Explore the Unknown

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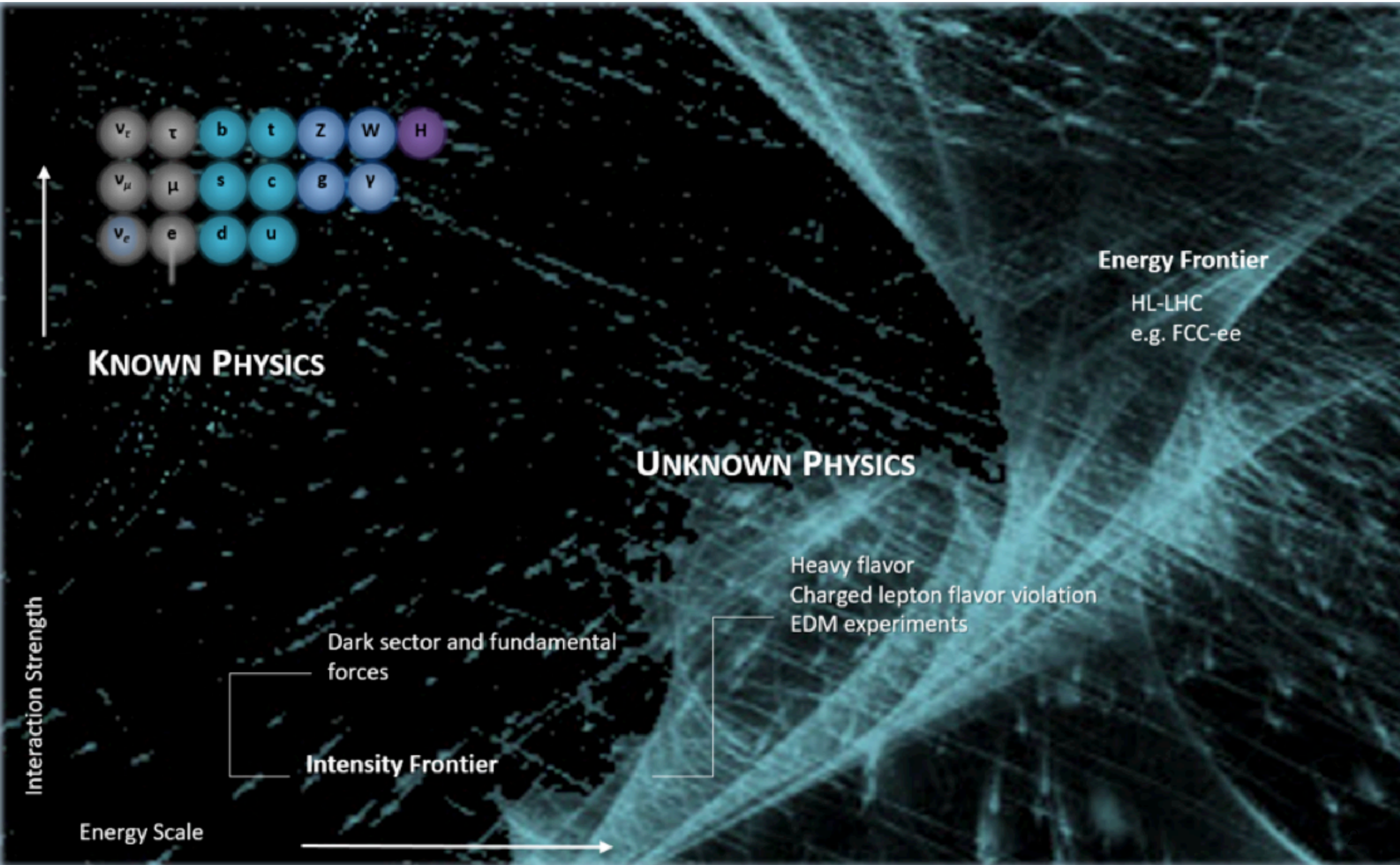
Work done with S. Demers (Yale), M.Reece (Harvard) and N.Serra (Zurich), with input from many other colleagues

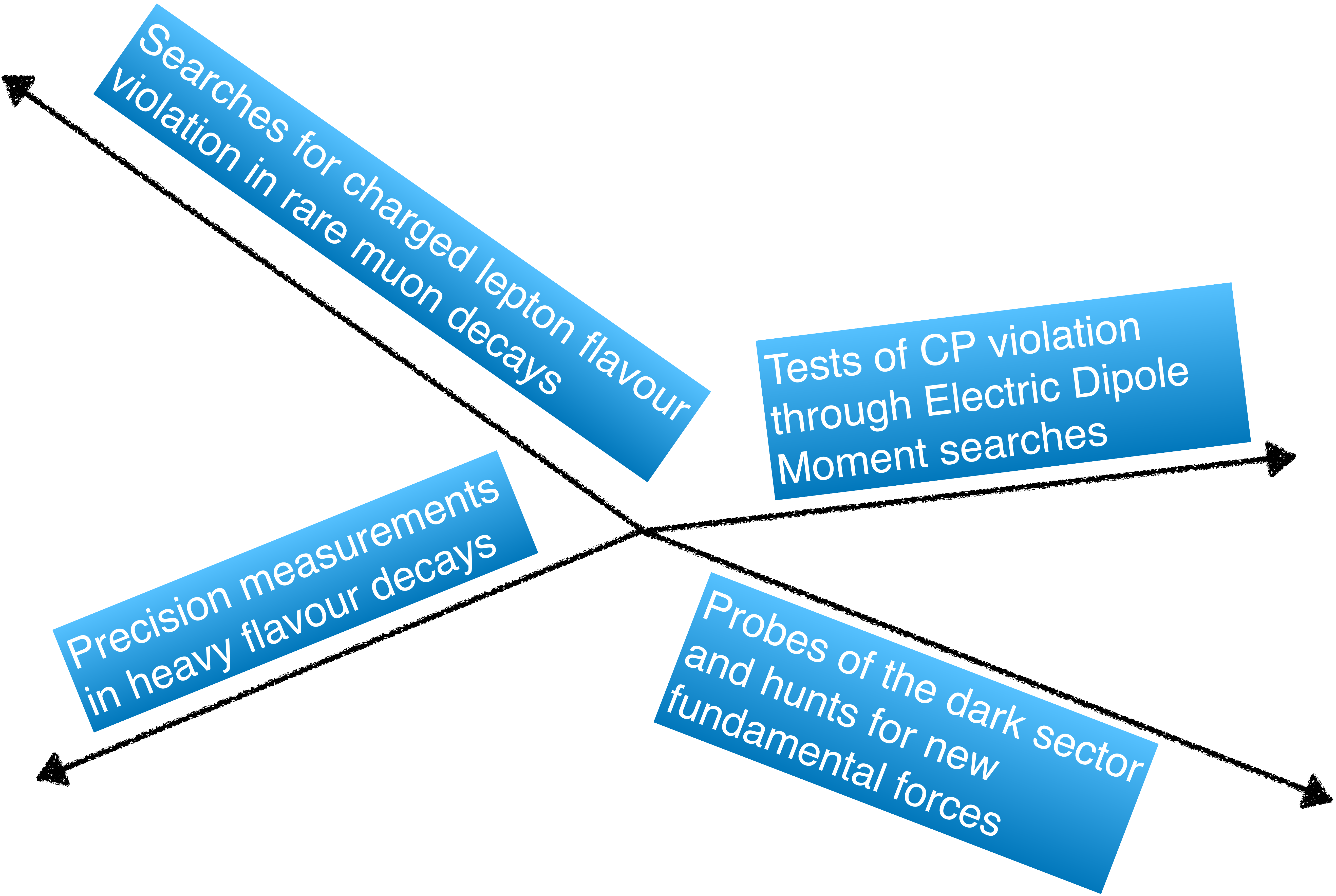
NP could evade discovery because it lies beyond the current energy reach or because it interacts weakly with matter



NP could evade discovery because it lies beyond the current energy reach or because it interacts weakly with matter

To Explore the Unknown, we must search for indirect, low-energy manifestations of high-energy physics (e.g. in flavour or CP-violation) or for feeble interactions.

