PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE

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Large Universal Electroweak Corrections:
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Bridging electroweak baryogenesis with LHC signatures: the aligned 2HDM

L. Biermann, T. Biekötter, **G. Coloretti**, A. Crivellin

(work in progress…. in <u>September</u> on the arXiv!)

Guglielmo Coloretti
INFN – Bologna

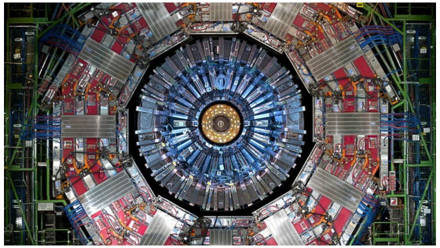
Workshop on Multi-Higgs Models
Lisbon – 28.08.2026

Outline

- Motivation
- Aligned 2HDM in the Higgs basis
- CP-violation without eEDM
- CP-violating collider signatures
- Phase transition and electroweak baryogenesis
- Case study: smoking gun and di-higgs

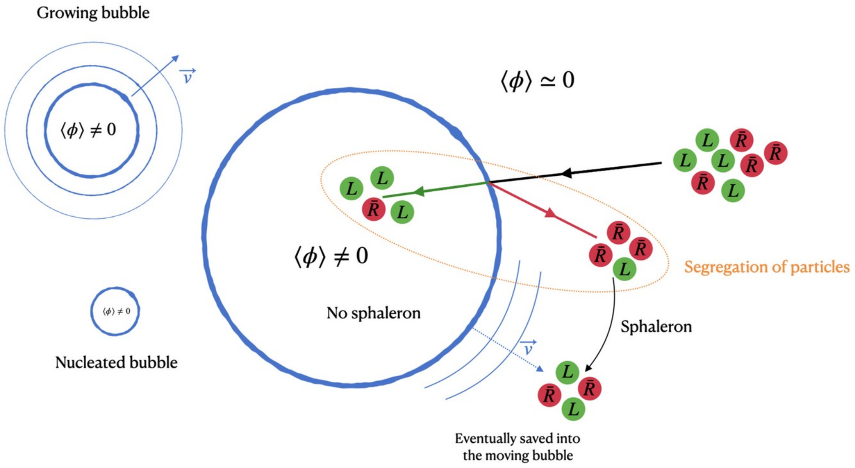
Motivation

- <u>General idea</u>: *finding a collider observable serving as the signal for electroweak baryogenesis*

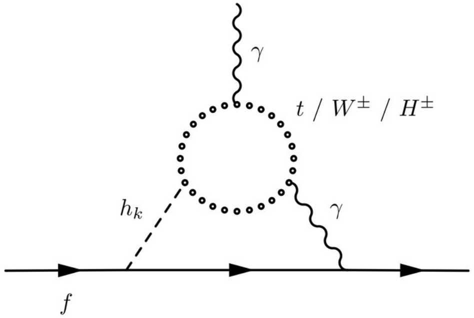


- In the 2HDM, a possible CP-violating signature is scalar to scalars decays (not-so-well constrained at the LHC)

- Can we correlate the CP-violation measured at colliders to electroweak baryogenesis?



- Constraints from low energy (electric dipole moments)



2HDM: scalar potential

[S. Davidson, H. E. Haber]

Arbitrary choice of basis
without Yukawa sector

$$\langle \Phi_1^0 \rangle = v c_\beta / \sqrt{2}$$

$$\langle \Phi_2^0 \rangle = v s_\beta e^{i\xi} / \sqrt{2}$$

Spontaneous
CP-violation

Unitary rotation in
Higgs flavor space

$$\langle \mathcal{H}_1 \rangle = v$$

$$\langle \mathcal{H}_2 \rangle = 0$$

Change of complex phases
under a rotation of $e^{-i\,\theta_s}\mathcal{H}_2$

$$\mathcal{V}_{\not{CP}} = [Y_3 \mathcal{H}_1^\dagger \mathcal{H}_1 + \Big\{ Z_5 (\mathcal{H}_1^\dagger \mathcal{H}_2)^2$$

$$+ \left[Z_6 \mathcal{H}_1^\dagger \mathcal{H}_1 + Z_7 \mathcal{H}_2^\dagger \mathcal{H}_2 \right] \mathcal{H}_1^\dagger \mathcal{H}_2 + \text{h.c.} \Big\}$$

A2HDM: Yukawa structure

[P. Tuzon, A. Pich]

$$
\begin{aligned}
-\mathcal{L}_Y = & Y_D \overline{Q}_L (\mathcal{H}_1 + a_D \mathcal{H}_2) d_R + \\
& Y_L \overline{L}_L (\mathcal{H}_1 + a_L \mathcal{H}_2) l_R \\
& Y_U \overline{Q}_L (\tilde{\mathcal{H}}_1 + a_U^* \tilde{\mathcal{H}}_2) u_R + \mathrm{H.c.}
\end{aligned}
$$

$\longrightarrow$

- No discrete symmetries
- Yukawa terms are aligned in flavor space
- No tree level FCNC

A2HDM: Yukawa structure

[P. Tuzon, A. Pich]

$$-\mathcal{L}_Y = Y_D \overline{Q}_L (\mathcal{H}_1 + a_D \mathcal{H}_2) d_R + Y_L \overline{L}_L (\mathcal{H}_1 + a_L \mathcal{H}_2) l_R \, Y_U \overline{Q}_L (\tilde{\mathcal{H}}_1 + a_U^* \tilde{\mathcal{H}}_2) u_R + \mathrm{H.c.}$$

$\longrightarrow$

- No discrete symmetries
- Yukawa terms are aligned in flavor space
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Many complex phases: we organize them as to isolate the CP-violation

- Scalar potential

$$\{Y_3, Z_5, Z_6, Z_7\} \approx \theta_s$$

- Yukawa structure

$$\{a_U, a_D, a_L\} \approx \theta_F$$

Physical CP-violating phase

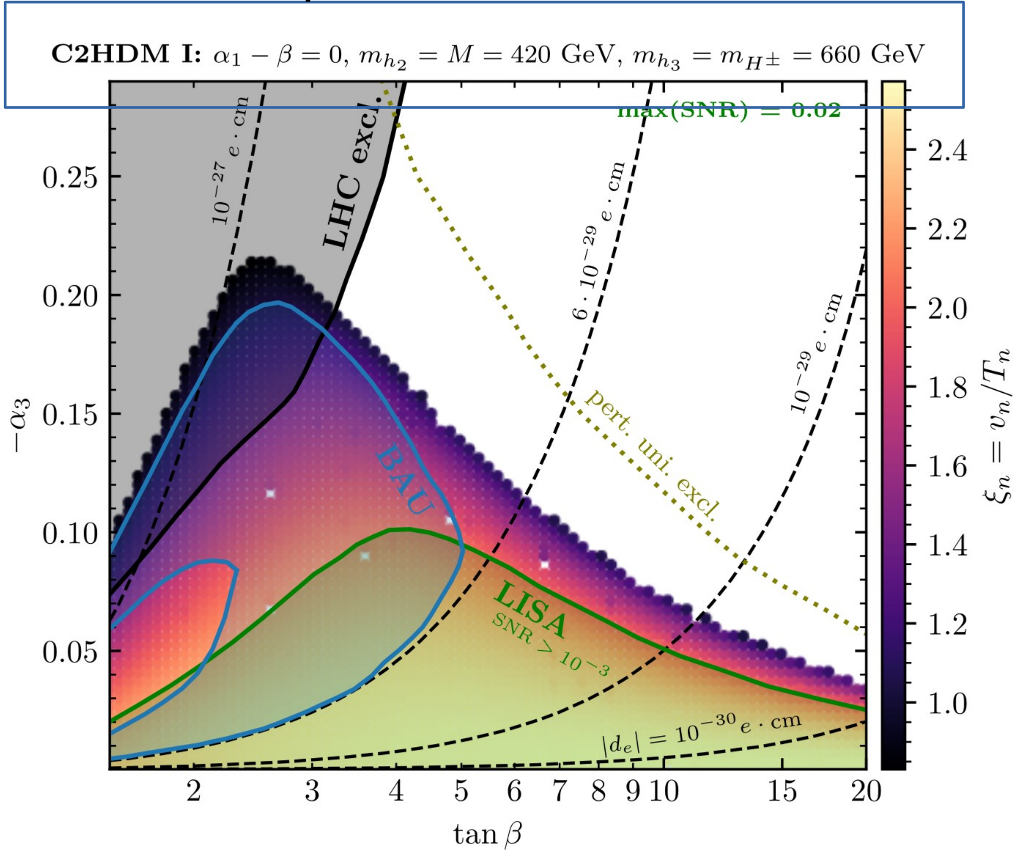
$$\theta_s - \theta_F$$

Is it all related to mixing of the neutral scalars?

