Big picture questions in particle physics

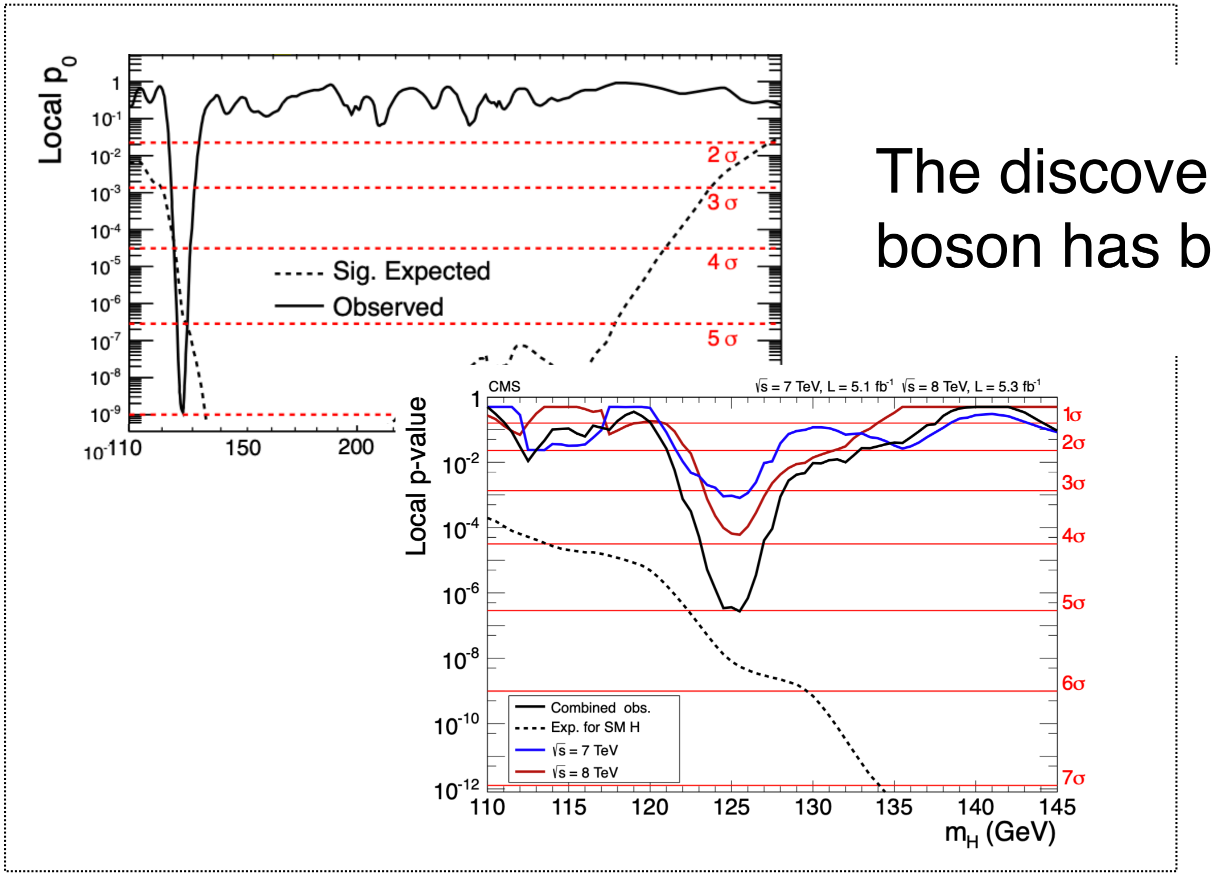
(from theory to experiments)

Stefania Gori
UC Santa Cruz

“The future of high energy physics: a new generation, a new vision”

