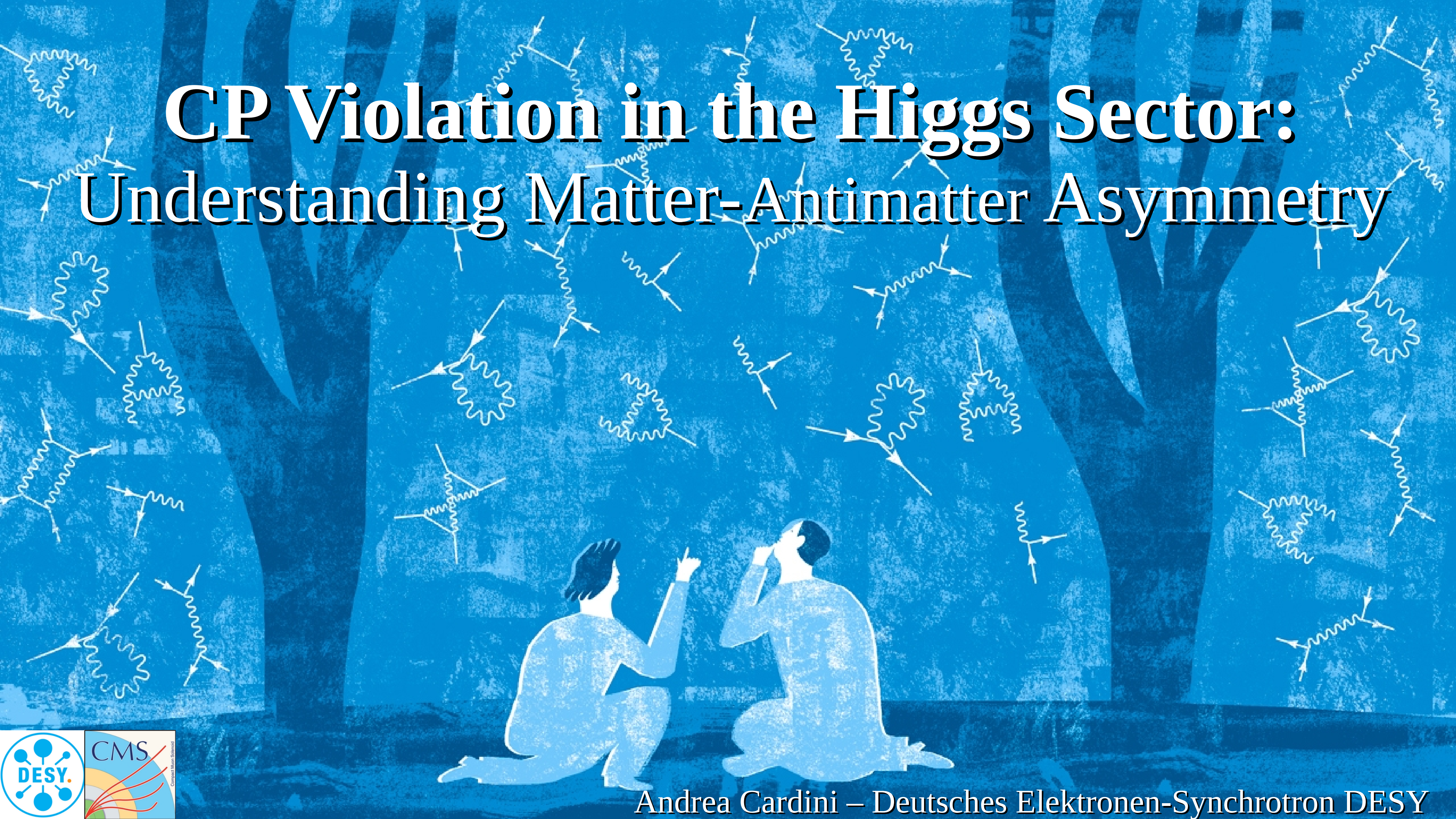
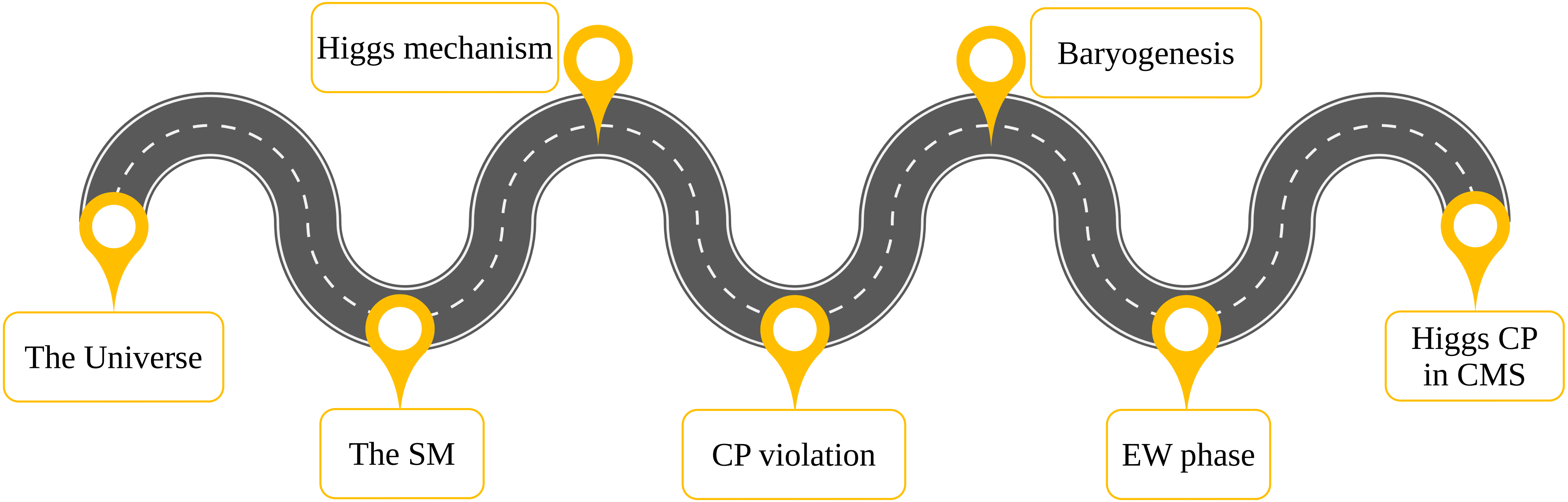
CP Violation in the Higgs Sector:
Understanding Matter-Antimatter Asymmetry



Andrea Cardini – Deutsches Elektronen-Synchrotron DESY

Road of the talk

- The aim:
  - general understanding of the mystery of absence of antimatter in the Universe
  - review of CP violation results in CMS that could help explain it



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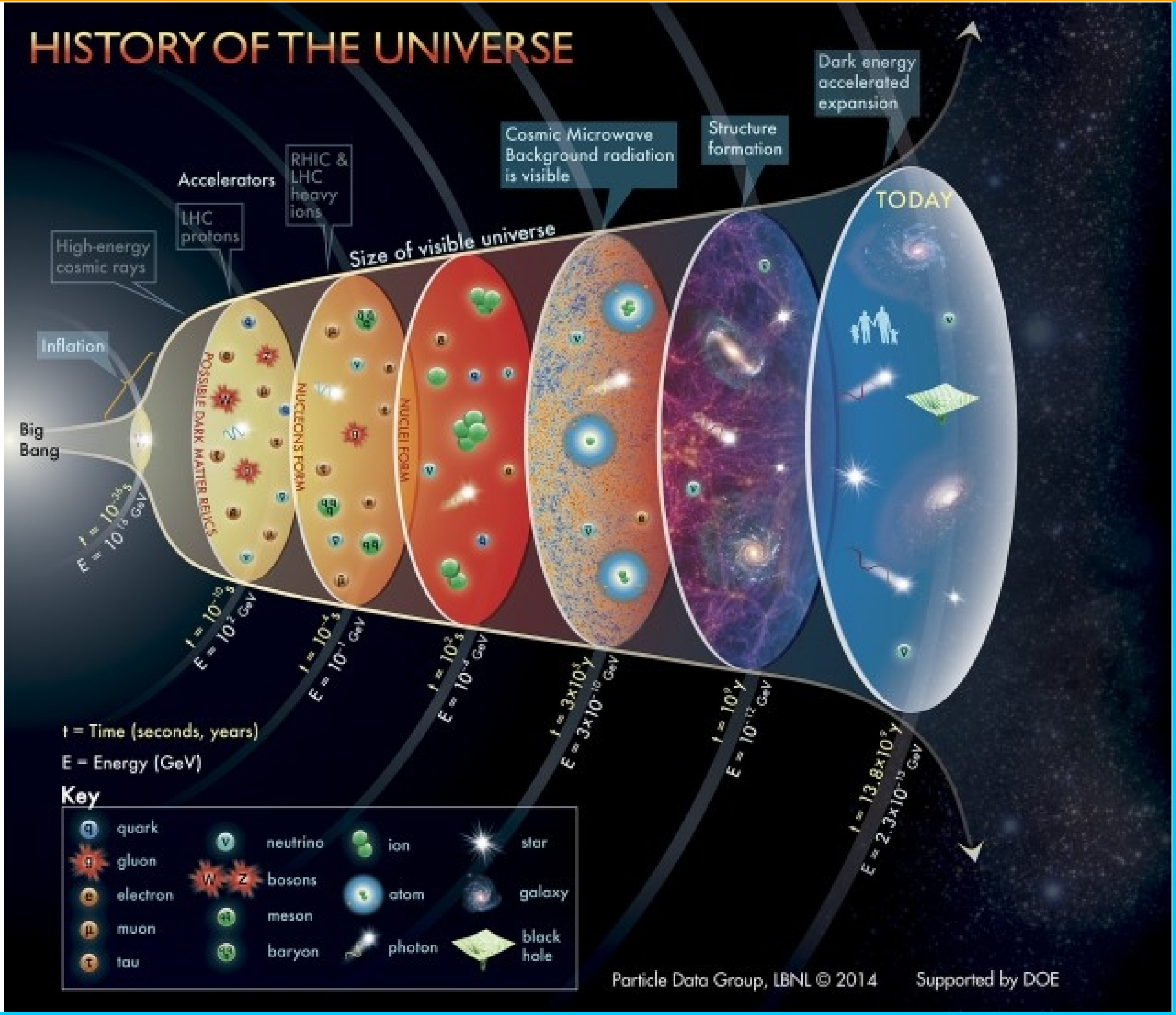

Once upon a time...

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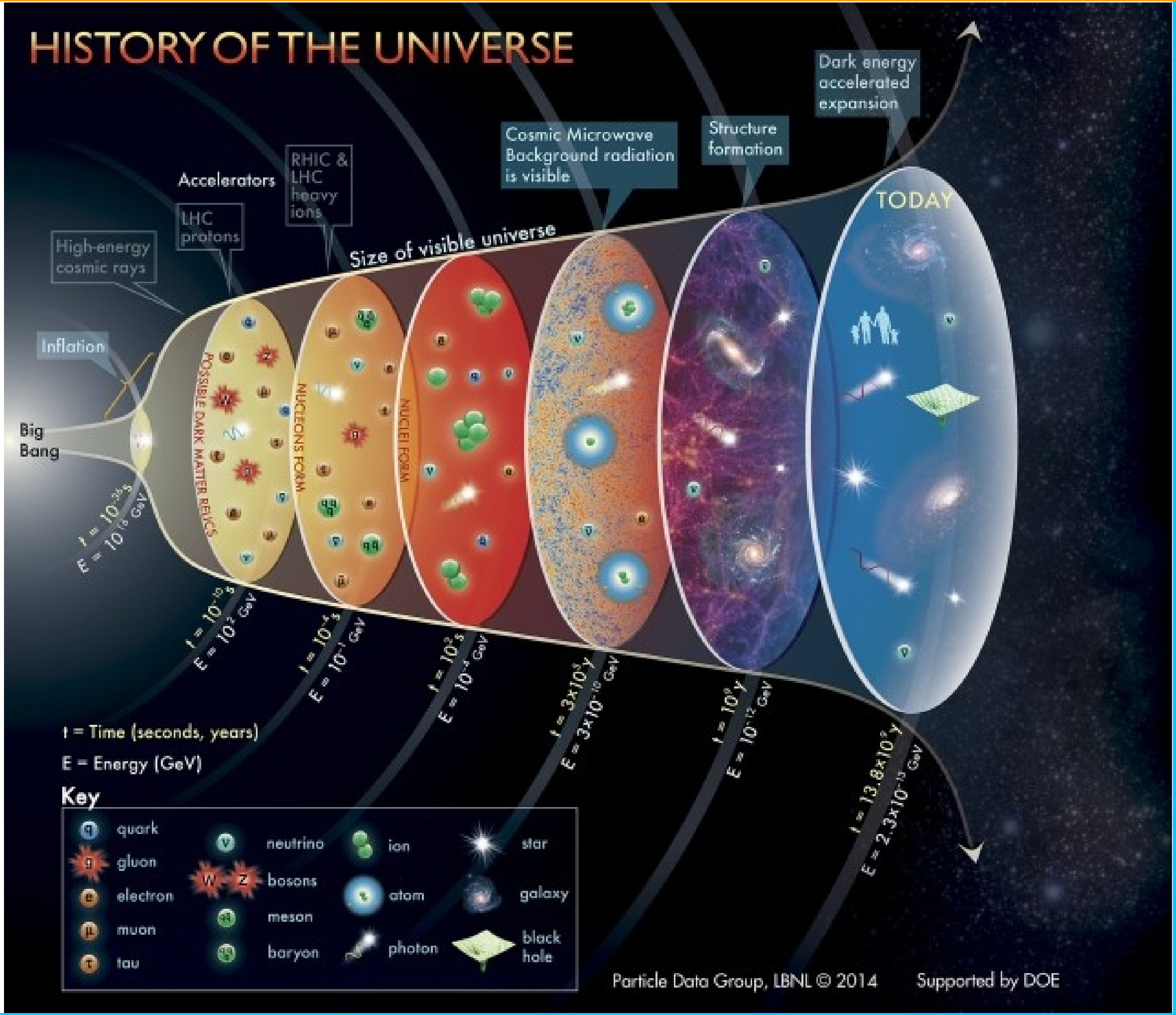

- the Universe was not like we see it today:
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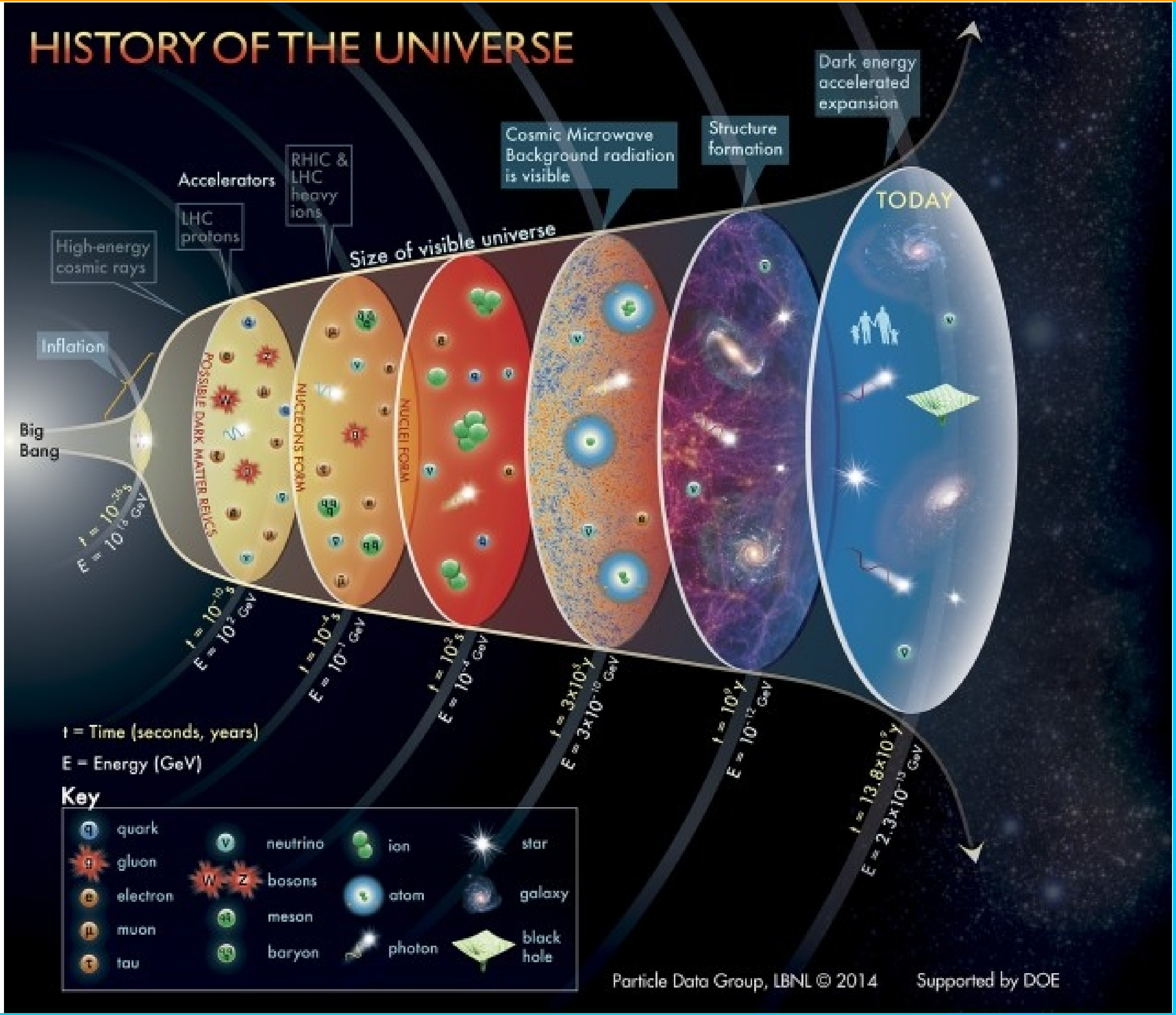
  - No Earth



Once upon a time...

