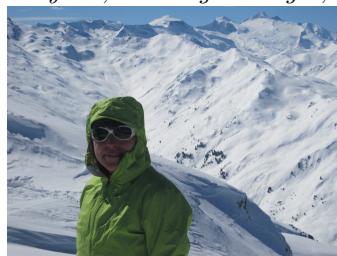


QCD AND HIGH ENERGY INTERACTIONS: MORIOND 2018 THEORY SUMMARY

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The highlights of the theory developments presented at the Rencontres de Moriond 2018 on QCD and High Energy Interactions are summarised and put into perspective.

1 Introduction

With the wealth of new experimental results presented at Moriond 2018 and still to come, theorists have to keep up with the increasing experimental precision, offer interpretations of the data, come up with new ideas how to probe the Standard Model and think ahead what could be beyond and how it could be tested. All these points have been addressed in many exciting talks, reflecting the current situation in particle physics from the QCD side, whose understanding in all aspects is of great importance, both in its own right and also in order to tell apart New Physics from QCD effects.

2 Higgs Physics and precision calculations

As the excitement about the Higgs boson discovery is ebbing away, we should not forget that we are just at the beginning of our exploration of the Higgs sector. The fact that the Higgs boson so far looks pretty Standard-Model-like means that higher order corrections in the Higgs sector are extremely important in order to establish that small deviations from the Standard Model (SM) predictions are indeed signs of New Physics. Therefore Higgs physics and precision calculations are closely related. As Keith Ellis¹ put it, new results in the Higgs sector are “guaranteed deliverables”, and therefore it should be our primary goal to scrutinise the Higgs sector, in particular get a handle on the Higgs couplings to light SM particles, the total and partial widths, invisible decays and the trilinear Higgs coupling. He also presented a comparison of various future collider options and put it into perspective for the upcoming European Particle Physics Strategy document.

An update on available predictions and their uncertainties for Higgs boson production and decay was given by Michael Spira². While for inclusive Higgs boson production the theoretical uncertainties nowadays are rather well under control^{3,4,5}, this was less the case for the Higgs

boson transverse momentum. Important progress on this subject was presented at Moriond 2018. Luca Rottoli reported on results^{6,7} based on momentum space resummation at N³LL, matched to NNLO in the heavy top limit, for the Higgs boson p_T spectrum, see Fig. 1(a). The same procedure also has been used to produce predictions at this level of precision for the Drell-Yan process, and the method allows to resum entire classes of observables. Results for the Higgs boson transverse momentum spectrum at N³LL, matched to NNLO also have been presented very recently in Ref.⁸. However, the heavy top limit is not a good approximation in the p_T -range where the energy is sufficient to resolve the top quark loops. Therefore the prediction of the Higgs boson p_T -spectrum at NLO with full top quark mass dependence was much in demand, and has been presented by Matthias Kerner⁹, showing that the full result differs from the NLO result in the heavy top approximation by about 9% at total cross section level¹⁰. The full top quark mass dependence significantly alters the tail of the $p_{T,H}$ -distribution, as can be seen from Fig. 1(b). Note that the top-bottom interference effects for Higgs+jet at NLO are also available¹¹.

