Theoretical summary of Moriond 2022: QCD and high-energy interactions

Kirill Melnikov

Institute for Theoretical Particle Physics, Department of Physics, Karlsruhe Institute of Technology, 76128, Karlsruhe, Germany

I review theoretical talks presented at the session on QCD and high-energy interactions of the Moriond 2022 conference.

1   Introduction

The 56th edition of Rencontres de Moriond held earlier this year was one of the first in-person conferences after almost two years of the pandemic isolation during which many interactions were limited to an on-line format. In fact, this was the very first in-person conference for me since a very long time. Although we all learned to appreciate the convenience of on-line conferences and meetings, participants' eagerness to talk to each other *in person* about physics was clearly seen at Moriond.

Theory talks at "QCD and high-energy interactions" session of Moriond covered many areas of contemporary particle physics often going beyond a conventional understanding of what "QCD Moriond" is all about. This is a great feature of this conference as it emphasizes the unity of particle physics, including its research goals and methodologies.

Particle physics is defined by big questions that it tries to answer. These questions are well-known; they include unification of known interactions, an underlying cause of electroweak symmetry breaking, origin of families, fermion masses and Yukawa couplings in the Standard Model, an asymmetry between visible matter and anti-matter, nature of dark matter, role of gravity and its connection to other known interactions etc.

It is well known that progress in addressing these questions has been quite slow and, clearly, not for the lack of trying. However, continuous attempts to study them challenge experimental and theoretical status quo in particle physics, and push the scientific frontier into unchartered territories. As the result, cases are often encountered where things do not work as expected and where tensions between theoretical expectations and experimental results become obvious. Although we often refer to such cases as the "anomalies", they are perhaps better viewed as the "growing pains" needed to get to a new level of understanding of fundamental laws of Nature. And, in spite of the fact that, time and again, a better mastery of the Standard Model, rather than the discovery of physics beyond it, emerges as the result of painstaking investigation of the anomalies, steady progress that is driven by points of content in particle physics is not to be overlooked.

Current anomalies in particle physics naturally became the focus points of the conference, with flavor anomalies, lepton non-universality and the muon anomalous magnetic moment dominating the discussion. In addition, we heard about new theoretical developments in QCD, an interplay between precision physics at the LHC and searches for physics beyond the Standard Model, as well as complex aspects of QCD dynamics. I will briefly review all the different theoretical talks delivered at the QCD Moriond 2022 starting with the discussion of the muon magnetic anomaly.

2 Muon magnetic anomaly

The puzzle of the muon anomalous magnetic moment has been with us for more than twenty years by now[1] and recently significant, $\mathcal{O}(4\sigma)$, discrepancy between theoretical predictions[2] and experimental measurements[1] has been confirmed by the first result[3] of the FNAL experiment. The difference between measured and expected values $a_\mu^{\text{th}} - a_\mu^{\text{exp}} = 251(59) \times 10^{-11}$ is quite large. In fact, it is a factor of two larger than the four-loop QED contribution to a_μ, more than fifty percent larger than the one-loop electroweak contribution to a_μ and is about twice as large as the so-called hadronic light-by-light scattering contribution to a_μ. On the contrary, it is just about 3.5 percent of the hadronic vacuum polarization contribution to a_μ, making good understanding of a_μ^{hvp} a very important issue.

Given the many existing checks of the QED and electroweak contributions as well as obvious difficulties with the theoretical description of low-energy hadron physics, current work on resolving the discrepancy focuses on the hadronic vacuum polarization and on the hadroninc light-by-light scattering contributions to the muon magnetic anomaly. Although these two hadronic contributions are mentioned in a single sentence, they are actually quite different. Indeed, as noted above, the hadronic vacuum polarization contribution is large and needs to be known to a few-percent precision whereas the hadronic light-by-light scattering contribution is rather small and knowing it to about twenty percent precision is sufficient. This difference between the two hadronic contributions is reflected in the way they are currently dealt with and discussed.

Let us start with the hadronic vacuum polarization. For the past sixty years, the standard way to compute it was to use the dispersion representation for the vacuum polarization function relating it to the measured cross section of e^+e^- annihilation to hadrons. Using experimental data for $\sigma(e^+e^- \to \text{hadrons})$, the dispersion integral is calculated numerically leading to a precise result for the hadronic vacuum polarization contribution to the muon magnetic anomaly. This standard approach was discussed in great detail by Zhang[4].

