Theory session overview

Luc Darmé

IP2I – CNRS

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A theoretician: what for?

- Design the mathematical tools to describe your data, and modelise the physical systems on which to apply these tools

  --> E.g. Quantum Field Theories, and the actual “fields” that we want to describe

- Actually make them work to obtain a prediction/fit a dataset

- The oyster theorem: looking for a lunch, you can find a pearl !

  --> tools are versatile and can be apply to a very large range of physical systems.

Giorgio Parisi

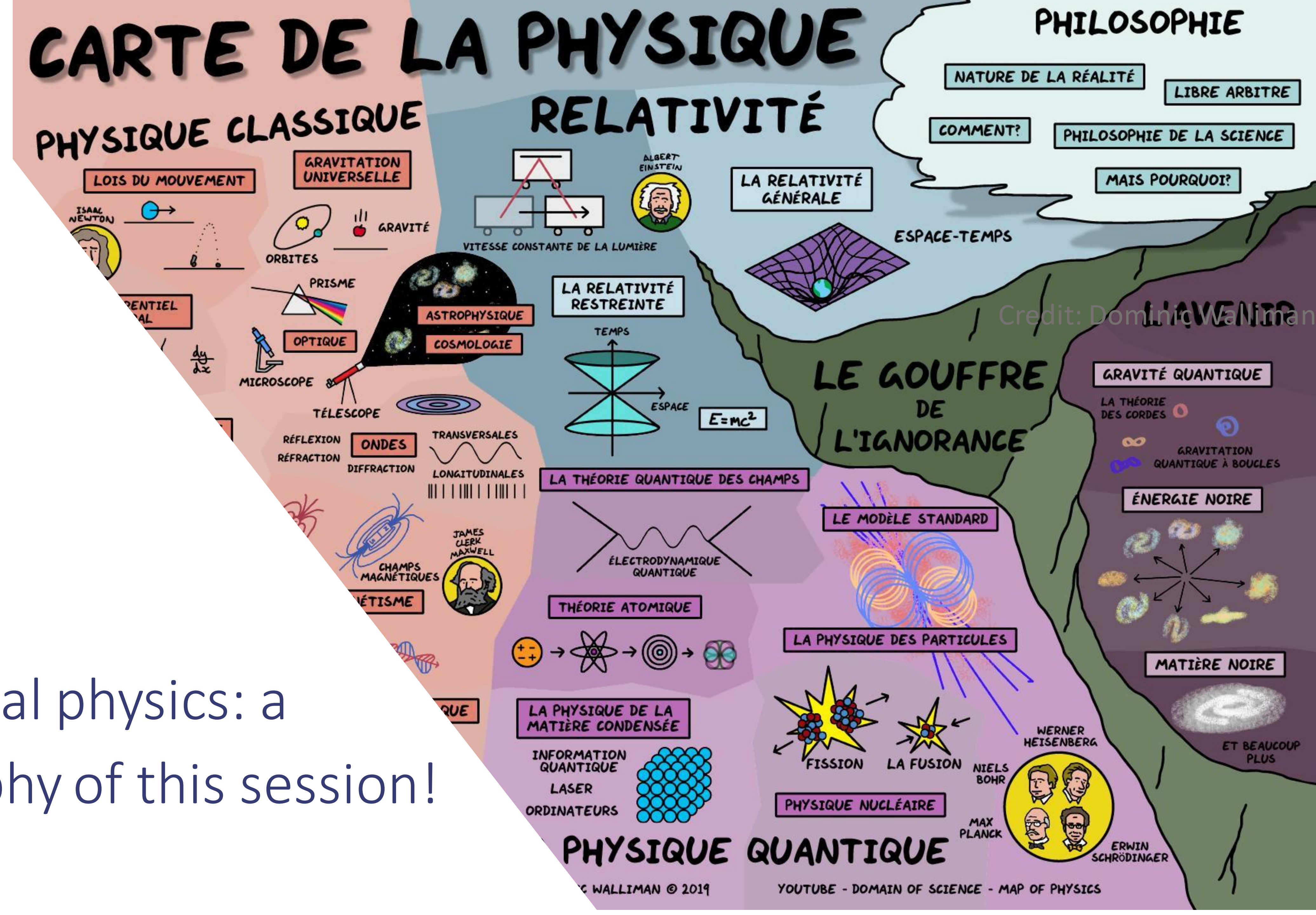
Ill. Niklas Elmehed © Nobel Prize Outreach

Giorgio Parisi
The Nobel Prize in Physics 2021

Born: 4 August 1948, Rome, Italy

Prize motivation: "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

(*) Also we are not very expensive: remember to ask your lab director for a theoretician once back home!



Theoretical physics: a cartography of this session!

