Precision measurements: paths to New Physics at low-energies and high-intensities

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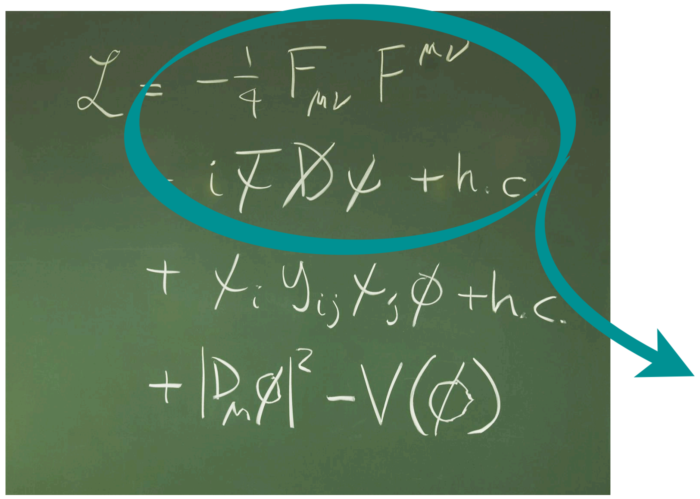
"Tests de précision à basse énergie des interactions fondamentales"

The SM: a history of success ... and 3+n caveats



A history of success!

Minimal formulation allowing to understand (and predict) most of the phenomena in particle physics

Electroweak & strong interactions in the **Standard Model:** tested with impressive precision since first dedicated searches

Theoretically, not "the perfect" picture: **unification** !?

$SU(3)_c \otimes SU(2)_L \otimes U(1)$ ↭ Unified interactions?

At which scale ? gravitation @ Λ_{Planck}... **Desert of scales...**

Strong interactions - confinement of quarks in matter (nucleons, nuclei, atoms...)

non-perturbative effects very hard to deal with

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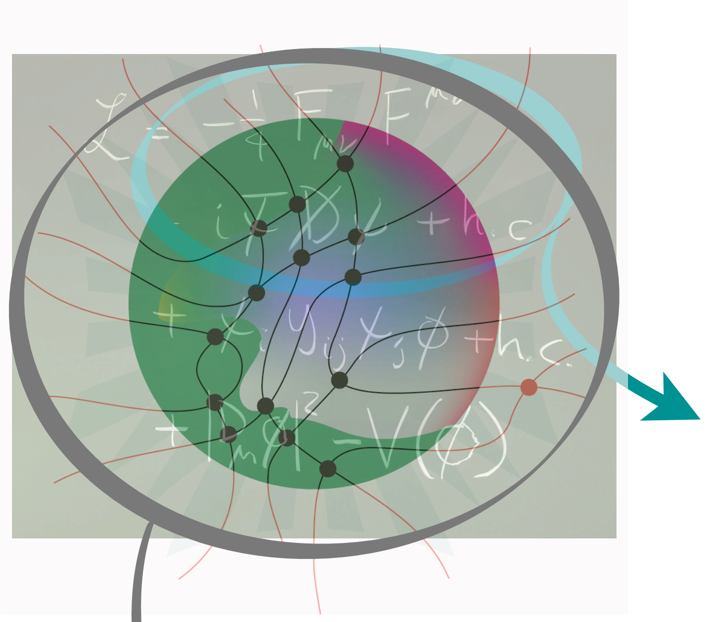

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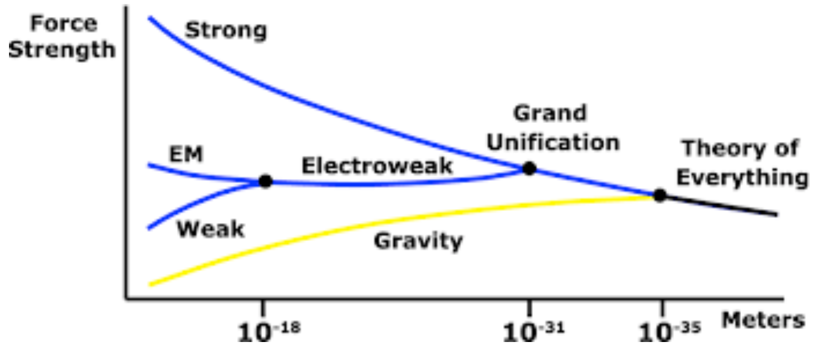
(4th) missing interaction: Gravity! -
not included in the SM formulation
non-negligible effects above the Planck scale



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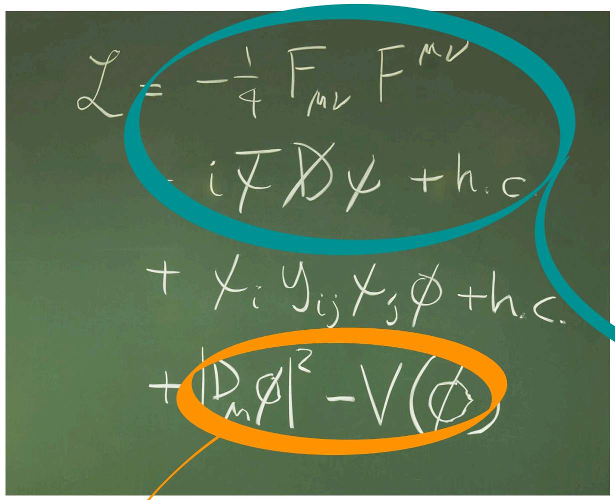

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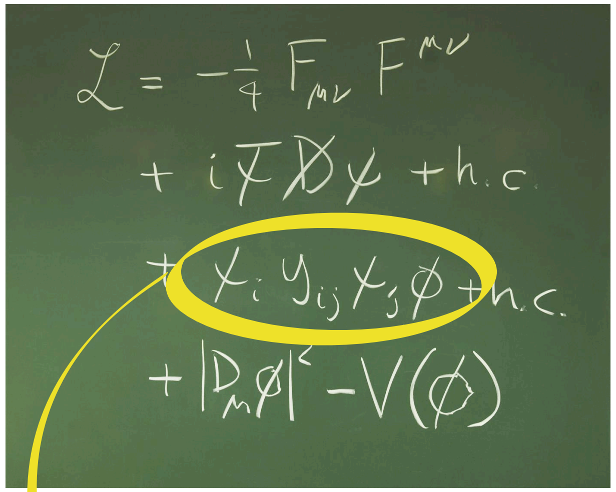
Higgs: CP even scalar doublet, in good agreement with expectation
Verification of the **mechanism of electroweak symmetry breaking**

Further *theory woes:* **fine-tuning** issues (**hierarchy** problem),
implications for **vacuum stability, ...**

The SM: a history of success ... and 3+n caveats



A history of success!

Minimal formulation allowing to understand (and predict) most of the phenomena in particle physics

Flavour in the **Standard Model:**
interactions between *fermion* families (and the *Higgs*)

Flavour has paved the way to the SM!
From prediction of *charm* quark ... to the existence of *3 families!*

Y^u_{ij}, Y^d_{ij} and Y^ℓ_{ij} $\rightsquigarrow$ encode **flavour** dynamics
(masses, mixings & CP violation)

$\Rightarrow$ **Flavour-universal** gauge interactions

$\Rightarrow$ **Lepton sector:** 3 massive $\ell^\pm$; **massless** ν; no leptonic mixing...

$\Rightarrow$ **Quark sector:** 6 massive states, $V^{ij}_{\text{CKM}}\ W^\pm\,\bar{q}_i\,q'_j$

SM flavour & CP: *accidental* symmetries (lepton & baryon number conservation, conservation of lepton flavours, lepton flavour universality of gauge interactions) and the **"CKM paradigm"**

The need for New Physics

A number of theoretical caveats... and observations unaccounted for in the SM:

baryon asymmetry of the Universe, viable dark matter candidate, ν oscillations

- **Matter dominated Universe:** explaining **the baryon asymmetry of the Universe (BAU)**
  - (i) **initial** asymmetric composition ✘ (incompatible with inflation)
  - (ii) **statistical fluctuations** during evolution ✘ (negligible effects)
  - (iii) large scale **spatial separation** ✘ (incompatible with evolution of primordial Universe)
  - ... **Dynamical generation! "Baryon-genesis"** ✔

Sakharov's conditions for a (successful) BAU

a priori, all are present in the SM! (electroweak baryogengesis)

- If originally symmetric Universe, **baryon number violation**

  Sphaleron production $\Rightarrow$ *B & L number violation*

- Differentiate matter from antimatter, **CP violation**

  CPV from CKM mechanism highly suppressed...

- Suppress inverse processes, **out of (thermal) equilibrium**

  Strong 1st order EW phase transition ? soft crossover for a "heavy Higgs" (125 GeV)

Explain the BAU $\Rightarrow$ BSM physics is also required!

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  Explain the BAU ⇒ BSM physics is also required!

- **Dark Matter in the Universe**

  PLANCK, WMAP, ... & Galactic dynamics ⇒ most **matter is "dark"** $\Omega_{\mathrm{CDM}} = 0.259 \pm 0.006$

  "ordinary (SM) matter" - a tiny fraction of mass-energy density $\Omega_{\mathrm{b}} = 0.049 \pm 0.001$

  Dark matter candidate: massive, non-luminous, no strong interactions...
  (at best) weakly interacting, stable!

  No such candidate in the Standard Model!

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- **Dark Matter in the Universe**

  Dark matter candidate: **necessarily from New Physics!**

- **Neutrino oscillations ⇒ massive neutrinos** and **non-trivial leptonic mixing!**

  1st "laboratory" discovery of *physics beyond the SM (BSM)*

  New **(Majorana)** fields? New sources of **CP violation?**

  (LNV & CPV → crucial for BAU!)

The need for New Physics

A number of theoretical caveats... and observations unaccounted for in the SM:

baryon asymmetry of the Universe, viable dark matter candidate, ν oscillations

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  Explain the BAU ⇒ BSM physics is also required!

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  Dark matter candidate: **necessarily from** New Physics!

- **Neutrino oscillations ⇒ massive neutrinos** and **leptonic mixing!**

New Physics is indeed needed - but which new physics model?

Models of **New Physics** generically introduce (at high scales):

(i) **new sources** of CP and flavour violation

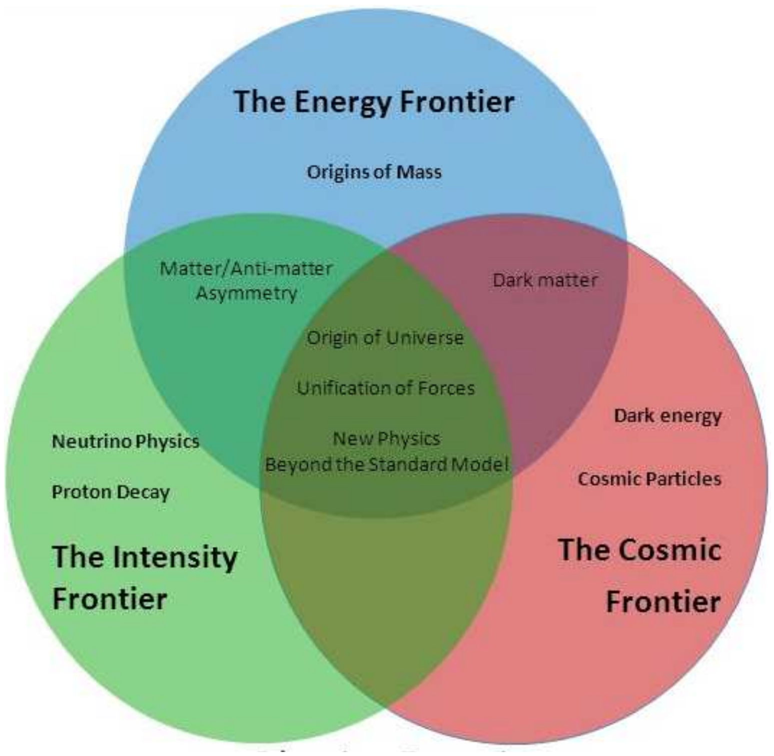
(ii) **new** Lorentz structure (beyond *V*-*A*)

(iii) **new** (heavy) **propagators**

How do we search for these new ingredients?

Searches for New Physics

New Physics searches at **three** "experimental" frontiers:



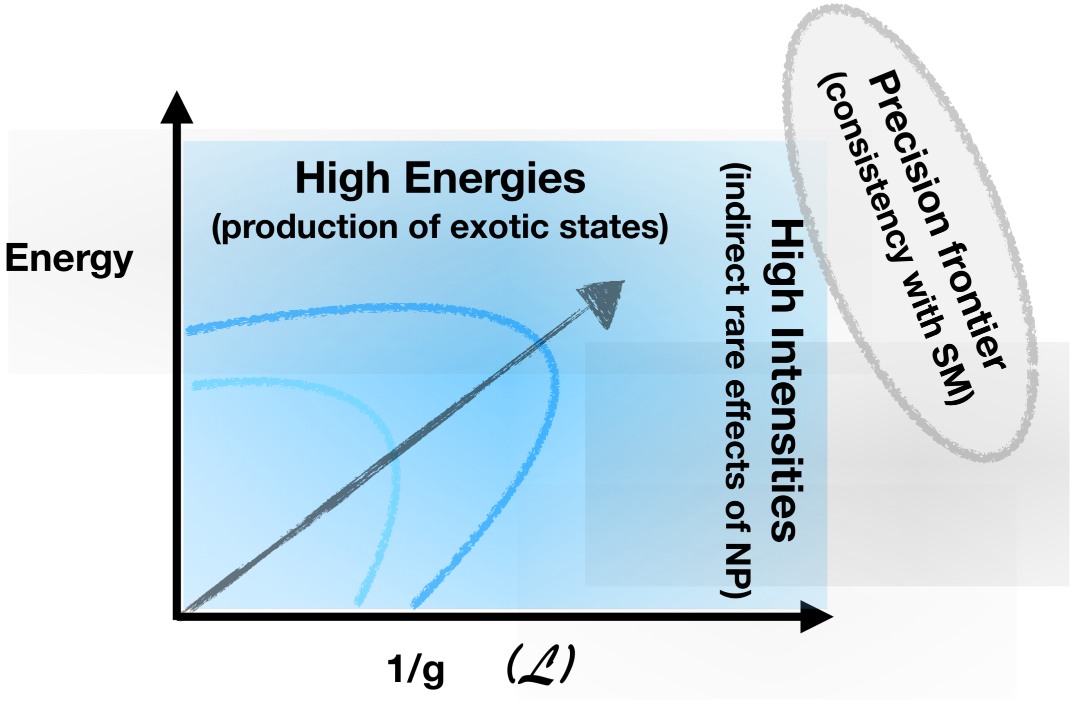
- Cosmic frontier: **cosmological** impact, evolution of the **Universe** (observation)
- **High-energy frontier:** new heavy states produced if sufficiently **large collision energy** (lepton or hadron beams)
- High-intensity frontier: indirect **"virtual" effects of NP states** (feebly coupled or very rare processes) for high "luminosities"

Precision tests of fundamental laws (SM, ...)
at high- and low-energies (& "tabletop energies")

⇒ test **predictions** to unprecedented **precision**

⇒ reveal tensions and inconsistencies

⇒ challenge "null" expectations
(conservation, forbidden processes, ...)



Discovery of New Physics

Intensity frontier & SM precision tests

Precision tests of the SM

Heavy flavours
(K, D and B meson oscillations and decays, ...)

Nucleons, nuclei and atoms
(EDM, weak decays, neutral currents, strong interaction tests, ...)

Proton decay

Charged leptons
(cLFV processes, $(g-2)_\ell$, EDMs, ...)

Light weakly coupled particles
(axions and ALPs, dark γ, ...)

Neutrinos
(oscillations, nature, mass interaction with matter, ...)

Weak equivalence principle

Intensity frontier & SM precision tests

Nucleons, nuclei and atoms
(EDM, weak decays, neutral currents, strong interaction tests, ...)

Precision tests of the SM

Charged leptons
(cLFV processes, $(g-2)_\ell$, EDMs, ...)

Weak equivalence principle

SM precision tests - a (brief) theory overview

- The need for New Physics - **searches at three frontiers**
- **Theory approaches:** effective approach (model-independent)
- cLFV rare decays: overview & impact for NP searches of cLFV in the muon sector
- CP violation in the hadron sector: neutron EDM
- EW precision tests in nuclear β decays: superallowed transitions & CKM anomaly
  searches for non (V-A) interactions
  CP violation in beta decays
- Testing the weak equivalence principle: gravity effects on antimatter

Extensive range of topics! Covered by a particle physics phenomenologist!

Highlight most relevant aspects - unorthodox approach
A tiny subset... subject to time constraints and personal "bias" 🙂

Complementary to subsequent presentations

Precision tests of the SM: constraining New Physics

EFT approach to New Physics

SM interpreted as a low-energy limit of a (complete, yet unknown) NP model

$\Rightarrow$ **Model-independent**, **effective field theory approach (EFT)**

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \dots)\, \mathscr{O}^n(\ell, q, H, \gamma, \dots)$$

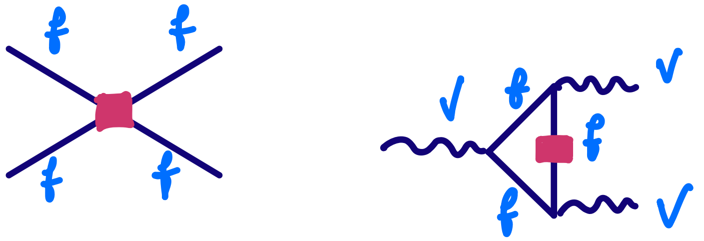
effective **operators**

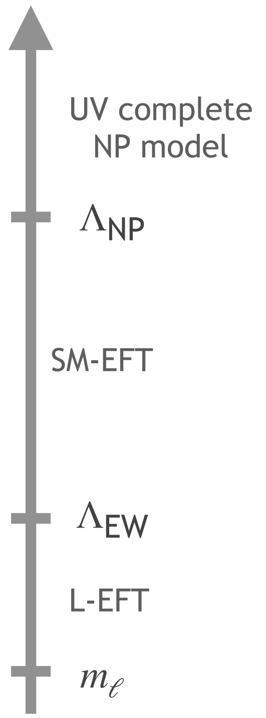
(unknown) NP **scale**

effective coefficients

$\mathscr{O}^5 \rightsquigarrow$ Weinberg operator (m_ν)

$\mathscr{O}^6 \rightsquigarrow$ flavoured contributions (among many others!)





UV complete NP model

Λ_{NP}

SM-EFT

Λ_{EW}

L-EFT

m_ℓ

Derive the new "effective" interactions (vertices, ...), and compute contributions to observables

Agnostic approach, allowing to generically parametrise NP effects

on observables forbidden in SM and/or observables suggesting deviations from SM

$$\mathscr{A} \sim \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \dots$$

$$\mathscr{A} \sim \mathscr{A}^{\text{SM}} + \mathscr{A}\left(\frac{\mathscr{C}^6}{\Lambda^2_{\text{NP}}}\right) + \dots$$

$\Rightarrow$ master SM prediction!

EFT approach to New Physics***

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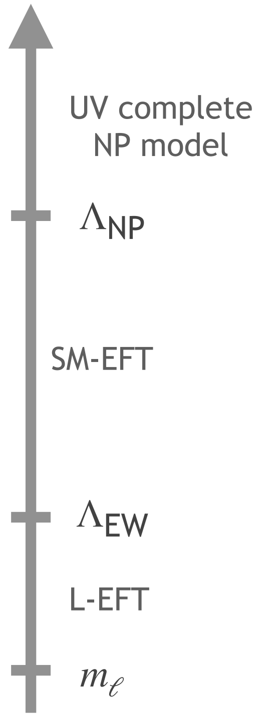
⇒ **Model-independent**, **effective field theory approach (EFT)**

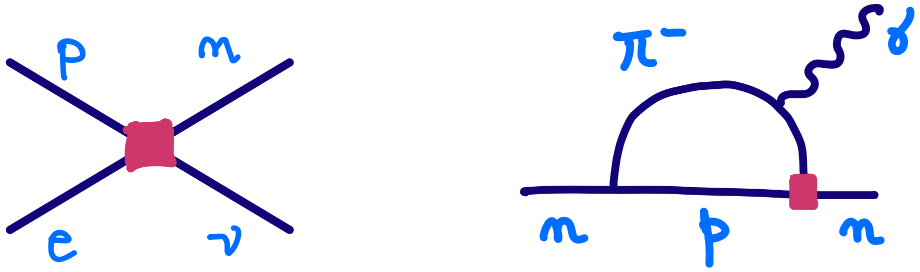


$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq5} \frac{1}{\Lambda^{n-4}}\, \mathscr{C}^n(g,Y,\dots)\, \mathcal{O}^n(p,n,\ell,\nu,\dots)$$

effective **operators**

(unknown) NP **scale**

effective coefficients



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effective **operators**

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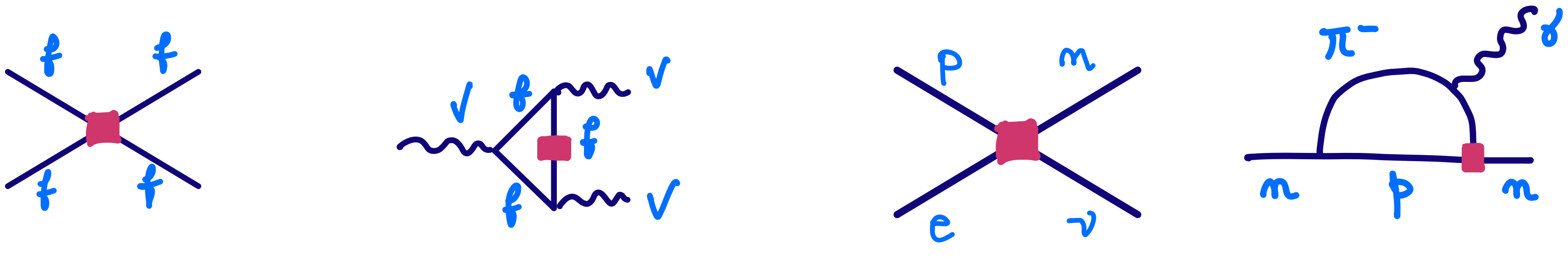
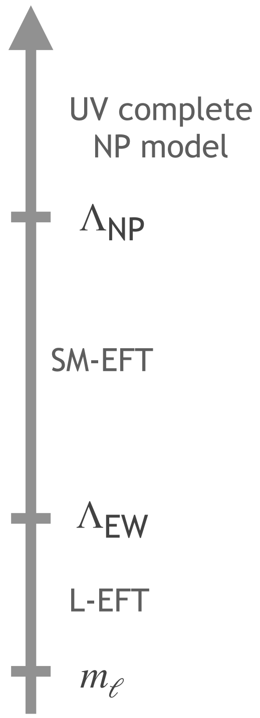




Cast current data (limits, ...) in terms of $\mathscr{C}^n_{ij}$ and Λ_{NP}

and attempt at **inferring info** on the dominating operator, and scale of NP

⇒ Beyond $(V-A)$ structure? New vector/axial, (pseudo)scalar or tensor currents?
Flavour violation beyond SM flavour paradigm?

⇒ But **many unknowns:** minimal assumptions must be made, e.g.

"natural" Λ_{NP} → constrain $\mathscr{C}^n_{ij}$

"natural" $\mathscr{C}^n_{ij} \approx 1$ → hint on Λ_{NP}

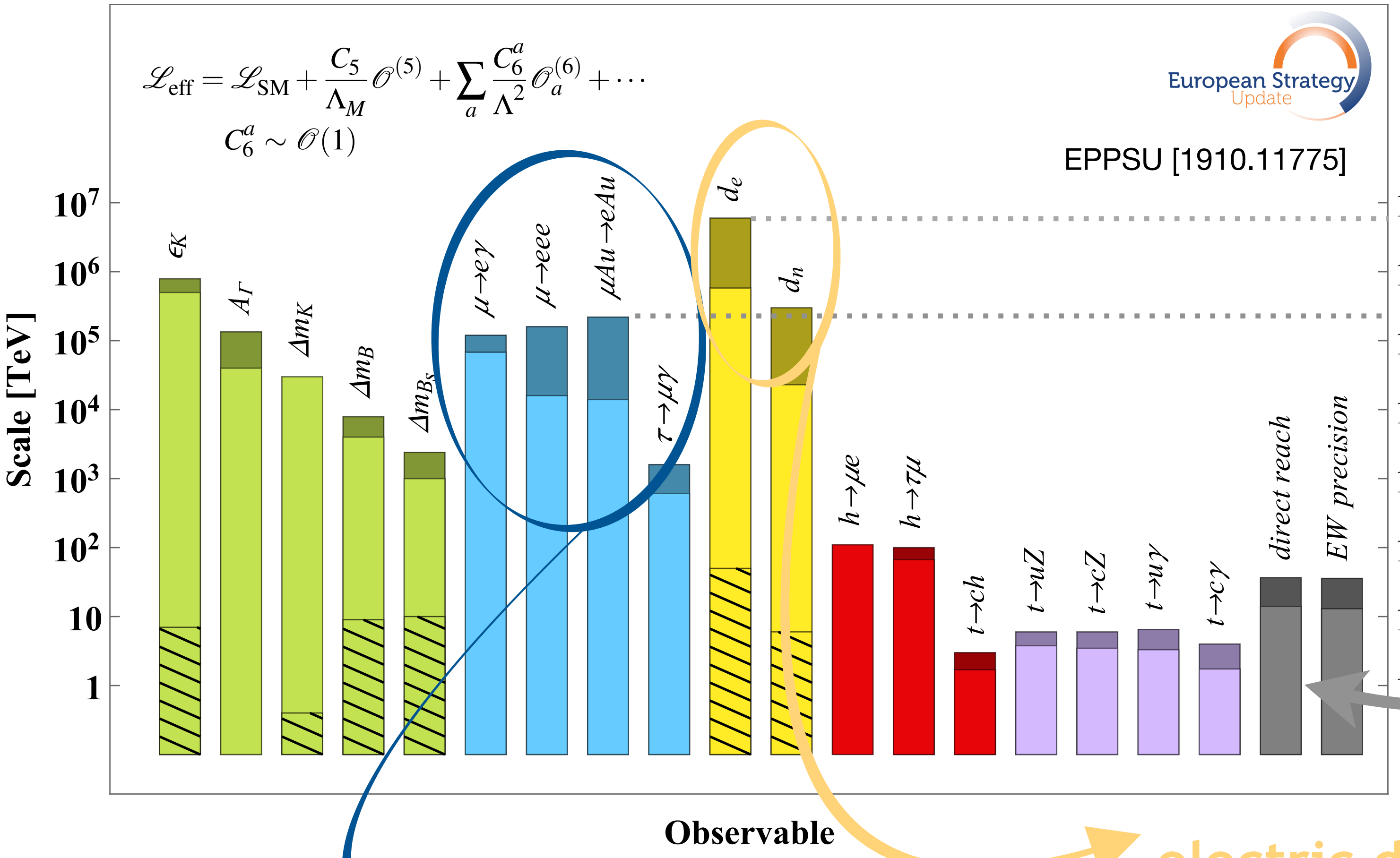
The probing power of flavour & CPV

SM interpreted as a low-energy limit of a (complete, yet unknown) NP model

⇒ **Model-independent, effective approach (EFT)**

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathscr{C}^n(g, Y, \ldots)\, \mathscr{O}^n(\ell, q, H, \gamma, \ldots)$$

Cast current "flavoured" data in terms of $\mathscr{C}^6_{ij}$ and Λ_{NP} : $\mathscr{C}^6_{ij} \approx 1 \Rightarrow$ **bounds on** Λ_{NP}



Flavour & CPV observables:
probes sensitive to very high NP **scales**

$\Lambda_{\text{NP}} \sim \mathscr{O}(10^5\ \text{TeV})$

well beyond collider's reach!

electric dipole moments

charged lepton flavour violating observables!

New Physics searches at the high-intensity frontier: (lepton) flavours and CP violation

Charged lepton flavour violation: muon sector opportunities

Lepton flavours: from ν oscillations...

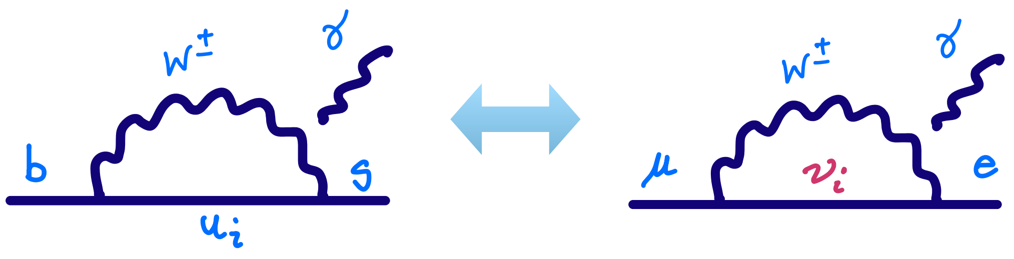
SM hadron sector: plethora of transitions and decays (and CPV!); **CKM paradigm**
theoretical predictions increasingly more precise (under control)

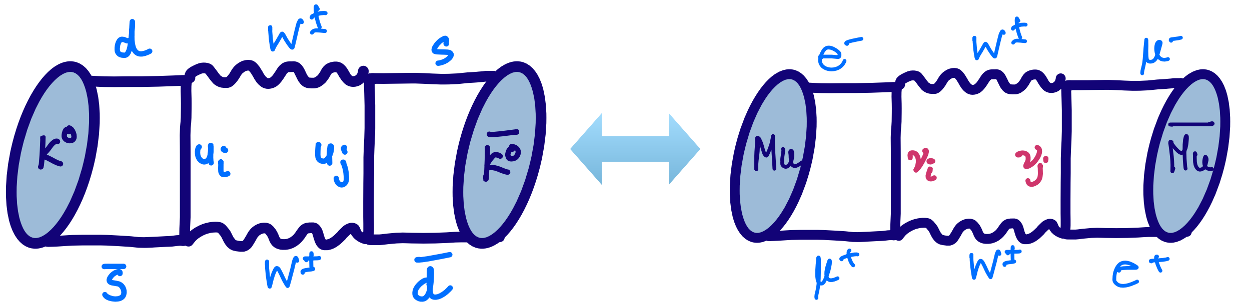
SM lepton sector: (strictly) **massless neutrinos**
conservation of total lepton number and lepton flavours
lepton flavour universality preserved (only broken by Yukawas)
tiny leptonic **EDMs** (4-loop... $d_e^{\text{CKM}} \leq 10^{-38} e$ cm)

Neutrino oscillations: SM description **insufficient!** Added complexity to the flavour problem...

In propagation $\nu_\alpha \to \nu_\beta \to \ldots \Rightarrow$ oscillations signal the **violation of neutral lepton flavours**

$\Rightarrow$ Violation of lepton flavour in neutral lepton sector opens a wide door
to **flavour violation in the charged lepton sector**





Similar flavour violating transitions in quarks & leptons ?!

Lepton flavours: from ν oscillations...

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theoretical predictions increasingly more precise (under control)

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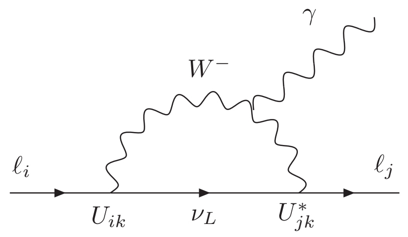
Neutrino oscillations: SM description **insufficient!** Added complexity to the flavour problem...
Extend the SM to accommodate $\nu_\alpha \leftrightsquigarrow \nu_\beta$: assume most **minimal extension SM$_{m_\nu}$**
[SM$_{m_\nu}$ = "ad-hoc" m_ν (Dirac), U_{PMNS}]

In SM$_{m_\nu}$: total **lepton number** still **conserved** (LNC)



BUT! flavour violation in neutral leptons ⇒ charged leptons as well!
cLFV possible... but **not observable!! BR($\mu \to e\gamma$)** $\sim 10^{-54}$
lepton EDMs still beyond observation (2-loop contributions from δ_{CP})

cLFV, LNV, lepton EDMs, ...: observation of **SM-forbidden leptonic modes**
⇒ **Discovery of New Physics!** (possibly before direct signal @ LHC)

Lepton flavours: from ν oscillations...

SM hadron sector: plethora of transitions and decays (and CPV!): **CKM paradigm**

SM l

Neut .

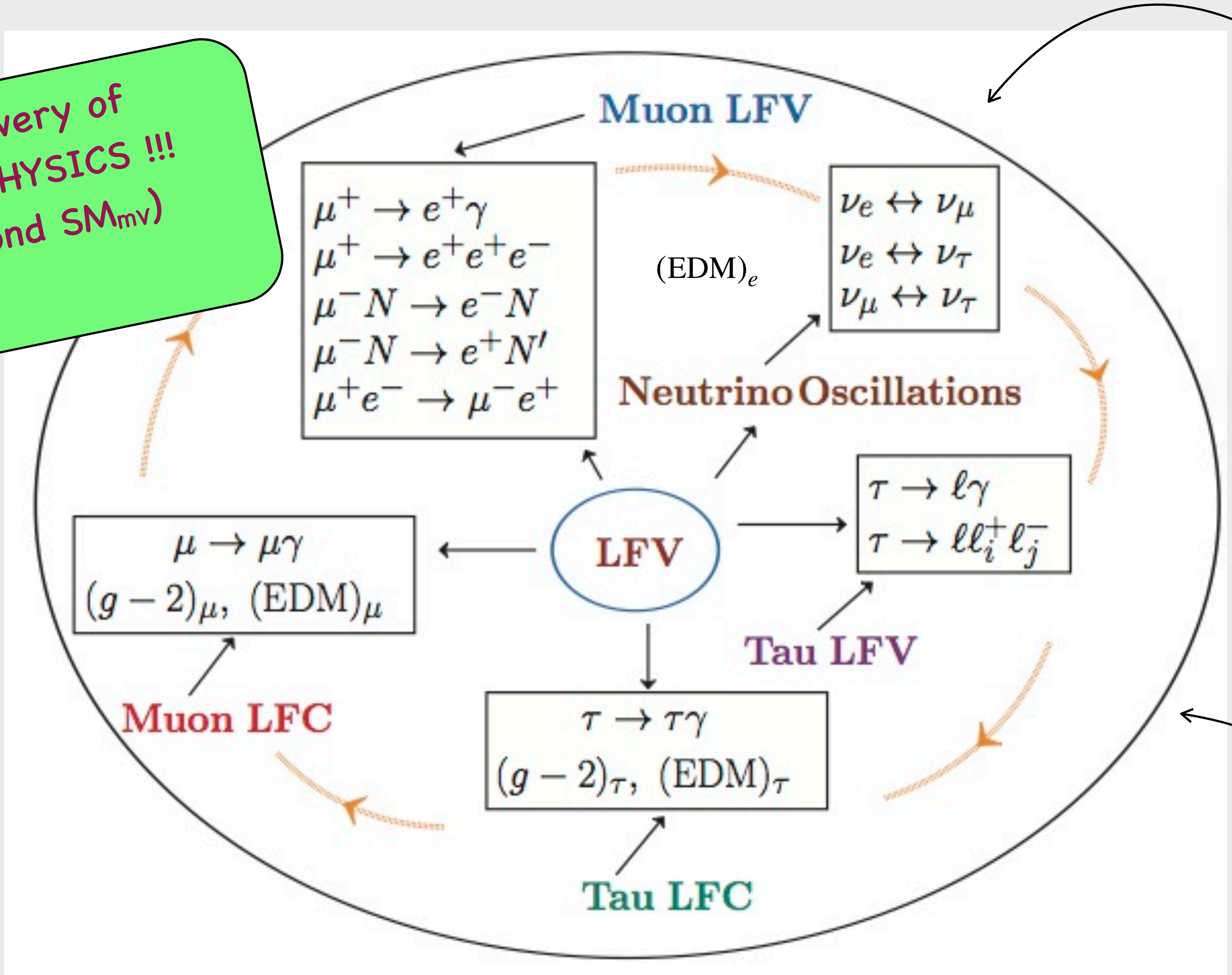
E

In SM l!

