These proceedings provide a brief summary of the theoretical topics that were covered at Moriond QCD 2009, including non-perturbative QCD, perturbative QCD at colliders, a small component of physics beyond the standard model and heavy-ion collisions.

1 Introduction

Of the $O(100)$ talks that were given at this year’s “Moriond QCD”, about one third were theoretical. As usual with the Moriond conference, the range of topics covered was rather broad, and the logic that I will follow in discussing them will be to progress in the total energy that is involved — that will take us from non-perturbative QCD, through perturbative QCD and the data-theory interface at high-energy colliders, to topics beyond the standard model, and finally to heavy-ion collisions.

2 Non (or barely) perturbative QCD

There are many reasons for investigating non-perturbative QCD. One good one is that it’s responsible for most of the nucleon mass and correspondingly for most of the visible mass in the universe. A more pragmatic reason is that flavour physics is usually done with hadrons, and our understanding of their non-perturbative dynamics is one of the limiting factors in the extraction of CKM matrix entries and new-physics constraints.

A powerful tool for handling non-perturbative QCD is to simulate it on the lattice. A recurrent issue for lattice QCD is the reliable handling of systematic errors, for example the dependence on the lattice spacing, the matching of lattice gauge theory to continuum QCD, finite-volume effects, and the treatment of light quarks, and the discussion of these issues was a common theme to the lattice talks at Moriond ’09.

Three light-quark treatments were discussed. Staggered fermions are the easiest to treat from a computational point of view, but this comes at a price: while the predictions agree with experimental results, it is not clear whether the staggered-fermion formulation is theoretically equivalent to QCD. Wilson fermions and domain-wall fermions are both OK from this point of view, but they are also more expensive computationally, especially the domain-wall fermions, which are those with the cleanest chiral ($m_q \to 0$) limit.

Two thirds of those were in the afternoon, which means that at roughly 95% confidence level, we can rule out the hypothesis that the organisers were equally likely to assign theory talks to morning and afternoon sessions.

In contrast with the Tevatron’s 95% exclusion limits on the standard-model Higgs boson with $160 < m_H < 500$. 
Figure 1: Left: dependence of the Ω and nucleon masses on the pion mass and lattice spacing from the BMW collaboration; middle: final results for the hadron mass spectrum from the BMW collaboration; right: results for the spectrum from the PACS-CS collaboration based on a linear extrapolation from the region 156 MeV < $m_\pi$ < 410 MeV.

Figure 1 (left) illustrates results from two talks about the hadron mass spectrum. The left-hand plot, presented by Fodor for the “BMW” collaboration, shows how the lattice calculation of the Ω and nucleon (N) masses depends on the squared pion mass (horizontal axis), i.e. the approach to the correct $u$ and $d$-quark masses, and on the lattice spacing $a$ (differently coloured points), together with a fit that provides an extrapolation to the physical light-quark masses. The corresponding results for the hadron spectrum are shown in the middle plot (lines and bands are experimental masses and widths, the points are the lattice result), with remarkable agreement for all the hadrons. This was presented as the first lattice-calculation of the baryon mass to have full control of uncertainties. Related results were presented by Kuramashi for the PACS-CS collaboration (right-hand figure). He, however, argued that for a fully controlled calculation one should carry out simulation directly with the physical light-quark masses (currently in progress). This is to avoid the extrapolation that is required in the BMW results and whose validity was the subject of debate during the conference. Though there does not yet seem to be a universal consensus within the lattice community as to whether the hadron spectrum is now reliably calculated, it is to be expected that clarification on the remaining issues will be forthcoming in the near future. Given the 35 years’ work on the subject, that is a major accomplishment, both in fundamental terms, and because it helps provide confidence when using lattice results for observables for which we don’t already know the answer.

The use of lattice calculation to obtain information that we don’t know was illustrated in two other talks. Izubuchi, representing the RBC/UKQCD collaboration, showed numerous results, including hadronic matrix element computations, and determinations of the up- and down-quark mass difference, and emphasised the value of the continuum chiral behaviour that is characteristic of the domain-wall fermions that were used.

Van de Water for the Fermilab Lattice and MILC collaborations (staggered fermions), discussed results for $B$-mesons and their relation with the determination of CKM matrix elements. Fig. shows how data for the $B \to \pi \ell \nu$ form factor from BABAR and from the lattice calculation have the same shape in the region of overlapping $q^2$ values, helping to provide confidence in the lattice calculation and the extraction of $V_{ub}$. The resulting value for $V_{ub} = (3.38 \pm 0.36) \times 10^{-3}$, while it has errors (11%) that are slightly larger than inclusive determinations (7–8%), is in better agreement with other determinations. However, it is, however, unclear quite what we learn from this!
agreement with unitarity triangle analyses $V_{ub} = (3.46 \pm 0.16) \times 10^{-3}$.

