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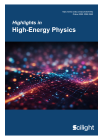

Review

About BSM Physics, with Emphasis on Flavour

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Abstract: This article is an account of a talk given at the Conference *The rise of Particle Physics* celebrating the 50th anniversary of the J/Ψ discovery. It contains some reflections on BSM physics and flavour in particular.

Keywords: BSM physics; flavour physics

1. A View of BSM Physics

The 50th anniversary of the November Revolution, marked by the discovery of the J/Ψ particle [1–3], represents a turning point in the history of physics. Since then, the rapid emergence of the Standard Model (SM) has established it as the reference theory for an entire quadrant of nature: Particle Physics. This is particularly evident when comparing how concisely the SM can be defined—see Figure 1—with the vast catalogue of independent observables it explains, often with remarkable numerical precision.

1. Symmetry group $L \times \mathcal{G}$

L = Lorentz (space-time)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local)

2. Particle content (rep.s of $L \times \mathcal{G}$)

	h	q_i	l_i	u_i	d_i	e_i
Lorentz	0	$1/2_L$	$1/2_L$	$1/2_R$	$1/2_R$	$1/2_R$
$SU(3)$	**1**	**3**	**1**	**3**	**3**	**1**
$SU(2)$	**2**	**2**	**2**	**1**	**1**	**1**
$U(1)$	$-1/2$	$1/6$	$-1/2$	$2/3$	$-1/3$	-1

3. All local operators of dimension d≤4 in $\mathcal{L}$

Figure 1. The SM unambiguously defined in the context of field theory. Each fermion field occurs in 3 replicas.

Not surprisingly however, as it happens for all great theories of nature, the SM leaves open a number of important questions, both of observational and of structural nature, as summarised in Figure 2. Since the first are well known, I briefly comment on the structural questions:

- **Which is the rationale for matter quantum numbers?** In particular the presence of an Abelian $U(1)$ factor in the gauge symmetries of the SM leaves in some way unexplained the quantization of electric charge, $Q = T_{3L} + Y$. The absence of gauge anomalies is enough to guarantee charge quantization in the case of a single fermion family [4] but not in the full SM, as defined in Figure 1 , due to the presence of additional anomaly-free global symmetries [5]. This is in sharp contrast with the bounds on the neutrality of matter, at the level of 10^{-21} relative to the electron charge, or on the neutrino charge, of about 10^{-14}, from plasmon decays into neutrinos in stars.
- **A single lacking operator of dimension** $d \leq 4$. The dimensionless coefficient of the operator $G_{\mu\nu}\tilde{G}^{\mu\nu}$, odd under CP, is bound to be less than 10^{-10} by the absence of any signal, so far, of an electric dipole moment of the neutron, equally odd under CP.

- **What about operators of dimension** $d > 4$? The stability of the Higgs potential, the convergence of the perturbative series and the Landau-pole problem [6] indicate that the SM cannot be valid at all energies. This leads to the expectation that higher dimensional operators could be present, weighted by dimensionful coefficients, which may, in turn, be related to some striking new phenomena. The neutrinos masses, which in the SM are predicted to be massless at $d = 4$, can be considered the first evidence of higher-dimensional operators.
- **A matter of calculability**. Of the seventeen particles of the SM two are massless, the photon and the gluon, due to gauge invariance. None of the remaining particle masses is predicted by the SM. The mass of the Higgs boson suffers from its sensitivity to any higher mass scale coupled to the Higgs, the so-called *naturalness problem*. All the fermion masses, aswell as the four physical parameters of the CKM matrix, constitute the *flavour puzzle*, itself strongly intertwined with the Higgs boson via the Yukawa couplings.

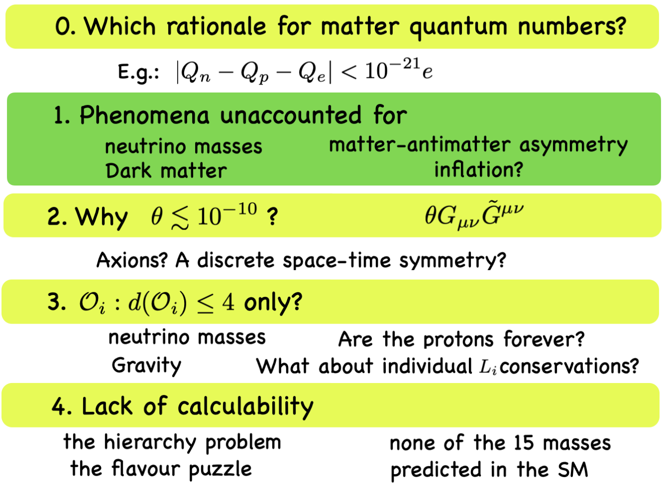

Figure 2. Questions raised by the SM, of observational (green) or structural (yellow) origin.