Although there are various caveats and difficulties related to the computation of the dispersion integral, including reliability of data, consistency between various experiments and treatment of radiative corrections, understanding its oder-of-magnitude is quite straightforward[5]. Indeed, all one needs to do is to account for three lightest spin-one hadronic resonances ρ, ω and φ in the dispersion integral treating them as narrow peaks with known masses and branching ratios to leptons. Supplementing their contribution to the dispersion integral with a continuum contribution to accommodate physics beyond the center-of-mass energy of $\mathcal{O}(1)$ GeV, one obtains the result[5] that accounts for about *ninety percent* of a_μ^{hvp}.

Of course, the problem with the hadronic vacuum polarization contribution is that it is so large ($a_\mu^{\text{hvp}} \approx 7000 \times 10^{-11}$), that knowing it to ninety percent is insufficient. To match the current experimental uncertainty, we need to understand it to better than a percent and reaching this precision is very challenging. Figuring out how to do this in a controllable way was the focus point of the practitioners of the dispersion-relations method in the past; these efforts were reviewed by Zhang[4]. In fact, in spite of a few open questions and tensions (e.g. KLOE data vs. BABAR data), it does appear that *no* foreseeable modification of either data or analysis methodology can shift a_μ^{hvp} beyond the estimated uncertainty ($\sim 40 \times 10^{-11}$)[4].

However, although the most precise results for the hadronic vacuum polarization were traditionally obtained with the help of dispersion relations and experimental data, the situation has changed in the past few years. Indeed, in 2020 the BMW collaboration published a lattice computation of the hadronic vacuum polarization contribution to the muon magnetic anomaly which is claimed to have a sub-percent precision. This calculation was presented by Szabo[6]. In a remarkable twist of fortunes for SM physics, the new calculation is about 140×10^{-11} larger, than estimates of the hadronic vacuum polarization obtained with the dispersive method and, although this shift represents just about 2% of the total hadronic vacuum polarization contri-

bution to the muon magnetic anomaly, it wipes out more than 50 percent (!) of the discrepancy between theory and experiment reducing it to a meager $\mathcal{O}(2\sigma)$. Hence, if correct, this result will be responsible for the major change in the muon magnetic anomaly story, forcing a prospective "harbinger of New Physics" to become "a poster child of the Standard Model".

However, we are not there yet since at this point there is no reason to trust the new lattice computation more than the results of the dispersive approach. The challenge, therefore, is to understand where and why the discrepancy between these two very different computations comes from. This question can be addressed in several ways. First, the result of the BMW collaboration should be confirmed or refuted by other lattice collaborations and this applies to both the central value and the uncertainty estimate. Second, lattice and dispersive computations need to be compared. This is not easy because lattice operates in the Euclidean space and, therefore, $\sigma(e^+e^- \to \text{hadrons})$ cannot be computed on the lattice. However, it is clearly possible to compute various *moments* of the hadronic vacuum polarization function using both the dispersion method and lattice QCD, and to construct these moments in such a way that contributions of particular energy intervals are strongly emphasized. If such a comparison is performed systematically, it should allow us to eventually pinpoint the energy intervals that are resposible for the discrepancy. This will be the most welcome development because such an understanding will have important implications beyond the muon magnetic anomaly. For example, both lattice and dispersive methods can be used to compute the fine structure constant $\alpha(M_z)$ whose value is highly relevant for the precision electroweak fit.

Another contribution to the muon magnetic anomaly which for a long time was considered to be the main "troublemaker" is the hadronic light-by-light scattering contribution. One of the main reasons it got this status was a sudden change in the *sign* of this contribution that led to its dramatic, overnight increase[7] from $\mathcal{O}(-100) \times 10^{-11}$ to $\mathcal{O}(+100) \times 10^{-11}$. Although the sign issue was later clarified to be an isolated incident which, at its core, proves that the FORM manual[8] is not an exciting read, the mistrust towards this contribution remained.

