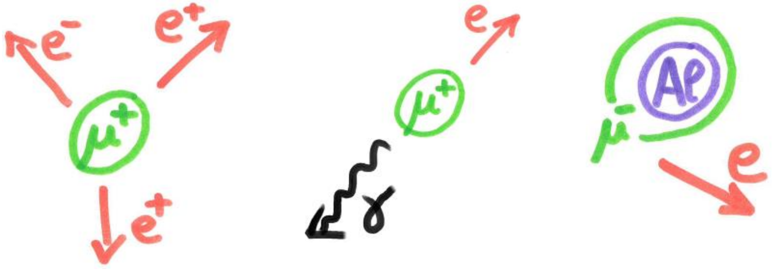
Forbidden processes at the precision frontier

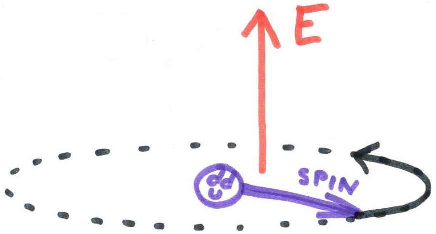
1 Charged lepton flavor violation

Physics case – current and future searches



Angela Papa
University of Pisa/INFN and Paul Scherrer Institute

2 Electric Dipole Moments



Physics case – current and future searches

Guillaume Pignol
Université Grenoble Alpes / LPSC-IN2P3

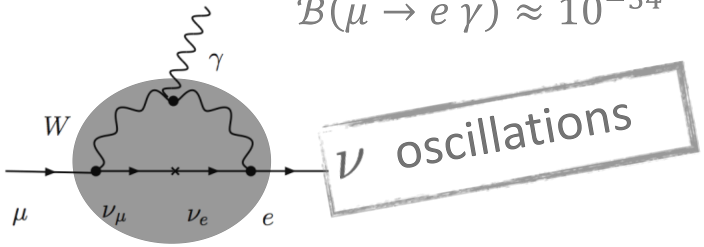
Lepton flavour violation

Neutral lepton flavour transitions: **observed in ν oscillations**

Charged lepton flavour transitions (cLFV): **not observed and forbidden**

SM with massive neutrinos (Dirac)

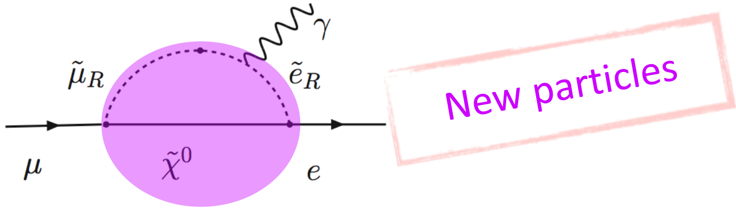
$\mathcal{B}(\mu \to e\,\gamma) \approx 10^{-54}$



too small to (ever) access experimentally

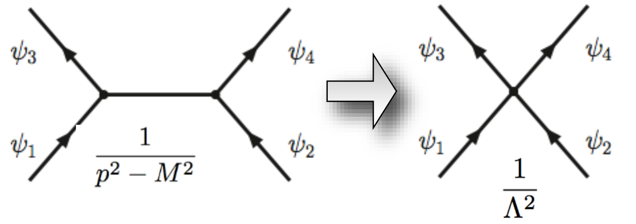
BSM

$\mathcal{B}(\mu \to e\,\gamma) \gg 10^{-54}$



If observed:

unambiguous signature of new physics

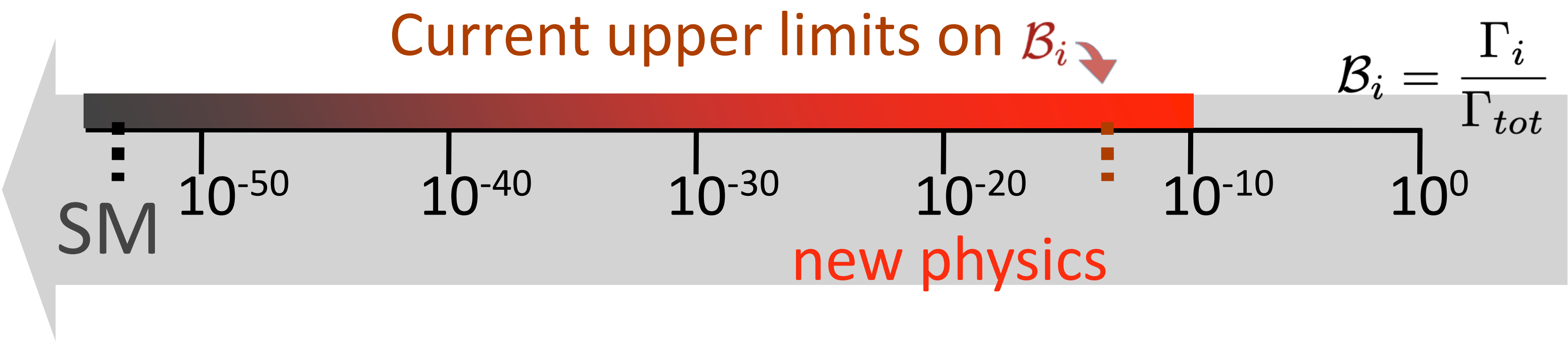


$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{D}<6} + \frac{1}{\Lambda^2}\sum_i c_i O_i^{(6)}$$

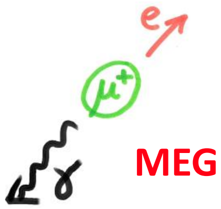
Indirect probe of new physics, at intensity frontier probe extreme energy scale

$\Lambda > 1$ PeV

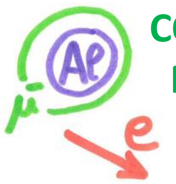
$$\mathcal{B}_i = \frac{\Gamma_i}{\Gamma_{tot}}$$



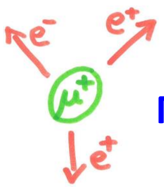
Three golden channels of cLFV with muons



MEG II (PSI)

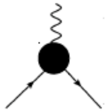
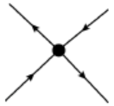


COMET (JPARC)
Mu2e (FNAL)



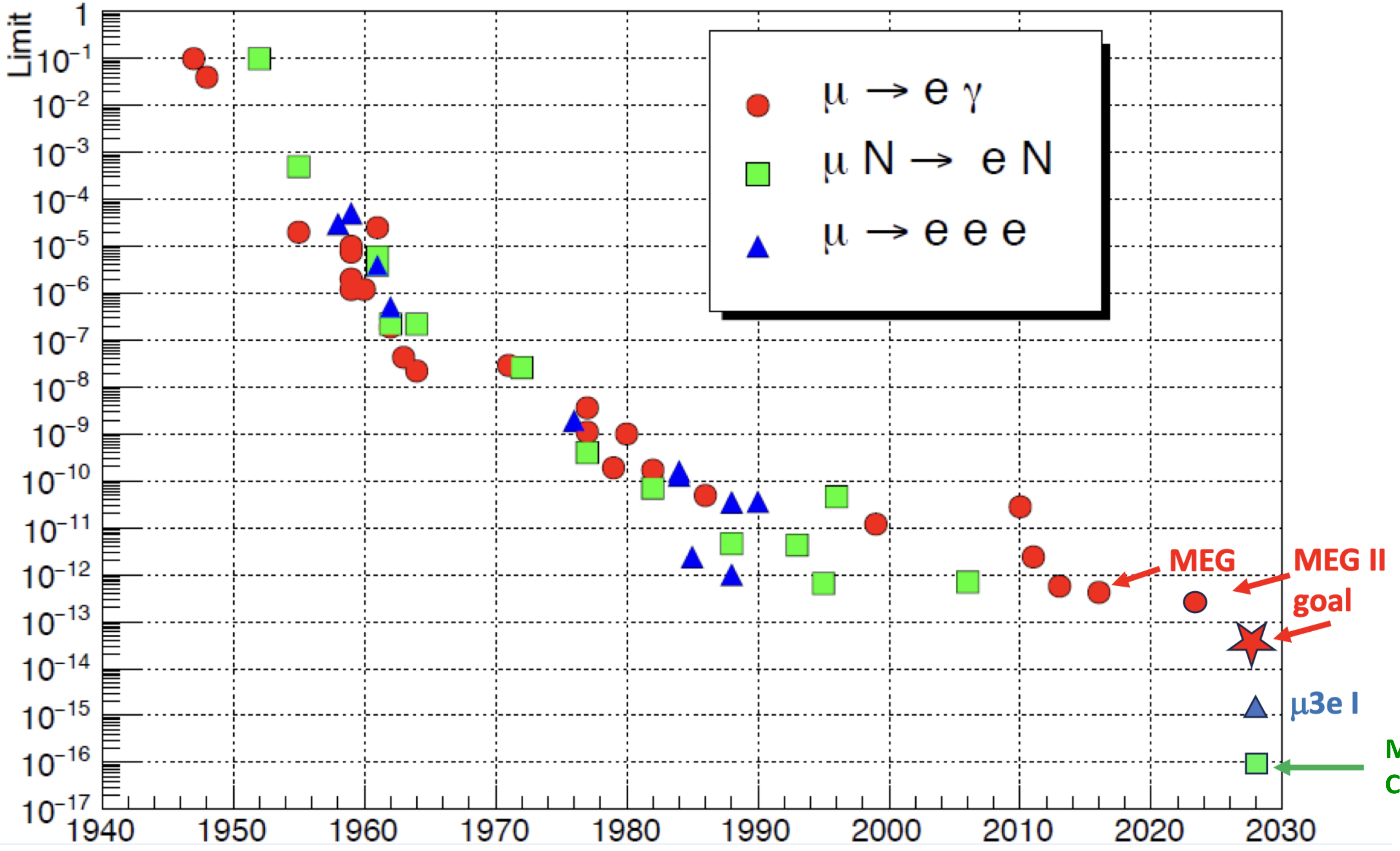
Mu3e (PSI)

