Physique des particules aux collisionneurs

(un point de vue un peu théorique, très partiel, très biaisé)

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

CSI-IN2P3, 22/6/17

LPT Orsay

Central question of particle physics

From the theoretical point of view (at least)

$$\mathcal{L} = ?$$

Central question of particle physics

From the theoretical point of view (at least)

$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?

Central question of particle physics

From the theoretical point of view (at least)

$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?

- Relativistic and quantum — Quantum Fied Theory
- Constituents — Spin-0,1/2,1 fields
- Interactions — Gauge symmetries and gauge bosons
- Mass spectrum — Symmetry breaking(s)

Central question of particle physics

From the theoretical point of view (at least)

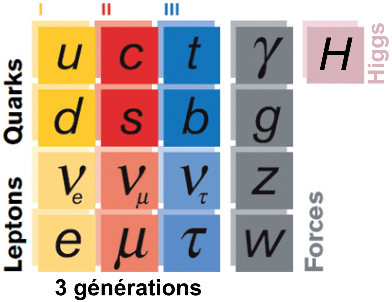
$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?

- Relativistic and quantum — Quantum Fied Theory
- Constituents — Spin-0,1/2,1 fields
- Interactions — Gauge symmetries and gauge bosons
- Mass spectrum — Symmetry breaking(s)

At least in some range of distances,
probed by colliders in some range of energies (among others)

Current answer: the Standard Model



Fermions (spin 1/2) : constituents

- 3 generations, with masses increasing
- only 1st generation stable
- quarks (all interactions) and leptons (electroweak)

Gauge bosons (spin 1) : interactions $SU_C(3) \times SU_W(2) \times U_Y(1)$

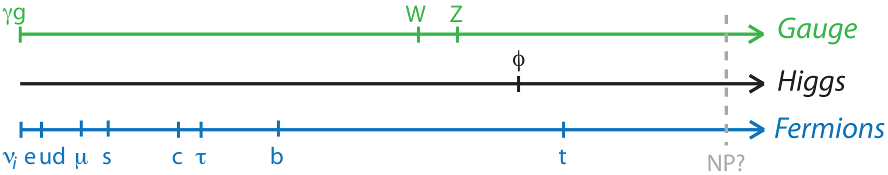
- electromagnetic, strong, weak interactions
- due to the exchange of gauge bosons (photon, gluons, W and Z)

Higgs field (spin 0) : masses

- W, Z by electroweak symmetry breaking (Higgs mechanism)
- fermions by Yukawa couplings (fermion coupling to Higgs field)
- remaining d.o.f. in the spectrum : Higgs boson

SM limits: internal questions

SM very well tested, but

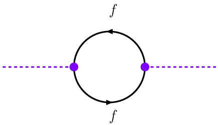


- At least 19 parameters, e.g., masses, completely arbitrary

$$m_e = 0.51 \text{ MeV} \to m_t = 170 \text{ GeV}$$

- structure in 3 generations ?
- charges and representations under the three interactions ?
- partial unification (electroweak separated from strong)
- neutrinos potentially problematic (if Majorana mass)
- no gravitation/general relativity

SM limits: embedding in a larger theory $\Lambda_{NP} \gg \Lambda_{EW}$

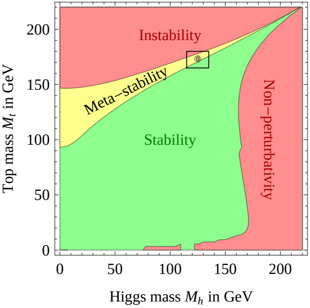


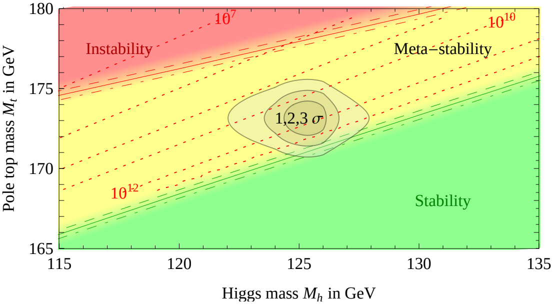
- Hierarchy "problem" with $m_H = 125$ GeV

$$m_H^2 = (m_H^2)_0 + \frac{N_f m_f^2}{4\pi^2 v^2}\left[\Lambda_{NP}^2 + \ldots\right]$$

fine tuning if $\Lambda_{NP} \simeq 10^{16\ldots19}$ GeV unific./Planck scale

- Analysis of NNLO SM Higgs potential
  - Vacuum stable up to Planck scale if $M_H > 129.4 \pm 1.8$ GeV
  - Current M_t and M_H (if SM Higgs) favour metastability of the vacuum





