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Conference summary and outlook

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A short account of the conference summary is given, focused on new physics results presented during the parallel and plenary sessions at ICHEP2022.

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It is hard to summarise a conference with 17 parallel sessions including about 900 presentation and 250 posters, in this summary I will mostly focus on new physics results shown for the first time at ICHEP2022 in Bologna. The first observation is that we do not have a specific session on Standard Model (SM) since ten years ago at ICHEP 2012 Melbourne: the standard theory is so successful that nowadays permeates all sessions including Beyond SM. An example of this success are the cross sections of single and associated production of fermions and bosons at LHC, with SM tested over 14 orders of magnitudes !

Ten years is also the time passed since the announcement of the Higgs boson discovery. As a matter of fact the quest for the Higgs boson has been a long scientific enterprise started early in the eighties. Before LEP the only region excluded in a non-ambiguous way was in the range 1.2 MeV to 52 MeV thanks to a beam dump experiment. With LEP1 the entire region below 65.6 GeV could be excluded at 95% CL, and the lower limit reached 114.4 GeV [1] at the end of LEP2. At the same time global fits of electroweak observables, including the mass of the recently discovered top quark, started giving indication of a rather low mass for the Higgs boson, with an upper limit reaching 144 GeV [2] before the start of LHC. The Higgs boson, if existed, was close ! Its discovery at LHC [3] was a major step forward in particle physics (the discovery of the first fundamental scalar).

After ten years, at the dawn of LHC Run 3, the knowledge of Higgs boson properties has increased enormously, as summarised by two beautiful publications submitted to Nature [4] by the ATLAS and CMS experiments at the time of this conference. The couplings of the new scalar boson to vector bosons have been measured at the 5% level, while the couplings to third-generation fermions are known at the 10–20% level. The investigation of the Higgs boson interaction with second-generation fermions has started, with evidence of its decays to a pair of muons and interesting bounds in the charm sector. In this sector, too, the SM has been tested over orders of magnitudes. Projections for the High Luminosity LHC phase, based on the present results, indicate the potential of reaching $\approx 1\%$ for some of the couplings (essentially for the Z and W couplings). More in general the investigation of the Higgs boson production and decays modes is now getting very detailed, with measurements of differential cross section and comparisons of experimental results to theory (as described in simulations) in various regions and corners of phase space.

As emphasised in several presentations at this conference it is getting more and more important to study the Higgs boson self-interactions, in other words after having identified the minimum of the Higgs boson potential we have to learn more about its shape and in particular measure the curvature at minimum. Here an important channel is double-Higgs production, where bounds are getting very interesting (a few times the expected SM cross section) especially in view of the Run 3 and HL-LHC. The Higgs boson self coupling can also be constrained by single-Higgs production, assuming that any deviation in the expected value is solely due the self-interaction; the ATLAS collaboration has presented at this conference an analysis combining single-Higgs and double-Higgs production measurements [5], with the assumption that new physics affects only the Higgs boson self coupling (λ) and found that values outside the interval $-0.4 < \kappa (= \frac{\lambda}{\lambda_{SM}}) < 6.3$ are excluded at 95% CL. Another interesting results provided by ATLAS is the observation of gauge boson joint polarisation states in WZ production from pp collisions [6]: this result complements the measurements of WW joint polarisation states at LEP and tests, in particular, the longitudinal W and Z polarisation components, which are intimately related to the electroweak breaking mechanism.