ℓ_i

cLF

Discovery of NEW PHYSICS !!! (beyond $SM_{m\nu}$)



LNV ($\Delta L = 2$):
$0\nu2\beta$
$\mu^-N \to e^+N'$
$M_1^+ \to M_2^- \ell_\alpha^+ \ell_\alpha^+$

LFUV (meson decays):
$R_{K^{(*)}}, R_{D^{(*)}}, R^\ell_{K,\pi}, \ldots$

Lepton flavours: from ν oscillations...

SM hadron sector: plethora of transitions and decays (and C): **CKM paradigm**

SM l

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In SM

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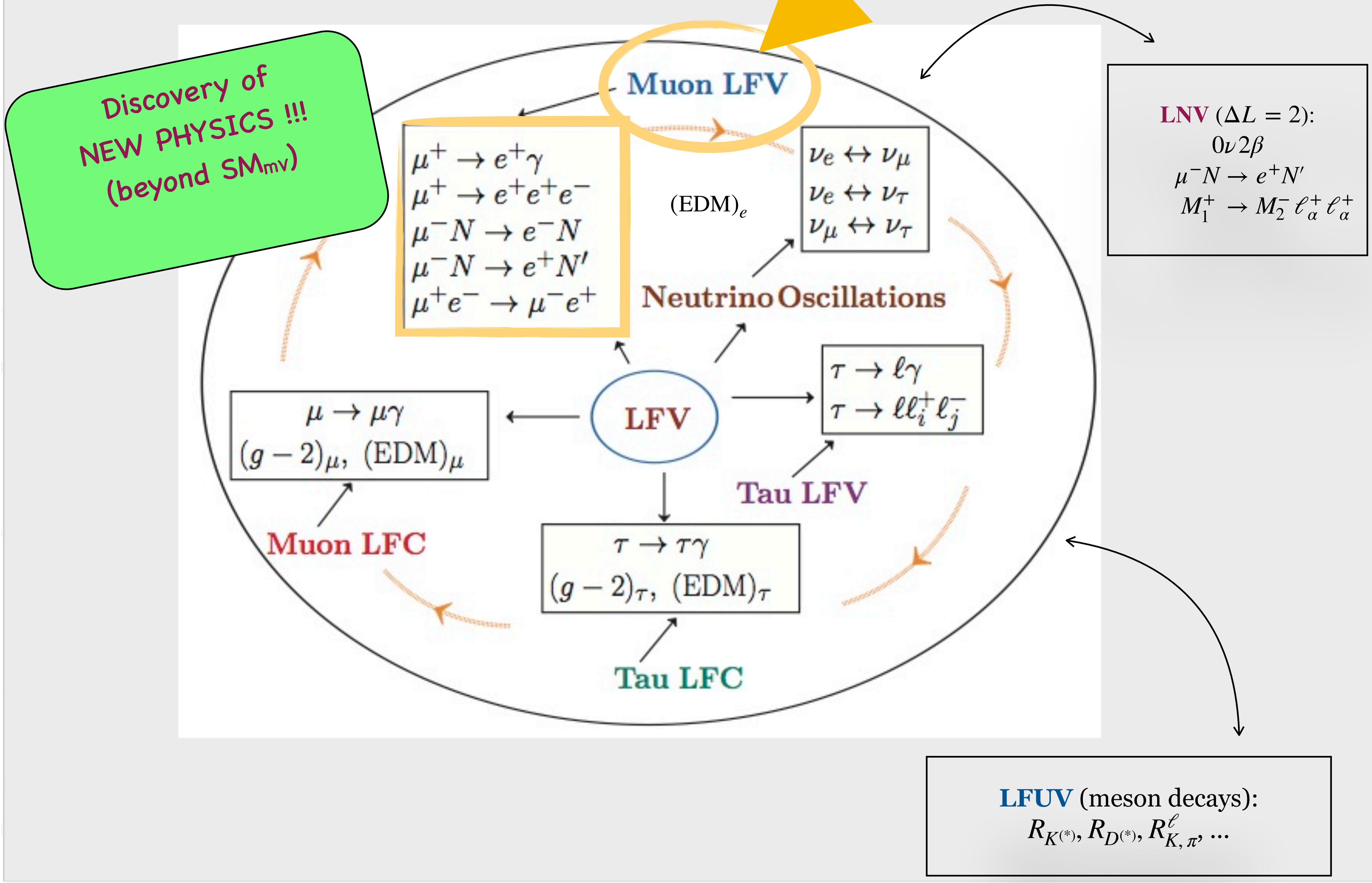


Discovery of NEW PHYSICS !!! (beyond $\text{SM}_{m\nu}$)

Muon LFV

$\mu^+ \to e^+\gamma$
$\mu^+ \to e^+e^+e^-$
$\mu^-N \to e^-N$
$\mu^-N \to e^+N'$
$\mu^+e^- \to \mu^-e^+$

$(\text{EDM})_e$

$\nu_e \leftrightarrow \nu_\mu$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_\mu \leftrightarrow \nu_\tau$

Neutrino Oscillations

LFV

$\tau \to \ell\gamma$
$\tau \to \ell\ell_i^+\ell_j^-$

$\mu \to \mu\gamma$
$(g-2)_\mu,\ (\text{EDM})_\mu$

Muon LFC

Tau LFV

$\tau \to \tau\gamma$
$(g-2)_\tau,\ (\text{EDM})_\tau$

Tau LFC

LNV $(\Delta L = 2)$:
$0\nu 2\beta$
$\mu^-N \to e^+N'$
$M_1^+ \to M_2^- \ell_\alpha^+ \ell_\alpha^+$

LFUV (meson decays):
$R_{K^{(*)}}, R_{D^{(*)}}, R^{\ell}_{K,\pi}, \ldots$

cLFV: muon observables

Muons - ideal **probe for NP**: from lepton **flavour universality** tests,
to **anomalous magnetic moments**, ... to **cLFV!**

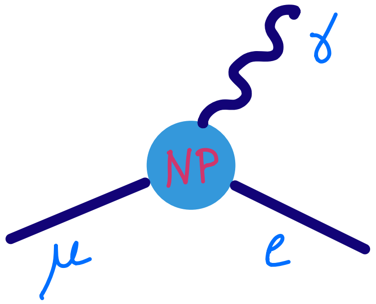
Muon cLFV - extensive opportunities, numerous observables, relying on very intense beams

- **Leptonic decays:** radiative $\mu \to e\gamma$ and three-body $\mu \to 3e$
  muonic atoms $\mu^-(A,Z) \to e^-(A,Z)$ & LNV $\mu^-(A,Z) \to e^+(A,Z-2)^*$
  nuclear assisted Coulomb decays $\mu^- e^- \to e^- e^-$
  Muonium oscillations $\mathrm{Mu}(\mu^+e^-) - \overline{\mathrm{Mu}}(\mu^-e^+)$ and decays $\mathrm{Mu}(\mu^+e^-) \to e^+e^-$
  Light "invisible" searches (e.g. $\mu \to e\phi$, ...)

- And further! **Semi-leptonic decays:** $M \to (M')\mu\ell$
  And at **colliders:** $Z \to \mu\tau$, $H \to \mu\tau$ (e.g. FCC-ee, CEPC, ...);
  high p_T dilepton tails in $pp \to \mu\ell$ ...
  Numerous channels at a future muon collider!

Muons: *lightest "unstables"* - clean objects, ideal & versatile probes for new physics searches
At the centre of a world-wide comprehensive programme - experiments *and* theory

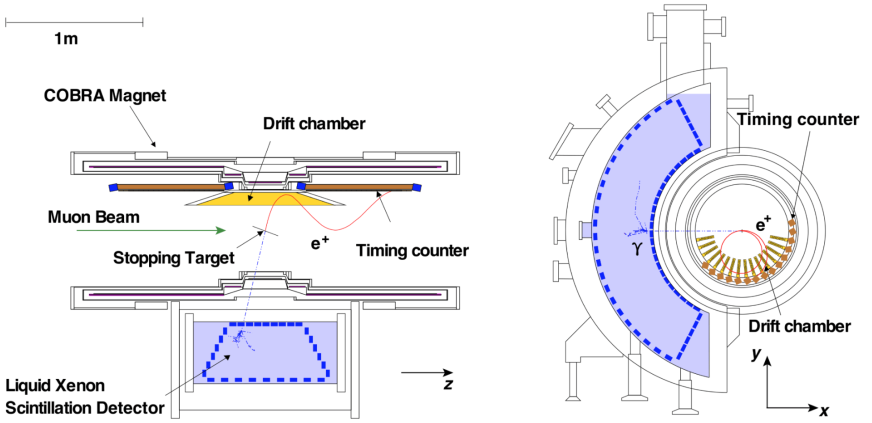
cLFV muon channels: radiative decays



- cLFV decay: $\mu^+ \to e^+\gamma$
- Event signature: $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)
  Back-to-back $e^+ - \gamma$ ($\theta \sim 180^\circ$); Time coincidence

- Backgrounds ⇒ prompt physics & accidental
  Prompt: radiative μ decays ($\mu \to e\,\bar\nu_e \nu_\mu \gamma$, very low E_ν) $[\propto R_\mu]$
  Accidental: coincidence of γ with positron from Michel decays $\mu \to e\,\bar\nu_e\nu_\mu$:
  photon from $\mu \to e\,\bar\nu_e\nu_\mu\gamma$; γ from in-flight e^+e^- annihilation $[\propto R_\mu^2]$

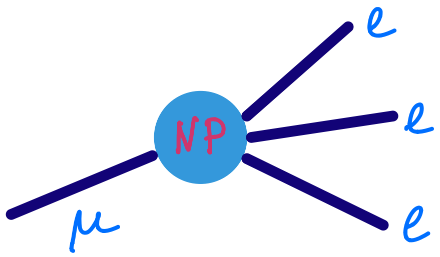
- Experimental status:
  First searches (!) in 1940's [MEG Coll., 1605.05081]
  Advent of intense muon beams in 2000's MEG @ PSI
  BR($\mu^+ \to e^+\gamma$) $\leq 4.2 \times 10^{-13}$ (90% CL)



- Future prospects: [MEG II Coll., 2201.008200]
  MEG II (@ PSI): BR($\mu^+ \to e^+\gamma$) $\leq 6 \times 10^{-14}$

very hard to go beyond 10^{-15} without conceptually different approach

cLFV muon channels: 3-body decays



- cLFV decay: $\mu^+ \to e^+ e^- e^+$
- **Event signature:** $\Sigma E_e = m_\mu \,;\, \Sigma \vec{P}_e = \vec{0}$
  common vertex; Time coincidence

- **Backgrounds** ⇒ physics & accidental

  Physics: multi-body μ decays ($\mu \to e\,\bar{\nu}_e \nu_\mu\, e^+ e^-$, very low E_ν)

  Accidental: Bhabha scattering of Michel e^+ from $\mu \to e\,\bar{\nu}_e \nu_\mu$ decays with atomic $e^+ e^-$
  Michel positrons with $e^+ e^-$ from γ conversion

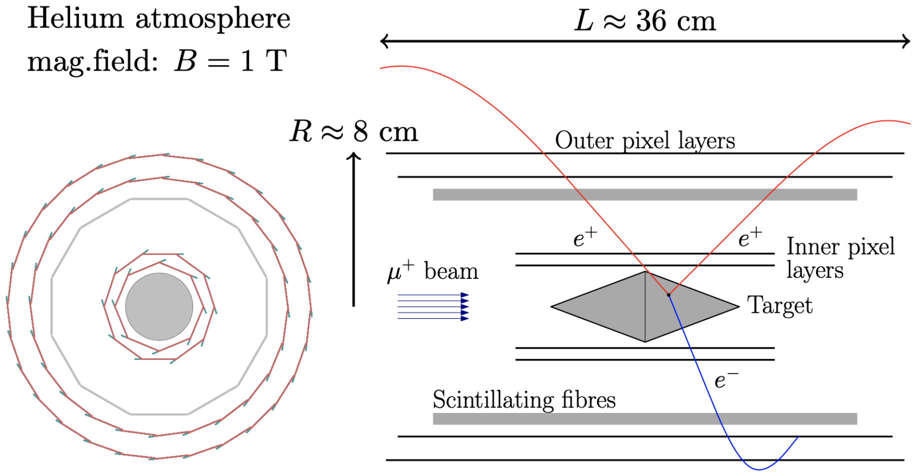
- **Experimental status:**

  SINDRUM @ PSI [SINDRUM Coll., '88]

  BR($\mu^+ \to e^+ e^- e^+$) $\leq 1.0 \times 10^{-12}$ (90% CL)

- **Future prospects:** [Mu3e Coll., 2009.11690]

  Mu3e (@ PSI): expected sensitivity $\mathcal{O}(10^{-15})$ for Phase I
  with HIMB, $\mathcal{O}(10^{-16})$ for Phase II



[Aiba et al, 2111.05788]

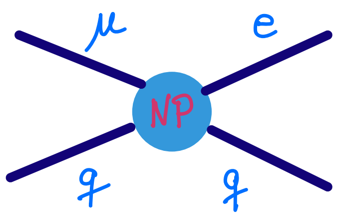
cLFV in muonic atoms: $\mu - e$ conversion

- **Muonic atoms:** 1s bound state formed when $\boldsymbol{\mu^-}$ stopped in target

  SM allowed processes: decay in orbit (DIO) $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

  nuclear capture $\mu^- + (A,Z) \to \nu_\mu + (A,Z-1)$

- In the presence of **New Physics** - cLFV neutrinoless $\boldsymbol{\mu^- - e^-}$ conversion



$$\boldsymbol{\mu^- + (A,Z) \to e^- + (A,Z)}$$

- **Event signature:** single mono-energetic electron

  $$E_{\mu e} = m_\mu - E_B(A,Z) - E_R(A,Z)$$

  For Aluminium, Lead, Titanium $\rightsquigarrow E_{\mu e} \approx \mathcal{O}(100\text{ MeV})$

  *Which target?** For coherent conversion, maximal rates for* $30 \le Z \le 60$

- **Backgrounds** ⇒ Only physics! μ decay in orbit, beam purity, cosmic rays, …

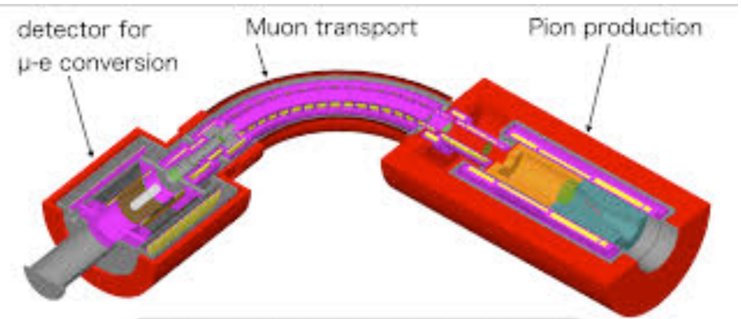
- **Experimental status:** [SINDRUM II Coll., '06]

  SINDRUM @ PSI: CR($\boldsymbol{\mu^- - e^-}$, Au) $\le 7.1 \times 10^{-13}$ (90% CL)

- **Future prospects:**

  Mu2e (@ FNAL) - $\mathcal{O}(10^{-17})$, [Bartoszek et al, 1501.05241]

  [Abramishvili et al, '20] **COMET (@ JPARC)** - $\mathcal{O}(10^{-15} - 10^{-17})$, …



COMET Phase-I Layout

cLFV in muonic atoms: $\mu - e$ conversion

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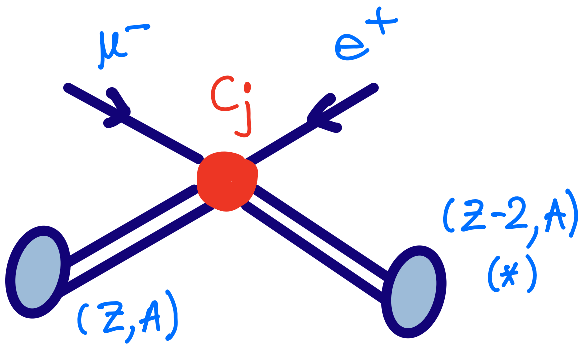
  nuclear capture $\mu^- + (A,Z) \to \nu_\mu + (A, Z-1)$

- In the presence of **New Physics** - cLFV & LNV $(\Delta L = 2)$ neutrinoless $\mu^- - e^+$ conversion

$$\boldsymbol{\mu^- + (A,Z) \to e^+ + (A, Z-2)^*}$$

$\mu^- - e^-$ conversion: coherent process, single nucleon, nuclear ground states

$\mu^- - e^+$ conversion: 2 nucleons $(\Delta Q = 2)$, possibly excited final state



- **Event signature:** single positron - but complex energy spectrum

$$E_{\mu e}^{\mathrm{N}^*} = m_\mu - E_B(A,Z) - E_R(A,Z) - \Delta_{Z-2^{(*)}}$$

For Aluminium (giant dipole resonance) $\rightsquigarrow E_{\mu^- e^+}^{\text{Al, GDR}} \approx \mathcal{O}(83.9 \text{ MeV})$

- **Experimental status:**

Collaboration	year	Process	Bound
PSI/SINDRUM	1998	μ^-+Ti$\to e^+$+Ca*	3.6×10^{-11}
PSI/SINDRUM	1998	μ^-+Ti$\to e^+$+Ca	1.7×10^{-12}

- **Future prospects:**

  Best sensitivity for Ca, S and Ti targets (possibly $\sim \mathcal{O}(\text{few} \times 10^{-15})$); Al@Mu2e?

cLFV in muonic atoms: $\mu - e$ conversion

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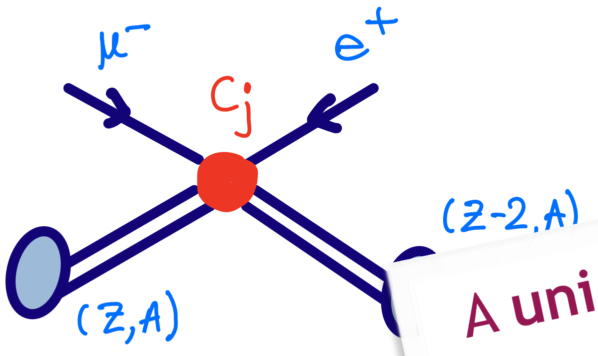

- **Event signatu** ergy spectrum

  $_R(A,Z) - \Delta_{Z-2^{(*)}}$

  imum (giant dipole resonance) $\rightsquigarrow E^{\text{Al, GDR}}_{\mu^- e^+} \approx \mathcal{O}(83.9\text{ MeV})$

A unique connection between **LNV** (in association with Majorana nature and possibly, **neutrino mass generation**) and **cLFV**

- **Experimental status:**

Collaboration	year	Process	Bound
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cLFV muonium transitions

- **Muonium: $\mu^+ e^-$**

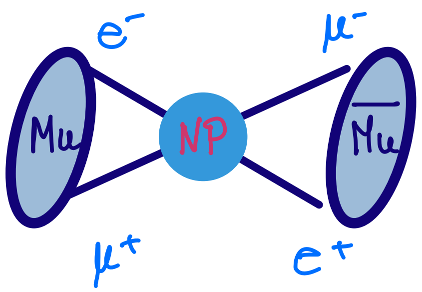
  Hydrogen-like Coulomb bound state, free of hadronic interactions!

  Powerful laboratory for **EW** tests and cLFV

- In the presence of **New Physics** - Muonium oscillations and Muonium decays

  - **Mu-$\overline{\text{Mu}}$ oscillation**

    Spontaneous conversion $\mu^+ e^- \leftrightsquigarrow \mu^- e^+$



    Reflects a double (individual) lepton number violation $|\Delta L_e| = |\Delta L_\mu| = 2$

    Rate (typically) suppressed by external magnetic fields

    Detection: reconstruct Michel electron from μ^- decays and shell positron

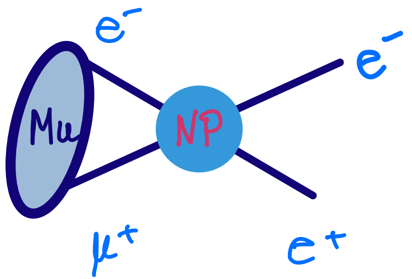
    Experimental status: MACS - $P(\text{Mu} - \overline{\text{Mu}}) < 8.3 \times 10^{-11}$ [Willmann et al, 1999]

    Future prospects: MACE, AMF (@FNAL)

    [Bai et al, 2203.11406]

- **Mu decays**

  $\mu^+ e^- \rightarrow e^+ e^-$

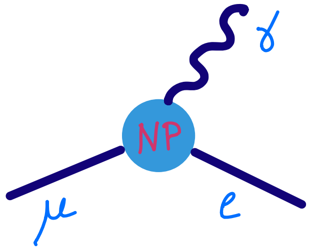


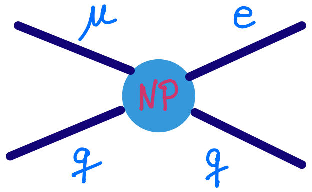
  Clear signal compared to SM-allowed muonium decay, Mu $\rightarrow e^+ e^- \bar{\nu}_\mu \nu_e$

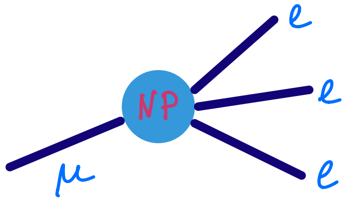
  No available bounds, no clear roadmap...

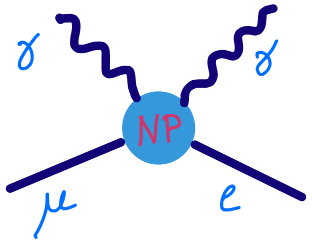
cLFV muon observables: experimental status

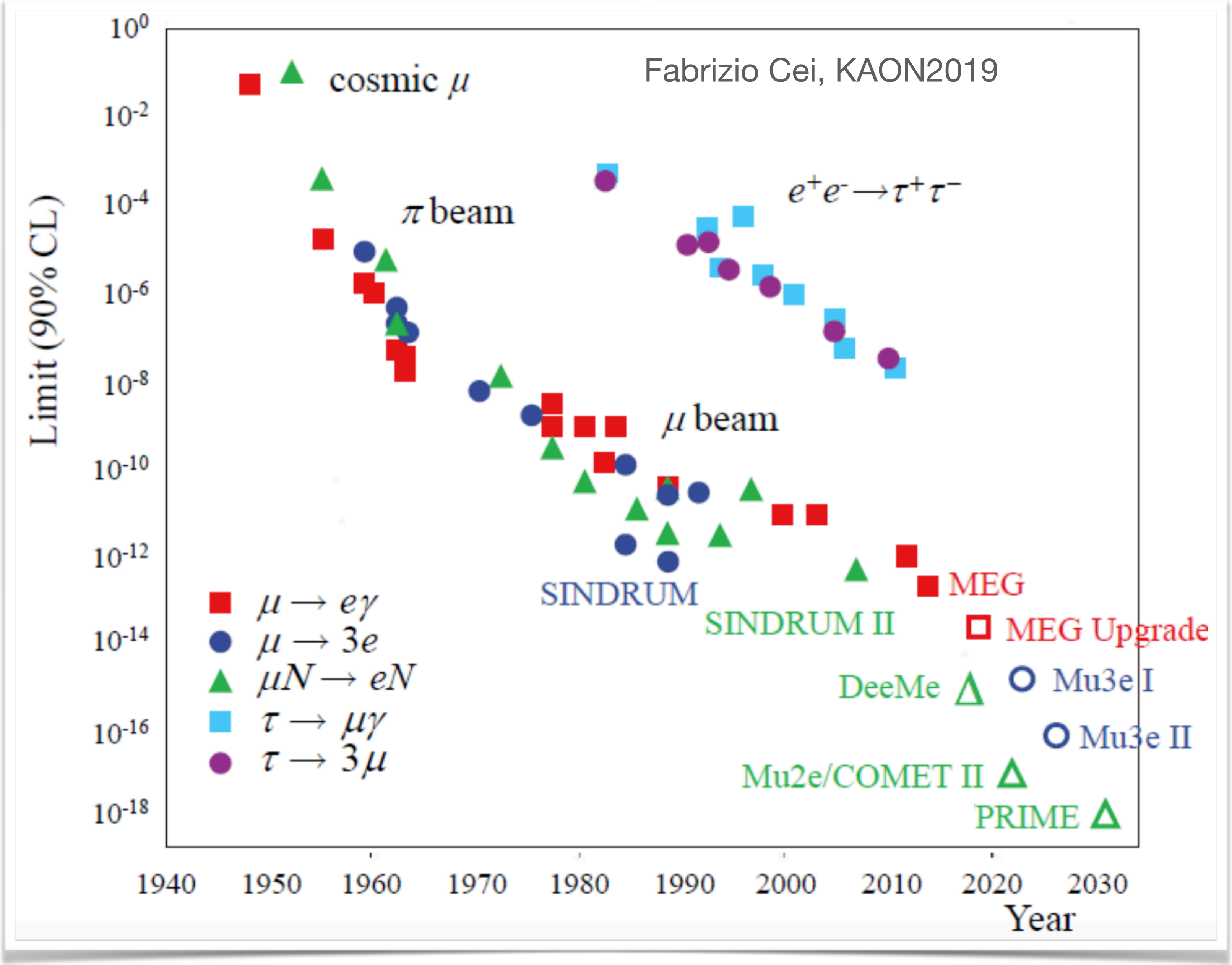
Searching for tiny cLFV effects ⇒ high-intensity sources for excellent sensitivities











⇒ **Need many many (really many!) muons:** excellent sensitivity with **current sources,**
Amazing prospects with advent of **high-intensity beams** (PSI, FNAL, JPARC)
and beyond?... ***Muon facility? Muon collider?***

Lepton flavours: from ν oscillations... EFT!

- **Generic New Physics observables** in the lepton sector:
  - Lepton number violation (e.g. neutrino masses, $0\nu 2\beta$ decays, ...)
  - Electric and (anomalous) magnetic moments - d_ℓ, $(g-2)_\ell$
  - **charged lepton flavour violation**

Here - a tiny tip of the iceberg!

Back to $\mathscr{L}^{\text{eff}}$: cast observables in terms of $\mathscr{C}_{ij}$ and Λ_{NP}

$$\mathscr{L}^{\text{eff}} = \mathscr{L}^{\text{SM}} + \frac{\mathscr{C}_5 \mathscr{O}^5}{\Lambda_{\text{LNV}}}(m_\nu) + \frac{\mathscr{C}_6 \mathscr{O}^6}{\Lambda^2_{\text{cLFV}}}(\ell_\alpha \leftrightarrow \ell_\beta) + \ldots + \frac{\mathscr{C}_7 \mathscr{O}^7}{\Lambda^3_{\text{LNV}}}(0\nu 2\beta) + \ldots$$

Majorana ν masses

Kinetic corrections, ...
EW precision, top physics, ...
Electric dipole & anomalous magnetic moments, ...
cLFV (dipole, 3 body, matter assisted, ...)

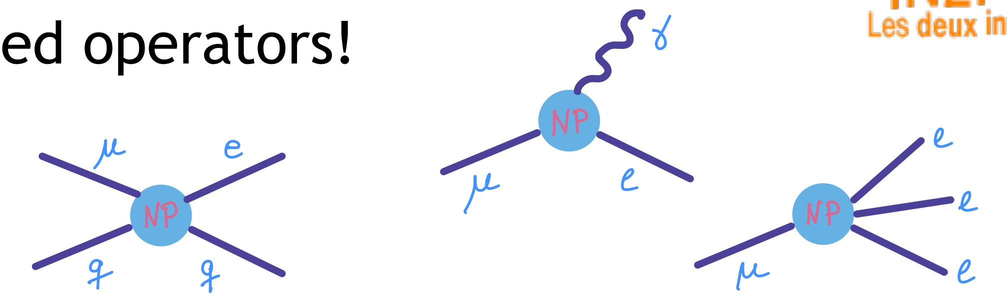
Lepton number violation,
cLFV & LNV,
...

Deceptively simple task... different new physics scales, numerous operators!

For **cLFV**, technically very involved, *even if no "SM background"...*

Muon cLFV: EFT approach to New Physics

- **QED & QCD & NP effective Lagrangian,** many involved operators!



$$\begin{aligned}\mathcal{L}_{\text{eff}} &= \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} \\ &\quad + \frac{1}{\Lambda^2}\Big\{ C_L^D O_L^D + \sum_{f=q,\ell} \left(C_{ff}^{V\,LL} O_{ff}^{V\,LL} + C_{ff}^{V\,LR} O_{ff}^{V\,LR} + C_{ff}^{S\,LL} O_{ff}^{S\,LL} \right) \\ &\qquad + \sum_{h=q,\tau} \left(C_{hh}^{T\,LL} O_{hh}^{T\,LL} + C_{hh}^{S\,LR} O_{hh}^{S\,LR} \right) + C_{gg}^{L} O_{gg}^{L} + L \leftrightarrow R \Big\} + \text{h.c.},\end{aligned}$$

$$\begin{aligned} O_L^D &= e\, m_\mu \left(\bar{e}\sigma^{\mu\nu} P_L \mu\right) F_{\mu\nu}, \\ O_{ff}^{V\,LL} &= \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_L f\right), \\ O_{ff}^{V\,LR} &= \left(\bar{e}\gamma^\mu P_L \mu\right)\left(\bar{f}\gamma_\mu P_R f\right), \end{aligned}$$

$$\begin{aligned} O_{ff}^{S\,LL} &= \left(\bar{e} P_L \mu\right)\left(\bar{f} P_L f\right), \\ O_{hh}^{S\,LR} &= \left(\bar{e} P_L \mu\right)\left(\bar{h} P_R h\right), \\ O_{hh}^{T\,LL} &= \left(\bar{e}\sigma_{\mu\nu} P_L \mu\right)\left(\bar{h}\sigma^{\mu\nu} P_L h\right), \\ O_{gg}^{L} &= \alpha_s\, m_\mu G_F \left(\bar{e} P_L \mu\right) G_{\mu\nu}^{a} G_a^{\mu\nu} \end{aligned}$$

... and further "mixing" effects, from RGE running (including loop effects) ...

- Simple examples: at leading order one has

BR($\mu \to e\gamma$) $\simeq 384\pi^2 \dfrac{v^4}{\Lambda^4}\left(|C_{D,L}|^2 + |C_{D,R}|^2\right)$

BR($\mu \to eee$) $\simeq \dfrac{v^4}{\Lambda^4}\Big[\dfrac{1}{8}|C_{S,LL}|^2 + 2|C_{V,RR} + 4eC_{D,L}|^2 + (64\ln\dfrac{m_\mu}{m_e} - 136)\, e\, |C_{D,L}|^2 + |C_{V,RL} + 4eC_{D,L}|^2\Big] + (L \leftrightarrow R)$

CR($\mu - e$, N): *far more involved* (nuclear target effects, spin (in)-dependent contributions, ...)

$$\approx \frac{1}{\Gamma_{\text{cap}}}\frac{m_\mu^5}{\Lambda^4}\left[\left| eC_L^D D_N + 4\left(G_F m_\mu m_p \tilde{C}_{(p)}^{SL} S_N^{(p)} + \tilde{C}_{(p)}^{VR} V_N^{(p)} + p \to n\right)\right|^2 + (L \leftrightarrow R)\right]$$

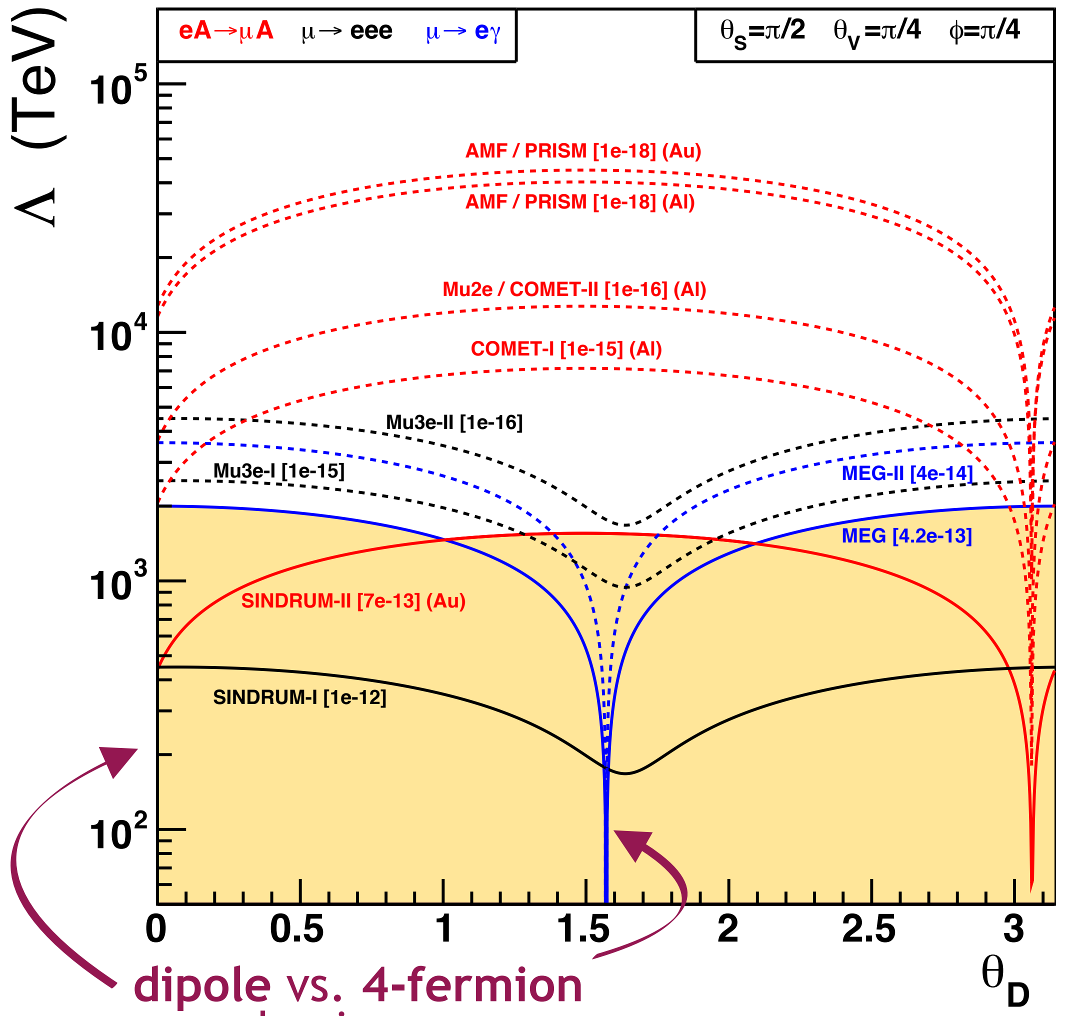
$D_N, S_N^{(p/n)}, V_N^{(p/n)}$: *nuclear "overlap integrals" between lepton wave functions and nucleon densities (target-dependent)*

Muon cLFV: EFT approach to New Physics

Results of a recent **EFT** approach to **muon transitions:**

$$\mathscr{L}^{\text{eff}}_{\text{NP, cLFV}} = \frac{1}{\Lambda^2}\Big[C_D(\bar e\sigma^{\nu\rho}P_R\mu)F_{\nu\rho} + C_S(\bar eP_R\mu)(\bar eP_Re) + C_{VR}(\bar e\gamma^\nu P_L\mu)(\bar e\gamma_\nu P_Re) + C_{VL}(\bar e\gamma^\nu P_L\mu)(\bar e\gamma_\nu P_Le) + \\ + C_{\text{N-light}}\mathcal{O}_{\text{N-light}} + C_{\text{N-heavy}\perp}\mathcal{O}_{\text{N-heavy}\perp}\Big]$$

$$\vec{C} = \{C_D, C_S, C_{VR}, C_{VR}, C_{VL}, C_{\text{N-light}}, C_{\text{N-heavy}\perp}\}$$



dipole vs. 4-fermion dominance

$$2\sqrt{2}\,C_D \approx \frac{\cos\theta_D}{\Lambda^2}$$

[Davidson & Echenard, 2204.00564]

$$\Rightarrow \textbf{BR}(\mu\to e\gamma) \simeq 384\pi^2\frac{v^4}{\Lambda^4}|\vec{C}\,.\,\hat e_{DR}|^2 \rightsquigarrow \lesssim \text{BR}^{\text{exp (future)}}$$

and likewise for other observables

*BR($\mu\to 3e$), **CR($\mu - e$, N)**, Muonium oscillations...*

Sensitivity to NP scales (current & future):

MEG ($\mu\to e\gamma$) $\leftrightsquigarrow$ $\Lambda_{\text{cLFV}} \sim \mathcal{O}(10^3$ **TeV**) [dipole]

SINDRUM II ($\mu - e$, Au) $\leftrightsquigarrow$ $\Lambda_{\text{cLFV}} \sim \mathcal{O}(10^3$ **TeV**) [4f]

Mu2e/COMET II ($\mu - e$, Al) $\leftrightsquigarrow$ $\Lambda_{\text{cLFV}} \lesssim \mathcal{O}(10^4$ **TeV**)
[either dipole or 4f]

Muon cLFV: EFT approach & conversion in nuclei

⇒ **cLFV data to constrain** $\mathscr{C}^6$ (and **infer sensitivity** of a process **to operator** $\mathscr{O}^6$)

- Fully exploring the potential of atomic (elastic) **muon-electron conversion,** CR($\mu - e$,N):

  Comparatively more involved theoretical approach!