With other observables it may currently be harder for lattice QCD to provide definitive predictions. One context where this was discussed, by Penin, concerned the mass of the recently discovered $\eta_b$, specifically the hyperfine mass splitting, measured to be $E_{hf} = M(\Upsilon(1S)) - M(\eta_b) = 71.4 \pm 2.7^{+2.3}_{-3.1}$ MeV. In the charmonium system, the experimental value is well reproduced by a perturbative calculation but this is not the case for the $\eta_b$, where the prediction was $E_{hf} = 39 \pm 11$ MeV. The lattice prediction is closer to the experimental result, however Penin argued that the lattice’s coarse spacing relative to the inverse $b$-quark mass implies substantial additional corrections ($\sim -20$ MeV), which would bring it into accord with the perturbative result. This leaves an interesting puzzle, perhaps to be resolved at a future Moriond!

Another context where the question of the lattice’s predictive ability naturally arose was the talk by Swanson about exotic hadronic states. An example that was particularly interesting (though it is unclear if it truly exists) was the $Z^\pm(4430)$, which decays to $\pi^\pm \psi'$ and so would call for either a tetraquark or a molecular interpretation. As progress in lattice calculations continues, one can only look forward to the day when they will be able to shed light on the existence and structures of the numerous $X,Y,Z$ resonances that are currently being seen by the experiments.

### 3 Perturbative QCD predictions

Perturbative QCD (pQCD) inevitably “happens” at HERA, the Tevatron and LHC. Backgrounds to possible new physics all involve a QCD component, and more often than not, possible signals either involve QCD directly (e.g. because a new particle decays to quarks) or are affected, e.g. by pQCD initial-state radiation.

#### 3.1 NLO

A number of the pQCD results presented here related to next-to-leading order (NLO) calculations. The importance of NLO predictions was nicely illustrated by Nilsen (for the DØ collaboration in his comparisons of data for the $Z$+jet cross-section to LO (matrix-element + parton-shower) and NLO predictions. It is clear that it is only at NLO that one has a reliable prediction. The usefulness of NLO predictions has led to the establishment of the so-called Les Houches wish-list of important processes to calculate at NLO, and this guides much of the current work on the subject.

The NLO results reported here can be split into two categories: those that push traditional Feynman-diagram based methods to their limit (Jäger, Weinzierl), and those based on
“unitarity” (Melnikov, Maître) for the 1-loop part of the computation.

Jäger discussed $pp \rightarrow VV jj$, via vector-boson fusion (VBF), which is an important background to Higgs production via VBF, and of interest also for studying WW scattering. She showed that the NLO corrections are modest, and lead to small scale-dependence in the final predictions, and illustrated how this might facilitate the identification of new physics signal in the gauge sector. Weinzierl discussed $p\bar{p} \rightarrow t\bar{t}j$ production, one of the last uncalculated $2 \rightarrow 3$ “Les Houches” processes, whose complexity stems from the significant number (450) of loop diagrams and the fact that they contain a mass scale, $m_t$. One of the interests of $t\bar{t}j$ production is that its LO contribution is the first order of $t\bar{t}j$ production that shows an asymmetry between the $t$ and $\bar{t}$ directions (jets are preferentially emitted when the $t$ goes in the direction opposite to the $p$). Curiously this asymmetry is largely washed out by higher order corrections, an effect that calls for a physical explanation.

The bottleneck in NLO calculations for a $2 \rightarrow n$ process is the $2 + n$-leg loop calculation, whose complexity scales factorially with the number of legs in Feynman-diagrammatic methods. Much recent work has been devoted to the use of “unitarity”, first introduced for QCD loop calculations over 15 years ago, which, essentially, involves sewing together tree-level amplitudes with specific kinematics in order to obtain the coefficients of the loop integral. Both Maître (for the Blackhat collaboration) and Melnikov (for the Rocket collaboration) reviewed the amazing progress that has taken place in recent years (see also ref. [21]), significant innovations including, among many others, the use of complex momenta, recursive building up of the number of legs, the determination of the full analytic structure of loop integrands based just on their numerical evaluation at a finite set of kinematic points, and extraction of results in $4 + 2\varepsilon$ dimensions from computations in integer $D > 4$ dimensions.

