

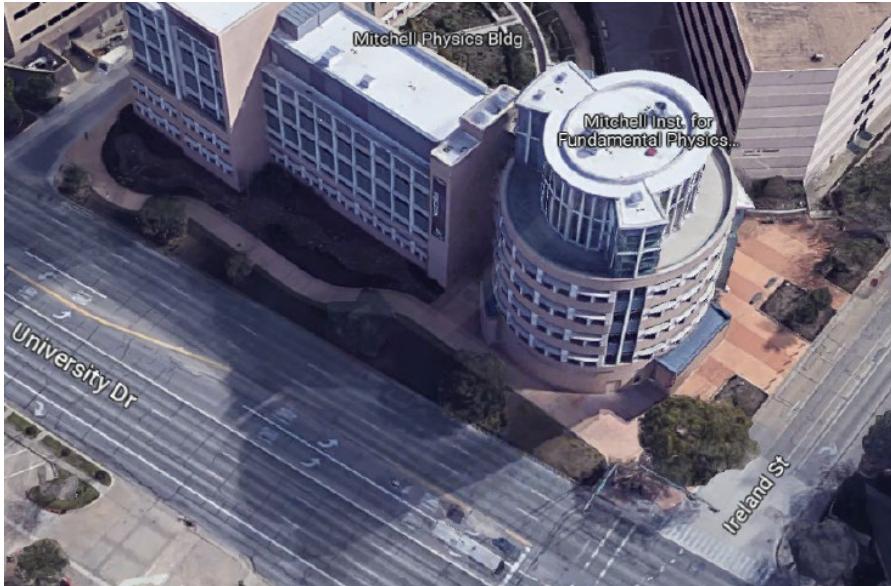


Light H^+ Search via $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{b}c\bar{b}$ at ILC

500 GeV

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National Taiwan University

May 16 @ Mitchell Conference, Texas A&M





0. Intro: Our Life & Times – Setting

I. General 2HDMII. EW BaryoGenesis & eEDM

III. LHC & Flavor Frontiers

IV. $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}b\bar{c}b$ at 500 GeV ILC

WSH, Jain, Modak, JHEP'22

V. Summary

0. Intro: Our *Life* & Times

$h(125)$ ✓ *New Physics* X



Where is SUSY/WIMP?

Beyond CKM CPV (Large)

EW BaryoGenesis (EWBG)

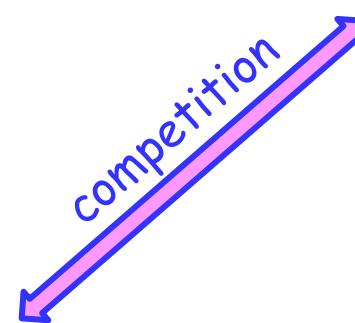
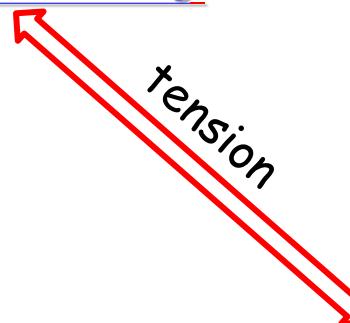
- more testable -

EWBG ought to be pursued
while LHC is still running!



LHC

- No New Physics -
NNP



eEDM: ACME14 → ~~ACME18~~ JILA22
- L.E. Precision Frontier -

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

Soaring to the Starry Heavens



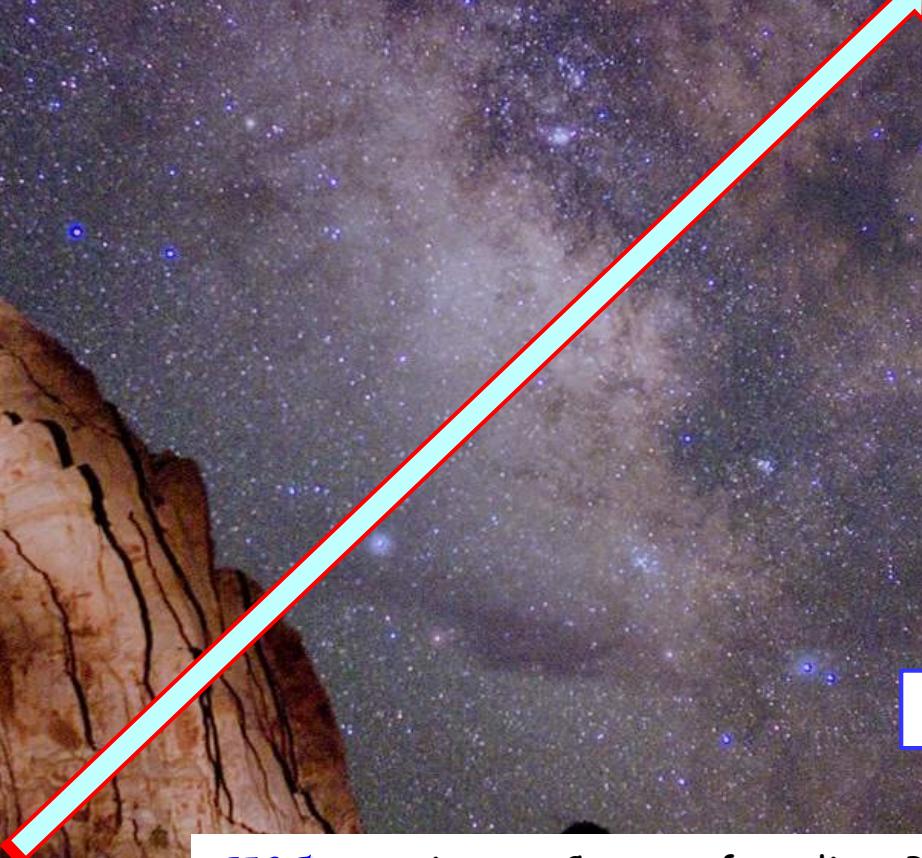
Enough CPV
for B.A.U. ?