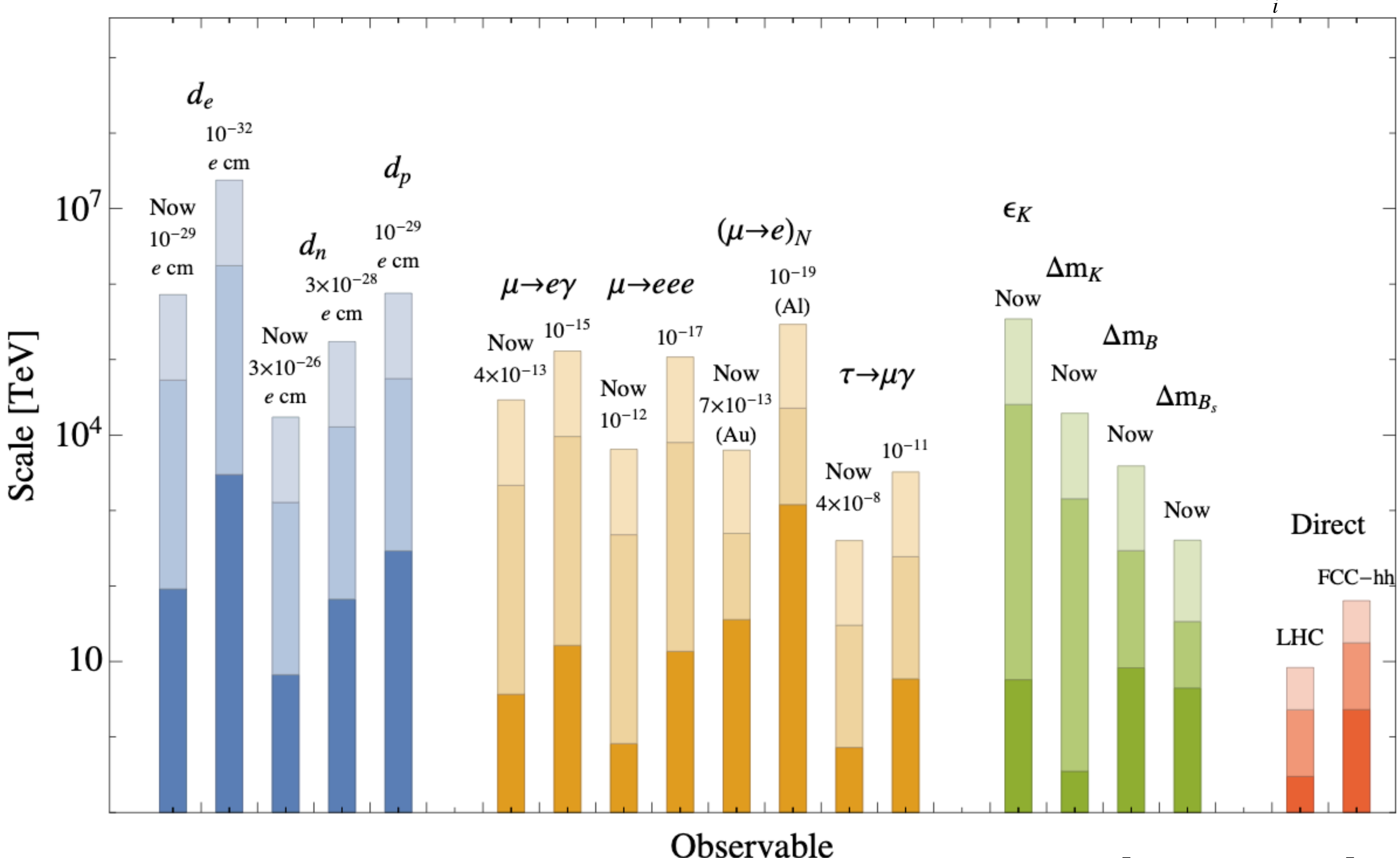
Making progress requires an open-minded search for clues.



Searches for charged lepton flavour violation in rare muon decays
Tests of CP violation through Electric Dipole Moment searches
Precision measurements in heavy flavour decays
Probes of the dark sector and hunts for new fundamental forces

Bounds on scale of NP for various indirect precision observables (current and future)

Bounds on Λ (scale of NP) for dimension six (4-fermion) operators O_i : $\sum_i \frac{C_i}{\Lambda^2} O_i$



[Matt Reece]

