PPG Benchmark measurements / processes

Physics Preparatory Group (PPG)

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A key goal of the 2026 update of the European Strategy for Particle Physics is the development of a concrete plan for the realisation of the next flagship project at CERN. The remit of the European Strategy Group (ESG), as defined by the CERN Council, states that the Strategy update should include the preferred option for the next collider at CERN and prioritised alternative options to be pursued if the chosen plan turns out not to be feasible or competitive.

In this context it is expected that several project proposals for the realisation of such a collider will be presented to the Strategy update by 31 March 2025. Detailed comparisons of the physics potential, technical feasibility, timeline, costs and human resources as well as of the environmental impact must be made in order to define a baseline as well as prioritised alternative options.

In order to allow for proper comparison of the physics potential of the various projects, the Physics Preparatory Group (PPG) has defined benchmark measurements and processes. It is expected that corresponding results will be included in the project's submissions.

In the following these benchmarks are summarised for the nine PPG working groups, covering the different physics areas and the technical areas of accelerators, detector instrumentation and computing. It should also be noted that the PPG will perform a comparison of the future sensitivity of different project proposals via appropriate Effective Field Theory (EFT) analyses, using the projected sensitivities on different observables provided by the collaborations. Details on this approach are also given.

1 Electroweak, Higgs and Top physics

1.1 Higgs physics benchmarks

- Precision of the measurement of the Higgs mass (and width, when a determination is possible).
- Single Higgs couplings: sensitivity to BSM in Higgs couplings to SM particles.
  - From Kappa fits, in combination with HL-LHC, two possible versions:
    - All SM coupling modifiers AND non-SM Higgs decays
    - All SM coupling modifiers WITHOUT non-SM Higgs decays
  - From SMEFT fits: Baseline established with BSM/Flavor WGs. (See also Effective Field Theory Interpretations section). Details on specific information about the inputs needed for these fits are provided below, regarding the Higgs/EW/Top sectors.
  - For the preparation of these studies we will need the projected uncertainties on the corresponding Higgs observables at each different energy and with correlations, when available.
    For instance, for e+e- Higgs factories, the signal strengths for each production x decay channel:
    $\sigma_{ee\to ZH}(incl.)$,
    $\sigma_{ee\to ZH}\times BR(H\to bb,cc,ss,gg,\tau\tau,\mu\mu,WW^*,ZZ^*,\gamma\gamma,Z\gamma)$,
    $\sigma_{ee->H\nu\nu(VBF)}\times BR(H\to bb,cc,ss,gg,\tau\tau,\mu\mu,WW^*,ZZ^*,\gamma\gamma,Z\gamma)$

- Shape of the Higgs potential. Precision on Higgs self-coupling
  - From HH production
  - From single-Higgs measurement, via SMEFT fit
  - In both cases, whenever possible:
    - Exclusive determination (i.e. assuming $\kappa\lambda$ as the only free parameter of interest and everything else fixed to the SM value)
    - Inclusive determination ($\kappa\lambda$ + any other parameter of interest entering in the relevant observables). Specify what extra parameters of interest are considered (i.e. not fixed to the SM value)

1.2 Electroweak physics benchmarks

- Precision Electroweak measurements:
  - Projected uncertainties on Electroweak precision observables (without imposing any assumption about fermion universality)
    - On-shell Z measurements: M_Z, Γ_Z, $\sigma^0_{\rm had}$, R_f, Asymmetries ($A^f_{\rm FB}$, A_f), etc. with $f = e, \mu, \tau, b, c, s$,...
    - On-shell W measurements: M_W, Γ_W, BR($W \to e\nu$, $\mu\nu$, $\tau\nu$),...
    - Other Observables/Pseudo-Observables. E.g. definitions and expected precision in observables used for determination of anomalous triple gauge couplings (aTGC) from diBoson production.
    - When reporting the uncertainties of these or any other observables where systematics are expected to be important, please **indicate explicitly any relevant assumptions made in the estimations of such systematics, and in particular those related to assumed improvement in the theory side.**
  - EW couplings: sensitivity to BSM in Z and W couplings to SM fermions.
    - From SMEFT fits: Same setup used in “Single Higgs Couplings”
- Other probes of Electroweak symmetry breaking/Multi-Boson processes
  - E.g. Longitudinal Vector Boson Scattering (VBS): Same-sign VBS @ Hadron colliders, VBF/VBS at lepton colliders.

