LCWS

lite H^+ Boson Search via $e^+e^- \rightarrow H^+H^- \rightarrow cbcb$ @ ILC500

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

July 10, 2024, LCWS @ Tokyo University

臺灣大學
National Taiwan University

Search for LIGHT H^+ Bosons via $e^+e^- \to H^+H^- \to c\underline{bc}b$ @ ILC500

Outline

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

(w/o Z_2)

5 Merits

I. General Two-Higgs Doublet Model (G2HDM)

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

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

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

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

[t → ch & ttc(bar) redux

IV. $e^+e^- \to H^+H^- \to c\bar{b}\bar{c}b$ @ ILC500

WSH, Jain, Modak, JHEP'22

V. Discussion & Conclusion

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V. Discussion & Conclusion

0. Our *impasse*

Physicists' Nightmare Scenario: The Higgs and Nothing Else

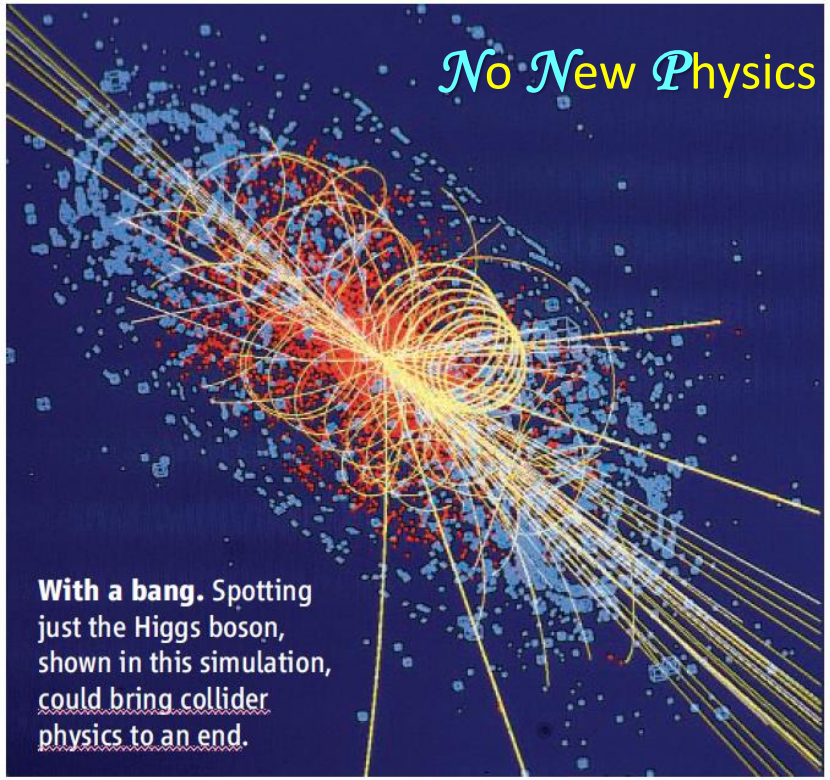
Adrian Cho

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

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

CPV

Merit

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

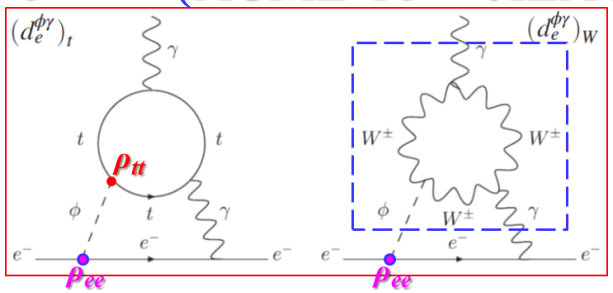
M①: extra top Yukawas ρ_{tt} and $\rho_{tc} \sim 1$ and complex, can drive EWBG, Fuyuto, WSH, Senaha PLB'18

Higgs quartic self-couplings η_i at $\mathcal{O}(1)$, $i = 1-7$, provide 1stOPhTr (→ primordial GW!)

Kanemura, Okada, Senaha, PLB'05

M②: CPV @ $\mathcal{O}(1)$ needed for EWBG → vulnerable to eEDM (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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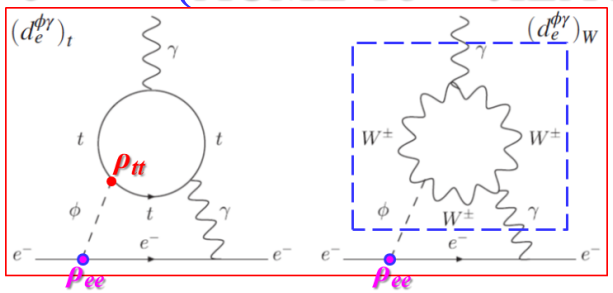

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Glashow-Weinberg PRD'77

M③: Glashow worried about FCNCs, such as t → ch;
but with h < t, it is a "PDG" duty to search!
Curiously, t → ch remains elusive

WSH, PLB'92
flavor-protected

— Nature threw in *alignment* (*small* h-H mixing) c_γ
to hide it so far! *Who* would have thought!?

