor* Era

Midterm Report: "my *BSM*" pp → ttc(bar) ATLAS & CMS

Same-sign top pair + jet

→ Natural to pursue cg → tH/tA → ttc(bar)





A/H → tc(bar)

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The CMS Collaboration * A. Hayrapetyan et al.

2311.03261

* NTUCMS started already 2/2020, but thanks to a good 5-yr grant, manpower could be built-up in time since 8/2021.

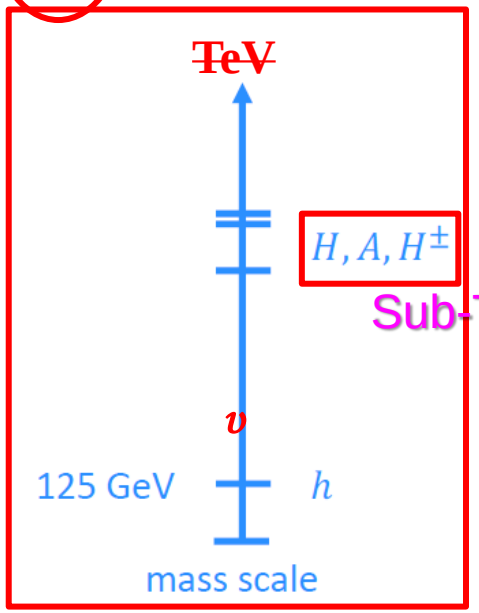
2nd ASP 8/2021 – 7/2026

WSH "**Decadal Mission**", 2109.02557, CJP'22

Academic Summit Project

Finite Chance for Discovery!

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



Decadal Mission of New Higgs/Flavor Era

1. CMS: H, A, H^+ search @ LHC
2. Belle II: $\tau \to \mu\gamma$; $B \to \mu\nu, \tau\nu$; $\tau\tau, \tau\mu$
   CMS: $B_{s,d} \to \mu\mu$
3. Lattice: Higgs Potential { 1st EWPT / Landau Pole
4. Steering: Pheno 粒子現象學

54 extra flavor param.
& 7 add'l Higgs param.

Kai-Feng (Jack) Chen

Paoti Chang

Kai-Feng (Jack) Chen

David C.J. Lin
(NYCU)

Wish us Luck!

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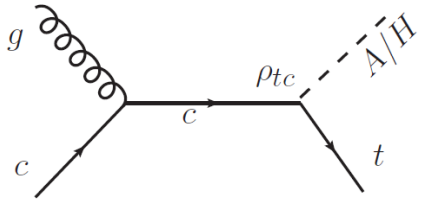
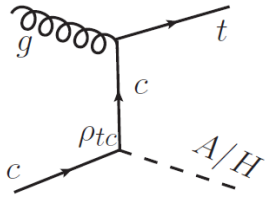
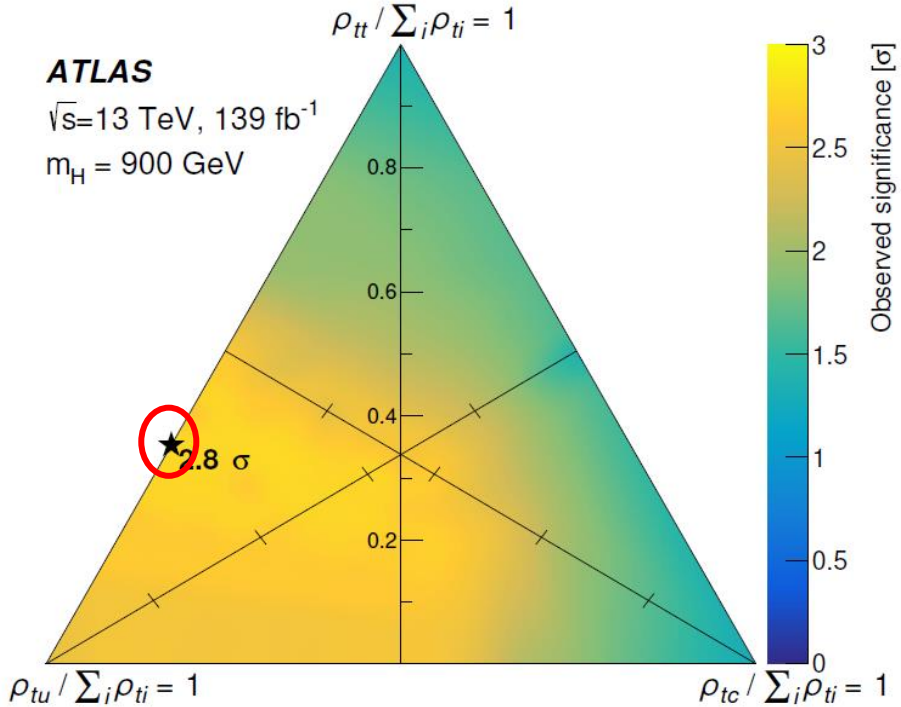
Same-sign top pair + jet

→ Natural to pursue cg → tH/tA → ttc(bar), ttt(bar)





A/H → tc(bar)



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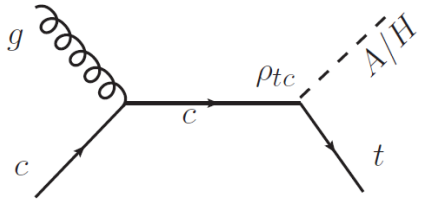
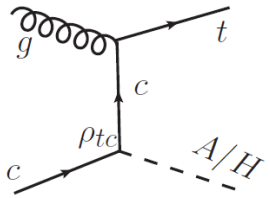