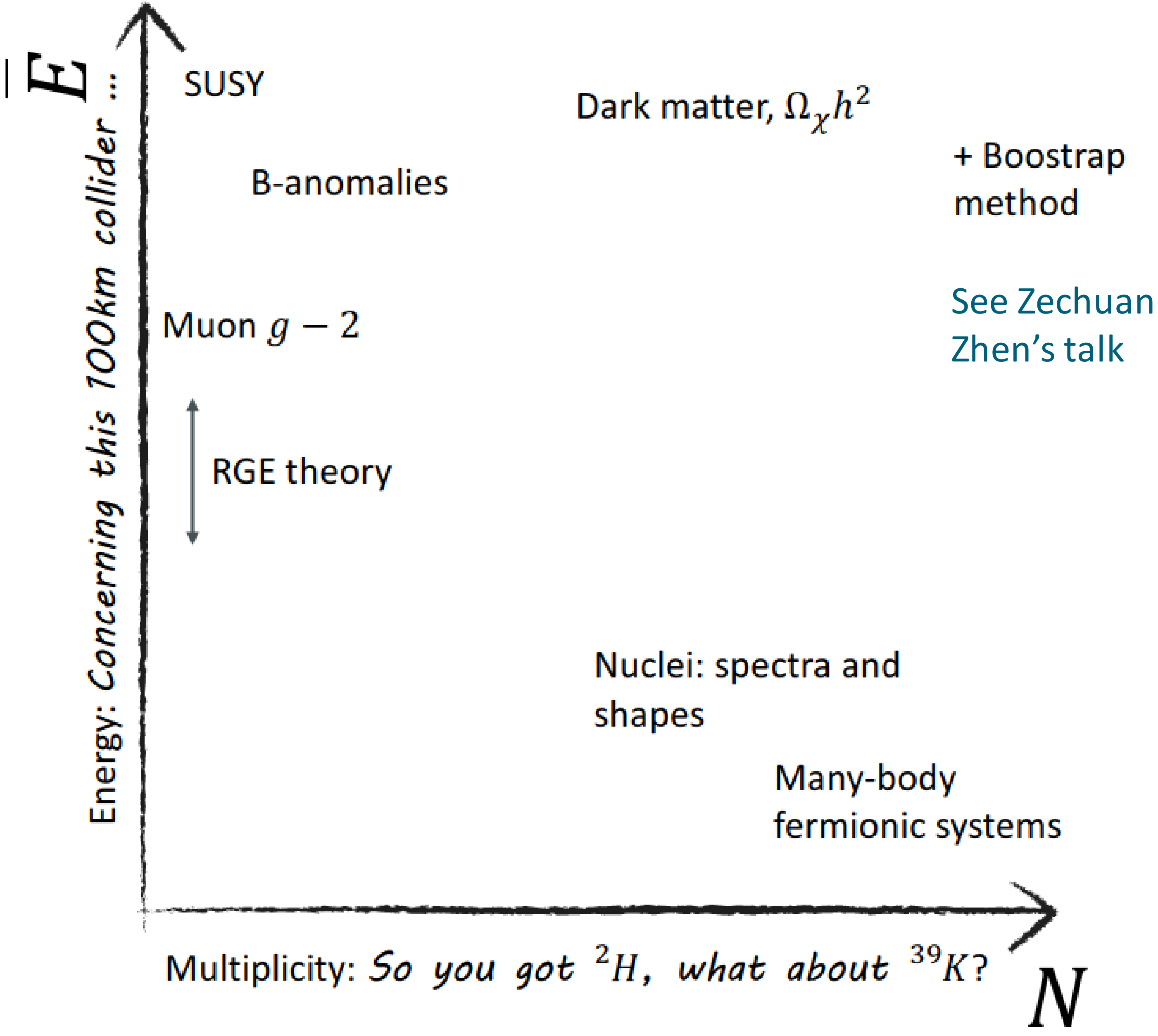
A very broad program in this session

- We are extremely lucky to have a VERY broad program!

  (*) And I have ~25 minutes to introduce most of modern theoretical physics: piece of cake…

--> Let's make some organising

- In both directions, something new to be found:
  - e.g. particles at high energy
  - New structures emerging at high multiplicity: "more is different" (Anderson)



Another good discriminant: interaction strength

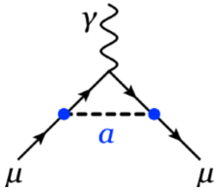
- In essence: how much is a system an ensemble of plain waves ?

$\ll 0{,}1$ — $O(0.1)$ — $\gtrsim 1$ — g

Are you sure there is something at all?

The main issue here is experimental: something very feebly coupled is simply hard to see

See Emmanuelle Pinsard's talk

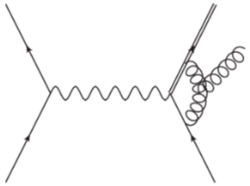


Perfect spot, let's use perturbation theory

Expands everything around a non-interacting, simple, system leading to a linearised problem.

$$g_{\mu\nu} \rightarrow \eta_{\mu\nu} + h_{\mu\nu}$$

Used in GR, Feynman diagrams, etc...



Definitely not a plain wave, we need another idea

New non-perturbative tools required

Evolution of scales and renormalisation group

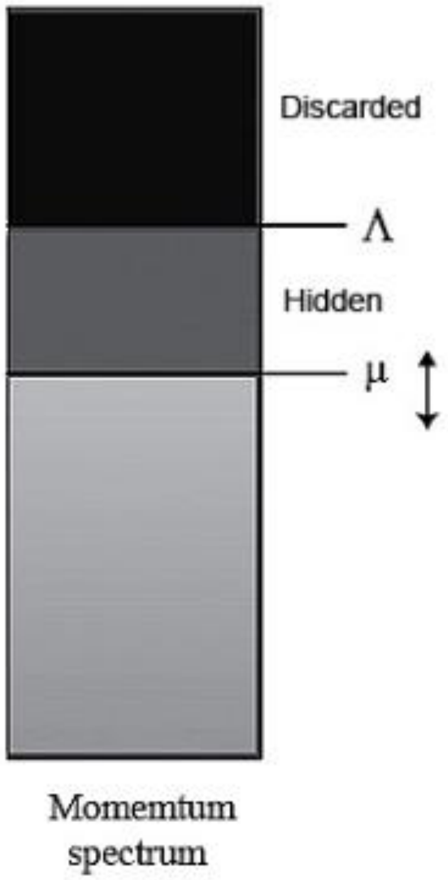
- The parameter g of a given theory depends on the energy scale/typical length at which it is probed
  - For instance QCD becomes perturbative at high energy
  - In particle physics, the ''relevant'' amount of quantum corrections depends on the energy available in a given process

In another words, the closer you stare at the electron, the more « dressed » in quantum fluctuations it becomes…

- The precise method depends on the system under considerations: Pauli-Villars, Dimensional Regularisation, etc …