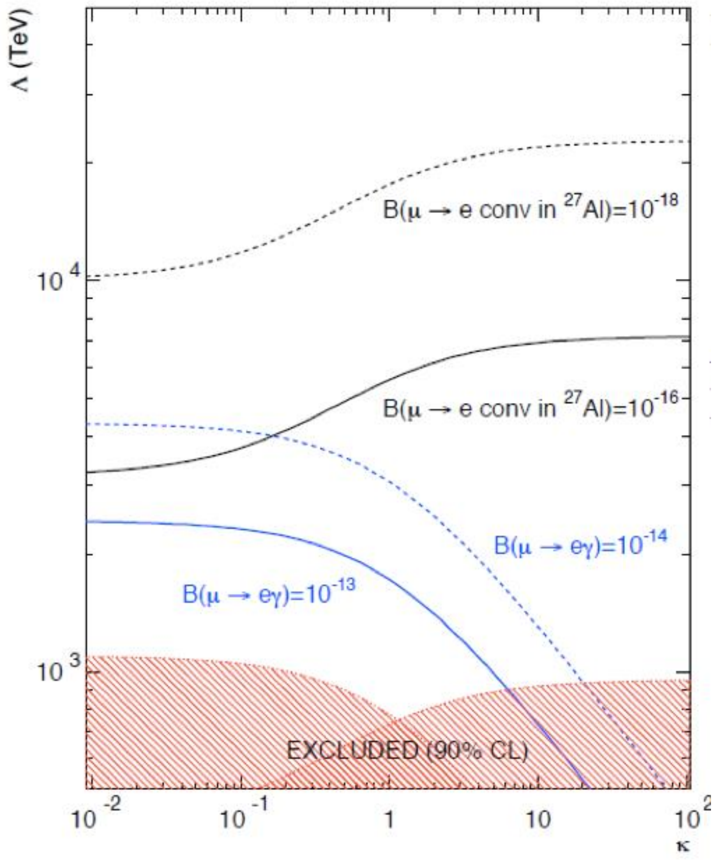
Complementarity of the 3 channels:
They probe different operators

$\frac{m_\mu}{(\kappa+1)\Lambda^2}\times$  $+\ \frac{\kappa}{(\kappa+1)\Lambda^2}\times$ 

$\mu \to e\,\gamma$

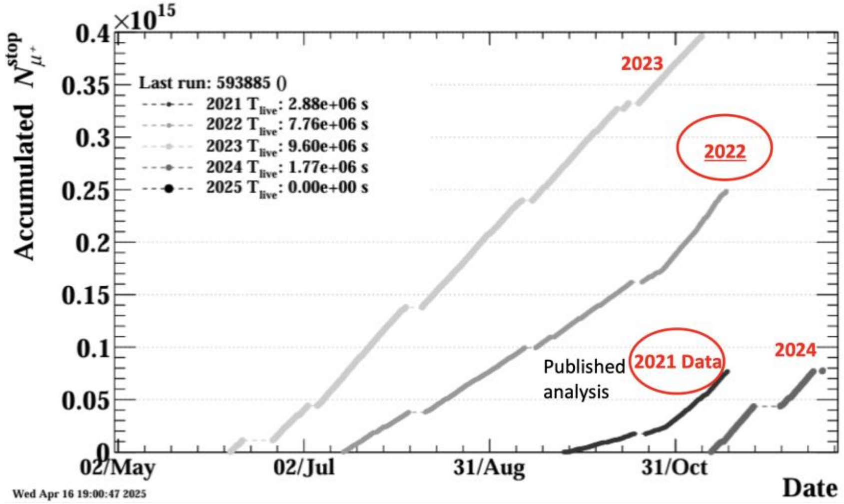
$\mu \to eee$
$\mu N \to eN$

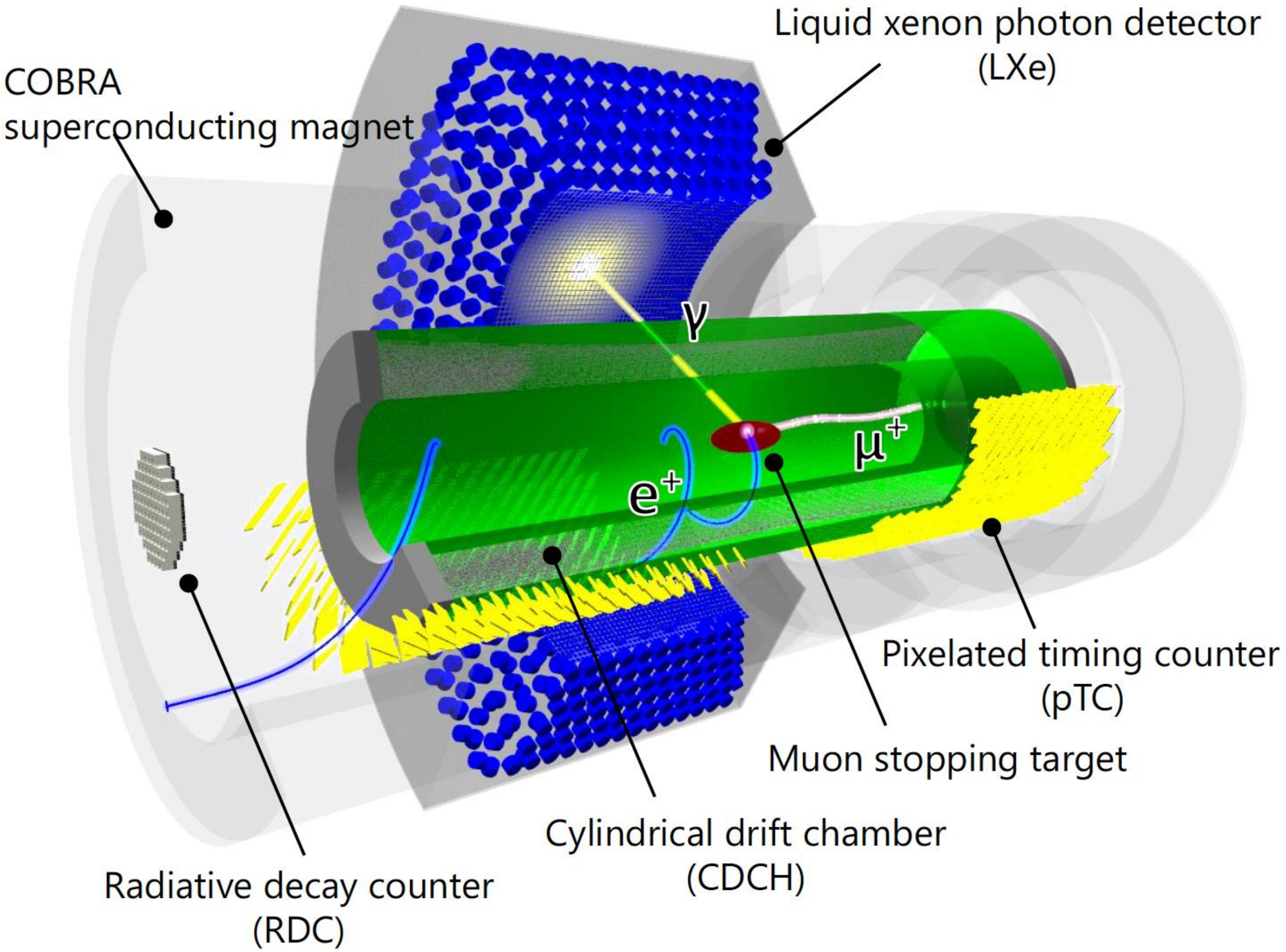




MEG II   data taking ongoing until 2026

2 body decay signature from stopped muons in the target (continuous, ~50 million μ⁺/s)





Result with 2021+2022 data

$$\mathcal{B}(\mu \to e\,\gamma) < 1.5 \times 10^{-13}$$

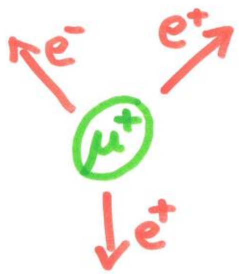
(90%CL)