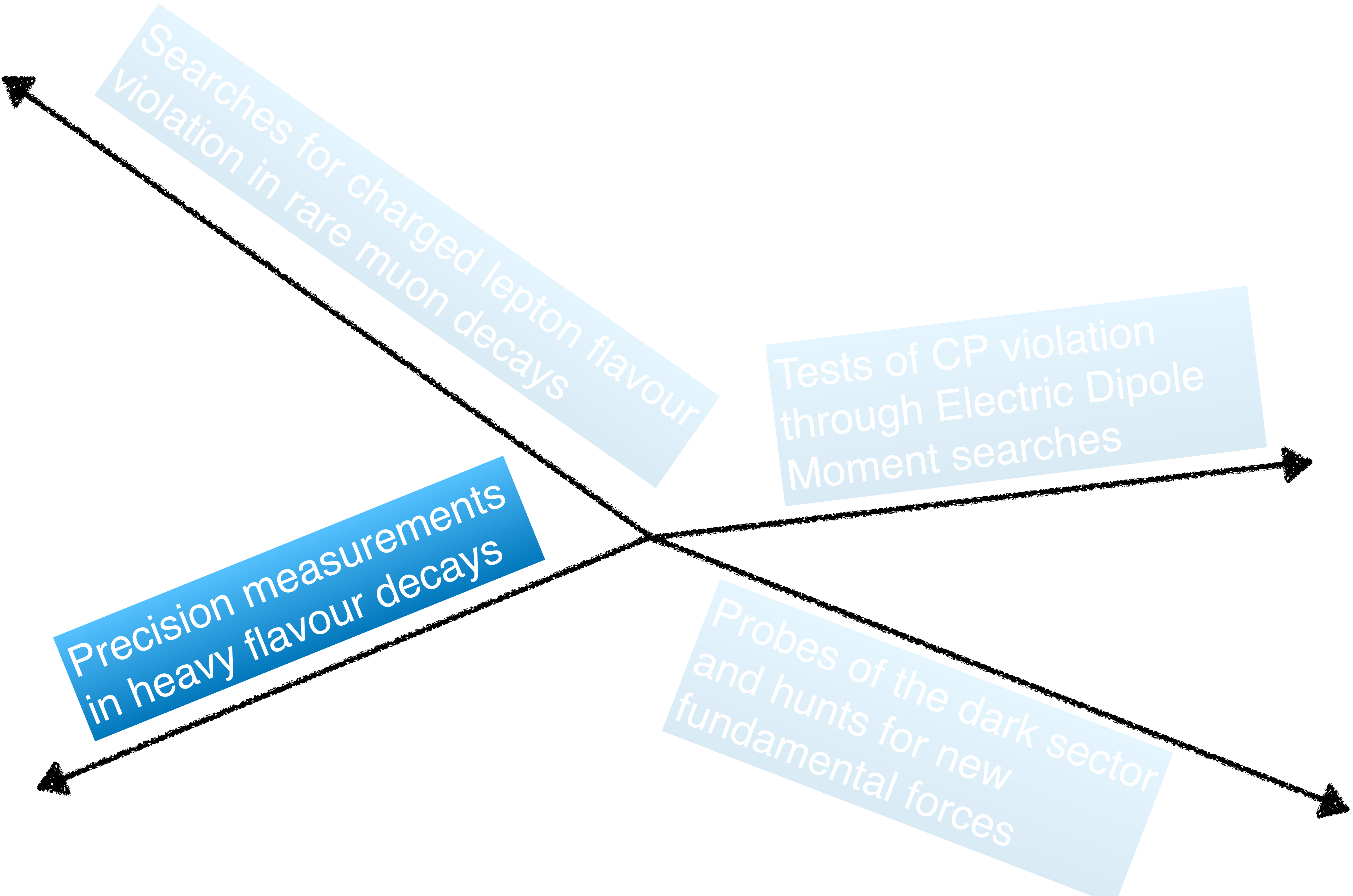
Many mysteries related to flavour…

- ..even if the SM is, at the current level of experimental precision and at the energies reached so far, the most successful and best tested theory of nature at a fundamental level.

    What determines the observed pattern of masses and mixing angles of quarks and leptons?

- In the SM, the only interaction distinguishing the three flavours is the Yukawa interaction (interaction of the matter fields with the Higgs boson). The complex phases present in the Yukawa couplings are also the only source of CP violation.

    Are there other sources of flavour (and CP) symmetry breaking, beside the SM Yukawa couplings?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Heavy flavour as a tool for discovery

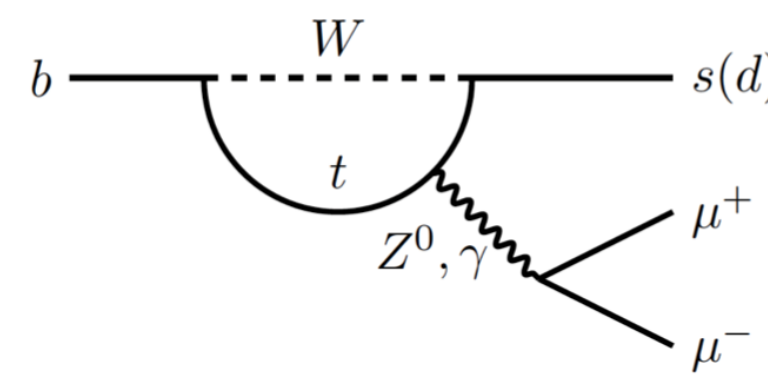
- In the SM, some rare decays are forbidden at tree level and can only occur at loop level (penguins and boxes), e.g. $B_{(s)} \to \mu^+\mu^-$

- NP can be competitive with SM processes: a new particle, too heavy to be produced at the LHC, can give sizeable effects when exchange in a loop.

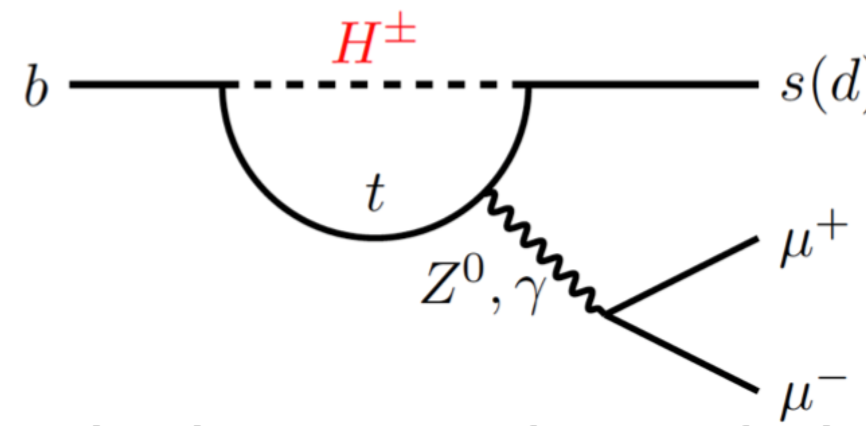
➡ Test precise SM predictions looking for discrepancies

- The SM also predicts charged lepton flavour universality. This can be tested in decay of heavy flavours and is a topic of great interest due to anomalies in $B \to K^{(*)}\ell^+\ell^-$ decays from LHCb.

SM penguin diagram



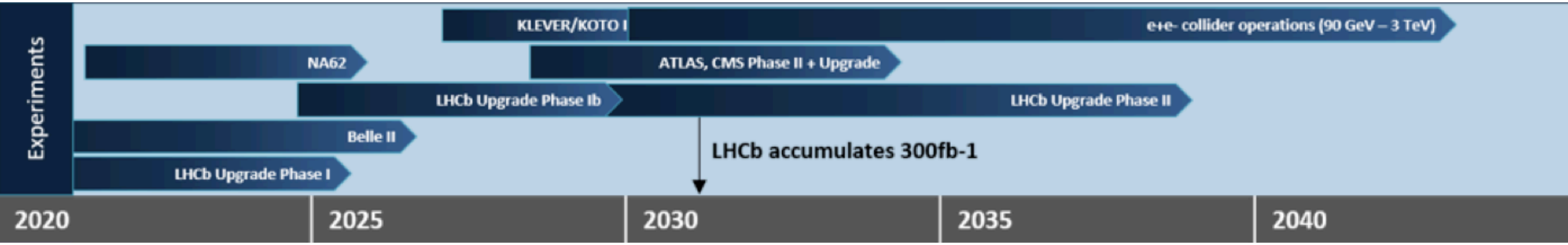
NP penguin diagram



$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(B \to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

