Modern LHC Physics and Global Analyses

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Modern LHC physics

Classic motivation

- dark matter?
- ************?
- origin of Higgs field?

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LHC physics

- fundamental questions
- huge data set
- first-principle, precision simulations
- complete uncertainty control

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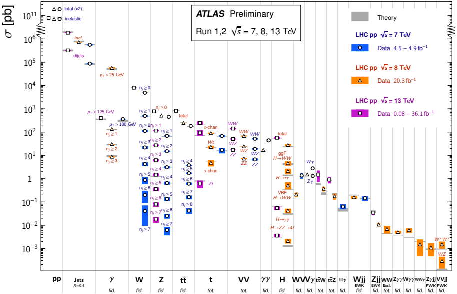
Successful past

- Higgs discovery
- measurements of event counts
- model-driven searches
- coupling measurements



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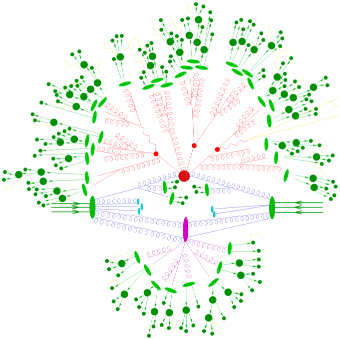
- start with Lagrangian
- calculate scattering using QFT
- simulate collisions
- simulate detectors

$\rightarrow$ LHC collisions in virtual worlds



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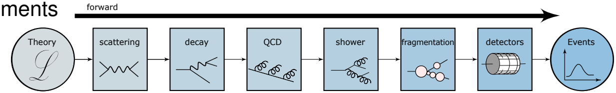
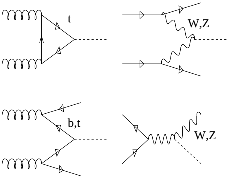
BSM searches

- compare simulations and data
- understand data systematically
- infer underlying theory [SM or BSM]
- publish useable results

$\rightarrow$ Experiment, theory, data science



Precision Higgs physics



How the LHC became a precision machine

- assume: narrow *CP*-even scalar
  Standard Model operators
- Lagrangian like non-linear symmetry breaking

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$

Production		Coupling		Decay
$gg \to H$ $gg \to H+j$ (boosted) $gg \to H^*$ (off-shell) $qq \to qqH$ $gg \to t\bar{t}H$ $qq' \to VH$	$\longleftrightarrow$	$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$	$\longleftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+\tau^-$ $H \to \gamma\gamma$ $H \to$ invisible

Brilliant Run 1 analyses, but...

1 predictions not renormalizable

2 no kinematic distributions

3 not testing Standrad Model

$\to$ Just an inspiring first step

Higgs-gauge operators

D6 Lagrangian for Run 2 [SMEFT]

- Higgs operators [renormalizable]

$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

- basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

- Higgs couplings [derivatives = momentum]

$$\begin{aligned} \mathcal{L}_{\text{D6}} = {} & g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ & + g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\ & + g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.}\right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots \end{aligned}$$

  plus Yukawa structure $f_{\tau,b,t}$

- one more operator for triple-gauge interactions

$$\mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\mu_\rho\right)$$

$\to$ Bosonic electroweak sector: 10 operators

LHC kinematics

Ideal LEP and flavor worlds

- unique EFT Lagrangian: linear realization matching unbroken phase
- chain of separated energy scales MeV $\ll$ GeV $\ll v \ll \Lambda_{\text{BSM}}$

$\to$ systematic expansion in E/Λ and α [example: ew precision data]

LHC realities

- range of (partonic) energy scales [making things worse $v \sim E_{\text{LHC}}$]
- limited precision

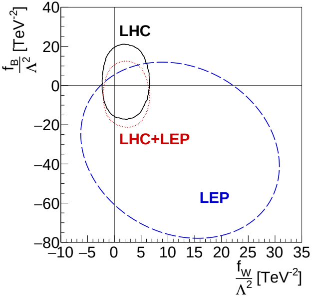
$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda_{\text{BSM}}^2} \approx 10\% \qquad \stackrel{g=1}{\Longleftrightarrow} \qquad \Lambda \approx 400 \text{ GeV}$$

- reach from high-energy tails

LHC vs LEP

- triple vertices g_1, κ, λ vs operators
- LEP driven by precision
  LHC driven by energy

$\to$ LHC the leading SMEFT machine from Run 1



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LHC theory task: SMEFT

- keep self respect
- SMEFT analysis just limit setting
- representation of classes of UV-models

