

A Deep Dive into Baryon Asymmetry - the C2HDM

Milada Muehlleitner

has participated in the

Workshop on Multi-Higgs Models 2026

Instituto Superior Técnico, Lisboa, Portugal, 25-28 August 2026

Based on common work with:
J. Plotnikov, R. Santos, J. Viana
arXiv: 2606.04229 [hep-ph]

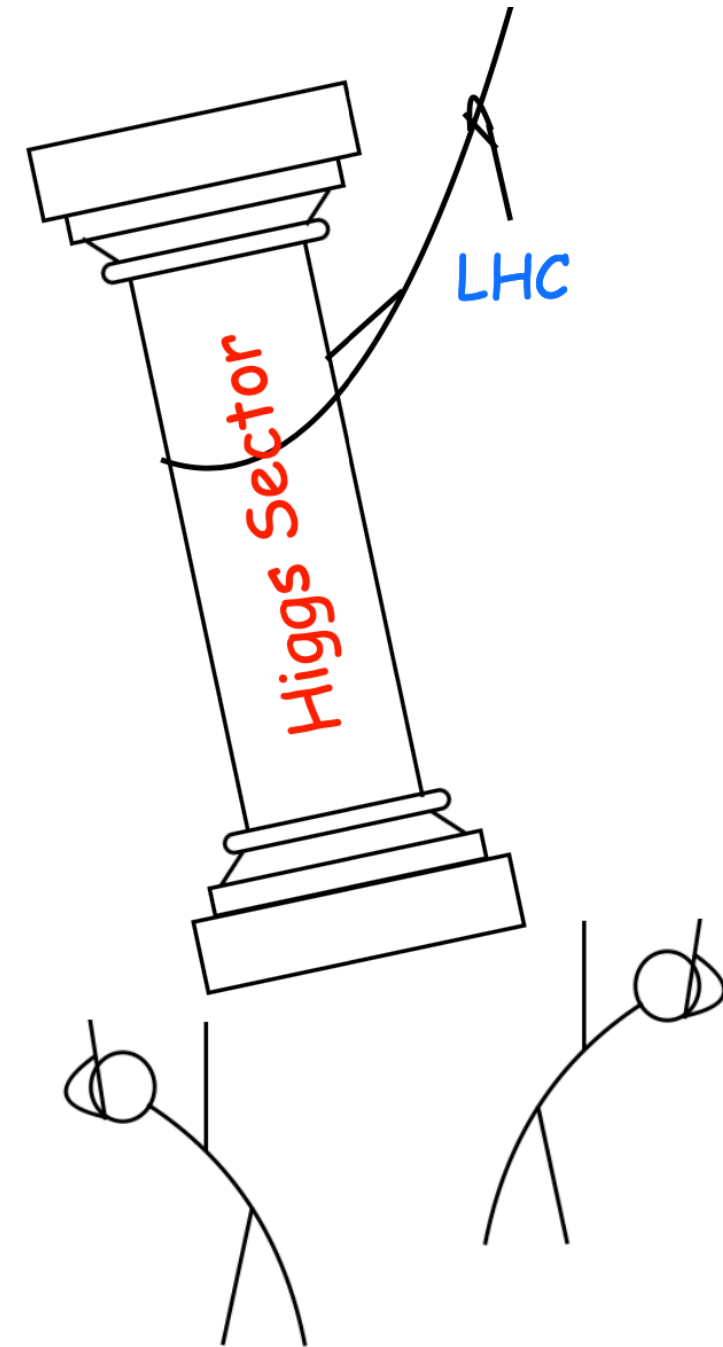
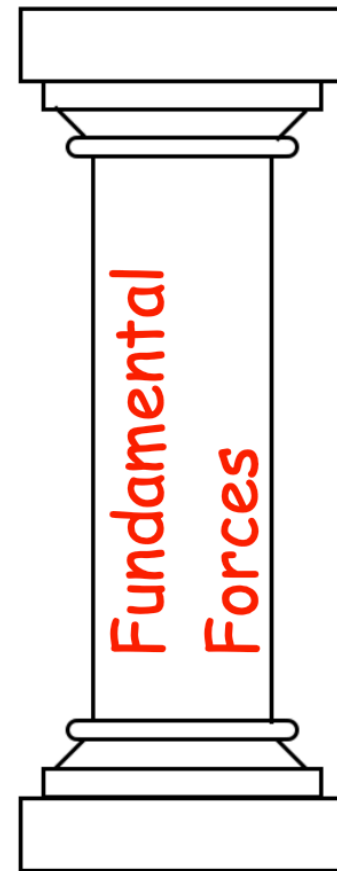
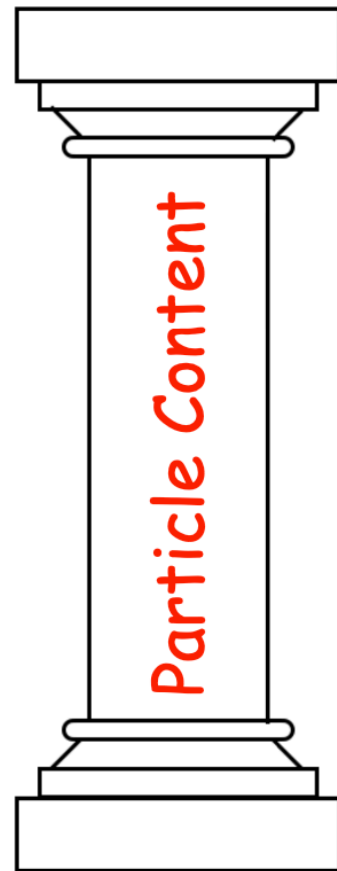
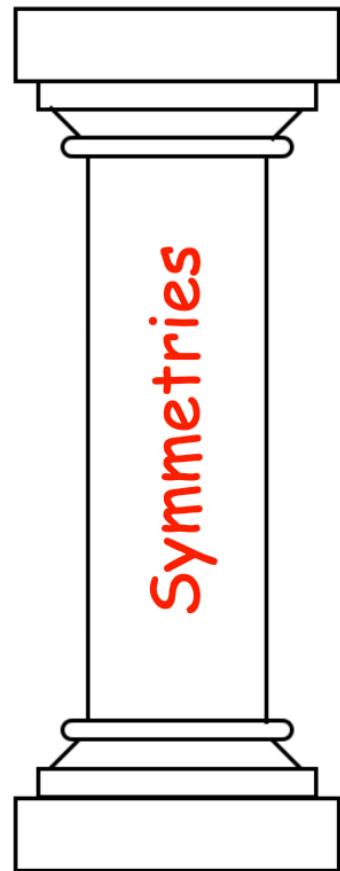
Workshop on
Multi-Higgs Models
25-28 Aug. 2026
(Lisbon - Portugal)

Milada Muehlleitner
KIT

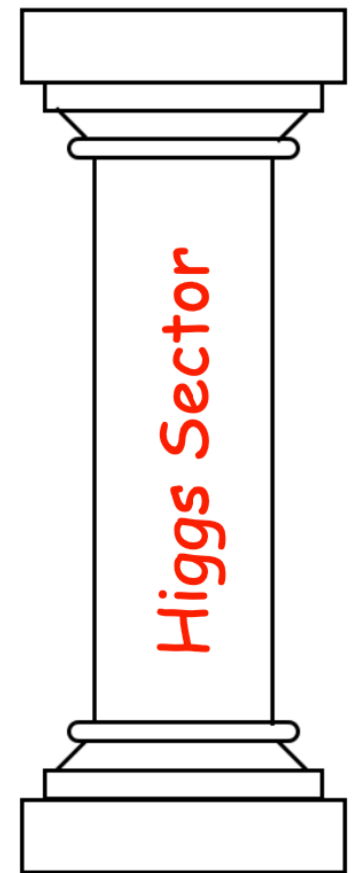
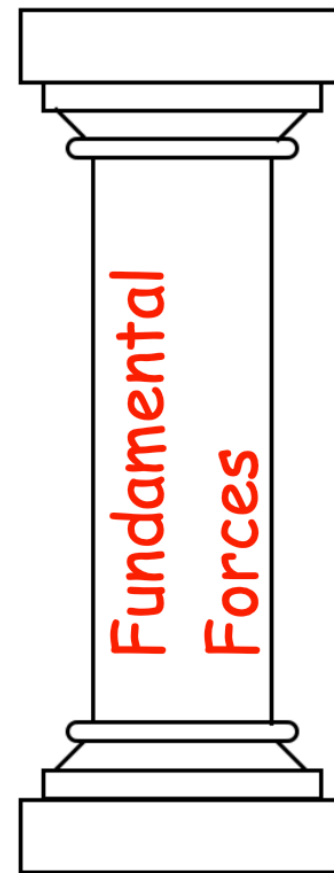
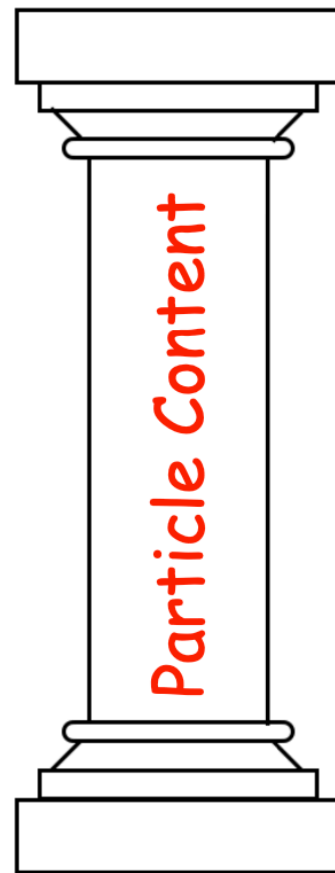
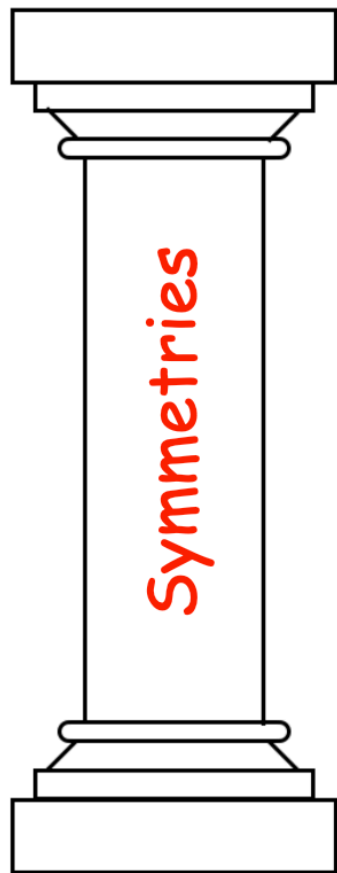
Outline

- Introduction
- Computation of the BAU
- The Models
- Numerical Analysis
 - Benchmark Model
 - C2HDM
- Benchmark Points
- Conclusions

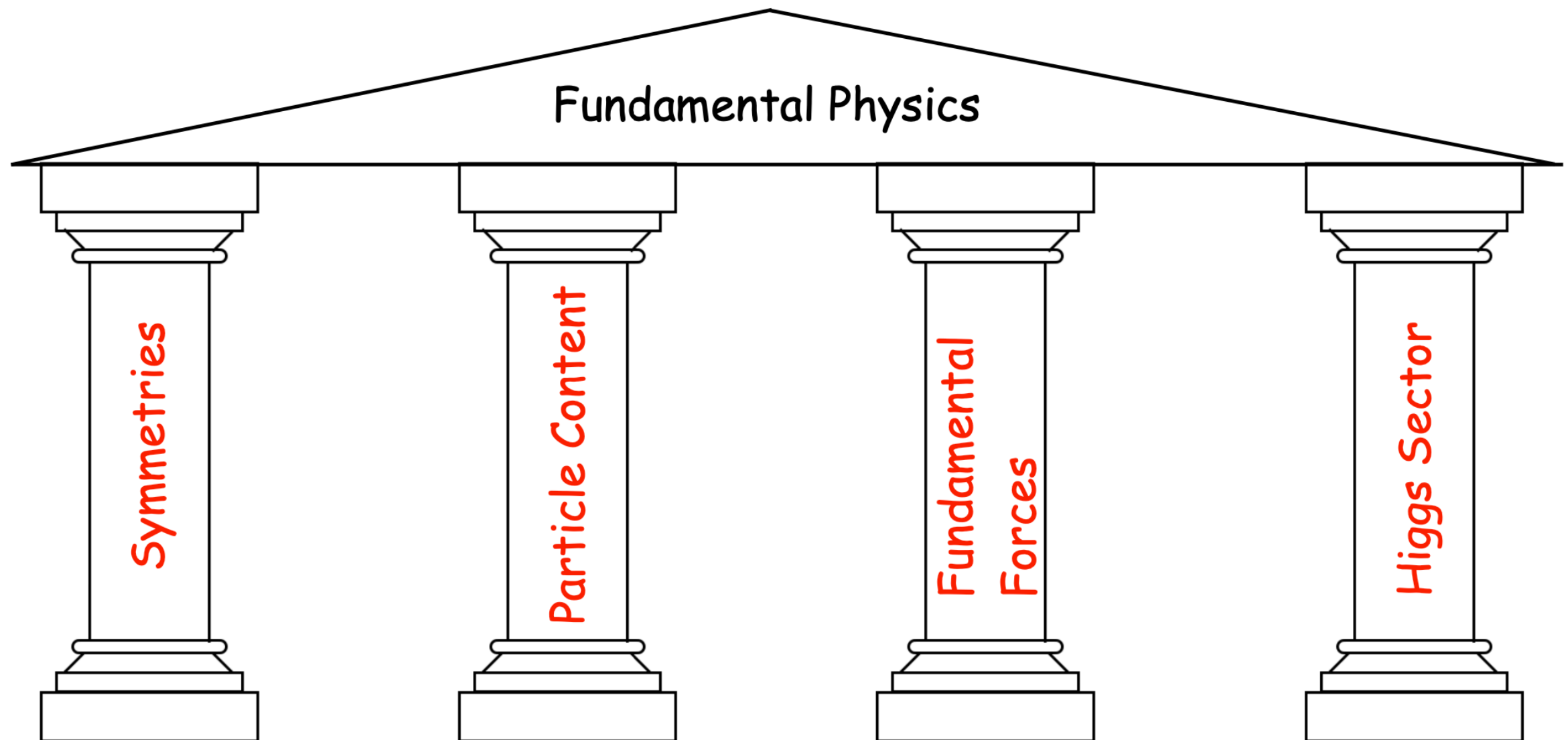
The Standard Model is Structurally Complete



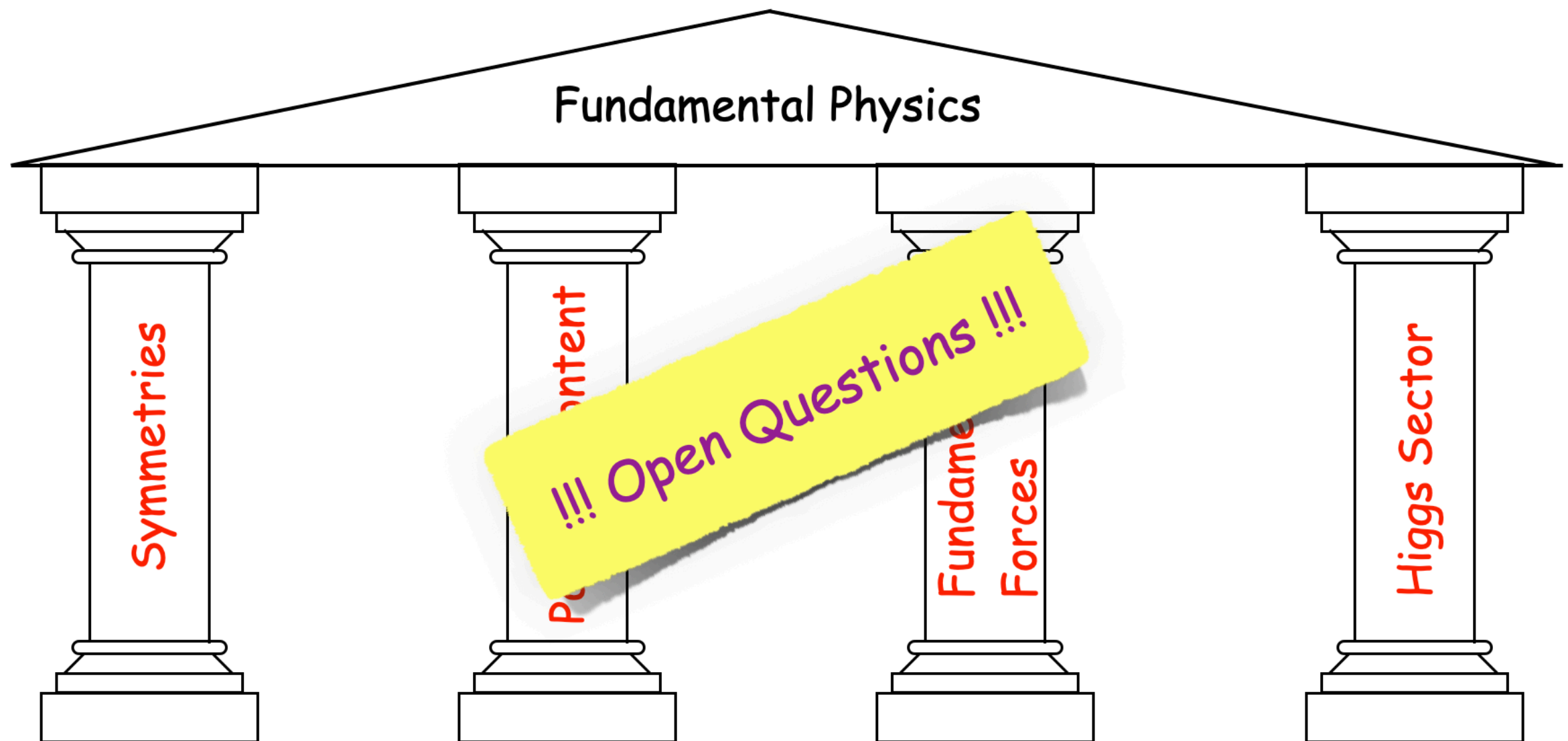
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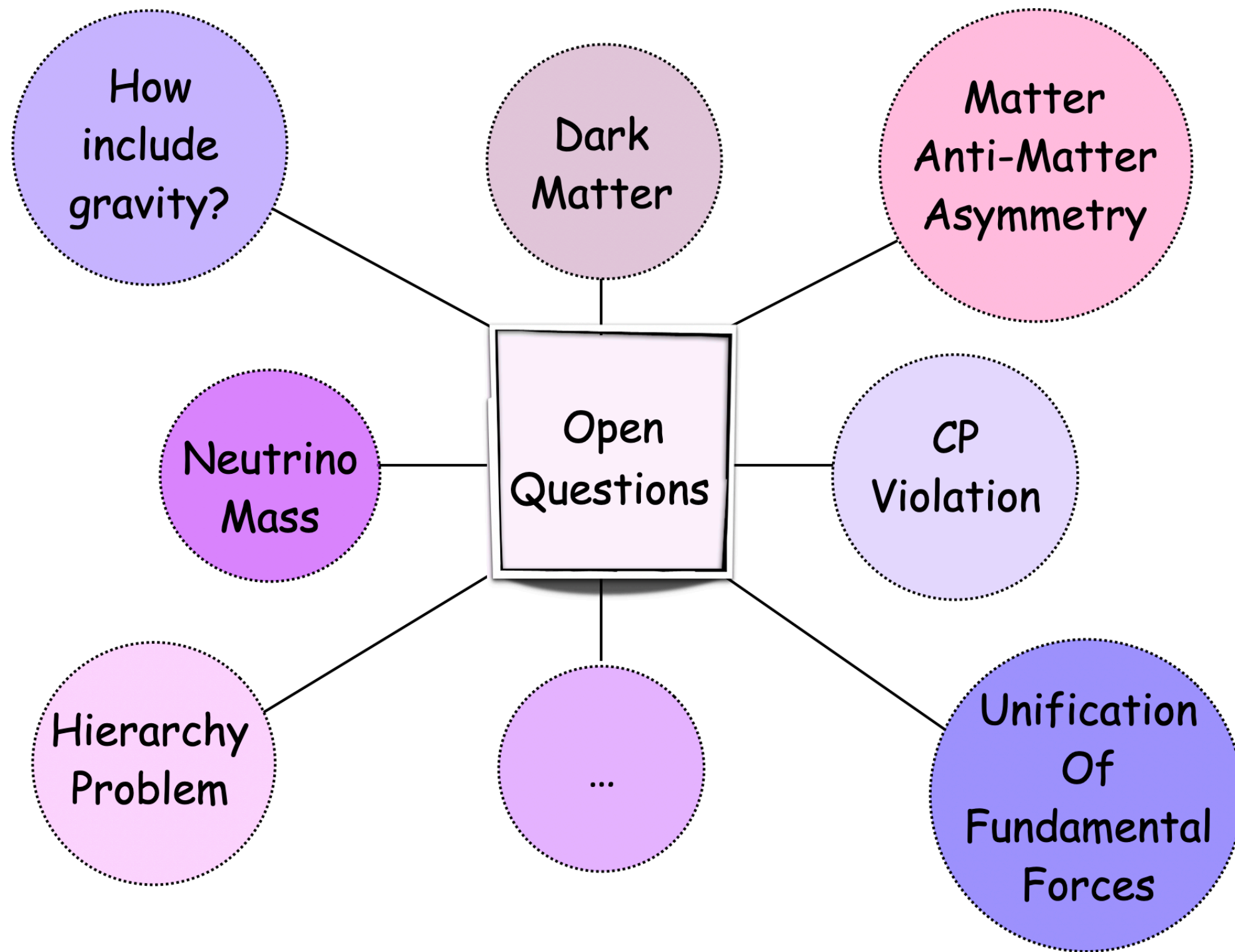
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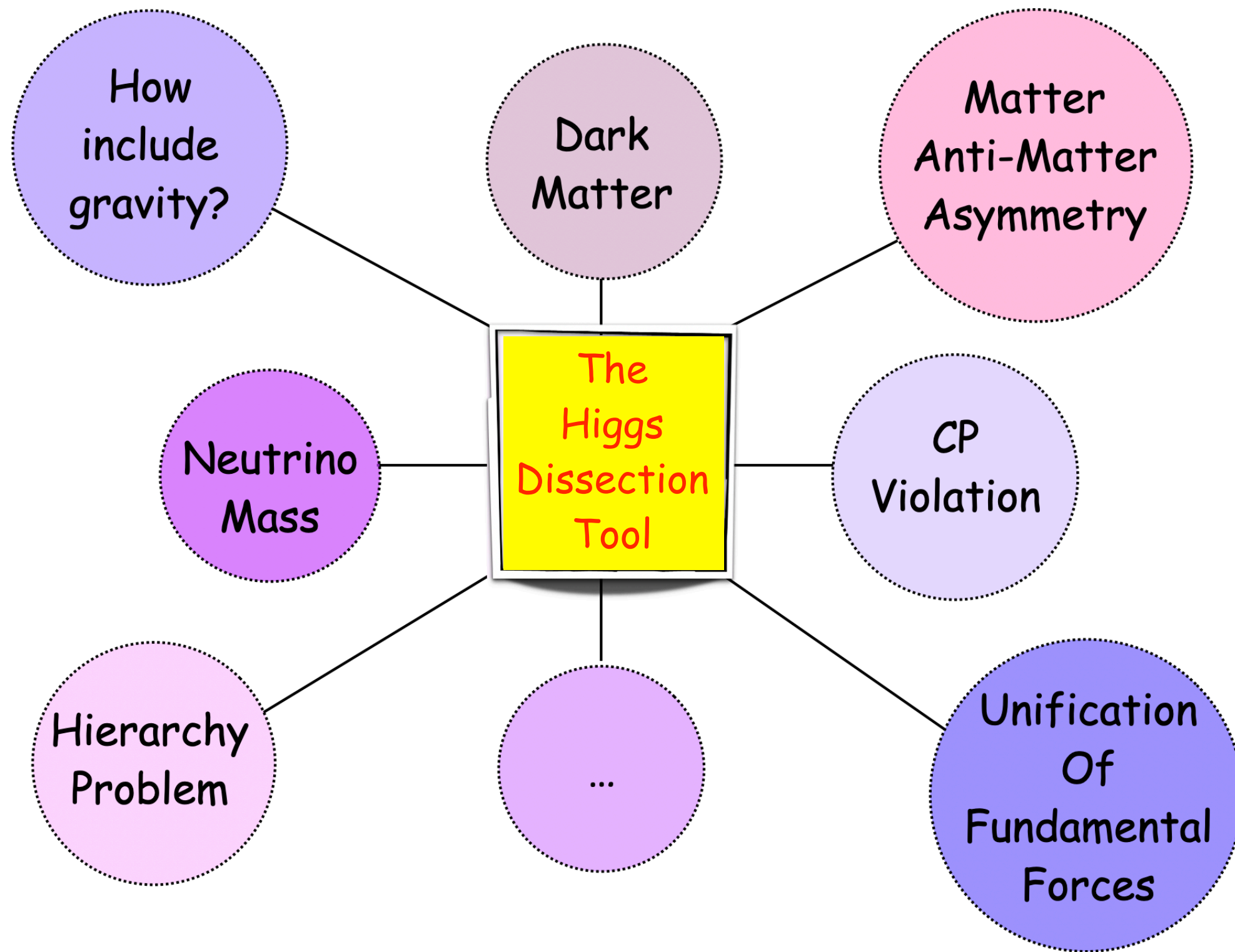
The Standard Model is Structurally Complete - But

