Perspectives and Outlook from HEP Window on the Universe

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This brief review grew out from the HEP Concluding Talk of the 25th Anniversary of the Rencontres du Vietnam, held August 2018 in Quy Nhon. The first two-thirds gives a Summary and Highlights, or snapshot, of High Energy Physics at the end of Large Hadron Collider (LHC) Run 2. It can be view as the combined effort of the program organizers, the invited plenary speakers, and finally filtered into the present mosaic. It certainly should not be viewed as comprehensive. In the second one-third, a more personal Perspective and Outlook is given, including my take on the flavor anomalies, and why the next 3 years, the period of Long Shutdown 2 plus first year (or more) of LHC Run 3, would be Bright and Flavorful, with much hope for uncovering New Physics. We advocate extra Yukawa couplings as the most likely, next, New Physics to be tested, the effect of which is already written in our Matter Universe.

Keywords: HEP; New Physics; Extra Yukawa.

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1. HEP Summary and Highlights at End of LHC Run 2

Happy 25th Anniversary, Rencontres du Vietnam!!

I returned to Taiwan in 1992 and missed the first Rencontres du Vietnam held in 1993. But, lured by the 1995 total solar eclipse, I did join the second one held in Ho Chi Minh City. I still have the conference T-shirt, which I wore as a personal tribute when giving the “HEP Summary and Outlook” at the 25th Anniversary.[3]

In the first part of this brief review, which is adapted from the talk, I will cover the Highlights at the LHC and the corresponding experimental subjects, then flavor physics[4] neutrinos and Dark Matter (DM), then theory, and finally on Asia in the World. As there were only 7 theory talks out of a total of 37 plenary talks (I apologize for not covering parallel talks, as well as any other negligence), our emphasis would be on experiment. In the second part, I will offer a Perspective and Outlook on the HEP Window on the Universe.

a The main discussion of the “flavor anomalies” are deferred to the Outlook part.
Our emphasis would be the HEP physicists’ yearning for New Physics, i.e. physics Beyond the Standard Model (BSM).

1.1. **LHC as Window on the Universe**

The LHC has delivered spectacular performance at Run 2 (see Fig. 1), where a total of \( \sim 150 \text{ fb}^{-1} \) pp collision data were recorded by both ATLAS and CMS before entering Long Shutdown 2 (LS2, namely 2019–2020), while LHCb collected about twice the data of Run 1, i.e. \( \sim 6 \text{ fb}^{-1} \), but at higher \( b\bar{b} \) cross section.

The ALICE experiment, which celebrated its own 25th anniversary (ATLAS and CMS celebrated a year earlier), asks for special Pb-Pb, Xe-Xe, p-Pb, as well as pp collision runs at various energies, and epitomizes the LHC as a *Window on the Universe*: if Astrophysics, as discussed in our companion *Window on the Universe* conference, takes us back to 380,000 years after the Big Bang, such as with CMB (Cosmic Microwave Background), then the study of quark-hadron phase transitions and exploring the quark-gluon plasma takes us back to within a few microseconds after the Big Bang. Experimental topics cover strangeness enhancement, resonance scattering and nuclear modification effects, with energy densities at LHC reaching several times that of RHIC, the predecessor at Brookhaven. One probes timescales and (hydro)dynamics, strongly coupled liquid with small viscosity, phase diagram, etc., which are relevant to the Early Universe.

Of course, the Energy and Intensity (as well as neutrino) frontiers covered below all offer Windows on our Universe, pointing towards much earlier times.

1.2. **SM and BSM Higgs**

Since its observation in 2012\(^a\)\(^b\), the 125 GeV boson has been demonstrated to resemble the Standard Model (SM) Higgs boson\(^a\)\(^c\) remarkably well!

\(^a\) The p-Pb and Xe-Xe collisions were not in the original design for heavy ion runs!
One major highlight of 2018 is the completion of direct measurements, by both ATLAS and CMS, of third generation Yukawa couplings: all were found to be consistent with SM expectations. This started with the jet-assisted observation (when combined with Run 1) of $H \to \tau^+\tau^-$ in 2017 by CMS and the subsequent observation using Run 2 data alone. Then there was the observation of $t\bar{t}H$ production before summer 2018 (more on this later in the Outlook part). And finally, the observation of $H \to b\bar{b}$ in $VH$ production, which was officially announced in a joint seminar at CERN in late August 2018, shortly after the Rencontres du Vietnam. ATLAS had already announced it at ICHEP2018 in Seoul, but the CMS Spokesperson traveled to Quy Nhon for the make-up first announcement, culminating in the two subsequently submitted, and readily accepted, papers. What is remarkable is that $Z \to b\bar{b}$ provides "in situ" validation of the method, where excess above the $Z$ can be clearly seen, and found consistent with $H \to b\bar{b}$ in mass and cross section. Combining all available data, ATLAS and CMS give the $H \to b\bar{b}$ signal strength $\mu = 1.01 \pm 0.20$ and $1.04 \pm 0.20$, respectively, for the ratio compared with SM expectation. Note that both central values are remarkably close to 1, although each were a combination of several different processes.

The measured signal strength, or $\mu$, values are given in Table 1. Note that for ATLAS, it is combining with Run 1 that turns $H \to \tau^+\tau^-$ into an observation. With the Yukawa couplings $\lambda_\tau$, $\lambda_b$ and $\lambda_t$ all directly measured and found consistent with SM,\textsuperscript{21} the drive now is for the 13 TeV combined fit, for differential distributions, $H \to \tau^+\tau^-$, and di-Higgs (or $HH$) production.

For BSM Higgs bosons,\textsuperscript{18} one typically adds an extra scalar singlet (real or complex), doublet (2HDM), or triplet, or some combination. 2HDM is the most popular form, with usual notation of $H^0$, $A^0$ ($CP$-odd scalar) and $H^\pm$ for the exotic bosons, while the observed 125 GeV boson is denoted as $h^0$. Having an extra triplet offers a doubly-charged $H^{\pm\pm}$ boson, but otherwise it is not so easy to distinguish from a 2HDM. The most popular model is 2HDM II that is automatic in minimal SUSY (MSSM): up-type quarks couple to one doublet, down-type quarks (and charged leptons) to the other doublet. As alluded to already, a special phenomenon that emerged from LHC Run 1 is that $\cos(\beta - \alpha)$, the $h^0-H^0$ mixing angle between $CP$-even Higgs bosons in 2HDM II, appears to be small, i.e. $h^0$ is rather close

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & $\mu_{\tau\tau}$ & $\mu_{t\bar{t}H}$ & $\mu_{H^0bb}$ \\
\hline
ATLAS & $1.09^{+0.35}_{-0.20}$ & $1.32^{+0.28}_{-0.26}$ & $1.01 \pm 0.20$ \\
CMS & $1.24^{+0.29}_{-0.27}$ & $1.26^{+0.31}_{-0.26}$ & $1.04 \pm 0.20$ \\
\hline
\end{tabular}
\caption{Signal strength $\mu$ for Higgs boson coupled to third generation fermions. See text for discussion and references.}
\end{table}

\textsuperscript{c} We note in passing that CMS has probed the sign of top Yukawa coupling via $tH$ production,\textsuperscript{17} favoring the SM positive sign.
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to the SM Higgs boson. This alignment phenomena, that Run 1 data prefers the $\cos(\beta - \alpha) \to 0$ limit, should be pursued with vigor using full Run 2 data.

BSM Higgs bosons are searched for in many channels by ATLAS and CMS, exploiting interesting techniques in boosted analyses and background estimations with multivariate analysis (MVA). Unfortunately, no significant excess has been found so far. Sample searches with 13 TeV data include:

- Charged Higgs $H^\pm$, e.g. $H^+ \to \tau^+\nu$ and $H^+ \to t\bar{b}$ processes;
- Neutral $H^0$, $A^0 \to \tau^+\tau^-$ with large tan $\beta$ enhancement as exclusion in $m_{A^0}$-$\tan \beta$ plane;
- $h(125) \to a^0a^0 \to \mu^+\mu^-\tau^+\tau^-$ where $a^0$ is a light exotic pseudoscalar;
- $\ell\nu q\bar{q}$ search for heavy scalar that can decay to $WV$ and
- $h(125) \to Z_dZ_d \to \ell\ell'\ell'\ell'$ where $Z_d$ is a dark boson.

1.3. SUSY

Absence of SUSY is the single most important non-observation so far at the LHC.

\[ a \]

A mild local excess (less than 3$\sigma$) is found above 1.5 TeV.

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**ATLAS SUSY Searches** - 95% CL Lower Limits

| Model | $f_{a^0} < M_{A^0}$ | $f_{a^0} > M_{A^0}$ | $f_{a^0} > M_{A^0}$ | $f_{a^0} > M_{A^0}$ |
|-------|----------------------|----------------------|----------------------|----------------------|
|       |                      |                      |                      |                      |
|       |                      |                      |                      |                      |

**ATLAS Preliminary**

| Model | $f_{a^0} < M_{A^0}$ | $f_{a^0} > M_{A^0}$ | $f_{a^0} > M_{A^0}$ | $f_{a^0} > M_{A^0}$ |
|-------|----------------------|----------------------|----------------------|----------------------|
|       |                      |                      |                      |                      |
|       |                      |                      |                      |                      |

Fig. 2. Summary table of ATLAS SUSY search lower limits at 95% C.L., as of July 2018 [Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/].
SUSY is a great theory that could\textsuperscript{13} (help) solve three problems at once: the hierarchy problem, unification of gauge couplings, DM. In 2010, many thought SUSY would be seen soon after startup, with just 100 pb\textsuperscript{-1}: some expected it to be the first major LHC discovery, even before the Higgs. But, as Run 2 has come to an end, the reality is that SUSY is so far a “No Show”. Perhaps\textsuperscript{13} it is heavier than we thought, perhaps it is more devious or obscure, e.g. more weakly coupled, or not fulfilling all three tasks. Could it be R-Parity Violating (RPV), or hiding via Long-Lived Particles (LLP)? Or maybe Nature simply did not adopt it at this scale.