The significance of these questions cannot be overstated. Unsurprisingly, they have long been, and continue to be, the driving force behind numerous ideas and inquiries in BSM physics—too many to list—though, as of yet, without any direct or unambiguous experimental evidence. Here I focus on the last item in Figure 2 with particular emphasis on the *flavour puzzle*, though not before expressing a personal view about the SM Lagrangian $\mathcal{L}_{SM}$. If one separates $\mathcal{L}_{SM}$ into two sectors, as in Figure 3, one notices that:

- (i) the "lack of calculability" alluded to in Figure 2 mostly resides in the Higgs sector, which includes as well the Cosmological Constant problem ("Λ"), of similar origin, from an EFT point of view, as the naturalness problem of the Higgs mass;
- (ii) the precision, experimental and theoretical, to which the two sectors have been tested so far is unequal: many observables in the gauge sector are correctly predicted at 1 ppm level or better [7], whereas flavour [8] or Higgs couplings [7] tests are more at about 10% level.

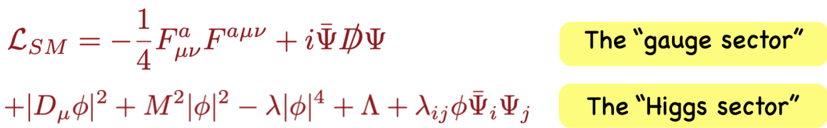

Figure 3. The SM Lagrangian with its two sectors defined: the "gauge" and the "Higgs" one.

Both sectors are each an unavoidable pillar of the SM. Nevertheless, jointly with the fact that the Higgs sector is where the Fermi scale originates, these considerations represent, in my view, a strong motivation for the next high energy collider. The LHC is currently exploring the Fermi scale, but a next step in precision and energy appears mandatory.

2. Flavour and BSM

From a generic EFT point of view, the strongest lower bounds on the BSM scale come from flavour physics. Figure 4, from the UTfit Collaboration [8], shows these bounds from actually observed processes related to $\Delta F = 2$ transitions. Bounds from null observations of $\mu \to e$ transitions are comparable or slightly stronger. Taken at face value, as well known, these bounds set the possible scale of BSM physics very far from the Fermi scale or even the MultiTeV scale. Is this contradicting the view expressed in the last paragraph of the previous Section?

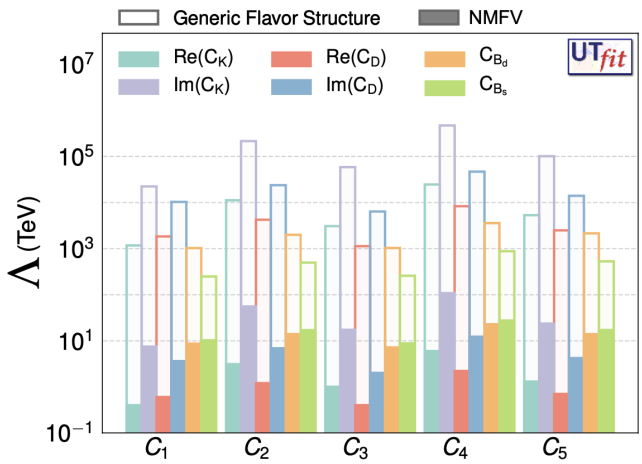

Figure 4. Constraints on the scale Λ weighting the $d = 6$ operators that mediate $\Delta F = 2$ transitions, taken from Ref. [8], for a generic EFT (empty) or by including in each operator an *ad hoc* CKM factor (coloured).

To try to address this question, let us consider what we know of the Yukawa couplings Y^f, $f = u, d, e$ in the SM, as defined in Figure 1. Diagonalising Y^f as $Y_f = U_L^{f+} Y_f^{diag} U_R^f$, the entries of Y_f^{diag} are strongly hierarchical and the CKM matrix $V_{CKM} = U_L^u (U_L^d)^+$ is close to the unit matrix. Figure 5 shows the structure of the quark Yukawa couplings if one takes $[U_L^{u,d}]_{i\neq j} \lesssim [V_{CKM}]_{i\neq j}$ but no special structure in $U_R^{u,d}$ (Figure 5 left) and if also $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$ (Figure 5 right).

