Let’s start with the LHC

The LHC is in a mature stage, already providing precision tests for the SM in most channels (excl the Higgs)

Precise tests of the full structure of the SM, based on QFT, symmetries (global/gauge) and consistent ways to break them non-trivial tests of perturb.->non-perturb.

QCD

Absence of excesses: interpreted as new physics exclusions
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QCD

Absence of excesses: interpreted as new physics exclusions

exclusions: rather impressive, many at the TeV
searches: outstanding coverage of possible topologies
any hints: (like in flavor) extremely tempting
So here we are

Light Higgs  Inflation  Neutrinos
Matter/Antimatter  CP QCD  Unification
Dark Energy  Dark Matter  Quantum Gravity

finding our path through SYMMETRIES & DYNAMICS

SM+GR

aiming for a UNIFIED FRAMEWORK
What we would hope for

Special relativity + equivalence principle

development of new, sophisticated mathematical framework

General relativity

Universe’s evolution

gravitational waves

black holes
Some years ago

String theory, the final theory
Mathematical consistency (anomalies, SUSY)
+guiding principles (QGrav, unification, 3 families)
trickle down to the SM, a boundary condition
Some years ago

String theory, the final theory
Mathematical consistency (anomalies, SUSY) + guiding principles (QGrav, unification, 3 families) trickle down to the SM, a boundary condition

This program has not lead to identifying the theory (see string landscape)

Instead, generated a vast number of new ideas: reformulations of gravity and QFT dualities incl AdS/CFT new scenarios for model-building incl duals of RS (composite higgs, clockwork), models for inflation
So here we are again, post-LHC Run2

the normal process for an empirical science prediction, test & exclusion or discovery
One way forward:
Connecting ideas/experiments
A cosmological Higgs

The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales. Exploiting complementarity with cosmo/astro probes.

Similar story for Axions and ALPs, scalars are versatile.
Many faces of Dark Matter

THEORY
- Discrete symmetries
- Dynamical stability
- Self-interactions
- Link to Higgs

COLLIDERS

CMB: relic, tilt

SIMULATIONS

DIRECT DETECTION

INDIRECT DETECTION
Back to the LHC:
Direct versus indirect searches
Direct searches for new phenomena

consistency of data vs SM predictions

ATLAS SUSY Searches* - 95% CL Lower Limits

*Only a selection of the available mass limits in new states or signatures is shown.
Coloured states to the very exotic

SUSY Benchmark  Jets+MET  some-SUSY  HSCPs

CMS

2.5 fb⁻¹ (13 TeV)
Tracker + TOF

Theoretical prediction
- gluino; 50% \( \tilde{g} \tilde{g} \)
- gluino; 10% \( \tilde{g} \tilde{g} \)
- stop (NLO+NLL)
- stop (NLO)
- stau, dir. prod. (NLO)
- stau; dir. prod.
- stau (NLO)
- stau
- DY \( |Q| = 1e \) (LO)
- DY \( |Q| = 2e \) (LO)
- DY \( |Q| = 1e \) (LO)
- DY \( |Q| = 2e \) (LO)

\( \tilde{g} \)-production, \( B(\tilde{g}) \)

4\( \text{ATLAS} \)
\( \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \)
- 0-leptons, 2-6 jets
- MET or FJR (Best Expected)
- All limits at 95% CL

Obs. limit (±1 \( \sigma_{SUSY}^{SUSY} \))
Exp. limits (±1 \( \sigma_{exp} \))
Exp. limits MEff
Exp. limits RFR
OL obs. limit (13 TeV, 3.2 fb⁻¹)
Indirect searches

Focus on SM particles’ behaviour
precise determination of couplings
and kinematics
comparison with SM,
search for deviations

Indirect searches using the Higgs
since 2012, relatively new
Higgs as a window to NP
expect deviations in its behaviour
Run2 data and beyond
precision Higgs Physics

e.g. Anomalous trilinear gauge
   couplings, aka TGCs

LEP, Tevatron, LHC
Casting a wide net: the new SM
Why EFT?

