Modelling in Particle Physics

Marek Schönherr

Durham, 02 May 2023

Overview

1. General considerations
2. Modelling in Particle Physics
3. How to compute physical predictions
4. Conclusions

Overview

1 General considerations

2 Modelling in Particle Physics

3 How to compute physical predictions

4 Conclusions

Theories and models in physics

In physics, both a **theory** and a **model** are mathematical descriptions of physical events. Both are judged by the extent to which their predictions agree with existing empirical observations, and their ability to make new predictions which have the potential to be falsified by new observations.

Often, it is understood that physical **theories** are comparably abstract and applicable to a wide range of phenomena by emphasising universal properties, whereas physical **models** focus on the application of a theory to a much narrower use case to make calculable predictions.

This, however, is often not reflected in canonical naming conventions.

I choose to understand **modelling** as the act of applying assumptions and/or simplifications to an existing physical theory in order to be able to actually calculate falsifiable predictions of said theory.

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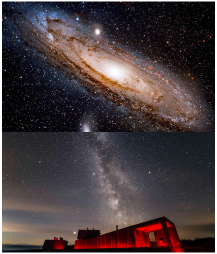
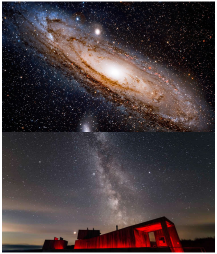


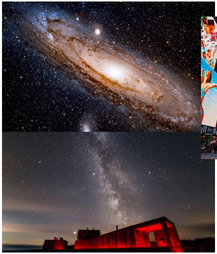
gravity

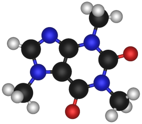
Theories in physics – examples



General Relativity

Theories in physics – examples





General Relativity

electromagnetism

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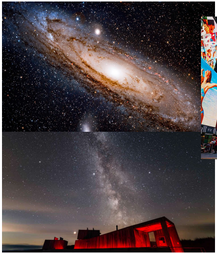

General
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Quantum
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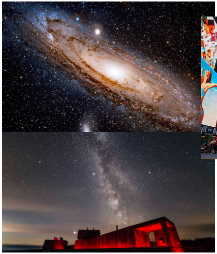

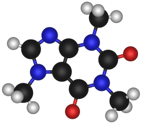

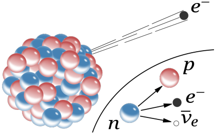

General Relativity

Quantum Electrodynamics

weak nuclear force

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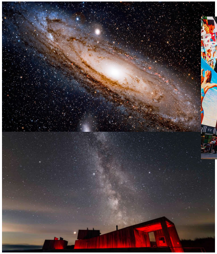

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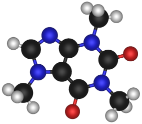

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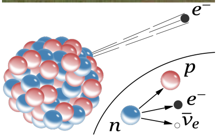

Electroweak Theory

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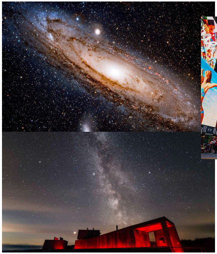

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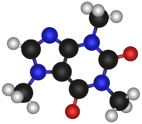

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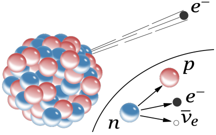

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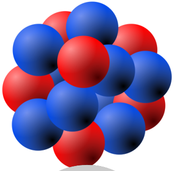

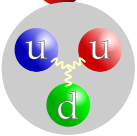

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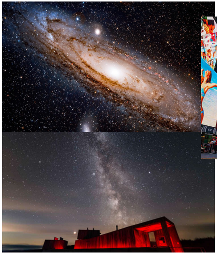

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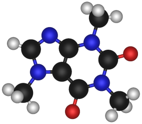

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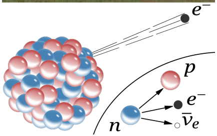

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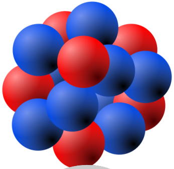

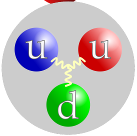

Quantum Chromodynamics

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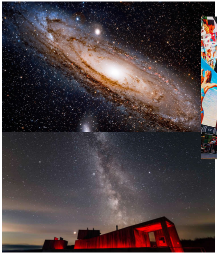