Many good ideas are still being explored\textsuperscript{13,26,27}, however, and SUSY is still a vibrant area of research, such as\textsuperscript{22} 1) compressed spectra (small mass splittings), 2) longer decay chains (less missing $p_T$), 3) lower rates (or\textsuperscript{13} “electroweakinos”), or complexities such as 4) LLPs (disappearing tracks, emerging jets), or 5) RPV. We will refer to these as 1)–5) in our Outlook, which may also refer to the five classes given in Fig. 2, where one can see the tremendous effort at ATLAS (with corresponding counterpart at CMS) with 13 TeV data. Although tendency is towards exploring higher masses with simplified models, there is plenty of unexplored model space at low mass.

It is now the duty of experiments to leave no stones unturned.

1.4. BSM/EXO

We know something new must appear somewhere, but what is the scale?

With emphasis on very heavy BSM particles, searches\textsuperscript{28} cover dibosons ($X \to WH, ZH, VV'$ and $HH$, as we have already seen in BSM Higgs search); vector-like quarks, or VLQ ($T \to bW, tZ, tH$, and $B \to tW, bZ, bH$), motivated as “top-partners” to help alleviate the hierarchy problem; and bosonic resonances with top in final state ($W' \to t\bar{b}, Z' \to t\bar{t}, t\bar{t}'$, and third generation leptoquark $LQ_3 \to \tau t$). These very massive particles produce highly boosted SM objects, hence reconstruction and identification of hadronic decays become critical to most searches. The hadronic decay tools often involve boosted jets or jet substructure at high $p_T$, such as a $W$-, $Z$- or $H$-jet, or a top-jet that merges a $b$- and $W$-jet, and MVA techniques are exploited to maximize the power of available statistics. In particular, we have witnessed rapid growth since 2017 in the application of deep neural nets and machine learning\textsuperscript{13,29,30}.

A common analysis issue is to tell a $W/Z \to q\bar{q}$ (or $t \to bq\bar{q}$, or $H \to b\bar{b}$) jet from a QCD jet, and one typically goes through\textsuperscript{28}

- Reconstruction: for example, CMS uses Particle Flow\textsuperscript{31} candidates as starting objects, and mitigate high pileup by using special tools such as PUPPI (PileUp Per Particle Identification)\textsuperscript{32}.

\begin{itemize}
  \item Particle Flow\textsuperscript{31} uses all available information to reconstruct physics objects, and produces a big improvement in jet energy resolution, tau-lepton identification, and helps with high pileup. It paves the way for future data analysis, and even detector design, at high energy hadron colliders.
\end{itemize}
**Fig. 3.** Summary table of ATLAS Exotics search lower limits at 95% C.L., as of July 2018 [Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/].

- **Grooming:** removal of soft and large-angle radiation to recover mass, such as (Jet) Trimming\(^{33}\) used in ATLAS, i.e. removal of any subjet within a cone of \(R = 0.2\) with less than 5% of the jet \(p_T\).
- **Tagging:** assign a “tag” to a jet, based on likelihood for “signal” or QCD, such as the use of Trimmed-jet mass, \(N\)-subjettiness\(^{34}\), and the ratio of the energy correlation function\(^{35}\) \(D_2\) by ATLAS.

Sample search results in 2018, based on Run 2 data, are:

- \(X \rightarrow VV'\) search in all-hadronic final states, via two highly-energetic large radius jets (ATLAS, \(\sim 80\) fb\(^{-1}\))\(^{36}\)
- \(X \rightarrow VH\) search with leptonic \(W\) and \(Z\) decays and \(H \rightarrow b\bar{b}\) merged jets (CMS, \(\sim 36\) fb\(^{-1}\))\(^{37}\)
- \(X \rightarrow WV\) search with \(W \rightarrow \ell\nu\) plus \(V \rightarrow q\bar{q}\) as single large radius jet (CMS, \(\sim 36\) fb\(^{-1}\))\(^{38}\)
- Search for VLQ pair production, namely \(TT\) or \(BB\) decay into final states with jets and no leptons\(^{39}\), as well as a combination paper\(^{40}\) of all VLQ pair production searches (ATLAS, \(\sim 36\) fb\(^{-1}\));
• Search for single VLQ production, i.e. $B \rightarrow tW$ with $t$ and $W$ highly boosted (CMS, $\sim 36$ fb$^{-1}$)$^{11}$

• Search for $W' \rightarrow T\bar{b}$ in the fully boosted $tH\bar{b}$ final state, involving $t$ and $H$ tagging besides usual $b$-tagging (CMS, $\sim 36$ fb$^{-1}$)$^{12}$

• Search for $Z' \rightarrow T\bar{t}$ production in lepton + jets, with $T \rightarrow bW, tZ$ and $tH$, where one top in $tZ\bar{t}$ or $tH\bar{t}$ decays semileptonically (CMS, $\sim 36$ fb$^{-1}$)$^{13}$

The boosted jet approach is intrinsically more sensitive for higher masses. Thus, heavy bosons are probed up to 3–4 TeV, and heavy fermions are probed up to 2 TeV. There are no clear signals so far.

Besides heavy BSM particles, there is a variety of other Exotics searches. In ATLAS, Exotics is defined as BSM without SUSY, though in CMS there is another group called B2G (Beyond 2nd Generation) aside from EXO, where EXO is the most productive physics group. Any given presentation on BSM/EXO search can cover only some limited slice of possible final states probed by ATLAS (see Fig. 3 for a Summer 2018 summary list) and CMS, and even LHCb. We give a snapshot of EXO topics$^{14}$ covered at Rencontres du Vietnam:

• Dijet resonance $X$ (e.g. technipion, $Z'$) search with $\ell = e, \mu$ trigger, probing $m_{jj}$ down to 0.25 TeV and up to 6 TeV (ATLAS, $\sim 80$ fb$^{-1}$)$^{15}$

• Inclusive dark photon $A' \rightarrow \mu^+\mu^-$ search, both prompt and long-lived (LHCb, 1.6 fb$^{-1}$)$^{46,47}$ which is a demonstration study by LHCb that follows a novel and promising phenomenological proposal$^{48}$ targeting Run 3.

• Search for heavy Majorana neutrino $N$ in same-sign dileptons plus at least one jet, i.e. $\ell N(q)$ production followed by $N \rightarrow \ell W$ (CMS, $\sim 36$ fb$^{-1}$)$^{50}$

• Search for Lepton-Flavor Violation (LFV): $X \rightarrow \ell\ell'$, where $X$ could be a $Z'$ or $\tau$-sneutrino, hence $\ell$ includes $\tau$ (ATLAS, $\sim 36$ fb$^{-1}$)$^{51}$

• Search for stopped LLPs, or Displaced Vertices, in calorimeter or muon system, during period of $> 700$ hours well separated from collision data (CMS, $\sim 39$ fb$^{-1}$)$^{13,52}$

To complement the last item, on theory side, a model of mirror fermions was presented$^{55}$ where an electroweak scale $\nu_R^H$ that belongs to a weak right-handed doublet offers$^{55}$ an example for LLP signature$^{6}$. The model provides a test of seesaw mechanism and a solution to the strong CP problem.

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$^f$ Interest in DM and dark photon search is not limited to LHC experiments. For instance, Belle has a recent result$^{20}$ that uses the dipion as tag in $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ decay, to search for $\Upsilon(1S) \rightarrow \gamma\chi\chi$, where $\chi$ is a low mass DM particle, with $\chi\chi$ off-shell or in resonance (from an $A^0$ mediator). Many flavor or other experiments have pursued DM or dark particle searches in various ways that we have not been able to cover.

$^g$ As we have mentioned LLPs many times already, we note the MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutral pArticles) proposal$^{55}$ a dedicated large-volume displaced vertex detector for the HL-LHC, which has now put forth the Letter of Intent$^{56}$. To operate on the surface above ATLAS or CMS, it claims better sensitivity than the two experiments by several orders of magnitude, and can search for LLPs at GeV mass or higher, up to $c\tau \sim 10^7$ m.
1.5. SM

Returning from Beyond SM back to SM itself\textsuperscript{57}, all measurements confirm it (see Fig. 4, which spans almost 10 orders of magnitude), but in the context of \textit{Windows on the Universe}, SM measurements play the essential role in testing our current understanding of the \textit{laws that govern} the Universe. On the other hand, for continued pursuit at High Energy and High Intensity frontiers, SM processes gives \textit{background} to all searches.