Standard Model Production Cross Section Measurements

CMS Preliminary

ATLAS Preliminary

Run 1.2 √s = 7, 8, 13 TeV
The SM is a good description of Nature at the LHC

==> new resonances/phenomena may be heavy

==> Our hopes for simple/natural models are not realised

==> We should adopt a more **model-independent** strategy when interpreting data
EFT approach

Well-defined theoretical approach
Assumes New Physics states are heavy
Write Effective Lagrangian with only light (SM) particles
BSM effects can be incorporated as a momentum expansion

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_{i}^{d=8} + \ldots \]

BSM effects  SM particles

dimension-6  dimension-8

**example:**
2HDM

\[ \frac{ig}{2m_W^2} \bar{c}_W \left[ \Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi \right] D_\nu W^{k,\mu\nu} \]

where \( \bar{c}_W = \frac{m_W^2 (2 \tilde{\lambda}_3 + \tilde{\lambda}_4)}{192 \pi^2 \tilde{\mu}_2^2} \)
EFT approach

**THEORY**

Model-independent parametrization deformations respect to the SM

Well-defined theory can be improved order by order in momentum expansion consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

**EXPERIMENT**

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

Higher-order precision in QCD/EW

Can treat EFT effects on backgrounds and signal consistently

The way to combine all Higgs channels and EW production
EFT and differential information

\[-\frac{1}{4} h g^{(1)}_{VV} V_{\mu\nu} V^{\mu\nu} - h g^{(2)}_{VV} V_{\nu} \partial_\mu V^{\mu\nu} - \frac{1}{4} h \tilde{g}_{VV} V_{\mu\nu} \tilde{V}^{\mu\nu}\]

\[h(p_1) \quad V(p_2) \quad V(p_3)\]

\[i\eta_{\mu\nu} \left( g^{(1)}_{VV} \left( \frac{s}{2} - m^2_V \right) + 2 g^{(2)}_{VV} m^2_V \right) \]

\[-i g^{(1)}_{VV} p_3^\mu p_2^\nu - i \tilde{g}_{VV} \epsilon^{\mu\nu\alpha\beta} p_2,\alpha p_3,\beta\]

+ off-shell pieces
Matching to UV theories

Within the EFT, connection to models is straightforward.

\[ c_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right] \frac{v^2}{192\pi^2 \mu_2^2} \]

\[ c_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right) \frac{v^2}{192\pi^2 \mu_2^2} \]

\[ c_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2) \frac{v^2}{192\pi^2 \mu_2^2} \]

\[ c_\gamma = \frac{m_W^2 \tilde{\lambda}_3}{256\pi^2 \mu_2^2} \]

\[ c_W = -\tilde{c}_{HW} = \frac{m_W^2 (2\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\pi^2 \mu_2^2} = \frac{8}{3} c_\gamma + \frac{m_W^2 \tilde{\lambda}_4}{192\pi^2 \mu_2^2} \]

\[ c_B = -\tilde{c}_{HB} = \frac{m_W^2 (-2\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\pi^2 \mu_2^2} = -\frac{8}{3} c_\gamma + \frac{m_W^2 \tilde{\lambda}_4}{192\pi^2 \mu_2^2} \]

\[ \tilde{c}_{3W} = \frac{\tilde{c}_{2W}}{3} = \frac{m_W^2}{1440\pi^2 \mu_2^2} \]
In this work:

Use EWPT, Higgs and diboson data, incl use STXS
Assume linear EWSB, CP-conservation and MFV
Present results in Warsaw and SILH bases, 20 operators
Matching to simplified UV models

e.g. WARSAW
SMEFT recent results

ELLIS, MURPHY, VS, YOU. 1803.03252

SMEFT: 20 deformations
SMEFT*: 13 deformations
(weakly coupled and renormalizable)

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\chi^2$</th>
<th>$\chi^2/n_d$</th>
<th>$p$-value</th>
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<tbody>
<tr>
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<td>0.987</td>
<td>0.532</td>
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<tr>
<td>SMEFT</td>
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<tr>
<td>SMEFT*</td>
<td>143</td>
<td>0.977</td>
<td>0.564</td>
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</table>