However, it has to be recognized that *already* since 2002 the hadronic light-by-light scattering contribution has been estimated to be close to 100×10^{-11}, with an uncertainty of about 20×10^{-11}, which is about a half of the estimated uncertainty in a_ν^{hvp} as discussed above. The point of view that the hadronic light-by-light scattering contribution is actually fairly well understood was presented in the talk by J. Green[9] who discussed the new lattice computation of a_μ^{hlbl}. Their result, $a_\mu^{\text{hlbl}} = 106(16) \times 10^{-11}$, is in agreement with many earlier estimates of this quantity obtained using a variety of phenomenological method. And, as a further illustration of the remarkable consistency of theoretical predictions for a_μ^{hlbl}, I cannot help but mention that its central value is identical to the result[10] of the so-called "Glasgow consensus" by J. Prades, E. de Rafael and A. Vainshtein, published already in 2009.

I would like to emphasize that the new lattice result reported in Green's talk[9] is very important as it provides further support to an understanding, that has been emerging for several years by now, that presumptive lack of theoretical control of the the hadronic light-by-light scattering contribution to the muon $g-2$ cannot be the *only* reason for the discrepancy of the muon magnetic anomaly. Whether the a_μ puzzle will eventually be resolved by a big problem in a_μ^{hvp}, or by a collection of small(ish) deviations in a_μ^{hvp}, a_μ^{hlbl} and in the experimental value of a_μ which all work just in the right way, or by a New Physics contribution, is impossible to say now and remains to be clarified in the future.

3   Flavor physics

Given the fact that some of the most persistent and unusual discrepancies between theoretical expectations and experimental results currently occur in flavor physics, talks on flavor physics were an exciting part of the conference. The discussion of flavor physics started with an overview talk on the current status of the anomalies by M. Neubert[11]. Clearly, as with any anomaly, a

proper evaluation of the situation requires good understanding of the quality of the Standard Model predictions, ideas about a possible explanation of the observed discrepancies by New Physics and a good overview of how such ideas fit into a global picture of checks of the Standard Model.

Two talks at the conference addressed the quality of the SM predictions in B-physics. Capdevila reported[12] a refined extraction of the CKM matrix element V_{cb} from inclusive semileptonic B-decays into final states with charm quarks. The refinement described by Capdevila comes from the inclusion of the recent N3LO QCD calculation of the partonic rate for $b \to c$ transition[13] into a theoretical prediction for $B \to X_c l \nu_l$ decay rate computed within the heavy quark expansion. If the N3LO QCD corrections are included into the analysis, the central value of V_{cb} remains practically unchanged when compared to an earlier NNLO QCD analysis, but the uncertainty in the extracted value is reduced by about twenty five percent.

This is both good and bad news. It is a good news because it shows that the extraction of V_{cb} from inclusive B-decays is theoretically robust. However, it is also a bad news because it leaves the discrepancy between exclusive and inclusive V_{cb} measurements unchanged, at the level of one to three standard deviations.

Gubernari[14] discussed the Standard Model predictions for the exclusive B decays into a strange meson (K, φ) and a lepton pair. Making accurate predictions for *exclusive* decays is difficult in general; in case of $B \to K l^+ l^-$ and $B \to \varphi l^+ l^-$ decays , the problem is enhanced because of the so-called charm loop contributions that are notoriously difficult to treat reliably. By using a clever combination of the operator product expansion and dispersion relations, Gubernari showed how to derive upper bounds on these complicated amplitudes. However, even after this theoretical refinement, the significant tension between the SM predictions and experimental measurements remains. In particular, is does not appear that a large discrepancy between measured and expected values observed in the distribution of the so-called P_5 observable can be attributed to the deficiencies of the SM predictions.

Given that the Standard Model predictions seem to be robust, it is important to discuss flavor anomalies from the perspective of beyond the Standard Model (BSM) physics. There were four theoretical talks on this subject and the unified message of these talks was that these anomalies can certainly be early manifestations of New Physics which, so far, could have avoided detection at the LHC in spite of the incredible amount of data collected there during the first two runs. This is a reassuring message that emphasizes the complementarity of different ways to probe Nature and the importance of low-energy physics as a path finder for the LHC.

The four talks on the BSM explanation of flavor anomalies showed that there are many different ways to accommodate them in a consistent framework. Allanach presented a particular Z' model[15] that explains lepton non-universality, does not (significantly) spoil precision electroweak fit and is practically unconstrained by the current searches for Z''s at the LHC. Iguro [16] pointed out that, due to relaxed constraints from the decay $B_c \to \tau \nu$, the charged-Higgs explanation of the R_{D^*} anomaly becomes possible and, if the charged Higgs boson is relatively light 140 GeV $< m_{H^-} <$ 400 GeV, there is no contradiction with the current LHC bounds. He then noted that this explanation of the R_{D^*} anomaly can be tested at the LHC already with the existing data provided that one uses the production of the Higgs boson in association with a b-jet, $g \bar{c} \to H^-(\tau \nu_\tau) b$, to suppress the large background from the Drell-Yan process $pp \to \tau \nu_\tau$.