Let us mention a few highlights:\textsuperscript{57}

- Weak mixing angle $\sin^2 \theta_{\text{eff}}$: The ATLAS 8 TeV combined error\textsuperscript{58} of $\pm 0.00036$ is approaching LEP single experiment sensitivity, as well as the Tevatron combined error\textsuperscript{59} at $\pm 0.00033$. This appears quite promising, and we look forward to the full Run 2 data update, which probably would take some time.
- $W$ mass: ATLAS 8 TeV measurement reaches an accuracy of 19 MeV\textsuperscript{60}, which is already better than LEP, and approaching the Tevatron combined error.
- Vector boson scattering (VBS) observations: CMS has observed\textsuperscript{61} with $\sim 36 \text{ fb}^{-1}$ at 13 TeV, VBS production of same-sign $W^\pm W^\pm$ at $5.5\sigma$ ($5.7\sigma$ expected), and the measured fiducial cross section is in agreement with LO theory prediction. ATLAS has observed\textsuperscript{62} the mode at $6.9\sigma$ ($4.6\sigma$ expected by Sherpa) based on data of similar size, while observing\textsuperscript{63} also the electroweak production of $W^\pm Z$ plus two jets at $5.6\sigma$ ($3.3\sigma$ expected). These two observations, however, are still at conference paper stage. In any case, since higher order calculations are lacking...
except for same-sign $W^\pm W^\pm jj$, experiment is pushing theory to make progress on modes such as $WZjj$.

We see that the weak mixing angle and $W$ mass measurements at the LHC compare well with the GFitter global electroweak fit results. In the longer term, VBS can check the unitarity of $VV \rightarrow VV$ scatterings, to confirm the role of the Higgs boson directly.

1.6. Top

The top quark was discovered in 1995, but now “Top quarks are everywhere” For instance, the LHCb experiment, designed for B physics, recently measured forward $t\bar{t}$ production at 13 TeV by CMS at $\sqrt{s_{NN}} = 8.16$ TeV. Top quarks are indeed everywhere at the LHC. Like $M_W$, top mass is a key parameter in SM. Being the heaviest, it arises from the top Yukawa coupling $\lambda_t \simeq 1$, which affects vacuum stability of our Universe, as well as sourcing all kinds of loop effects such as in B decays and aggravating the hierarchy problem (hence motivating “top partners”).

As for top for its own sake, we touch two topics.

One topic is spin correlations in $t\bar{t}$ production and decay. Since the top quark decays before it hadronizes (there are no “top mesons”), the spin information is preserved. QCD-produced $t\bar{t}$ would be unpolarized, but NP could change this. Thus, spin-correlations, which can be extracted via the leptonic decays of the top pair ($pp \rightarrow e\mu b\bar{b}X$ signature), is in fact a probe of potential NP, and has been studied since Tevatron days. A recent result from ATLAS based on $\sim 36$ fb$^{-1}$ data at 13 TeV, indicates a rise in differential cross section w.r.t. the angular difference $\Delta\phi$ between the two charged leptons from $W^+W^-$ decay, with spin correlation larger than SM prediction by 3.7$\sigma$ (3.2$\sigma$ when theory uncertainty is included). This continues an earlier trend but with better precision. Let’s see how this evolves further, first with the corresponding CMS result, and with the full Run 2 updates.

A second, larger topic is the search for FCNC (Flavor Changing Neutral Couplings). After the 125 GeV boson was discovered, the pursuit of $t \rightarrow cH$ has been

![Fig. 5. Diagrams for singly produced top from $tqH$ coupling, or $t\bar{t}$ pair production followed by $t \rightarrow qH$ decay, both with $H \rightarrow bb$]
It is hard to separate a $c$-jet from a light quark jet in actual search. Further, it is common now to search for $t \rightarrow qH$ via both single top $qg \rightarrow tH$ production, as well as usual $gg \rightarrow t\bar{t}$ production followed by one top decaying via $t \rightarrow qH$, where $q$ stands for $u$ and $c$ (see Fig. 5). This is the case for a recent search by CMS, using $H \rightarrow b\bar{b}$ decay and based on $\sim 36 \text{ fb}^{-1}$ at 13 TeV. The signature is single lepton + 2/3/4 b jets for $tuH$ ($tcH$) coupling. Other final states are $h \rightarrow \gamma\gamma$, and multi-leptons (combining $WW^*$, $\tau^+\tau^-$ and $ZZ^*$). The current best limit, $B(t \rightarrow cH) < 0.16\%$ at 95% C.L., is by ATLAS using $\sim 36 \text{ fb}^{-1}$ at 13 TeV with $H \rightarrow$ multi-lepton final states. ATLAS has combined their results for TOP2018, setting 95% C.L. bounds for $B(t \rightarrow cH)$ and $B(t \rightarrow uH)$ at $1.1 \times 10^{-3}$ and $1.2 \times 10^{-3}$, respectively, with expectation at $8.3 \times 10^{-4}$ for both modes.

The usual FCNC $t \rightarrow cZ$ decay has been searched for since top discovery. With SM expectation far below $10^{-10}$, any discovery would indicate NP. Although CMS led the way initially, the current best limits are from ATLAS $B(t \rightarrow cZ) < 2.4 \times 10^{-4}$ ($3.2 \times 10^{-4}$) and $B(t \rightarrow uZ) < 1.7 \times 10^{-4}$ ($2.4 \times 10^{-4}$) at 95% C.L., with expectation in parenthesis. The ultra-rare decays $t \rightarrow c\gamma$, $c\gamma$ have also been searched for.

Current tCNC search limits are summarized in Fig. 6, and compared with theory expectations taken from 2013 Snowmass summer study. The search for $t \rightarrow cH$ is a current frontier where discovery could occur at any time (more discussion in context when more Higgs bosons are implied, but here we stick to notation used by the experiments.)
Outlook). In contrast, $t \to cZ$ seems to lack NP motivation nowadays. For example, the extra-dimension or RS model projection (see Fig. 1) is receding as direct searches place more stringent bounds.

1.7. Flavor & CPV

Flavor physics and CP violation (CPV) is a highlight subject. We keep this subsection short as we defer the discussion of flavor anomalies\textsuperscript{78,79} and the related theory, as well as the up and coming Belle II and kaon experiments, to the Outlook part.

Here, we just cover very briefly some CPV topics,\textsuperscript{80} where LHCb is pushing the current frontier. First, the measurement of the CKM phase angle $\gamma$ (called $\phi_3$ by Belle), which is the CPV phase of $V_{ub}$ in the standard PDG convention, is now dominated by LHCb, with error $\sim 5^\circ$ at present, and would continue to improve. Note that this parameter is as fundamental as the fine structure constant, $\alpha$. Furthermore, the measurement, based on interference of tree-level $B^+ \to \bar{D}^0(\ast)K^+$ and $D^0(\ast)K^+$ decays to common final states,\textsuperscript{81} is a key probe of CKM unitarity that can, in the limit of large statistics, become free from hadronic uncertainties.

Second, LHCb has found first evidence\textsuperscript{82} for CPV in the baryon sector at 3.3$\sigma$ in localized asymmetry measurements, i.e. in the $a_T^{T-\text{odd}}$ variable measured in phase space and $\Phi$-dependent (where $\Phi$ is the angle between the two decay planes formed by $p\pi^-_{\text{fast}}$ and $\pi^-_{\text{slow}}\pi^+$) binning of four-body $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays. The result is based on 3 fb$^{-1}$ data from Run 1.

Third, LHCb has found no evidence\textsuperscript{83} down to $10^{-3}$ precision, for indirect CPV in the variables $A_T$ via $t$-dependent study of $D^0 \to \pi^+\pi^-$, $K^+K^-$ decay, namely $A_T(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$ and $A_T(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$. Thus, there is no evidence so far for CP violation in the charm sector, which is in itself not too surprising. But one should recall the backdrop, that LHCb had once found evidence in early data (0.62 fb$^{-1}$) for direct CPV difference, $\Delta A_{\text{CP}}$, between the $D^0 \to \pi^+\pi^-$, $K^+K^-$ decay modes at the % level\textsuperscript{84} which caused some sensation, but unfortunately turned out to be a fluctuation\textsuperscript{85}.

1.8. Spectroscopy: XYZ States and Others

Charmonium-like XYZ particles\textsuperscript{86} started with the Belle discovery\textsuperscript{87} of X(3872) in 2003\textsuperscript{1} opening the window to multiquark hadrons, which has flourished as a subfield since. Sample reviews are Refs. 88 and 89. At the Rencontres du Vietnam, BESIII reported for the first time\textsuperscript{86} the 5.2$\sigma$ observation of $X(3872) \to \pi^0\chi_{c1}$ decay mode, with no evidence involving $\chi_{c0}$ or $\chi_{c2}$ in final state, which disfavors the $\chi_{c1}(2P)$ interpretation of X(3872).

What makes the case for four-quark (or molecular) states even more compelling are the “charged charmonium” states, such as Zc(3900) observed by Belle and BE-
SIII in 2013. For more detailed discussion, see Ref. [88]. At the Rencontres du Vietnam, BESIII also reported for the first time[86] strong evidence, at 4.3σ statistical significance, the \( Z_c \rightarrow \rho^- \eta_c \) decay mode in \( e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta_c \) production. In a recent paper published by D0[90] strong evidence (at 4.6σ) was found[59,86] for \( Z_c \) production in \( b \)-hadron decays to \( Y(4260) \), the famed \( 1^{--} \) state discovered by BaBar[91]. That is, \( Y(4620) \rightarrow Z^{\pm}c \pi^{\mp} \) with \( Z^{\pm}c \rightarrow \pi^{\pm}J/\psi \).