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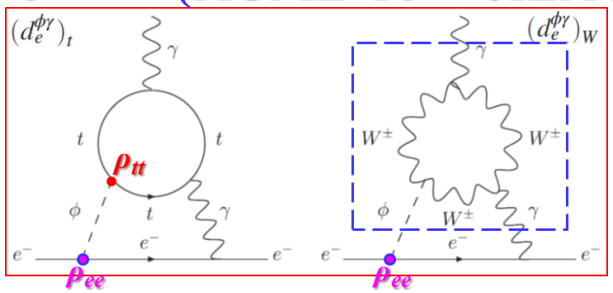

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sub-TeV H, A, H⁺

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➔ 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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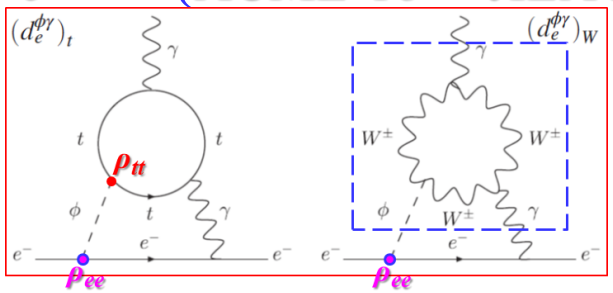

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WSH, Kikuchi EPL'18

$s_\gamma \to 1$

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

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

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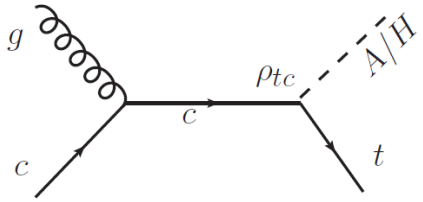
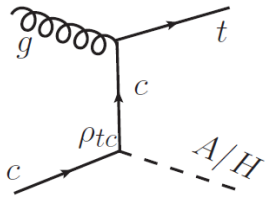
Same-sign top pair + jet

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





A/H → tc(bar)

JHEP

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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

Contents lists available at ScienceDirect

Physics Letters B

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Letter

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The CMS Collaboration ⋆ A. Hayrapetyan et al.

2311.03261

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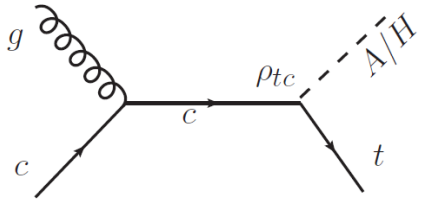

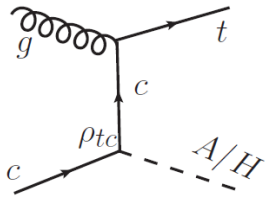

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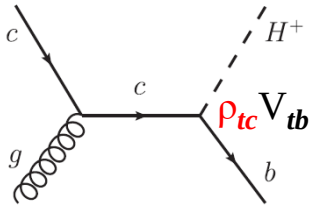
Neither ATLAS ... *Nor* CMS saw a signal.

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

[ttc(bar) & t → ch redux

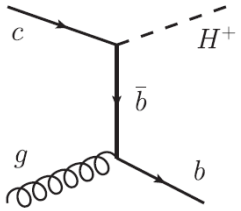
→ Better: cg → bH⁺ → btb(bar)