$H = K^+, H = K*$

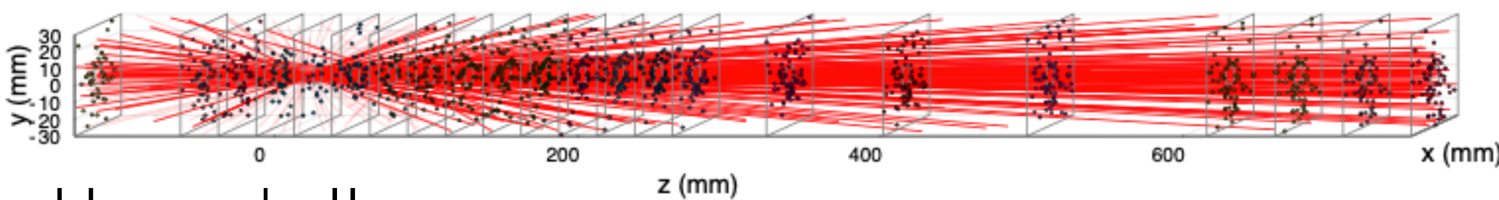
Timeline for the heavy flavour physics program



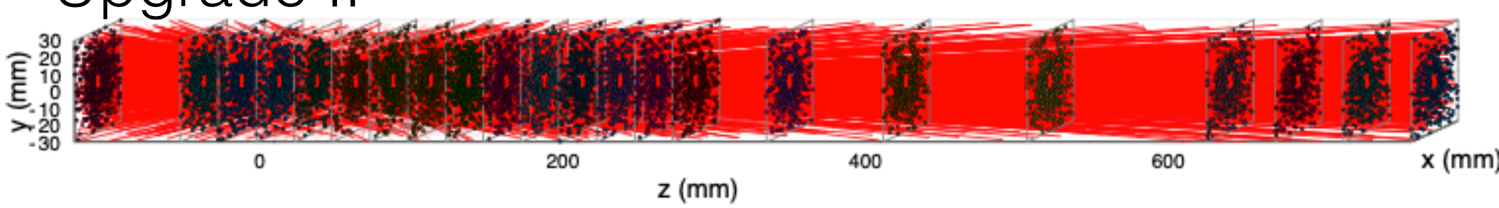
- The LHCb Upgrade II detector is central to the future of the heavy flavour experimental program
  - Goal > 30 times the current integrated luminosity
  - Pile-up ~40 (@$1.5\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$), from ~5 for Run3/4 (today's challenge)
- In the high-occupancy environment where future flavour physics experiments will operate, event reconstruction will be very challenging → Adding timing becomes essential

Using timing in tracking

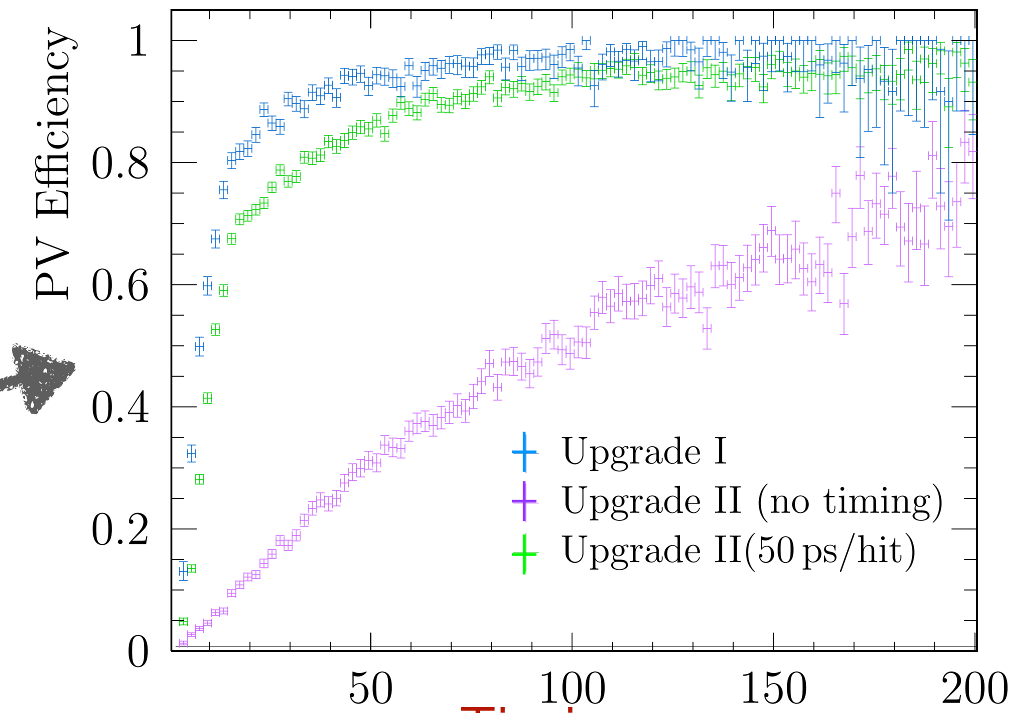
Upgrade I



Upgrade II

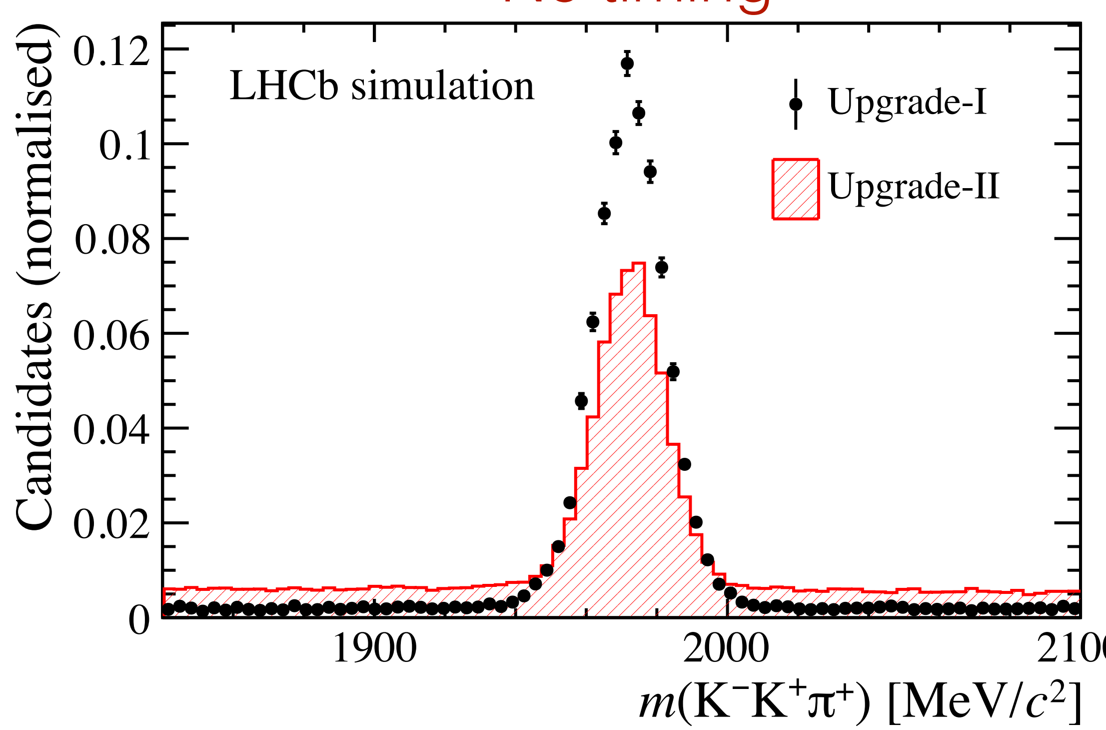


[LHCb Upgrade II workshop ’20, Laurent Dufour]