--> the space on which the system lives is also important

--> See Madjouline Borji's talk

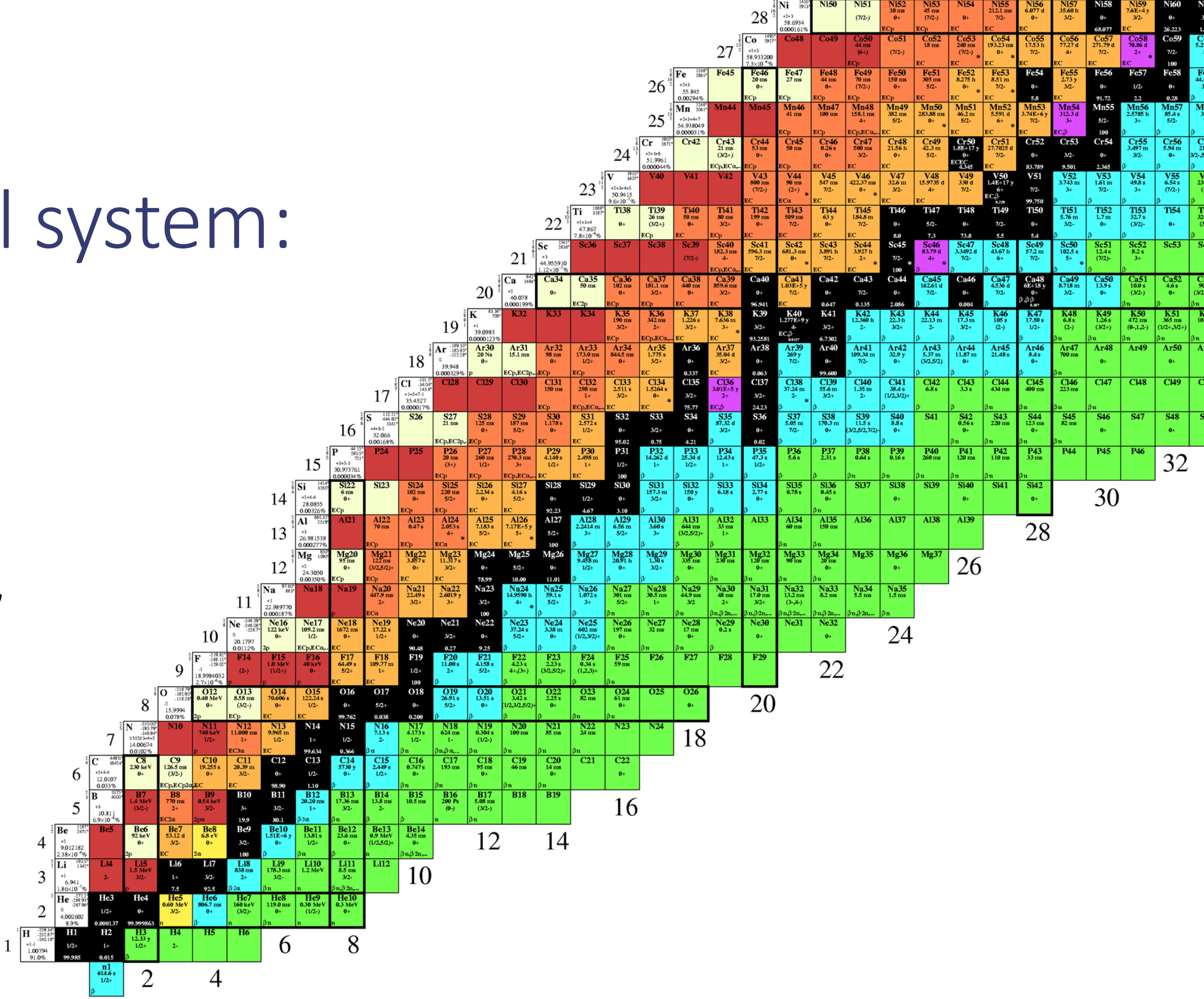


Wilson's approach:
From Huang 1310.5533

First physical system:

NUCLEI

(what have not been spoiled by the nuclear session)



A world of nuclei

- A nucleus is in itself a complex system, must be treated as

Strongly-interacting quantum many-body system

Non perturbative methods required
-->There is no “plain wave” nucleon

Each nucleon is a degree of freedom of both spin and isospin
--> Even moderately heavy nuclei are thus a multi-body system!

- At the microscopic level nucleus wave function can thus be written as

$$\Psi[(\vec{r}_1, \sigma_1, q_1); (\vec{r}_2, \sigma_2, q_2); \ldots ; (\vec{r}_A, \sigma_A, q_A)]$$

Even simple nuclei can need hundred of variables …
--> it gets very hard very fast

--> The nucleons-nucleons potential itself is quite complex to obtain!

Getting spectra and binding energies

Smirnova et al. 1909.00628

- The goal is to obtain the properties of nuclei, spectra and binding energies.
- Ab initio: use full wave function + NN and 3N potentials, works only for light nuclei

(One of the) --> The difficulty lies both in the multi-body system AND in actually finding the potentials

See Zhen Li's talk

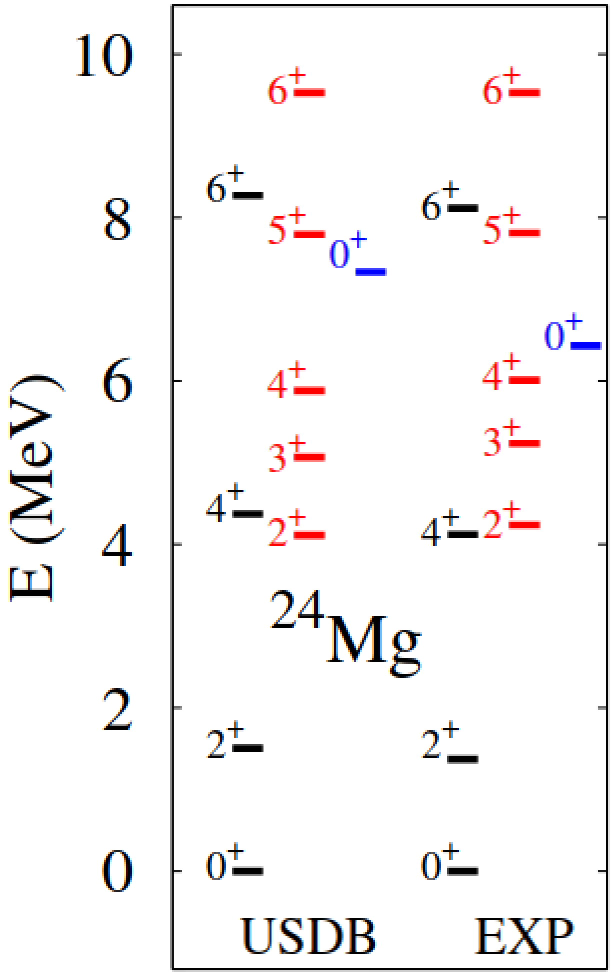
- For larger nuclei, rely instead on mean field-derived methods

  --> Replace nucleons by new degrees of freedom interacting only via a shared potential

(One of the) --> Difficulty lies in again find the appropriate interaction for these states (e.g. Skyrme interaction)

