Decadal Mission for the New Physics Higgs/Flavor Era
— Searching for Extra Higgs Boson Effects in General 2HDM

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

January 7, 2025, Colloquium @ ASIoP

National Taiwan University

Outline

0. Our current *impasse:* 𝒩o 𝒩ew 𝒫hysics (𝒩𝒩𝒫)

5 Merits

I. General Two-Higgs Doublet Model (G2HDM) (w/o Z_2)

More Dim-4's (two extra sets of couplings)

Take Home Msg

Don't EFT yet!!

Two Maxims

Φ Φ'

1. Seen one Higgs Doublet → A Second is a No-brainer.
   Augmented by fermion repetition.

2. Any added *Assumption* should cost $\mathcal{O}(\alpha)$ in Likelihood.

   → ***No*** Z_2.

Outline

0. Our current *impasse:* *No New Physics* (*NNP*)

5 Merits

I. General Two-Higgs Doublet Model (G2HDM) (w/o Z_2)

More Dim-4's (two extra sets of couplings) ➡ Take Home Msg: Don't EFT yet!!

2nd 攻頂

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

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

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

[t → ch & ttc(bar) redux

IV. G2HDM as *Next NP*?! & w/lot's of *Flavor*

V. Discussion & Conclusion

0. Our *impasse*

Physicists' Nightmare Scenario: The Higgs and Nothing Else

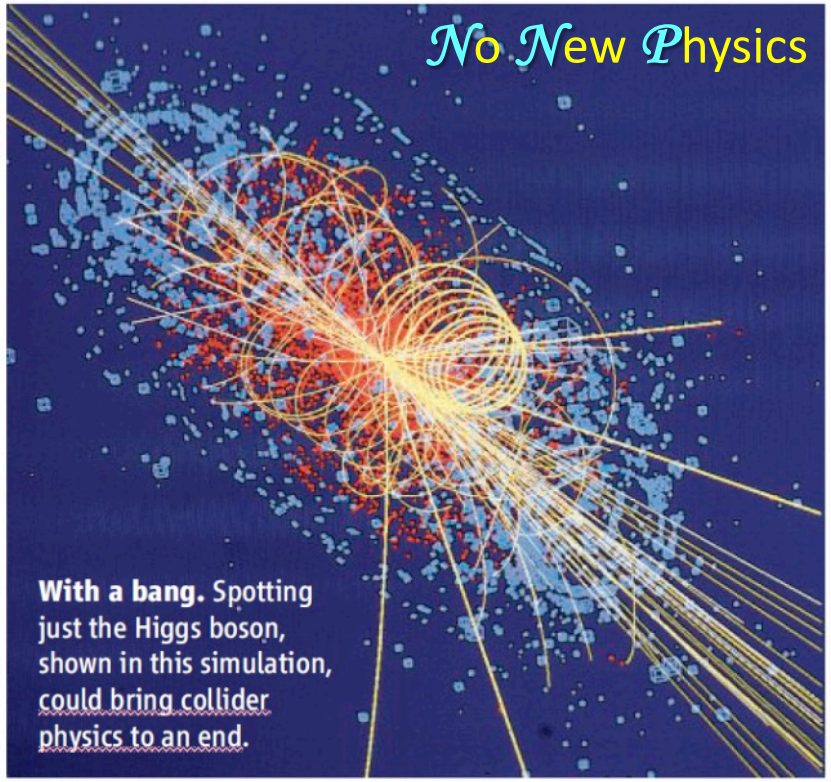
Adrian Cho

Many fear the LHC will cough up only the one particle they've sought for decades. Some would rather see nothing new at all

fear nothing more than the possibility that you were wrong and the particle doesn't exist, right? Not exactly.

Many particle physicists say their greatest fear is that their grand new machine—the Large Hadron Collider (LHC) under construction at the European particle physics laboratory, CERN, near Geneva, Switzerland—will spot the Higgs boson and nothing else. If so, particle physics could grind to halt, they say. In fact, if the LHC doesn't reveal a plethora of new particles in addition to the Higgs, many say they would rather it see nothing new at all.

That may seem perverse, but put yourself again in the shoes of a particle physicist. In the 1960s and 1970s, researchers hammered out a theory called the Standard Model that, in



With a bang. Spotting just the Higgs boson, shown in this simulation, could bring collider physics to an end.

SCIENCE VOL 315 23 MARCH 2007

If it has the right mass, the Higgs and nothing else **"would be the real five-star disaster, because that would mean there wouldn't need to be any new physics."**

—Jonathan Ellis, CERN

SM renormalizable up to Planck Scale.

Ten years after the Higgs, physcists face the nightmare of finding nothing else

Adrian Cho

Unless Europe's Large Hadron Collider coughs up a surprise, the field of particle physics may wheeze to its end

13 JUN 2022 · 1:30 PM · BY ADRIAN CHO

I. G2HDM

w/o Z_2 → ∃ extra { Yukawas: ρ^f ; Quartics: η_i

two identical weak doublets

Merit

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

CPV

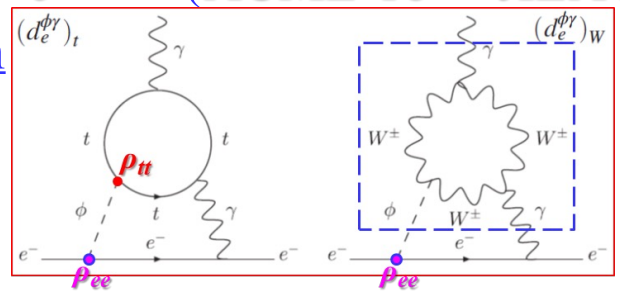
M①: extra top Yukawas ρ_{tt} and $\rho_{tc} \sim 1$ and complex, can drive EWBG, Fuyuto, WSH, Senaha PLB'18

Higgs quartic self-couplings η_i at $\mathcal{O}(1)$, $i = 1-7$, provide 1st OPhTr (→ 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?

$\arg \rho_{ee} = -\arg \rho_{tt}$

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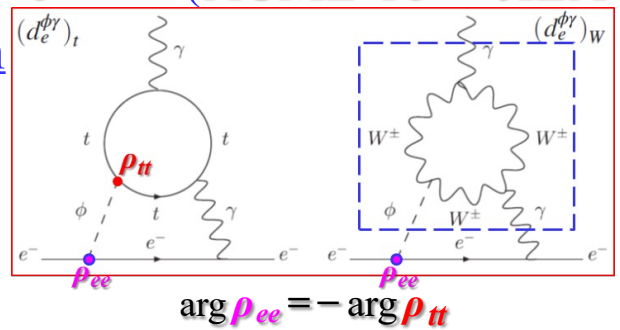

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M③: Glashow worried about FCNCs, such as t → ch;

WSH, PLB'92
flavor-protected

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

Curiously, t → ch remains elusive c_γ

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

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

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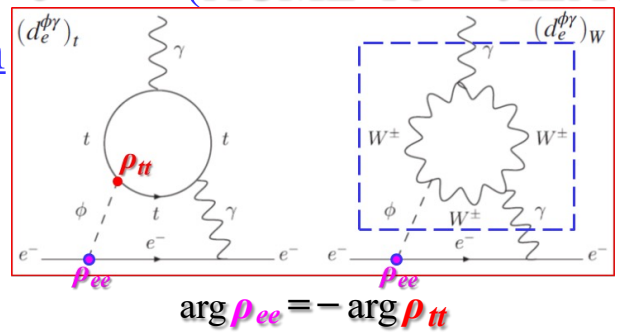

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sub-TeV | H, A, H^+

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

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

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

WSH, Kikuchi EPL'18

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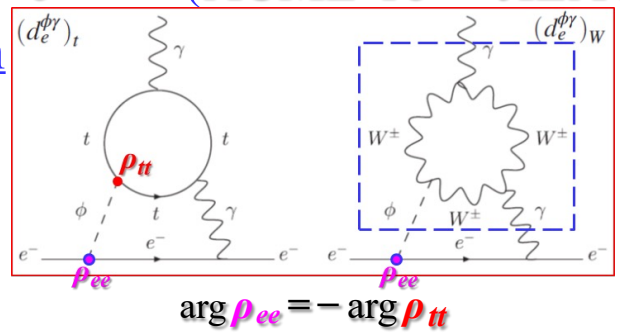

