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Samuel Jones

# Searching for Squarks

## in Compressed States and States with Jets from Charm Quarks with the Atlas Detector

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# Searching for Squarks

## in Compressed States and States with Jets from Charm Quarks with the Atlas Detector

Doctoral Thesis accepted by
University of Sussex, Brighton, United Kingdom

Springer

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ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-030-54287-0 ISBN 978-3-030-54288-7 (eBook)
https://doi.org/10.1007/978-3-030-54288-7



This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

# Supervisor's Foreword

Among the techniques used in particle physics to advance the field, that of colliding particles dates back to the beginning of the twentieth century: Ernest Rutherford pioneered the technique and discovered the existence of the atomic nucleus by bombarding a golden foil with alpha particles. Since then, and in particular, in the second half of the century, the field has advanced immensely, bringing crucial contributions to our understanding of the microscopic world of elementary particles. The discovery of the charm, bottom and top quark, the tau lepton, the electroweak bosons, and the understanding of the internal structure of nucleons and hadrons, in general, are the most relevant scientific results achieved by accelerating particles to high energy and then smashing them head-on, or on fixed targets.

The Large Hadron Collider is the last generation product of this prolific technique. The LHC accelerates proton beams[1] up to high energies in opposite directions, and collides them together, achieving a centre-of-mass energy of 14 TeV by design (13 TeV at the time of writing). Thanks to this remarkable machine, the last missing piece of the Standard Model of Particle Physics, the Higgs boson, has finally been experimentally identified and measured with great precision.

Together with these great achievements, the LHC has also made very clear that the Standard Model is a far better theory than many expected: it has successfully predicted the outcome of each one of the hundreds of measurements performed in this new energy regime. Many paradigms extending the Standard Model, developed to address theoretical problems connected with the stability of the Higgs boson mass under quantum corrections, have been scrutinised in great detail and put under considerable pressure by the lack of evidence supporting the best motivated models.

Electroweak scale Supersymmetry is arguably one of the best motivated extensions of the Standard Model: one of the key predictions is the existence of a new particle with spin 0, otherwise sharing all gauge quantum numbers of the top quark. This top s-quark, or stop, should have a mass within the reach of the LHC. ATLAS is a collaboration of more than 3000 scientists recording and analysing the

[1]The LHC can also accelerate heavy nuclei. However, this remarkable aspect of the LHC is not relevant for the thesis presented in this book.

results of the proton-proton collisions produced by the LHC. This collaboration developed a remarkable programme for the search for the stop. It is in this context that Dr. Samuel Jones developed his research work. Dr. Jones focused on models not well explored before, where the decay products of the stop carry low momentum. He has made two novel contributions to the field:

- Together with German colleagues, he developed a novel search for the stop decaying into a charm quark. The constraints imposed on new models by this analysis were world leading at the time of the writing.
- He developed new algorithms to identify very low-momentum hadrons containing b-quarks. This paved the way for a series of searches that explored (and will explore) previously un-examined models.

Dr. Jones's thesis work was remarkable from many points of view: the scientific outcome, in the form of strong experimental constraints, will help guide the theory community in further developing extensions to the Standard Model. At the same time, some of the original tools developed by Dr. Jones during his work will be a great experimental support for the years to come.

Brighton, UK
April 2020

Prof. Iacopo Vivarelli

# Abstract

This thesis presents a search for R-parity conserving Supersymmetry with the ATLAS detector, in final states with missing transverse momentum and jets. A search is designed, targeting pair produced scalar top quarks decaying as $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ and scalar charm quarks decaying as $\tilde{c}_1 \rightarrow c\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the lightest neutralino. Charm tagging methods are used to identify jets originating from charm quarks. This search is based on LHC proton-proton collision data collected by ATLAS in 2015 and 2016, amounting to 36.1 $\text{fb}^{-1}$ of integrated luminosity. No significant excess of data beyond Standard Model expectations was observed and squarks were excluded up to a mass of 850 GeV for a massless neutralino and up to 500 GeV for a mass splitting between the squark and neutralino of less than 100 GeV. All limits assume a 100% branching ratio to the $c\tilde{\chi}_1^0$ final state.