Three mass parameters are particularly important for the understanding of the electroweak landscape: the Higgs boson mass, the W mass and the top mass. Together, they are key ingredients for electroweak tests, once other key parameters, the Z mass, the Fermi constant (G_F) and the fine structure constant ($\alpha(M_Z)$) are precisely known. For all three parameters, new information have been provided or discussed at this conference. A new result has been provided by ATLAS for the $H \to 4\ell$ channel based on the full LHC Run 2 statistics, yielding better than 1.5 permil precision on an individual channel. This channel, measured by both ATLAS and CMS, is still dominated by the statistical uncertainty ($m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})$ GeV) [7], therefore the precision is expected to increase with Run 3 data and with the combination of the two experiments. The top quark mass has reached a precision of 2 permil on individual measurement, the most precise result is from the CMS collaboration in the lepton+jets final state ($m_{top} = 171.77 \pm 0.38$ GeV) [8]. The top quark is a coloured fermion, it decays before hadronising, transferring its colour charge to the b quark, that eventually must connect to another coloured system. There is no way to assign unambiguously the final states particles to the original top quark and the measured pole mass has an inherent uncertainty, which is of the order of $\Lambda_{QCD} \approx 0.2$ GeV. For the interpretation of the top mass parameter as measured by hadron colliders and to better assess its uncertainty, it is important to test variables sensitive to the final state definition and to measure the mass with techniques having different sensitivities to QCD effects. The discussion on the recent measurement of the W mass by the CDF collaboration [9], with a very small uncertainty and significantly deviating from other results (and from the expectation of electroweak fits in the SM hypothesis) has dominated the discussion on this parameter at the conference. The impact of the proton PDF on the systematic uncertainty, for W mass measurements done at hadron colliders, is very relevant: it is crucial to understand the different treatment of these and other common uncertainties before comparing the measurements in a meaningful way.

Several recent measurements related to the production of SM particles at LHC have been shown at the conference. As an example a new measurement of W+charm production properties has been presented by the CMS collaboration [10], which is particular important to improve our understanding of the s-quark PDF in the proton. In the top quark sector ATLAS [11] has shown for the first time evidence for single top production in the s channel at a centre-of-mass energy of 13 TeV and CMS [12] has shown a precise measurement of W+top associated production at the same centre-of-mass energy.

The past 10 years have witnessed an enormous progress in flavour physics, as can be seen by looking at the progress on the knowledge of the parameters of the CKM unitarity matrix [13]. At this conference the LHCb collaboration has presented the first evidence direct CP violation in charm decays. This measurement builds on another measurement done in 2019, when LHCb observed for the first time CPV in charm by using the difference in CP asymmetries of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. Now the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ components are separated for the first time to investigate the nature of CPV in the two decay modes. Direct CPV is seen in $D^0 \to \pi^+\pi^-$ at the level of 3.8 σ [14]. This is a tiny asymmetry, it is interesting to see that CP asymmetries can be sizeable in certain region of phase space, as shown by the analysis of $B^\pm \to D[K^-\pi^+\pi^+\pi^-]h^\pm$ decays [15]. The first interesting results in the flavour sector from Belle 2, based on the already collected 424 fb^{-1}, have been shown at this conference. A joint analysis of Belle+Belle 2 data in the $B^0 \to \pi^0\pi^0$ channel, measuring the γ angle with a 15% uncertainty, demonstrates the experiment's capability to measure decays with neutrals (note that the Belle 2 result is competitive with respect

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to Belle with just one third of integrated luminosity, thanks to the better performance of the new apparatus). Another important result shown at ICHEP 2022 is the most precise measurement of the $B^0_s \to \mu\mu$ branching fraction by a single experiment, presented by the CMS collaboration: $BR(B^0 \to \mu\mu) = 3.95^{+0.39}_{-0.37}(stat)^{+0.29}_{-0.24}(syst)\ 10^{-9}$. This decay is taking place thanks to higher order diagrams (in particular penguin diagrams) and it is very sensitive to new physics; the CMS result is consistent with the SM expectation. There is no sign, for the moment, of $B^0_d \to \mu\mu$ decays. CMS has also measured precisely the effective B^0_s lifetime in this channel, which is dominated by the higher mass B^0_s eingenstate. There were no new results on the so-called "B anomalies", testing electron/muon universality through the R_K, R_{K^*} parameters, shown at this conference, however Belle 2 has shown a new result on the $B^+ \to J/\psi K^+$ control channel. In the charged lepton sector the MEG 2 experiment at the PSI has started taking data in 2022, heading to an improved search for the $\mu \to e\gamma$ decay, with an expected sensitivity on the branching fraction better than $6\ 10^{-14}$. The data taking of the g-2 experiment at Fermilab is progressing toward completion, expecting a factor of 4 improvement on the uncertainty for the value of the muon anomaly. The MUonE experiment is progressing as well, aiming at a direct measurement of the leading hadronic contribution of g-2. The MU2E experiment at Fermilab, dedicated to the detection of $\mu \to e$ transition in the Al nuclei Coulomb field, is continuing its construction. There are exciting years ahead for lepton physics !