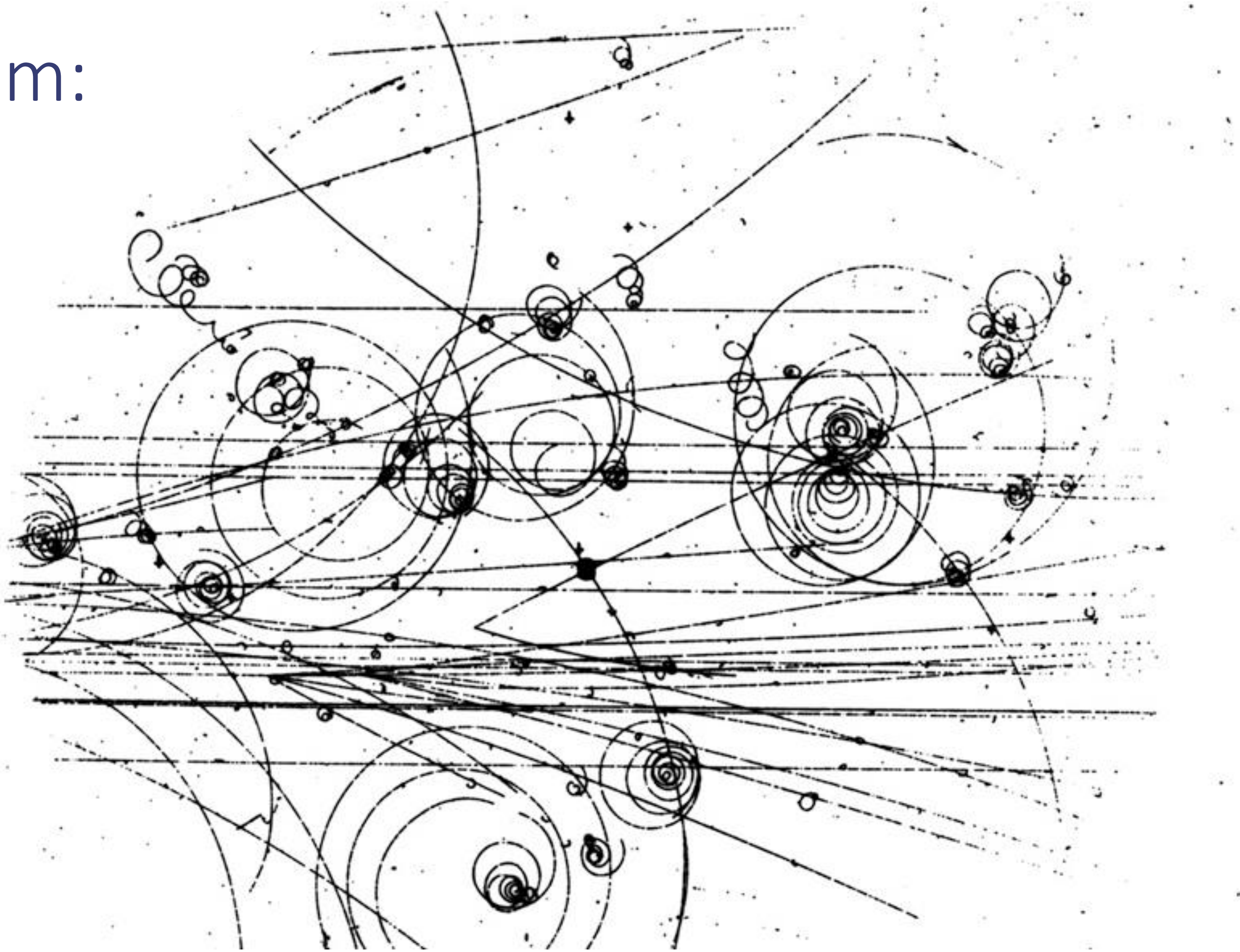
See Philippe Da costa's talk

See Thomas Czuba, on going beyond mean field for interacting fermions



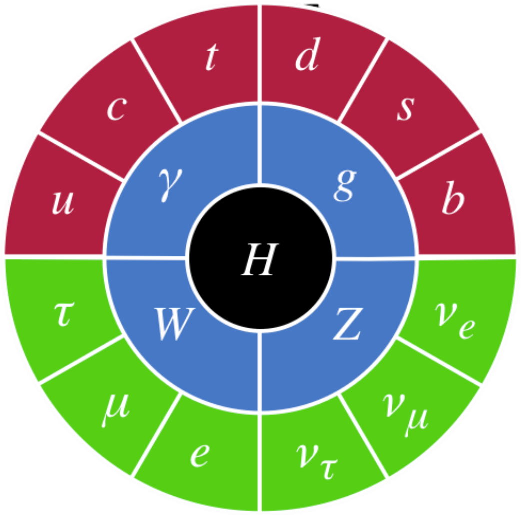
Second physical system:

PARTICLES



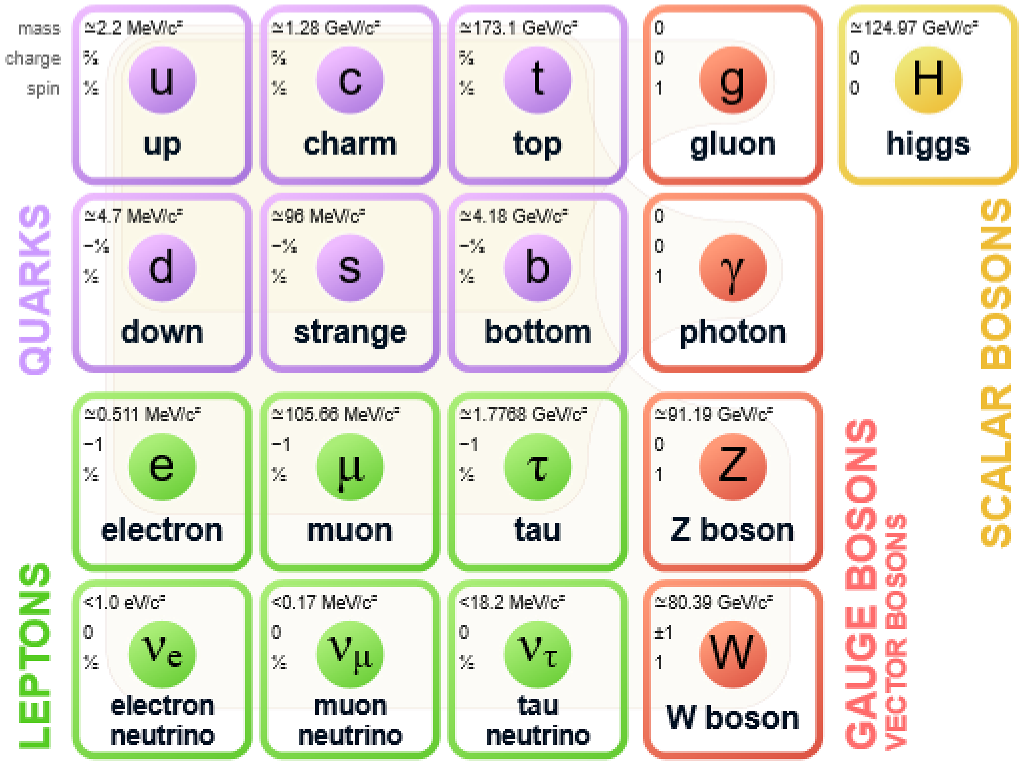
The Standard Model: the basics

- The Standard Model of particle physics represents basically the starting point for most of new physics constructions
  --> but how to present the corresponding particle content?



The « everything is complete » way

The descriptive way



The SM *after* electroweak symmetry breaking

$$SU(3)_c \times SU(2)_W \times U(1)_Y \;\rightarrow\; SU(3)_c \times U(1)_{em}$$

- The first form does single-out the Higgs boson: the only fundamental scalar

Fondamental scalar vs the world

- The Higgs mass term is the *only* dimension-full parameter of the SM

--> Once the potential is minimised it fixes directly the electroweak Vacuum Expectation value, and thus the Fermi constant of weak decays …

Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory

Leonard Susskind*

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 5 July 1978)

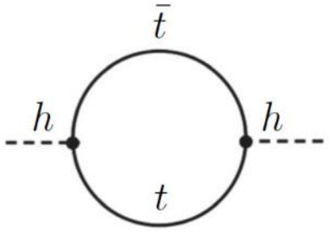
We argue that the existence of fundamental scalar fields constitutes a serious flaw of the Weinberg-Salam … he symmetry breaking is induced by a new

(from March-Russel)

ACKNOWLEDGMENT

I would like to thank K. Wilson for explaining the reasons why scalar fields require unnatural adjustments of bare constants.