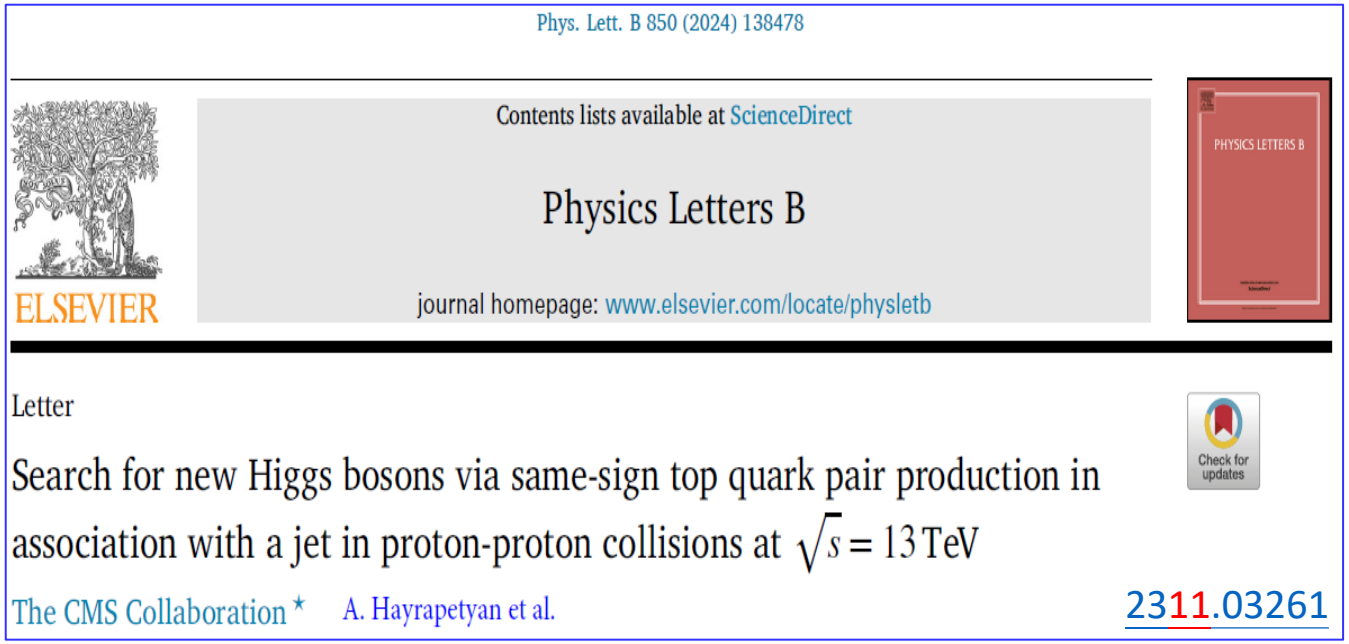
A/H → tc(bar)

Table 3

Observed (expected) lower limits on m_A at 95% CL. For the scenario without interference, the limits on m_H and m_A are the same.

	Observed (expected) mass limit [GeV]		
	without interference	with interference	with interference
	m_A or m_H	m_A	m_H
ρ_{tu}			
0.4	920 (920)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}			
0.4	no limit	340 (370)	290 (320)
1.0	770 (680)	810 (670)	760 (620)