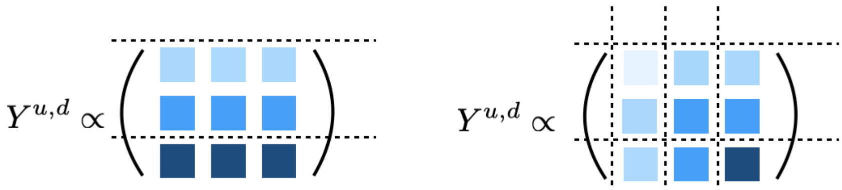

Figure 5. Representation of the Yukawa couplings with the colour intensity reflecting the typical size of the corresponding matrix elements, assuming $[U_L^{u,d}]_{i\neq j} \lesssim [V_{CKM}]_{i\neq j}$ (**left**) and also $[U_R^{u,d}]_{i\neq j} \lesssim [U_L^{u,d}]_{i\neq j}$ (**right**). The dotted lines indicate the emergence of approximate global symmetries, see text.

To the extent that the relatively smaller matrix elements can be neglected, Figure 5 left shows the emergence of an (approximate) $U(2)_q$ symmetry acting on the first two generations of left handed quarks as a doublet, whereas Figure 5 right an (equally approximate) $U(2)_q \times U(2)_u \times U(2)_d$ symmetry. In fact a further suppression of the elements of the first column in Figure 5 right can be associated with a $U(1)_u \times U(1)_d$ subgroup acting on the first generation of right-handed u, d quarks.

The potential relevance of these symmetries, suitably broken, in reducing the scale associated with BSM flavour changing interactions has been pointed out in Ref. [9] and recently confirmed in general EFT analyses [10,11]. In particular their possible role in the case of Higgs compositeness, with the *flavour* and the *naturalness problem* strongly tied to each other, has also been emphasised [12] and keeps being examined in general [13] and in specific constructions [14,15]. All this leads to wonder about the origin, if any, of these symmetries, about the source of their breaking and, last but not least, about specific experimental manifestations at scales not too far from the Fermi scale.

3. Flavour Deconstruction

Recent models [16–19] that try to understand the origin of these approximate symmetries share the following features:

- The $SU(3) \times SU(2) \times U(1)$ gauge interactions at high energies are (fully or in part) flavour non-universal. Note that this is unlike the case of an additional flavour non-universal gauge group that commutes with $SU(3) \times SU(2) \times U(1)$ (See, e.g., [20] and references therein).
- In the unbroken gauge limit the Higgs field couples to one single chiral generation only: $y_3^f f_{L3} H f_{R3}$.
- The flavour universal gauge interactions observed so far are a low energy manifestation of a stepwise breaking of the gauge group at different scales. It is this stepwise breaking that is responsible for the hierarchical

structure of the Yukawa couplings.

3.1. An Example

For concreteness an explicit example of this picture, fully based on $d = 4$ and specifically aimed at generating the pattern of Figure 5 right with its approximate flavour symmetries, is as follows [19]:

- The gauge group is

$$G = SU(3) \times SU(2) \times U(1)_Y^{[3]} \times U(1)_{B-L}^{[12]} \times U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]}, \tag{1}$$

  where $SU(3)$ and $SU(2)$ act universally on the three fermion families, as in the SM, whereas the $U(1)$ groups act non-universally only on one or two families, as indicated by the corresponding superscripts. E.g. $q_3 = (3,2)_{(1/6,0,0,0)}$ and similarly for all other chiral fermions.
- The full particle content, scalars and vector-like (VL) fermions, other than the usual chiral fermions (which include two right-handed neutrinos $\nu_{1,2}$ needed to cancel the gauge anomalies associated with $U(1)_{T_{3R}}^{[2]} \times U(1)_{T_{3R}}^{[1]}$) is shown in the following Tables (The abundance of U(1) charges in these Tables as well as in the implicit table for the standard chiral fermions raises the question of electric charge quantization. At variance with the SM with three families, however, the model under consideration, with the inclusion of the most general Yukawa couplings, does not have any non-anomalous global symmetry, hence electric charge is quantised. In particular one can show that $Q = T_{3L} + Y^{[3]} + (B-L)^{[12]}/2 + T_{3R}^{[2]} + T_{3R}^{[1]}$ is not a convention (as $Q = T_{3L} + Y$ in the SM with a single family)).

