Beyond the Standard Model



Laboratoire de Physique des 2 Infinis



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JRJC 2022 October 25th, 2022 - Saint-Jean-de-Monts

The SM: a theoretical success

- Founded on gauge invariance principles
 - $SU(3) \times SU(2) \times U(1) \implies EW$ and strong interactions
- Is completed with a scalar sector (Higgs)
 - new complex scalar doublet with a potential with a v.e.v. $\neq 0$
- Is a renormalizable QFT that is valid up to the Planck scale

The SM is a beautifully elegant theory of Nature's mechanisms



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The SM : an experimental success

Standard Model Production Cross Section Measurements



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Status: February 2022

Astonishing capability to describe the observations of collider experiments

- The SM is a solid theory well corroborated by experiments
- Are we back to the end of the XIX century where *"it seems* probable that most of the grand underlying principles have been firmly established" (Albert Michelson)?

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So why BSM?



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- Astrophysical observations and cosmological considerations dark matter
- - matter/antimatter asymmetry
 - isotropy and homogeneity of early universe (\rightarrow inflation)
- Theoretical limitations or puzzles
 - vacuum stability
 - hierarchy problem
 - neutrino masses
 - why 3 families?
 - . . .

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Several limitations of the SM

The SM cannot explain our Universe Physics beyond the SM needed to address these questions











Astrophysical motivations: dark matter



Clear astrophysical evidences for dark matter...

- the gravitational behaviour differs from the one expected from visibile matter
- but no suitable dark matter candidate in SM!
- DM is 85% of the total matter in the Universe

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- If DM is a particle and has minimal interactions with the SM particles, search for
 - its annihilaton (astro)
 - its production (collider)
 - its scattering (direct detection)



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A dark sector of the SM

- Traditional simplified models at the LHC: one DM particle and one mediator
- But a more rich "dark sector" might exist
 - a "dark mirror" or the SM with its own particle content and interactions
 - messengers connect the dark sector to the SM (e.g. Higgs portals models)



- particles

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SM

Dark sector

Dark sector and SM weakly coupled \rightarrow long lifetime of dark

Can be produced at the LHC in pp collisions, decay back to SM particles within the volume of the detector \Rightarrow emerging jets

Challenging signatures for detectors

 \rightarrow Talk by Guillaume Albouy

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Matter / antimatter asymmetry

Sakharov conditions

- 1. baryon number violation (we expect universe to start symmetric between B and anti-B)
- 2. CP violation (treat B and anti-B differently to remove antimatter)
- 3. out-of-thermal equilibrium (suppress inverse processes)
- The observed asymmetry between baryons and anti-baryons is 10¹⁷ larger than the SM prediction no mechanism for baryogenesis can be build within the SM to accommodate this level of asymmetry
- Physics beyond the SM needed to explain the observed imbalance

Where has all antimatter gone?

→ Talk by Christopher Greenberg

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- Any particle contributing with a large term to m_H other massive SM particles are protected by symmetries but no symmetry protects the Higgs boson itself
- A very accurate cancellation must happen to maintain m_H close to the EW scale

Loop corrections to m_H are divergent

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A very accurate cancellation must happen to maintain m_H close to the EW scale

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It's like finding exactly the same number of mogettes in different jars

Not forbidden, but highly unlikely

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At this stage, a random physicist would be like "CP should still be conserved, right..... right??? I'd bet all my mogettes on it!"

Machine I approache position re

Mogetts Mojahed Abushawish,

is $B_{\text{mogette}} = 11.3 \,\mu\text{T}$ 1e-27 1.0 problematic field 0.8 configurations 0.6 $\stackrel{\text{alse}}{\leftarrow}_{Hg}[10^{27}]$ 25 15 30 20 $B_0[\mu T]$

A very accurate cancellation must happen to maintain m_H close to the EW scale



Or like finding a mention of mogettes in several talks in a particle physics meeting

Not forbidden, but there is likely a hidden reason behind

The Higgs boson mass is improbably small

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cancellation of divergences

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A mechanism to ensure that divergent contributions cancels

Supersymmetry: each fermion (boson) has a supersymmetric boson (fermion) partner: natural

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Supersymmetry at the LHC



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

Thoroughly tested at the LHC in a multitude of signatures

No sign of SUSY particles

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ATLAS SUSY Searches* - 95% CL Lower Limits