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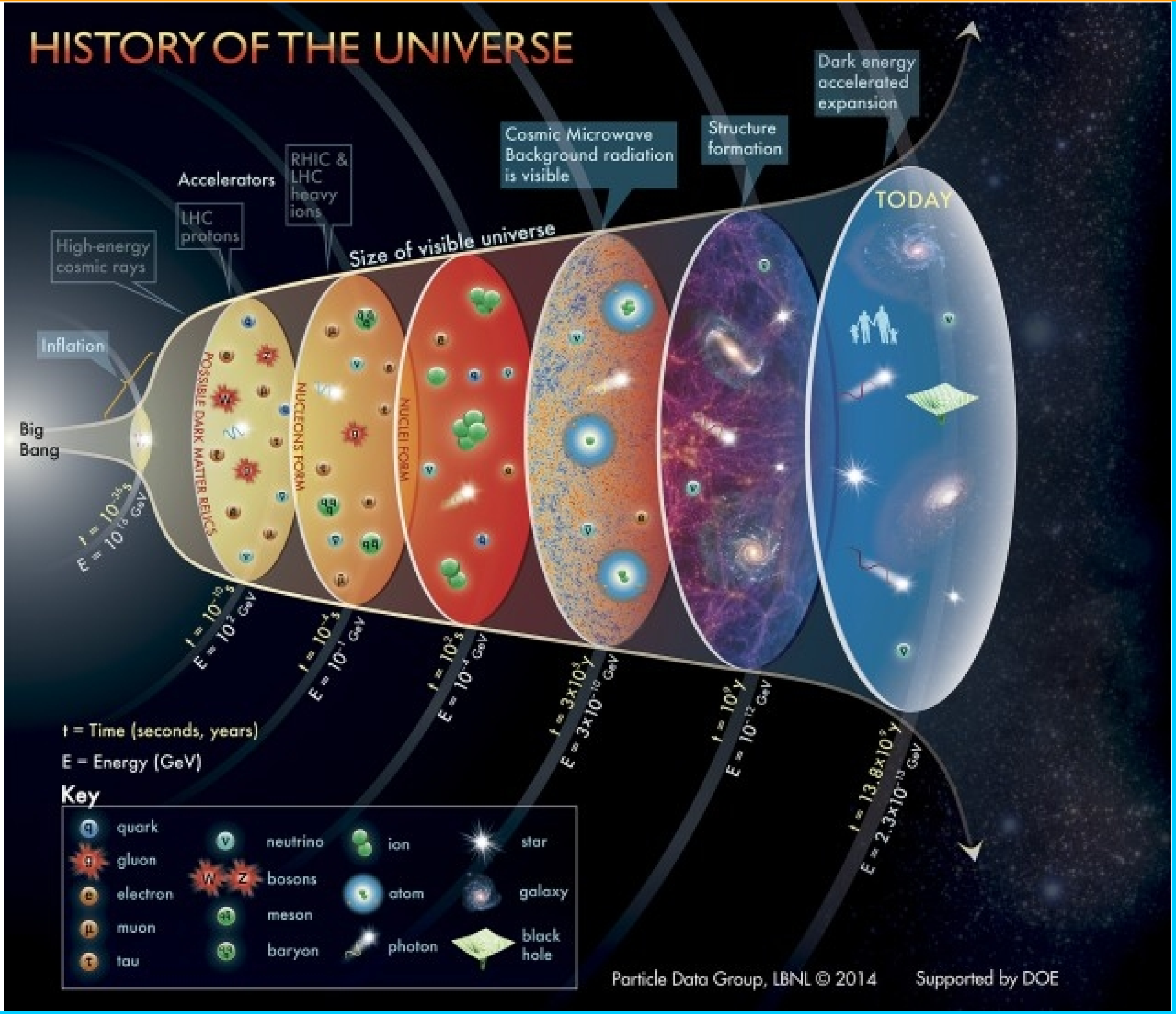
  - No Galaxies



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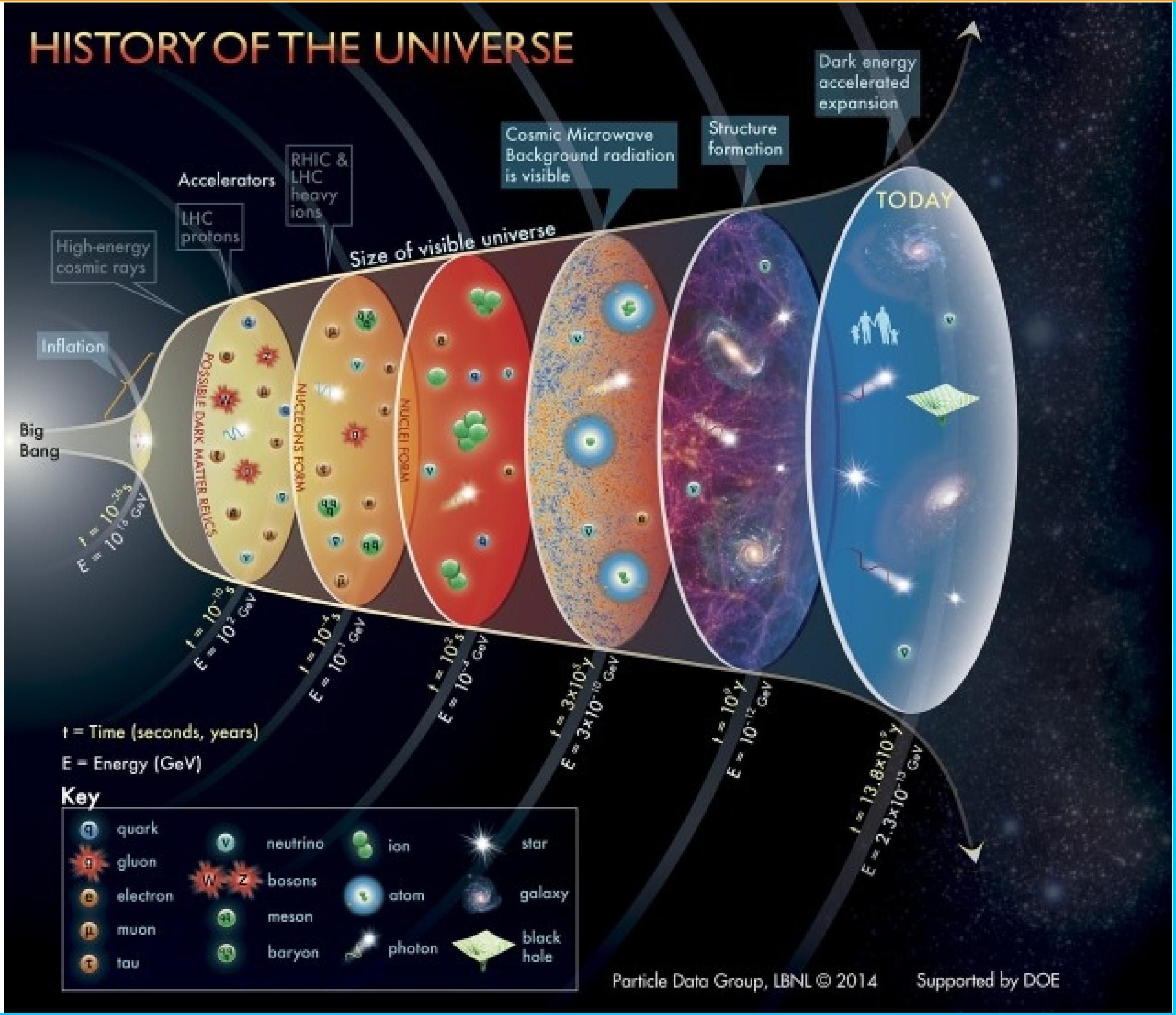

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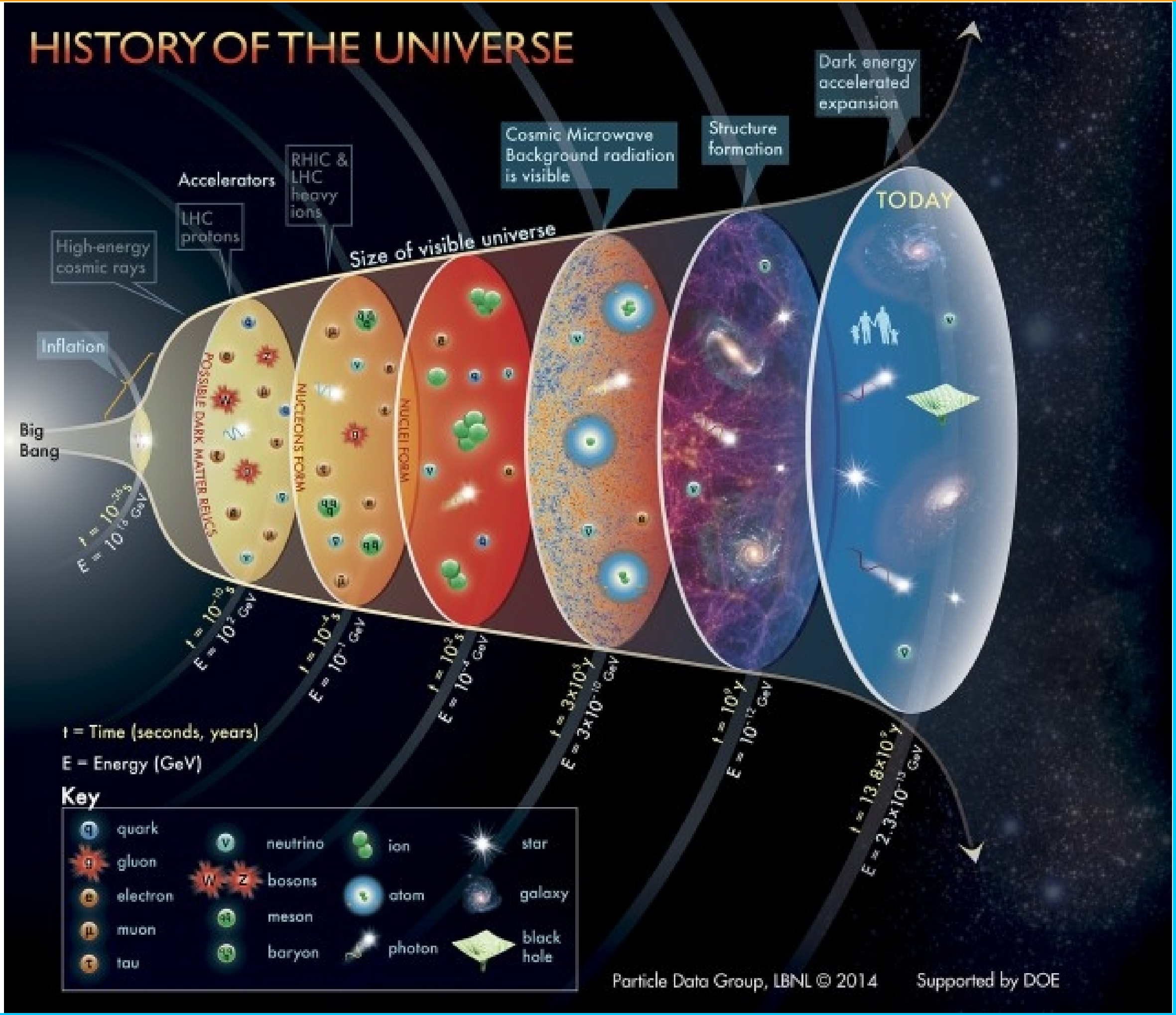

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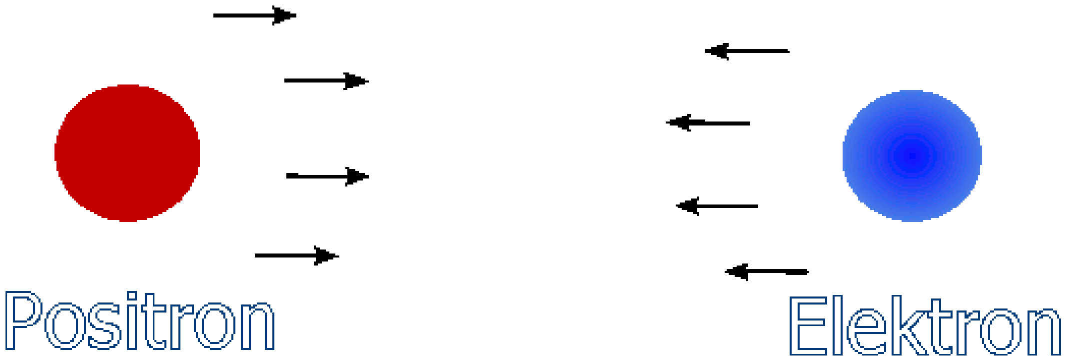

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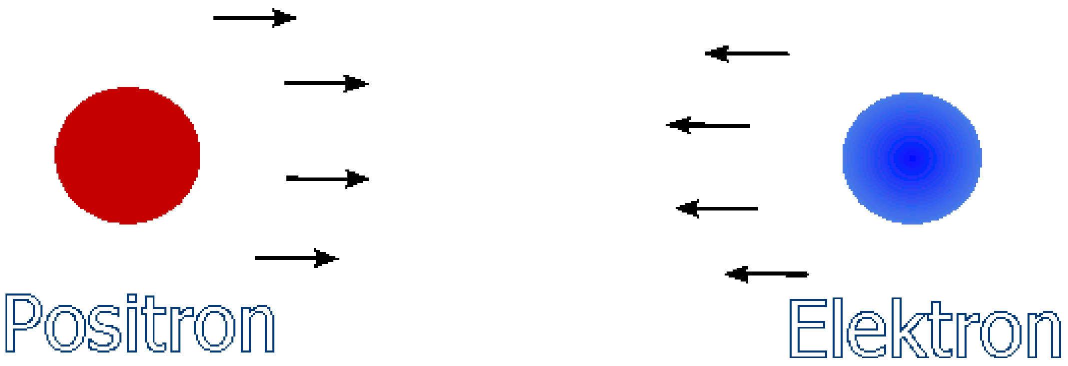
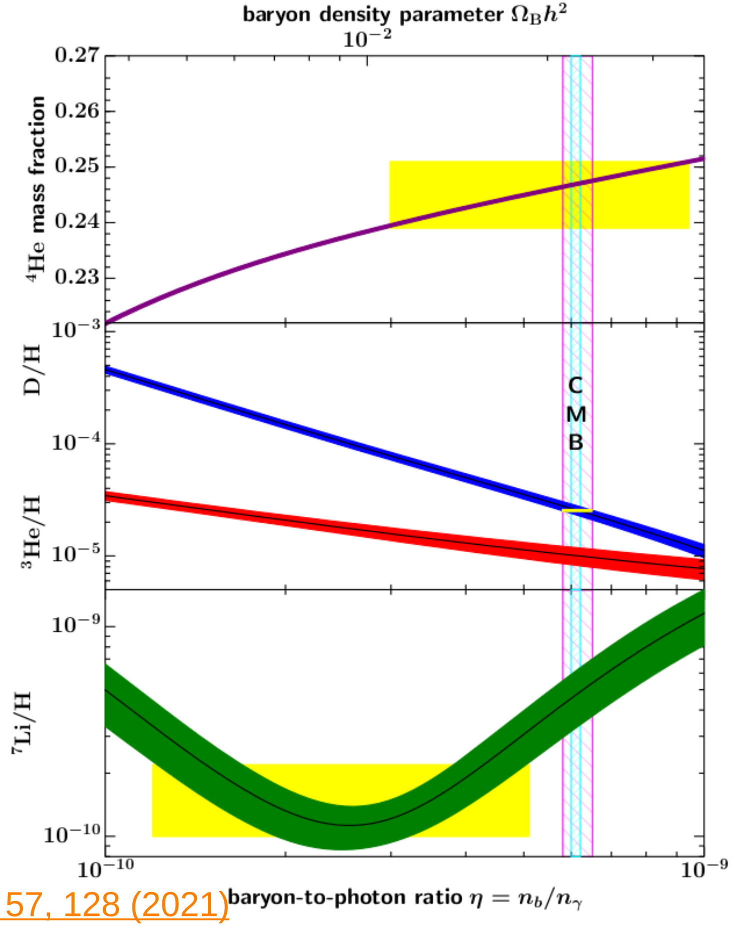
- The primordial Universe contained both **matter** and **anti-matter**
- Energy was converting into matter and anti-matter which then annihilated to create again energy
- This cycle was broken, and the Universe now is made just of matter
- Where did the anti-matter go?



- Our Universe is now made of matter, forming the baryons and leptons which make up the atoms and molecules we are made of
- This required an **asymmetry** between matter and anti-matter in the primordial Universe
  - **Baryon Asymmetry in the Universe** (BAU)
  - Matter : Antimatter
    1’000’000’001 : 1’000’000’000
- More specifically, the asymmetry is encoded in the ratio of baryons over photons in the Universe
- From the cosmic microwave background this is

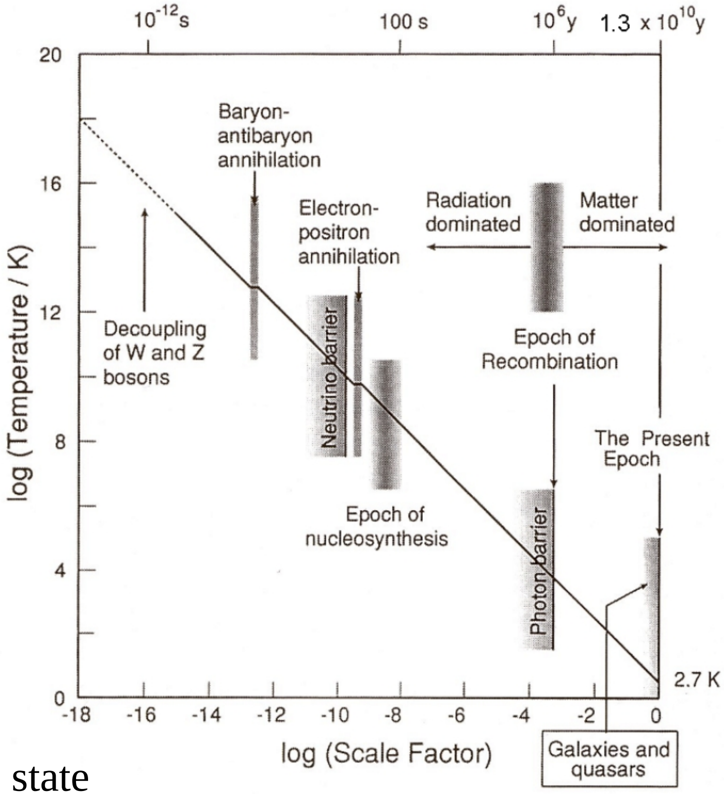
$$\eta = \frac{(n_B - n_{\bar{B}})}{n_\gamma} = \frac{n_{B,relic}}{n_\gamma} \approx 6 \times 10^{-10}$$



Eur. Phys. J. A 57, 128 (2021)

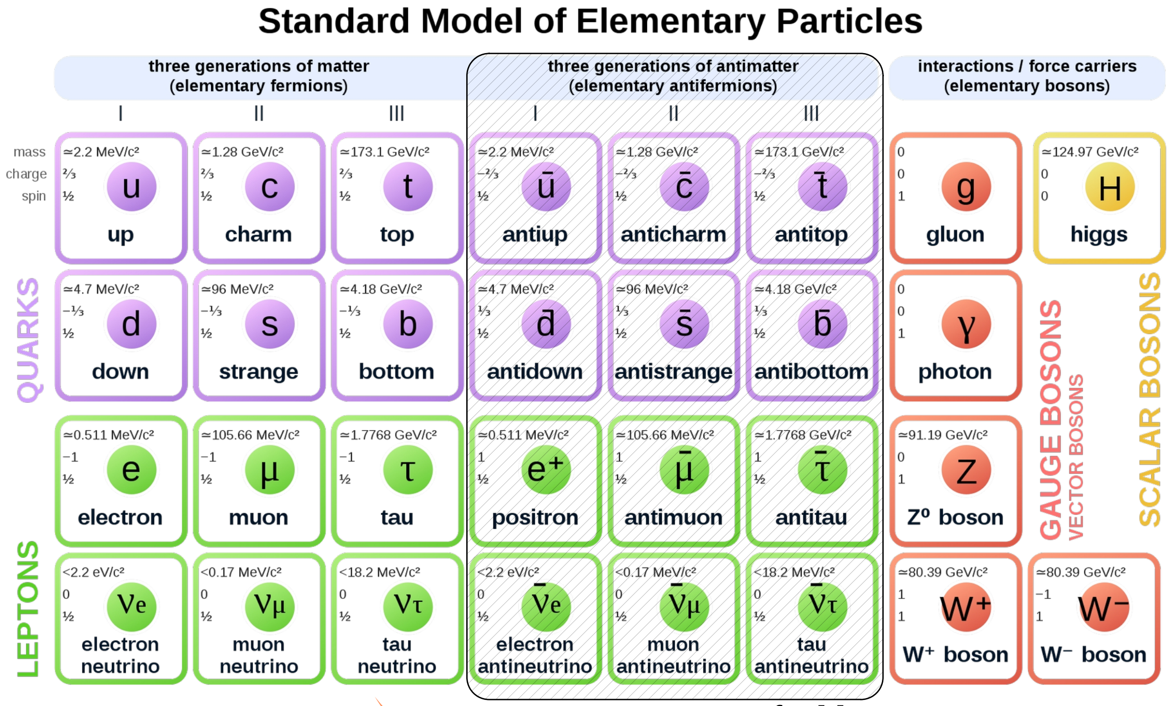
Evolution of the Universe

- The cosmic microwave background originated when the Universe cooled off enough that the photons were free to propagate
  - Epoch or recombination: formation of atoms
- Going backward in time particle density and temperature increase:
  - formation of nuclei
  - cosmic neutrino background
  - **the baryon-antibaryon annihilation** → the matter asymmetry should have been present before this moment
- Sakharov theorized 3 conditions **necessary** for a CPT conserving theory to explain the BAU:
  - Baryon number violation: generate asymmetry in a symmetric Universe
  - C and CP violation: asymmetric interaction to remove antimatter
  - Deviation from thermal equilibrium: to prevent reverting to a symmetric state
- Is there a theory that satisfies all 3 conditions?



