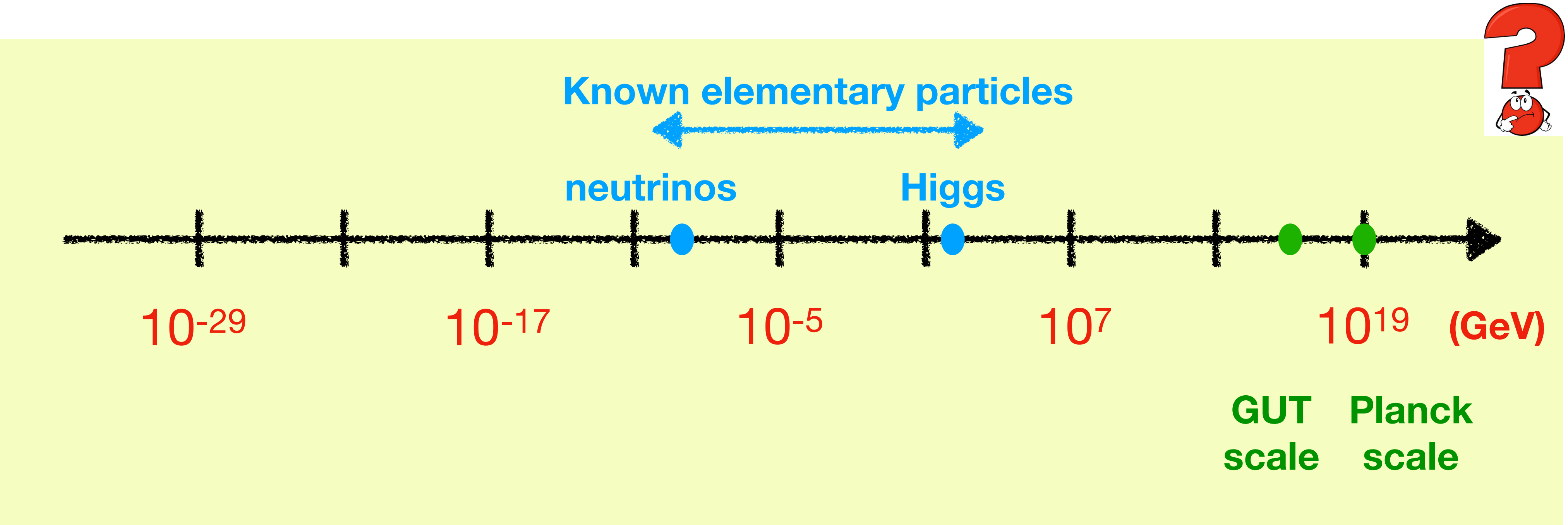
What can we learn about new physics through precision experiments?

Stefania Gori
UC Santa Cruz

ICFA Seminar, 2023

DESY
December 1, 2023

The next New Physics (NP) scale



Open problems in particle physics

Dark Matter

Neutrino masses

Strong CP problem

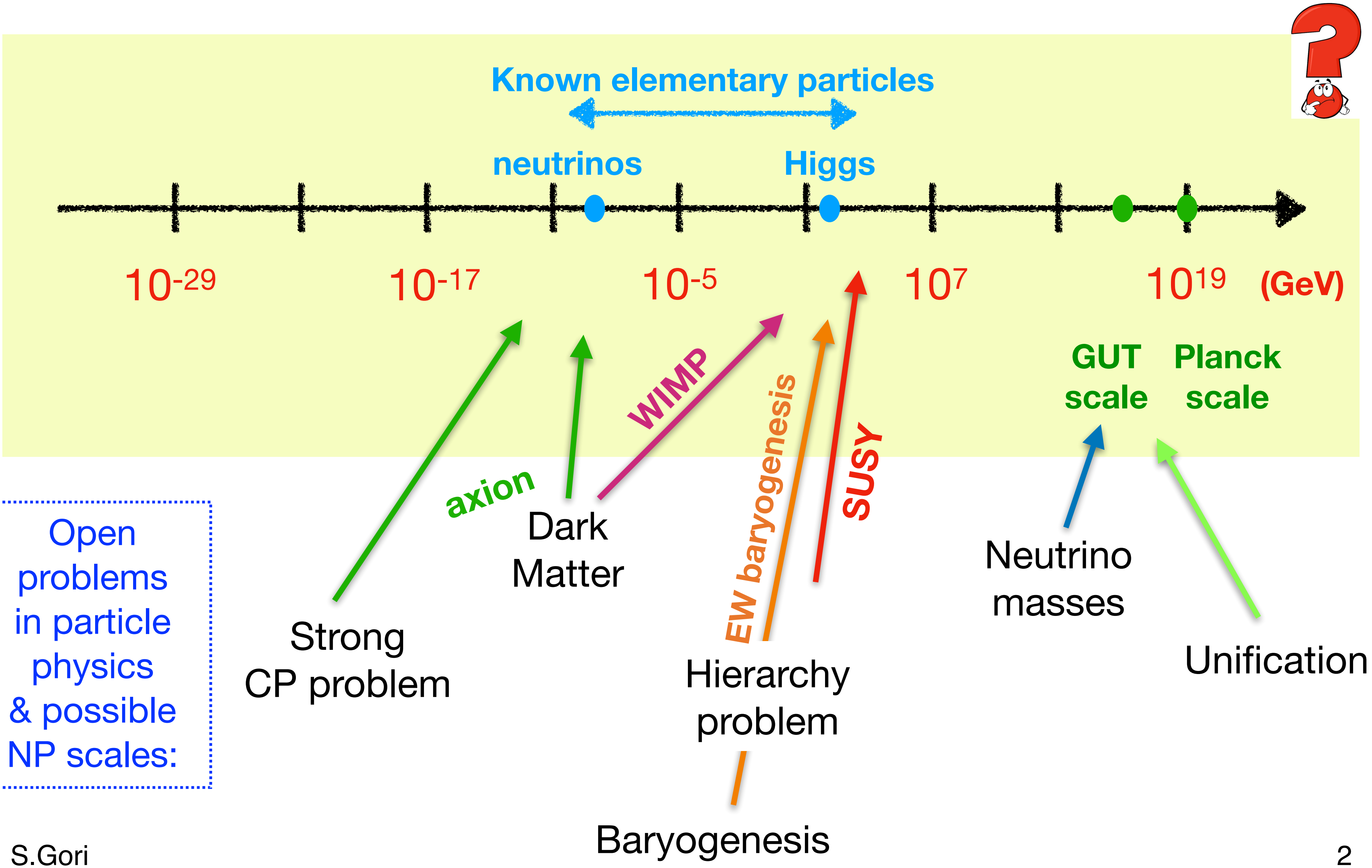
Hierarchy problem

Unification

Baryogenesis

S.Gori

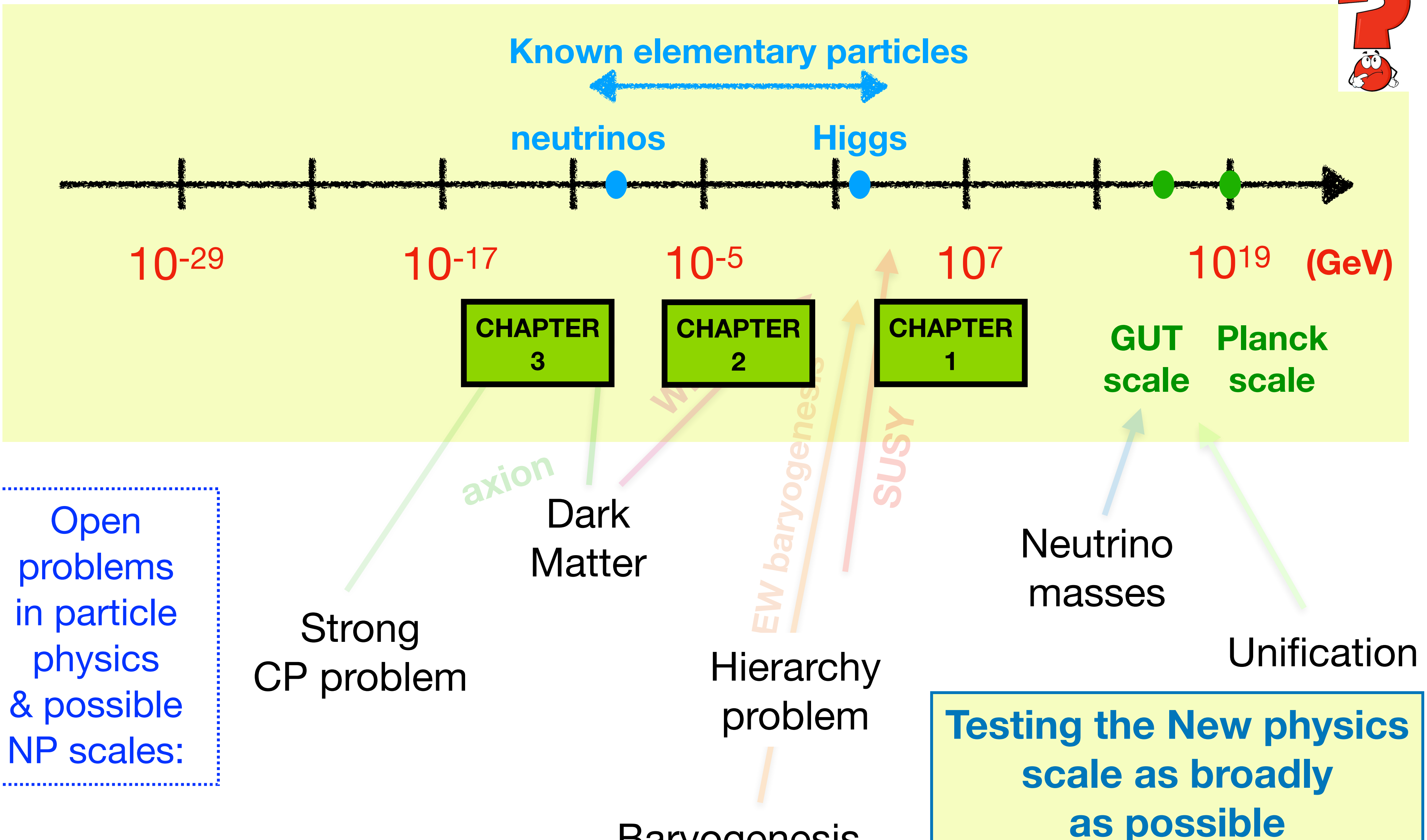
The next New Physics (NP) scale



Open problems in particle physics & possible NP scales:

S.Gori

The next New Physics (NP) scale



Known elementary particles

neutrinos

Higgs

10^{-29} 10^{-17} 10^{-5} 10^{7} 10^{19} **(GeV)**

CHAPTER 3

CHAPTER 2

CHAPTER 1

GUT scale

Planck scale

axion

WI

EW baryogenesis

SUSY

Strong CP problem

Dark Matter

Hierarchy problem

Baryogenesis

Neutrino masses

Unification

Open problems in particle physics & possible NP scales:

Testing the New physics scale as broadly as possible

S.Gori

The power of precision experiments

1. Tests of the validity of the Standard Model (SM).

Particle physics is **not only about the discovery of new particles**.

It's about the laws of nature, which include the interactions and properties of the particles that we have already discovered.

The power of precision experiments

1. Tests of the validity of the Standard Model (SM).

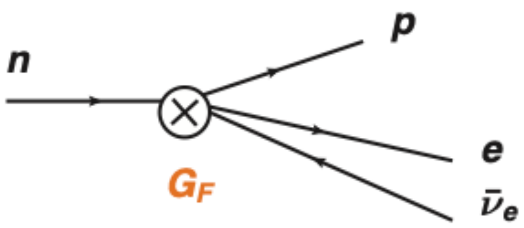
Particle physics is **not only about the discovery of new particles**.

It's about the laws of nature, which include the interactions and properties of the particles that we have already discovered.