CMS-PLB 2311.03261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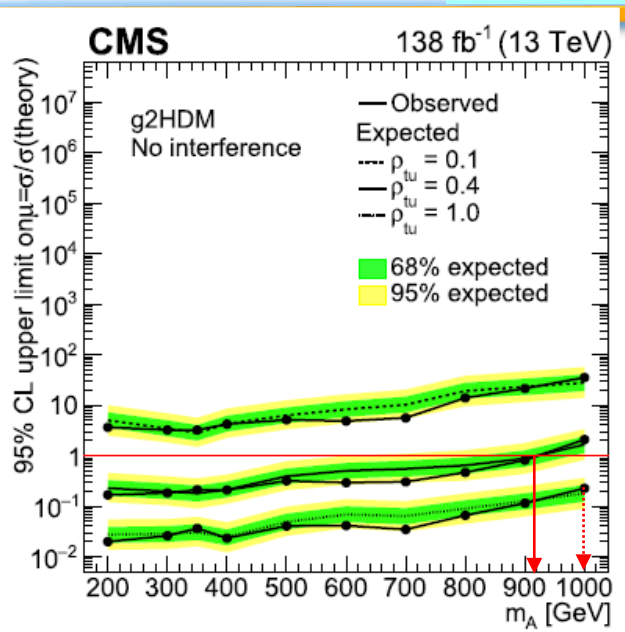
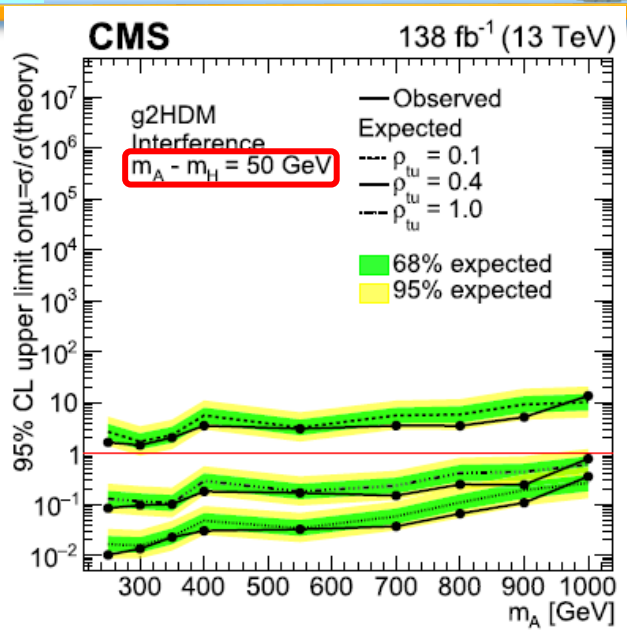
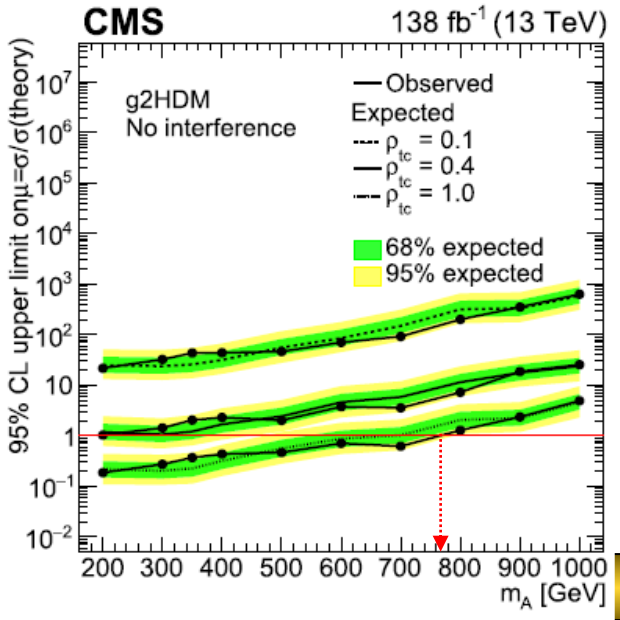
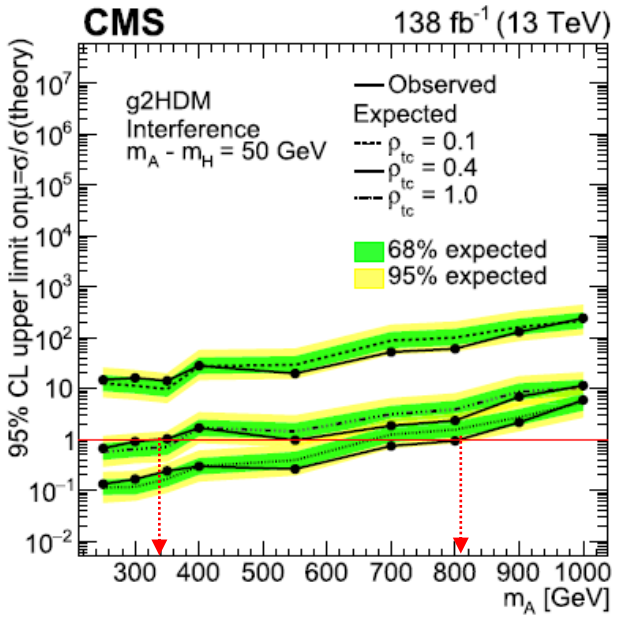
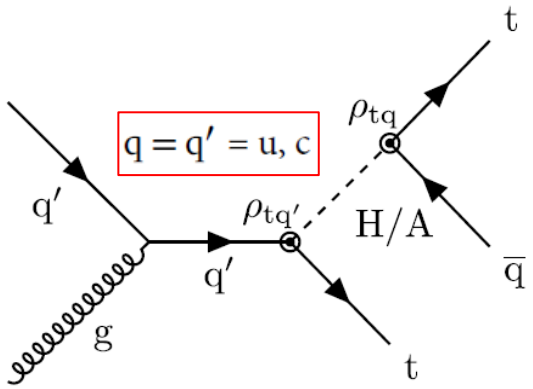
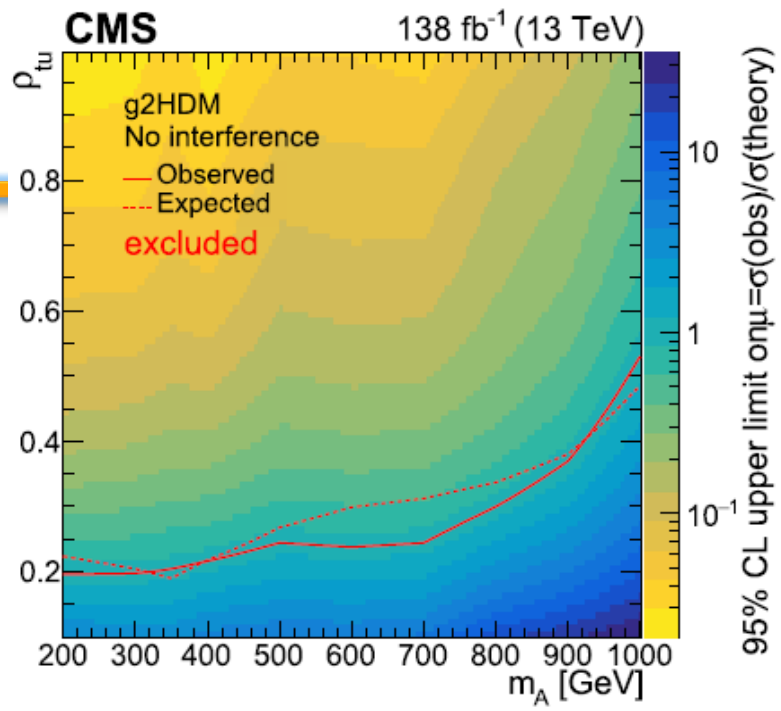