The power of these methods was conveyed through the list of 1-loop amplitudes available in the “Rocket” program: all 1-loop $N$-gluon scattering amplitudes, $qq + N$-gluons, $Wq\bar{q} + Ng$, $Wqq\bar{q} + Ng$, $tt + Ng$ and $tq\bar{q} + Ng$. In terms of phenomenological applications, it seems that $2 \rightarrow 4$ and $2 \rightarrow 5$ processes are within realistic reach, at least in the large-$N_c$ limit, and significant work is now being devoted to the combination of the $2 \rightarrow n$ 1-loop result with the $2 \rightarrow n+1$ tree-level result (Blackhat uses Sherpa, Rocket uses MCFM). Both groups showed first results for $pp \rightarrow W + 3$ jets, one of the major $2 \rightarrow 4$ Les Houches processes (it’s a major background to SUSY searches). The results were in the large-$N_c$ limit (which should be good to a few percent), and in the case of Rocket with just the $Wq\bar{q}ggg$ subprocess and without fermion loops (good to $20–30\%$). Some of them are reproduced in fig. 4, including a comparison to data from the CDF collaboration.

These developments represent a major step forward and the start of a new era in practical NLO calculations for the LHC and one can almost certainly expect significant progress on the remaining technical issues in the coming year or two.

3.2 Not NLO

Plain NLO calculations are not the only means available to us for obtaining predictions at colliders and a number of varyingly related methods were presented at this year’s Moriond.

It can be useful to combine NLO predictions with a parton-shower Monte Carlo simulation. White discussed this in the context of MC@NLO for $pp \rightarrow Wt$ production. An issue that

\[ ^{\text{A vexing issue here is that the data have been obtained with the JetClu jet algorithm, which is severely IR unsafe and causes even the LO perturbative prediction to be ill-defined. To obtain finite NLO predictions, the Blackhat group instead used the SISCone jet algorithm. It would probably be worth supple}} \]

\[ ^{\text{menting this with a calculation that uses an alternative such as anti-$k_t$, insofar as JetClu is probably intermediate in its behaviour between anti-$k_t$ and SISCone, once one accounts for the all-orders perturbative and non-perturbative impact of the IR unsafety of JetClu.}} \]
arises at NLO is the appearance of the $pp \to Wt\bar{b}$ process, which interferes with non-resonant $t\bar{t}$ production. This is a non-trivial problem, and to have a solution that allows $pp \to Wt$ to be incorporated in MC@NLO is a very useful development.

Part of the interest of parton showers is that they resum logarithmically enhanced terms to all orders. The best resummation precision is, however, to be obtained with analytic calculations, which were discussed by Ferrera for the $p_t$ distribution of a $Z/\gamma^*$ system. A context for this is that the $p_t$ distribution for the Higgs boson (which is calculated in a similar way), is an important ingredient in Higgs searches, and it is valuable to be able validate the calculational framework for predicting this, which is very similar in the Higgs and the $Z$ cases.

Resummations may also be relevant in predicting the structure of multi-jet events. Normally multi-jet predictions are based on tree-level calculations, but it was pointed out by Andersen that in the case of Higgs plus multijet production, it is technically difficult to obtain exact predictions for multijet prediction. He thus discussed an interesting approach based on the Fadin-Kuraev-Lipatov high-energy approximation, which compares well to exact tree-level calculations in the cases where they are known. This is an interesting complement to normal fixed order methods, in part also because it provides a natural way of including virtual corrections. The relevance of the high-energy approximation was also emphasised by Hautmann, because of the expected relevance at LHC of configurations in which multiple emissions may have commensurate transverse momenta (by default not included in parton shower Monte Carlos).

Rather than trying to calculate all orders in some logarithmic approximation, one can also try to obtain just one order further than NLO, i.e. NNLO. Work towards an efficient program for fully exclusive NNLO prediction of $pp \to Z$ was presented by Ferrera. Theoretical developments were discussed by Heslop on the calculation of two-loop diagrams (one of the ingredients of NNLO predictions) for a theory related to QCD, $\mathcal{N} = 4$ supersymmetric (SUSY) Yang-Mills (YM) theory, specifically for maximal-helicity-violating (MHV) amplitudes. That large number of acronyms is indicative of how distant this is from a general full QCD calculation. Yet the progress made is impressive. In particular, Heslop discussed a conjecture that relates gluon loop amplitudes to Wilson loops, and showed that if it holds, then one can calculate all planar two-loop MHV n-gluon scattering amplitudes in $\mathcal{N} = 4$ SUSY-YM for any number of gluon legs $n$. This, for two-loop diagrams, is analogous to the type of progress that was being made 15 years ago for one-loop diagrams and that recently has been playing a big role in NLO calculations,
In discussing perturbative predictions for high-energy colliders, it is important to remember that non-perturbative effects can often be as large as higher-orders of perturbation theory. This is especially true when it comes to the underlying event and pileup at the LHC, and the simulation of these effects was discussed by Pierog, in the context of the EPOS Monte Carlo program for minimum-bias physics, including the question of how one can incorporate constraints from cosmic-ray air showers in the modelling of minimum-bias collisions.