  Explore target-nucleus dependence to distinguish dominant operator (hint on **NP** model!)

  [extensive contributions since Kitano et al, 0203110! see Davidson et al, 1810.01884; Heeck et al, 2203.00702, ...]

  In the advent of an observation (@ Mu2e, COMET ⤳ using Aluminium targets)

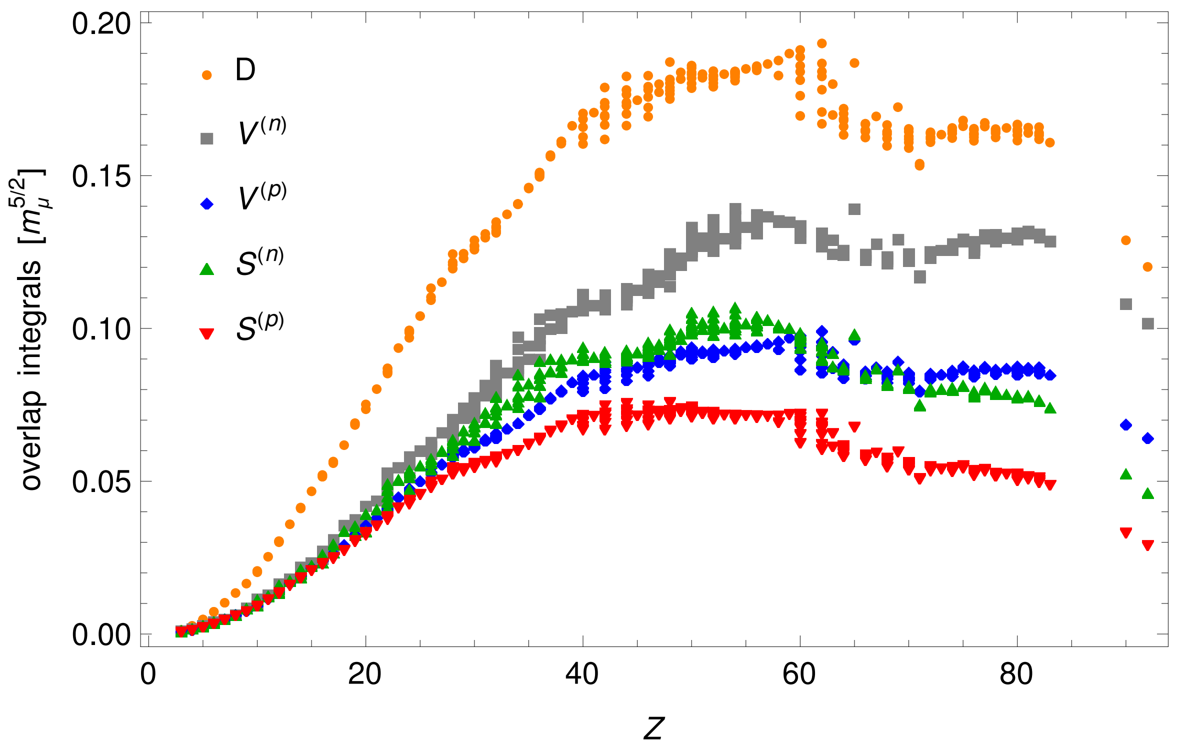
  prepare **choice of future targets**

  Which offer the largest complementarity with respect to Al?

$$\mathrm{BR}_{\mathrm{SI}}(\mu A \to e A) = \frac{32 G_F^2}{\Gamma_{\mathrm{capture}}} \Bigg[\Big| C^{pp}_{V,R} V^{(p)} + C^{pp'}_{S,L} S^{(p)} + C^{nn}_{V,R} V^{(n)} + C^{nn'}_{S,L} S^{(n)} + C_{D,L} \frac{D}{4} \Big|^2 + \{L \leftrightarrow R\} \Bigg] .$$

Overlap integrals:
more distinguishable at large Z !

Better disentangle dominant NP contributions...



[Heeck et al, 2203.00702]

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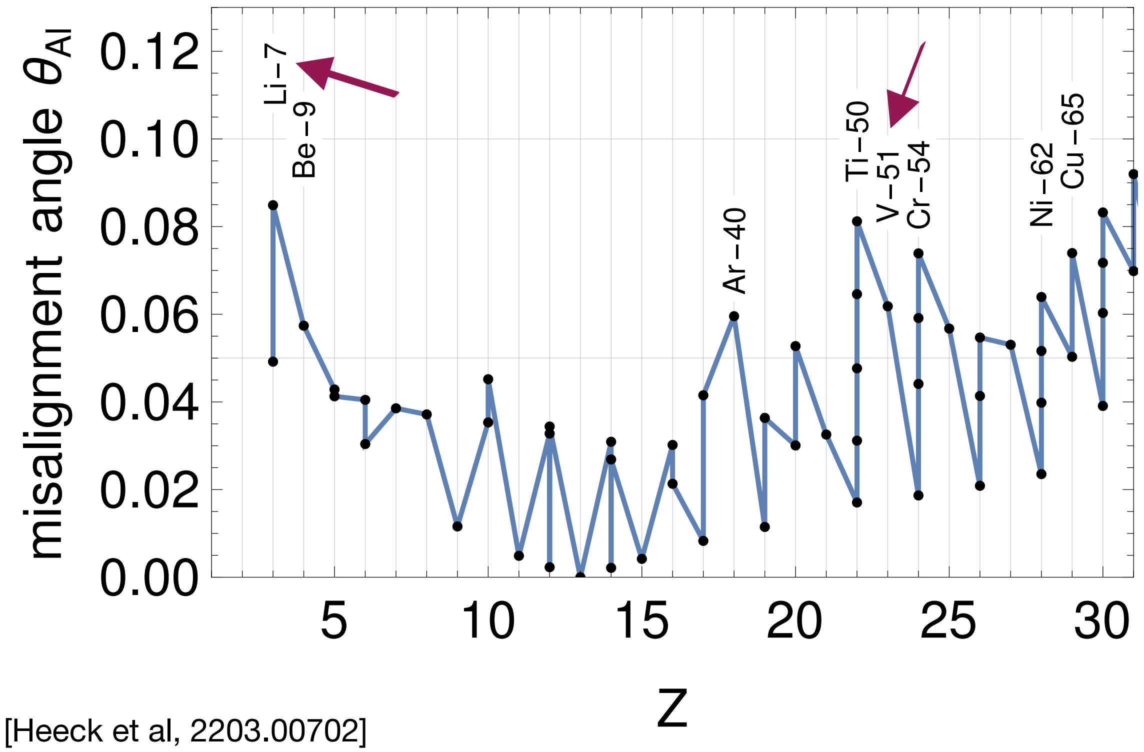
Which offer the **largest complementarity** with respect to Al? $\boldsymbol{\theta_{\mathrm{Al}}}$



[Heeck et al, 2203.00702]

- **Heavier nuclei** (Au, Pb)! ... not feasible...

  (pulsed beams)

- Among experimental-friendly $Z \leq 25$ targets

  several (theoretically good) candidates

  Li-7, Ti-50, Ti-49, Cr-54, .., V-51

⇒ **Li-7 and/or V-51 :** preferable **"second" targets**

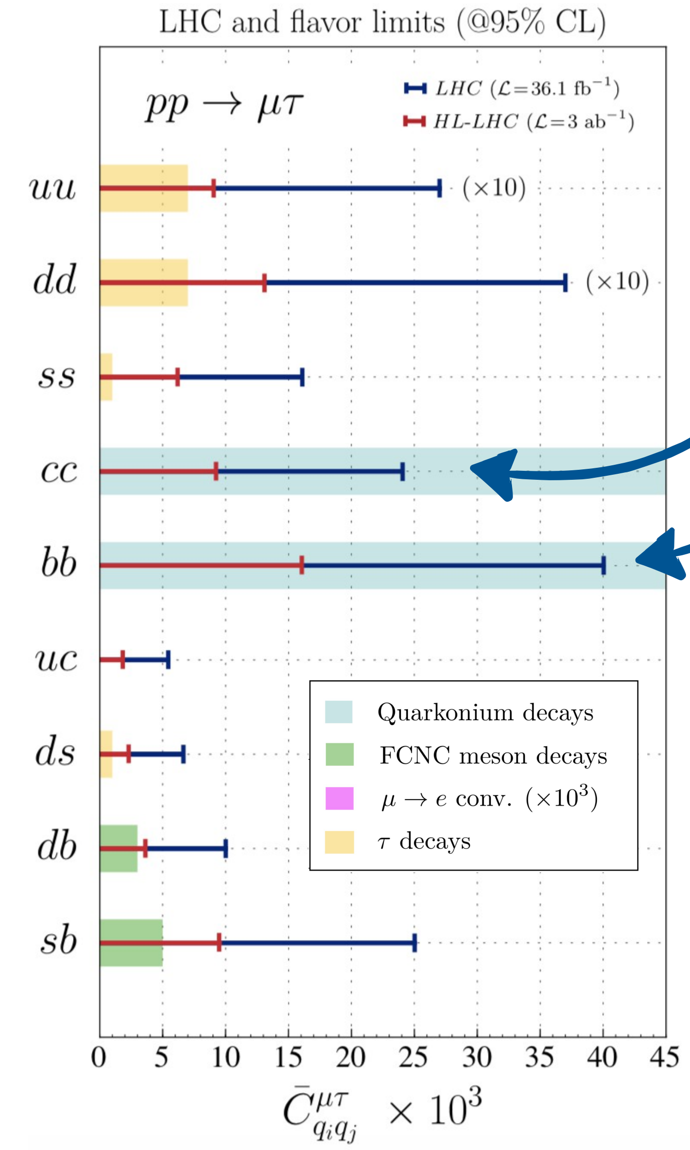
post CR($\mu - e$,Al) observation

$\mu - e$ conversion: "unbeatable" NP probe

- Albeit leading to **formally different transitions**, the same leptonic and semi-leptonic operators can be at the origin of flavour violating transitions in very distinct contexts

LHC $\rightsquigarrow$ abundant sources of flavour in pp collisions

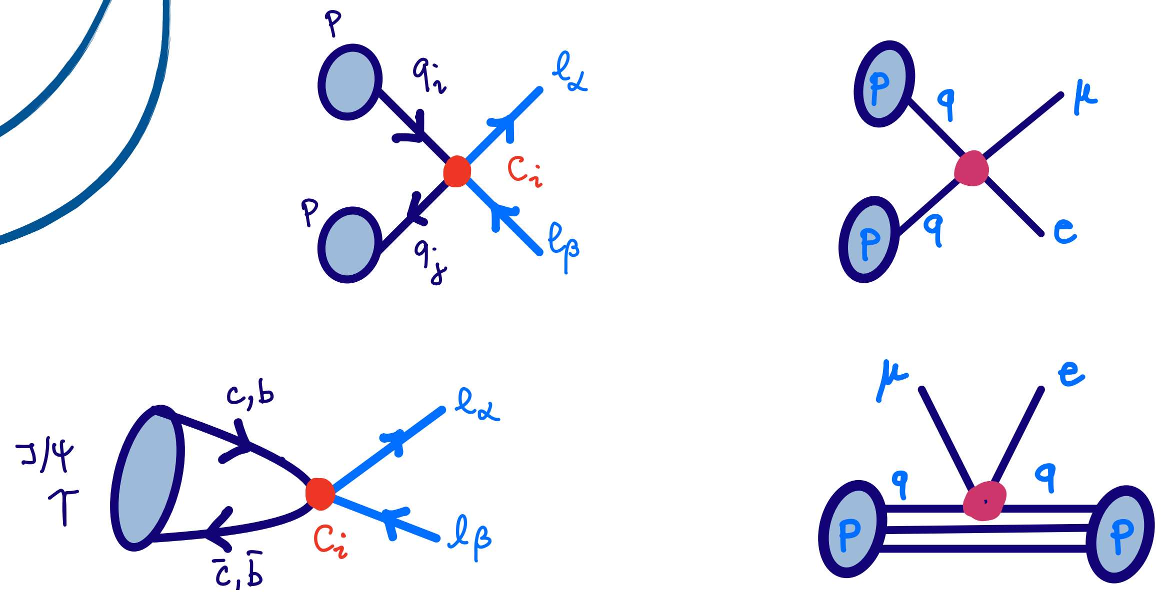
Drell-Yan $q_i\bar{q}_j \to \ell_\alpha \ell_\beta (\ell_\alpha \nu_\beta)$ probe similar operators, **but** at high p_T

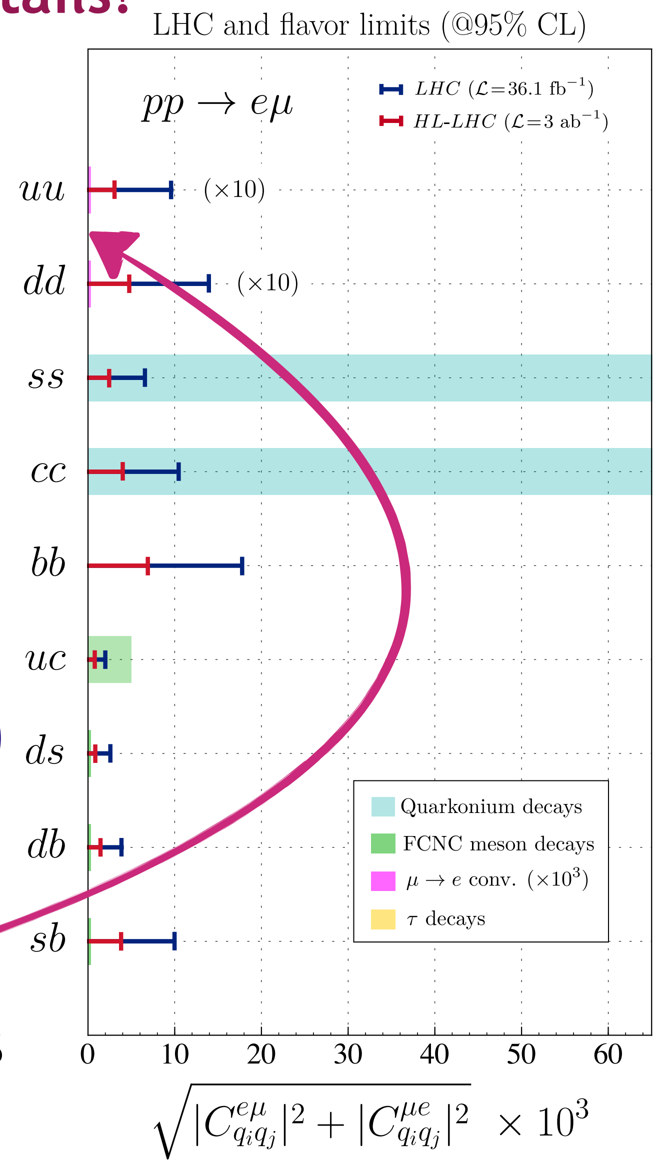


⇒ **LHC limits very competitive** for $\mu\tau$ **tails!**

Better than **quarkonium**-decays

[Angelescu et al, 2002.05684]





⇒ **Impossible** for μe **tails**
to out-perform cLFV searches
($\mu - e$, N) **conversion bounds**

[Constraints from quarkonia decays, see also Calibbi et al, 2207.10913]

$\mu - e$ conversion: "unbeatable" NP probe

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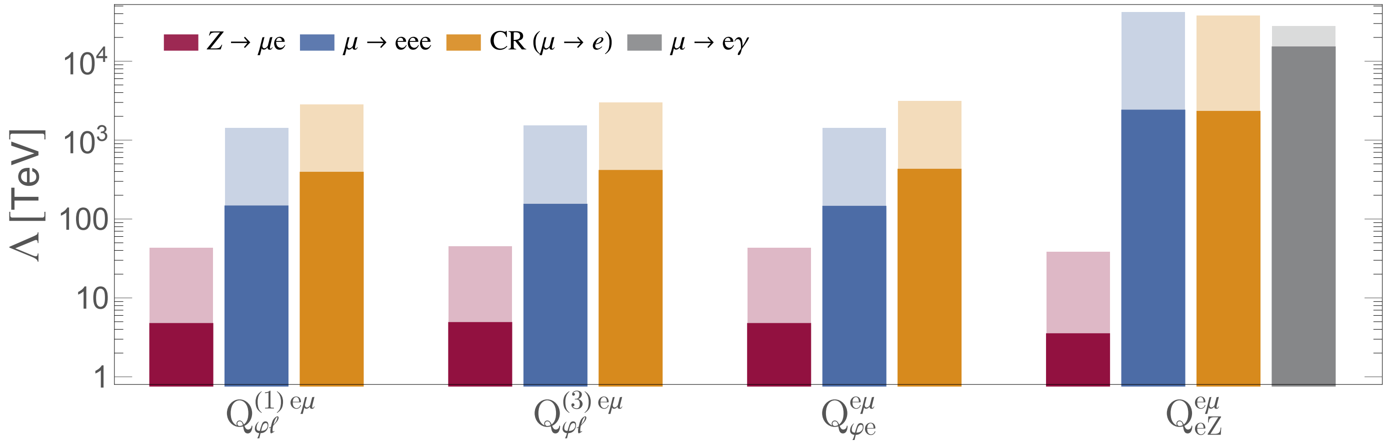
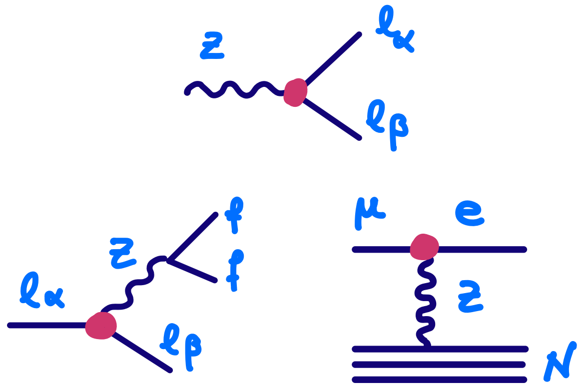
TeraZ factory (FCC-ee, CEPC) ⤳ **EW precision & flavour violation**



[Calibbi et al, 2107.10273]

For $Z \to \mu e$ **much** better sensitivity of **dedicated (low-energy) cLFV searches**

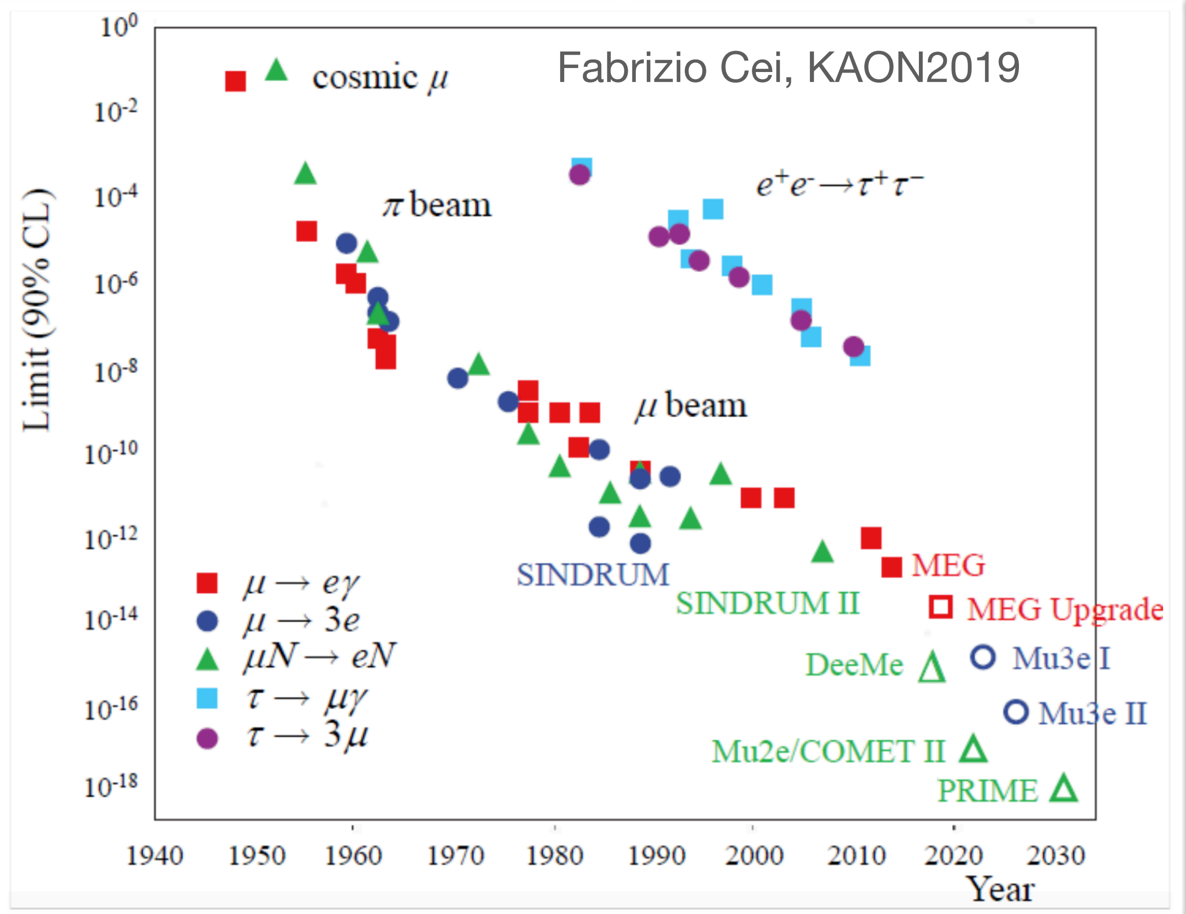
$\mu \to eee$, $\mu - e$ conversion



TeraZ factory ⤳ cLFV Z decays

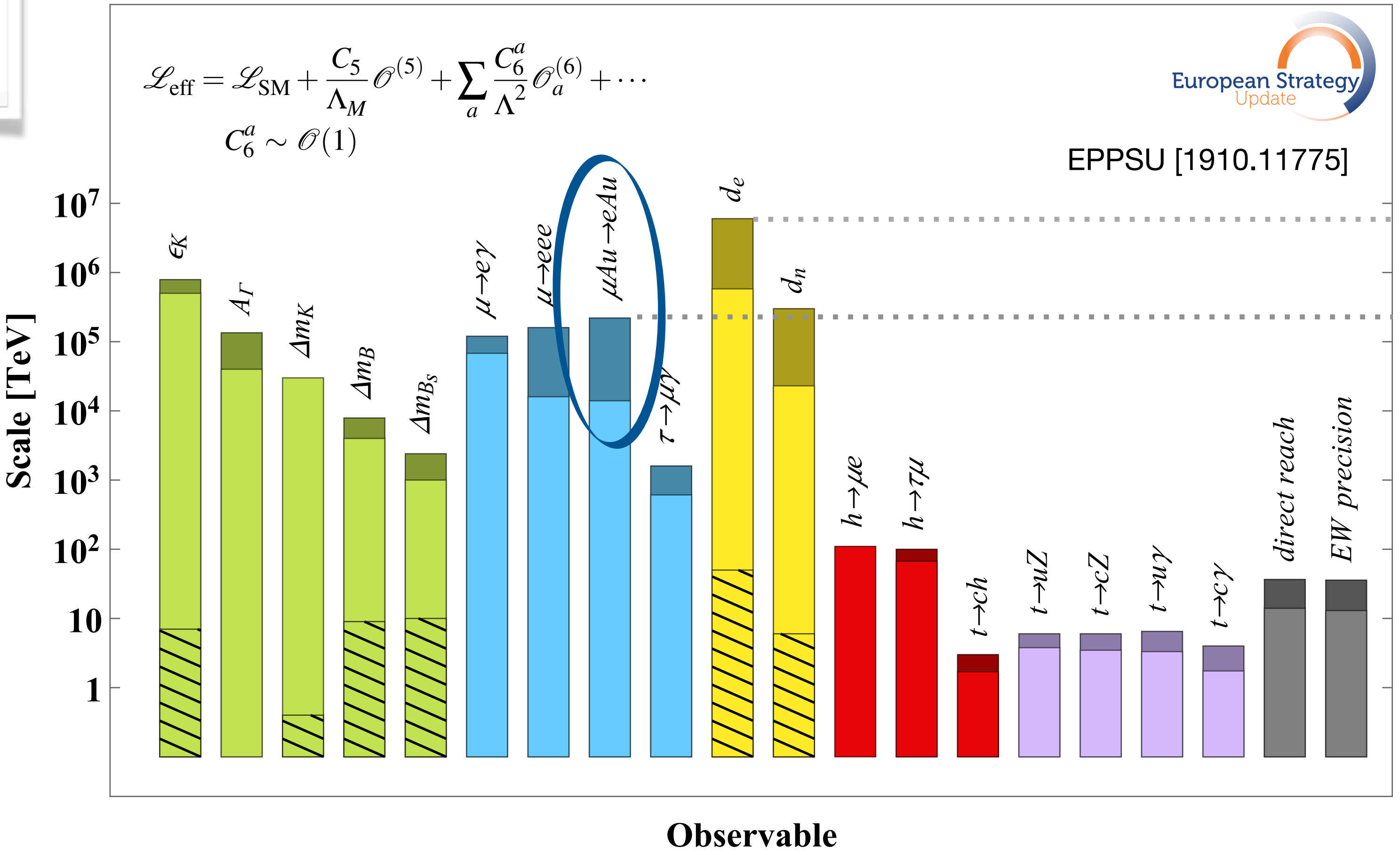
Promising potential of **TeraZ factory** for $Z \to \tau\ell$ decays
(competitive with low-energy cLFV)

Muon cLFV prospects



Muons: *lightest "unstables"* - clean objects, ideal & versatile probes for NP searches

At the centre of a world-wide comprehensive programme - experiments *and* theory



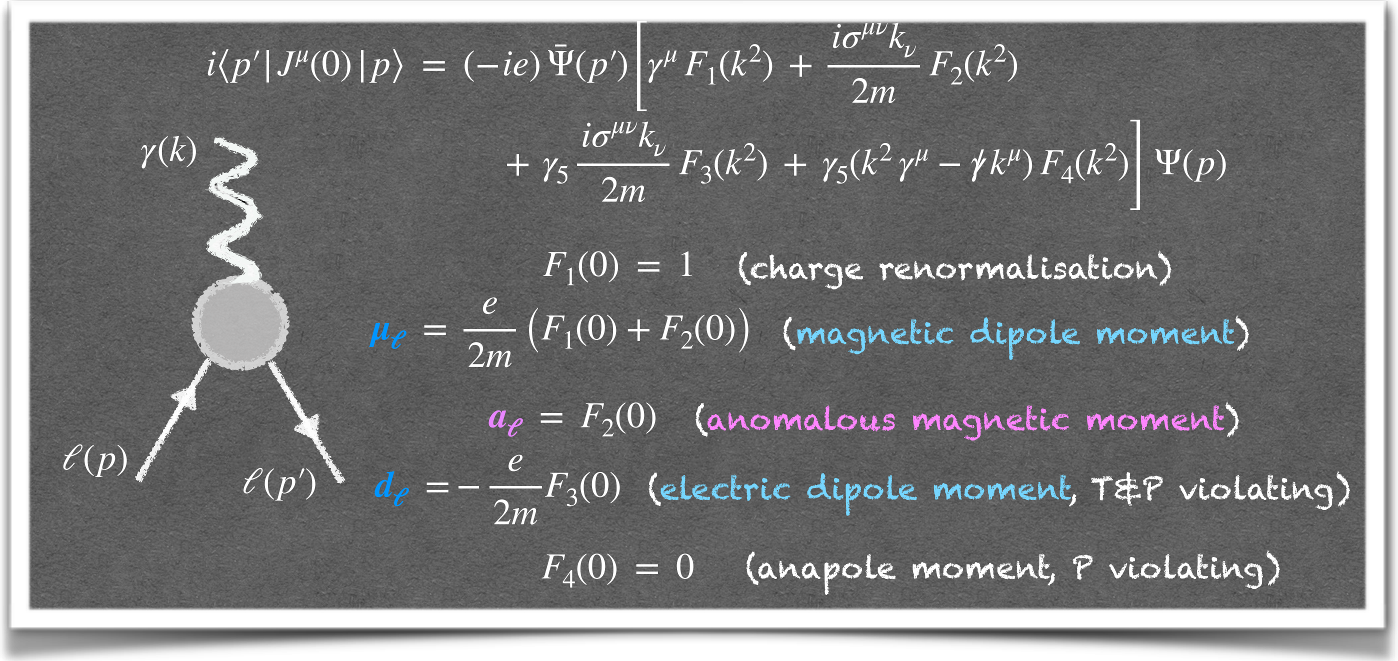
cLFV $\mu - e$ conversion in nuclei:

most **sensitive flavoured probe** of **NP!**

Unprecedented sensitivity $\mathcal{O}(10^{-17})$

Unique opportunities for NP discovery

Electric dipole moments (EDM)



$$i\langle p'|J^\mu(0)|p\rangle = (-ie)\,\bar\Psi(p')\left[\gamma^\mu F_1(k^2) + \frac{i\sigma^{\mu\nu}k_\nu}{2m}F_2(k^2) + \gamma_5\frac{i\sigma^{\mu\nu}k_\nu}{2m}F_3(k^2) + \gamma_5(k^2\gamma^\mu - \not{k}k^\mu)F_4(k^2)\right]\Psi(p)$$

$F_1(0) = 1$ (charge renormalisation)

$\mu_\ell = \frac{e}{2m}\left(F_1(0) + F_2(0)\right)$ (magnetic dipole moment)

$a_\ell = F_2(0)$ (anomalous magnetic moment)

$d_\ell = -\frac{e}{2m}F_3(0)$ (electric dipole moment, T&P violating)

$F_4(0) = 0$ (anapole moment, P violating)

Electric dipole moments (EDM)

Flavour & CPV: the "usual graveyard of BSM electroweak theories"

Neutron EDM: observable (likely) responsible for falsifying the largest number of BSM...

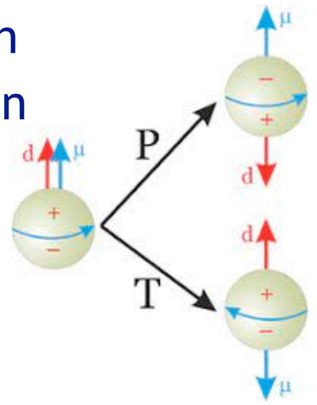
Electric dipole moments (EDM)

Electric Dipole Moments - observables **sensitive to CP violation**

non-relativistic approach: $\mathscr{H} \propto -(\mu_f\, \vec{\sigma} \,.\, \vec{B} \;+\; d_f\, \vec{\sigma} \,.\, \vec{E})$

relativistic generalisation $\leadsto$ $\mathscr{L}_{\text{CP-odd}} = -\dfrac{i}{2}\, d\, \bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi F_{\mu\nu}$

P & T violation
⇒ CP violation

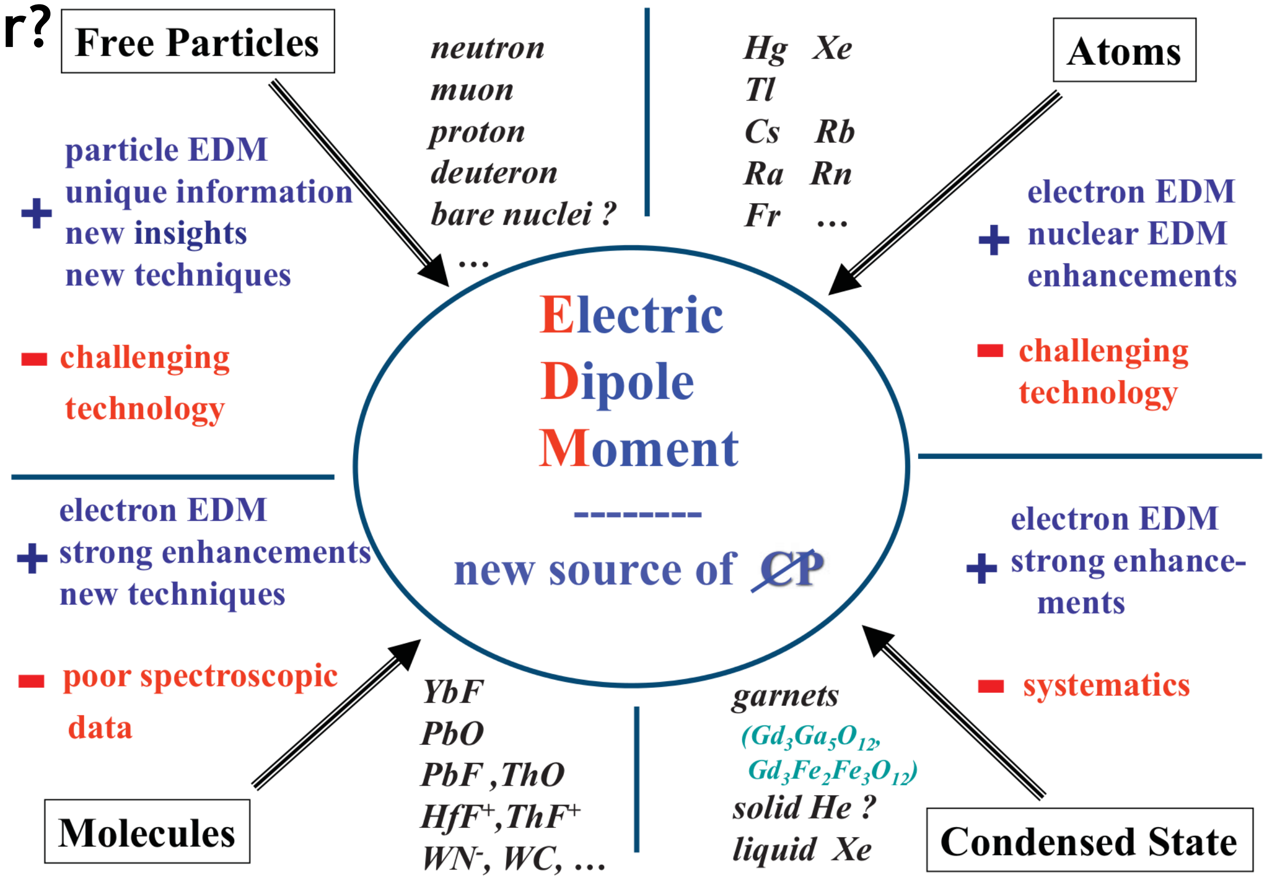


EDMs: sensitive to **SM sources of CP violation** (weak δ_{CKM} and strong $\bar{\theta}$),
and **NP CPV interactions** - required to **explain the BAU** (*baryo- or leptogenesis*)
(especially "flavour blind" new phases)

- Which **EDM observables** are being **"hunted" for?**

  As many as possible!