→ Quantum corrections, estimated at the EW scale, depends quadratically on the UV theory scale (e.g. new particle masses)



$$\Sigma(p^2) \supset -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

Using Λ as a cut-off scale in the loop integral

In Dimensional regularisation, the same divergence is somehow obfuscated, see e.g 1308.2783

- Physical phenomena at two widely different scales do not decouple!

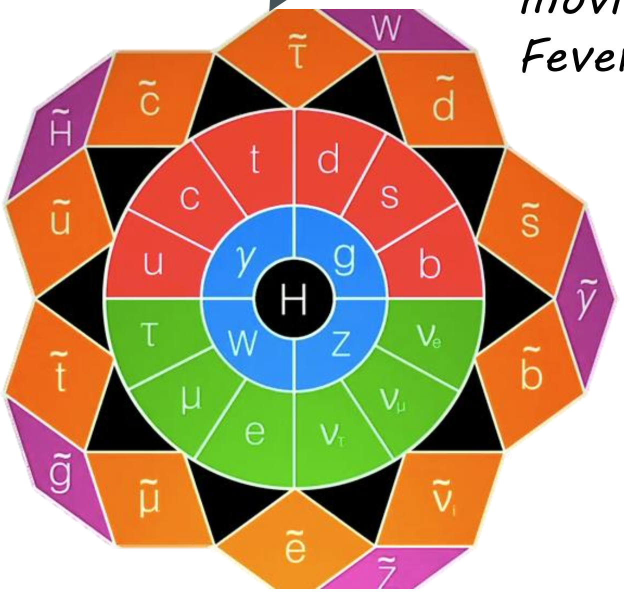
Protecting scale separations from (nasty) scalars

- We need a mechanism to protect the scale separation between the Higgs mass and any heavy NP scale
  - How about adjusting the tree-level value at 10^{-28} ?
    → it actually works ! But admittedly not extremely insightful
  - The Higgs is not « fundamental »
    → a composite object, which nature is revealed at the scale Λ
  - We can instead tame the quantum corrections themselves
    --> Replace the fundamental SM fields by larger objects which self-cancel in the loop: SUSY

Weyl fermion *Chiral supermultiplet*

$$Q_L \to (Q_L, \tilde{Q}_L)$$

The artistic SUSY way (from the movie Particle Fever)



Background for Amine Boussejra and Marco Palmiotto's talk

Note: there are other methods, based for instance on dynamical effects

Chiral SM and flavour

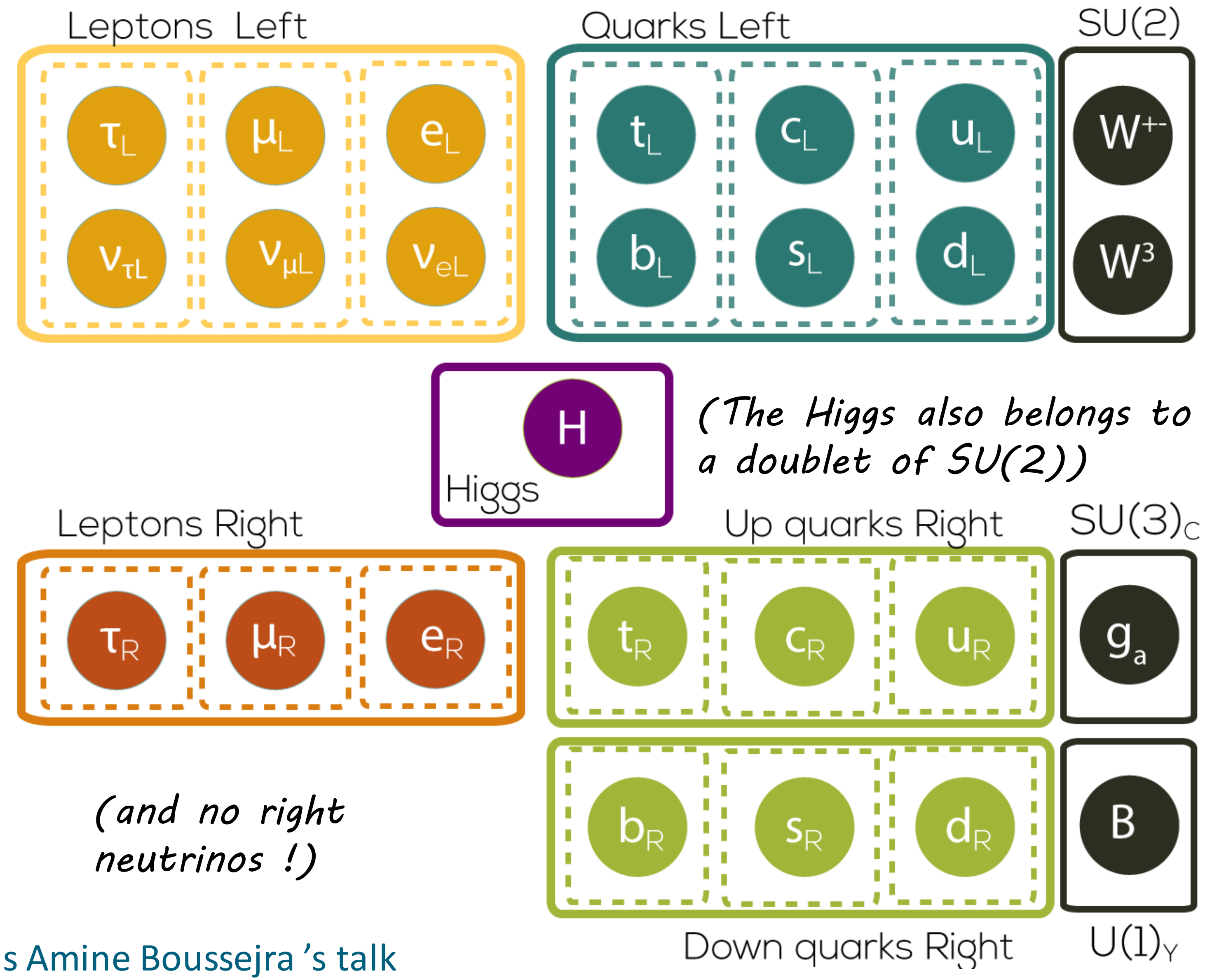
- Let us re-organise a bit: SM Lagrangian is hopelessly chiral

    --> No neutrino masses …

- Only the Higgs "sees" the difference between generations

    --> Understanding how this came to be and the huge mass hierarchies is the realm of flavour physics

    --> Intriguing hints in LHCb that they may be more to this …



See Jonathan Kriewald ans Amine Boussejra 's talk

Flavour and Yukawa interactions

- In the SM, the fermion masses arises from the chiral Yukawa coupling

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\, d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.},$$

$$\Phi \xrightarrow{\text{EWSB}} \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$$

Yukawa couplings: this is a 3x3 complex matrix

Left-handed quark doublet

Higgs SU(2) doublet

Right-handed quark, not a doublet of SU(2); note the flavour indices, there are 3 copies here