CP-violation: EDMs

[T. Biekötter, M. O. Olea-Romacho]

Benchmark point:



- eEDM sets stringent bounds on the amount of CP-violation
- In the C2HDM the region with enough BAU is in tension with eEDM measurements
- Even a tiny mixing generates too large eEDM

CP-violation: EDMs

[W. Altmannshofer, S. Gori et al.]
[W. Altmannshofer, J. Brod et al.]
[S. Kanemura et al.]

- For the same benchmark point, close to the alignment limit (and a_F real):

$$d_e \approx \left[\left(-2.7\times10^{-29}\right)\,a_D + \boxed{\left(7.5\times10^{-27}\right)\,a_L + \left(7.3\times10^{-27}\right)\,a_U\right]\,\theta_{13}}$$

$$+\,\mathcal{O}(\theta_{ij}^2)$$

Top-Yukawa

CP-violation

[both necessary for electroweak baryogenesis]

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$$+ \boxed{\left(-3.0\times 10^{-29}\right) a_L\, \Im Z_7} + \mathcal{O}(\theta_{ij}^2)$$

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Top-Yukawa

CP-violation

[both necessary for electroweak baryogenesis]

Not in mass matrix!

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \Re Z_6 & -\Im Z_6 \\ \Re Z_6 & \frac{1}{2}\left[Z_{4c} + \Re Z_5\right] & -\frac{1}{2}\Im Z_5 \\ -\Im Z_6 & -\frac{1}{2}\Im Z_5 & \left[Z_{4c} - \Re Z_5\right] \end{pmatrix}$$

CP-violation: EDMs

[W. Altmannshofer, S. Gori et al.]
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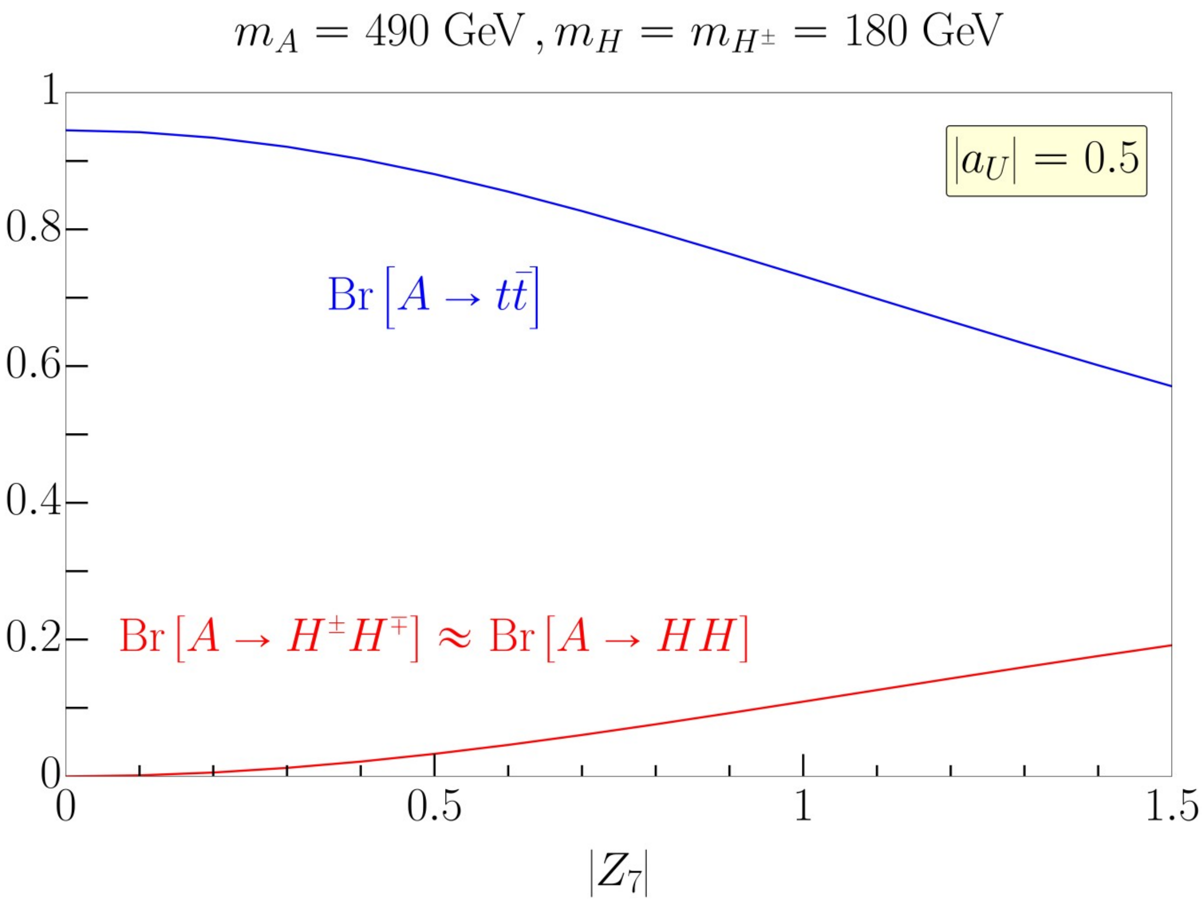
- Sizable Top-Yukawa and CP-violation mediated by Z_7 with suppressed eEDM!
- Seclude CP-violation to a sector not sensitive to eEDM

Collider signatures



- <u>Close to the alignment limit</u>, the scalar coupling Z_7 induces the $AH^\pm H^\mp$ and the AHH coupling

$$\sigma(pp \to A) \approx$$
$$k\,|a_U^*|^2\,\sigma(pp \to h^{\rm SM})$$

$$\Gamma_{A\to H^\pm H^\mp / A \to HH} \approx$$
$$\frac{1}{2!}|\Im Z_7|^2 \frac{1}{16\pi\, m_A^2}\sqrt{m_A^2 - 4m_{H^\pm/H}^2}$$

[GC, H. E. Haber, A. Crivellin]
<u>and see Howie's talk!</u>

EW Phase Transition

- We employ the one-loop daisy-resummed (Arnold-Espinosa) effective potential as implemented in BSMPTv3 [P. Basler, L. Biermann, M. Mühlleitner, R.Santos et al.] [P. Bittar, S. Roy, C.E.M. Wagner]