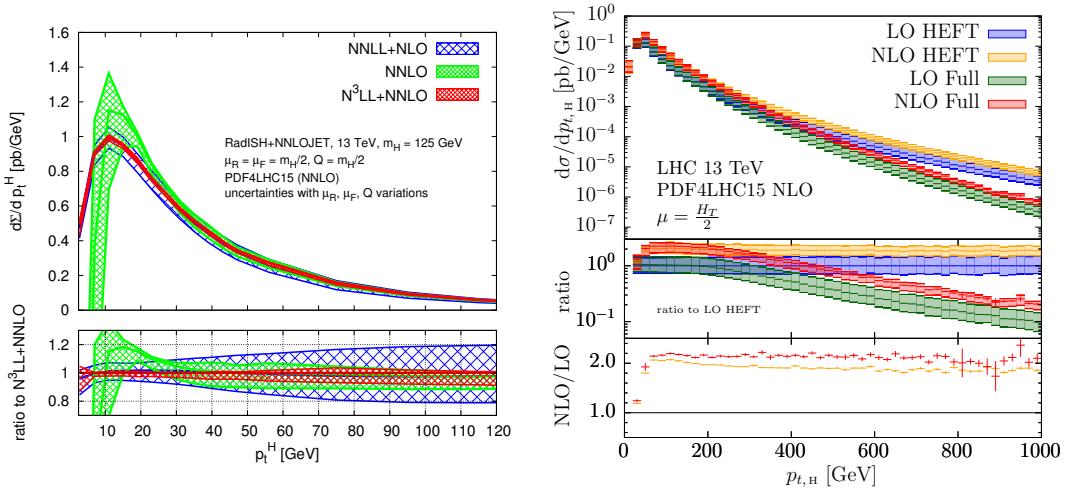


Figure 1 – Left: comparison of the transverse momentum distribution for Higgs boson production at NNLO and N³LL+NNLO, NNLL+NLO, and NNLO for a central scale choice of $\mu_R = \mu_F = m_H/2$. Right: Higgs boson transverse momentum spectrum at LO and NLO QCD in the $m_t \rightarrow \infty$ limit (HEFT) and with full top-quark mass dependence. The upper panel shows the differential cross sections, the middle panel the ratio to the LO HEFT prediction, the lower panel the differential K-factors for both the HEFT (orange) and the full theory (red).

Precision calculations within models suggesting an extended Higgs sector, for example the Two-Higgs Doublet Model, are important for BSM searches. Stefan Dittmaier reported on a calculation of NLO electroweak and QCD corrections to the decay $h \rightarrow WW/ZZ \rightarrow 4$ fermions of the light CP-even Higgs boson within various types of Two-Higgs-Doublet Models, available in Prophecy4f^{12,13}, comparing also various renormalisation schemes.

Certainly, model independent approaches to the search for non-SM phenomena in the Higgs sector are also very important, and many creative ideas, also including deep learning algorithms, are emerging rapidly these days. For example, optimisations of measurements in the Higgs sector based on information geometry, was presented by Felix Kling^{14,15}.

3 Perturbative QCD at work

In the discussion session with the title “Where is New Physics?” the question was raised how well “QCD backgrounds” are under control. The answer is: better and better! At Moriond 2018, the record of loops+legs was held by Ben Ruijl (5 loops, 2 legs) and Ben Page (5 legs, 2 loops). Ben Page presented results for planar 2-loop 5-gluon amplitudes^{16,17}, obtained by numerical

unitarity and finite field reconstruction, thus using a method which may replace standard two-loop reduction methods at some point.

Ben Ruijl¹⁸ presented a generalised R^* operation¹⁹ to extract pole parts from multi-loop Feynman graphs with numerators, which has been worked out in order to calculate the 5-loop β -function²⁰. He also showed results for Higgs decays to gluons at N^4LO ²¹, which reduce the scale uncertainties by almost a factor of 4 compared to N^3LO , such that the uncertainties due to the truncation of the perturbative series now play a sub-leading role in $\Gamma_{H \rightarrow gg}$ compared to other effects (e.g. top mass effects, α_s).

Fabrizio Caola²² reported about an efficient method to handle infrared divergent real radiation at NNLO, called “nested soft-collinear subtraction”²³, which has been used to calculate $pp \rightarrow WH, H \rightarrow b\bar{b}$ at NNLO²⁴. Large corrections have been found at NNLO in regions which are not populated by LO, as well as interesting effects related to the fact that the b -quark is treated as massless.

Rhorry Gauld presented a study of the angular coefficients which parametrise the angular dependence of the decay to leptons in Z -boson production at NNLO^{25,26}, based on a calculation of $Z + X$ in the NNLOJET framework²⁷. These coefficients have been measured and a tension with previous predictions has been observed for $A_0 - A_2$. It turned out that NNLO is necessary to describe the data.