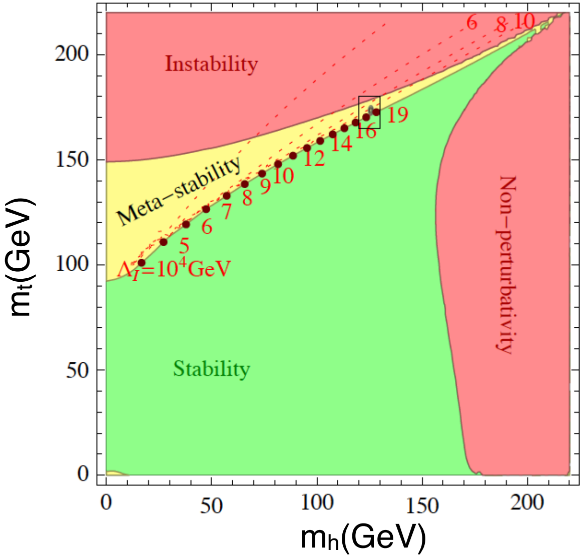
Aspen center for physics
March 26, 2024

The LHC: a discovery machine



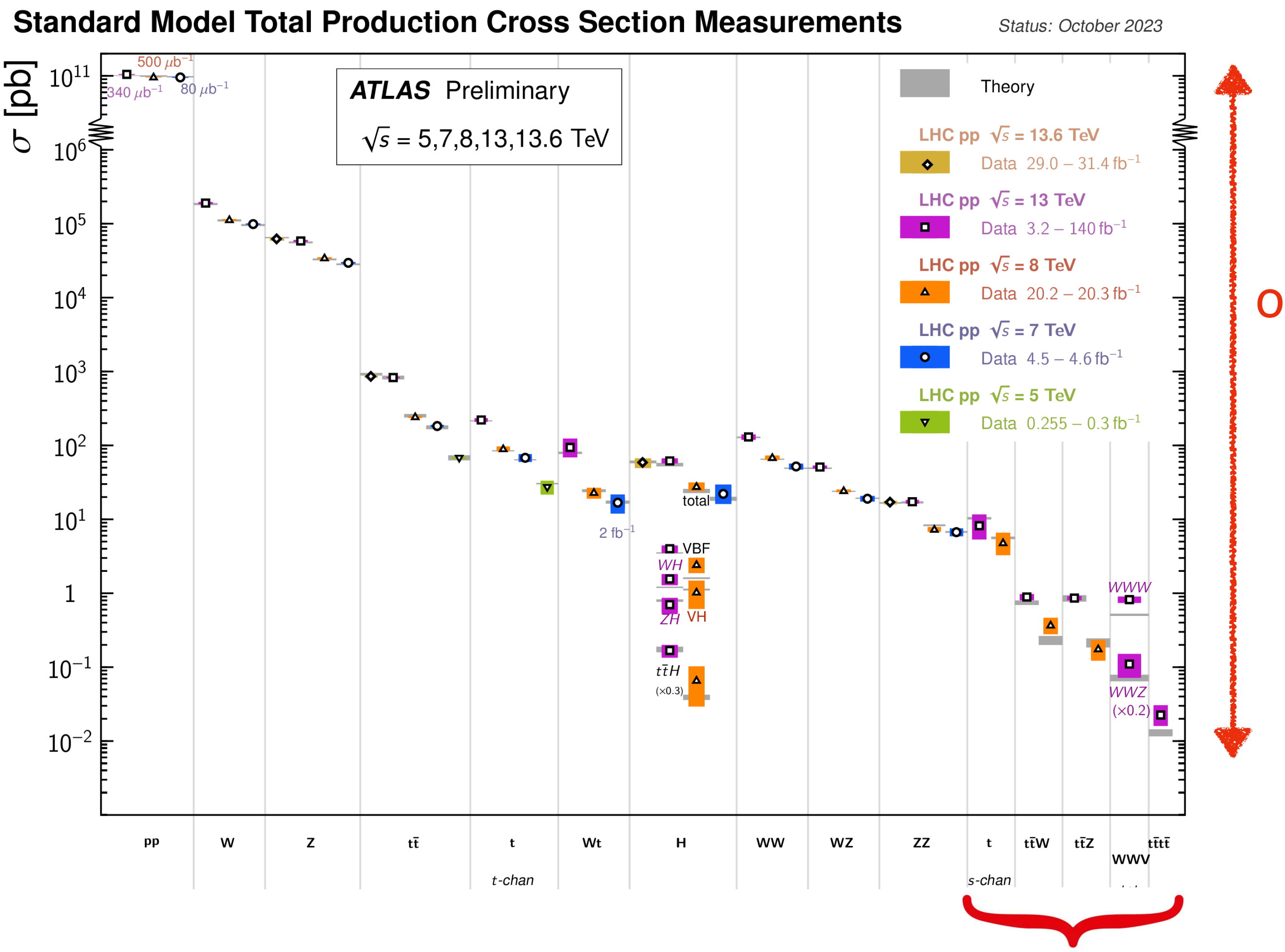
The discovery of the Higgs boson has been a turning point.

Buttazzo et al, 1307.3536



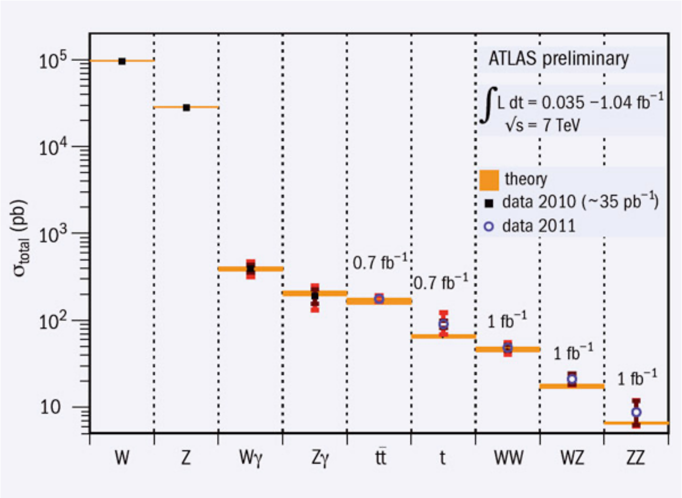
With the discovery of the Higgs at 125 GeV, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