Boussejra[17] pointed out that SUSY models with non-minimal flavor violation can also explain flavor anomalies without getting into a conflict with other precision observables and the negative results from LHC searches. Finally, Crivellin[18] emphasized the importance of taking a high-level view on flavor and related anomalies since many of them can actually be linked to each other within BSM models. To illustrate this point he presented a model that simultaneously explains the so-called Cabibbo anomaly, the old $Z \to b\bar{b}$ anomaly and the $\tau \to \mu \nu \nu$ anomaly which, at first sight, do not need to be related.

It is well-known that B-physics observables are computed starting from an effective Hamil-

tonian which involves effective operators weighted with their Wilson coefficients. These Wilson coefficients have particular values in the Standard Model, so that many of the flavor anomalies can be thought of as differences in their measured and expected SM values. To explain an anomaly with a BSM theory, it is essential to re-compute the Wilson coefficients of operators in the effective Hamiltonian in a new theory. Although it is very well understood how to do this, the bookkeeping is challenging. Santiago presented a tool, dubbed Matchmaker, which allows one to automatically compute the Wilson coefficients by matching new BSM theory to an effective field theory through one-loop [19]. One can hope that the availability of such a tool will be helpful for further exploration of the theory space using experimental data on B-decays.

4   Dark matter

Dark matter was not the major focus of the QCD Moriond, but there were several talks on this exciting topic. White described [20] a comprehensive global fit for a Dirac fermion dark matter, that also showcased impressive capabilities of the GAMBIT program [21]. White's message was that although significant parts of the parameter space can be excluded, the Dirac DM is still a viable option.

Rolbiecki pointed out [22] that it is possible to use the monojet signature to improve constraints on electroweakino dark matter in a situation where mass splittings between electroweakinos are small. A standard experimental analysis to explore such a scenario employs the monojet signature. However, as Rolbiecki explained, stronger constraints are obtained by recasting searches for squarks and gluinos, where "jets + missing energy" signatures are also studied, into bounds on the electroweakino DM.

Finally, Ruderman [23] described a new mechanism of how the dark matter density can be generated in the early Universe. He pointed out that, in case there is an interaction term in the Lagrangian between three dark matter particles and one Standard Model particle, a new collision term appears in the Boltzmann equations that forces DM density to grow exponentially. This new mechanism changes the famous relation between the DM equilibrium density and the annihilation cross section between dark matter particles, so it is useful to be aware of the fact that there are cases where such a relation does not hold and a very different mechanism for producing the DM density is at play.

5   Collider physics

Development of theoretical methods that can be used to describe hard scattering processes at colliders has accelerated in recent years [24]. In particular, the appearance of robust subtraction and slicing schemes for higher-order perturbative computations, as well as advances in technologies for computing multi-loop amplitudes, resulted in a number of impressive results for basic collider processes obtained recently. Some of these results were presented at QCD Moriond.

Perhaps the best-known process that occurs at a hadron collider is the Drell-Yan process $pp \to l_1 l_2 + X$. Depending on the final state, it is facilitated by a neutral or by a charged current. Studies of the Drell-Yan processes are very important for the LHC phenomenology; they include such physics topics as properties of Z and W bosons, parton distribution functions, calibration of the detectors, searches for BSM physics and more.

It is therefore not surprising that theoretical studies of these processes are extremely advanced. Just *how* advanced they are became evident from the three talks on the cutting-edge computations of higher-order perturbative corrections to the Drell-Yan process. Yang [25] described the calculation of N3LO QCD corrections to the rapidity distribution of a vector boson, while Rottoli [26] presented a computation of fiducial cross sections of the Drell-Yan processes at the same perturbative order. Finally, Buonocore [27] discussed the calculation of mixed QCD-electroweak corrections to the neutral-current-mediated dilepton production both at the reso-

nance and in the high-invariant mass region of a dilepton pair. The bottom line of these tour de force computations seems to be that various observables in the Drell-Yan process can be described with an astounding precision of about 1-2 percent.