4 The Data–Theory interface

Work at the interface between data and theory is crucial if we are to make the best possible use of both. The topics that fell under this heading were rather varied.

Stelzer discussed the Gfitter project for electroweak fits of the standard model (and beyond). It can be seen as an alternative to a tool like against Zfitter, and has also been validated against it. Stelzer quoted a central value for the Higgs mass of $83^{+30}_{-23}$ GeV, to be compared with that from the Tevatron’s electroweak fit of $m_H = 90^{+36}_{-27}$ GeV (small details of the fit are responsible for the difference in results). Including the latest results for the direct Higgs searches gives $m_H = 116^{+15}_{-13}$ GeV, with the $\Delta \chi^2$ as a function of $m_H$ shown in fig. 5 (left).

Still on the subject of using data to constrain theory, Williams discussed a program called HiggsBounds, which incorporates results of all experimental Higgs-boson searches into a single package. The list of searches that are included in the program (too long to reproduce here) makes for an impressive and valuable collation of information. It can be useful for testing new models (and there is a convenient web interface), or even new standard-model cross sections, and Williams illustrated how it had been used to show that a previous 95% exclusion limit on the Higgs boson from the Tevatron disappeared once one used updated PDFs.

The question of PDFs is one that arises in many places, not surprisingly given how crucial an input they are for Tevatron and LHC studies. A major issue in standard PDF fits is the determination of the uncertainties. The two main groups, CTEQ and MSTW, both estimate them using a $\delta \chi^2$ of order 50. However reasonable the final results, one can’t but help feeling a little uncomfortable with this choice. A second issue is that standard fits use somewhat restricted parametrisations, which may bias the final results. An approach that attempts to work around these issues was presented by Del Debbio, for the NNPDF collaboration. One innovation is that they carry out individual fits to a large number of Monte Carlo replica experiments so as to obtain an ensemble of PDFs (i.e. a direct measure of uncertainties, without needing to choose
a $\delta \chi^2$ value). Additionally, they use neural networks to provide bias-free parametrisations of the PDFs. Fig. 5 (right) shows results of fits for the up-quark distribution compared to MRST results. There are two fits each, one using a full data set and the other a reduced “benchmark” data set. Ideally, the original fit should be within the error band for the benchmark fit, and the latter should have significantly larger errors in the region lacking data. This is the case for NNPDF, but less so for MRST, perhaps a consequence of the in-built parametrisation, which provides a constrained extrapolation into the region with limited data. At the moment the NNPDF fit lacks heavy-quark effects and $pp$ data, which limits its usefulness, however work is in progress to resolve these issues. Once this is done, it seems likely that the NNPDF approach will become a serious competitor to the CTEQ and MSTW groups.

As well as using data to learn more about theory, one can also take the reverse approach and ask how theoretical insight can be exploited to better use data. This was illustrated in the talk by Rubin about a proposal for a new LHC search strategy for a light Higgs boson that decays to $b\overline{b}$. In an ATLAS study of the $pp \rightarrow HW$, $H \rightarrow b\overline{b}$ and $W \rightarrow l\nu$ channel, it was found that the signal to background ratio was very low, as was the significance, with the signal only a tiny perturbation close to a peak in the background distribution. Rubin concentrated on the subset of $WH$ events where the $W$ and $H$ both have high transverse momenta. Though only a small fraction of $WH$ events are in this configuration, it turns out the fraction for the background events is smaller still. One challenge in then that the $H \rightarrow b\overline{b}$ decay is quite collimated and the $b\overline{b}$ may end up in the same jet. However, using a QCD-motivated dedicated subjet ID strategy, this issue can be resolved and, based on Monte Carlo study, one expects that with $30 \text{fb}^{-1}$ one could obtain a $4 - 5\sigma$ significance for discovery of a 115 GeV Higgs boson at a 14 TeV LHC, cf. fig. 6.