The Standard Model of particle physics

- Successful theory predicting the behavior of matter constituents (**fermions**)
- Interactions mediated by **gauge bosons**, gravity not included



C Inversion of additive quantum numbers

- Relevant symmetries:
  - Gauge: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
  - Parity (P)
  - Charge conjugation (C)
    → **CP**
  - Time reversal (T)
  - Chirality: χ_L , χ_R
- The decoupling of the weak and electromagnetic forces is a key moment in the history of the Universe

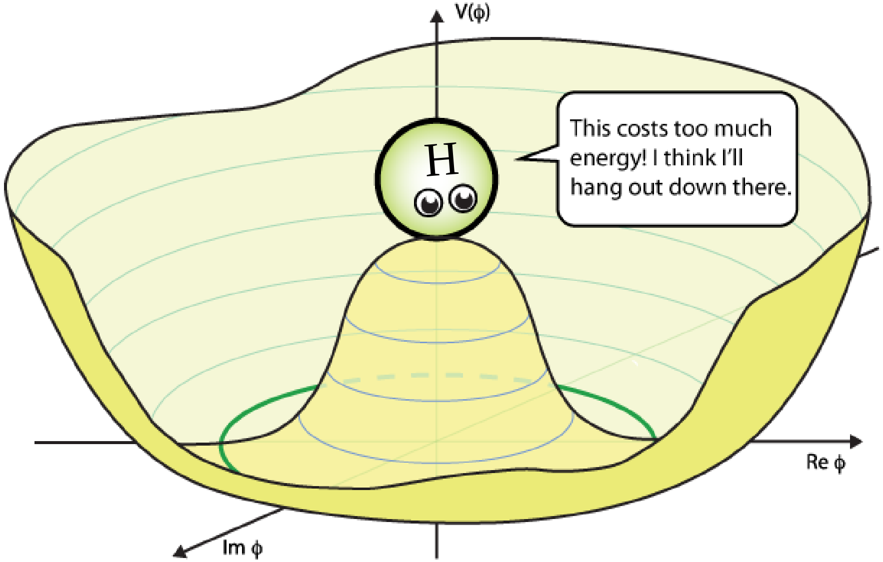
Electroweak Symmetry Breaking

- The gauge invariance of the SM would prevent mass terms for the vector bosons and the fermions
- The Higgs boson was introduced to softly break the electroweak symmetry and give mass to the particles
- EWSB: $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$
  - Gauge bosons gain mass directly through Higgs kinetic term

$$L_{mWZ} = \left(\frac{v^2 g^2}{4} W^{\dagger}_{\mu} W^{\mu} + \frac{v^2 (g^2 + g'^2)}{8} Z_{\mu} Z^{\mu} \right)$$

  - Fermions gain mass via **Yukawa coupling**

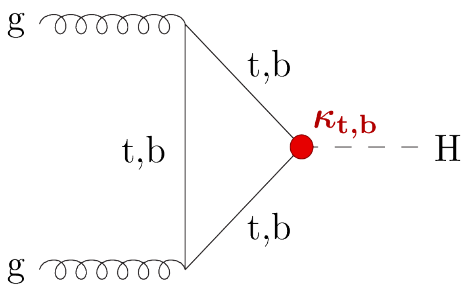
$$L_Y^f = - \underbrace{m_f (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)}_{\text{fermionic mass term}} - \underbrace{\frac{m_v}{v} (\bar{\psi}_L H \psi_R + \bar{\psi}_R H \psi_L)}_{\text{coupling of the Higgs to fermions}}$$

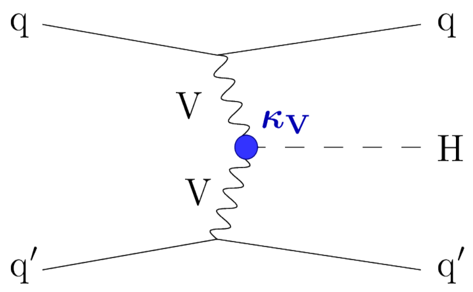


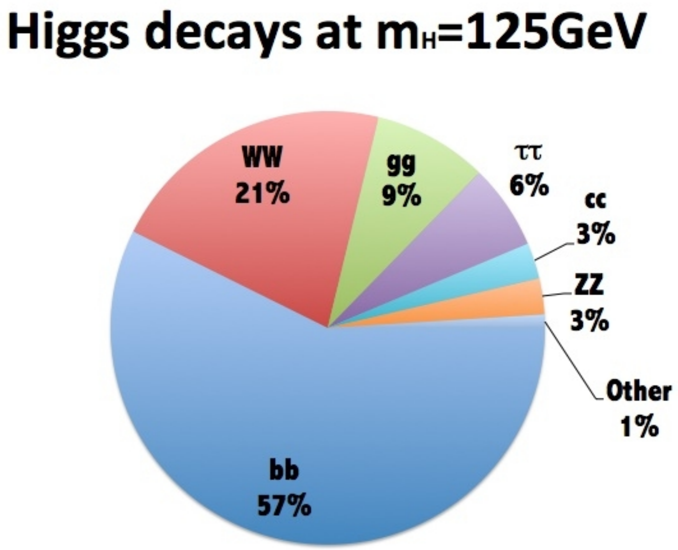
- Fermions form the matter our Universe is made of → Look for CP violation in the Higgs sector

The Higgs boson – short recap

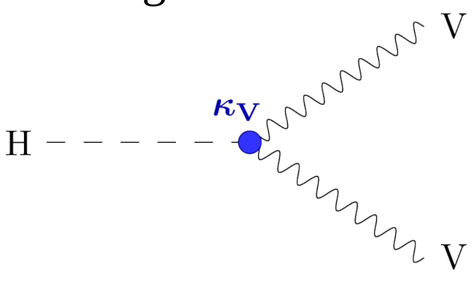
- At the LHC the main way to produce the Higgs boson is via gluon-gluon fusion
- Production via vector boson fusion, Higgs-strahlung and in association with top or bottom quarks are rarer

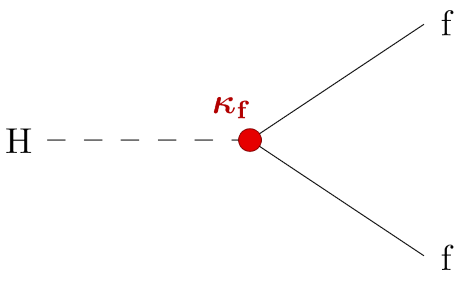




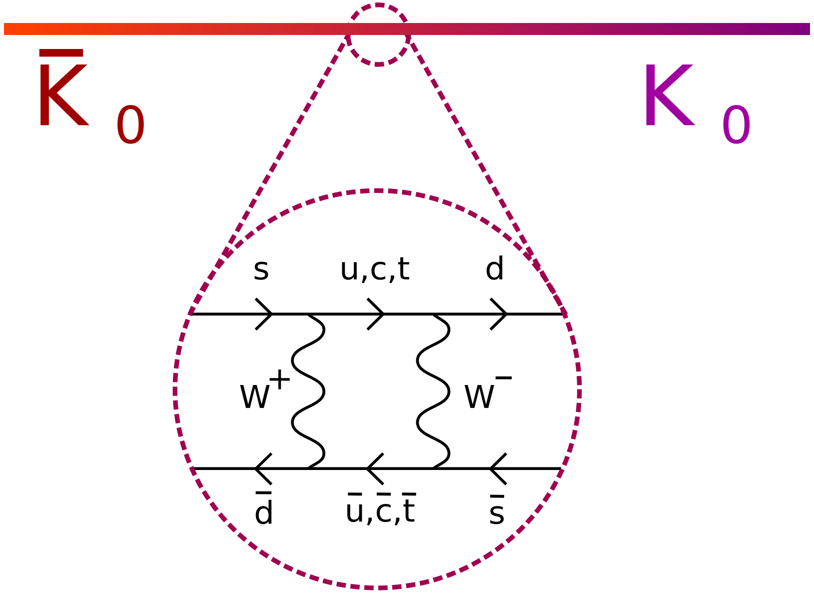


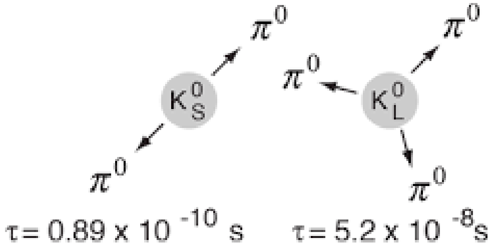
- The Higgs boson is not stable and decays immediately
- It can decay directly to W and Z bosons, and to all fermions via Yukawa coupling
- Via intermediate fermion or boson loop it can also decay to photons and gluons





- Weak interactions massively violates C and P symmetries, it also violates CP: K_0 oscillation → K_S and K_L decays – Cronin and Fitch in the 60s





$$K_S^0 = \frac{K^0 - \bar{K}^0}{\sqrt{2}}$$

$$K_L^0 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}$$

- The most notable violation of C, P and CP in the SM comes from flavor changing currents in the weak interaction
- CP violation located in the complex phase in the Cabibbo-Kobayashi-Maskawa matrix
- The matrix was introduced to describe the quark mixing in the weak interaction

The CKM matrix and Yukawa interaction

- The quark mixing and the quark masses have a common origin: the Yukawa interaction
- The Higgs boson gives mass to the particles and defines the fermion generations
- $$\mathcal{L}_{\phi q} = -\sum_{ij} G_{ij} \begin{pmatrix} \bar{U}_{iL} & \bar{D}_{iL} \end{pmatrix} \cdot \begin{pmatrix} \phi^{0\dagger} \\ -\phi^{-} \end{pmatrix} U_{jR}$$ ⟶ Yukawa for up-type quarks

  C

  $$-\sum_{ij} H_{ij} \begin{pmatrix} \bar{U}_{iL} & \bar{D}_{iL} \end{pmatrix} \cdot \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} D_{jR} + H.c.$$ ⟶ Yukawa for down-type quarks

  with the indices i,j running over the quark generations

- After EWSB the quarks acquire mass via the Higgs vacuum expectation value
- $$\mathcal{L}_{m} = -\sum_{ij} \bar{U}_{iL} m^{U}_{ij} U_{jR} - \sum_{ij} \bar{D}_{iL} m^{D}_{ij} D_{jR} + H.c.$$
- No theoretical requirement for the m_{ij} matrices to be diagonal **but** the SM Lagrangian is invariant under unitarity transformations

The CKM matrix

- We can multiply all fields by unitary matrices and redefine the quark fields to diagonalize the mass matrices

$$m_{ij}^U = \frac{1}{\sqrt{2}} G_{ij} v \qquad m^{U\prime} = A_L^U m^U A_R^{U\dagger}$$

$$m_{ij}^D = \frac{1}{\sqrt{2}} H_{ij} v \qquad m^{D\prime} = A_L^D m^D A_R^{D\dagger}$$

- Cannot diagonalize both mass matrices at once → diagonalize one mass matrix and redefines the fields for either up or down type quarks

- The lightest quarks are **u**, **d** and **s** → the quark mixing was observed for kaon decays between the **d** and **s** quarks → the mass term diagonalized is the one for up-type quarks

- $V_{CKM} = A_L^U (A_L^D)^{-1}$ → $q_{uL} = \left(\frac{1-\gamma_5}{2}\right) \begin{pmatrix} u \\ V_{ud} d + V_{us} s + V_{ub} b \end{pmatrix}$

CP violation in the SM

- The CKM matrix is unitary **but** is not required to be Real → it can have a complex phase leading to direct CP violation in the electroweak sector

- $$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- The complex phase $\delta = 1.196 \pm 0.045$ [rad] is the main source of CP violation allowed in the SM

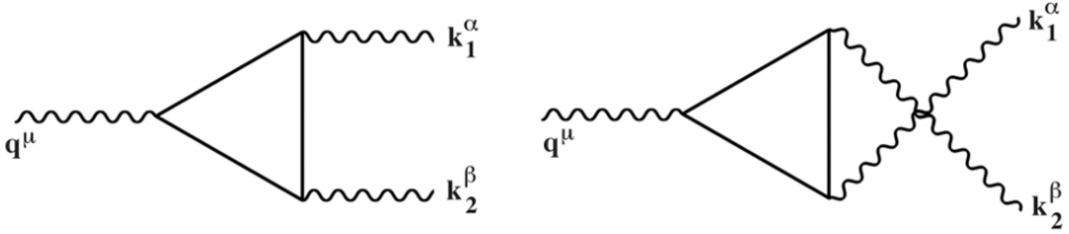
- Another source of CP violation *could** be found in the neutrino oscillation if the PMNS matrix presents a complex phase

- The strong interaction does not seem to violate CP experimentally… however in QCD CP-violating terms can arise leading to the question of why no signs of CP violation have been observed

**there is no experimental consensus on a CP-violating phase in the PMNS matrix*

EW baryogenesis – B violation

- The main source of CP violation in the SM comes from the EW sector and is linked to the Higgs boson
- What about the other 2 Sakharov's conditions?
  - Baryon number violation → is there baryon number violation in the SM?
    - In the SM the baryon (B) and lepton (L) number are conserved only via accidental symmetries – there are no gauge invariant operators of dim 4 that violate them
    - **Anomalies** appear at triangular loop level due to the chiral structure of the SM – Adler, Bell and Jackiw (ABJ) anomalies



$$\partial_\mu J^\mu_{\mathrm{B}} = -\frac{\alpha_2}{8\pi} N_g W_i^{\mu\nu}\tilde{W}_{i\mu\nu} + \frac{\alpha_1}{8\pi} N_g \left(\frac{4}{9} + \frac{1}{9} - \frac{1}{18}\right) Y^{\alpha\beta}\tilde{Y}_{\alpha\beta}$$

$$\partial_\mu J^\mu_{\mathrm{L}} = -\frac{\alpha_2 N_g}{8\pi} W_i^{\mu\nu}\tilde{W}_{i\mu\nu} + \frac{\alpha_1}{8\pi} N_g \left(1 - \frac{1}{2}\right) Y^{\alpha\beta}\tilde{Y}_{\alpha\beta} \;.$$

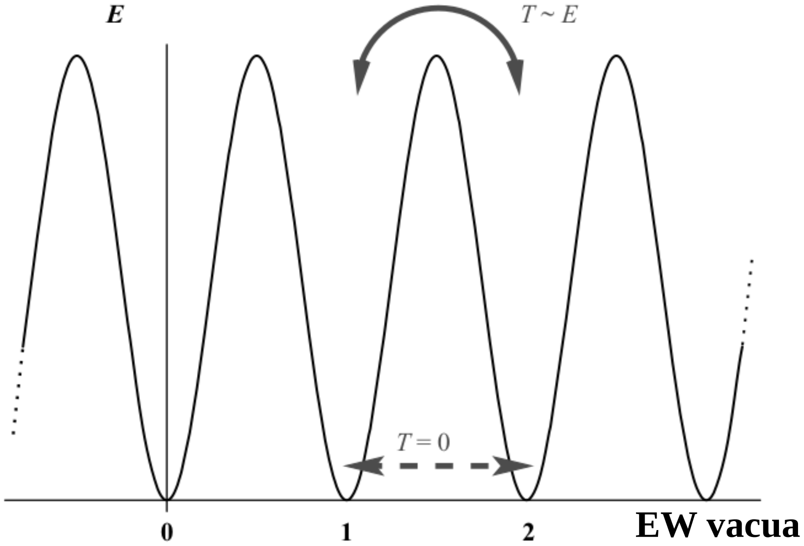
→ Violation of baryon and lepton number violation at loop level

Sphalerons

- $U(1)_B$ and $U(1)_L$ are broken at quantum level, as is B+L, however **B-L is preserved**
  - $$\partial_\mu J^\mu_{\mathrm{B+L}} = \frac{\alpha_1^2}{8\pi} N_g Y^{\alpha\beta}\tilde{Y}_{\alpha\beta} - \frac{\alpha_2^2}{4\pi} N_g W_i^{\alpha\beta}\tilde{W}_{i\alpha\beta}$$
  - $$\partial_\mu J^\mu_{\mathrm{B-L}} = 0\ .$$
- At low temperatures the B violation is low, but at high temperature it can proceed via **sphaleron** production

F. R. Klinkhamer and N. S. Manton Phys. Rev. D 30, 2212

  - A Sphaleron – from Greek Σφαλερός ready to fall – is a static, but unstable, solution for the electroweak theory
  - It allows the transition between distinct EW vacuum states (different baryon or lepton number)
  - $E_{sph} \sim 8\pi\, v(T)/g_W$ – the energy is proportional to the vacuum expectation value of the Higgs field



M. Dine (2016). Supersymmetry and String Theory

Electroweak phase transition

- The last condition necessary for matter-antimatter asymmetry to occur is that the CP violating interactions take place out of thermal equilibrium
- We need a **phase transition:** an interaction outside of thermal equilibrium
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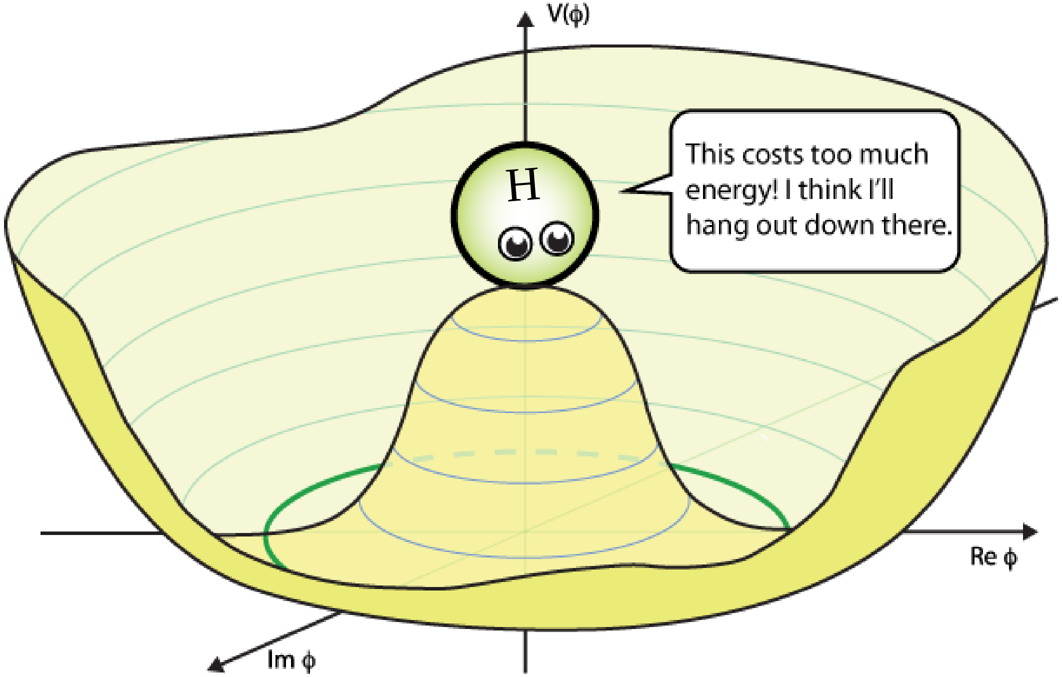