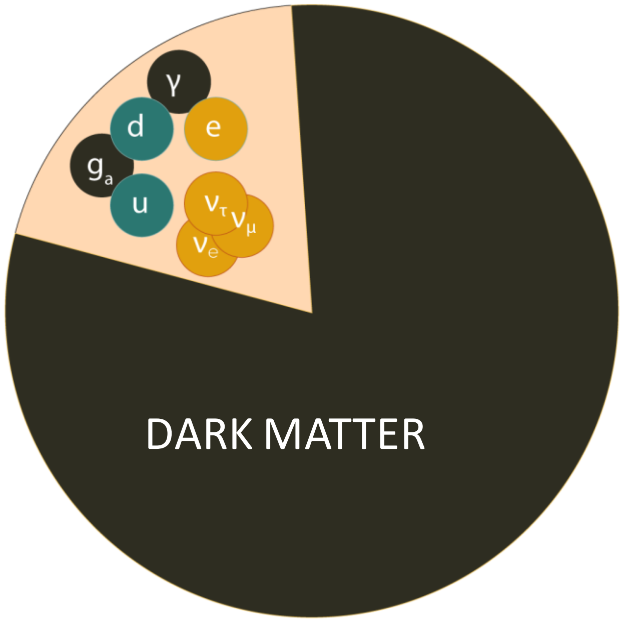
- The Higgs-induced breaking of the $SU(2) \times U(1)$ SM electroweak gauge group transmits the flavour-breaking structure to the gauge interaction via the CKM matrix

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W^+_\mu \boxed{V_{\text{CKM}}}\begin{pmatrix}d_L\\ s_L\\ b_L\end{pmatrix} + \text{h.c.}, \qquad V_{\text{CKM}} \equiv V^u_L V^{d\dagger}_L$$

This matrix is NOT diagonal, thus allowing for flavour-violating decays

The SM per universe matter content

- The SM describes only a fraction of the universe total matter content



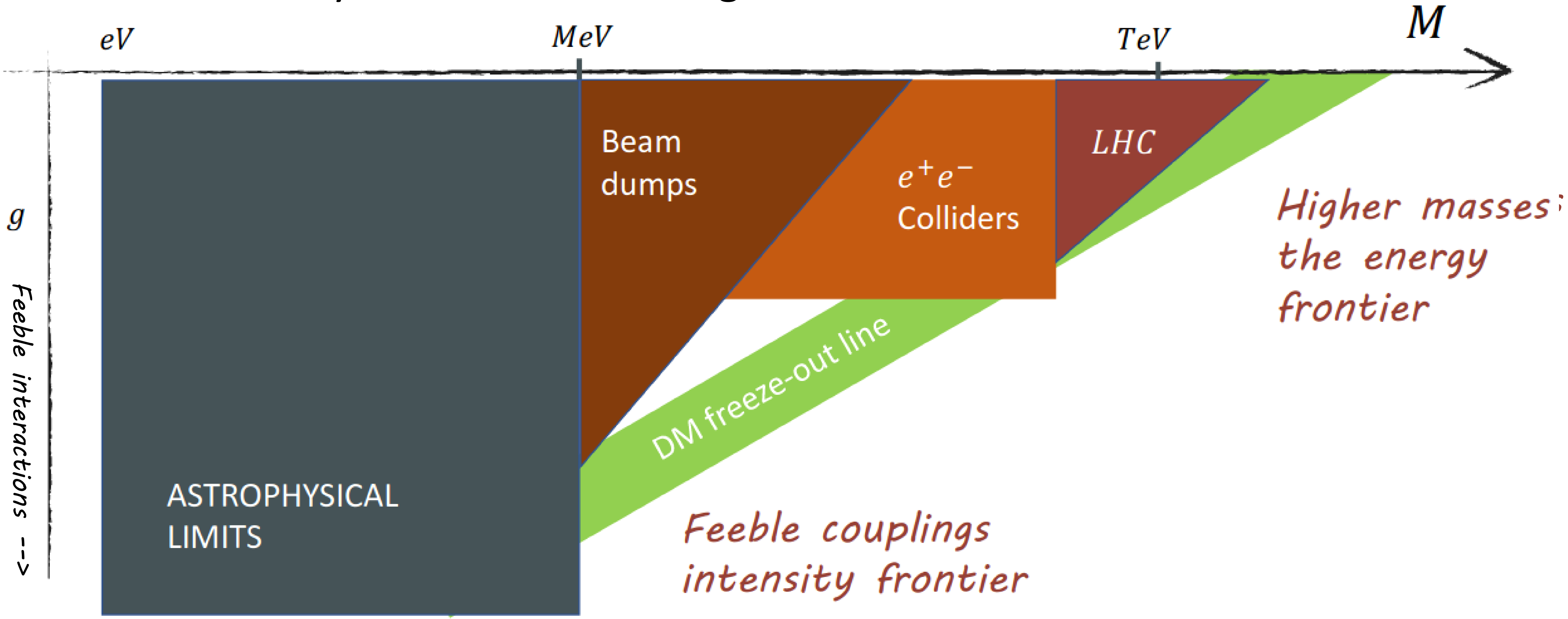
GR was not harmed in the process of getting this dark matter plot: no modified gravity

- Vastly more dark matter than baryonic matter in the universe
  Albeit sightly less than the number of dark matter models cooked up by theoreticians
- Automated codes to find the final relic density are an important tool for model building

See Marco Palmiotto's talk

Where can you hide new particles ?

- Particle physics proceeds "diagonally" in the search for new physics: schematically we have something like that



See Emanuelle Pinsard's talk

Portal interactions

- A simple way of parametrising FIPs interaction with the SM rely on “portal” operators

--> A neutral particle, must be coupled to a neutral “current” in the SM

	SM operator		FIPs / dark sector	examples …
Scalar portal	$\|H\|^2 \quad (d=2)\,,$	$\longleftrightarrow$	$\|S\|^2$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$	$F'^{\mu\nu}$	Dark photon
Neutrino portal	$LH \quad (d=5/2)$	$\longleftrightarrow$	N	HNL
Axion portal / fermion portal	$\bar{f}_i\,\Gamma^\mu f_j \quad (d=3)$	$\rightarrow$	$\partial_\mu a\,, V_\mu$	$ALP/L_\mu\text{-}L_\tau\ldots$
		$\rightarrow$	$\Psi\Gamma_\mu\Psi$	Dark fermions

Conclusion

Our menu

QFT theory

Majdouline Borji: Perturbative renormalization of the semi-infinite massive Phi_4^4 theory

~~Gala night~~ --> A good night sleep !

Particles

Jonathan Kriewald: On the B-meson decay anomalies --> 9am !!

