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Working group report: Collider and flavour physics

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Abstract. The activities of the working group took place under two broad subgroups: Collider Physics subgroup and Flavour Physics subgroup. Reports on some of the projects undertaken are included. Also, some of the leading discussions organized by the working group are summarized.

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1. Collider physics subgroup

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With the Large Hadron Collider (LHC) at the doorsteps, the collider subgroup's activity was naturally focussed on physics issues pertaining to the early phase of the experiment. These include tuning of different event generators, understanding and extracting the Standard Model (SM) backgrounds, Higgs physics and finally the study of possible new physics signatures and their implications for the relic density of dark matter (in the form of weakly interacting massive particles). Once there is a concrete indication of new physics in the data, the issue of deciphering its broad nature is likely to be a challenging one, presenting us with the so-called 'inverse problem' (from data to theory). Studies were undertaken on this aspect as well.

The leading discussions pertained to issues of significant interest at the Tevatron and the LHC and the lessons one could take from the former at the LHC-startup stage. These include extraction of parton distribution functions (PDFs) from the LHC data, uncertainties in the same and their impact on collider searches, status of event generators for the LHC, multi-channel and, in particular, multi-lepton searches as a powerful tool for unravelling physics beyond the SM, issues with Higgs searches in the early LHC era.

Given an encouraging overlap in the programmes of collider subgroup and that of the beyond Standard Model (BSM) working group, some joint sessions were mutually agreed upon so that the problems identified could have a broader ambit. One such activity is reported separately in this volume. There had been several expository sessions on the updated usage of popular event generators like Herwig++ (by David Grellscheid) and CalcHEP (by Alexander Belyaev). Also, there were a couple of talks by the graduate students on their own works. Short summaries of the leading discussions and brief reports (in original form as obtained from the contributors) on some of the projects undertaken follow.

1.1 *Generators for the LHC: Concerns for the start-up*

Albert De Roeck discussed the pressing issues with the event generators in the data-reach era of the LHC. With so many tools (e.g., the matrix element Monte Carlos (MC), parton shower MCs, NLO MCs, matching MCs) interfaced to each other no single generator would adequately reproduce the physics for the complete programme. Since processes at LHC have access to a huge kinematic regime, it would be essential to understand which particular techniques are applicable to which kinematic regimes. Tuning the event generators to the LHC data would thus be crucial. For example, one has to measure W, Z, top + n-jets (standard candles) in the first LHC data in available control regions and then tune/normalize the MCs with them and extrapolate in new regions (tails). This requires a thorough understanding of the underlying events, multiple interactions, parton showers etc. Particular care should be taken of missing p_{T} processes and the incorporation of higher-order matrix elements. More and more theoretical scenarios (that lead to potentially new signatures) should be incorporated in the generators. Also, for reliable handling of 10–30 fb^{-1} of data (during 2008–2010) the generators should better contain (i) full NLO–QCD corrections to $pp \to t\bar{t} \to b\bar{b} + 4f$, (ii) NLO–QCD corrections to $t\bar{t}j, t\bar{t}\gamma, W/Z+ \geq$ 3-jets and (iii) NNLO–QCD corrections to PDFs, 2-jets productions.

1.2 *Higgs search in CMS*

Sunanda Banerjee gave an updated account of Higgs search strategies at CMS, for both SM and MSSM Higgs bosons. For the SM Higgs boson, searches in final states like $\gamma\gamma$, $4\ell(4e, 4\mu, e^+e^-\mu^+\mu^-)$ were discussed. It was mentioned that for the $\gamma\gamma$ mode the trigger efficiency would be very high with a superb photon reconstruction efficiency of ∼99.5%. The vector boson fusion channel was also discussed with the Higgs bosons decaying to $\tau\tau$, W^+W^-, 2γ and $b\bar{b}$. To tag the forward jets, a coverage of up to $|\eta| \leq 5$ is needed and removal of fake jets would be crucially required. It was reported that Higgs mass can be measured to better than 1% with 30 fb^{-1} of data and width of the Higgs boson is measurable for $m_{\rm H} > 160$ GeV. It was indicated that SM Higgs boson can be observed with one year of data taking at low (nominal) luminosity. In the MSSM case, the searches of the heavy CP-even Higgs (H), the CP-odd Higgs (A) and the charged Higgses ($H^{\pm}$) were discussed in brief.