天

CPV → BAU



地



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

JILA experiment: Current frontline, Probe
CPV via eEDM, put check on Baryogenesis.

Capital Reef National Park
(c) Wally Pacholka

CPV: BAU- d_e



Gell-Mann (1969 sole Laureate)

“Everything not forbidden is compulsory.”



the “Totalitarian Principle of Truth” (Wiki)

\exists Weak Higgs Doublet

$$\underline{v \approx 246 \text{ GeV}}$$

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \\ \varphi^- \end{pmatrix} \xrightarrow[\text{S.S.B.}]{\langle \varphi^0 \rangle \neq 0} \begin{pmatrix} G^+ \\ v + h^0 + G^0 \\ G^- \end{pmatrix}$$

Observed.

Higgs Mechanism

$$h(125) \checkmark$$

No Reason to forbid
a Second Higgs,

so \exists Second Higgs Doublet

$$\Phi' = \begin{pmatrix} \varphi'^+ \\ \varphi'^0 \\ \varphi'^- \end{pmatrix} \xrightarrow{\langle \varphi'^0 \rangle = 0} \begin{pmatrix} H^+ \\ H^0 + iA \\ H^- \end{pmatrix}$$

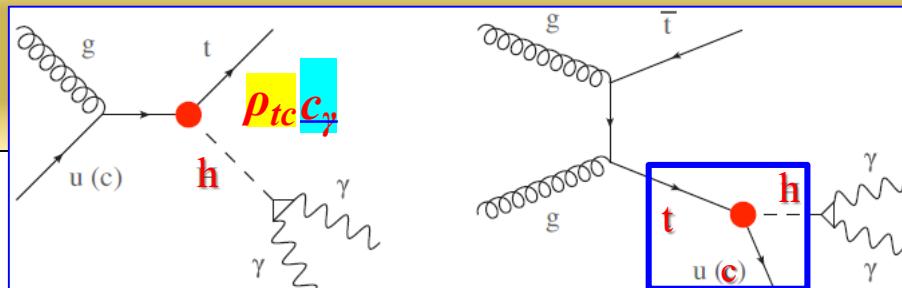
ad hoc



(1979 Laureates)

Glashow-Weinberg sought to
forbid Second Set of Yukawa's,
usually implemented by a Z_2 ,
refuted by my PLB'92 & EPL'18 (next pages).

- Still Minority View -

2015-2016
alignment c_γ small

h-H mixing

WSH, PLB'92 (PSI-PR-91-34)
Chen, WSH, Kao, Kohda, PLB'13

PHYSICAL REVIEW LETTERS 129, 032001 (2022)

one should leave the final say
on the matter to experiments

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

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 $\mathcal{B}(t \rightarrow Hu)$ and 0.073% (0.051%) for $\mathcal{B}(t \rightarrow Hc)$. These are the strictest upper limits yet determined.

< 0.00073



I. General 2HDM



Two Higgs Doublet Model w/o Z_2

$$V(\Phi, \Phi') = \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 |\Phi'|^2 - (\cancel{\mu_{12}^2} \Phi^\dagger \Phi' + h.c.) + \frac{1}{2} \eta_1 |\Phi|^4 + \frac{1}{2} \eta_2 |\Phi'|^4$$

$$+ \eta_3 |\Phi|^2 |\Phi'|^2 + \eta_4 |\Phi^\dagger \Phi'|^2 + \left[\frac{1}{2} \eta_5 (\Phi^\dagger \Phi')^2 + (\eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2) \Phi^\dagger \Phi' + h.c. \right]_{1/2}$$

H^+
 $H^- iA$

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

$$\eta_i \text{ with } i = 1-7; \mu_{22}^2/v^2$$

WSH & Kikuchi, EPL'18

H, A, H^+ sub-TeV

Needed for 1st order Phase Transition

Yukawa

$$-\frac{1}{\sqrt{2}} \sum_{f=u,d} \bar{f}_i \left[\left(\lambda_i^f \delta_{ij} c_\gamma - \rho_{ij}^f s_\gamma \right) H - i \operatorname{sgn}(\mathcal{Q}_f) \rho_{ij}^f A \right] R f_j$$

$$- \bar{u}_i \left[\left(V \rho^d \right)_{ij} R - \underbrace{\left(\rho^{u\dagger} V \right)_{ij} L}_{d_j H^+} \right] d_j H^+ + h.c.$$

$\mathcal{O}(1)$

ρ_{tt} the driver; ρ_{tc} the backup

EWBG

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

$$H^+ \rightarrow c\bar{b}, t\bar{b}$$

$$\rho_{tc} V_{tb}, \rho_{tt} V_{tb}$$

equal footing (drop CKM suppr.)

