Hunting for new strong forces with Lattice simulations

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The DiRAC BSM activity

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Main References:
L. Del Debbio *et al.*, Phys. Rev. D80 (2009) 074507 [arXiv:0907.3896];
L. Del Debbio *et al.*, Phys. Rev. D82 (2010) 014509 [arXiv:1004.3197];
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L. Del Debbio *et al.*, Phys. Rev. D84 (2011) 034506 [arXiv:1104.4301];
A. Athenodorou *et al.*, Phys.Rev. D91 (2015) no.11, 114508 [arXiv:1412.5994];
J.-W. Lee *et al.*, JHEP 1704 (2017) 036 [arXiv:1701.03228];
E. Bennett *et al.*, JHEP 1803 (2018) 185 [arXiv:1712.04220]

Standard Model and beyond

- The strong and electroweak interactions successfully described by the standard model (QCD for the strong sector, $SU(2)_L \otimes U(1)_Y$ with Higgs mechanism for the electroweak sector)
- The strong sector is believed to be valid at high energies, while the weak sector has a natural cut-off at the scale of the TeV
- Various hypotheses have been formulated to extend the electroweak sector of the SM above the TeV
- All the extensions require assumptions to be tractable analytically $\Rightarrow$ Need of a framework for computations from first principles

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Outline

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The electroweak sector of the Standard Model

- $SU(2)_L \otimes U(1)_Y$ gauge theory coupling doublets of left-handed fermions to four gauge bosons
- In addition, a complex doublet of scalars (Higgs field) with a quartic self-interaction potential with minima at a non-perturbative vacuum is present
- The scalar field gets a non-trivial *vev*, breaking the gauge symmetry to $U(1)_{EM}$ and providing mass to the other three gauge bosons
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Beyond the Standard Model

The hierarchy problem

The Higgs mass is expected to get corrections of the order of the natural cut-off (Planck scale); what does keep it of the order of one hundred GeV?

UV completion

To explain this feature and to maintain the consistency of the model at very high energy, we can replace the Higgs sector with a theory defined at a higher scale that gives the physics of the Higgs as a low energy effective theory

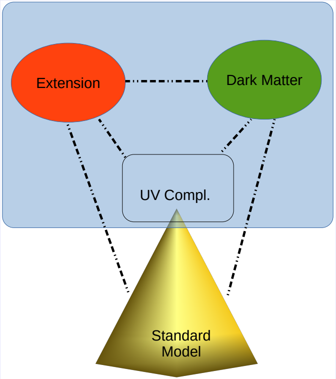
The constraints

An extension of the Standard Model must

1. give mass to the fermions and break the gauge symmetry while keeping the theory consistent
2. be compatible with electroweak precision measurements (including the presence of a light scalar doublet)
3. solve the problems of the current formulation
4. hopefully predict new physics

Completion, dark matter, portals, . . .

Various possibilities for theories beyond the standard model



- In order to make sense of new potential discoveries in a timely fashion we need to better understand strongly interacting gauge theories
- Lattice simulations provide a first-principle approach to this class of problems

Some extensions

1. Supersymmetry
   A new symmetry that interchanges bosons with fermions valid for scales ≈ 1 TeV is conjectured; the Higgs is the lowest scalar state of this theory
2. (Compact) extra dimensions
   Fields are defined in 4+D dimensions, with 4 the dimensions detectable to us; field modes in the extra dimensions give rise to a tower of particles, among which could be the Higgs
3. Strongly interacting dynamics
   A new strongly-interacting sector exists that breaks the electroweak symmetry dynamically (*Dynamical Electroweak Symmetry Breaking*, or DESB) and whose phenomenology gives rise to the Higgs sector at low energies

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QCD as a template

The strong interaction is described by QCD, an $SU(N)$ gauge theory ($N = 3$) that couples $N_f = 6$ families of quarks transforming in the fundamental representation of the gauge group with eight gluons transforming in the adjoint representation

At energies above 1 GeV the coupling is less than one and the theory is perturbative

At energies around 1 GeV the coupling becomes order one and the perturbative expansion breaks down

Non-perturbative phenomena: confinement and chiral symmetry breaking (χSB)

χSB: global symmetry broken

E.g. with two massless quarks)

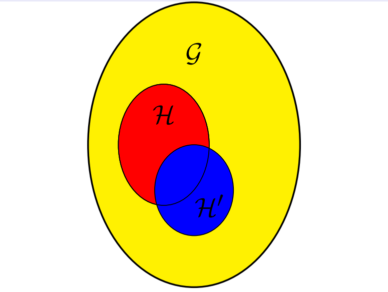
$$SU(2)_L \times SU(2)_R \times U(1) \to SU(2)_V \times U(1)$$

and the pions are the Goldstone bosons of this breaking

Remnant of this symmetry breaking pattern also in standard QCD, with $m_\pi \simeq 140$ MeV $\ll 1$ GeV and $\langle \bar{u}u + \bar{d}d \rangle = 8\pi f_\pi^3 \gg m_{u,d}$.