Scalars

Field	$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3) \times SU(2)$
$H_{u,d}$	$-1/2$	0	0	0	$(\mathbf{1},\mathbf{2})$
χ^q	$-1/6$	$1/3$	0	0	$(\mathbf{1},\mathbf{1})$
χ^l	$1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
ϕ	$1/2$	0	$-1/2$	0	$(\mathbf{1},\mathbf{1})$
σ	0	0	$1/2$	$-1/2$	$(\mathbf{1},\mathbf{1})$

VectorLike fermions

		$U(1)_Y^{[3]}$	$U(1)_{B-L}^{[12]}$	$U(1)_{T_{3R}}^{[2]}$	$U(1)_{T_{3R}}^{[1]}$	$SU(3) \times SU(2)$
light VL ($\alpha = 1,2$)	U_α	$1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	D_α	$-1/2$	$1/3$	0	0	$(\mathbf{3},\mathbf{1})$
	E_α	$-1/2$	-1	0	0	$(\mathbf{1},\mathbf{1})$
heavy VL	U_3	0	$1/3$	$1/2$	0	$(\mathbf{3},\mathbf{1})$
	D_3	0	$1/3$	$-1/2$	0	$(\mathbf{3},\mathbf{1})$
	E_3	0	-1	$-1/2$	0	$(\mathbf{1},\mathbf{1})$

The scalar fields are responsible for the breaking of the $U(1)$ factors of the gauge group in two steps, by $\langle\sigma\rangle >> \langle\phi,\chi\rangle$, as well as for EW symmetry breaking by the two doublets $H_{u,d}$, distinguished by a softly broken Z_2 symmetry which makes them couple to the up-type quarks/neutrinos and to the down-type quarks/charged leptons respectively.

The full set of Yukawa-like couplings and fermion mass terms is determined by the transformation properties of these scalars and of the fermions, chiral or VL. For example in the up-quark sector $(i = 1,2, \alpha = 1,2)$

$$\begin{aligned}\mathcal{L}_Y^u \quad = \quad & (y_3^u\, \bar{q}_3 u_3 H_u + y_{i\alpha}^u\, \bar{q}_i U_\alpha H_u + y_\alpha^{\chi_u}\, \bar{U}_\alpha u_3 \chi^q + y_{\alpha 2}^{\phi_u}\, \bar{U}_\alpha u_2 \phi + y_{\alpha 3}^{\phi_u}\, \bar{U}_{R\alpha} U_{L3} \phi \\ & + \hat{y}_{\alpha 3}^{\phi_u}\, \bar{U}_{L\alpha} U_{R3} \phi + y_1^{\sigma_u}\, \bar{U}_3 u_1 \sigma + \text{h.c.}) + M_{U_3}\, \bar{U}_3 U_3 + M_{U_\alpha}\, \bar{U}_\alpha U_\alpha \end{aligned} \tag{2}$$

where, unless specified, the chirality component is left understood since non ambiguous $(q \equiv q_L, u \equiv u_R)$, and similarly in the down and charged lepton sector.

The emerging overall picture is summarised in Figure 6 with the following noteworthy points:

- As manifest from Equation (2) in the limit of infinitely heavy VL fermions, $M_{\alpha,3} \to \infty$, the Yukawa couplings exhibit a $U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_l \times U(2)_e$ global symmetry, reduced to $U(1)^3 \equiv U(1)_u \times U(1)_d \times U(1)_e$ if only $M_3 \to \infty$.
- For finite $M_{\alpha,3}$, after integrating out the heavy VL fermions, the breaking of these symmetries is controlled by three parameters,

$$\epsilon_\phi = \frac{\langle\phi\rangle}{M_\alpha}, \quad \epsilon_\chi = \frac{\langle\chi\rangle}{M_\alpha}, \quad \epsilon_\sigma = \frac{\langle\sigma\rangle}{M_3}, \tag{3}$$

  represented in Figure 6 by the vertical lines with two arrows.