Neutrino oscillations are described by the PNMS matrix, which includes the three neutrino flavours mixing angles, the neutrino mass differences, a CP violation phase and a Majorana phase. The parameters of this leptonic mixing matrix are still poorly known, as can be seen by comparing their uncertainties to the typical uncertainties of the quark mixing matrix case discussed above [13]. Even the neutrino mass ordering is unclear and a subject of investigation at present and future experiments. These include neutrino appearance and disappearance experiments at accelerators and reactors, the investigation of atmospheric and solar neutrinos, and dedicated underground experiments for the measurement of the Majorana phase. Important projects are in the preparatory phase, such as DUNE, HyperK, JUNO, Km3net: in the next decade the knowledge of the PNMS matrix is expected to greatly improve. It has been reported at this conference that the ICARUS experiment at the Fermilab SBN site [16] has been recently completed with the installation of the overburden and June 2022 has marked the start of its Run 1. The Dirac or Majorana nature of the neutrino will be investigated by double beta decay experiments, such as LEGEND, Kamland2 and SNO, searching for the $0\nu\beta\beta$ final state. Even non-observation of the process is useful because it sets limits on the neutrino mass scale, as the decay rate is $\Gamma = G_F|M|^2 m^2_{\beta\beta}$, where G_F is the Fermi constant, M is the matrix element of the process and $m^2_{\beta\beta}$ corresponds to the sum of the three neutrinos masses multiplied by the relevant PNMS parameters squared. Current limits from Kamland-Zen are $m^2_{\beta\beta} < 36, 156$ meV depending on the mass ordering, future experiments should reach the $m^2_{\beta\beta} \approx 1$ meV level. Neutrinos are also copiously produced in pp collisions at the LHC. The SND@LHC experiment, located 480 metres off the ATLAS interaction point, has completed construction just before this conference and started collecting data. Together with the FASER experiment at LHC, it will explore neutrino-nucleus interactions for all neutrino flavours in a still unexplored region ($E_\nu \approx 1$ TeV) and provide information, for the first time using neutrinos, on proton PDFs. Most recent results on neutrino physics were given for the first time at the Neutrino 2022 conference [17], however a few results were new at ICHEP 2022 and are reported here. The NOvA experiment, a long baseline experiment located in Minnesota, 810 km away from the neutrino production site at Fermilab, has presented a new interpretation of their results including Non Standard Interactions (NSI) in data analysis. NSI are anomalous interactions between neutrinos and matter; it has been shown that they can have a sizeable effect on the measurement of the CP phase, while their effect on neutrino mixing angles and mass differences is small. Final results from the STEREO experiment on the Reactor Antineutrino Anomaly (RAA) were given at this conference. The Stereo detector is positioned 10 m away from a research reactor in Grenoble. The neutrino interaction occurs in 1800 litres of gadolinium (Gd) loaded liquid scintillator. The Reactor Antineutrino Anomaly is related to a $\approx$ 6% deficit observed in measured reactor antineutrino fluxes and could be explained by the presence of sterile neutrinos. The new STEREO results seems to exclude most of the RAA allowed parameter space.

Hadron spectroscopy is a subject that has developed considerably over the past years, with 62 new hadron states discovered at LHC, most of them by LHCb, and many others at charm (BES III) and beauty factories (Belle, BaBar). The interpretation of some of them includes tetraquark and pentaquark hypotheses, hadron molecules and other exotic objects. At this conference LHCb has presented the observation of a new pentaquark candidate, ($\mathrm{P}^{\Lambda}_{\Psi\mathrm{s}}$), with strange content ($c\bar{c}uds$), close to the $\Xi_c^+ D^-$ threshold, with a significance larger than 10 σ. LHCb has also reported [18] the first observation of a doubly charged mesonic exotic state, together with its neutral partner, both compatible with the tetraquark interpretation.The CMS, ATLAS and LHCb Collaborations [19] have studied the X(6900) structure in the $J/\psi J/\psi$ final state. In this region the CMS experiment clearly resolves three resonances, which are compatible with cccc tetraquark states. The BES III experiment has observed new exotic states in e^+e^- collisions, in particular new resonance structures in $e^+e^- \rightarrow \pi^+\pi^-\psi(3823)$ and a new neutral tetraquark, $Z_{cs}(3985)$ with $c\bar{c}s\bar{d}$ minimal content.