This thesis also presents a novel technique to identify low momentum *b*-hadrons using tracks from the ATLAS inner detector. This technique is developed to target compressed Supersymmetry models where the mass splitting between the squark and neutralino is small, leading to low momentum *b*-hadrons in the final state. With this technique, *b*-hadrons with transverse momentum in the range $10-20$ GeV can be identified with an efficiency of $\sim 20\%$ with a mis-identification rate corresponding to $\sim 2.5\%$ of simulated events with no *b*-hadrons.

# Acknowledgements

I am extremely grateful to my supervisor Iacopo, who has been a patient mentor, providing invaluable advice and guidance throughout my Ph.D. I will always admire your experience and insights. I am also grateful to Antonella, my second Ph.D. supervisor and first supervisor for my masters project, who had the faith to allow me to continue with ATLAS at Sussex following this project. I must, of course, mention Kerim, who has been an extra supervisor throughout my Ph.D., and shared all my tea!

My entire career in physics has been at Sussex, where I have spent the last 9 years, from my access course to undergraduate studies to the submission of my Ph.D. thesis. It is a wonderful department, although, admittedly, I have a sample size of one… I am grateful to my undergraduate project supervisors, Diego Porras (also my academic advisor) and Veronica Sanz (who help me on my trajectory toward SUSY searches). I am grateful to the entire Sussex EPP team: faculty, post docs and Ph.D. colleagues. They are all wonderful people, to the last person. I give special mention to Suf, who was my mentor at the beginning of my time working on ATLAS for my masters project, and to my CERN drinking buddies: Fabio, Emma, Fab, Nicola, Mark, Olly and the rest. Thanks to Fabio, you will never forget: you'll never get a better bit of butter on your knife!

I am grateful to my Dad, who loves physics as much as I do and has always taken so much interest in my physics journey. I am grateful to my Mum, who is always there to catch me out with a surprise question about an obscure topic from the corner of physics. I am grateful to the rest of my family, more accurately described as a horde. It would take too long to thank them all, so I give my thanks to the Jones Hive Mind! I thank all my Hastings and Portway friends for their support, without you my thesis would have been completed six months faster, and to a standard twice as high.

I thank my wonderful wife Anne, who has supported me throughout this journey more than anyone else, unjealously humouring my passion for physics, even through my affair with SUSY.

And finally, with a quote, I give a nod to Oliver and Clemens, who helped to kindle my love of physics with discussions about chaos theory, quantum mechanics and special relativity during R.E. classes at secondary school: *the drummer from Def Leppard only has one arm…*

# Contents

# Acronyms

| | |
|---|---|
| ALFA | Absolute Luminosity For ATLAS |
| ALICE | A Large Ion Collider Experiment |
| AMSB | Anomaly Mediated Symmetry Breaking |
| AOD | Analysis Object Data |
| ASIC | Application-Specific Integrated Circuit |
| ATLAS | A Toroidal Lhc ApparatuS |
| BBN | Big Bang Nucleosynthesis |
| BDT | Boosted Decision Tree |
| CB | ComBined (muon) |
| CERN | European Centre for Nuclear Research |
| CKKW | Catani-Krauss-Kuhn-Webber |
| CKM | Cabibbo-Kobayashi-Maskawa |
| CMB | Cosmic Microwave Background |
| CMS | Compact Muon Solenoid |
| CMX | Extended Cluster Merger Module |
| CP | Charge-Parity (Chap. 1) or Cluster Processor (Chap. 2) |
| CR | Control Region |
| CSC | Cathode-strip Chamber |
| CT | Calorimeter-Tagged (muon) |
| CTP | Central Trigger Processor |
| DAOD | Derived Analysis Object Data |
| DGLAP | Dokshitzer Gribov Lipatov Altarelli Parisi (authors) |
| DQ | Data Quality |
| ECAL | Electromagnetic CALorimeter |
| EF | Event Filter |
| EM | ElectroMagnetic |
| EMEC | ElectroMagnetic End-Cap |
| EWSB | Electro-Weak Symmetry Breaking |
| FCAL | Forward CALorimeter |
| FCNC | Flavour Changing Neutral Current |