1.3 *Diffractive and forward processes at the LHC*

Albert De Roeck explained the prospects of diffractive and forward physics at the LHC with reference to soft and hard diffractions, single and double diffractions and diffractive processes with double- and multi-Pomeron exchanges. It was pointed out that the gap dynamics in pp scattering was not fully understood. The forward detectors under different LHC experiments would play crucial roles in this programme. Together, the LHC detectors cover virtually the entire rapidity range ($|\eta|\lesssim 12$) of interest. It was reported that there are plans to use both rapidity gap (based on central detectors) and proton-tagging techniques (based on forward detectors) and experience from both HERA and Tevatron would be vital. The diffractive structure of di-jet events at low and medium luminosities were discussed along with the importance of the exclusive central Higgs production like $pp \to pHp$. Issues pertaining to anomalous WW production and possibility of high-mass exclusive productions were also touched upon in this context.

1.4 *Standard Model backgrounds for $pp \to 4l + X$ $(l = e, \mu)$*

A Belyaev, E Castaneda-Miranda, A K Datta and B Mellado

Here we briefly report on the expected rates of Standard Model processes giving rise to $pp \to 4l + X$ $(l = e, \mu)$ production at the LHC. The rate of at least four high transverse momentum charged leptons at the LHC is expected to be dominated by ZZ production. With the application of a convenient event selection cuts this background process can be severely suppressed. We make a rough estimate of the cross-sections for the most relevant Standard Model process that may survive such an event selection. In our analysis we consider two groups of processes:

- *Production of top quarks.* This includes $t\bar{t}$, $t\bar{t}t\bar{t}$ and $t\bar{t}ll$ $(l = e, \mu)$ production. The MC@NLO package is used to generate events for the $t\bar{t}$ process [1a]. Detector effects are taken into account by smearing MC quantities. The Ws from the top quark decays are allowed to decay into $l = e, \mu, \tau$. The b-quarks from the top decay are hadronized. The semi-leptonic decay of B-mesons give rise to multi-lepton final states. The CalcHEP package is used to generate events for $t\bar{t}t\bar{t}$ and $t\bar{t}ll$ $(l = e, \mu)$ production. The latter includes the complete set of Feynman diagrams among which $t\bar{t}Z/\gamma^{\star}$ forms dominant gauge-invariant subset. For the $t\bar{t}t\bar{t}$ and $t\bar{t}ll$ $(l = e, \mu)$ production the leptonic branching fraction of τs from $W \to \tau\nu$ is assumed to be 1 [1b].

- *Production of weak bosons.* This includes ZZ, $ZW^{\pm}$, W^+W^-ll ($l = e, \mu$) and $W^+W^-W^+W^-$. The PYTHIA package is used to produce samples of $ZZ, ZW^{\pm} \to ll$ ($l = e, \mu, \tau$) events [1c]. Detector effects are included. CalcHEP is used to generate W^+W^-ll ($l = e, \mu$) and $W^+W^-W^+W^-$ events. The leptonic branching fraction of τs is assumed to be 1.

The following generic event selection is chosen:

(I) Require at least four charged leptons ($l = e, \mu$) with transverse momentum, $p_{\rm T} > 20$ GeV/c in the pseudorapidity range $|\eta| < 2.5$. At this point we require that the total charge of the leptons be equal to zero.

(II) Suppression of Z production. We look for all combinations of opposite sign and same flavour leptons. If the invariant mass, m_{ll}, of at least one lepton combination lies in the range $71 < m_{ll} < 111$ GeV/c^2, the event is rejected.

(III–V) Cuts on the missing transverse momentum, $\not{E}_{\rm T} > 50, 100, 200$ GeV/c.