II.1 EWBG: CPV Top interactions



CPV source term

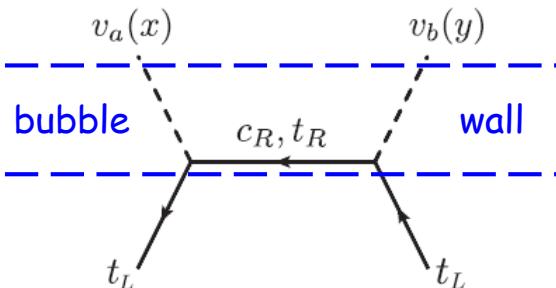
$$S_{i_L j_R}(Z) = N_C F \text{Im}[(Y_1)_{ij} (Y_2)_{ij}^*] v^2(Z) \partial_{t_Z} \beta(Z)$$

$Z = (t_Z, Z)$	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

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



ρ_{tt}, ρ_{tc}
BAU \Leftarrow CPV Top interactions
at Bubble Wall

left-handed Top density

coord. oppo. bubble exp. dir.



n_L

skip detail
(Transport)



CPV source term

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

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

lifted from Guo,Li,Liu,Ramsey-Musolf,Shu PRD'17

To understand the plot of next page, suppose

(exercise)

$$(Y_1)_{tc} \neq 0, (Y_2)_{tc} \neq 0, (Y_1)_{tt} = (Y_2)_{tt} \neq 0 \quad (\text{3 params.})$$

all else vanish, and take $t_\beta = 1$ for convenience

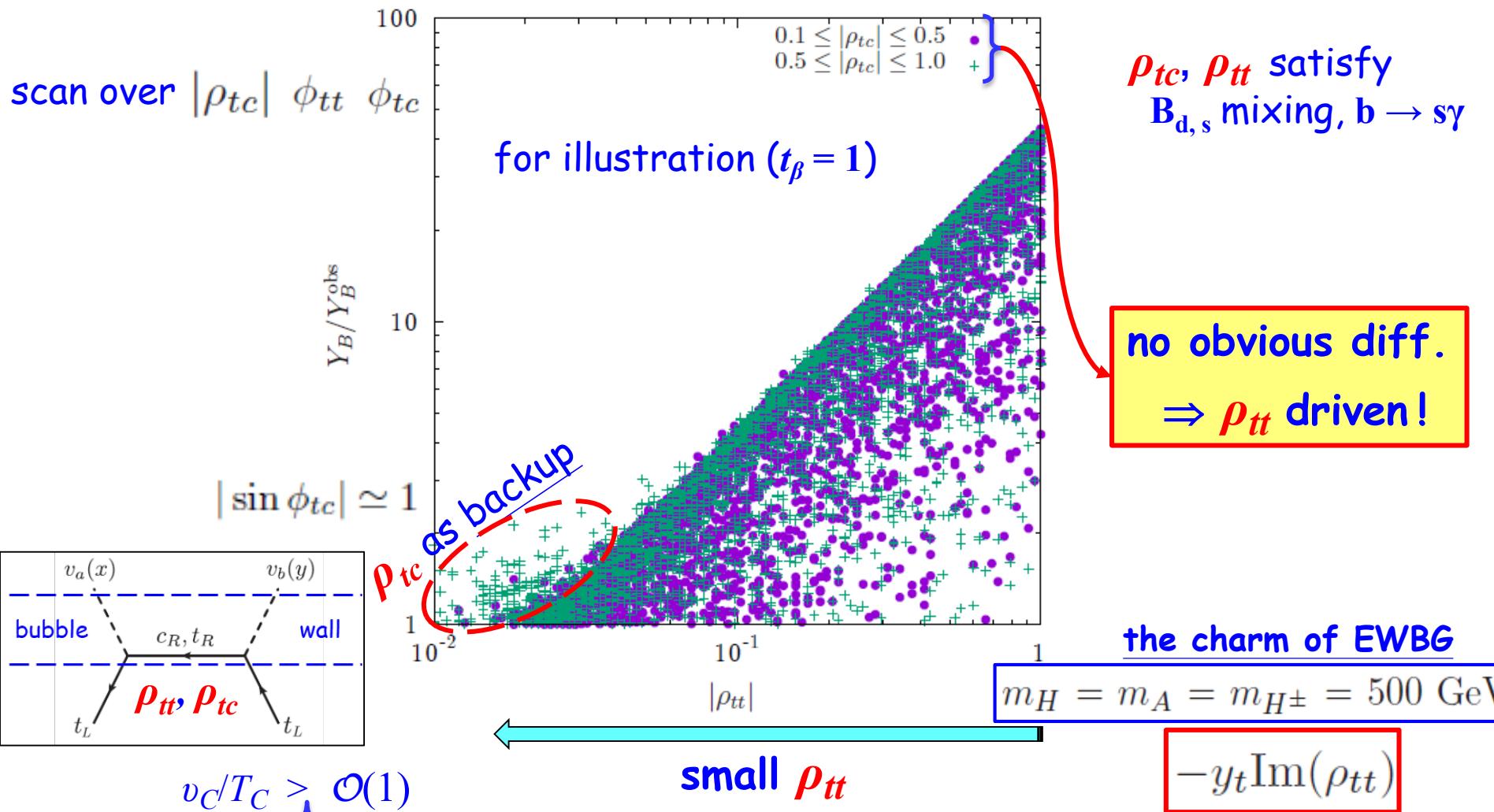
then

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

but

$$-Y_1 + Y_2 \quad \text{not diag.}$$

→ $\text{Im}[(Y_1)_{tc} (Y_2)_{tc}^*] = -y_t \text{Im}(\rho_{tt}), \quad \rho_{ct} = 0$ pheno