Amine Boussejra: New physics scenarios in the Non Minimal Flavour Violating MSSM

Marco Palmiotto: Computation of relic densities within freeze-out mechanism

Emanuelle Pinsard: Solving (g-2) with a new light gauge boson

Coffee break

Multiplicity

Zechuan Zheng: Analytic and Numerical Bootstrap for One-Matrix Model and "Unsolvable" Two-Matrix Model

Thomas CZUBA: Quantum dynamics beyond the independent particle picture

More nuclei!

Zhen Li: Microscopic interactions for the nuclear shell model

Philippe Da costa: Shapes of heavy and super-heavy atomic nuclei with Skyrme Energy Density Functionals

Theory sessions

- We will be exploring a large variety of physical systems, driven by (motivated theoreticians and) the difficulty in describing physical systems
  - with a large number of degrees of freedom
  - where the actual degrees of freedom are unknown
  - where the degrees of freedom interacts non-pertubatively

- Please do not refrain in asking the speakers even naive questions !

--> Understanding a theory is definitely useful when it comes to testing its predictions

- Keep in mind that sometimes the data needs a new theory to be designed, but sometimes old, theory-driven tools find new applications

--> Basic communication between communities is the key

Renormalisation, Yang-Mills theories, string theories, etc ...

Backup

Feebly-Interacting Particles

- FIPs= "new neutral particle which interacts with the SM via suppressed new interactions"

*Bonus: pNGB in composite models

What is the origin of flavour?

The nature of dark matter?

Origin of the ν masses?

Why does QCD respect CP ?

And a dozen of anomalies ...

Axions, ALPs, Light dark matter, dark photon, dark Higgs, HNL, etc...

Half of the "grands instruments scientifiques" of l'IN2P3 have a sensitivity to this type of physics!

Belle-II, NA62, KOTO
Mono-γ, Rare B,K decays, etc.

XENON-1T, EDELWEISS, LISA:
DM scattering, Phase transition and GW.

T2K, KM3Net, DUNE, JUNO
Light dark matter scattering , neutrino sterile oscillations.

ATLAS, CMS, LHCb (+ LLP program: FASER, Codex-B...)
LLP anlysis, hidden valleys

A non-exhaustive list of low-energy anomalies

ASTROPHYSICS/COSMO

- Low primordial Li^7 (e.g 1203.3551) → Decaying FIP …
- Magnificent Seven (e.g 1910.04164) → Axions…
- Stellar cooling hints (e.g. 2003.01100) → Axions…
- Xenon 1T e-scattering (2006.09721) → LDM
- Hubble rate tension (2103.01183) → Decaying DM, axion, …
- DM small-scale (e.g. 1912.06681) → LDM with FIP mediator

PRECISION/NEUTRINOS

- Proton charge radius (e.g 1502.05314) → Scalar/vector FIP …
- $(g-2)_{e,\mu}$ (e.g. 2006.04822 and 1812.04130, Morel 2020) → Scalar/vector FIP …
- Atomki X17 (1910.10459) → Scalar/vector FIP …
- MiniBooNE ν_e excess (e.g 1812.08768) → ν_R+ light FIPs

SAVEUR

- $b \to s$ et $b \to c$ non-universalité (e.g 1807.11373) → FIP + UV physics
- CKM non-unitarité (e.g 2103.05549)
- KOTO $K_L \to \pi^0 inv.$ anomalie (1910.07148) → Scalar FIP
- Kaons CPV ratios and ΔA_{CP} in D^0 (e.g. 1911.06211)

High-energy

- Hints in top-observables (e.g. 2011.06514) → Sub-EW scale top-philic particle

Complexity in diversity

$H_u^0\ H_d^0\ H_u^+\ H_d^-$
$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$
$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$
$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$
$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$
$\widetilde{g}$
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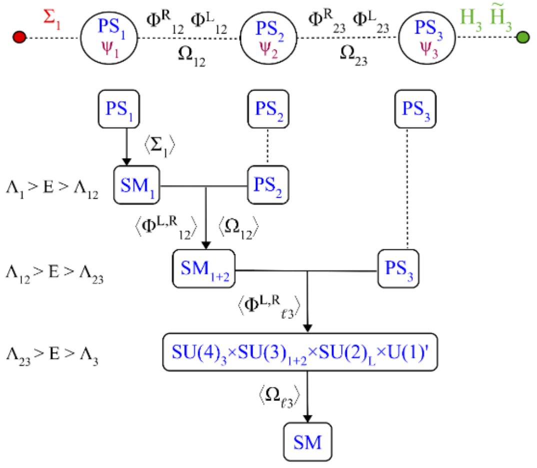
New SUSY states



$$\mathrm{PS}^3 \equiv \mathrm{PS}_1 \times \mathrm{PS}_2 \times \mathrm{PS}_3$$

Model for flavour anomalies
(Bordone et al. 2017)

... and an endless stream of models with a really large particle contents

- New symmetries in the UV mean typically more particles once everything is broken down to the SM symmetries

  --> Often they are NOT very heavy, and aim at being whithin reach of current (future) colliders

- Well-designed and versatile numerical codes are critical

See Marco Palmiotto's talk

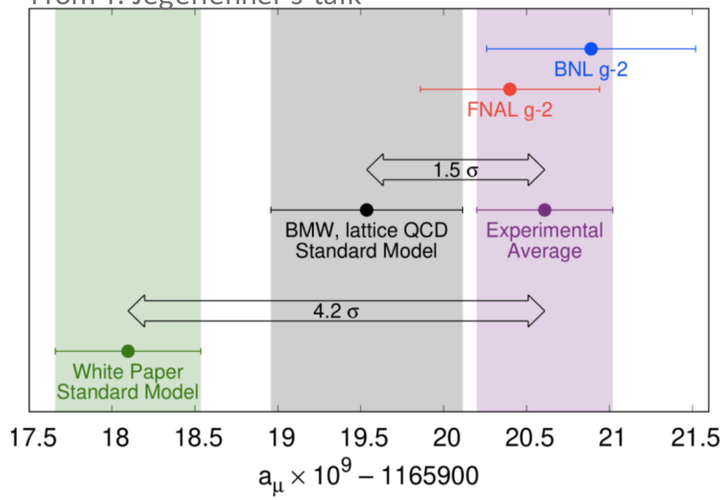
Anomalous magnetic moments

- Pheno of experimental anomalies in lepton magnetic moment is at a cross-road

Large anomaly in $(g-2)_\mu$

w.r.t data-driven SM theory estimates

From F. Jegerlehner's talk



Confused situation for $(g-2)_e$

on the exp. side

$$\Delta a_e \equiv a_e^{\rm SM} - a_e = +(4.8 \pm 3.0) \cdot 10^{-13}$$
(LKB – 2020)

$$\Delta a_e \equiv a_e^{\rm SM} - a_e = -(8.7 \pm 3.6) \cdot 10^{-13}$$
(Berkeley-2018)