Lines of attack towards an EDM



Free Particles

neutron
muon
proton
deuteron
bare nuclei ?
…

\+ particle EDM
unique information
new insights
new techniques

− challenging
technology

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
Fr …

\+ electron EDM
nuclear EDM
enhancements

− challenging
technology

**Electric
Dipole
Moment**
----
new source of $\not{C}\not{P}$

Molecules

\+ electron EDM
strong enhancements
new techniques

− poor spectroscopic
data

YbF
PbO
PbF ,ThO
HfF^+,ThF^+
WN^-, WC, …

Condensed State

garnets
($Gd_3Ga_5O_{12}$,
$Gd_3Fe_2Fe_3O_{12}$)
solid He ?
liquid Xe

\+ electron EDM
strong enhancements

− systematics

[adapted from Jungmann, 2013]

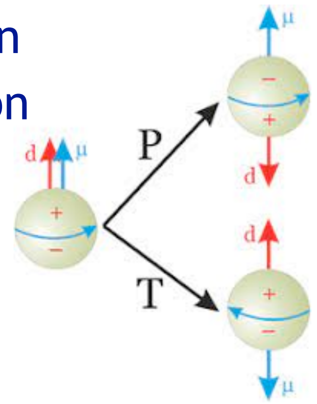
Electric dipole moments (EDM)

Electric Dipole Moments - observables **sensitive to CP violation**

non-relativistic approach: $\mathscr{H} \propto -(\mu_f\, \vec{\sigma}\,.\,\vec{B} + \boldsymbol{d_f\, \vec{\sigma}\,.\,\vec{E}})$

relativistic generalisation $\rightsquigarrow$ $\mathscr{L}_{\text{CP-odd}} = -\frac{i}{2}\, \boldsymbol{d}\, \bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi F_{\mu\nu}$

P & T violation
⇒ CP violation



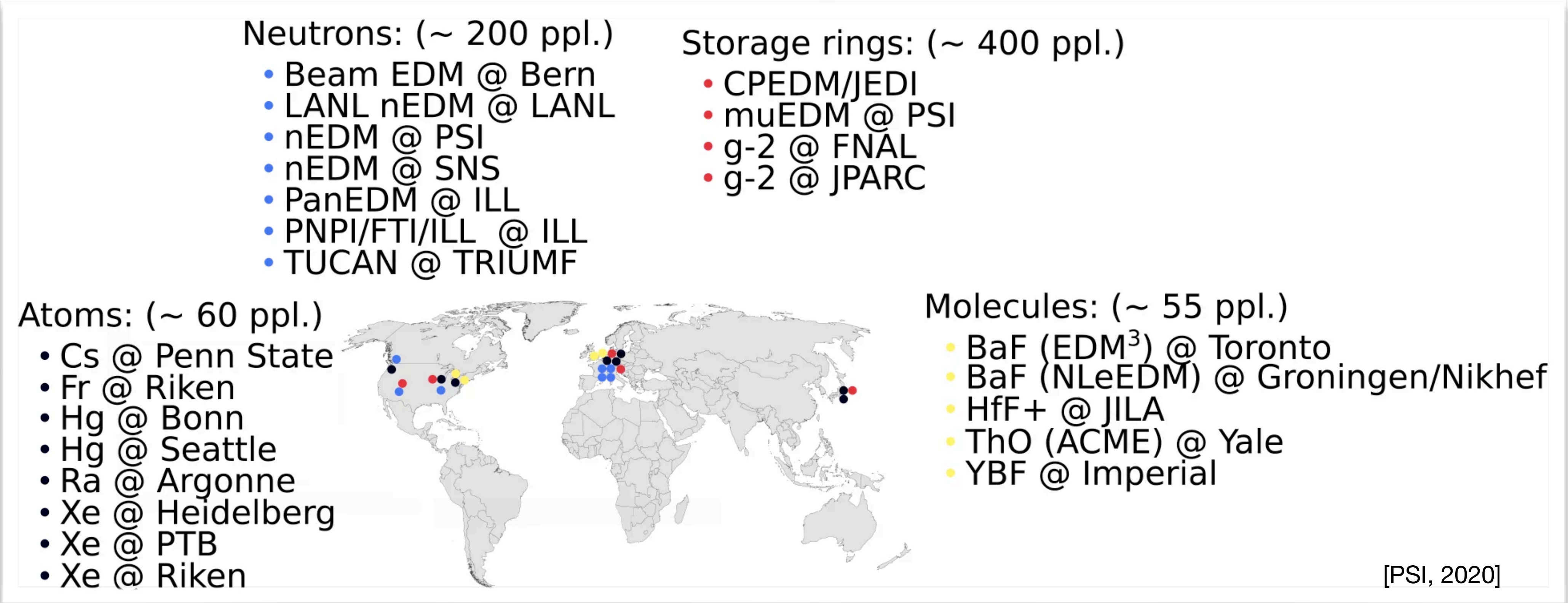
EDMs: sensitive to **SM sources of CP violation** (weak δ_{CKM} and strong $\bar{\theta}$),

and **NP CPV interactions** - required to **explain the BAU** (*baryo- or leptogenesis*)

(especially "flavour blind" new phases)

- **Which EDM observables are being "hunted" for?** *As many as possible!*
- **Where?**

Worldwide!



Neutrons: (~ 200 ppl.)
- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

Atoms: (~ 60 ppl.)
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Hg @ Seattle
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken

Molecules: (~ 55 ppl.)
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

[PSI, 2020]

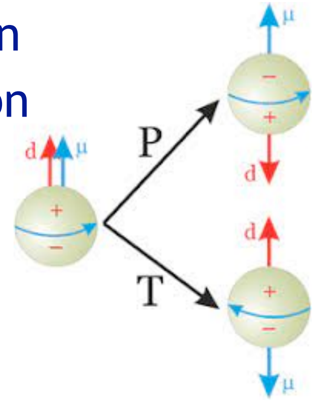
Electric dipole moments (EDM)

Electric Dipole Moments - observables **sensitive to** **CP violation**

non-relativistic approach: $\mathcal{H} \propto -\left(\mu_f\, \vec{\sigma} \,.\, \vec{B} \,+\, \boldsymbol{d_f}\, \vec{\boldsymbol{\sigma}} \,.\, \vec{\boldsymbol{E}}\right)$

relativistic generalisation $\rightsquigarrow$ $\mathcal{L}_{\text{CP-odd}} = -\frac{i}{2}\, \boldsymbol{d}\, \bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi F_{\mu\nu}$

P & T violation
⇒ CP violation

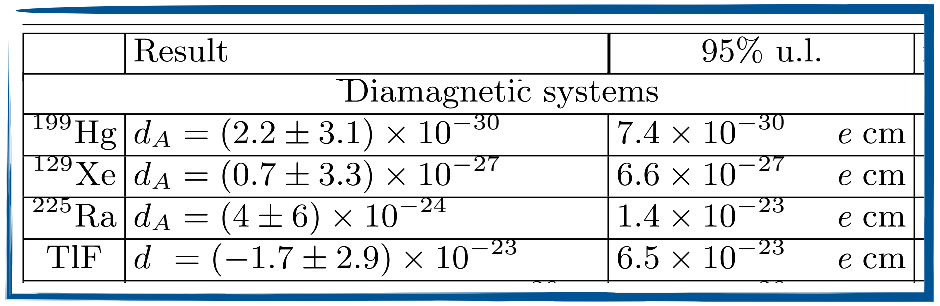


EDMs: sensitive to **SM sources of CP violation** (weak δ_{CKM} and strong $\bar{\theta}$),

and **NP CPV interactions** - required to **explain the BAU** (*baryo- or leptogenesis*)

(especially "flavour blind" new phases)

- **Which EDM observables are being "hunted" for?** *As many as possible!*
- **Where?** *Worldwide!*
- **Bounds obtained?** *Impressive!*

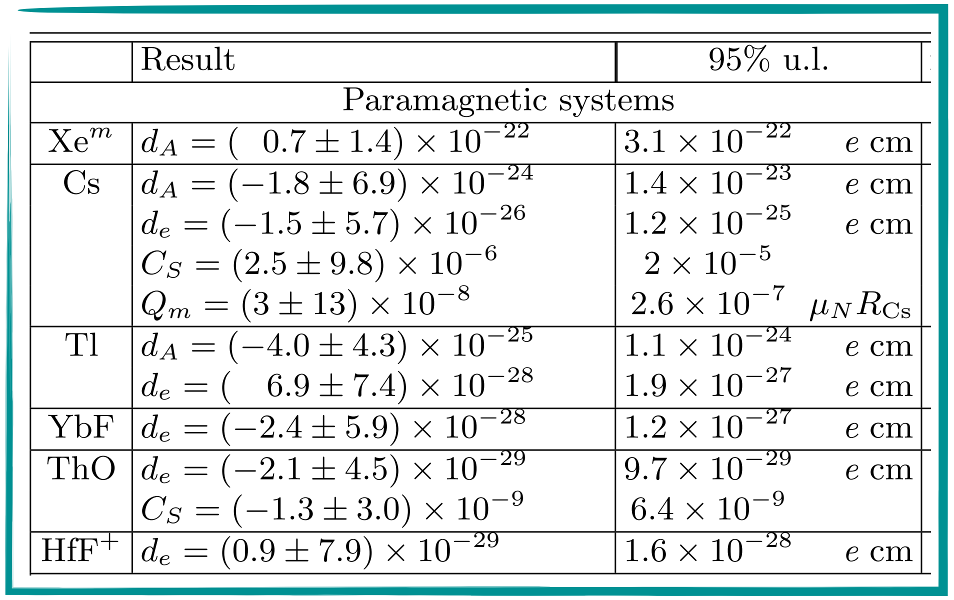


	Result	95% u.l.	
	Diamagnetic systems		
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30}	e cm
^{129}Xe	$d_A = (0.7 \pm 3.3) \times 10^{-27}$	6.6×10^{-27}	e cm
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23}	e cm
TlF	$d = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23}	e cm

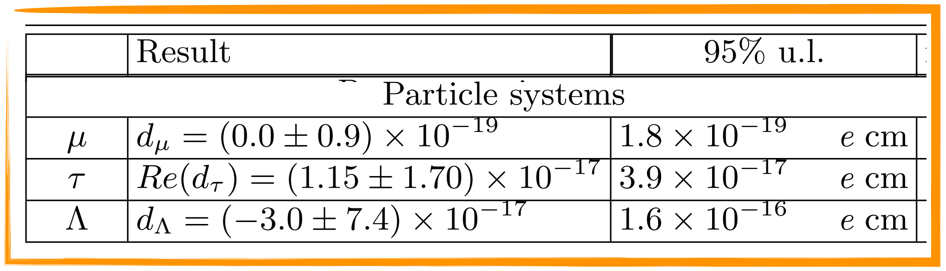
ACME (ThO)
$|d_e| < 1.1 \times 10^{-29} e\,.\,\text{cm}$

$d_n = (0.0 \pm 1.2) \times 10^{-26} e\,.\,\text{cm}$
$|d_n| < 1.8 \times 10^{-26} e\,.\,\text{cm}$

[nEDM Coll - Abel et al, 2001.11966]



	Result	95% u.l.	
	Paramagnetic systems		
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22}	e cm
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23}	e cm
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25}	e cm
	$C_S = (2.5 \pm 9.8) \times 10^{-6}$	2×10^{-5}	
	$Q_m = (3 \pm 13) \times 10^{-8}$	2.6×10^{-7}	$\mu_N R_{\text{Cs}}$
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24}	e cm
	$d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27}	e cm
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27}	e cm
ThO	$d_e = (-2.1 \pm 4.5) \times 10^{-29}$	9.7×10^{-29}	e cm
	$C_S = (-1.3 \pm 3.0) \times 10^{-9}$	6.4×10^{-9}	
HfF$^+$	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	1.6×10^{-28}	e cm



	Result	95% u.l.	
	Particle systems		
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19}	e cm
τ	$Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$	3.9×10^{-17}	e cm
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	1.6×10^{-16}	e cm

[Chupp et al, 1710.02504]

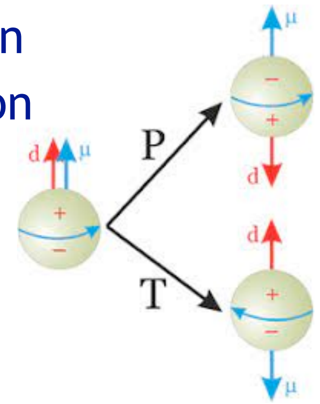
Electric dipole moments (EDM)

Electric Dipole Moments - observables **sensitive to** CP violation

non-relativistic approach: $\mathscr{H} \propto -(\mu_f \vec{\sigma}\,.\,\vec{B} + \boldsymbol{d_f}\,\vec{\boldsymbol{\sigma}}\,.\,\vec{\boldsymbol{E}})$

relativistic generalisation ⤳ $\mathscr{L}_{\text{CP-odd}} = -\frac{i}{2}\, \boldsymbol{d}\, \bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi F_{\mu\nu}$

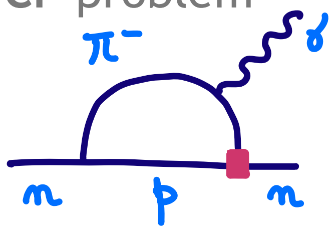
P & T violation
⇒ CP violation



Sources of CP violation in the Standard Model

Strong interactions: $\mathscr{L}^{\text{QCD}}_{\text{CP}} = \boldsymbol{\theta}\frac{g^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu} - i\,\bar{q}\,\text{Im}(\boldsymbol{M_q})\,\gamma_5\, q$ $\qquad \bar{\boldsymbol{\theta}} = \theta + \text{Arg}[\det(M_q)]$

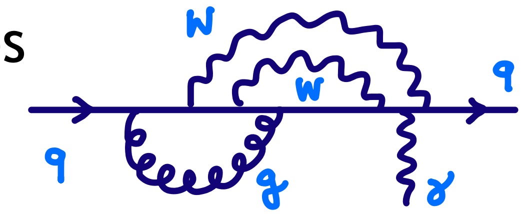
$\bar{\theta} < 10^{-10}$ ⤳ **Strong CP** problem



Electroweak CPV: $Y^f \rightsquigarrow \delta_{\text{CKM}}$

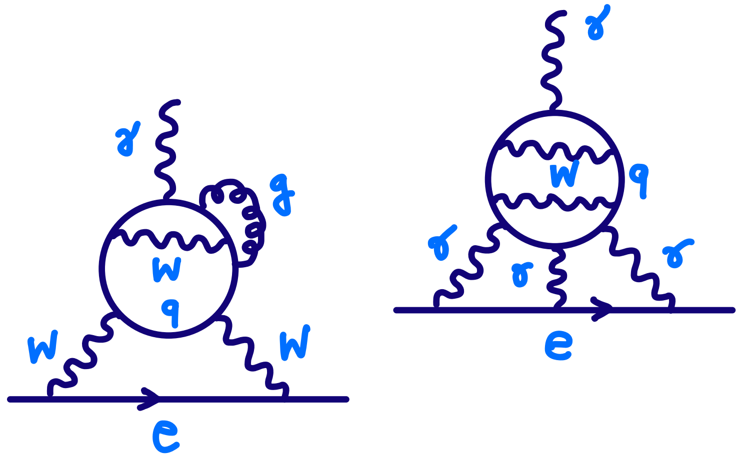
$(J_{CP} = \mathscr{I}[V^*_{ts}V_{td}V^*_{ud}V_{us}] \approx 3\times10^{-5})$

"quark" EDMs @ 3 loops



lepton EDMs @ 4 loops

(no leptonic sources of CPV in the SM...)



⤳ **tiny theoretical predictions** $(d_e, d_N, d_{Hg}, \ldots)$

EDMs: CPV (SM and beyond)

- A ***non-trivial theory problem:***
  numerous scales and approaches
  (elementary, QCD, nuclear & atomic physics,
  and effective description...)
- **Paramagnetic & diamagnetic** observables

SM pioneering results for EDMs (J_{CP}):

$$d_N \;\propto C_{qq}(J_{CP}) \;\propto J_{CP} G_F^2 \sim \;\mathcal{O}(10^{-32})$$

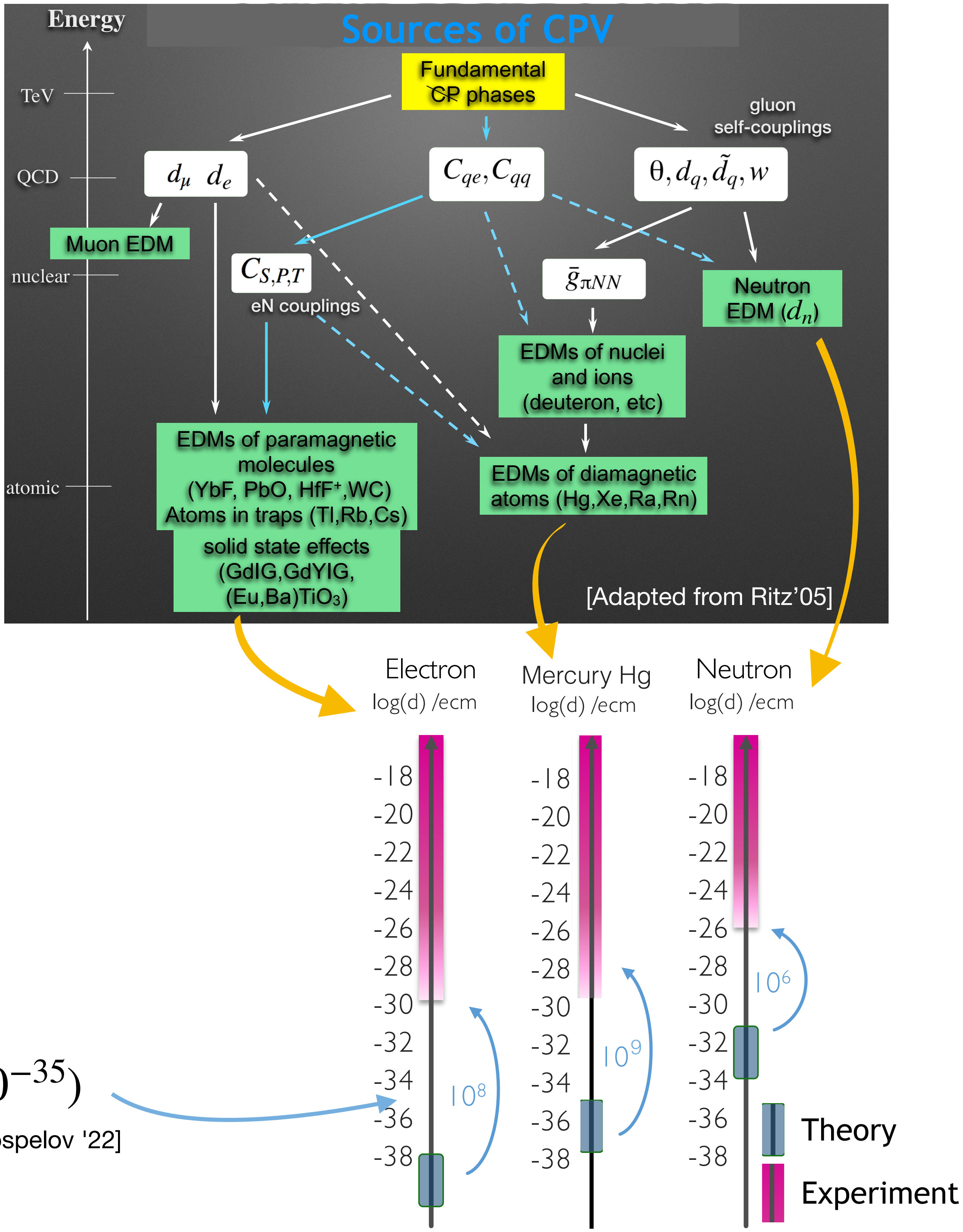
[Khriplovich, Zhitnistsky '82; McKellar et al '87; Mannel, Uraltsev '12]

$$d_{Hg} \;\propto C_{qq}(J_{CP}) \;\propto J_{CP} G_F^2 \sim \mathcal{O}(10^{-36})$$

[Flambaum et al '84; Donoghue et al '87]

$$d_e^{equiv} \;\propto rC_S(J_{CP}) \;\propto rJ_{CP} G_F^2 \sim \mathcal{O}(10^{-38})$$

[Pospelov, Ritz '13]



⇒ **Recent developments in d_e^{equiv} : larger CP-odd**
electron-nucleon interaction! $d_e^{equiv} \sim \mathcal{O}(10^{-35})$

[Ema, Gao, Pospelov '22]

⇒ **Still** - *room for New Physics sources of CPV!*

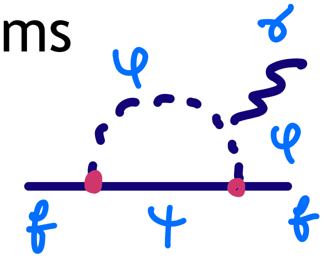
New physics contributions to EDMs

New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

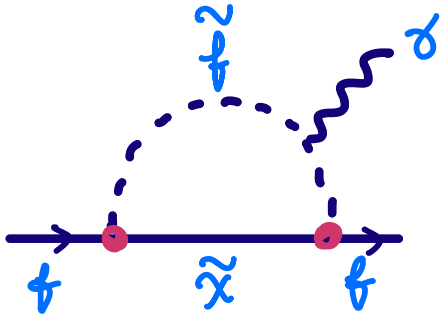
And from **generic sources** present in **SM extensions...**

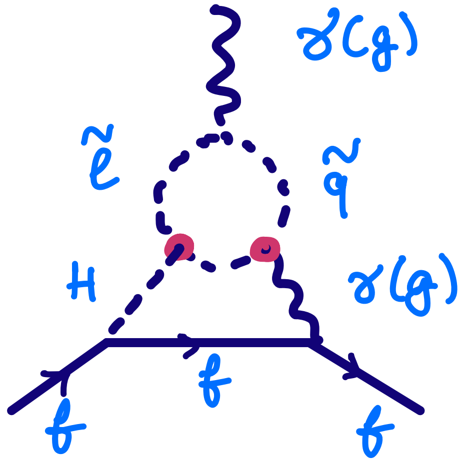
- **EDM constraints** on **New Physics** sources of **CP violation**
  - A very *naïve* example - Supersymmetry
  - Generically - numerous **flavour-blind CP phases** in the soft SUSY-breaking terms
    - **"Light"** scalar states, **extra CPV** ⇒ **SUSY EW baryogenesis!**

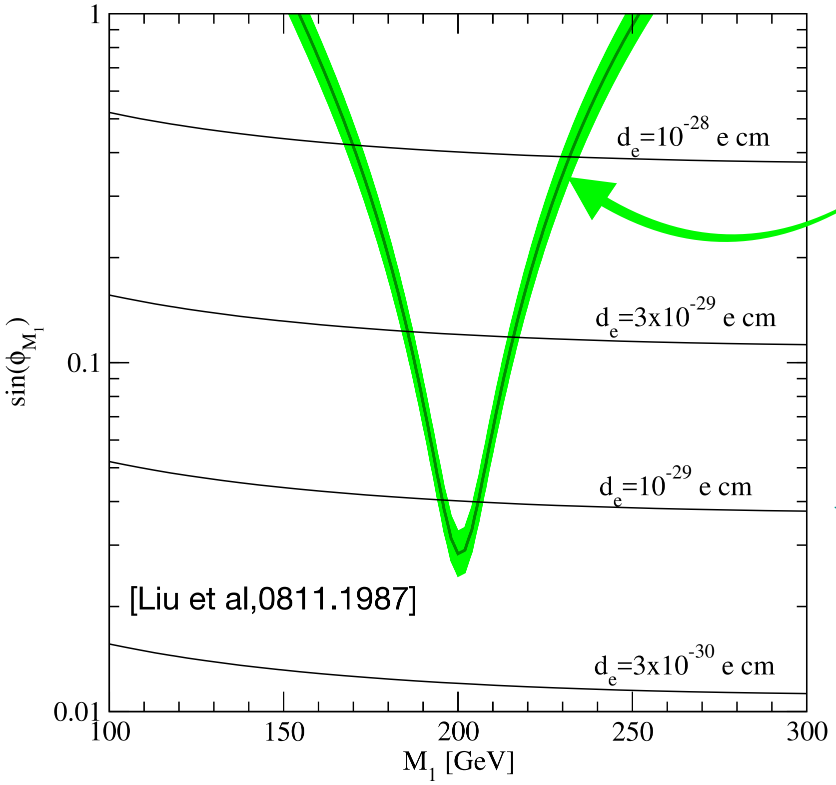


But... unless very **heavy s-particles**, **EDMs constrain** phases to be *unnaturally small*

SUSY CP (and flavour) problem







[Liu et al,0811.1987]

SUSY (MSSM)
BAU-compatible

ACME bound

Pre-LHC regimes

New physics contributions to eEDM

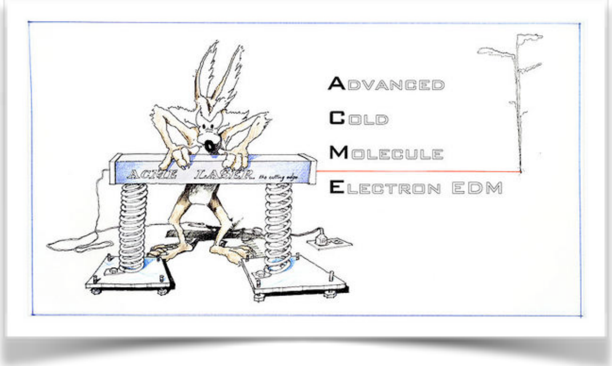
New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

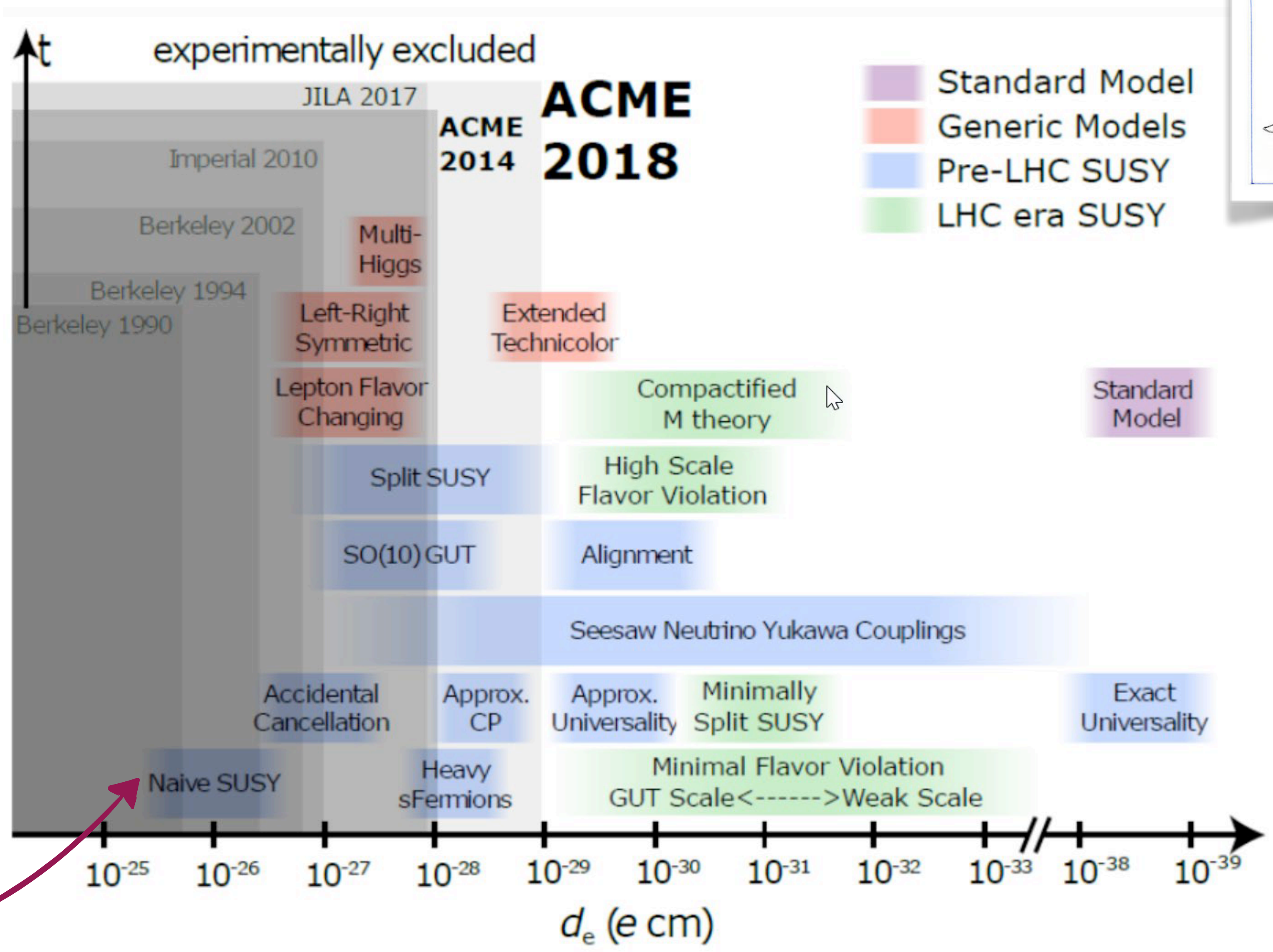
From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

And from **generic sources** present in **SM extensions...**

Phenomenological approach *(for well-motivated, simple realisations of* ***NP models****)*

ACME (2018): $|d_e| < 1.1 \times 10^{-29}$ e.cm





[ACME (compiled by DeMille)]

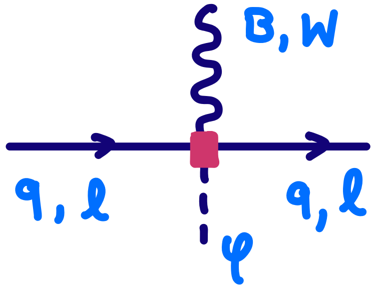
SUSY
CP & flavour
problem

New physics contributions to EDMs (EFT)

New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

And from **generic sources** present in **SM extensions...**

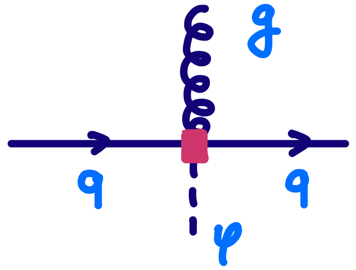


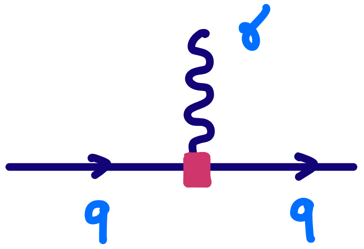
EFT approach (dim 6 operators, *flavour conserving but CP violating*)

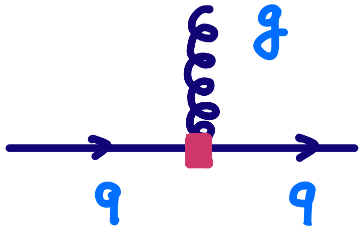
$$\mathscr{L}^{\text{dim 6}} \supset (\mathscr{C}^{6\,\alpha\beta}_{eB}/\Lambda^2)\,(\bar{L}_\alpha H\,\bar{\sigma}^{\mu\nu}\bar{E}^c_\beta)\,B_{\mu\nu} + (\mathscr{C}^{6\,\alpha\beta}_{eW}/\Lambda^2)\,(\bar{L}_\alpha\sigma^k H\,\bar{\sigma}^{\mu\nu}\bar{E}^c_\beta)\,W^k_{\mu\nu} +$$

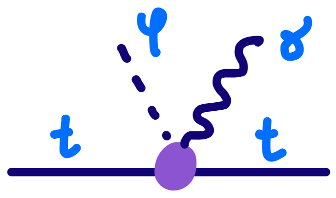
$$+ (\mathscr{C}^{6\,\alpha\beta}_{uG}/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,T^a\bar{\sigma}^{\mu\nu}\bar{U}^c_\beta)\,G^a_{\mu\nu} + (\mathscr{C}^{6\,\alpha\beta}_{dG}/\Lambda^2)\,(\bar{Q}_\alpha H\,T^a\bar{\sigma}^{\mu\nu}\bar{D}^c_\beta)\,G^a_{\mu\nu} + \ldots + H.c.$$

$$+ (\mathscr{C}^{6\,\alpha\beta}_{uH}/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,\bar{U}^c_\beta)\,H^\dagger H + \ldots$$

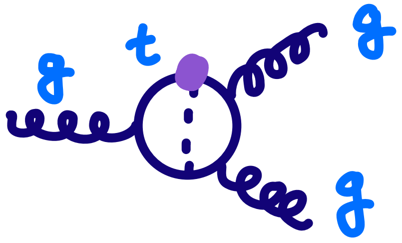






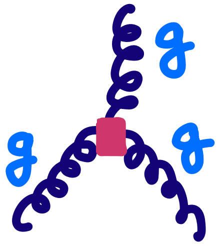


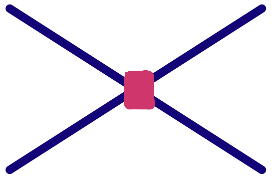
At low energies:

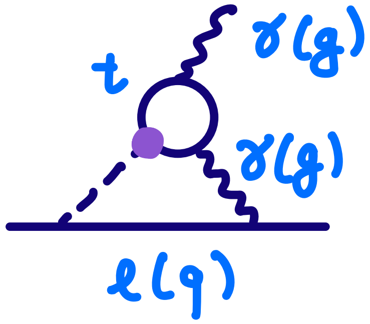


"diamagnetic" EDMs

(neutron, ^{199}Hg, ^{225}Ra, ...) $\bar{\theta}$

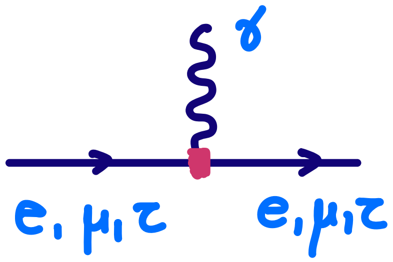


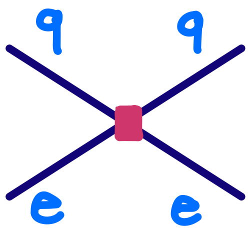




"paramagnetic" EDMs

(muon, ^{205}Ta, ThO, HfF, ...)





New physics contributions to eEDM (EFT)

New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

And from **generic sources** present in **SM extensions...**

EFT approach (dim 6 operators, *flavour conserving but CP violating*)

$$\mathscr{L}^{\text{dim 6}} \supset \boxed{(\mathscr{C}^{6\,\alpha\beta}_{eB}\,/\Lambda^2)\,(\bar{L}_\alpha H\,\bar{\sigma}^{\mu\nu}\bar{E}^c_\beta)\,B_{\mu\nu}} + (\mathscr{C}^{6\,\alpha\beta}_{eW}\,/\Lambda^2)\,(\bar{L}_\alpha\sigma^k H\,\bar{\sigma}^{\mu\nu}\bar{E}^c_\beta)\,W^k_{\mu\nu} +$$
$$+ (\mathscr{C}^{6\,\alpha\beta}_{uG}\,/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,T^a\bar{\sigma}^{\mu\nu}\bar{U}^c_\beta)\,G^a_{\mu\nu} + (\mathscr{C}^{6\,\alpha\beta}_{dG}\,/\Lambda^2)\,(\bar{Q}_\alpha H\,T^a\bar{\sigma}^{\mu\nu}\bar{D}^c_\beta)\,G^a_{\mu\nu} + \ldots + H.c.$$
$$+ (\mathscr{C}^{6\,\alpha\beta}_{uH}\,/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,\bar{U}^c_\beta)\,H^\dagger H + \ldots$$

$$\Rightarrow d_e = -2\sqrt{2}\,\cos\theta_w v\,\mathscr{I}([\mathscr{C}^6_{eB}]_{11}/\Lambda^2)$$

ACME (2018): $|d_e| < 1.1\times 10^{-29}$ e.cm $\Rightarrow \dfrac{|\mathscr{I}[\mathscr{C}^6_{eB}]_{11}|}{\Lambda^2} \leq \dfrac{1}{(1.9\text{EeV})^2}$

Sensitivity to New Physics: $\mathscr{I}(\mathscr{C}^6_{eB}) \sim \mathscr{O}(1) \rightarrow \boldsymbol{\Lambda \geq 10^6}$ **TeV**

$\mathscr{I}(\mathscr{C}^6_{eB}) \sim \mathscr{O}(Y^e) \rightarrow \Lambda \geq 10^3$ TeV

well above that of direct LHC (or any collider) discovery!