$\to$ Goal: describe LHC using QFT

Fermionic operators

Enlarging operator basis

- gauge-fermion operators visible [$qqVH$ vertex]

$$\mathcal{O}_{\phi L}^{(1)} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{L}_i \gamma^\mu L_i) \qquad \mathcal{O}_{\phi e}^{(1)} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{e}_{R,i} \gamma^\mu e_{R,i}) \qquad \mathcal{O}_{\phi L}^{(3)} = \phi^\dagger \overleftrightarrow{D}^a_\mu \phi (\bar{L}_i \gamma^\mu \sigma_a L_i)$$

$$\mathcal{O}_{\phi Q}^{(1)} = \cdots \qquad \mathcal{O}_{\phi d}^{(1)} = \cdots \qquad \mathcal{O}_{\phi Q}^{(3)} = \cdots$$

$$\mathcal{O}_{\phi ud}^{(1)} = \tilde{\phi}^\dagger \overleftrightarrow{D}_\mu \phi (\bar{u}_{R,i} \gamma^\mu d_{R,i}) \qquad \mathcal{O}_{\phi u}^{(1)} = \cdots \qquad \mathcal{O}_{LLLL} = (\bar{L}_1 \gamma_\mu L_2)\,(\bar{L}_2 \gamma^\mu L_1)$$

- bosonic operators bounded by EWPD

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$

- bigger and better basis

$$\mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2} \mathcal{O}_{WWW}$$
$$+ \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2} + \sum_{\tau bt} \frac{m_f}{v} \frac{f_f}{\Lambda^2} \mathcal{O}_f + \frac{f_{\phi,1}}{\Lambda^2} \mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2} \mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2} \mathcal{O}_{LLLL}$$
$$+ \frac{f_{\phi Q}^{(1)}}{\Lambda^2} \mathcal{O}_{\phi Q}^{(1)} + \frac{f_{\phi d}^{(1)}}{\Lambda^2} \mathcal{O}_{\phi d}^{(1)} + \frac{f_{\phi u}^{(1)}}{\Lambda^2} \mathcal{O}_{\phi u}^{(1)} + \frac{f_{\phi e}^{(1)}}{\Lambda^2} \mathcal{O}_{\phi e}^{(1)} + \frac{f_{\phi Q}^{(3)}}{\Lambda^2} \mathcal{O}_{\phi Q}^{(3)}$$

→ Physics: rates vs kinematics vs EWPD

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$\to$ Physics: rates vs kinematics vs EWPD

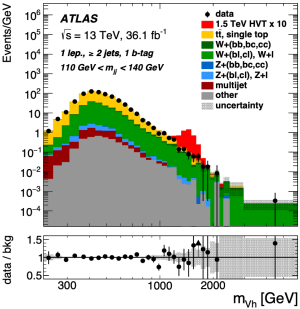
Higgs constraints from no-Higgs measurements

- m_{VH} perfect SMEFT kinematics

Search for heavy resonances decaying into a *W* or *Z* boson and a Higgs boson in final states with leptons and *b*-jets in 36 fb^{-1} of $\sqrt{s}$ = 13 TeV *pp* collisions with the ATLAS detector

The ATLAS Collaboration

A search is conducted for new resonances decaying into a W or Z boson and a 125 GeV Higgs boson in the $\nu\bar{\nu}b\bar{b}$, $\ell^\pm\nu b\bar{b}$, and $\ell^+\ell^-b\bar{b}$ final states, where $\ell^\pm = e^\pm$ or $\mu^\pm$, in pp collisions at $\sqrt{s}$ = 13 TeV. The data used correspond to a total integrated luminosity of 36.1 fb^{-1} collected with the ATLAS detector at the Large Hadron Collider during the 2015 and 2016 data-taking periods. The search is conducted by examining the reconstructed invariant or transverse mass distributions of Wh and Zh candidates for evidence of a localised excess in the mass range of 220 GeV up to 5 TeV. No significant excess is observed and the results are interpreted in terms of constraints on the production cross-section times branching fraction of heavy W' and Z' resonances in heavy-vector-triplet models and the CP-odd scalar boson A in two-Higgs-doublet models. Upper limits are placed at the 95% confidence level and range between 9.0×10^{-4} pb and 8.1×10^{-1} pb depending on the model and mass of the resonance.



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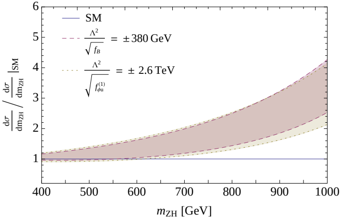
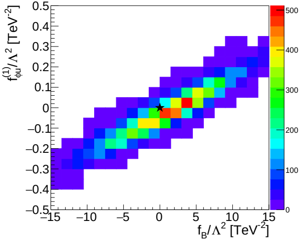
- hierarchy $\mathcal{O}^{(1)}_{\phi u} \to g_{qqZH}$ vs $\mathcal{O}_W \to g_{ZZH}$