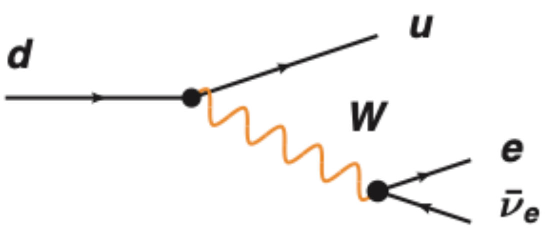
Focus of this talk

Chap.1

2. Indirect discovery of heavy New Physics:



Effective field theory (EFT)



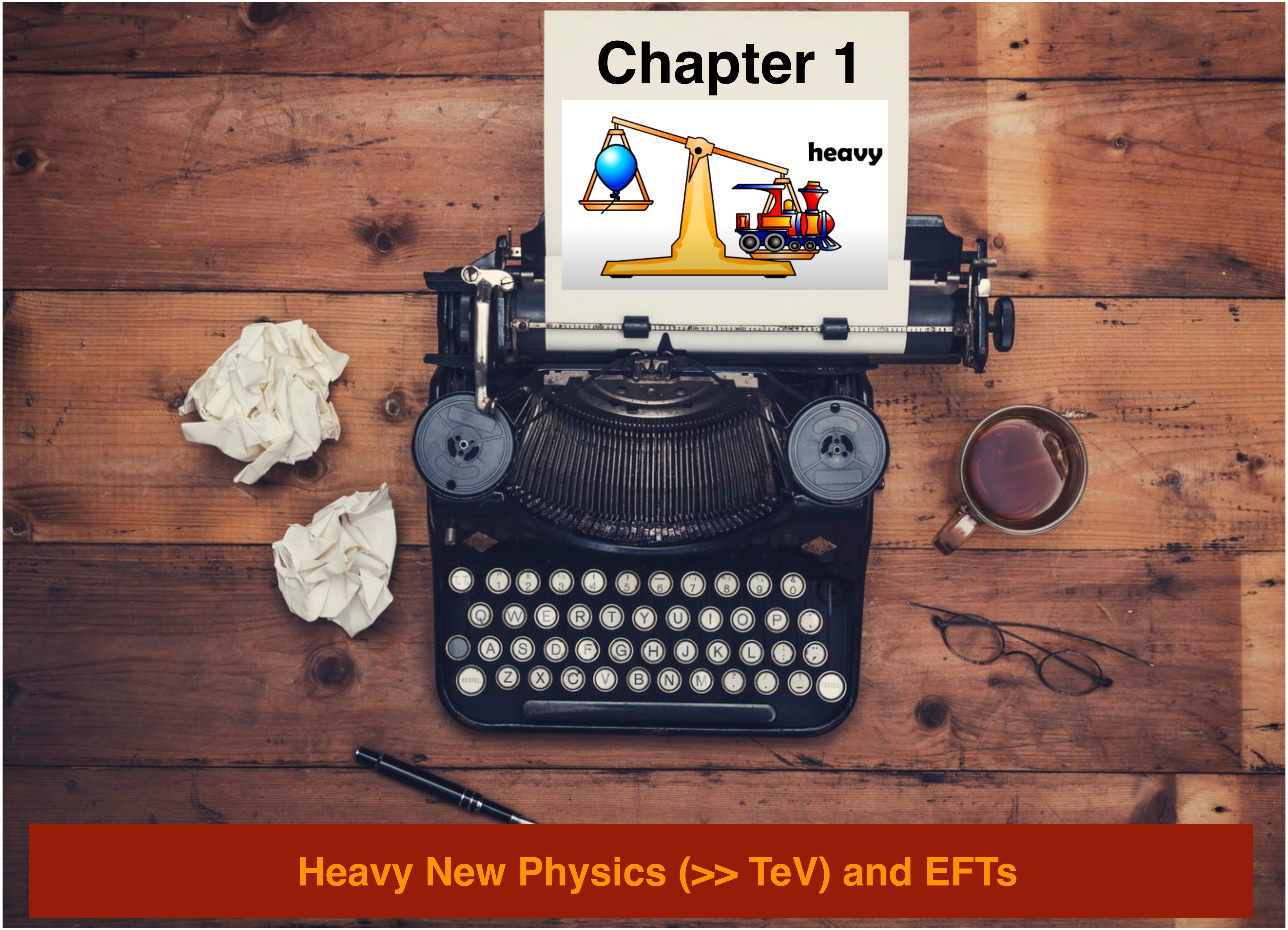
Full theory

Disclaimer: a selected set of topics

New physics through the observation of effects of virtual particles.

3. Detection of very rare events induced from light New Physics.

Chap.2,3



Chapter 1

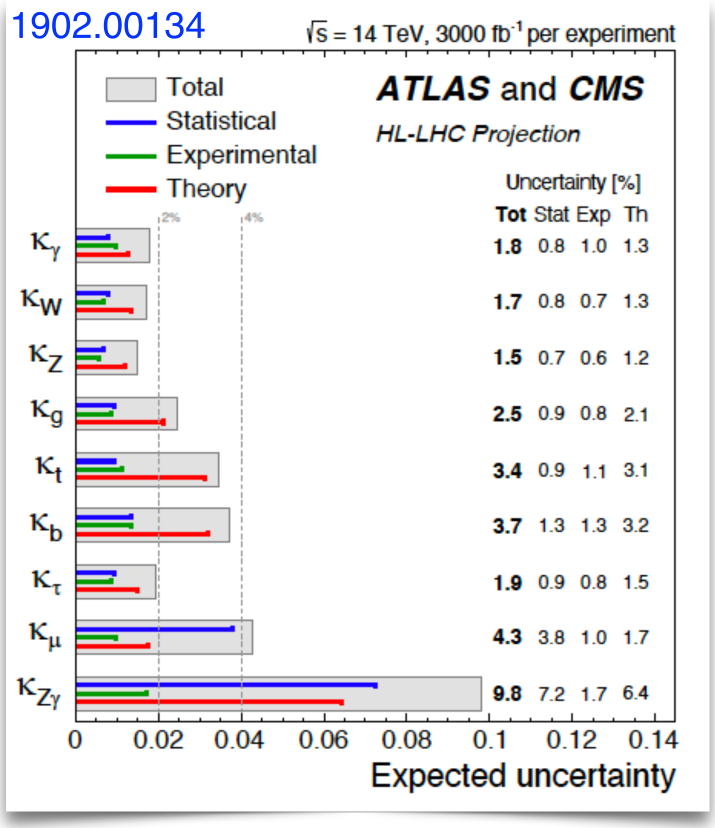
Heavy New Physics (>> TeV) and EFTs

Higgs precision couplings and NP

At Run 2, measurement precision is at the ~5-10% level

ATLAS-CONF-2020-027, CMS-PAS-HIG-19-005

1902.00134



Uncertainty [%]

	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

Projections assume theory uncertainties are halved.

“k framework”:

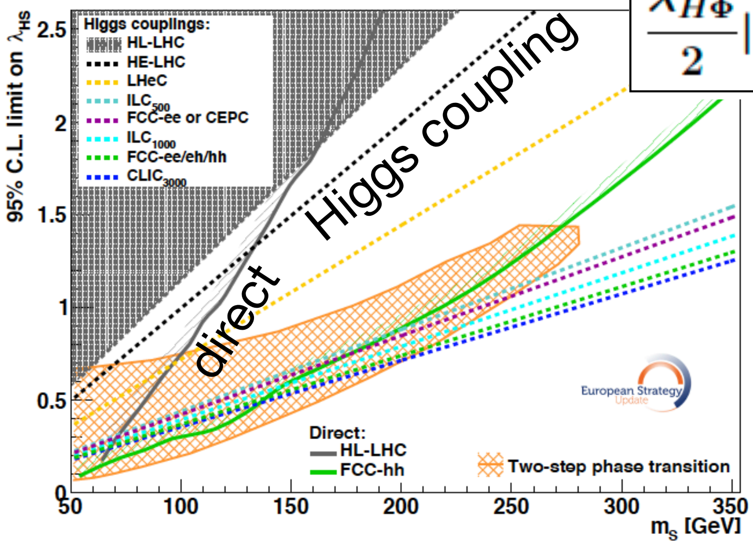
In any NP model.

$$\kappa \equiv \frac{\text{Coupling}^{\text{NP}}_{\text{Higgs}}}{\text{Coupling}^{\text{SM}}_{\text{Higgs}}}$$

We can extract these via measuring the Higgs rates at the LHC

New particles generically affect the Higgs couplings

$$\frac{\lambda_{H\Phi}}{2}|H|^2|\Phi|^2$$



Physics briefing book, 1910.11775

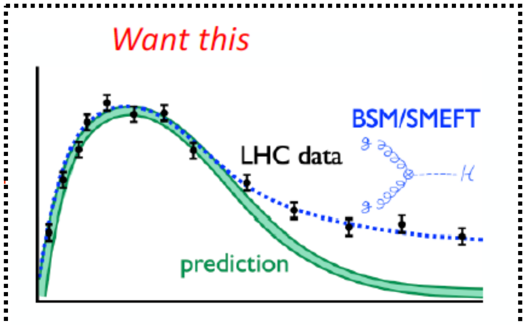
Higgs distributions & SMEFT

The LHC not only measures Higgs rates but also Higgs event distributions.

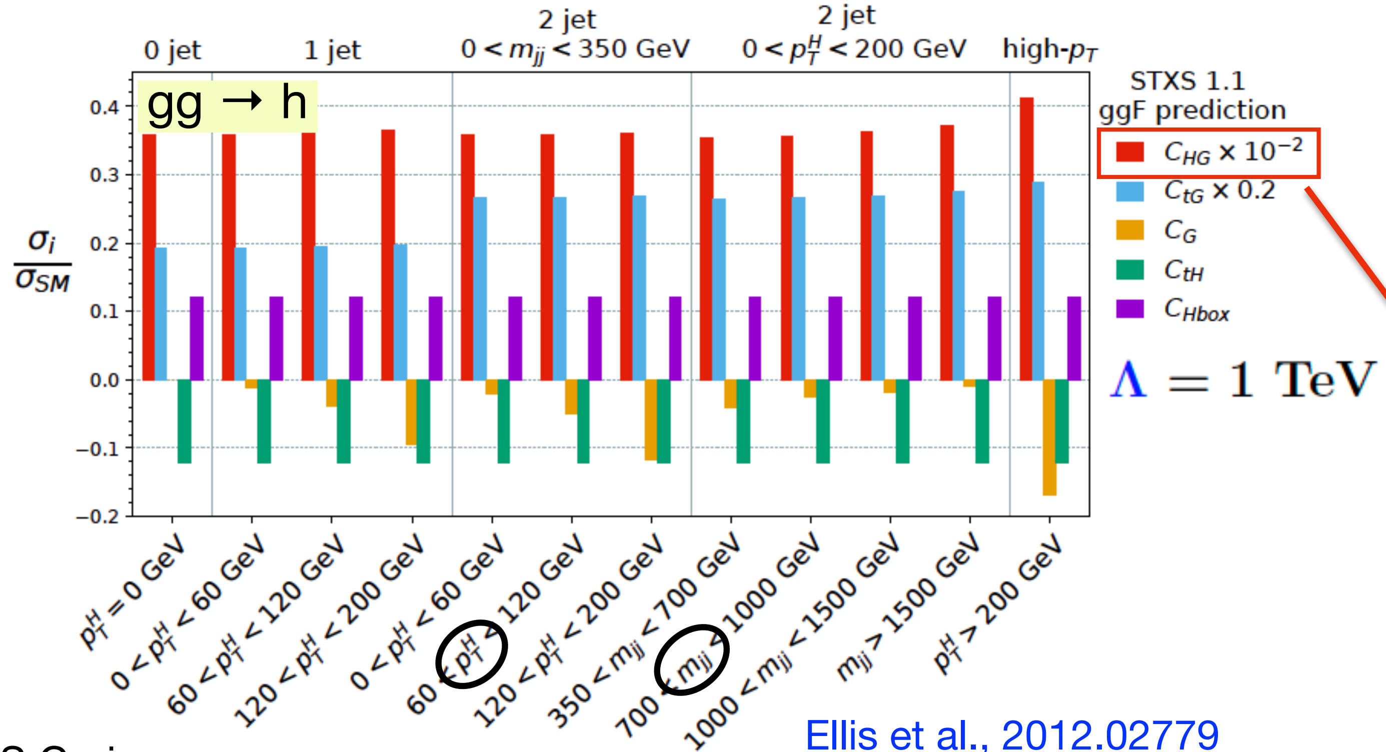
These can be used to set bounds on the SMEFT Lagrangian.

(The idea is to write the most general Lagrangian containing SM particles up to dimension 6 satisfying the SM gauge symmetry and assuming flavor universality)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^6}{\Lambda^2}\mathcal{O}_i$$



Zanderighi



$$\Lambda = 1\ \text{TeV}$$

Ellis et al., 2012.02779

Example:

$$\boxed{\mathcal{O}_{HG}} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}$$

S.Gori

Collider precision program

It’s not just the Higgs

- top quark data,
- gauge boson pair production,
- EW precision observables,
- di-lepton production,…

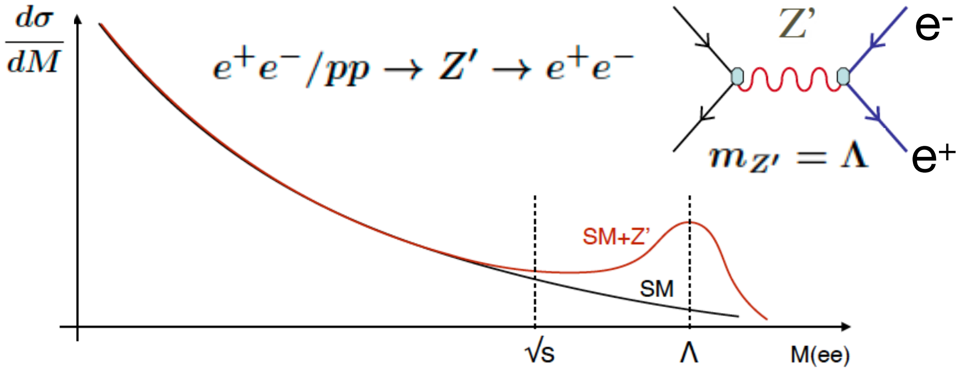
all contribute to constrain SMEFT.

Collider precision program

It’s not just the Higgs

- top quark data,
- gauge boson pair production,
- EW precision observables,
- di-lepton production,…

all contribute to constrain SMEFT.