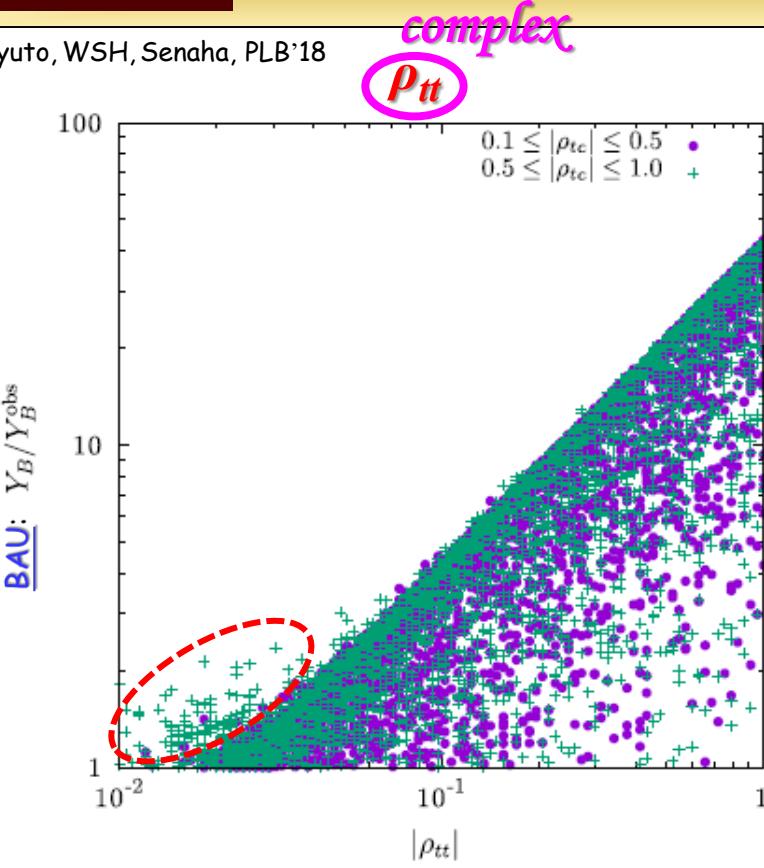
$T_C = 119.2 \text{ GeV}$	$v_C = 176.7 \text{ GeV}$	$v_w = 0.4$	$\Delta\beta = 0.015$	$D_q = 8.9/T$	$D_H = 101.9/T$
$m_{t_L} = 0.59T$	$m_{t_R} = 0.62T$	$m_{c_R} = 0.50T$	$\Gamma_{q_{L,R}} = 0.22T$	$\Gamma_B^{(s)} = 120\alpha_W^5 T$	$\Gamma_{ss} = 16\alpha_s^4 T$

II.2 Baryogenesis & electron EDM



Fuyuto, WSH, Senaha, PLB'18

complex



EWBG

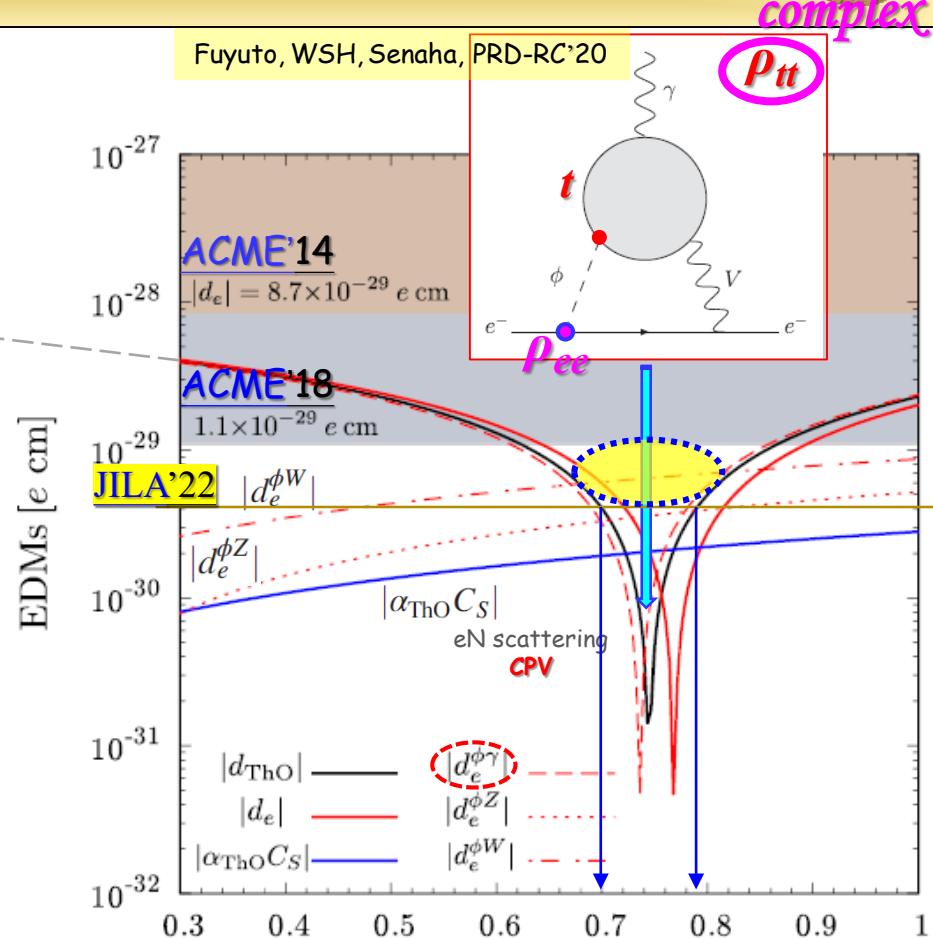
 $\lambda_t \text{Im} \rho_{tt}$ robust driver

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

[ρ_{tc} as backup]

Fuyuto, WSH, Senaha, PRD-RC'20

complex

simplified
“Ansatz”

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

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

“Know” SM Hierarchy!