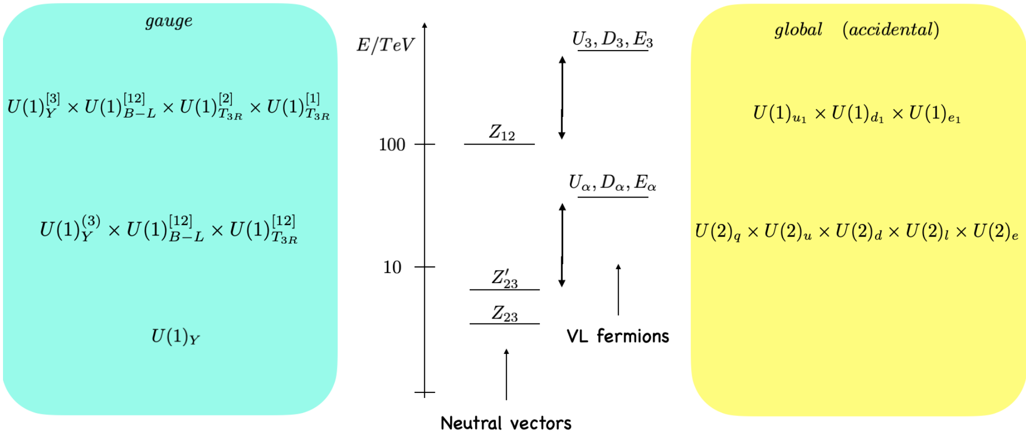

Figure 6. Overall representation of the model. On the left and on the right are shown the different gauge ($SU(3) \times SU(2)$) and global symmetries (Universal $U(1)_B \times U(1)_L$), which appear as (almost) unbroken at a given energy. In the centre are the masses of the new particles: neutral vectors, Z_{23}, Z'_{23}, Z_{12}, and VL $SU(2)$-singlet fermions, $U_i, D_i, E_i, i = 1, 2, 3$. The vertical lines with two arrows denote the separation of scales which controls the breaking of the global symmetries.

By integrating out the heavy VL fermions one gets the true Yukawa couplings of the chiral fermions. In the up-type case one obtains

$$Y_u \approx \begin{pmatrix} y^u_{1\alpha}\hat{y}^{\phi_u}_{\alpha 3} y^{\sigma_u}_1 \epsilon_\sigma \epsilon_\phi & -y^u_{1\alpha} y^{\phi_u}_{\alpha 2}\epsilon_\phi & -y^u_{12} y^{\chi_u}_2 \epsilon_\chi \\ y^u_{2\alpha}\hat{y}^{\phi_u}_{\alpha 3} y^{\sigma_u}_1 \epsilon_\sigma \epsilon_\phi & -y^u_{2\alpha} y^{\phi_u}_{\alpha 2}\epsilon_\phi & -y^u_{22} y^{\chi_u}_2 \epsilon_\chi \\ \approx 0 & \approx 0 & y^u_3 \end{pmatrix} \tag{4}$$

and similarly for $Y_{d,e}$. For $v_u/v_d \approx 10$ and $\epsilon_\phi \approx \epsilon_\chi \approx \epsilon_\sigma \approx 0.05 - 0.1$ the charged fermion masses and quark mixings are described by all the Yukawa couplings y's in Equation (2) in the 0.1–1 range. In particular the matrix elements of $U_L^{u,d.e}$ have similar size to the matrix elements of V_{CKM} (with $U_L^u U_L^{d+} = V_{CKM}$) and $[U_R^{u,d,e}]_{i\neq j} << [U_L^{u,d,e}]_{i\neq j}$.

3.2. Phenomenology

Phenomenological effects of Flavour Deconstruction at the TeV scale are due to the exchanges of the lightest new gauge bosons ($Z_{23}^{(')}$ in the example above) and to their mixing with the Z-boson. They occur in:

- ElectroWeak Precision Tests. In the above example, a particularly important effect is the correction to the Z-mass proportional to $(m_Z/m_{Z_{23}})^2$ [21];
- High p_T effects in $pp \to ll, l = e, \mu$ via Drell-Yan $q\bar{q} \to Z_{23}^{(')} \to ll$. In the example under consideration the negative searches by ATLAS [22] and CMS [23] set the nominally stronger lower bound on $m_{Z_{23}}$ at about 5 TeV [21];
- Flavour changing effects in $\Delta F = 2, b \to sll(\nu\nu), K \to \pi\nu\nu, \tau \to 3\mu, \mu \to 3e$, controlled by the matrix elements $[U_L^f]_{i3}[U_L^f]^*_{j3}$ with $i, j; f$ depending on the process under consideration. A peculiarity of the model above is the cancellation in the $b \to sll$ transitions of the operator $O_{10} = \bar{b}_L \gamma^\mu s_L \bar{\mu}\gamma_\mu\gamma_5\mu$ that contributes, e.g., to $B_s \to \mu\mu$[21].

The exchange of the heavier gauge boson, Z_{12}, produces effects in $\Delta S = 2$ transitions, controlled by the matrix elements $[U_R^d]_{12}[U_R^d]^*_{22}$, which require the Z_{12}-mass to be heavier than about 100 TeV [19].