q = q′ = u, c
q′
g
q′
$\rho_{tq'}$
H/A
ρ_{tq}
t
$\bar{q}$
t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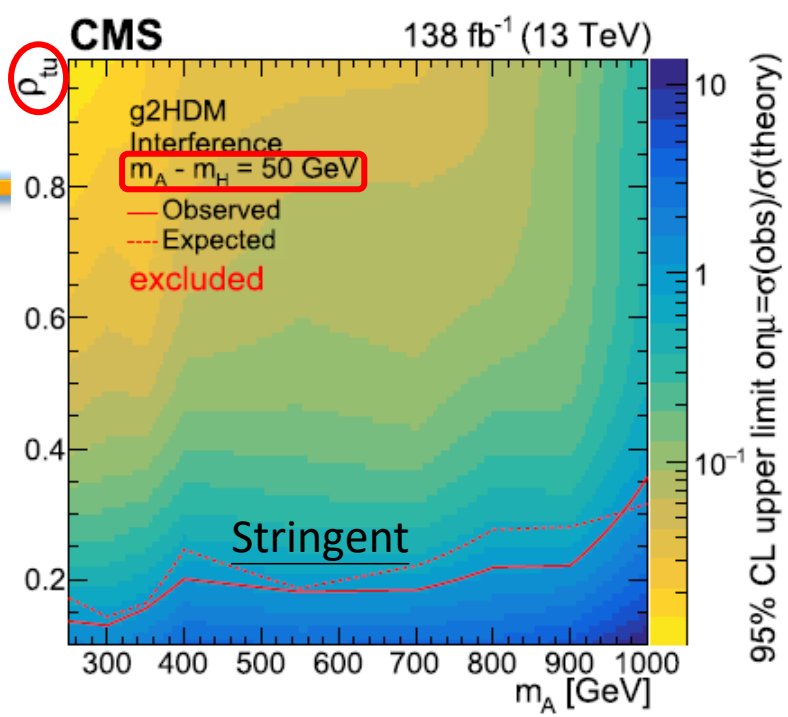
m_A [GeV]
95% CL upper limit onμ=σ(obs)/σ(theory)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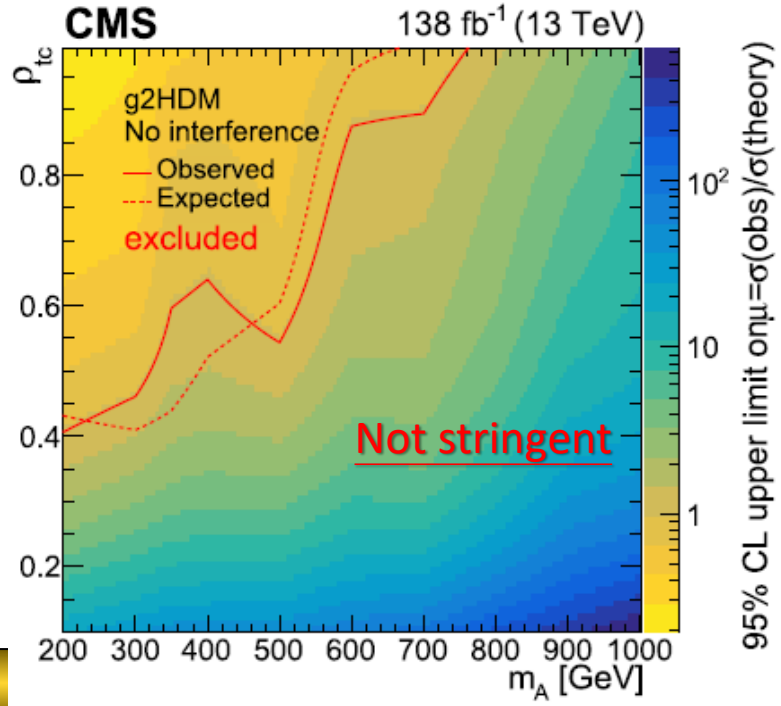
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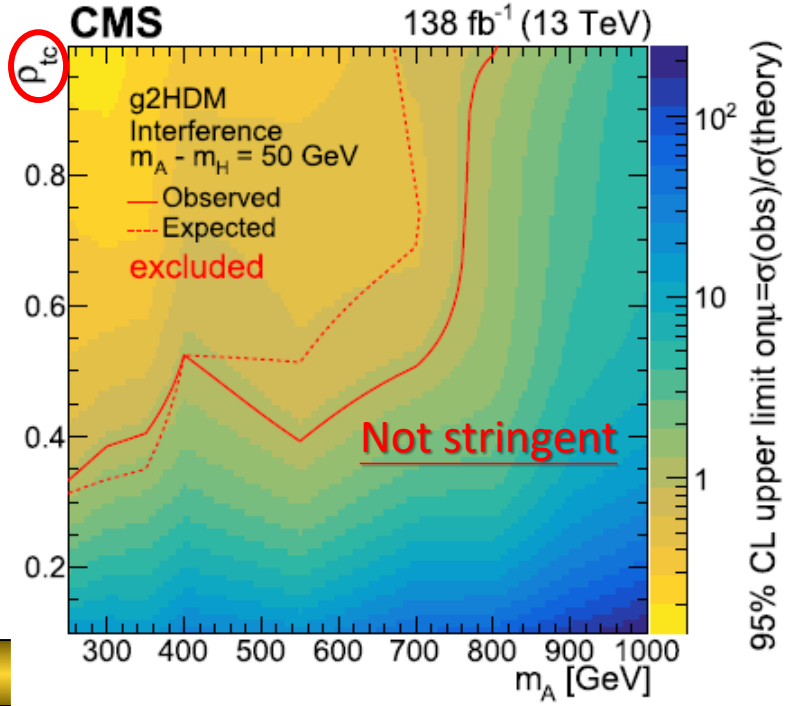
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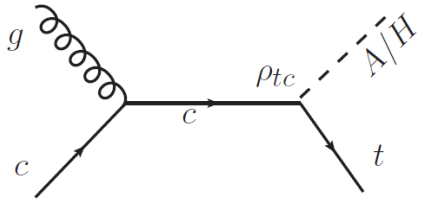

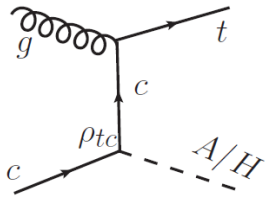

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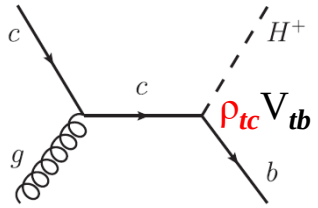
Neither ATLAS ... *Nor* CMS saw a signal.

III. Post-Midterm: pp → bH⁺ → btb(bar); ttt(bar) @ CMS

[ttc(bar) & t → ch redux

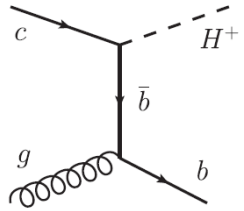
→ Better: cg → bH⁺ → btb(bar)

Ghosh, WSH, Modak PRL'20



V_{tb}/V_{cb} enhanced

w.r.t. 2HDM-II



H⁺ → tb(bar) $\rho_{tt} V_{tb}$

also: cg → tH/tA → ttc(bar), ttt(bar) [H/A → tt(bar)]

redux adding Run 3 data

t → ch

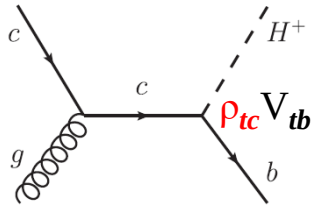
As the study is ongoing, I can say nothing!