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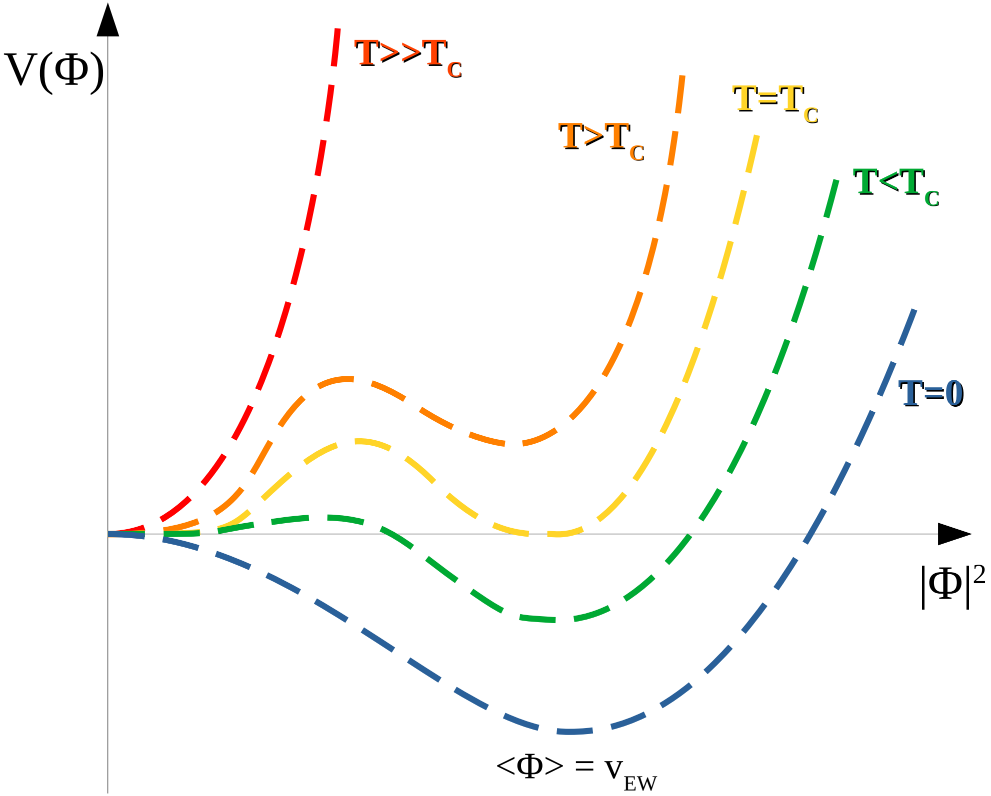
- We need a **phase transition:** an interaction outside of thermal equilibrium
- The electroweak symmetry breaking provides the appropriate conditions
- The Higgs potential in the present has the usual *sombrero* shape you are familiar with
- The electroweak phase transition started at $T<T_C$ – when the the absolute minima of the system became $|\Phi|^2 > 0$
  - 1^{st} order PT: the system goes to the absolute minima via tunnelling



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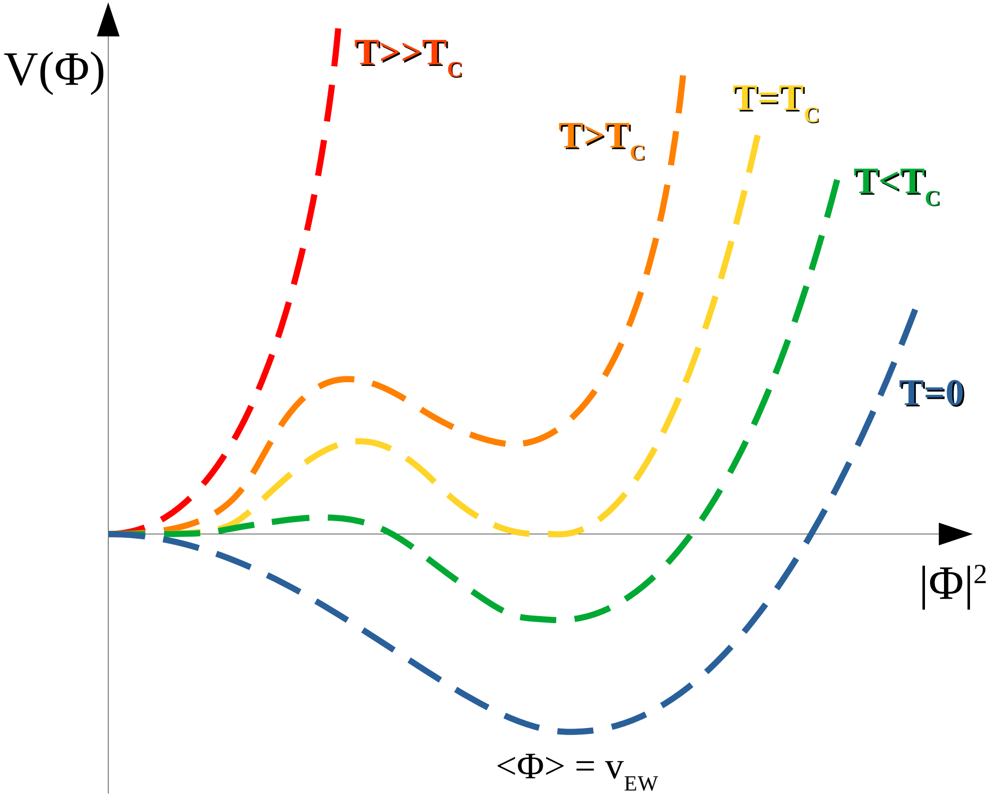
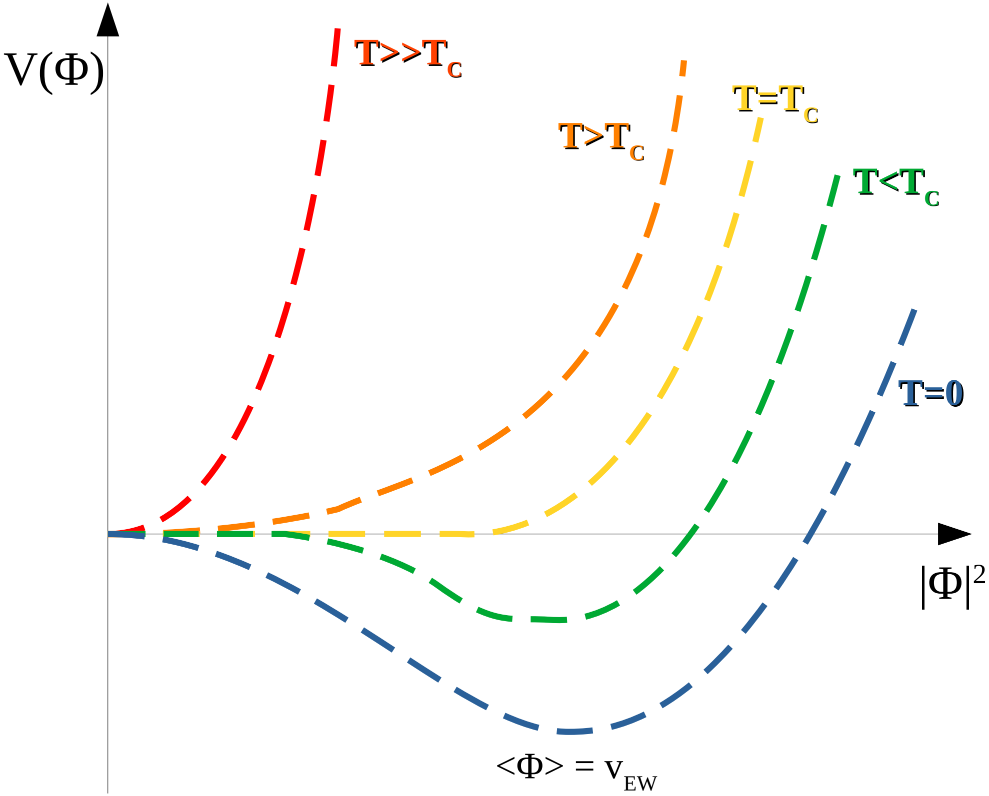
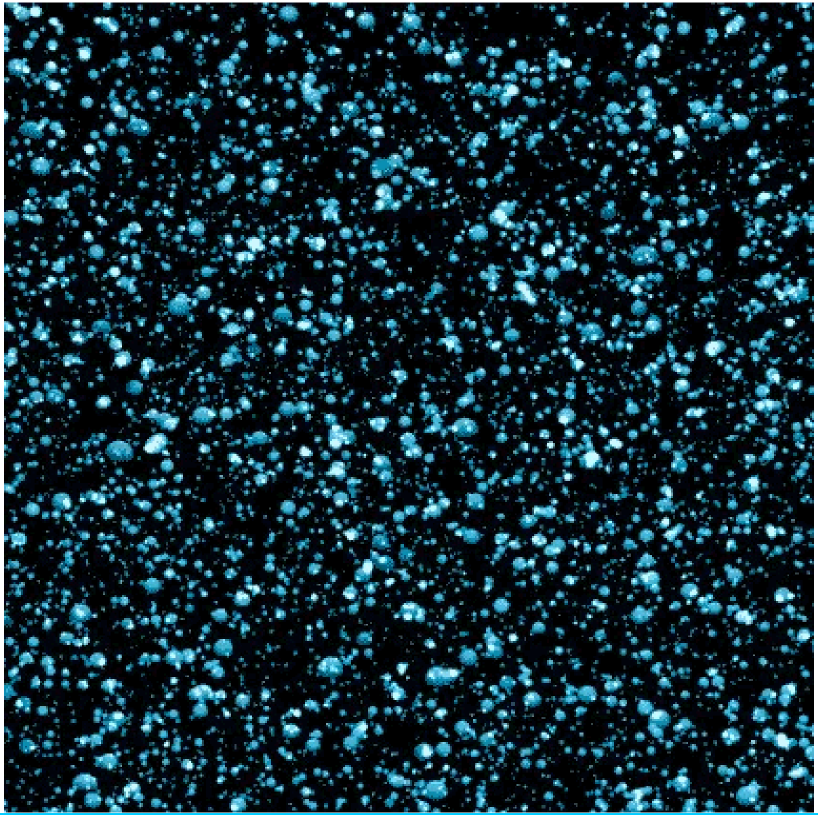


2^{nd} order PT: there is no energy barrier and the system goes to the minimum *smoothly*



Higgs bubbles

- Like when boiling water, the entire Universe did not reach EWPT instantaneously everywhere



giphy.com

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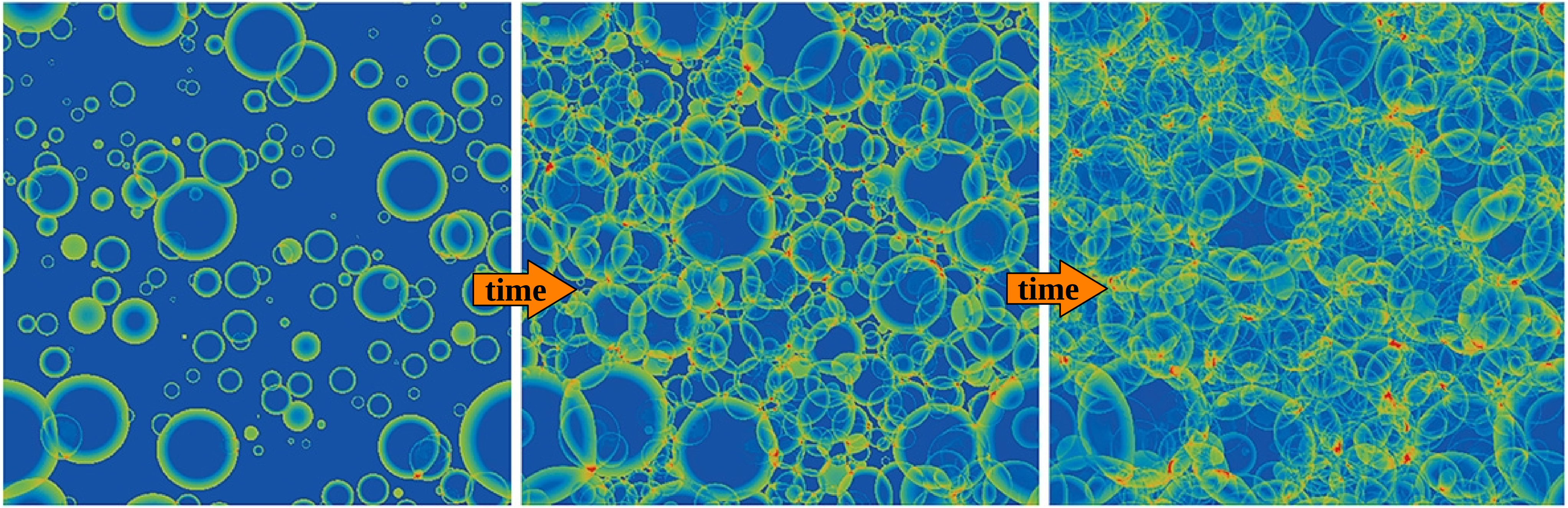

JCAP 04(2021)014

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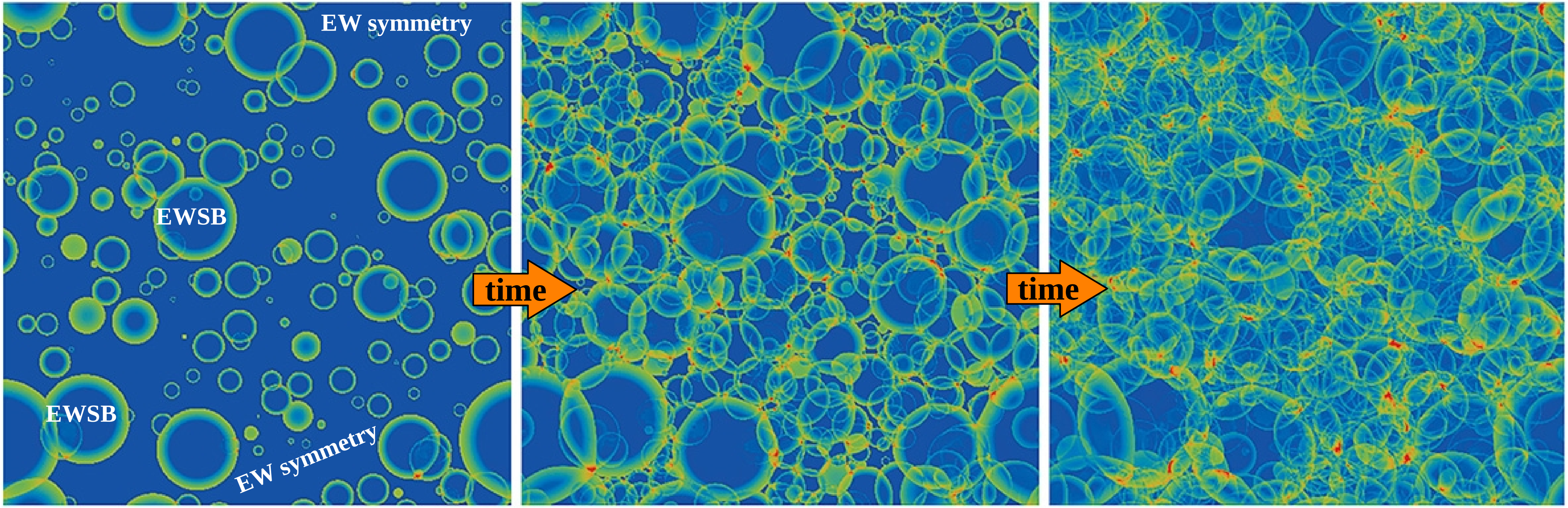

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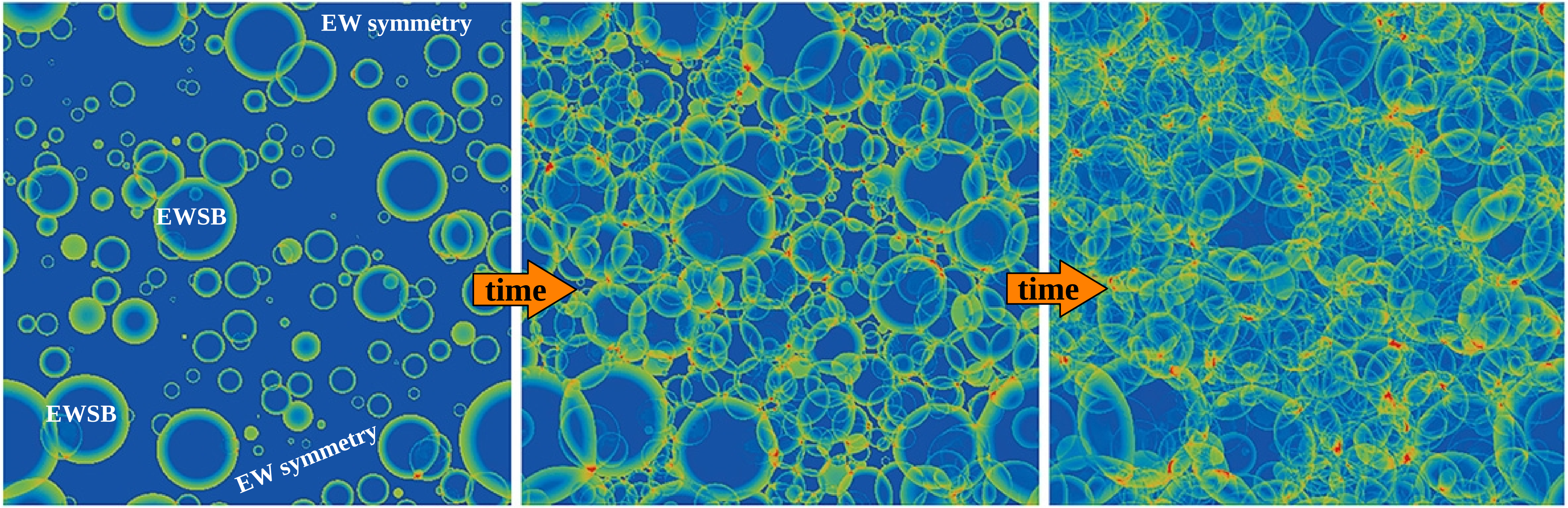
Higgs bubbles

- Like when boiling water, the entire Universe did not reach EWPT instantaneously everywhere
- The transition happened along expanding *bubbles* where the EW symmetry breaks
- Along the bubble walls – transition from the symmetric state to the broken EW one
- Fields on the bubble walls are highly out of equilibrium → satisfy the 3rd Sakharov's condition



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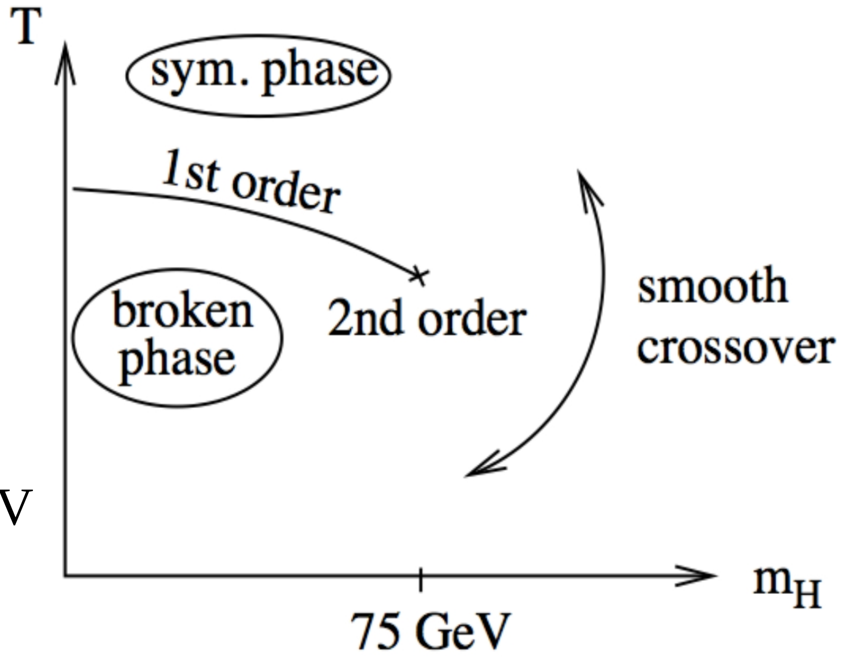
The SM Higgs and the EWPT

- B violating processes have different rates in the EW symmetric or broken phases
  - In the unbroken phase T is high enough to have a continuous sphaleron production → B-L is preserved but the rate of B violating processes is high
  - At the wall they are Boltzmann suppressed
  - In the broken phase they are exponentially suppressed
- To have baryon asymmetry inside the bubble and freeze it, the sphaleron processes need to shut down quickly
  → **require a strong 1st order phase transition**
- Problem: this would require a Higgs of mass < 80 GeV
  - The SM provides the conditions for generating some baryon asymmetry but not enough for the observed BAU