- At finite temperature, we parametrize the VEVs of the Higgs doublets

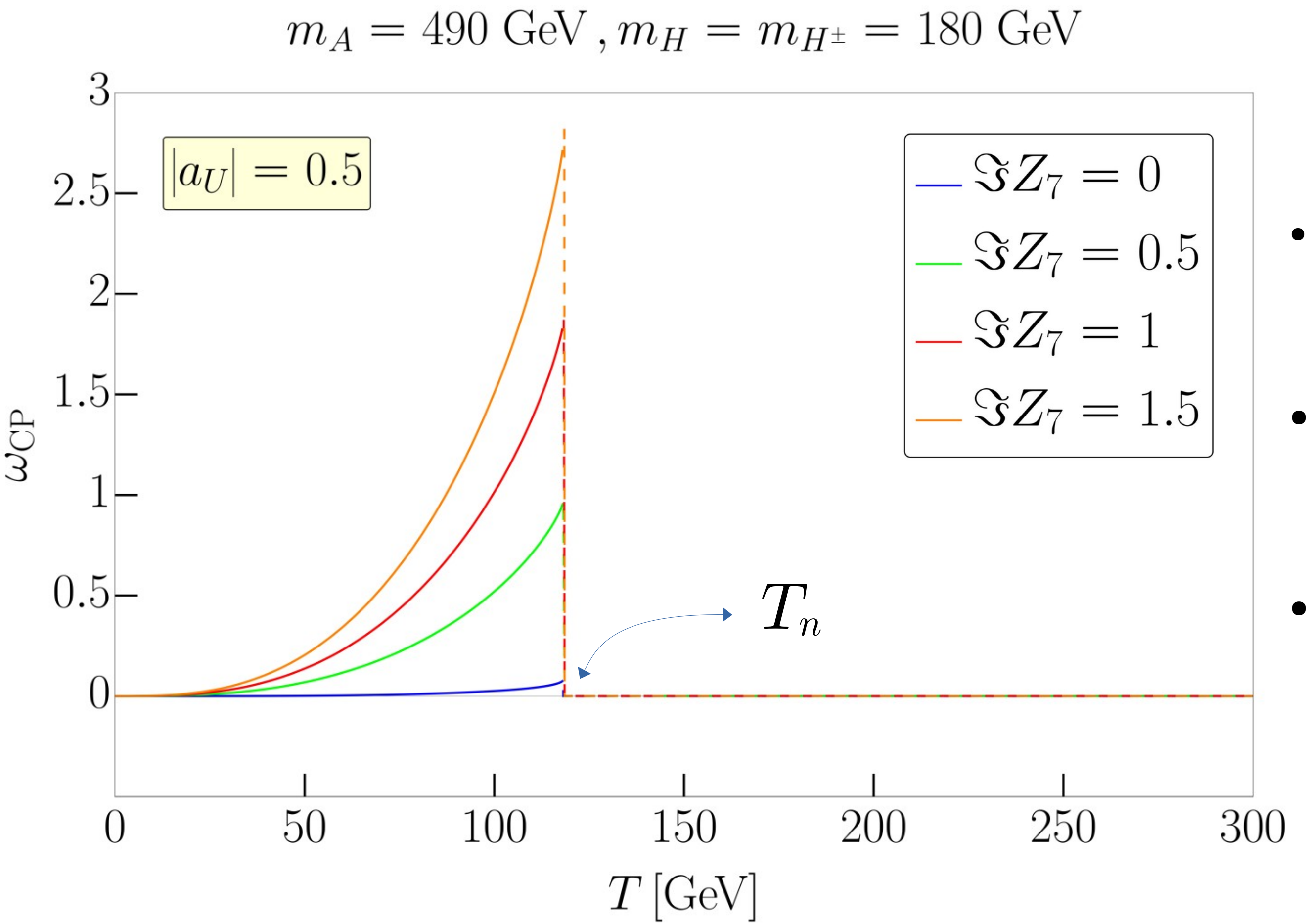
$$\langle \mathcal{H}_1(T) \rangle = \begin{pmatrix} 0 \\ \omega_1(T) \end{pmatrix}, \quad \langle \mathcal{H}_2(T) \rangle = \begin{pmatrix} \omega_{\mathrm{CB}}(T) \\ \omega_2(T) + i\, w_{\mathrm{CP}}(T) \end{pmatrix}$$

- Strength of the phase transition at the nucleation temperature T_n

$$\xi_n \equiv \frac{\sqrt{\omega_1(T_n)^2 + \omega_2(T_n)^2 + \omega_{\mathrm{CP}}(T_n)^2}}{T_n}$$

[J. Annala, K. Rummukainen, T.V.I. Tenkanen]
[M. Ramsey-Musolf, P. Schicho et al.]

EW Phase Transition



- ξ_n is mostly a function of the mass spectrum
- The complex phase $\omega_{\rm CP}$ is 'linearly' dependent on $\Im Z_7$
- $\Im Z_7$ transfers the amount of CP-violation at finite T

EW Baryogenesis

- The complex phase is a function of the Top-Yukawa and Z_7 (through $\omega_{\rm CP}$)
  [J.M. Cline, K. Kainulainen, M. Trott]

$$m_t(z) = \frac{Y_t}{\sqrt{2}} e^{i\theta_1} \left[\omega_1 + a_u^* (\omega_2 + i\,\omega_{\rm CP})\right] =$$

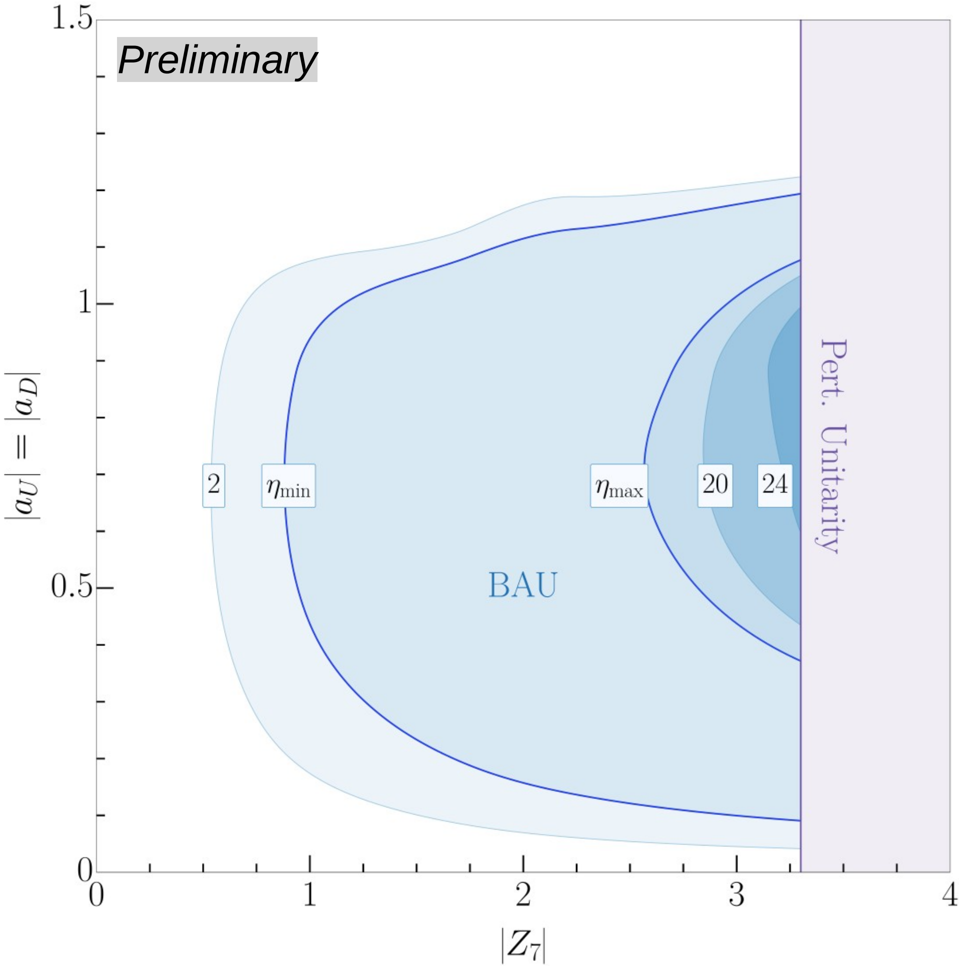
$$= \frac{Y_t}{\sqrt{2}} \left(\omega_1 + |a_u^*||\omega_2 + i\,\omega_{\rm CP}| e^{i(\theta_2 - \theta_u)}\right)$$

$$\theta_t = \tan^{-1}\left[\frac{|a_u^*||\omega_2 + i\,\omega_{\rm CP}| \sin(\theta_2 - \theta_u)}{\omega_1 + |a_u^*||\omega_2 + i\,\omega_{\rm CP}| \cos(\theta_2 - \theta_u)}\right]$$