More tension between both exp. measurements than with the SM prediction …

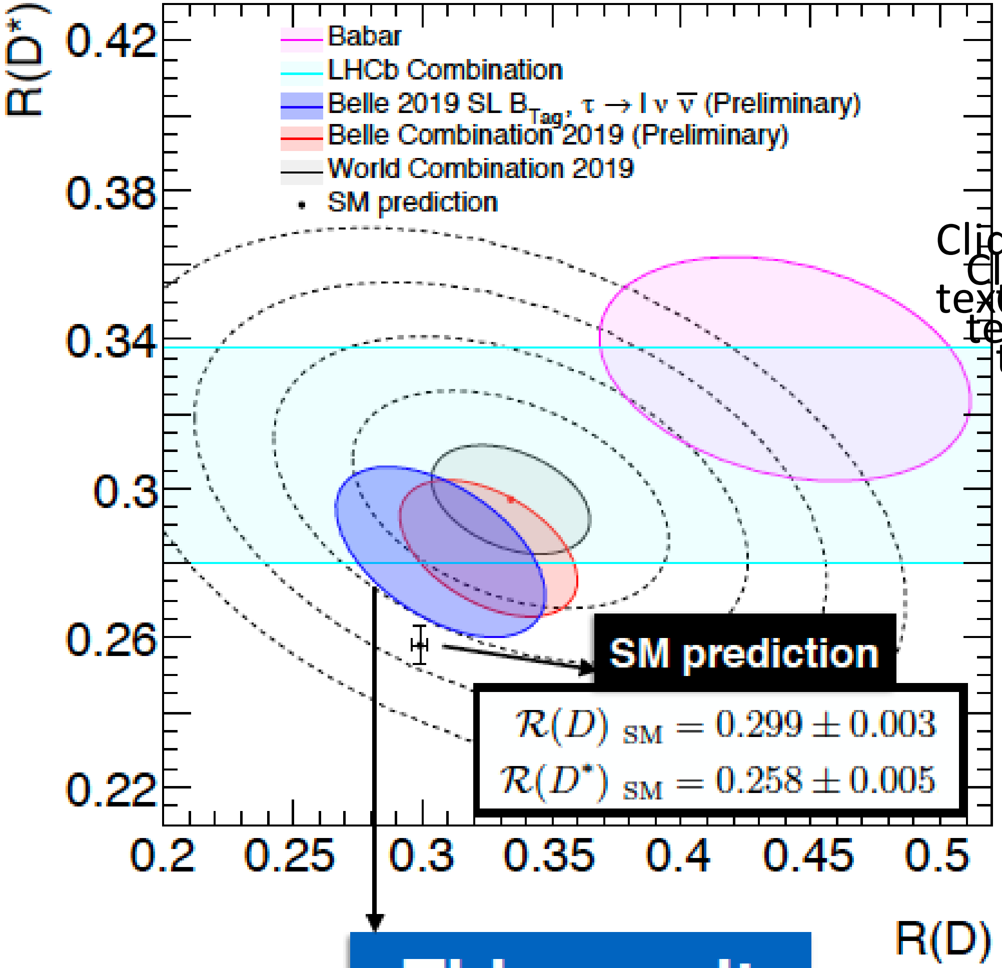
- On the pheno-side, we don't have a very clear target to fit for both anomalies

Status B-anomalies

Altmannshofer, Stangl, 2103.13370

1. Updated Belle measurement of R_{K^*} Talk by M. Prim

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu\mu)}{\mathrm{BR}(B \to K^* ee)} = \begin{cases} 0.90^{+0.27}_{-0.21} \pm 0.10\,, & \text{for } 0.1\,\mathrm{GeV}^2 < q^2 < 8\,\mathrm{GeV}^2 \\ 1.18^{+0.52}_{-0.32} \pm 0.10\,, & \text{for } 15\,\mathrm{GeV}^2 < q^2 < 19\,\mathrm{GeV}^2 \end{cases}$$



G. Ciara's talk @ MoriondEW2019

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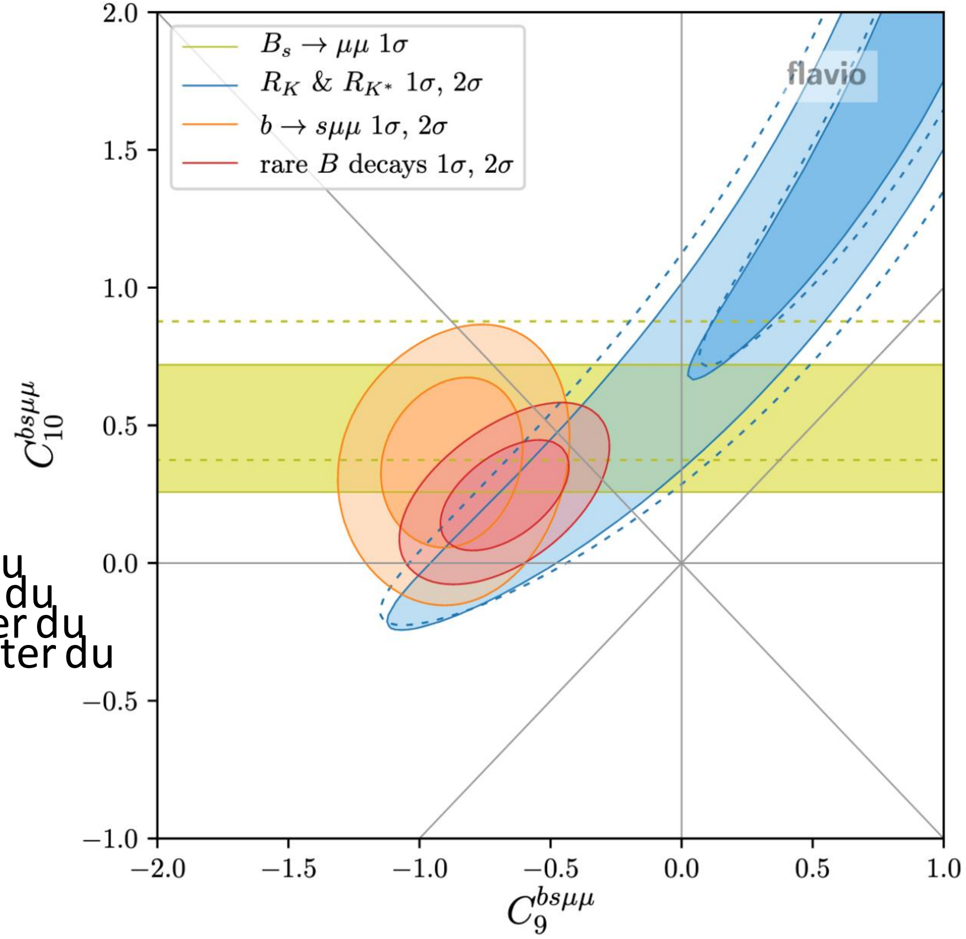

2. Updated LHCb measurement of R_K Talk by T. Humair

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} = 0.846\ ^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}\,,$$

LHCb 5 fb^{-1}
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
[PRL122191801]

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
[LHCb-PAPER-2021-004]