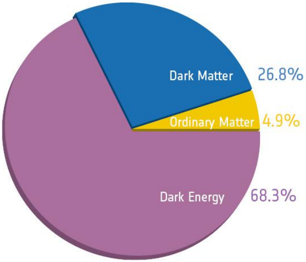
SM limits: confronting cosmology

Higher-energy processes needed to

- Generate matter/antimatter asymmetry observed (particle/antiparticle asymmetry in SM too small)
- Explain inflation period (cannot be SM electroweak transition)

Cosmic Microwave Background analysis (Planck)

- 5% of ordinary matter
- 27% of dark matter
  - only seen through gravitational pull
  - heavy weakly interactive particle, nof SM
- 68% of dark energy
  - Can be interpreted as cosmological cst
  - If computed in SM valid up to Planck scale, completely off (120 orders of mag)



Many different models

Trying to solve some of these questions with an alternative to SM

$$\mathcal{L} = ?$$

Modifying	Example of models
• Relativistic and quantum/QFT	Extra-dimensions
• Constituents/fields	Supersymmetry
• Interactions/gauge symmetries	Grand unified theories
• Spectrum/symmetry breaking	Composite models

Many different models

Trying to solve some of these questions with an alternative to SM

$$\mathcal{L} = ?$$

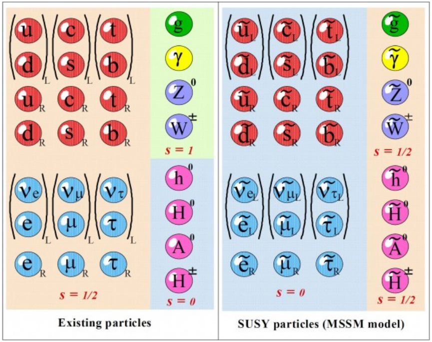
Modifying	Example of models
Relativistic and quantum/QFT	Extra-dimensions
Constituents/fields	Supersymmetry
Interactions/gauge symmetries	Grand unified theories
Spectrum/symmetry breaking	Composite models

SM very well-tested reference at lower energies,
so decoupling theories restoring the SM much below Λ_{NP}

$$\mathcal{L} \underset{E \ll \Lambda_{NP}}{\simeq} \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n}{\Lambda_{NP}^{d-4}} O_n$$

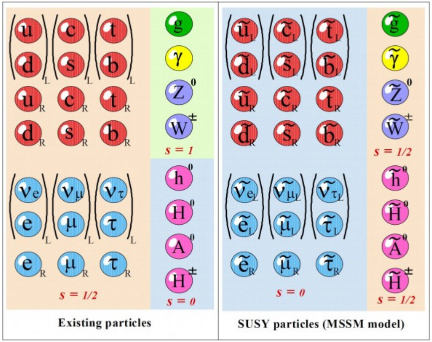
Additional operators O_n trigger NP effects/processes
e.g., dim. 5 effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$

Many different models: supersymmetry



- Additional symmetry relating particles of different spins
- Doubling of the spectrum
- Remove fine-tuning for M_H, if Λ_{susy} close to Λ_{EW}
- Unification of gauge couplings at high scale ($\simeq 10^{16}$ GeV)
- Same couplings for susy and SM, perturbative computations

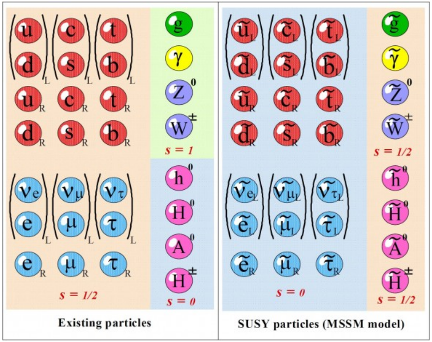
Many different models: supersymmetry



- Additional symmetry relating particles of different spins
- Doubling of the spectrum
- Remove fine-tuning for M_H, if Λ_{susy} close to Λ_{EW}
- Unification of gauge couplings at high scale ($\simeq 10^{16}$ GeV)
- Same couplings for susy and SM, perturbative computations

- Susy breaking with many new parameters, additional differences between 3 generations compared to SM (NP flavour problem)
- Simplified models assuming equality between parameters (constrained MSSM, phenomenological MSSM...)