Tables 1 and 2 show the effective cross-sections (in fb) after the application of cuts I–V. The efficiencies (in %) of each of the process after cuts are also quoted in the tables. It is interesting to note that the rate of four high $p_{\rm T}$ leptons coming from the $t\bar{t}ll$ production is larger than that of $t\bar{t}$, in which at least two leptons arise from the semi-leptonic decays of B-mesons. This is the case even after cut II: One can see from table 1 that the 4-lepton rate from $t\bar{t}ll$ process is about one order of magnitude higher than that from $t\bar{t}$. Actually, one can expect this suppressed rate for $t\bar{t}$ vs. $t\bar{t}ll$. In the case of $t\bar{t}$ production, $4l$ signature requires both b-quarks to fake the isolated leptons. This probability is about few per mils (parts per thousand) for each b-quark, while probability of $t\bar{t}$ to radiate extra lepton pair is of the order of $\alpha_{\rm em}^2$. The cross-sections and efficiencies for the $ZW^{\pm}$ process are omitted in table 2 since the effective cross-section for this process after cut I is found to be negligible. The production of $t\bar{t}t\bar{t}$ and $W^+W^-W^+W^-$ displays a very large $\not{E}_{\rm T}$ which is manifested by their large efficiency vs. cuts III–V.

After cut II ZZ remains the leading process. At this stage most of the ZZ events involve leptonic τ decays. These events exhibit little $\not{E}_{\rm T}$ and, as a result, the efficiency vs. cuts III–V appears small. After the application of $\not{E}_{\rm T}$ cuts the $t\bar{t}ll$ process becomes the dominant background.

In conclusion, the rate of $pp \to 4l + X$ ($l = e, \mu$) with the charged lepton $p_{\rm T} > 20$ GeV/c in the Standard Model is ≈0.1 fb after the application of cut II. With the increase of $\not{E}_{\rm T}$ cut up to 200 GeV/c, the total effective cross-section drops down to ≈0.01 fb level.

1.5 *Uncertainties in collider predictions*

N Agarwal, A K Datta, M Guchait, S Gupta, D Indumathi, M C Kumar, G Majumder, P Mathews, V Ravindran and A Tripathy

Quantum chromodynamics (QCD) provides a framework to successfully compute various important observables at the hadron colliders. Recent progresses in the computation of higher-order QCD corrections have led to predictions with unprecedented accuracy for physics studies at the Tevatron as well as at the upcoming LHC.

Table 1. Expected effective cross-sections (in fb) and relative efficiencies (in %) after the application of cuts I–V (see text) for $t\bar{t}ll$ ($l = e, \mu$), $t\bar{t}t\bar{t}$ and $t\bar{t}$ productions.

	$t\bar{t}ll$		$t\bar{t}t\bar{t}$		$t\bar{t}$	
Cut	σ	ϵ	σ	ϵ	σ	ϵ
I	0.68558	–	0.00401	–	0.01825	–
II	0.03650	5.32	0.00257	64.08	0.00456	51.66
III	0.03264	89.45	0.00257	100.00	0.00741	81.41
IV	0.02020	61.88	0.00253	98.40	0.00057	59.06
V	0.00572	28.36	0.00184	73.01	0.00057	17.33

Table 2. Expected effective cross-sections (in fb) and relative efficiencies (in %) after the application of cuts I–V (see text) for ZZ, W^+W^-ll ($l = e, \mu$) and $W^+W^-W^+W^-$ productions.

	ZZ		W^+W^-ll		$W^+W^-W^+W^-$	
Cut	σ	ϵ	σ	ϵ	σ	ϵ
I	12.89184	–	0.10400	–	0.00047	–
II	0.05688	0.44	0.00716	6.89	0.00031	65.94
III	0.00948	16.67	0.00638	89.15	0.00031	100.00
IV	0.00316	33.33	0.00428	66.88	0.00031	98.20
V	0.00000	0.00	0.00164	38.35	0.00023	76.68

QCD allows us to transfer information about one cross-section to another through the parton distribution functions (PDF). These include interesting Standard Model processes such as the Higgs production rate. They also include new physics signals such as the production of superpartners of SM particles and the SM backgrounds to these processes such as W+jets. There are two kinds of uncertainties that plague this transfer:

(1) Since QCD predictions are computed in a power series in the strong coupling constant α_s (to different orders for different processes), there may be some incompatibility in using these computations. Complications such as this should be termed as irreducible theory (IT) uncertainties.

(2) PDFs are extracted from data which have statistical and systematic uncertainties. As a result, PDF sets have inherent uncertainties which are also often called QCD uncertainties, but should really be termed theory-filtered experimental (TFE) uncertainties.