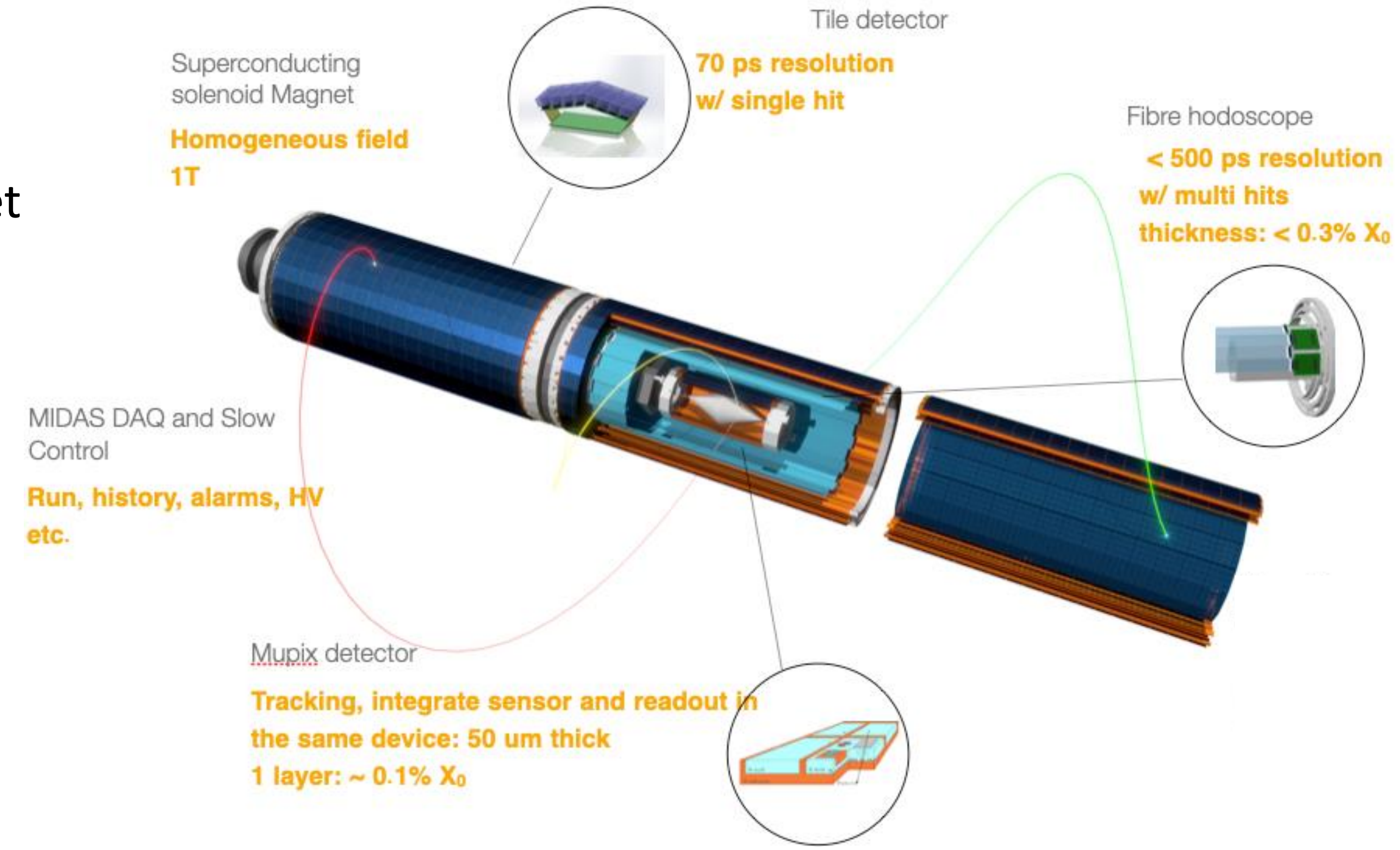
Expected sensitivity in 2026

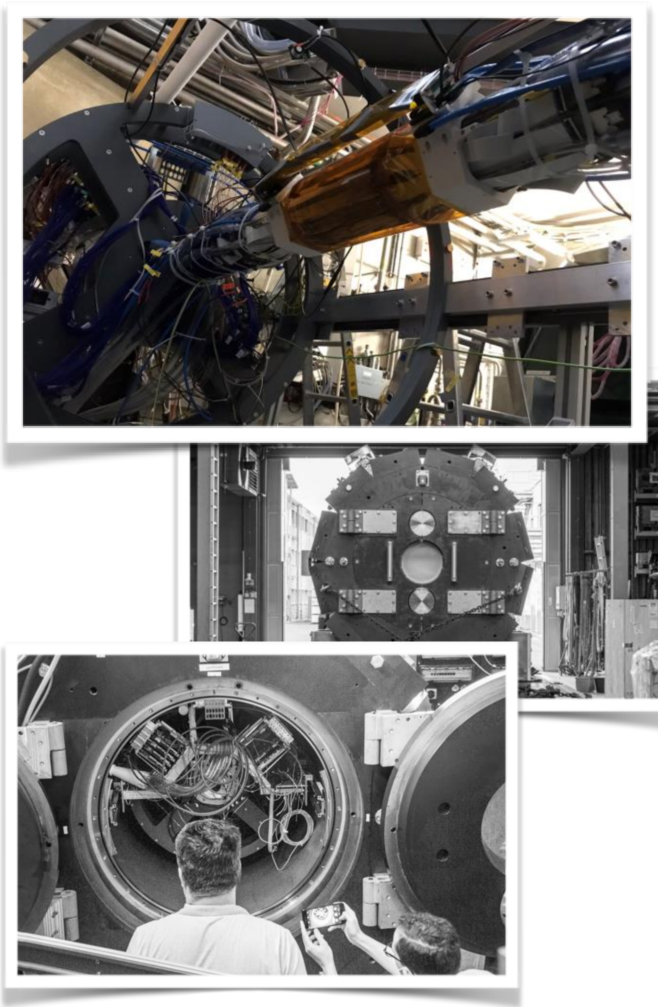
$$\mathcal{B}(\mu \to e\,\gamma) \sim 6 \times 10^{-14}$$

Mu3e approaching the start of physics run

Event signature from stopped muons in the target ($\sim$100 million μ^+/s during 2023 test)







Previous limit (SINDRUM@PSI)

$\mathcal{B}(\mu \rightarrow eee) < 1 \times 10^{-12}$ (90%CL)

Mu3e phase I, starting 2026

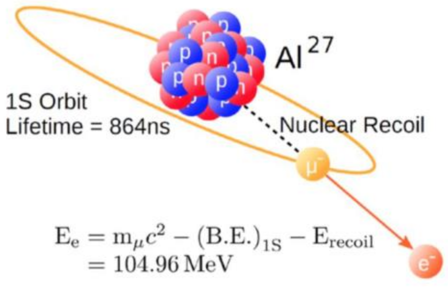
$\mathcal{B}(\mu \rightarrow eee) \sim 1 \times 10^{-15}$ expected sensitivity ($\sim$2030)