The issue of very small signal to background ratios is one that is common to many of the experimental analyses discussed at this year’s Moriond QCD. In nearly all the cases the analyses used a neural network (NN), or some other multi-variate technique, to obtain a measure of how much a given event is “signal-like” versus background-like, and then showed the distribution for this measure as their main result.

In informal discussions during the conference, many people expressed discomfort at this trend (myself included). It is natural of course to seek to use the best tools at hand in order to maximise one’s chances of seeing a signal. However, ultimately, the aim is not merely to get the largest possible value for some number such as $S/\sqrt{B}$, but, just as importantly, to convince the reader/audience that one has actually seen (or excluded) a signal. From this point of view, neural networks may actually be a hindrance, because they fail to communicate what it is about a certain set of events that leads one to believe that they correspond to a signal. One can perhaps mitigate this drawback, to some extent, by showing the correlation between the neural network output and various physical distributions for background and signal. However, a suggestion for a more general rule of thumb might be the following: if a NN improves the signal significance by (say) 20% compared to a cut-based analysis, then one should also show the latter, because it is likely to be just as convincing (if not more so). If, instead, the NN improves the significance by a factor of two, then this suggests that there is some underlying physical characteristic of the signal that could be used also to improve a traditional analysis, and one should figure that out.

Another way of saying this is that one ought not to excessively favour silicon-based neural networks over their
5 Beyond the Standard Model

Two kinds of “New phenomena” were discussed at this year’s Moriond. Those that relate to theories that we know well (QCD), but that may have yet-to-be discovered exotic behaviour, for example in heavy-ion collisions, as discussed below; and those that relate to extensions of the standard model.

One of the issues with the most popular extension of the standard model, supersymmetry (SUSY), is that of how this extra symmetry between fermions and bosons gets broken. Various schemes exist in the literature, such as gravity-mediated SUSY breaking, or gauge-mediated SUSY breaking. Lalak pointed out that, contrary to standard assumptions, it is possible that real-world SUSY breaking could be a mixture of these.

SUSY is far from being the only viable extension of the Standard Model. Kanemura discussed a specific model in which the dynamics of an extended Higgs sector and TeV-scale right-handed neutrinos provide a framework for neutrino oscillation, dark matter, and baryon asymmetry of the Universe. In particular tiny, physical, neutrino masses are generated at the three loop level, a singlet scalar field is a candidate of dark matter, and a strong first-order phase transition is realised for successful electroweak baryogenesis.

One of the most economical ideas for the explaining the electroweak scale involves the idea that the Higgs is composite (a bit like pion), with its mass generated by non-perturbative dynamics of a new QCD-like theory, technicolour, but whose coupling grows strong near 1 TeV rather than near 1 GeV. Technicolour is often considered to be difficult to reconcile with precision electroweak measurements, but as was discussed by Brower, this is based on calculations that assume that technicolour is similar to QCD. If one instead supposes that technicolour is only marginally similar to QCD (e.g. it has many more active flavours, with a small \( \beta \)-function coefficient), then it might be a rather different theory. Would this too then be excluded? The only way of being sure would be through lattice calculations. In this respect, the fact (cf. section 2) that we are finally reaching an era of full control over the systematics of lattice calculations means that we might also be to use them to reliably address questions like this about technicolour.

6 Heavy-Ion Collisions

The key question in the study of heavy-ion collisions (HIC) is that of whether we can understand the “medium” that is produced in such a collision. Ways of addressing this question include direct modelling/calculation of the medium, and the use of probes that traverse it to measure its characteristics.

Direct calculation can be performed with lattice calculations at finite temperature (albeit only for equilibrium, static media, i.e. an idealisation of what is to be found in true HICs). Schmidt described a lattice calculation of the equation of state for the medium. One interesting result was for the Taylor expansion of the pressure as a function of temperature and quark chemical potential \( \mu_{uds} \) to temperature \( T \),

\[
\frac{p}{T^4} = \frac{1}{V T^3} \ln Z(V, T, \mu_u, \mu_d, \mu_s) = \sum_{i,j,k} c_{u,d,s}^{i,j,k} \left( \frac{\mu_u}{T} \right)^i \left( \frac{\mu_d}{T} \right)^j \left( \frac{\mu_s}{T} \right)^k
\]  

(1)