The elevated current H, A, H⁺ search program @ CMS.

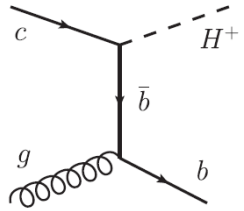
III. Post-Midterm: $pp \to bH^+ \to btb(bar)$; ttt(bar) @ CMS

[ttc(bar) & t → ch redux

→ Better: $cg \to bH^+ \to btb(bar)$



$H^+ \to tb(bar)$ $\rho_{tt} V_{tb}$



also: $cg \to tH/tA \to$ ttc(bar), ttt(bar) [$H/A \to tt(bar)$]

redux adding Run 3 data

t → ch

Ghosh, WSH, Modak PRL'20

V_{tb}/V_{cb} enhanced w.r.t. 2HDM-II

The elevated current H, A, H^+ search program @ CMS.

IV. G2HDM as *Next NP?!*

$\tau \to \mu\gamma$ induced by 2-loop diagrams.

WSH, Kohda, Modak, Wong PLB'20

The above H^+ CKM enhancement first uncovered in $B \to \mu\nu, \tau\nu$; ratio $\neq 0.0045$

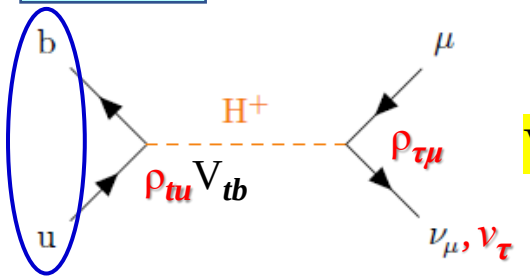
→ Rule out SM/2HDM-II.

Belle II will study this (if more data).

CMS: $B_{s,d} \to \mu\mu$

$B \to \mu\nu$: stat. dom. ← takes time

$B \to \tau\nu$: syst. dom. ← imprv method



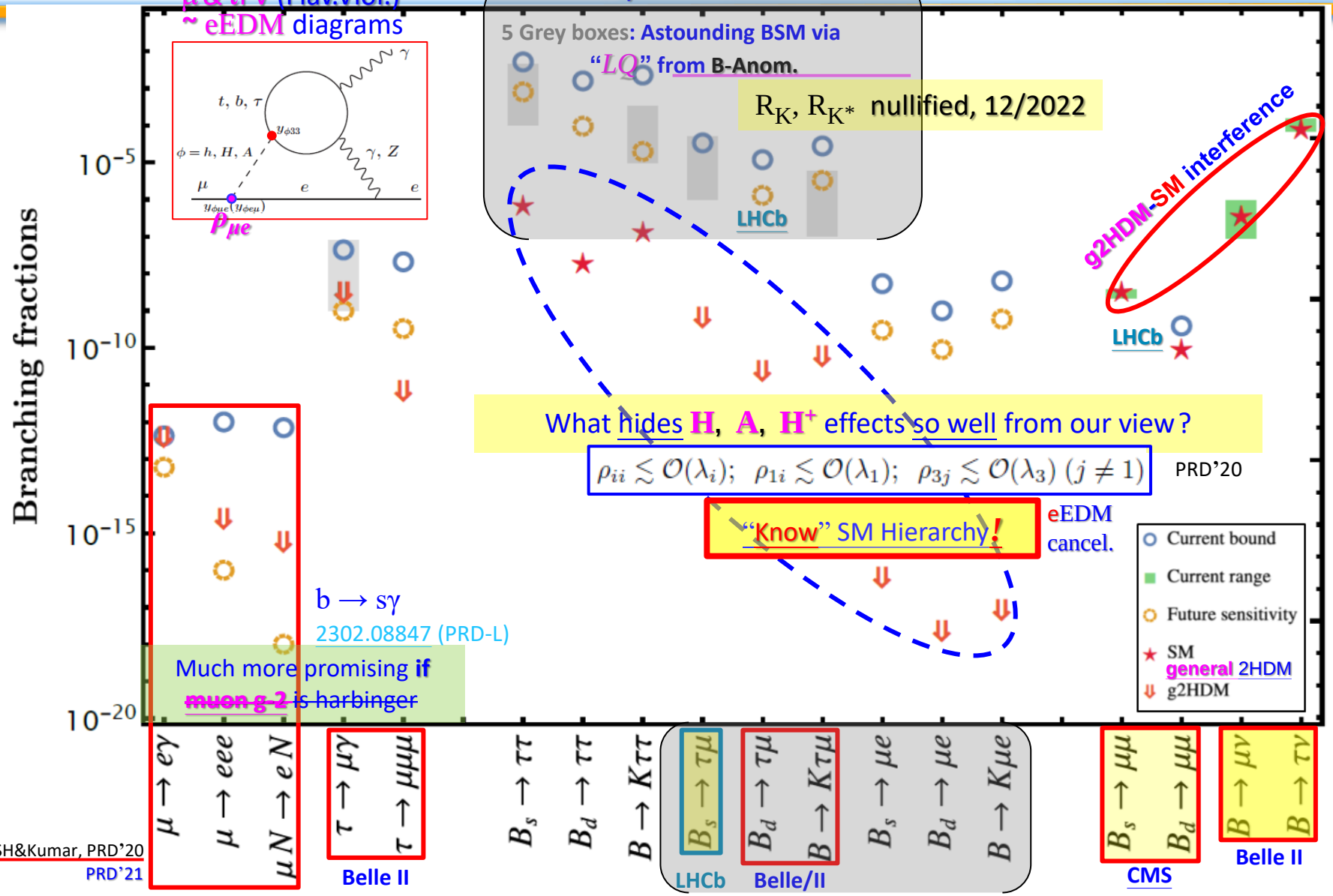
V_{tb}/V_{ub} enhanced!