Many different models: supersymmetry



- Additional symmetry relating particles of different spins
- Doubling of the spectrum
- Remove fine-tuning for M_H, if Λ_{susy} close to Λ_{EW}
- Unification of gauge couplings at high scale ($\simeq 10^{16}$ GeV)
- Same couplings for susy and SM, perturbative computations

- Susy breaking with many new parameters, additional differences between 3 generations compared to SM (NP flavour problem)
- Simplified models assuming equality between parameters (constrained MSSM, phenomenological MSSM...)

Consequences: doubling of spectrum with masses close to Λ_{EW}, charged Higgs bosons, dark matter candidate...

Many different models: exotics

Many different models: exotics

- Grand unified theories
  - Simpler/larger gauge group/interactions
  - Observable proton decay (in simple cases)
  - Consequences: leptoquarks, heavy gauge bosons

Many different models: exotics

- Grand unified theories
  - Simpler/larger gauge group/interactions
  - Observable proton decay (in simple cases)
  - Consequences: leptoquarks, heavy gauge bosons
- Extra dimensions
  - Additional space dimensions
  - Geometrical explanation for fermion masses/Yukawa couplings
  - Consequences: Excited quarks, heavy gauge bosons

Many different models: exotics

- Grand unified theories
  - Simpler/larger gauge group/interactions
  - Observable proton decay (in simple cases)
  - Consequences: leptoquarks, heavy gauge bosons
- Extra dimensions
  - Additional space dimensions
  - Geometrical explanation for fermion masses/Yukawa couplings
  - Consequences: Excited quarks, heavy gauge bosons
- Composite models
  - Higgs field as bound state, avoid pbs with spin 0 elementary
  - New fermions, mixing with SM fields
  - Consequences: vector-like quarks, dark matter candidate

Many different models: exotics

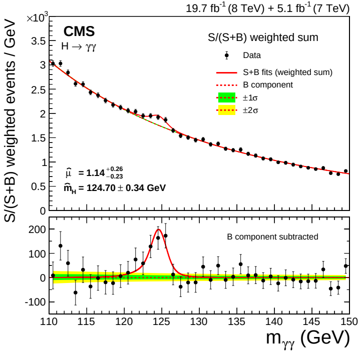
- Grand unified theories
  - Simpler/larger gauge group/interactions
  - Observable proton decay (in simple cases)
  - Consequences: leptoquarks, heavy gauge bosons
- Extra dimensions
  - Additional space dimensions
  - Geometrical explanation for fermion masses/Yukawa couplings
  - Consequences: Excited quarks, heavy gauge bosons
- Composite models
  - Higgs field as bound state, avoid pbs with spin 0 elementary
  - New fermions, mixing with SM fields
  - Consequences: vector-like quarks, dark matter candidate
- Left-right symmetry
  - Restoration of parity symmetry, broken in SM
  - See-saw mechanism for neutrinos, new mechanisms for CP violation
  - Consequences: heavy gauge bosons, charged scalars

Many different models: exotics

- Grand unified theories
  - Simpler/larger gauge group/interactions
  - Observable proton decay (in simple cases)
  - Consequences: leptoquarks, heavy gauge bosons
- Extra dimensions
  - Additional space dimensions
  - Geometrical explanation for fermion masses/Yukawa couplings
  - Consequences: Excited quarks, heavy gauge bosons
- Composite models
  - Higgs field as bound state, avoid pbs with spin 0 elementary
  - New fermions, mixing with SM fields
  - Consequences: vector-like quarks, dark matter candidate
- Left-right symmetry
  - Restoration of parity symmetry, broken in SM
  - See-saw mechanism for neutrinos, new mechanisms for CP violation
  - Consequences: heavy gauge bosons, charged scalars
- `<insert your favorite model here>`

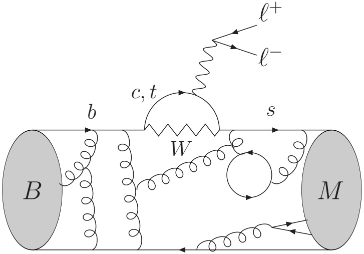
Two approaches to test SM and NP theories

Relativistic path: $E = mc^2$



Collisions with enough energy
to produce directly particles
beyond the SM
Higher energy/lower intensity
"Direct" proof