Signature	$\int \mathcal{L} dt [\mathbf{f}\mathbf{b}^{-1}]$	Mass limit	Reference
$\begin{array}{ccc} 0 \ e, \mu & 2-6 \ { m jets} & E_{T { m is}}^{ m mis} \ { m mono-jet} & 1-3 \ { m jets} & E_{T}^{ m mis} \end{array}$	^{ss} 139 ^{ss} 139	\tilde{q} [1×, 8× Degen.] 1.0 1.85 $m(\tilde{\chi}_1^0) < 400 \text{GeV}$ \tilde{q} [8× Degen.] 0.9 $m(\tilde{\chi}_1^0) = 5 \text{GeV}$	2010.14293 2102.10874
$0 e, \mu$ 2-6 jets E_T^{mis}	^{ss} 139	$ \begin{array}{c} \tilde{g} \\ \tilde{g} \\ \tilde{g} \\ \hline{g} \\ \hline{forbidden} \\ \hline \hline \hline{forbidden} \\ \hline \hline \hline{forbidden} \\ \hline \hline \hline \hline{forbidden} \\ \hline $	2010.14293 2010.14293
1 <i>e</i> , <i>µ</i> 2-6 jets	139	\tilde{g} 2.2 m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
$ee, \mu\mu$ 2 jets E_T^{mis}	^{ss} 139	\tilde{g} 2.2 m($\tilde{\chi}_1^0$)<700 GeV	CERN-EP-2022-01
$\begin{array}{ccc} 0 \ e, \mu & \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$	^{ss} 139 139	$ \begin{array}{c} \tilde{g} \\ \tilde{g} \\ \end{array} \begin{array}{c} 1.97 \\ m(\tilde{\chi}_1^0) < 600 \text{GeV} \\ m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200 \text{GeV} \\ \end{array} $	2008.06032 1909.08457
$\begin{array}{ccc} \text{0-1} \ e,\mu & \text{3} \ b & E_T^{\text{mis}} \\ \text{SS} \ e,\mu & \text{6} \ \text{jets} \end{array}$	^{ss} 79.8 139	$ \begin{array}{c} \tilde{g} \\ \tilde{g} \\ \tilde{g} \\ \end{array} \begin{array}{c} 2.25 \\ m(\tilde{\chi}_1^0) < 200 \text{ GeV} \\ m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV} \\ \end{array} $	ATLAS-CONF-2018- 1909.08457
$0 e, \mu$ $2 b$ E_T^{mis}	^{ss} 139	$ \begin{array}{c c} \tilde{b}_1 & & 1.255 & & m(\tilde{\chi}_1^0) < 400 {\rm GeV} \\ \tilde{b}_1 & & 0.68 & & 10 {\rm GeV} < \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20 {\rm GeV} \\ \end{array} $	2101.12527 2101.12527
$\begin{array}{ccc} 0 \ e, \mu & 6 \ b & E_{T \mathrm{is}}^{\mathrm{mis}} \\ 2 \ \tau & 2 \ b & E_{T}^{\mathrm{mis}} \end{array}$	^{ss} 139 ^{ss} 139	$ \begin{array}{c cccc} \tilde{b}_1 & & & & & \\ \hline{b}_1 & & & & & \\ \hline{c}_1 & & & & & \\ \hline{c}_2 & , \tilde{\chi}_1^0) = 130 \ \text{GeV}, \ m(\tilde{\chi}_1^0) = 100 \ \text{GeV}, \\ \Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130 \ \text{GeV}, \ m(\tilde{\chi}_1^0) = 0 \ \text{GeV} \\ \end{array} $	1908.03122 2103.08189
0-1 $e, \mu \ge 1$ jet E_T^{mis}	^{ss} 139	\tilde{t}_1 1.25 m $(\tilde{\chi}_1^0)$ =1 GeV	2004.14060,2012.03
1 e, μ 3 jets/1 b E_{T}^{mis}	^{ss} 139	\tilde{t}_1 Forbidden 0.65 m($\tilde{\chi}_1^0$)=500 GeV	2012.03799
1-2 τ 2 jets/1 b E_T^{mis}	^{ss} 139	\tilde{t}_1 Forbidden 1.4 $m(\tilde{\tau}_1)=800 \text{GeV}$	2108.07665
$\begin{array}{ccc} 0 \ e, \mu & 2 \ c & E_{\text{min}}^{\text{min}} \\ 0 \ e, \mu & \text{mono-jet} & E_{T}^{\text{min}} \end{array}$	^{ss} 36.1 ^{ss} 139	$\begin{array}{cccc} \tilde{c} & & & & & \\ \tilde{t}_1 & & & & 0.55 \end{array} & & & & & & \\ m(\tilde{t}_1) = 0 \text{ GeV} & & & & \\ m(\tilde{t}_1, \tilde{c}) - m(\tilde{t}_1) = 5 \text{ GeV} & & & \\ \end{array}$	1805.01649 2102.10874
1-2 e, μ 1-4 b E_T^{mis}	^{ss} 139	\tilde{t}_1 0.067-1.18 m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
$3 e, \mu$ $1 b$ E_T	139	t_2 Forbiaden 0.86 $m(\chi_1^*)=360 \text{ GeV}, m(t_1)-m(\chi_1^*)=40 \text{ GeV}$	2006.05880