| | |
|---|---|
| FE | Front-End |
| FPGA | Field Programmable Gate Array |
| GMSB | Gauge-Mediated Supersymmetry Breaking |
| GRL | Good Runs List |
| GSC | Global Sequential Calibration |
| GSF | Gaussian Sum Filter |
| GUT | Grand Unified Theory |
| HEC | Hadronic End-cap Calorimeter |
| HLT | High Level Trigger |
| IBL | Insertable B-Layer |
| ID | Inner Detector |
| IP2D | 2-Dimensional Impact Parameter |
| IP3D | 3-Dimensional Impact Parameter |
| ISR | Initial State Radiation |
| JEP | Jet/Energy-sum Processor |
| JER | Jet Energy Resolution |
| JES | Jet Energy Scale |
| JVT | Jet Vertex Tagger |
| KLFitter | Kinematic Likelihood Fitter |
| KLN | Kinoshita-Lee-Nauenberg |
| L1 | Level 1 |
| L1Calo | Level 1 Calorimeter |
| L1Muon | Level 1 Muon |
| L1Topo | Level 1 Topological Processor |
| L2 | Level 2 |
| LAr | Liquid Argon |
| LB | Luminosity Block |
| LEP | Large Positron Electron Collider |
| LH | LikeliHood |
| LHC | Large Hadron Collider |
| LHCb | Large Hadron Collider b |
| LH$\chi$SF | Left-Handed Chiral SuperField |
| LINAC2 | LINear Accelerator 2 |
| LLP | Long-Lived Particle |
| LLR | Log-Likelihood Ratio |
| LO | Leading Order |
| LSP | Lightest Supersymmetric Particle |
| LUCID | LUminosity measurement using Cerenkov Integrating Detector |
| MACHO | MAssive Compact Halo Objects |
| MC | Monte Carlo |
| MCM | Multi-Chip Module |
| MDT | Monitored Drift Tube chamber |
| ME | Matrix Element (Sect. 4.3 and Chap. 5) or Muon, Extrapolated (Sect. 4.4.3) |
| MIP | Minimum-Ionising Particle |

| | |
|---|---|
| MLM | Michelangelo L. Mangano |
| MoEDAL | Monopole and Exotics Detector at the LHC |
| MSSM | Minimal Supersymmetric Standard Model |
| MUCTPI | Muon to Central Trigger Processor Interface |
| MVA | Multi-Variate Analysis |
| NLL | Next to Leading Logarithm |
| NLO | Next to Leading Order |
| nMCM | new Multi-Chip Module |
| NN | Neural Network |
| NP | Nuisance Parameter |
| OP | Operating Point |
| OS | Opposite Sign |
| PCL | Primary Calibration Loop |
| PDF | Parton Distribution Function |
| PMT | PhotoMultiplier Tube |
| PS | Proton Synchotron |
| PV | Primary Vertex |
| QCD | Quantum ChromoDynamics |
| QFT | Quantum Field Theory |
| RF | Radio Frequency |
| RGE | Renormalisation Group Equation |
| RH$\chi$SF | Right-Handed Chiral SuperField |
| RMS | Root Mean Squared |
| ROC | Receiver Operating Characteristic |
| ROD | ReadOut Driver |
| ROI | Region Of Interest |
| ROS | ReadOut System |
| RPC | Resitive Plate Chamber |
| RPV | R-Parity Violating |
| SCT | SemiConductor Tracker |
| SFOS | Same Flavour Opposite Sign |
| SM | Standard Model |
| SPS | Super Proton Synchotron |
| SR | Signal Region |
| ST | Segment-Tagged (muon) |
| SUSY | Supersymmetry |
| SV | Secondary Vertex |
| SVF | Secondary Vertex Finder |
| TDAQ | Trigger and Data AcQuisition |
| TGC | Thin Gap Chamber |
| TOTEM | TOTal Elastic and diffractive cross section Measurement |
| TRT | Transition Radiation Tracker |
| TST | Track-based Soft Term |
| UV | Ultra-Violet |
| VEV | Vacuum Expectation Value |

| | |
|---|---|
| VR | Variable Radius (Chap. 4) or Validation Region (Chap. 5) |
| VSF | Vector SuperField |
| WIMP | Weakly Interacting Massive Particle |
| WMAP | Wilkinson Microwave Anisotropy Probe |
| ZDC | Zero Degree Calorimeter |