See ALSO
MORE RECENT
GONZALEZ-GARCIA ET AL
1812.01009
PLEHN ET AL.
1812.07587
SIMILAR RESULTS
# Constrains on simple extensions of the SM

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>$\chi^2/n_d$</th>
<th>Coupling</th>
<th>Mass / TeV</th>
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<td>-</td>
<td>-</td>
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<tr>
<td>$S_1$</td>
<td>156</td>
<td>0.986</td>
<td>$</td>
<td>s_{51}</td>
</tr>
<tr>
<td>$\varphi$, Type I</td>
<td>156</td>
<td>0.986</td>
<td>$Z_6 \cdot \cos \beta = -0.64 \pm 0.59$</td>
<td>$M_\varphi = (0.9, 4.3)$</td>
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<tr>
<td>$\Xi$</td>
<td>155</td>
<td>0.984</td>
<td>$</td>
<td>\kappa_{\Xi}</td>
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<tr>
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<td>0.990</td>
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<tr>
<td>$\Sigma$</td>
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<td>$</td>
<td>\lambda_{\Sigma}</td>
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<td>$Q_5$</td>
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<td>\lambda_{T_1}</td>
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<td>$B_1$</td>
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<td>0.993</td>
<td>$</td>
<td>\tilde{g}_{B_1}</td>
</tr>
</tbody>
</table>
EFT precision—next steps

- incorporate higher-order QCD and EW effects
- quantify higher-order EFT effects (dimension-8)

Lots of progress on this front, some projects involved in

**NLO QCD MC**

POWHEG-BOX
Mimasu, VS, Williams. 1512.02572

aMC@NLO
Degrande, Fuks, Mawatari, Mimasu, VS.
1609.04833
NEW: CP-violating terms—request

**DIMENSION-EIGHT**

FeynRules—>UFO—>aMC@NLO
Hays, Martin, VS, Setford. 1808.00442
Warsaw—>Other using Rosetta
Mimasu et al. 1508.05895

incorporate these tools to the experimental analyses
Next direction: Machine Learning

Capture subtle details in “images” supervised or anomaly detection lots of activity in the last months this is where the cutting-edge is

Asimov significance vs Luminosity systematics 50%

FREITAS, KAUR AND VS. 1902.05803
Experiments keep coming in:
There is a lot to explore ahead of us
For the LHC, this is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data. Funding ensured until 2035.

LHC hopefuls

- gains from more data and better understanding of the environment
- Testing non-standard kinematic features
- Reaching high-precision in Higgs physics
- Searches for invisible particles (monoX)
- Blind spots (DV, disap. tracks, quirks)

and, of course, FLAVOUR

with Belle-II, NA62 complementing LHCb
Smaller experiments may be key

Narrower focus

BUT

cheaper, shorter time-scale
develop creative experimental techniques
often enlarge the initial physics focus

LZ  ACT  BICEP3  Darwin
DUNE  g-2  Qbic  ANTARES  Euronu
ADMX  Icecube  SHIP  Tb2K  Moedal
NEXT  MADMAX  T2K  Mu2e
nuSTORM  MATHUSLA  Qbic  T2K  Moedal
And what about the cool/crazy stuff?

Dark Energy and its interaction with us

Alternatives to space-time symmetries (e.g. emergent gravity)

Very light dark matter (new exp techniques)

Dark moments in the Universe’s history, pre-BBN

Connections between IR and UV physics, e.g. BHs

We need to challenge the well-stabilished paradigms, may be quickly ruled out but one always learn something new from these explorations
Conclusions

- Here we are, looking for a way to advance our understanding of nature, to reach discovery.

- Scaling back from an ambitious program to find the theory of everything. Facing the challenges/opportunities that more data brings.

- Use of simplified models to organize/interpret searches, less model biased, and suitable to complementarity studies. Yet theoretical advances require more than simplified models, asking difficult questions from model building.

- Keeping at the edge of the interpretation of data: bringing many towards precision (akin to SM) and to Artificial Intelligence techniques (NNs and the likes), but we should not lose track of our core mission:
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  Understanding Nature
  (and having fun on the way!)