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

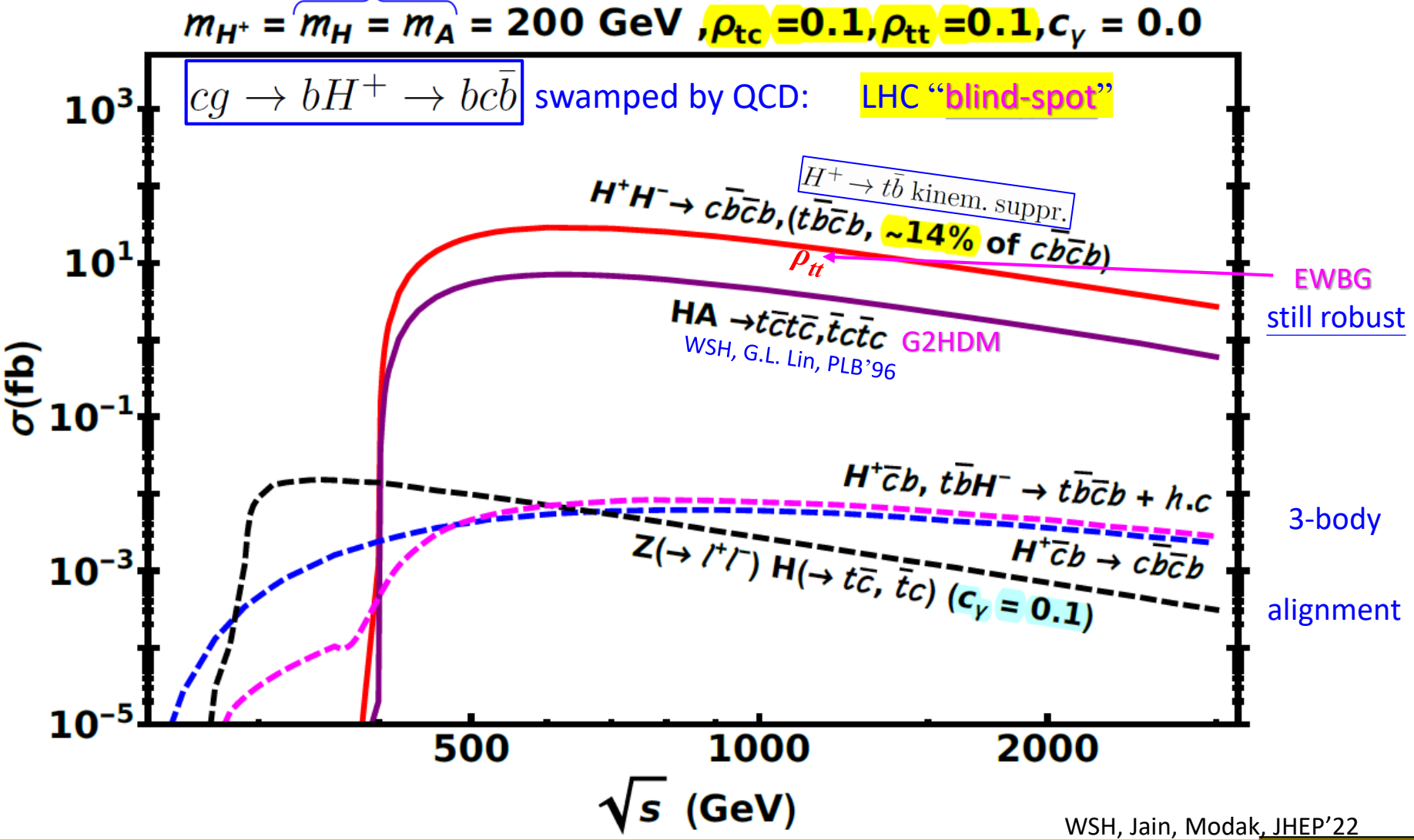
t → ch

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

IV. $e^+e^- \to H^+H^- \to c\bar{b}\bar{c}b$ @ ILC500

A "what if" situation at LHC.