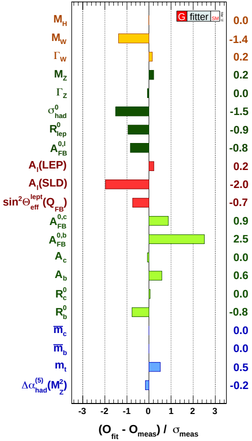
Quantum path: $\Delta E \Delta t \geq \hbar/2$



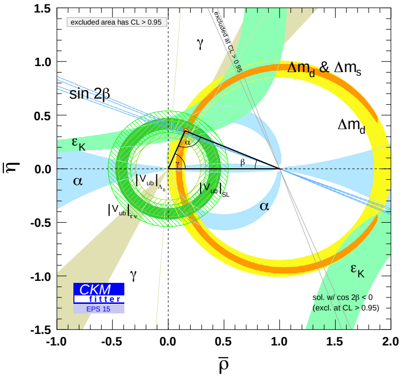
Small deviations from
intermediate states
with heavy particles
Lower energy/higher intensity
"Indirect" proof

Tests of the SM at colliders: before run 1

- All fields observed, apart from Higgs
- Strong and electromagnetic interactions well tested

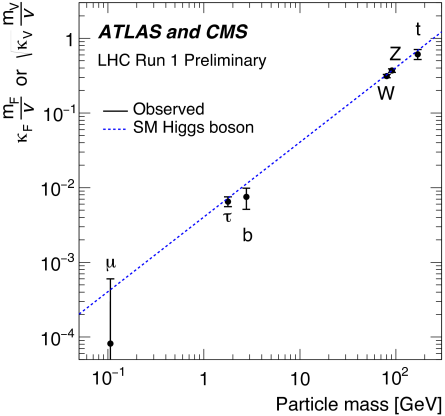


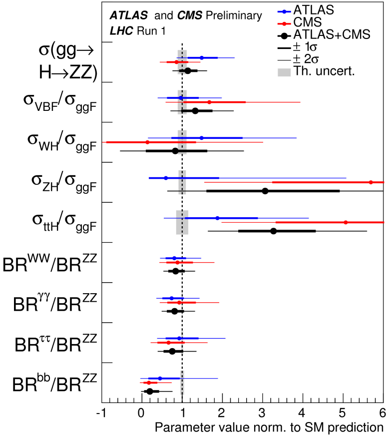
Electroweak sym breaking
(Electroweak precision obs)



Yukawa couplings/CP-violation
(Cabibbo-Kobayashi-Maskawa)

Tests of the SM at colliders: after run 1 (1)

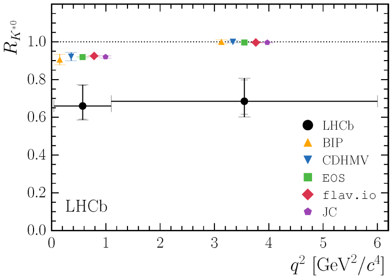




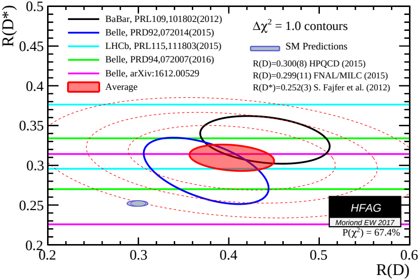
- Must have additional element at Λ_{EW} (*WW* unitarity)
- ATLAS and CMS observe the Higgs boson, in agreement with SM
- No indication for other massive particles by direct production
- Many SM proc tested : jets, *W* and *Z* prod, CP-viol (QCD and EW)

Tests of the SM at colliders: after run 1 (2)

- A few deviations seen by LHCb in some b transitions (partly confirmed by other expts)
  - $b \to s\ell\ell$, $\ell = e, \mu$ (rare)
  - $b \to c\ell\nu$, $\ell = e, \mu, \tau$ (common)
  - Hints of violation of lepton flavour universality (combined 4-5 σ) (different couplings for e, μ, τ, which does not occur in SM)



$Br(B \to K^*\mu\mu)/Br(B \to K^*ee)$



$Br(B \to D^{(*)}\tau\nu)/Br(B \to D^{(*)}\ell\nu)$

Theoretical approaches in this context

Obviously, we should let the analyses of run 2 take place but likely

- No new particles directly produced and seen at 13-14 TeV
- *b*-physics deviations remaining on the table

We leave the SM cross-check era to enter a NP deviation era

Theoretical approaches in this context

Obviously, we should let the analyses of run 2 take place but likely

- No new particles directly produced and seen at 13-14 TeV
- *b*-physics deviations remaining on the table