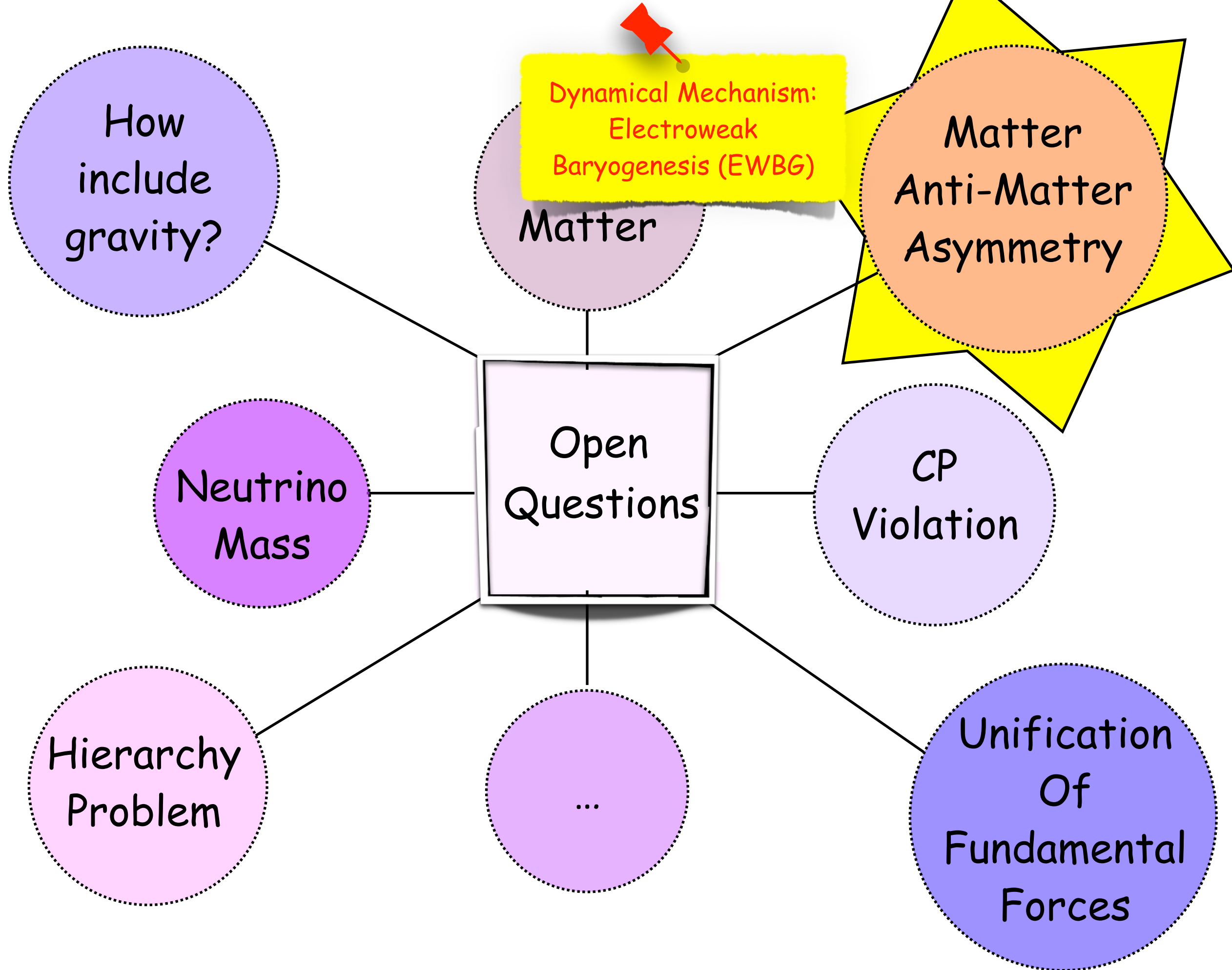


The Standard Model is Structurally Complete - But



The Standard Model is Structurally Complete - But





Electroweak Baryogenesis

- **Electroweak Baryogenesis (EWBG):** generation of the observed baryon-antibaryon asymmetry in the electroweak phase transition (EWPT) [Riemer-Sorensen, Jenssen '17]

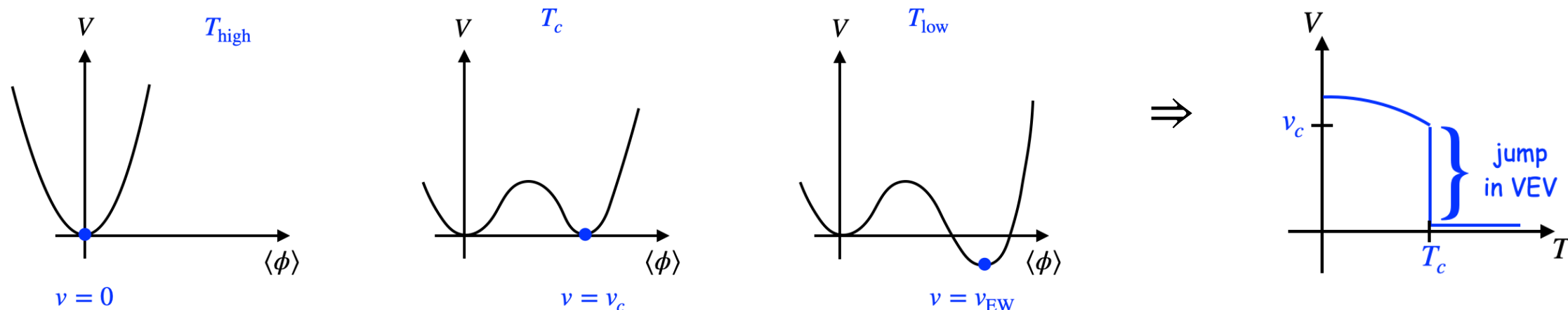
$$5.8 \cdot 10^{-10} < \frac{n_B - n_{\bar{B}}}{n_\gamma} < 6.6 \cdot 10^{-10}$$

- **Sakharov Conditions:**

[Sakharov '67]

- * (i) B number violation (sphaleron processes)
- * (ii) C and CP violation
- * (iii) Departure from thermal equilibrium

- **Additional constraint:** EW phase transition must be strong first order PT [Quiros '94; Moore '99]



Strong-First-Order Phase Transitions (SFOPT) and Gravitational Waves

Directly probe echo of
Cosmological FOPT

Discovery of Physics
Beyond the SM

SFOEWPT
(for EWBG)

can source

Gravitational Waves
(GW)

sensitive to

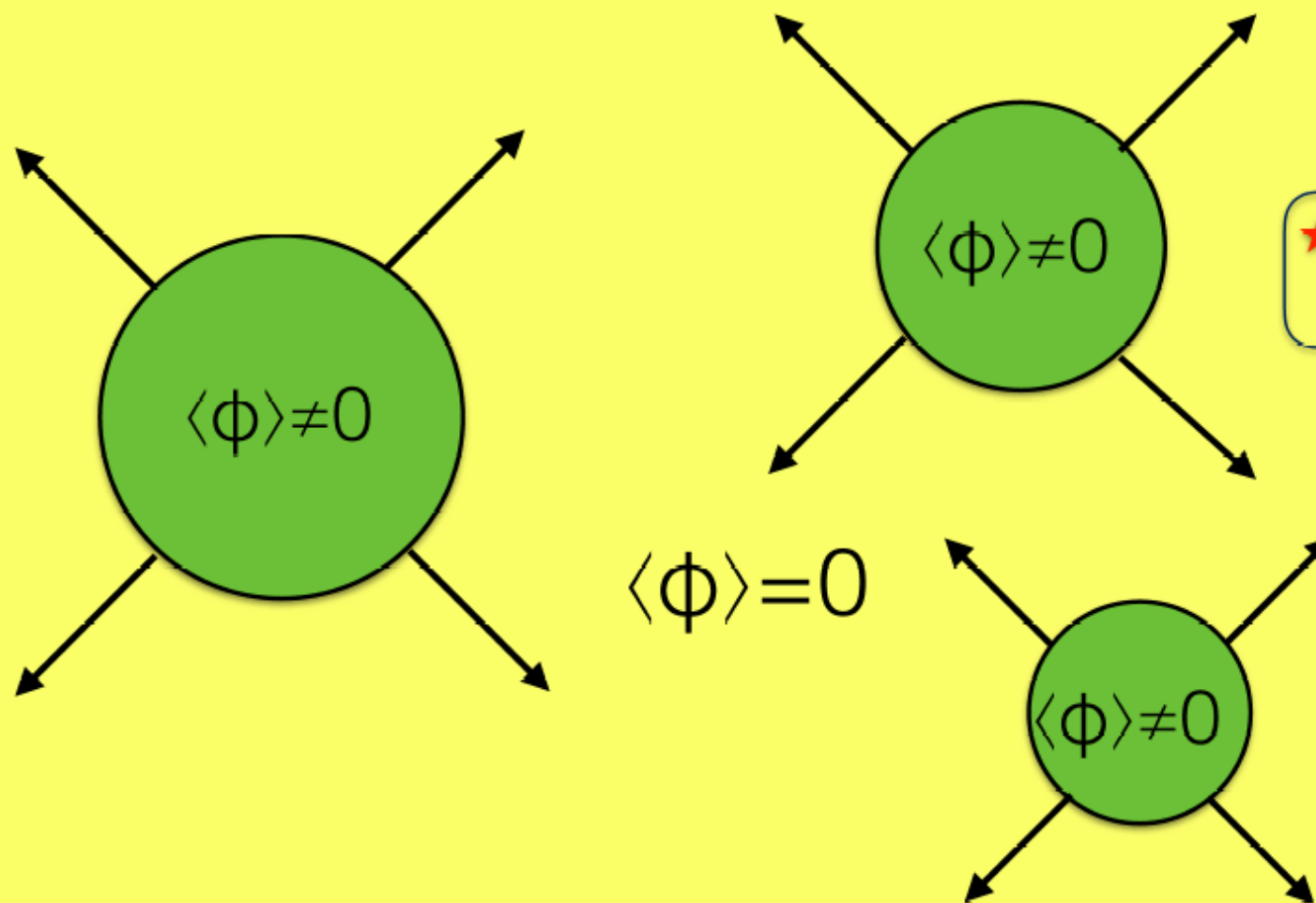
Pulsar timing arrays, LISA
(space bound interferometer)



Electroweak Baryogenesis in a Nutshell

Bubbles of the non-zero Higgs field VEV nucleate from the symmetric vacuum

They expand & particles in plasma interact with the phase interface in a CP-violating way



CP-asymmetry is converted into a baryon asymmetry by sphalerons in the symmetric phase in front of bubble wall

Produced baryons must not be washed out by sphaleron processes in symmetric phase in front of bubble wall ★

Combine collider phenomenology
and cosmological observations

Challenge: large range of energy scales
involving different physics

Requires: consistent combination of
information from collider
physics and cosmology

Complexity: numerical solution of problem

Needed: code performing whole chain
from particle physics model to BAU
and to GWs

[For a review cf. Athron, et al., 2305.02357]

Numerous Public Codes - Here an Incomplete List

- CosmoTransitions [Wainwright,'11]: phase tracing, bounce solution, T_c , T_n^{approx}
- Vevacious, VevaciousPlusPlus [Camargo-Molino eal,'13,'14,'15]: finding minima
- AnyBubble [Masoumi eal,'17]: bounce solution
- EVADE [Hollik eal,'18,'19]: finding minima, bounce solution
- BubbleProfiler [Athron eal,'19]: bounce solution
- PhaseTracer/+2 [Athron eal,'20,'24]: phase tracing, T_c /+ bounce solution, GW spectra
- SimpleBounce [Sato,'19]: bounce solution
- FindBounce [Guada eal,'18,'20]: bounce solution
- OptiBounce [Bardsley,'21]: bounce solution
- TransitionListener: phase tracing, bounce solution, characteristic temperatures, GW spectra
[Ertas,Kahlhöfer,Tasillo,'21;Matuszak,Tasillo,'26] user-specified V
- WallGo [Ekstedt eal,'24]: wall velocity
- BARYONET [Barni,'25]: computation of BAU based on WKB approach

BSMPTv4(to appear): phase tracing, bounce solution, thermal parameters, GW spectra, BAU (WKB)
for arbitrary extended Higgs sectors

Computation of the BAI



New Implementation of BAU in BSMPT

- **The Code BSMPT:** All the way from the particle physics model at $T=0$ to GW and BAU

v1: [Basler,MM,1803.02846] v2: [Basler,MM,Müller, 2007.01725] v3: [Basler,Biermann,MM,Müller,Santos,Viana, 2404.19037]

<https://github.com/BSMPT/BSMPT/>

- ✦ Model-independent implementation of the one-loop resummed, T -dependent effective potential
- ✦ On-shell-like renormalization scheme
- ✦ Local minimum tracking, identification of phase overlaps and multi-step PT histories
- ✦ Calculates decay rate of false into true vacuum
- ✦ Derivation of the gravitational waves spectrum from strong first-order phase transitions
- ✦ Calculation of BAU in implemented BSMPTv2 for the C2HDM

[MM,Plotnikov,Santos,Viana,'26]

- **New implementation of BAU in BSMPTv4(to appear):** New features w.r.t. to BSMPTv2

- ✦ based on **WKB ansatz** [Cline eal,'97;'00; Kainulainen eal,'01,'02; Fromme,Huber,'07; Cline,Kainulainen,'20]
w/ **recent developments*** [Cline,Kainulainen,'20; Kainulainen,'21; Kainulainen,Venkatesan,'24]
(*high wall velocities, higher order terms in moment expansion, $n = 50$ in BSMPT)
- ✦ Proper implementation of **boundary conditions** for the solution of the transport equations
- ✦ Implementation of **two different truncation schemes** in the solution of the transport equations
- ✦ Possibility to derive and apply the **VEV profile from the solution of the equations of motion**
- ✦ **New computation of the top-Yukawa rate at non-zero temperature**

Transport Equations

Goal: Describe how the distribution functions of the particles and anti-particles in the plasma evolve as they come into contact with a moving bubble wall

Transport equations: **key assumption** $L_w T_* \gg 1$ (L_w wall width, T_* transition temperature)

based on **WKB ansatz** [Cline et al., '97; '00; Kainulainen et al., '01, '02; Fromme, Huber, '07; Cline, Kainulainen, '20]

w/ recent developments*

[Cline, Kainulainen, '20; Kainulainen, '21; Kainulainen, Venkatesan, '24]

(*high wall velocities, higher order terms in moment expansion)

Semiclassical source/WKB source: describes difference in force for particle and antiparticle modes

arising from the change in the mass when crossing the bubble wall

z -dependent mass: for a fermion moving in a CP-violating VEV background (z distance to bubble wall)

$$\hat{m}(z) = m(z) \exp(i\theta(z))$$

CP-violating phase

Transport Equations

Boltzmann equation:

$$\mathcal{L}[f_h^\pm] = \mathcal{C}_h^\pm [f_h^\pm]$$

Liouville operator:
encodes dynamics of
the particle bath

Collision operator:
encodes interaction between
different particle species

$f_h^\pm$: distribution function for particle (+), antiparticle (-)

z : distance to the bubble wall

Liouville Operator:

$$\mathcal{L}[f_h^\pm] \equiv \left(v_h^\pm \partial_z + F_h^\pm \partial_{p_z} \right) f_h^\pm .$$

group velocity

semi-classical force

Collision Operator: must include all relevant rates driving system back into equilibrium
(decays, annihilation, scattering processes)

Collision Operator

Considered collision network:

left-/right-handed top quark (t_L/t_R), left-handed bottom quark (b_L), Higgs boson (h),
with the collision operators $\bar{C}^i$ [Barni,'25]

$$\begin{aligned}\bar{\mathcal{C}}^{t_L} &= \hat{\Gamma}_y(\mu_{t_L} - \mu_{t_R} + \mu_h) + 2\hat{\Gamma}_m(\mu_{t_L} - \mu_{t_R}) + \hat{\Gamma}_W(\mu_{t_L} - \mu_{b_L}) + \hat{\Gamma}_{ss}[\mu_i] , \\ \bar{\mathcal{C}}^{b_L} &= \hat{\Gamma}_y(\mu_{b_L} - \mu_{t_R} + \mu_h) + \hat{\Gamma}_W(\mu_{b_L} - \mu_{t_L}) + \hat{\Gamma}_{ss}[\mu_i] , \\ \bar{\mathcal{C}}^{t_R} &= -\hat{\Gamma}_y(\mu_{t_L} + \mu_{b_L} - 2\mu_{t_R} - 2\mu_h) + 2\hat{\Gamma}_m(\mu_{t_R} - \mu_{t_L}) - \hat{\Gamma}_{ss}[\mu_i] , \\ \bar{\mathcal{C}}^h &= \frac{3}{2}\hat{\Gamma}_y(\mu_{t_L} + \mu_{b_L} - 2\mu_{t_R} + 2\mu_h) + \hat{\Gamma}_h\mu_h .\end{aligned}$$

Collision rates: [Barni,'25]

$$\hat{\Gamma}_m \approx \frac{0.26 |m_t(z)|^2}{T} , \quad \hat{\Gamma}_h \approx \frac{1.5 |m_W(z)|^2}{T} , \quad \hat{\Gamma}_{ss} \approx 2.7 \cdot 10^{-3} T , \quad \hat{\Gamma}_W = \hat{\Gamma}_{\text{tot}}^h ,$$

Yukawa helicity flipping rate

Higgs number violating rate

strong sphaleron rate

W scattering rate

Top-Yukawa rate $\hat{\Gamma}_y$: updated value by [MM,Plotnikov,Santos,Viana,'26]

$$\hat{\Gamma}_y \approx 6 \cdot 10^{-3} T$$

$$(\hat{\Gamma}_y \approx 4.2 \cdot 10^{-3} T \text{ [Huet,Nelson,'96]},$$

most recent value in the literature $\hat{\Gamma}_y \approx 1 \cdot 10^{-2} T$ [Barni,'25])