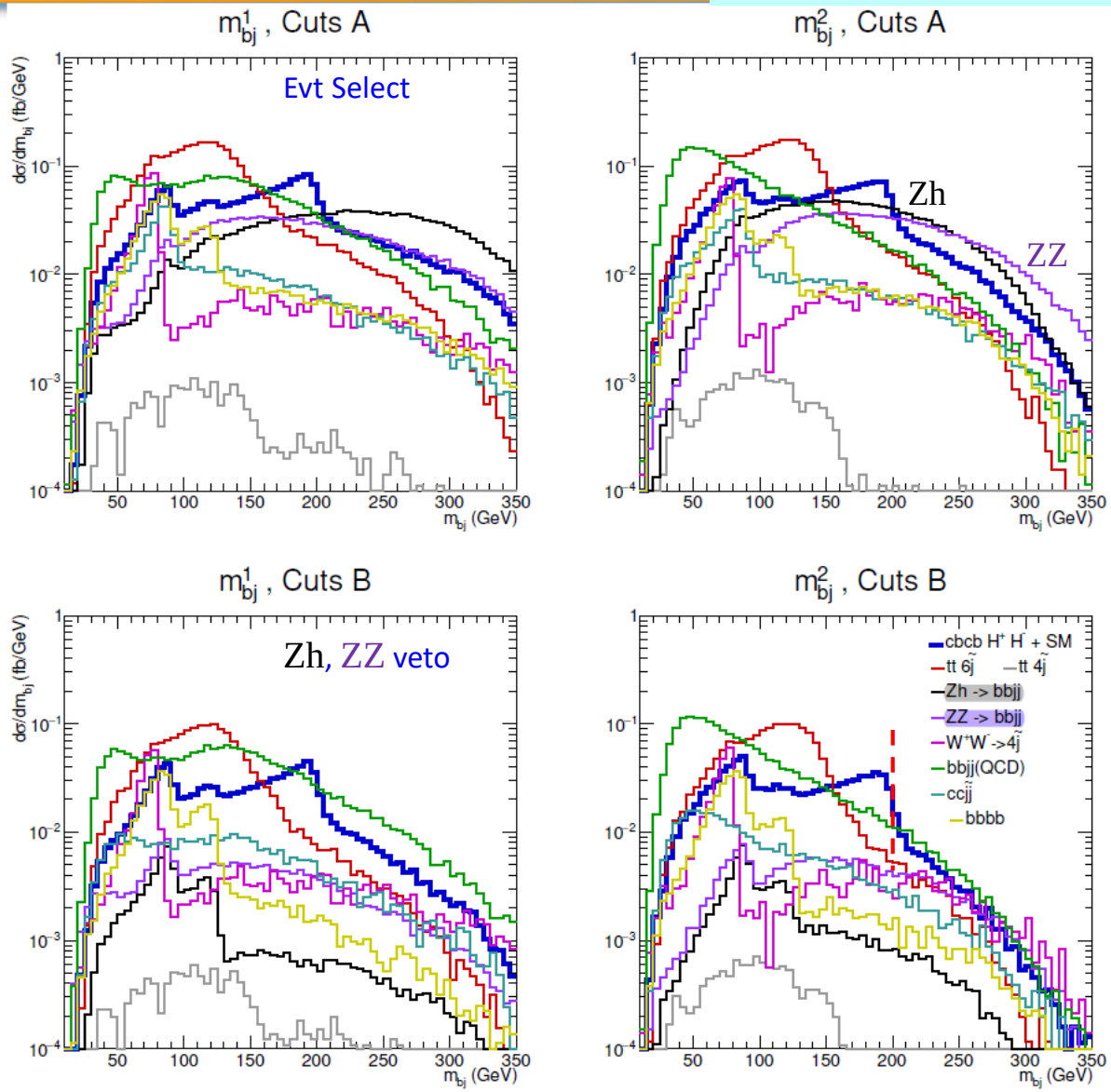
cg → tH/A → ttc(bar) ttc(bar) cancel



WSH, Jain, Modak, JHEP'22

Event Selection & Zh, ZZ veto

Madgraph + Feyrules + PYTHIA6.4 + Delphes3.5.0(ILD)



light-*j* pair w/ *b* by angular prox.,
not quite effective at 500 GeV.

Process	Cuts A	Cuts B
$c\bar{b}\bar{c}b$ $(H^+H^- + \mathrm{SM})$	10.2 fb	5.0 fb
$c\bar{b}\bar{c}b$ (SM-only)	4.9 fb	1.7 fb
$t\bar{t}$	15.3 fb	8.3 fb
$b\bar{b}jj$ (QCD)	13.1 fb	9.7 fb
$c\bar{c}\tilde{j}\tilde{j}$ (QCD)	2.7 fb	1.6 fb
$b\bar{b}b\bar{b}$	3.3 fb	1.7 fb
ZZ	6.3 fb	1.0 fb
Zh	7.8 fb	0.4 fb
W^+W^-	2.5 fb	1.7 fb
Total (SM-only)	55.8 fb	26.1 fb
Total $(H^+H^- + \mathrm{SM})$	61.1 fb	29.5 fb
Significance $(\mathcal{L} = 1\,\mathrm{ab}^{-1})$	22.1	20.2

$$Z(n|n_{\mathrm{pred}}) = \sqrt{-2\,ln\frac{L(n|n_{\mathrm{pred}})}{L(n|n)}}$$

$$L(n_1|n_0) = e^{-n_1} n_1^{n_0}/n_0!$$

But, H^+ mass?