The properties of quark-gluon plasma (QGP) have been studied at LHC in heavy ion (PbPb) collisions, important complementary information is coming also from pPb and pp interactions. The ALICE experiment has presented a study of quarkonium melting by using J/ψ and ψ_{2s} signatures. Quarkonium production is suppressed by QGP because of colour screening, the effect is suppressed at low p_T and in central rapidity due to cc regeneration. ALICE data demonstrates that suppression is much stronger in the looser ψ_{2s} state and a first evidence of regeneration at low p_T has been reported. Another effect of QGP is jet quenching, ALICE has studied jets recoiling against a high-p_T hadron and observed jet quenching and jet angular deflection of soft large-R jets. The effect has been studied by comparing PbPb to pp collision and a clear suppression and deflection effect has been observed, the latter presumably related to large-angle scattering on QGP constituents. Following the recent observation of the so called "dead cone effect" by ALICE in pp collisions [20], which is related to the reduction of small-angle gluon radiation for high-mass quarks, the experiment has studied the energy loss dependence on QGP density and on quark mass. It has been observed that in PbPb collision a lower hadron-formation suppression is seen for (non-prompt) D mesons from B decays with respect to prompt D mesons, as expected from the lower gluon radiation in the medium [21]. Another interesting study shown by the ALICE collaboration at this conference concerns the measurement of charm fragmentation in PbPb collisions. The breaking of fragmentation universality from e^+e^- to pp collisions is a well-established effect, with an enhancement of baryon production in the pp case. ALICE has shown hints of additional dynamics in central PbPb collisions, with clear evidence of $\frac{\Lambda_c}{D^0}$ enhancement at intermediate p_T. The material of the ALICE detector has been used as a target, in a non conventional measurement presented for the first time at this conference, to extract the inelastic cross section for anti-helium ($^3\overline{He}$) in the momentum range $1.17 < p < 10$ GeV/c [22]. This inelastic cross section is used as a input to calculations of the transparency of our galaxy, which is important, for example, for the interpretation of AMS data. Moving to general QCD features in hadron collisions, the ATLAS experiment, thanks to Alpha forward spectrometer, has confirmed the presence of an odderon component in pp elastic scattering [23], as originally observed by the D0 and TOTEM experiments [24].

Several new results concerning searches for physics beyond the SM have been presented at ICHEP 2022, only a few examples are described here. An important subject of investigation at colliders is the search for dark matter candidates. The ATLAS collaboration has searched for single top plus missing energy production, yielding a lower limit of about 5 TeV for heavy mediators produced in resonant mode, coupled to dark matter (χ, with 10 GeV mass) and top quarks [25]. The same search can be used to set limits on vector-like quarks (VLQ), whose existence is expected by composite Higgs models. Other searches for VLQ, in the third generation, have been presented by the CMS collaboration using the top quark plus Higgs boson final state [26]. Searches for leptoquarks have been recently revitalised because their existence would provide a viable interpretation of heavy flavour anomalies; searches in this sector with final states involving top quarks or tau leptons have been presented by ATLAS [27] and CMS [28, 29]. The investigation of displaced vertexes at collider experiments has become a common tool for searches of new physics signatures; the ATLAS collaboration has presented a search for long-lived, massive particles in events with displaced vertexes and multiple jets and a search of diphoton/dielectron final states for displaced production of Higgs or Z bosons [30]. No deviations with respect to the standard model expectation have been seen in all previously described searches, instead a $\approx 3\sigma$ deviation has been observed in a search for resonances (X) decaying to H/Y(bb)H($\gamma\gamma$) by the CMS collaboration [31]. It is intriguing that the deviation is seen for (bb=125 GeV, $\gamma\gamma \approx 90$ GeV) with X $\approx$ 650 GeV, mass regions where a few excesses were seen in other channels in the past [32], making the LHC Run 3 interesting. The Belle 2 experiment is also providing interesting results in the BSM sector, as an example a search for lepton-flavour-violating axion-like particles (ALPs, α) in the $\tau \to \mu\alpha$ and $\tau \to e\alpha$ final state has been presented, considerably improving the previous bounds given by the ARGUS experiment [33].