- <u>Large uncertainties!</u> Considered a region to provide reliable estimates

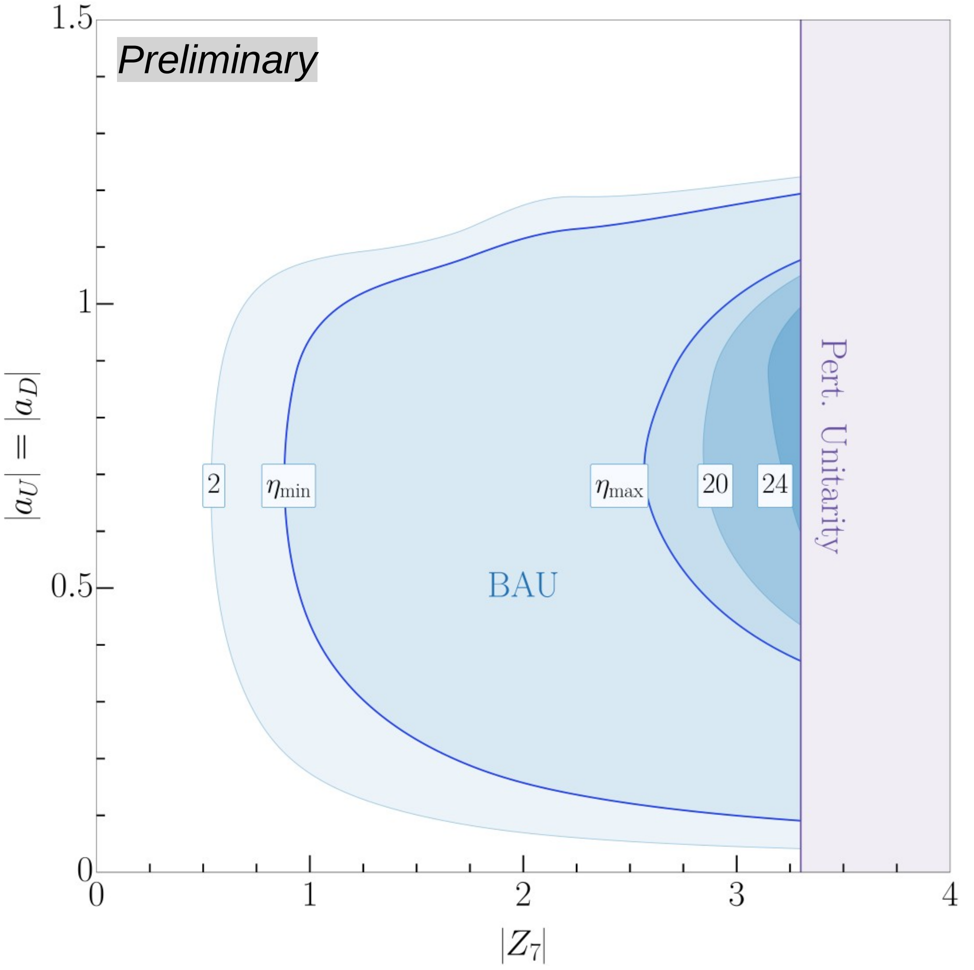
$$\eta_{\rm obs}/2 \leq \eta \leq 2\eta_{\rm obs}$$

Smoking gun $(A \to ZH)$



m_H	m_A	$m_{H^\pm}$	θ_{ij}
420	660	660	0.001

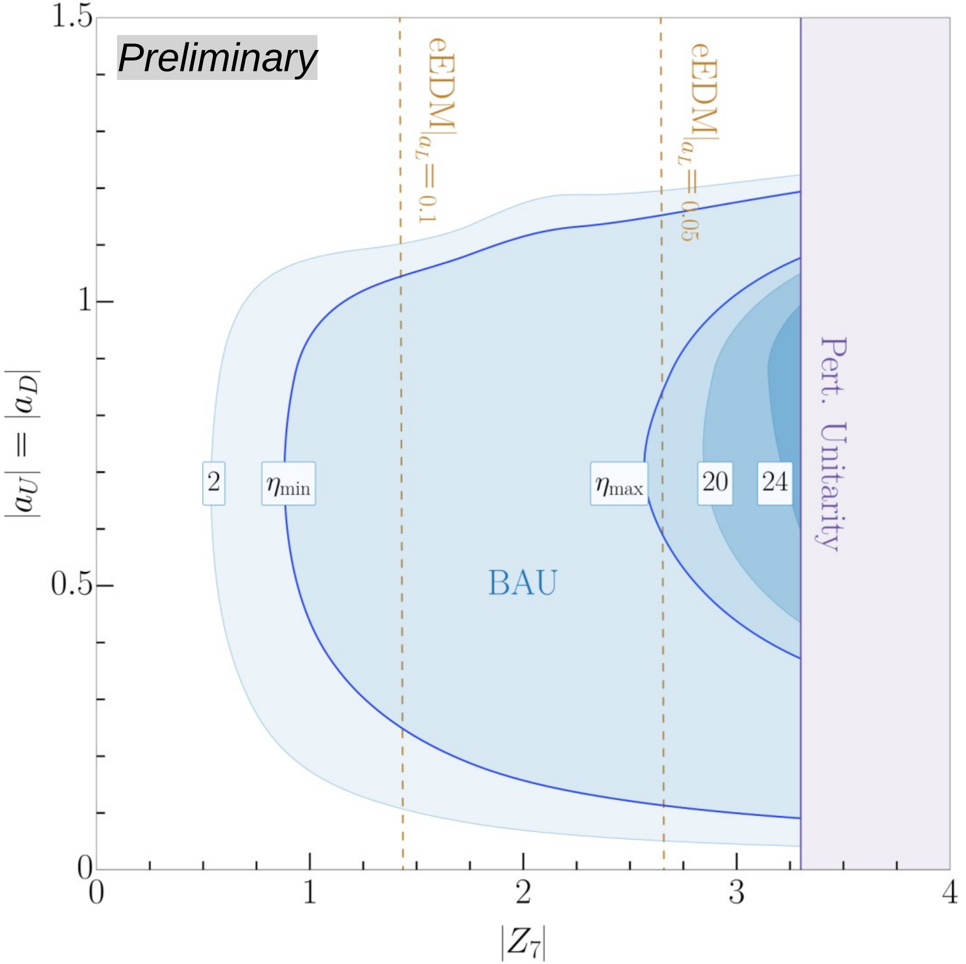
Smoking gun $(A \to ZH)$



m_H	m_A	$m_{H^\pm}$	θ_{ij}
420	660	660	0.001

- $\Im Z_7$ drives the amount of BAU up to $\eta \approx \mathcal{O}(10)$
- For <u>any</u> value of the Top-Yukawa we need $\Im Z_7 \approx \mathcal{O}(1)$

Smoking gun $(A \to ZH)$



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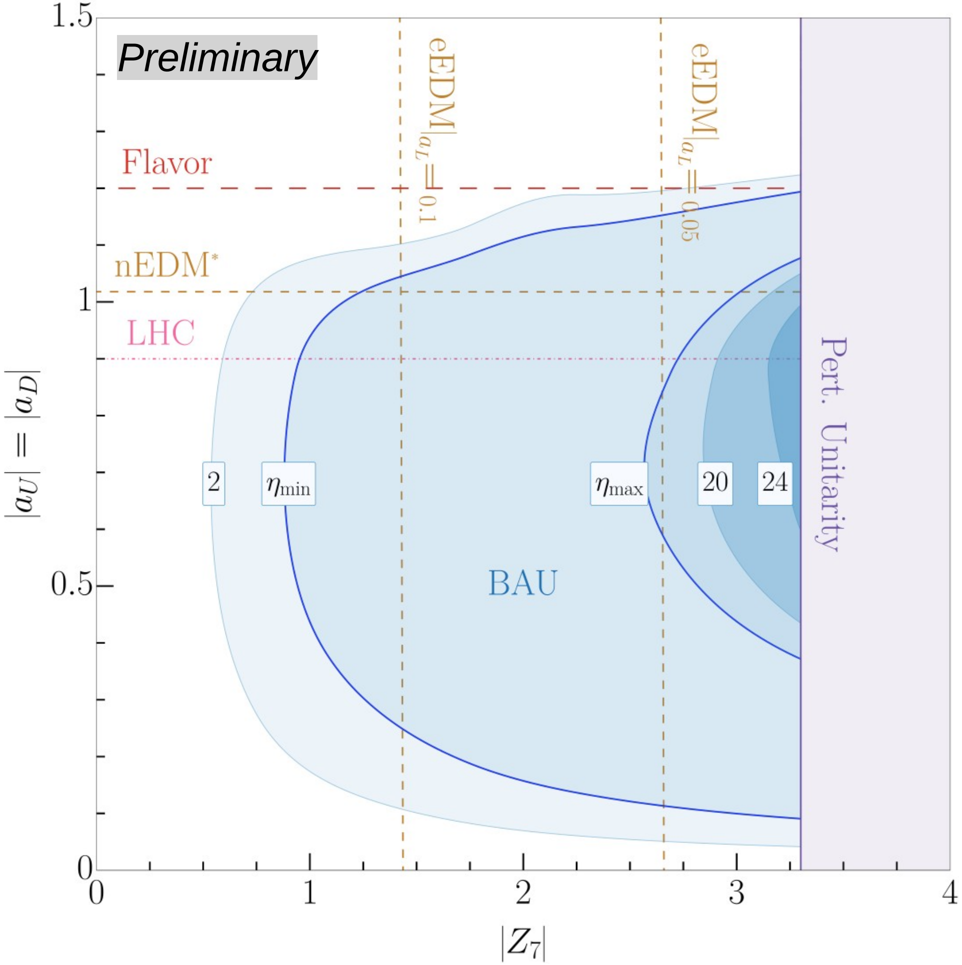
- eEDM is independent of Top-Yukawa (bounds evaded for small Lepton-Yukawa)

