Broken symmetries in particle physics

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Outline

- Symmetries and conservation laws
- CPT invariance and antimatter
- Broken mirror symmetries: P, CP, T
- Global and local gauge invariance
- Spontaneous symmetry breaking and masses
- Open problems of the Standard Model
- New physics? Supersymmetry?
- Plans and hopes at LHC

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Symmetries in Particle Physics

Wigner’s name is associated with symmetries in physics
The particle theory, the Standard Model, is based on symmetries

Continuous symmetries $\Rightarrow$ conservation laws (Noether’s theorem):
- space-time shift and rotation $\Rightarrow$ momentum, energy and angular momentum conservation
- Spin SU(2), Dirac U(1) and colour SU(3) gauge symmetries $\Rightarrow$ conservation of spin, fermion current and colour charges (source of strong interaction)

Discrete symmetry: CPT (simultaneous Charge conjugation, Parity switch and Time reflection)

Standard Model: Three interactions are derived of local gauge symmetries, strong from local SU(3) and electroweak from local U(1)$\otimes$SU(2) gauge invariance with spontaneous symmetry breaking.
E. P. Wigner on gauge invariance

In quantum theory, invariance principles permit even further reaching conclusions than in classical mechanics.

HOWEVER:

This gauge invariance is, of course, an artificial one, similar to that which we could obtain by introducing into our equations the location of a ghost. The equations must then be invariant with respect to changes of coordinates of that ghost. One does not see, in fact, what good the introduction of the coordinates of the ghost does.

CPT invariance

Basic assumption of field theory:

\[ CPT |p(r, t)\rangle \sim |\overline{p}(-r, -t)\rangle \sim |p(r, t)\rangle \]

meaning free antiparticle

\sim

particle going backwards in space and time.

Giving up \textit{CPT} one has to give up:

- \textbf{locality} of interactions \Rightarrow \textbf{causality}, or
- \textbf{unitarity} \Rightarrow \textbf{conservation} of matter, information,
- ... or Lorentz invariance

Motivation to doubt:

- Asymmetric Universe: no antimatter galaxies
Broken (violated) symmetries

„... the fundamental equations of physics have more symmetry than the actual physical world does”


„Accidental symmetries”  Steven Weinberg

- Parity (P, CP), flavour-SU(2) in weak interaction
- Electroweak BEH-mechanism
- Supersymmetry??
The Standard Model

Derive 3 interactions of local $U(1)$, $SU(2)$ and $SU(3)$ symmetries

Unify and separate e-m $U(1)$ and weak $SU(2)$ interactions using spontaneous symmetry breaking:

(Anderson-Englert-Brout-Higgs-Guralnik-Hagen-Kibble (BEH) mechanism, 1963-64)

Add a 4-component, symmetry breaking field to vacuum.

Separate a good $U(1)$ local symmetry from the ruined $U(1) \otimes SU(2)$

$\downarrow$

electromagnetism + zero-mass photon, OK!

Turn 3 d.f. of BEH field to create masses for $Z$, $W^+$, $W^-$, get a correct weak interaction with 3 heavy gauge bosons.

4th degree of freedom: heavy scalar Higgs boson.
The zoo of the Standard Model

3 fermion families:
1 pair of quarks and
1 pair of leptons in each

3 kinds of gauge bosons:
the force carriers

All identified and studied!

Higgs boson ($M_H = 125$ GeV)

Colour: the charge of the strong interaction

colored quarks $\Rightarrow$ colourless composite hadrons of 2 kinds

hadrons = mesons ($q\bar{q}$) + baryons (qqq)

The Standard Model describes all known particles and phenomena of the microworld
Glory road of the Standard Model

Includes hundreds of measurements of all experiments

Expt – theory

expt. uncertainty

All within statistics

Slightly deviating quantity:

forward-backward asymmetry of

\( e^+e^- \rightarrow Z \rightarrow b\bar{b} \)