From M. Mangano, LISHEP 2023

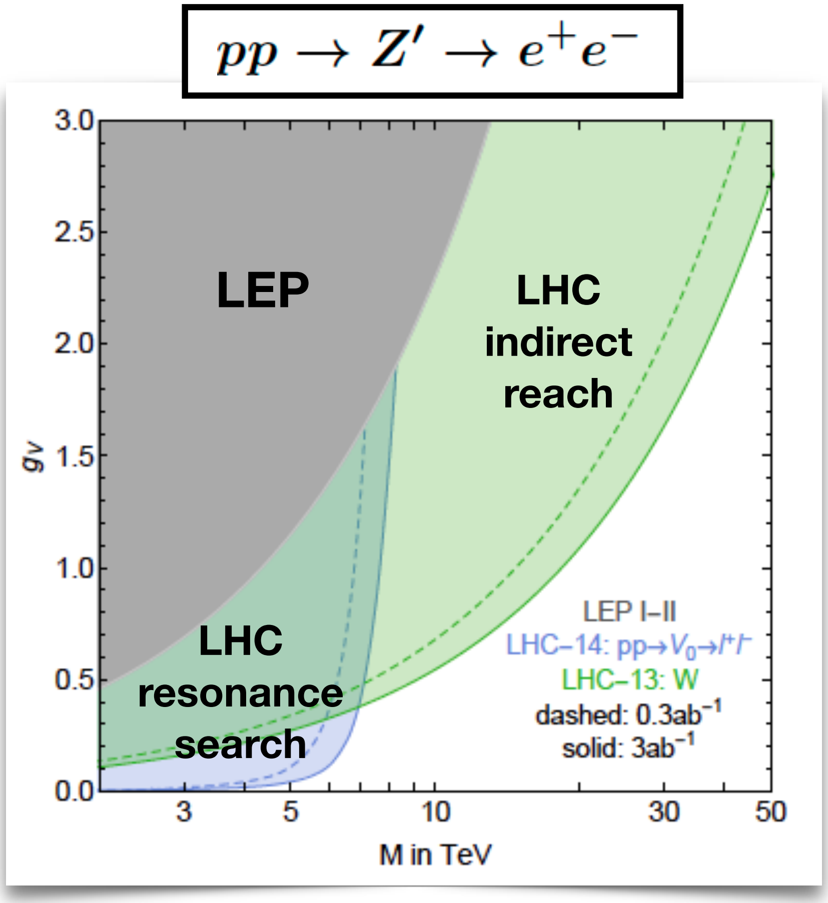
$$\sigma = \sigma_{\rm SM} \times \left(1 + g^2 \frac{s}{\Lambda^2}\right)$$

$$\Rightarrow \Lambda_{\rm max} \sim g\frac{\sqrt{s}}{\sqrt{\Delta\sigma/\sigma}}$$

← kinematic reach (numerator $\sqrt{s}$)

← precision (denominator $\sqrt{\Delta\sigma/\sigma}$)

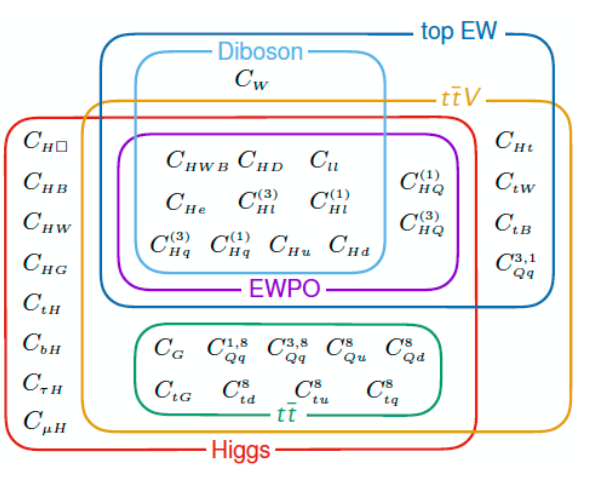
g large → the reach of precision measurements can be higher than the kinematical reach

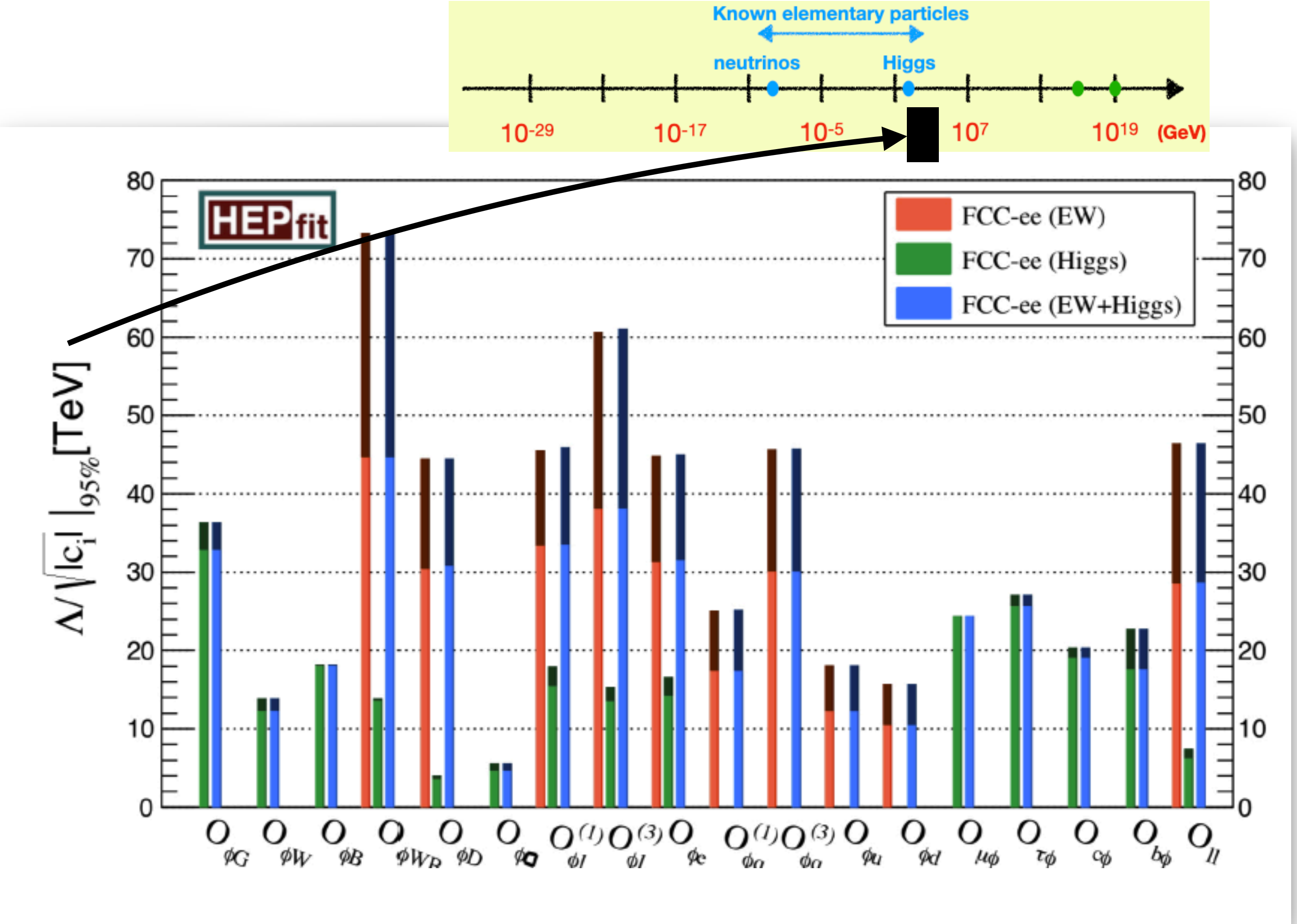


Farina et al., 1609.08157

Towards global fits of SMEFT coefficients

Ellis et al., 2012.02779





Theorists are at the forefront of SMEFT fits. Lot of work still needed for better understanding uncertainties.

100 TeV is the appropriate CoM energy to directly search for new physics appearing indirectly through precision electro-weak (EW) and H measurements at the future e^+e^- collider

Flavor and precision

We do not know if the flavor symmetry of quarks and leptons ($SU(3)^5$) is only broken by the Standard Model Yukawa couplings.

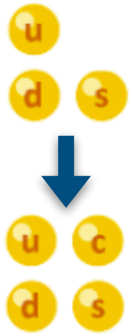
→ New contributions to flavor transitions can occur.

Historically, measuring rare flavor transitions led to big discoveries in particle physics:

Suppression of the branching ratio of $K_L \to \mu^+\mu^-$

→ prediction of the charm quark

(Glashow, Iliopoulos, Maiani, 1970)



Flavor and precision

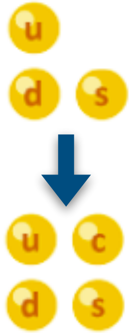
We do not know if the flavor symmetry of quarks and leptons ($SU(3)^5$) is only broken by the Standard Model Yukawa couplings.

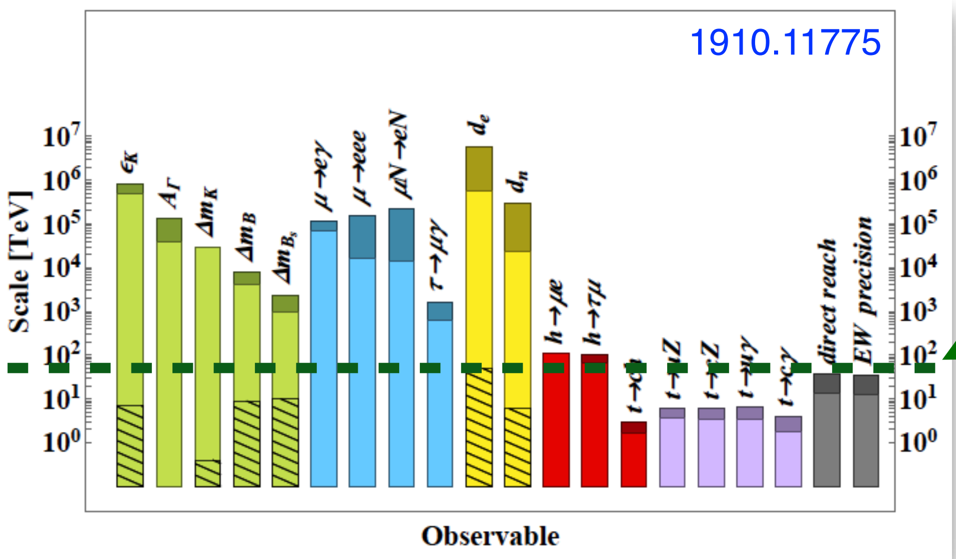
→ New contributions to flavor transitions can occur.

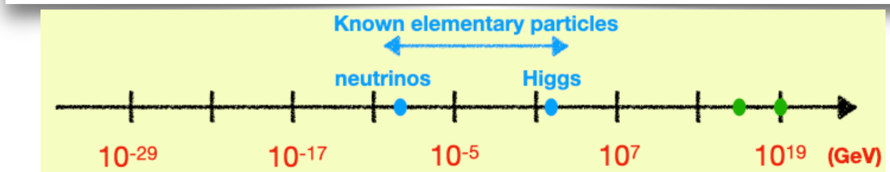
Historically, measuring rare flavor transitions led to big discoveries in particle physics:

Suppression of the branching ratio of $K_L \to \mu^+\mu^-$

→ prediction of the charm quark (Glashow, Iliopoulos, Maiani, 1970)







<u>Flavor transitions</u>: access to very high New physics scales, not directly accessible at collider experiments.

Caveat: this is assuming O(1) flavor breaking coupling.

E.g., $\frac{1}{\Lambda^2}(\bar{b}_R d_L)(\bar{b}_L d_R)$

[redacted]

Flavor and precision

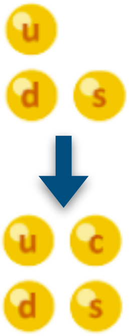
We do not know if the flavor symmetry of quarks and leptons ($SU(3)^5$) is only broken by the Standard Model Yukawa couplings.

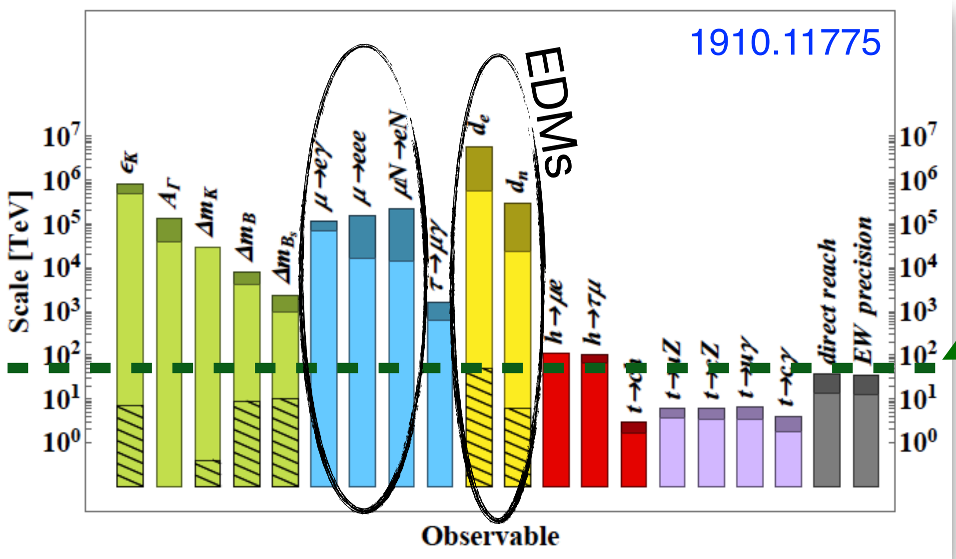
→ New contributions to flavor transitions can occur.