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WSH, Kikuchi EPL'18

$s_\gamma \to 1$

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

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

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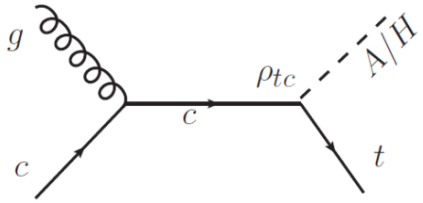

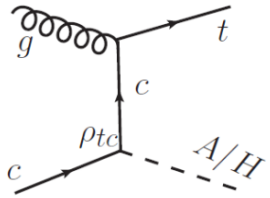

A/H → tc(bar), tt(bar)

JHEP

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ATLAS EXPERIMENT

The ATLAS collaboration

2307.14759

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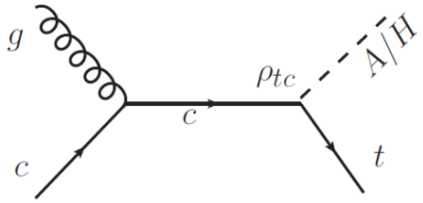

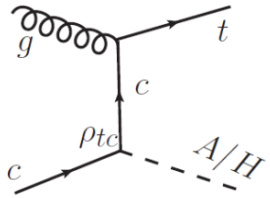

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Neither ATLAS ... *Nor* CMS saw a signal.

Soaring to the Starry Heavens

Baryon Asymmetry of Universe

le Raison d'être

Enough CPV for BAU ?

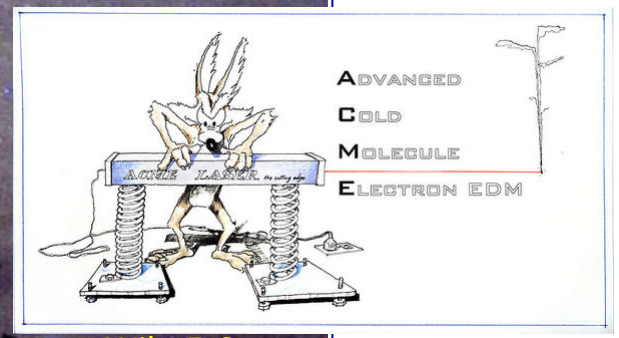
$\lambda_t \mathrm{Im}\rho_{tt}$

天 CPV→BAU

Where have all the *Antimatter* Gone?

BAU: an issue as ***Big*** as the *Universe*.

Billions
&
billions of stars …
all burning protons



Wile-E-Coyote

JILA'23

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

Search H, A, H^+ @ LHC!

地

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

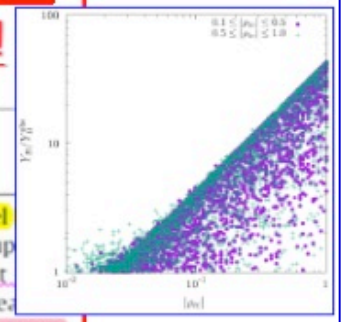
Electroweak baryogenesis driven by extra top Yukawa couplings

Kaori Fuyuto [a,*], Wei-Shu Hou [b], Eibun Senaha [c]

[a] Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts Amherst, MA 01003, USA
[b] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[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 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 lea 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.

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

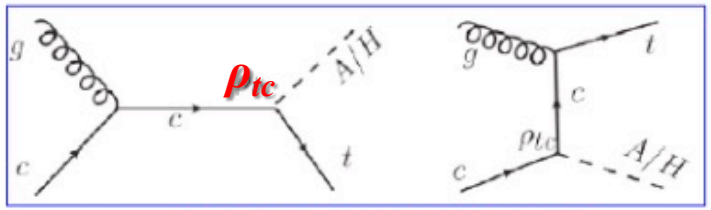
Fit for LHC

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

Production Processes

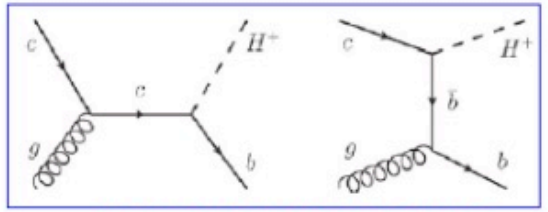
1710.07260

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



PLB 776 (2018) 379-384

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



PRL 125 (2020) 221801

$H^+ \to tb(bar)$ unsuppressed by alignment

ATLAS-CONF-2022-039 (ICHEP)

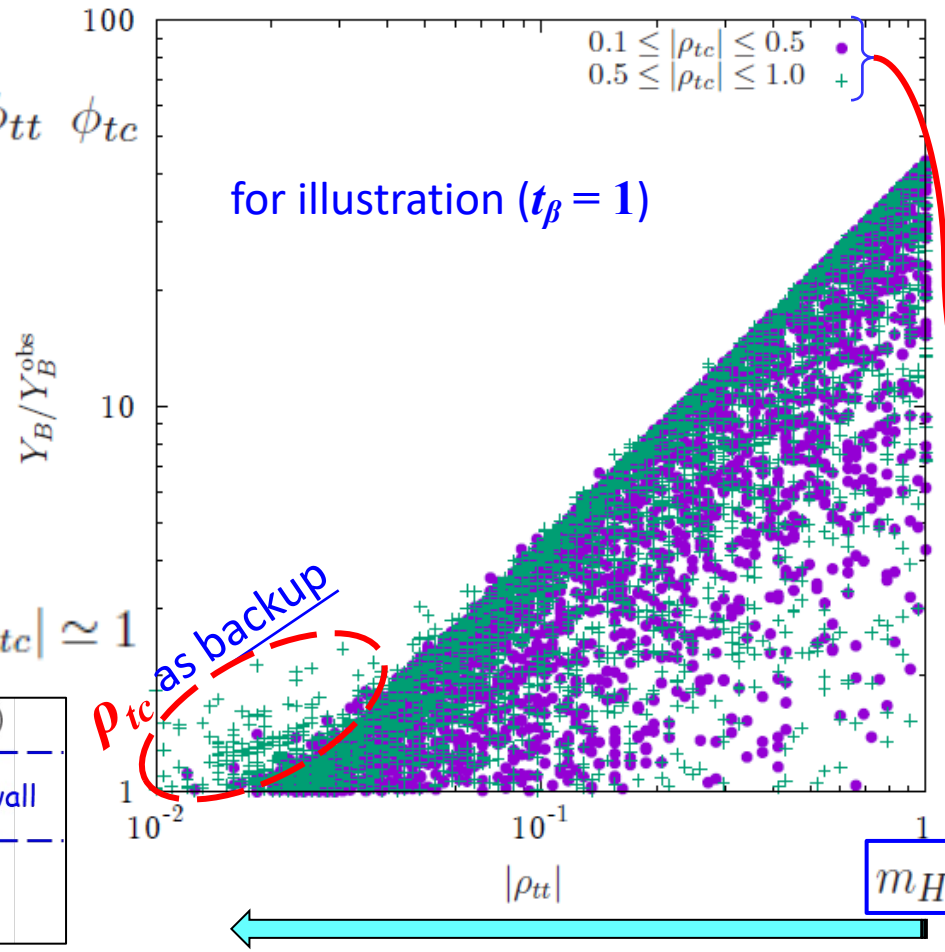
Search Started 2/2020.

Fruition 11/2023!

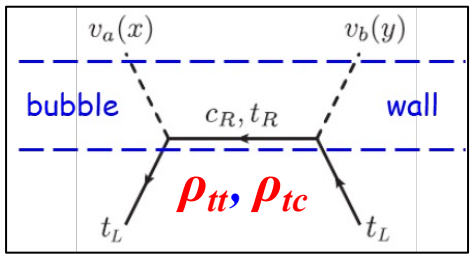
Robust: Large Parameter Space for EWBG

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

for illustration ($t_\beta = 1$)



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



small ρ_{tt}

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

no obvious diff.