Normally, one takes a certain set of input cross-sections measured in experiments (DATA box), and fits common parton density sets to them using QCD predictions at a certain available order (QCD box) using certain statistical methods for parameter extraction (STAT box). The output of this phase of the analysis is a published PDF set (which may or may not include statistical uncertainties). Users interested in other processes then write codes for the processes they are interested in (NEW-QCD box) and use the PDF sets as inputs to investigate cross-sections for these processes. The uncertainties in the results are usually estimated in fairly crude ways.

This proposal is about building a toolset for colliders which do the following: (1) allows users to systematically investigate either IT or TFE, or the two together, (2) allows for reusing written codes, (3) allows for adding new codes to the repertoire of available tools and (4) smoothly joins new data to the analysis as it becomes available.

The main physics job is to carefully define the interfaces between the DATA, QCD, STAT and NEW-QCD boxes, and a replacement of the PDF sets by a pipeline (which we might call, obviously, the PDF-pipe). It was pointed out that different groups use different methods of statistical analysis, and so the interface of the STAT box has to be sufficiently general. The PDF-pipe does not have to be human readable, and hence can contain much more information about statistical properties of the PDFs than is customarily published (the specification should also allow for less information). One has to take care that the interfaces to the modules inside the QCD box and the NEW-QCD box should be good enough to 'plug and play'. If one writes a NEW-QCD module (say for $pp \to Z + \bar{b}b$), it should be possible to move it to the QCD box when data on this process become available. At the same time, the DATA box should have an interface general enough so that new data can be included while old data can be selectively removed in a given computation.

Members of the group involved in this project have identified the initial task. This involves the documentation of all the relevant theory results such as beta function of the QCD, splitting functions for the DGLAP evolution equations and parton level cross-sections for various processes. A dedicated work along this line is important in order to have consistent notations and formulae at hand before implementation. Work is in progress by various members of the collaboration and it is expected that this will be accomplished by the end of this year.

2. Flavour physics subgroup

A K Alok, N G Deshpande, A Dighe, N Gaur, A K Giri, D Hitlin, A Kundu, B Mishra, R Mohanta, S Nandi, S Pakvasa, N Sinha, R Sinha and A Soni

The focal theme of the flavour physics subgroup was the search for new physics (NP) in B, B_s, and possibly D decays and oscillation. The motivation was simple: there is, in all probability, some NP beyond the SM, whose direct signals may be discovered at the LHC. To have detailed information about its flavour structure, the indirect signals are essential. Apart from this, from the observed baryon-to-photon ratio of the universe, we know that there must be some source of large CP violation beyond the CKM paradigm.

The B-factories BaBar and Belle have outperformed their expectations. The collected integrated luminosity should go up to 2 ab^{-1}. LHC-B is coming on line in a few months. This makes it a transition era: from establishing the CKM picture to a precision study of it, and hence looking for NP. The way to look for NP was emphasized in talks by Soni, Hitlin, and Pakvasa. Several NP signals, and possible ways of observing them, were discussed in the short presentations by Alok, Mishra and Nandi. There was also a talk by Mathur, jointly organized with WG-3, on the recently discovered X-, Y-, and Z-mesons, and their possible interpretations.

Here follows a short summary of the projects taken up by the subgroup. The length of the individual reports are not necessarily proportional to the progress; it is solely based on the data available with the coordinator.

2.1 *Consequences of a sequential fourth generation on the CKM fit*

A K Alok, A K Giri, B Mishra, R Mohanta, S Nandi and A Soni

(also participated in the discussion: N G Deshpande, A Dighe, A Kundu, S Pakvasa, N Sinha, R Sinha)

This project focusses on the effect of a sequential fourth generation of quarks (t', b') on the standard CKM fit. Some of the processes with $b \to s$ transition show a non-trivial tension with the SM fit. They include the direct CP asymmetry in the decays $B^0 \to \pi^\mp K^\pm$ and $B^\pm \to \pi^0 K^\pm$; the mixing-induced CP asymmetry in $B \to \phi K_S$ $(\sin 2\beta)$ *vis-á-vis* $B \to J/\psi K_S$, and the mixing phase in the B_s system [1].