Smoking gun $(A \to ZH)$



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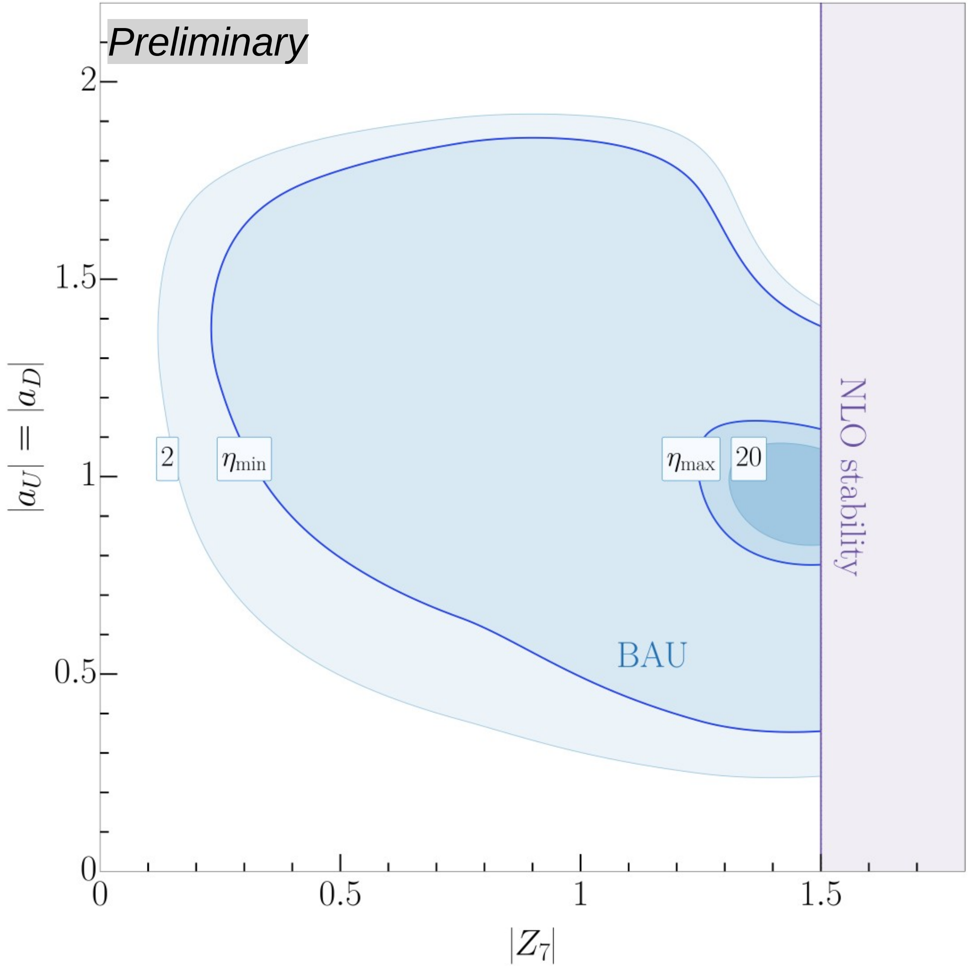
- For any value of the Top-Yukawa we need $\Im Z_7 \approx \mathcal{O}(1)$
- eEDM is independent of Top-Yukawa (bounds evaded for small Lepton-Yukawa)
- LHC / Flavor / nEDM bounds allow most of the parameter space

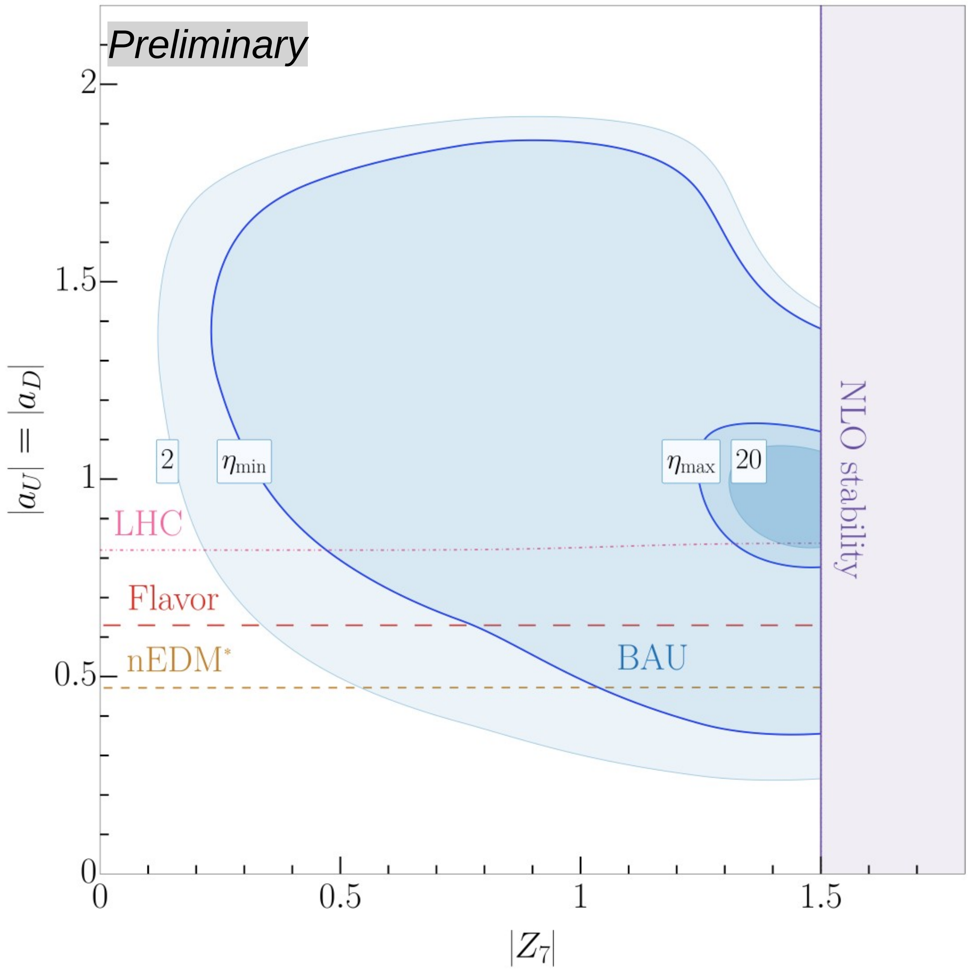
Di-Higgs



m_H	m_A	$m_{H^\pm}$	θ_{ij}	$\lvert a_L \rvert$
180	490	180	0.001	0.01

- $\Im Z_7$ drives the amount of BAU up to $\eta \approx \mathcal{O}(10)$
- Lepton-Yukawa chosen to avoid eEDM limits