$\Rightarrow \rho_{tt}$ driven !

the charm of EWBG

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

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

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

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

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Same-sign top pair + jet

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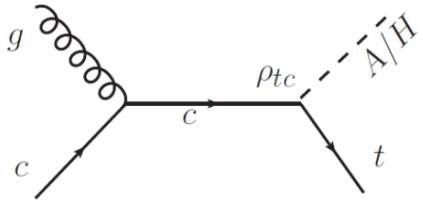

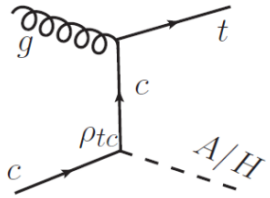

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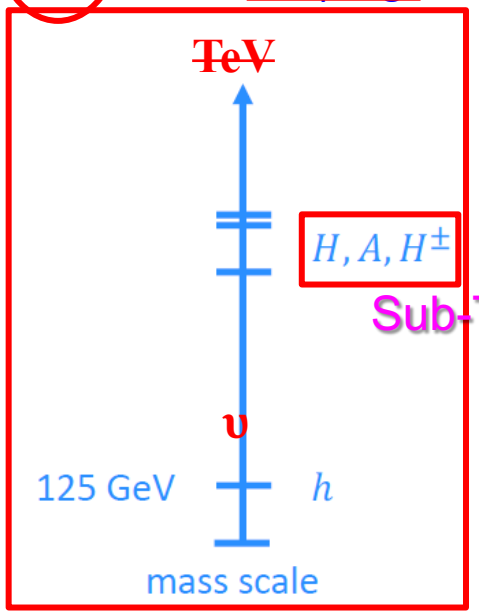
* NTUCMS started already 2/2020, but thanks to a good 5-yr grant, manpower could be built-up in time since 8/2021.

2nd ASP 8/2021 – 7/2026

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

David C.J. Lin
(NYCU)

Wish us Luck!

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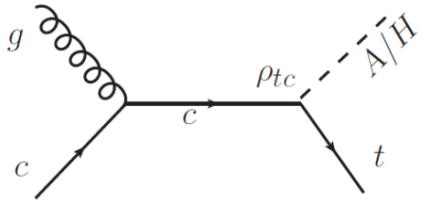

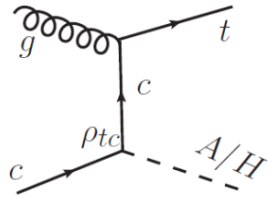

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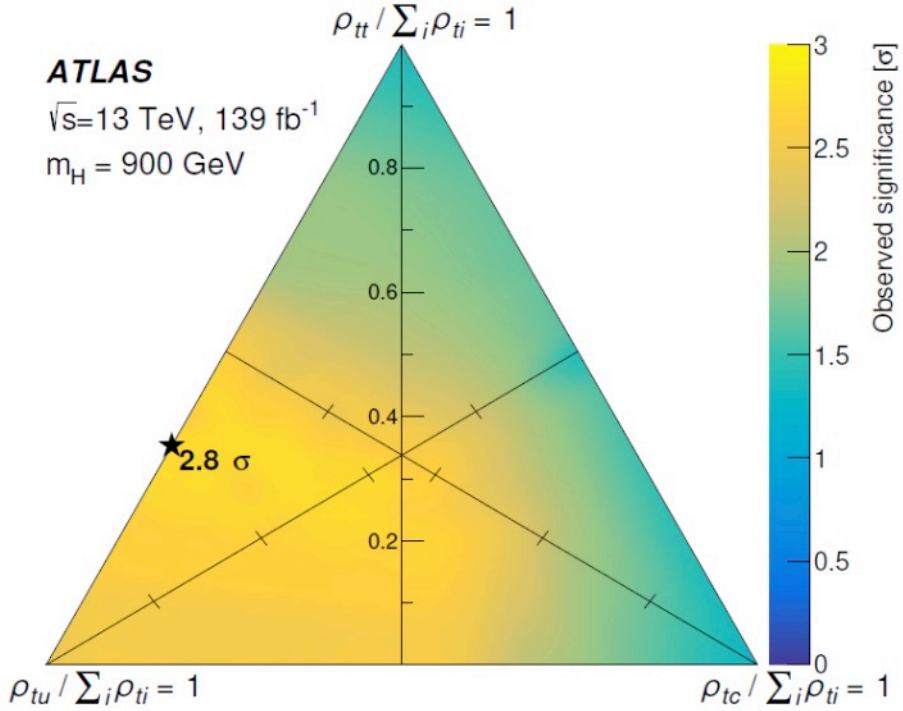

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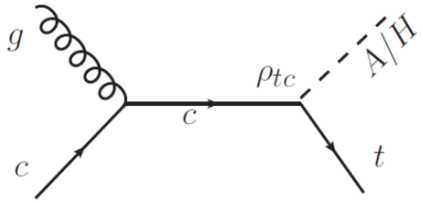
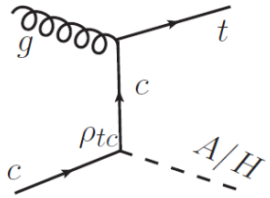




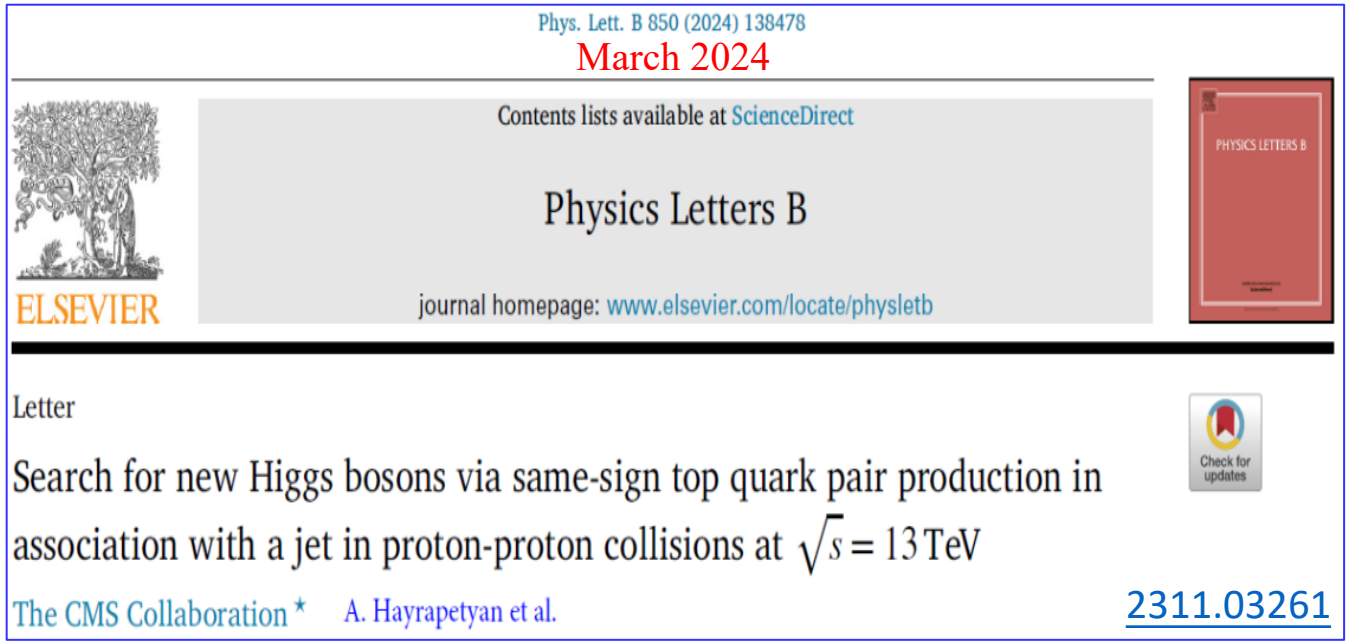
A/H → tc(bar)

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



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

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)