The fourth-order Taylor coefficient, \( c_4^{u,d,s} \) is shown as a function of temperature in fig. and one sees a clear peak near 200 MeV. This, together with the behaviour of the other expansion coefficients, hints at the existence of a critical point at that temperature — something that the experiments may look for explicitly in their data.
Greiner\textsuperscript{70} discussed a microscopic approach to the quark-gluon plasma, the “Boltzmann Approach of MultiParton Scatterings” (BAMPS), a transport algorithm that solves the Boltzmann equations for on-shell partons with perturbative QCD interactions, essentially including a $2 \rightarrow 2$ scattering term and a $2 \rightarrow 3$ term, the latter being important for thermalisation. This gives a very good description of the elliptic flow, $v_2$ (a non-trivial achievement)\textsuperscript{71}, but significantly oversuppresses high-$p_t$ particle production, giving $R_{AA} \simeq 0.05$ as opposed to the experimental value of $R_{AA} \simeq 0.2$. So, while a microscopic description can provide much insight, it seems that it remains a challenge to describe the entire body of data.

A complementary approach to the calculation of medium properties is to investigate the influence of the medium on probes that traverse it, so as to obtain a measure of its properties (albeit a somewhat indirect one).

One classic probe is the $J/\psi$, on the grounds that in a hot medium it would “melt” and so its production would be suppressed. Ferreiro\textsuperscript{72} pointed out that to make sense of $AA$ data, it is important\textsuperscript{73} to understand not only the high-temperature effects, but also phenomena such as nuclear shadowing that occur even in cold nuclear matter. Another “early-time” probe was discussed by Kerbikov\textsuperscript{74}, specifically $\pi \Xi$ correlations, of interest because models predict an early decoupling of multi-strange hadrons like the $\Xi$.

A probe that has seen very extensive study in recent years is a hard parton that traverses the medium. The main indicator that has been discussed so far is the amount of energy lost during this traversal, which has been modelled in terms of medium-enhanced radiative energy loss, as well as collisional energy loss.

Zakharov\textsuperscript{75} discussed an additional source of energy loss. He argued that certain models of the quark-gluon plasma, such as “anomalous viscosity”\textsuperscript{76}, imply the presence of chromomagnetic fields that are sufficient to induce substantial synchrotron radiation from a gluon that goes through them.\textsuperscript{77} He estimated that synchrotron energy loss should be of similar magnitude to collisional energy loss, and each of them about 25\% of radiative energy loss.

The fact that many mechanisms may contribute to parton energy loss motivates more exclusive studies, which look not just at leading particle spectra, but the properties of particle and energy flow in the vicinity of a leading particle. To help interpret such studies, it is essential to have more exclusive modelling tools, such as “medium-aware” Monte Carlo generators. Salgado\textsuperscript{78} discussed a modification of Pythia\textsuperscript{79} Q-Pythia,\textsuperscript{69} that incorporates an additional medium-induced gluon emission term in the parton shower. Fig. \textsuperscript{7} (right) shows the angular

![Figure 7: Left: the fourth-order coefficient of the Taylor expansion of the equation of state in lattice simulations of finite temperature QCD\textsuperscript{67,68} with structure at $T \simeq 200$ MeV that is suggestive of a critical point. Right: the angular distribution of particles in that are produced from the showering of a 100 GeV gluon in the vacuum, and in a medium with transport coefficient $\hat{q} = 5, 50$ GeV$^2$/fm, as simulated with Q-Pythia\textsuperscript{69}.](image-url)
distribution of particles emitted from a 100 GeV gluon, both in the vacuum and in a medium, and illustrates the significant differences that are to be seen, both in multiplicity and in typical angle. This kind of tool promises to be very useful, both in testing the underlying modelling, and in designing experimental analyses to further probe the mechanism of jet quenching.

The final talk of the conference, by Warringa, discussed the effects of topological charge change in heavy-ion collisions. He argued for the following chain of events: 1) there are topological charge fluctuations in the hot medium (like instantons); 2) that topological charge fluctuations induce fluctuations in chirality, e.g. more right-handed quarks and antiquarks (i.e. with the spin aligned along the direction of motion) than left-handed ones; 3) that if there is a (QED) magnetic field in the medium, this will orient the spins of the $u_L, d_L, u_R, d_R$ quarks parallel (and the others anti-parallel) to the direction of the magnetic field; 4) that together with a fluctuation in chirality, (say more R), this will lead to $u_R d_R$ (positive charge) moving in the direction of the field, and $\bar{u}_R \bar{d}_R$ (negative charge) moving in the opposite direction; 5) that in a non-central AA collision there is a (QED) magnetic field, perpendicular to the reaction plane, generated as the two charged nuclei go past each other, and therefore that this orients net charge flow along a direction perpendicular to the reaction plane; 6) that this can be seen in AA collisions, by plotting a variable $\langle \cos(\phi_i^+ + \phi_j^± - 2\Psi_{RP}) \rangle$ (where $\Psi_{RP}$ is the angle of the reaction plane) as a function of centrality. Remarkably, a preliminary STAR measurement shows that this quantity becomes significantly different from zero (in the direction expected) for the least central collisions, precisely those that are expected to have the strongest magnetic field. Given how long the theoretical community has been discussing topological charge in SU(N) theories, this is a very interesting development. One can only look forward to further cross-checks, and one interesting one would for example be the experimental verification of appropriate scaling with nuclear charge $Z$ for constant $A$.