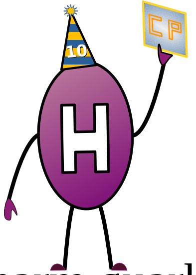


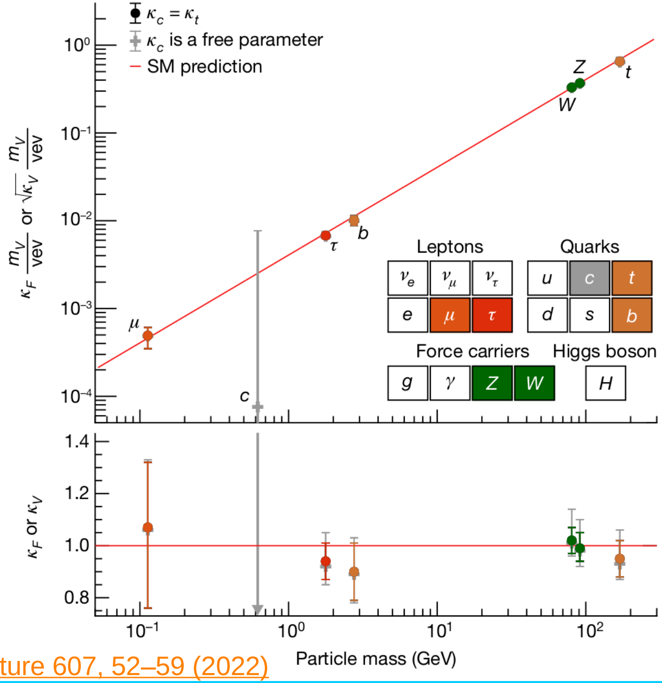
- To explain the BAU we need either
  - More Higgs bosons ⟶ extra Higgs doublets/singlets, SUSY, etc.
  - More sources of **CP violation** ⟶ today's topic

  } Not mutually exclusive

    - As the Higgs boson is intrinsically linked to the SM contributions to the baryogenesis it is a good candidate to look for additional CPV

- What do we know about the Higgs boson now?
  - Discovery announced in 2012 by the ATLAS and CMS experiments – over 10 years ago
  - Established couplings to 3rd generation fermions
  - Coupling to W and Z well studied since Run 1
  - More recently studied are decays to muons and charm quarks, and evidence for Zγ has been established





Nature 607, 52–59 (2022)

CP violation in the Higgs sector

- Higgs boson predicted to have spin-parity $0^+ \rightarrow$ direct coupling to Z and W bosons
- CP violation in the Higgs sector:
  - HVV couplings (V= Z,W bosons)
    - studied in 4 lepton final state / VBF production

      Phys. Rev. D 104 (2021) 052004 Phys. Rev. D 108 (2023) 032013

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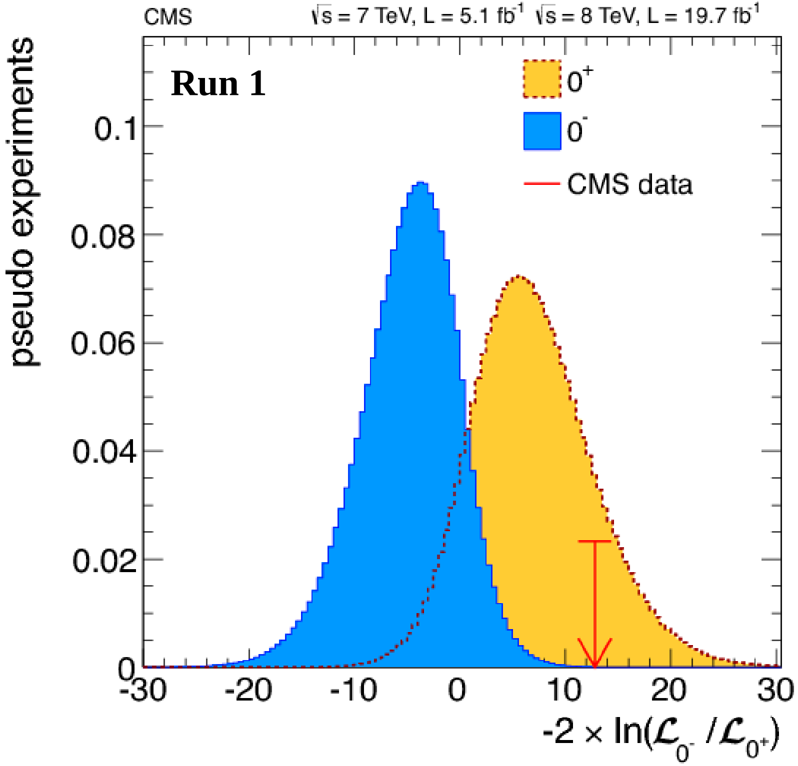
Pure CP odd excluded
already with Run 1 data →
search for anomalous couplings



Phys. Rev. D 89 (2014), 092007

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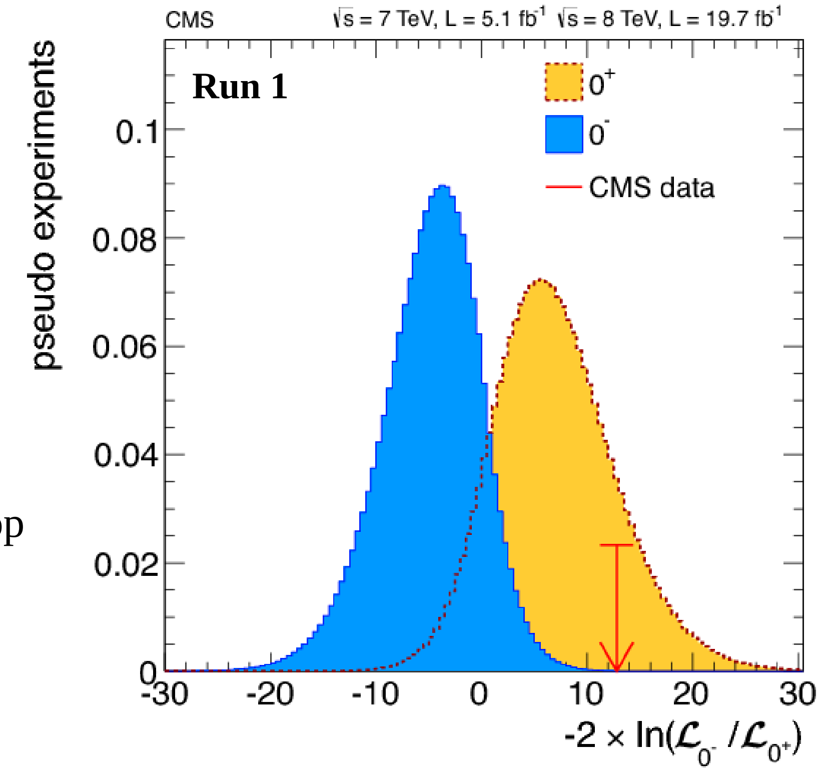
  - Yukawa coupling of Higgs to fermions
    - gg → H +jets: effective Higgs-gluon coupling via top quark loop
      - Phys. Rev. D 104 (2021) 052004



Phys. Rev. D 89 (2014), 092007

CP violation in the Higgs sector

- Higgs boson predicted to have spin-parity 0^+ → direct coupling to Z and W bosons
- CP violation in the Higgs sector:
  - HVV couplings (V= Z,W bosons)
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      Phys. Rev. D 104 (2021) 052004   Phys. Rev. D 108 (2023) 032013

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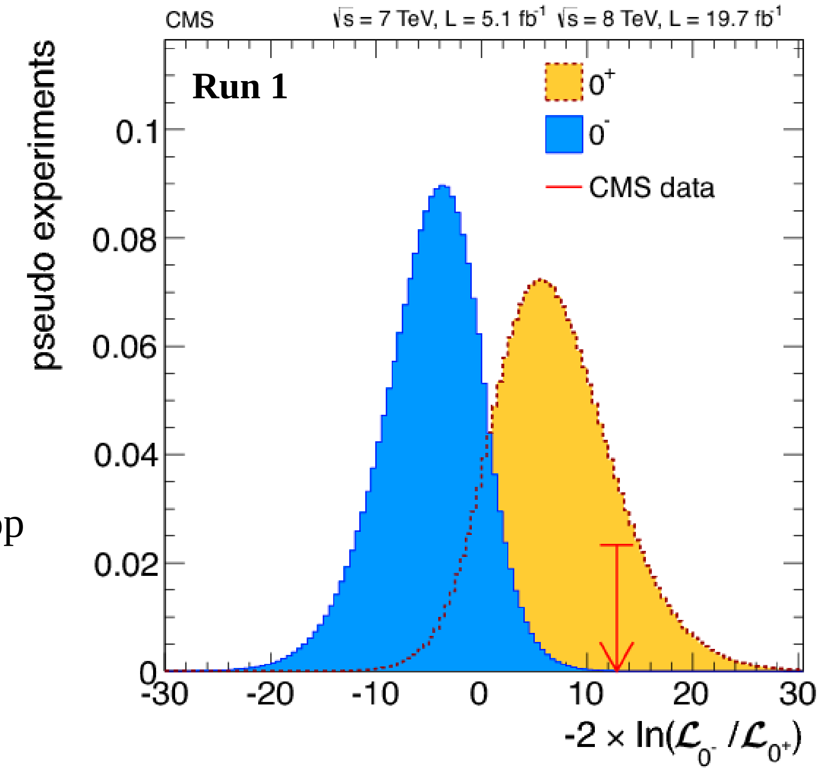

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      Phys. Rev. D 104 (2021) 052004 Phys. Rev. D 108 (2023) 032013

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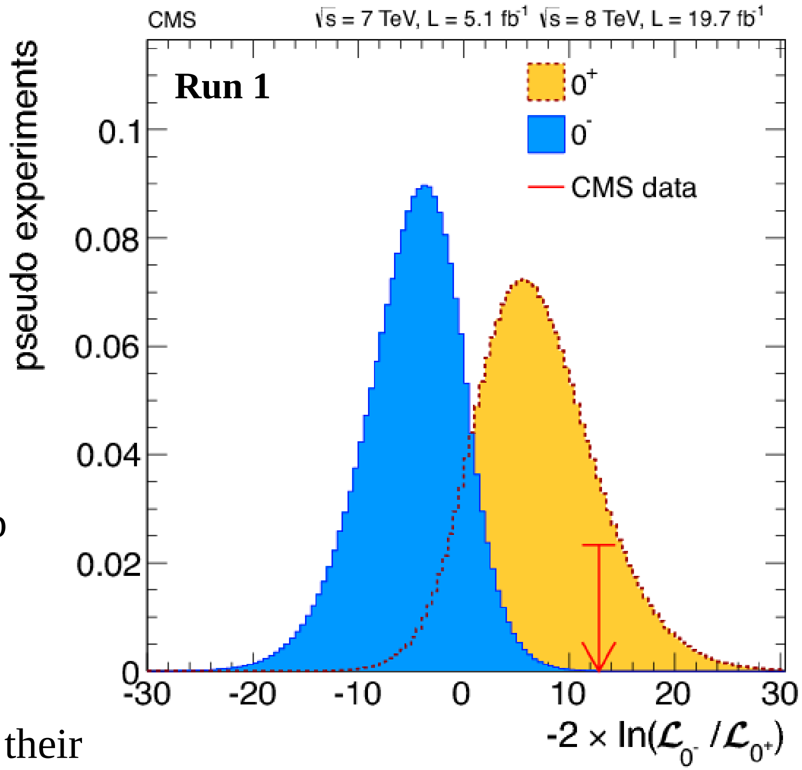
    - H → ττ decays: exploit spin correlation between tau leptons and their decay products
      - JHEP 06 (2022) 012



Phys. Rev. D 89 (2014), 092007

CP violation in HVV (and ggH)

- Investigating CP violation in HVV couplings with an EFT approach
  - Amplitude for Higgs coupling to two spin 1 particles (VV= WW, ZZ, Zγ, γγ, gg etc.) with operators up to dimension 6
  - Tree level CP-even coupling (=0 if absent in SM) — CP-even anomalous higher order couplings

$$\mathscr{A}(HVV) \simeq \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV} (q_1 + q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_V^2 \varepsilon^*_{V1} \varepsilon^*_{V2}$$

$$+ a_2^{VV} f^{*(1)}_{\mu\nu} f^{*(2)\mu\nu} + a_3^{VV} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2)\mu\nu} ,$$

CP-even anomalous coupling — CP-odd anomalous coupling

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$$+ a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu} ,$$

CP-even anomalous coupling

CP-odd anomalous coupling

$$f_{a3} = \frac{\sigma(a_3=1, a_{i!=3}=0)}{\sum_i \sigma_i}$$

  - Effect on cross-section parametrized as the fractional contribution of the anomalous coupling to the total cross-section

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  $$f_{a3} = \frac{\sigma(a_3 = 1, a_{i!=3} = 0)}{\sum_i \sigma_i}$$

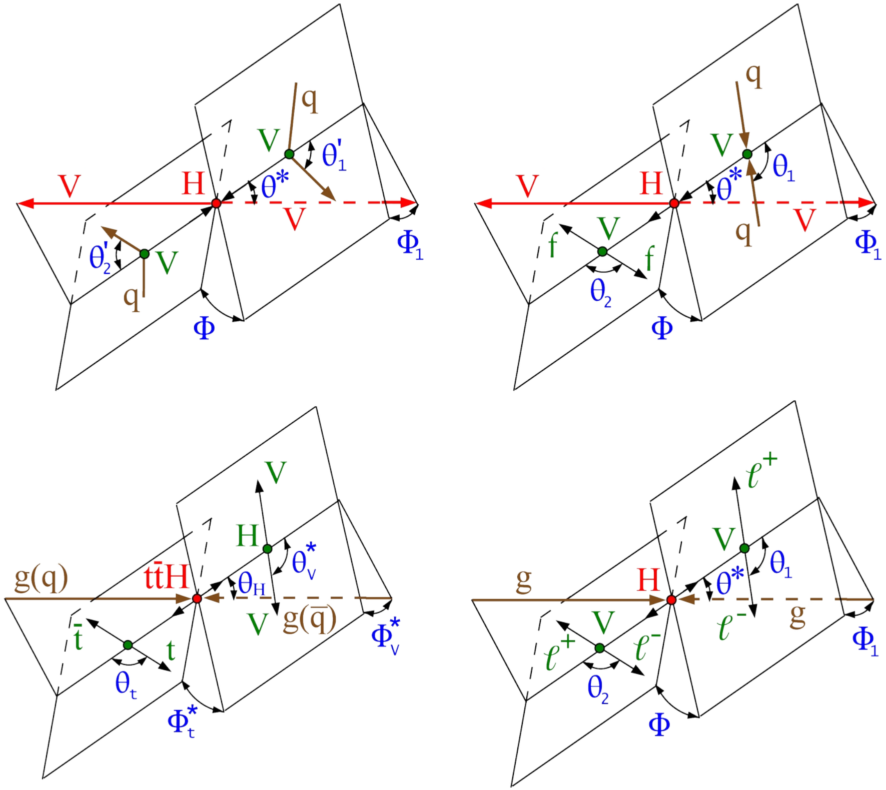
  > Effect on cross-section parametrized as the fractional contribution of the anomalous coupling to the total cross-section

- Theoretical approach includes also Hγγ and Hgg with tree level coupling being set to 0

CP violation in HVV (and ggH)

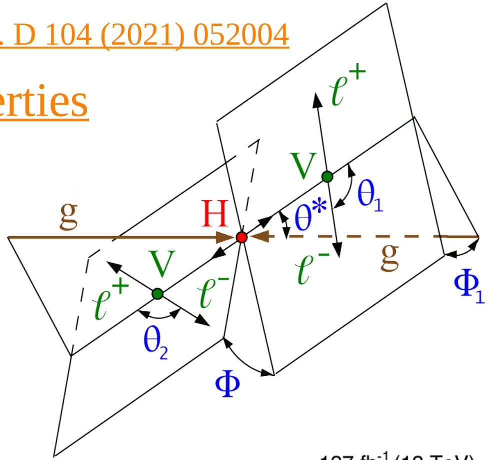
- Higgs direct and effective couplings to vector bosons studied both in production and decay
- Decay:
  - Target process: **H → VV → 4 leptons**
  - Uses kinematics of leptons in the final state
- Production:
  - Target process: **Vector Boson Fusion (VBF)**
  - Higgs CP nature affects kinematics of jets from the initial state
  - Studied in Higgs decays to ττ, 4 leptons and γγ

Phys. Rev. D 104 (2021) 052004



CP violation in H → 4 leptons

- Higgs decays to 4 leptons were used already in the Higgs discovery [Phys. Rev. D 104 (2021) 052004](#)
- Excellent handle to measure Higgs properties: mass, spin, width, and CP properties
  - Used in Run 1 to exclude pure pseudoscalar HVV coupling and investigate other spin hypotheses



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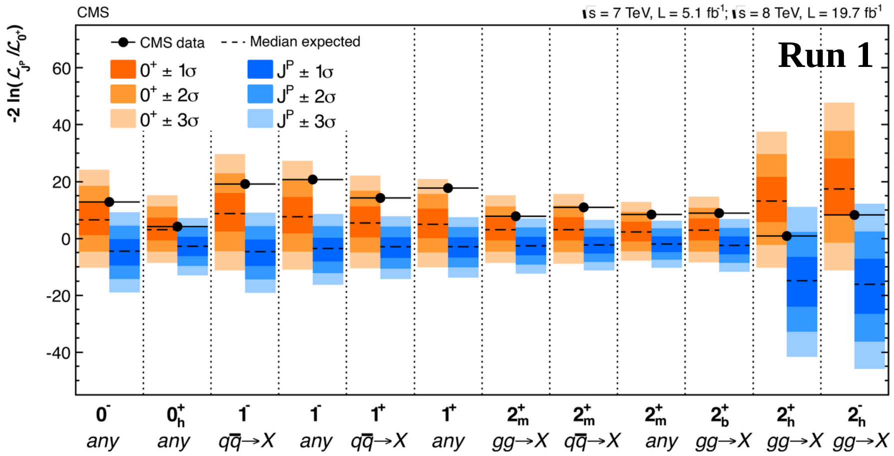
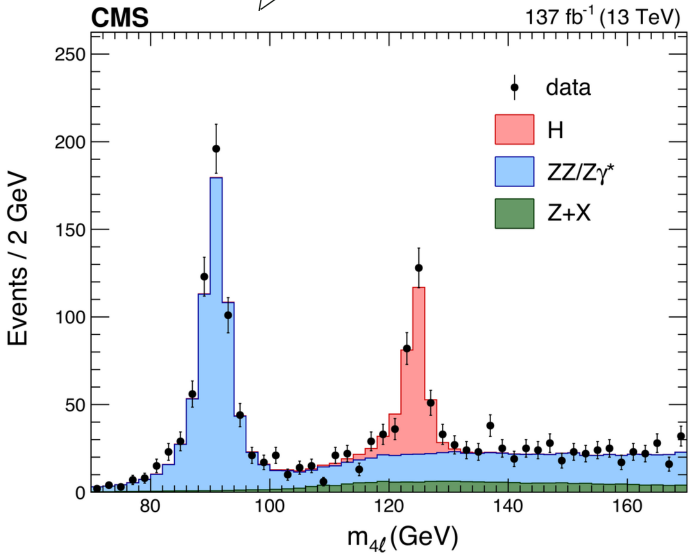