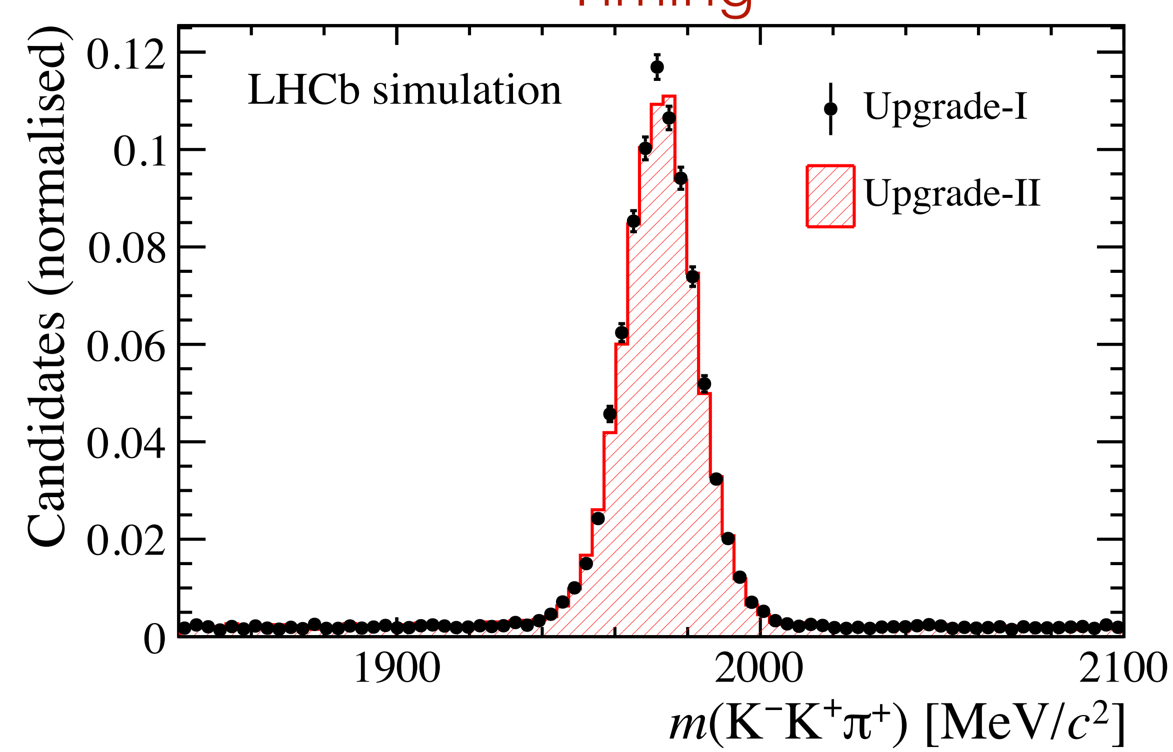


Having a per-hit timestamp drastically helps in reconstructing vertices, both primary and secondary

No timing

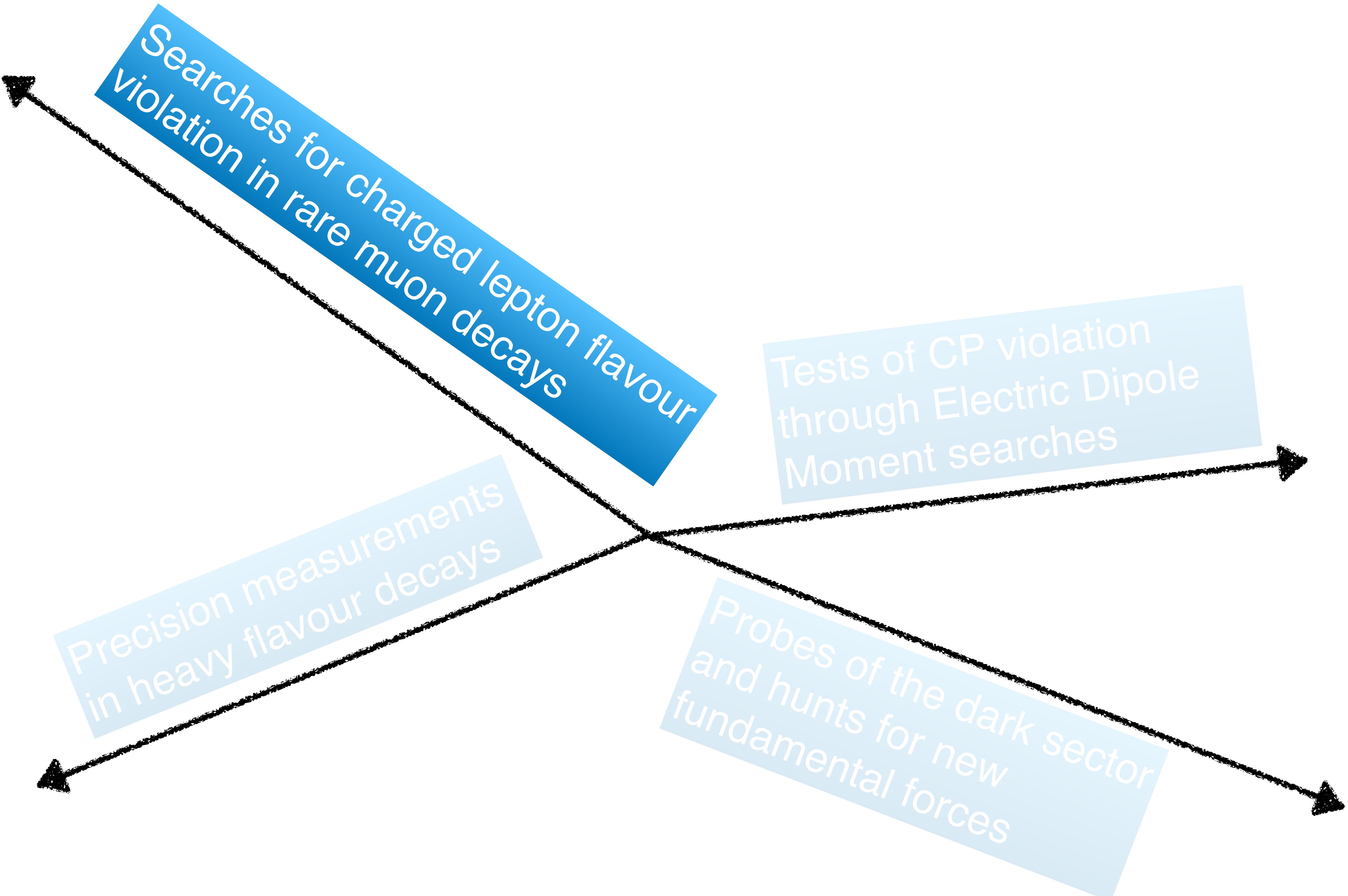


Timing



Experimental challenges

- Tracking detectors : simultaneously precise timing, high granularity, high-rate readout and radiation hardness
- High-quality PID : high-granularity photodetectors with fast timing information for RICH detectors
- Electromagnetic calorimeters : radiation hardness, high granularity and fast timing information
- Trigger and data processing : processing in real time and reduction by at least 4–5 orders of magnitude before recording to permanent storage (with offline quality alignment, calibration and reconstruction); pile-up suppression as early as possible in processing chain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Searches for CLFV