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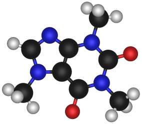

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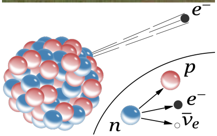

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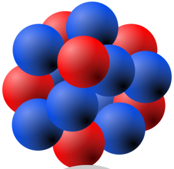

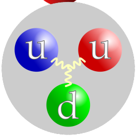

Quantum Chromodynamics

Standard Model of Particle Physics

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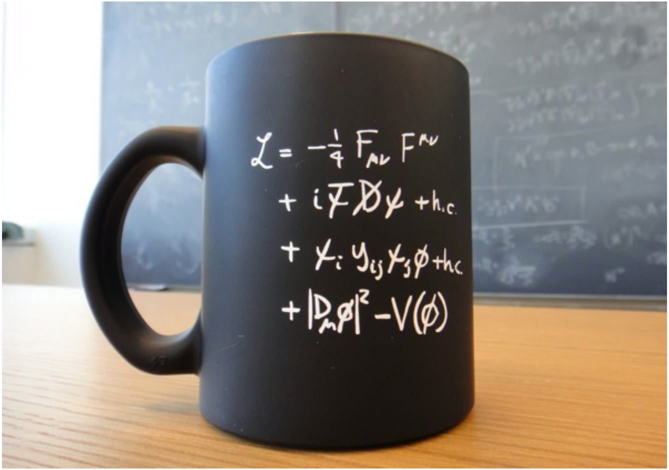
The Standard Model of Particle Physics



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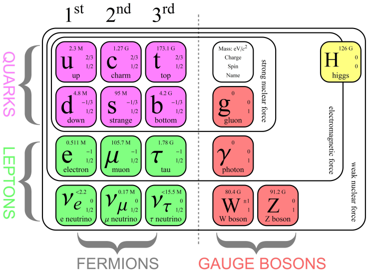

The Standard Model (SM) successfully describes all subatomic phenomena that have been observed.

All its predictions since its inception in the '60s (Glashow, Salam, Weinberg) that could be tested so far have been observed.

We have not been able to falsify it yet.

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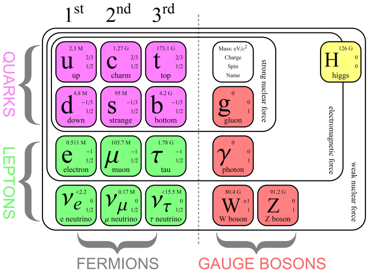

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However, we cannot compute its predictions in its entirety.
We have to make **suitable approximations**

- perturbative expansion (e.g. α, α_s)
- non-perturbative phenomenological models (e.g. quarks-to-hadron transitions)
- discrete spacetime (lattice)

Limitations of the Standard Model

Why do we need to test the Standard Model further and further?

We know the SM is incomplete.

It does not describe a range of observed phenomena.

1) gravity, dark matter, dark energy
2) neutrino masses and oscillations
3) Baryon asymmetry

It contains 19 parameters.
These parameters need to be fine tuned for our universe to exist.

- α protons decay and neutrons are stable
- m_t vacuum unstable
- m_h quantum corrections are about 10^{16} times larger than observed Higgs mass

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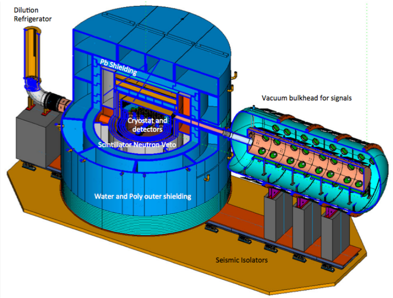
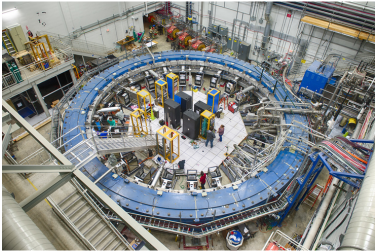
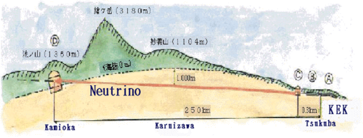
Experimental tests