# Chapter 1
# Introduction

The Standard Model of particle physics is a theoretical framework for describing fundamental particles and their interactions. It is a remarkably successful theory, compatible with decades of collider data. In the Standard Model, $W$ and $Z$ bosons acquire mass through the Higgs mechanism, which predicts the existence of a scalar boson. The discovery and measurement of a Standard Model Higgs by ATLAS and CMS at the Large Hadron Collider completes the Standard Model. The Standard Model in its current form cannot account for a number of important observations. For example, it provides no candidate for dark matter and no mechanism that can explain electroweak baryogenesis. Another shortcoming of the Standard Model is the apparent instability of the Higgs mass to the large variations of scales associated to the fundamental interactions, which requires fine tuning of parameters to reproduce its measured value, the so-called Hierarchy problem. Many extensions to the Standard Model have been proposed to address these limitations.

Central to the Standard Model is the notion of symmetries. Symmetries have long been associated with aesthetics and can simplify seemingly complex systems. It was Emmy Noether who first demonstrated the deep connection between symmetries and conservation laws in nature, and the relativistic fields described by the Standard Model are representations of the Poincaré symmetry group. The force mediators of the Standard Model, which describe the fundamental interactions, arise from local gauge symmetries. Supersymmetry is an extension to the Standard Model that posits an additional symmetry of nature between fermions and bosons, introducing a bosonic partner for each fermion, and vice versa. Miraculously, the consequences of assuming such a symmetry can address many of the limitations of the Standard Model. Supersymmetry can provide a candidate for dark matter, a mechanism for electroweak baryogenesis and stabilise the Higgs mass. Together with its theoretical appeal, this provides strong motivation for Supersymmetry searches at the Large Hadron Collider.



S. Jones, *Searching for Squarks*, Springer Theses,
https://doi.org/10.1007/978-3-030-54288-7_1

The ability of Supersymmetry to address the limitations of the Standard Model depends on the masses of Supersymmetric particles. In particular, for Supersymmetry to stabilise the Higgs mass without reintroducing the need for fine tuning, Supersymmetric particles should be below 1 TeV, accessible to the Large Hadron Collider. At the time of writing, Supersymmetry is conspicuous by its absence, with no search to date finding significant evidence for any Supersymmetric model. The ATLAS and CMS Supersymmetry search program comprises dozens of individual searches targeting simplified models, and each null result provides exclusion coverage for part of the Supersymmetry parameter space. This thesis presents a search for Supersymmetry in final states with missing transverse energy and jets from charm quarks using 36.1 $fb^{-1}$ of data collected by ATLAS in 2015 and 2016. This search provides additional coverage in the search for discovery, or eventual exclusion, of Supersymmetry as a solution to the Hierarchy problem.

At the time of writing, Run 2 of the Large Hadron Collider has ended. With data taking on hold for at least two years, it becomes crucial not only to improve the particle identification capabilities of the ATLAS detector in preparation for Run 3, but also to extend the reach of ATLAS searches in existing data. One important limitation of particle reconstruction at ATLAS is the loss of low momentum $b$-hadrons, which are present in the experimental signature of many interesting models of Supersymmetry. This thesis presents a new algorithm that allows these low momentum $b$-hadrons, previously beyond the reach of the ATLAS detector, to be recovered, extending the sensitivity of ATLAS Supersymmetry searches.

The work of this thesis was conducted as part of the ATLAS collaboration. The data collected by the ATLAS detector must be processed, reconstructed and simulated for interpretation. This involves hundreds of auxiliary measurements and studies, a highly collaborative effort involving thousands of physicists. The author of this thesis contributed significantly to the ongoing calibration of the ATLAS electron trigger from 2015–2017, the results of which are used by analyses throughout ATLAS, including those documented in this thesis. This work is reported in a dedicated appendix.