- Most sensitive searches involve muons from intense muon beams:

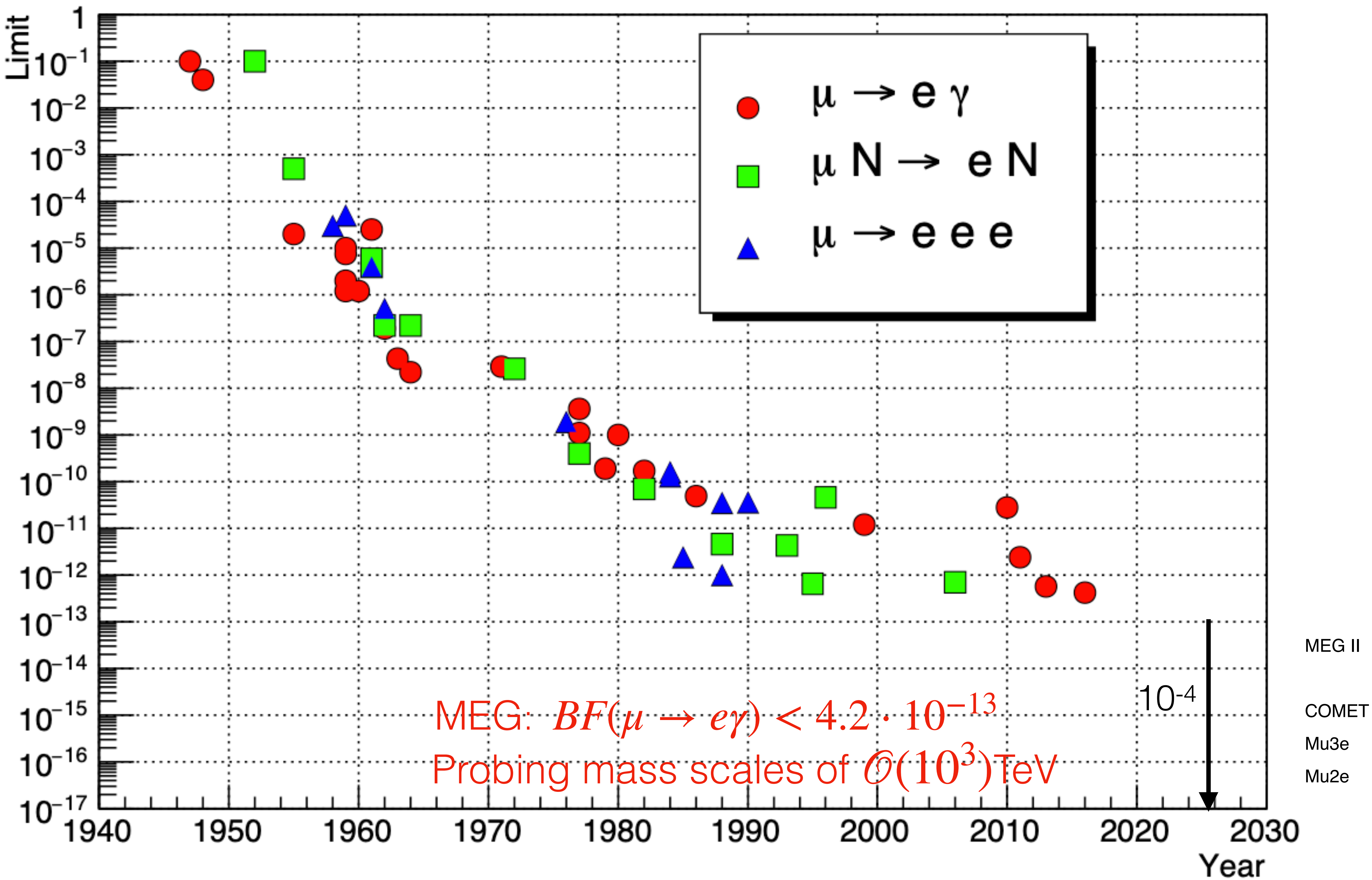
  $\mu \to e\gamma$ $\mu \to eee$ $\mu \to e$ conversions in nuclei

  - Also searched for in τ to e and τ to μ transitions - particularly interesting as 3rd generation lepton - and in K or B decays …
    (e.g. $\tau \to e\gamma, \tau \to \mu\gamma, \tau \to \mu\mu\mu, K_L^0 \to \mu e, B^0 \to \mu e, Z \to \mu e \ldots$)

- Once the SM is extended to include ν masses, it provides a mechanism for CLFV via lepton mixing in loops, however vanishingly small, e.g. $BF(\mu \to e\gamma) \lesssim 10^{-54}$

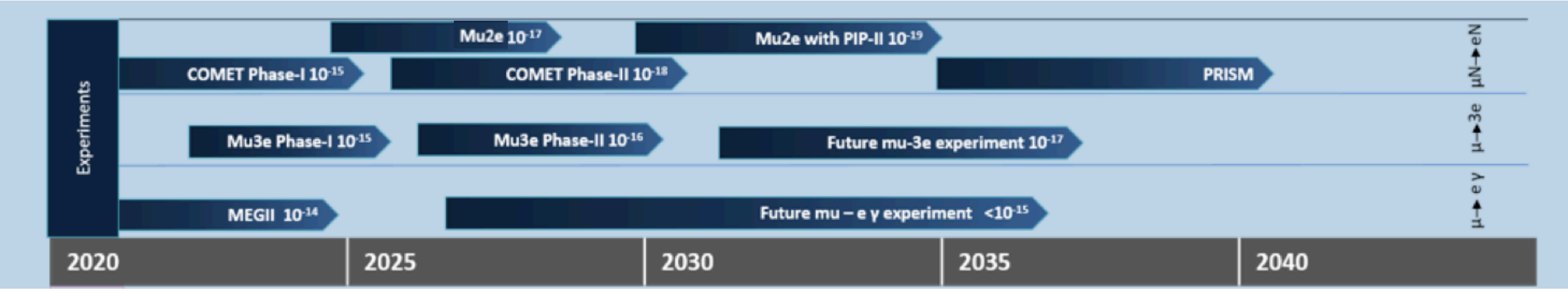
- Many NP models provide enhancements to these rates to observable levels (e.g. in certain seesaw models) → CLFV experiments are unique probes of NP , particularly of models explaining the neutrino mass hierarchy and matter-antimatter asymmetry of the universe via leptogenesis (synergy with neutrino oscillation research program)