Clear impact on CPV models of new physics...

New physics contributions to EDMs (EFT)

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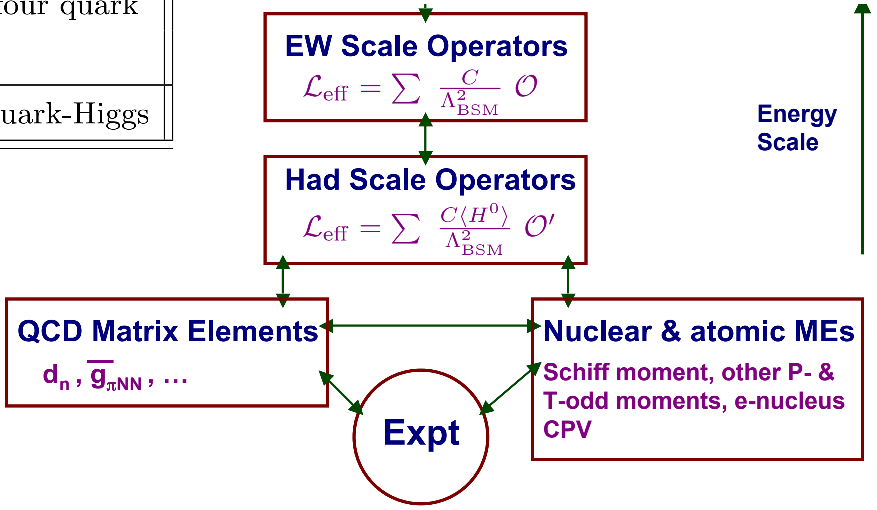
$$+ (\mathscr{C}^{6\,\alpha\beta}_{uG}\,/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,T^a\bar{\sigma}^{\mu\nu}\bar{U}^c_\beta)\,G^a_{\mu\nu} + (\mathscr{C}^{6\,\alpha\beta}_{dG}\,/\Lambda^2)\,(\bar{Q}_\alpha H\,T^a\bar{\sigma}^{\mu\nu}\bar{D}^c_\beta)\,G^a_{\mu\nu} + \ldots + H.c.$$
$$+ (\mathscr{C}^{6\,\alpha\beta}_{uH}\,/\Lambda^2)\,(\bar{Q}_\alpha\tilde{H}\,\bar{U}^c_\beta)\,H^\dagger H + \ldots$$

[Engel et al, 1303.2371]

$\mathcal{O}_{fW}$	$(\bar{F}\sigma^{\mu\nu}f_R)\tau^I\Phi\,W^I_{\mu\nu}$	fermion $\mathrm{SU}(2)_L$ EDM
$\mathcal{O}_{fB}$	$(\bar{F}\sigma^{\mu\nu}f_R)\Phi\,B_{\mu\nu}$	fermion $\mathrm{U}(1)_Y$ EDM
$\mathcal{O}_{uG}$	$(\bar{Q}\sigma^{\mu\nu}T^A u_R)\widetilde{\varphi}\,G^A_{\mu\nu}$	u-quark Chromo EDM
$\mathcal{O}_{dG}$	$(\bar{Q}\sigma^{\mu\nu}T^A d_R)\varphi\,G^A_{\mu\nu}$	d-quark Chromo EDM
Q_{ledq}	$(\bar{L}^j e_R)(\bar{d}_R Q^j)$	CP-violating semi-leptonic
$Q^{(1)}_{lequ}$	$(\bar{L}^j e_R)\epsilon_{jk}(\bar{Q}^k u_R)$	
$Q^{(3)}_{lequ}$	$(\bar{L}^j\sigma_{\mu\nu}e_R)\epsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}u_R)$	
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	CP-violating 3 gluon
$Q^{(1)}_{quqd}$	$(\bar{Q}^j u_R)\epsilon_{jk}(\bar{Q}^k d_R)$	CP-violating four quark
$Q^{(8)}_{quqd}$	$(\bar{Q}^j T^A u_R)\epsilon_{jk}(\bar{Q}^k T^A d_R)$	
$Q_{\varphi ud}$	$i\,(\tilde{\varphi}^\dagger D_\mu\varphi)\,\bar{u}_R\gamma^\mu d_R$	CP-violating quark-Higgs

EFTs across scales & systems


EW Scale Operators

$\mathcal{L}_{\text{eff}} = \sum \frac{C}{\Lambda^2_{\text{BSM}}}\,\mathcal{O}$

Had Scale Operators

$\mathcal{L}_{\text{eff}} = \sum \frac{C\langle H^0\rangle}{\Lambda^2_{\text{BSM}}}\,\mathcal{O}'$

QCD Matrix Elements

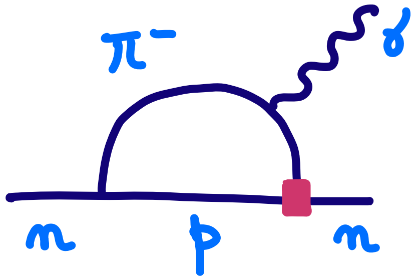
d_n, $\overline{g}_{\pi NN}$, …

Nuclear & atomic MEs

Schiff moment, other P- & T-odd moments, e-nucleus CPV

Expt

Energy Scale



Nucleon level:

$$\mathscr{L}^S_{\text{N}} = -\frac{G_F}{\sqrt{2}}(\bar{e}i\gamma_5 e)\,\bar{N}\left[C^{(0)}_S + C^{(1)}_S\tau_3\right]N$$

$$\mathscr{L}^T_{\text{N}} = \frac{8G_F}{\sqrt{2}}(\bar{e}\sigma_{\mu\nu}e)\,v_\nu\,\bar{N}\left[C^{(0)}_T + C^{(1)}_T\tau_3\right]S_\mu N$$

$$C_{S,T} = C_{S,T}(g_{S,T}, \Im C_{\ell equ(d)}, (v/\Lambda_{\text{NP}})^2, \ldots)$$

New physics contributions to eEDM

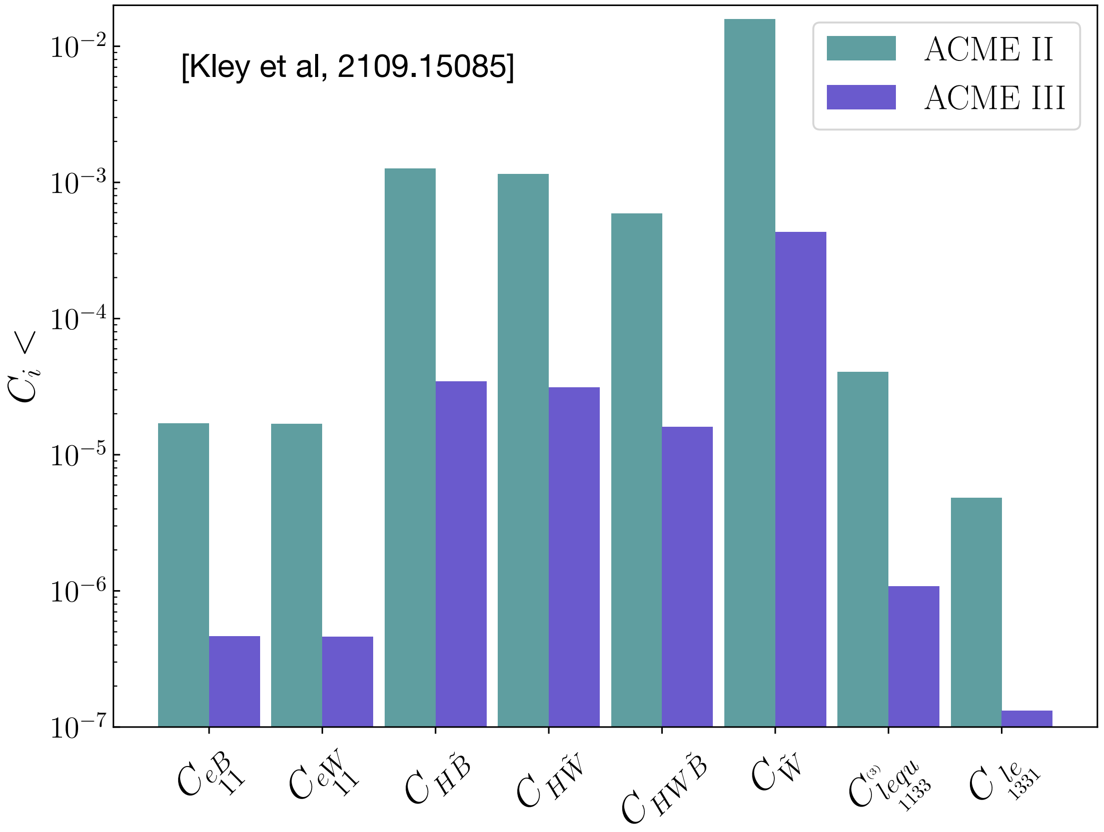
New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

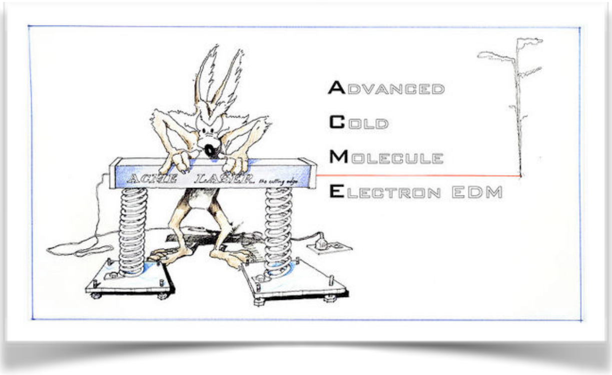
From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

And from **generic sources** present in **SM extensions...**

- **EDM constraints** on **New Physics** sources of **CP violation** - **Wilson coefficients** $\mathscr{C}_{ij}$

(assuming $\Lambda_{\text{NP}} \approx 5$ TeV)





⇒ **Impact of ACME III expected sensitivity:** over **one order of magnitude** in $\mathscr{C}_{ij}$ bounds

New physics contributions to nEDM

New CPV sources must necessarily **be present in Nature** - **not enough CPV for BAU**

From the **mechanism of neutrino mass generation** (Dirac & Majorana phases) !?

And from **generic sources** present in **SM extensions...**

- **EDM constraints** on **New Physics** sources of **CP violation** - **Wilson coefficients** $\mathscr{C}_{ij}$

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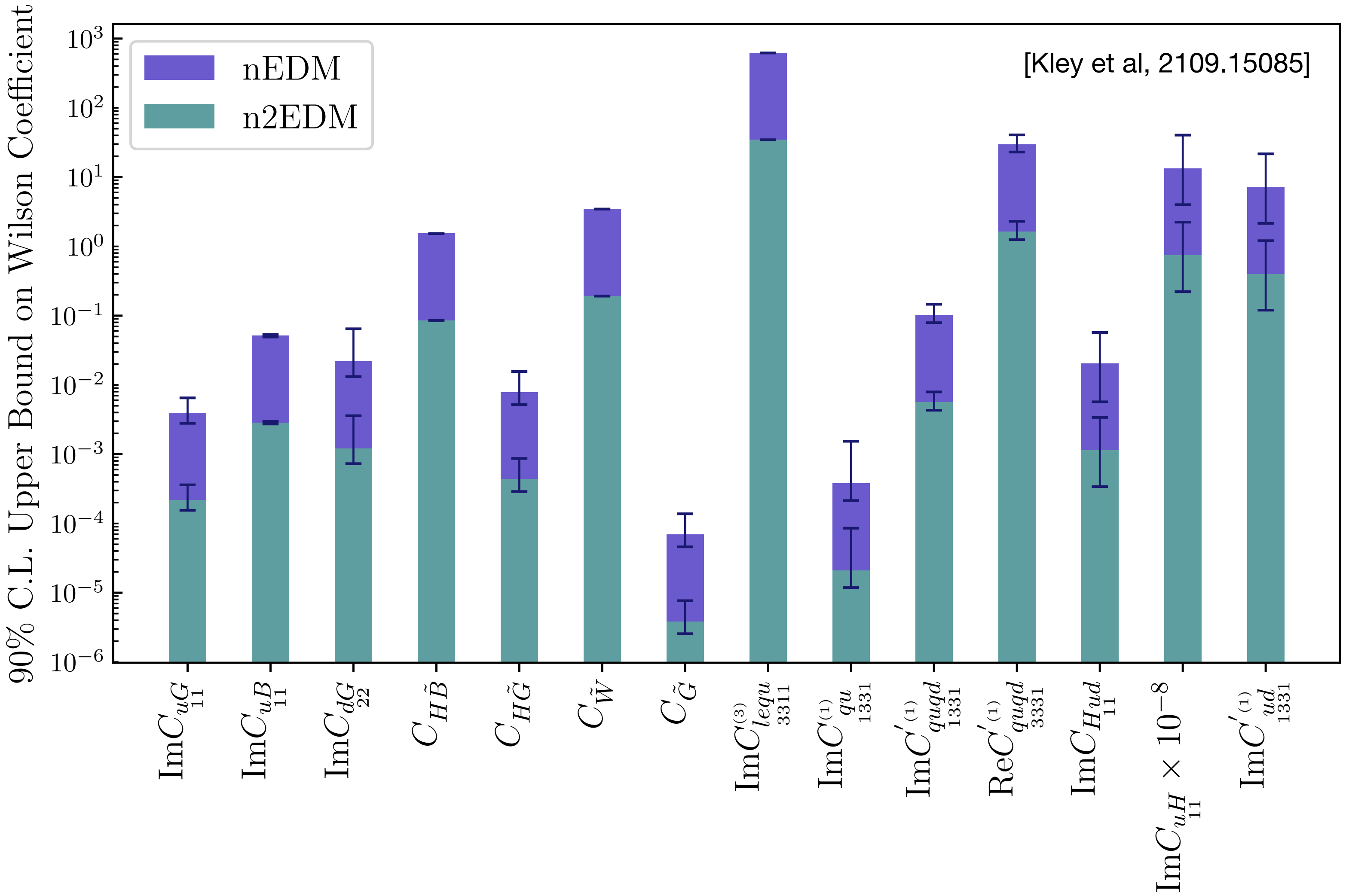
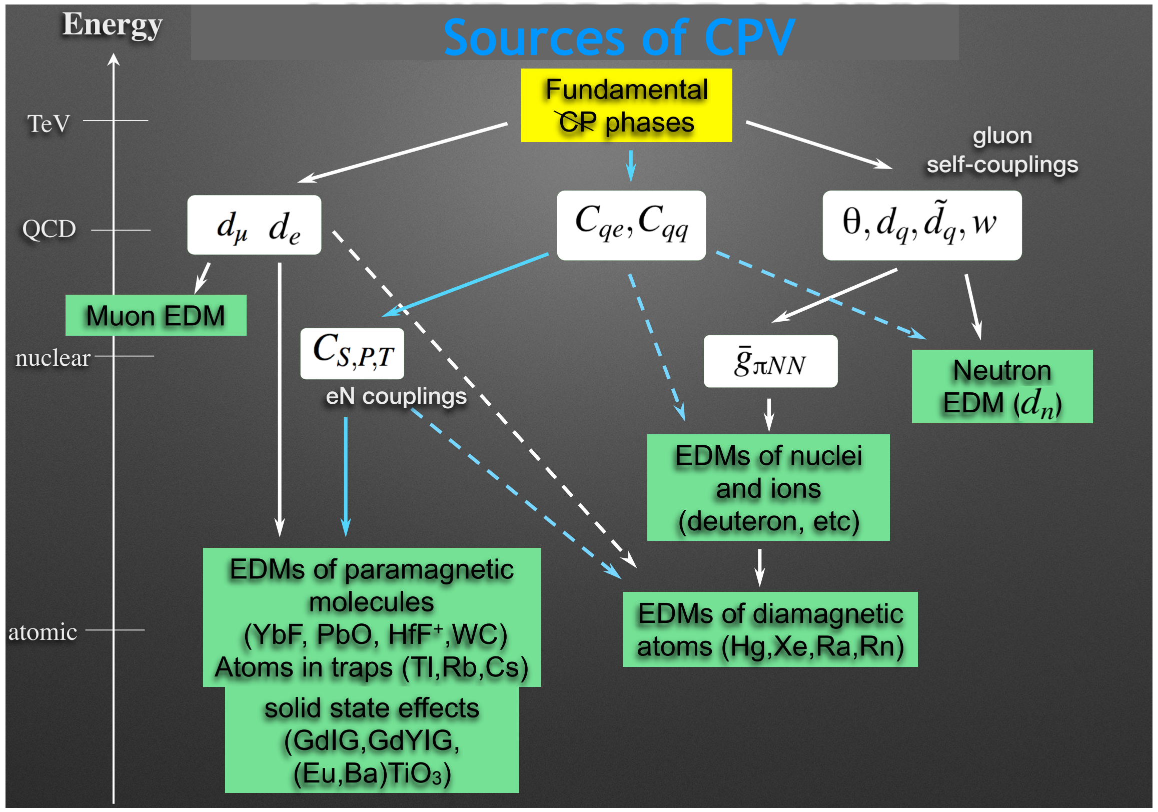


⇒ **Impact of n2EDM expected sensitivity:** over **one order of magnitude** in $\mathscr{C}_{ij}$ bounds as well!

Flavour and CP: powerful probes of New Physics

New CPV sources must **be present**- **not enough CPV for BAU**

EDM searches: powerful probes for **New Physics** sources of **CP violation**

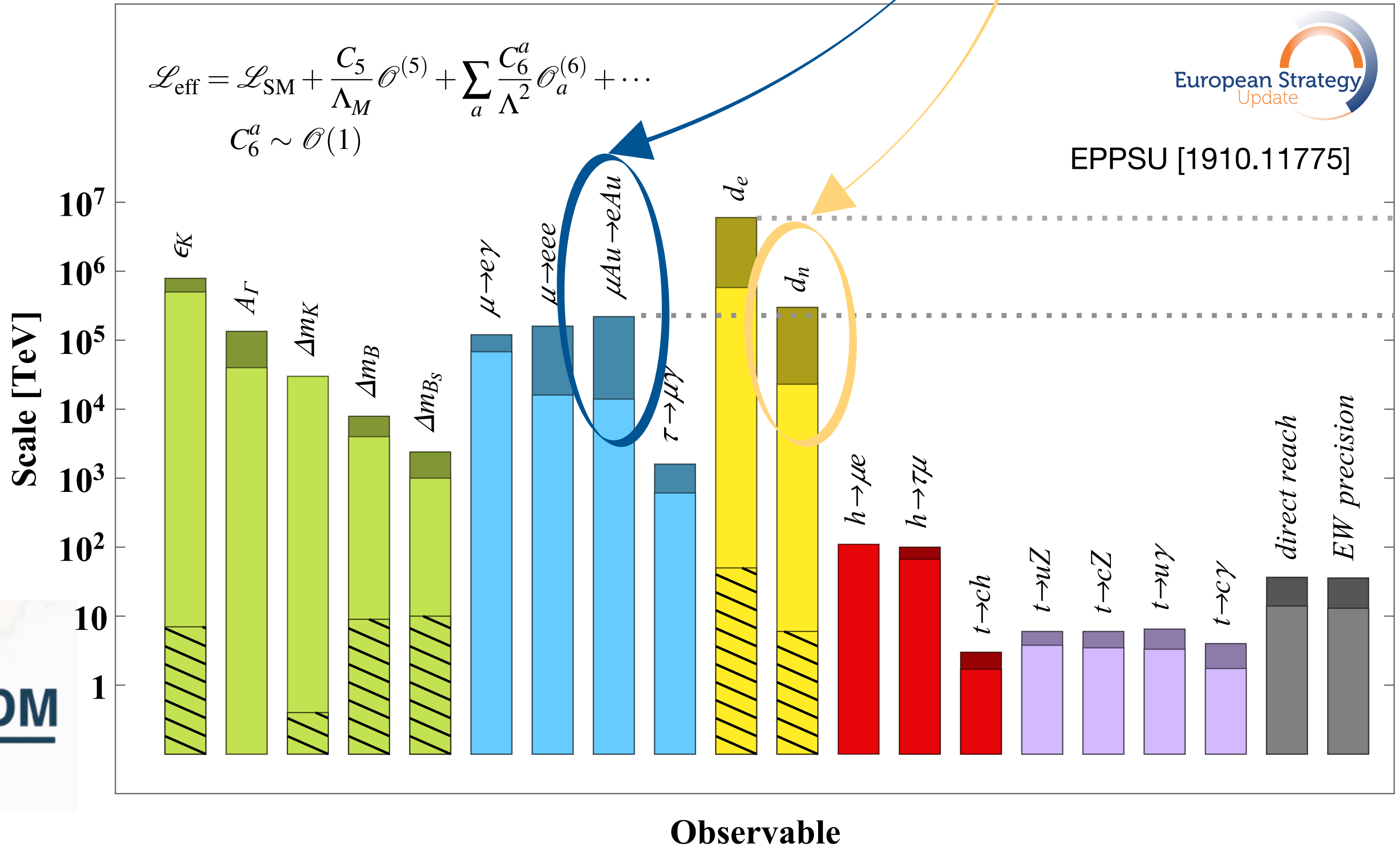


Sources of CPV

Energy
TeV
QCD
nuclear
atomic

Fundamental CP phases
gluon self-couplings
$d_\mu \;\; d_e$
C_{qe}, C_{qq}
$\theta, d_q, \tilde{d}_q, w$
Muon EDM
$C_{S,P,T}$
eN couplings
$\bar{g}_{\pi NN}$
Neutron EDM (d_n)
EDMs of nuclei and ions (deuteron, etc)
EDMs of paramagnetic molecules (YbF, PbO, HfF⁺,WC) Atoms in traps (Tl,Rb,Cs)
solid state effects (GdIG, GdYIG, (Eu,Ba)TiO₃)
EDMs of diamagnetic atoms (Hg,Xe,Ra,Rn)

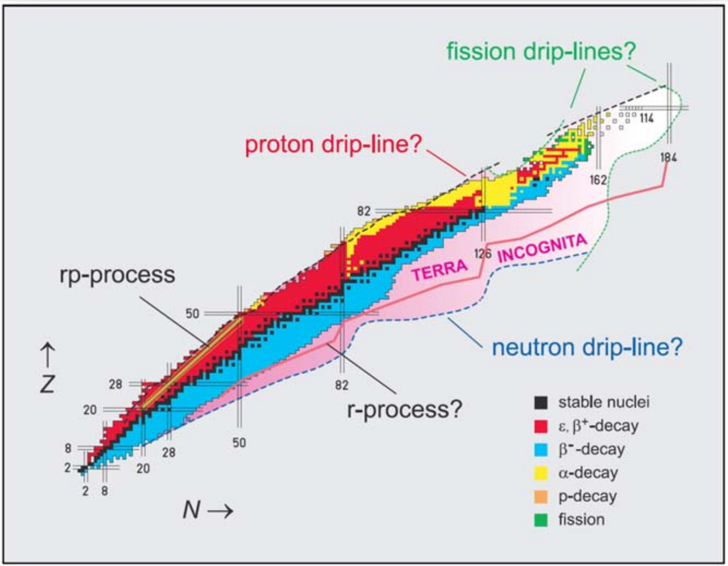
$\mu - e$ conversion & d_n:
reaching unreachable scales



Neutron EDM:
among the most **sensitive probes** of **NP!**
Instrumental in the path to **understanding** the **BAU**

n2EDM

New Physics searches: electroweak precision tests in nuclear beta decays



Precision tests of weak interactions: β decays

- **Nuclear β decays:** instrumental in **determining the structure of weak interactions** and **establishing the SM** (hadrons, charged leptons and neutrinos!)

SM semileptonic charged-current (weak) processes

(i) **dominant $V-A$** component

$V+A, S, P, T$ only at **higher orders** in radiative corrections (or recoil momentum)

(ii) **effective Fermi constants** (extracted from β decays) obey

lepton and quark-lepton (Cabibbo) **universality** ⇒ **unitarity of CKM matrix**

Low-energy charged-current interaction **Lagrangian** sensitive to many SM extensions

Theoretical and experimental progress ⇒ 0.1% level precision

powerful constraints and hints on **BSM realisations at the TeV scale**

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  lepton and quark-lepton (Cabibbo) **universality** ⇒ **unitarity of CKM matrix**

- **"Broad band" probes of New Physics**

  Superallowed $0^+ \to 0^+$ transitions (& theoretical progress on radiative corrections...)

  ⇒ $\delta V_{ud} \sim 3 \times 10^{-4}$ (sensitivity to $\Lambda_{\text{NP}} \sim 10$ TeV)

  Measurement of τ_{n} and **β-asymmetry** (& LQCD precise determination of nucleon g_A)

  ⇒ probe right-handed currents @subpercent level...

  Superallowed transitions & **neutron** decay & **mirror** β decays

  ⇒ **strong limits on strength** of $V+A, S, P, T$ interactions ($\leq 0.001 g_w$)

  Angular correlations of β decay products

  ⇒ search for non-standard sources of **CP violation!**

Precision tests of weak interactions: β decays

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  $V + A, S, P, T$ only at **higher orders** in radiative corrections (or recoil momentum)

  (ii) effective Fermi constants (extracted from β decays) obey

  lepton and quark-lepton (Cabibbo) universality $\Rightarrow$ unitarity of CKM **matrix**

- "Broad band" probes of New Physics

- In the **LHC** era, β decays remain uniquely precise probes of New Physics, highly **competitive** on their own, and **complementary** to searches at high-energies

  Charged- and neutral current Drell-Yann production at LHC - directly access the **TeV scale;**

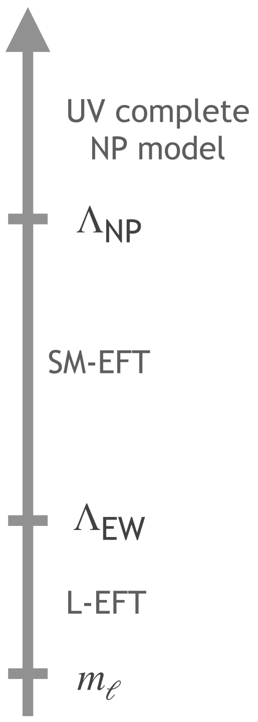
  $$pp \rightarrow e + \nu + X$$

  $\Rightarrow$ **synergy of constrains** places strong bounds on EFT couplings!

Nuclear (effective) interactions

- At **low-energies** ($\mu \sim 2$ GeV), relevant information on **underlying physics** (**SM**, **NP**) for β decays - involving CC transitions in first family (u, d and e)

$$\mathscr{L}^{\text{eff}}_{\text{CC}} = -\frac{G_F^{(0)}\, V_{ud}}{\sqrt{2}} \Big[(1+\delta_\beta)\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_e\; \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_L\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell\; \bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\epsilon_S\, \bar{e}(1-\gamma_5)\nu_\ell\; \bar{u}d + \tilde{\epsilon}_S\, \bar{e}(1+\gamma_5)\nu_\ell\; \bar{u}d$$
$$-\epsilon_P\, \bar{e}(1-\gamma_5)\nu_\ell\; \bar{u}\gamma_5 d - \tilde{\epsilon}_P\, \bar{e}(1+\gamma_5)\nu_\ell\; \bar{u}\gamma_5 d$$
$$+\epsilon_T\, \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T\, \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell\; \bar{u}\sigma^{\mu\nu}\gamma_\mu(1+\gamma_5)d$$


UV complete NP model

Λ_{NP}

SM-EFT

Λ_{EW}

L-EFT

m_ℓ

A few remarks:

$G_F^{(0)} = \sqrt{2}\dfrac{g^2}{8M_W^2}$ (**tree-level Fermi** constant); $G_F^{(0)} = G_\mu^{\text{exp}}(1-\delta_\mu-\epsilon_e)$

$\delta_{\mu(\beta)} \rightsquigarrow$ **SM EW corrections** in purely (semi)leptonic decays

ϵ (**left-handed** neutrino currents); $\tilde{\epsilon}$ (**right-handed** neutrino currents)

$$\Rightarrow \Gamma \propto f(\epsilon), g(\tilde{\epsilon}^2), h(\tilde{\epsilon}\times m_\nu/E_\nu)$$

"All" associated operators can produce collider signatures!

Nuclear (effective) interactions

- Studying nuclear and hadronic transition **amplitudes -** far more involved!
  - short-distance couplings evolved to appropriate matching scale
  - hadronic & nuclear matrix elements

Inferring **information on the** **Wilson coefficients** (sensitive to the presence of **NP**) from nuclear and hadronic observables ⇒ knowledge of the **matrix elements!**

A few examples:

- (Semi)leptonic decays of mesons $M \to \ell\nu$ and $M \to M'\ell\nu$:
  - decay constants and form factors from LQCD!

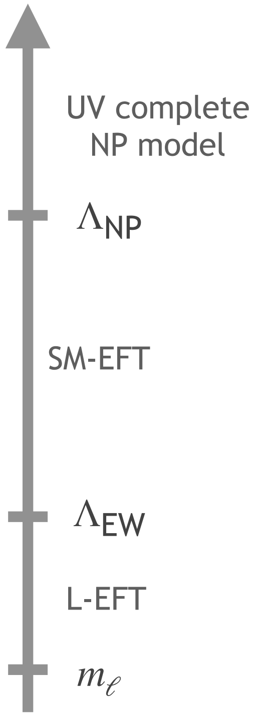
- At the **nucleon** level, **matrix elements** of **neutron to proton decays** (dim-3 quark bilinears)

- And the ultimate **challenge,** from **nucleon level to nuclear beta decays...**
  - numerous spin sequences, unstable daughter nucleus (under em or strong interactions)
    - large Q-value (e^- and e^+)...

Nuclear (effective) interactions

- **SM precision tests** in nuclear decays: **identify NP contributions** in ϵ and $\tilde{\epsilon}$ from **low-energy observables!**

⇒ connect the **quark-level Lagrangian** to the **nucleon-level** formulation



$$\begin{aligned}\mathscr{L}^{\text{eff}}_{\text{L-Y}} = &- \bar{p}\gamma^\mu n\left(C_V \bar{e}\gamma_\mu\nu - C'_V \bar{e}\gamma_\mu\gamma_5\nu\right) + \bar{p}\gamma^\mu\gamma_5 n\left(C_A \bar{e}\gamma_\mu\gamma_5\nu - C'_A \bar{e}\gamma_\mu\nu\right)\\ &- \bar{p}n\left(C_S \bar{e}\nu - C'_S \bar{e}\gamma_5\nu\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T \bar{e}\sigma^{\mu\nu}\nu - C'_T \bar{e}\sigma_{\mu\nu}\gamma_5\nu\right)\\ &- \bar{p}\gamma_5 n\left(C_P \bar{e}\gamma_5\nu - C'_P \bar{e}\nu\right) + \text{H.c.}\end{aligned}$$

Relating coefficients: $C^{(\prime)} = \bar{C}^{(\prime)}\, V_{ud} G_F^{(0)}/\sqrt{2}$

$$\begin{aligned}\bar{C}^{(\prime)}_V &= g_V\left(1 + \delta_\beta + \epsilon_L + \epsilon_R \pm \tilde{\epsilon}_L \pm \tilde{\epsilon}_R\right)\\ \bar{C}^{(\prime)}_A &= -\, g_A\left(1 + \delta_\beta + \epsilon_L - \epsilon_R \mp \tilde{\epsilon}_L \pm \tilde{\epsilon}_R\right)\\ \bar{C}^{(\prime)}_S &= g_S\left(\epsilon_S \pm \tilde{\epsilon}_S\right)\\ \bar{C}^{(\prime)}_P &= g_P\left(\epsilon_P \mp \tilde{\epsilon}_P\right)\\ \bar{C}^{(\prime)}_T &= 4 g_T\left(\epsilon_T \pm \tilde{\epsilon}_T\right)\end{aligned}$$

g_V, g_A, g_S, g_P, g_T

vector, axial, (pseudo)scalar and tensor *nuclear* charges

⇒ determined from LQCD or other theoretical methods....

[Gonzalez-Alonso et al, 1803.732]

Charge	Value	Ref.
g_A	1.278(33)	[35]
g_T	0.987(55)	[34]
g_S	1.02(11)	[24]
g_P	349(9)	[24]

⇒ Understand the role of short-distance couplings ϵ and $\tilde{\epsilon}$ (and constrain them!) from β decays and other low-energy observables

Nuclear (effective) interactions

- **SM precision tests** in nuclear decays: **identify NP contributions** in ϵ and $\tilde{\epsilon}$ from **low-energy observables! Which hadronic and nuclear observables?**

  $\Rightarrow$ Ideally, looking for experimentally feasible set-ups,
  investigating systems theoretically "under control" (small degree of uncertainties),
  thoroughly exploring decays (rates, angular correlations, spectrum shape, recoil, ...)

- **"Standard" experimental systems:** allowed **Fermi** and/or **Gamow-Teller** decays
  - **Neutron decays** - simplest baryon!
    - Theoretical description mastered to high precision (progress in LQCD, ...)
  - **(Super)allowed decays** - small number of matrix elements
    - Theoretical precision challenged...
  - **Mirror nuclei** - **mixed** Fermi and Gamow-Teller
    - Excellent field for CPV searches and right-handed neutrino currents
  - $T = 1$ (isospin triplet) pure Gamow-Teller decays
    - Small theoretical uncertainties, access to exotic tensor currents

- **"New" opportunities?**

  Pseudoscalar decays? Unique forbidden beta decays?

Total decay widths (integrated rates)

- **Allowed beta transitions** - total decay widths

Fierz term

$$\Gamma_i \;=\; (1+\delta_i)\,\mathscr{M}\,\frac{m_e^5}{4\pi^3}\,\xi_i\left(1+\gamma_i\, b_i \left\langle \frac{m_e}{E_e}\right\rangle_i\right) f_V^i$$

radiative corrections

phase space integral

$$f_V^i = m_e^{-5}\int_{m_e}^{\Delta_i} F_i(\Delta_i - E_e)^2\, p_e\, E_e\, dE_e$$

$$\gamma_i \equiv \sqrt{1-(\alpha Z_i)^2}$$

Fermi function

(Coulomb corrections)

matrix element $\mathscr{M}$

(j, m) - isospin of parent nucleus

Dependency on (new) operators!

$\xi_i = \xi_i(C_V, C_A, C_S, C_T)$

$b_i\,\xi_i = b_i\,\xi_i(C_V, C_A, C_S, C_T)$; In the SM, $b_i = 0$!

$$\xi \;=\; |M_{\mathsf{F}}|^2\left(|C_V|^2+|C_V'|^2+|C_S|^2+|C_S'|^2\right)\;+\;|M_{\mathsf{GT}}|^2\left(|C_A|^2+|C_A'|^2+|C_T|^2+|C_T'|^2\right)$$

$$\boldsymbol{b}\,\boldsymbol{\xi}\;=\pm\sqrt{1+\alpha^2 Z^2}\;\Re\left[|M_{\mathsf{F}}|^2\left(C_V C_S^* + C_V' C_S'^*\right)\;+\;|M_{\mathsf{GT}}|^2\left(C_A C_T^* + C_A' C_T'^*\right)\right]$$

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radiative
corrections

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Corrected half-life: $\mathscr{F}t_i \equiv \dfrac{f_V^i(1+\delta_i)\log 2}{\Gamma_i} = \dfrac{4\pi^3\,\log 2}{M_F^2\, m_e^5}\left(\xi_i + \gamma_i\, b_i\, \xi_i\left\langle\dfrac{m_e}{E_e}\right\rangle_i\right)^{-1}$

Total decay widths (integrated rates)

- **Allowed beta transitions** - **total decay widths**

  Extensively studied in the literature for numerous nuclei (and the neutron!)