$$e^+e^- \to H^+H^- \to c\bar{b}\bar{c}b$$

Cut C

$$|m^1_{bj} - m^2_{bj}| < 0.1 \times m^1_{bj}$$

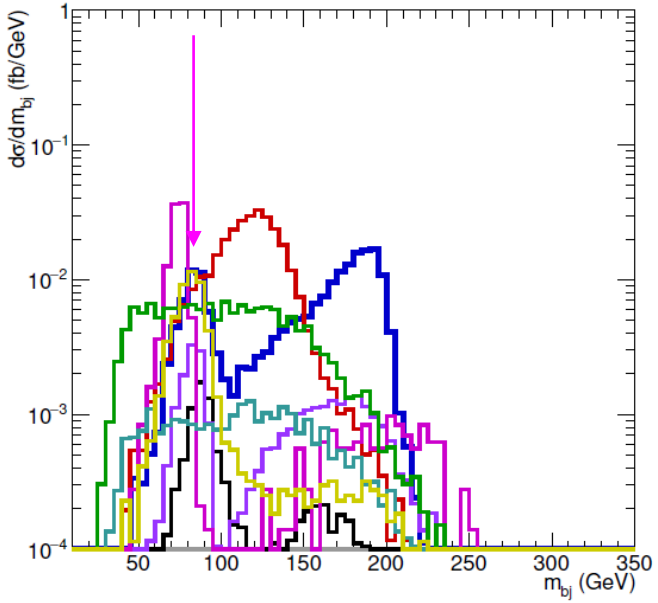
0.1 not optimized

Mass Cut

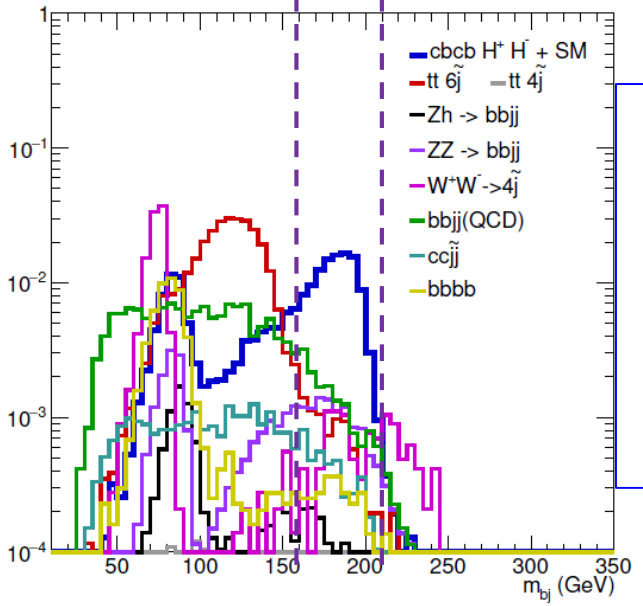
$$160\,\text{GeV} \leq m_{bj} \leq 210\,\text{GeV}$$

Process	Cut C	Mass Cut
$c\bar{b}\bar{c}b$ (H^+H^- + SM)	0.99 fb	0.51 fb
$c\bar{b}\bar{c}b$ (SM-only)	0.29 fb	0.02 fb
$t\bar{t}$	1.51 fb	0.03 fb
$b\bar{b}jj$ (QCD)	0.77 fb	0.06 fb
$c\bar{c}\tilde{j}\tilde{j}$ (QCD)	0.13 fb	0.02 fb
$b\bar{b}b\bar{b}$	0.27 fb	0.01 fb
ZZ	0.15 fb	0.04 fb
Zh	0.04 fb	0.01 fb
W^+W^-	0.55 fb	0.02 fb
Total (SM-only)	3.72 fb	0.21 fb
Total (H^+H^- + SM)	4.42 fb	0.68 fb
Significance ($\mathcal{L} = 1\,\text{ab}^{-1}$)	11.1	26.3

m^1_{bj} , Cut C



m^2_{bj} , Cut C

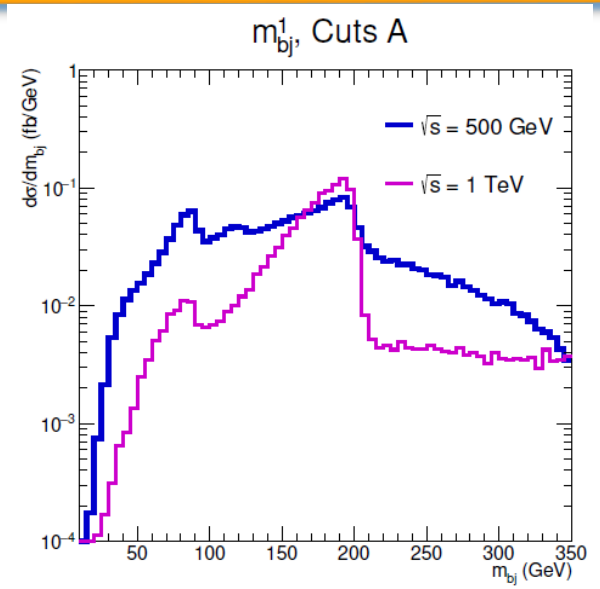


Cut C pairs correctly, w/o inputting mass, suppressing much BG; Mass Cut reduces background further.