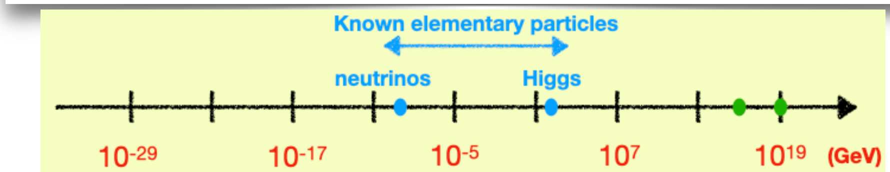
Historically, measuring rare flavor transitions led to big discoveries in particle physics:

Suppression of the branching ratio of $K_L \to \mu^+\mu^-$

→ prediction of the charm quark (Glashow, Iliopoulos, Maiani, 1970)







Flavor transitions: access to very high New physics scales, not directly accessible at collider experiments.

Caveat: this is assuming O(1) flavor breaking coupling.

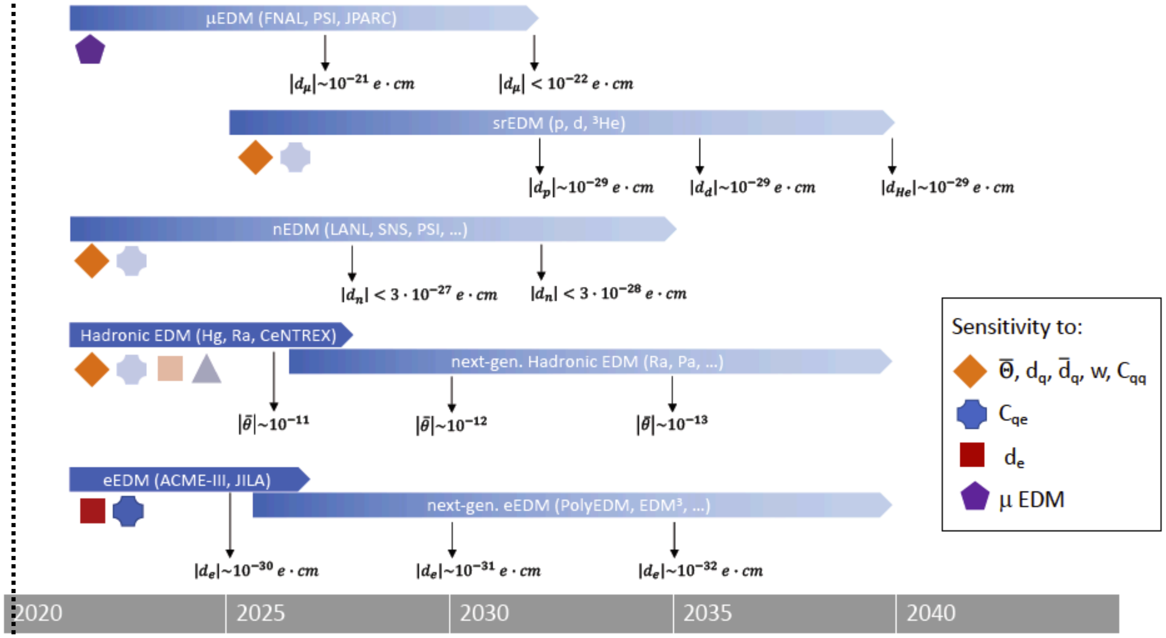
E.g., $\frac{1}{\Lambda^2}(\bar{b}_R d_L)(\bar{b}_L d_R)$

[redacted]

Electric dipole moments (EDMs)

To explain the baryon-antibaryon asymmetry of the Universe we generically need new sources of CP violation (CPV) beyond the Standard Model CKM phase.
New sources of CPV are highly constrained by searches for EDMs.

Remarkable precision of present and future searches:



Blum, Winter, et al., Snowmass, 2209.08041

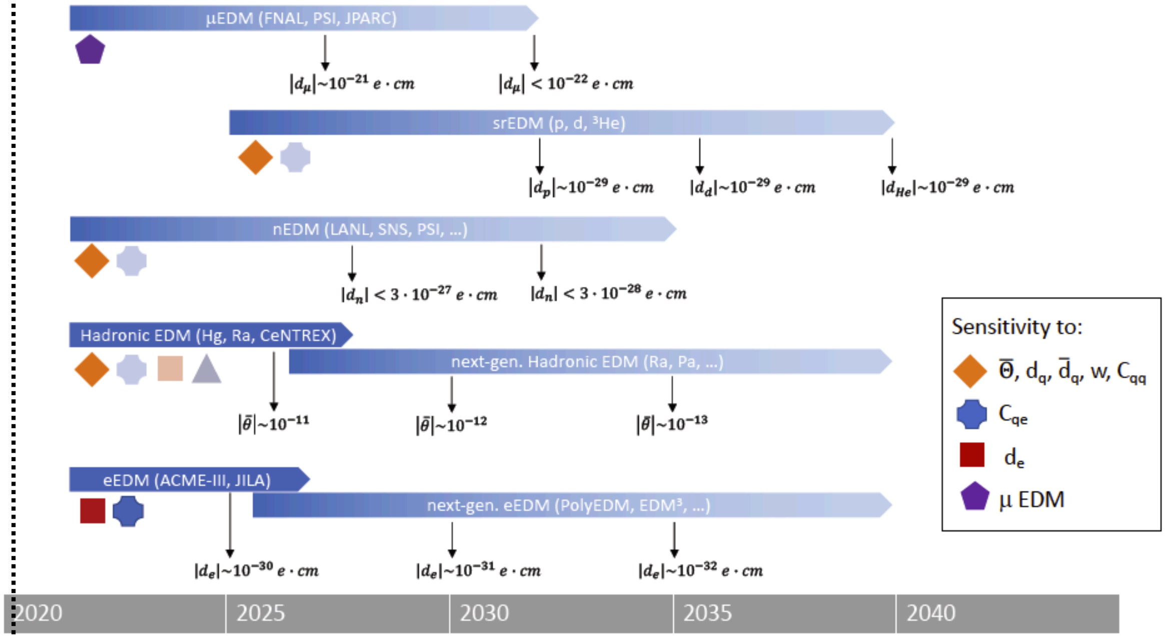
scales at the level of 10^7 TeV will be probed

S.Gori see also Alarcon et al., Snowmass, 2203.08103

Electric dipole moments (EDMs)

To explain the baryon-antibaryon asymmetry of the Universe we generically need new sources of CP violation (CPV) beyond the Standard Model CKM phase.
New sources of CPV are highly constrained by searches for EDMs.

Remarkable precision of present and future searches:

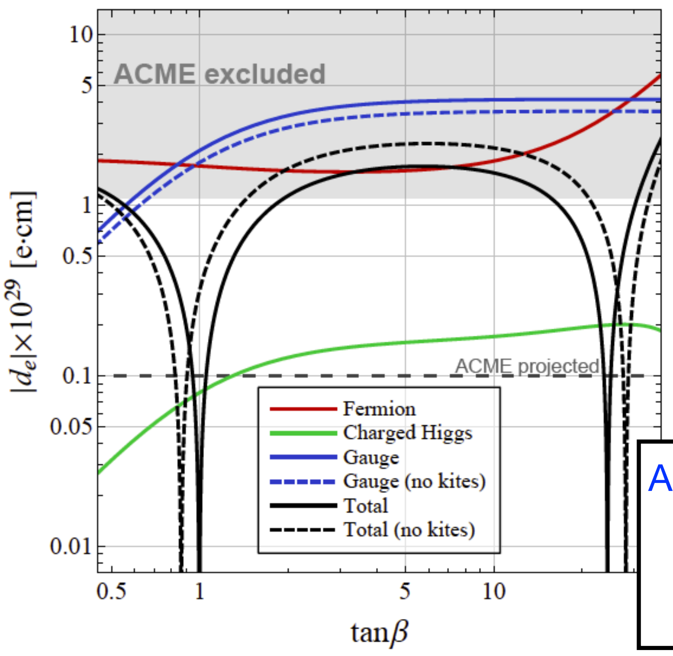


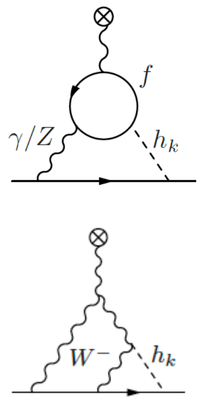
Blum, Winter, et al., Snowmass, 2209.08041

scales at the level of 10^7 TeV will be probed

If O(1) CPV and EW scale, then we generically need cancelations.