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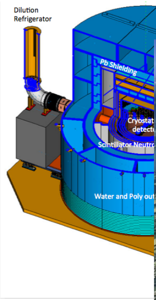
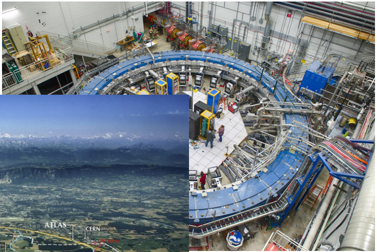
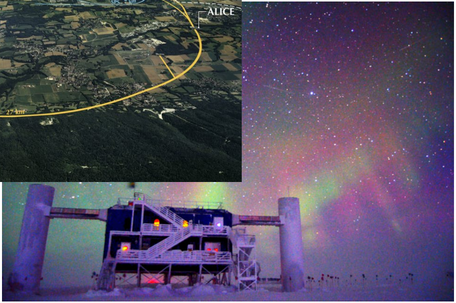
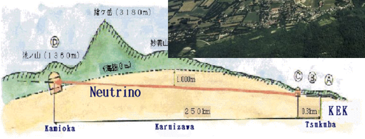


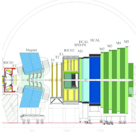


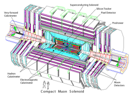


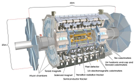


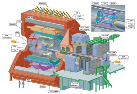
Predictions for the Large Hadron Collider

The Large Hadron Collider experiments (ATLAS, CMS, LHCb, ALICE) measure complex multiparticle final state configurations every 25ns ($4 \cdot 10^7\ \frac{1}{s}$) with 5-10$\cdot 10^7$ read-out channels.









About 500 events/s are stored, generating $\sim$ 7 PB/a of data.

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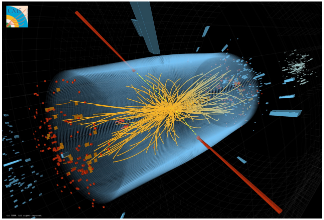
Collider measurements and event generators



Factorise event into processes at different characteristic scales

hard partonic scatter – perturbative expansion in α and α_s
$\rightarrow$ only able to calculate small ensemble

parton shower – extract dominant terms from all orders in the pert. series
$\rightarrow$ describe dominant terms of much larger ensemble

soft physics:
multiple parton interactions, hadronisation, hadron decays
non-perturbative solutions, phenomenological models fitted to data

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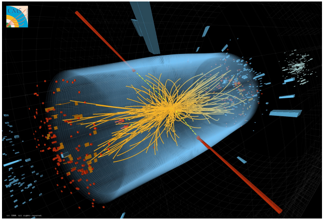

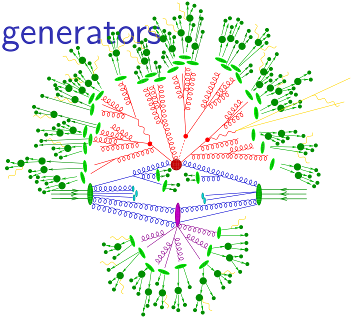

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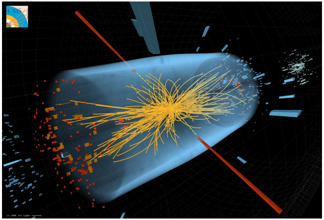

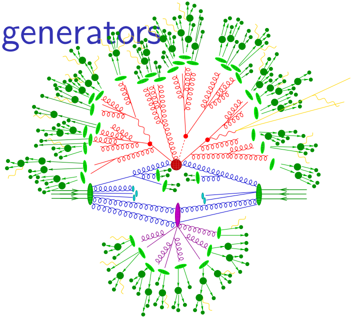

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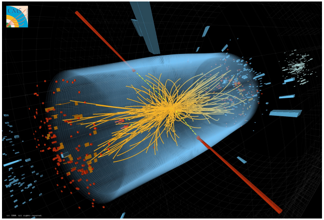

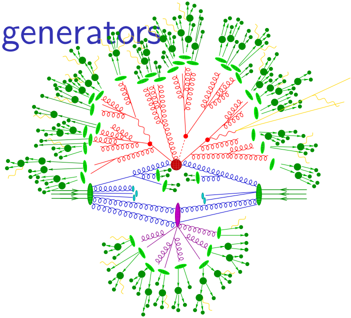

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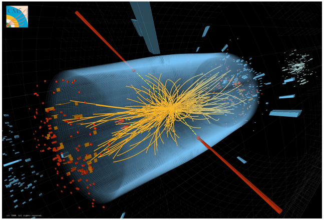