Di-Higgs



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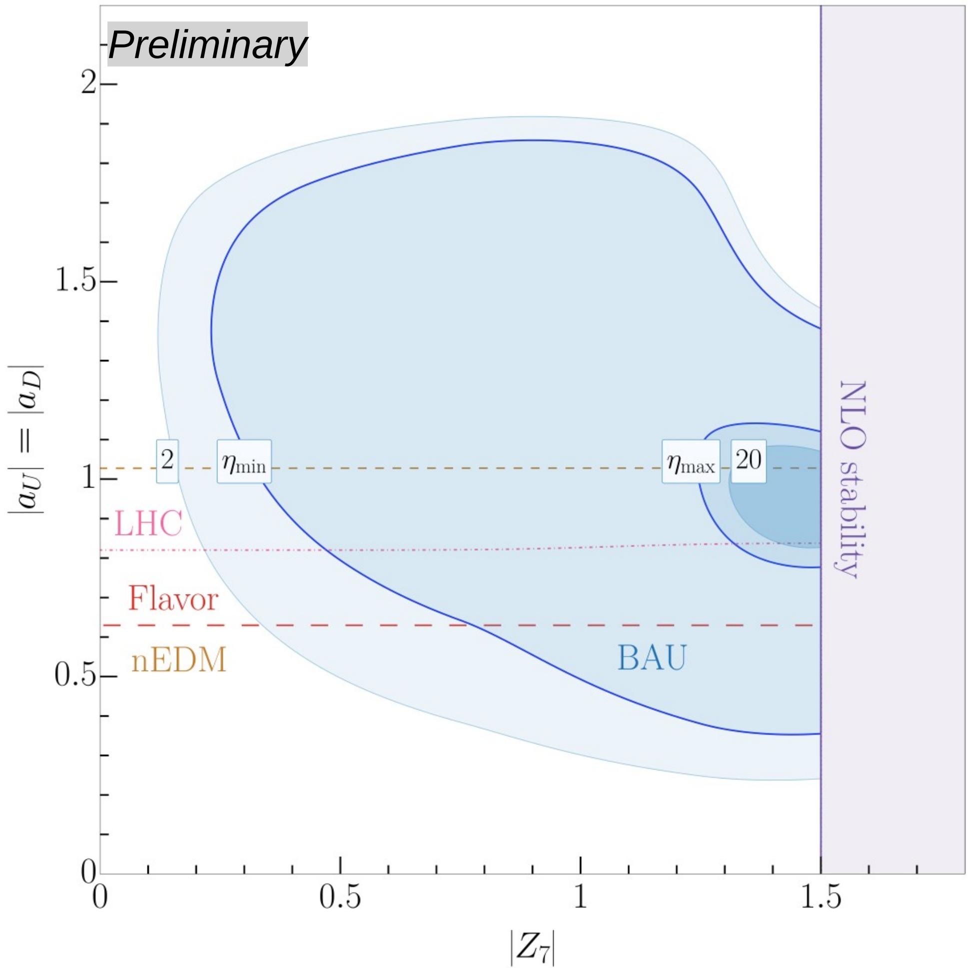
- LHC limits ($H^\pm \to tb$) and nEDM prospects
- Interplay with flavor bounds

[M. Jung, A. Pich, P. Tuzon]
[C. Degrassi, P. Slavich]
[A. Crivellin et al.]

Di-Higgs



m_H	m_A	$m_{H^\pm}$	θ_{ij}	$\|a_L\|$
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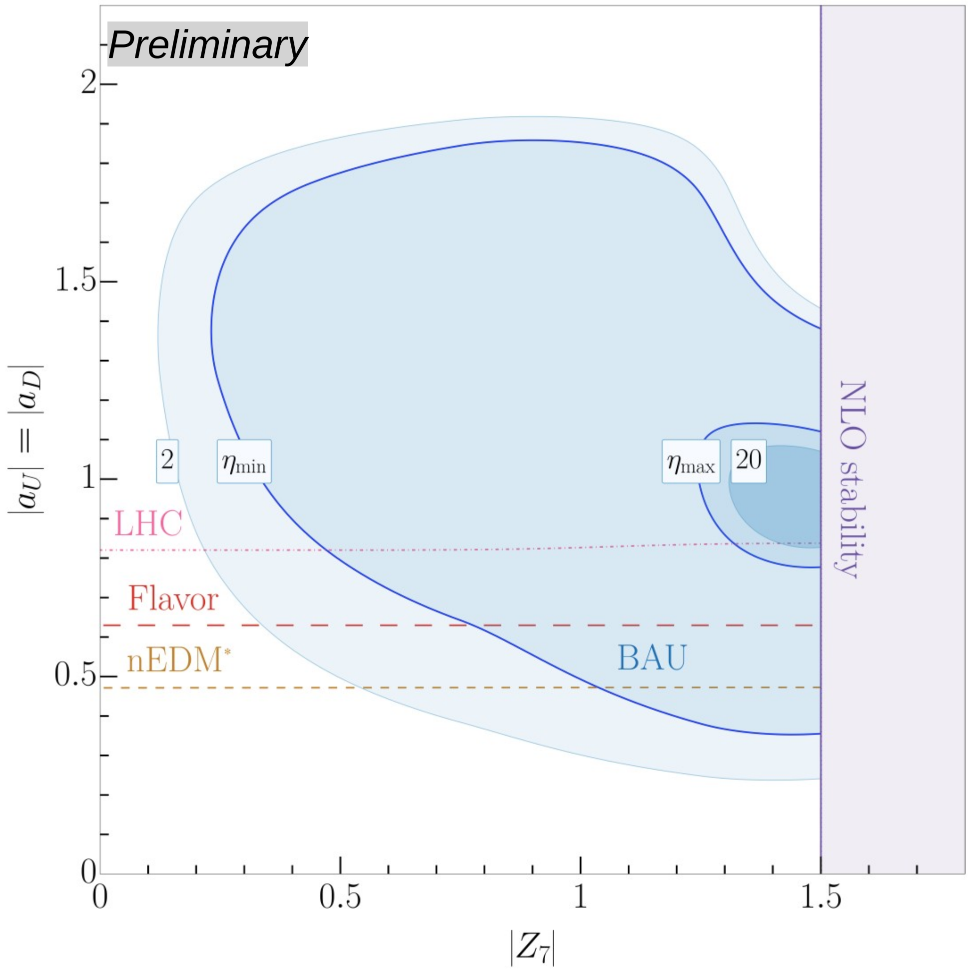

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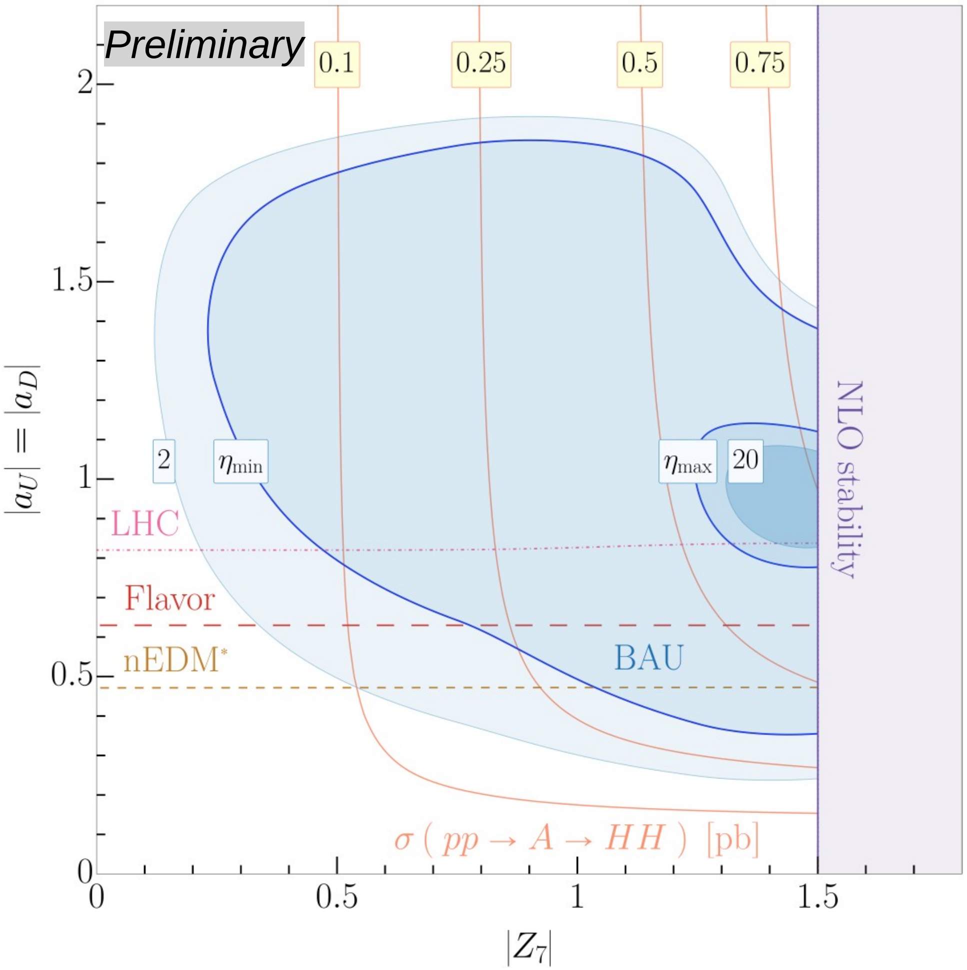
Di-Higgs