WSH & Kumar PRD'20

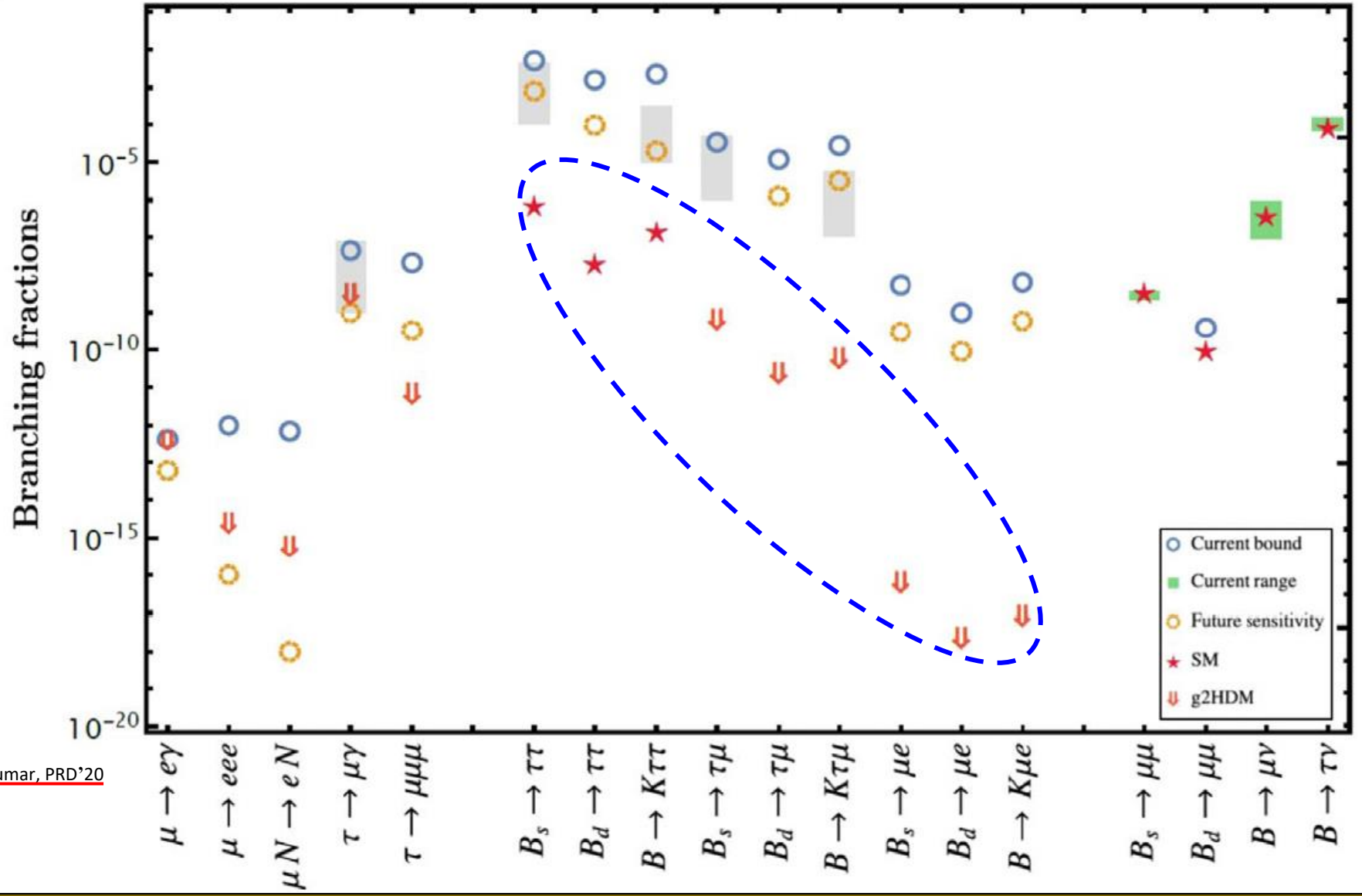
Glimpse of the *New Flavor* Era

WSH "Decadal Mission" 2109.02557, CJP'22

Glimpse of coming New *Flavor* Era in G2HDM



Glimpse of the *New Flavor* Era



WSH&Kumar, PRD'20

Rule of Thumb

$$\rho^f_{3j} \lesssim \lambda^f_3 \quad (j \neq 1),$$

$$\rho^f_{i1} \lesssim \lambda^f_1$$

Flavor Control

"Decadal Mission"

CJP'22

V. Discussion & Conclusion

High Scale SUSY?

Justify FCC/CEPC?

{Blank to Fill}

unconventional-Conventional

Road Not Taken

Extra Higgs Doublet w/

Extra Weinberg Couplings

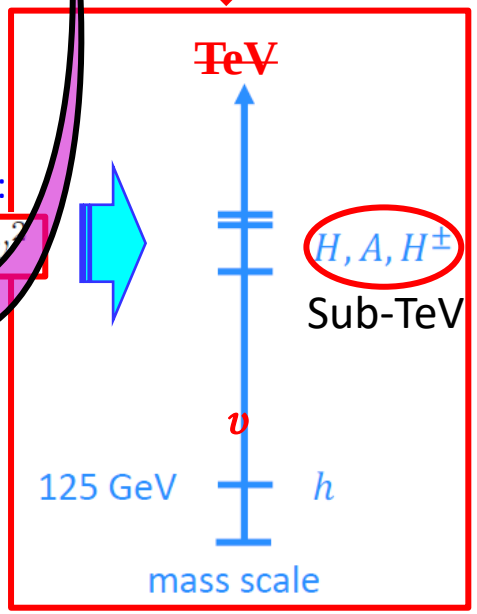
& Extra Quartics

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

η_i with $i = 1$–7; μ_{22}^2/v^2

➔ Landau Pole ~ 10-20 TeV

WSH, Kikuchi EPL'18



V. Discussion & Conclusion

Thus, our *Decadal Mission*:

"*Find* the ***extra H, A, H^+ bosons***;

Crack the ***Flavor code***;

*Solve** the *Mysterious B.A.U.!*"

Is this it?!