It is worth pointing out that N3LO QCD corrections to observables in the DY processes turned out to be not much smaller than the NNLO QCD ones[25,26] and, therefore, larger than expected. This fact was already noted when calculations of N3LO QCD corrections to the total cross sections of Z and W production at the LHC appeared[28,29]. The explanation of *why* this happens is probably multi-facet. At least partially, it may be attributed to the fact that NNLO QCD corrections to the Drell-Yan processes are probably smaller than they should be because of accidental cancellations between contributions of different partonic channels. Another reason can be that parton distribution functions at N3LO QCD are not yet known.

Clearly, it is important to go beyond admiring the technical wizardry behind these computations and to figure out how to use higher precision of theoretical predictions to learn more about physics. Although full appreciation of the opportunities that the new results[25,26,27] open up is still to come, first glimpses of what can be expected could already be seen at the conference. For example, Schott[30] pointed out that a very competitive value of the strong coupling constant, $\alpha_s(m_Z) = 0.1185 \pm 0.0015$, can be obtained from the transverse momentum spectrum of the Z bosons. In fact, Schott's analysis does not include all available perturbative corrections to the Z-boson transverse momentum distribution so that, in principle, it can be be further refined if necessary.

Another interesting opportunity, described by Scimemi[31], is to use data on the Drell-Yan process, together with high-precision theoretical predictions, to extract transverse-momentum dependent (TMD) parton distribution functions. These functions are needed to descirbe the $p_\perp$-distribution of a vector boson at very low $p_\perp$ where tiny transverse momenta of colliding quarks cannot be neglected. Scimemi pointed out that because of the factorization theorems, there is an intimate relation between TMD PDFs and regular PDFs which implies that any uncertainty intrinsic to collinear PDFs gets transferred to an uncertainty in TMD PDFs. He also argued that it is very important to account for flavor dependences of TMD PDFs in the global fit and that if one does that, the consistency of TMD PDFs extracted from various data sets significantly increases.

It is intuitively clear that the availability of more precise SM results should allow for stronger constrains on BSM contributions to basic hard processes such as Drell-Yan, and Giuli[32] described an example of this in his talk. He considered the case of a heavy and relatively broad resonance contributing to the dilepton spectrum and pointed out that it is difficult to detect it using conventional bump-hunting methods. He then pointed out that one can observe shape modifications in the dilepton invariant mass distribution caused by a broad resonance provided that there is a good control of parton distribution functions at high values of the Bjorken x, and that high-precision QCD predictions for the dilepton invariant mass spectrum are available. He argued that by including data on the charge asymmetry and the forward-backward asymmetry into a simultaneous fit for high-x parton distribution functions and a prospective resonance contribution to the dilepton invariant mass spectrum, reach for broader and heavier resonances improves.

LHC physics requires good understanding of final states with QCD jets and there were a few talks at QCD Moriond that described recent advances in this endeavor. Poncelet reported[33] on a computation of NNLO QCD corrections to 3-jet production at the LHC. This is a very impressive result that further highlights an enormous technical progress that occurred in the field of perturbative QCD in recent years. Without a doubt, this tour de force calculation, one of the most complicated calculations in perturbative QCD ever performed, will find many phenomenological applications in the future, including the determination of the strong coupling constant and refined studies of jet dynamics.

Definition of jets requires certain prescriptions to combine energies of various particles into

directional energy flows; these prescriptions are known as "jet algorithms". Over time jet algorithms evolved[34] from experimentally-convenient but theoretically-problematic seed cone algorithms to modern ones, such as e.g. the anti-$k_\perp$ algorithm, which is practically impeccable from both the experimental and theoretical points of view. However, even if a great solution is available, one can always try to do better. In this spirit, Cerro discussed[35] a new algorithm for clustering hadrons into jets based on machine learning methods. A few examples were shown which demonstrated that in certain cases the new algorithm outperforms the conventional ones. It is clear that many more studies are needed before this algorithm will get close to becoming as widely accepted as the anti-$k_\perp$ one, but it will be interesting to watch how this story develops further.