David d’Enterria revisited the forward-backward asymmetry of b -quarks in $e^+e^- \rightarrow Z(\rightarrow b\bar{b})$, asking the question whether the large (2.8σ) discrepancy between data and theory predictions in $A_{FB}^{0,b}$, determined at LEP times, persists if the QCD uncertainties are re-assessed with modern simulation tools²⁸. Interestingly it turns out that the QCD uncertainties are overall slightly smaller but still consistent with the original ones.

4 PDFs, non-perturbative QCD and Spectroscopy

Cranking up the orders in perturbative QCD is useful only if the gain in precision is not spoiled by non-perturbative effects. Major contributions to this subject concern PDF determinations and a better understanding of hadron physics.

4.1 New developments related to PDFs

German Sborlini showed us that QED effects can compete with NNLO QCD effects and therefore it is important to take a photon content of the proton into account, as has been pointed out in²⁹. He presented a calculation of the mixed QED-QCD splitting functions³⁰ and also showed a calculation of NLO QED corrections to diphoton production, pointing out that jet vetos can lead to enhanced QED effects³¹.

R. Zlebcik presented a new method to calculate transverse momentum dependent parton distribution functions and its implementation into **xFitter**³², together with applications to the p_T distribution of the Z -boson and dijet decorrelations³³. The version **xFitter-2.0.0** and its various functionalities has been presented by F. Giulii³⁴, focusing in particular on the inclusion of small- x resummation. J. Fiaschi pointed out that the forward-backward asymmetry from Drell-Yan production could also be useful to be included in PDF fits³⁵. Promising results have been shown from the Lattice community by S. Zafeiropoulos³⁶. A new approach based on ratios of matrix elements leads to quark PDFs from first principles which are competitive with PDFs from global fits.

4.2 Non-perturbative QCD and hadron physics

News about modelling quantum effects in hadronisation, in particular on a model which provides an explanation for the emergence of Bose-Einstein-like correlations without additional free

parameters, have been reported by S. Todorova-Nova^{37,38}. B. Kerbikov proposed a dynamic model for sound absorption and bulk viscosity near the critical temperature^{39,40}.

Chris Quigg pointed out that stable heavy tetra-quark mesons of type $Q_i Q_j \bar{q}_k \bar{q}_l$ must exist in the limit of very heavy quarks Q . He predicts that double-beauty states will be stable against strong decays, while the double-charm states and mixed beauty-charm states will dissociate into pairs of heavy-light mesons. Observation of such states would establish the existence of tetra-quarks, and comparison with theoretical predictions for their production rate and lifetime would teach us about the role of heavy colour-antitriplet di-quarks as hadron constituents⁴¹.

Shi-Yuan Li also pursued the deeper understanding of multi-quark states and emphasised the importance of studying hadron correlations in this context⁴².

An explanation why the lifetimes of five Ω_c excited states – recently found by LHCb and confirmed by Belle – are so small, has been offered by M. Praszalowicz⁴³, based on an extension of the chiral quark-soliton model, where the two narrowest states are interpreted as penta-quarks belonging to the **15** representation of $SU(3)$.

Cai-Dian Lu offered calculations of branching fractions for several doubly charmed baryon states⁴⁴, and in fact the Σ_{cc}^{++} state has been discovered by LHCb in the decay channel $\Lambda_c^+ K^- \pi^+ \pi^+$, which has been calculated to have the largest branching fraction.