The LHC: a precision machine



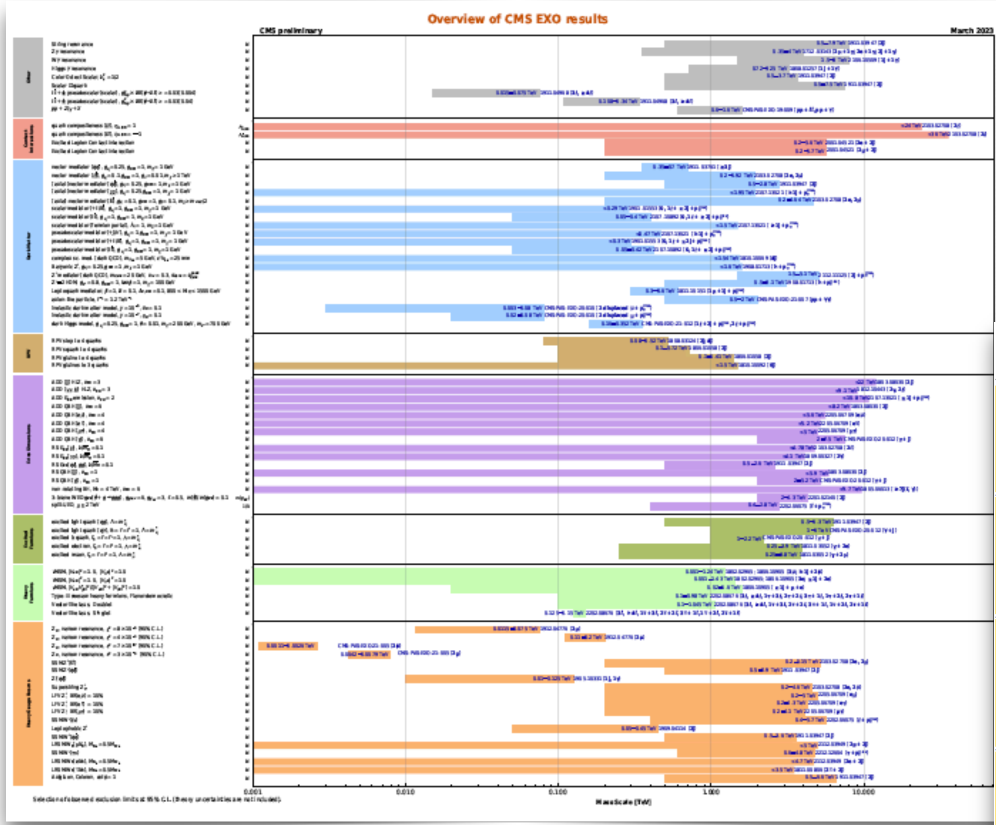
13 orders of magnitude

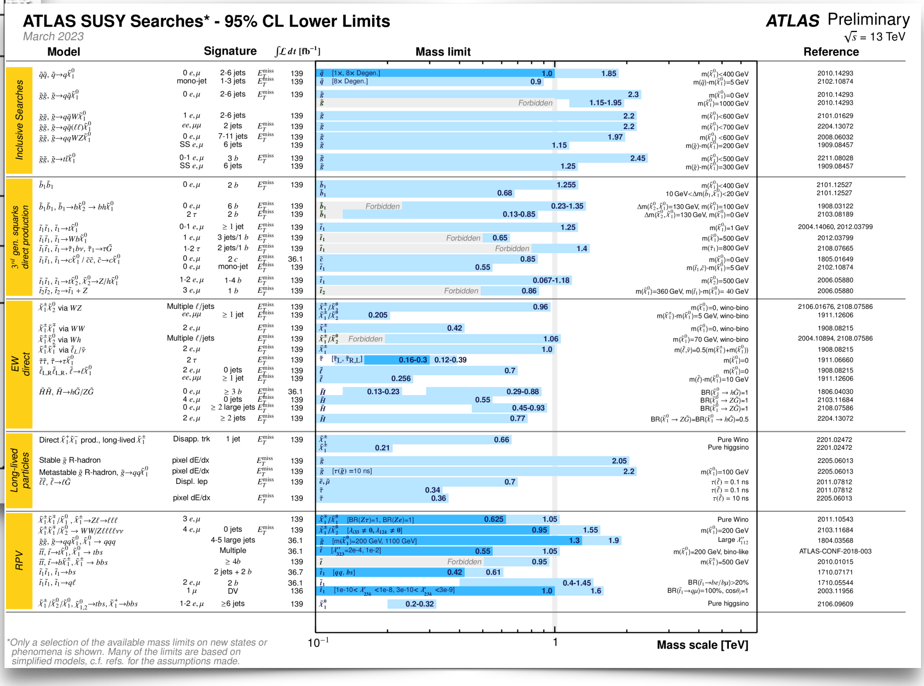
As at the end of 2011:

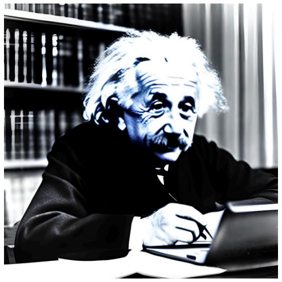


LHC Run 1 & 2: Experimental and theoretical triumph

The LHC: a machine that challenges us theorists!







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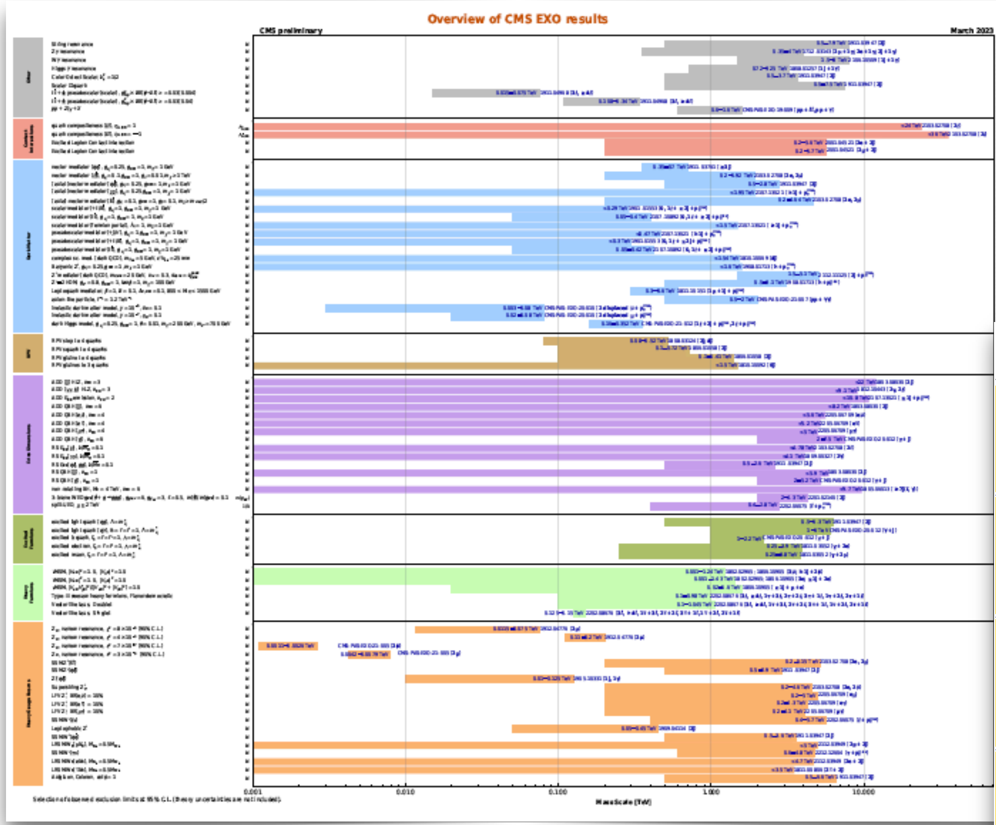