Dreyer[36] discussed resummation of the so-called non-global logarithms for QCD observables at lepton colliders. Non-global logarithms represent a particular class of enhanced contributions to observables that appear if radiation to certain phase-space regions is restricted. The problem of the resummation of non-global logarithms is known to be rather difficult but significant simplifications occur if it is studied in the large-N_c limit. In fact, in this case, resummation of non-global logarithmic contributions at next-to-leading-logarithmic accuracy can be performed using a relatively simple extension of the so-called Banfi-Marchesini-Smye equation[37]. Progress with the understanding of non-global logarithms and their resummation reported by Dreyer is a welcome development since it is essential for designing parton showers with the next-to-next-to-leading logarithmic accuracy.

We now change gears and talk about physics of top quarks which was also discussed in theoretical talks at Moriond QCD. Top quark physics is a big part of the LHC research program since the LHC is a top quark factory. This fact enables detailed studies of various processes with top quarks, including searching for possible contributions of physics beyond the Standard Model, and the exploration of top quark properties.

Jezo[38] pointed out that *off-shell* contributions to signatures that are used to identify top quark pair production and study top quark properties may be important. Although the importance of these contributions – or lack of it – must depend on details of experimental analyses, there is a theoretical aspect that is worth emphasizing. Indeed, the development of computational methods during the past decade resulted in a situation where, for many processes, it is more straightforward (if not simpler) to provide predictions for $pp \to bWbW + X$ final states than to split them into double-resonant, single-resonant and non-resonant contributions. This fact further implies that the relative importance of various contributions, including signal-background interference etc., are decided by experimental constraints imposed on a *single* theoretical calculation, and do not require complex, poorly justified constructions that were used earlier to combine the different contributions.

However, it is not always possible to pursue this program since for certain final states complete computations remain too complicated even with modern methods. According to Jezo, this happens when W-bosons in top decays are allowed to decay *hadronically*. To make progress, Jezo proposed to consider *on-shell* W-bosons since in the $\Gamma_W \to 0$ limit decay products of W-bosons cannot interact with other parts of the process by QCD exchanges. Because of this, a connection between corrections to fully-leptonic and semileptonic signatures in the off-shell $t\bar{t}$ production process arises and the computation of QCD corrections in the semileptonic case simplifies enormously.

Devoto discussed a calculation of the $t\bar{t}$ pair production at the LHC with the NNLO QCD accuracy[39]. So far this calculation is performed for stable top quarks and in this limit it confirms earlier pioneering computations of Czakon et al.[40]. This is a strong check on both calculations because Devoto's calculation employs a different method to combine separately-divergent real emission contributions and virtual corrections. Another interesting point mentioned by Devoto is that this computation will become part of a new release of a publicly-available program MATRIX[41] which is quite useful since so far there is no public program for calculating kinematic

distributions for top quark pair production in hadron collisions with the NNLO QCD accuracy.

I believe that when a typical participant of QCD Moriond thinks about measurements of the top quark and the Higgs boson masses, collider, rather than cosmological, aspects of this problem come to mind. However, it is well known that the precise knowledge of these masses has very important implications for the stability of electroweak vacuum[42]. Santos[43] reminded us about this connection in his talk, albeit in a slightly different context. He pointed out that under certain circumstances uncertainties in m_t and m_H may preclude an interpretation of the signal of gravitational waves that originate in the course of the first-oder phase transition in the early Universe. Santos' observation provides yet another motivation for measuring the top quark mass more precisely and advanced theoretical predictions for top quark production cross sections and kinematic distributions play a particular important role in this endeavor.

We have seen yet another example of the creative use of high-precision theory in a talk by Altakach[44] where he discussed a possibility to constrain BSM physics by comparing fiducial cross sections with high-precision predictions for signals and backgrounds. He considered a particular model of New Physics where a Z' boson couples to quarks of the first and the third generations but not to leptons. This Z' is also relatively broad so that it is not possible to discover it by searching for a peak in the $t\bar{t}$ invariant mass distribution. Altakach showed that by improving theoretical predictions for the signal process and the various backgrounds, one indeed obtains better bounds on the Z' mass. However, these bounds are still somewhat worse[44] than the bounds on the parameters of this model that are obtained from dedicated experimental searches, presumably because kinematic information, rather than just fiducial cross sections, is used there.

Moving beyond the top quark physics, Neuwirth[45] reported on a study of NLO QCD corrections to squark-gaugino production at the LHC supplemented with the soft gluon resummation. He showed that the soft-gluon resummation, consistently combined with the NLO QCD computation, increases the cross section by about six percent and reduces the QCD scale uncertainty to about 5 percent. Hopefully these results will be used to further constrain the parameter space of supersymmetric models or, perhaps, help to infer properties of squarks and gauginos if they are finally discovered.