5 Flavour Physics

The flavour sessions started with a talk by Gudrun Hiller⁴⁵ stating the experimental facts and their possible theory implications: there are hints in semi-leptonic B-meson decays ($b \rightarrow sll$ transitions) pointing towards a violation of lepton-universality. The ratios

$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\mathcal{B}/dq^2(\bar{B} \rightarrow \bar{H}\mu\mu)}{\int_{q_{\min}^2}^{q_{\max}^2} dq^2 d\mathcal{B}/dq^2(\bar{B} \rightarrow \bar{H}ee)} \quad (1)$$

for $H = K$ and K^* have been measured to deviate from unity at the $\sim 2.6\sigma$ level^{46,47}, while the radiative corrections do not exceed the percent level. The dimension six operators which can be responsible for a violation of lepton-universality can be clearly identified^{48,49}. The measured ratios R_D and R_{D^*} ($b \rightarrow cl\nu$ transitions) also seem to indicate signs of lepton-non-universality (LNU). Rather minimal extensions of the Standard Model to account for LNU would be $U(1)$ extensions (Z' -models) with gauged lepton flavour⁵⁰ or leptoquarks, see Section 6. Collider searches for such states will certainly give important information complementary to the data from LHCb and Belle II.

Robert Fleischer⁵¹ reported on a theoretical framework to study leptonic decays $B_q^0 \rightarrow l^+ l^- (q = s, d)$, which belong to the cleanest rare B decays, and therefore offer an outstanding opportunity to explore the flavour sector. So far, only $B_s^0 \rightarrow \mu^+ \mu^-$ has been observed, and agrees with the Standard Model expectation. On the other hand, another promising decay, $B_s^0 \rightarrow e^+ e^-$, has received little attention so far because of its helicity suppressed Standard Model branching ratio, which however may be hugely enhanced through new (pseudo)-scalar contributions which lift the helicity suppression. He also pointed out that new sources of CP violation may enter the game, and presented observables which are well suited to explore in this direction, while not giving up flavour universality^{51,52}. Utilising $B \rightarrow \pi K$ decays as a probe of new physics, in particular with regards to CP asymmetries, is another interesting subject. Ruben Jaarsma has presented a new state-of-the-art analysis, including also effects from electroweak penguin diagrams, which confirms the tension with current data^{53,54,55}.

Roman Zwicky explained that the contamination of right-handed currents in $B \rightarrow V\gamma$ (or $B \rightarrow V l\bar{l}$) decays due to long-distance effects can be controlled by considering in addition the corresponding decay $B \rightarrow A\gamma (l\bar{l})$, where V/A are vector/axial vector mesons, exploiting the opposite relative sign of left- versus right-handed amplitudes^{56,57}.

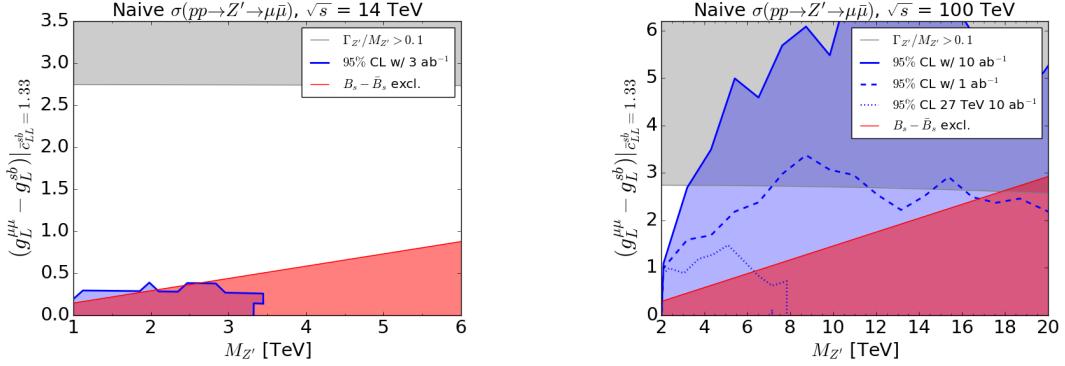


Figure 2 – Coverage of the parameter space for a minimal Z' -model that could explain the anomaly in $B \rightarrow K^{(*)}\mu^+\mu^-$. Left: HL-LHC, right: FCC at 100 TeV.

Giancarlo D’Ambrosio gave us a broad overview on recent developments in Kaon physics⁵⁸, also listing models which address the ϵ'/ϵ anomaly and discussing the interplay with B-anomalies. More details will be provided in the following section.