We leave the SM cross-check era to enter a NP deviation era

How to analyse these results

- Λ_{NP} likely to be significantly higher than Λ_{EW}
- No clear indication about value of the NP energy scale
  ($\neq$ search for W, Z or EWSB mechanism where G_F, Λ_{EW} known)
- NP in deviations at $E \ll \Lambda_{NP}$ (quantum path rather than relativistic)
- Requires comparison with precise SM predictions

Theoretical approaches in this context

Obviously, we should let the analyses of run 2 take place but likely

- No new particles directly produced and seen at 13-14 TeV
- *b*-physics deviations remaining on the table

We leave the SM cross-check era to enter a NP deviation era

How to analyse these results

- Λ_{NP} likely to be significantly higher than Λ_{EW}
- No clear indication about value of the NP energy scale
  ($\neq$ search for W, Z or EWSB mechanism where G_F, Λ_{EW} known)
- NP in deviations at $E \ll \Lambda_{NP}$ (quantum path rather than relativistic)
- Requires comparison with precise SM predictions

- Always good to consider specific models (top down)
- But better to use model-independent approaches (bottom up)
- Already used in the past (constraints on m_c, m_t, M_H)
- SM = effective low-energy theory from
  an underlying, more fundamental and yet unknown, theory

Effective field theories

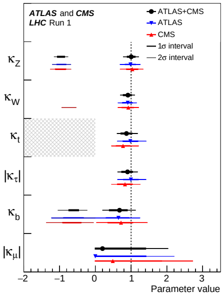
$$\mathcal{L} = \mathcal{L}_{SM,low} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n$$

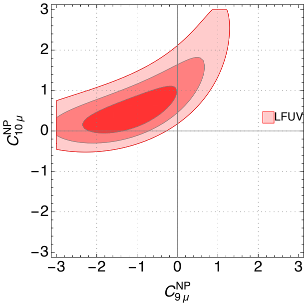
- O_n describe impact of New Physics on ”low-energy” physics
- Made of SM fields below the scale Λ
- Split high energies c_n and low energies O_n, separated by scale Λ
- Determine couplings and deviations from SM expectations
- Partial info on fundamental theory: structure of $\mathcal{O}$, value of c_n/Λ^{d-4}

Effective field theories

$$\mathcal{L} = \mathcal{L}_{SM,low} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n$$

- O_n describe impact of New Physics on "low-energy" physics
- Made of SM fields below the scale Λ
- Split high energies c_n and low energies O_n, separated by scale Λ
- Determine couplings and deviations from SM expectations
- Partial info on fundamental theory: structure of $\mathcal{O}$, value of c_n/Λ^{d-4}





Two current applications

- Higgs couplings (SMEFT): $\Lambda = \Lambda_{EW}$, couplings κ
- *b*-quark transitions (effective Hamiltonian): $\Lambda = m_b$, couplings C_i

Perspectives in the NP deviation era

Worst-case scenario for LHC: no new particle discovered at run 2

- Cross-checks of electroweak sym breaking: W, Z and top
- Properties of H boson: couplings to fermions, self-coupling
- Check if NP signals not hidden in backgrounds in non-trivial way

Context for High-Lumi LHC

Persisting deviations in b-quark transitions

- Confirmation from LHCb with higher statistics, checked systematics
- Interesting to study related transitions in other environments

Context for Belle-II

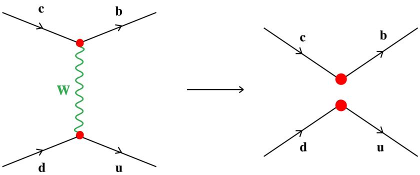
Other cross checks: rare K decays, neutrinos, charged lepton-flavour violation, electric dipole moments, $(g-2)_\mu\ldots$

In all cases, study of deviations with respect to SM, requiring joint theoretical and experimental work for interpretation

From Fermi to SM: an effective approach

Fermi-like approach : separation between different scales

- Short distances : numerical coefficients
- Long distances : local operator

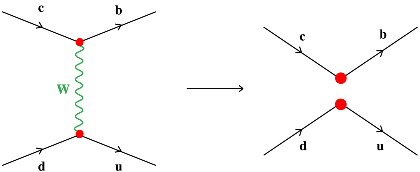


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

From Fermi to SM: an effective approach

Fermi-like approach : separation between different scales

- Short distances : numerical coefficients
- Long distances : local operator



$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Before/below SM, Fermi theory carried info on yesterday's NP (=EW)