6   Parton distribution functions

Predictions for hadron collider physics are impossible without knowledge of parton distribution functions (PDFs). Learning about them requires complicated machinery that is usually managed by highly-specialized collaborations. Two theoretical talks on the issue of PDFs' extractions which addressed unorthodox aspects of PDF physics were presented at Moriond.

Magni[46] argued that LHCb data on Z+charm production show evidence of non-perturbative component of the charm PDF in the proton. This, of course, is an interesting result; discussions about whether or not there is an "intrinsic charm" in the proton have been going on since quite a long time[47] so that a confirmation of this idea would be illuminating. However, at this point it does not appear that a decisive conclusion about this matter is possible since the evidence is rather weak, about one sigma[46]. Moreover, the non-perturbative component by itself is not large; according to the analysis by Magni[46] the intrinsic charm carries about one percent of the proton momentum and (not surprisingly) the intrinsic-charm PDF is peaked at the large x-values. Given all that, it can be expected that reaching a definite verdict on the issue of the intrinsic charm in the proton will probably be difficult, but it is quite interesting that there are attempts to make progress in that direction.

Bertone[48] discussed uncertainties in the extracted value of the strong coupling constant and parton distributions due to the imprecise knowledge of the anomalous dimensions and β-functions as well as simplifications made in the renormalization group equations that allow one to solve them analytically. Bertone finds that if PDFs are defined at low scales and then computed

at an electroweak scale by solving Altarelli-Parisi equations, such truncations may lead to errors of a few percent. To be sure, percent-level uncertainties in PDFs are not unheard of but it is clearly important to identify *all* sources of such uncertainties including pure theoretical ones.

7 Unorthodox topics

Often, it is not too difficult for an experienced person to predict topics which will be discussed at a conference dedicated to QCD and high-energy interactions. This is a reflection of the fact that the scientific progress is continuous, at least most of the time. However, at every conference there are a few talks beyond the expected narrative and such talks often become some of the most interesting ones simply because they are unexpected. A number of such talks were presented at QCD Moriond this year.

Zanderighi[49] pointed out that one can find many things in the proton, including leptons and photons. In a way, this observation should extend the notion of the complimentarity of lepton and proton colliders – those of us who thought that LHC was colliding quarks and gluons will probably have to think again! Of course, the fact that one can find electrons or photons in a proton is not very surprising since, rhetoric aside, one simply talks about high-order QED processes. What is perhaps unexpected is that *rates* of such processes are strongly enhanced because of the kinematics of the quasi-collinear splittings. The result of such an enhancement is that effects that could have been neglected completely become somewhat relevant and can often be best described by using the notion of distribution functions of leptons and photons in a proton.

Zanderighi explained[49] that one can determine photon and lepton PDFs from the known structure functions measured in deep-inelastic scattering, and use this information to set up theoretical description of QED-initiated processes retaining full information of the events' kinematics, which is important for the LHC physics. She also showed a few examples where presence of leptons and photons in the proton becomes somewhat of a game changer. For example, a significant lepton component of the proton leads to additional contributions to leptoquark production in proton proton collisions, and sometimes these contributions are large enough to affect the exclusion limits in a significant way[49].

Schott[30] proposed to search for instantons at the LHC. Instantons are QCD field configurations that describe a transition between two non-equivalent QCD vacua. It is expected that the instanton-production process can manifest itself through a production of a spherically-symmetric multi-particle final state with certain polarization features of final-state partons. Unfortunately, it is very difficult to predict the production cross section for instantons in hadron collisions and it is also hard to say if imprints of quark polarization can be observed in features of mesons and baryons that are actually measured. At any rate, this unorthodox proposal is quite interesting and it clearly provides a new motivation for many people[51] to think about an old problem, namely how to observe quasi-classical solutions, present in non-abelian gauge theories, experimentally.

Tantary[50] described a perturbative calculation of a free energy in $N = 4$ SUSY Yang-Mills theory. Interestingly, this computation can be used to reconstruct the exact free energy function since in this theory the free energy can also be computed in the non-perturbative regime using gauge-gravity duality. Extrapolating between perturbative and non-perturbative regimes can be done using Pade approximation. Higher-order perturbative computations, performed by Tantary, show convergence towards the Pade result constructed using the information at lower orders. Hence, we have an example of a theory where the free energy is known *exactly*, for any value of the strong coupling. It is an interesting question what, if anything, can be learned from this result for thermodynamics of QCD plasma; at this point, I don't think there are clear ideas about this.