E.g., in a CPV Two-Higgs-Doublet-Model

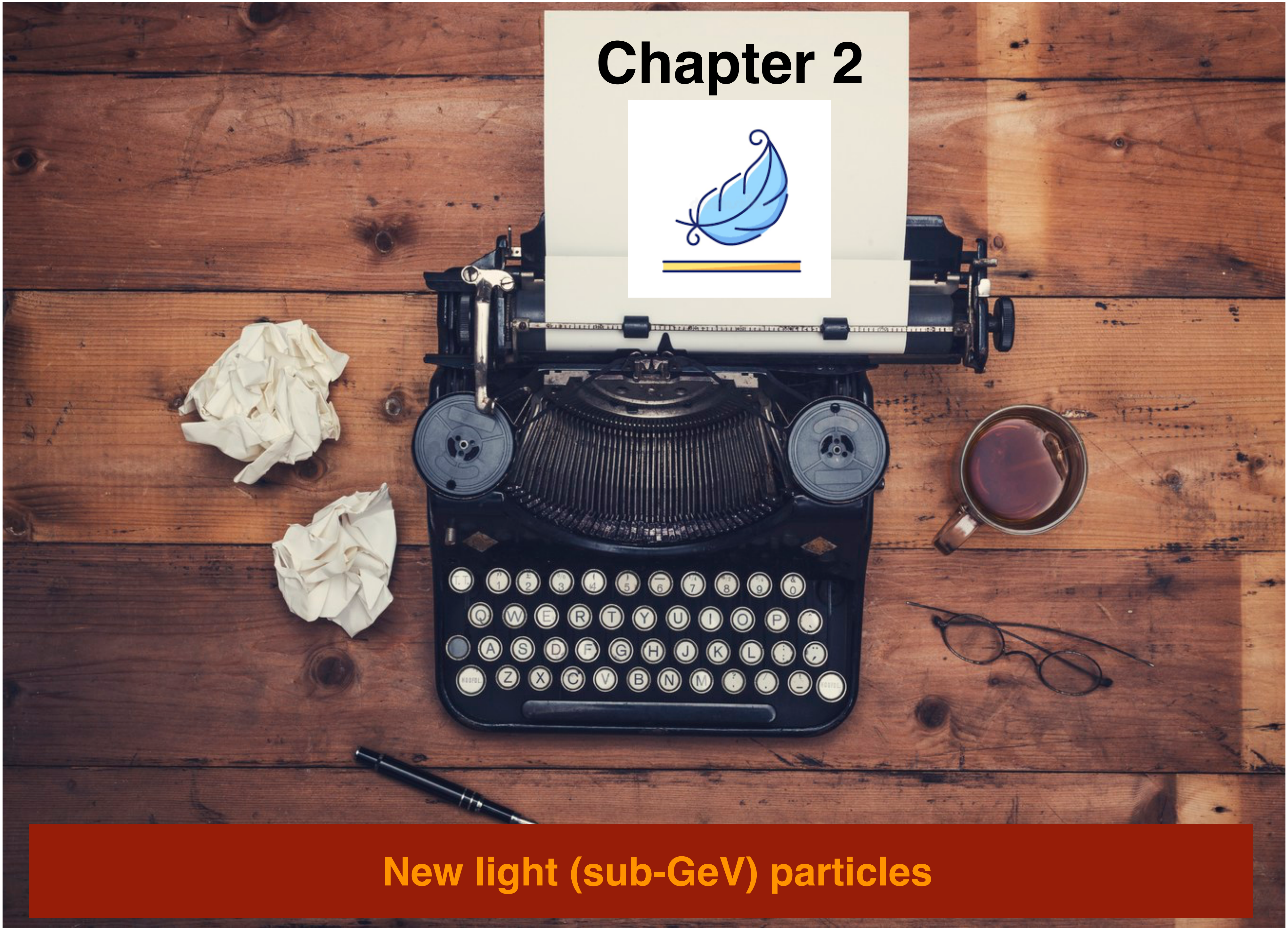




Altmannshofer, SG, Hamer, Patel, 2009.01258

Complementarity with direct searches for CPV at the LHC

see also Alarcon et al., Snowmass, 2203.08103

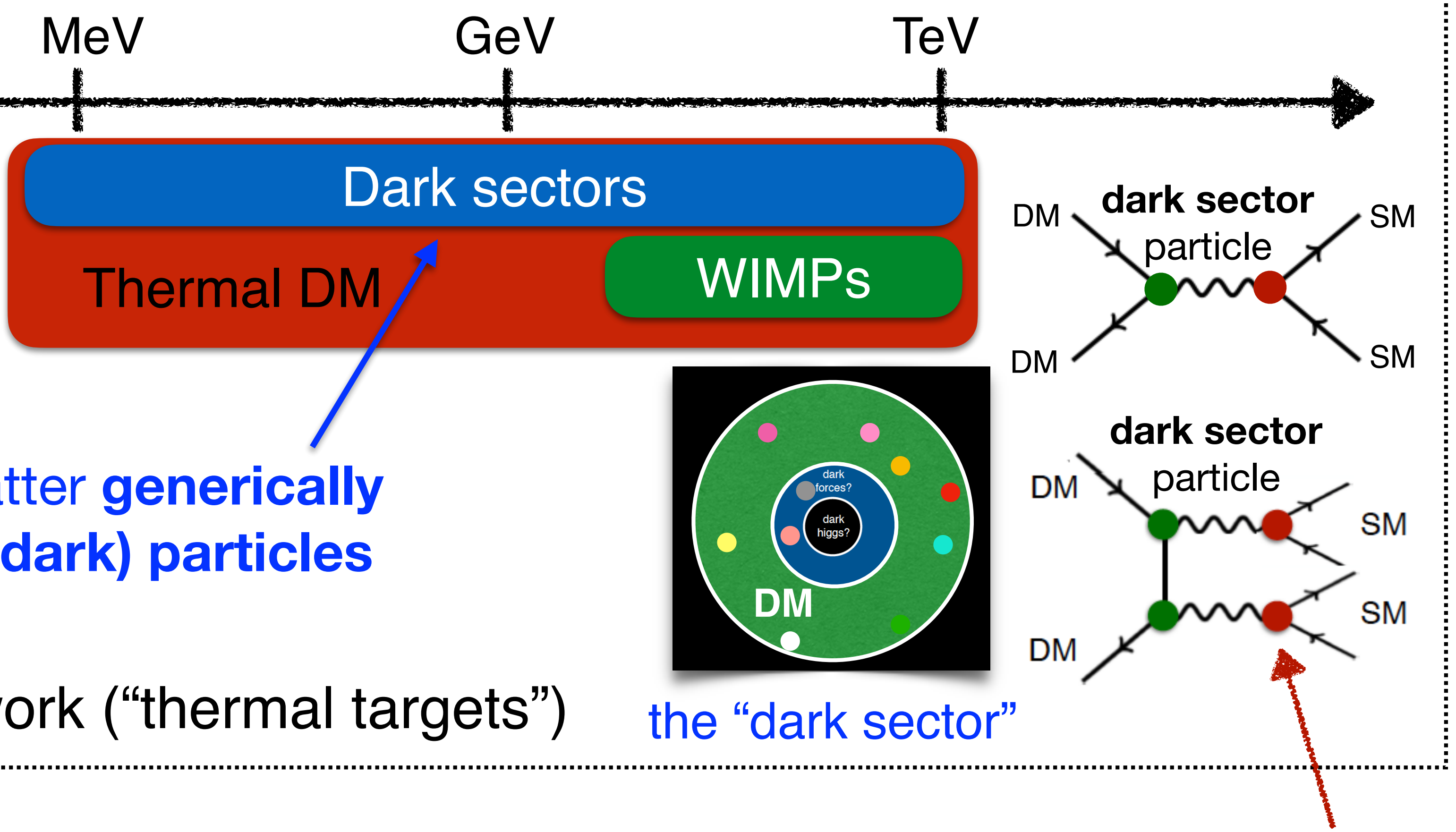


Chapter 2

New light (sub-GeV) particles

Motivations for new sub-GeV particles

The DM mass scale



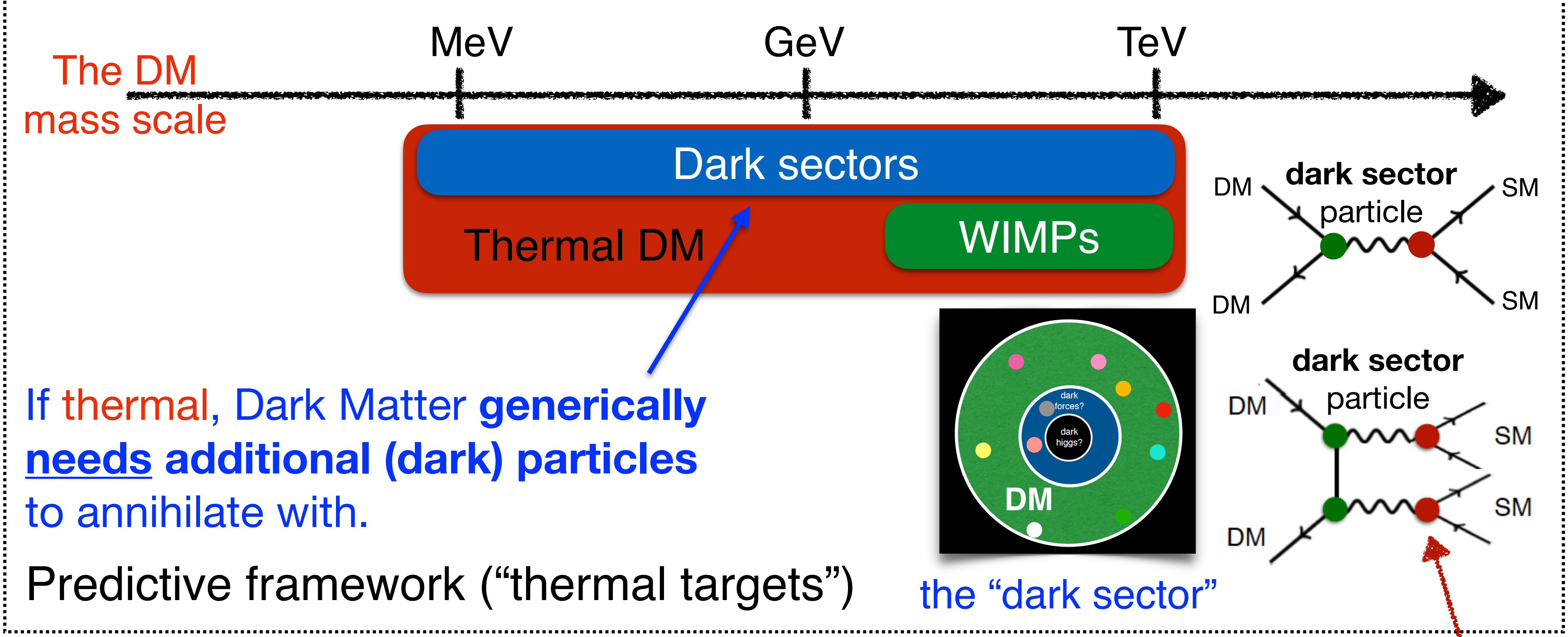
the “dark sector”

If thermal, Dark Matter **generically** **<u>needs</u> additional (dark) particles** to annihilate with.

Predictive framework (“thermal targets”)

generically small couplings (need precision)

Motivations for new sub-GeV particles



If thermal, Dark Matter **generically** **<u>needs</u> additional (dark) particles** to annihilate with.

Predictive framework (“thermal targets”)

the “dark sector”

generically small couplings (need precision)

Sub-GeV dark sectors also arise in theories

- that address the strong CP problem (e.g., axion-like-particles);
- with a spontaneously broken global symmetry;
- that generate neutrino masses (e.g., sterile neutrinos);
- that address anomalies in data; …

The role of precision experiments to test dark sectors

Accelerator experiments can produce and detect dark sector particles.

These are generically very rare events that can be searched for at precision experiments.

High and low energy colliders

Meson factories

Fixed target (beam dump) experiments

see e.g. the Snowmass report “Dark Sector Physics at High-Intensity Experiments” SG, Williams et al., 2209.04671

The role of precision experiments to test dark sectors

Accelerator experiments can produce and detect dark sector particles.

These are generically very rare events that can be searched for at precision experiments.

High and low energy colliders

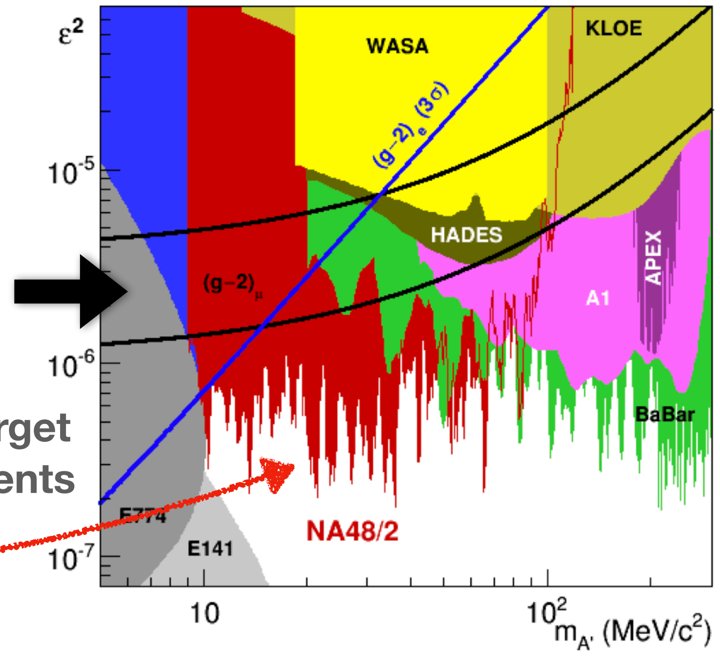
Meson factories

Fixed target (beam dump) experiments

Several milestones have been reached in the past. For example:

1. Minimal dark photon explanation of **$(g-2)_\mu$** is fully probed.

Phys. Lett. B 746 (2015) 178



Low energy colliders

Meson factories

Fixed target experiments

How rare is rare?

$\mathrm{BR}(\pi^0 \to \gamma A') < \mathcal{O}(10^{-6})$

The role of precision experiments to test dark sectors

Accelerator experiments can produce and detect dark sector particles.

These are generically very rare events that can be searched for at precision experiments.

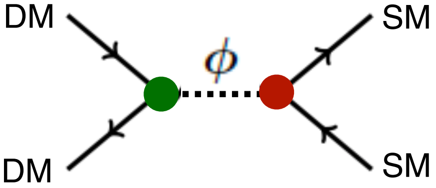
High and low energy colliders

Meson factories

Fixed target (beam dump) experiments

Several milestones have been reached in the past. For example:

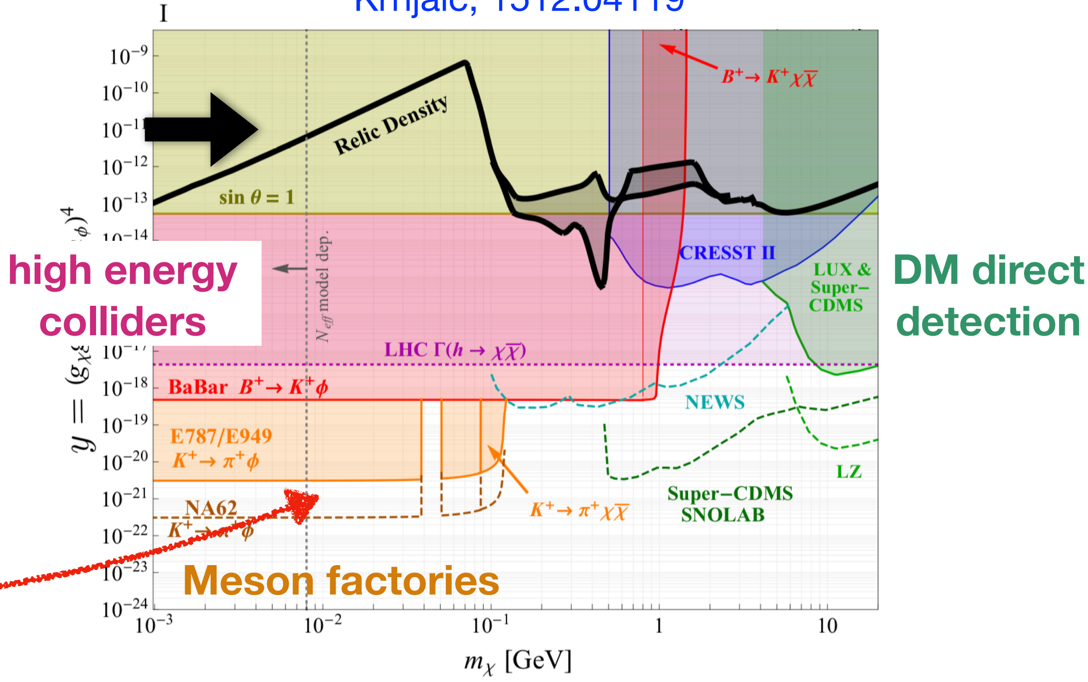
2. Minimal scalar-mediated thermal DM is fully probed.