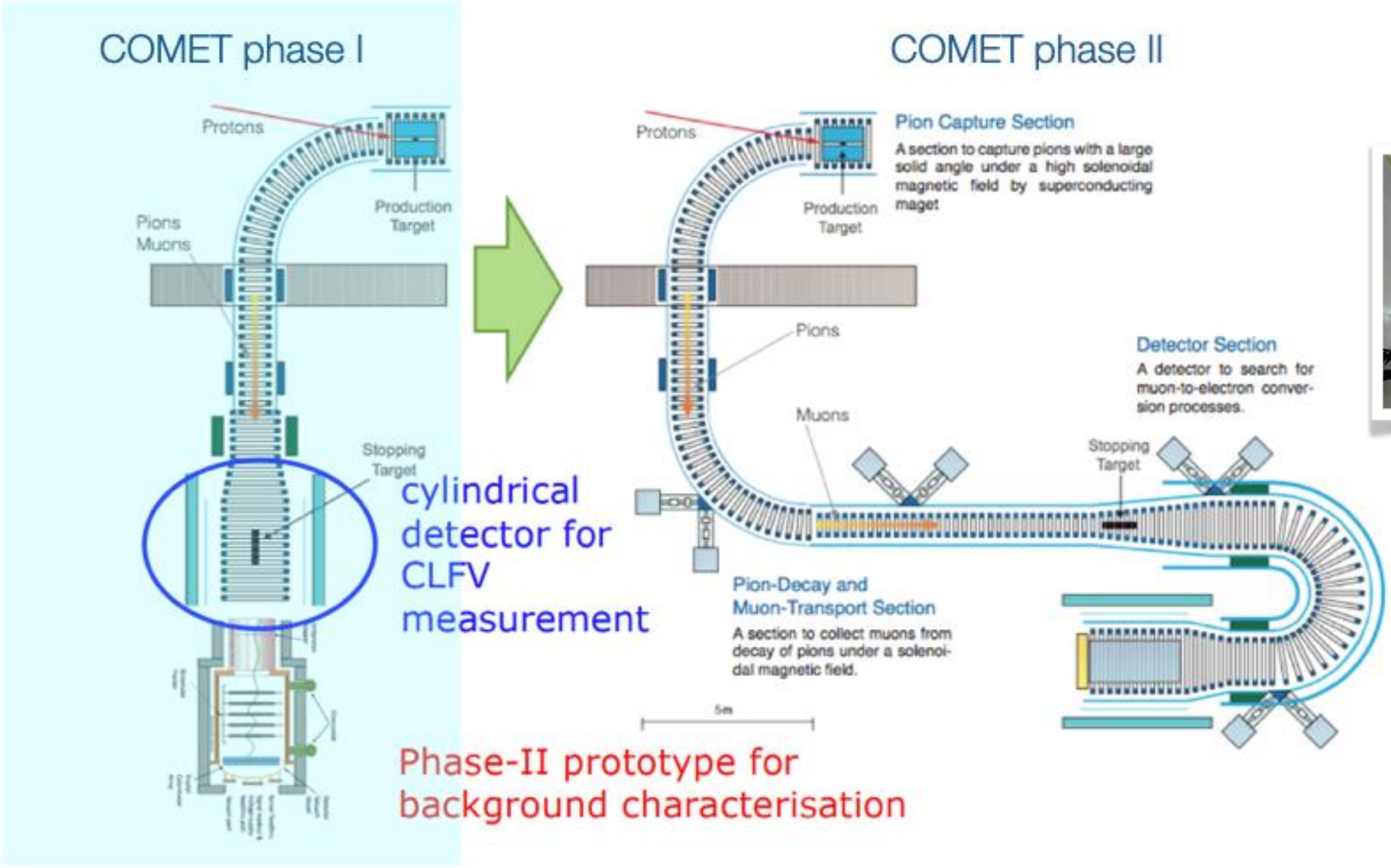
Mu3e phase II at HiMB, 10^9 μ/s

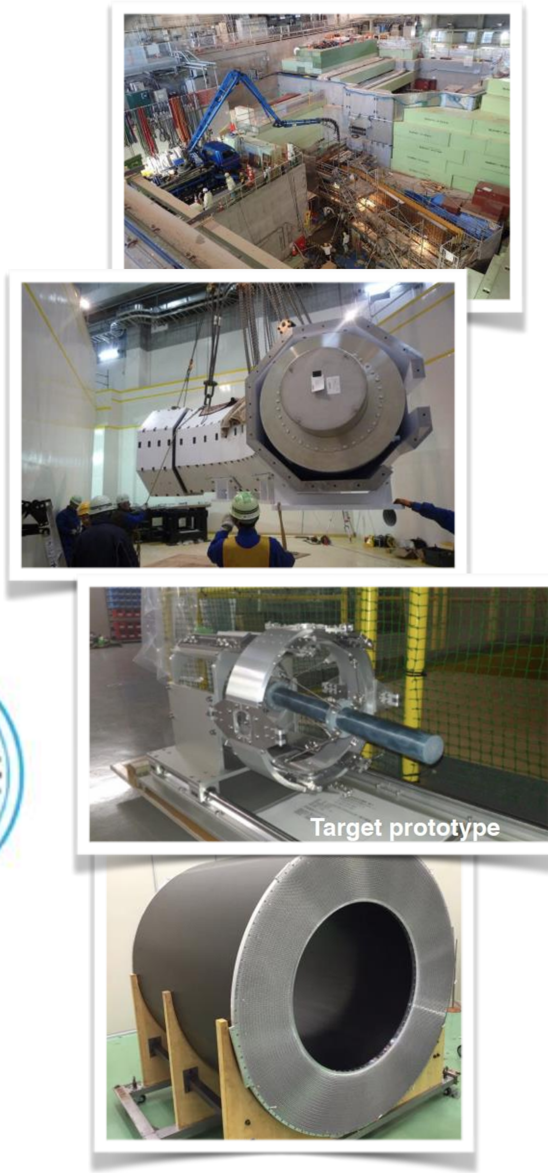
$\mathcal{B}(\mu \rightarrow eee) \sim 1 \times 10^{-16}$ expected sensitivity($\sim$2035)

COMET preparation of the physics run

Event signature from stopped muons in the target (pulsed beam)







Previous limit (SINDRUM@PSI)

$\mathcal{B}(\mu N \to eN) < 7 \times 10^{-13}$ (90%CL)

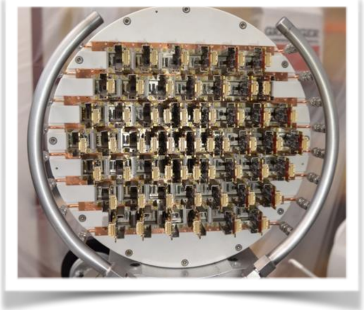
COMET Phase I, starting in 2026

$\mathcal{B}(\mu N \to eN) \sim 3 \times 10^{-15}$ expected sensitivity (~2030)

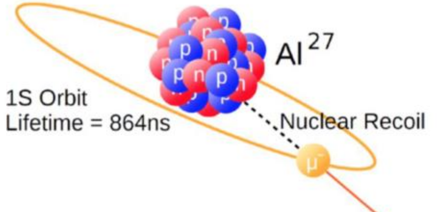
COMET Phase II

$\mathcal{B}(\mu N \to eN) \sim 3 \times 10^{-17}$ expected sensitivity (~2035)

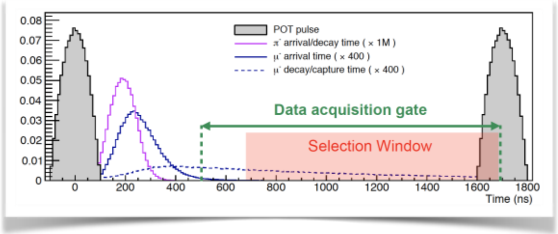
Mu2e Installation ongoing



Event signature from stopped muons in the target (pulsed beam)

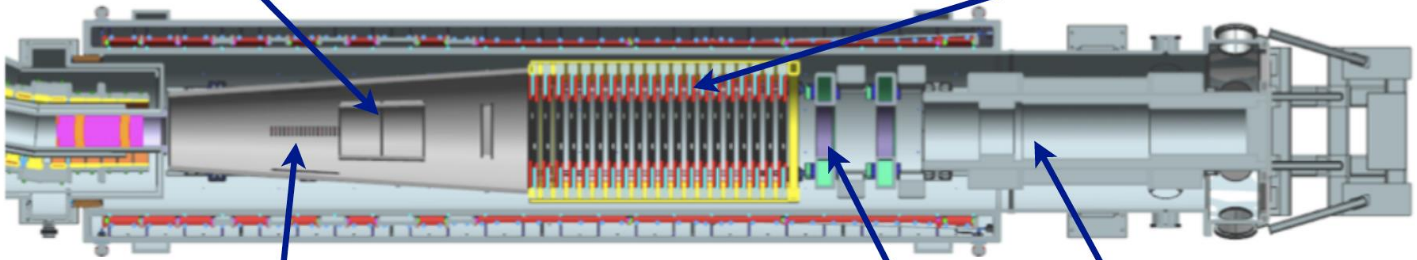


$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\ \text{MeV}$$



- **Proton absorber:**
  - ❖ made of high-density polyethylene
  - ❖ designed in order to reduce proton flux on the tracker and minimize energy loss

- **Tracker:**
  - ❖ ~20k straw tubes arranged in planes on stations, the tracker has 18 stations
  - ❖ Expected momentum resolution < 200 keV/c



- **Targets:**
  - ❖ 34 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- **Calorimeter:**
  - ❖ 2 disks composed of undoped CsI crystals

- **Muon beam stop:**
  - ❖ made of several cylinders of different materials: stainless steel and polyethylene

Previous limit (SINDRUM@PSI)

$$\mathcal{B}(\mu N \to eN) < 7 \times 10^{-13}$$

(90%CL)

Mu2e Phase I, starting in 2026

$$\mathcal{B}(\mu N \to eN) \sim 3 \times 10^{-15}$$

expected sensitivity (~2030)

Mu2e Phase II

$$\mathcal{B}(\mu N \to eN) \sim 3 \times 10^{-17}$$

expected sensitivity (~2035)

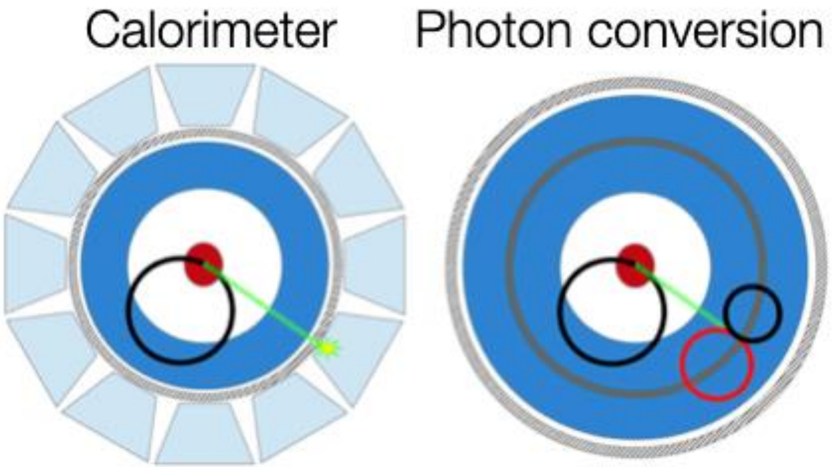
Future cLFV searches: a community is growing up

$\mu \to e\,\gamma$ limited by accidental coincidences $e\,\gamma$ from different muon decays.

To exploit higher muon rates (HiBM at PSI, >10^9 μ/s):
needs to improve the discrimination, which relies on

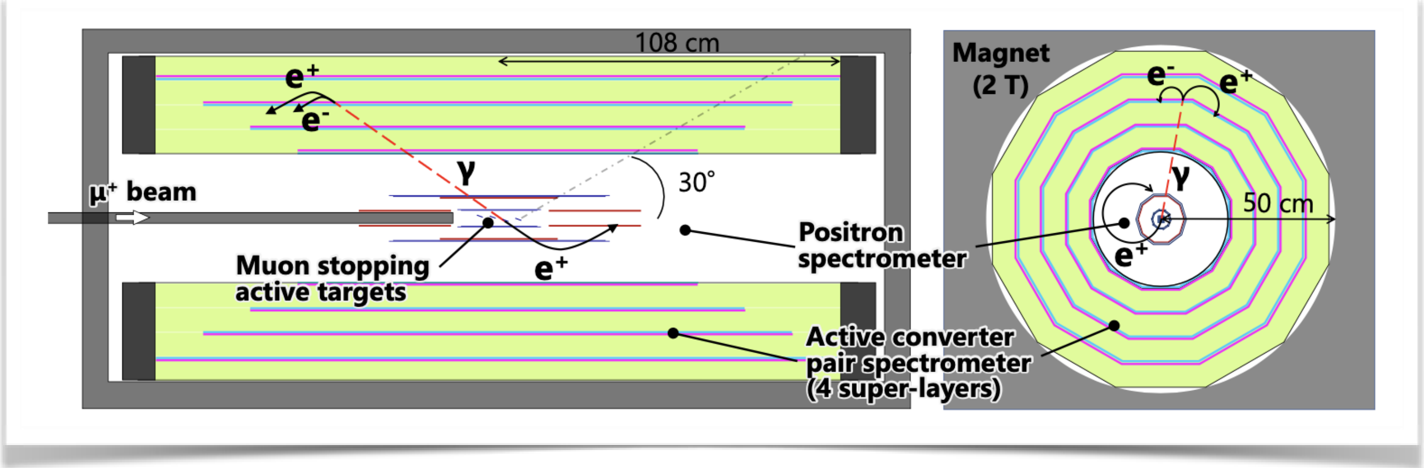
- Times of $e - \gamma$
- Energy $e - \gamma$
- Direction $e - \gamma$