On a somewhat negative note, the \( X(5568) \) state that was claimed[92] by D0 may not be there. D0 claimed strong evidence (4.8σ) for \( X(5568) \rightarrow B_0^0 \pi^\pm \) decay in \( B_0^0 \rightarrow J/\psi \phi \). If true, this would be the first tetraquark with all four different flavors. However, besides further support[59] from D0 in \( B_0^0 \rightarrow \mu D_s^0 + X \) semileptonic decay, searches[86] by LHCb, CMS[93], CDF[95] and ATLAS[96] all turned out negative.

To show the vitality of the field of heavy flavor spectroscopy and the prowess of LHC experiments, we note some recent results by LHCb[78] and CMS:

- Doubly charmed baryon \( \Xi^{++}_{cc} \): Discovered only in 2017 by LHCb via \( \Xi^{++}_{cc} \rightarrow \Lambda^+_c K^- \pi^+ \pi^+ \). The experiment has measured the lifetime[97] and uncovered[98] a second channel, \( \Xi^{++}_{cc} \rightarrow \Xi^+_c \pi^+ \). All these results are based on 1.7 fb\(^{-1}\) from Run 2.

- \( \Omega^0_c \) lifetime: One of the striking results for summer 2018 is the LHCb measurement, based on 3 fb\(^{-1}\) from Run 1, finding \( \tau_{\Omega^0_c}^{\text{LHCb}} \approx 268 \text{ fs} \), which is four times the PDG value of \( \tau_{\Omega^0_c}^{\text{PDG}} \sim 69 \text{ fs} \)![99] This definitely needs to be digested by theory.

- New \( \Xi_0(6227)^- \) resonance: Observed[100] by LHCb in \( \Xi_0^0 \pi^- \) and \( \Lambda_0^0 K^- \) final states, with 3 fb\(^{-1}\) from Run 1 plus 1.5 fb\(^{-1}\) from Run 2.

- Resolved \( \chi_{bJ}(3P) \) mass splitting[101]. The \( \chi_b(3P) \) state, first observed around 10.5 GeV by ATLAS[102], is closest to the \( bb \) continuum, and could be[103] the “\( X_b \)” state[104] that corresponds to \( X(3872) \). With its strong 3.8T magnetic field and using 80 fb\(^{-1}\) of Run 2 data, CMS was able to resolve the \( J = 1 \) and 2 states via \( \chi_{bJ}(3P) \rightarrow \Upsilon(3S)\gamma^\prime \), with \( \Upsilon(3S) \rightarrow \mu^+\mu^- \) and \( \gamma^\prime \rightarrow e^+e^- \) (conversion in silicon tracker). Individual masses are measured at \( m_{\chi_{b1}(3P)} = 10513.42 \pm 0.41 \pm 0.18 \text{ MeV} \) and \( m_{\chi_{b2}(3P)} = 10524.02 \pm 0.57 \pm 0.18 \text{ MeV} \), with mass splitting at

![Fig. 7. Mass distribution for [left] \( \chi_{bJ} \rightarrow \Upsilon(nS)\gamma^\prime \), and [right] \( \chi_{bJ}(3P) \rightarrow \Upsilon(3S)\gamma^\prime \).](image-url)
10.60 ± 0.64 ± 0.17 MeV (see Fig. 7).

1.9. **Dark Matter**

DM is a vast subject at the intersection of astrophysics and particle physics that begs for improved understanding. We can only briefly touch the particle physics side, and what we present should be viewed as “windows” on subjects of pursuit.

Let us start with the classic WIMP (Weakly Interacting Massive Particle) search at the LHC, then direct search with novel approaches, and then into alternatives.

1.9.1. **WIMP: DM @ LHC**

DM search at LHC follows the WIMP paradigm, largely utilizing missing energy and mass, or “mono–X” processes, where $X$ is some tag particle, such as $q/g$-jet, photon, $W/Z$, $b/\bar{b}$ or $t/\bar{t}$, Higgs. A simplified model approach is adopted, parametrized by 4 free parameters (see Fig. 8): mediator and DM masses $m_{\text{Med}}$ and $m_{\chi}$, and mediator couplings to quarks ($g_q$) and DM ($g_{\chi}$).

A wide range of searches are pursued by ATLAS, CMS and LHCb with no excess observed so far, placing bounds on DM and mediator masses, including axial-vector and (pseudo-)scalar mediators. Some of the bounds can be found in Figs. 2 and 3.

New developments, such as emerging jets based on LLP type of ideas, are also being explored. An example is new particle search via “a jet and an emerging jet”, where the emerging jet corresponds to multiple displaced vertices, i.e. multiple tracks with large impact parameter. We have also discussed in Sec. 1.4 the related long-lived (hence displaced vertex) Dark Photon search by LHCb, and mentioned there in a footnote a recent search for low mass DM by Belle to illustrate the broad interest.

Our discussion is rather incomplete, and the analyses are evolving towards full Run 2 data. But the main point is that, unfortunately, there are no hints so far for any DM candidates from LHC searches or other accelerator searches.

1.9.2. **WIMP: Direct Detection**

As evidence for DM is gravitational, we live actually in the galactic DM cloud. Direct detection of WIMP particles is based on the recoil of some nucleus from collision
with cosmic DM particle, $\chi$. Because of our lack of understanding of the true nature of the DM particle(s), including spin, there is room for ingenuity, and DM direct detection has flourished into a global enterprise with many experiments\cite{SABRE}, including in East Asia and Australia (SABRE). The current bounds are illustrated by solid lines in Fig. 9 with dashed lines projecting into the future. This is quite exquisite a field, which we cannot go into any detail.

Two boundaries are being pushed. One is the Xenon-based large (> 1 ton) detectors, such as LUX/LZ\cite{LUX}, XENON\cite{XENON}, PandaX\cite{PandaX} aiming for large exposure time. These would push down in traditional WIMP mass range, towards the atmospheric neutrino background “floor”. But the relatively heavy Xenon loses sensitivity for DM mass below $\sim 10$ GeV\footnote{Hence recent developments in liquid Argon, such as DarkSide\cite{DarkSide} which explores far less radioactive underground, Argon sources, aiming eventually for background-free kton-year searches.}. This less explored region is the realm of cryogenic semiconductor (such as Silicon or Germanium) detectors pushing for low thresholds and amplified signals, such as SuperCDMS\cite{SuperCDMS} or CRESST\cite{CRESST}. We also see the development of ultra-pure Ge detectors, such as CDEX\cite{CDEX} at the deep China Jinping Underground Laboratory, where PandaX is also located.

Business for DM is by far not yet finished, but looking at the coverage in Fig. 9, the absence of a signal bears resemblance to the situation at the LHC. Are we on the right track?

1.9.3. **FIMP alternative\footnote{SuperCDMS\cite{SuperCDMS} aims for moving to SNOLAB (https://www.snolab.ca/) with iZIPs (interleaved Z-sensitive Ionization and Phonon) Ge detectors, and to start operation ca. 2020.} Search for milli-Q and Other Approaches**

Absence of any signal so far for WIMPs, both at the LHC and in direct detection, has stimulated thoughts for non-WIMP scenarios, such as “FIMP”\footnote{Hence recent developments in liquid Argon, such as DarkSide\cite{DarkSide} which explores far less radioactive underground, Argon sources, aiming eventually for background-free kton-year searches.}

The FIMP idea is based on a dark photon $\gamma'$ (often denoted as $A'$, as is the
case for the LHCb inclusive $A' \rightarrow \mu^+\mu^-$ search) that provides a portal to some hidden sector, where small kinetic mixing with the photon gives rise to some “hidden” milli-charged particles of unknown mass. Thus, instead of the WIMP freeze-out, cosmic abundance of DM is built up from slow production, which is called Freeze In (FI). In this case, traditional direct detection tests the idea in $t$-channel, and could be enhanced for light $\gamma$. If DM are milli-charged, hidden sector particles, they act as MIPs with very feeble $dE/dx$ and can traverse long distances. Proposed experiments such as milliQan can detect such particles produced in the CMS detector, passing through bedrock and well shielded from cosmic rays. A 1% demonstrator was installed in 2017, and has been running since. If funding arrives in time, a full-scale experiment could be installed during LS2, and run for Run 3 and beyond. We mention also the Light Dark Matter eXperiment (LDMX) concept, which covers other Light DM particles and mediators as well. For neutral Long-Lived Particles, we have already mentioned MATHUSLA in Sec. 1.4. There is also MoEDAL at the LHCb site (Point 8), searching for monopoles and other exotics.

Our coverage here is of course far from complete, and DM search is certainly not limited to WIMPs or even FIMPs. A very popular field of research is axion DM and its extension to ALPs (Axion-Like Particles). We refer to the short review of Ref. for the diverse and very active experimental approaches. Not to be forgotten are the indirect detection searches of astro-DM annihilation, such as the famous positron excess observed by PAMELA and followed up by AMS.

Understanding the nature of DM is of utmost importance, and LHC search is only part of a very broad program, which goes beyond traditional HEP.

1.10. Neutrino

We group present and future long baseline neutrino experiments, short baseline neutrino experiments, as well as neutrinoless double beta decay ($0\nu\beta\beta$) under the banner of neutrino physics.