Kohda, Modak, WSH PLB'18

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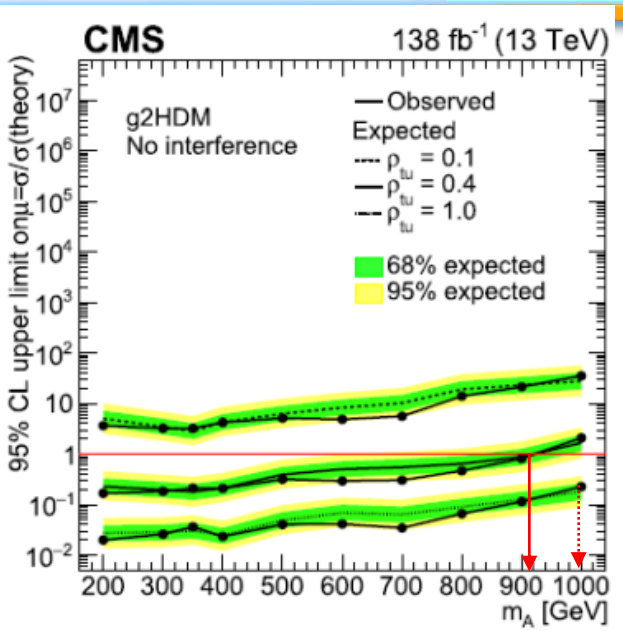
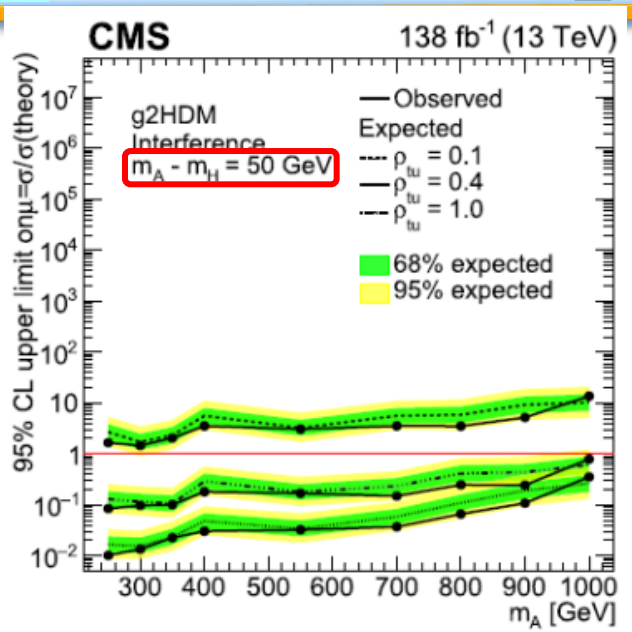
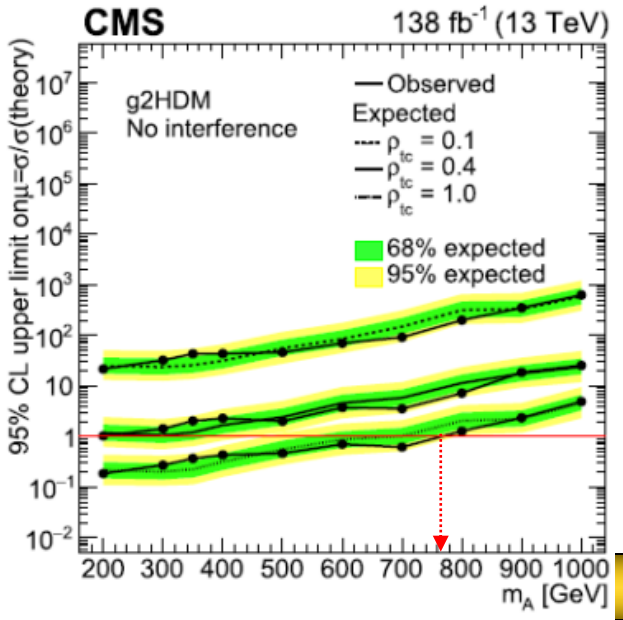
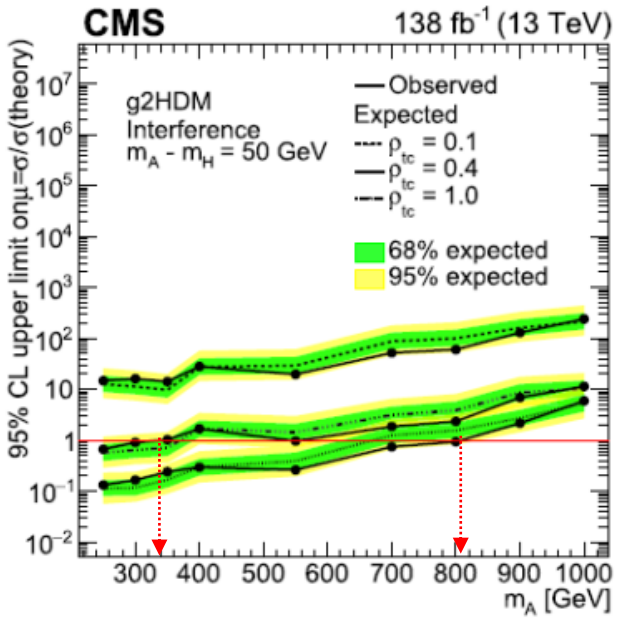
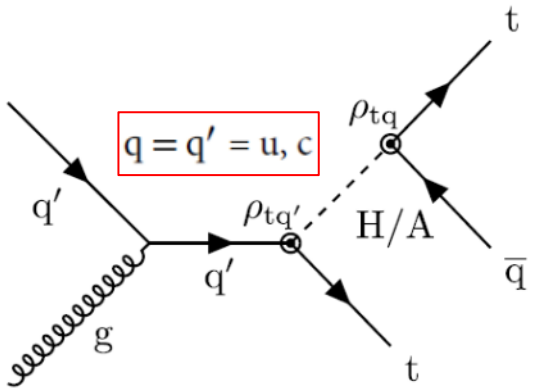
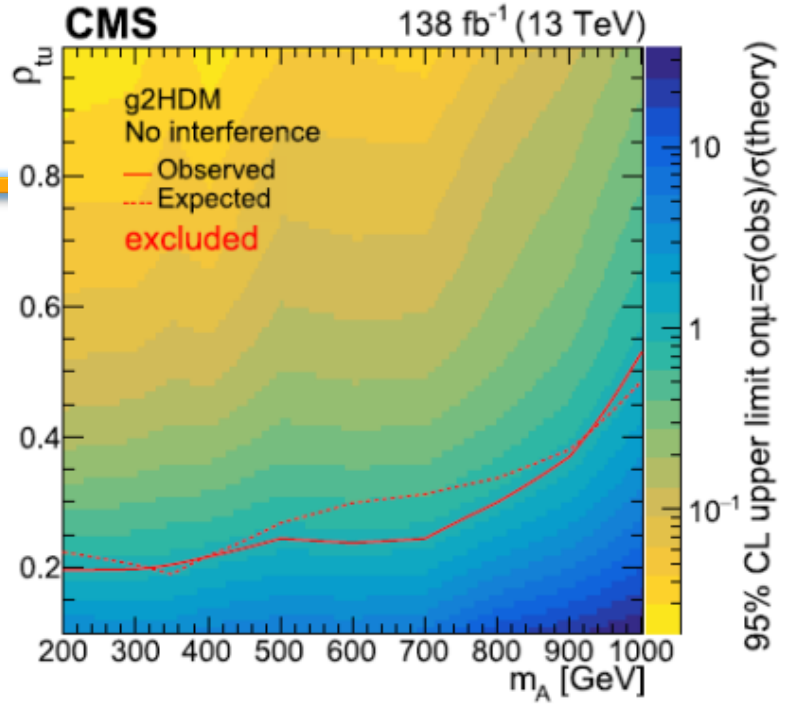