needs **better γ detection**,
in particular the direction



Improved calorimeter
Increased angular acceptance

Improved photon energy reconstruction
Improved photon direction reconstruction



Conceptual and R&D phase for a photon conversion detector

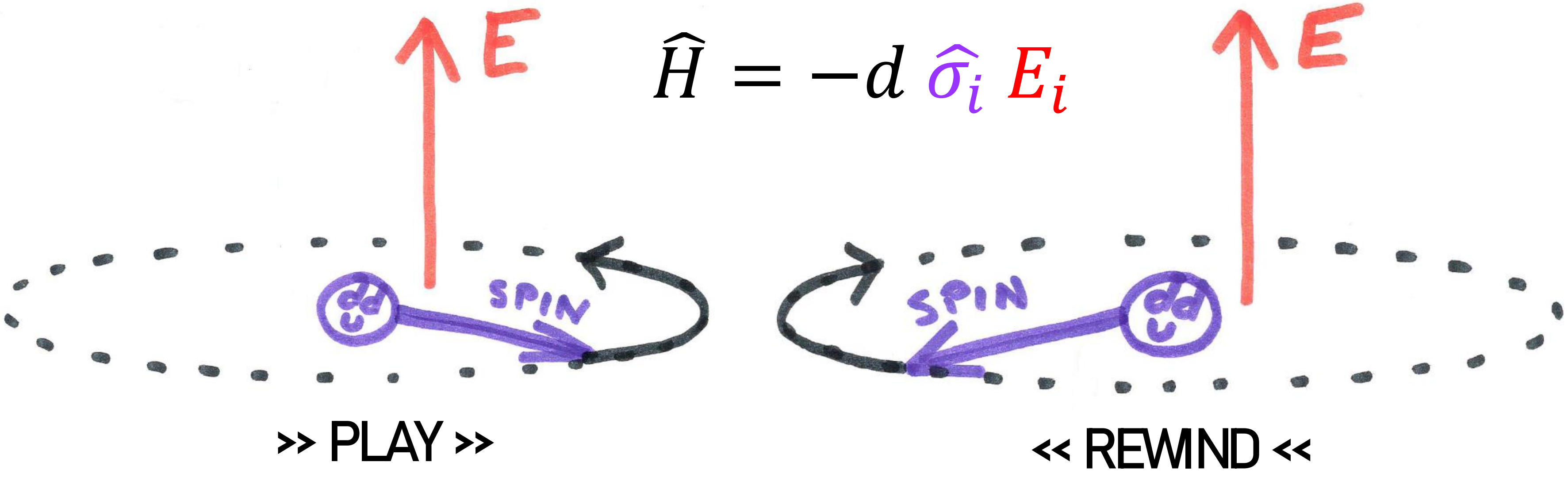
- Target sensitivity $\mathcal{B}(\,\mu \to e\,\gamma) \sim 10^{-14}$
- Possibly combined with $\mu \to eee$

Part 2

Searches for Electric Dipole Moments

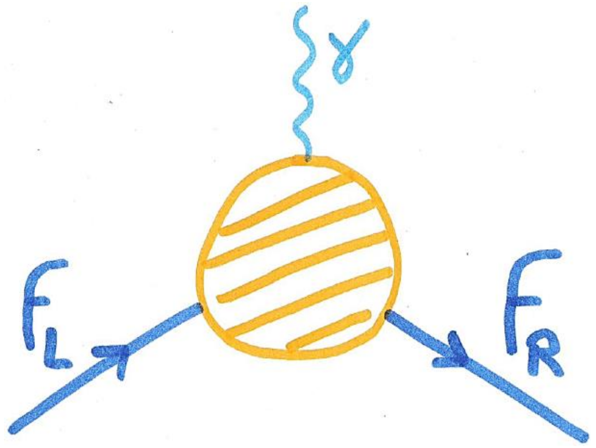
EDMs: probe of T-symmetry

Experimentalist perspective:
The EDM is the coupling of spin to E field.
Violates P and T.



$$\hat{H} = -d\,\hat{\sigma}_i\,E_i$$

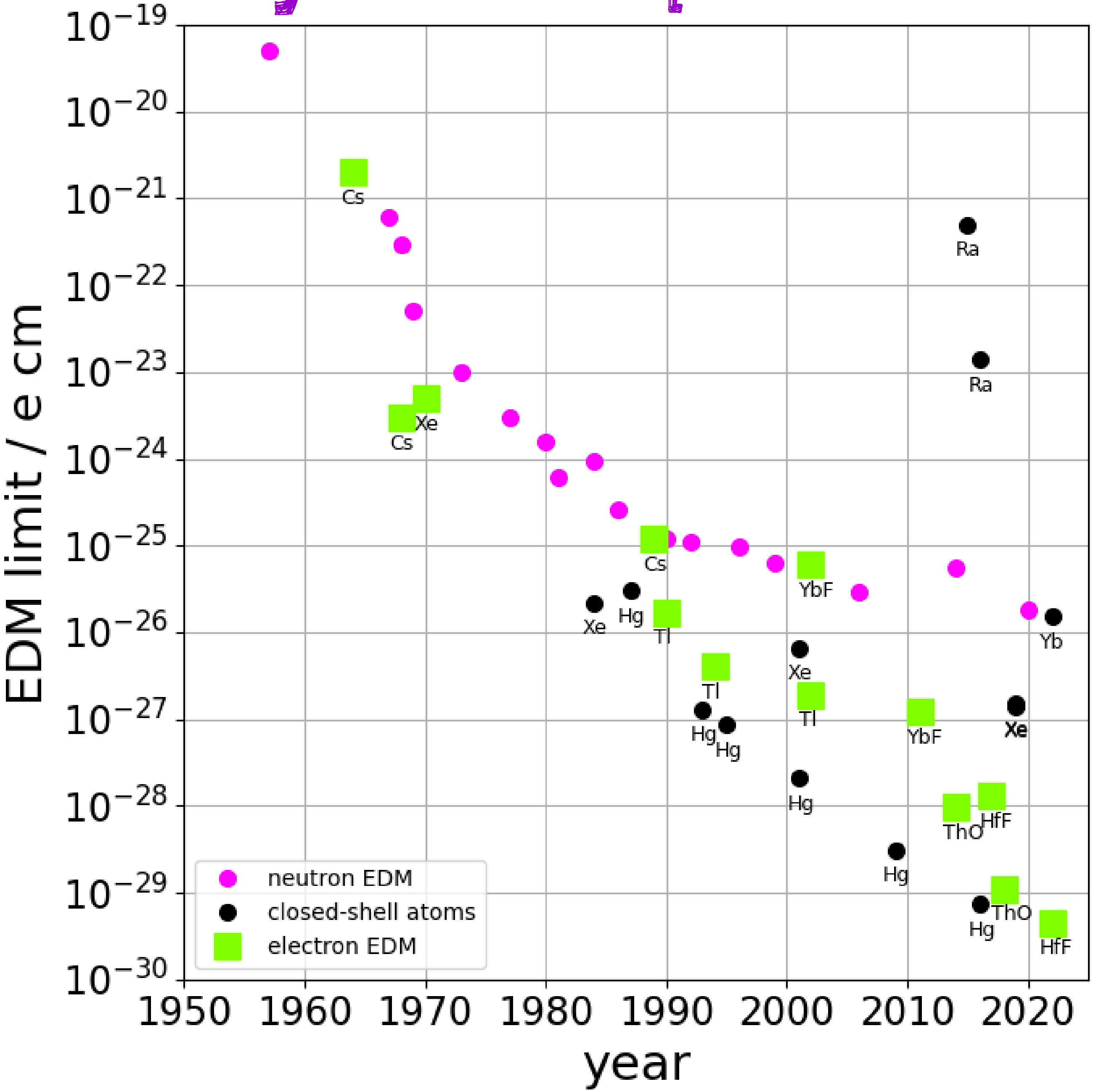
HEP theorist perspective:
Effective vertex fermion-photon
Imaginary part of the magnetic moment.
Violates CP.



$$\mathcal{L}_{\text{dip}} = \frac{1}{2}(\boldsymbol{\mu} + i\boldsymbol{d})\bar{f}_L\sigma_{\mu\nu}f_R\,F^{\mu\nu} + h.c.$$

Non-relativistic limit $\hat{H} = -\boldsymbol{\mu}\hat{\sigma}_i B_i - \boldsymbol{d}\hat{\sigma}_i E_i$