(Note the WW → cscs pairing)

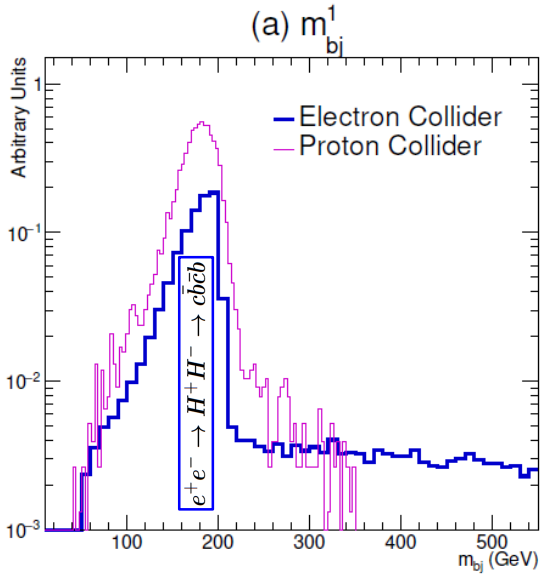
Two-body prod. is key.

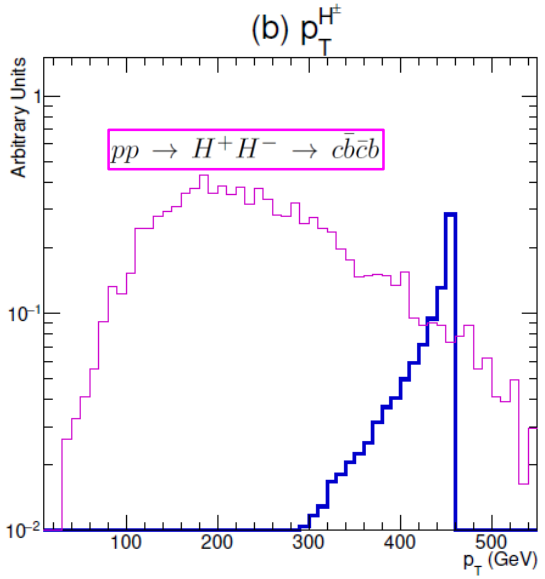
Some Comments



Pairing by angular proximity improves with Energy. E.g. at 1 TeV, the "**Edge**" is sharper.

At pp collider, H^+H^- production not in CM frame, w/ p_T of H^+H^- unknown, while cross sections much smaller than QCD processes.





V. Summary

the Alpha and the Ω

Still my goal & hope.

I could have told you up front:

H^0, A^0, $H^\pm$ ~ 500 GeV
can generate **B.A.U.**
accommodates eEDM

CAN
Verify at LHC.
and $\mathcal{FPCP}$ Probes !

← Fantastic !!

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A perverse "what if": $\rho_{tc} = \rho_{tt} = 0.1$, H, A, H^+ degenerate at 200 GeV?

- A 500 GeV ILC can still cover this thru $e^+e^- \to H^+H^- \to c\bar{b}\bar{c}b$
- Reconstruct H^+ mass and probe $e^+e^- \to HA \to t\bar{c}t\bar{c}$ to affirm G2HDM
- Measure $\rho_{tt} = 0.1$ to affirm EWBG!

Viva ILC!

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?!

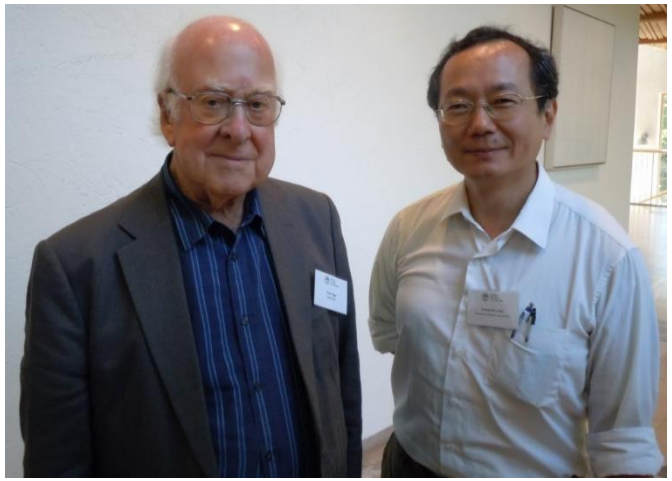
$|\rho_{ee}/\rho_{tt}| \sim \lambda_e/\lambda_t$!

the flavor code?