Loop effect are potentially important both in dipole moments and in $\Delta S = 2$ effective operators due to the exchange of heavy VL fermions. In the special case of the example described above, however, they do not set bounds more significant than the tree level ones. In the case of the dipoles this is because of a strong alignment of the dipole operators with the corresponding effective Yukawa couplings [21].

4. Summary

During the half-century since the November Revolution, the catalogue of observables correctly accounted for by the Standard Model (SM)—in many cases with great numerical precision—has increased enormously. Alongside the lack of any observed deviation from SM expectations, this establishes the SM as one of the most successful theories of a quadrant of nature ever formulated. At the same time, and entirely consistent with this success, the SM leaves us with a number of unanswered questions, both of observational and, at least equally important, of structural nature.

The variety of these questions, as summarized in Section 1 and Figure 2, suggests a wide front of attack. In this talk, I have drawn attention to the distinction between the two pillars of the SM—the gauge sector and the Higgs sector (see Figure 3)—emphasizing two points: the accumulation of questions emerging from the Higgs sector and the differing numerical precision to which the two sectors have been tested so far.

In general terms, these considerations, together with the fact that the Higgs sector is where the Fermi scale originates, strongly motivate the development of the next high-energy collider. On a shorter timescale, but based on similar considerations, increased precision in flavour tests appears highly motivated as well. An extended Table of Flavour Precision Tests at a typical 1% level in many observables is eagerly awaited and may be within reach of the so-called *mid-term* flavour program. The hope is that the emergence of clear deviations from the SM in such a table will lend credence and give substance to daring hypotheses like flavour non-universal $SU(3) \times SU(2) \times U(1)$ gauge interactions, as described in Section 3.

Acknowledgments

I am indebted to Gino Isidori for his collaboration and for many useful discussions on the general subject touched upon in this paper.

Conflicts of Interest

The author declares no conflict of interest.

Appendix A. Raul Gatto and the November Revolution

It so happened that Raul Gatto and I ended up together at CERN around the time of the November revolution. Raul, visiting from Roma La Sapienza, was already well known as a strong theorist and an effective mentor of students and young collaborators. I was a fellow of the CERN Theory Division, after having worked on QED and QED bound states in particular.

The discovery of the J/Ψ and the subsequent works of Appelquist, De Rujula, Glashow, and Politzer [24–26] naturally led to our collaboration, focusing on the non-relativistic (NR) $c\bar{c}$ bound-state interpretation of the new resonances. First we worked on the spectrum of the $c\bar{c}$ resonances, with only the first two $J = 1^{--}$ states, Ψ, Ψ', observed at that time [27,28]. As other groups [29,30] we were using a NR potential that included a Coulomb-like one-gluon exchange term and a long-distance linear term, complemented with suitable relativistic corrections in part also due to the one-gluon exchange.

Most of all, however, our attention was attracted to the idea that the total width of a charmonium state into light hadrons is due to the annihilation of a pair of $c\bar{c}$ into gluons, capable of explaining the narrowness of the J/Ψ. With my experience on positronium, it was then straightforward to apply this idea to the $0^{++}, 2^{++}$ P-waves decaying into two gluons, obtaining the result [31]

$$\frac{\Gamma(2^{++})}{\Gamma(0^{++})} = \frac{4}{15}, \tag{5}$$

independent from the charmonium wave function, at leading order in α_S. The case of the remaining P-wave was more tricky, since the 1^{++} state does not decay into two gluons due to a generalisation of the Landau-Yang theorem which forbids the decay of a $J = 1$ state into two massless vectors. The decay into three gluons is readily computed but, at the same order in α_S, the decay into one gluon and a pair of light $q\bar{q}$ has a logarithmic divergence when the momentum of the emitted gluon goes to zero and the external $c\bar{c}$ quarks are assumed free. In the charmonium case, however, the c-quark propagator is not free due to its localisation inside the charmonium radius, which is what provides the cutoff of the logarithmic divergence. This allowed a rough estimate of $\Gamma(1^{++})$ as well, which is summarised into the overall leading-order prediction [32]

$$\Gamma(2^{++}) : \Gamma(0^{++}) : \Gamma(1^{++}) = 15 : 4 : 1 \tag{6}$$

for the widths of the annihilation into light hadrons. The relatively precise determination of these widths had to wait for the production of these states in $p\bar{p}$ collisions at Fermilab [33,34]. The current values give

$$\Gamma(2^{++}) : \Gamma(0^{++}) : \Gamma(1^{++}) = 12 : 2.4 : 1 \tag{7}$$

with a typical 10% experimental uncertainty. Corrections of different origins to Equation (6) have been introduced in the following decades. For a review see Ref. [35].