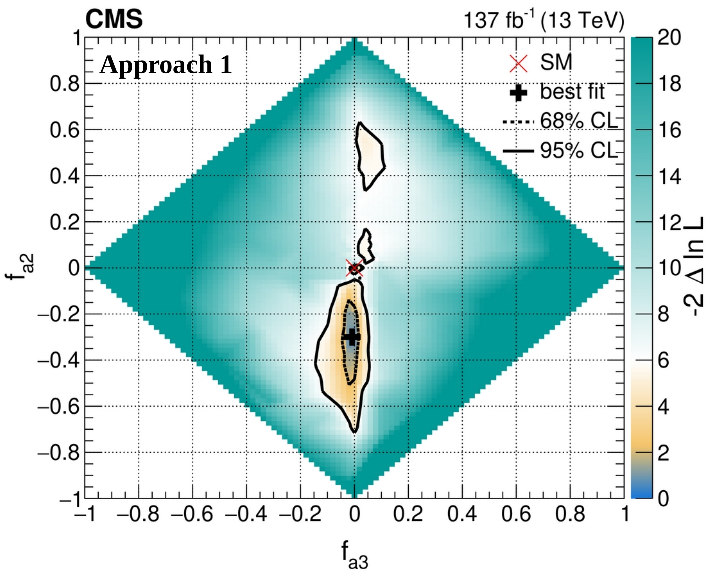


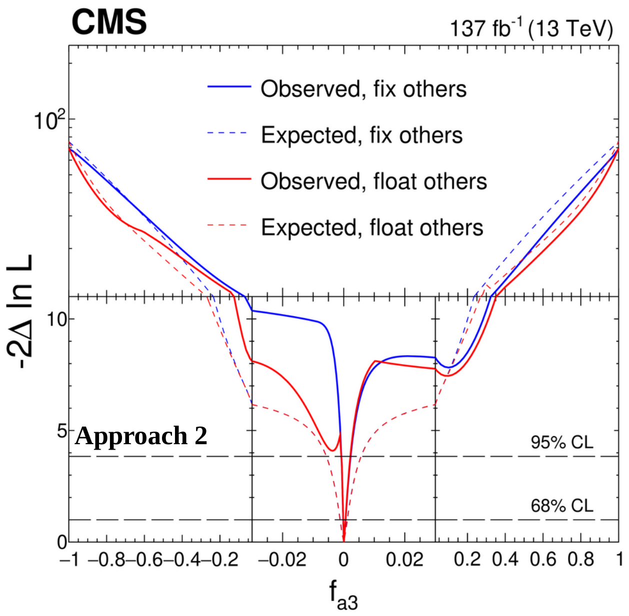
  - Analysis with full Run 2 also targets interference terms of anomalous couplings with other hypothesis using MVA classifiers

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})\ \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}}$$

- Constraints expressed in several scenarios based on the possible symmetries imposed on the couplings:
  - Approach 1: $a_i^{WW} = a_i^{ZZ}$
  - Approach 2: SU(2) × U(1) symmetry

Phys. Rev. D 104 (2021) 052004

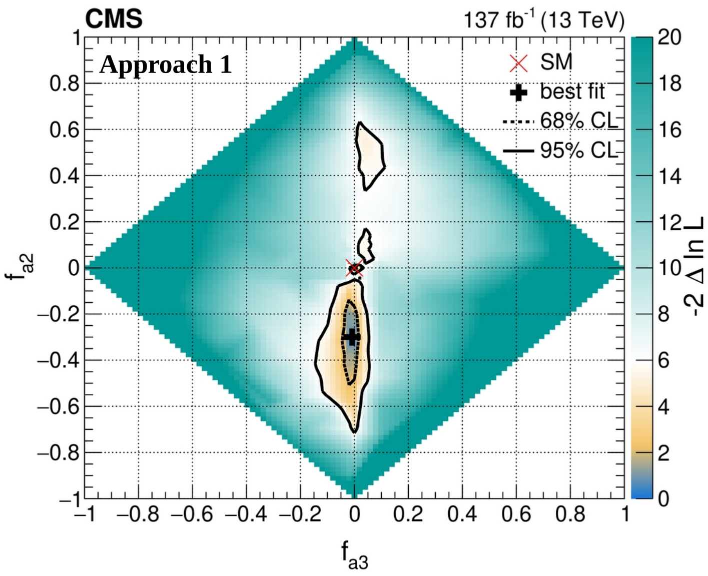


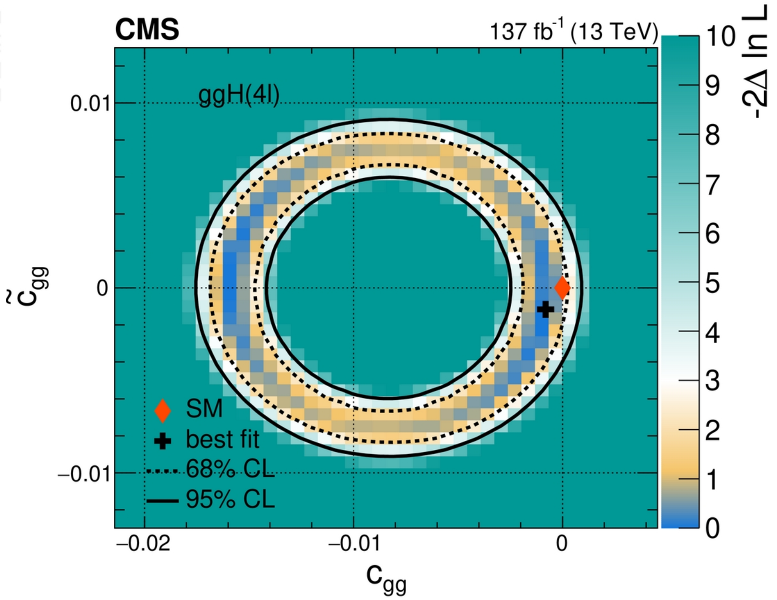


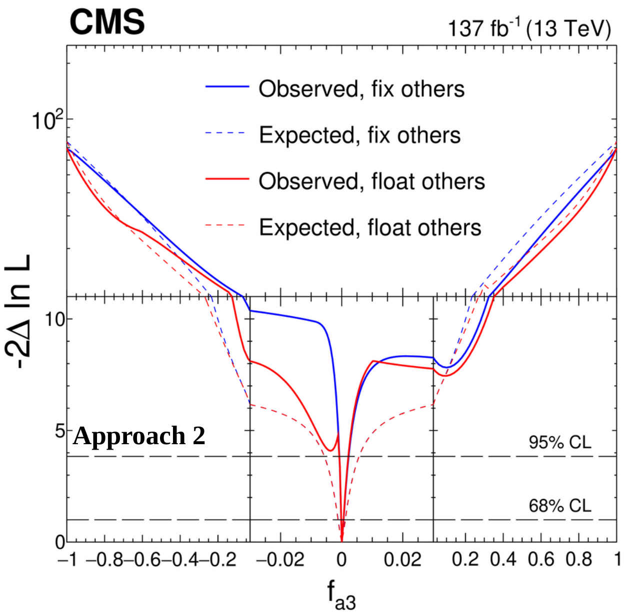
CP violation in $H \to 4$ leptons

- Constraints expressed in several scenarios based on the possible symmetries imposed on the couplings:
  - Approach 1: $a_i^{WW} = a_i^{ZZ}$
  - Approach 2: SU(2) × U(1) symmetry
- The 4 lepton final state is also used to target Hgg and Htt couplings

Phys. Rev. D 104 (2021) 052004

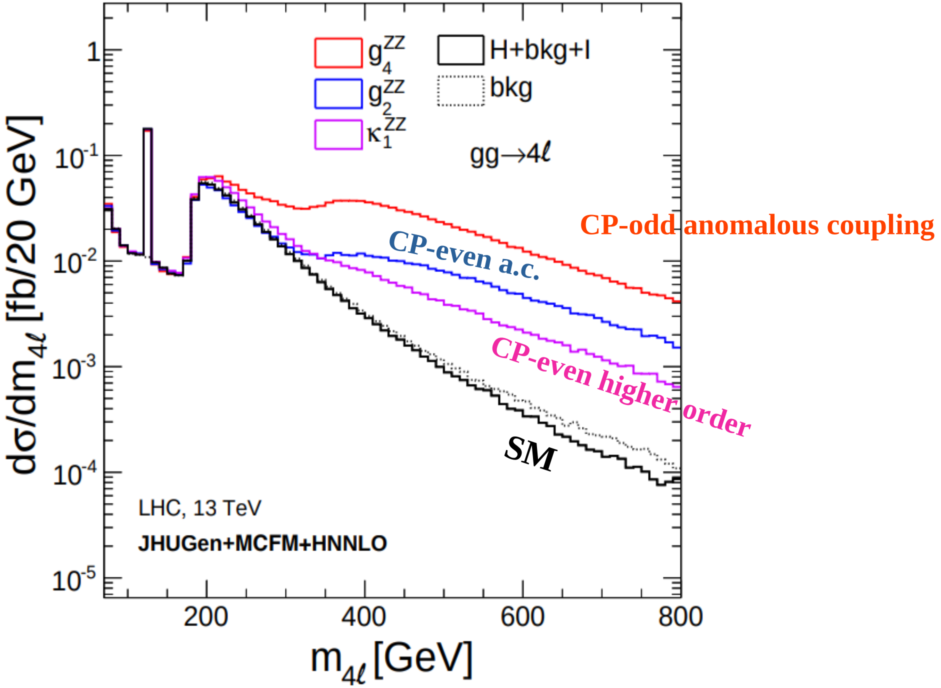






Combination with off-shell H → 2l2ν/4 lepton

- Off-shell Higgs production can provide additional sensitivity to anomalous couplings
  - CP-odd anomalous coupling constrained between [-4.6,11] × 10^{-4} at 95% CL



Phys.Rev.D102(2020)056022

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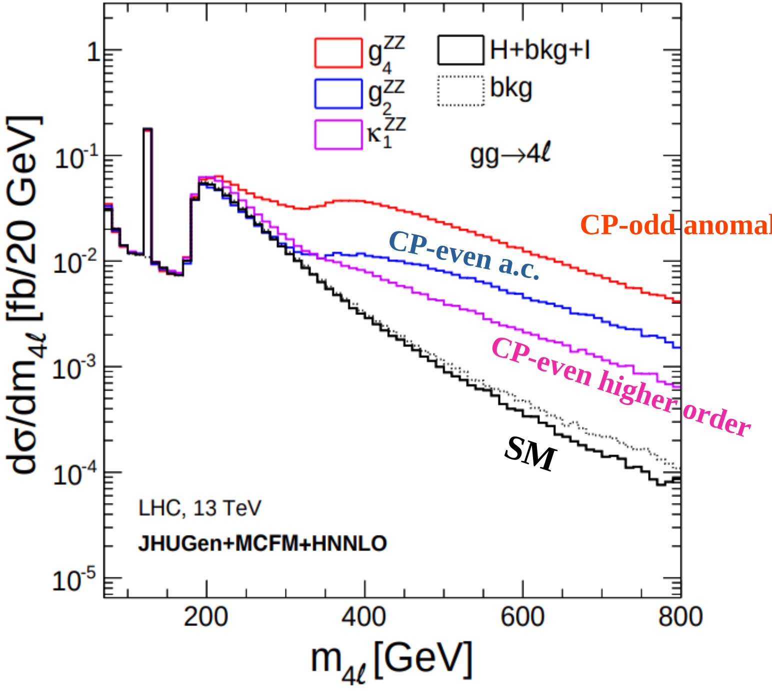
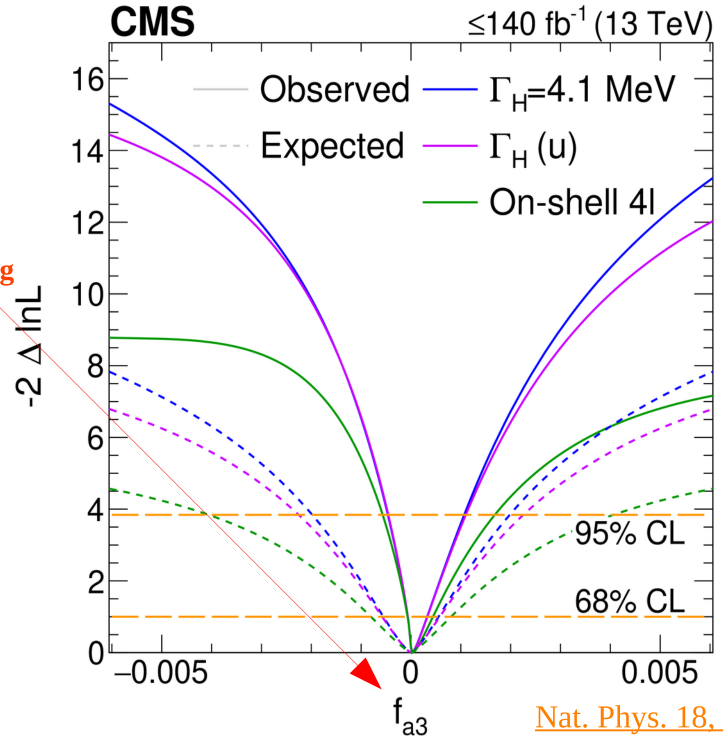


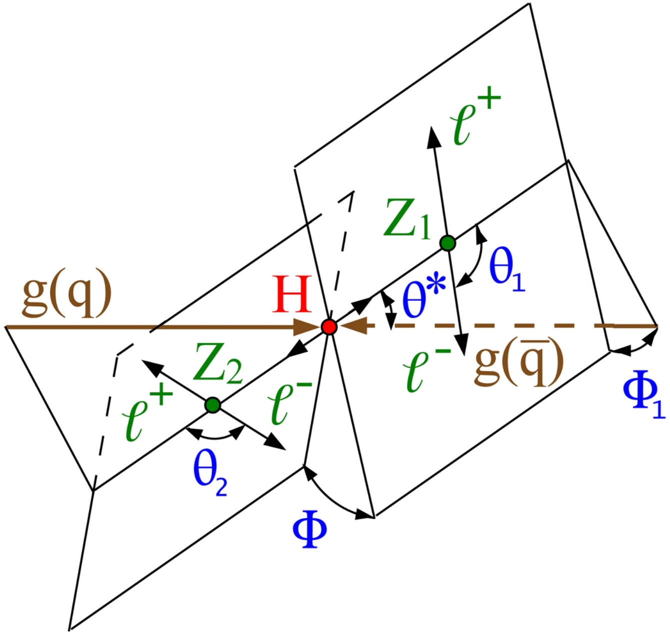
Phys.Rev.D102(2020)056022



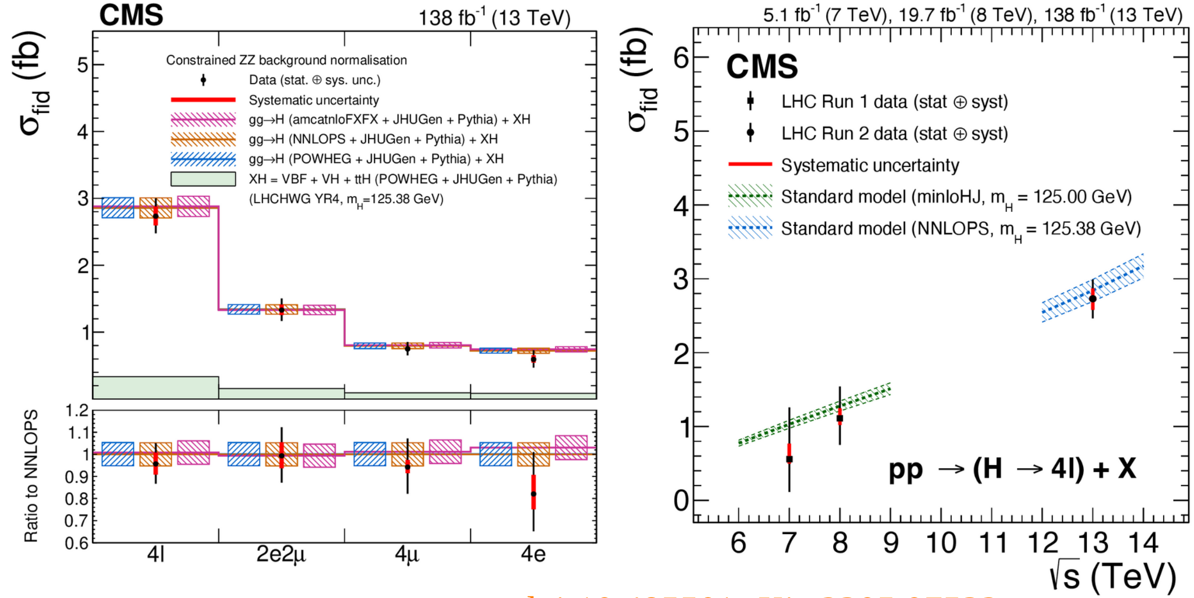
Nat. Phys. 18, 1329–1334 (2022)

H → ZZ* → 4 leptons differential cross-section

- H → 4 leptons also studied differentially
- Differential measurement performed with respect to angular variables, Higgs momentum, and accompanying jet pT → sensitivity to loop correction and BSM operators



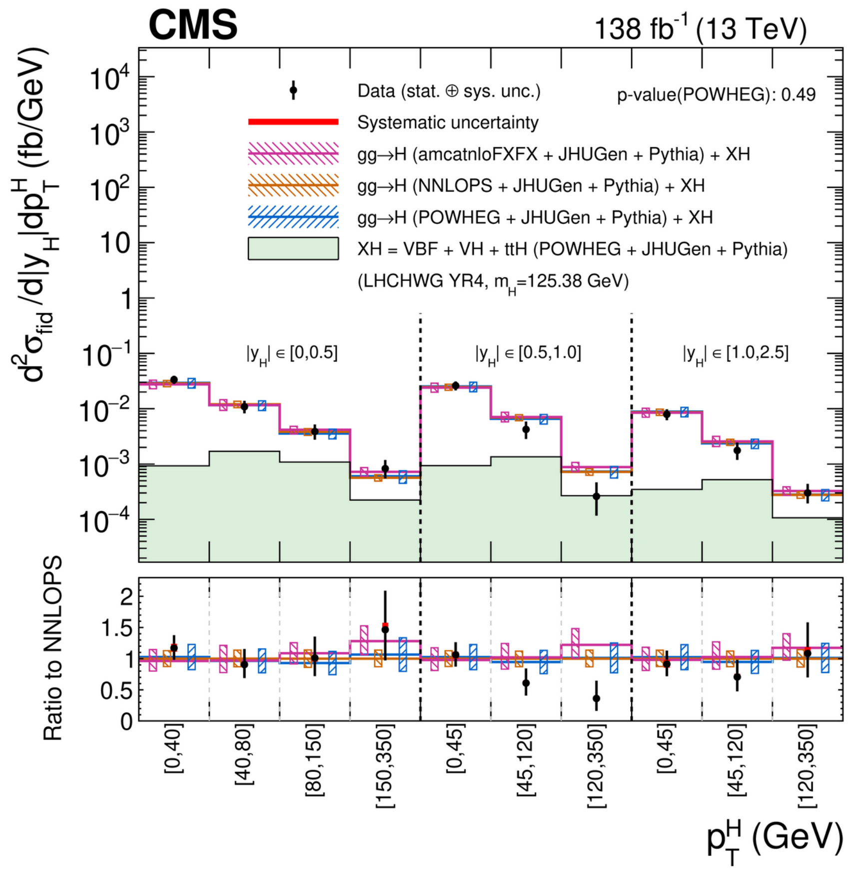
Inclusive fiducial cross-section

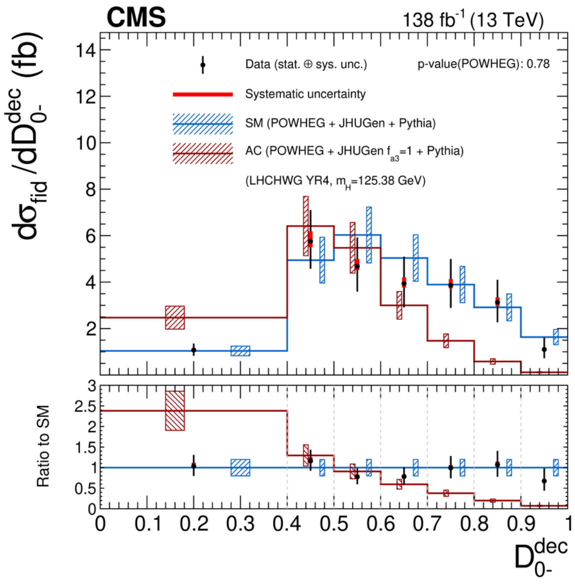


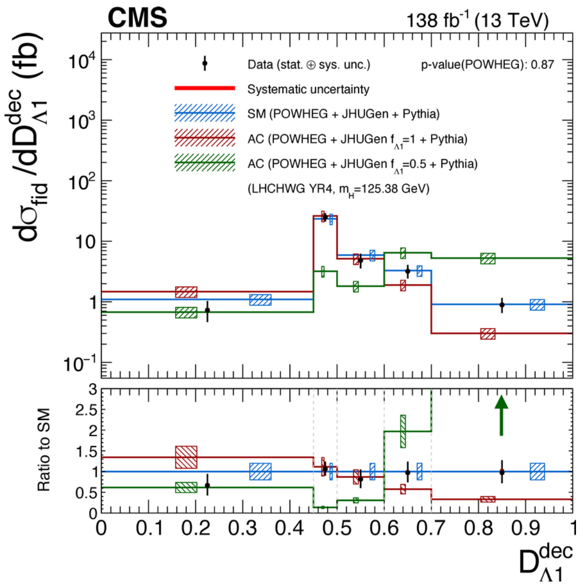
[doi:10.48550/arXiv.2305.07532](https://doi.org/10.48550/arXiv.2305.07532)