1.10.1. NOvA

NOvA is a second-generation long baseline ($\sim 800$ km) experiment on the NuMI beamline from Fermilab, and is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations. It took neutrino data with $8.85 \times 10^{20}$ POT (protons on target) up to early 2017, the result of which was published recently. Anti-neutrino data taking continued until summer 2018, but a preliminary joint analysis of neutrino and anti-neutrino data (corresponding to $6.9 \times 10^{20}$ POT) was reported at Rencontres du Vietnam. NOvA finds $> 4\sigma$ evidence for $\nu_e$ appearance, the first such result for this channel. Less significantly, NOvA prefers normal mass hierarchy (NH) at $1.8\sigma$ level, and excludes $\delta_{CP} = \pi/2$ for the $CP$ phase at $3\sigma$ for inverted hierarchy (IH). Future running can reach $3\sigma$ sensitivity for normal mass hierarchy by 2020 if one has $\delta_{CP} = 3\pi/2$, and will cover a significant range of $\delta_{CP}$ by 2024.
1.10.2. Future Long Baseline Experiments

More intense beam power and larger detectors are needed for the next generation long baseline experiments to measure CPV, where effects are more pronounced at lower energies. Two main experiments are planned:

- **HK**: baseline of 295 km from J-PARC using water Cherenkov technology.\(^{134}\)
- **DUNE**: baseline of 1300 km from Fermilab, using liquid Argon technology.\(^{135}\)

Based on the success of Kamiokande and SuperK, which led to two Nobel prizes, it is natural to pursue an ever larger detector. Tokyo University announced\(^{136}\) in September 2018 for receiving “seed money” for HK (Hyper-Kamiokande), which by Japanese tradition implies that funding could start in 2019. Construction could then start in 2020, with data taking slated for 2026.\(^{134}\) This follows the proposal\(^{137}\) to extend T2K running (T2K-II) to \(20 \times 10^{21}\) POT, with continuous beam power increase to 1.3 MW for HK. The physics aims cover\(^{134,138}\) exclusion of \(\delta_{CP} = 0\): with a decade of running, 80% coverage of > 3\(\sigma\) exclusion, and can reach 8\(\sigma\) for \(\delta_{CP} = -\pi/2\), the current T2K best fit\(^{139}\) for Normal Hierarchy (see Fig. 10, lower curve).

By combining atmospheric and beam data, HK can determine mass hierarchy, and it will of course also address proton decay anew.\(^{1}\)

DUNE (Deep Underground Neutrino Experiment) and LBNF (Long Baseline Neutrino Facility) is the Fermilab answer\(^{135,141}\) to HK and T2HK, which arose after long soul-searching on how to transform itself as the only remaining dedicated HEP lab in the US. Since the DUNE Conceptual Design Report (CDR), the Near Detector (ND) design is now approaching final, with a CDR targeted for 2019. The Far Detectors would consist of \(4 \times 10\) kton LAr Time Projection Chambers (TPC), where two 1/20 scale “proto-DUNE” detectors (single and dual phase) have been constructed and tested recently at CERN (see *CERN Courier* October 2018 issue). DUNE TDR is expected in 2019, with schedule and target similar to HK. The beam

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1. It certainly would be nice to place a second HK in Korea\(^{138}\) downstream from HK in Japan, i.e. to have T2/HKK. But how this would materialize remains to be seen.
power of 1.2 MW is upgradable to 2.4 MW.

As a (heavy) flavor physics person, let me state, in envy: In contrast to the hierarchical pattern reflected in the CKM matrix, neutrino physics is privileged with three large mixing angles in the PMNS matrix, making $\delta_{CP}$ relatively accessible. But the interconnection between quark and neutrino flavor is not understood. Are the CKM and PMNS matrices related in any way? What about charged fermion vs neutrino masses?

CPV measurement, however, is further down in the timeline. The current race is for the aforementioned neutrino mass hierarchy: we know that $\nu_1-\nu_2$ are closer to degeneracy, but is $\nu_3$ higher (NH) or lower (IH)? Let us mention another worthy contender in this race: JUNO (Jiangmen Underground Neutrino Observatory). JUNO, a 20 kton liquid scintillator detector located in the Guandong province of China, is the successor to the successful DayaBay Neutrino Experiment which led the discovery, also in 2012, of sizable $\sin^2 \theta_{13} \simeq 0.09$, the third neutrino mixing angle. Benefiting from this, JUNO is fully funded and under construction, with start of data taking aimed for 2020.

1.10.3. Short Baseline Experiment

Interest here relates to the question of the possible existence of sterile neutrinos, beyond the three known active ones, which does matter for the Universe. Experimentally, it traces back to the LSND experiment in the 1990’s, then MiniBooNE and reactor neutrino measurements, giving a chain of anomalous excesses of $\nu_e$ in $\nu_\mu$ beam, or $\nu_e$ deficits from $\nu_e$ sources, typically at $L/E \sim 1 \text{ m/MeV}$.

The ongoing MiniBooNe experiment announced recently an excess of $\nu_e$-like events at too short a distance, and is consistent with a sterile neutrino interpretation of the old LSND result (see Fig. 11), where the two experiments have quite different systematics. But, of course, not everything fits perfectly on this subject.

![Fig. 11. Consistency between MiniBooNE $\nu$ and $\bar{\nu}$ data with LSND](image)
More sensitive tests are coming soon from reactor-based SoLiD, DANSS, NEOS, STEREO, PROSPECT experiments, and at the Fermilab Short Baseline Neutrino (SBN) program where a trio (SBND, MicroBooNE and ICARUS) of accelerator-based experiments using LAr TPCs are coming online by 2019–2020. The large number of experiments illustrates the keen interest.

The sterile neutrino landscape will certainly be scrutinized further!

1.10.4. $\nu_{\beta\beta}$: Quest for Majorana Neutrinos

In terms of experimental methodology, the pursuit of neutrinoless double beta decay ($0\nu\beta\beta$) measurement overlaps with some of the approaches with DM direct search.

Neutrinoless double beta decay can occur if the neutrinos are Majorana particles, i.e. their own antiparticles. The GERDA experiment reported recently new results on background-free search for $0\nu\beta\beta$, reaching half-life sensitivity at $8 \times 10^{25}$ ($\sim 10^{26}$) yr at 90 % C.L. Together with Majorana Demonstrator, linear improvement is expected, and as reported at the Rencontres du Vietnam, the next generation experiments (e.g. LEGEND) aim at a 100 fold increase in sensitivity, reaching $10^{28}$ yr!

This definitely should be watched and followed.

1.11. H.E. Universe: from IceCube to Theory

We group the recent IceCube result and a few theory topics under the H.E. Universe.

1.11.1. IceCube and the H.E. Universe

IceCube is an instrumented km$^3$ cube of ice at the South Pole, a multipurpose detector with main aim for cosmic neutrino detection. A pair of Science articles highlight some recent observations. A high-energy ($\sim 290$ TeV) muon neutrino track event, IceCube-170922A, points back to a known $\gamma$-ray blazar, TXS 0506+056. With direction and time window known, this triggered a multi-messenger confirmation of the blazar being in a flaring state, and IceCube finding a dozen of H.E. neutrinos (3.5$\sigma$) during 2014–2015. Thus, blazars appear to be a source of astrophysical $\nu$’s. Though not HEP per se, it offers a startling Window on the H.E. Universe!

IceCube itself has contributed to cosmic and atmospheric neutrino studies, astro-DM search, and a host of other interesting HEP topics.

1.11.2. Theory and the H.E. Universe

As a snapshot, we mention briefly some theory topics covered at the Rencontres du Vietnam (again, flavor anomaly discussion is deferred to Outlook):

\[ m_{\bar{\nu}_e} \text{ with sub-eV sensitivity} \]

We note that the ambitious tritium beta decay experiment, KATRIN, has started data taking in 2018, which would continue for 5 years. The aim is to measure $m_{\bar{\nu}_e}$ with sub-eV sensitivity.
• Pushing the Emergence Frontier.
  Using half-filled Landau levels in condensed matter physics to illustrate the Emergence of composite Dirac fermions, and implications for HEP, duality, etc.

• Inflation as Cosmological Collider.
  Viewing inflation as a cosmological collider at the Hubble scale, characteristics of very massive particles could be recorded in the primordial non-Gaussianities.

• Gravitational Waves (GW) as Probe of Early Universe.
  GWs from first order phase transitions (collision of bubble walls) and cosmic defects are detectable by detectors such as LISA, which can probe both the Early Universe, as well as High Energy Physics. See Ref. [169] for a review.

• Ideas on Origin of the Weak Scale.
  Newer ideas of twin Higgs, relaxion (making Higgs mass dependent on the axion field), and “Intelligent Ultraviolet Completion” (IUVC). The latter is high-scale SUSY where Higgs mass is protected by a symmetry invisible from 4D.

1.12. ILC/CEPC: Asia! (?)

There is no doubt that Asia is ascendant economically, but it may also be ascendant in world HEP, or the HEP world. This is especially potent an issue at this 25th anniversary of the Rencontres du Vietnam. How would things look at the 50th anniversary!