- **A class of nuclear beta decays** emerges as a uniquely powerful **probe** of the SM description of quark flavour violation **(CKM paradigm)**

  ⇒ **superallowed $0^+ \to 0^+$ decays:** depend uniquely on **vector part** of interaction

  $\rightsquigarrow$ decay width directly related to C_V

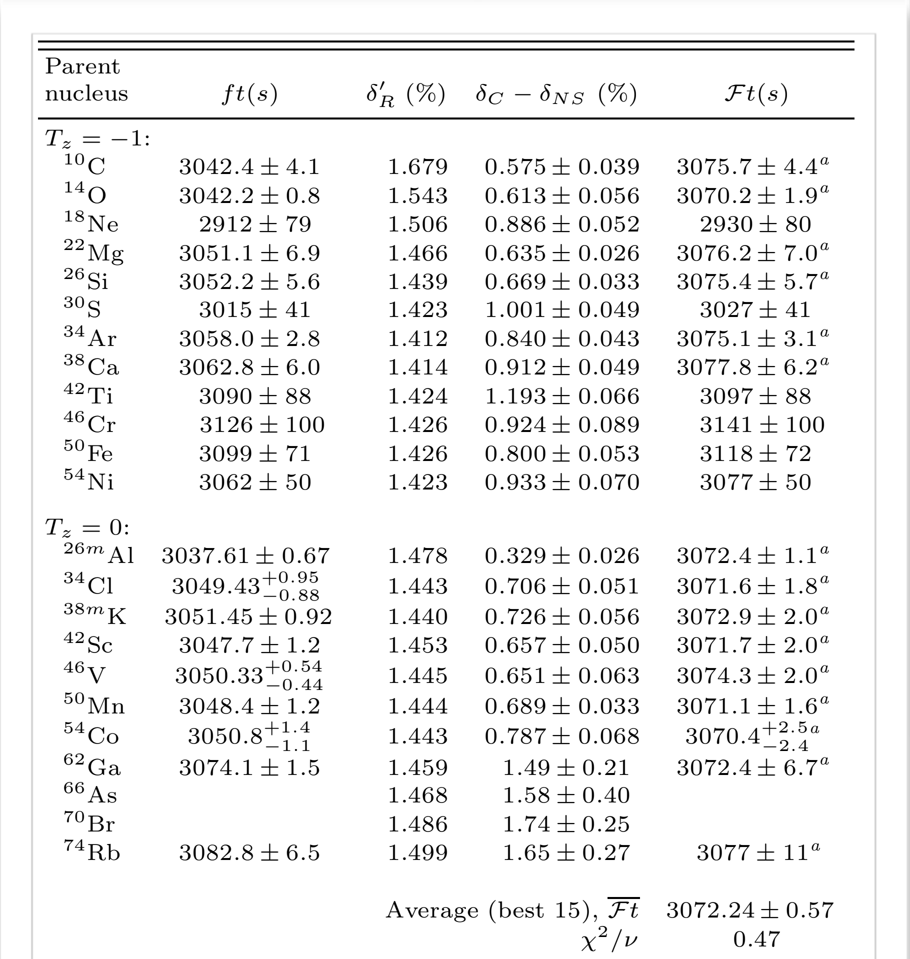
$$\mathcal{F}t = \frac{K}{2\,G_F^2\,\bar{V}_{ud}^2\,(1+\Delta_R^V)}$$

$K = 2\pi^3\hbar\log 2\,(\hbar c)^6/(m_e c^2)^5$

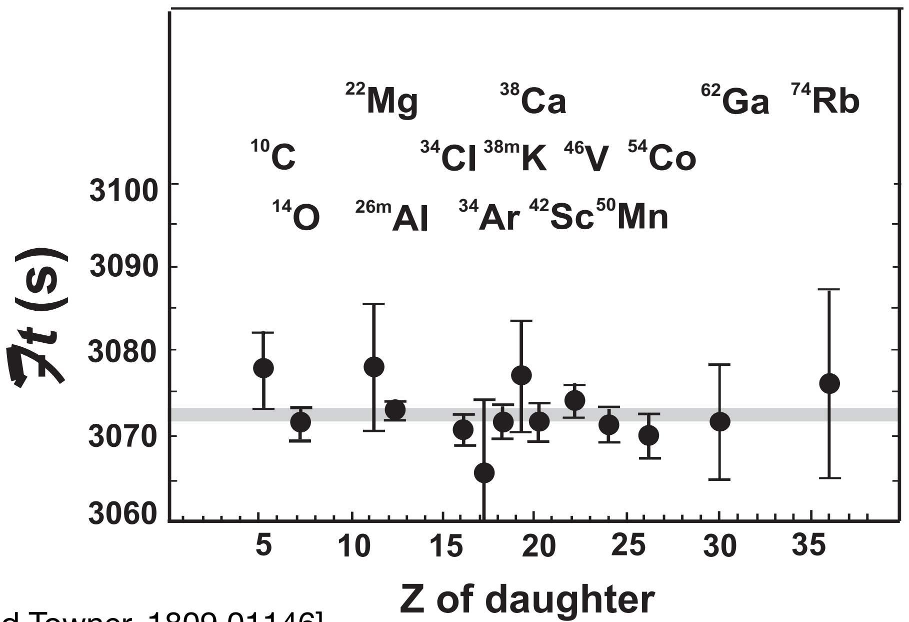
Δ_R^V - transition independent RC

$\mathcal{F}t$ values almost "constant" for **superallowed $0^+ \to 0^+$ decays**

[Hardy and Towner, '15 - '21]



Parent nucleus	$ft(s)$	δ'_R (%)	$\delta_C - \delta_{NS}$ (%)	$\mathcal{F}t(s)$
$T_z = -1$:				
^{10}C	3042.4 ± 4.1	1.679	0.575 ± 0.039	3075.7 ± 4.4^a
^{14}O	3042.2 ± 0.8	1.543	0.613 ± 0.056	3070.2 ± 1.9^a
^{18}Ne	2912 ± 79	1.506	0.886 ± 0.052	2930 ± 80
^{22}Mg	3051.1 ± 6.9	1.466	0.635 ± 0.026	3076.2 ± 7.0^a
^{26}Si	3052.2 ± 5.6	1.439	0.669 ± 0.033	3075.4 ± 5.7^a
^{30}S	3015 ± 41	1.423	1.001 ± 0.049	3027 ± 41
^{34}Ar	3058.0 ± 2.8	1.412	0.840 ± 0.043	3075.1 ± 3.1^a
^{38}Ca	3062.8 ± 6.0	1.414	0.912 ± 0.049	3077.8 ± 6.2^a
^{42}Ti	3090 ± 88	1.424	1.193 ± 0.066	3097 ± 88
^{46}Cr	3126 ± 100	1.426	0.924 ± 0.089	3141 ± 100
^{50}Fe	3099 ± 71	1.426	0.800 ± 0.053	3118 ± 72
^{54}Ni	3062 ± 50	1.423	0.933 ± 0.070	3077 ± 50
$T_z = 0$:				
^{26m}Al	3037.61 ± 0.67	1.478	0.329 ± 0.026	3072.4 ± 1.1^a
^{34}Cl	$3049.43^{+0.95}_{-0.88}$	1.443	0.706 ± 0.051	3071.6 ± 1.8^a
^{38m}K	3051.45 ± 0.92	1.440	0.726 ± 0.056	3072.9 ± 2.0^a
^{42}Sc	3047.7 ± 1.2	1.453	0.657 ± 0.050	3071.7 ± 2.0^a
^{46}V	$3050.33^{+0.54}_{-0.44}$	1.445	0.651 ± 0.063	3074.3 ± 2.0^a
^{50}Mn	3048.4 ± 1.2	1.444	0.689 ± 0.033	3071.1 ± 1.6^a
^{54}Co	$3050.8^{+1.4}_{-1.1}$	1.443	0.787 ± 0.068	$3070.4^{+2.5a}_{-2.4}$
^{62}Ga	3074.1 ± 1.5	1.459	1.49 ± 0.21	3072.4 ± 6.7^a
^{66}As		1.468	1.58 ± 0.40	
^{70}Br		1.486	1.74 ± 0.25	
^{74}Rb	3082.8 ± 6.5	1.499	1.65 ± 0.27	3077 ± 11^a
			Average (best 15), $\overline{\mathcal{F}t}$	3072.24 ± 0.57
			χ^2/ν	0.47



[Hardy and Towner, 1809.01146]

Extremely precise determination!

Total decay widths (integrated rates)

- **Allowed beta transitions** - **total decay widths**

  Extensively studied in the literature for numerous nuclei (and the neutron!)

- **A class of nuclear beta decays** emerges as a uniquely powerful **probe** of the **SM** description of quark flavour violation **(CKM paradigm)**

  $\Rightarrow$ **superallowed $0^+ \to 0^+$ decays:** depend uniquely on **vector part** of interaction

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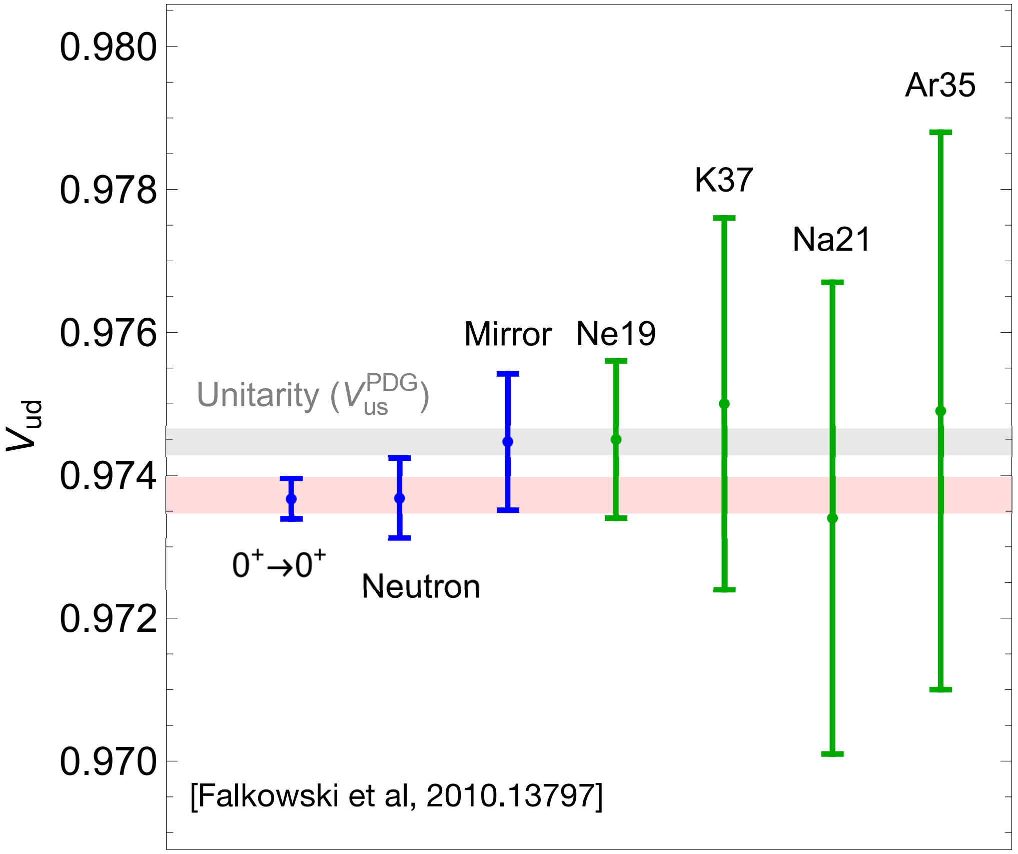
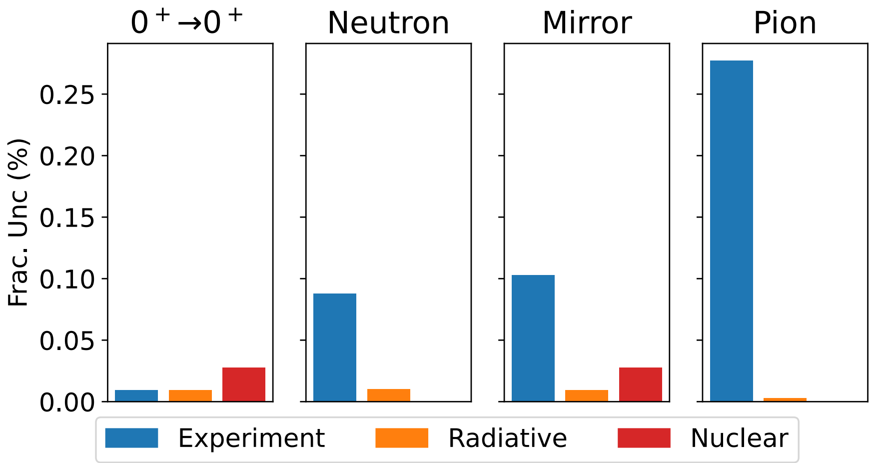
Δ_R^V - transition independent RC



Determination of $\bar{V}_{ud}$ dominated by **superallowed $0^+ \to 0^+$ decays** (very precise! $\delta \sim 0.03\,\%$)



[Brodeur et al, 2301.03975]

Best determination of $\bar{V}_{us}$ from **Kaon decays** ($K_{\ell 2}, K_{\ell 3}$)

Testing the CKM paradigm

CKM paradigm of flavour mixing: FV encoded in *strongly hierarchical* ***unitary*** matrix

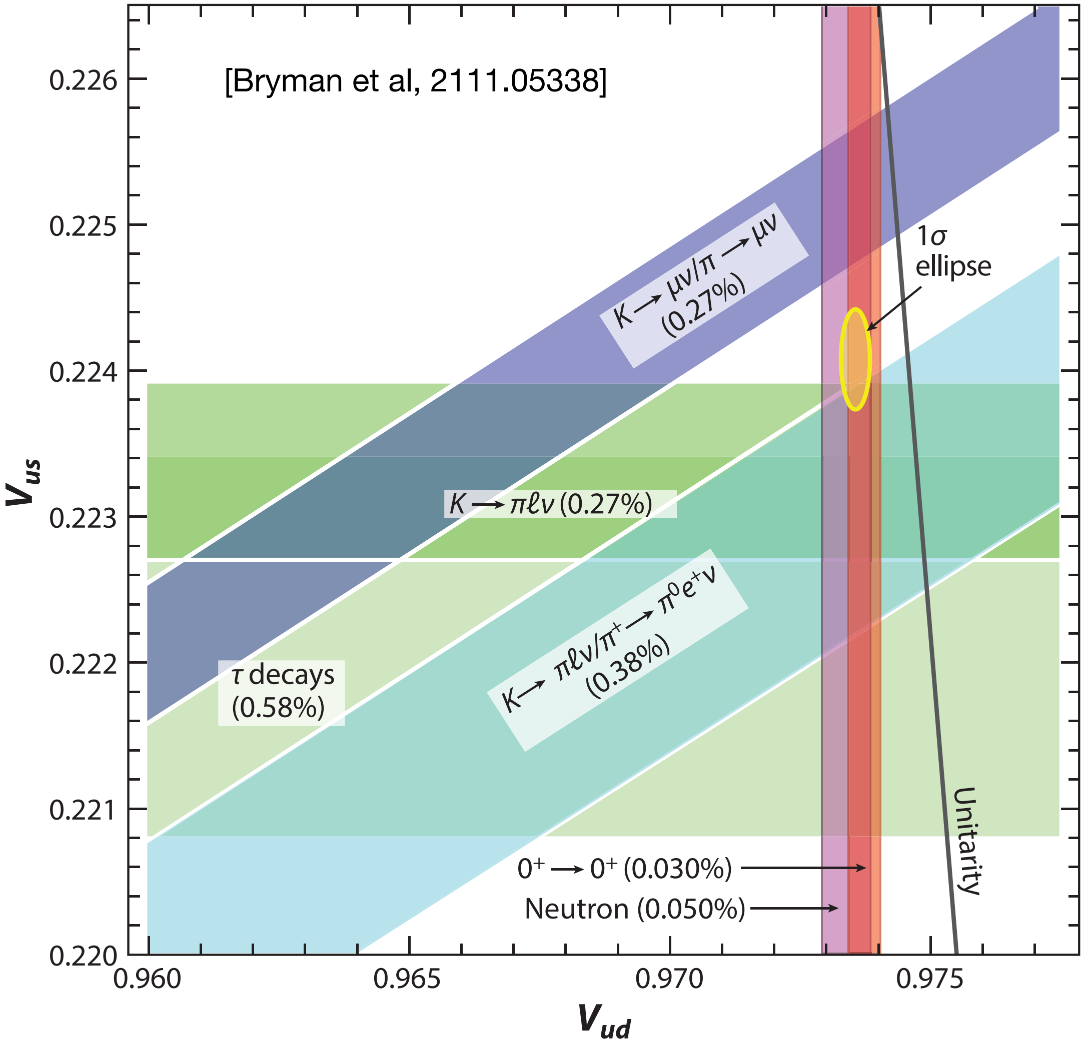
Mostly **successful description** of **hadron flavour dynamics!**

EW fit and **$V_{\rm CKM}$ fit** appear to be in good agreement with **SM hypotheses!**

But recent **tensions** in the determination of the **"Cabibbo angle"** (and of V_{ud} and V_{us})

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1 \;\Rightarrow\; \sin\theta_C = V_{ud}\,, \cos\theta_C = V_{us}$$

$$\Rightarrow\; \Delta_{\rm CKM} = |\bar V_{ud}|^2 + |\bar V_{us}|^2 - 1 = 0$$


[Bryman et al, 2111.05338]

Phenomenological determination of

$\bar V_{ud}$ and $\bar V_{us}$ (recall that $|\bar V_{ub}| \approx \mathcal{O}(10^{-3})$)

$\Rightarrow$ **test unitarity of 1st row of CKM**

Overview of $\bar V_{ud}$ and $\bar V_{us}$ constraints:

nuclear, nucleon, meson & τ decays (1σ bands for V_{ij})

Global fit: $V_{ud} = 0.97379 \pm 0.00025$

$V_{us} = 0.22405 \pm 0.00035$

$\Rightarrow \Delta_{\rm CKM} = (-19.5 \pm 5.3) \times 10^{-4}$

[Crivellin et al, 2212.06862]

$\Rightarrow$ Deviation from **SM unitarity** @ 2.8σ

Differential decay distributions

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of angular correlations between **decay products!**

- **Differential decay distributions** - very sensitive to the underlying Lorentz structure

  $\Rightarrow$ searches for non $(V - A)$ **components** in **weak interactions!**

$$\frac{d^3\Gamma}{dE_e\, d\Omega_e\, d\Omega_\nu} = \frac{1}{(2\pi)^5}\, p_e E_e (E_0 - E_e)^2\, \boldsymbol{\xi} \left\{ 1 + \boldsymbol{b}\,\frac{m_e}{E_e} + \boldsymbol{a}\,\frac{\vec{p_e}\,.\,\vec{p_\nu}}{E_e\, E_\nu} + <\frac{\vec{J}}{J}> . \left[\boldsymbol{A}\,\frac{\vec{p_e}}{E_e} + \boldsymbol{B}\,\frac{\vec{p_\nu}}{E_\nu} + \boldsymbol{D}\,\frac{\vec{p_e}\times\vec{p_\nu}}{E_e\, E_\nu} + \right] + \ldots \right\}$$

Parent nucleus polarisation $\vec{J}$

Fierz interference term

$e - \bar{\nu}_e$ correlation

beta asymmetry

$\bar{\nu}_e$ asymmetry

T-odd term (CPV!)

Asymmetries and angular correlations

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$\bar{\nu}_e$ asymmetry

T-odd term (CPV!)

Some remarks:

Overall factor ξ, and correlation coefficients depend on $M_{\mathrm{F,\,GT}}$, on $C_i^{(\prime)}$ (and possibly E_e)

$$\boldsymbol{\xi} \;=\; |M_{\mathrm{F}}|^2 \left(|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2 \right) \;+\; |M_{\mathrm{GT}}|^2 \left(|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2 \right)$$

$$\boldsymbol{a}\,\boldsymbol{\xi} \;=\; |M_{\mathrm{F}}|^2 \left(|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2 \right) \;-\; \frac{1}{3} |M_{\mathrm{GT}}|^2 \left(|C_A|^2 + |C_A'|^2 - |C_T|^2 - |C_T'|^2 \right)$$

$$\boldsymbol{b}\,\boldsymbol{\xi} \;= \pm \sqrt{1 + \alpha^2 Z^2}\, \Re \left[|M_{\mathrm{F}}|^2 \left(C_V C_S^* + C_V' C_S'^* \right) \;+\; |M_{\mathrm{GT}}|^2 \left(C_A C_T^* + C_A' C_T'^* \right) \right]$$

[Gonzalez-Alonso et al, 1803.08732]

Asymmetries and angular correlations

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Fierz interference term

$e - \bar{\nu}_e$ correlation

beta asymmetry

$\bar{\nu}_e$ asymmetry

T-odd term (CPV!)

Some remarks:

Overall factor ξ, and correlation coefficients depend on $M_{\mathrm{F,\,GT}}$, on $C_i^{(\prime)}$ (and possibly E_e)

$$\xi = |M_{\mathrm{F}}|^2 \left(|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2 \right) + |M_{\mathrm{GT}}|^2 \left(|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2 \right)$$

If **pure Fermi** transitions, dependence only on $C_{V,S}^{(\prime)}$

If **pure Gamow-Teller,** dependence only on $C_{A,T}^{(\prime)}$

If **mixed** (e.g. neutron decay), combination of $C_{V,S}^{(\prime)}$ & $C_{A,T}^{(\prime)}$

Asymmetries and angular correlations

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$$\frac{d^3\Gamma}{dE_e\, d\Omega_e\, d\Omega_\nu} = \frac{1}{(2\pi)^5}\, p_e E_e (E_0 - E_e)^2\, \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e\, E_\nu} + < \frac{\vec{J}}{J} > \cdot \left[A\,\frac{\vec{p_e}}{E_e} + B\,\frac{\vec{p_\nu}}{E_\nu} + D\,\frac{\vec{p_e}\times\vec{p_\nu}}{E_e\, E_\nu} + \right] + \ldots \right\}$$

And further remarks:

To a good *first* approximation, and for **pure F(GT) transitions**

$$b_{\mathrm{F}} \approx \pm\,\Re\left(\frac{C_S + C_S'}{C_V}\right) \text{ and } b_{\mathrm{GT}} \approx \pm\,\Re\left(\frac{C_T + C_T'}{C_A}\right); \quad a_{\mathrm{F}} \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2} \text{ and } a_{\mathrm{GT}} \approx -\frac{1}{3} + \frac{1}{3}\,\frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}$$

Measurement of the **Fierz** term, $e - \bar{\nu}_e$ **asymmetry** and **correlation parameters**

$\Rightarrow$ probe (combinations) of **non-standard** (particle-level) **coefficients**

in particular ϵ_S and ϵ_T

If measured, a, A, B include contributions from **Fierz** term

$$\tilde{a} = \frac{a}{1 + \alpha(E_e)\, b}$$

Asymmetries and angular correlations

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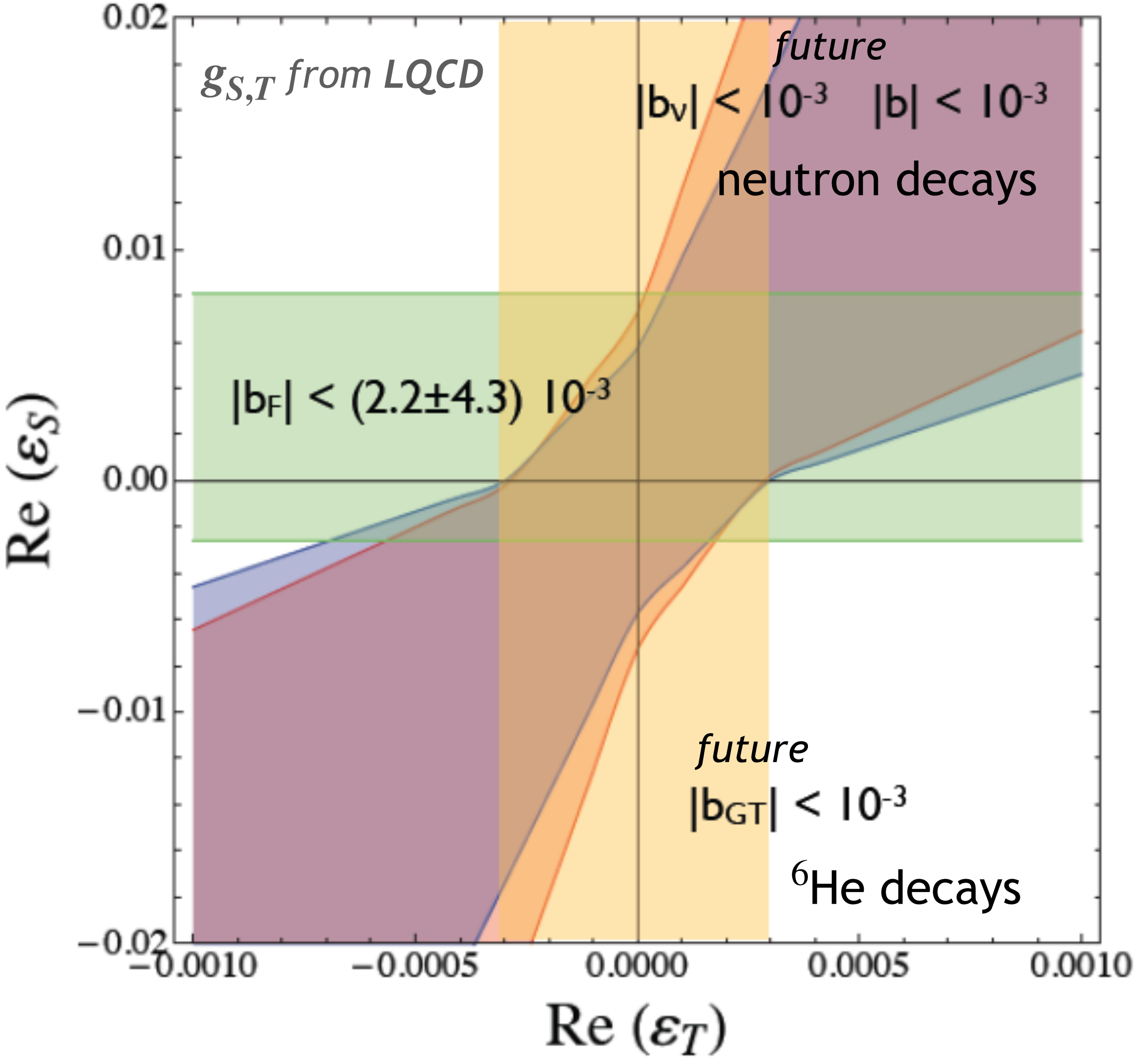


[Cirigliano et al, 1303.6953]

A **summary** of important constraints:

ϵ_S - superallowed decays

ϵ_T - Dalitz plot study of $\pi^+ \to e^+\nu_e\gamma$

Bounds from other observables (ϵ_S, ϵ_T)

^{60}Co measurements of A_{GT}

$|g_T\, \Re\epsilon_T| < 10^{-2}$ (similar from ^{114}In decays)

Long. polarisation of **photon** $P_{\mathrm{F}}/P_{\mathrm{GT}}$

$|g_S\, \Re\epsilon_S + 4g_A/g_V\, g_T\, \Re\epsilon_T| < 10^{-2}$

Long. polarisation of e^+ from polarised ^{107}In

$|g_T\, \Re\epsilon_T| < 3\times 10^{-3}$

… … …

Recent comprehensive "global fit" [Falkowski et al, 2010.13797]

Angular correlations & recoil spectroscopy

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of angular correlations between **decay products!**

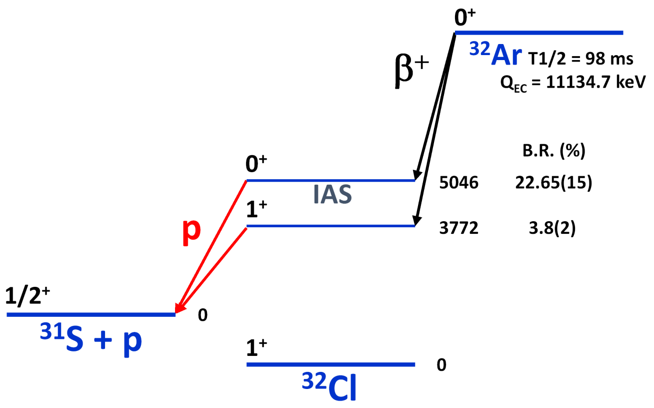
- Recoil spectroscopy offers many interesting and **(powerful) features** - access to both a and b
  - ⇒ **direct measurement** of daughter nucleus recoil
  - ⇒ **kinematic shifts** in energy spectrum of secondary (energetic) emitted particles
    determination of (unstable) **daughter momentum**
  - ⇒ simultaneous study of multiple decay transitions ;
    precise determination of $\tilde{a}$ ⇝ $\delta\tilde{a}_{\mathrm{F(GT)}} \sim 5\times10^{-3}\,(3\times10^{-3})$

$$\tilde{a} = \frac{a}{1+\alpha(E_e)\,b}$$

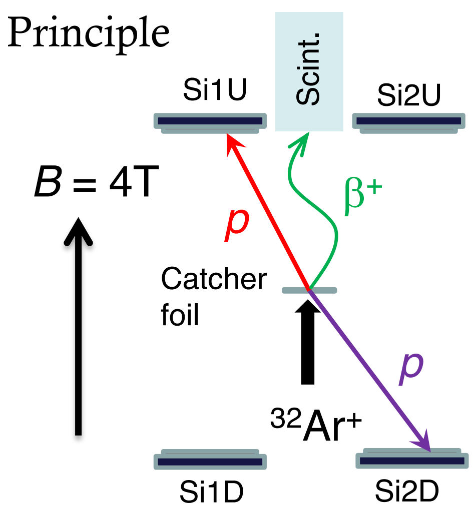
WISArD: **Fermi (and Gamow-Teller)** transitions in ^{32}Ar

simultaneous determination of $\tilde{a}_{\mathrm{F}}$ and $\tilde{a}_{\mathrm{GT}}$

$(\delta\tilde{a}_{\mathrm{F}} < 10^{-3})$



Principle



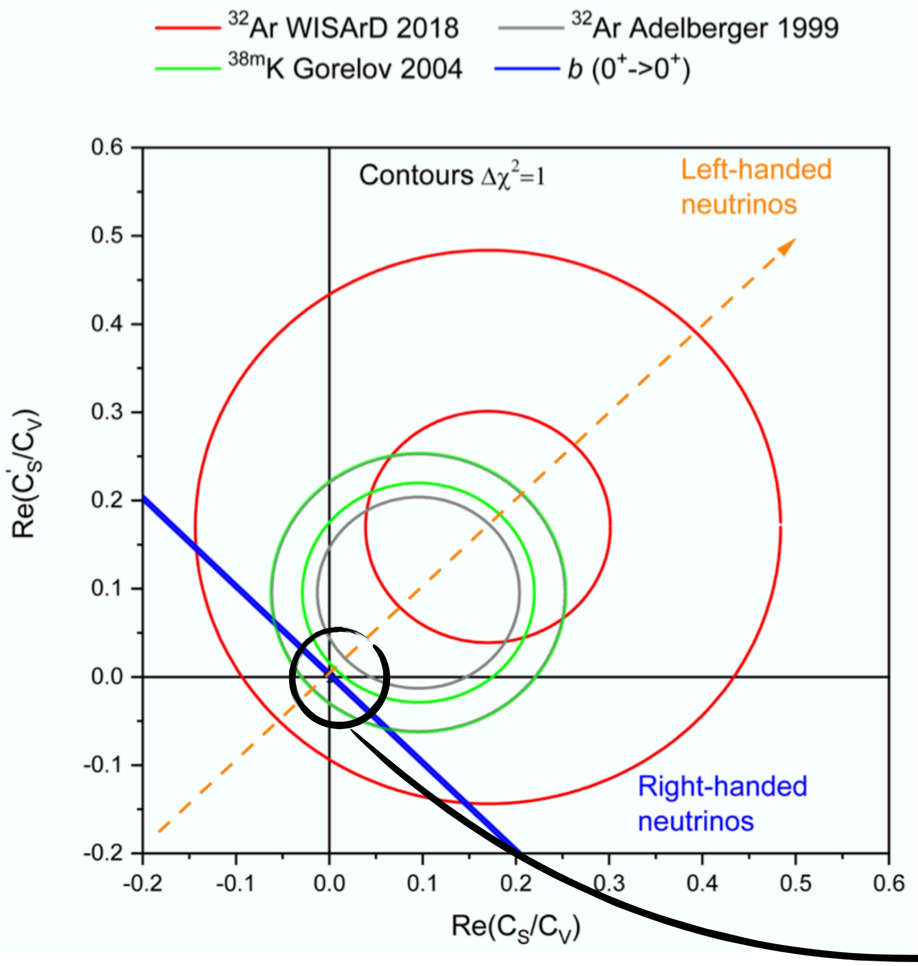
[Araujo-Escalona et al, 1906.05135]

Angular correlations & recoil spectroscopy

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of angular correlations between **decay products!**

- **Differential decay distributions** - very sensitive to the underlying Lorentz structure

  $\Rightarrow$ searches for non $(V - A)$ **components** in **weak interactions!**

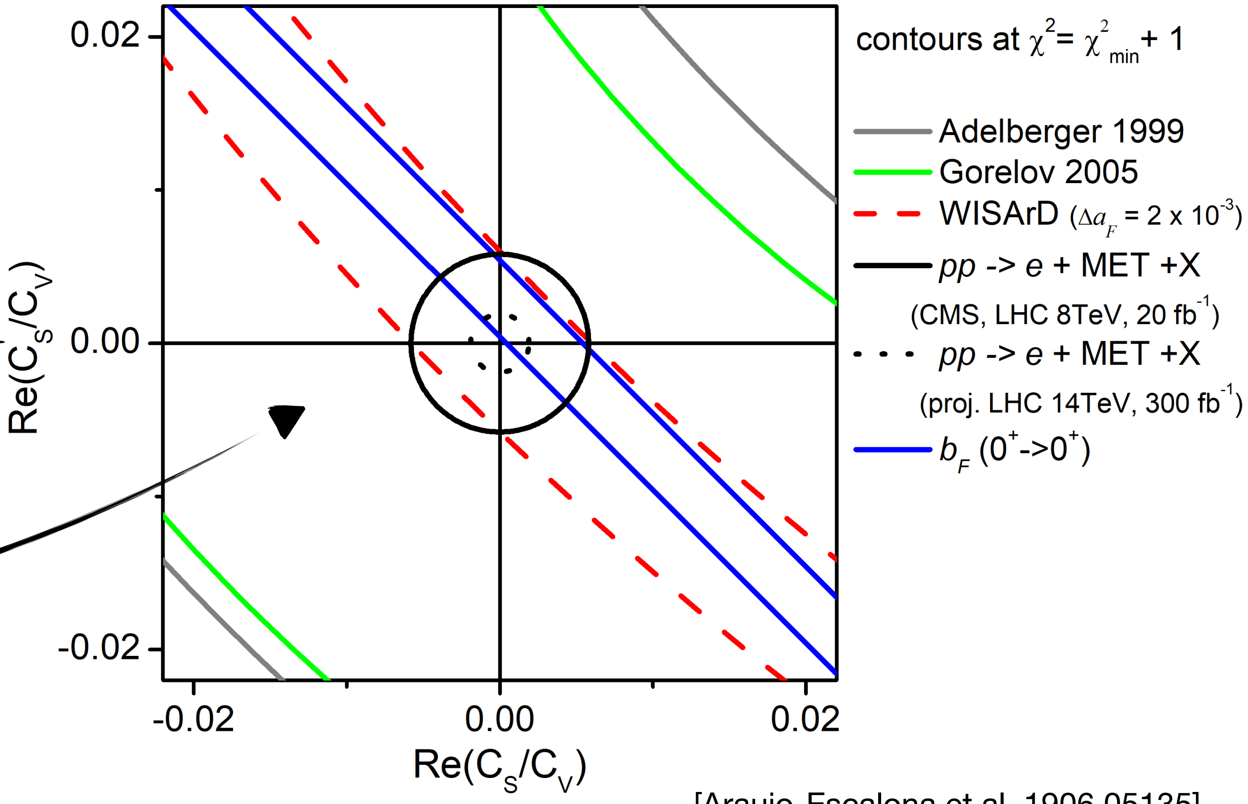


[WIZArD@PANIC 2021]

- **Recoil spectroscopy** offers access to both a and b

  $\Rightarrow$ expect significant (near) future progress

  precise determination of $\tilde{a}$



[Araujo-Escalona et al, 1906.05135]

Shape of beta spectrum

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of **angular correlations** between **decay products!**

- **Shape of β energy spectrum** (upon integration of angular distributions)

$$W(E_e)\, dE_e = \frac{F(\pm Z, E_e)}{2\pi^3}\, p_e\, E_e\, (E_0 - E_e)^2\, \xi \left(1 + \boxed{b\, \frac{m_e}{E_e}}\right) dE_e$$

β spectrum shape modified by **Fierz term!**

For transparency $b_{\text{Fierz}} \approx \pm \frac{1}{1+\rho^2}\left[\Re\left(\frac{C_S + C_S'}{C_V}\right) + \rho^2 \Re\left(\frac{C_T + C_T'}{C_A}\right)\right]$

$$\rho = \frac{C_V}{C_A}\,\frac{M_{\text{GT}}}{M_{\text{F}}}$$

$\Rightarrow$ **sensitivity** to **BSM scalar** and **tensor** operators

$$b_{\text{Fierz}} \approx \pm \frac{2\gamma}{1+\rho^2}\left[\Re \frac{g_S \epsilon_S}{g_V(1 + \epsilon_L + \epsilon_R')} + \rho^2 \frac{4 g_T \epsilon_T}{-g_A(1 + \epsilon_L - \epsilon_R')}\right]$$

$\Rightarrow$ *fully explore the **experimental precision*** (and **maximise sensitivity to NP**)

include *SM QCD form factors:* dominant "weak electromagnetism" term

$$b\, \frac{m_e}{E_e} \to b\, \frac{m_e}{E_e} + \mathcal{O}(b_{\text{wm}}\, E_e/m_e)$$

[See, e.g., Severijns and Naviliat-Cuncic, '13; Fenker et al, '16;]

Shape of β spectrum

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$$W(E_e)\,dE_e \;=\; \frac{F(\pm Z, E_e)}{2\pi^3}\, p_e\, E_e\,(E_0 - E_e)^2\,\xi\,\left(1 + \boxed{b\,\frac{m_e}{E_e}}\right) dE_e$$

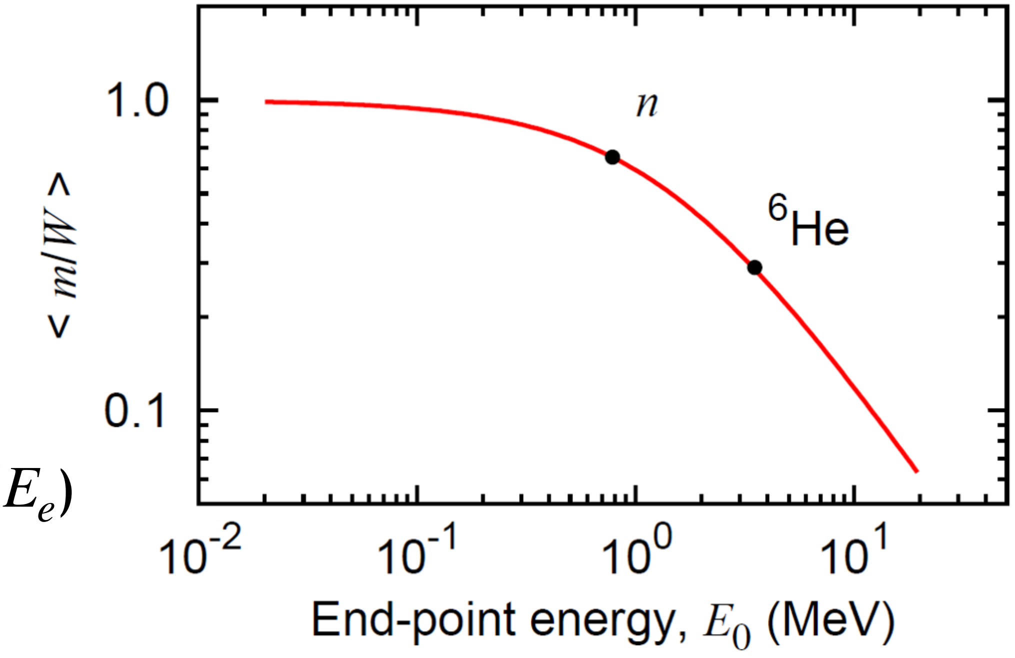
β spectrum shape modified by Fierz term!

