The Rare processes and Precision measurements (RPF) frontier

A crossroad for the next HEP physics landscape
The team

Apologies for the incomplete acknowledgement of their work!

Thanks to the many white paper contributors!
Develop and sustain diverse an experimental program well-motivated by the P5 science driver *Explore the unknown: new particles, interactions, and physical principles*, with connections to the energy and neutrino frontiers.

We believe there should be a new science driver centered on flavor physics, aiming at uncovering the physics behind the multifaced patterns of couplings, sources of CP violation and the mass scale and nature of the new physics, with strong connections to the neutrino frontier.

Many experimental approaches: experiments investigating heavy and light quarks, charged leptons, precision tests of fundamental forces and symmetries, dark matter, and the dark sector.

Support the associated theory, phenomenological and lattice QCD, which enables and inspires this experimental program.
Our treasure hunt

- The origin of flavor, generations, and quark and lepton mass hierarchies
- The exploitation of flavor transitions as precision probes of all the sectors of the Standard Model and windows to new physics
- The motivation underlying discrete SM symmetries and mechanisms for symmetry breaking
- The origin of baryon and lepton number violation and connections to the baryon asymmetry of the universe
- Mapping of the wealth of conventional and exotic hadrons already discovered or in the horizon into organized multiplets of QCD bound systems
Our treasure map

A portfolio of accelerator dark sector experiments

Charged lepton flavor violation experiments

High-precision experiments with special focus on b and charm decays

- Experiments studying discrete& space-time symmetry breaking, electrical dipole moments & baryon/lepton number violation

- Phenomenological and lattice QCD theory efforts
- Innovations in instrumentation,
- Computing & accelerator physics
Disclaimer

- Attempt to capture a snapshot of the exciting physics we are proposing, I hope that you get a taste of the variety of exciting physics, a more complete and thoughtful picture will emerge in our report.
Precision measurements of weak decays of heavy flavored hadrons can further our understanding of fundamental interaction and observed baryon asymmetry of the universe in a unique way.

Tantalizing hints of new physics are starting to emerge from measurements by the BaBar, Belle and LHCb experiments.

Next 10-20 years will see unprecedented development of a highly synergistic program of experiments at both pp and e+e- colliders, complemented and inspired by phenomenological and lattice QCD theoretical advances.
hadron colliders

**Large Hadron Collider (LHC)**
- **Run2**: 9 fb⁻¹ → Upgrade I
- **LS2**: 35 fb⁻¹ → Upgrade I
- **Run3**: 450 fb⁻¹ → Phase-2 Upgrade
- **LHCb**: 190 fb⁻¹ →
- **ATLAS/CMS**: 190 fb⁻¹ →

**High Luminosity LHC (HL-LHC)**
- **Run4**: 50 fb⁻¹ → Upgrade II
- **LS4**: 300 fb⁻¹ →
- **Run5**: 3 ab⁻¹ →

**2017**  **2018**  **2019**  **2020**  **2021**  **2022**  **2023**  **2024**  **2025**  **2026**  **2027**  **2028**  **2029**  **2030**  **2031**  **2032**  **2033**  **2034**  **2035**  **2039**

**Belle II**: 430 fb⁻¹ → Upgrade(s)

**SuperKEKB**
- **BESIII**: 5 fb⁻¹ @ √s = 3.773 GeV
- 3 fb⁻¹ @ √s = 4.178 GeV
- 3 fb⁻¹ @ √s = 4.64 GeV →
- **20 fb⁻¹ @ √s = 3.773 GeV →**
- **1 ab⁻¹ @ √s = 3.773 GeV →**

**e⁺e⁻ colliders**
Exploring lepton flavor universality violation

- Several tensions emerging
- Complementary studies in light meson decays
  - $\pi$ decays to $e$ and $\mu$ [PIONEER]
  - Rare $\eta$ decays [REDTOPI]

[Link to arXiv paper](https://arxiv.org/abs/2204.12175)
Precision tests of fundamental properties and symmetries

- Electric dipole moments (CP violation):
  - EDMs (besides QCD theta-term) instant discovery of new physics with energy scales up to 1000’s TeV
  - Broad experimental approach due to a variety of possible CPV sources
  - HEP opportunity: storage ring proton EDM

- Magnetic dipole moments (focus on the muon):
  - Search for physics beyond the SM at the few TeV scale
  - Large theory effort in the next years to determine the hadronic contributions

- Precision experiments (HEP and AMO communities):
  - Search for fundamental symmetry violation (C, T, P, Lorentz, CPT)
  - Tests with gravity: fundamental symmetries, GR, quantum nature, short-range corrections
  - Wide set of low-energy approaches complementary to large-scale facilities
Charged lepton flavor violation

- Decays of $\mu$, $\tau$ (and mesons)

$\mu \rightarrow e\gamma$, $\mu \rightarrow e\bar{e}e$, $\mu (A, Z) \rightarrow e (A, Z)$