The most important thing, at time of Rencontres du Vietnam, is to hear the positive decision by end of 2018 from the Japanese government on whether, or not, to host ILC250 in Japan and start the international negotiations. Signs at the dedicated LCWS2018 conference held October in Arlington, Texas, looked promising. The ideal timeline would be construction start in $\sim 5$ years, and completion by another 9 years. Unfortunately, the Science Council of Japan issued a negative report in December 2018. But all is not lost, as the final decision is with the Japanese government, and things in Japan are “subtle”, i.e. often not as it seems on the surface. MEXT of Japan has announced that the decision would be deferred until before the joint meeting of LCB (Linear Collider Board) and ICFA (International Committee for Future Accelerators), to be held early March 2019 in Tokyo.

The world is clearly waiting and watching for Japan’s decision on the ILC. The other large Asian economy, China, has proposed the CEPC-SPPC, which is the 100 km analog of LEP-LHC, i.e. a Super-LEP/LHC complex, starting with the CEPC (Circular Electron Positron Collider) “Higgs Factory”. Since the 2015 Pre-CDR, or the preliminary studies, the CDR was finally completed in 2018.

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\(a\) During Rencontres du Vietnam, ICTP announced that Prof. Dam Thanh Son, the speaker on this subject, received the Dirac Medal, for work that crosses high energy and condensed matter (even nuclear) physics boundaries. Congratulations, and even better works to come!

\(o\) At the last iteration of the ILC (International Linear Collider) saga, ca. 2016–2017, the proponents decided to shorten the length to reduce (initial) cost, relying on the extendability, and progress in klystron or acceleration technology, for future extensions.
The next step is the TDR, and ideally construction could start in 2022, taking also \( \sim 9 \) years towards completion.

It would be nice if CEPC and ILC could run in parallel initially as Higgs factories to crosscheck each other. But they would take different evolution paths. If both the ILC and CEPC could be realized, Asia would definitely take center stage in world HEP by the 50th anniversary of the *Rencontres du Vietnam*! We give in Fig. 12 the map of the current AsiaHEP member states. The amalgamation of ACFA and AsiaHEP is planned for early 2019, to make it closer to ECFA in structure, composition and mission. With its economy fast rising, Vietnam is welcome to join when its HEP community matures.

2. Perspective and Outlook

LHC Run 2 has ended, and Long Shutdown 2 has began. Judging from the past, the “Run 2 Era” extends well beyond LS2 into at least 2021. With data increase by a factor of 5 from Run 1 and almost double the collision energy to 13 TeV, there is much to look forward to. Besides LHC data-mining, with turn-on and data collection at many new facilities and experiments, especially along the flavor front, *the Outlook is Bright (and Flavorful)*.

2.1. No New Physics: SM Checks Out, Again

One thing impressed me greatly in summer 2011:

"Unfortunately, no hint of New Physics in the LHC data (yet)."

\(^p\) As of 2018: Australia, China, India, Japan, Korea and Taiwan, plus Novosibirsk.
This was up to 1/2/3 TeV mass bounds, depending on the type of New Physics. Unfortunately, to date the statement rings true, and there is Angst at the LHC! Take SUSY for example. To quote Dan Piraro (Bizarro comics: elephant in the room):

“If you were in the middle of the room the whole time, why can we not find a single witness to corroborate your testimony?”

The same holds true for any NP. Note that the bulk of “the room” has been quickly scanned already. So, the search continues, but in Cracks? This reminds us of the 1)–5) vibrant search areas mentioned in Sec. 1.3 of our Summary and Highlights (see Fig. 1). As NP with SM coupling strength seems exhausted up to a few TeV, there may still be particles out there with couplings weaker than in SM (and they need not be LLPs!), and that is why we have to run the full course of the HL-LHC, to gain the statistical power. We must dutifully walk the walk, and we may get rewarded that way. Who knows.

So, No New Physics in sight, and SM checks out real well. Along this line, the top three highlights at the LHC so far are (to me):

- Discovery of $h(125)$ in 2012 by ATLAS and CMS and that it so resembles the SM Higgs boson. If SUSY is not seen, “No Higgs” is definitely gone, and we have stressed the remarkable proximity of $h$ to SM-Higgs, the mysterious alignment phenomenon. What would full Run 2 data reveal to us?
- Finding $B_s$-mixing CPV phase $\varphi_s \sim 0$ by LHCb in 2011, prior to the Higgs boson discovery. One should recall that there were some good hope, both theoretical and experimental, even at the Tevatron, for a sizable $\varphi_s$ that deviated significantly from SM. With the hope dashed, it has been, and would be, slow motion towards measurement of $\varphi_s^{[SM]}$. There still might be discovery along the way.
- Observation of the very rare $B_s \to \mu^+\mu^-$ decay in 2015, by combining CMS and LHCb Run 1 data, which LHCb could reaffirm as single experiment in 2017 by adding 1.4 fb$^{-1}$ Run 2 data. Though the end result may disappoint, it is the crowning glory of the high-stakes saga, especially at the Tevatron, that SUSY or the related 2HDM type II could have greatly enhanced $B_s \to \mu^+\mu^-$ by $\tan^6 \beta$. We will have to see whether $B_d \to \mu^+\mu^-$ can be observed with full Run 2 data.

And the highlight of 2018? To me it is the observation of $t\bar{t}H$, by both CMS and ATLAS (see Fig. 13). By fate — help of “the red line”, the largish Run 1 result at 3.2$\sigma$ — CMS could publish with $\sim 36$ fb$^{-1}$ data at 13 TeV, but ATLAS had to add more Run 2 data to some of the modes. The process is just radiating $H$ off the top in the QCD production of $t\bar{t}$. But why is there no hoopla? From my Flavor background, the direct measurement of the Top Yukawa coupling, $\lambda_t$, and finding consistency with the expected SM value of $\sim 1$, is a true landmark event.
After all, $\lambda_t$ is the Mother of most SM loop effects, be it Flavor/B-Physics, or effective $ggH, \gamma\gamma H$ couplings. Alas, it went also largely ignored by flavor folks at the FPCP2018 conference held July 2018 in Hyderabad, India.

Together with observation of $H \to \tau^+\tau^-$ and $H \to b\bar{b}$ (see Table 1), all consistent with SM expectations, we have now measured third generation Yukawa couplings directly, confirming $\lambda_f = \sqrt{2} m_f / v$, where $v$ is the vacuum expectation value (v.e.v.) of the SM Higgs field. But people seem to want signs for New Physics so badly, observing SM-like $t\bar{t}H$ (and $H\tau^+\tau^-$ and $Hb\bar{b}$) coupling is not good enough.

### 2.2. Flavor, where the Anomalies/hoopla are!

There is no doubt that all current “anomalies” are in the flavor sector\cite{78,79} We have, in order of the first announcements\cite{81}

- $R_{D^{(*)}}$ anomaly: the ratio of $B \to D^{(*)}\tau\nu$ rate with $B \to D^{(*)}\mu\nu$;
- $P_5'$ anomaly: the angular variable in some $q^2 = m_{\ell\ell}^2$ bin(s) of $B \to K^+\mu^+\mu^-$;
- $R_{K^{(*)}}$ anomaly: the ratio of $B \to K^{(*)}\mu^+\mu^-$ rate with $B \to K^{(*)}e^+e^-$. 

#### 2.2.1. High $p_T$ Response to Flavor Anomalies

After much hoopla from theorists in the past 5–6 years, two popular NP pictures have caught the attention of high-$p_T$ experiments in 2018: $Z'$, and leptoquark (LQ).

But let us first stress the impressive fit (see Fig. 14[left]), that $R_{K^{(*)}}$ and $P_5'$ can be accounted for by a shift\cite{180} $\Delta C_9 \simeq -1$, in the $C_9$ Wilson coefficient, hence of similar strength to SM, where we cite only a sample reference (similarly below). A common interpretation is a $Z'$ mediating the $b \to s\ell^+\ell^-$ decays, which could be\cite{154} the gauge boson of $L_{\mu} - L_{\tau}$ symmetry. CMS took notice of this\cite{13} and made a specific search for the $L_{\mu} - L_{\tau}$ gauge boson\cite{154} via on-shell $Z \to \mu^+\mu^-Z' \to \mu^+\mu^-\mu^+\mu^-$ using $\sim 77$ fb$^{-1}$ at 13 TeV\cite{154} which is illustrated in Fig. 14[center]. Note that searching in $Z$ decay limits sensitivity to relatively light $Z'$.

When all things are considered, LQ is favored for the $R_{D^{(*)}}$ anomaly, which can in principle also account for $R_{K^{(*)}}$. High $p_T$ again took notice, and CMS made it a
highlight result at the ICHEP2018 summer conference held in Seoul, pursuing singly produced \( \tau b \)-LQ via \( b g \to \tau^– LQ \to \tau^– \tau^+ b \), to probe the parameter space (see Fig. 14[right]) of some combined model projection. The vertical line in the plot at \( \sim 850 \) GeV is from an earlier LQ-pair production search, which has just been updated by CMS to 1.02 TeV, to be compatible with the 13 TeV dataset used for the single-LQ production search.

While I would emphatically state my bias against LQs (“Why LQs Now!?”), the significance of these two searches is that high-\( p_T \) experiments are now paying attention to flavor anomalies.