Chronology of CLFV experiments with μ decays



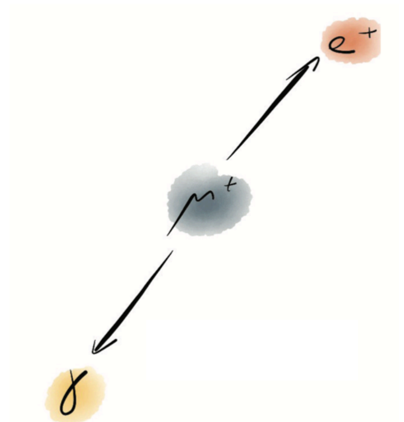
[Calibbi & Signorelli]

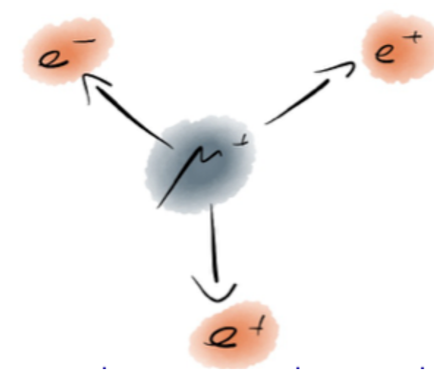
Timeline for the three primary muon-to-electron transitions

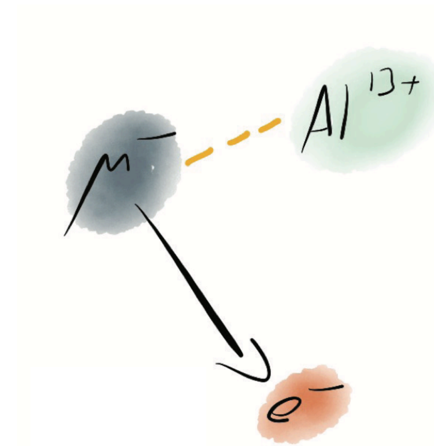


- Mu2e at Fermilab and COMET at J-PARC: experiments in neutrinoless $\mu \to e$ conversions in the field of a nucleus; Mu3e: $\mu \to eee$ and MEGII: $\mu \to e\gamma$ at PSI
- These golden channels provide complementary sensitivity to new sources of CLFV
- Future upgrades could extend the sensitivity by one to two additional orders of magnitude by utilising improved accelerator beam lines at Fermilab, J-PARC and PSI.

Experimental challenges







- Detectors designed to precisely determine the energy, momentum, and timing of particles originating from the muon stopping target
- Future upgrades will be very challenging due to the busy detector environment and the level of control of background needed to reach the required sensitivity (e.g. searches for $\mu \rightarrow e\gamma$ need to reduce accidental background below 10^{-15} level)
- They will benefit from low-mass trackers with excellent momentum resolution and timing information and low-cost calorimeters that can withstand high radiation doses and provide excellent vertex assignment

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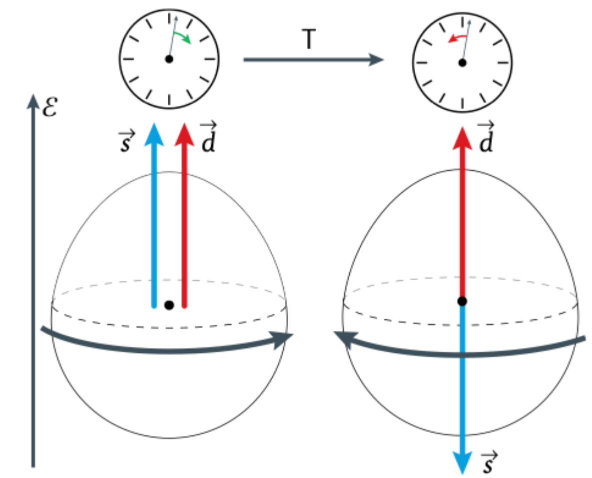
EDM searches



- The EDM is an asymmetric charge distribution along the particle's spin
- EDM violates time reversal symmetry (and P); through CPT conservation → CP violation
- CP violation is required to generate a cosmological matter-antimatter asymmetry. It is present in the SM, through the complex phase in CKM matrix. However, many orders of magnitude below what is necessary!

CP violation beyond the SM must exist!

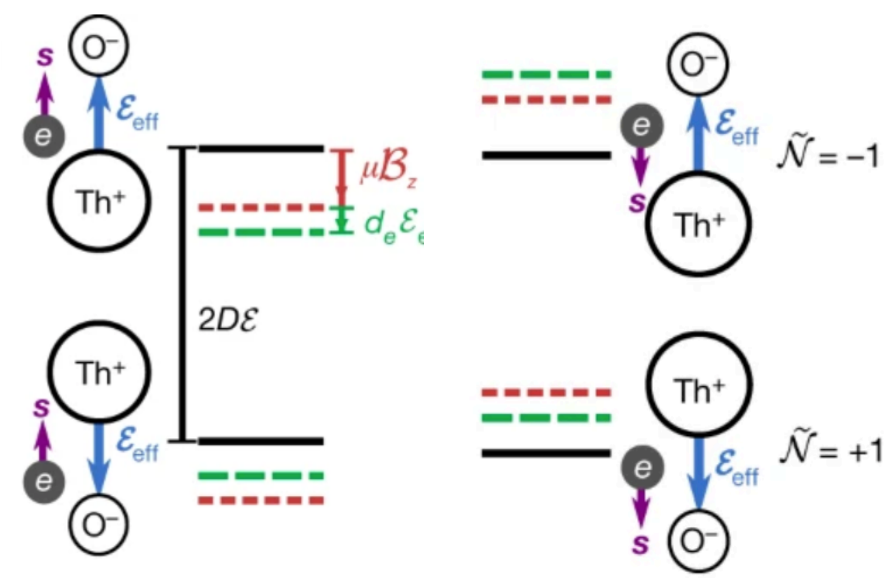
- EDMs in the SM are tiny $(d_e < 10^{-38}\mathrm{e}\cdot\mathrm{cm})$, but most SM extensions include new CP violating phases that contribute to EDMs

This makes EDMs an ideal probe for detecting NP associated with CP violation and a powerful window on energy scales much larger than those that can be probed directly at the LHC