Dark matter candidates as the WIMPs (χ) and ALPs mentioned above in the context of collider searches are mere examples, the potential candidates are spanning 80 orders of magnitudes (!) in mass. Concerning the WIMP hypothesis and direct detection, new underground experiments, as DarkSide or DARWIN are expected to reach a sensitivity close to the background expected from neutrinos (the so-called neutrino floor). During this conference, the first results from the LUX-ZEPLIN (LZ) experiment arrived [34], leading to an improvement in the WIMP mass bounds from direct detection.

For the results related to many experiments in the astro-particles area, cosmic rays and gravitational waves I refer to the excellent reviews presented at this conference [35]. During the conference the first amazing image from the NASA's James Webb Space Telescope arrived [36], showing in a visual way the beauty of deep space and the effect of gravitational lensing. I refer to the corresponding reviews also for the accelerators, detectors and theory sessions [37].

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References

[1] ALEPH, DELPHI, L3 and OPAL Collaborations, The LEP Working Group for Higgs Boson Searches, Phys. Lett. **B565** (2003) 61

[2] The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, (2006) CERN-PH- EP/2006-042, hep-ex/0612034

[3] ATLAS Collaboration, Phys. Lett. **B716** (2012) 1
CMS Collaboration, Phys. Lett. **B716** (2012) 30

[4] ATLAS Collaboration, Nature **607** (2022) 52
CMS Collaboration, Nature **607** (2022) 60

[5] ATLAS Collaboration, ATLAS-CONF-2022-050

[6] ATLAS Collaboration, ATLAS-CONF-2022-053

[7] ATLAS Collaboration, arXiv:2207.00320

[8] CMS Collaboration, CMS-PAS-TOP-20-008

[9] CDF Collaboration, Science **376** (2022) 170

[10] CMS Collaboration, CMS-PAS-SMP-21-005

[11] ATLAS Collaboration, ATLAS-CONF-2022-030

[12] CMS Collaboration, CMS-PAS-TOP-21-010

[13] https://pdg.lbl.gov

[14] https://agenda.infn.it/event/28874/contributions/169315/

[15] https://agenda.infn.it/event/28874/contributions/169355/

[16] https://sbn.fnal.gov/

[17] https://neutrino2022.org/

[18] https://agenda.infn.it/event/28874/contributions/169025/
https://agenda.infn.it/event/28874/contributions/169018/

[19] ATLAS Collaboration, ATLAS-CONF-2022-040
CMS Collaboration, CMS-PAS-BPH-021-003
LHCb Collaboration, LHCb Science Bullein 65 (2020) 1983

[20] ALICE Collaboration, Nature **605** (2022) 7910, 440

[21] ALICE Collaboration, arXiv:2202.00815

[22] ALICE Collaboration, arXiv:2202.01549

[23] ATLAS Collaboration, https://agenda.infn.it/event/28874/contribu:ons/169014/

[24] D0 and TOTEM Collaborations, arXiv:2012.03981

[25] ATLAS Collaboration, https://agenda.infn.it/event/28874/contributions/169410/

[26] CMS Collaboration, CMS-PAS-B2G-21-007

[27] ATLAS Collaboration, https://agenda.infn.it/event/28874/contributions/169444/

[28] CMS Collaboration, CMS-PAS-EXO-21-009

[29] CMS Collaboration, CMS-PAS-EXO-19-016

[30] ATLAS Collaboration, https://agenda.infn.it/event/28874/contributions/169435/

[31] CMS Collaboration, CMS-PAS-HIG-21-011

[32] CMS Collaboration, Phys. Lett. **B793** (2019) 320
CMS Collaboration, CMS-PAS-HIG-21-001
CMS Collaboration, CMS-PAS-HIG-20-016

[33] BELLE2 Collaboration, https://agenda.infn.it/event/28874/contributions/169331/

[34] LUX-ZEPLIN Collaboration, arXiv:2207.03764

[35] https://agenda.infn.it/event/28874/contributions/171911/
https://agenda.infn.it/event/28874/contributions/171912/
https://agenda.infn.it/event/28874/contributions/171914/

[36] https://webb.nasa.gov/

[37] https://agenda.infn.it/event/28874/contributions/171927/
https://agenda.infn.it/event/28874/contributions/171940/
https://agenda.infn.it/event/28874/contributions/171906/
https://agenda.infn.it/event/28874/contributions/171907/