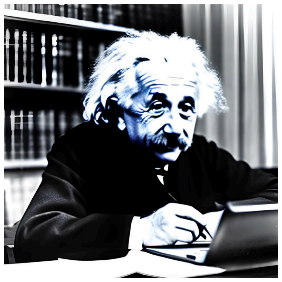

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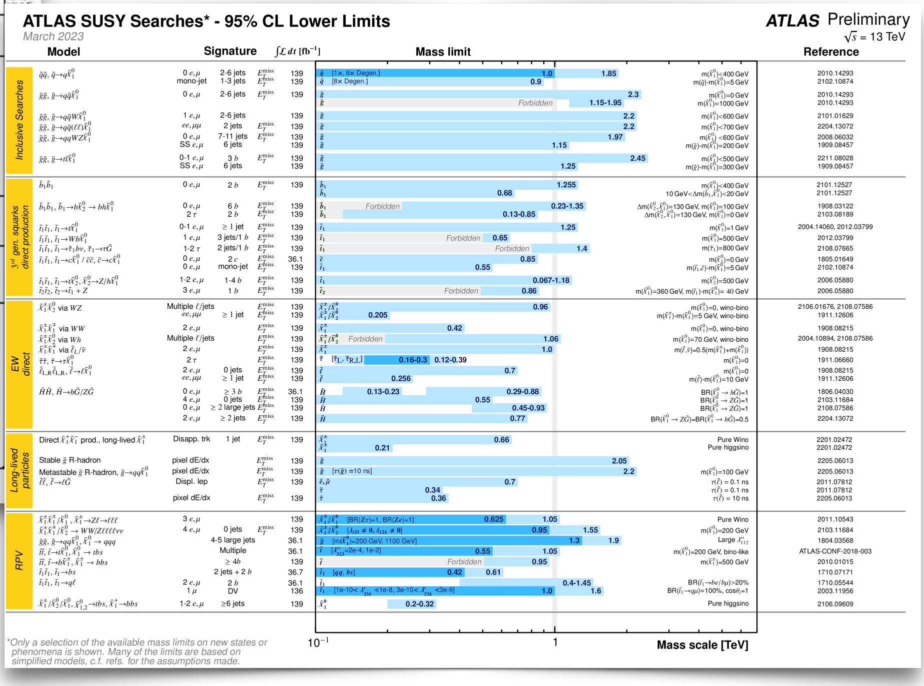

Where do we go from here?

There is not anymore a no-loose theorem that connects naturalness to discoveries at colliders.

+ stringent bounds on WIMPs.

A diversification of the field

HEP has dramatically broadened in the past 10 years

SUSY
Composite Higgs
Extra dimensions
Neutral naturalness
Relaxion models
Clockwork
NNaturalness
UV/IR mixing


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WIMP
Axion DM
Dark sectors
Sterile neutrinos
Strongly interacting DM
Feebly interacting particles
Primordial black holes

Effective field theories

Axions &
Axion-like-particles

Extended Higgs sectors

Leptoquarks

HEP is closer than ever to other fields in physics:
gravitational waves, condensed matter, atomic physics, …

Stronger and stronger complementarity.

What can we discover next?

Theoretical guidance

Observational puzzles

Nature of Dark Matter (DM)
Matter-antimatter asymmetry
Origin of neutrino masses

Theory puzzles

Origin of the electroweak scale
Flavor problem
Strong CP problem

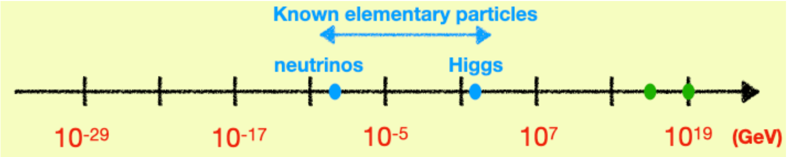
Anomalies in data?

(Hubble tension, $(g\text{-}2)_\mu$, SBN neutrino anomalies, …)

……

Overarching question:
what is the unknown?

the known unknown



No clear New Physics scale associated to these open problems

the unknown unknown

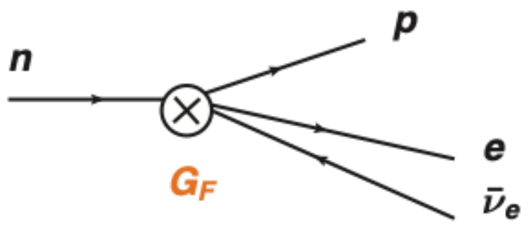
Testing more particle physics

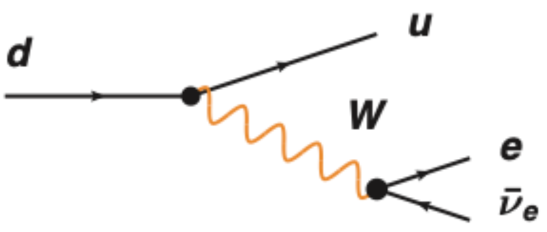
1. Tests of the validity of the Standard Model (SM).

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.

New discoveries are relatively frequent

2. Indirect discovery of heavy New Physics:



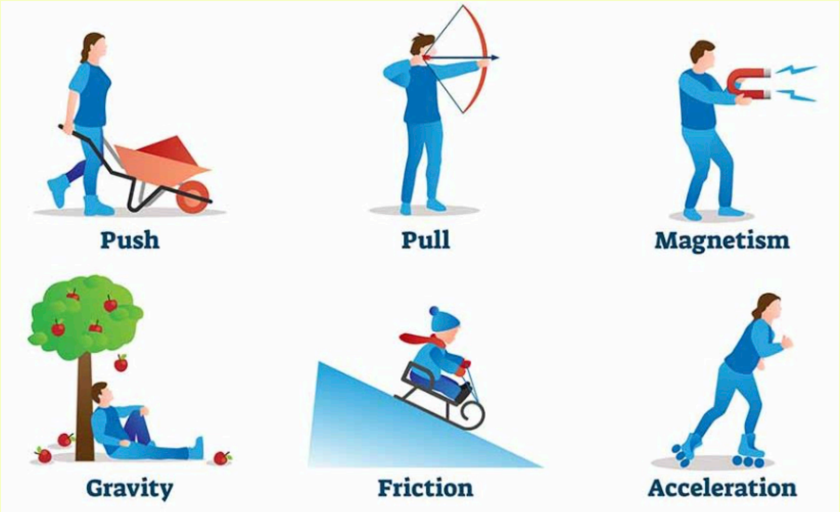


Effective field theory (EFT) → **Full theory**

New physics through the observation of effects of virtual particles.