N.B. r depend on loop functions

Why G2HDM hiding so well?

extra Yukawas reflect SM Yukawa pattern

III. H/A/H⁺ Search & Flavor Frontier

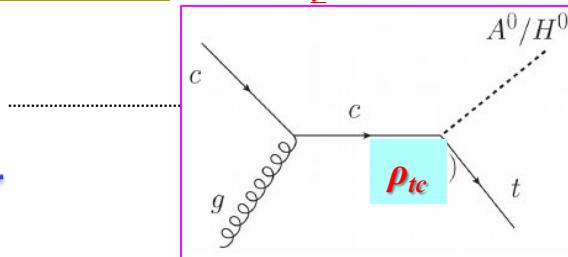
LHC

Leading Search Modes at the LHC



G2HDM

sub-TeV Spectrum

H/A/H⁺ SearchNot c_γ suppressed

WSH, Kikuchi, EPL'18

Search at ATLAS/CMS started
ATLAS-CONF-2022-039 (ICHEP)

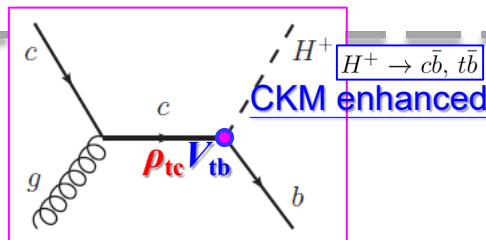
Search Zone

 $cg \rightarrow tH/A \xrightarrow{\rho_{tc}} t\bar{t}(bar)$

Same-Sign Top + jet

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

Search since 2/2020 @ NTUCMS

 $cg \rightarrow bH^+ \rightarrow b\bar{t}b(bar)$ Top w/ two p_T b-jets (H⁺)Ghosh, WSH, Modak, 1912.10613 ([PRL'20](#))

v.e.v.

t

W^Z

neutrino

e $\mu\tau$
leptond s b
down-typeu c
up-type γg
vector

scalar

GeV

800

700

600

500

400

300

200

100

H, A, H⁺t \bar{t}

h

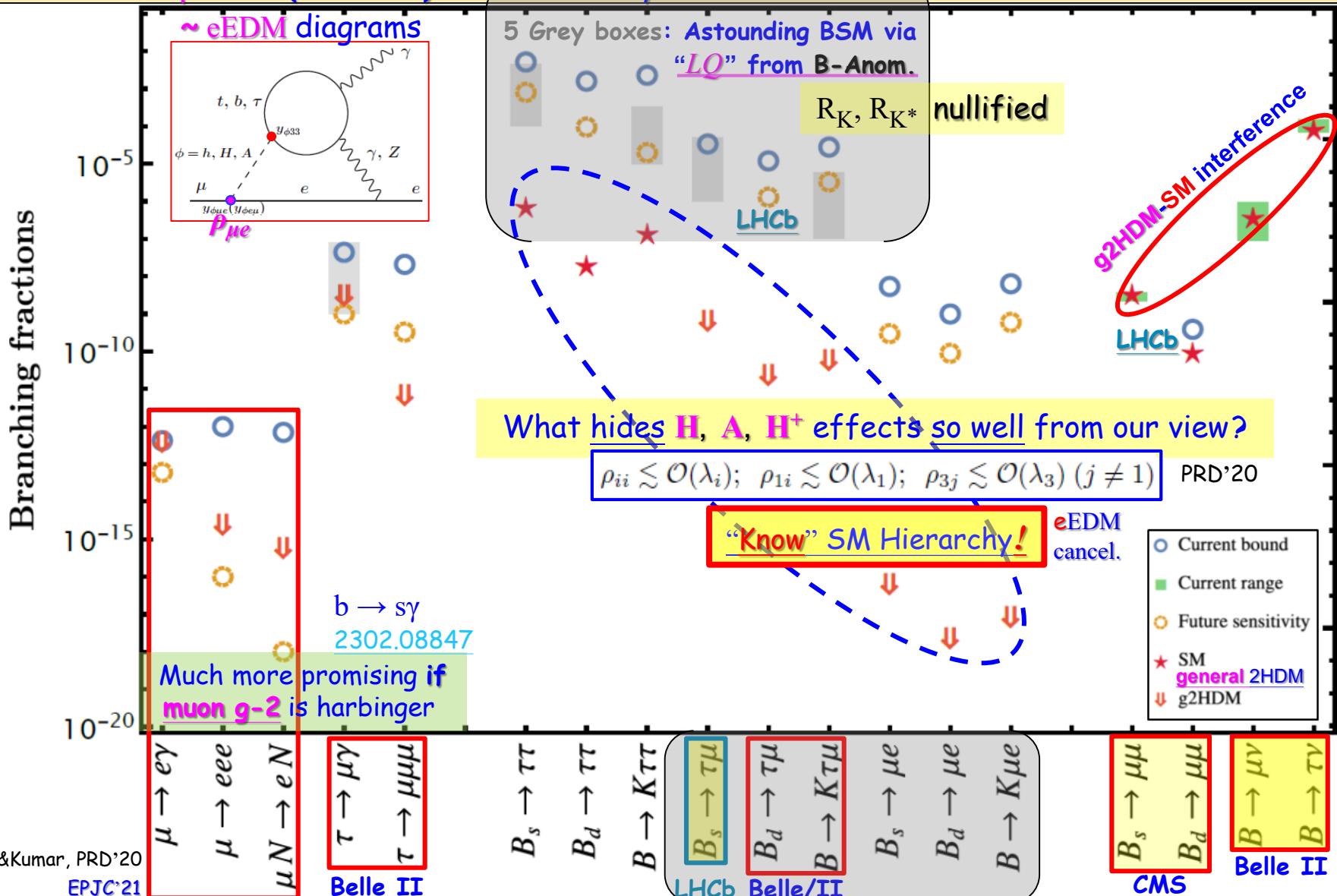
HKM, PLB'18



Glimpse of coming New *Flavor* Era in G2HDM

$\mu \& \tau$ FV (Flav.Viol.)