History of the quest for EDMs of various systems



Belle (2022)
$d_\tau = (-0.6 \pm 0.6) \times 10^{-17}\ e\ \mathrm{cm}$
COLLIDER

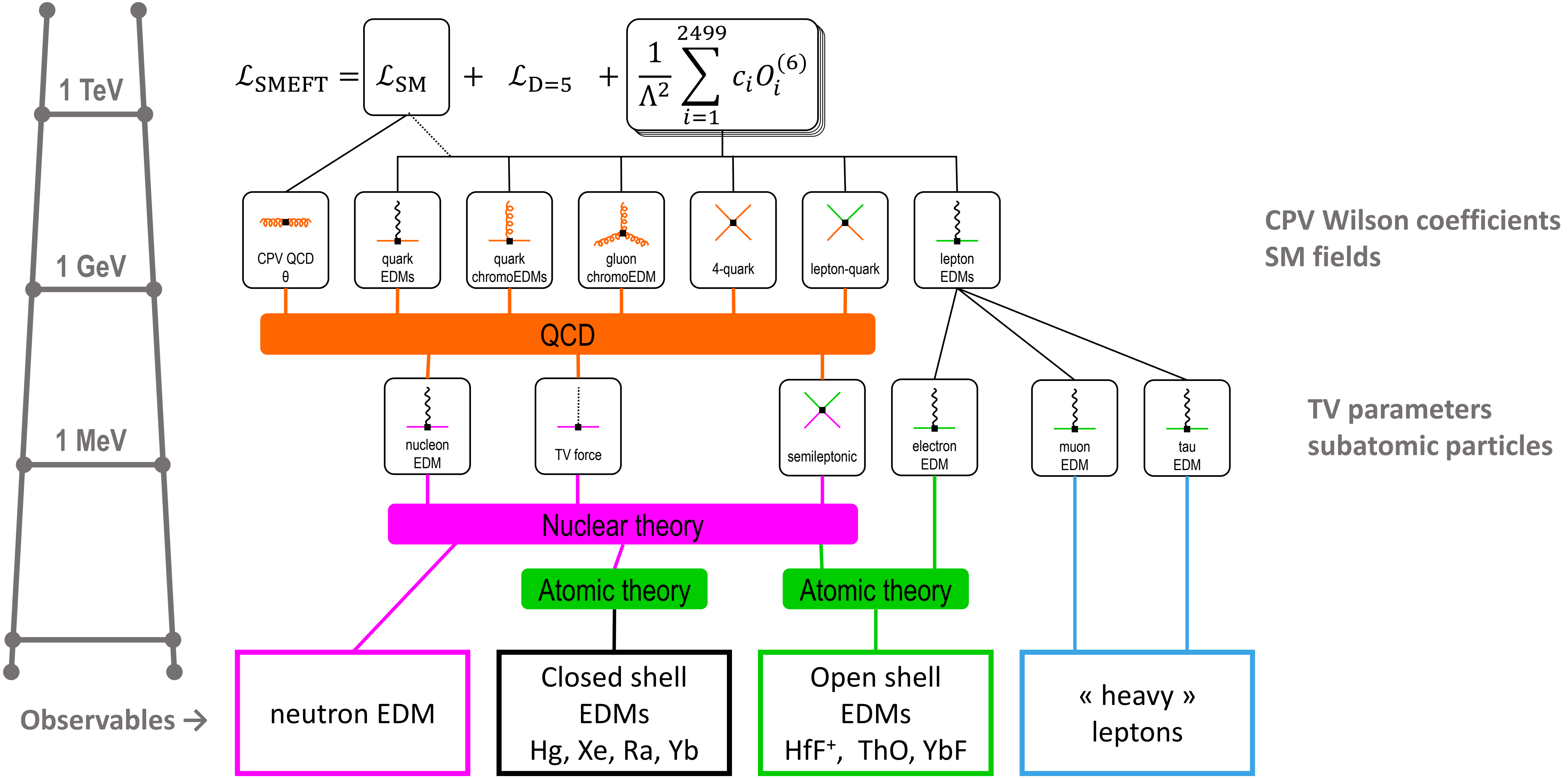
Muon g-2 (2009)
$d_\mu = (0.0 \pm 0.9) \times 10^{-19}\ e\ \mathrm{cm}$
STORAGE RING

PSI nEDM (2020)
$d_n = (0.0 \pm 1.1) \times 10^{-26}\ e\ \mathrm{cm}$
ULTRACOLD NEUTRONS

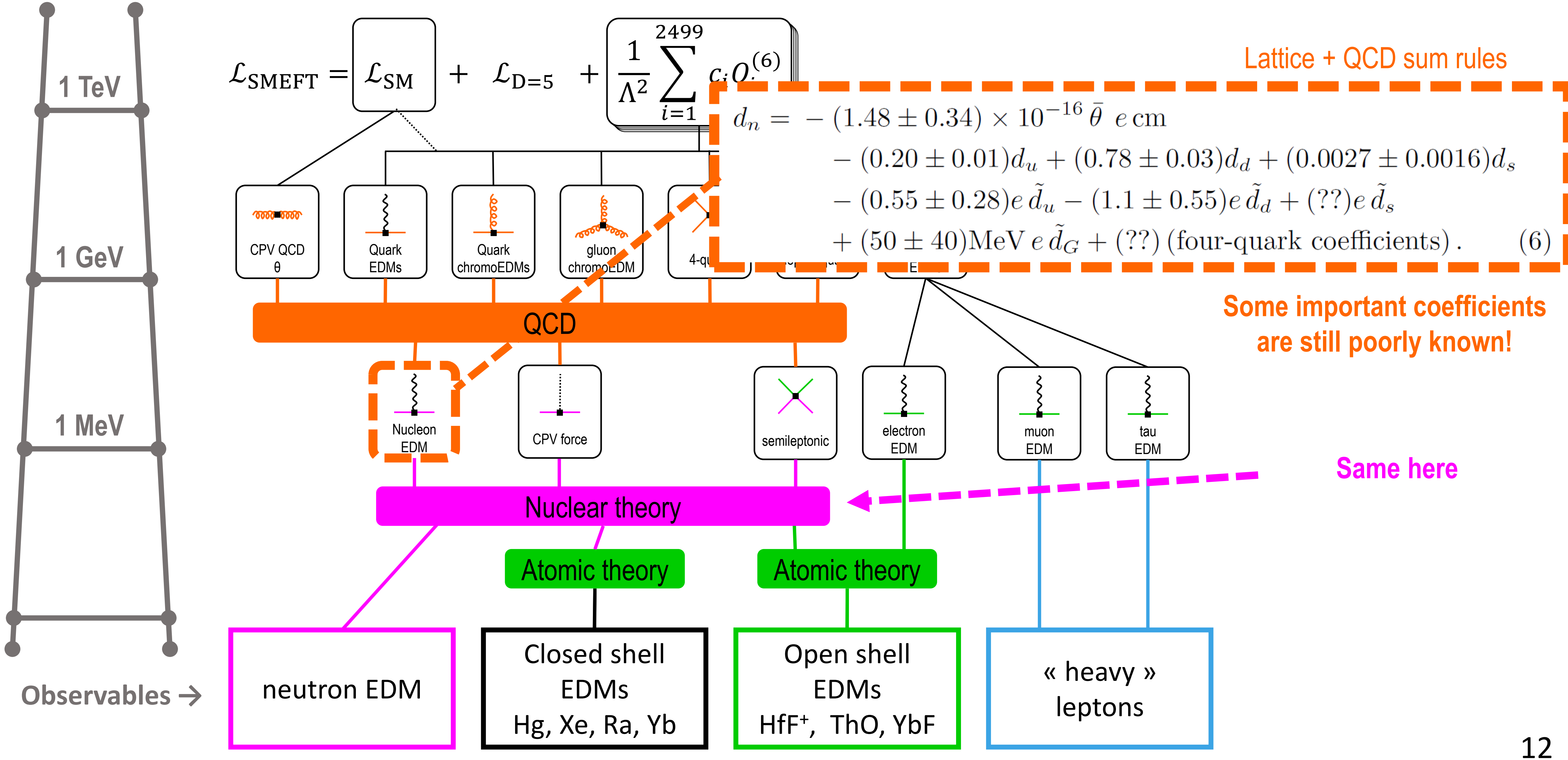
Seattle ^{199}Hg (2016)
$d_{\mathrm{Hg}} = (-2 \pm 3) \times 10^{-30}\ e\ \mathrm{cm}$
CLOSED-SHELL ATOMS

Boulder HfF^+ (2023)
$d_e = (-1 \pm 2) \times 10^{-30}\ e\ \mathrm{cm}$
OPEN-SHELL MOLECULES

EDM connection programme: EFT ladder



EDM connection programme: EFT ladder



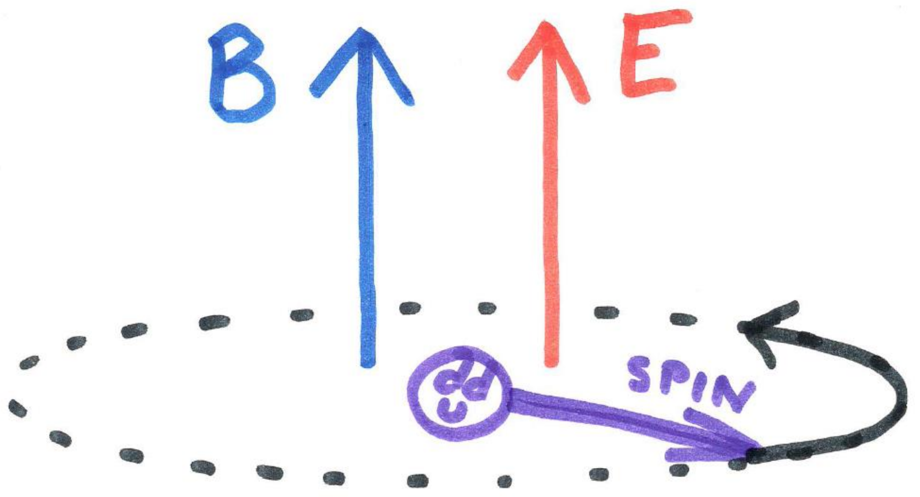
Lattice + QCD sum rules

$$
\begin{aligned}
d_n = & -(1.48 \pm 0.34) \times 10^{-16}\,\bar{\theta}\ e\,\mathrm{cm} \\
& -(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.0016) d_s \\
& -(0.55 \pm 0.28) e\,\tilde{d}_u - (1.1 \pm 0.55) e\,\tilde{d}_d + (??) e\,\tilde{d}_s \\
& +(50 \pm 40)\mathrm{MeV}\ e\,\tilde{d}_G + (??)\ (\text{four-quark coefficients})\,. \qquad (6)
\end{aligned}
$$

Some important coefficients are still poorly known!