How rare is rare?

$$\mathrm{BR}(K^+ \to \pi^+ \phi) < \mathcal{O}(10^{-11})$$

Krnjaic, 1512.04119



Future: testing light DM at precision experiments

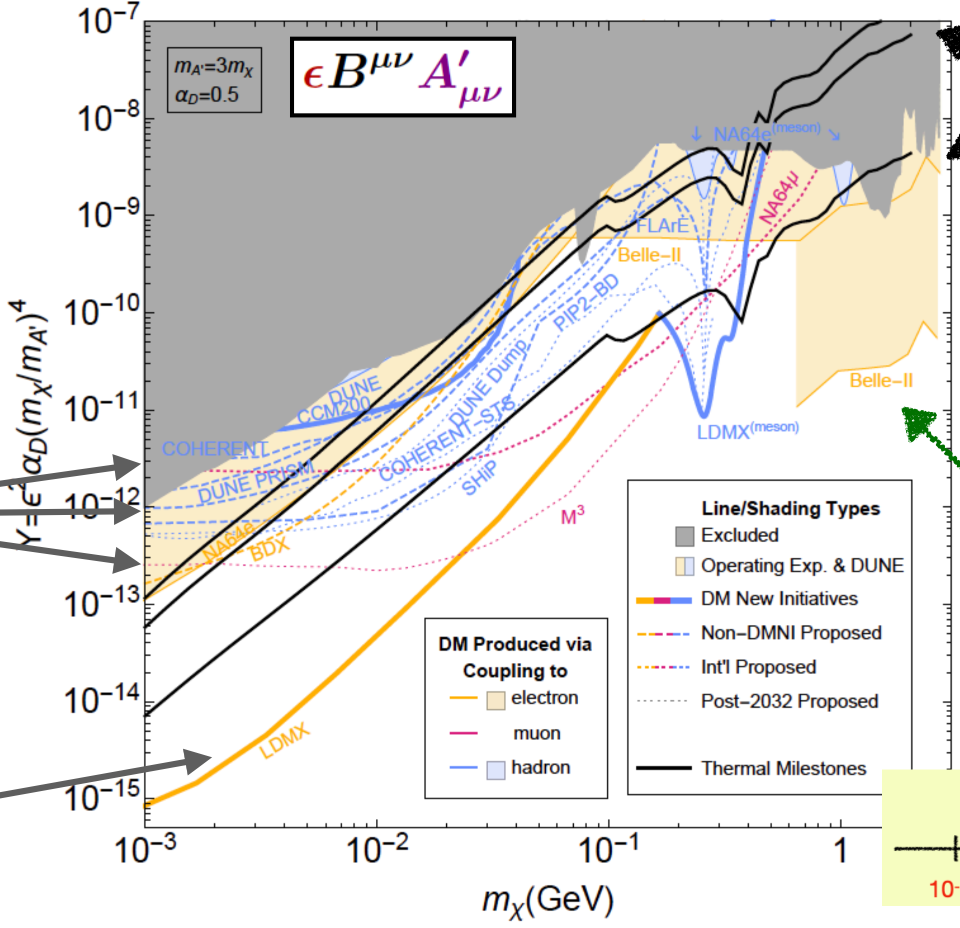
Accelerator experiments are optimal for the discovery of DM whose interactions are suppressed at low velocities, including thermal freeze-out through a dark photon, A’, with generic spin and mass structure.

Future: testing light DM at precision experiments

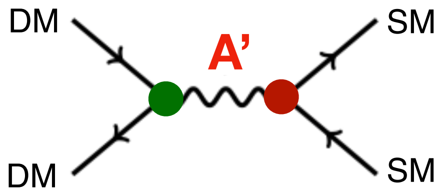
Accelerator experiments are optimal for the discovery of DM whose interactions are suppressed at low velocities, including thermal freeze-out through a dark photon, A', with generic spin and mass structure.

In the coming decade, we will have the opportunity to **broadly probe the thermal freeze-out framework**

Snowmass report, Krnjaic, Toro, et al., 2207.00597



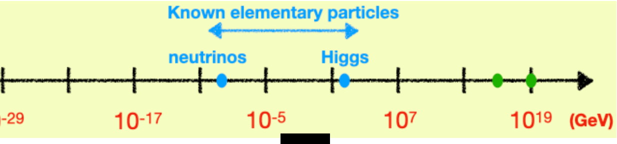
benchmarks for thermal DM



Meson factories (missing energy)

Beam dump (Re-scattering)

Fixed target (Missing momentum)



[redacted]

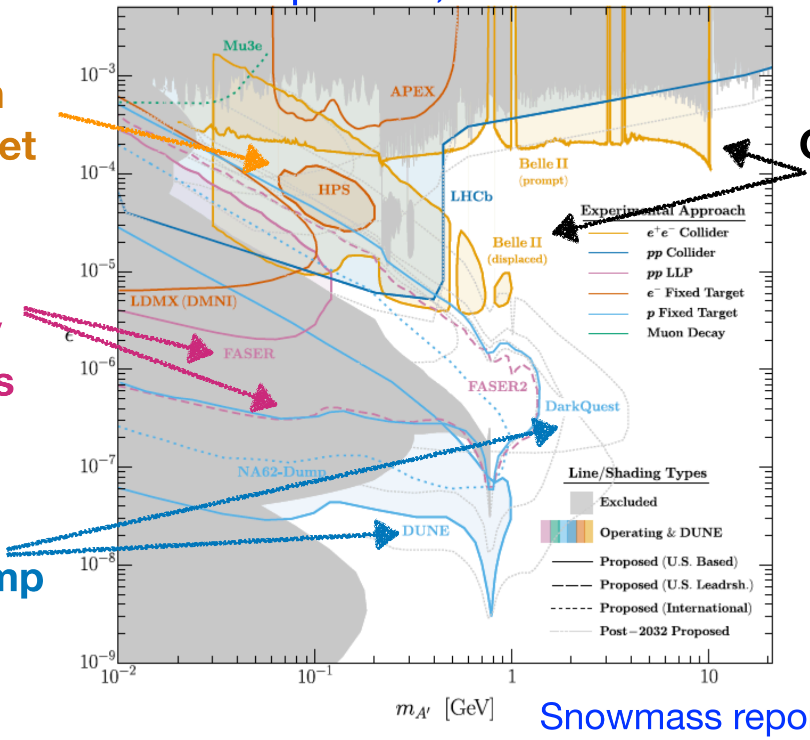
Future: Testing light dark particles at precision experiments

Dark particles that decay back to SM particles are a generic feature of dark sector models. Present and future colliders, meson factories, and beam dump experiments will reach new milestones.

Future: Testing light dark particles at precision experiments

Dark particles that decay back to SM particles are a generic feature of dark sector models. Present and future colliders, meson factories, and beam dump experiments will reach new milestones.

Dark photon, A’ → SM SM



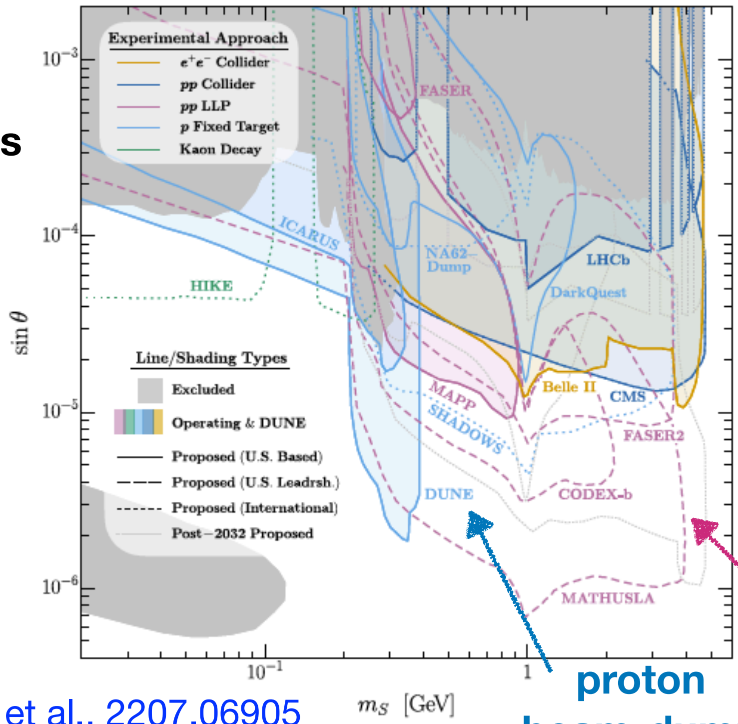
electron fixed target

LHC auxiliary detectors

proton beam-dump

Colliders

Dark scalar, S → SM SM

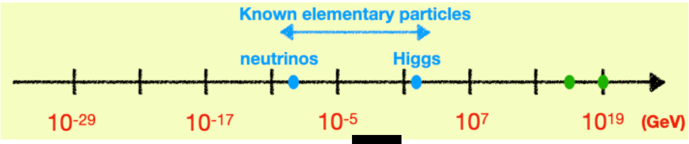


LHC auxiliary detectors

proton beam-dump

Snowmass report, Batell et al., 2207.06905

+ searches for <u>non-minimal</u> dark sectors, in which some of the particles are metastable
(inelastic DM, strongly interacting massive particles, …)



[redacted]

Chapter 3

New ultra-light wave-like particles

Sub eV-scale New Physics

Why sub-eV particles?

- The QCD axion is one of the most motivated Dark Matter candidates
- More generic light axion-like-particles possibly connected to the strong CP problem
- “Fuzzy” dark matter candidates
- Majorons to generate neutrino masses, or to ameliorate the Hubble tension
- Relaxions to address the hierarchy problem; …

Sub eV-scale New Physics

Why sub-eV particles?

- The QCD axion is one of the most motivated Dark Matter candidates
- More generic light axion-like-particles possibly connected to the strong CP problem
- “Fuzzy” dark matter candidates
- Majorons to generate neutrino masses, or to ameliorate the Hubble tension
- Relaxions to address the hierarchy problem; …

Sub-eV particles described by an oscillating classical field

Phenomenological effects:

- precession of nuclear or electron spins
- production of photons and currents in electromagnetic systems
- equivalence principle-violating accelerations of matter
- modulation of the values of the fundamental constants of nature

For a review, see Safronova, Budker et al, 1710.01833

Interplay between particle physics and condensed matter, AMO

Development in quantum sensors, magnets, and cavities will lead to a broad exploration of these wave-like particles. Experiments with high sensitivity/precision.

Sub eV-scale New Physics

Why sub-eV particles?

- The QCD axion is one of the most motivated Dark Matter candidates
- More generic light axion-like-particles possibly connected to the strong CP problem
- “Fuzzy” dark matter candidates
- Majorons to generate neutrino masses, or to ameliorate the Hubble tension
- Relaxions to address the hierarchy problem; …

Sub-eV particles described by an oscillating classical field

Phenomenological effects:

- precession of nuclear or electron spins
- production of photons and currents in electromagnetic systems
- equivalence principle-violating accelerations of matter
- modulation of the values of the fundamental constants of nature

For a review, see Safronova, Budker et al, 1710.01833

Interplay between particle physics and condensed matter, AMO

Development in quantum sensors, magnets, and cavities will lead to a broad exploration of these wave-like particles. Experiments with high sensitivity/precision.

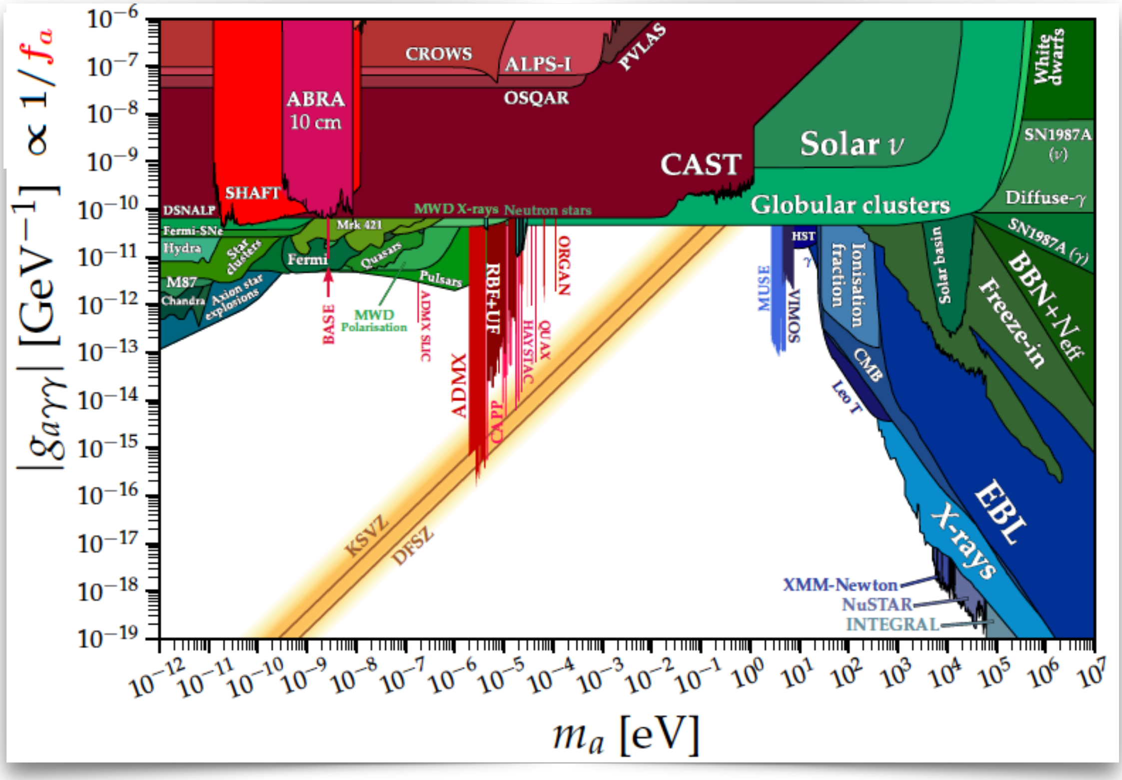
Present and future QCD axion detection prospects