$|\rho_{ee}/\rho_{tt}| \sim \lambda_e/\lambda_t$!

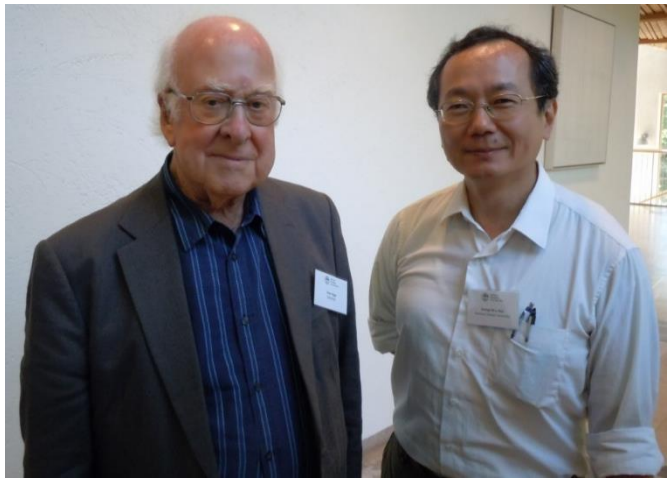
the flavor code?

* We are also conducting a Lattice study of $\mathcal{O}(1)$ quartics for 1stOPhTr → New Scale?

Leaders: David C.J. Lin
Alberto Ramos

Up to *Nature* whether our "Wish for *Discovery*" is Granted … or Not …

Thank You!



a Higgs, and a 2nd Higgs …

EWBG ought to be pursued while LHC is still running!

No SUSY, No Nothin'!

Beyond CKM CPV

EW BaryoGenesis (EWBG)

- more testable -

tension

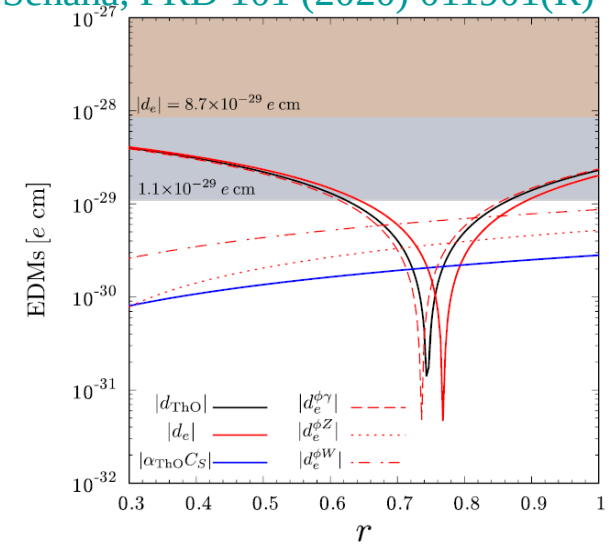
LHC

- No New Physics -

tension

competition

Fuyuto, WSH, Senaha, PRD 101 (2020) 011901(R)



JILA'22

eEDM: ACME14 → ~~ACME18~~

- L.E. Precision Frontier -

0.41

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

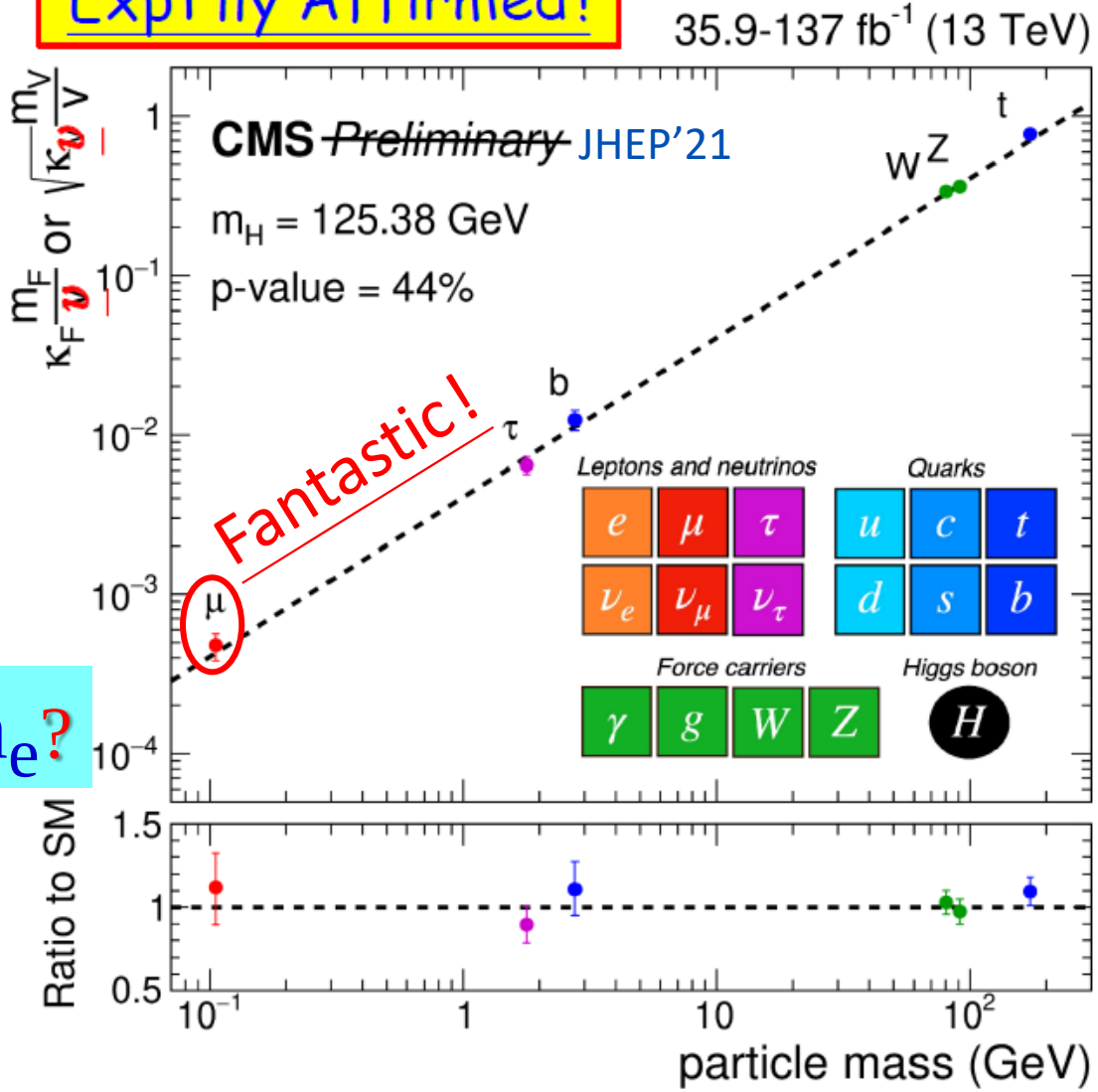
A *Natural* Cancellation Mechanism!