The analyses presented in this thesis build on years of previous work, and were carried out by teams of researchers. In such a collaborative environment it can be difficult to distinguish the contribution of an individual from the organisation as a whole. In some cases the boundaries between contributions may not be easy to define, for example calibration results that are used by hundreds of analyses that use ATLAS data. A list of publications to which the author of this document played a central role, along with the key contributions to each, is given below:

- *Search for supersymmetry in final states with charm jets and missing transverse momentum in 13 TeV pp collisions with the ATLAS detector* [1], the subject of Chap. 5.
  - This analysis was conducted by a small research team within the ATLAS SUSY working group. The author of this thesis was one of two PhD students working in the team, contributing to most aspects of the analysis. These contributions include: signal region development, background estimation (particularly relat-

ing to the one-lepton and multijet backgrounds), optimisation of charm tagging operating points and the derivation of associated efficiencies and systematic uncertainties and the evaluation of the final results.

- *Soft b-hadron tagging for compressed SUSY scenarios* [2], the subject of Chap. 6.
  - The above publication describes three techniques for the identification of soft $b$-hadrons with the ATLAS detector. Chapter 6 focuses almost entirely on the development of one of these techniques: the reconstruction of $b$-hadrons by reconstructing their decay vertices in clusters of tracks. This analysis is the author's own work.
- *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at* $\sqrt{s} = 13$ TeV [3] and *Performance of electron and photon triggers in ATLAS during LHC Run 2* [4], both using the results of Appendix A.
  - These publications document electron trigger efficiency of the ATLAS detector in Run 2 of the LHC. The author of this thesis provided the official electron trigger efficiency measurements used by ATLAS for all of 2016 and 2017 data taking, and continued to contribute in 2018 in a more supervisory capacity.

This thesis is structured as follows: Chap. 2 presents an overview of the Standard Model, highlighting some of its important limitations, and introduces Supersymmetry and its current status. Chapter 3 describes the Large Hadron Collider and the ATLAS detector, with attention given to each of its main subsystems, including the hardware of the trigger system. Chapter 4 gives details for data acquisition, processing and reconstruction, including details of the Monte Carlo simulations that are essential for interpreting the data. Chapter 5 presents a search for Supersymmetry in final states with missing transverse energy and jets from charm quarks, and Chap. 6 presents a new algorithm for the identification of low momentum $b$-hadrons at ATLAS. The electron trigger calibration work and additional analysis details are given in the appendices.

## References


1. The ATLAS Collaboration Search for supersymmetry in final states with charm jets and missing transverse momentum in 13 TeV $pp$ collisions with the ATLAS detector JHEP 09 (2018) 050. https://doi.org/10.1007/JHEP09(2018)050
2. The ATLAS Collaboration Soft $b$-hadron tagging for compressed SUSY scenarios ATLAS-COM-CONF-2019-027 (2019). https://cds.cern.ch/record/2682131
3. The ATLAS Collaboration Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at $\sqrt{s} = 13$ TeV Eur. Phys J C 79:639 (2019). https://doi.org/10.1140/epjc/s10052-019-7140-6
4. The ATLAS Collaboration Performance of electron and photon triggers in ATLAS during LHC Run 2 Submitted to Eur Phys J C. arxiv.org/abs/1909.00761

# Chapter 2
# Theoretical Background

The experimental searches detailed in this thesis concern supersymmetry (SUSY) and the Standard Model (SM). This chapter develops the theoretical background necessary to set these searches in context. Section 2.1 describes the SM and Sect. 2.2 its limitations. Section 2.3 introduces SUSY and its phenomenology at the LHC, focusing on the SUSY models considered by the analyses presented in this thesis. Finally, Sect. 2.3.6 expands the scope, discussing more general SUSY models and the wider SUSY search effort, and presents some of the current limits on SUSY parameters.

## 2.1 The Standard Model

The Standard Model[1] of particle physics is a quantum field theory that successfully accounts for three of the four fundamental forces of nature. The fourth, gravity, is too weak to play a significant role at energies accessible to modern particle physics experiments. Particle physics processes are described in terms of spin $\frac{1}{2}$ fermionic fields interacting through bosonic mediator fields with integer spin. Developed in the 1970s, the SM is the culmination of more than seven decades of experimental and theoretical discovery. This section provides a brief discussion of some the key ingredients in the development of the SM and a summary of the SM itself.