- Haloscopes: axions being the dark matter (ADMX, HAYSTACK, CAPP, MADMAX, DMRadio, ...);
- Helioscopes: axions produced inside the Sun (IAXO, ...);
- Experiments that produce and detect axions in the laboratory. No astrophysical or cosmological assumption (ALPS-II, ...)

future experiments

see talk by Lindner at this meeting

Adams at al., Snowmass white paper, 2203.14923



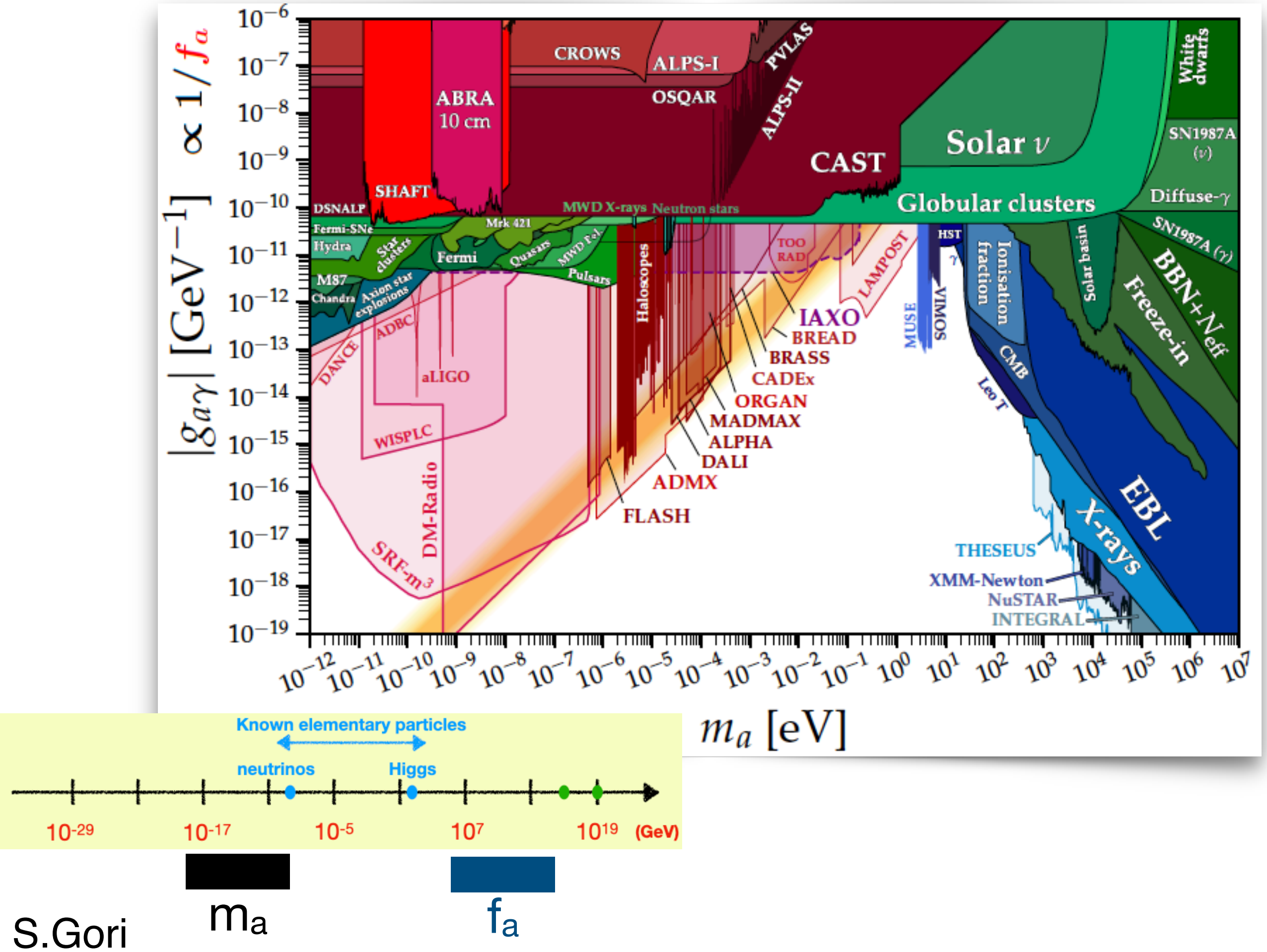
Present and future QCD axion detection prospects

- Haloscopes: axions being the dark matter (ADMX, HAYSTACK, CAPP, MADMAX, DMRadio, ...);
- Helioscopes: axions produced inside the Sun (IAXO, ...);
- Experiments that produce and detect axions in the laboratory. No astrophysical or cosmological assumption (ALPS-II, ...)

future experiments

see talk by Lindner at this meeting

Adams at al., Snowmass white paper, 2203.14923



If we discover the axion in a cavity experiment, we have an automatic precision measurement of its mass

$$\Delta m_a \sim \frac{m_a}{Q} \sim 10^{-6} m_a$$

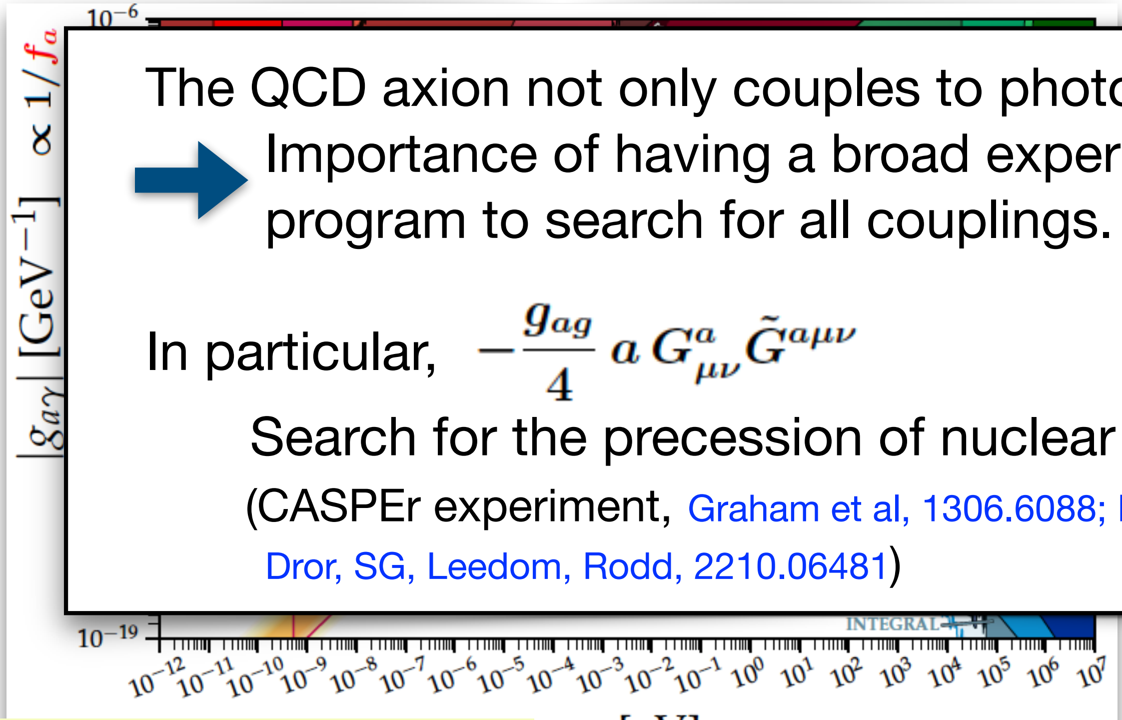
Present and future QCD axion detection prospects

- Haloscopes: axions being the dark matter (ADMX, HAYSTACK, CAPP, MADMAX, DMRadio, ...);
- Helioscopes: axions produced inside the Sun (IAXO, ...);
- Experiments that produce and detect axions in the laboratory. No astrophysical or cosmological assumption (ALPS-II, ...)

future experiments

see talk by Lindner at this meeting

Adams at al., Snowmass white paper, 2203.14923



The QCD axion not only couples to photons.

→ Importance of having a broad experimental program to search for all couplings.

In particular, $-\frac{g_{ag}}{4}\, a\, G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu}$

Search for the precession of nuclear spins.

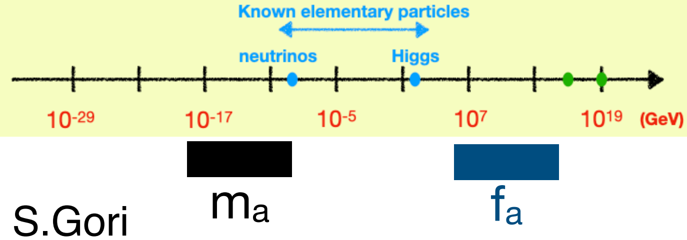
(CASPEr experiment, Graham et al, 1306.6088; Budker et al, 1306.6089; Dror, SG, Leedom, Rodd, 2210.06481)

on in a

have an

ass

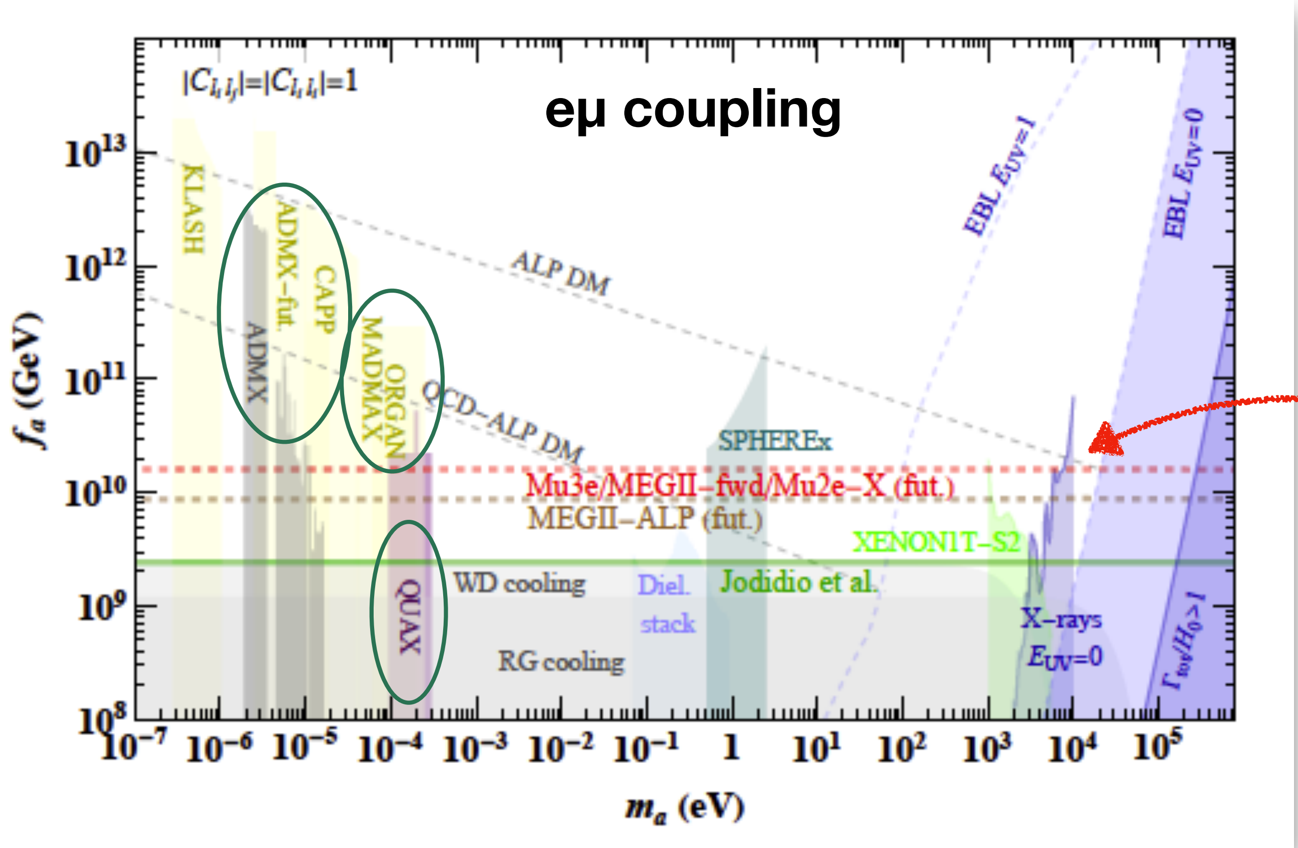
$^{-6} m_a$



Axions beyond the minimal QCD axion

In all generality, axions will have flavor violating couplings

$$\frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j, \quad i \neq j$$



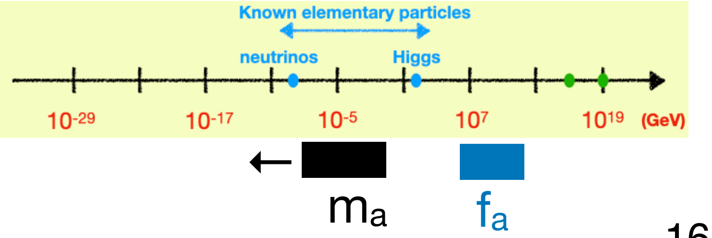
Hill, Plestid, Zupan, 2310.00043

see also Calibbi et al., 2006.04795

High-intensity precision experiments discussed in chapter 2!
Complementarity with QCD axion experiments.