The "God" Particle: the Origin of Mass

h(125): observed 7/4/2012 ✓

λ_f : Yukawa *Couplings*

Expt'lly Affirmed!



m_e?

$g \simeq 2m_V/v$ ca. 2015

$\lambda_f \simeq \sqrt{2}m_f/v$ t/b/τ: 2018

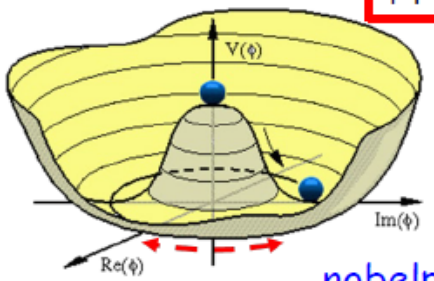
μ: 2020

Higgs "potential": Simplest!!

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

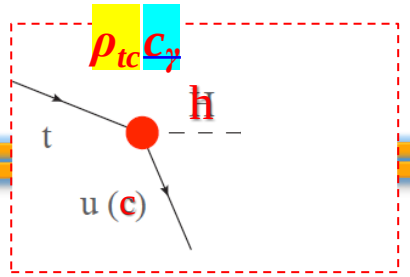
$$\Rightarrow \quad |\varphi^0|^2 = v^2 \sim \mu^2/\lambda$$

$v \approx 246$ GeV



nobelprize.org (2013)

First Fruit



"alignment"
c_γ *small*
emergent

c_γ: h-H mixing

Extra Higgs Doublet w/
Extra Yukawa Couplings
Extra Quartic Couplings

***General* 2HDM**

Before Top Quark was Discovered: WSH, PLB'92 (PSI-PR-91-34)

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

Correction on formulation with "SM"-like Higgs h: Chen, WSH, Kao, Kohda, PLB'13

CMS (ATLAS similar)

World Best Bound:

$t \to ch < 0.00073$

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.

國立臺灣大學 National Taiwan University

So, How "Steered"?

2017 was "a Good Year".

Explaining BAU

1705.05034

Physics Letters B 776 (2018) 402–406

Electroweak baryogenesis driven by extra top Yukawa couplings

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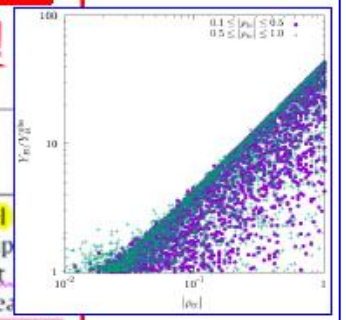
[c] Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34051, Republic of Korea

EWBG Driven by $\lambda_t \mathrm{Im}\rho_{tt}$

Grand Motivation!



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ABSTRACT

We study electroweak baryogenesis driven by the top quark in a general two Higgs doublet model with flavor-changing Yukawa couplings, keeping the Higgs potential CP invariant. With Higgs sector coup and the additional top Yukawa coupling ρ_{tt} all of $\mathcal{O}(1)$, one naturally has sizable CP violation that the cosmic baryon asymmetry. Even if ρ_{tt} vanishes, the favor-changing coupling ρ_{tc} can still le successful baryogenesis. Phenomenological consequences such as $t \to ch$, $\tau \to \mu\gamma$ electron electric dipole moment, $h \to \gamma\gamma$, and hhh coupling are discussed.

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

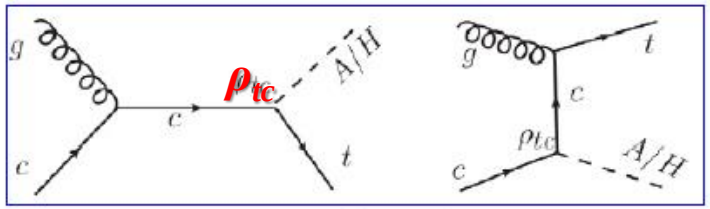
Fit for LHC

1706.07694 Sub-TeV H, A, H^+ @ LHC; G2HDM well-hidden so far. EPL 123 (2018) 11001

Production Processes

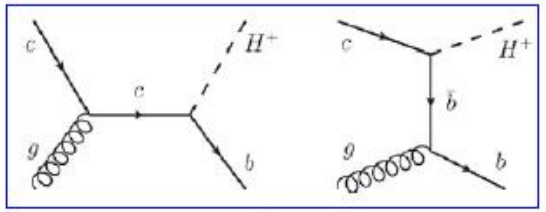
1710.07260

$cg \to tA/H \to tt\bar{c}, t\bar{t}t$



PLB 776 (2018) 379-384

$cg \to bH^+ \to bt\bar{b}$



PRL 125 (2020) 221801

unsuppressed by alignment

ATLAS-CONF-2022-039 (ICHEP)

Search Started 2/2020.

Fruition 2023!