[1]For readers less familiar with the Standard Model and its theory, *Introduction to Elementary Particles* [1] is an excellent reference aimed at advanced undergraduates.



S. Jones, *Searching for Squarks*, Springer Theses,
https://doi.org/10.1007/978-3-030-54288-7_2

### 2.1.1 Quantum Field Theories

The SM is a *quantum field theory*.[2] Quantum field theory (QFT) is a theoretical framework that incorporates quantum mechanics and special relativity. This is achieved through a procedure of quantisation of relativistic fields, with particles understood as excitations of these fields.

The language of QFT is the Lagrangian formalism,[3] where the dynamics of a system are summarised by the Lagrangian density $\mathcal{L}(\phi, \partial\phi)$, a function that depends on relativistic fields and their derivatives. The equations of motion of a system are derived by minimising the action $\mathcal{S}$:

$$\mathcal{S} = \int d^4x\mathcal{L}. \tag{2.1}$$

The S-matrix[4] element for a scattering process is computed in the interaction picture, where the Lagrangian density is split into two components:

$$\mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}}, \tag{2.2}$$

where $\mathcal{L}_{\text{free}}$ describes free fields and $\mathcal{L}_{\text{int}}$ the interactions between these fields. The S-matrix can be represented as a perturbative expansion in powers of $\mathcal{L}_{\text{int}}$. Once the S-matrix has been determined, it can be used to make predictions about observable quantities, for example cross-sections and decay rates.

Terms in the perturbative expansion can be represented diagrammatically using Feynman diagrams,[5] composed of vertices, lines and propagators, each representing a factor in the final expression for the S-matrix . To first order the S-matrix is simply the sum of the first order *tree level* Feynman diagrams. Higher order diagrams contain *loop* corrections which typically contribute divergent integrals to the expression for the S-matrix. A set of prescriptions exists to treat such divergences, collectively known as *renormalisation*.

Renormalisation[6] proceeds by splitting the Lagrangian into infinite and finite pieces:

$$\mathcal{L} = [\mathcal{L} - \delta\mathcal{L}(E)] + \delta\mathcal{L}(E), \tag{2.3}$$

where the energy $E$ is some cutoff scale, and $\delta\mathcal{L}$ is the measurable part of the Lagrangian. $\delta\mathcal{L}$ is constrained such that the measurable quantities, for example the

[2]For an introduction to quantum field theory, the author recommends *An Introduction To Quantum Field Theory* [2] and *The Quantum Theory of Fields: Foundations Volume 1* [3].

[3]The Lagrangian formalism is developed in Chap. 11 of Ref. [1], Chap. 7 of Ref. [3] and a brief discussion can be found in Chap. 2 of Ref. [2].

[4]A detailed description of the S-matrix is given in Chap. 3 of Ref. [3].

[5]More details on Feynman diagrams can be found in Chap. 6 of Ref. [1] and Chap. 4 of [2].

[6]A brief discussion of renormalisation can be found in Chap. 7 of Ref. [1], and more detail can be found in Refs. [2, 3].

coupling constants and particle masses, do not depend on the cutoff energy. This restriction gives rise to the renormalisation group equations (RGEs), which describe how the coupling constants of the fundamental forces run with energy. For a QFT to be predictive, it must be renormalisable. Any physically descriptive QFT must therefore include only renormalisable terms in the Lagrangian.

### *2.1.2 Symmetries in Particles Physics*

A field theory is said to possess a symmetry[7] if a transformation leaves the action $\mathcal{S}$ of the theory unchanged. Noether's theorem [4] states that for any continuous symmetry of $\mathcal{S}$ a corresponding conserved current can be derived. For example, the Noether current associated to the invariance of the action $\mathcal{S}$ under space and time translations gives rise to momentum and energy conservation, respectively. Noether's theorem demonstrates how the symmetries displayed by the Lagrangian reveal important information about the behaviour of a theory.