Same here

nEDM: experimental challenges



Larmor frequency

$\sim 30\ \mathrm{Hz}\ @\ B = 1\ \mu\mathrm{T}$

$$f_n = \frac{2\mu_n}{h} B \pm \frac{2d_n}{h} |E|$$

If $d_n \sim 10^{-26}\ e\ \mathrm{cm}$ and $E \sim 10\ \mathrm{kV/cm}$

Duration of one full turn ~ 1 year

Challenges to detect such a minuscule effect:

1) Maximize the exposure to the electric field:

$$E\ T\ \sqrt{N}$$

- **Ultracold neutrons (UCN)**

2) Control the B-field:

- **Magnetic shielding**
- **Quantum magnetometry**

Prospects neutron EDM

TUCAN TRIUMF - construction

Sensitivity target $1 \times 10^{-27} e$ cm

nEDM Los Alamos - construction

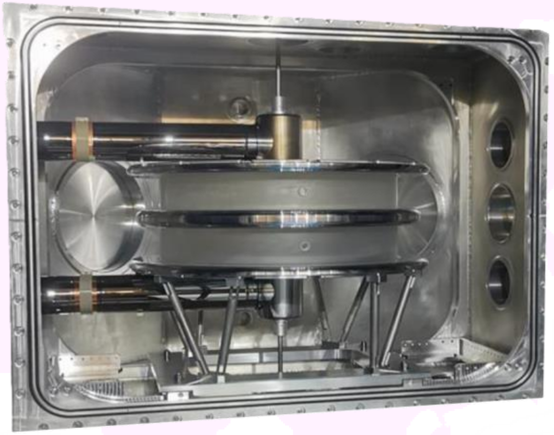
Sensitivity target $2 \times 10^{-27} e$ cm

panEDM ILL - commissioning

Sensitivity target $0.8 \times 10^{-27} e$ cm

n2EDM PSI - commissioning

Sensitivity target $0.5 \times 10^{-27} e$ cm



2025 – 2035 exploitation

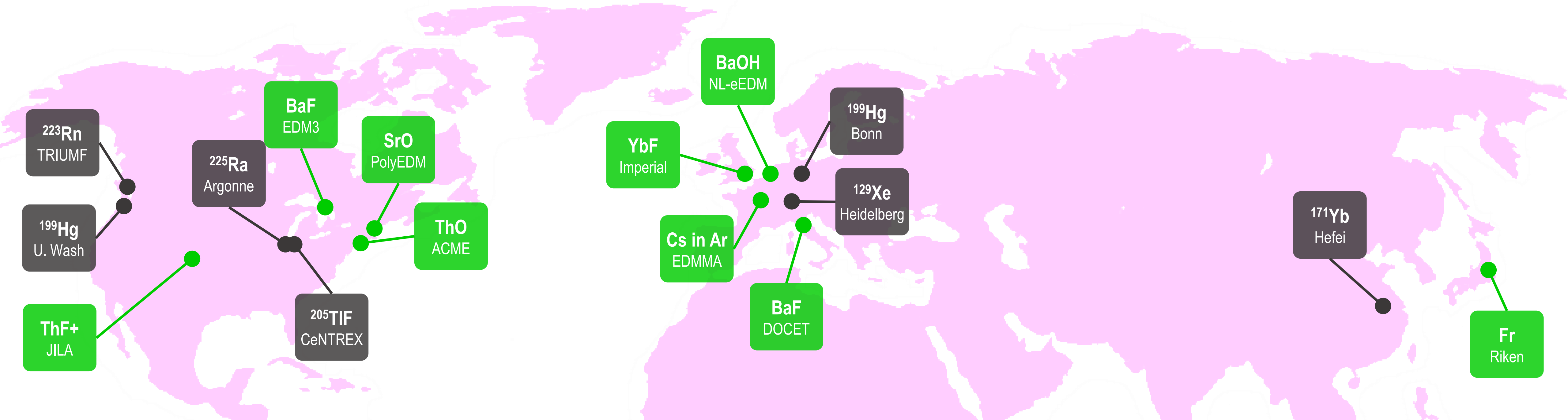
Four new generation of UCN experiments (double-chambers at room temperature) to start datataking in the coming years

Post 2035 pathways

Need to secure access to big European neutron sources (ESS, FRMII, PSI)

- Advanced UCN production
- Concept of in situ UCN production in superfluid helium, sensitivity 1×10^{-28} e cm

EDMs of atoms & molecules



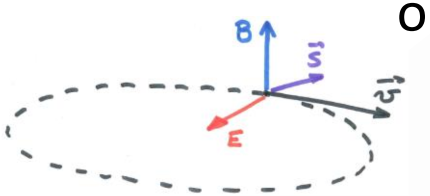
OPEN SHELL
paramagnetic atoms/molecules
sensitive to the electron EDM
Large internal E-field in molecules

CLOSED SHELL
diamagnetic atoms/molecules
sensitive to hadronic CPV

not shown on the map:
R&D for radioactive atoms/molecules: Pa, Rn, RaF…

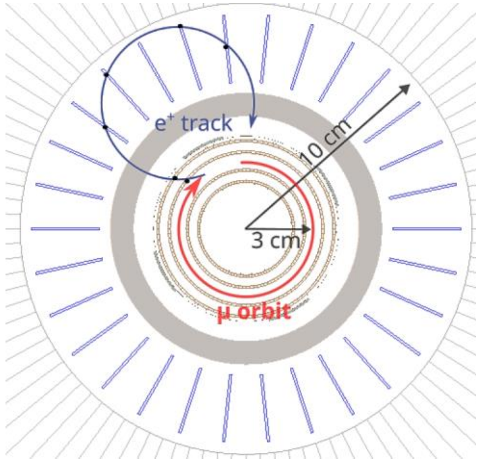
EDMs of charged particles

EDM causes spin to rotate out of the plane of the orbit



Prospects on muon EDM:

- With the g-2 experiments at FNAL and JPARC, sensitivity $\sim 10^{-21}\ e$ cm
- Dedicated μEDM project at PSI

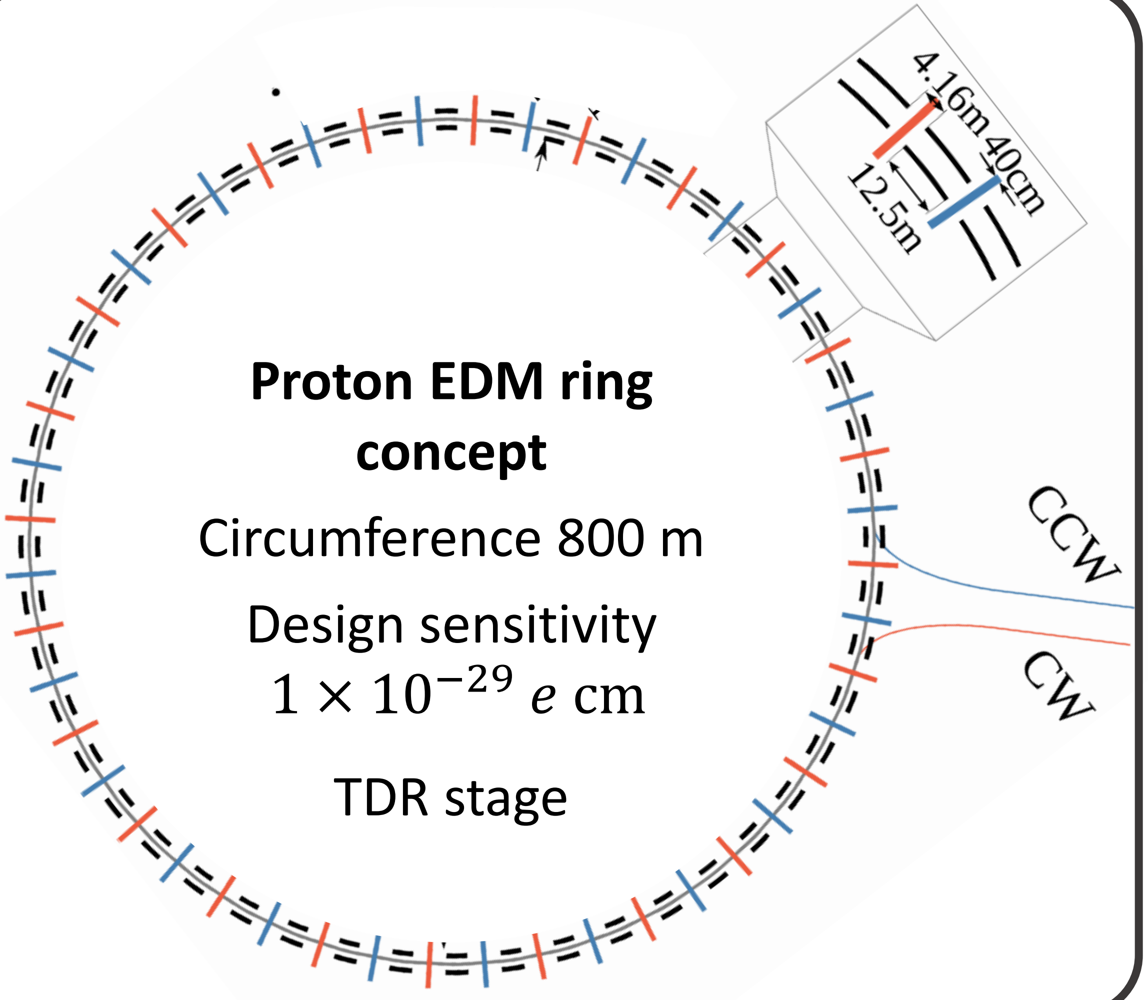


Phase 1 – commissioning
$4 \times 10^{-21}\ e$ cm

Phase 2 – post 2030
$6 \times 10^{-23}\ e$ cm

Prospects on heavy flavour EDMs at colliders

- ALLADIN: a fixed-target experiment at LHC
  MDM and EDM of charmed baryons $\Lambda_c^+\ \Xi_c^+$
- Super Tau-Charm Factory expects to improve on τ EDM by factor ~10