The Gfitter Group:

arxiv.org:1407.3792

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CMS, 2016: $\alpha_s$ running with energy
The Higgs boson of the Standard Model

Spontaneous symmetry breaking

Spinless, neutral, heavy particle
The scalar particle needed for renormalisation
Does it really exist? SM: it must!
Accelerators of CERN

- **LHC**: Large Hadron Collider
- **SPS**: Super Proton Synchrotron
- **AD**: Antiproton Decelerator
- **ISOLDE**: Isotope Separator On Line Device
- **PSB**: Proton Synchrotron Booster
- **PS**: Proton Synchrotron
- **LINAC**: Linear Accelerator
- **LEIR**: Low Energy Ion Ring
- **CNGS**: Cern Neutrinos to Gran Sasso

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LHC and its main experiments

14 TeV

p → LHCb, LHCb, CERN

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Dipole magnets of LHC in the tunnel

LHC is like Formula 1: boring without collisions
CMS: Compact Muon Solenoid

14000 ton digital camera:
200 M pixel, 40 M pictures/sec, 1000 GB/sec data
Processes cc. 1000 pictures/sec ⇒ intelligent filter!!
Production of the SM Higgs boson in p-p collisions at LHC

![Graph showing SM Higgs production cross-sections for different processes.](image-url)

- **gg → h**
- **qq → qqh**
- **qq → Wh**
- **bb → h**
- **qb → qth**
- **gg,qq → tth**
- **qq → Zh**

TeV4LHC Higgs working group

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Decay of the SM Higgs boson

At 125 GeV many decay processes compete.
Best identified ($\Delta M/M = 1 \cdots 2\%$):

$H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell^+ \ell^- \ (\ell = e, \mu)$: $BR = 1.24 \times 10^{-4}$, $S/B > 1$

$H \rightarrow \gamma \gamma$: $BR = 2.27 \times 10^{-3}$, $S/B \ll 1$

LHC Higgs Cross Section Working Group, arXiv:1610.07922
Production & decay of SM Higgs boson

relative signal strengths $\mu = \text{expt/theory}$ in Run 1

Excellent agreement in all channels for both experiments

[ATLAS and CMS Collaborations, 5113 authors], JHEP 1608 (2016) 045.
A CMS event: $H \rightarrow \gamma\gamma$ candidate
H → 4ℓ

Invariant mass spectra at $\sqrt{s} = 13$ TeV

**ATLAS** Preliminary

$H \rightarrow ZZ^* \rightarrow 4\ell$
13 TeV, 36.1 fb$^{-1}$

$124.88 \pm 0.37$ (stat) $\pm 0.05$ (syst)

**CMS**

$125.26 \pm 0.20$ (stat) $\pm 0.08$ (syst)

Both statistically limited.

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– p. 20
$H \rightarrow \gamma\gamma$

Invariant mass spectra at $\sqrt{s} = 13$ TeV

ATLAS Preliminary

CMS Preliminary

$125.11 \pm 0.21$ (stat) $\pm 0.36$ (syst)

ATLAS-CONF-2017-046

$125.4 \pm 0.15$ (stat) $\pm (0.2 \ldots 0.3)$ (syst)

CMS-PAS-HIG-16-040
Top vs. Higgs: vacuum stability

How stable is our EW vacuum? Depends on the masses of the Higgs boson and of the top quark

What next?

Supersymmetry (SUSY)?

Why? Who needs that?
Problems of the Standard Model – 1

- 3 independent (?) components:
  \[ U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \]
- Gravitation? \( S = 2 \) graviton?
- Asymmetries: right \( \Leftrightarrow \) left World \( \Leftrightarrow \) Antiworld
- Artificial mass creation: Higgs-field \textit{ad hoc}
- Many fundamental particles:
  \[ 8 + 3 + 1 + 1 = 13 \text{ bosons} \]
  \[ 3 \times 2 \times (2 + 3 \times 2) = 48 \text{ fermions} \]
- Charge quantization: \( Q_e = Q_p, Q_d = Q_e/3 \)
- Why the 3 fermion families?
  Originally: Who needs the muon??
- Nucleon spin: how \( 1/2 \) produced?
Problems of the Standard Model – 2