$H \rightarrow ZZ^* \rightarrow 4$ leptons differential cross-section

- The increased sensitivity allows to constrain better CP-violating terms and validate our current theoretical understanding





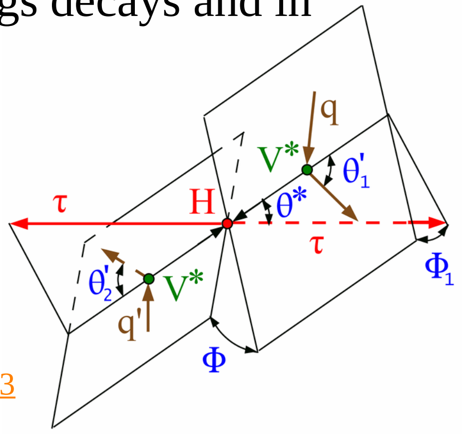


doi:10.48550/arXiv.2305.07532

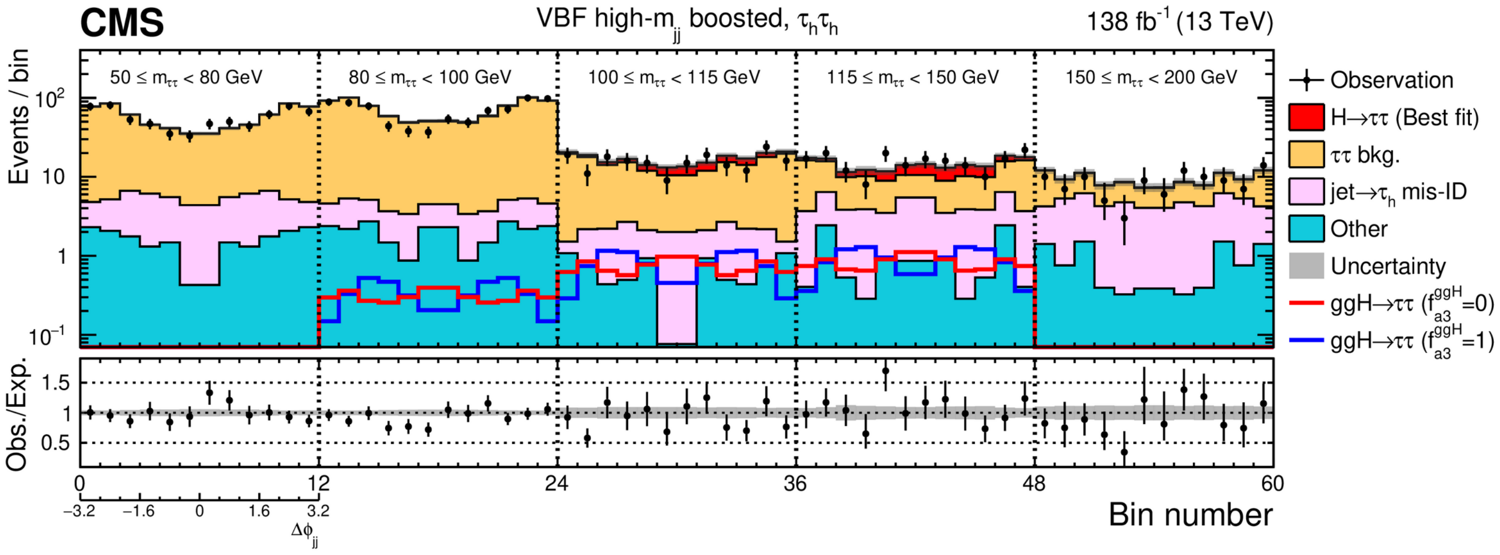
- All differential distributions agree with the latest SM predictions

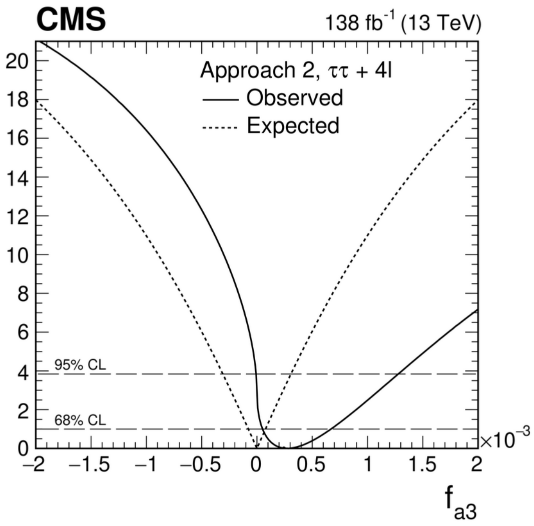
VBF production with H → ττ decays

- Higgs decays to tau leptons can be used as a probe both for CP violation in Higgs decays and in combination with H → 4l for the search of CP violation in production
  - When studying Higgs CP in production the H → ττ vertex is kept SM-like
  - The azimuthal angle between jets coming from the initial state offers sensitivity to the Higgs CP quantum number

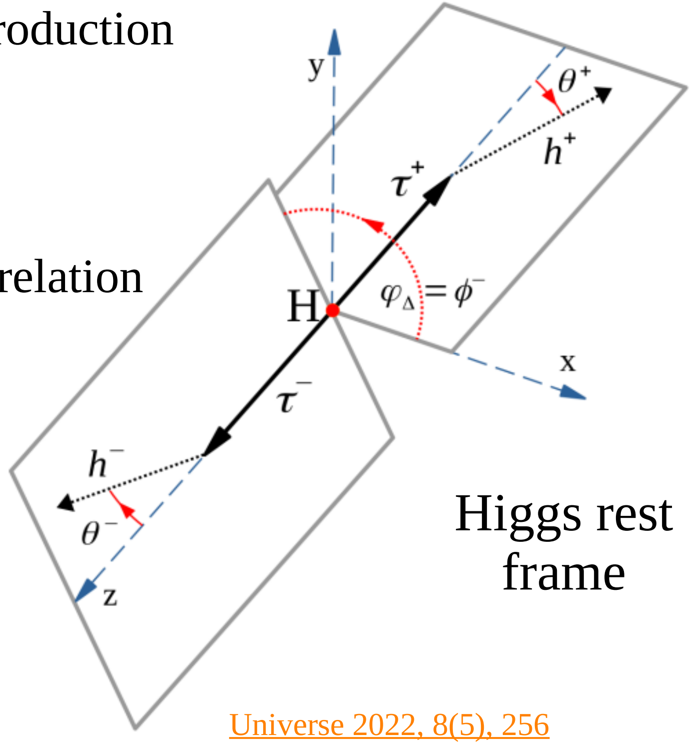


Phys. Rev. D 108 (2023) 032013





- Higgs Yukawa interaction can be parametrized as follows:
  - $\mathcal{L}_{Y,f} = -\frac{m_f}{v}\bar{\psi}_f(\kappa_f + i\gamma^5\tilde{\kappa}_f)H\psi_f$
  - Higgs direct coupling to top quarks investigated in ttH and tH production
    - CP-odd anomalous coupling affects top quark(s) kinematics
    - Investigated with MVA techniques
  - Higgs coupling to τ leptons investigated in decays via τ spin correlation
    - CP mixing encoded in $\alpha^{H\tau\tau}$:
      - $\kappa_\tau = \sqrt{\mu^{\tau\tau}}\cos\left(\alpha^{H\tau\tau}\right)$
      - $\tilde{\kappa}_\tau = \sqrt{\mu^{\tau\tau}}\sin\left(\alpha^{H\tau\tau}\right)$
    - Mixing angle can be accessed via the angle between τ decay planes



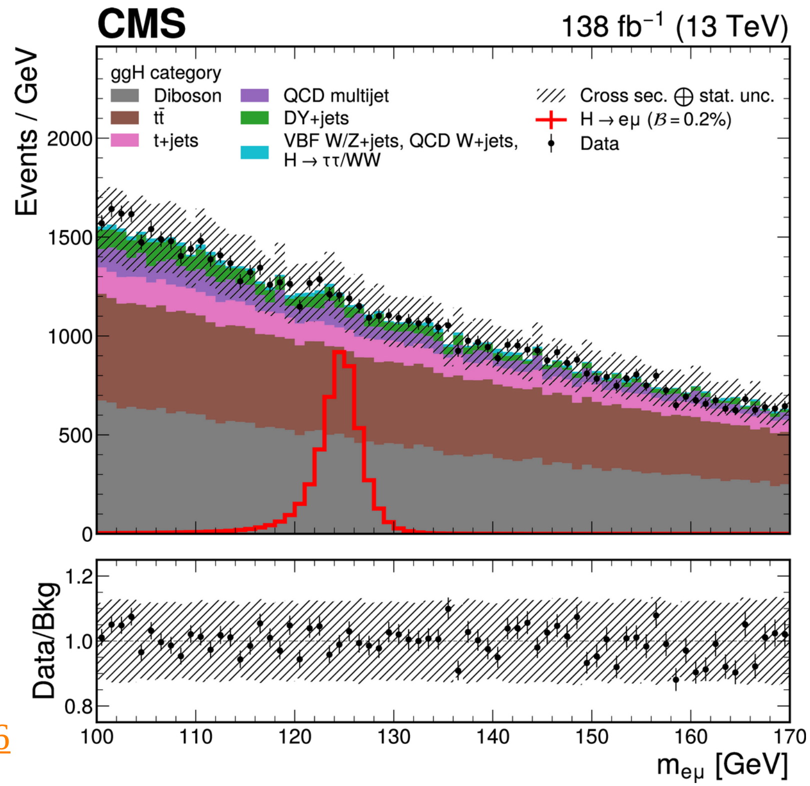
Higgs rest frame

Universe 2022, 8(5), 256

Lepton Flavor Violation

- Beyond the coupling to top quarks and tau leptons we also look for lepton flavor violation
  - Lepton flavor is conserved → the Yukawa matrix is diagonal wrt lepton generations

- In analogy with the CKM matrix we can look for CP violation also by studying off-diagonal elements of the lepton Yukawa matrix
  - A search for $H \rightarrow e\mu$ decays can hint towards sources of new physics
  - Search performed in mass window $110 < m_{e\mu} < 160$ GeV
  - Analysis exploits BDT to improve S/B ratio in two signal categories: ggH and VBF

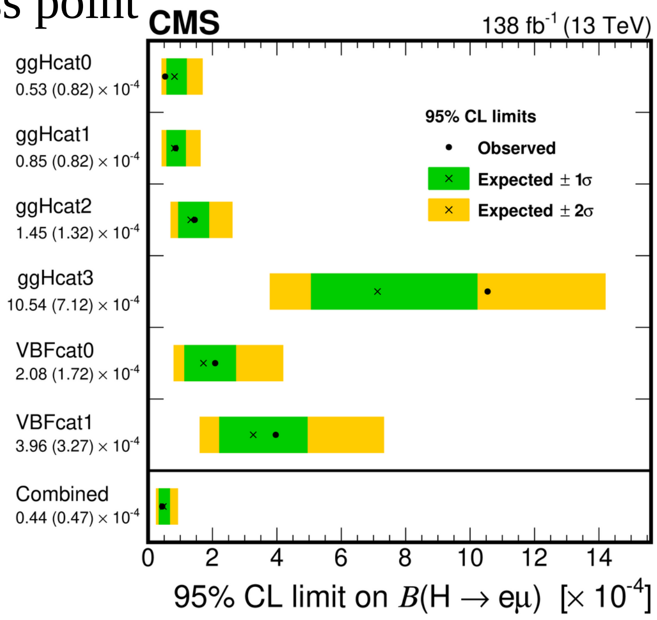


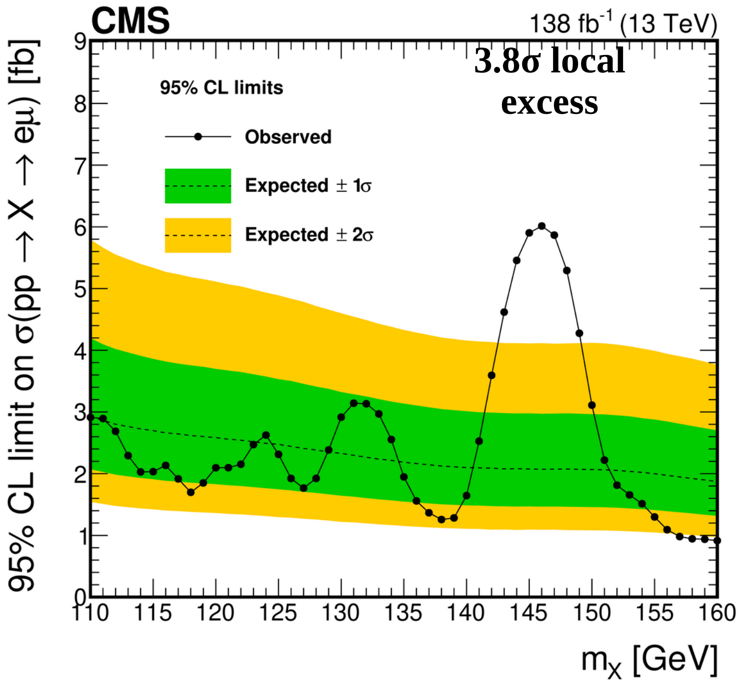
doi:10.48550/arXiv.2305.18106

H → eμ LFV decays

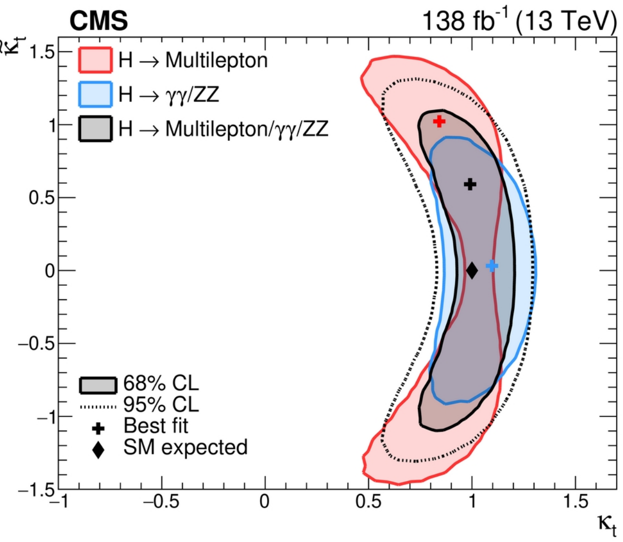
- Constraints on the H → eμ branching fraction determined for SM-like H(125) and more generally for generic scalar particle X of mass between 110 and 160 GeV
  - **First direct search for eμ resonance in chosen mass range**
- Observed (expected) limit on $\mathcal{B}(H \to e\mu) < 4.4\ (4.7) \times 10^{-5}$ at 95% for a SM-like Higgs
- The X → eμ search presents a local (global) excess of 3.8σ (2.8σ) for the 146 GeV mass point
- The best fit signal for this mass point has a cross-section of 3.89±1.25 fb
- More data is needed to investigate this excess

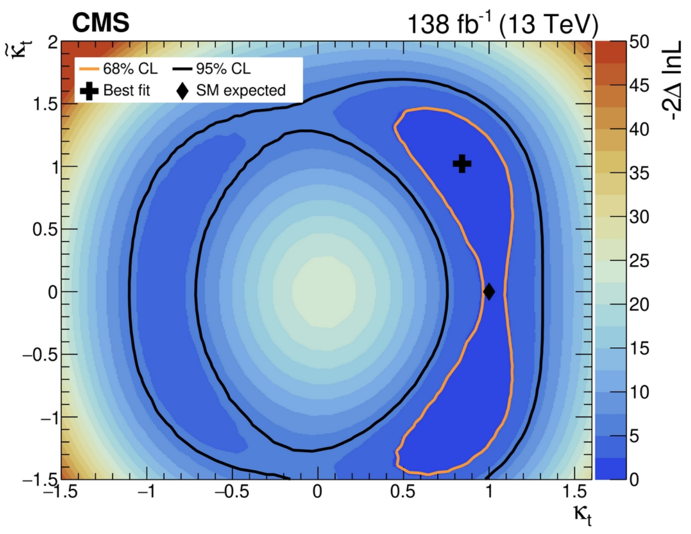
doi:10.48550/arXiv.2305.18106





CP violation in Higgs-top couplings

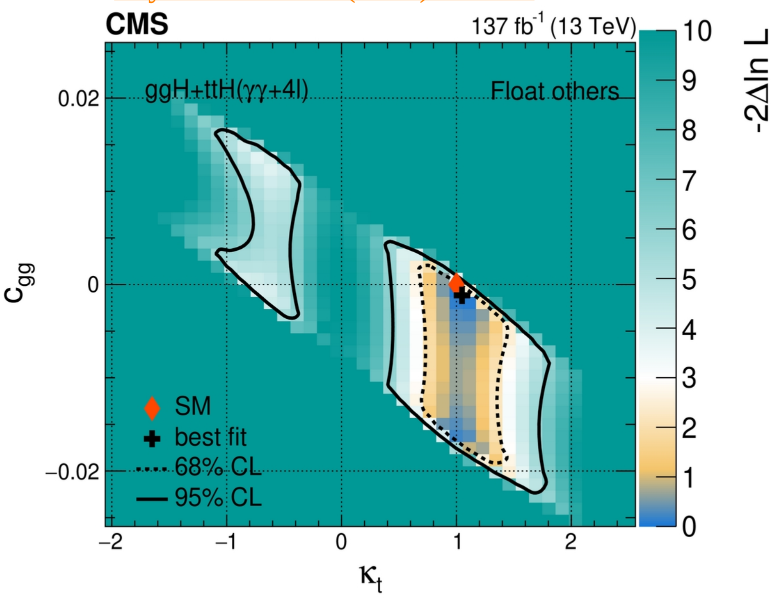




JHEP 07 (2023) 092

- Higgs couplings are proportional to the mass → enhanced coupling with the top quark → target ttH and tH production
- Htt coupling CP structure was probed in the H→ WW, ττ (multilepton) γγ and ZZ decays

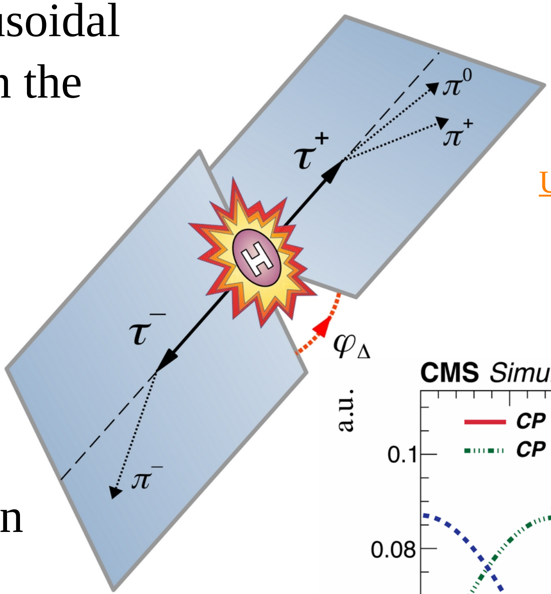
Phys. Rev. D 104 (2021) 052004



- Top quark loop has leading contribution to ggH effective coupling → simultaneous fit of CP-odd contribution ggH and ttH production
  - Combination performed under hypothesis that ggH loop is dominated by top quark

- The cross section of the H → ττ decay acquires a synusoidal dependence on the azymuthal angle spanned between the two τ polarimeters

$$\frac{d\sigma}{d\varphi_{CP}} \propto const - \cos(\varphi_{CP} - 2\varphi_{\tau\tau})$$