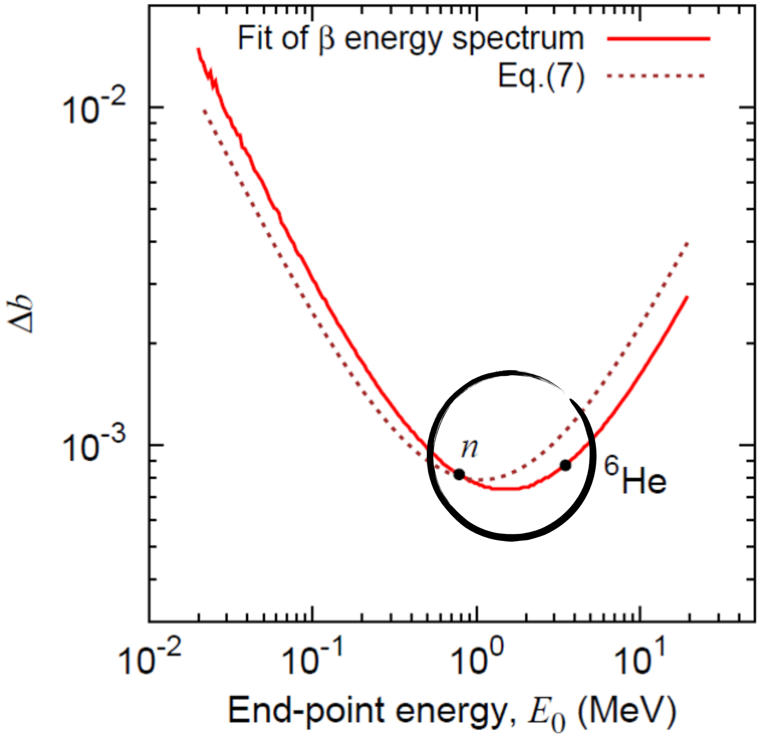
- **Maximal effects** (sensitivity to New Physics effects) for **endpoint energies** $\sim 1-2$ MeV

(rapid decrease for smaller/larger values)

[Gonzalez-Alonso et al, 1607.08347]

Sensitivity factor (m_e/E_e)





Shape of β spectrum

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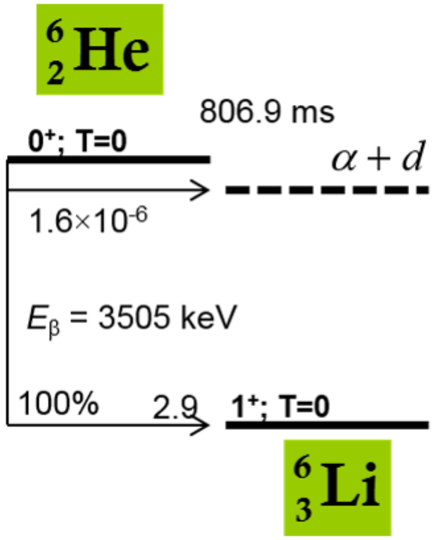
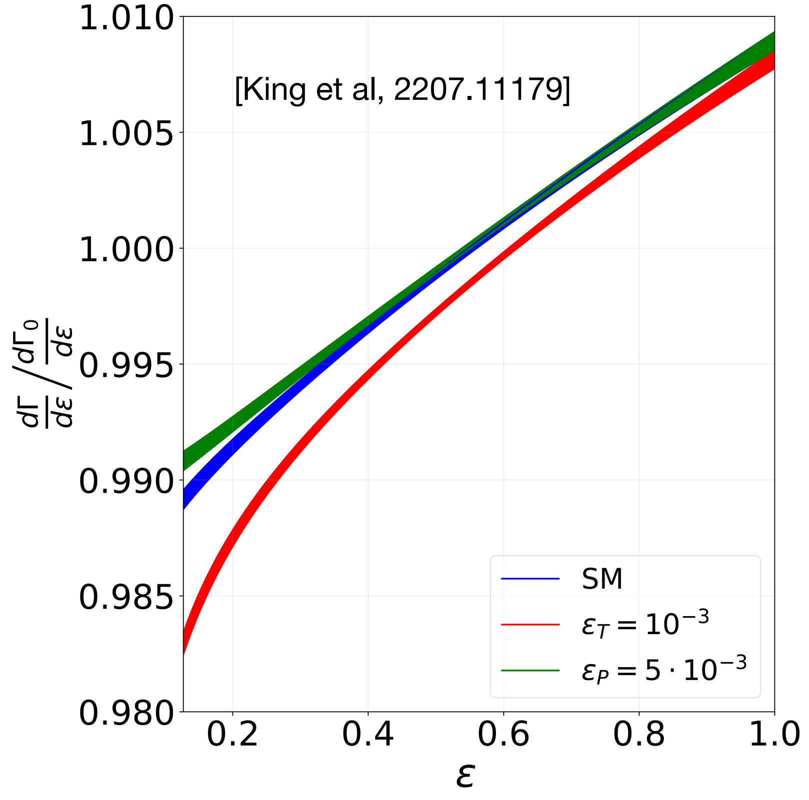
β spectrum shape **modified** by **Fierz term!**



- **Excellent candidate ^{6}He: pure Gamow-Teller** transition to ground state

Energy endpoint ~ 3.5 MeV

$b_{\rm GT} \propto g_T\, \Re\epsilon_T$

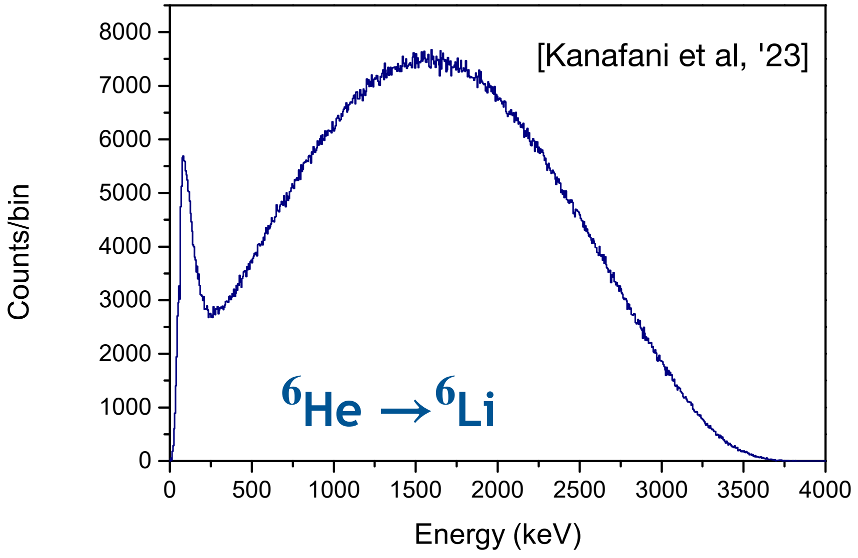


b-STILED:

pure Gamow-Teller ^{6}He $\rightarrow$ ^{6}Li

Expected precision on $b_{\rm GT}$

$$\delta b_{\rm GT} \sim 10^{-3}$$



"Ab-initio" calculations of ^{6}He beta decays for BSM !

[Glick-Magid et al, 2107.10212]

Shape of β spectrum

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of **angular correlations** between **decay products!**

- **Shape of β energy spectrum** (upon integration of angular distributions)

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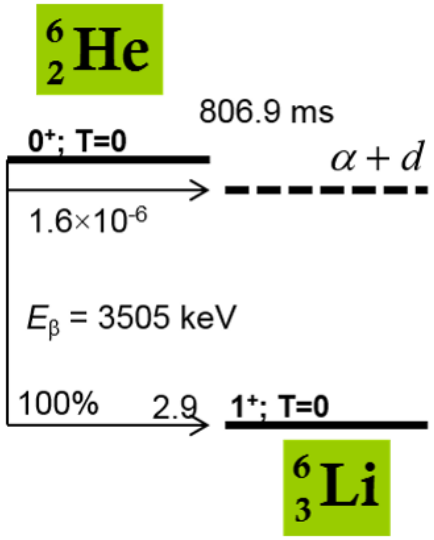
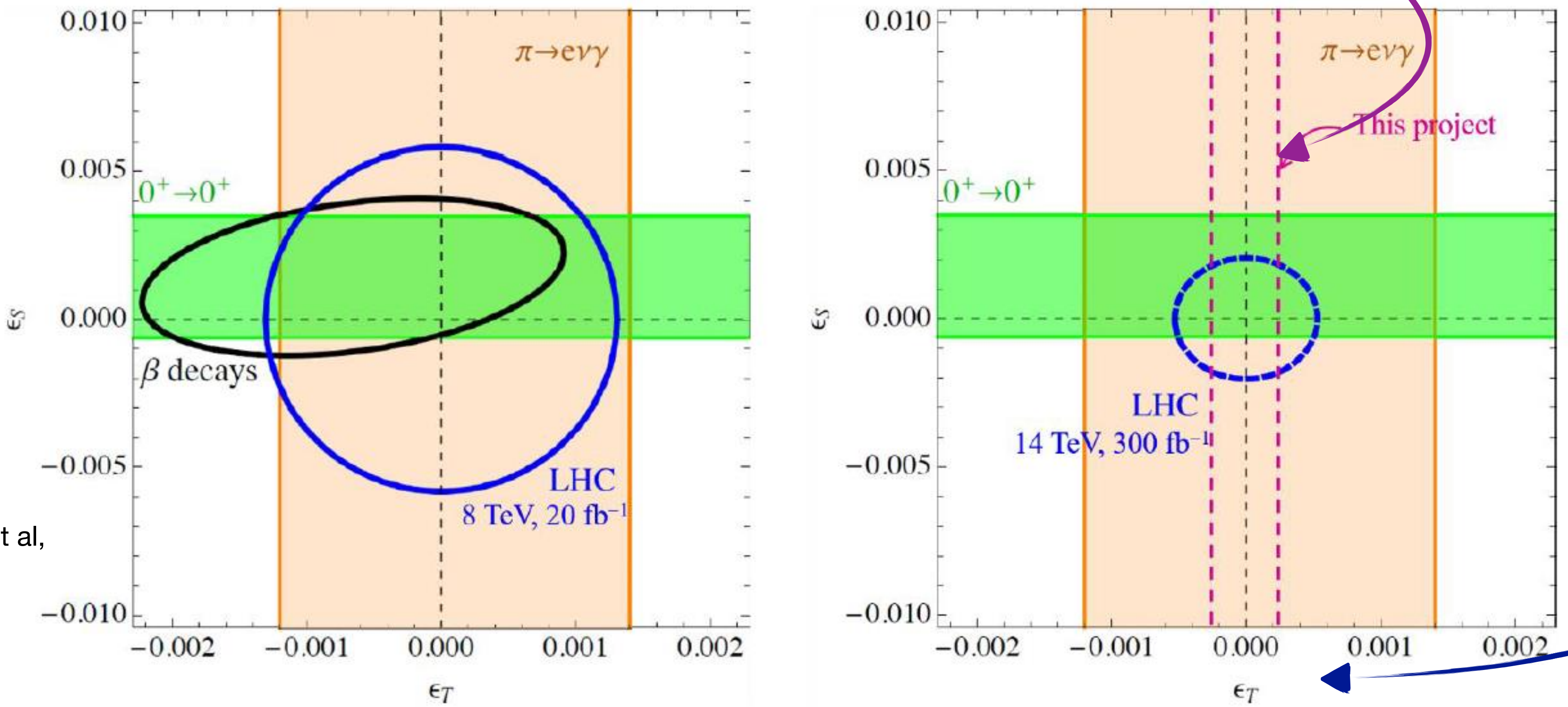


β spectrum shape modified by **Fierz term!**

b-STILED: pure **Gamow-Teller ^{6}He →^{6}Li precision $\delta b_{\rm GT} \sim 10^{-3}$**



[Adapted from Gonzalez-Alonso et al, 1803.08732]

Constraints on ϵ_T!

Angular correlations and T-odd terms

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of angular correlations between **decay products!**

- Differential decay distributions - very sensitive to the underlying Lorentz structure and to **new sources** of **T-violation** (if CPT ⇒ **CP violation**)

A correlation of **odd number of spins & momenta:** among other possibilities D-correlation

$$\boldsymbol{D}\,\frac{\overrightarrow{p_e}\times\overrightarrow{p_\nu}}{E_e\,E_\nu}$$

probed in mixed Fermi/Gamow-Teller transitions

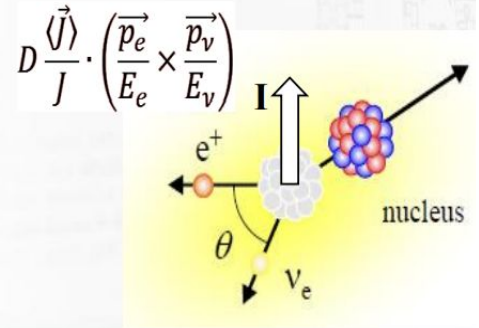
Contributions to D: T-violating interactions and **final state effects**

$$D \;=\; D_{\mathsf{TV}} + D_{\mathsf{FSI}}$$

$$D_{\mathsf{FSI}} \approx D_1\,\frac{p_e}{p_e^{\mathsf{max}}} + D_2\,\frac{p_e^{\mathsf{max}}}{p_e}$$

$$D_1 \sim \mathcal{O}(10^{-5\div-4})$$

$$D_2 \sim \mathcal{O}(10^{-6\div-5})$$



Neutron: $D_{\mathsf{FSI}} \approx 1.2\times10^{-5}$

$\delta \lesssim 1\,\%$

[Jackson et al, '57; Callan and S.B. Treiman, '67; Ando et al, 2009]

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$$\boldsymbol{D}\,\frac{\vec{p_e}\times\vec{p_\nu}}{E_e\,E_\nu}$$

probed in **mixed Fermi/Gamow-Teller** transitions

Contributions to D: **T-violating interactions** and **final state effects**

$$D \;=\; D_{\mathsf{TV}} \,+\, D_{\mathsf{FSI}}$$

$$D_{TV} \approx \frac{1}{1+3\,|\,\lambda\,|^2} \times \left[-2\frac{\Im(C_V\,C_A^*)}{|\,C_V|^2} + \frac{\Im(C_S\,C_T^* + C_S'\,C_T'^*)}{|\,C_V|^2} + \frac{\alpha\,m_e}{p_e}\,\Re\left(\lambda^*\frac{C_T + C_T'^*}{C_A^*} - \lambda^*\frac{C_S + C_S'^*}{C_V^*}\right)\right]$$

$$D \approx \frac{4r\,g_V\,g_A}{g_V^2 + r^2 g_A^2}\sqrt{\frac{J}{J+1}}\,\Im\left[\epsilon_R(1+\epsilon_L^*) + \frac{g_S\,g_T}{2g_V\,g_A}(\epsilon_S\,\epsilon_T^* + \tilde{\epsilon}_S\,\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\,\tilde{\epsilon}_L^*\right]$$

Angular correlations and T-odd terms

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Contributions to D: T-violating interactions and **final state effects**

$$D \;=\; D_{\mathsf{TV}} + D_{\mathsf{FSI}}$$

⇒ Can nucleons and nuclei unveil new sources of CP violation?

Very much needed to overcome SM observational problems!

$$p_e \Big(\frac{\quad\;^*}{C_A^*} - \lambda^* \frac{C_S + C_S'^*}{C_V^*} \Big) \Big]$$

$$D \approx \frac{4r\,g_V\,g_A}{g_V^2 + r^2 g_A^2}\sqrt{\frac{J}{J+1}}\,\Im\left[\epsilon_R(1+\epsilon_L^*) + \frac{g_S\,g_T}{2g_V\,g_A}(\epsilon_S\,\epsilon_T^* + \tilde{\epsilon}_S\,\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\,\tilde{\epsilon}_L^*\right]$$

Angular correlations and T-odd terms

- **SM precision tests** in **nuclear β decays:** a vast array of additional observables from the exploration of angular correlations between **decay products!**

- Differential decay distributions - very sensitive to the underlying Lorentz structure and to **new sources** of **T-violation** (if CPT ⇒ CP violation)

  And we **do need new CPV sources!**

So far, experimental searches in **only two systems** - neutron and ^{19}Ne ($J = 1/2$)

[Calaprice et al, '85] ^{19}**Ne** $\rightsquigarrow D = 0.0001(6)$

[PDG, '20] **neutron** $\rightsquigarrow D_{\rm n} = -0.00012(20)$ (world average)

... consistent with **absence** of new sources of CPV in exotic **scalar** and **tensor** interactions

Under the assumptions of **no new CPV**, constrain $\phi_{AV} = 180.012^\circ \pm 0.028^\circ$

[Chupp et al, 1205.6588]

$$\phi_{AV} = \arg\lambda \equiv \arg C_A/C_V$$

- **New** experimental **directions** & sensitivity to NP: β decays have different sensitivities to ϕ_{AV}

  Sensitivity $\rightsquigarrow D_{\rm n,N} = F(\rm n,N)\ \sin\phi_{AV}$

  ⇒ Maximise $D_{\rm N}$ and polarisation degree !

Angular correlations and T-odd terms

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  Only two systems explored: neutron and ^{19}Ne ($J = 1/2$)

- **New** **experimental** **directions** & **sensitivity to NP** ⇒ Maximise D_{N} and polarisation degree !

	n	^{19}Ne	^{23}Mg	^{35}Ar	^{39}Ca
Sensitivity *F(X)*	0,43	-0,52	-0,65	0,41	0,71
D_1 (x10^{-4})	0,108	2,326	1,904	0,386	-0,489
D_2 (x10^{-4})	0,023	0,169	0,099	0,010	-0,024

[Delahaye et al - MORA project 1802.02970]

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

First focus: ^{23}Mg (easier to polarise...) ⇝ future ^{39}Ca

Expected precision δD_{Mg} ~ few $\times 10^{-5}$

Sensitivity to ϕ_{AV} : $\phi_{AV} = (1.6 \pm 6.3) \times 10^{-4} \to \mathcal{O}(10^{-5})$

Synergy with other searches of **New Physics sources of CP?**

Searches for CP violation: complementarity

- If **new sources of CP violation** are present - as required to **explain the BAU**
  generically expect **contributions** to a vast **array of CP-odd observables**
  from **LHC**, to **meson-decay** observables (asymmetries), ...,
  EDMs (elementary, nucleon, atomic...) and **nuclear decays!**

- **Synergy** between **EDMs** and D_{TV} - a very naïve first approach

Consider T-violating dim-6 term

$$\mathscr{L}^{\text{eff}}_{\text{SMEFT}} \supset i\mathscr{C}^{6}_{Hud}\tilde{H}^{\dagger}D_{\mu}H\,(u^{c}\sigma^{\mu}\bar{d}^{c}) + \text{H.c.}$$

$$\mathscr{L}^{\text{eff}}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^{2}}\left[(\bar{e}\bar{\sigma}_{\mu}\nu)\,(\bar{u}\bar{\sigma}_{\mu}d) + \frac{v^{2}}{2V_{ud}}\mathscr{C}^{11}_{Hud}(\bar{e}\bar{\sigma}_{\mu}\nu)\,(u^{c}\sigma_{\mu}\bar{d}^{c})\right]$$

At nucleon level ⇒ $D_{\text{n}} \approx \dfrac{4g_{V}g_{A}}{g_{V}^{2}+g_{A}^{2}}\,\mathfrak{I}\epsilon_{R} \approx 0.4v^{2}\mathfrak{I}\mathscr{C}^{11}_{Hud}$

But **nEDM constrains** $|v^{2}\,\mathfrak{I}\mathscr{C}^{11}_{Hud}| \leq 6\times 10^{-6}$

$\Rightarrow D_{\text{n}} \lesssim 2\times 10^{-6}$ **??**

(Recall however that cancellations might occur and final implications are model-dependent)

Searches for CP violation: complementarity

- If **new sources of CP violation** are present - as required to **explain the BAU** generically expect **contributions** to a vast **array of CP-odd observables** from **LHC**, to **meson-decay** observables (asymmetries), ..., **EDMs** (elementary, nucleon, atomic...) and **nuclear decays!**

- **Synergy** between **EDMs** and D_{TV} - a very naïve first approach

Likewise one also finds $|d_n| \approx 1 \times 10^{-19} e\,.\,\mathrm{cm}\,|D_{TV}/\kappa|$

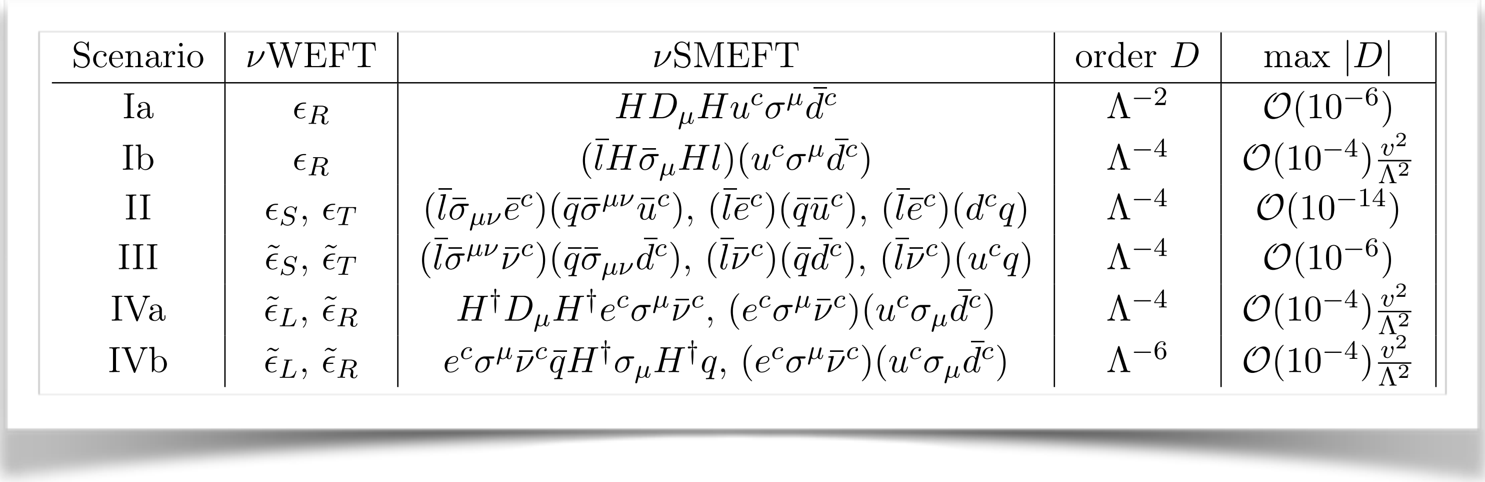
$$|d_{\mathrm{Hg}}| \approx 7 \times 10^{-24} e\,.\,\mathrm{cm}\,|D_{TV}/\kappa|$$

[Ng and Tulin, 1111.0649]

$$|d_{\mathrm{D}}| \approx 4.5 \times 10^{-20} e\,.\,\mathrm{cm}\,|D_{TV}/\kappa|$$

$$\kappa = \frac{4 g_V g_A M_{\mathrm{F}} M_{\mathrm{GT}}}{g_V^2 M_{\mathrm{F}}^2 + g_A^2 M_{\mathrm{GT}}^2} \sqrt{\frac{J}{J+1}}$$

Bounds generically apply to classes of UV-models leading to distinct operators in $\mathscr{L}^{\mathrm{eff}}$



Scenario	νWEFT	νSMEFT	order D	max $\|D\|$
Ia	ϵ_R	$H D_\mu H u^c \sigma^\mu \bar{d}^c$	Λ^{-2}	$\mathcal{O}(10^{-6})$
Ib	ϵ_R	$(\bar{l} H \bar{\sigma}_\mu H l)(u^c \sigma^\mu \bar{d}^c)$	Λ^{-4}	$\mathcal{O}(10^{-4}) \frac{v^2}{\Lambda^2}$
II	$\epsilon_S,\ \epsilon_T$	$(\bar{l} \bar{\sigma}_{\mu\nu} \bar{e}^c)(\bar{q} \bar{\sigma}^{\mu\nu} \bar{u}^c),\ (\bar{l} \bar{e}^c)(\bar{q} \bar{u}^c),\ (\bar{l} \bar{e}^c)(d^c q)$	Λ^{-4}	$\mathcal{O}(10^{-14})$
III	$\tilde{\epsilon}_S,\ \tilde{\epsilon}_T$	$(\bar{l} \bar{\sigma}^{\mu\nu} \bar{\nu}^c)(\bar{q} \bar{\sigma}_{\mu\nu} \bar{d}^c),\ (\bar{l} \bar{\nu}^c)(\bar{q} \bar{d}^c),\ (\bar{l} \bar{\nu}^c)(u^c q)$	Λ^{-4}	$\mathcal{O}(10^{-6})$
IVa	$\tilde{\epsilon}_L,\ \tilde{\epsilon}_R$	$H^\dagger D_\mu H^\dagger e^c \sigma^\mu \bar{\nu}^c,\ (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$	Λ^{-4}	$\mathcal{O}(10^{-4}) \frac{v^2}{\Lambda^2}$
IVb	$\tilde{\epsilon}_L,\ \tilde{\epsilon}_R$	$e^c \sigma^\mu \bar{\nu}^c \bar{q} H^\dagger \sigma_\mu H^\dagger q,\ (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$	Λ^{-6}	$\mathcal{O}(10^{-4}) \frac{v^2}{\Lambda^2}$

[Falkowski and Rodriguez-Sanchez, 2207.02161]

(Recall however that cancellations might occur and final implications are model-dependent)

Searches for CP violation: complementarity

- If **new sources of CP violation** are present - as required to **explain the BAU**
  generically expect **contributions** to a vast **array of CP-odd observables**
  from **LHC**, to **meson-decay** observables (asymmetries), ...,
  EDMs (elementary, nucleon, atomic...) and **nuclear decays!**

- **Synergy** between **EDMs** and D_{TV} - a very naïve first approach ⇒ **strong constraints** on D_{TV}
  (Recall however that cancellations might occur and final implications are model-dependent)

- A **strong case** for the **precise determination** of D_{TV} in **nuclear beta decays:**

  EDM measurements offer **stronger bounds** on new **CP violation** sources
  However, a *single EDM measurement has little discriminating power*

  Especially in the **advent of EDM observation,**
  more **independent observables required!**

  Sensitivity of D_{TV} to **exotic currents** might help **untangling nature of CPV!**

Synergy with LHC!

- **SM precision tests** in **nuclear β decays: LHC** probing the same **parton level** processes

  Contributions of common set of **EFT operators** to $pp \to e + \text{MET}(+X)$

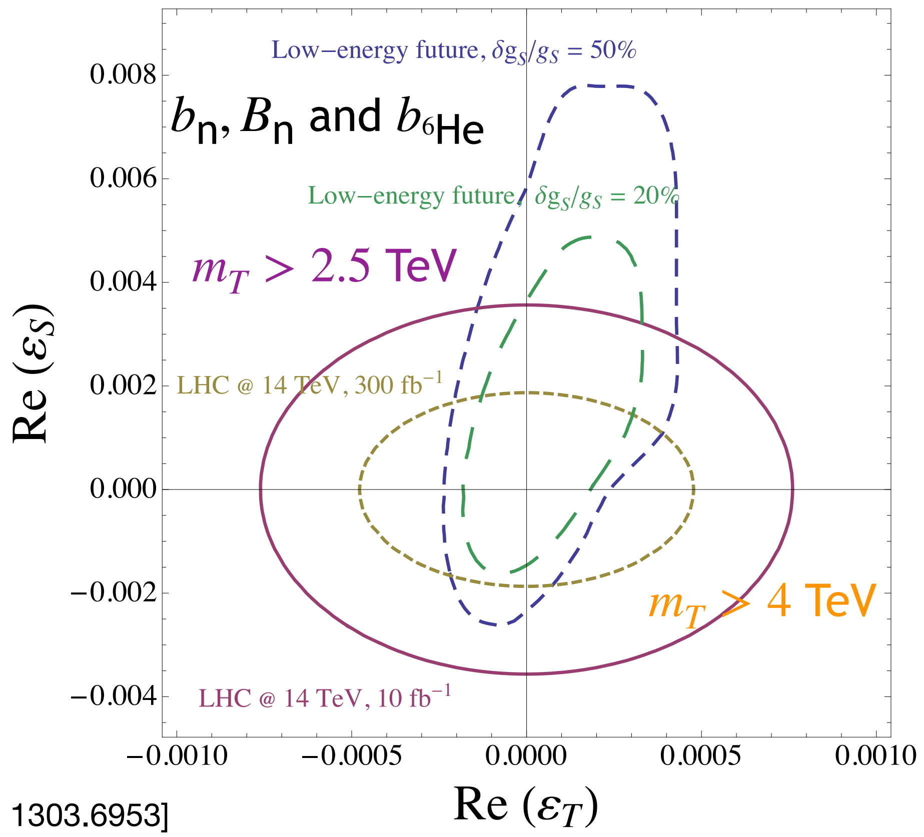
  Unsuppressed effects at collider energies $\Rightarrow \mathcal{O}(s^2/v^4)$ enhancement

If $m_T \equiv \sqrt{2E_T^e\, E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$ *larger than threshold production*

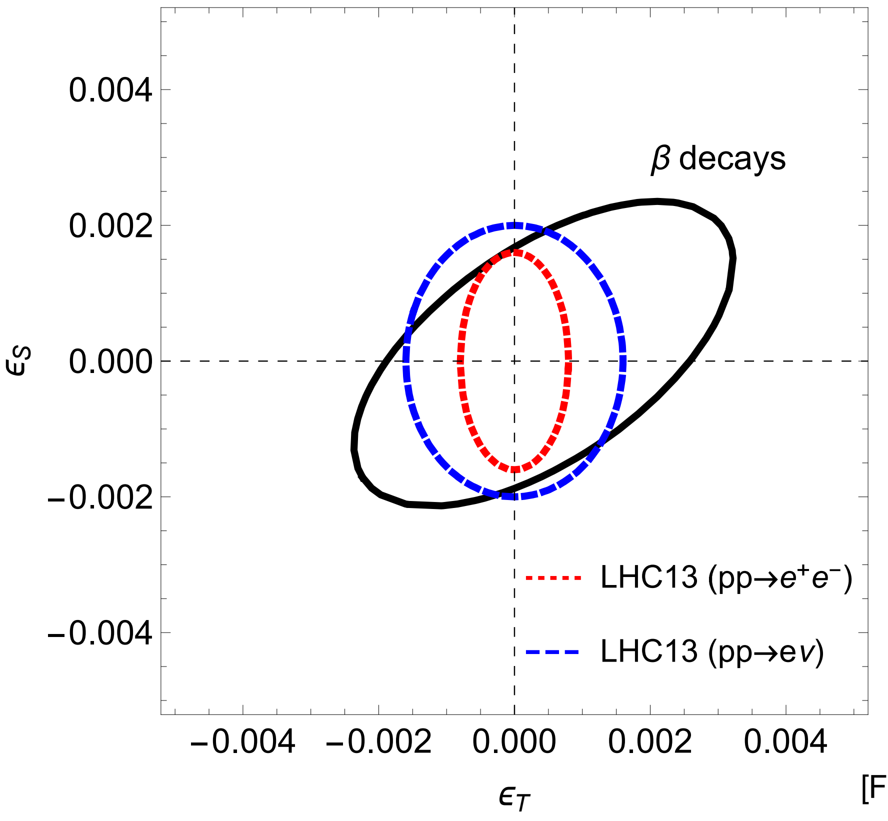
$$\sigma(m_T > m_{\bar{T}}) = \sigma_W \left[(1 + \epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2\sigma_{WL} \Re(\epsilon_L^{(c)} + \epsilon_L^{(c)}\epsilon_L^{(v)*})$$

$$+\sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right] + \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right]$$

[See, e.g., Cirigliano et al, 1210.4553]