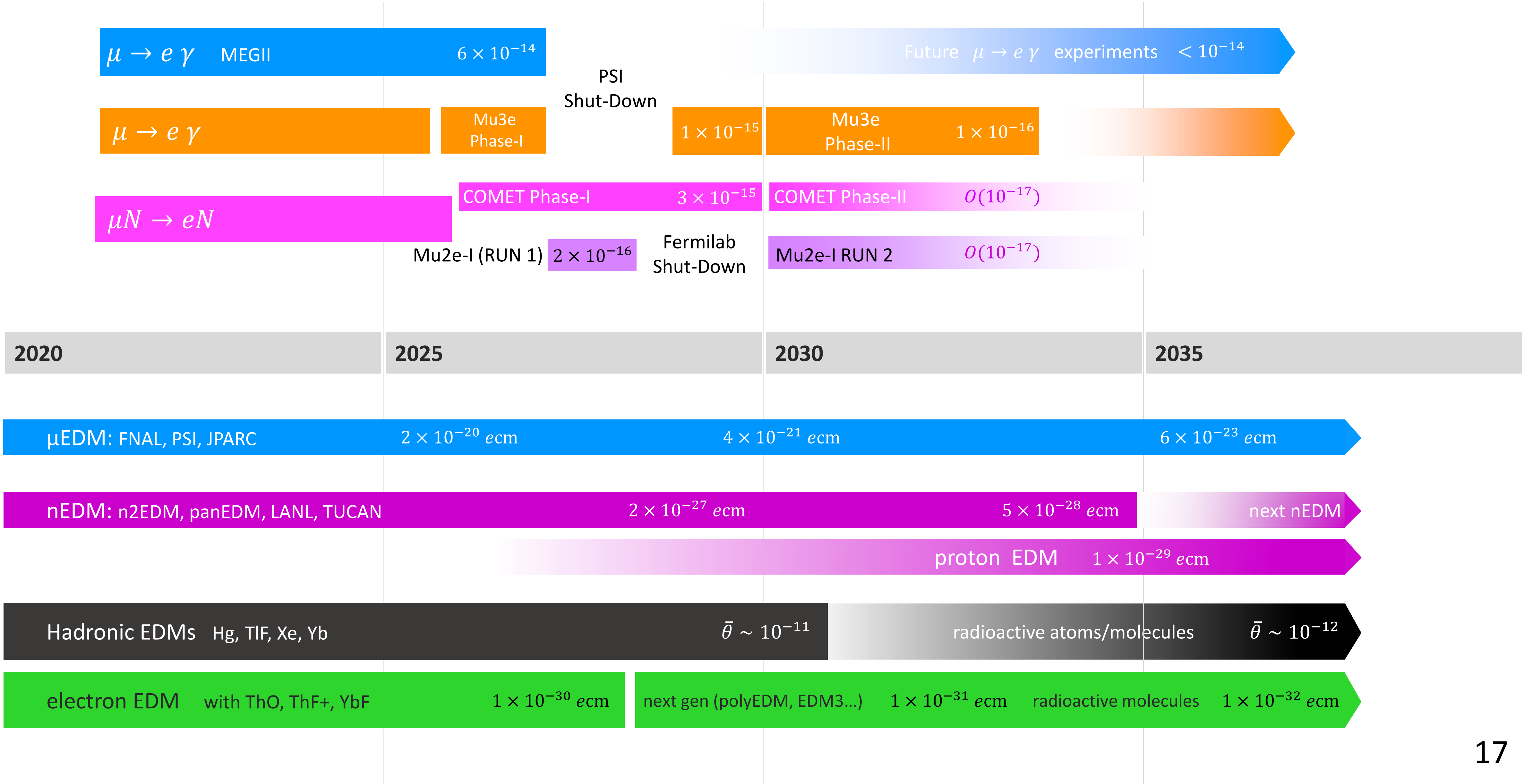
Proton EDM ring concept

Circumference 800 m

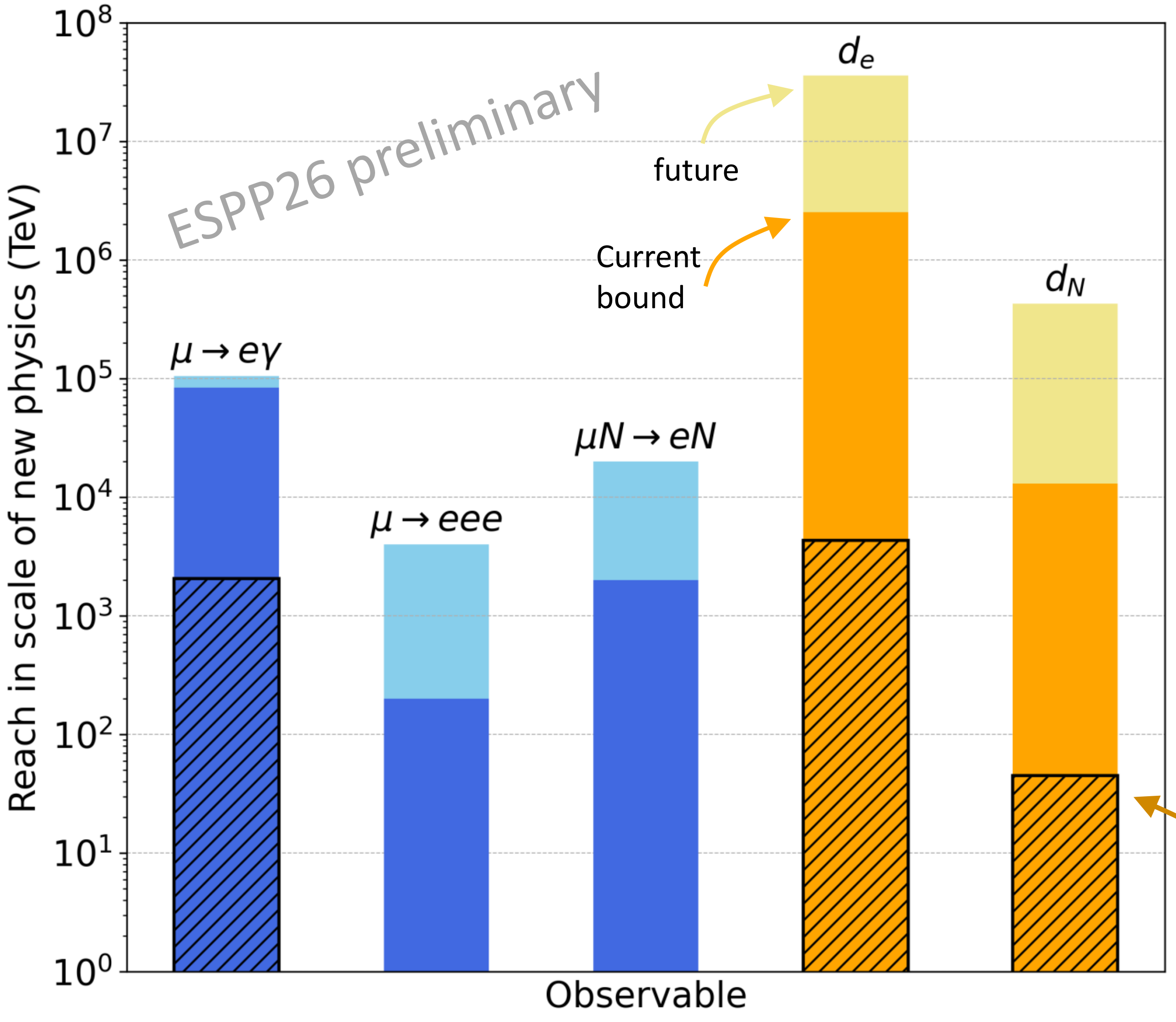
Design sensitivity
$1 \times 10^{-29}\ e$ cm

TDR stage

Summary: projection timeline



Summary: fantastic discovery potential



Key points on **sensitivity to new physics**

- **Null tests** - no CKM background

cLFV with muons

- $\Gamma \sim \frac{v^2 m_\mu^3}{\Lambda^4}$ or $\Gamma \sim \frac{m_\mu^5}{\Lambda^4}$ (chiral suppression)
- High intensity muon beams available

EDM

- $d \sim \frac{v}{\Lambda^2}$ or $d \sim \frac{m_f}{\Lambda^2}$ (chiral suppression)
- Long observation times of spins
- "never measure anything but frequencies"

Muon cLFV: concluding messages

Muon-based searches for cLVF …

… are among the most powerful probes of new physics (multi PeV)
These efforts represent a leading edge in the global cLFV program and **deserve strong support.**

- The most stringent limits come from experiments at the **Paul Scherrer Institute (PSI) in Europe**
- Relies on **high intensity muon beams** from proton accelerators, continuous and pulsed.
  The emergence of next-generation beamlines at PSI, Fermilab, and J-PARC underscores the growing importance and global commitment to this research area.
- Requires **dedicated detectors**, and new detection technologies. New proposals are emerging.
- **Three complementary golden channels:** $\mu^+ \to e^+ \gamma$, $\mu^+ \to e^+ e^+ e^-$ and $\mu^- N \to e^- N$
  All of them must be fully exploited.
  - The MEG II and Mu3e at PSI are actively working to significantly enhance sensitivity to $\mu \to e\,\gamma$ and $\mu \to eee$
  - The Mu2e at FERMILAB and COMET at JPARC are pushing down the sensitivity of the $\mu N \to eN$ conversion
  - In both cases the European community is strongly involved

EDMs: concluding messages

EDM searches …

… achieve a **unique sensitivity** to generic new CPV physics
and will **continue to progress on a multi-disciplinary front**

- **Theory progress is required**
  to connect physics at multiple scales: lattice QCD - nuclear theory – atomic theory - global fits

- **Neutron EDM** - European experiments have led the field for 50 years
  2025 – 2035: Exploitation of four new apparatuses will lead to a x10 sensitivity gain.
  post 2035: Relies on secure access to neutrons sources for fundamental physics (ESS, PSI, FRM2)
  ESS has a broad program for fundamental physics with neutrons, which should be supported.

- **EDMs of charged particles**
  Proton: essential complement to nEDM in the long term, a design should be advanced to the TDR stage.
  Great prospects for **μEDM** (PSI), **charmed baryons** (dedicated setup at LHC), **tau** (STCF).

- **Atomic and molecular EDMs**
  Elegant experiments using advanced AMO and quantum technologies carried out by small collaborations.
  Highest sensitivities on the electron EDM
  A must to be continued. New routes with radioactive atoms and molecules should be pursued.