We have already mentioned that there is no lack of theory activities on the flavor anomalies, and they are indeed too numerous to mention. The plenary speaker at Rencontres du Vietnam, Gino Isidori, also chose to present a perspective (that bypassed \( P_5' \)). It was first emphasized that the stated anomalies, “IF taken together, . . . is probably the largest ‘coherent’ set of NP effects in present data . . . ” And that, “What is particularly interesting, is that these anomalies are challenging an assumption – LUV – that we gave for granted for many years (without much good theoretical reasons . . . ).” With LUV standing for Lepton Universality Violation, we certainly concur with the last statement, as well as to keep an eye on \( \tau \to \mu \) LUV processes. We have already cited the simplified LQ model work that CMS set forth to probe, as discussed above. But Gino went on to sophisticated (UV) model building, such as “PS3” i.e. having 3 copies of Pati-Salam symmetry to accommodate the flavor (mass and mixing) hierarchies, which is becoming a bit much for our taste. It does illustrate that there are no convincing models out there to cover all the flavor anomalies.

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\[ \text{It should be mentioned that there was a hint by CMS Run 1 data for sizable } h \to \tau \mu \text{ decay, at } \sim 1\% \text{ level with } 2.4 \sigma \text{ significance. Together with the theory suggestion that prompted the } h \to \tau \mu \text{ search at LHC, interest in } \tau \to \mu \text{ LUV processes such as } \tau \to \mu \gamma, \text{ and other modes should still be watched.} \]
2.2.2. Experimental Caution/Reminder on Flavor Anomalies

Inasmuch as they are our current Best Hopes for BSM indications, but keeping in mind that Physics is an experimental science, let me put forth the grains of salt I have regarding these flavor anomalies from the experimental viewpoint.

LUV: $R_K$, $R_{K^*}$ Anomalies

Must Love the LUV: The $R_{K^{(*)}}$ ratios which test Lepton Universality are theoretically clean! But, after the original $R_K$ result\textsuperscript{194} of 2014 that showed $-2.6\sigma$ discrepancy with SM for $q^2$ in $1.0 - 6.0$ GeV$^2$, it took 3 years for LHCb to put forth\textsuperscript{195} the $R_{K^*}$ measurement (see Fig. 15). The two $R_{K^*}$ bins are for $q^2$ in $0.045 - 1.1$ GeV$^2$ and $1.1 - 6.0$ GeV$^2$, showing $-2.2\sigma$ and $-2.4\sigma$ downward shifts, respectively. Looks brilliant. However, why change from 1.0 to 1.1 GeV$^2$? It is to cover the $\phi$ meson: the lower $R_{K^*}$ bin is dominated by the photon. But the photon coupling to $e$ and $\mu$ is certainly Universal. So, at EPSHEP2017 summer conference held in Venice, I had cautioned relatively loudly with something like, “I will bet that LHCb measured the lower $R_{K^*}$ bin as a sanity check, since it is expected to be consistent with SM.” If SM was confirmed in the lower bin, LHCb would have proclaimed victory, and then combine the two corresponding (in $q^2$) $R_K$ and $R_{K^*}$ bins. Given the common drop for all three measurements, I stress that one ought to follow Occam’s advice and keep in mind the “simpler” explanation: rather than NP, could it be some common systematics, perhaps traced to normalizing\textsuperscript{195} on $B \to K^{(*)}J/\psi (\to \mu^+\mu^-, e^+e^-)$?

Is $P_5'$ Anomaly Real?

Published in 2013 using 1 fb$^{-1}$ data\textsuperscript{196} the $P_5'$ anomaly was LHCb’s first, finding $3.7\sigma$ discrepancy with SM in a particular $q^2$ bin of the angular variable $P_5'$. This already lead to many theory papers toting $\Delta C_9 \sim -1$ in 2013, but questions also arose whether this was a fluctuation among many measurables, or possibly due to

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\textsuperscript{1} Well, call it the advice from an “Experimentheorist”.

\textsuperscript{2} In fact, the downward shift from 1.0 is the largest for the lower $q^2$ bin, but its SM expectation is lower because of dimuon threshold effect.
the $c\bar{c}$ threshold, i.e. hadronic, effects. But perhaps more symptomatic was when LHCb announced the 3 fb$^{-1}$ result at Moriond 2015, significance of the discrepancy dropped slightly to 3.4σ, despite the increase in statistics allowed splitting the bin into two. That is, while errors improved, the central values of both bins moved closer to SM. Statistically speaking, there is nothing “wrong” with this, but when I first learned about it, I quipped that this is “Not Good, Not Bad . . . Not Too Good”. If the original measurement was close to “Truth”, one would expect the significance to improve somewhat when data tripled. It also makes the $c\bar{c}$ threshold issue more troubling. Adding on top of this was the CMS announcement in 2017, based on 8 TeV data, where the values in the two bins are consistent with SM. Note that Belle has one broad bin that is consistent with LHCb but with less resolution, while ATLAS lacks a second bin, even though the first bin shows wide deviation.

The issue can only be resolved by more data, preferably by multiple experiments.

Is $R_{D^*}$ Anomaly Real?

Fig. 16 from Heavy Flavor Averaging Group (HFLAV) gives the history and evolution of $R_D$–$R_{D^*}$ measurement, where discrepancy of world average (central “red” ellipse) and SM (very small gray ellipse) is at 3.7σ. The two larger ellipses are the measurements by BaBar and Belle in 2012 and 2015, respectively, with Belle disagreeing neither with BaBar, nor with SM. The BaBar result of course already caught interest of theorists. But the surprise announcement by LHCb in 2015 of its prowess to measure $R_{D^*}$, where the horizontal dashed-line band concurred with BaBar, turned it into a sensation for the theory world. What we wish to caution is in regards the two most recent results: the $R_{D^*}$ measurement by LHCb and the $R_{D^*}$ and $\tau$-polarization measurement by Belle both published in 2018 and utilize $\tau \to 3$-prong (rather than $\tau \to \mu\nu\nu$ for all previous studies), and are in full

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1 The acronym was changed from HFAG since Moriond 2017.
agreement with SM. Could there be some common systematics in taking the ratio of $B \to D^{(*)}\tau\nu$ to $B \to D^{(*)}\mu\nu$ with $\tau \to \mu\nu\nu$ decay?

The issue clearly can only be resolved by more data, plus diligence.

2.3. Whither Extra Yukawas?

While we eagerly await the LHCb update of any of the flavor anomalies with Run 2 data (indeed, the silence has been deafening), let me finally offer some personal perspective, on Extra Yukawa Couplings, which I deem as the most likely, next, New Physics.

All CPV measured in the laboratory so far are accountable by the Kobayashi-Maskawa phase, which is rooted in Yukawa couplings, as are CKM matrix elements. This naturally begs the question: Are there Extra Yukawas?

After all, the Jarlskog invariant is way too small in SM for the disappearance of Antimatter from the Universe. With a second Higgs doublet, one would naturally have a second set of Yukawa couplings. Alas, extra Yukawas in usual 2HDM were killed by the Natural Flavor Conservation (NFC) condition of Glashow and Weinberg (usually realized by a $Z_2$ symmetry), for fear of FCNH couplings.

2.3.1. Nothing Natural about NFC

But with one Higgs doublet confirmed by the $h(125)$ discovery, a 2nd doublet is now highly plausible, and the NFC condition should be reexamined. We advocated recently the $tch$ coupling, where $\rho_{tc}$ belongs to the least constrained extra Yukawa couplings in a 2HDM without $Z_2$: $\rho_{cc}$, $\rho_{ct}$, $\rho_{tt}$. The $\rho_{ct}$ coupling is actually constrained by $H$ physics to be rather small, and I now think $\rho_{tt}$ should be $O(\lambda_t)$, i.e. $\rho_{cc}$ should be suppressed by $m_c/v \lesssim 0.005$, but $\rho_{cc}$, $\rho_{tt}$ ought to be $O(\lambda_t) \sim 1$.

Eq. (1) improves on the Cheng–Sher trickle-down argument (which I coined the “type III 2HDM” name) when I first advocated $t \to ch$ decay a long time ago. The $tch$ coupling is modulated by $\cos(\beta - \alpha)$, the $h-H$ mixing angle, where $H$ is the exotic $CP$-even neutral Higgs of the extra Higgs doublet. In this sense, if $\cos(\beta - \alpha)$ is small, which is reflected in the apparent alignment phenomenon that $h$ appears rather close to SM Higgs, the non-observation of $t \to ch$ so far (see Sec. 1.6 and Fig. 6) need not imply a small $\rho_{tc}$ as yet. So, in place of NFC, the trickle-down flavor pattern, alignment, and $1/m_H$ suppression can work together to suppress effects of off-diagonal $\rho^{(f)}_{ij}$ Yukawa couplings, where $f = u, d, \ell$. Glashow and Weinberg need not have invoked NFC over 40 years ago to protect against FCNH.

Note that, without a $Z_2$ symmetry, one cannot actually distinguish the $\Phi_1$ and $\Phi_2$ doublets, hence $v_1$ and $v_2$, and thus $\tan \beta = v_1/v_2$ is ill-defined. We therefore
replace $\cos(\beta - \alpha)$ in Eq. (1) by $\cos \gamma$, the notation which was first used in Ref. 210. We note that this reference provides a one-loop protection mechanism for alignment: with the right sign, $\rho_{tt} \sim O(1)$ can restore $|\sin \gamma| \to 1$ from sizable bosonic loop corrections arising from $O(1)$ Higgs quartic couplings.