1.3 Top physics benchmarks

- Top-quark properties and interactions:
  - Top-quark mass precision
  - Top-quark properties from SMEFT fits:
    - Top-quark EW couplings (Ztt, Wtb)
    - Top-quark Yukawa coupling
    - Other interactions entering in Top processes, depending on assumptions chosen in SMEFT fit, e.g. four-fermion interactions, Top-dipole operators
  - As in the EW and Higgs part, it would be useful to have the definitions and projected uncertainties of the observables used in the interpretation.

2 Strong Interactions

The benchmark measurements in the area of the strong interaction are reported in the following for the four main physics research directions. Clearly, this is not an exclusive list of the observables and measurements that the working group will cover. The input documents are anticipated to have a much broader coverage, which will be taken into account. The list of benchmarks will be used to summarise and highlight the complementarity and strengths of the future measurements at existing (e.g. SPS, HL-LHC) and proposed colliders (leptonic, hadronic, electron–hadron). The presentation of results will be organised by the working group in communication with the contact persons of submitted inputs.

- Precision QCD
    - $\alpha_S(m_Z)$ and its Q^2 dependence;
    - Strong interaction effects for precision measurements of top and W masses (see comments at the end of the section);
        - Comment on top and W masses: while these are formally EW parameters, the strong-interaction aspects are important for their experimental and theoretical determination. For example, we propose to report the expected experimental performance for the following approaches to t and W mass measurements.
            - ee collisions: m_t from threshold scan around $\sqrt{s} = 340$ GeV; m_W from threshold scan for W^+W^- production (leptonic decays);
            - ep collisions: m_t from heavy-quark DIS (top-quark structure function measurements); m_W from inclusive DIS (charged-current structure function measurements);
            - pp collisions: m_t from $t\bar{t}$ production rates, multi-differential in $m_{t\bar{t}}, y_{t\bar{t}}$; m_W from p_T^ℓ distributions.
- Inner structure of protons and nuclei
    - Longitudinal and transverse proton PDF(x, Q^2): parton flavours, Bjorken-x and Q^2 ranges for which new constraints and reduction of uncertainties are expected;
    - Longitudinal and transverse nuclear PDF(x, Q^2); same as above;
- Hot and dense QCD
    - Heavy-flavour and quarkonium hadron production (rare states, kinematic coverage): expected novel access to low-cross-section open and hidden heavy-flavour hadrons, multi-differential observables (such as correlations), transverse momentum and rapidity ranges;
    - QGP transport coefficients (heavy quarks, jets): expected precision for observables that constrain the transport coefficients that characterise parton energy loss and heavy-quark interactions in the QGP;
    - QGP thermal radiation, sensitivity to temperature: expected precision for measurements of thermal radiation and parameters that map to the temperature of the hot and dense system formed in heavy-ion collisions at different centre-of-mass energies and regions of the QCD phase diagram;
- QCD connections with hadronic, nuclear and astro(particle) physics
    - Constraints on nature of exotic hadrons from spectroscopy and h-h correlations; expected measurements that can help understanding the structure of exotic heavy-flavour hadrons (e.g. compact tetraquark vs. hadron molecule), including direct measurements of yields, resonant states, kinematic distributions in different collision systems, and hadron-hadron momentum correlation functions that have sensitivity to bound states;

  - Precision on anti-nuclei production and absorption relevant for cosmic-ray physics: production of light anti-nuclei (e.g. $\bar{p}$, $\bar{d}$, $^3\bar{H}e$) that constrain production processes and kinematic distributions in primary cosmic-ray interactions; annihilation cross sections for anti-nuclei on nuclei, relevant for the propagation of cosmic anti-nuclei in space (e.g. from Dark Matter decays);

3 Flavour physics

Flavour physics is one of the areas with the largest number of interesting observables. The benchmarks we propose are meant to compare the potential, in this area, of the multi-purpose experiments at lepton or hadron colliders, hence are focused only on heavy quarks (b and c) and τ physics. This by no means implies that other class of observables, such as EDMs or rare decays of light quarks and leptons will not be considered: simply they do not require an explicit list of benchmarks and will be analysed on a case-by-case basis. Also in the case of heavy quarks and τ physics the list below is far from exhaustive; however, it serves the purpose of comparing the potential of different multi-purpose facilities. With these caveats, this is the proposed list.