Solution of the Transport Equations

Solution: extremely complicated $\rightsquigarrow$ perform moment expansion

Truncation: not enough equations to determine the derivative of the velocity moment $u'_{o,n}$ $\rightsquigarrow$
truncation scheme introduced to fix $u'_{o,n}$

Constant Truncation Scheme: $u'_{o,n} = R u'_{o,n-1}$ for constant R

[Fromme, Huber, '07;
Cline, Kainulainen, '20]

Variance Truncation Scheme: $u'_{o,n} = \sum_{i=1}^{n-1} R_i u'_{o,i}$ with

[Kainulainen, Venkatesan, '24]

$$R_1 = -n^2(-u_{o,1})^{n-1} + \sum_{k=2}^{n-1} \binom{n}{k} (n-k) u_{o,k} (-u_{o,1})^{n-k-1}$$

$$R_i = -\binom{n}{i} (-u_{o,1})^{n-i} \quad , i \in [2, n-1]$$

Bubble Profile

Common choice: kink profile for fields developing an EW VEV

$$\phi_i(z) = \phi_{t,i} + (\phi_{f,i} - \phi_{t,i}) \frac{1}{2} \left(1 + \tanh \left(\frac{z - \delta_i}{L_{w,i}} \right) \right)$$

$\vec{\phi}_t$: true vacuum, $\vec{\phi}_f$: false vacuum, z : distance to bubble wall, L_w : bubble width, $\vec{\delta}$: displacement

Phase also modeled with kink profile:

$$\theta(z) = \left(\theta_{\text{brk}} - \frac{\theta_{\text{brk}} - \theta_{\text{sym}}}{2} \left(1 + \tanh \frac{z}{L_w} \right) \right)$$

Estimate of length scale:

$$L_w = \frac{v_t}{\sqrt{8V_b}}, \quad v_t \equiv \sqrt{\sum_i \omega_i(z = -\infty)}: \text{EW VEV in the broken phase}$$

V_b : potential barrier

Bubble Profile

Improved calculation of bubble profile in BSMP:

solution of the equations of motion for the fields in the plasma

$$\frac{d^2 \vec{\phi}}{dz^2} + \mu \frac{d\vec{\phi}}{dz} = \vec{\nabla} V(\vec{\phi})$$

friction coefficient [Liu et al., '92]

μ is not a free parameter:

$$\mu \int_{-\infty}^{\infty} \left[\frac{d\vec{\phi}}{dz} \right]^2 dz = \Delta V$$

with $\Delta V = V(\vec{\phi}(\infty)) - V(\vec{\phi}(-\infty))$

potential value
at false vacuum

potential value
at true vacuum

Computation of the Baryon Asymmetry

Chemical potential: sphalerons only couple to the left-handed particles $\rightsquigarrow$
baryon chemical potential generated from the left-handed particles

$$\mu_{B_L} \equiv \frac{1}{2} \sum_q \mu_{q_L}(z)$$

Baryon asymmetry:

$$\eta_B = \frac{n_B(-\infty)}{s} = - \frac{45 n_f N_c}{4\pi^2 v_w \gamma_w h_{\text{eff}T}} \int_{-\infty}^{\infty} dz \Gamma_{ws}(z) \mu_{B_L}(z) \exp \left[- \frac{A n_f}{2 v_w \gamma_w} \int_{-\infty}^z \Gamma_{ws}(z') dz' \right]$$

$n_B(-\infty)$ baryon asymmetry in true vacuum, $s = h_{\text{eff}} \frac{2\pi^2}{45} T^3$ entropy density,

h_{eff} number of effective d.o.f. for the entropy density, N_c number of colours, v_w wall velocity, γ_w Lorentz factor, Γ_{ws} weak sphaleron rate, $A = 15/2$

The Models



Benchmark Model

Benchmark Model with:

[Kainulainen, Venkatesan, '24]

massless left-chiral bottom quarks, massless Higgs boson, heavy top quark
coupling via gauge and Yukawa interactions + singlet field

and the dimension-5 operator:

$$i \frac{s}{\Lambda} \bar{Q}_3 H t_R$$

Q_3 , left-handed third generation quark doublet, H Higgs doublet, s singlet field, Λ new physics scale

Spatially varying complex top mass:

$$m_t(z) = y_t h(z) \left(1 + i \frac{s(z)}{\Lambda} \right) \text{ with absolute value and phase } |m_t(z)| = y_t h(z) \sqrt{1 + \frac{s(z)^2}{\Lambda^2}}, \quad \theta(z) = \arctan \frac{s(z)}{\Lambda}$$

y_t top-quark Yukawa coupling

VEV profiles of scalar fields $h(z)$ and $s(z)$: kink ansatz

$$h(z) = \frac{v_n}{2} \left(1 - \tanh \frac{z}{L_w} \right), \quad s(z) = \frac{\omega_n}{2} \left(1 + \tanh \frac{z}{L_s} \right)$$

Input parameters: $v_n = \frac{1}{2} \omega_n = T_n$, $\Lambda = 1 \text{ TeV}$, $L_w = L_s = \frac{5}{T_n}$, $T_n = 100 \text{ GeV}$

The CP-violating 2-Higgs Doublet Model (C2HDM)

- **CP violation:** one of the three Sakharov conditions for the generation of the baryon-anti baryon asymmetry through electroweak baryogenesis

- **C2HDM Higgs potential:** w/ softly broken $\mathbb{Z}_2$ symmetry

[Ginzburg, Krawczyk, Osland, '02]

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c. \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + h.c. \right]$$

All parameters are real except for m_{12}^2 and λ_5 : $m_{12}^2 = |m_{12}^2| e^{i\phi(m_{12}^2)}$, $\lambda_5 = |\lambda_5| e^{i\phi(\lambda_5)}$

The two complex phases are not independent of each other

$$2\text{Re}(m_{12}^2) \tan \phi(m_{12}^2) = v_1 v_2 \text{Re}(\lambda_5) \tan \phi(\lambda_5)$$

Ensure CP violation (both phases cannot be removed simultaneously) by choosing:

$$\phi(\lambda_5) \neq 2\phi(m_{12}^2)$$

The CP-violating 2-Higgs Doublet Model (C2HDM)

- **Mass spectrum and mixing:** CP violation $\leadsto$ neutral formerly CP-even (h, H) and CP-odd (A) states mix to **mass eigenstates H_i ($i = 1, 2, 3$) with indefinite CP quantum number**

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + \rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

with $R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$ and $m_{H_1} \leq m_{H_2} \leq m_{H_3}$

only two masses are independent:

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12} \tan \beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22} \tan \beta - R_{21})}{R_{33}(R_{31} - R_{32} \tan \beta)}$$

Charged Higgs sector is unchanged w.r.t 2HDM.

- **Yukawa coupling:** $\mathcal{L}_Y = - \sum_{i=1}^3 \frac{m_f}{v} \bar{\psi}_f [c^e(h_i f f) + i c^o(h_i f f) \gamma_5] \psi_f h_i$

The CP-violating 2-Higgs Doublet Model (C2HDM)

- **Mass spectrum and mixing:** CP violation $\leadsto$ neutral formerly CP-even (h, H) and CP-odd (A) states mix to **mass eigenstates H_i ($i = 1, 2, 3$) with indefinite CP quantum number**

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \underline{v}_1 \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

with $R = \begin{pmatrix} - & - & - \\ - & - & - \\ - & - & - \end{pmatrix}$

3 neutral CP-mixed Higgs bosons: H_1, H_2, H_3 ,

with $m_{H_1} \leq m_{H_2} \leq m_{H_3}$

2 charged Higgs bosons: H^+, H^-

$m_{H_1} \leq m_{H_2} \leq m_{H_3}$

only two masses are independent:

$$m_{H_3}^2 = \frac{m_{H_1}^2 R_{13}(R_{12} \tan \beta - R_{11}) + m_{H_2}^2 R_{23}(R_{22} \tan \beta - R_{21})}{R_{33}(R_{31} - R_{32} \tan \beta)}$$

Charged Higgs sector is unchanged w.r.t 2HDM.

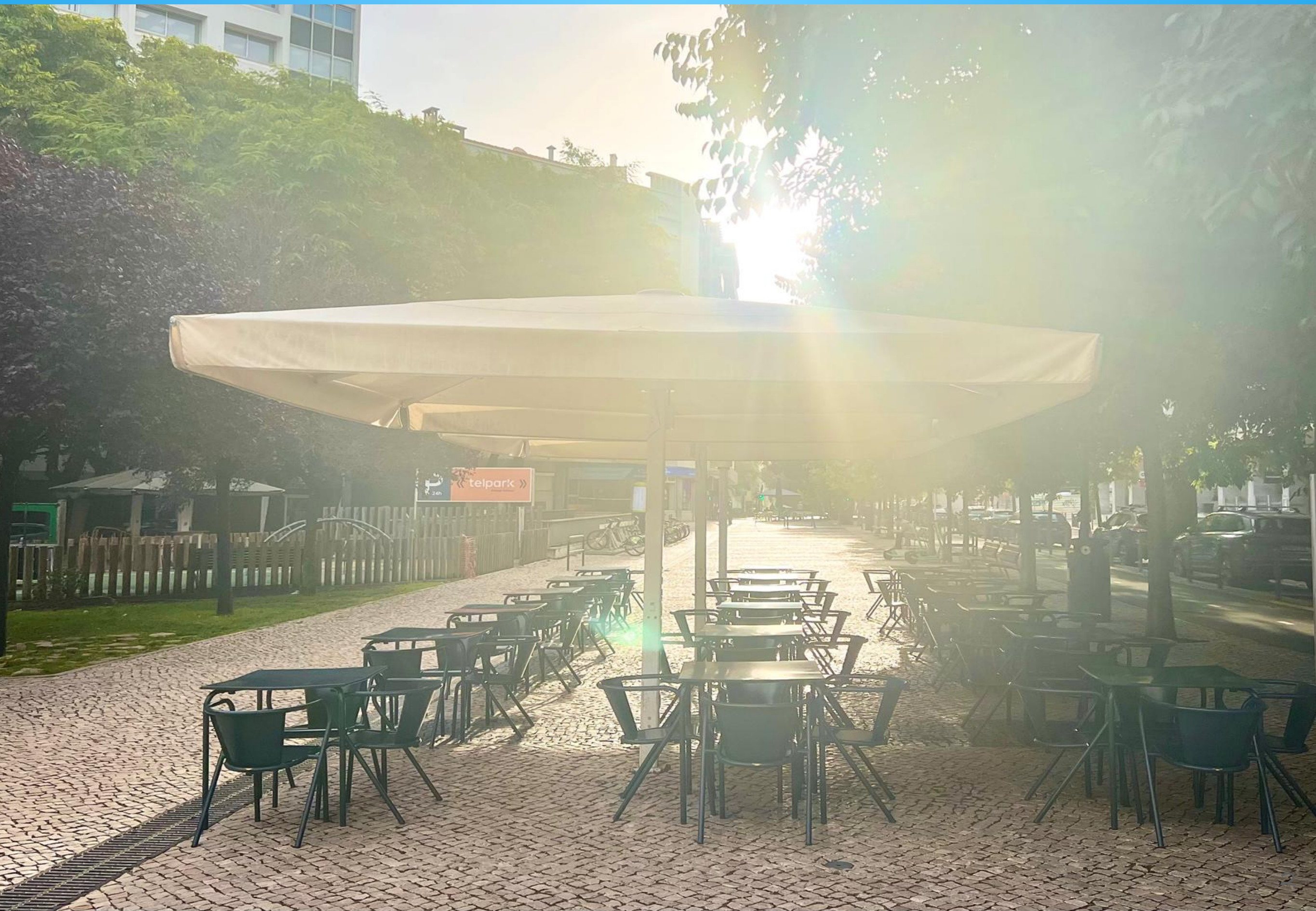
- **Yukawa coupling:** $\mathcal{L}_Y = - \sum_{i=1}^3 \frac{m_f}{v} \bar{\psi}_f [c^e(h_i f f) + i c^o(h_i f f) \gamma_5] \psi_f h_i$

We will consider the C2HDM Type-I and II

Numerical Analysis



Benchmark Model



Benchmark Model - Chemical Potentials

[MM,Plotnikov,Santos,Viana,'26]

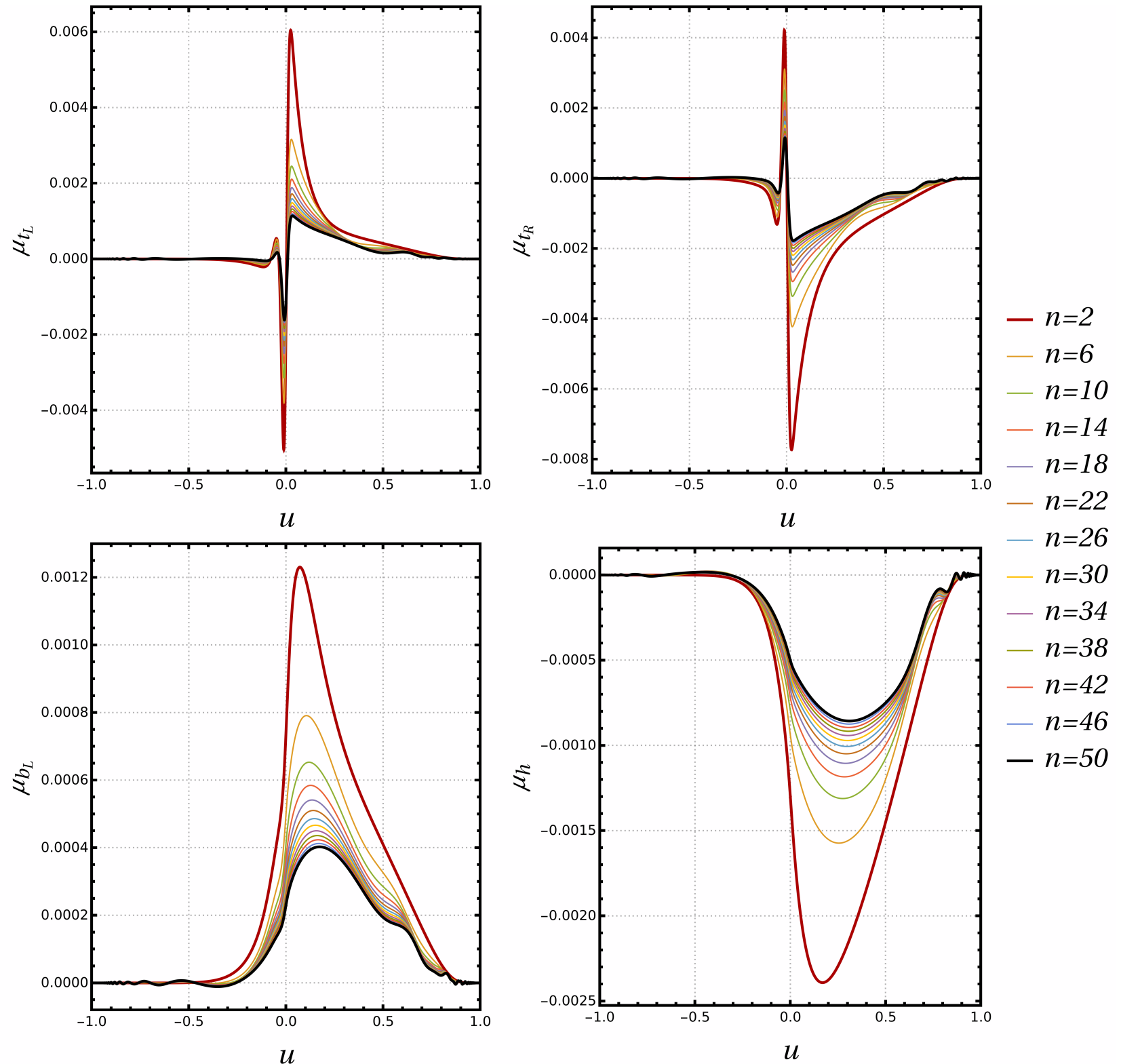
Constant truncation scheme:

$R = -v_w$ as a function of compactified wall distance

$$u = \frac{\sqrt{1+z^2}-1}{z} \text{ for up to}$$

$n = 50$ moment equations.

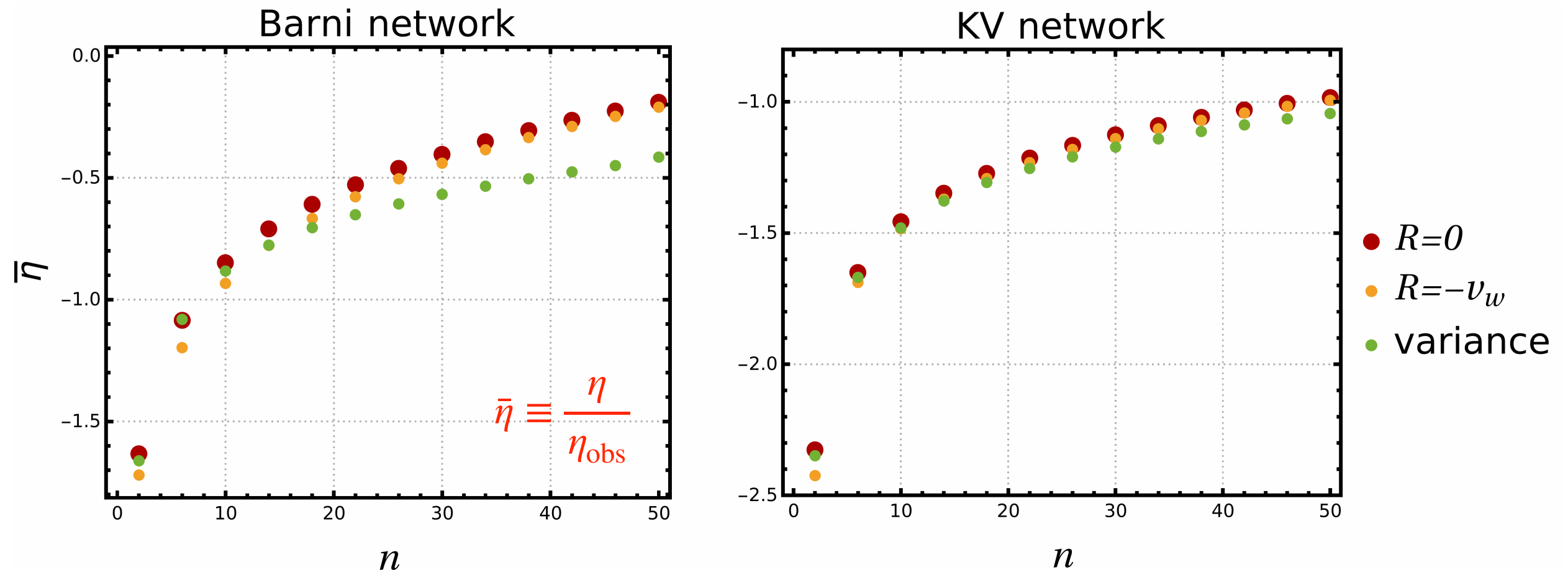
Observation of same behaviour as in [Kainulainen,Venkatesan,'24]



Benchmark Model - Comparison of Networks

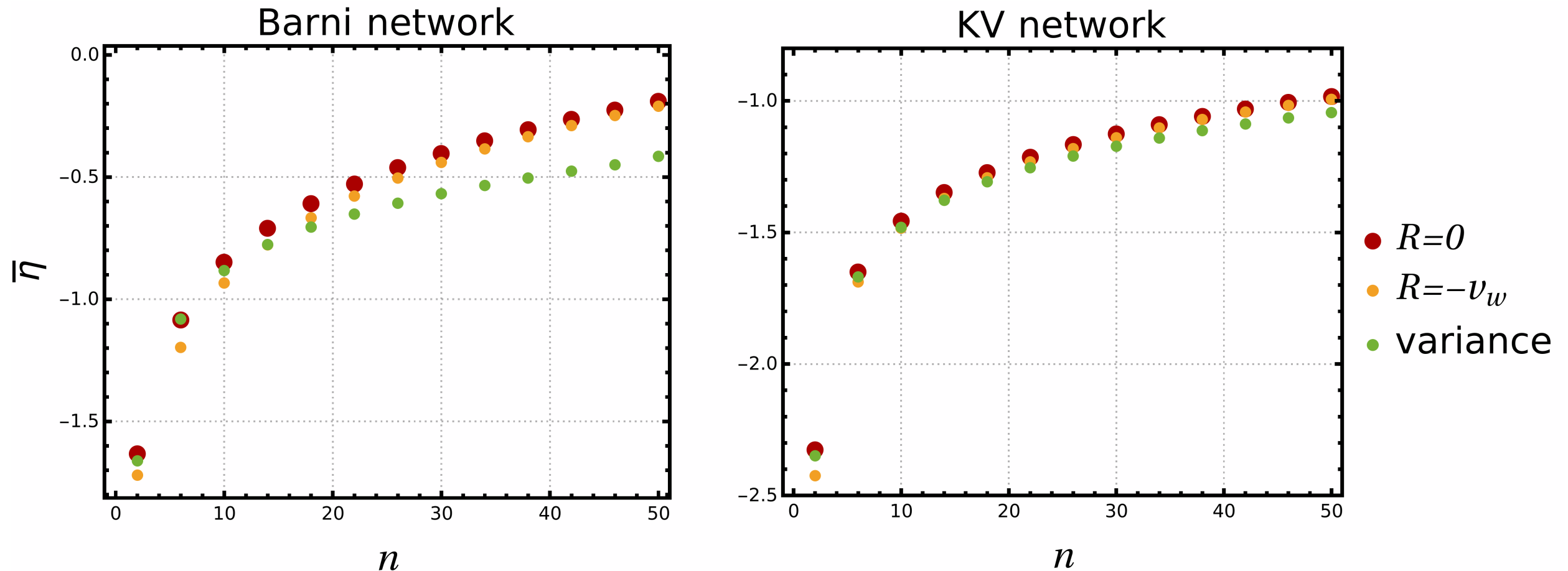
Default network in BSMPPT: "Barni network" [Barni,'25] (but we use our top-Yukawa rate), differs from "KV network" [Kainulainen,Venkatesan,'24] in some prefactors in the collision network and implements the most recent rates