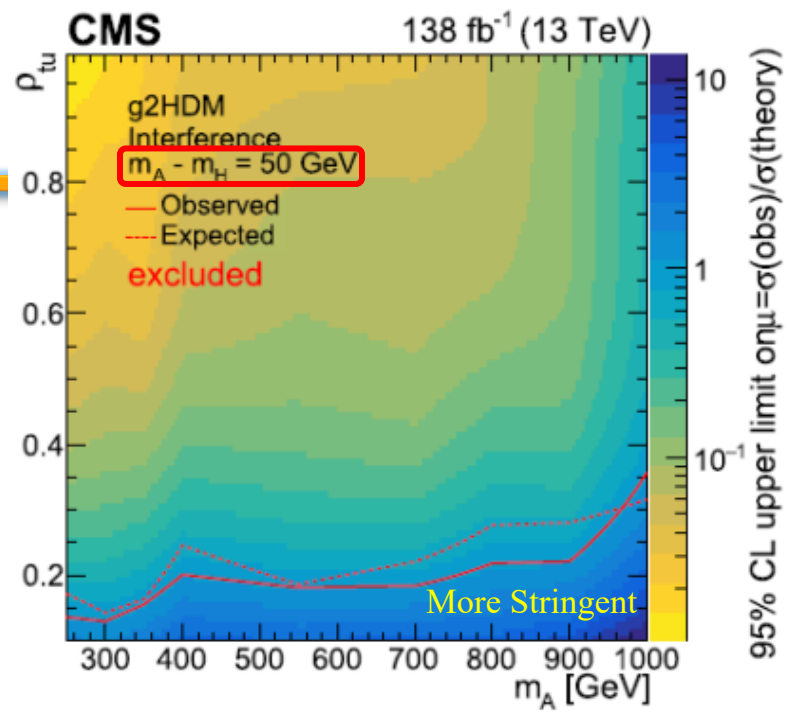


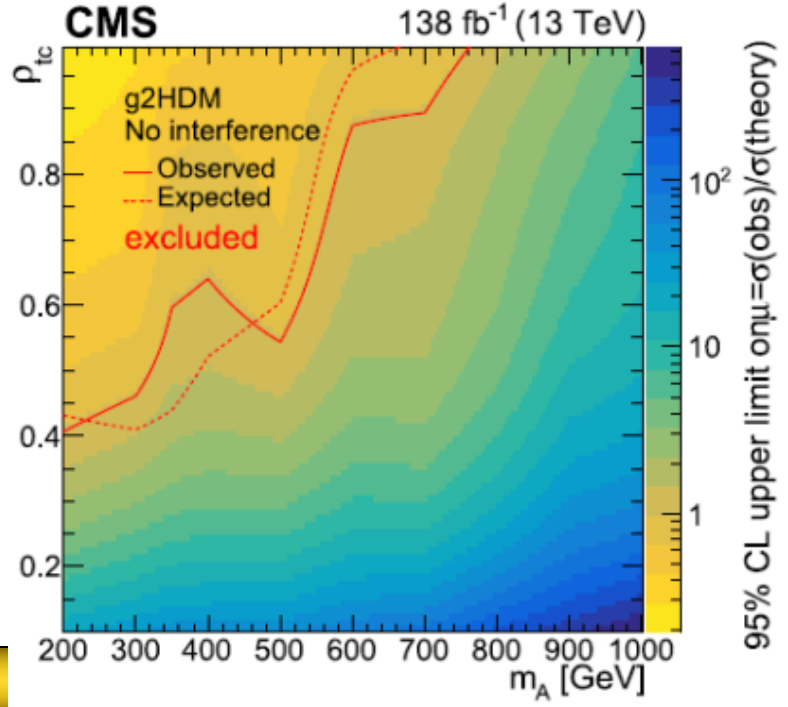


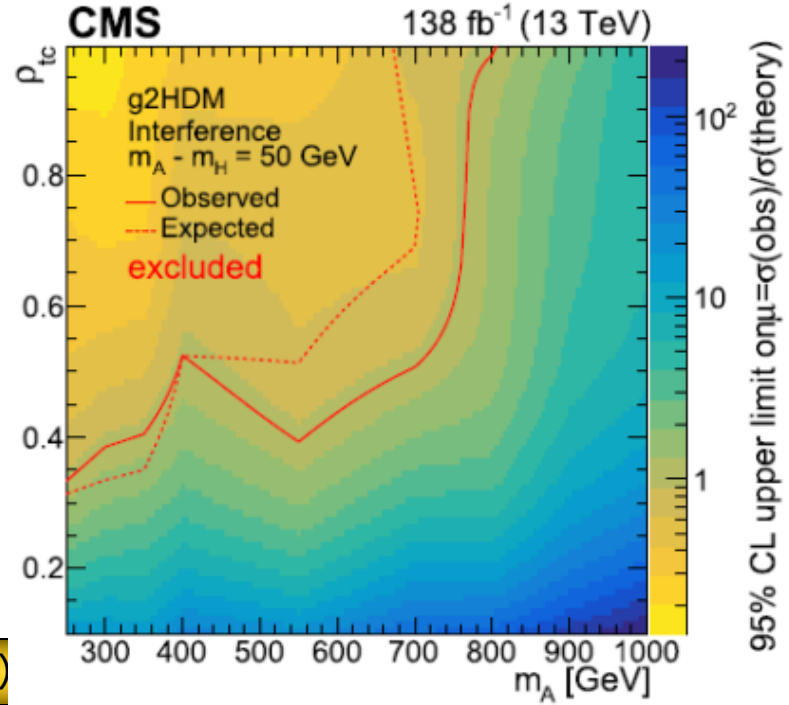



t
ρ_{tq}
$q = q' = u, c$
q′
$\rho_{tq'}$
H/A
$\bar{q}$
q′
g
t


CMS
138 fb^{-1} (13 TeV)
ρ_{tu}
g2HDM
No interference
Observed
Expected
excluded
m_A [GeV]
95% CL upper limit on μ=σ(obs)/σ(theory)


CMS
138 fb^{-1} (13 TeV)
ρ_{tu}
g2HDM
Interference
$m_A - m_H$ = 50 GeV
Observed
Expected
excluded
More Stringent
m_A [GeV]
95% CL upper limit on μ=σ(obs)/σ(theory)


CMS
138 fb^{-1} (13 TeV)
ρ_{tc}
g2HDM
No interference
Observed
Expected
excluded
m_A [GeV]
95% CL upper limit on μ=σ(obs)/σ(theory)


CMS
138 fb^{-1} (13 TeV)
ρ_{tc}
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Interference
$m_A - m_H$ = 50 GeV
Observed
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m_A [GeV]
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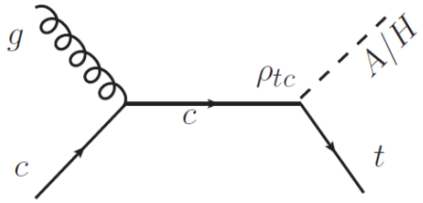
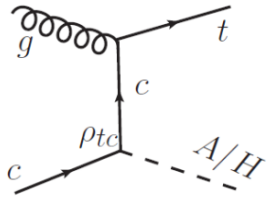
Kohda, Modak, WSH PLB'18





A/H → tc(bar), tt(bar)

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *July 28, 2023*
ACCEPTED: *October 5, 2023*
PUBLISHED: *December 12, 2023*

Search for heavy Higgs bosons with flavour-violating couplings in multi-lepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

2307.14759

Phys. Lett. B 850 (2024) 138478

March 2024

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Search for new Higgs bosons via same-sign top quark pair production in association with a jet in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration * A. Hayrapetyan et al.

2311.03261

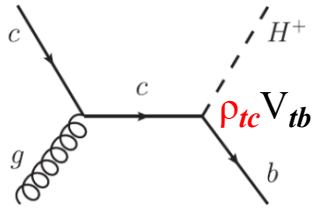
Neither ATLAS ... *Nor* CMS saw a signal.