- Rare FCNCs with ν's and τ,s: $BR(B \to K^{(*)}\tau\tau)$, $BR(B \to K^{(*)}\nu\nu)$
- Rare leptonic B decays: $BR(B_{s,d} \to \mu\mu)$
- LFV in τ decays: $BR(\tau \to 3\mu)$, $BR(\tau \to \mu\gamma)$,
- τ lifetime, $BR(\tau \to \mu\nu\nu)$ and $BR(\tau \to e\nu\nu)$ (τ universality tests)
- CP violation in neutral D-meson mixing
- Time-dependent CP violation in $B_s \to \phi\phi$
- CKM elements from W decays

4 BSM physics

The main goal is to collect the information from the input to the strategy to explore the potential of on-going and future experiments to answer open questions that need physics beyond the standard model.
This group naturally overlaps with the activities of the Flavor, Electroweak, and Neutrino physics and cosmic messengers and Dark sectors. In this section, we foresee to focus on:
Specific questions and corresponding new physics scenarios that can be constrained or discovered at present and future experiments, through multi-pronged approaches, combining collider data with other experiments and observations at different scales.

- New gauge forces (Z', W'...): U(1)-Y-universal, U(1)$_{B-L}$ (universal and 3rd gen), HVT SU(2)$_L$ custodial, HVT Right-handed
- Compositeness (indirectly from EFT fits): Scenario discussed in 1905.03764 + 4q, 2q-2l
- Extension of the minimal real scalar sector giving 1$^{\text{st}}$ order EW phase transition and possibly stability: scenario discussed in e.g. 2303.03612
- Minimal dark matter (WIMP) global: see e.g. 2107.09688
- Flavor (together with flavor group): scalar and vector leptoquarks with third generation specificities
- SUSY (direct only collider, global on with specific assumptions): see Briefing Book 2020
- Portals (dark photon, dark higgs, HNLs, axions, ALPs): see Briefing Book 2020

5 Neutrinos and cosmic messengers

Neutrino physics and cosmic messengers is a vast subject. The scope of this working group will be to review the prospects of key measurements in neutrino physics including neutrino masses and mixing angles, the violation of CP in neutrino interactions or the nature Dirac/Majorana of neutrinos that can reveal the existence of a new physics scale. Improving the knowledge of neutrino cross sections from coherent neutrino scattering all the way to PeV range could help reduce systematic uncertainties in neutrino oscillation experiments, but also provide important input to understand the structure of the proton and the nucleus, or search for elusive new physics. Neutrino experiments can search for new physics in complementary ways to collider experiments and we will review the sensitivity to a few well motivated and extensively studied possibilities. Regarding the area of cosmic messengers the focus will be on the areas with more synergies with particle and neutrino physics. We will review the sensitivity of neutrino telescopes and gravitational wave experiments, in particular regarding their capabilities to identify sources, and on the complementarity of multimessenger signals to understand the mechanism of particle acceleration in the cosmos and the origin of cosmic rays. The detection of a stochastic GW background can give us a picture of the Universe at very early times and therefore to very high energy phenomena inaccessible to colliders.

- Neutrino Oscillation Physics: Neutrino Masses & Mixings, Leptonic CP violation:
  - sensitivity to CP violation
  - precision on delta as a function of true delta
  - sensitivity to mass ordering
  - precision on mixing angles and mass differences in PMNS
- Absolute Neutrino Mass and Neutrino Nature:
  - sensitivity to neutrinoless double-beta decay
  - sensitivity to absolute neutrino mass
- Neutrino cross-sections (CEnNS, reactors, SBL, forward physics at LHC):
  - impact of reducing neutrino cross section uncertainties in LBL on the CPV sensitivity and the precision on mixing angles/masses
  - precision on high-energy (>TeV) neutrino cross sections
  - precision on CEnNS cross-section for different nuclei
- Direct BSM searches in neutrino experiments:
  - limits on light sterile neutrinos (mass versus mixing angle) and non-unitarity
  - non-standard neutrino interactions (NSI, SMEFT)
  - Heavy Neutral Leptons constraints
  - sensitivity to proton decay
- Cosmic messengers:
  - high energy cosmic neutrinos:rate versus energy and flavour composition
  - sensitivity to supernova neutrinos:rate, flavour, time and energy resolution
  - GW strain sensitivity versus frequency
  - pointing/timing capabilities of neutrino and GW experiments to identify sources
  - multi-messenger signal sensitivity to cosmic-ray acceleration mechanisms

6 Dark matter and dark sector

Dark sector physics can give rise to phenomena across a wide variety of experimental techniques. As a result, it is proposed to consider benchmark models, rather than processes. In this way models which give rise to signatures in different experimental settings can be compared. For instance, direct detection, indirect detection and colliders may be sensitive to the same dark matter model through entirely different processes.