[MM,Plotnikov,Santos,Viana,'26]



Benchmark Model - Comparison of Networks

[MM,Plotnikov,Santos,Viana,'26]

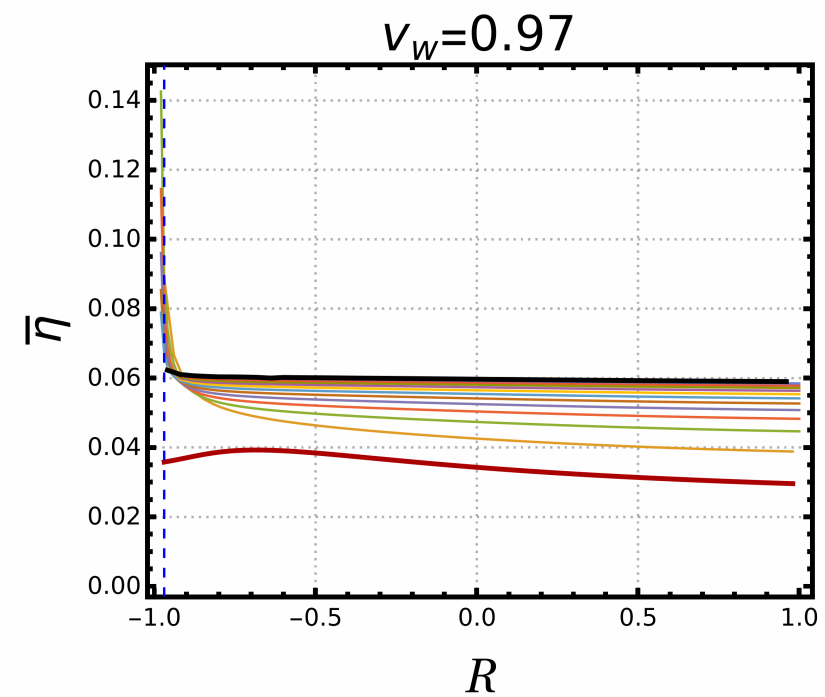
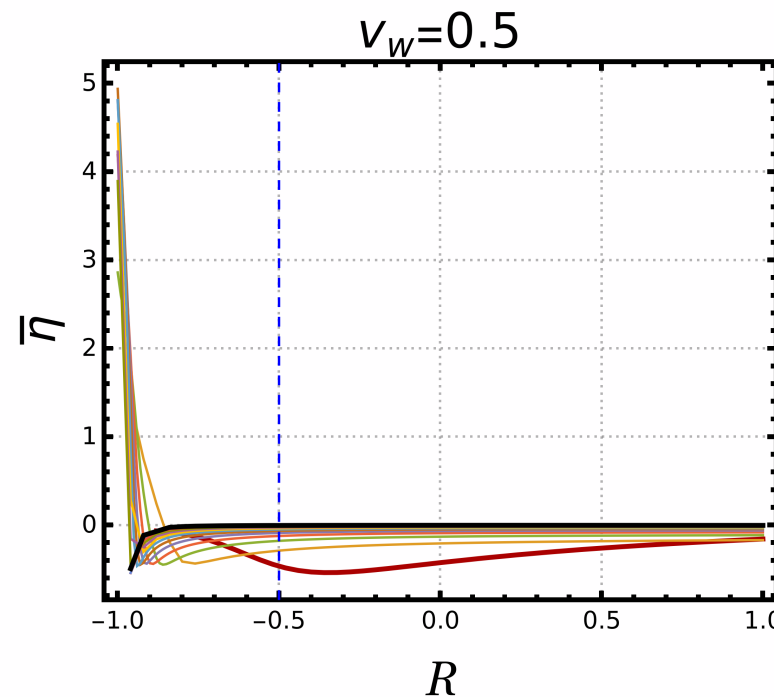
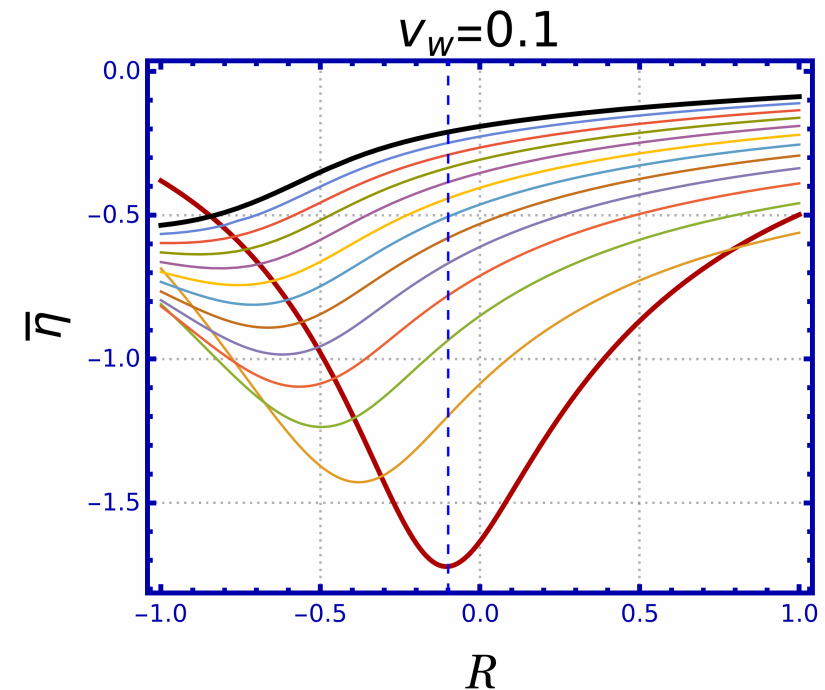
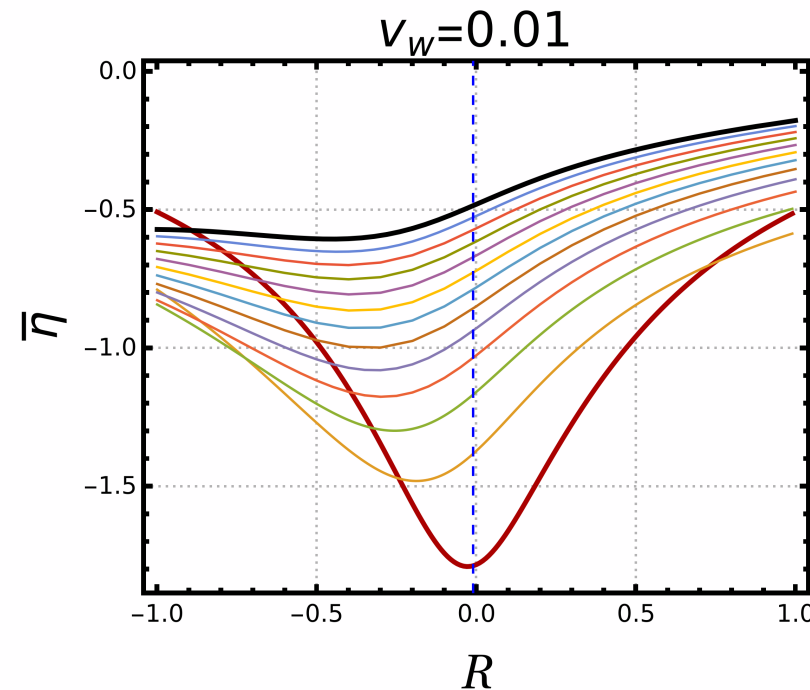


- BAU in "Barni network" smaller than in "KV network": collision rates equilibrating the chemical potentials are larger in the Barni network.
- Both networks: absolute value of $\bar{\eta}$ decreases with n , but does not stabilize to a constant value for all truncation schemes.
- Results for variance truncation agree well with KV results in [Kainulainen,Venkatesan,'24]; significant discrepancy for the constant truncation scheme, we see truncation scheme independence $\rightsquigarrow$ further investigation required

Truncation Scheme Dependence - v_w and n

[MM,Plotnikov,Santos,Viana,'26]

- Small v_w and small n : strong truncation scheme dependence
- From $v_w = 0.5$ on: convergence at $n = 50$
- As $R \rightarrow -1$: numerical instabilities for large v_w
- Firm conclusions on R independence for $n \rightarrow \infty$ require further analyses
- Calculations for large n are computationally very costly

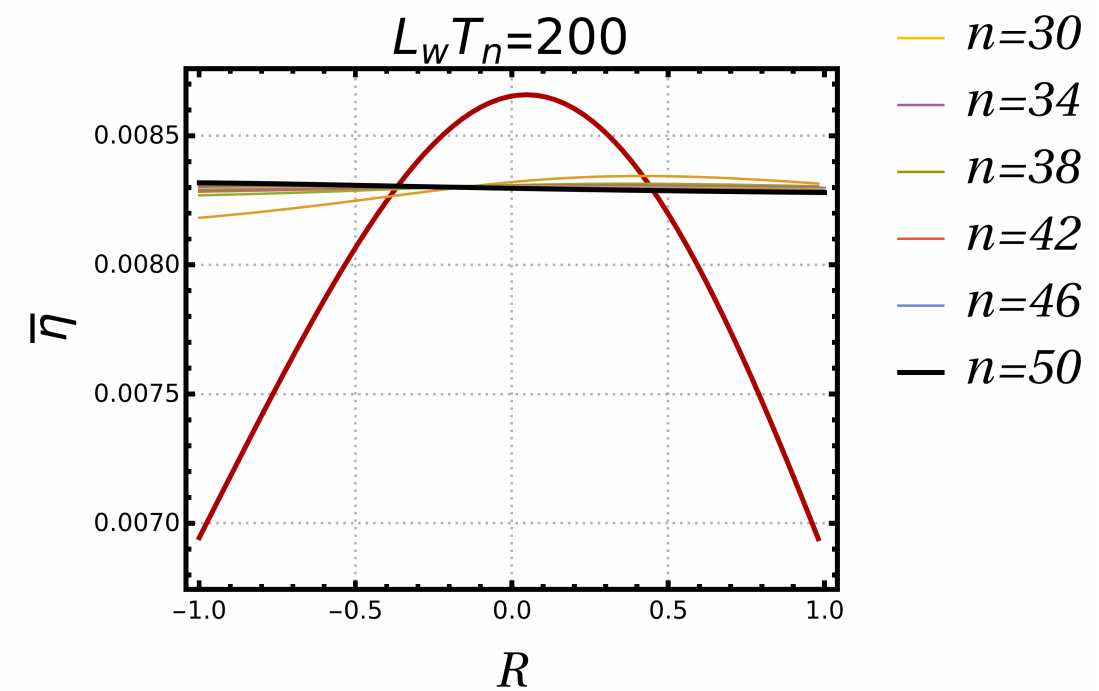
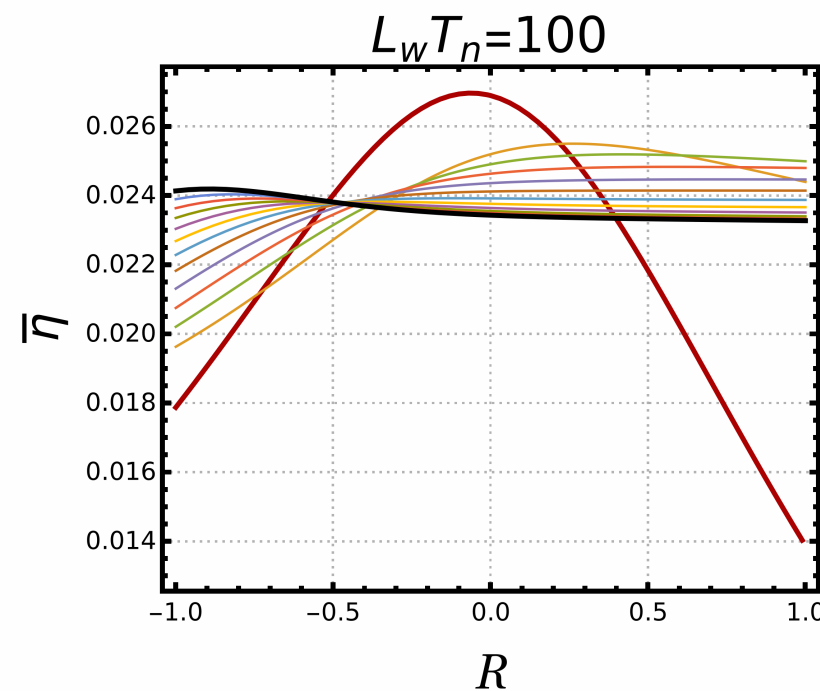
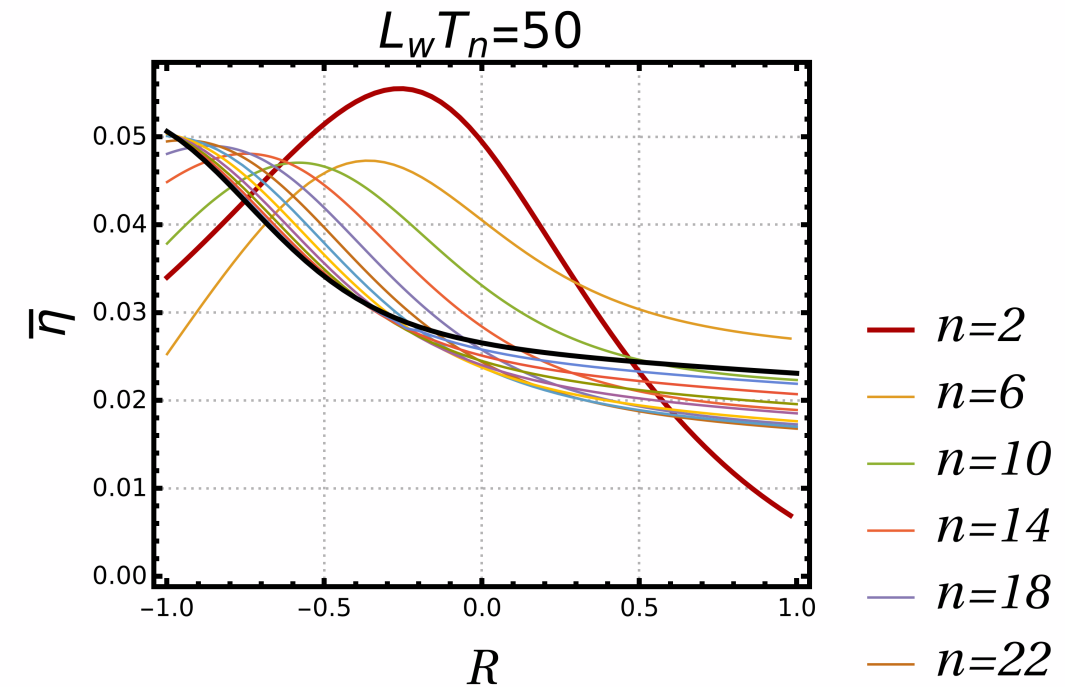
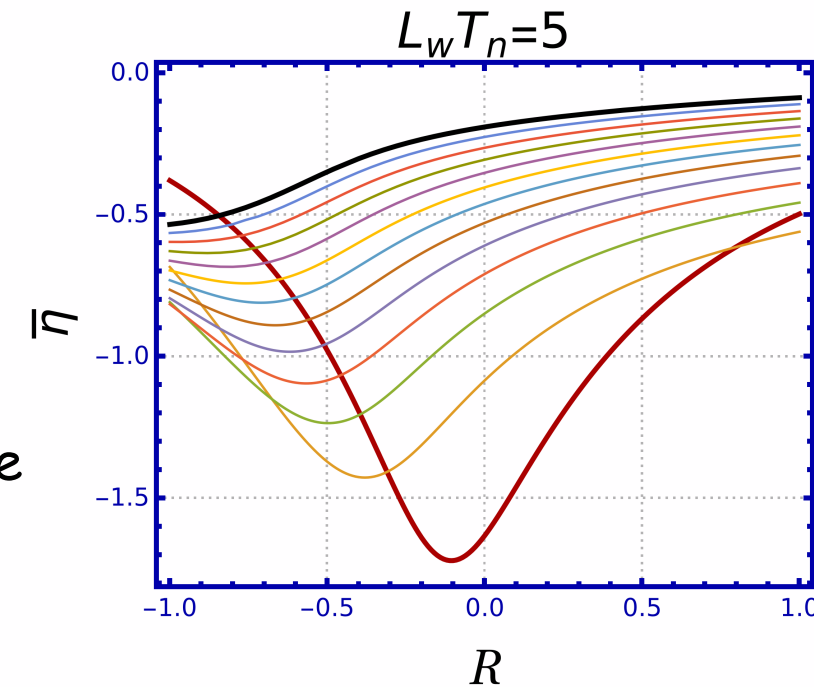


- $n=2$
- $n=6$
- $n=10$
- $n=14$
- $n=18$
- $n=22$
- $n=26$
- $n=30$
- $n=34$
- $n=38$
- $n=42$
- $n=46$
- $n=50$

Truncation Scheme Dependence - $L_w T_n$ and n

[MM,Plotnikov,Santos,Viana,'26]