References

1. Aubert, J.J.; Becker, U.; Biggs, P.J.; et al. Experimental Observation of a Heavy Particle J. *Phys. Rev. Lett.* **1974**, *33*, 1404–1406. https://doi.org/10.1103/PhysRevLett.33.1404.
2. Augustin, J.E.; Boyarski, A.M.; Breidenbach, M.; et al. Discovery of a Narrow Resonance in e^+e^- Annihilation *Phys. Rev. Lett.* **1974**, *33*, 1406–1408. https://doi.org/10.1103/PhysRevLett.33.1406.
3. Bacci, C.; Celio, R.B.; Bernardini, M.; et al. Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation *Phys. Rev. Lett.* **1974**, *33*, 1408. https://doi.org/10.1103/PhysRevLett.33.1408.
4. Bouchiat, C.; Iliopoulos, J.; Meyer, P. An Anomaly-Free Version of Weinberg's Model. *Phys. Lett. B* **1972**, *38*, 519–523. https://doi.org/10.1016/0370-2693(72)90532-1.
5. Foot, R.; Lew, H.; Volkas, R.R. A Model with Fundamental Improper Space-Time Symmetries *J. Phys. G* **1993**, 19, 361–372. https://doi.org/10.1088/0954-3899/19/3/005.
6. Abrikosov, A.A.; Landau, L.D.; Khalatnikov, I.M. On the elimination of infinities in quantum electrodynamics. *Dokl. Akad. Nauk SSSR* **1954**, *95*, 497.
7. de Blas, J.; Ciuchini, M.; Franco, E.; et al. Electroweak precision observables and Higgs-boson signal strengths in the Standard Model and beyond: present and future. *J. High Energy Phys.* **2016**, *12*, 135. https://doi.org/10.1007/JHEP12(2016)135.
8. Bona, M.; Ciuchini, M.; Derkach, D.; et al. Overview and theoretical prospects for CKM matrix and CP violation from the UTfit Collaboration. *PoS* **2024**, *45*7, 7. https://doi.org/10.22323/1.457.0007.
9. Barbieri, R.; Isidori, G.; Jones-Perez, J.; et al. $U(2)$ and minimal flavour violation in supersymmetry. *Eur. Phys. J. C* **2011**, *71*, 1725. https://doi.org/10.1140/epjc/s10052-011-1725-z.
10. Greljo, A.; Palavrić, A.; Thomsen, A.E. Adding Flavor to the SMEFT. *JHEP* **2022**, *10*, 005. https://doi.org/10.1007/JHEP10(2022)005.
11. Allwicher, L.; Cornella, C.; Stefanek, B.A.; et al. New Physics in the Third Generation: A Comprehensive SMEFT Analysis and Future Prospects. *arXiv* **2023**, arXiv:2311.00020.
12. Barbieri, R.; Buttazzo, D.; Sala, F.; et al. A 125 GeV composite Higgs boson versus flavour and electroweak precision tests. *JHEP* **2013**, *5*, 069. https://doi.org/10.1007/JHEP05(2013)069.
13. Glioti, A.; Rattazzi, R.; Ricci, L.; et al. Exploring the Flavor Symmetry Landscape. *arXiv* **2024**, arXiv:2402.09503.
14. Davighi, J.; Isidori, G. Non-universal gauge interactions addressing the inescapable link between Higgs and flavour. *JHEP* **2023**, *7*, 147. https://doi.org/10.1007/JHEP07(2023)147.
15. Covone, S.; Davighi, J.; Isidori, G.; et al. Flavour deconstructing the composite Higgs. *JHEP* **2025**, *1*, 41. https://doi.org/10.1007/JHEP01(2025)041.
16. Davighi, J.; Isidori, G.; Pesut, M. Electroweak-flavour and quark-lepton unification: a family non-universal path. *JHEP* **2023**, *4*, 30. https://doi.org/10.1007/JHEP04(2023)030.
17. Navarro, M.F.; King, S.F. Tri-hypercharge: a separate gauged weak hypercharge for each fermion family as the origin of flavour. *JHEP* **2023**, *8*, 20. https://doi.org/10.1007/JHEP08(2023)020.
18. Davighi, J.; Stefanek, B.A. Deconstructed Hypercharge: A Natural Model of Flavour. *arXiv* **2023**, arXiv:2305.16280.
19. Barbieri, R.; Isidori, G. Minimal flavour deconstruction. *JHEP* **2024**, *5*, 33. https://doi.org/10.1007/JHEP05(2024)033.
20. Belfatto, B.; Berezhiani, Z. How light the lepton flavor changing gauge bosons can be. *Eur. Phys. J. C* **2019**, *79*, 202. https://doi.org/10.1140/epjc/s10052-019-6724-5.
21. Barbieri, R. Phenomenology of Minimal Flavour Deconstruction at the lowest new scale. *arXiv* **2024**, arXiv:2409.08657.
22. Aad, G.; Abbott, B.; Abbott, D.C.; et al. Search for high-mass dilepton resonances using 139 fb-1 of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector *Phys. Lett. B* **2019**, *796*, 68–87. https://doi.org/10.1016/j.physletb.2019.07.016.
23. Sirunyan, A.M.; Tumasyan, A.; Adam, W.; et al. Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13$ TeV. *JHEP* **2021**, *7*, 208. https://doi.org/10.1007/JHEP07(2021)208.
24. Appelquist, T.; Politzer, H.D. Heavy Quarks and e^+e^- Annihilation. *Phys. Rev. Lett*. **1975**, *34*, 43. https://doi.org/10.1103/PhysRevLett.34.43.
25. Rujula, A.D.; Glashow, S.L. Is Bound Charm Found? *Phys. Rev. Lett.* **1975**, *34*, 46–49. https://doi.org/10.1103/PhysRevLett.34.46.
26. Appelquist, T.; Rujula, A.D.; Politzer, H.D.; et al. Spectroscopy of the New Mesons. *Phys. Rev. Lett.* **1975**, *34*, 365. https://doi.org/10.1103/PhysRevLett.34.365.
27. Barbieri, R.; Gatto, R.; Kogerler, R.; et al. Meson hyperfine splittings and leptonic decays. *Phys. Lett. B* **1975**, *57*, 455–459. https://doi.org/10.1016/0370-2693(75)90267-1.
28. Barbieri, R.; Kogerler, R.; Kunszt, Z.; et al. Meson masses and widths in a gauge theory with linear binding potential. *Nucl. Phys. B* **1976**, *105*, 125–138. https://doi.org/10.1016/0550-3213(76)90064-X.
29. Eichten, E.; Gottfried, K.; Kinoshita, T.; et al. Spectrum of Charmed Quark-Antiquark Bound States. *Phys. Rev. Lett.* **1975**, *34*, 369–372. https://doi.org/10.1103/PhysRevLett.34.369.