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References

1. S. Pagan Griso, these proceedings, arXiv:0905.2090 [hep-ex].
2. Z. Fodor, these proceedings.
3. Y. Kuramashi, these proceedings, arXiv:0906.0126 [hep-lat].
4. S. Durr et al., Science 322 (2008) 1224.
5. K. I. Ishikawa et al. [PACS-CS Collaboration and PACS-CS Collaboration and PACS-CS Collaboration], arXiv:0905.0962 [hep-lat].
6. B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 98 (2007) 091801.
7. J. A. Bailey et al., arXiv:0811.3640 [hep-lat].
8. T. Izubuchi, these proceedings.
9. R. Van de Water, these proceedings.
10. F. Di Lodovico (HFAG), update presented at ICHEP 2008, 
http://www.slac.stanford.edu/xorg/hfag/semi/ichep08/home.shtml
11. J. Charles et al. (CKMfitter), preliminary results for Summer 2008, 
http://ckmfitter.in2p3.fr/plots_Summer2008/ckmEval_results.html
[98] L. Silvestrini (UTFit), preliminary result presented at Lattice 2008, 
http://www.utfit.org/
12. A. A. Penin, these proceedings, arXiv:0905.4296 [hep-ph].
13. B. Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 101 (2008) 071801 [Erratum-ibid. 102 (2009) 029901].
14. B. A. Kniehl, A. A. Penin, A. Pineda, V. A. Smirnov and M. Steinhauser, Phys. Rev. Lett. 92 (2004) 242001.
15. A. Gray et al., Phys. Rev. D 72 (2005) 094507.
16. E. Swanson, these proceedings.
17. H. Nilsen, these proceedings, arXiv:0906.0229 [hep-ex].
18. V. M. Abazov et al. [D0 Collaboration], arXiv:0903.1748 [hep-ex].
19. J. M. Campbell and R. K. Ellis, Phys. Rev. D 65 (2002) 113007.
20. S. Hoche, F. Krauss, N. Lavesson, L. Lonnblad, M. Mangano, A. Schalicke and S. Schumann, arXiv:hep-ph/0602031.
21. Z. Bern et al. [NLO Multileg Working Group], arXiv:0803.0494 [hep-ph].
22. C. Englert, B. Jager, M. Worek and D. Zeppenfeld, these proceedings, arXiv:0904.2119 [hep-ph].
23. B. Jager, C. Oleari and D. Zeppenfeld, JHEP 0607 (2006) 015; G. Bozzi, B. Jager, C. Oleari and D. Zeppenfeld, Phys. Rev. D 75 (2007) 073004.
24. S. Dittmaier, P. Uwer and S. Weinzierl, these proceedings, arXiv:0905.2299 [hep-ph].
25. S. Dittmaier, P. Uwer and S. Weinzierl, Phys. Rev. Lett. 98 (2007) 262002.
26. C. F. Berger et al., these proceedings, arXiv:0905.2735 [hep-ph].
27. K. Melnikov, these proceedings.
28. R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B 725 (2005) 275.
29. C. F. Berger, Z. Bern, L. J. Dixon, D. Forde and D. A. Kosower, Phys. Rev. D 74 (2006) 036009.
30. G. Ossola, C. G. Papadopoulos and R. Pittau, Nucl. Phys. B 763 (2007) 147.
31. W. T. Giele, Z. Kunszt and K. Melnikov, JHEP 0804 (2008) 049.
32. W. T. Giele and G. Zanderighi, JHEP 0806, 038 (2008).
33. T. Gleisberg, S. Hoche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert and J. Winter, JHEP 0902, 007 (2009).
34. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. D 77, 011108 (2008).
35. G. P. Salam, Acta Phys. Polon. Supp. 1, 455 (2008).
36. G. P. Salam and G. Soyez, JHEP 0705, 086 (2007).
37. M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804, 063 (2008).
38. C. F. Berger et al., arXiv:0902.2760 [hep-ph].
39. R. K. Ellis, K. Melnikov and G. Zanderighi, JHEP 0904 (2009) 077.