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

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

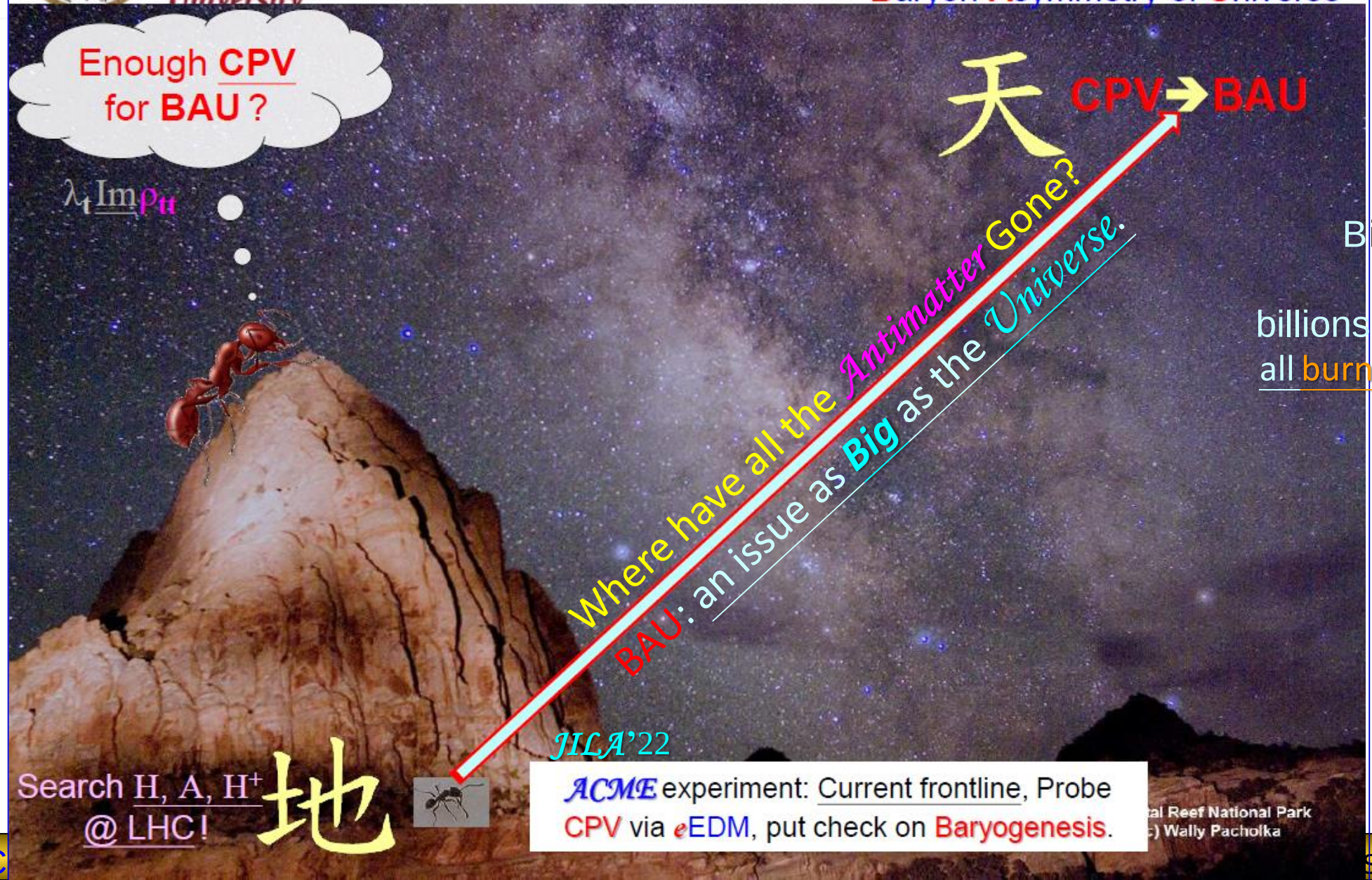
Thank You!



a Higgs, and a 2nd Higgs …

Soaring to the Starry Heavens

Baryon Asymmetry of Universe



le Raison d'être

Billions
&
billions of stars …
all burning protons

National Taiwan University

So, How "Steered"?

2017 was "a Good Year".

Explaining BAU

1705.05034 Physics Letters B 776 (2018) 402–406

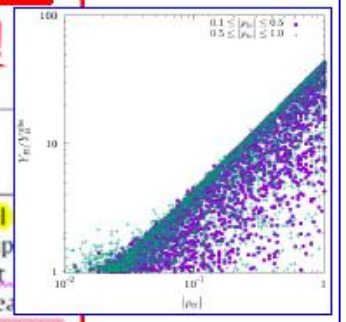
Electroweak baryogenesis driven by extra top Yukawa couplings

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 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.