in B decay

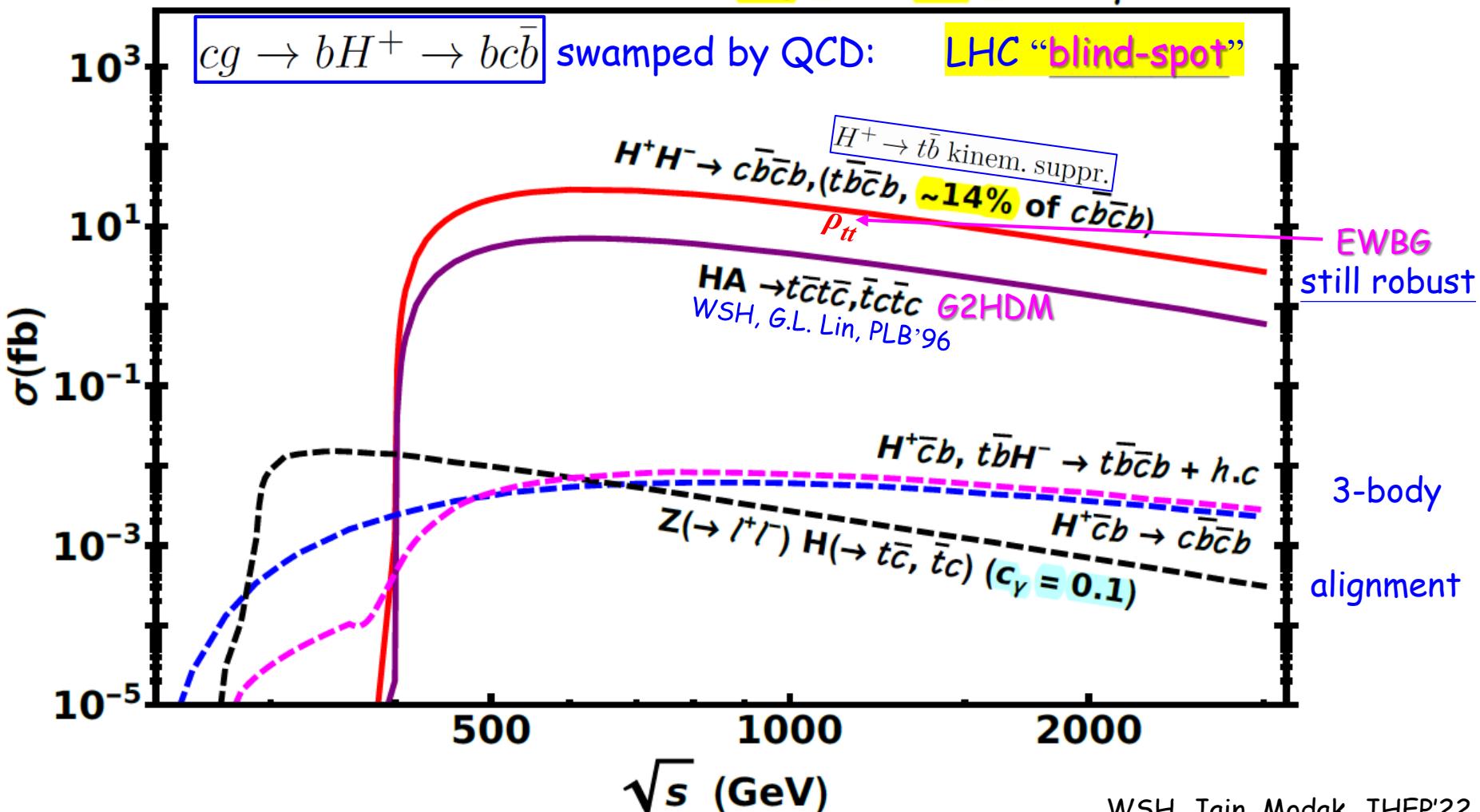


IV. $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}b\bar{c}b$ at 500 GeV ILC

A “what if” situation at LHC.

$cg \rightarrow tH/A \rightarrow tt\bar{c}\bar{c}$ (cancel)

$$m_{H^+} = m_H = m_A = 200 \text{ GeV}, \rho_{tc} = 0.1, \rho_{tt} = 0.1, c_\gamma = 0.0$$

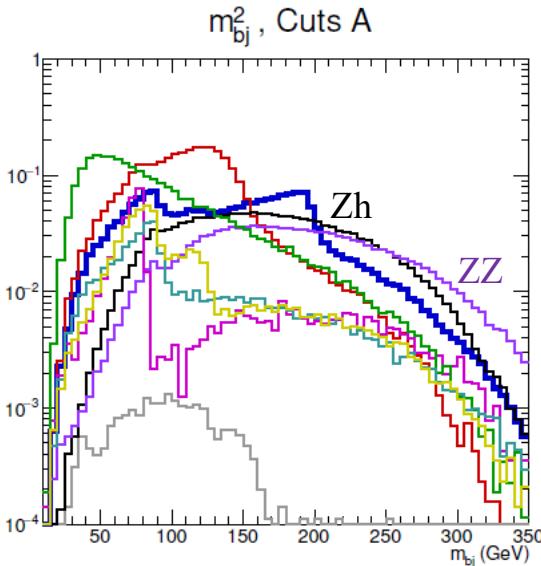
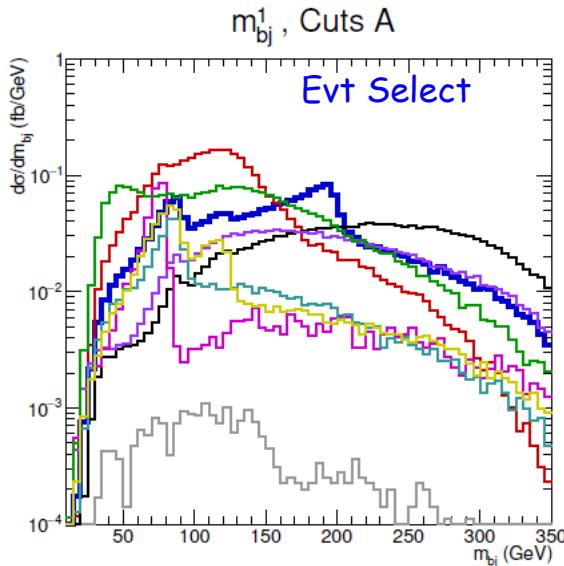