30. Kang, J.S.; Schnitzer, H.J. Dynamics of light and heavy bound quarks. *Phys. Rev. D* **1975**, *12*, 841. https://doi.org/10.1103/PhysRevD.12.841.
31. Barbieri, R.; Gatto, R.; Kogerler, R. Calculation of the annihilation rate of P wave quark-antiquark bound states. *Phys. Lett. B* **1976**, *60*, 183–188. https://doi.org/10.1016/0370-2693(76)90419-6.
32. Barbieri, R.; Gatto, R.; Remiddi, E. Singular binding dependence in the hadronic widths of 1^{++} and 1^{+-} heavy quark antiquark bound states *Phys. Lett. B* **1976**, *61*, 465–468. https://doi.org/10.1016/0370-2693(76)90729-2.
33. Bagnasco, S.; Baldini, W.; Bettoni, D.; et al. New measurements of the resonance parameters of the $\chi_{c0}(1^3P_0)$ state of charmonium. *Phys. Lett. B* **2002**, *533*, 237–242. https://doi.org/10.1016/S0370-2693(02)01657-X.
34. Andreotti, M.; Bagnasco, S.; Baldini, W.; et al. Measurement of the resonance parameters of the $\chi_1(1^3\mathrm{P}_1)$ and $\chi_2(1^3\mathrm{P}_2)$ states of charmonium formed in antiproton–proton annihilations. *Nucl. Phys. B* **2005**, *717*, 34–47. https://doi.org/10.1016/j.nuclphysb.2005.03.042.
35. Brambilla, N.; Eidelman, S.; Heltsley, B.K.; et al. Heavy quarkonium: progress, puzzles, and opportunities. *Eur. Phys. J. C* **2011**, *71*, 1534. https://doi.org/10.1140/epjc/s10052-010-1534-9.