8 The future

It is peculiar that the *very first theoretical talk* at QCD Moriond provided an outlook on the future of collider physics [52]. Perhaps, this simply shows how urgent this matter is, as multi-decade planning for future facilities is a commonplace in particle physics. Given this, it is important to ask how to optimize the process of moving forward and to obtain the richest outcome in terms of physics in the shortest amount of time. Franceschini [52] provided many instructive examples and interesting considerations comparing the physics reach of different colliders that are being discussed as potential successors to the LHC.

Acknowledgments

References

1. G.W.Bennett *et al.*, *Phys. Rev.* D **73**, 072003 (2006).
2. T. Aoyama, N. Asmussen, *et al. Phys. Rept.* **887**, 1 (2020).
3. B. Abi *et al.*, *Phys. Rev. Lett.* **126**, 141801 (2021).
4. Z. Zhang, these proceedings.
5. K. Melnikov and A. Vainshtein, Theory of the muon anomalous magnetic moment, *Springer Tracts Mod. Phys.* **216**, 1 (2006).
6. K. Szabo, these proceedings.
7. M. Knecht, A. Nyffeler, M. Perrottet and E. de Rafael, *Phys. Rev. Lett.* **88**, 071802 (2002).
8. See https://www.nikhef.nl/~form/maindir/documentation/reference/man.pdf
9. J. Green, these proceedings.
10. J. Prades, E. de Rafael and A. Vainshtein, *Adv. Ser. Direct. High Energy Phys.* **20**, 303 (2009).
11. M. Neubert, these proceedings.
12. B. Capdevila, these proceedings.
13. M. Fael, K. Schönwald and M. Steinhauser, *Phys. Rev.* D **104**, 016003 (2021).
14. N. Gubernari, these proceedings.
15. B. Allanach, these proceedings.
16. S. Iguro, these proceedings.
17. M. Boussejra, these proceedings.
18. A. Crivellin, these proceedings.
19. J. Santiago, these proceedings.
20. M. White, these proceedings.
21. P. Athron *et al.* [GAMBIT], *Eur. Phys. J.* C **77**, 784 (2017).
22. K. Rolbiecki, these proceedings.
23. J. Ruderman, these proceedings.
24. G. Heinrich, *Phys. Rept.* **922**, 1 (2021).
25. T. Yang, these proceedings.
26. L. Rottoli, these proceedings.
27. L. Buonocore, these proceedings.
28. C. Duhr, F. Dulat and B. Mistlberger, *JHEP* **11**, 143 (2020).
29. C. Duhr, F. Dulat and B. Mistlberger, *Phys. Rev. Lett.* **125**, 172001 (2020).
30. M. Schott, these proceedings.
31. J. Scimemi, these proceedings.

32. F. Giuli, these proceedings.
33. R. Poncelet, these proceedings.
34. G. Salam, *Eur. Phys. J* C**67**, 637 (2010).
35. G. Cerro, these proceedings.
36. F. Dreyer, these proceedings.
37. A. Banfi, G. Marchesini and G. Smye, *JHEP* **08**, 006 (2002).
38. T. Jezo, these proceedings.
39. S. Devoto, these proceedings.
40. M. Czakon, D. Heymes and A. Mitov, *Phys. Rev. Lett.* **116**, 082003 (2016).
41. M. Grazzini, S. Kallweit and M. Wiesemann, *Eur. Phys. J.* C **78**, 537 (2018).
42. See e.g. G. Degrassi *et al.*, *JHEP* 1208, 098 (2012).
43. R. Santos, these proceedigns.
44. M. Altakach, these proceedings.
45. A. Neuwirth, these proceedings.
46. G. Magni, these proceedings.
47. S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, *Phys. Lett.* B **93**, 451 (1980).
48. V. Bertone, these proceedings.
49. G. Zanderighi, these proceedings.
50. U. Tantary, these proceedings.
51. Many of these issues were discussed at a recent workshop at CERN, see https://indico.cern.ch/event/965112/ for more details.
52. R. Franceschini, these proceedings.