WSH, Jain, Modak, JHEP'22

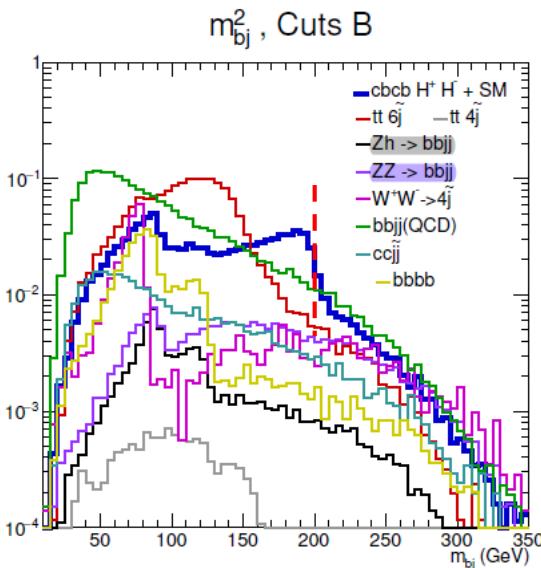
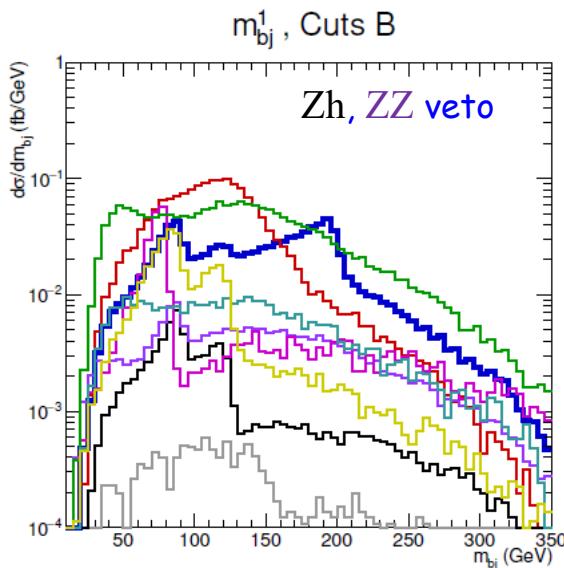
Event Selection & Zh, ZZ veto



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
<u>$c\bar{b}\bar{c}b$ ($H^+H^- + \text{SM}$)</u>	10.2 fb	5.0 fb
<u>$c\bar{b}\bar{c}b$ (SM-only)</u>	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
$c\tilde{c}j\tilde{j}$ (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 ($H^+H^- + \text{SM}$)	61.1 fb	29.5 fb
<u>Significance</u> ($\mathcal{L} = 1 \text{ ab}^{-1}$)	22.1	20.2

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

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

But, H^+ mass?

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

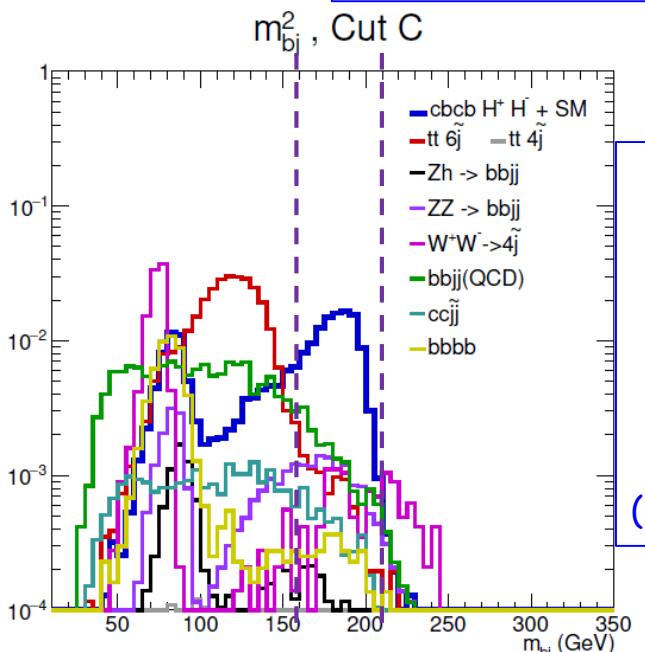
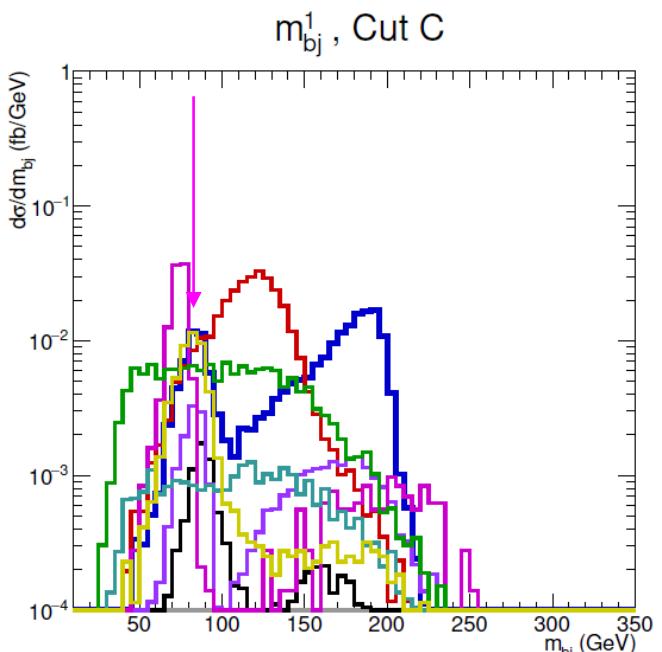
Cut C