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

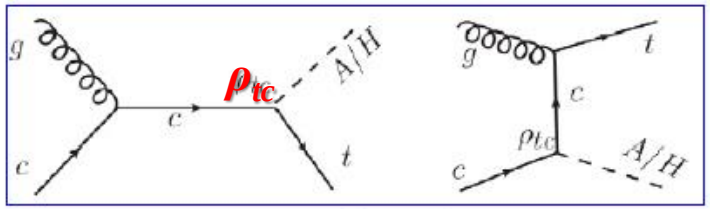
Fit for LHC

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

Production Processes

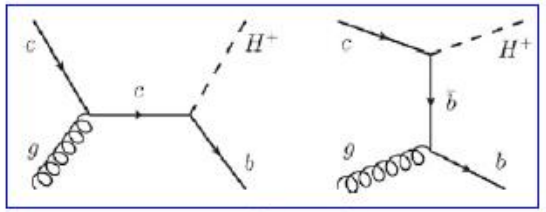
1710.07260

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



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.

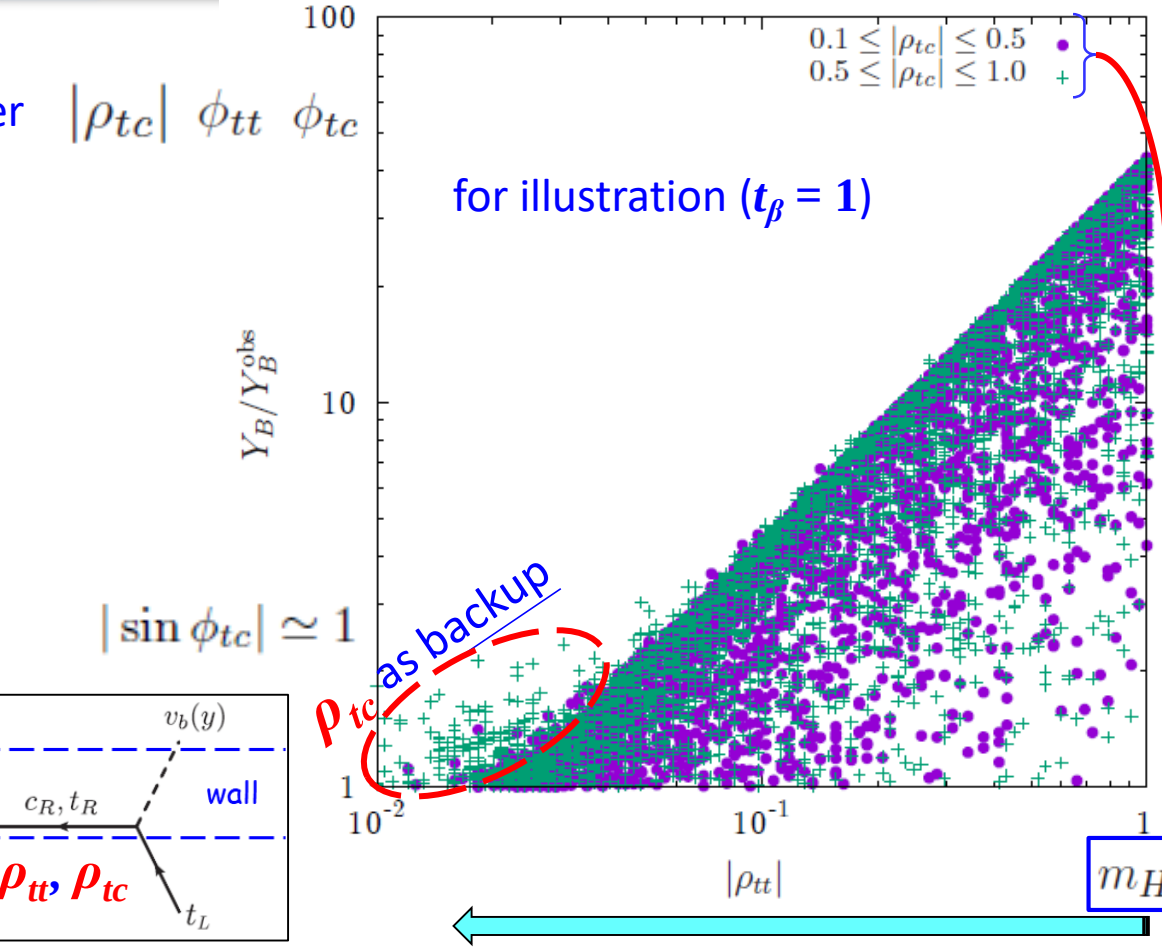
Fruition 2023!

Robust: Large Parameter Space for EWBG

scan over $|\rho_{tc}|$ ϕ_{tt} ϕ_{tc}

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

for illustration ($t_\beta = 1$)



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

no obvious diff.

$\Rightarrow \rho_{tt}$ driven !

the charm of EWBG

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

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

small ρ_{tt}

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

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