3. Direct searches (production+detection) of new particles both above and below the electroweak scale.

1. New processes of Nature



The future Higgs discoveries

“The Higgs is SM-like” but…

several processes predicted by the SM need still to be discovered

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We need to understand **if the Higgs interacts with the 2nd generation**

Before the Higgs discovery, no evidence for **Yukawa** force between fundamental particles

Now, we have established it and we are eagerly awaiting for the discovery of the muon yukawa!
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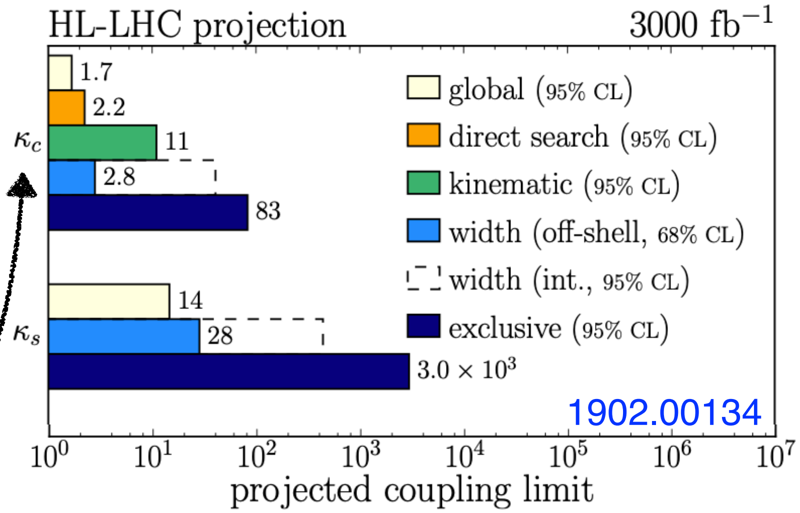
Muon:
~2-3σ evidence at Run II
Expected discovery at Run III.
~5% level measurement at the HL-LHC

Charm:
$|\kappa_c| < 8.5(12.4)$ ATLAS: 2201.11428
$1.1 < |\kappa_c| < 5.5$ (< 3.4) CMS: 2205.05550



1902.00134

Lot of theory effort proposing new methods to explore this Yukawa

Models that ameliorate the **flavor puzzle** can predict an enhancement of second generation couplings (and all other couplings SM-like), e.g. flavorful 2HDM 1507.07927, 1508.01501, 1908.11376

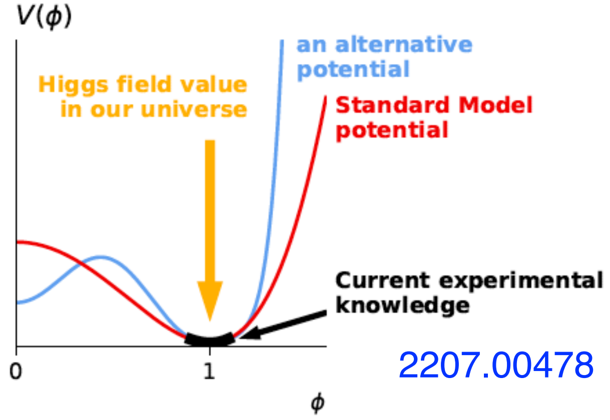
The future Higgs discoveries

"The Higgs is SM-like" but…
several processes predicted by the SM need still to be discovered

We need to understand **if the Higgs interacts with itself**

In the SM, the Higgs self-interactions are fully determined:

$$V(h) = \frac{m_h^2}{2}h^2 + \frac{m_h^2}{2v}h^3 + \frac{m_h^2}{8v^2}h^4$$



2207.00478

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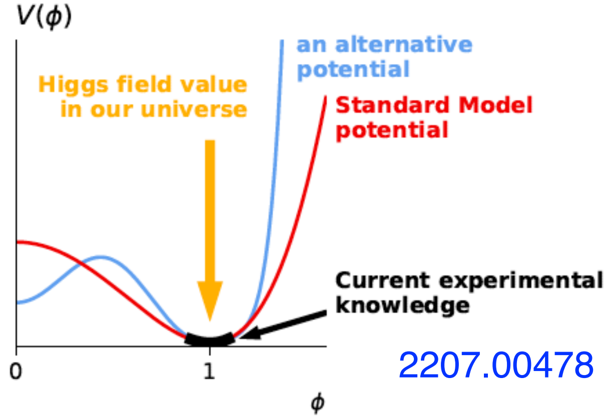