6 Beyond the Standard Model

The contributions about physics beyond the Standard Model can roughly be divided into two categories: the ones which address specifically the flavour anomalies, and the ones which don’t.

In the first category (see also⁵⁹ for a small review) is a class of models presented by Andreas Crivellin^{60,61}, which is of Pati-Salam type, i.e. based on a gauge group where lepton number is the fourth colour. Implementing this gauge symmetry in a 5D Randall- Sundrum background, the mass scales of the Kaluza-Klein resonances, in particular the vector leptoquarks, can be in the few TeV range. The model naturally accommodates the R_{K,K^*} anomalies, and in a non-minimal version also can offer an explanation of the tensions in the anomalous magnetic moment of the muon.

Abhishek Iyer also offered an explanation for the anomalies in B - and rare K -decays, in the context of custodial Randall-Sundrum models^{62,63}. Two solutions are possible within such models, one where both muons and electrons play a role in lepton non-universality, and one where primarily muons play a role. More data on rare Kaon decays could serve to distinguish the two possibilities⁵⁸.

What is next if (some of) the indirect signs of New Physics in the flavour sector turn out to be firmly established? Tevong You addressed the interesting question whether we can reach the scale of New Physics which may be behind the flavour anomalies at future colliders^{64,65}. Focusing on rather minimal Z' and leptoquark models, the conclusion is that for narrow width Z' models there is a good but not complete sensitivity at the HE-LHC, whereas FCC-hh would almost guarantee a discovery, see Fig. 2. If leptoquarks are responsible, the conclusion depends critically on the leptoquark masses, but for masses below 4.5 TeV a discovery at HE-LHC would be very likely.

Extended Higgs sectors can offer solutions to open questions like the origin of dark matter, baryogenesis or unexplained hierarchies. Howie Haber gave a classification of extended Higgs sectors within the framework of two-Higgs doublet models (THDMs)^{66,67}. In particular, he showed how alignment without decoupling can be achieved. George Hou presented models with extra Higgs bosons, where alignment emerges naturally, which should lead to distinctive signatures like triple top production^{68,69}. Margherita Ghezzi talked about doubly charged scalars, which can arise in many BSM models, and pointed out the importance of taking finite width effects into account⁷⁰. Luc Darmé gave convincing arguments that scenarios with light thermal dark matter might be naturally accompanied by a corresponding light dark sector,

offering prospects to detect a dark Higgs boson in the light spectrum^{71,72}. Matthew McCullough offered two different solutions to the hierarchy problem⁷³, a linear dilaton model⁷⁴ which would lead to oscillatory signals in the $m_{\gamma\gamma}$ spectrum, and a “hyperbolic Higgs” model⁷⁵, where the Higgs boson becomes partially its own top partner.

How to compare a plethora of BSM models to data? GAMBIT^{76,77} can help: it provides a general global fitting framework, including many statistical and scanning options, a fast likelihood calculator, and an extensive model database, which can be extended straightforwardly to additional models.

7 Conclusions

The Moriond QCD 2018 edition contained a discussion session with the title “Where is New Physics?”, and one named “Heavy Flavour indirect search for New Physics”. Should we combine this into the slogan “Heavy Flavour: here goes New Physics”? Even though the flavour anomalies seem to be intriguingly persistent and consistent with each other, it is certainly too early make a definite statement, but the good news is that we will have more information from the experimental side in the not too distant future, awaiting eagerly results from LHCb and Belle II.

In any case we have seen plenty of progress to improve the precision of Standard Model predictions in various aspects. Some results are showpieces of perturbation theory in QCD, others operate at the interface between QCD and electroweak corrections, or concern the deeper understanding of non-perturbative QCD. There is also much progress in providing convenient observables as well as tools to confront theory predictions with data and to identify interesting regions in the vast BSM parameter space. Some intriguing ideas about possible extensions of the Standard Model have been presented, and it is not unlikely that the model builders may soon get more hints about which direction to take.

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