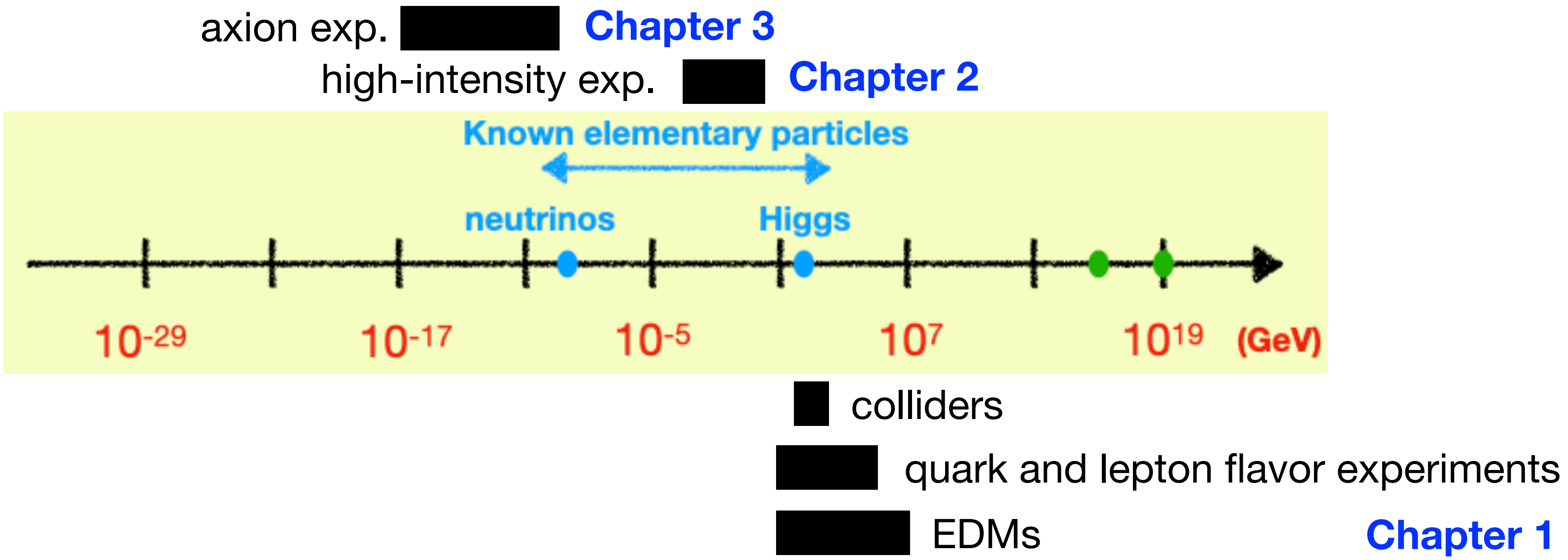
In particular, $\mu \to ea$ at Mu2e-X, Mu3e

$$\mathrm{BR} \propto \left(\frac{m_\mu}{f_a}\right)^2$$



Outlook & take home messages

We do not know what the next New Physics scale will be.
Precision experiments give us the opportunity to test many different scales.



axion exp. **Chapter 3**

high-intensity exp. **Chapter 2**

colliders

quark and lepton flavor experiments

EDMs **Chapter 1**

“Precision measurements are not only a way of testing and consolidating known theories, but also an extremely powerful tool for detecting hints of new phenomena in a way that is complementary to and — in some cases — more far-reaching than direct exploration.”

A roadmap for the future

CERN Director-General Fabiola Gianotti and Gian Giudice, Head of CERN's Theory Department, comment on the scientific vision and priorities for the field laid out in the recently updated European Strategy for Particle Physics

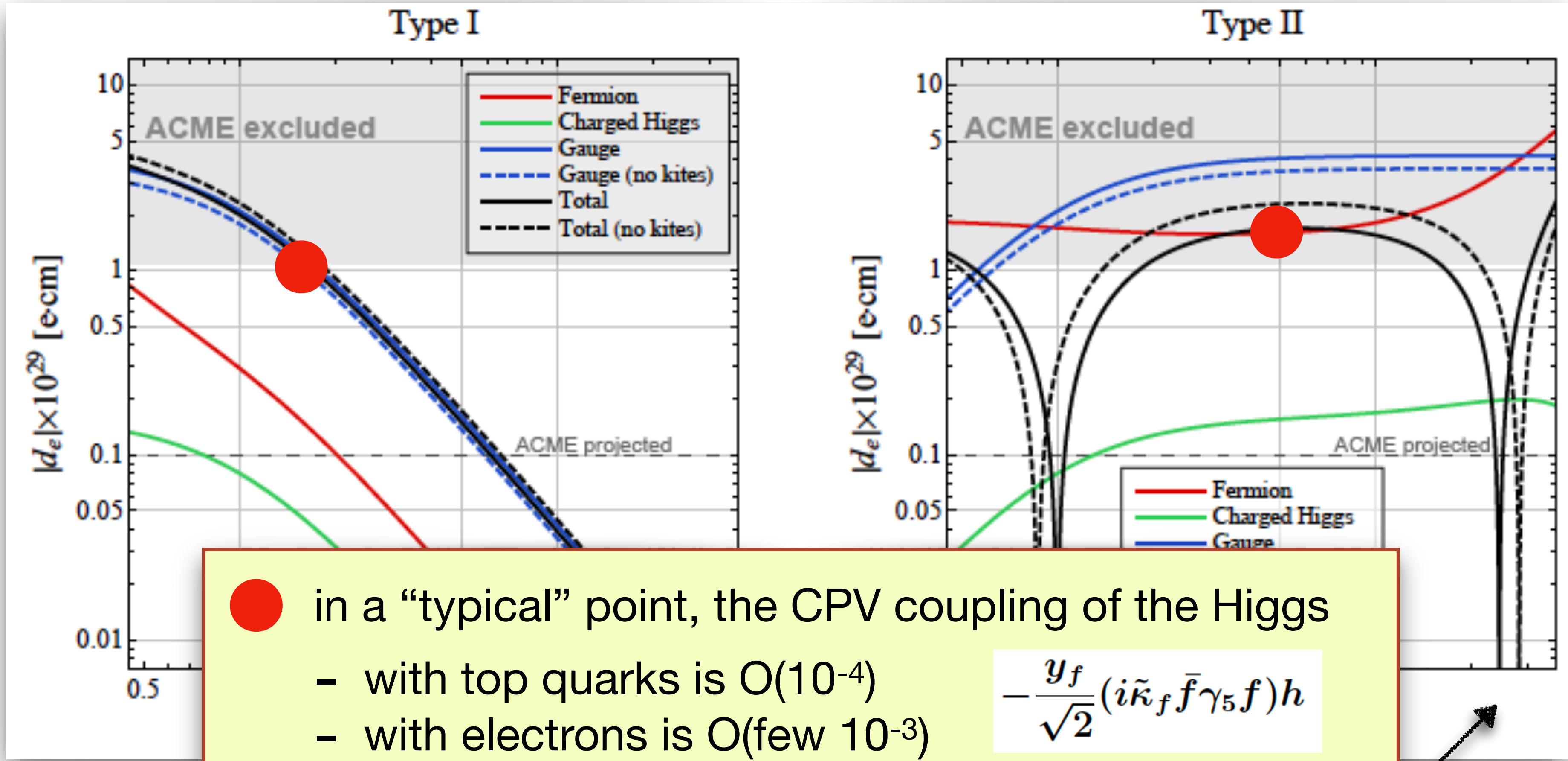
2 OCTOBER, 2020

Nature Physics volume 16, pages 997–998 (2020)

EDMs, 2HDM results

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



- ● in a “typical” point, the CPV coupling of the Higgs
  - with top quarks is $O(10^{-4})$
  - with electrons is $O(\text{few } 10^{-3})$

$$-\frac{y_f}{\sqrt{2}}(i\tilde{\kappa}_f\bar{f}\gamma_5 f)h$$

Cancellations

In the decoupling limit:

$$\text{Type I:}\quad d_e = -1.06\times10^{-27}e\,\mathrm{cm}\times\left(\frac{1\,\mathrm{TeV}}{M}\right)^2\mathrm{Im}(\lambda_5)\quad\cos^2\beta\left[1+0.07\ln\left(\frac{M}{1\,\mathrm{TeV}}\right)\right],$$

$$\text{Type II:}\quad d_e = \quad 0.47\times10^{-27}e\,\mathrm{cm}\times\left(\frac{1\,\mathrm{TeV}}{M}\right)^2\mathrm{Im}(\lambda_5)\left\{\sin^2\beta\left[1+0.16\ln\left(\frac{M}{1\,\mathrm{TeV}}\right)\right]-1.26\cos^2\beta\right\}$$

The dark sector: a guideline for new experiments

The physics of dark sectors is vast and motivated by many open problem in particle physics (not only DM, but also the strong CP problem, neutrino masses, …).
This physics has motivated the flourishing of proposals for new experiments and detectors.

The intense collaboration between theorists and experimentalists enabled these proposals to happen.
Work at the interface between theory and experiment should be encouraged.

At CERN:

THE MILLIQAN EXPERIMENT

MAPP MoEDAL

SHiP Search for Hidden Particles

FASER

CODEX-b

MATHUSLA

FACET

SND@ LHC

ANUBIS

FPF Forward Physics Facility

SHADOWS

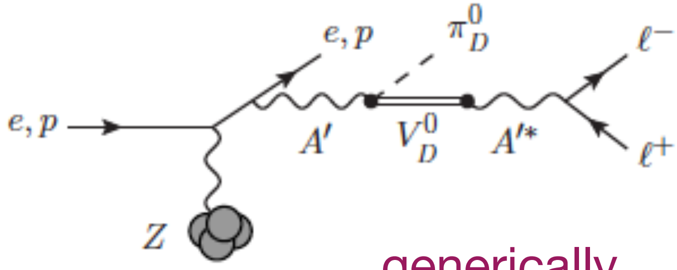
DM in a strongly interacting dark sector

Dark Matter can be the lightest state of a dark QCD-like theory (e.g. a dark pion)

Novel process responsible of freeze-out: $3 \rightarrow 2$ annihilation ⇦ Motivation to consider MeV-GeV DM!

The additional dark states will lead to a richer phenomenology

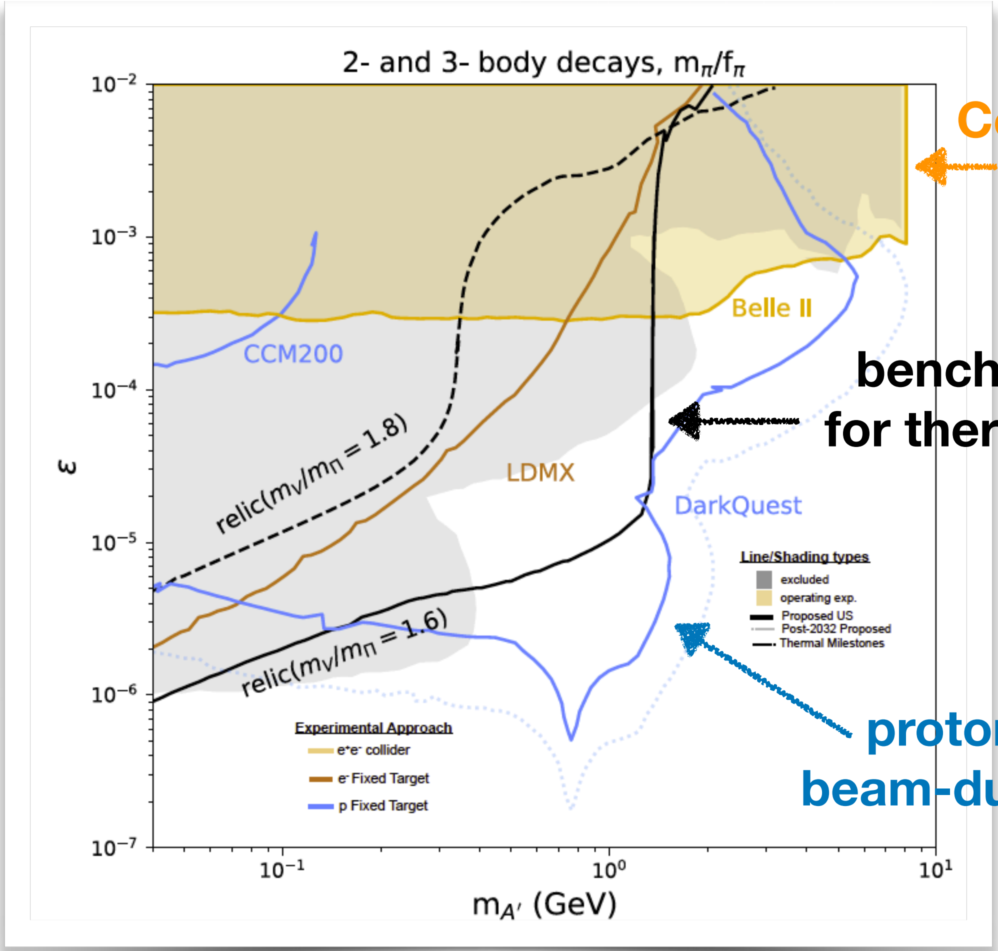
For example:



generically long-lived

$$A' \rightarrow V_D \pi_D$$ ← DM state

$$V_D \rightarrow A'^* \rightarrow e^+e^-$$



Colliders

benchmarks for thermal DM

proton beam-dump