40. C. D. White, these proceedings, arXiv:0905.2066 [hep-ph].
41. S. Frixione and B. R. Webber, JHEP 0206, 029 (2002).
42. S. Frixione, E. Laenen, P. Motylinski, B. R. Webber and C. D. White, JHEP 0807 (2008) 029.
43. G. Ferrera, these proceedings.
44. J. R. Andersen, these proceedings.
45. J. R. Andersen, V. Del Duca and C. D. White, JHEP 0902 (2009) 015.
46. E. A. Kuraev, L. N. Lipatov and V. S. Fadin, Sov. Phys. JETP 44 (1976) 443 [Zh. Eksp. Teor. Fiz. 71 (1976) 840].
47. F. Hautmann, these proceedings.
48. P. Heslop, these proceedings.
49. C. Anastasiou, A. Brandhuber, P. Heslop, V. V. Khoze, B. Spence and G. Travaglini, arXiv:0902.2245 [hep-th].
50. Z. Bern, L. J. Dixon, D. C. Dunbar and D. A. Kosower, Nucl. Phys. B \textbf{425} (1994) 217, Nucl. Phys. B \textbf{435} (1995) 59.
51. T. Pierog, these proceedings, arXiv:0906.1459 [hep-ph].
52. H. Flacher, M. Goebel, J. Haller, A. Hocker, K. Moenig and J. Stelzer, Eur. Phys. J. C \textbf{60} (2009) 543.
53. J. Stelzer, these proceedings.
54. M. Dittmar \textit{et al.}, arXiv:0901.2504 [hep-ph].
55. A. B. Arbuzov \textit{et al.}, Comput. Phys. Commun. \textbf{174} (2006) 728.
56. P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein and K. E. Williams, these proceedings, arXiv:0905.2190 [hep-ph].
57. P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein and K. E. Williams, arXiv:0811.4169 [hep-ph].
58. L. Del Debbio, these proceedings.
59. R. D. Ball \textit{et al.} [NNPDF Collaboration], Nucl. Phys. B \textbf{809} (2009) 1 [Erratum-ibid. B \textbf{816} (2009) 293].
60. J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. \textbf{100} (2008) 242001.
61. M. Rubin, these proceedings, arXiv:0905.2124 [hep-ph].
62. ATLAS, Detector physics performance technical design report, CERN/LHCC/99-14/15 (1999).
63. Z. Lalak, these proceedings.
64. M. Aoki, S. Kanemura and O. Seto, these proceedings, arXiv:0905.3958 [hep-ph].
65. M. Aoki, S. Kanemura and O. Seto, Phys. Rev. Lett. \textbf{102} (2009) 051805; arXiv:0904.3829 [hep-ph].
66. R. Brower, these proceedings.
67. C. Schmidt, these proceedings.
68. M. Cheng \textit{et al.}, Phys. Rev. D \textbf{79} (2009) 074505.
69. N. Armesto, L. Cunqueiro and C. A. Salgado, arXiv:0809.4433 [hep-ph].
70. C. Greiner, these proceedings.
71. Z. Xu and C. Greiner, Phys. Rev. C \textbf{79} (2009) 014904.
72. E. Ferreiro, these proceedings.
73. L. V. Bravina, K. Tywoniuk, A. Capella, E. G. Ferreiro, A. B. Kaidalov and E. E. Zabrodin, arXiv:0902.4664 [hep-ph].
74. B. Kerbikov, these proceedings.
75. B. G. Zakharov, these proceedings.
76. M. Asakawa, S. A. Bass and B. Muller, Phys. Rev. Lett. \textbf{96} (2006) 252301.
77. B. G. Zakharov, JETP Lett. \textbf{88} (2008) 475.
78. N. Armesto, L. Cunqueiro and C. A. Salgado, these proceedings, arXiv:0906.0754 [hep-ph].
79. T. Sjostrand, L. Lonnblad, S. Mrenna and P. Skands, arXiv:hep-ph/0308153.
80. H. Warringa, these proceedings.
81. D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A \textbf{803} (2008) 227.
82. H. Caines, for the STAR Collaboration, these proceedings, arXiv:0906.0305 [nucl-ex].