$M_\mu - \bar{M}_\mu$, $\mu \rightarrow e\alpha$

$\tau \rightarrow e\gamma$, $\tau \rightarrow e\bar{\nu}_e\nu_e$, $\tau \rightarrow e\gamma$

$Y = P, S, V, P\bar{P}, ...$

Modified from Calibbi-Signorelli 1709.00294

Ongoing / planned
- MEG-II
- DeeMee
- Mu2e
- Mu2e, COMET
- Mu2e-II
- AMF - PRISM
Muon campus at Fermilab

- A new facility at FNAL could provide:
  - orders of magnitude increase in sensitivity for all three muon channels, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, and $\mu N \rightarrow eN$ and open new possibilities in $\mu N \rightarrow eN$ at high $Z$
  - It can host a dark matter experiment + other muon measurements can be performed at this facility.
  - technical challenges are synergistic with the muon collider R&D
The existence of dark matter motivates a dark sector neutral under the SM forces.

Dark sectors are a compelling possibility for new physics, with potential relevance to:
- Lightness of SM neutrinos, baryon-antibaryon asymmetry,
- Hierarchy problem, strong-CP problem (e.g., axions, axion-like-particles), anomalies in data.

Dark sectors are generically weakly coupled to SM matter (via portal interactions) and can naturally have MeV-to-GeV masses.

- Only mild constraints from precision atomic physics & high-energy colliders
- Intensity-frontier experiments offer unique and unprecedented access to:
  - Light dark matter production (focus on thermal dark matter)
  - Systematic exploration of dark sector portal interactions
  - Searches for new flavors and rich structures in dark sectors

Thanks to S. Gori
To promote US leadership in dark sector studies at high intensities:

- Exploit the capabilities of existing multi-purpose experiments, especially Belle-II and LHCb.
- Invest in the completion of the Dark Matter New Initiatives (DMNI) program.
- Expand DMNI to include experiments with a focus on complementary signatures with visible final states (especially long-lived particles) – proposals include proton and lepton beam-dump experiments, auxiliary detectors.
- Support theory efforts to explore dark sector models and collaborate in dark-sector experiments – this has been at the foundation of many ongoing and planned experimental activities in this growing field.
Experiments/facilities

Modest upgrades enable transformative physics

Dark sector at high intensity timeline
The RPF recommendations I

- The physics of our frontier **needs a new P5 driver** to be represented adequately in the HEP landscape, broadly identified as **physics of flavor**
- The **LHCb and its Upgrade II and Belle II/KEKb and their upgrades** are part of a portfolio of exciting physics opportunities that explore a vast array of **new physics** in beauty and charm decays, and in rare $\tau$ decays, In addition they investigate the pattern of bound states as manifestations of **QCD in the non-perturbative regime** and contribute significantly to the exploration of the **dark sector**.
- A portfolio of accelerator-based dark sector experiments that are well-motivate, unique and affordable should be considered.
- Experiments investigating **charged lepton flavor violation** and **lepton number violation** in the $\mu$ sector are integral components of our exploration of mass scales currently unreached with direct detection.. R&D towards a new muon program at PIP-II should be given strong consideration to enable a concrete proposal for the next P5.
A portfolio of experiments of different cost and time scales are an integral part of our physics program. They include:

- EDM measurement, including storage ring DM and experiments exploiting AMO techniques
- Experiments leveraging on light mesons decays to uncover physics beyond the Standard Models, including anomalies and portals to the dark sectors [REDTOP, PIONEER]
- Contributions to experimental studies of rare K decays should be encouraged

We need to support theoretical efforts that inspire and elucidate the implications of our experimental findings
Concluding remarks

The six (?)-degrees of separation theory: **We are all connected!**

- **Instrumentation frontier:** ps timing, DAQ, software trigger, massless trackers
- **Computational frontier:** Massive data storage/processing, real time triggers/ distributed intelligence, ML
- **Community engagement frontier:** Leadership opportunities for young scientist, attention to training in an inclusive and nurturing environment, connections with industrial partners
- **Theory frontier:** interpretation and inspiration
- **Energy frontier:** direct searches for new physics
- **Accelerator frontier:** new muon campus, polarized beams at KEK-b
- **Neutrino frontier:** Leptogenesis/baryogenesis, PMNS versus CKM, Majorana or Dirac?
- **Cosmic frontier:** baryogenesis, the nature of dark matter
- **RPF frontier**
- **Connections with other communities:** nuclear physics [e.g neutrinoless $\beta\beta$ Decay, AMO (EDM, fundamental symmetries..)]
The end
Future prospects: two snapshots

Belle II

\( B \to K \nu \bar{\nu} \)

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.


An emerging anomaly ???

4% experimental error on \( B \to K^* \nu \bar{\nu} \) with 250ab\(^{-1}\)