$\begin{array}{ll} \text{Multiple } \ell/\text{jets} & E_T^{\text{mis}} \\ ee, \mu\mu & \geq 1 \text{ jet} & E_T^{\text{mis}} \end{array}$	^{ss} 139 ^{ss} 139	$\begin{array}{cccc} \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} & & & & \\ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} & & & & \\ m(\tilde{\chi}_{1}^{0})=0, \text{ wino-bino} \\ m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV, wino-bino} \end{array}$	2106.01676, 2108.07 1911.12606
$2 e, \mu$ E_{T}^{mis}	^{ss} 139	$\tilde{\chi}_1^{\pm}$ 0.42 m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
Multiple ℓ /jets E_T^{mis}	^{ss} 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden 1.06 m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07
$2 e, \mu$ E_T^{mis}	^{ss} 139	$\tilde{\chi}_1^{\pm}$ 1.0 $m(\tilde{\ell}, \tilde{\gamma}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	1908.08215
2τ E_T^{min}	^{ss} 139	τ [$\tau_L, \tau_{R,L}$] 0.16-0.3 0.12-0.39 m($\tilde{\chi}_1^0$)=0	1911.06660
$2 \ e, \mu$ 0 jets E_T^{min} $ee, \mu\mu$ ≥ 1 jet E_T^{min}	^{ss} 139 ^{ss} 139	$ \begin{array}{c} \ell & & & & \\ 0.7 & & & \\ \tilde{\ell} & & 0.256 \end{array} \\ \end{array} $	1908.08215 1911.12606
$0 e, \mu \ge 3 b E_T^{\text{mis}}$ $4 e, \mu = 0$ jets E^{mis}	^{ss} 36.1 ^{ss} 139	\tilde{H} 0.13-0.23 0.29-0.88 BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030 2103 11684
$0 \ e, \mu \ge 2$ large jets E_T^{his}	^{ss} 139	$\tilde{H} = \begin{array}{c} 0.00 \\ \tilde{H} \end{array} \qquad \begin{array}{c} 0.00 \\ 0.45 \text{-} 0.93 \end{array} \qquad \begin{array}{c} \text{Br}(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1 \\ \text{Br}(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1 \end{array}$	2108.07586
Disapp. trk 1 jet E_T^{mis}	^{ss} 139		2201.02472 2201.02472
pixel dE/dx E_T^{mis}	^{ss} 139	<i>ğ</i> 2.05	CERN-EP-2022-02
pixel dE/dx E_T^{mis}	^{ss} 139	\tilde{g} [$\tau(\tilde{g}) = 10 \text{ ns}$] 2.2 m($\tilde{\chi}_1^0$)=100 GeV	CERN-EP-2022-02
Displ. lep E_T^{mis}	^{ss} 139	$\tilde{e}, \tilde{\mu}$ 0.24 $\tau(\tilde{\ell}) = 0.1 \text{ ns}$	2011.07812
pixel dE/dx E_T^{mis}	^{ss} 139	$ au = 0.34 au = 0.1 \text{ ns} \\ au = 0.36 au = 10 \text{ ns} $	CERN-EP-2022-02
3 <i>e</i> , <i>µ</i>	139	$\tilde{\chi}_{1}^{+}/\tilde{\chi}_{1}^{0}$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05 Pure Wino	2011.10543
4 e, μ 0 jets E_T^{mis}	^{ss} 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.95 1.55 m($\tilde{\chi}_{1}^{0}$)=200 GeV	2103.11684
4-5 large jets	36.1	\tilde{g} [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9 Large λ_{112}''	1804.03568
Multiple	36.1	<i>t</i> $[\chi''_{323}=2e-4, 1e-2]$ 0.55 1.05 m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-
$\geq 4b$	139	\tilde{t} Forbidden 0.95 m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
2 jets + 2 b	36.7	$t_1 [qq, bs] 0.42 0.61$	1710.07171
$2 e, \mu$ $2 b$ 1μ DV	36.1 136	t_1 t_1 [1e-10< λ'_{au} <1e-8, 3e-10< λ'_{au} <3e-9] 1.0 1.6 BR $(t_1 \rightarrow be/b\mu) > 20\%$ BR $(t_1 \rightarrow be/b\mu) > 20\%$ BR $(t_1 \rightarrow au) = 100\%$. cos $\theta_r = 1$	1/10.05544 2003.11956
$1-2e\mu > 6$ iets	130	$\tilde{\chi}^0$ 0.2-0.32	2106 09609
- <u>-</u> <i>c</i> ,μ <u>-</u> ο joio			2100.03003