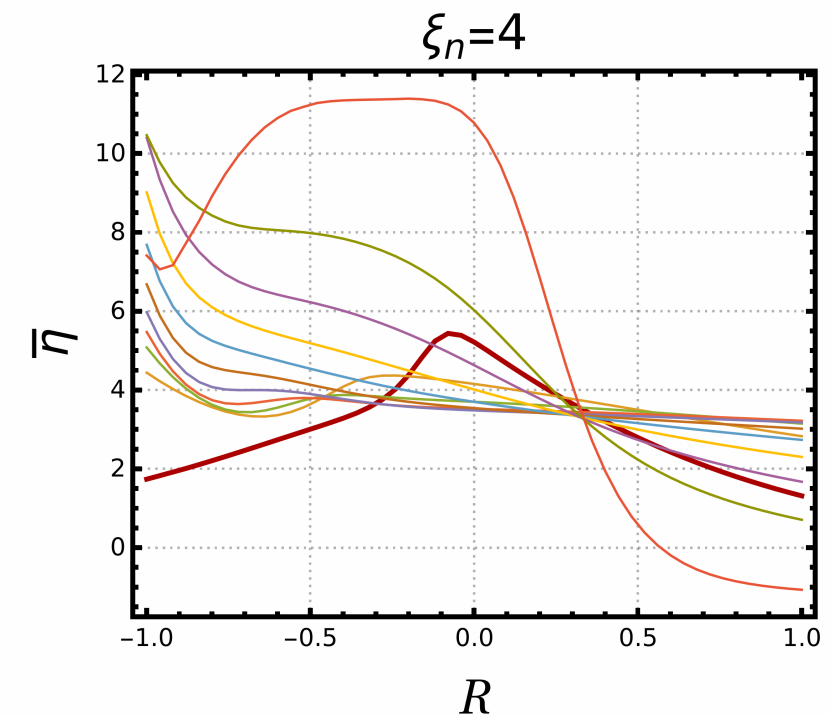
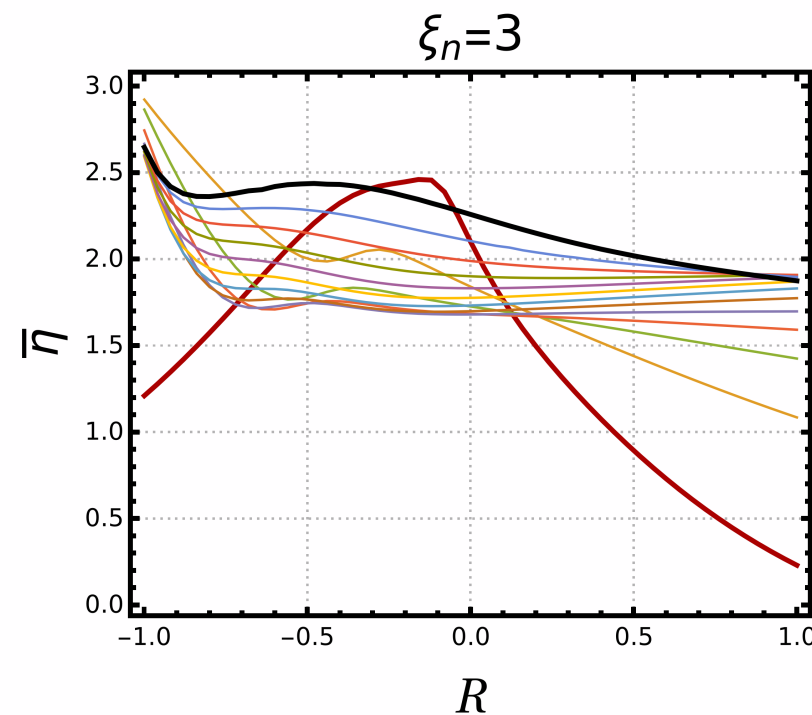
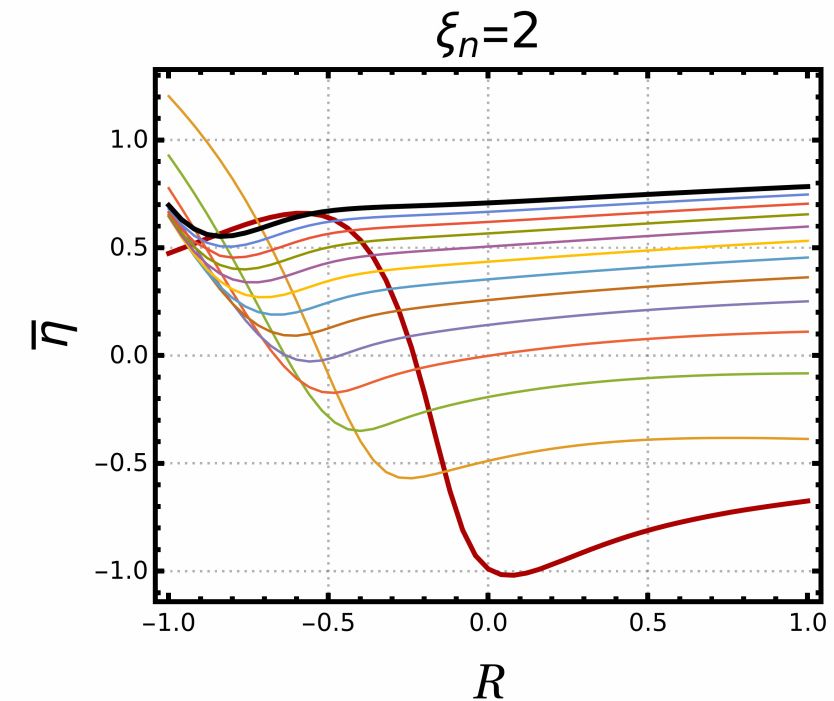
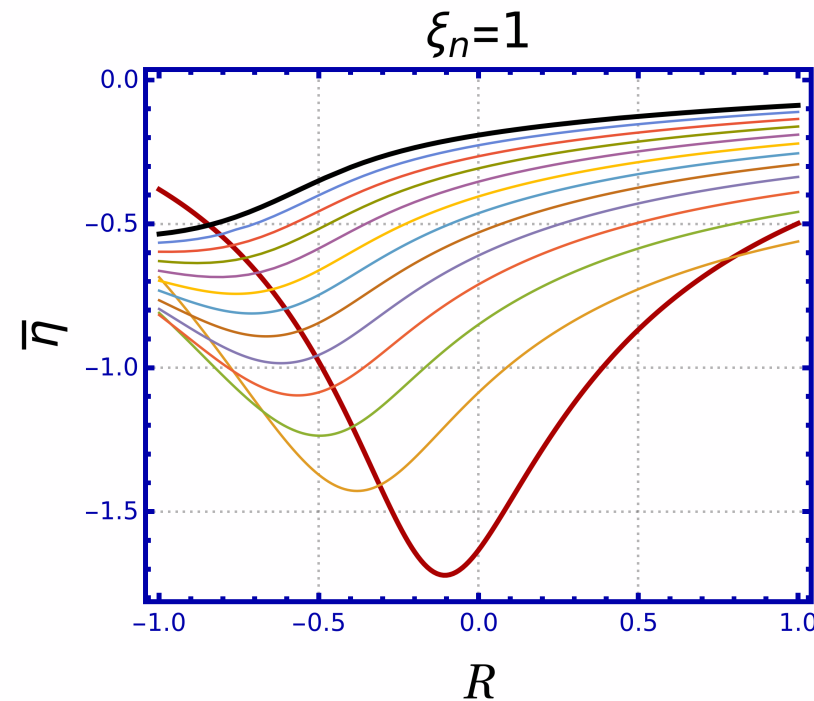
- strong truncation scheme dependence for small n
- Flattening for larger n in particular for large $L_w T_n$
- For $L_w T_n = 200$ convergence to constant value already at $n = 14$
- Rapid convergence for large $L_w T_n$ expected (assumption of WKB Ansatz)
- Convergence to constant value for small $L_w T_n$ at large n requires further analyses
- Large $L_w T_n$: $\bar{\eta}$ decreases



Truncation Scheme Dependence - ξ_n and n

[MM,Plotnikov,Santos,Viana,'26]

- $\xi_n = 1, 2, 3$: flattening with increasing n
- $\xi_n = 4$: erratic behaviour, unclear if it will eventually become independent of R



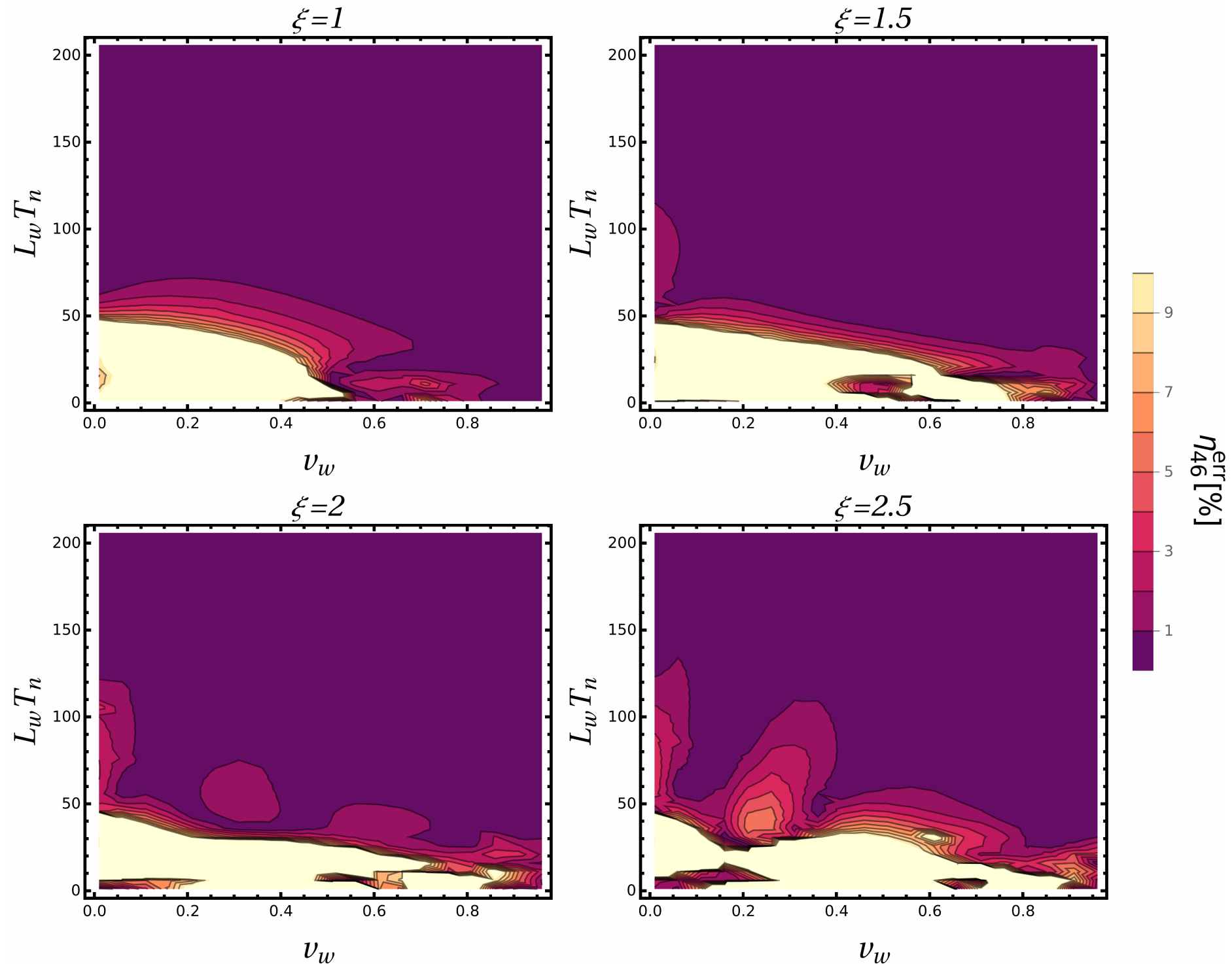
$n=2$
 $n=6$
 $n=10$
 $n=14$
 $n=18$
 $n=22$
 $n=26$
 $n=30$
 $n=34$
 $n=38$
 $n=42$
 $n=46$
 $n=50$

Quantitative Assessment of Moment Convergence

[MM,Plotnikov,Santos,Viana,'26]

- Error quantity:

$$\eta_n^{\text{err}} \equiv \left| \frac{\eta_{n+4} - \eta_n}{\eta_n} \right|$$
- For convergence to constant value:
 $\eta_n^{\text{err}} \rightarrow 0$ if $n \rightarrow \infty$
- Plots shown for $R = 1$
- $L_w T_n \gtrsim 50$ ** needed for sufficiently small error
- Also large v_w lead to better convergence, but this alone is not sufficient
- Caveat: η_n^{err} is solely a measure of how convergent the result is for certain n ; not error compared to "true" value at $n \rightarrow \infty$



** [Kent eal,'25] suggest that $L_w T_n \gtrsim 2$ is sufficient

Light yellow regions: $\eta_n^{\text{err}} \geq 10 \%$

The C2HDM



C2HDM Analysis

Benchmark setting for transport equations in the C2HDM Type I and II analyses:

- ◇ transition temperature: percolation temperature T_p
- ◇ constant truncation scheme with $R = -v_w$
- ◇ moment truncation at $n = 2$
- ◇ wall velocity $v_w = 0.5$
- ◇ VEV profile from solution of e.o.m. of the field

In the following scatter plots from scan w/ scan ranges (check of constraints w/ ScannerS)

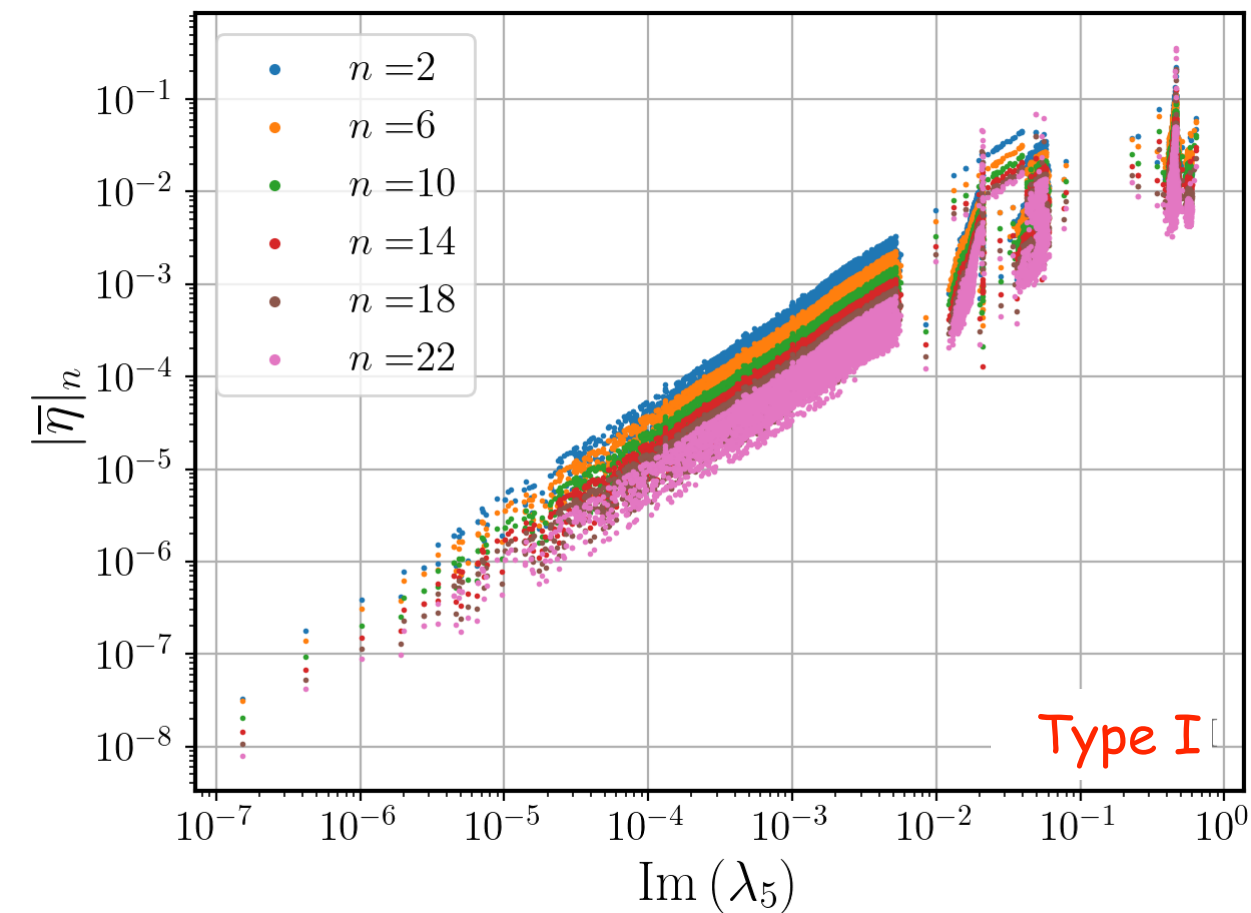
Parameter	Type I		Type II		Scale	Units
	Lower	Upper	Lower	Upper		
m_1	—	125.09	—	125.09	linear	[GeV]
m_2	130	1000	130	1000	linear	[GeV]
$m_{H^\pm}$	80	1000	580	1000	linear	[GeV]
$\tan \beta$	0.3	30	0.3	30	linear	
α_1	$-\pi/2$	$\pi/2$	$-\pi/2$	$\pi/2$	linear	
α_2	$-\pi/2$	$\pi/2$	$-\pi/2$	$\pi/2$	linear	
α_3	$-\pi/2$	$\pi/2$	$-\pi/2$	$\pi/2$	linear	
m_{12}^2	$\pm 10^{-1}$	$\pm 10^7$	$\pm 10^{-1}$	$\pm 10^7$	log	[GeV] ²

Uncertainties

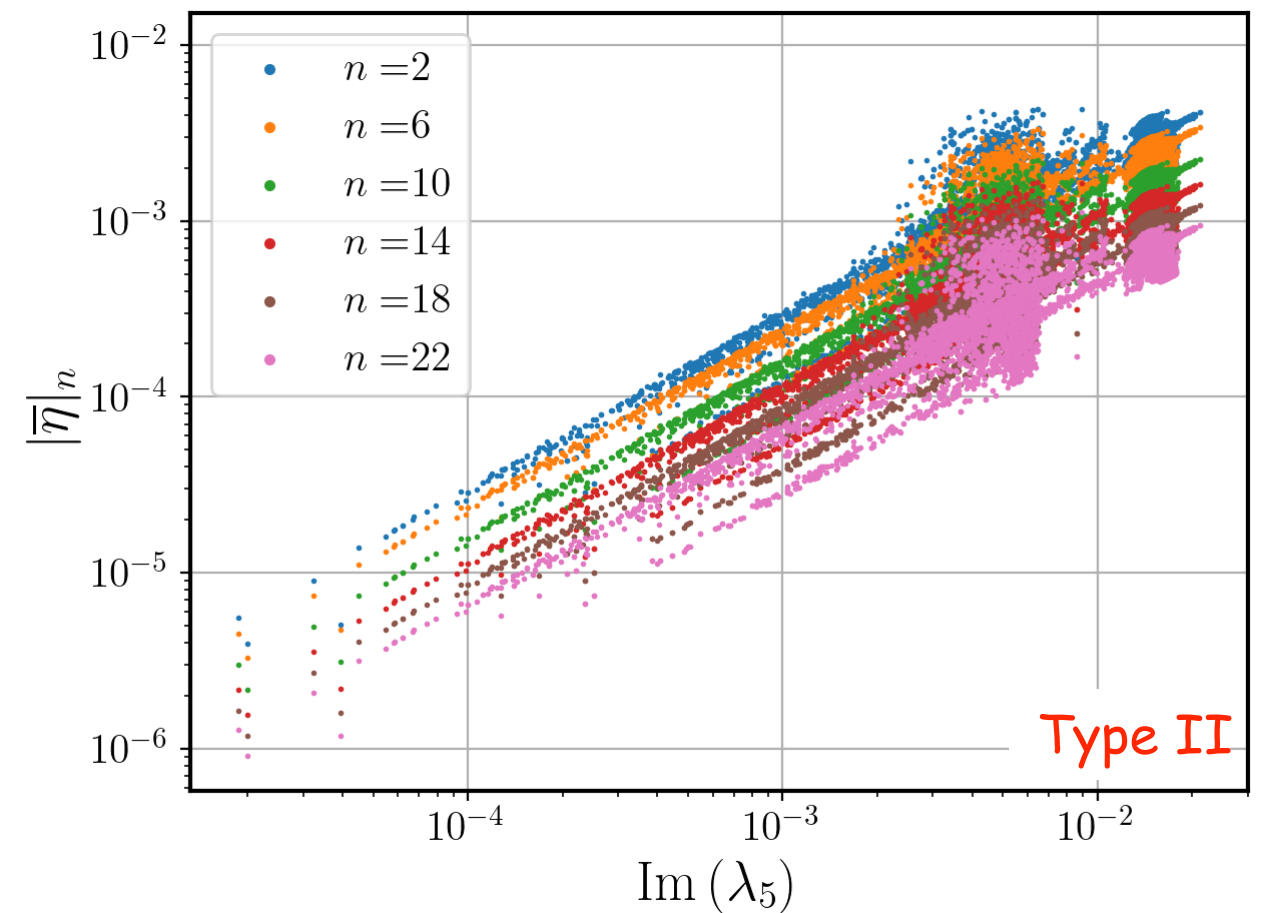


Impact of Number n of Transport Equations

[MM,Plotnikov,Santos,Viana,'26]



- We will present results for maximally $n = 22$
- Large n : better convergence expected, but computationally costly
- $\bar{\eta}$ decreases with increasing n
- Find large dependence on truncation scheme for $n = 2$