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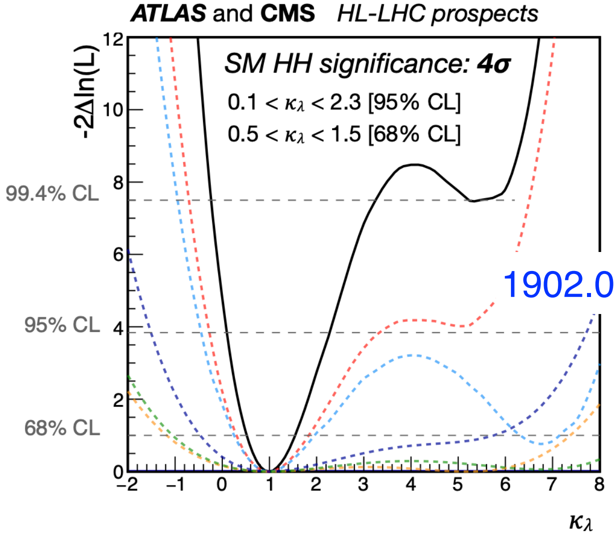

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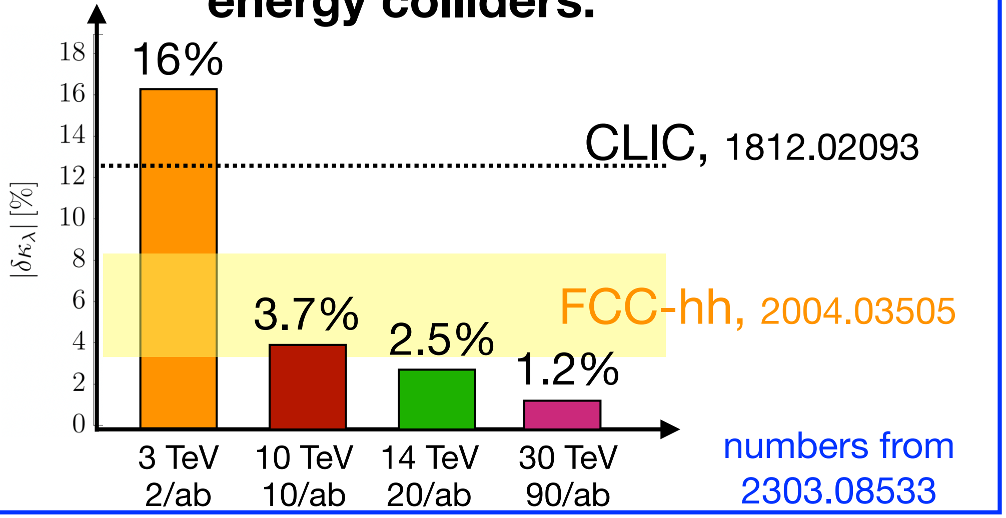
$$\kappa_\lambda \equiv \frac{\lambda_{\mathrm{HHH}}}{\lambda_{\mathrm{HHH}}^{\mathrm{SM}}}$$

Hope for a discovery?

… and precision measurement at future high energy colliders:

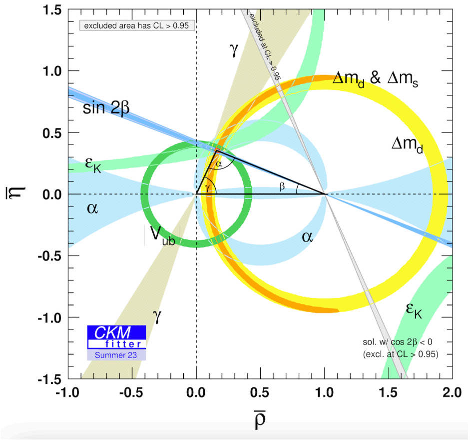


numbers from 2303.08533

Testing the laws of Nature in flavor physics

Despite the many (22) free parameters in the quark/lepton Yukawa sector of the SM, the system is overdetermined by the many measurements of flavor transitions.

Many flavor violating processes predicted by the SM need still to be discovered experimentally, and they are in reach of running experiments.