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Mass scale [TeV]

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10⁻¹

ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}$



Addressing the hierarchy problem



- cancellation of divergences
- (both L and R charged currents)
 - masses around 1 TeV
 - decays to 1 boson + 1 quark

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- \rightarrow Talk by Ji Eun Choi
- → Talk by Benjamin Blancon

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A mechanism to ensure that divergent contributions cancels

Supersymmetry: each fermion (boson) has a supersymmetric boson (fermion) partner: natural

Vector-like fermions: new quarks that receive mass with direct mass terms and are non-chiral



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Searching for BSM physics at colliders

Direct

Detection of new **BSM** particles

Resonances New particles





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Stress-test of the SM predictions searching for deviations

Precision

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BSM searches

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Searching for BSM physics at colliders

Direct

Detection of new **BSM** particles

Resonances New particles

"Traditional" searches for new states decaying to SM particles (WW, ZZ, HH, µµ, $\tau \tau$, ...)



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Unconventional signatures

If BSM decays are suppressed, particles are long-lived

- weak decay interaction
- very compressed spectra (low density of final state)
- Gives rise to many unconventional signatures that require an usage of detector information beyond its traditional purpose
 - highly displaced vertices / tracks
 - slow charged particles
 - disappearing tracks
- Target dedicates searches are necessary to maximise sensitivity
- → Talk by Raphael Haeberle

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Searching for BSM physics at colliders



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Indirect

Stress-test of the SM predictions searching for deviations

Precision

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Precision measurements as a probe of BSM



New physics can manifest in quantum loops Reach scales not directly accessible at the LHC

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Requires exceptional control of experimental effects ad thorough validation and cross-checks

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Effective field theories

What if new physics is out of the direct reach of a collider?

- Modification of SM predictions modelled with an "effective" theory
 - not a "good" renormalizable theory: breaks when $E \sim \Lambda$ because new physics appears
 - good "effective" description at low energy
- Analogous to the Fermi theory of a neutron decay





High-scale BSM physics studied from low-energy effects

Precision SM measurements are effectively searches for BSM physics

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Effective field theories

EFT : expansion of SM Lagrangian (d = 4) with higher order operators



- Various choices of the EFT "type" are possible
 - linear (SMEFT: H is a doublet) or non linear (EwChL / HEFT) realisations
 - subsets of SM symmetries can be imposed (e.g. flavour) to restrain number of parameters
- Great tool to coherently treat different measurements
 - theoretically sound combination of Higgs, top, EW, ...
 - use the full information from collider data (kinematic, rates, ...)
 - specific UV models can be mapped to a EFT
- Highly complex parameter space
 - in SMEFT, 1 dim-5 operator (Maiorana) but O(3000) dim-6 operators!
 - experimentally requires the selection of those with leading effects
 - non trivial treatment of truncation

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Violation of the SM symmetries

- Some symmetries in the SM are realised, but not protected by "first principles"
- Lepton number conservation: violated by neutrinos oscillations
- $\mu \rightarrow e decay$
 - BR ~ 10^{-54} in the SM
 - any LFV process can enhance this up to 10⁻¹⁵ in BSM models!

Any strong violation of "accidental" SM symmetries is a smoking gun for BSM physics

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Neutrinoless $\mu \rightarrow e$ decay



Search with $\mu \rightarrow e + \gamma$ (coincidence)

Search with $\mu N \rightarrow eN$ (mono-energetic e)



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→ Talk by Nicolas Chadeau











Conclusions

The SM is a blessing and a curse

- beautiful and elegant theory, valid up to the Planck scale
- but astrophysical, cosmological and theoretical considerations call for new physics beyond it
- no clear theoretical indications of what BSM could be : up to experiments to find new hints
- Broad programme of BSM searches spanning several domains of particle physics
 - direct searches
 - precise verification of the SM predictions
 - search for phenomena forbidden by the SM
- A sea of possibilities to be explored experimentally!



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