- 19 free parameters (too many ??):
  - 3 couplings: $\alpha$, $\Theta_W$, $\Lambda_{\text{QCD}}$
  - 2 Higgs: $M_H$, $\lambda$
  - 9 fermion masses: $3 \times M_\ell$, $6 \times M_q$
  - 4 parameters of the CKM matrix: $\Theta_1$, $\Theta_2$, $\Theta_3$, $\delta$
  - QCD-vacuum: $\Theta$

- $M_\nu > 0 \Rightarrow +3$ masses, +4 mixing matrix

- Gravitational mass of the Universe:
  - 4% ordinary matter (stars, gas, dust, $\nu$)
  - 23% invisible dark matter
  - 73% mysterious dark energy

- Naturalness (hierarchy):
  The mass of the Higgs boson quadratically diverges due to radiative corrections. Cancelled if fermions and bosons exist in pairs.
Beyond the Standard Model

Supersymmetry (SUSY)

**Hypothesis:** Fermions and bosons exist in pairs:

\[ Q|F> = |B>; \quad Q|B> = |F> \quad m_B = m_F \]

Identical particles, just spins different \( (\tilde{S} = S - \frac{1}{2}) \)

Broken at low energy, no partners: much larger mass?

Almost 50 % (SM) discovered already!! 😊
SUSY: coupling constants

Unification OK!
Bend at low energies: SUSY enters with many new particles ⇒ more loop corrections
Many-many alternative models
SUSY search

Production in pairs, decay to other SUSY particle

Lightest (LSP) stable, neutral, not observable

Neutral LSP: excellent dark matter candidate

Signal for observation: missing energy

2 Higgs doublets $\Rightarrow$ masses to upper and lower fermions

5 Higgs bosons: $h^0$, $H^0$, $A^0$, $H^\pm$

Simplest SUSY models (105 $\Rightarrow$ 4 parameters) are excluded by LHC data

Even if SUSY is valid, minimal models may not be.

- Search for more Higgs bosons or

- Check simplified phenomenology
CMS SUSY summary plot, 2017

Selected CMS SUSY Results - SMS Interpretation

CMS Preliminary
\[ \sqrt{s} = 13 \text{TeV} \]
\[ L = 12.9 \text{ fb}^{-1}, L = 35.9 \text{ fb}^{-1} \]

For decays with intermediate mass, 
\[ m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) \cdot m_{\text{LSP}} \]

Simplified Model Spectrum (SMS) topologies

*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe "up to" the quoted mass limit for \( m_{\text{LSP}} = 0 \text{ GeV} \) unless stated otherwise
ATLAS SUSY summary plot, 2017

Gluino $\sim 2$ TeV

Stop $\sim 950$ GeV

Chargino/neutralino $\sim 1$ TeV

RPV and long-lived decays $\sim 2$ TeV

Xu, Da (Blois 2017)

For all results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
CMS: search for exotica

CMS Preliminary

Leptoquarks

13 TeV

8 TeV

RS Gravitons

CMS Exotica Physics Group Summary – IICHEP 2016
Conclusion

- **Broken symmetries** play a fundamental role in particle physics.
- At LHC we have observed the SM Higgs boson in 8 TeV p-p collisions and it does not look like a Higgs boson of a more general model.
- Since 2015 the LHC collides protons at 13 TeV and its luminosity is steadily increasing. Let us hope for some deviation from the Standard Model (although none seen yet).
- The simplest SUSY models do not seem to be supported by experimental data (g-2, LEP, WMAP, LHC, ...)
- Simplified approaches: search for non-SM phenomena in simple reactions with on-shell particles. If found, try to relate the new observation with possible models
- Adjust theory to data, not the other way around.
Thank you for your attention
Spare slides for questions
Production of the SM Higgs boson in p-p collisions at LHC (Run 2)