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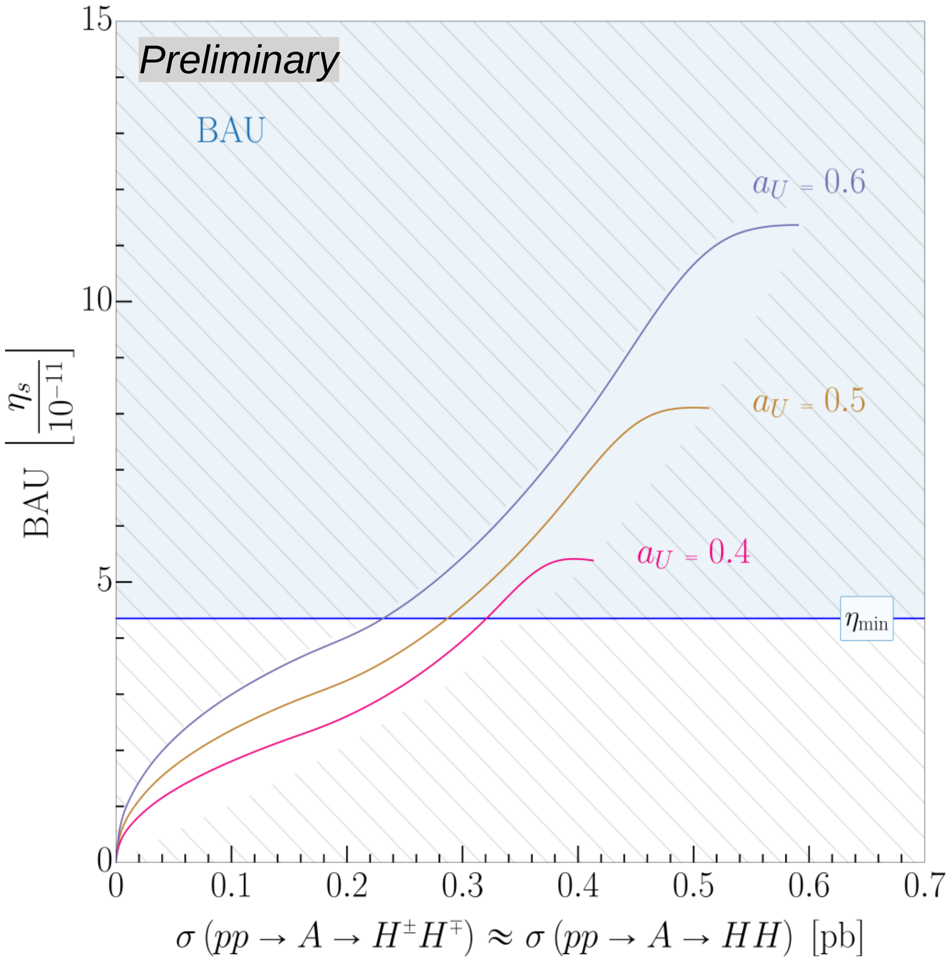
- Lepton-Yukawa chosen to avoid eEDM limits
- LHC limits ($H^\pm \to tb$) and nEDM prospects
- Interplay with flavor bounds [M. Jung, A. Pich, P. Tuzon] [C. Degrassi, P. Slavich] [A. Crivellin et al.]
- $\Im Z_7$ drives a visible cross-section at the LHC! [ATLAS]

Di-Higgs: LHC and cosmology



m_H	m_A	$m_{H^\pm}$	θ_{ij}	$\lvert a_L \rvert$
180	490	180	0.001	0.01

Z_7 as a driver of CP-violation

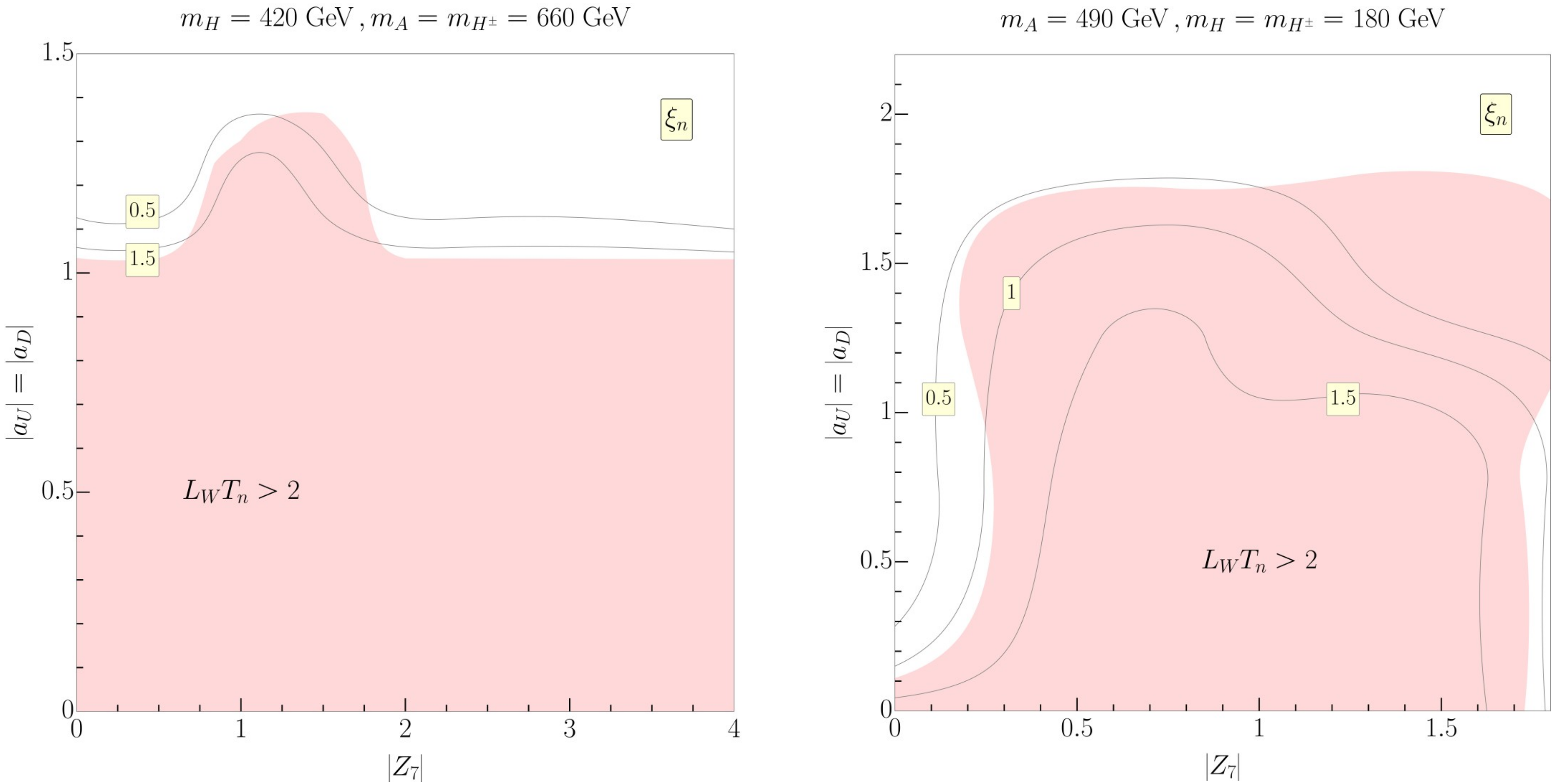
Correlation between a **measurable** LHC signature and a cosmological observable (BAU)!