In a recent publication [2] it has been shown that, by using the input from the lattice for the non-perturbative matrix elements of the four-Fermi operators of $\Delta F = 2$, the value of $\sin 2\beta$ as extracted from the CKM fit deviates from that measured directly in B-factory experiments. The root of this is the discrepancy of the extracted value of $\sin(2\beta)$ from $b \to c\bar{c}s$ and $b \to s\bar{s}s$. The former, which includes the golden channel $B \to J/\psi K_S$, gives 0.668 ± 0.028. This deviates by 2.4σ from that measured in, say, $B \to \phi K_S$. Note that while the former process is tree-level and Cabibbo and colour allowed in the SM, the latter is a penguin; hence, it is more probable for new physics to show up in the latter.

The second puzzle is the measurement of direct CP asymmetries: $A_{\rm CP}(B^0 \to \pi^\mp K^\pm) = -0.097 \pm 0.012$, $A_{\rm CP}(B^\pm \to \pi^0 K^\pm) = 0.050 \pm 0.025$, both of which receive the dominant contribution from $b \to s$ transition. While we expect these two direct CP asymmetries to be the same, the data show $\Delta A_{\rm CP} = A_{\rm CP}(B^\pm \to \pi^0 K^\pm) - A_{\rm CP}(B^0 \to \pi^\mp K^\pm) = 0.14 \pm 0.029$. The theoretical prediction is close to zero. For example, QCD factorization model predicts [3] $\Delta A_{\rm CP} = (2.5 \pm 1.5)\%$. This is about 3.5σ away from the data.

The quark mixing matrix V becomes a 4×4 one with a sequential fourth generation. This contains six real angles and three complex phases. There are several parametrizations of the 4×4 CKM matrix (CKM4) [4,5]. In the parametrization of [4], the elements V_{td}, V_{ts}, $V_{t'd}$ and $V_{t's}$ have complex phases. The t' quark contributes to processes like B_q–$\bar{B}_q$ mixing and $b \to s, d$ penguins. For example, for B_q–$\bar{B}_q$ mixing $(q = d, s)$, the expression for the mass difference or oscillation frequency is given by

$$\Delta M_q = 2M_{12q}^{\rm SM} = \frac{G_{\rm F}^2}{6\pi^2}\hat{\eta}_{B_q} M_{B_q} B_{B_q} f_{B_q}^2 M_W^2 [(V_{tb}^* V_{tq})^2 S_0(x_t) + (V_{t'b}^* V_{t'q})^2 S_0(x_t')] \tag{1}$$

where $G_{\rm F}$ is the Fermi constant, M_X is the mass of particle X, $x_i = M_i^2/M_W^2$, and V_{ij}s are the CKM matrix elements. The short distance behaviour is contained in $\hat{\eta}_{B_q}$, which incorporates the QCD corrections, and in the Inami–Lim function

$$S_0(x) = \frac{4x - 11x^2 + x^3}{4(1-x)^2} - \frac{3x^3 \ln x}{2(1-x)^3} \,. \tag{2}$$

The decay constant f_{B_q} and the bag factor B_{B_q} take care of the hadronic matrix element.

On the other hand, the CP violating observable ϵ_K in K–$\bar{K}$ mixing is given by

$$\begin{aligned}\epsilon_K = \frac{G_{\rm F}^2 F_K^2 B_K m_K M_W^2}{12\pi^2\sqrt{2}\,\Delta M_K} {\rm Im}\Big[&\lambda_c^{*2}\eta_c S_0(x_c) + \lambda_t^{*2}\eta_t S_0(x_t) \\ &+2\lambda_c^*\lambda_t^*\eta_{c,t}S_0(x_c,x_t) + \lambda_{t'}^{*2}\eta_t S_0(x_{t'}) \\ &+2\lambda_c^*\lambda_{t'}^*\eta_{c,t'}S_0(x_c,x_{t'}) + 2\lambda_t^*\lambda_{t'}^*\eta_{t,t'}S_0(x_t,x_{t'})\Big]\exp^{(i\pi/4)},\end{aligned} \tag{3}$$

where $\lambda_q = V_{qd}V_{qs}^*$.