- G_F: scale of NP physics
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Obviously not all info (gauge structure, Z^0 ...), but a good start

From SM to NP: an effective approach

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

From SM to NP: an effective approach

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
  e.g., dim. 5 effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$
- Split high energies c_n and low energies O_n, separated by scale Λ

From SM to NP: an effective approach

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

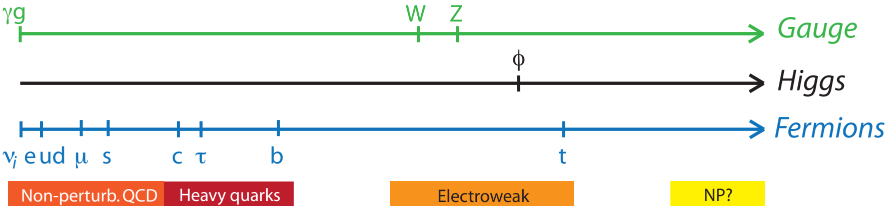
$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
  e.g., dim. 5 effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$
- Split high energies c_n and low energies O_n, separated by scale Λ

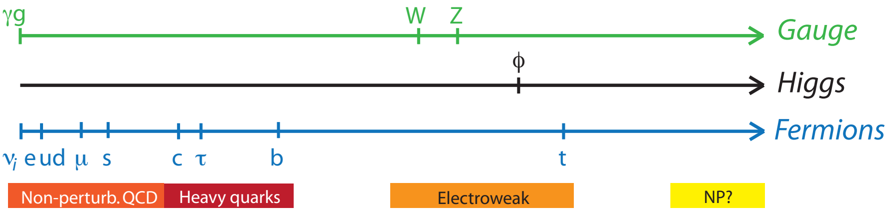
- New d.o.f. and energy scale of NP ?
- Symmetries and structure ?

A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales
  BSM $\to$ SM+1$/\Lambda$ (Λ_{EW}/Λ) $\to$ $\mathcal{H}_{eff}$ (m_b/Λ_{EW}) $\to$ *eff. th.* (Λ_{QCD}/m_b)

A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

  BSM $\to$ SM+1/Λ (Λ_{EW}/Λ) $\to$ $\mathcal{H}_{eff}$ (m_b/Λ_{EW}) $\to$ *eff. th.* (Λ_{QCD}/m_b)
- Main theo problem from hadronisation of quarks into hadrons:

  description/parametrisation in terms of QCD quantities

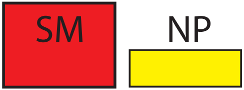
  decay constants, form factors, bag parameters. . .
- Long-distance non-perturbative QCD: source of uncertainties

  lattice QCD simulations, effective theories. . .

Different processes for different goals

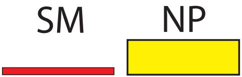
SM expected to be dominant (tree-dominated processes)

Metrology of SM



SM and NP competing (loop-dominated processes)

Constraints on NP



SM zero or very small (SM symmetry forbidden proc.)

Smoking guns of NP

Separation between the last two categories hinge on theorists' beliefs concerning the size of NP, theoretical accuracy of SM prediction and experimental measurements. . .

Bounding NP using neutral meson-mixing

Operator	Bounds on Λ in TeV ($c_n = 1$) Re	Im	Bounds on c_n ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

[Isidori, Nir, Perez 2010]

Neutral meson mixing ($\Delta F = 2$) SM-like, and c_i/Λ^2 must be small:

- Significant mass gap
- Couplings with close-to-SM pattern of flavour violation
- Additional selection rules

Bounding NP using neutral meson-mixing

Operator	Bounds on Λ in TeV ($c_n = 1$) Re	Bounds on Λ in TeV ($c_n = 1$) Im	Bounds on c_n ($\Lambda = 1$ TeV) Re	Bounds on c_n ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

[Isidori, Nir, Perez 2010]

Neutral meson mixing ($\Delta F = 2$) SM-like, and c_i/Λ^2 must be small:

- Significant mass gap
- Couplings with close-to-SM pattern of flavour violation
- Additional selection rules

NP flavour problem: BSM models with many flavour violation sources

- Decoupling *[Λ large compard to Λ_{EW}, loop suppression]*
- Universality *[Minimal Flavour Violation: all flavour violation from Y]*
- Alignment *[Loops with NP only, coupling only within a generation]*