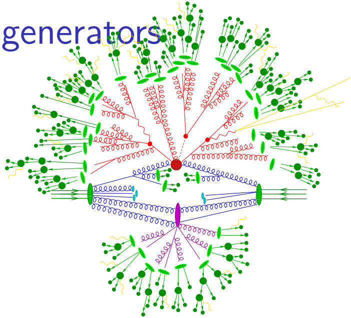

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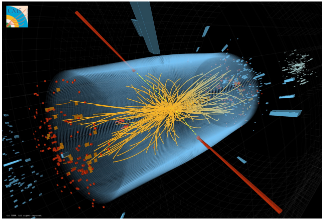

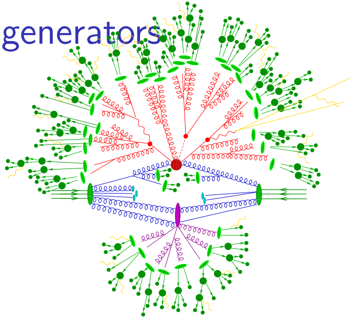

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Example: hard scattering interaction

Formulate as integral equation

$$\sigma = \int \mathrm{d}\Phi \int \mathrm{d}x_a \mathrm{d}x_b \; f_a(x_a) f_b(x_b) \; \hat{\sigma}(x_a, x_b, \Phi) \,,$$

where

- partonic cross section $\hat{\sigma}$ expanded in perturbation theory (α, α_s) to finite order,
- parton luminosities f_i are the solutions to coupled differential equations with leading contributions from all orders in perturbation theory and parametrisation of non-perturbative regime,
- phase space element $\mathrm{d}\Phi$ is $(3n - 4)$ dimensional.

Solve using Monte-Carlo integration (refine using importance sampling, multichannel integration, self-adaptive algorithms, . . .).

Collider measurements and event generators

$$\sigma = \int \mathrm{d}\Phi \int \mathrm{d}x_a \mathrm{d}x_b \; f_a(x_a) f_b(x_b) \; \hat{\sigma}(x_a, x_b, \Phi)$$

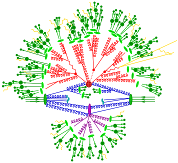
Event generator:
We interprete every phase space point as phys. event of probability $f_a \, f_b \, \hat{\sigma}$.

Create optimal statistical ensemble by sampling with a PDF that corresponds to the integrand.
This PDF is in general unknown, generated with hit-and-miss against the best adapted PDF.

$\Rightarrow$ **unweighted events** (events with uniform weight)

Used by experiments as "simulated data" to understand the response of the detector **and** theory prediction.

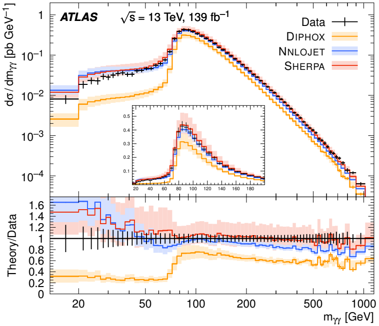
Durham, IPPP: SHERPA

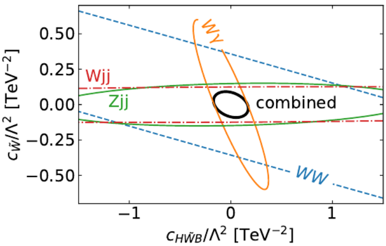


SHERPA – event generator for particle collisions

- $\approx 400,000$ lines of code,
  code generator for more involved processes
- often more than one physics model for a given event stage to allow for testing modelling uncertainties
- 10^{12} CPU-*s* spent by ATLAS using SHERPA

Example results





- deviations traced to incomplete physics modelling
- absence of deviation when all important effects are included constrains contributions of beyond-the-Standard-Model physics

Overview

1. General considerations
2. Modelling in Particle Physics
3. How to compute physical predictions
4. Conclusions

Conclusions

- modelling (approximating a physical theory in order to be able to calculate predictions) is at the core of testing (trying to falsify) ideas of the law's of nature
- the Standard Model of Particle Physics is a well-tested theory, known to be incomplete, that we need to actually see break
- it has held up so far, within uncertainties
  $\rightarrow$ need to probe further, deeper or differently
- event generators play a crucial role in providing theory predictions to compare to experimental data to account for all relevant physical processes in sufficient (??) accuracy

Thank you!