The CMS Collaboration (2017)

- 5250 participants from 198 institutions of 45 countries
- 995 engineers, 279 technicians
- 1963 physicists with PhD (326 women, 1637 men)
- 922 doctoral students (202 women, 720 men)
- 994 MSc students (241 women, 753 men)
- Participants by countries of institutes (in 2012): USA: 1149, Italy: 439, Germany: 298, Russia: 234
- 70 petabytes of data, 700 publications

CMS detector: huge joint effort
3000 people worked on it for 20 years!
H \rightarrow W^+W^-

3rd most significant decay channel for the 125 GeV Higgs boson: observed and studied.

When in 2012 added to $\gamma\gamma$ and $4\ell$, increased the observed significance for ATLAS from $5\sigma$ to $6.1\sigma$ and decreased it for CMS to $4.9\sigma$.

- **ATLAS, Run 1**: $6.8\sigma$ and $\mu = 1.22^{+0.23}_{-0.21}$
- **CMS, Run 1**: $4.8\sigma$ and $\mu = 0.90^{+0.23}_{-0.21}$
- **ATLAS + CMS in Run 1**: $\mu = 1.09^{+0.18}_{-0.16}$

CMS vs. ATLAS: Run 1 masses

Combined ATLAS + CMS Higgs-boson mass:

$$125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{(syst)} \text{ GeV}$$

[ATLAS and CMS Collaborations, 5113 authors],
CMS strategies for discovery

- $\alpha_T$ search for early discovery in (forced) 2-jet events ($E_T(J_1) > E_T(J_2)$):
  
  $$\text{Cut } \alpha_T = \frac{E_T(J_2)}{M_T(J_1,J_2)}$$

  $$= \frac{E_T(J_2)}{\sqrt{(E_T(J_1)+E_T(J_2))^2-(p_x(J_1)+p_x(J_2))^2-(p_y(J_1)+p_y(J_2))^2}}$$

  Exclusive 2-jet, inclusive 3-jet search

- Jets + $H_T$ for $> 2$ jets, inclusive
  
  Scalar mom. sum: $H_T = \sum_i |p_T(J_i)|$;

  Missing transverse mom.:
  $MHT = H_T = | - \sum_i p_T(J_i) |$

- Razor search: test kinematic consistency for pair production of heavy particles
  
  Two jets (inv. mass $M_R$) + 0 or 1 lepton
# The missing MSSM menagerie

<table>
<thead>
<tr>
<th>Kind</th>
<th>spin</th>
<th>R parity</th>
<th>gauge eigenstate</th>
<th>mass eigenstate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs bosons</td>
<td>0</td>
<td>+1</td>
<td>$H_1^0, H_2^0, H_1^+, H_2^-$</td>
<td>$h^0, H^0, A^0, H^\pm$</td>
</tr>
<tr>
<td>squark</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$</td>
<td>$\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$</td>
</tr>
<tr>
<td>slepton</td>
<td>0</td>
<td>-1</td>
<td>$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\mu}_L, \tilde{\mu}<em>R, \tilde{\nu}</em>\mu$</td>
<td>same</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tilde{\tau}_L, \tilde{\tau}<em>R, \tilde{\nu}</em>\tau$</td>
<td>$\tilde{\tau}_1, \tilde{\tau}<em>2, \tilde{\nu}</em>\tau$</td>
</tr>
<tr>
<td>neutralino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$</td>
<td>$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$</td>
</tr>
<tr>
<td>chargino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{W}^\pm, \tilde{H}_1^+, \tilde{H}_2^-$</td>
<td>$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$</td>
</tr>
<tr>
<td>gluino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{g}$</td>
<td>same</td>
</tr>
<tr>
<td>goldstino</td>
<td>1/2</td>
<td>-1</td>
<td>$\tilde{G}$</td>
<td>same</td>
</tr>
<tr>
<td>gravitino</td>
<td>3/2</td>
<td></td>
<td></td>
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