Therefore, the phases and amplitudes of V_{td}, V_{ts}, $V_{t'd}$ and $V_{t's}$ can be constrained using the observables like ΔM_d, $\sin 2\beta$ ($B \to J/\psi K_s$), $\frac{\Delta M_d}{\Delta M_s}$, $|\epsilon_K|$ along with the branching fractions $\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B \to X_s l^+ l^-)$ and $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$. In order to reduce the number of free parameters one has to replace $V_{tb}V_{td}$ and $V_{tb}V_{ts}$ by

$$\begin{aligned}V_{tb}V_{td}^* &= -(V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{t'b}V_{t'd}^*) \\ V_{tb}V_{ts}^* &= -(V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{t'b}V_{t's}^*),\end{aligned} \tag{4}$$

and, thus, the phase of V_{ub} will play an important role in constraining the phases of V_{td} or V_{ts}.

The effective Hamiltonian describing the decay $B^- \to \pi^0 K^-$ and $\bar{B}^0 \to \pi^+ K^-$, including fourth generation, is given by

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}}\left[\lambda_u(C_1O_1 + C_2O_2) - \lambda_t\sum_{i=3}^{10}C_iO_i - \lambda_{t'}\sum_{i=3}^{10}C_i^{t'}O_i\right], \tag{5}$$

and that describing the decay $B \to \phi K_S$ is given by

$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}}\left[-\lambda_t\sum_{i=3}^{10}C_iO_i - \lambda_{t'}\sum_{i=3}^{10}C_i^{t'}O_i\right]. \tag{6}$$

Therefore, the phases of V_{td}, V_{ts}, $V_{t'd}$ and $V_{t's}$ will play an important role in predicting the value for $\Delta A_{\rm CP}$ and $S_{\phi K_s}$. The aim is to constrain the parameter space for CKM4 elements using the data for the processes as mentioned above and then to find out whether such parameter space can explain $\Delta A_{\rm CP}$ and $S_{\phi K_s}$ simultaneously.

It was shown [6] that the fourth generation t' with $m_{t'} > 700$ GeV provides a rather natural explanation for the several indications of new physics that have been observed involving CP asymmetries of the b-quark. The built-in hierarchy of the 4×4 mixing matrix is such that t' readily provides a needed perturbation

(∼15%) to $\sin(2\beta)$ and simultaneously is the dominant source of CP asymmetry in $B_s \to J/\psi\phi$. The difference in direct CP asymmetries in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ requires $m_{t'} > 600$ GeV. The correlation between CP asymmetries in $B_s \to J/\psi\phi$ and the difference $[\sin(2\beta)_{J/\psi K_S} - \sin(2\beta)_{\phi K_S}]$ suggests a stronger bound: $m_{t'} > 700$ GeV. Such heavy masses point to the tantalizing possibility that the fourth family plays an important role in the electroweak symmetry breaking as the Pagels–Stokar relation in fact requires quarks of masses around 700 GeV for dynamical mass generation to take place.

The final version has recently appeared on the web [6].

2.2 *Three-body decay modes of B-mesons*

D Hitlin, N Sinha and R Sinha

This project was on the determination of the weak phases and hence looking for indirect signals of NP from various B-decay channels.

2.3 $B \to \tau^+\tau^-$ *with* τ *polarization study to constrain NP*

N Gaur, B Mishra, N Sinha and R Sinha

This project planned to use the fact that the polarization of the final state τs will be different depending on whether they come from a scalar or a vector. Study of the angular distributions and correlations of the final-state hadrons should provide important insight on the structure of the underlying physics.

2.4 *CP violating effects in* D^0–$\bar{D}^0$ *mixing*

D Hitlin, A Kundu, S Nandi, S Pakvasa, N Sinha and R Sinha

The D^0–$\bar{D}^0$ mixing parameters x_D and y_D have been measured and they are more than 3σ away from zero. The SM calculation was first done in [7]; various NP models and their contributions to these parameters were considered in [8]. The CP asymmetry is expected to be very small in the SM: $\mathcal{O}(10^{-4})$. However, various NP models (non-minimal flavour violation type) can enhance this to $\mathcal{O}(10^{-2})$. While this seems interesting, the data from KK, $K\pi$ and $\pi\pi$ modes suggest that the actual CP asymmetry is indeed small, namely $\mathcal{O}(10^{-3})$. Thus, the NP window, as far as CP violation is concerned, is fast closing. Still, a detailed study of CP violating effects is worthwhile in the sense that it can act as a tight constraint on the parameter space of NP models, in particular on the sector relevant for CP violation.