[Cirigliano et al, 1303.6953]



[Falkowski et al, 2010.13797]

Nuclear decays and neutrino physics

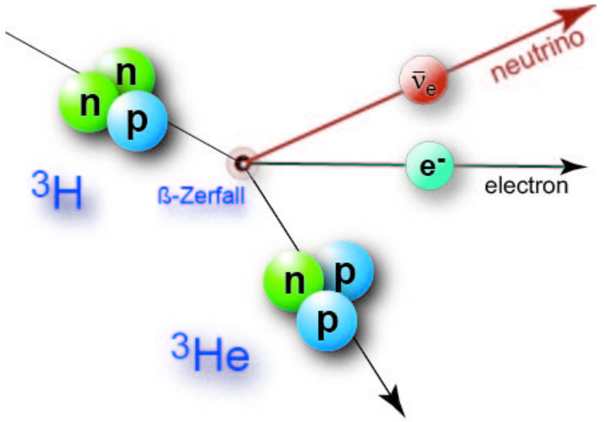
- Historically, a **treasure trove** for neutrinos: from discovery, to the characterisation of fundamental properties (mass, nature, ...) & searches for new (sterile) states

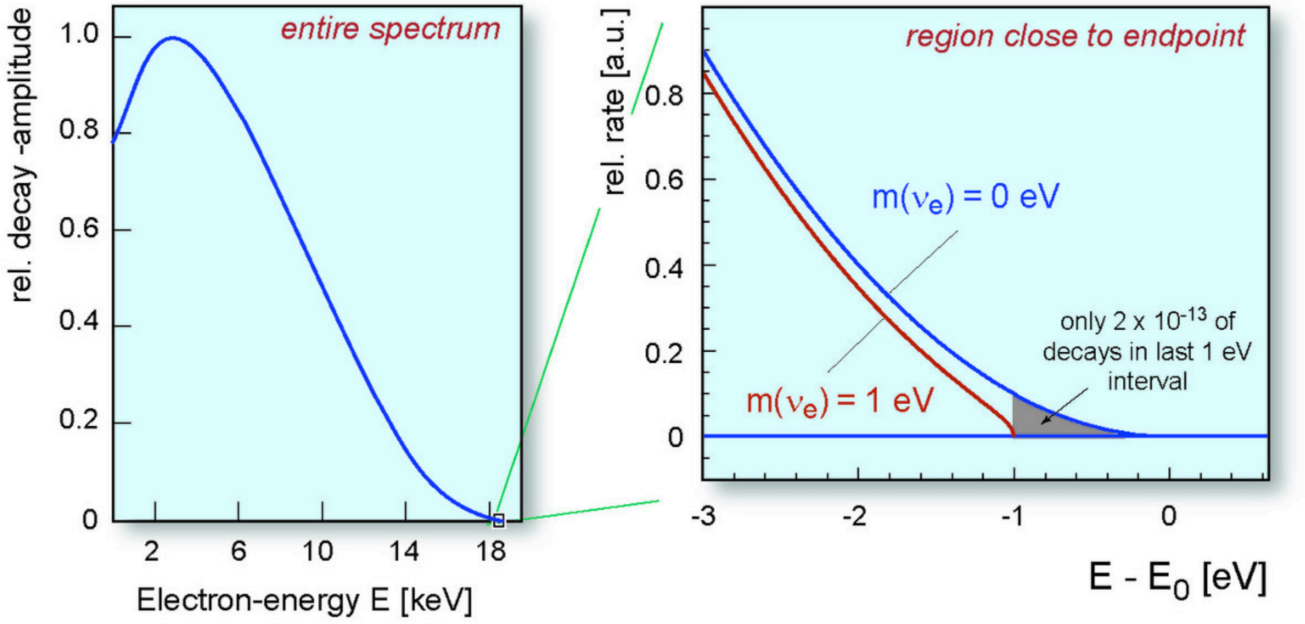
- **Highlights:** Tritium decays $^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$

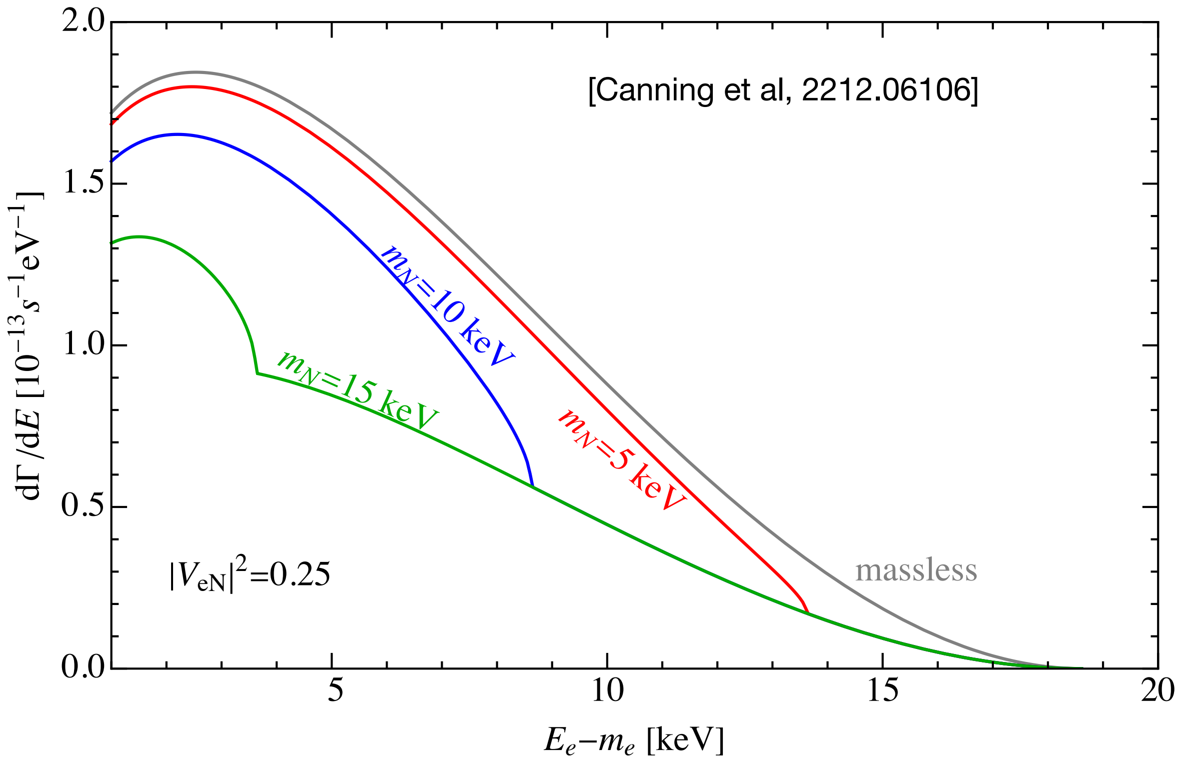
  measure the shape of beta spectrum, at its endpoint

  $\Rightarrow$ determine neutrino mass $m_\beta < 1.1$ eV; $m_\beta \sim 0.2$ eV

  (little sensitivity to exotic currents)







$\Rightarrow$ search for light sterile states

(non-negligible mixings)

Kurie plots, **differential decay rates**

Nuclear decays and neutrino physics

- Historically, a **treasure trove** for neutrinos: from discovery, to the characterisation of fundamental properties (mass, nature, ...) & searches for new (sterile) states

- **Highlights:** massive neutrinos and the role of sterile neutrinos

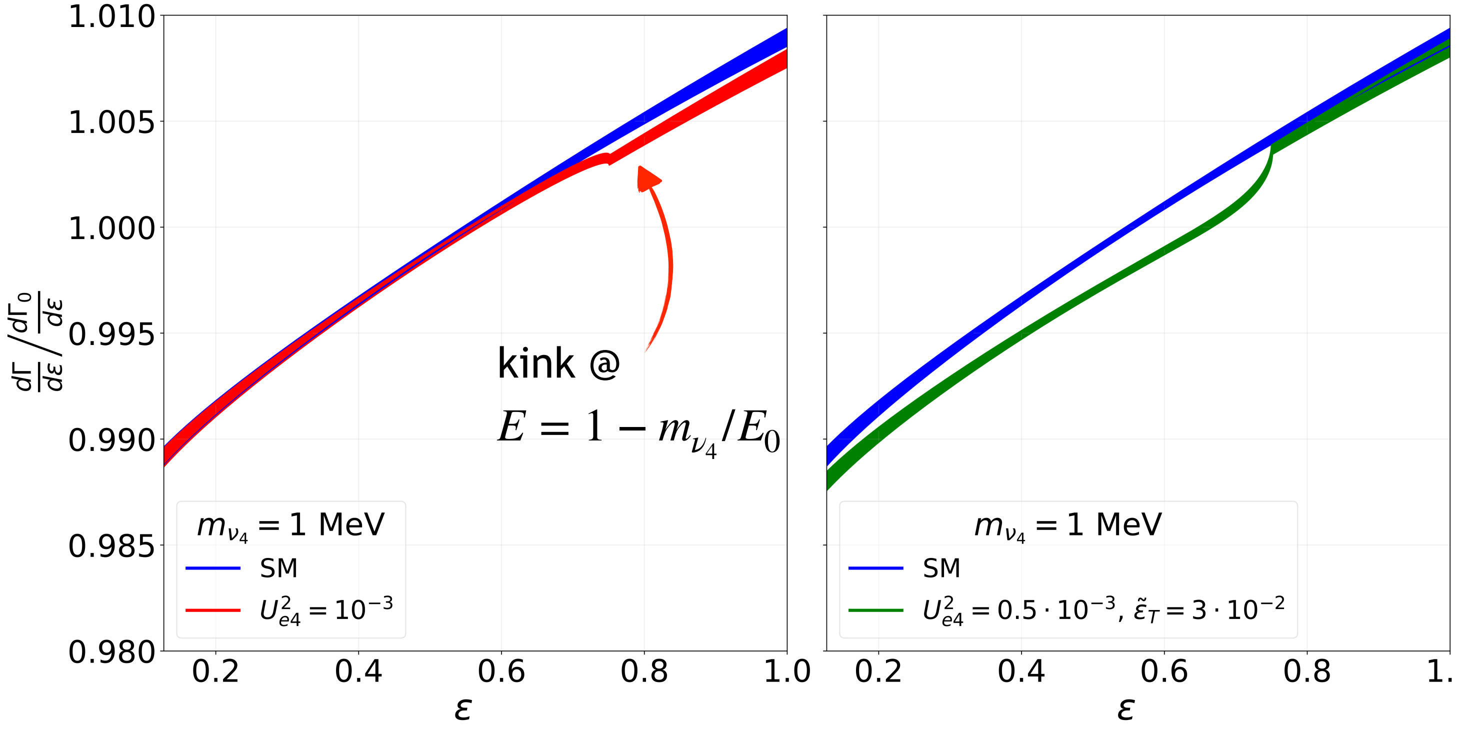
Modified charged current interactions (PMNS matrix) $\nu_\alpha = U^{\text{PMNS}}_{\alpha i}\,\nu_i$

$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e \quad \Rightarrow \quad m_\beta \to \left(\sum_k |U_{ek}|^2\, m^2_{\nu_k}\right)^{1/2}$$ & kinks on the beta spectrum!

If sterile states decoupled, or if negligibly light ($m_{\nu_s} \ll M_N$) **neglect ν_s operators**

If $m_{\nu_s} \approx \mathcal{O}(m_e)$ **new terms** in $\mathscr{L}^{\text{eff}}$, e.g. $\propto V_{ud}\,U_{e4}(1+\epsilon_L)(\bar{e}_L\gamma_\mu\nu_4)(\bar{u}_L\gamma^\mu d_L)$ +

$V_{ud}\,U_{e4}\epsilon_T(\bar{u}_R\sigma_{\mu\nu}d_L)\,(\bar{e}_R\sigma^{\mu\nu}\nu_4)$ + ...



kink @ $E = 1 - m_{\nu_4}/E_0$

$\Rightarrow$ **Corrections** to the β spectrum

[King et al, 2207.11197]

NP discoveries through β decays: TH challenges

- **SM precision tests** in **nuclear β decays:** a possible path to **NP discovery!**

  Improvement in numerous experimental fronts ⇒ and $\Lambda_{\rm NP}$ sensitivities

  Complementary to LHC direct searches and to other high-intensity probes

- **Identifying tensions between theoretical prediction and expectation**

  excellent experimental precision, and reduction of theoretical uncertainties

On the **theory** side, *many mountains to climb:*

computation of nuclear charges, reduce approximations in $V_{us}(\mathscr{F}t)$,

proper inclusion of small effects (critical for SM-like observables) -

radiative corrections, induced hadronic form factors, ...

⇒ Excellent news from **first principle approaches: LQCD** and **ab-initio nuclear computations**

- *Discrepancy between nuclear observable and SM prediction ...*

  ⇒ Identifying the **UV particle physics model at work!**

  ⇒ Relate nucleonic **form factors** with quark level **(NP) charges!**

Understanding the nature of antimatter & ultimate tests of the weak equivalence principle

Matter and antimatter

- "Immediate" **Universe** is composed of **matter:** electrons, protons, neutrons, nuclei and atoms...

  antimatter only in cosmic rays, (certain) radioactive decays or laboratory produced

- Matter and antimatter in the **SM: identical elementary particles,** with **opposite CP charges** (or strictly identical in the case of *Majorana neutral fermions!*)

- **SM gauge interactions** only distinguish matter and antimatter via **"sign" of charges** $(\pm|\lambda|)$

  What about **mass?** No kinematical difference between electrons and positrons...

  p and $\bar{p}$ charge-to-mass ratio: identical (precision of 16 parts in a trillion!)

  [BASE Collaboration, 2022]

- What about **gravitation?**

  Observation suggests that **gravity effects** on the motion of neutral antimatter (H̄)

  $$\bar{g} = (0.75 \pm 0.13_{\text{sys+stat}} \pm 0.16_{\text{sim}})\, g$$

  [ALPHA-g Collaboration, 2023]

  ⇒ **consistent with a downward gravitational acceleration** $(1\,g)$ for antihydrogen

Is there still room for **non-standard gravitational interactions?** What would be the impact? (for gravity theories and particle physics!)

Weak Equivalence Principle

- **One principle to challenge (or confirm!):**

  "In a uniform gravitational field, all objects **(regardless of nature and composition)** free-fall with precisely the same acceleration"

Newtonian interpretation ⇒ identity of inertial and gravitational masses ($m^g \equiv m^I$)

Asymmetry in gravitational interactions: challenge universality of free-fall acceleration

$$g_{(i)} = m^g / m^I_{(i)}$$

$$\eta^{\oplus}_{ij} = \frac{\Delta g^{\oplus}}{< g^{\oplus} >} = \frac{g_i^{\oplus} - g_j^{\oplus}}{(g_i^{\oplus} + g_j^{\oplus})/2}$$

(Eötvös parameter)

Extensive tests of WEP violation for bodies of different compositions falling in the Earth's field:

variations on free torsion pendulum experiments to constrain $\eta^{\oplus}$ between pairs of *matter* elements

[Torsion pendulum used in Eöt-Wash experiments]

Experiment	Test bodies	Measurement
Eöt-Wash	Be - Ti	$\eta_{\oplus,\text{Be-Ti}} = (0.3 \pm 1.8) \times 10^{-13}$
Eöt-Wash	Be - Al	$\eta_{\oplus,\text{Be-Al}} = (-1.5 \pm 1.5) \times 10^{-13}$
Eöt-Wash	Be - Cu	$\eta_{\oplus,\text{Be-Cu}} = (-1.9 \pm 2.5) \times 10^{-12}$

$\eta^{\oplus}_{\text{E-W}} \lesssim \mathcal{O}(10^{-12})$

[See, e.g., Wagner et al, 1207.2442]

MICROSCOPE (satellite experiment): $\eta^{\oplus}_{\text{Ti-Pl}} \lesssim \mathcal{O}(10^{-15})$

[MICROSCOPE Collaboration, 2209.15487]

Antimatter and modified GR - havoc for QFTs!

Having antimatter gravitating in a district way corresponds to the more general possibility that different forms of energy **gravitate differently**...

Two broad classes of theoretical possibilities

(i) modified General Relativity

(ii) **new forces,** mediated by vectors and/or scalars, **(sub)gravitational strength**

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(i) Modified gravitation (subatomic scales) ⇝ *impact fundamental principles* of **GR and QFT** (**CPT** invariance, **Lorentz** invariance, ...)

CPT: invariance of local Lorentz-invariant QFTs (point-like particles) - e.g. QED, SM, ...

Does this hold for more fundamental theories, upon **combining the SM and gravity?**

In string theory one can have spontaneous breaking of CPT and Lorentz...

Can one look for laboratory signals of CPT & Lorentz violation (at the Planck scale)?

Exceptionally sensitive experiments required...

⇒ Hydrogen and antihydrogen spectroscopy!

[See, for instance, Charlton et al, 2002.09348]

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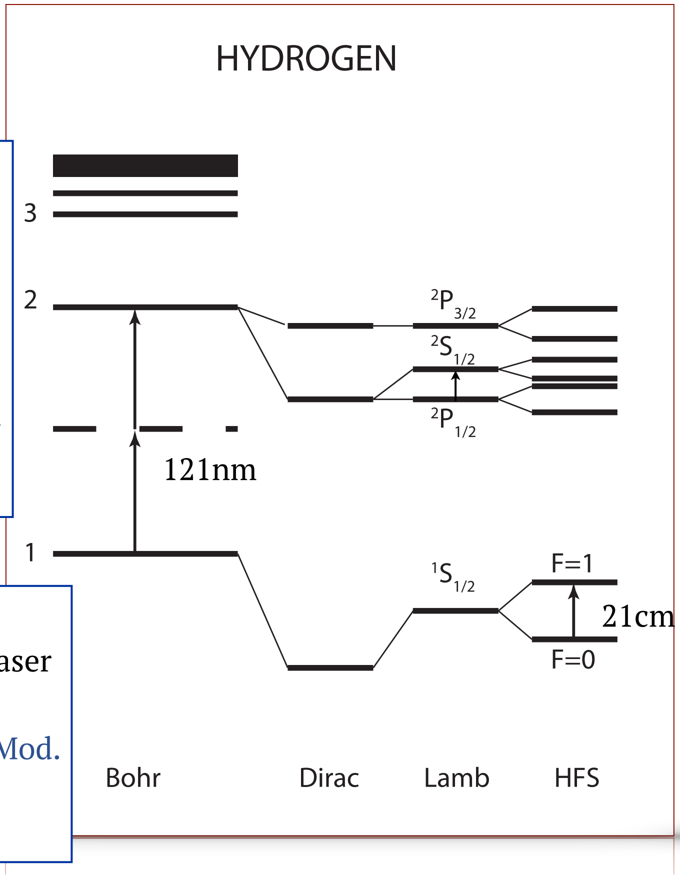
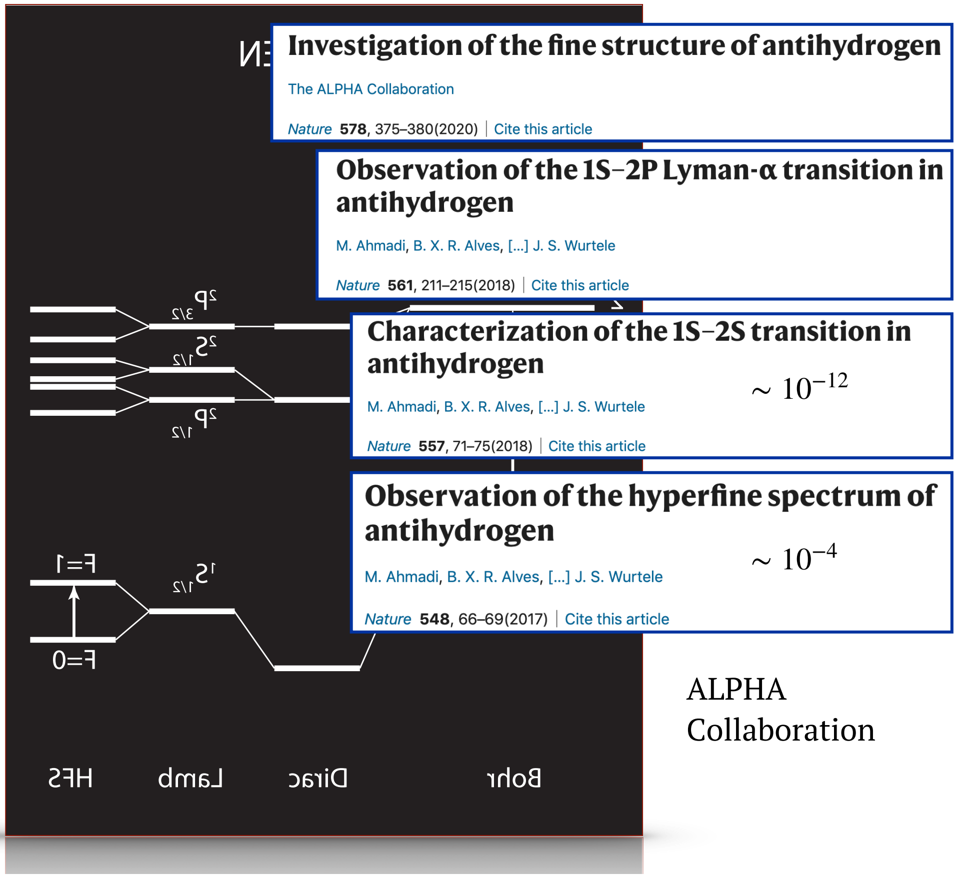
Extraordinary progress in recent years!

1S-2S: two photon transition
4×10^{-15} (~10 Hz)
in a cold (~6K) atomic beam
G. Parthey et al. Phys. Rev. Lett. 107 (2011)

hyperfine splitting measurement in maser
$\sim 10^{-12}$ (~1 mHz)
Ramsey, N. F. Rev. Mod. Phys. 62, 541–552 (1990).





Investigation of the fine structure of antihydrogen

The ALPHA Collaboration

Nature **578**, 375–380(2020) | Cite this article

Observation of the 1S–2P Lyman-α transition in antihydrogen

M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele

Nature **561**, 211–215(2018) | Cite this article

Characterization of the 1S–2S transition in antihydrogen

$\sim 10^{-12}$

M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele

Nature **557**, 71–75(2018) | Cite this article

Observation of the hyperfine spectrum of antihydrogen

$\sim 10^{-4}$

M. Ahmadi, B. X. R. Alves, [...] J. S. Wurtele

Nature **548**, 66–69(2017) | Cite this article

ALPHA Collaboration

[From Malbrunot, CERN'21]

Antimatter and modified gravity

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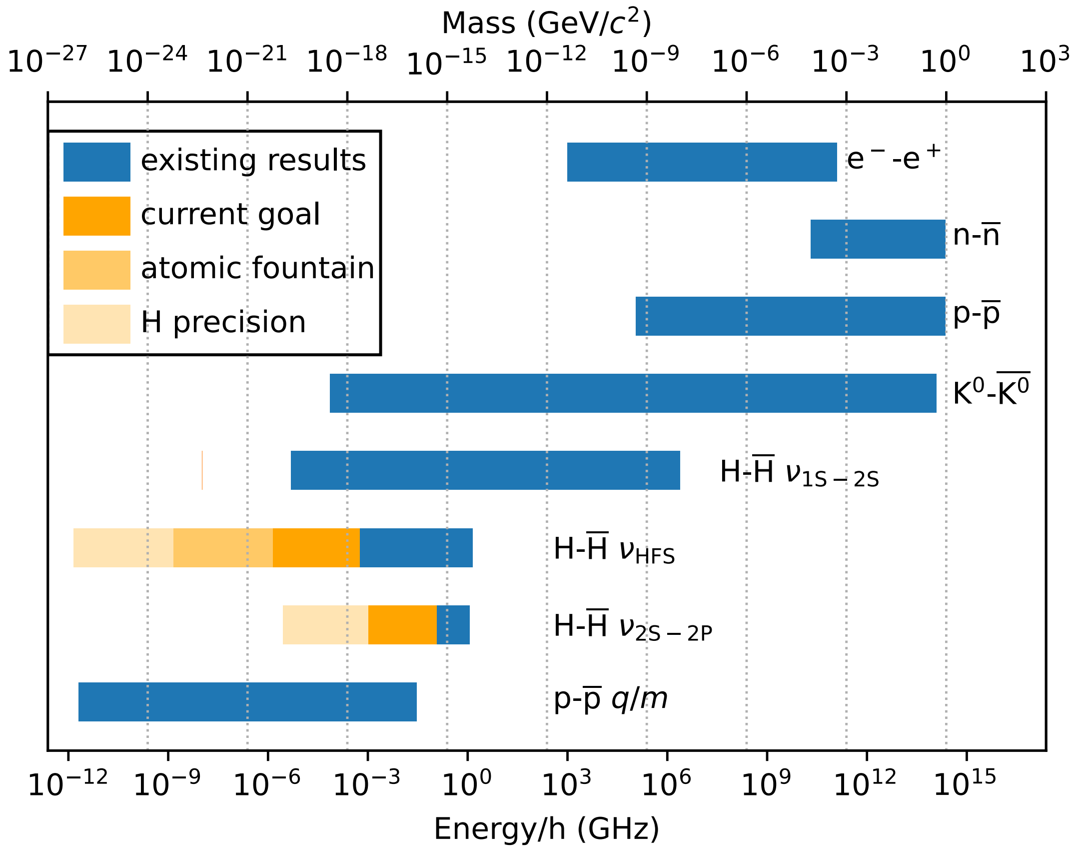
(**CPT** invariance, **Lorentz** invariance, ...)

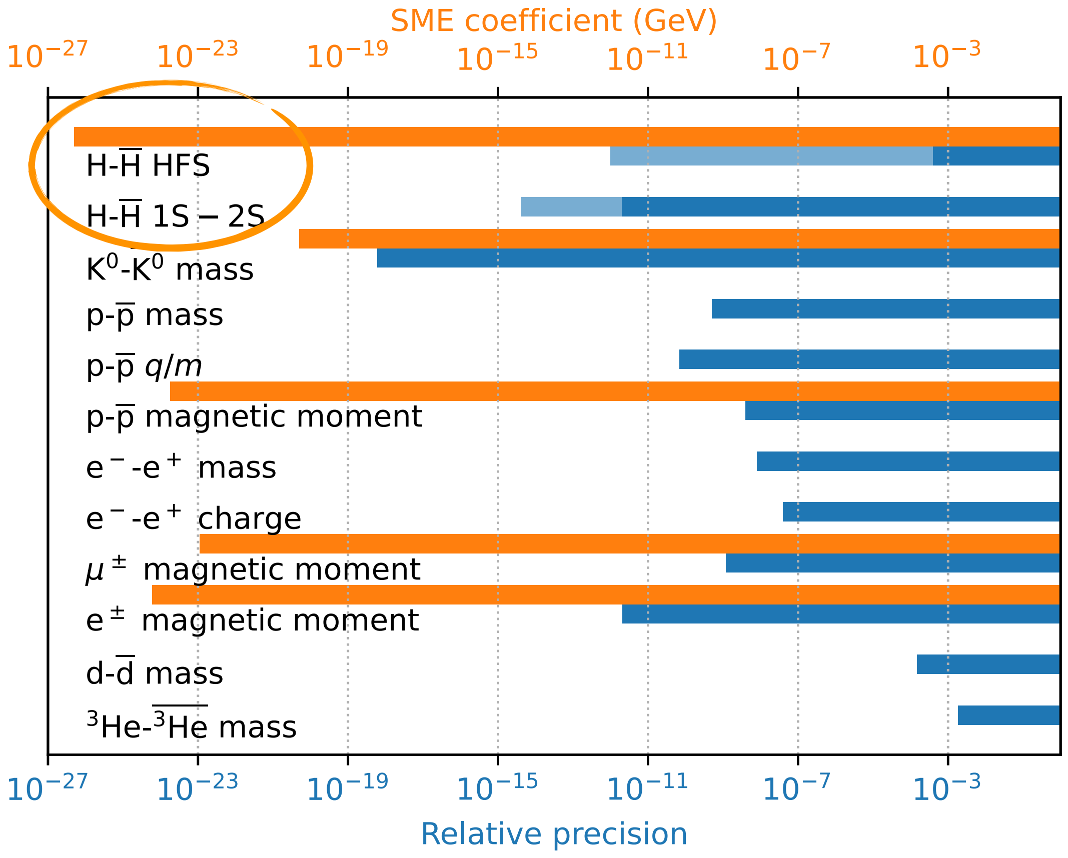
Can one look for **laboratory signals of CPT & Lorentz violation** (at the Planck scale)?

Exceptionally sensitive experiments required...

⇒ **Hydrogen and antihydrogen spectroscopy!**

Extraordinary progress in recent years! **Impressive results for CPT violation tests!**





[Widmann et al, 2111.04056]

Antimatter and new forces

Having **antimatter** gravitating in a district way corresponds to the more general possibility that **different forms of energy** **gravitate differently**...

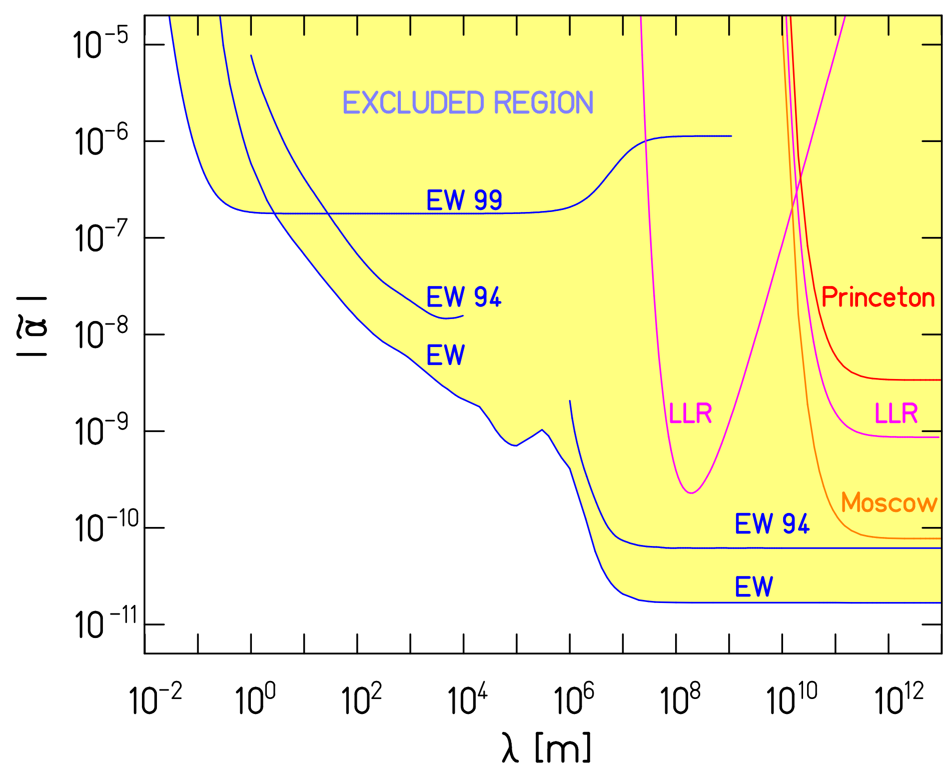
Two broad classes of theoretical possibilities

(i) modified General Relativity

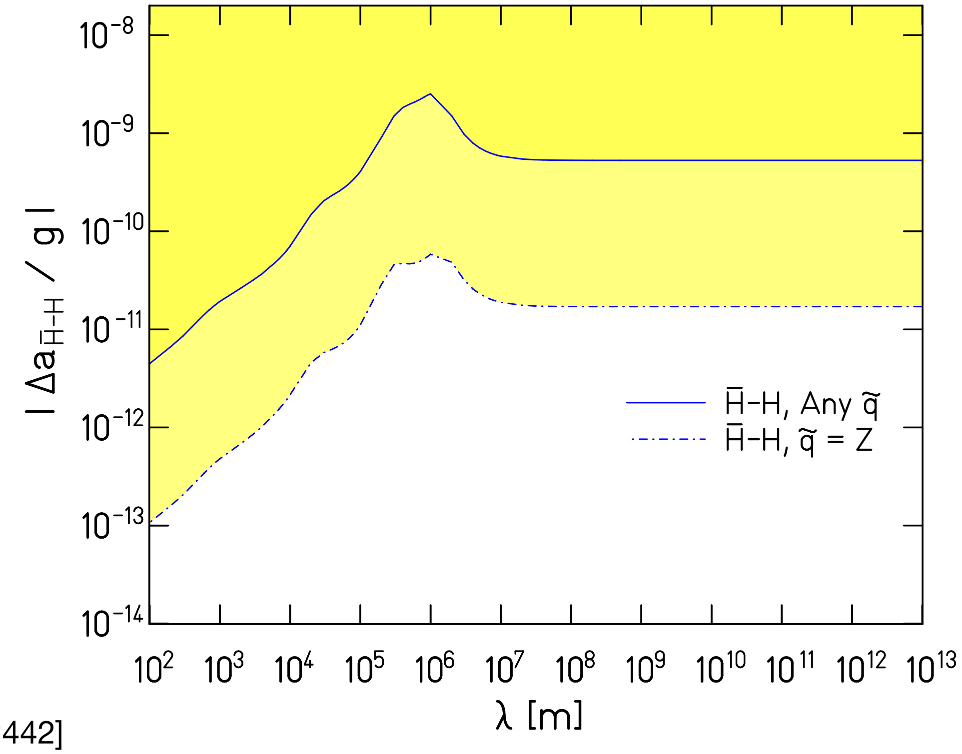
(ii) **new forces**, mediated by vectors and/or scalars, **(sub)gravitational strength**

A new (5th force) interaction: potentially **much weaker than gravity** mediated by **bosons** (M_B), **strength** $\tilde{g}$, coupling to **fermions** ($\tilde{q}$)

bounds on $\tilde{\alpha}$ for new vector interaction (with $\tilde{q} = B - L$) vs. range



bounds on $(g_{\mathrm{H}} - g_{\bar{\mathrm{H}}})/g_{\mathrm{H}}$



[Wagner et al, 1207.2442]

Thorough characterisation of antimatter

- Explaining a pressing observational problem **of the SM:**

  the matter-antimatter asymmetry of the Universe

  The **SM** offers a *strikingly simple description of antimatter:* Charge-Parity transformation

Can antimatter couple differently to gravity? Free-fall in **Earth's gravitational field**

How to study matter made of anti-constituents? Anti-hydrogen is the **best object** to consider

⇒ thorough **studies** (spectroscopy, ...) with the best available precision!

⇒ $\bar{\mathrm{H}}$ free-fall in **Earth's gravitational field** and **direct measure** of $\bar{g}$!

Recent results: $\bar{g} = (0.75 \pm 0.13_{\text{sys+stat}} \pm 0.16_{\text{sim}})\, g$

[ALPHA Collaboration, 2023]

Improve precision to ascertain $g = \bar{g}$ ⇒ **GBAR:** below 1%!

A first step in understanding gravity effects in nuclear and elementary interactions:

Couplings to virtual pairs? Couplings to binding energies? Flavour content of valence q?

⇒ Aim at **precision well below** 10^{-2}**!**

From **antihydrogen** to **antimatter** - a long road ahead! Muonium as a next stop?

Concluding remarks and theory prospects

Outlook and perspectives

- New Physics paths to discovery at **three frontiers**

  Precision tests of the SM offer uniquely promising prospects

- Explored here **several fronts:**

  cLFV transitions in the muon sector ⇒ muon-electron conversion offers an amazing probing power to NP

  EDMs in the quest for new sources of CPV ⇒ neutron EDM remarkably competitive

  EW precision tests in beta-decays ⇒ so many observables to explore, offering a joint probing power of NP sources of CPV and of NP interactions
  strong **synergy with direct LHC** searches and **EDMs!**

  Precision tests of WEK - **antihydrogen** and new gravitational interactions!

- Very strong experimental prospects!

  Theory must **reduce its uncertainties** to be **on par with experimental precision!**

  EFT is an extremely **powerful tool** ⇝ explore (UV) models of New Physics!

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Thank you for the attention!

Additional material