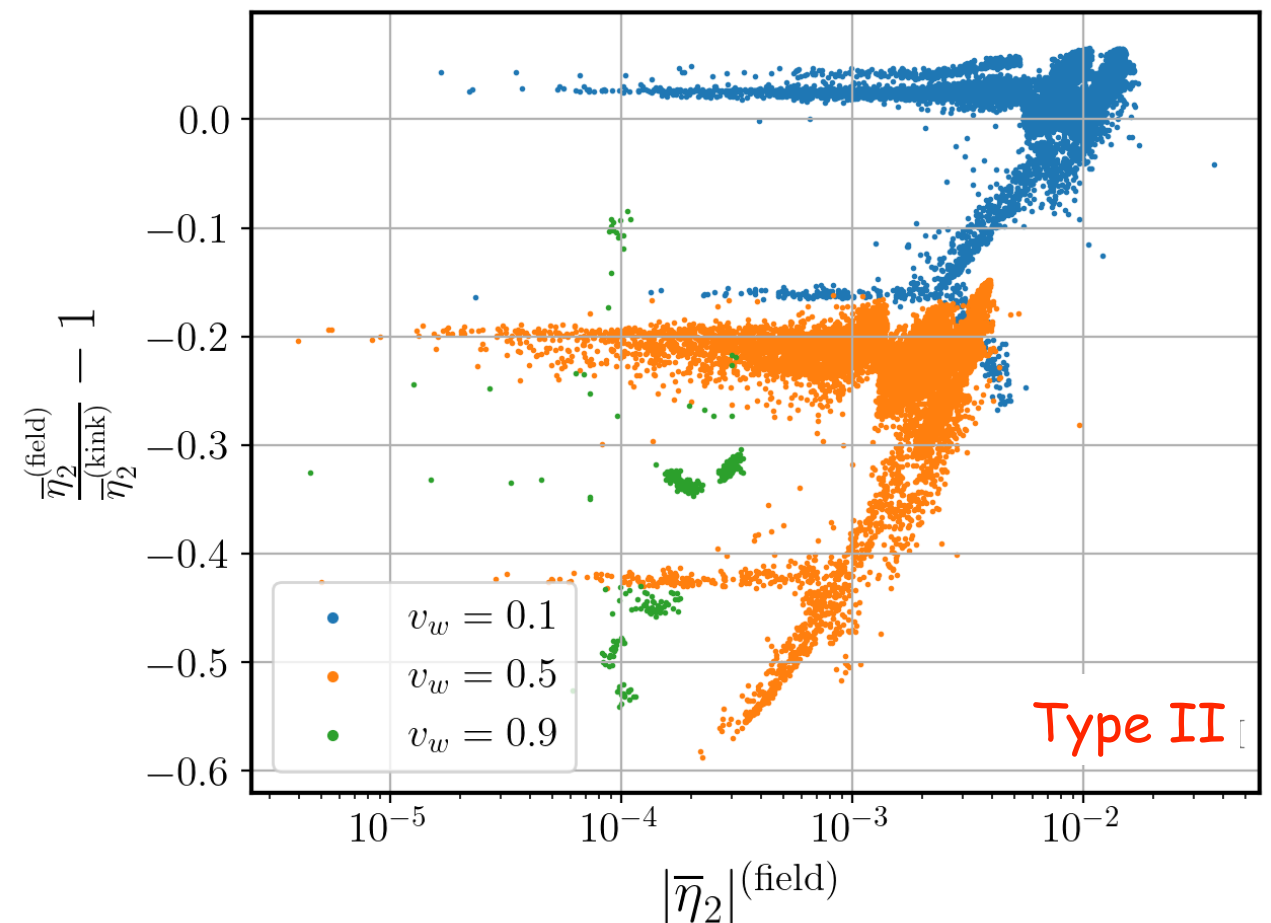
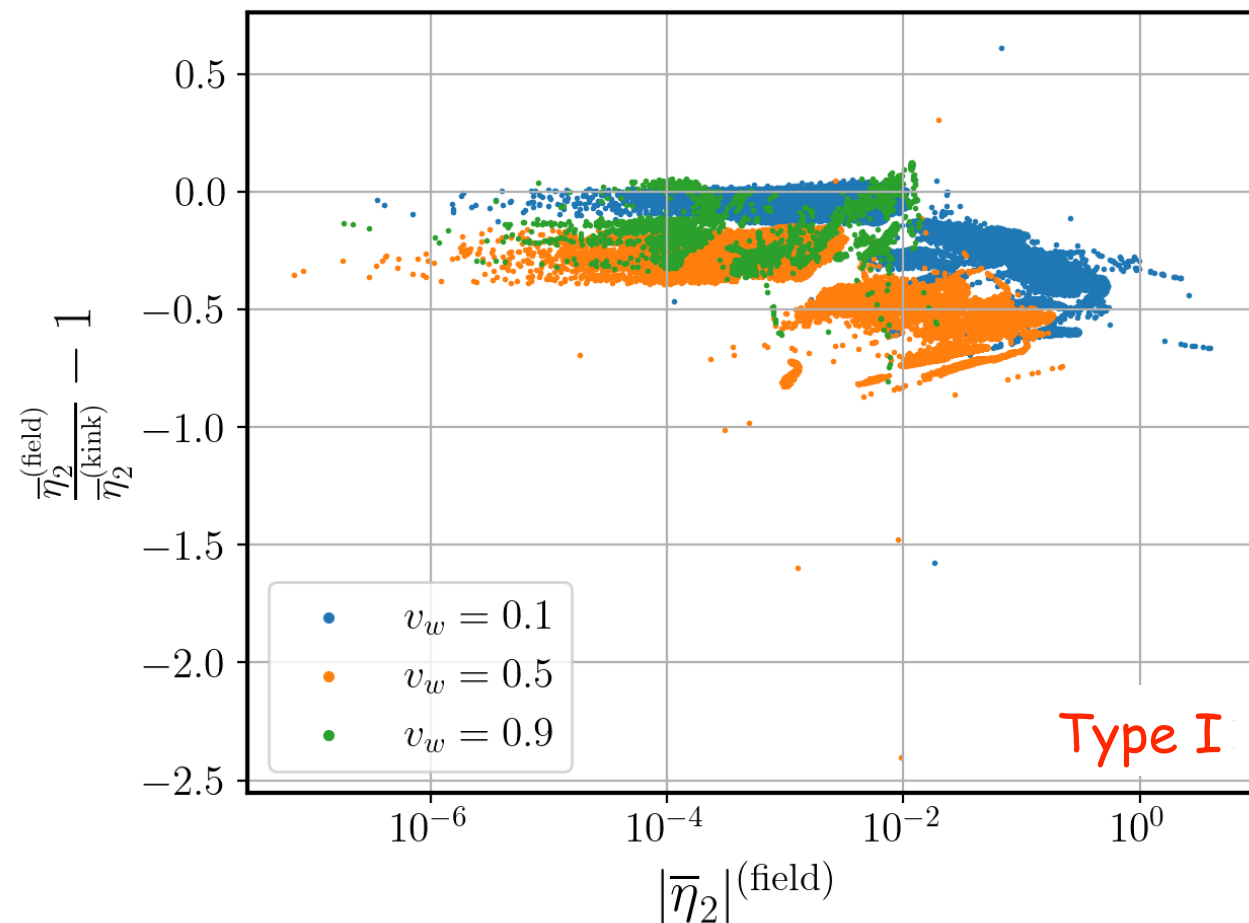
- Sign of $\bar{\eta}$ has a physical meaning
- Due to C2HDM transformation properties: negative BAU can be turned in positive by changing sign of $\text{Im}(m_{12}^2)$
- But make sure that $\bar{\eta}$ does not change sign with changing n

Impact of VEV Profile

Comparison: field solution and kink solution for the VEV profile $\rightsquigarrow$ models the complex quark masses

$n = 2$

[MM,Plotnikov,Santos,Viana,'26]

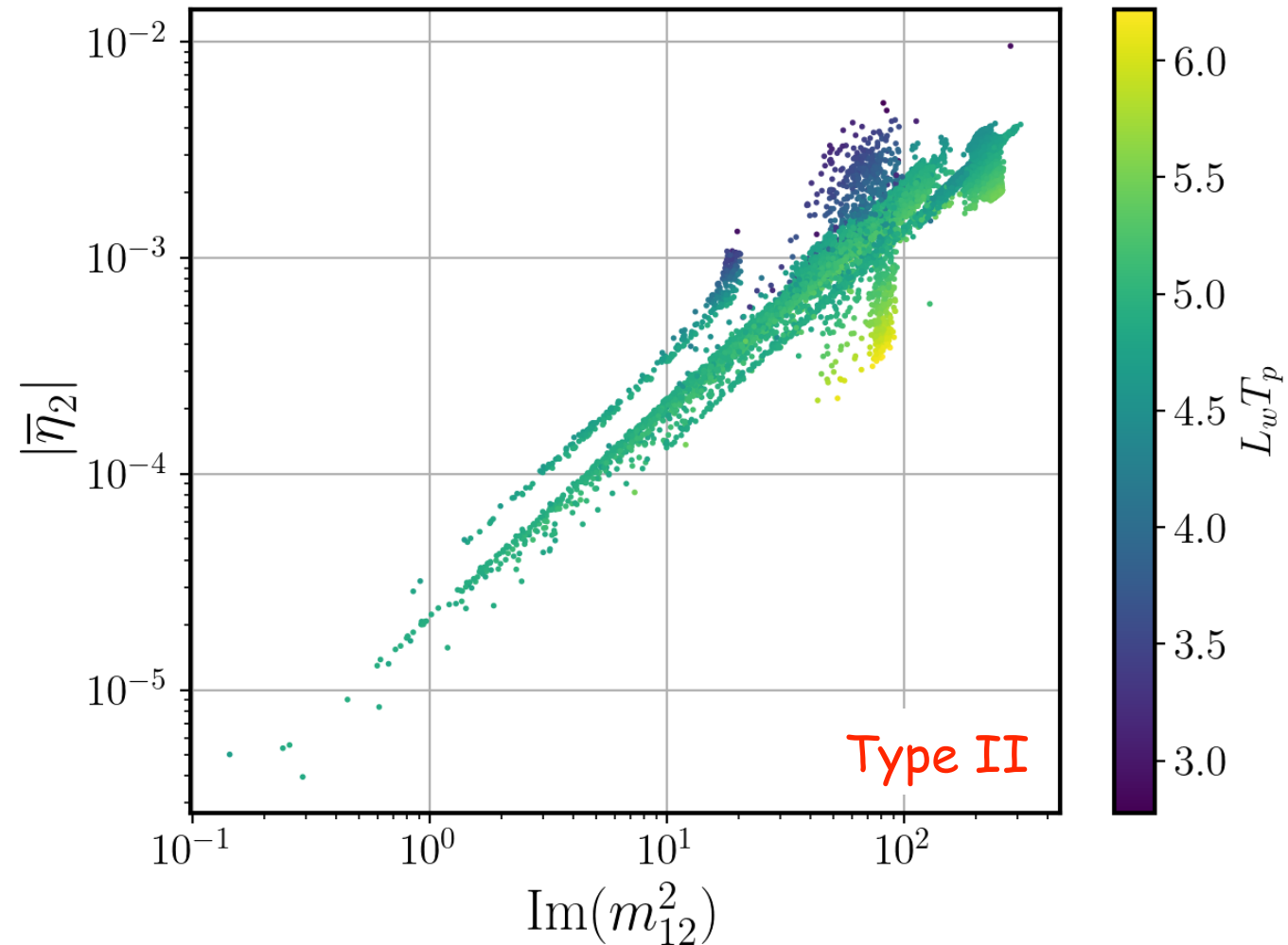
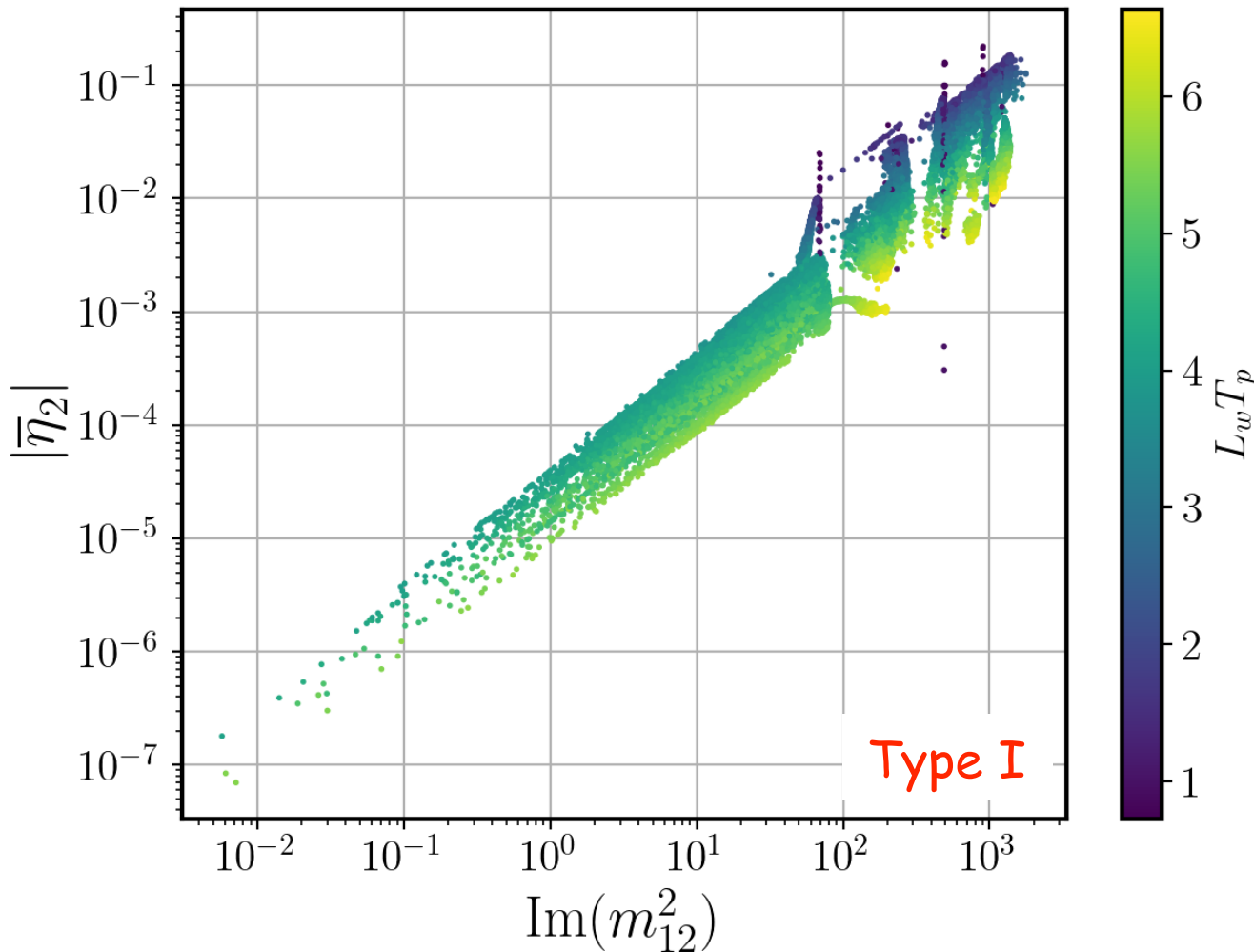


- For both solutions: BAU of same order of magnitude
- $n = 2$: majority of points has $\bar{\eta}_2^{(\text{kink})} > \bar{\eta}_2^{(\text{field})} \leftarrow$ field solution usually leads to larger L_w
larger L_w decreases BAU

The Parameter $L_w T_p$

[MM,Plotnikov,Santos,Viana,'26]

$n = 2$



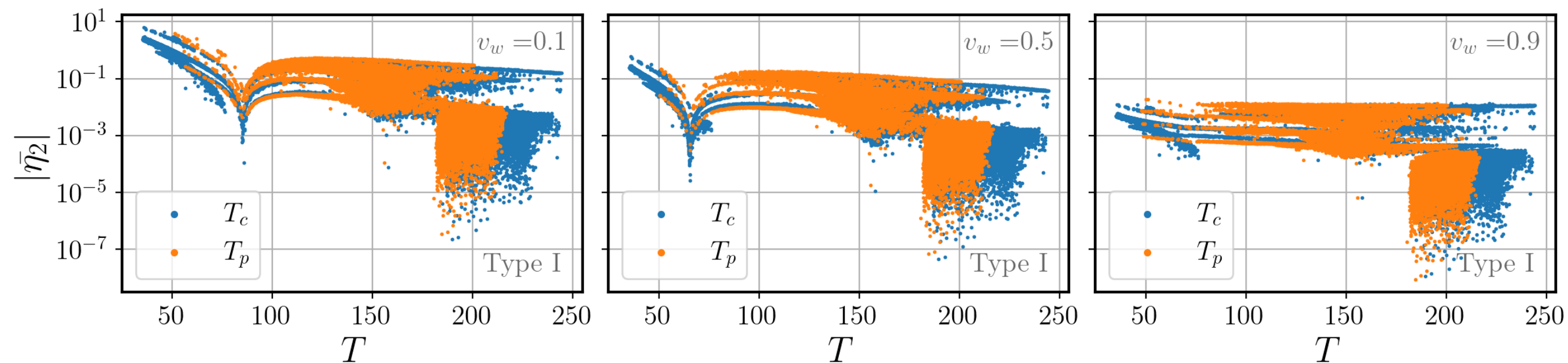
- Kink profile: $L_w = \frac{v_t}{\sqrt{8V_b}}$, $v_t \equiv \sqrt{\sum_i \omega_i(z = -\infty)}$
- $L_w T_p < 7 \rightsquigarrow$ major source of uncertainty as WKB method require $L_w T_p \gg 1$
- Benchmark model: $L_w T_n \gtrsim 50$ for stable results (see above)

Impact of Transition Temperature and wall velocity

$n = 2$

Type I

[MM,Plotnikov,Santos,Viana,'26]



- Transition temperature: T_c blue points, T_p orange points
- $T_p < T_c \rightsquigarrow$ points for T_p shifted to the left
- Points for T_c extend to lower temperatures:
points calculated with T_p are (almost) vacuum trapped here
- Points w/ maximal BAU for T_c are left to the points of $T_p \rightsquigarrow$
Computation of BAU with T_c might overestimate the BAU
- BAU decreases with increasing v_w

Caveat: v_w ad hoc input parameter and not calculated consistently from the solution of the coupled system of scalar field, hydrodynamic and Boltzmann equations taking into account out-of-equilibrium corrections

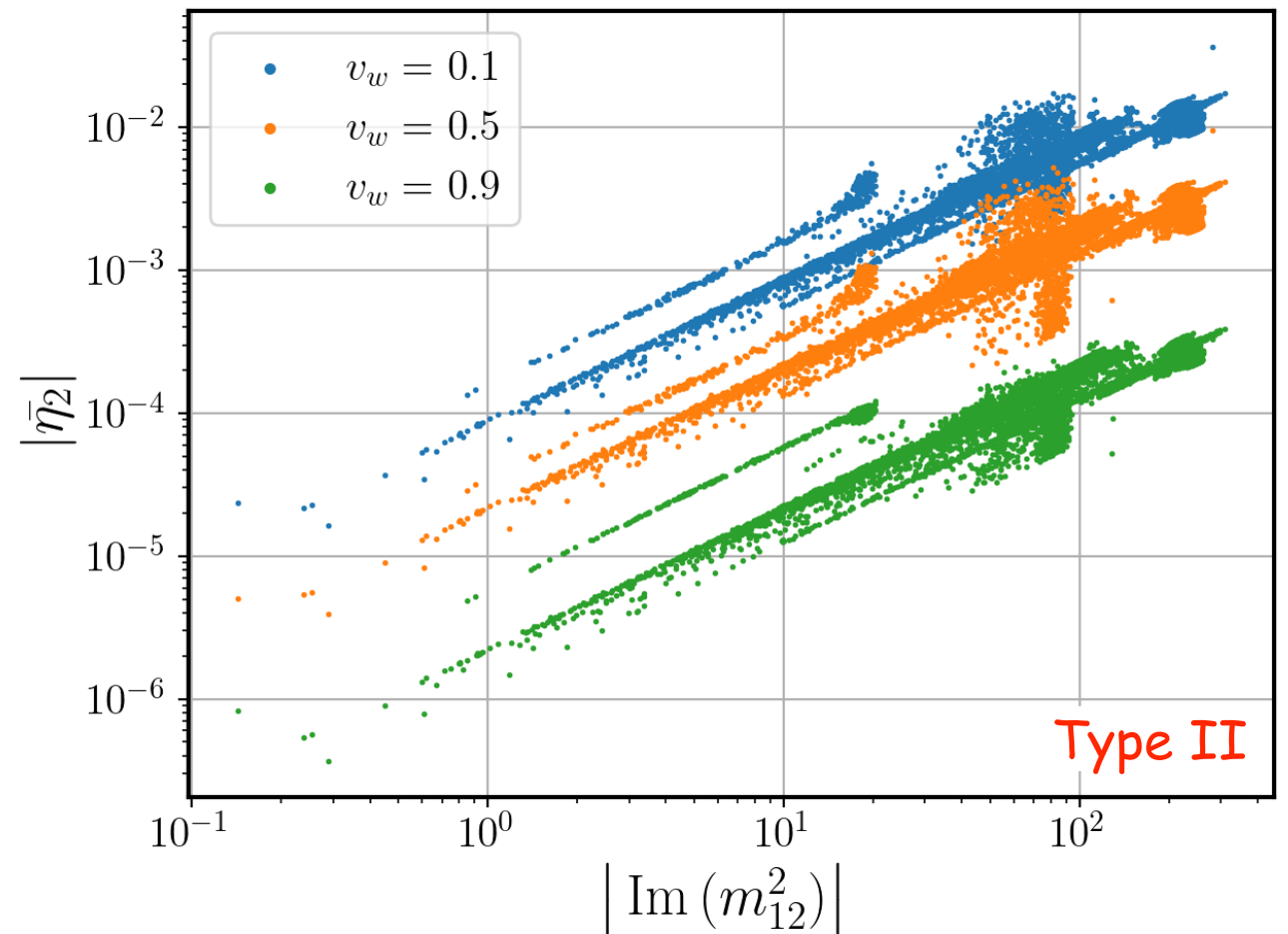
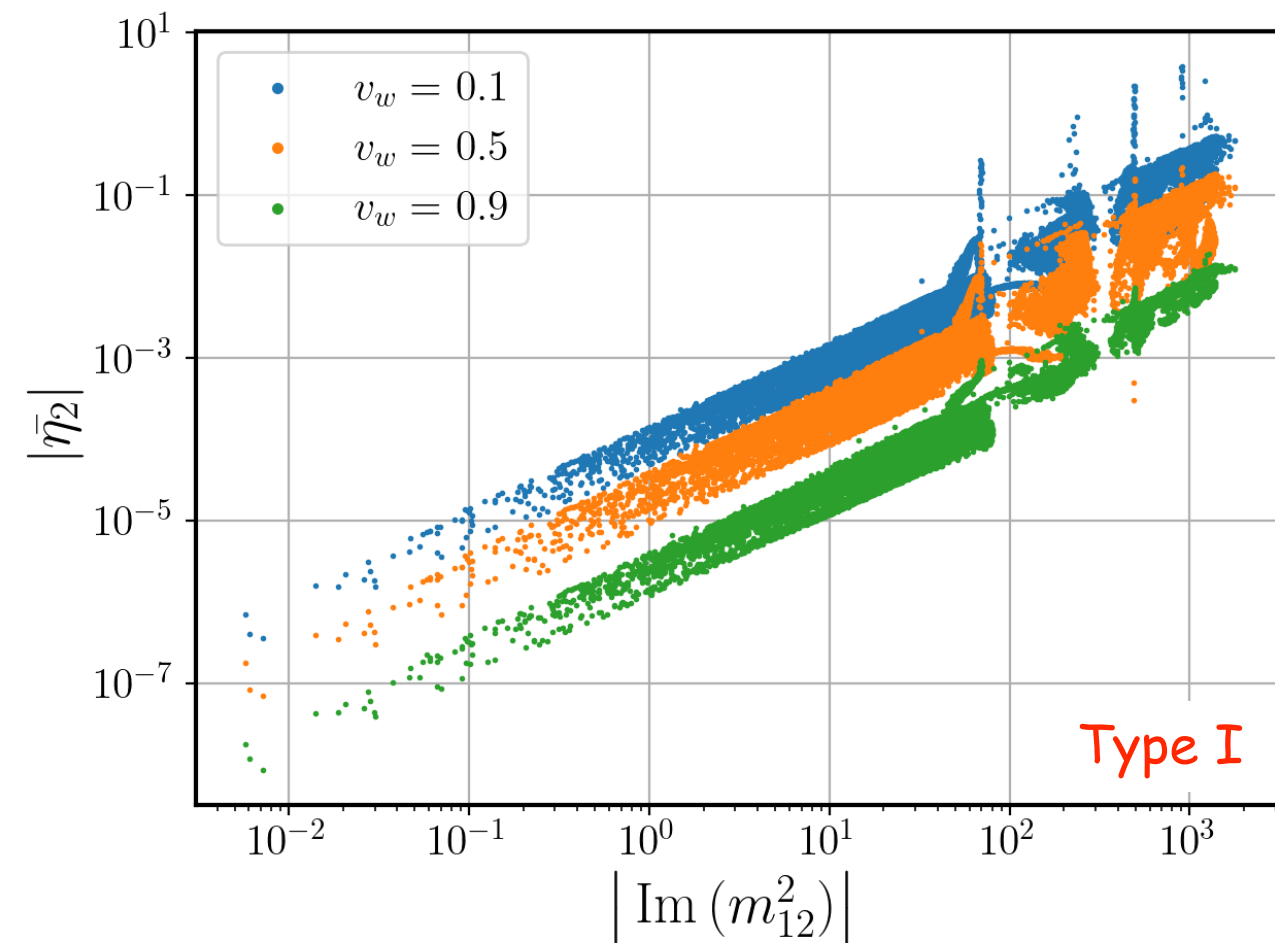
Phenomenology