2.5 *Possible parametrization of CPT violation in the B-system*

A Dighe, A Kundu and S Nandi

The assumption of Lorentz invariance is required for the CPT theorem. The reverse is not true: Lorentz violation only allows for, but does not require, CPT violation, even if the other properties of standard quantum field theory are assumed.

Many observational results are sensitive to CPT violation but not directly to Lorentz violation. So the study of CPT violation is important in order to understand Lorentz violation. In a realistic four-dimensional theory with spontaneous CPT and/or partial Lorentz violation, detectable effects might occur in interferometric experiments with neutral kaons, neutral B_d- and B_s-mesons, or neutral D-mesons. For example, the quantities parametrizing indirect CPT violation in this systems could be non-zero.

It is necessary to develop, within an effective theory approach, a plausible CPT-violating extension of the minimal Standard Model (SM) that provides a theoretical basis for establishing quantitative bounds on CPT invariance. Following Colladay and Kostelecky [9], the simplest way to do this is to write down the Lagrangian density of a single massive Dirac field $\psi(x)$ in four dimensions as

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}', \tag{7}$$

where $\mathcal{L}_0$ is the usual free field Dirac Lagrangian for a fermion ψ of mass m and $\mathcal{L}'$ contains extra CPT-violating term. The next question is the possible forms of $\mathcal{L}'$ that could arise as effective contributions from spontaneous CPT-violation in a more complete theory. To keep the treatment as general as possible one could assume that the spontaneous CPT violation arises from non-zero expectation values acquired by one or more Lorentz tensors T. So $\mathcal{L}'$ is taken to be an effective four-dimensional Lagrangian obtained from an underlying theory involving Poincaré-invariant interactions of ψ with T. Since the expectations $\langle T\rangle$ of the tensors T are assumed to be Lorentz and possibly CPT-violating, any term that survives in $\mathcal{L}'$ after the spontaneous symmetry breaking must, on physical grounds, be suppressed, presumably by at least one power of $1/M$ where M is some high scale, possibly the Planck scale.

Thus, a hierarchy of possible terms, suppressed by M^k with $k = 0, 1, 2, ...$ appear in the effective theory. The leading CPT-violating term with $k \le 2$ have the schematic form

$$\mathcal{L}' \supset \frac{\lambda}{M^k}\langle T\rangle\bar{\psi}\Gamma(i\partial)^k\psi + \text{h.c.} \tag{8}$$

Here λ is some dimensionless constant, and Γ is some combination of the γ matrices. Terms with $k \ge 3$ are further suppressed.

For $k = 0$ we find two possible types of CPT-violating terms:

$$\mathcal{L}'_a \equiv a_\mu\bar{\psi}\gamma^\mu\psi, \quad \mathcal{L}'_b \equiv b_\mu\bar{\psi}\gamma_5\gamma^\mu\psi\,. \tag{9}$$

For $k = 1$,

$$\mathcal{L}'_c \equiv \frac{1}{2}c^\alpha i\bar{\psi}\overleftrightarrow{\partial_\alpha}\psi, \quad \mathcal{L}'_d \equiv \frac{1}{2}d^\alpha i\bar{\psi}\gamma_5\overleftrightarrow{\partial_\alpha}\psi, \quad \mathcal{L}'_e \equiv \frac{1}{2}e^\alpha i\bar{\psi}\sigma^{\mu\nu}\overleftrightarrow{\partial_\alpha}\psi\,, \tag{10}$$

where a_μ, b_μ, c^α, d^α and $e^\alpha_{\mu\nu}$ are invariant under CPT transformation. Together with the standard CPT transformation properties ascribed to ψ, this invariance causes the terms in eqs (9) and (10) to break CPT.

Including all the terms in eq. (9) the model Lagrangian can be written as

$$\mathcal{L} = \frac{1}{2} i\bar{\psi}\gamma^\mu \overleftrightarrow{\partial_\mu}\psi - a_\mu\bar{\psi}\gamma^\mu\psi - b_\mu\bar{\psi}\gamma_5\gamma^\mu\psi - m\bar{\psi}\psi\,. \tag{11}$$

One can do a similar job with the terms in eq. (10). While this formalism is available in [9], the goal of the project was to construct the low-energy effective operators out of these terms and study their effects on the B-systems.

References

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