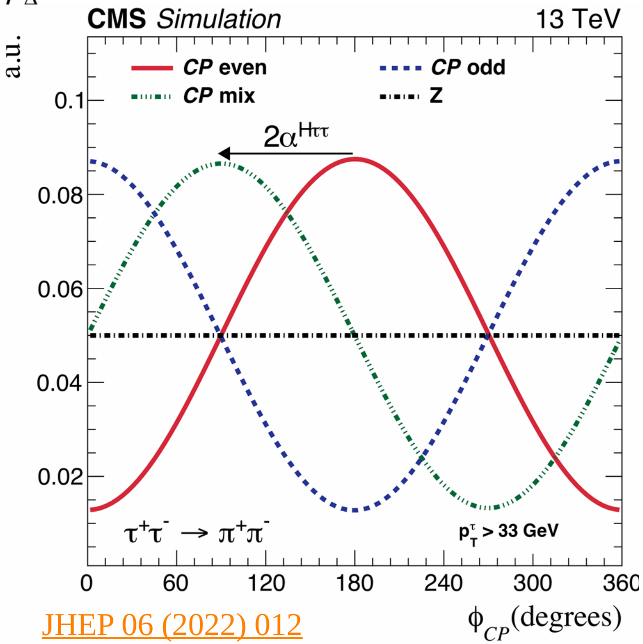


Universe 2022, 8(5), 256

- CP mixing appears as a **phase-shift** in the distribution

- Measuring the Higgs CP mixing angle requires accessing the azymuthal difference between the polarimetric vectors

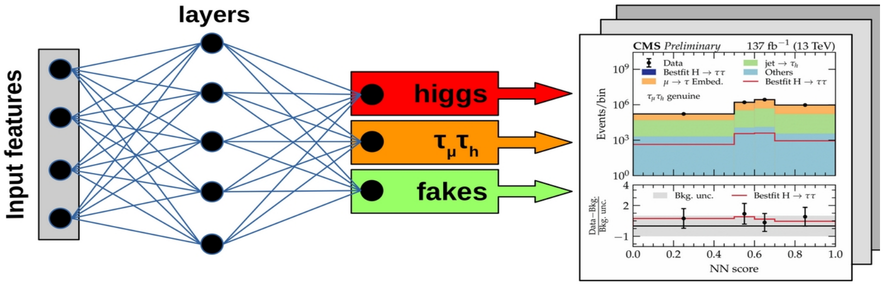
- This angle can be generalized to the angle between the τ decay planes, an **acoplanarity angle**



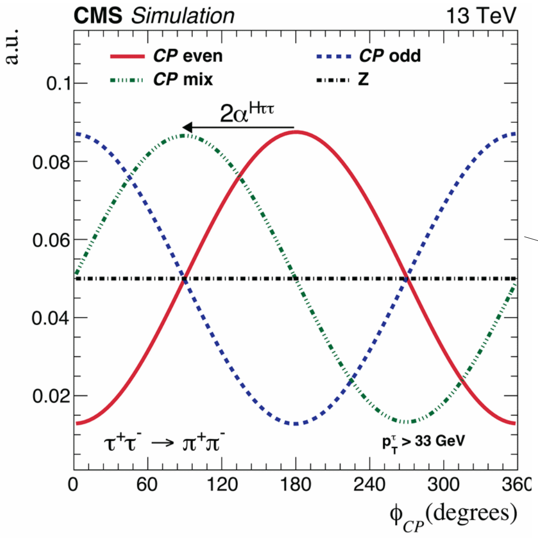
JHEP 06 (2022) 012

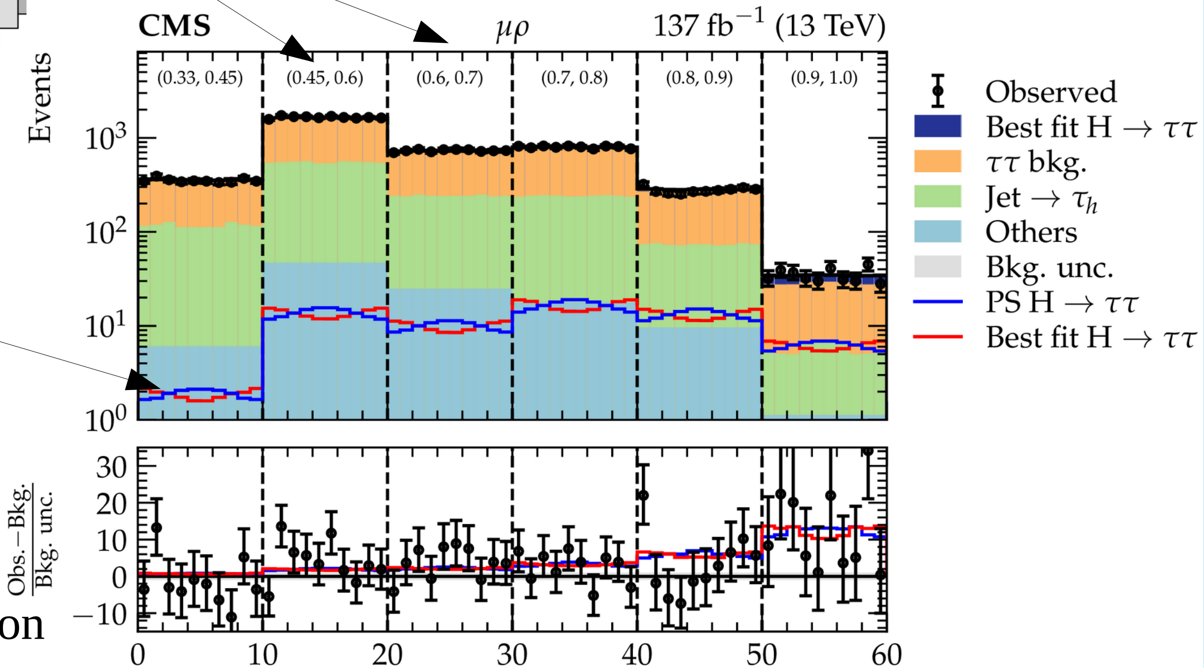
CP violation in H→ ττ decays

doi:10.3204/PUBDB-2021-03550



- Use of ML classifiers to identify the Higgs boson

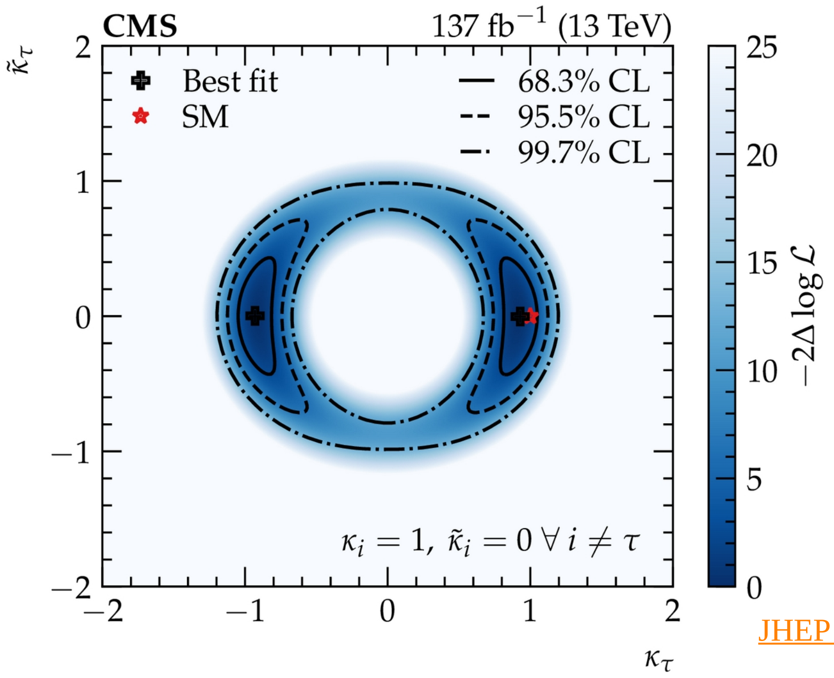




- Modulation of the differential cross-section can be used to probe the CP mixing angle

JHEP 06 (2022) 012

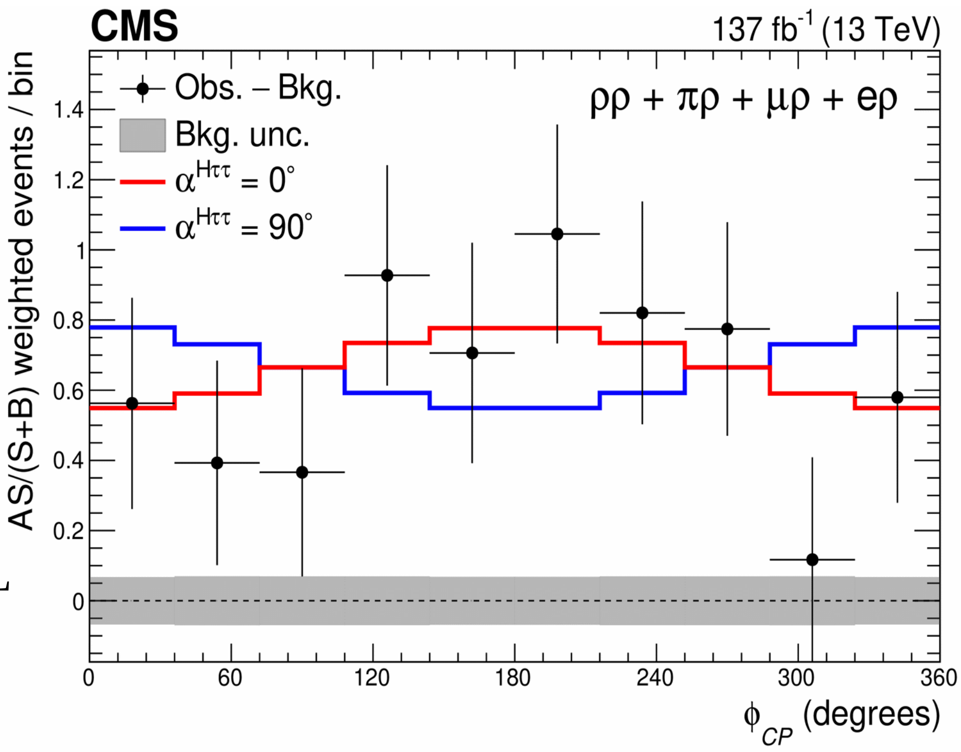
CP-even/odd couplings



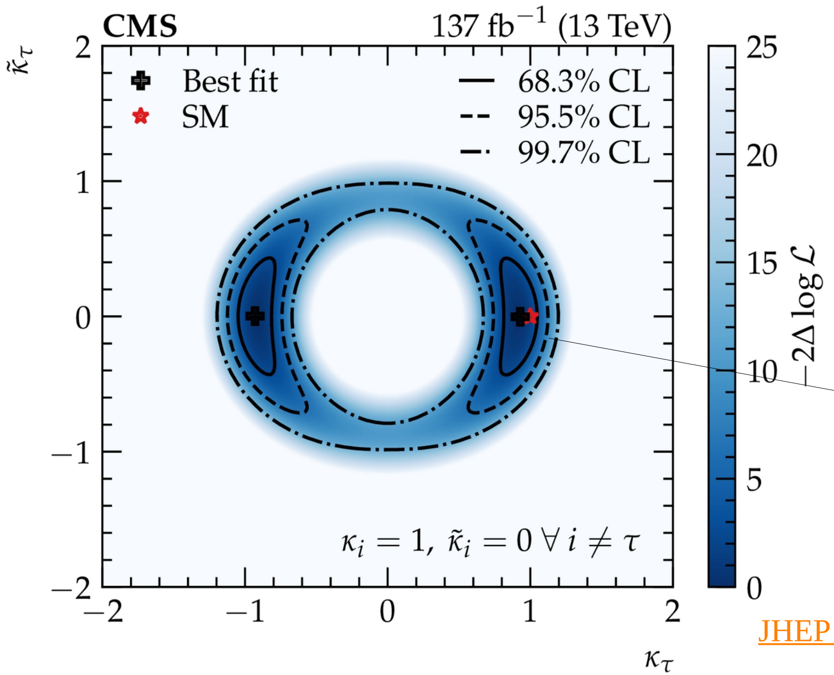
JHEP 06 (2022) 012

- CP mixing angle:

$$\alpha^{H\tau\tau} = -1 \pm 19\,(\text{stat}) \pm 1\,(\text{syst}) \pm 2\,(\text{bin-by-bin}) \pm 1\,(\text{theo})^\circ$$

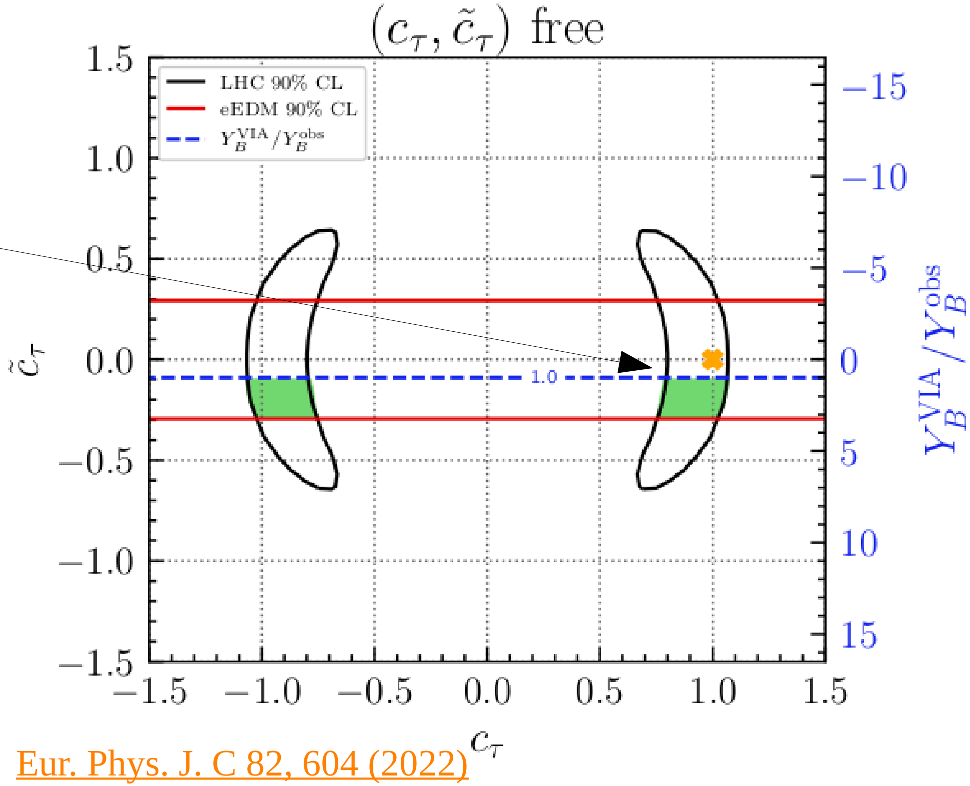


- Couplings consistent with SM hypothesis at 68% CL
  - Observed (exp.) exclusion of pure CP-odd hypothesis significance = **3.0σ** (2.6σ)



JHEP 06 (2022) 012

- Interesting for MSSM interpretation to test CP mixing angle of 7° → good target for future measurement



Eur. Phys. J. C 82, 604 (2022)

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Summary and prospects

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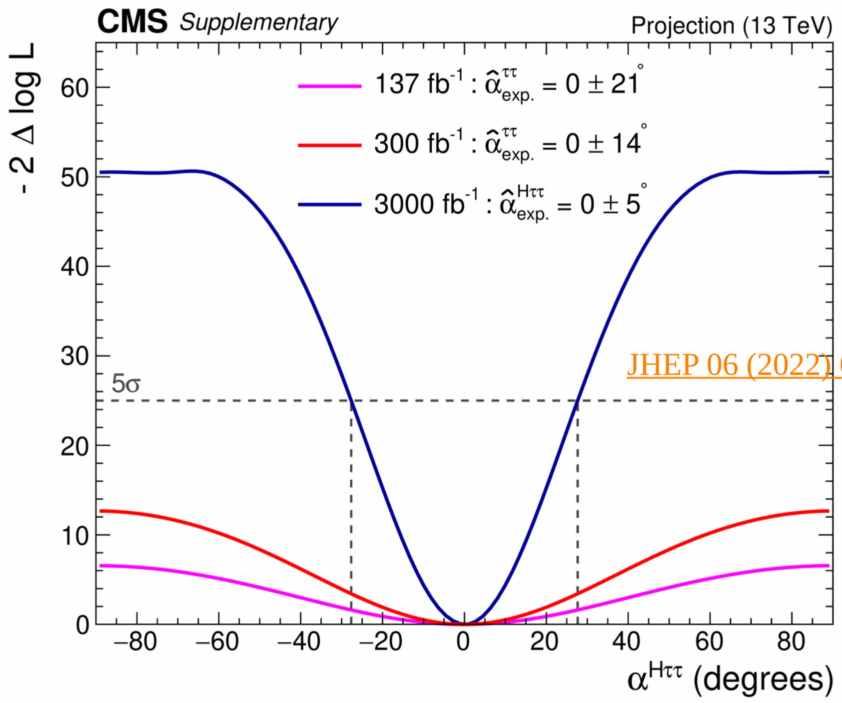
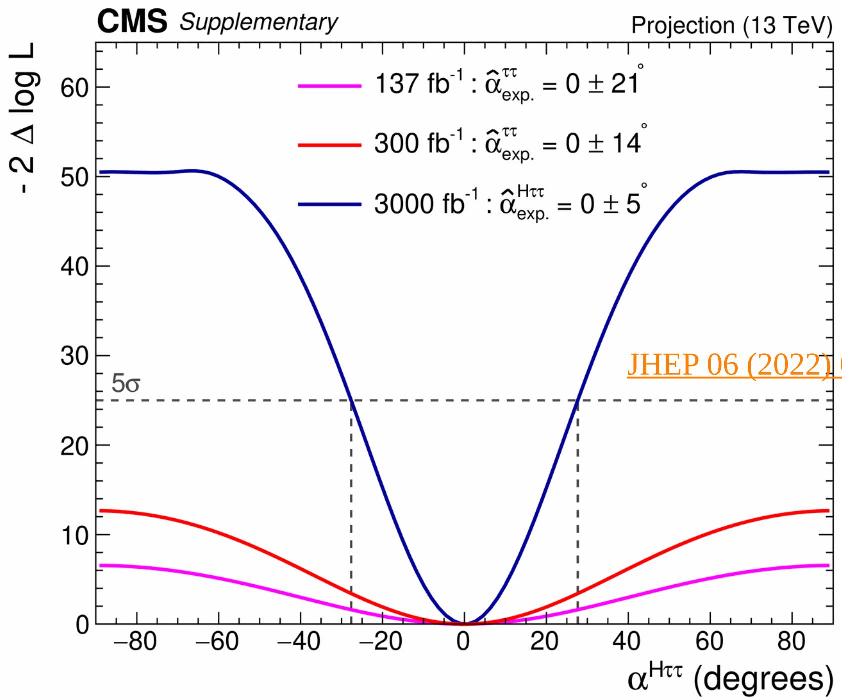
  - Htt: $|f_{CP}^{Htt}| < 0.55$ at 68% CL
  - Hττ: tan $(\alpha^{H\tau\tau}) < 0.36$ at 68% CL
- All analyses exclude pure CP-odd hypothesis and agree with SM prediction



JHEP 06 (2022) 012

Summary and prospects

- Higgs boson couplings have been investigated looking for CP-odd contributions which could help explaining the baryon asymmetry in the Universe
- Exclusion limits for pure CP-odd Higgs couplings:
  - HVV couplings: $|f_{a3}| <$ O(10^{-3}) at 95% CL in combination with off-shell production
  - Htt: $|f_{CP}^{Htt}| < 0.55$ at 68% CL
  - Hττ: tan ($\alpha^{H\tau\tau}$) < 0.36 at 68% CL
- All analyses exclude pure CP-odd hypothesis and agree with SM prediction
- Promising future for CP violation studies at Run3, HL-LHC, and in combination with ATLAS



JHEP 06 (2022) 012

Continuing

in **Run 3**

CP Violation in the Higgs Sector:

Understanding Matter-Antimatter Asymmetry

Keep looking for more!

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