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

0.1 not optimized

Mass Cut

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

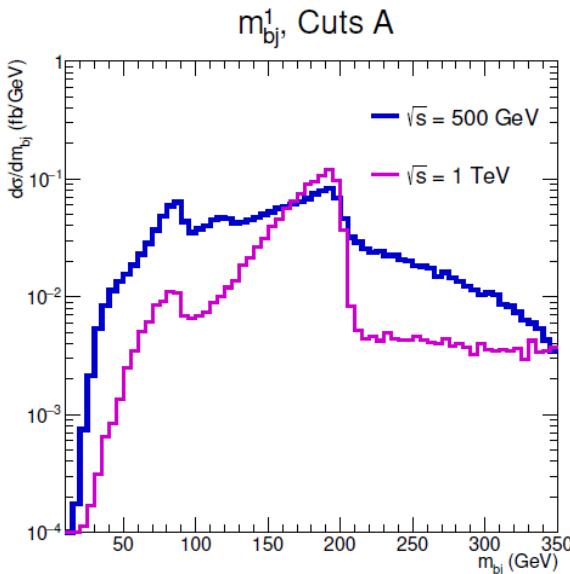


Process	<u>Cut C</u>	<u>Mass Cut</u>
$c\bar{c} b\bar{b}$ ($H^+ H^- + \text{SM}$)	0.99 fb	0.51 fb
$c\bar{c} b\bar{b}$ (SM-only)	0.29 fb	0.02 fb
$t\bar{t}$	1.51 fb	0.03 fb
$b\bar{b} jj$ (QCD)	0.77 fb	0.06 fb
$c\bar{c} jj$ (QCD)	0.13 fb	0.02 fb
$b\bar{b} b\bar{b}$	0.27 fb	0.01 fb
ZZ	0.15 fb	0.04 fb
Zh	0.04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

Cut C pairs correctly,
w/o inputting mass,
suppressing much BG;
Mass Cut reduces
background further.
(Note the $WW \rightarrow ee$ pairing)

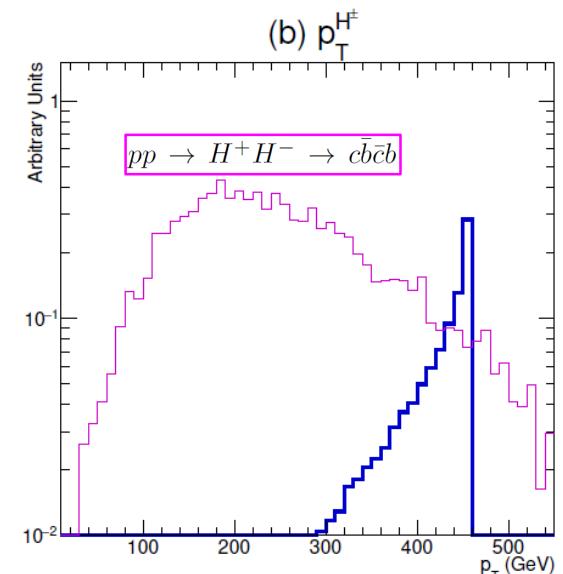
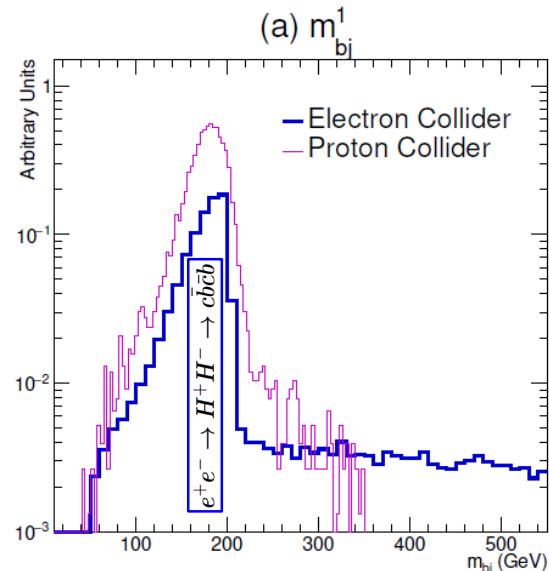
Two-body prod. is key.

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 Omega

Still my goal & hope.

I could have told you up front:

$H^0, A^0, H^\pm \sim 500 \text{ GeV}$
can generate **B.A.U.**
accommodates *e*EDM

} CAN
Verify at LHC. ←
and FPCP Probes !

Fantastic!!

V. Summary



the Alpha and the Omega

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CAN
Verify at LHC. ←
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Fantastic!!

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 $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}b\bar{b}$
- Reconstruct H^+ mass and probe $e^+e^- \rightarrow HA \rightarrow t\bar{c}t\bar{c}$ to affirm **G2HDM**
- Measure $\rho_{tt} = 0.1$ to affirm **EWBG!**

Viva ILC!

Thank you!

[Join the Mission](#)



Caution: Good reasoning does not mean Nature has to oblige ...

a Higgs; and a 2nd Higgs ...