The models, broken down by mass range, are

- Ultralight DM: Axion, ALPs, Dark Photon (Z')
- Light DM: ALPs, Z' (Dark Photon), Freeze-In Dark Matter
- Heavy DM: Wino & Higgsino, Higgs Portal, Scalar and Pseudoscalar mediator simplified models (O1 and velocity-dependent)
- Exotica: Dark Showers, Dark Compact Objects (PBH + Exotic Compact Objects)

In scenarios where an experiment does not have sensitivity to a particular benchmark model it can be omitted from the submission concerned.

7 Effective Field Theory Interpretations

The PPG will perform a comparison of the future sensitivity of different project proposals via appropriate EFT analyses, using the projected sensitivities on different observables provided by the collaborations.

This does not mean that specific EFT analyses provided by the collaborations are not welcome. However, in such a case we encourage the proponents to provide to the PPG the full information on the experimental pseudo-data (list of observables, expected uncertainties and correlations) and also on the definition and assumptions (and motivations) of the EFT they have adopted, so that the results can be reproduced in principle.

One of the goals of the EFT analyses to be performed by the PPG, is to establish the reach for specific UV models. In this context, it is important to make specific assumptions about the flavour structure of the underlying theory. As a baseline, for collider and electroweak observables, we propose to adopt the flavour symmetry

$\mathrm{U}(2)_{q_L}$ x $\mathrm{U}(2)_{u_R}$ x $\mathrm{U}(2)_{d_R}$ x $\mathrm{U}(1)_e$ x $\mathrm{U}(1)_\mu$ x $\mathrm{U}(1)_\tau$,

i.e. to consider the first two quark generations “equivalent”, single out the third quark generation, and treat separately each lepton flavour (requiring individual lepton flavour conservation).

We stress that the most useful input for the PPG will be in terms of observables and their precision, in a manner that can be interpreted (at least) within the above flavour assumptions, e.g. electroweak precision observables.

Finally, in those cases where interpretations are done by the collaborations exclusively in terms of a single parameter of interest, i.e. assuming everything else to be SM-like, and this is suggested as input for the EFT fit, the precise definition of the observable used in such analyses would be required in order to perform a global interpretation.

8 Accelerator technologies

For large accelerator projects guidelines for input have already been defined in a separate document which is available via the Strategy web pages:

https://europeanstrategyupdate.web.cern.ch/sites/default/files/Project_inputs_ESPP2026.pdf

9 Detector instrumentation

The PPG requests that the following information and/or specifications (instead of “benchmarks”) be given for each proposal submitted to the ESPPU dealing with detector instrumentation. Each project, be it on individual detection technologies or on devices/systems (tracker, calorimeter,...), should address the following points:

- What are the key performance indicators (KPIs) of your technology and which performance does your technology achieve in terms of these KPIs?
- What is the current technology readiness level (TRL, in the spirit of ISO norm 16290:2013) of your technology? How do you expect the technology to scale from lab prototypes to full detector systems (concerning mechanical integration, powering, cooling, readout)? If applicable: please start from the assessment by the ECFA detector roadmap and report updates.
- What are status and time scales for the project? At which point in time have you achieved or do you intend to achieve: proof of principle, concept validation (by full simulation), initial prototype, lab test, beam test, “slice” of full system, full system? Cover hardware, software and firmware aspects.
- Which DRD collaboration(s) are the most relevant to your technology? Is your technology already covered in one or more of them?
- What is the environmental impact of your technology/device/system and which measures are taken to reduce it?

10 Computing

- Describe the amount and type of **resources** you expect to need along the timeline of the initiative:
  - With resources split into [computing resources | interconnections | facilities | person power required] in the various expected runs/periods.
  - Add which external initiatives | events the planning is depending on.
- Furthermore, specific input on the **software tools** and environment should be provided in meaningful detail:
  - Use and/or design of specific software tools for diverse required activities.
  - A special emphasis should be provided on the envisaged role of the AI/ML tools in these use-cases.
  - A special emphasis on the external (commercial) software requirements should be provided (e.g. virtualization tools, storage solutions, database solutions).
  - What type of collaboration you think the software tool development would need between different institutions.