2.3.2. Electroweak Baryogenesis

With $O(1)$ Higgs quartic couplings able to give rise to 1st order electroweak phase transition (EWPT), it was noted recently that $\rho_{tt} \sim O(1)$ can come hand in hand to provide a rather robust mechanism for electroweak baryogenesis (EWBG). The extra top Yukawa coupling $\rho_{tt}$ is naturally complex, and as the 33 element of the combination of the two Yukawa matrices that is orthogonal to the one that gave the up-type mass matrix, it is also naturally $O(1)$. A study of the top scattering at the expanding bubble wall (from 1st order EWPT) gives the leading CPV source as

$$\lambda_t \text{Im}\rho_{tt},$$

(2)

which suffers no suppression factors, compared with the multiple suppression by small-Yukawa-couplings for the Jarlskog invariant in SM.

Scanning over $|\rho_{tc}|$ and the phases of $\rho_{tt}$ and $\rho_{tc}$, we produce the scatter plot (Fig. 17) of $Y_B/Y_B^{obs}$, the ratio of baryon production with respect to what is observed (e.g. by Planck), versus $|\rho_{tt}|$. With a “margin” of almost two orders of magnitude, the mechanism is indeed rather robust. We note also that, in case $\rho_{tt}$ is accidentally small, from the (green) crosses that correspond to larger $|\rho_{tc}|$ values, a second backup mechanism can come from sizable $\rho_{tc}$ with near maximal CPV phase. In making this plot, $\rho_{tc}$ and $\rho_{tt}$ are checked against $B_d, B_s$ mixings and $b \to s\gamma$ constraints. Also, the exotic Higgs bosons were held degenerate at $m_H = m_A =$
2.3.3. Extra Yukawa as Experimental Issue

The existence of Extra Yukawas is actually an experimental issue.

When we discovered $m_h < m_t$, nothing stops the experimentalist, young or old, to search for $t \rightarrow ch$, because it can, and must (PDG entry!), be done. However, unlike most New Physics arising from some high scale, this is a dimension-4 term, i.e. a regular Lagrangian term in the form of a Yukawa coupling, hence immediately implies the possible existence of an extra doublet that can give rise to extra Yukawas.

Thus, logically, ever since the Higgs boson discovery, we have been probing for Extra Yukawa couplings via $t \rightarrow ch$ (and $h \rightarrow \tau\mu$) search. If discovery is made any time soon, it would have to be a tree-level effect, rather than the ultra-suppressed loop-induced effect in SM. This explains my advocacy, or fondness, of Fig. 6.

The logical extension, then, is to treat all extra Yukawas, $\rho_{ij}^{(f)}$ ($f = u, d, \ell$), as experimental issues.

2.3.4. Curious: Alignment as Emergent

From the proximity of $h$ to the SM-Higgs, we have already mentioned that $|\sin \gamma|$ is rather close to 1, hence $|\cos \gamma|$, the mixing parameter between $h$ and $H$, is rather small. This is a little puzzling if $m_H$ is sub-TeV (rather than decoupled at several TeV). What may be worse, it superficially runs against $O(1)$ Higgs quartic couplings, which can be felt as generally inducing sizable $|\cos \gamma|$.

With this fuzzy backdrop, it was found\cite{213} that, curiously, there is considerable parameter space for alignment. As Higgs quartics are numerous in number, and also to face electroweak precision measurement constraint, we illustrate\cite{213} in Fig. 18 the allowed parameter space in Higgs quartic couplings $\eta_1$ and $\eta_6$ corresponding to alignment (small $\cos \gamma$).

$m_{H^+} = 500$ GeV for simplicity. On one hand, the parameter space is even broader. On the other hand, the sub-TeV values make the scenario even more attractive.
allowed parameter space in $\eta_1$ (controls $m_h$) vs $\eta_6$ (controls $h-H$ mixing) where custodial SU(2) symmetry is assumed such that $m_A = m_{H^+}$ so the $T$ parameter constraint is easier to accommodate (which cuts off the horn shaped regions for given $m_A = m_{H^+}$). To the lower left, the tip of the horn, one has extreme alignment as $\eta_6 \to 0$ and $\eta_1 \to m_h^2/v^2$. But there is much solution space for $\eta_6$, even $\eta_1$, being $O(1)$. The true solution space is even larger if one just impose the EW precision constraints, but it becomes harder to plot. Thus, the alignment phenomenon is not difficult to accommodate for sub-TeV exotic Higgs bosons. Away from extreme alignment, or alignment limit, one has $|\cos \gamma| < 1/4$ for sufficiently large $m_H^2 - m_h^2$ splitting but sizable $\eta_6$. In fact a finite $\eta_6$ mixing parameter can help by level repulsion, as can also be seen from Fig. [18]. We note that the diagonal contribution to $m_H^2$ is fed by the Higgs quartics $\eta_3, \eta_4, \eta_5$ and the decoupling mass $\mu_2^2$, and could easily be larger than $m_h^2$, which has only the diagonal contribution coming from $\eta_1$.

2.3.5. Upshot: Top-Higgs, to “Flavored” Higgs, to SM2?

To summarize, two observations

(1) $O(1)$ Higgs quartic couplings plus $O(1)$ complex $\rho_{tt}$ (or $\rho_{tc}$) give remarkably efficient EWBG

(2) $O(1)$ Higgs quartic couplings, needed for 1st order EWPT, can readily support approximate alignment!

convince me that “Extra Yukawas via 2HDM without $Z_2$" may well be the next New Physics. To reduce the mouthful of words by removing redundancy, we recently dubbed [31] it “SM2”, i.e. SM with a 2nd Higgs doublet — no added assumptions and just let Nature speak. This SM2 can be probed at LHC via $cg \to tH^0$, $tA^0 \to t\bar{t}c$ (same-sign top), $tt\bar{t}$ (triple-top) signatures and may impact on $B^+ \to \mu^+\nu$ and electron electric dipole moment (e-EDM) to name just a few processes.

If I may raise any caution, I must say that we know very little, experimentally, about the Higgs potential, or Higgs sector self-couplings. But the flavor side, i.e. extra Yukawa couplings, stand on firmer ground, as we already know that a plethora of Yukawa couplings exists in SM, which Nature has expressed the nontrivial mass and mixing hierarchies.

\[ \cos \gamma \simeq \frac{-\eta_6 v^2}{m_H^2 - m_h^2}, \]

where one can easily achieve $|\cos \gamma| < 1/4$ for sufficiently large $m_H^2 - m_h^2$ splitting but sizable $\eta_6$. In fact a finite $\eta_6$ mixing parameter can help by level repulsion, as can also be seen from Fig. [18]. We note that the diagonal contribution to $m_H^2$ is fed by the Higgs quartics $\eta_3, \eta_4, \eta_5$ and the decoupling mass $\mu_2^2$, and could easily be larger than $m_h^2$, which has only the diagonal contribution coming from $\eta_1$.
3. Run 2 Era Looks Bright, and Flavorful

The LHC Run 2 has come to an end. However, with all data now at hand, in a sense the Run 2 Era has just begun. Judging from Run 1 and LS1, many good results based on full Run 2 data would appear during LS2, extending actually into 2021, the first year of Run 3 start, and even beyond. Thus, I will continue to call 2019–2021, the next three years, as “Run 2 Era”.

The ATLAS and CMS experiments have collected more than $5\times$ the data of Run 1, and at higher energy. The LHCb experiment has collected more than $2\times$ the data of Run 1, and at higher energy. This already makes the Outlook Bright, brighter than anticipations for Run 3 Era, where only a doubling of Run 2 data is expected, with little change in energy. Furthermore, the $B$ physics program of Belle II would commence in Spring 2019, ushering in a new decade where dark photon, $R_D$–$R_{D^*}$ anomaly, $B^+ \rightarrow \mu^+\nu$ and other measurements, clarifications and searches could fall into our “Run 2 Era” (i.e. by 2021). See the Belle II Physics Book for more discussion.

Besides Belle II and the LHCb-driven flavor anomalies, there are many experiments related to flavor that are ongoing, such as

- First result by NA62 at CERN on $K^+ \rightarrow \pi^+\nu\nu$ search targeting SM measurement eventually;
- The recent order of magnitude improvement of $K_L \rightarrow \pi^0\nu\nu$ bound by KOTO at KEK, and search for exotic $K_L \rightarrow \pi^0X^0$ where $X^0$ is a “dark” object with mass around $\pi^0$, with more data at hand plus continued running;
- The new muon g–2 experiment at Fermilab, where we may hear first results as early as 2019, then the second installment in 2020 (where data taking will end), and the definitive result might be delivered by 2021 (!);
- Having reached the impressive $B(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ at 90% C.L., MEG II at PSI aims to improve by almost another order of magnitude in the next few years; it remains to be seen whether the two new $\mu$ to $e$ conversion experiments, COMET at KEK vs Mu2e at Fermilab, would produce results within this time frame, but the competition is strong.

In conclusion, our Run 2 Era of 2019–2021 is not only Bright, but would be Flavorful, and let’s hope it would be Wonderful. While we have put forth grains of salt for each of the flavor anomalies, if just one of them holds true, we would have lucked out. And with so many directions that we have mentioned, the next three years, the extended Run 2 Era, may just be Golden! And it may well extend into a decade. We advocate a most likely, next New Physics, to reveal itself in the next 3–5 years, would arise from Extra Yukawa Couplings.

v Partially in response, LHCb is rebuilding its detector, Upgrade 1, during LS2. LHCb has also announced its formidable Upgrade 2 plan.
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