Impact of CP violation

$n = 2$

[MM,Plotnikov,Santos,Viana,'26]

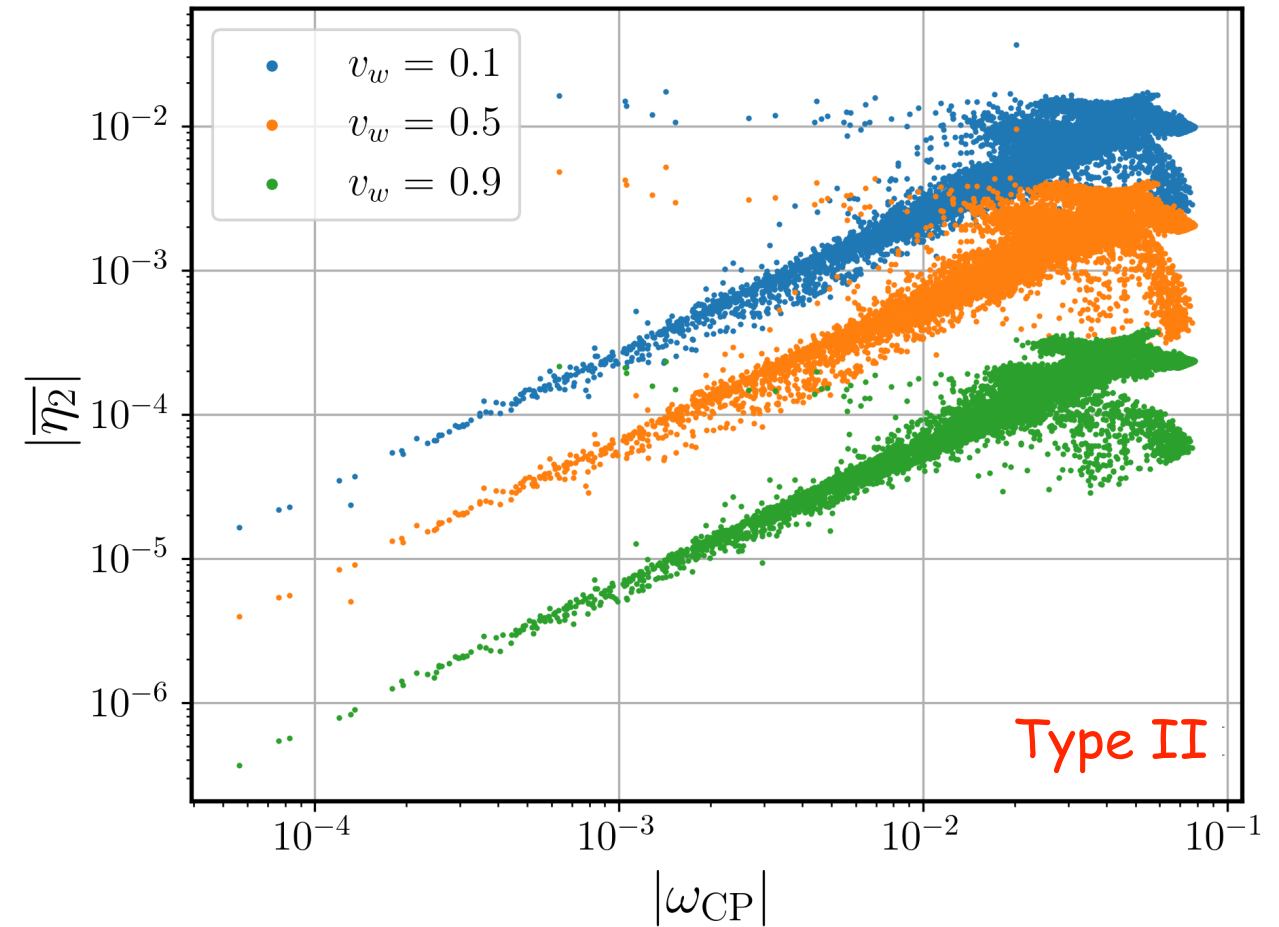
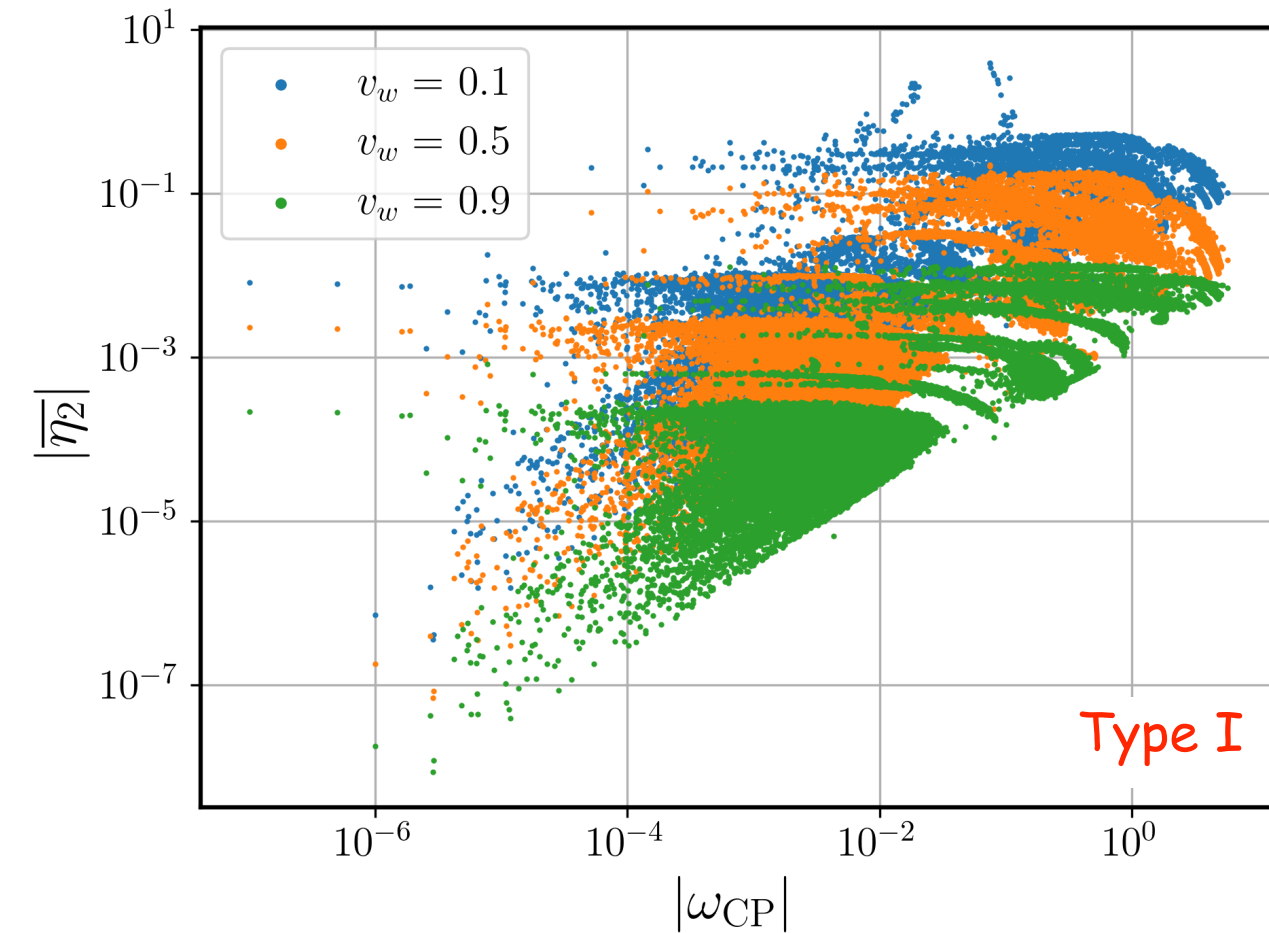


- Strong positive correlation between BAU and explicitly CP-violating parameter $\text{Im}(m_{12}^2)$
 $\leftarrow$ input parameter (easy to control)
- Amount of CP violation is decisive for the size of the generated BAU
- $|\bar{\eta}_2| \rightarrow 0$ for $\text{Im}(m_{12}^2) \rightarrow 0$
- This conclusion is rather robust despite the large uncertainties
- Focus on regions where $\text{Im}(m_{12}^2)$ and hence $\text{Im}(\lambda_5)$ is maximal considering all constraints $\rightsquigarrow$ guideline for future model building

Spontaneous CP Violation

$n = 2$

[MM,Plotnikov,Santos,Viana,'26]

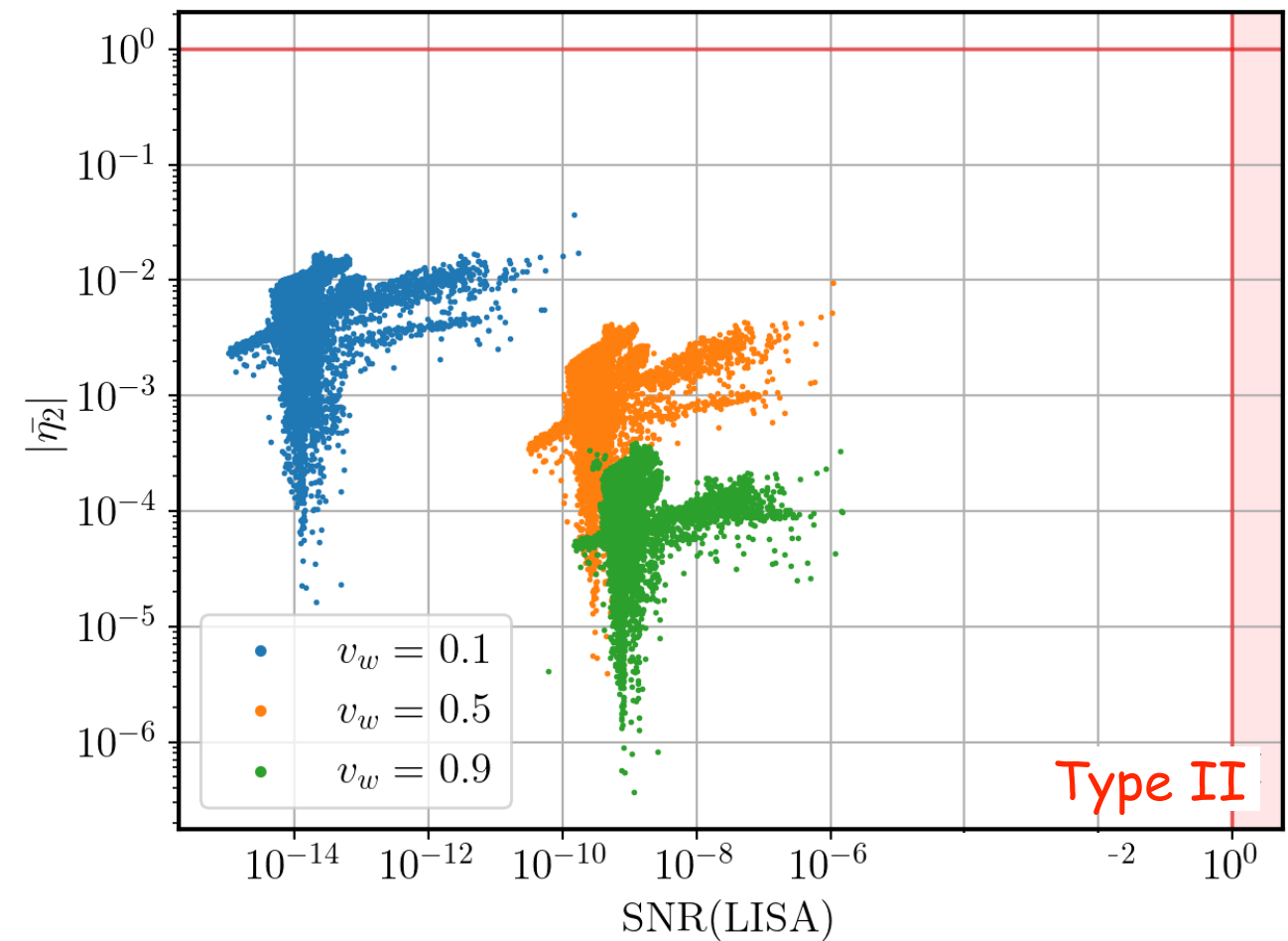
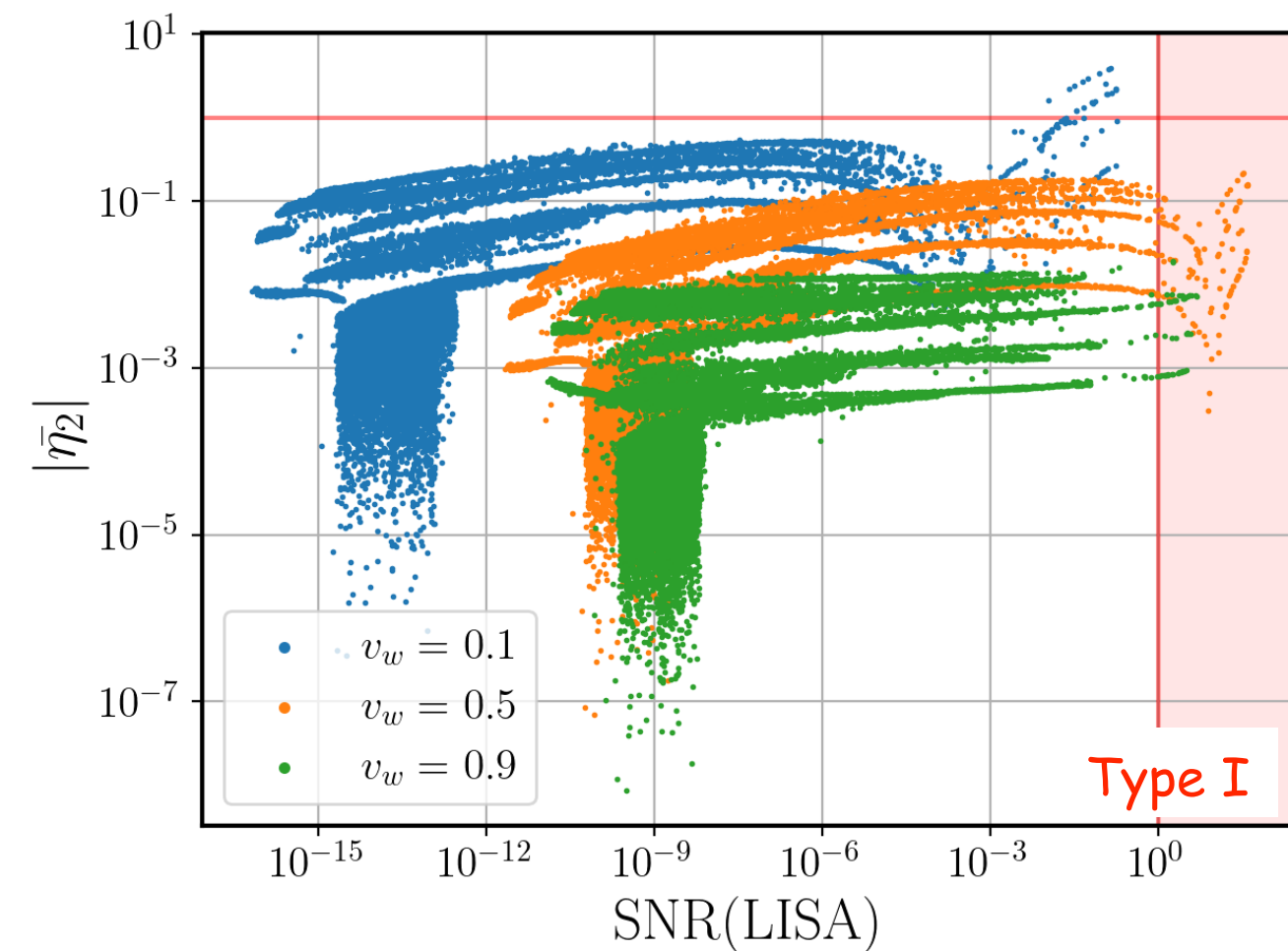


- $|\omega_{CP}|$: absolute value of the imaginary VEV in the true minimum at T_p
- Spontaneous CP violation, **only if** $\text{Im}(m_{12}^2) \neq 0$ at $T = 0$
- BAU vanishes as $|\omega_{CP}| \rightarrow 0$
- More severe constraints on C2HDM type II at $T = 0 \rightsquigarrow |\omega_{CP}^{\max}|$ smaller in type II
- Note: VEV ω_{CP} in the wall can be different from the $|\omega_{CP}|$ shown in the plots

Gravitational waves (GW) signal

$n = 2$

[MM,Plotnikov,Santos,Viana,'26]



- Signal-to-noise ratio (SNR) for GWs at LISA after 3 years of data taking
- Red line $|\bar{\eta}_2| = 1$, red region: $\text{SNR} > 1$
- Type I: $v_w = 0.1$ has $|\bar{\eta}_2| \geq 1$ but $\text{SNR} < 1$; $v_w = 0.5, 0.9$ has $\text{SNR} \geq 1$ but $|\bar{\eta}_2| < 1$
- Type II: all below 1 due to more severe constraints at $T = 0$

Benchmark Points



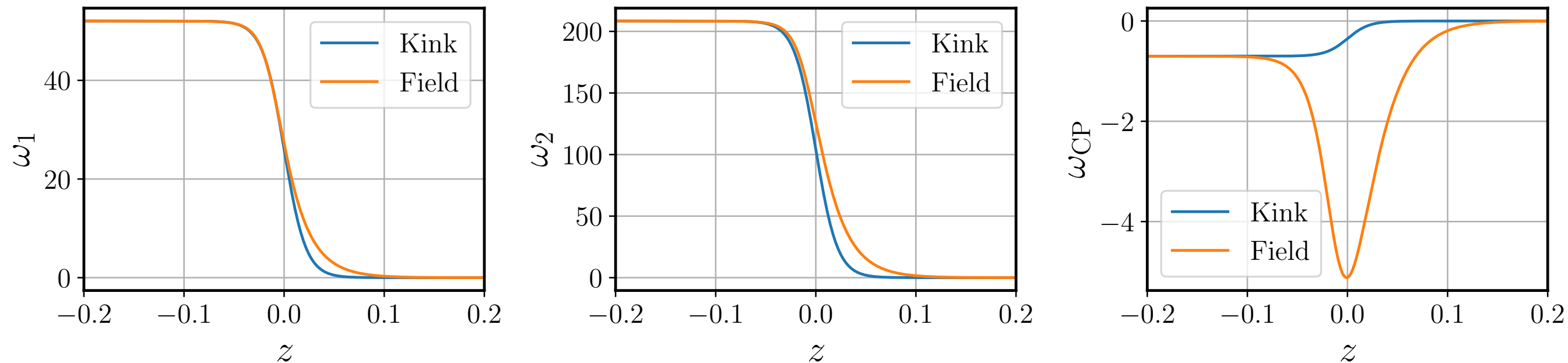
Selected Benchmark Points

- Four selected benchmark points for C2HDM type I: dedicated analysis of impact of VEV profiles, z dependence of top quark mass, the CP-violating phase, n transport equations
- Properties of benchmark points:
 - ◇ BP1 - C2HDM example point (shipped with BSMPT).
 - ◇ BP2 - Largest $L_w T_p$.
 - ◇ BP3 - Largest $|\bar{\eta}_2|$.
 - ◇ BP4 - Second largest $|\bar{\eta}_2|$, with the peculiarity of having a rather low T_p .
- Choices for BAU calculation: transition temperature $T_\star = T_p$, wall velocity $v_w = 0.5$, constant truncation scheme with $R = -v_w$, VEV profile: kink solution

BP1: VEV Profiles

BP1

[MM,Plotnikov,Santos,Viana,'26]