Conclusions

- eEDM can be suppressed in the alignment limit and with a small Lepton-Yukawa
- In the aligned 2HDM: CP-violation and Top-Yukawa can survive without mixing and a Lepton-Yukawa $\rightarrow$ indepentent of eEDM!
- $\Im Z_7$ drives scalar signatures visible at the LHC (if phase space allows for it) and the CP-violating VEV at finite temperature inducing the BAU
- Nice correlations between collider observables and cosmology!

THANK YOU FOR THE ATTENTION!

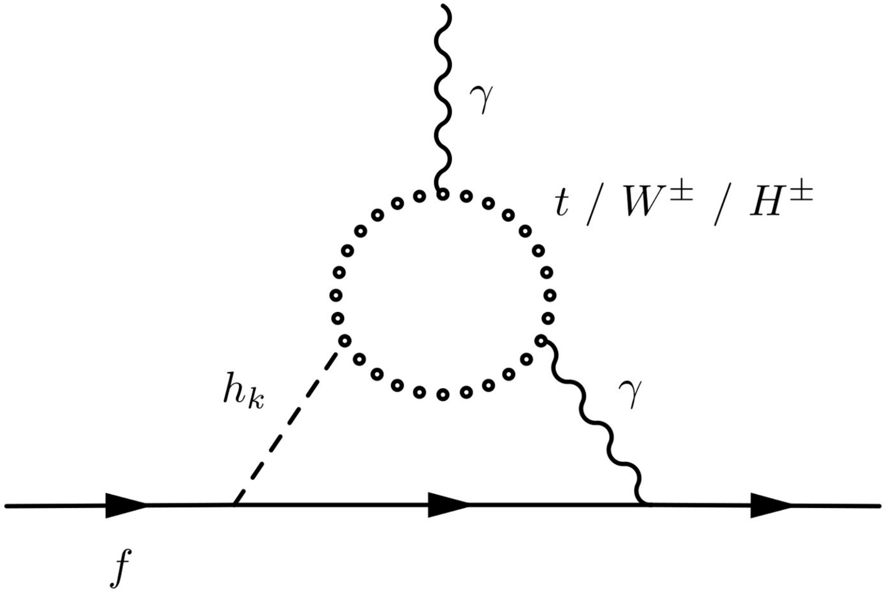
Back-up



$m_H = 420$ GeV , $m_A = m_{H^\pm} = 660$ GeV
ξ_n
0.5
1.5
$L_W T_n > 2$
$|a_U| = |a_D|$
$|Z_7|$
$m_A = 490$ GeV , $m_H = m_{H^\pm} = 180$ GeV
ξ_n
1
0.5
1.5
$L_W T_n > 2$
$|a_U| = |a_D|$
$|Z_7|$

Back-up

- The structure of the interactions roughly organize the contributions in separate pieces (notice that θ_{23} is not physical in the Higgs basis)



$$M_{t-\mathrm{loop}} \propto a_u \theta_{13}$$

$$M_{b-\mathrm{loop}} \propto a_d \theta_{13}$$

$$M_{W-\mathrm{loop}} \propto a_L \theta_{13}$$

$$M_{H^\pm-\mathrm{loop}} \propto a_L \Im Z_7$$

Back-up

- Analytical approximation to compute the BAU

[S.J. Huber, K. Mimasu, J.M. No]
[M. Mühlleitner, J. Plotnikov, R. Santos, J. Viana]
and see Maggie's talk!

$$\frac{\eta}{10^{-11}} \approx 6 \times 10^2 \frac{\sin(\theta_t)\xi_n^2}{L_W T_n}$$

Phase of the top quark mass throughout the nucleation bubble

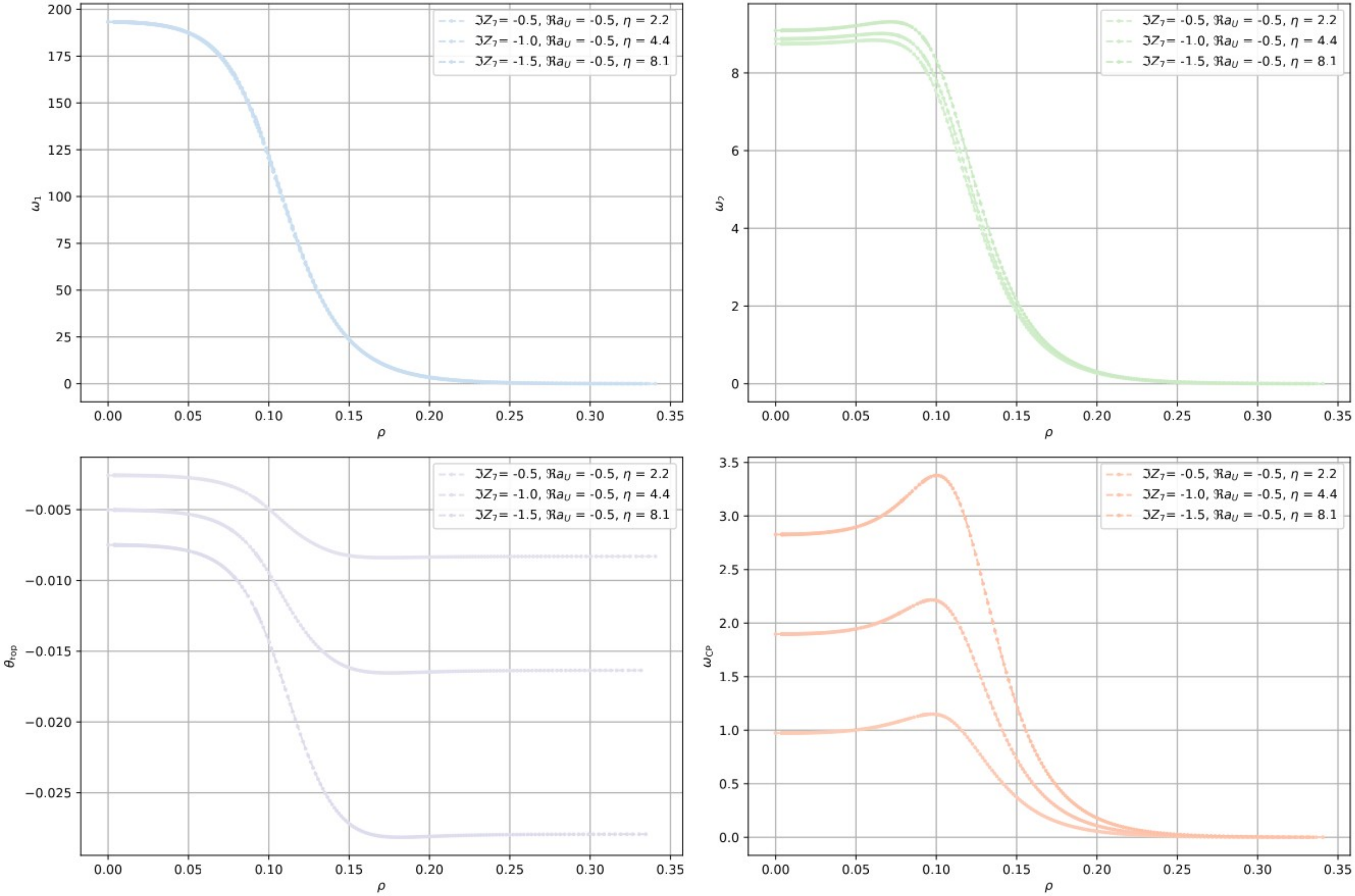
Strength parameter

Wall width at nucleation

Nucleation temperature

- Sub-sonic wall velocities $(v_w \leq 0.2)$
- VEVs profiles with a constant slope in the tunneling paths

Back-up



- The tunneling profiles of the VEVs at the nucleation temperature resemble a kink function