The DESB framework

Consider a gauge theory with some gauge group $\mathcal{G}'$ coupled to fermionic matter



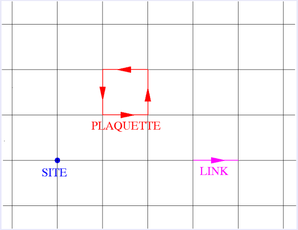
Global symmetry group $\mathcal{G}$ spontaneously broken to $\mathcal{H} \subset \mathcal{G}$
$\Rightarrow$ Number of Goldstone bosons: $\dim_{\mathcal{G}}$ - $\dim_{\mathcal{H}}$

Gauge some $\mathcal{H}' \subset \mathcal{G}$ such that $SU(2)_L \otimes U(1)_Y \subset H'$

Two main possible scenarios:

- Technicolour if $\mathcal{H}' \cap \mathcal{H} \neq \mathcal{H}'$
- Pseudo-Nambu-Goldstone-Boson (PNGB) Higgs if $\mathcal{H}' \subset \mathcal{H}$

The computational challenge



- Need to perform an integral in $\approx 10^{10}$ dimensions $\Rightarrow$ use Monte Carlo methods
- Memory requirements $\approx 0.1 - 1$ TB
- Storage requirements > 100 TB
- When parallelised, requires very frequent exchange of short messages $\Rightarrow$ state-of-the art low-latency interconnects required

Lattice Field Theories are one of the most demanding HPC problems

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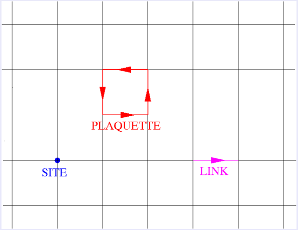

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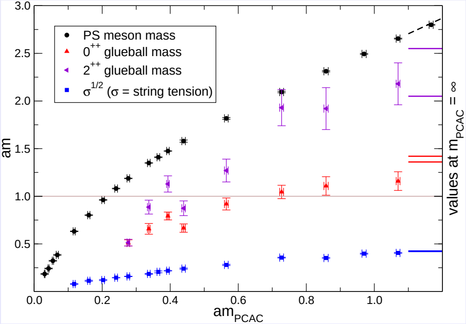
Outline

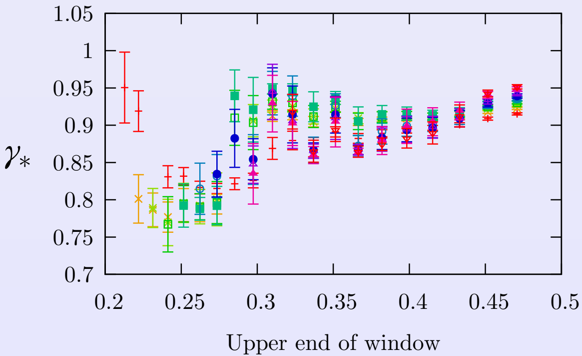
SU(2) with 2 adjoint Dirac Flavours



- First numerical evidence for the existence of theories that are technicolour-like (near-conformal)
- First evidence for light scalars
- First robust determination of the mass anomalous dimension

(L. Del Debbio *et al.*, arXiv:0907.3896)

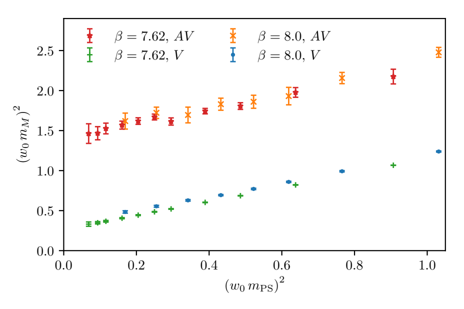
SU(2) with one adjoint Dirac Flavours



First evidence for a large anomalous dimension

(A. Athenodorou *et al.*, arXiv:1412.5994)

Sp(4) with two fundamental Dirac flavours



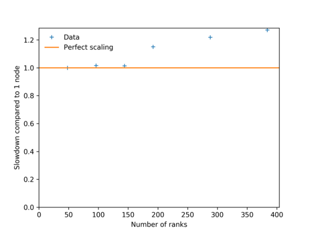
- First numerical investigation of the mass spectrum
- First *ab-initio* determination of effective theory parameters

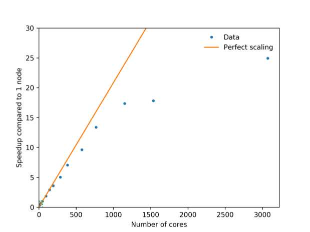
(E. Bennett *et al.*, arXiv:1712.04220)

Outline

The code

Weak scaling | **Strong scaling**



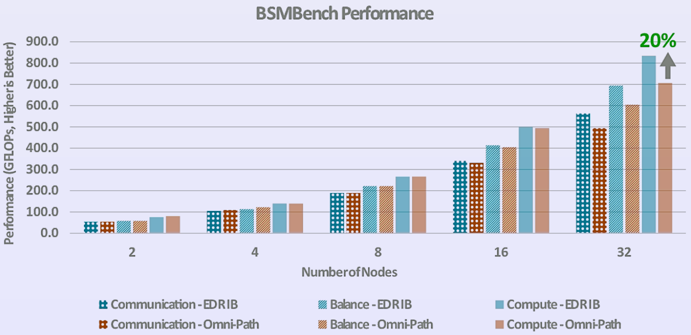


Code used: HiRep (developed in collaboration by Edinburgh University, Swansea University and The University of Southern Denmark)

Principles:

- Flexibility
- Portability
- Scalability

BSMBench



- Flexible benchmarking tool derived from HiRep
- Originally developed by IBM and Swansea University
- Used by Industry (e.g. Atos, Dell, IBM, Mellanox) and Academia (e.g. Supercomputing Wales, Pisa Dell Excellence Centre)
- Available from https://gitlab.com/edbennett/BSMBench

Outline

Conclusions

- Understanding the physics beyond the Standard Model is of fundamental importance in current particle physics
- Lattice Field Theory is a crucial tool for understanding this non-perturbative physics
- Numerical simulations are more demanding than in QCD and require (yet another) bespoke software package
- So far, most of the efforts dedicated to extensions of the standard model
- More recently, dark matter has emerged as a new exciting direction $\Rightarrow$ Opportunity for cross-collaborations?