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

[ttc(bar) & t → ch redux

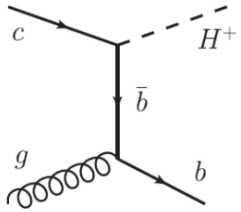
→ Better: cg → bH⁺ → btb(bar)

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 t → ch

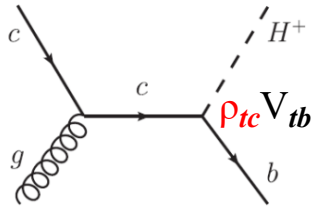
adding Run 3 data

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

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

[ttc(bar) & t → ch redux

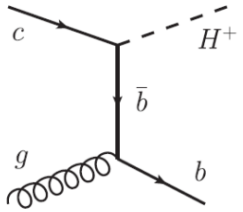
→ Better: cg → bH⁺ → btb(bar)



$\rho_{tc} V_{tb}$

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

Ghosh, WSH, Modak PRL'20



H⁺ → tb(bar) $\rho_{tt} V_{tb}$

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

redux t → ch adding Run 3 data

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

IV. G2HDM as *Next NP*?!

τ → μγ induced by 2-loop diagrams.

WSH, Kohda, Modak, Wong PLB'20

The above H⁺ CKM enhancement first uncovered in B → μν, τν; **ratio ≠ 0.0045**

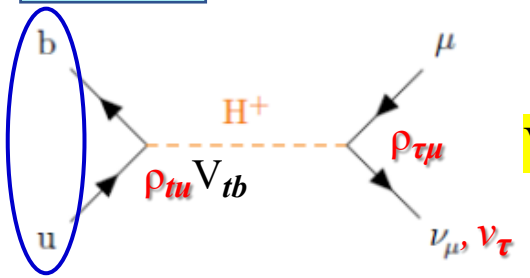
→ Rule out SM/2HDM-II*.

Belle II will study this.

CMS: $B_{s,d}$ → μμ

B → μν: stat. dom. ← takes time

B → τν: syst. dom. ← imprv method



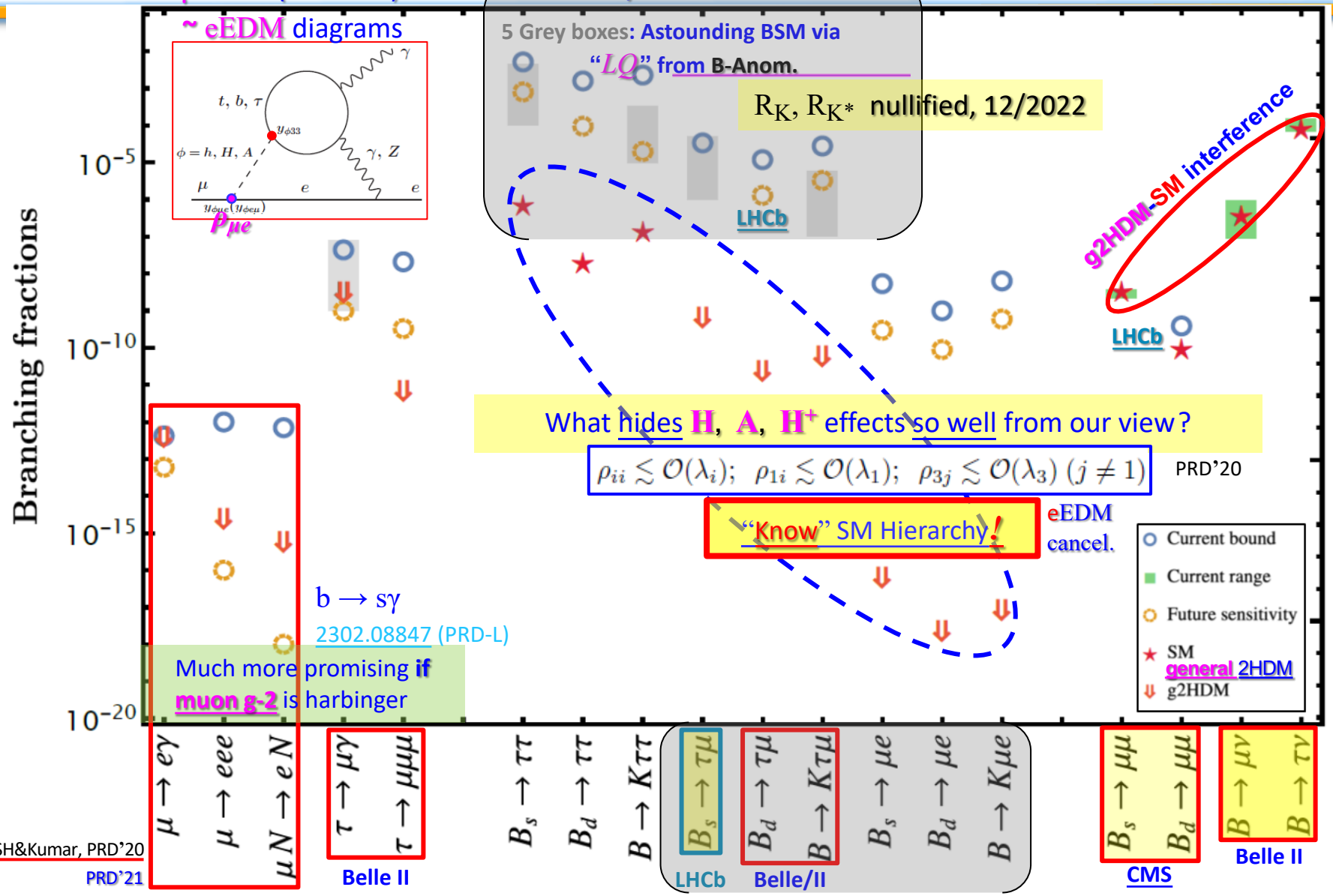
V_{tb}/V_{ub} enhanced!