EDM experiments

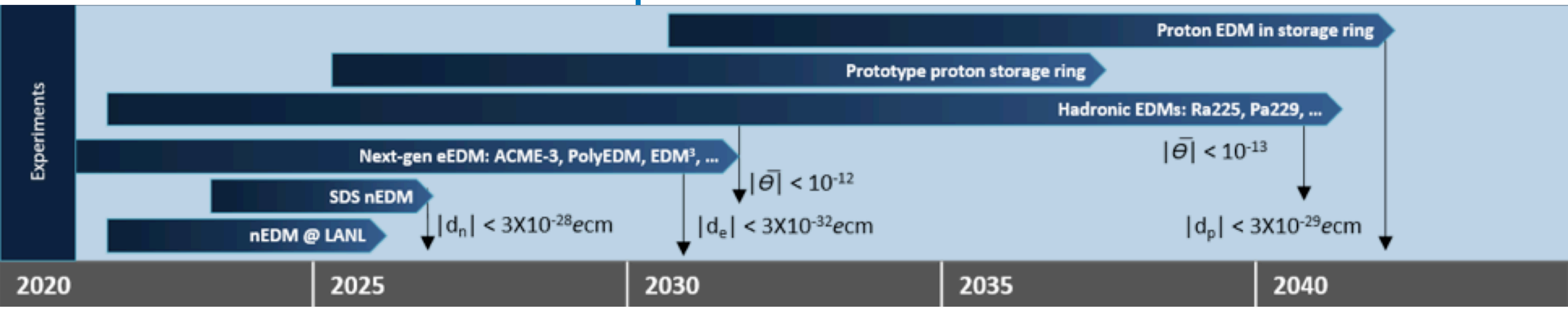
- Current best limit from ACME II experiment on electron EDM $(|d_e| < 1.1 \cdot 10^{-29} \mathrm{e} \cdot \mathrm{cm} \ @\ 90\,\%\,\mathrm{CL})$ based on cryogenic molecular beam of the heavy-polar thorium-oxide molecule ThO

  - electron exposed to huge effective intramolecular electric field $\varepsilon_{\rm eff} \sim 8 \cdot 10^{10}$ V/cm
  - structural properties that greatly reduce sensitivity to key systematic errors
  - long coherence time
  - suitable for use in a cryogenic molecular beam that enables much larger flux → high counting rates



- ACME II constrains new T-violating physics for broad class of models with masses in the range 3-30 TeV

Timeline for possible future EDM experiments

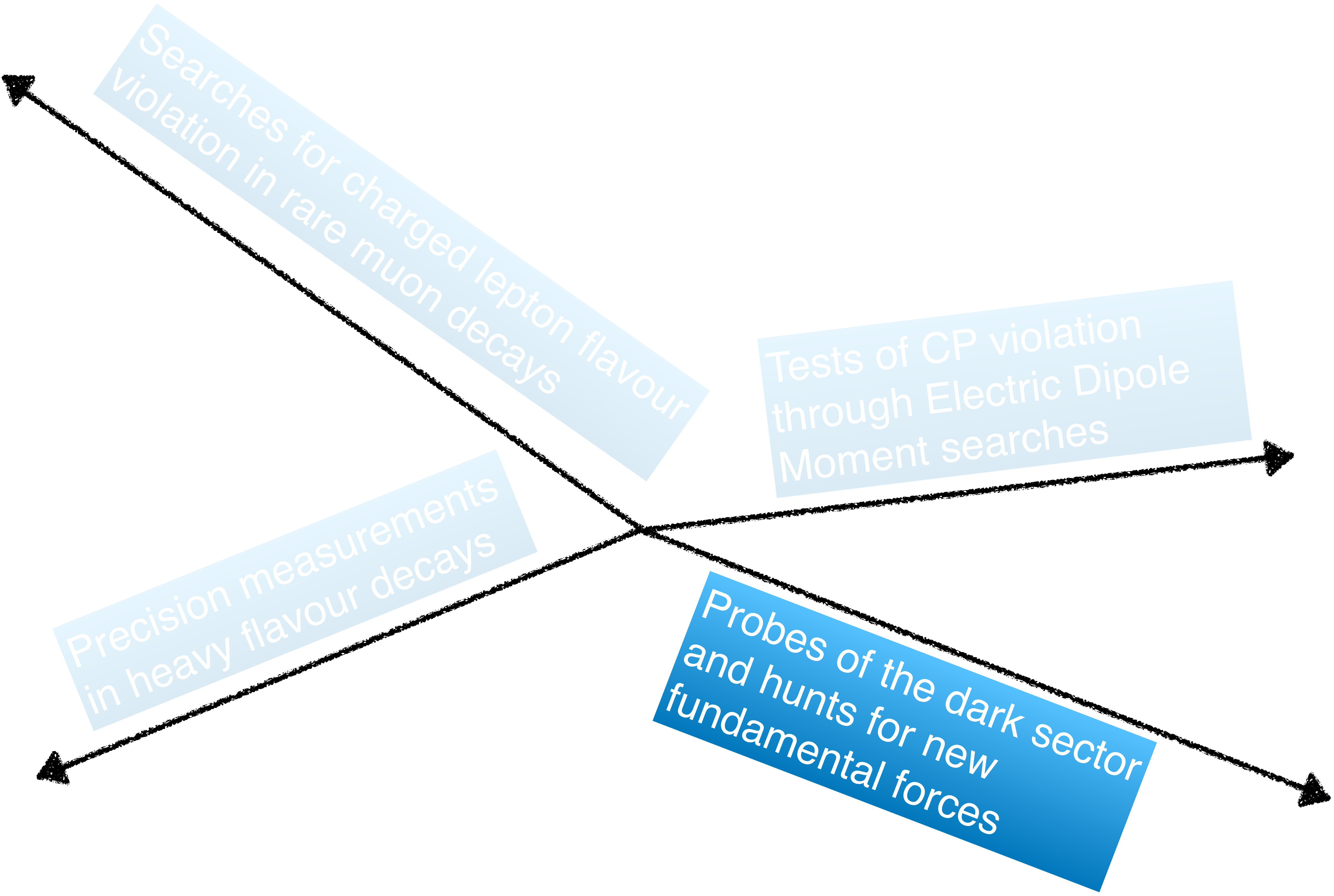


- Proton EDM can be searched at dedicated storage rings; neutron EDM would benefit from development of dedicated ultracold neutron source

- For molecular EDM experiments, statistical uncertainty $\delta d_e \sim \dfrac{\hbar}{2\varepsilon_{\text{eff}}\tau\sqrt{N_{\text{obs}}}}$
  - Controlled preparation of many coherent particles; laser cooling and trapping of molecules to increase coherence times
  - Characterize additional molecules

Particularly interesting for their high sensitivity, relatively low cost and short time between successive experiments

- Understanding any positive EDM signal requires measurement of multiple systems (particles or molecules)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Dark sector and fundamental forces

- Interesting class of experiments searching for particles that interact very weakly with the SM (or for very weakly interacting fundamental forces), e.g. a dark photon

- Dark sectors can be searched at existing colliders experiments or at dedicated experiments (e.g. FASER II, MATHUSLA, Codex-B, SHIP). These experiments are located far away from the interaction point → no radiation hardness requirements, but require large area detectors with good timing capabilities (e.g. would benefit from low-cost photosensors).

- Exotic interactions could produce subtle energy perturbations detectable with precision quantum sensors (eg. atomic clocks, atomic interferometers, atomic magnetometers, high-Q cavities,…) → push the precision frontier of quantum sensors to maximise sensitivity

Take home message

In the current physics context, where we have many unsolved mysteries, but lack evidence of the scale of NP, it is crucial to maintain a broad and diverse physics program.

The program that we have outlined along the four major lines of Precision measurements in heavy flavour decays, Searches for CLFV, Searches for EDMs and Probes of the dark sector or new fundamental forces has the potential to indicate the scale of NP and provide insights into its nature.

A vibrant R&D program is necessary in order to realise this potential and to inspire new ideas for experiments that have not yet been imagined.

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