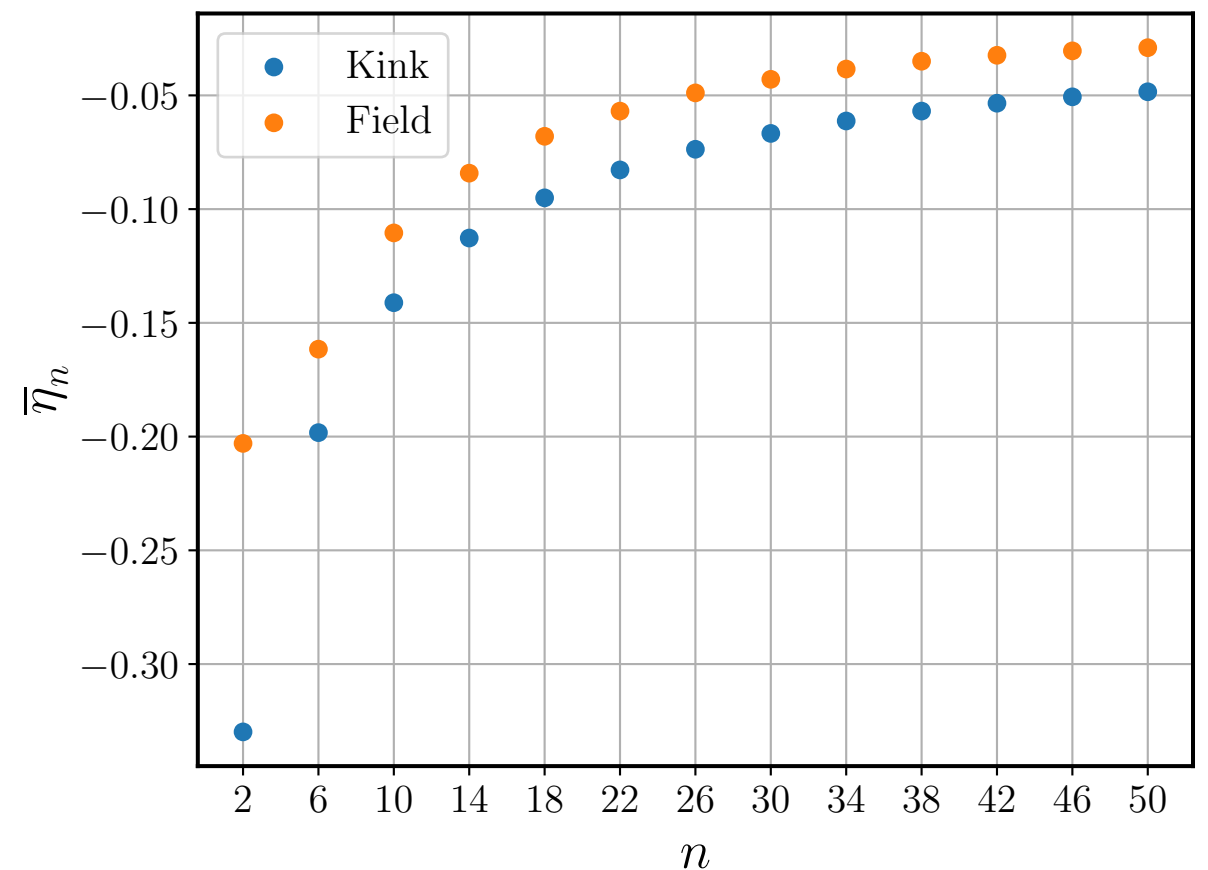
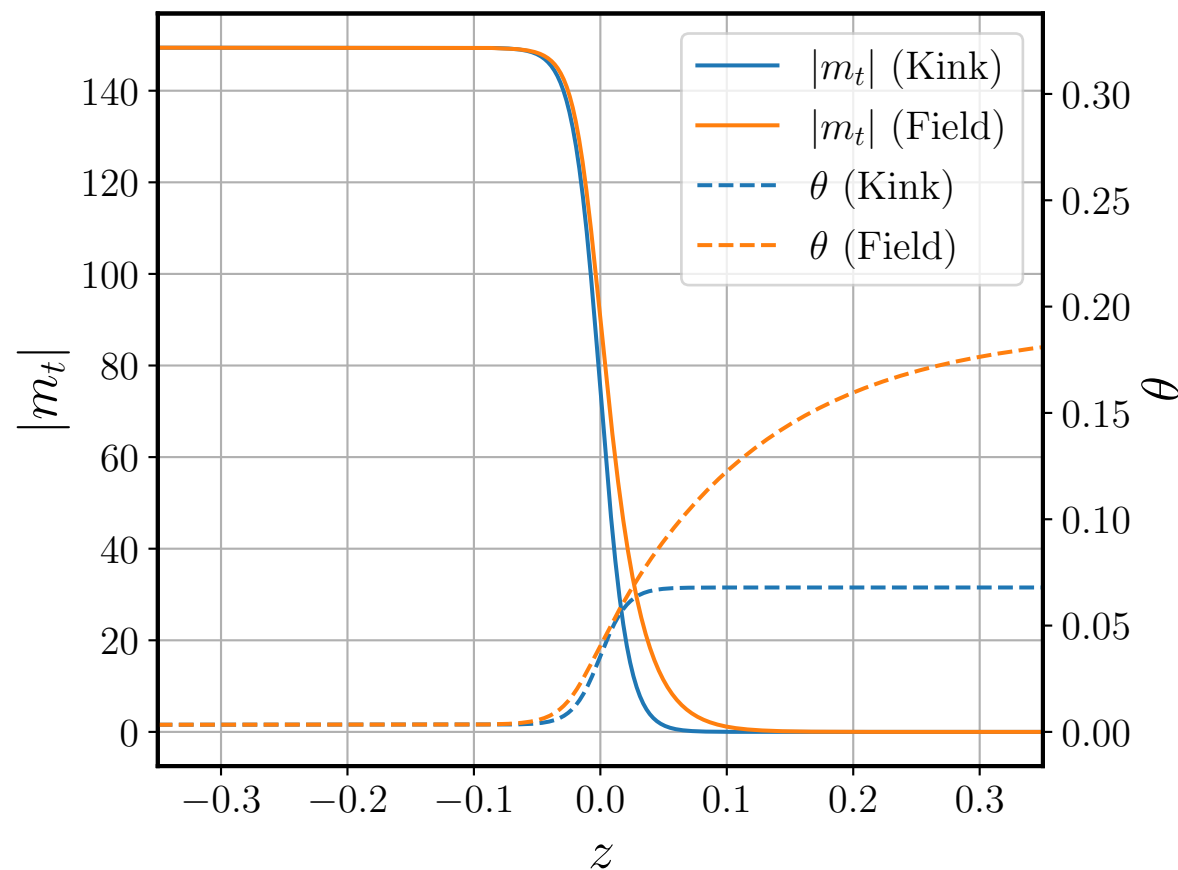


- Electroweak VEVs $\omega_{1,2}$: rough agreement for both profiles (kink, field), field solution has slightly larger effective wall width L_w
- ω_{CP} has roughly kink profile for kink solution, but field solution reaches almost $\omega_{CP} \approx -5$ inside bubble wall before reaching its true vacuum value $\omega_{CP} \approx -0.7$
- Effective wall width L_w much larger in CP direction than in electroweak direction for field solution profile $\rightsquigarrow$
- Each VEV profile may have different length scale!

BP1: top mass, BAU

BP1

[MM,Plotnikov,Santos,Viana,'26]



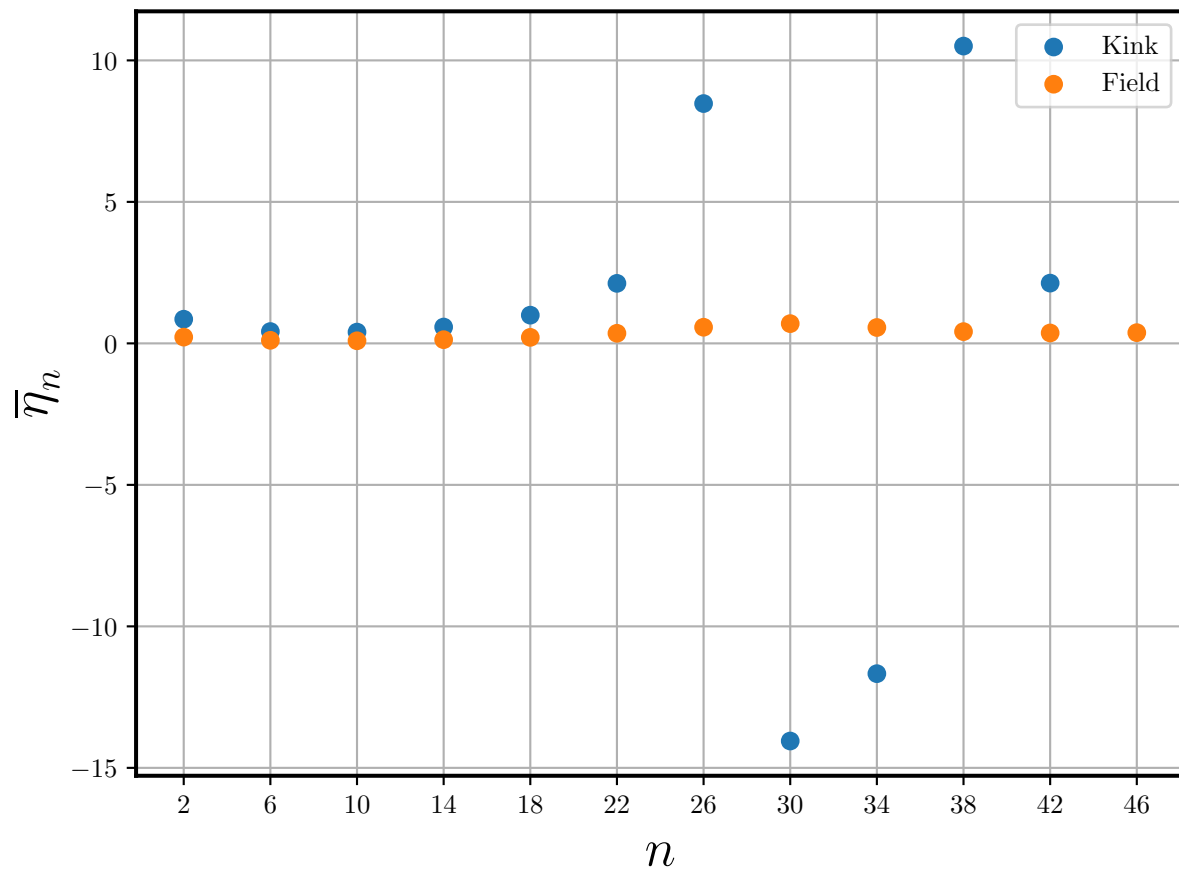
- Absolute top mass value:
about the same for both profiles
- Disagreement in top phase θ in wrong vacuum:
ill-defined here as $\omega_2 = \omega_{\text{CP}} = 0$
- No problem as source term for transport
equations vanishes here $\leftarrow (m_t^2)' = 0$

- $\bar{\eta}_n$ seems to converge to constant value for
large n : firm conclusion needs larger n
- Rough agreement of dependence for field
and kink solutions for VEV profile
- Field solution leads to smaller BAU due to
larger L_w

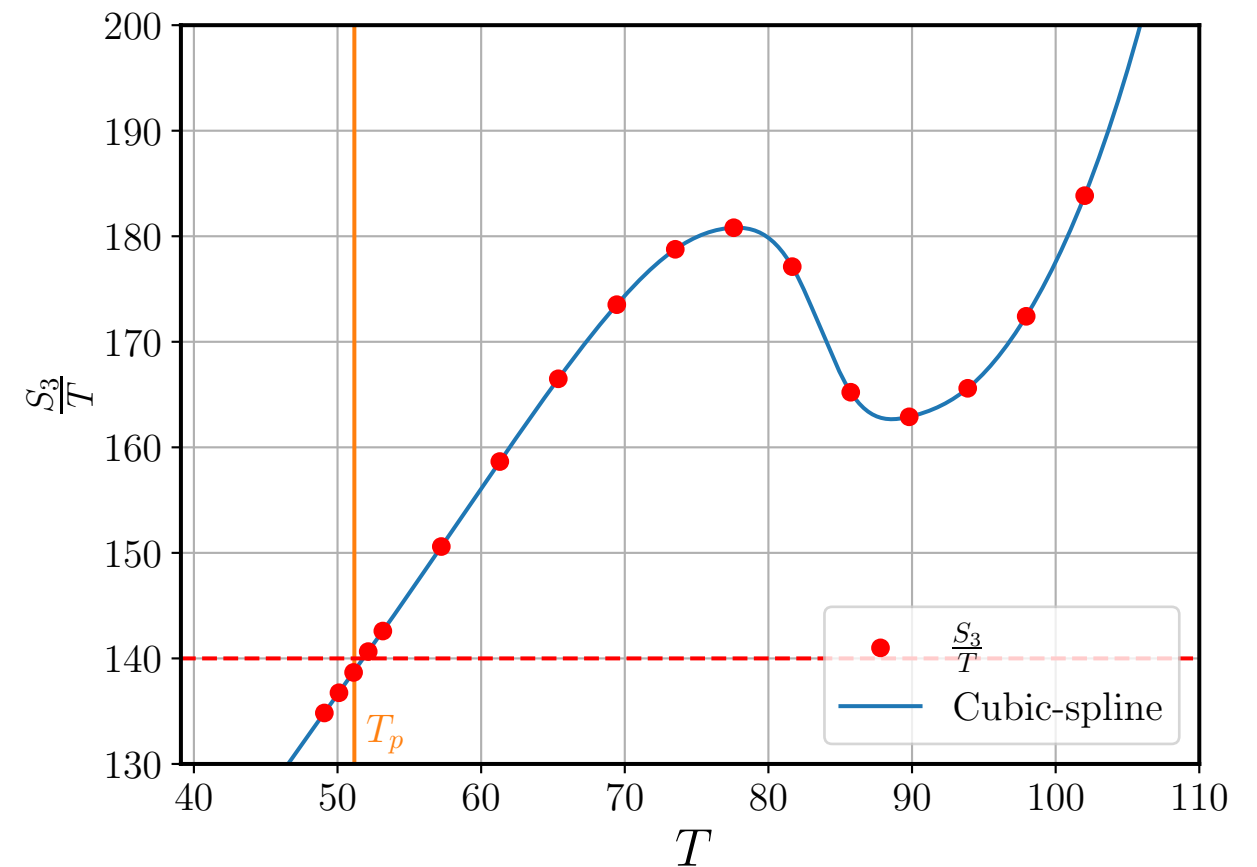
BP4: BAU and Effective Action

BP4

[MM,Plotnikov,Santos,Viana,'26]



- Results for kink solution much more erratic
- For field solution more stable results are expected due to larger L_w



- Euclidean action S_3/T : for tunneling rate
- Rate increases with decreasing S_3/T
- Plot: back-and-forth in tunneling rate $\rightsquigarrow$ transition at rather low $T \rightsquigarrow$ boosts BAU
- Behavior most relevant for low v_w
- Verified: Points w/ low T_p show back-and-forth behaviour

Conclusions

- New implementation of BAU calculation in BSMP, based on WKB ansatz and generalization of transport equations to arbitrary number of moments
- **New:** Proper implementation of boundary conditions, two different truncation schemes, VEV profile from kink solution and solution of equations of motion; top Yukawa rate newly computed at $T \neq 0$
- **Benchmark model:**
 - reduced dependence of BAU on truncation scheme for large n ;
better convergence for larger v_w and $L_w T_n$
 - moment expansion: **stable results require $L_w T_n \gtrsim 50$** (WKB ansatz: $L_w T_n \gtrsim 2$)
 - BAU decreases w/ v_w and $L_w T_n$; for firm statements: larger n required
- **C2HDM:**
 - type I reaches measured BAU, type II not (more constrained)
 - uncertainties decrease w/ large n , $L_w T_p$ - however, this reduces also the BAU
 - **$L_w T_p$ remains below 7 $\Rightarrow$ large source of uncertainty**
 - lower T_* , v_w increases BAU $\Rightarrow$ importance of T_* choice,
importance of consistent v_w calculation and derivation of wall width
 - VEV profile has significant impact on BAU: kink profile leads for most points to larger BAU (depends on n)

Conclusions

- Despite uncertainties: **impact of CP violation on BAU clearly visible:**
larger $\text{Im}(m_{12}^2)$ and spontaneously generated ω_{CP} increase BAU
- **BAU and GW** signal from first-order PTs sensitive to v_w , **however w/ opposite dependencies on v_w**
- **Benchmark points** - discussion of impact of VEV profile:
 - **VEV profile has significant impact**
 - simple assumption of taking **same L_w** in all VEV directions not valid
 - **BAU i.g. smaller and more stable for field profile** ($\leftarrow$ larger L_w)
- **Our results:** show directions for future improvements in calculation of BAU and give guidance for model building

*Thank you for
your attention!*

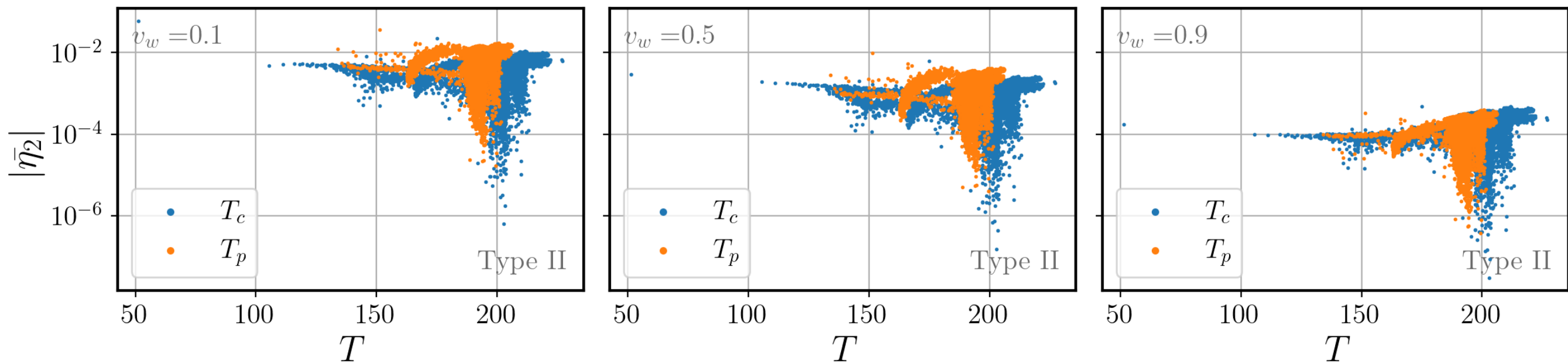


Impact of Transition Temperature and wall velocity

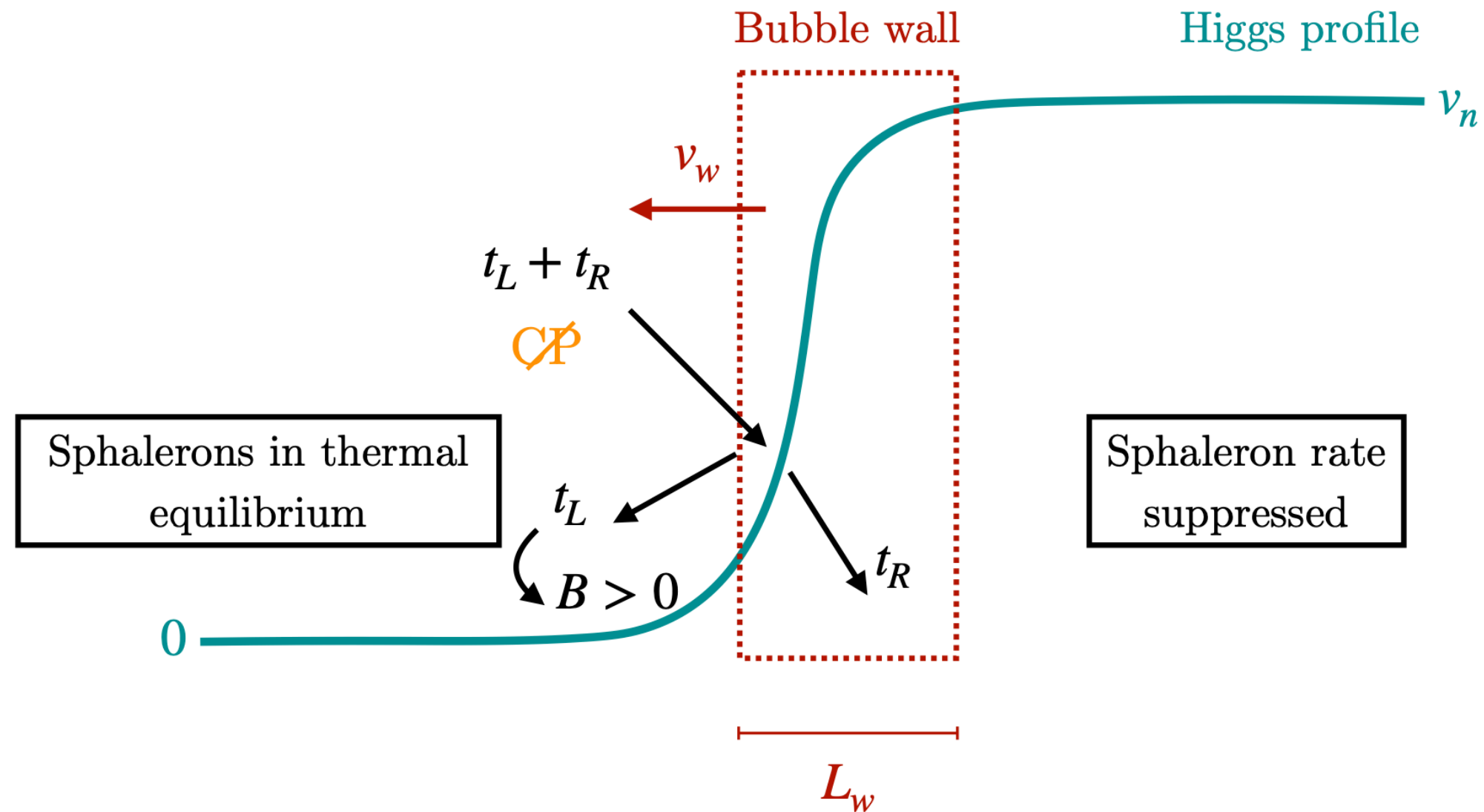
$n = 2$

Type II

[MM,Plotnikov,Santos,Viana,'26]



Electroweak Baryogenesis in a Nutshell



[Fig. taken from van de Vis et al., '25]