WSH & Kumar PRD'20

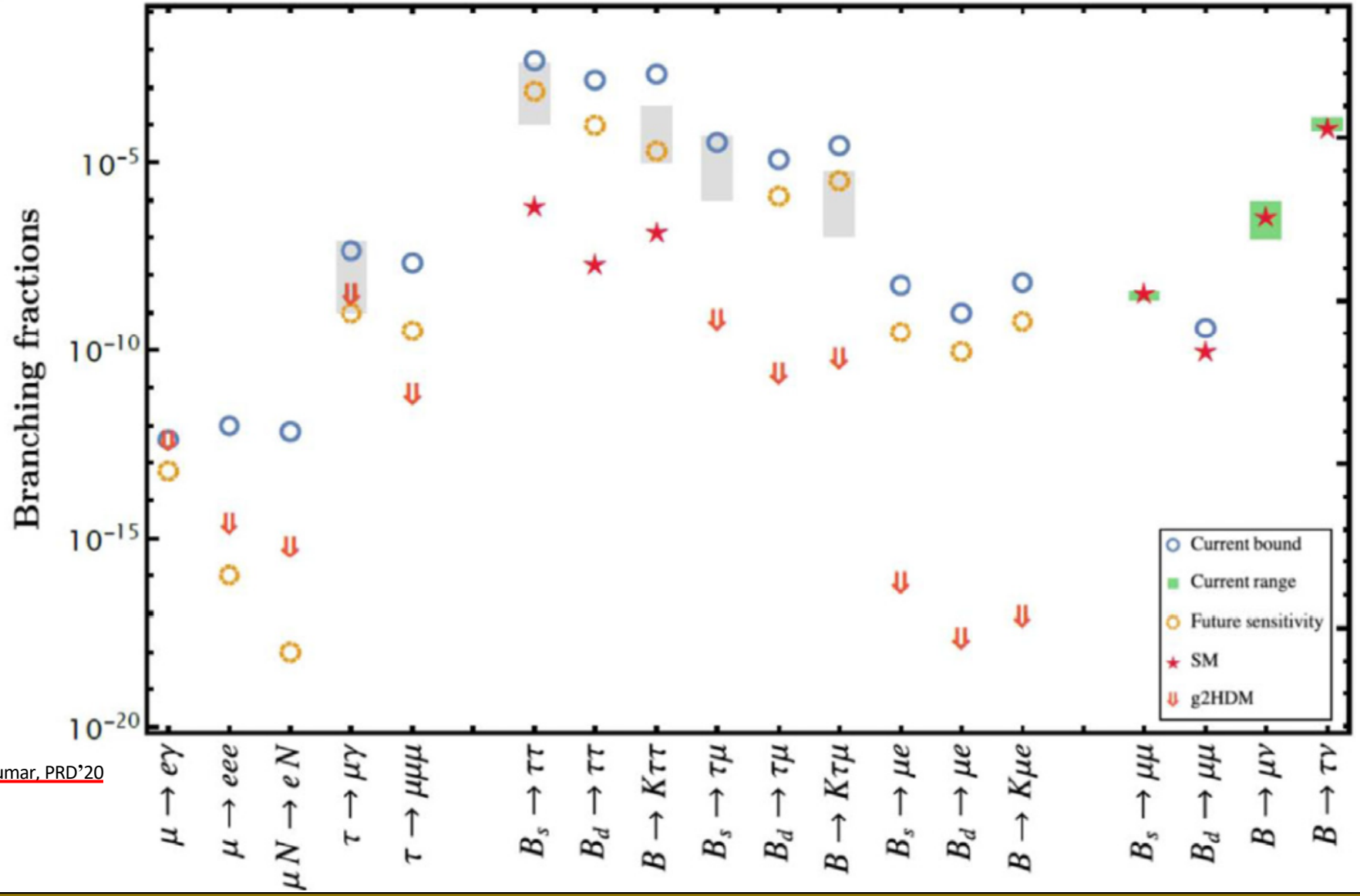
Glimpse of the *New Flavor* Era

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-SppC?

{Blank to Fill}

unconventional-Conventional

Road Not Taken

Extra Higgs Doublet w/

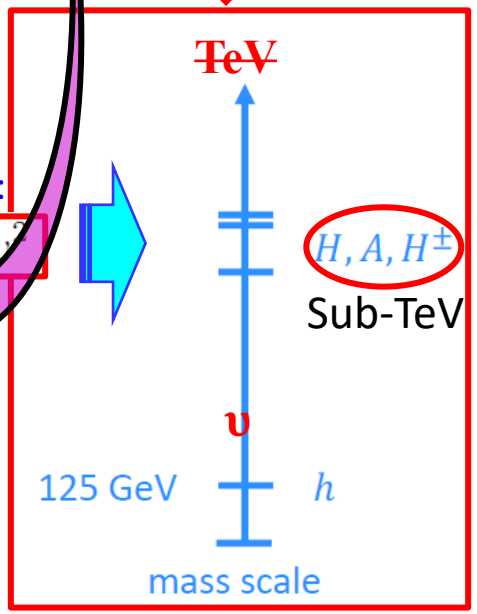
Extra Weinberg Couplings

& 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



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?!

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

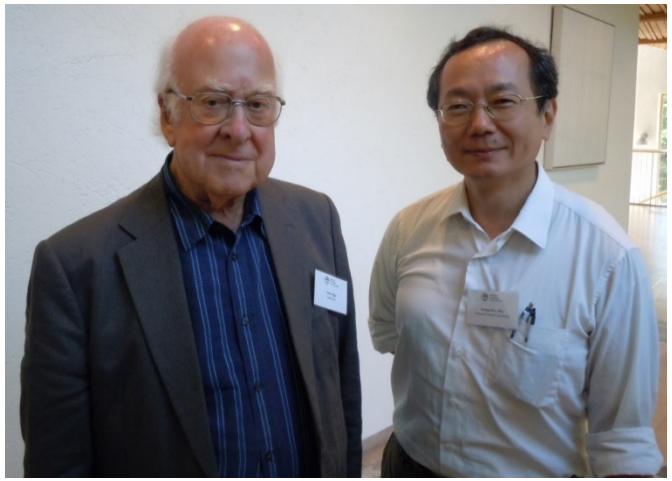
the flavor code?

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

David C.J. Lin

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

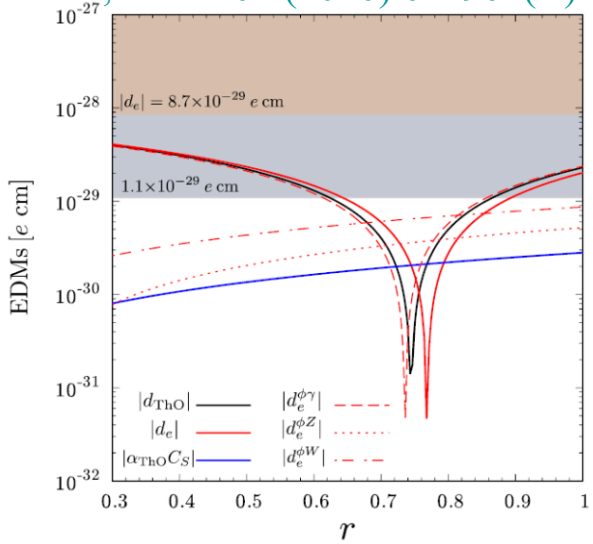
LHC

- No New Physics -

tension

competition

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



JILA'23

*e*EDM: ACME14 → ~~ACME18~~

- L.E. Precision Frontier -

$$|d_e| < \overset{0.41}{\cancel{1.1}} \times 10^{-29}\ e\ \text{cm}$$

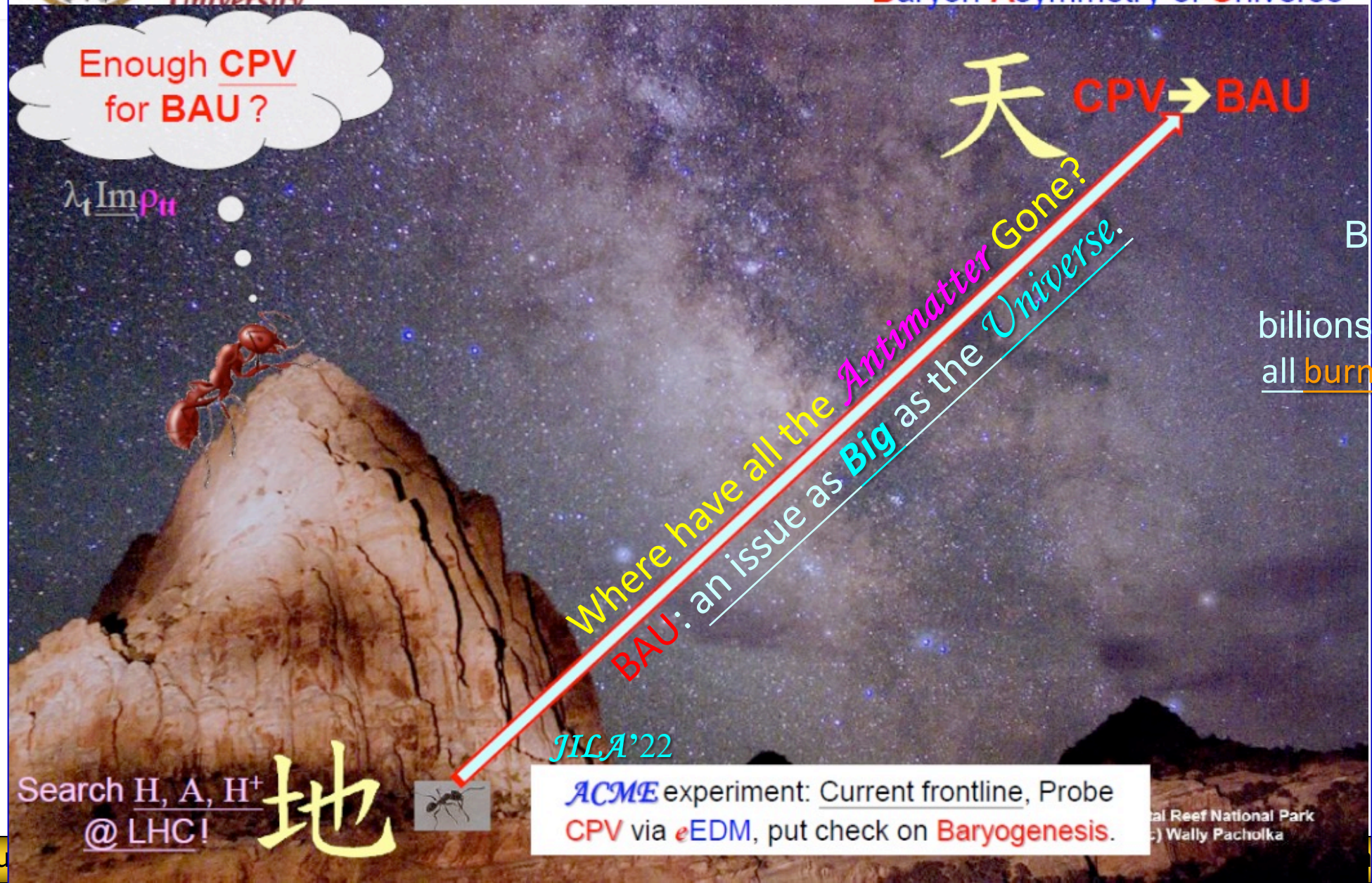
A *Natural* Cancellation Mechanism!