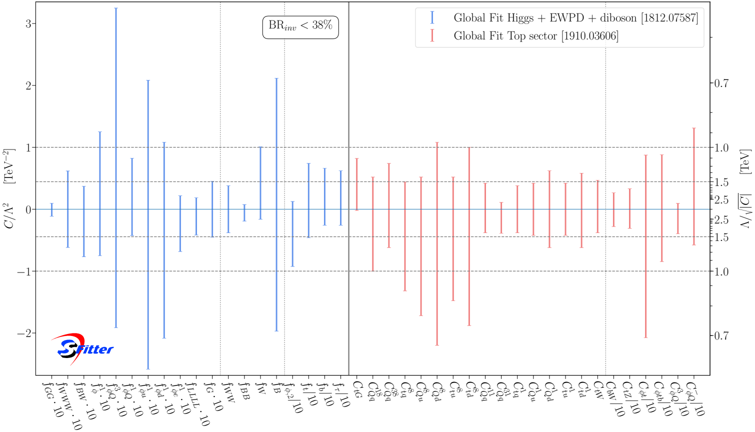


Run 2 legacy

Combined analysis [also Sanz etal, Maltoni etal]

- Higgs–gauge and top sectors, also QCD [flavor]
- rates and distributions
- precision calculations

→ Closing in on SMEFT interpretation of all of LHC



EFTs for the LHC

Construction

- define Lagrangian from particle content and symmetries
- perturbative series in coupling(s)
  series in operator dimensionality
- running and matching through renormalization group

→ Symmetries and new particles as input

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Challenges

- assuming scale hierarchy
  ew symmetry breaking/phase transitions problematic
- cut-off scale limiting interpretation
- consistency and uncertainties unclear

$\rightarrow$ Limited in questions

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Strengths

- representing range of models
- describing all observables
- renormalizable theory

→ Global LHC analysis framework

SFitter

SFitter global analyses

- combination of Lagrangian and nuisance parameters
- uncorrelated ATLAS/CMS measurements
- statistical/systematic/theory uncertainties
- theory uncertainties flat [RFit]
- Markov chains weighted, cooling, etc

$\rightarrow$ Exclusive likelihood

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Profiling vs marginalization [for results see Nina's talk]

- correlations through nuisance parameters
- 1D limits and 2D correlations interesting
- remove nuisance/physics parameters
  Bayes' theorem $\rightarrow$ integration with prior vs projection [Konstantin's talk]
- identical for uncorrelated Gaussians $\rightarrow$ adding in quadrature
  profiling flat $\times$ Gauss $\rightarrow$ RFit scheme
  profiling flat $\times$ flat $\rightarrow$ linearly added errors

$\rightarrow$ Both implemented, profiling conservative

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SFitter analyses

- 2004: SUSY projections
  2009: Higgs coupling projections
- 2012: Higgs couplings
  2013: SUSY dark matter
  2015: Higgs-SMEFT: Run 1 legacy
  2016: Fermi-LAT dark matter
- 2018: Higgs-SMEFT: Run 2 legacy
  2019: top-SMEFT: Run 2 legacy
- 2021: Higgs-SMEFT: model matching
  2022: Higgs-SMEFT: profiling vs marginalization
  2023: top-SMEFT: experimental likelihoods

→ EDMs next in line...

Testing CP

Do not test CP in global analyses

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- marginalizing/profiling removes the best measurements
- kinematics can mimick CP violation

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Recap: C and P and T and $\hat{T}$ and testing them [CPT generally assumed]

- transformations on state with spin/momentum [review: Valencia]

$$\mathrm{C}\,|\phi(p,s)\rangle = \left|\phi^*(p,s)\right\rangle \quad \mathrm{P}\,|\phi(p,s)\rangle = \eta_\phi\,|\phi(-p,s)\rangle \quad \mathrm{T}\,|\phi(p,s)\rangle = \langle\phi(-p,-s)|$$

- naive time reversal $\hat{T}$ avoiding inital $\leftrightarrow$ final state

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- genuine U-odd is what we want [U=C,P,T]

$$\langle O\rangle_{\mathcal{L}=\text{U}\mathcal{L}\text{U}^{-1}} = 0$$

U-odd is what we get

$$O(\text{U}\,|i\rangle \to U\,|f\rangle) \overset{\text{odd}}{=} -O\,(|i\rangle \to |f\rangle) \quad \overset{p(|i\rangle)=p(\text{U}|i\rangle)}{\Longrightarrow} \quad \langle O\rangle_{\mathcal{L}=\text{U}\mathcal{L}\text{U}^{-1}} = 0$$

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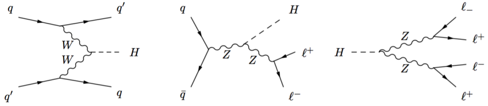
$\to$ genuine $\hat{\text{T}}$-odd observable means CP-violating theory, provided