Central to QFTs is the Poincaré symmetry group, which describes translations, rotations and boosts in Minkowski space. A causal theory is constructed by requiring that the action $S$ be invariant under Poincaré transformations:

$$x_\mu \rightarrow x'_\mu = \Lambda^\nu_\mu x_\nu + a_\mu, \tag{2.4}$$

where the $\Lambda$ is a general Lorentz transformation and $a$ is an additional translation in spacetime coordinates. Any relativistic field is a representation of the Poincaré group. QFTs are the result of quantisation of these fields.

The SM is a *gauge theory*, constructed by imposing invariance under a set of gauge transformations. A gauge transformation is a continuous set of local transformations, forming a Lie group, which can be represented through a basis of linear transformations. The independence of the chosen gauge in a theory represents redundant degrees of freedom in the Lagrangian. To ensure invariance of the Lagrangian under a gauge transformation, a corresponding gauge covariant derivative is defined, introducing additional gauge fields in the Lagrangian. These gauge fields relate the symmetry transformations at different points in spacetime, and are realised as force mediators. The strong, electromagnetic (EM) and weak interactions can be associated to specific gauge groups.

The basic recipe for constructing the SM is then to assume a set of fermion spinor fields to correspond to the known fundamental particles of matter, assume a set of gauge symmetries that can account for the fundamental interactions, and then write down the most general, renormalisable Lagrangian.

---

[7] Both of Refs. [2, 3] provide discussions of the symmetries described in this section: Noether's theorem, the Poincaré symmetry group and gauge theory.

### 2.1.3 The Electroweak Interaction

The EM and weak interactions are unified in the SM according to the Glashow-Salam-Weinberg mechanism [5, 6]. Below the electroweak scale, $\mathcal{O}(246)$ GeV, they split into the familiar EM and weak interactions through the mechanism of electroweak symmetry breaking (Sect. 2.1.4).

Electroweak theory is described by the gauge group $SU(2)_L \times U(1)_Y$ acting on fermionic spinor fields, which can be represented in terms of left- and right-handed chiral projections:

$$\psi = \psi_L + \psi_R = \frac{1}{2}(1-\gamma^5)\psi + \frac{1}{2}(1+\gamma^5)\psi, \tag{2.5}$$

where $\gamma^5$ is the fifth gamma matrix.[8] In the theory, left-handed fermions form doublets under $SU(2)_L$ and right-handed fermions form $SU(2)_L$ singlets. As a result, the weak interaction couples only to left-handed chiral fields; this property is denoted by the subscript $L$. The chirality of the weak interaction is not an emergent property of the gauge symmetry, but necessary to account for experimental evidence of maximal parity violation in weak interactions [7]. The $Y$ subscript in $U(1)_Y$ denotes the weak hypercharge which relates the unified electroweak interaction to electromagnetism (see Eq. 2.10, later in this section).

Invariance of the Lagrangian under $SU(2)_L \times U(1)_Y$ can be enforced by introducing the covariant derivative

$$\partial_\mu \to D_\mu = \partial_\mu + igW_\mu^a t^a + ig' B_\mu Y, \tag{2.6}$$

where $a$ runs over $1, 2, 3$ and $g$, $g'$ are coupling constants. The three gauge fields $W_\mu^a$ are associated to $SU(2)_L$ and $B_\mu$ to $U(1)_Y$. Fermion and scalar fields are assigned weak isospin $I = 0, \frac{1}{2}$ and weak hypercharge $Y$ quantum numbers. The $t^a$ are defined

$$t^a = \begin{cases} 0 & \text{for} \quad I = 0, \\ \sigma^a & \text{for} \quad I = \frac{1}{2}, \end{cases} \tag{2.7}$$

where $I = \frac{1}{2}, 0$ for fermions with left- and right-handed chirality, respectively. The gauge fields for charged currents arise as a linear combination of $SU(2)_L$ eigenstates:

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}. \tag{2.8}$$

The physical neutral fields are obtained through the mixing of $SU(2)_L$ and $U(1)_Y$:

[8] Definitions for the five gamma matrices are given in Refs. [1–3].