le Raison d'être

國立臺灣大學 National Taiwan University

Soaring to the Starry Heavens

Baryon Asymmetry of Universe



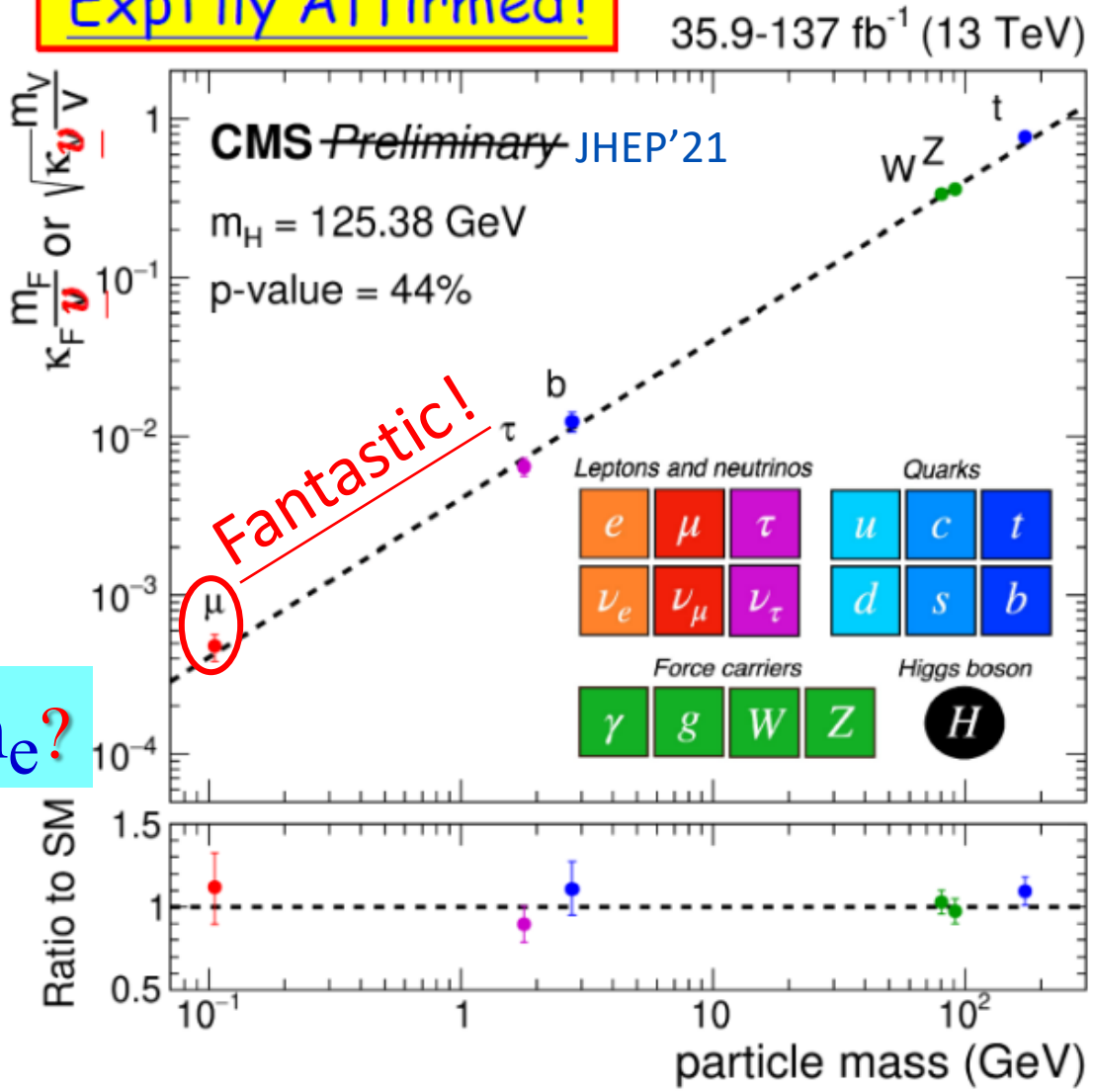
Billions
&
billions of stars …
all burning protons

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

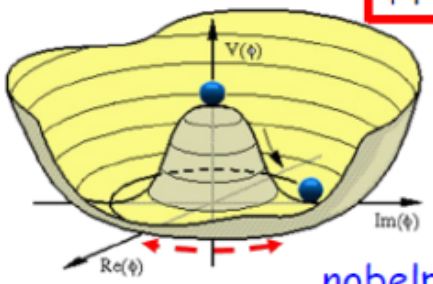
μ: 2020

Higgs "potential": Simplest!!

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

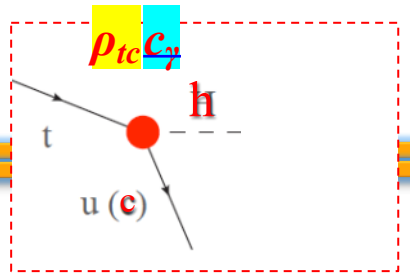
$$\Rightarrow \quad |\varphi^0|^2 = v^2 \sim \mu^2/\lambda$$

$v \approx 246$ 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

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

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

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.

National Taiwan University

So, How "Steered"?

2017 was "a Good Year".

Explaining BAU

1705.05034

Physics Letters B 776 (2018) 402–406

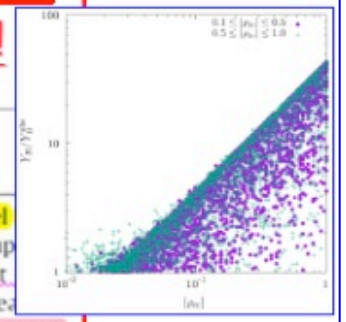
Electroweak baryogenesis driven by extra top Yukawa couplings

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

Grand Motivation!

Kaori Fuyuto [a,*], Wei-Shu Hou [b], Eibun Senaha [c]

[a] Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts Amherst, MA 01003, USA
[b] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[c] Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34051, Republic of Korea



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ABSTRACT

We study electroweak baryogenesis driven by the top quark in a general two Higgs doublet model 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.

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

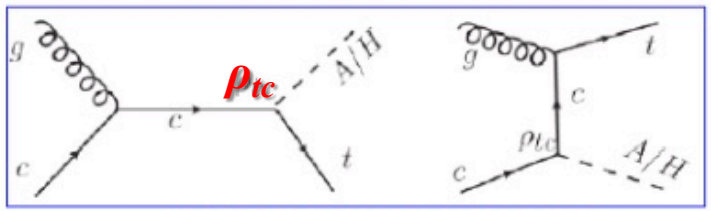
Fit for LHC

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

Production Processes

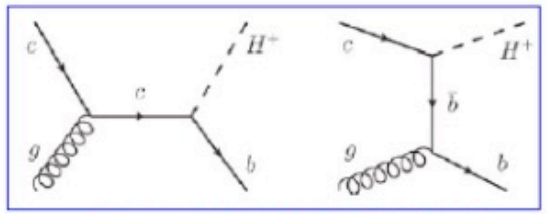
1710.07260

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



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!