1- phase space $\hat{\text{T}}$-symmetric [inclusive analyses]
2- initial state distribution invariant under $\hat{\text{T}}$ [*pp*-collisions]
3- no re-scattering, means no phase [not foreseen in EFT]

CP observables



CP-violation in SMEFT-Higgs

- CP-violating operators

$$\mathcal{O}_{B\tilde{B}} = -\frac{g'^2}{4} (\phi^\dagger \phi) \widetilde{B}_{\mu\nu} B^{\mu\nu} \qquad \mathcal{O}_{W\tilde{W}} = -\frac{g^2}{4} (\phi^\dagger \phi) \widetilde{W}^k_{\mu\nu} W^{\mu\nu\, k}$$

- 4 external masses
  6 P-even, and $\hat{\text{T}}$-even scalar products
  1 C-even, P-odd, and $\hat{\text{T}}$-odd observable with Levi-Civita-tensor

1. CP-odd and $\hat{\text{T}}$-odd
   for symmetric initial state also genuine CP-odd and genuine $\hat{\text{T}}$-odd
   non-zero expectation value means CP violation
2. CP-odd and $\hat{\text{T}}$-even [for our LHCb friends]
   for symmetric initial state also genuine CP-odd
   but without re-scattering, $\hat{\text{T}}$-expectation value zero
   need complex phase for $\langle O \rangle$

$\Rightarrow$ Dedicated CP observables

LHC processes

Testing CP in WBF

- C-even, P-odd, $\hat{T}$-odd observable

$$O \equiv \epsilon_{\mu\nu\rho\sigma}\ k_1^\mu\ k_2^\nu\ q_1^\rho\ q_2^\sigma\ \text{sign}\left[(k_1 - k_2)\cdot(q_1 - q_2)\right]$$

- azimuthal angle difference [lab frame]

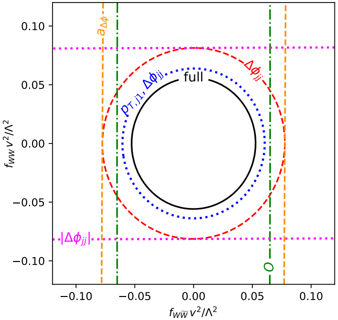
$$O = 2E_-(\vec{q}_- \times \vec{q}_+)\cdot\vec{k}_+ \quad \to \quad \sin\Delta\phi_{jj}$$

- CP asymmetry

$$a_{\Delta\phi_{jj}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{jj}) - \mathrm{d}\sigma(-\Delta\phi_{jj})}{\mathrm{d}\sigma(\Delta\phi_{jj}) + \mathrm{d}\sigma(-\Delta\phi_{jj})}$$

- help from dimension-6 kinematics

→ Testing CP, assuming no re-scattering



LHC processes

Testing CP in WBF

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- help from dimension-6 kinematics

$\to$ Testing CP, assuming no re-scattering

Testing CP in ZH

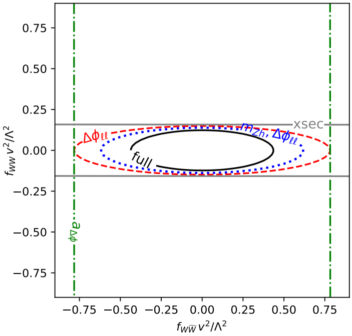
- same one CP-odd and $\hat{\text{T}}$-odd observable

$$\mathcal{O} \sim \Delta\phi_{\ell\ell}$$

- CP asymmetry as for WBF

$$a_{\Delta\phi_{\ell\ell}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) - \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) + \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}$$

$\to$ Testing CP without assumptions [to leading order]

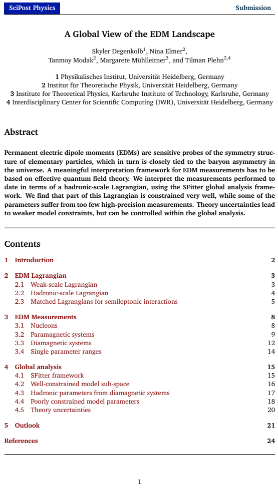


General features

Modern LHC physics

- all of LHC understood in terms of QFT
- SMEFT interpretation framework
- global precision analysis including kinematics
- symmetries input, not output of EFT
- dedicated observables for CP

→ Ask Nina about EDM application



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A Global View of the EDM Landscape

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Abstract

Permanent electric dipole moments (EDMs) are sensitive probes of the symmetry structure of elementary particles, which in turn is closely tied to the baryon asymmetry in the universe. A meaningful interpretation framework for EDM measurements has to be based on effective quantum field theory. We interpret the measurements performed to date in terms of a hadronic-scale Lagrangian, using the SFitter global analysis framework. We find that part of this Lagrangian is constrained very well, while some of the parameters suffer from too few high-precision measurements. Theory uncertainties lead to weaker model constraints, but can be controlled within the global analysis.

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