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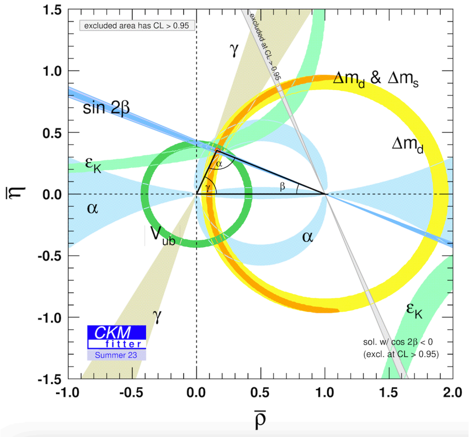


Two golden modes:

$$K \to \pi\bar\nu\nu$$

$$\mathrm{BR}(K^+ \to \pi^+\bar\nu\nu) = [10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{sys}}] \times 10^{-11}$$

NA62, 2103.15389

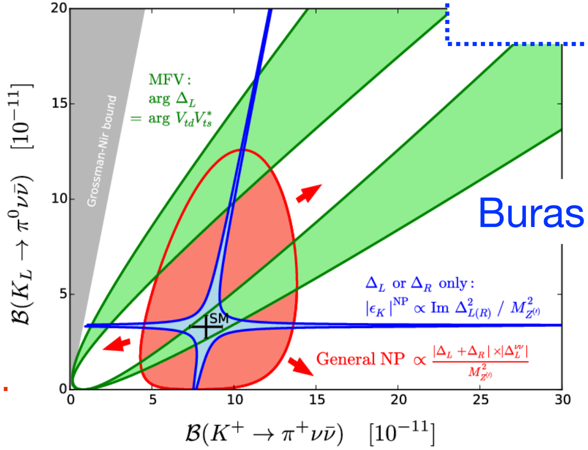
3.4 σ evidence

$$\mathrm{BR}(K_L \to \pi^0\bar\nu\nu) < 3 \times 10^{-9}$$

KOTO, 1810.09655

Grossman-Nir bound, 9701313:

$$\frac{\mathrm{BR}(K_L \to \pi^0\bar\nu\nu)}{\mathrm{BR}(K^+ \to \pi^+\bar\nu\nu)} \lesssim 4.3$$



Buras et al, 1507.08672

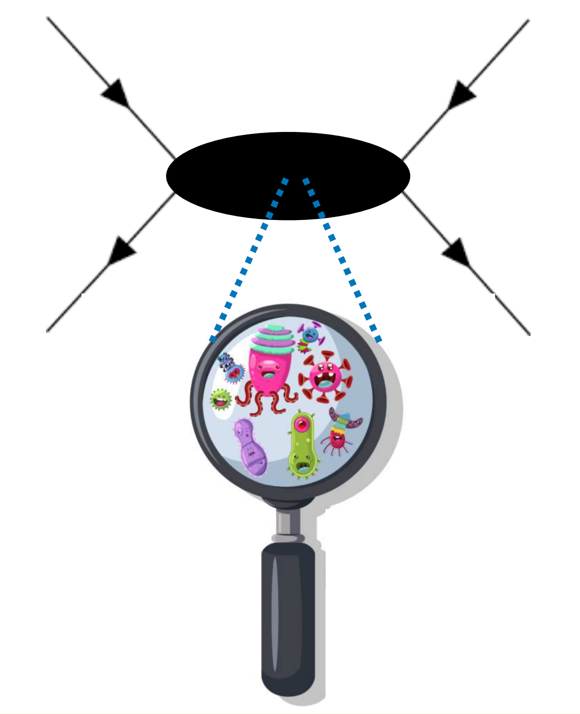
$$B^+ \to K^+\bar\nu\nu$$

$$\mathrm{BR} = [2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})] \times 10^{-5}$$

Belle-II, 2311.14647

3.5 σ evidence

2. Indirectly testing heavy new particles



Collider precision program

The LHC is not only about the Higgs and new particle direct searches

Many precision measurements contribute to constrain the SMEFT Lagrangian
(Higgs couplings, EW precision observables, gauge boson pair production,
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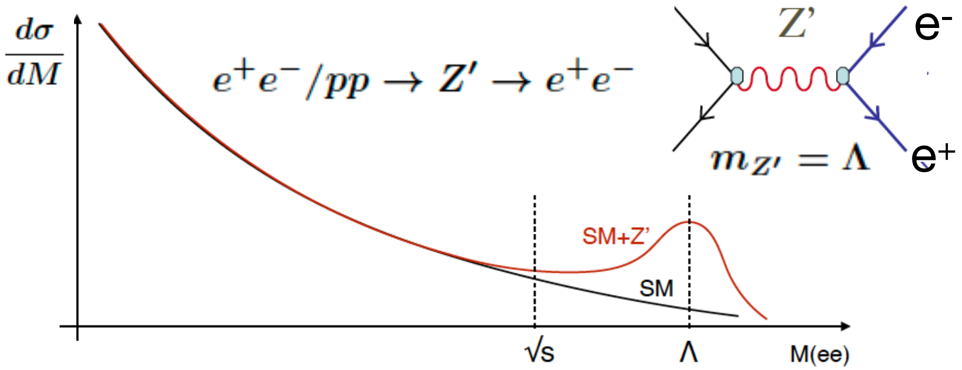


From M. Mangano, LISHEP 2023

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

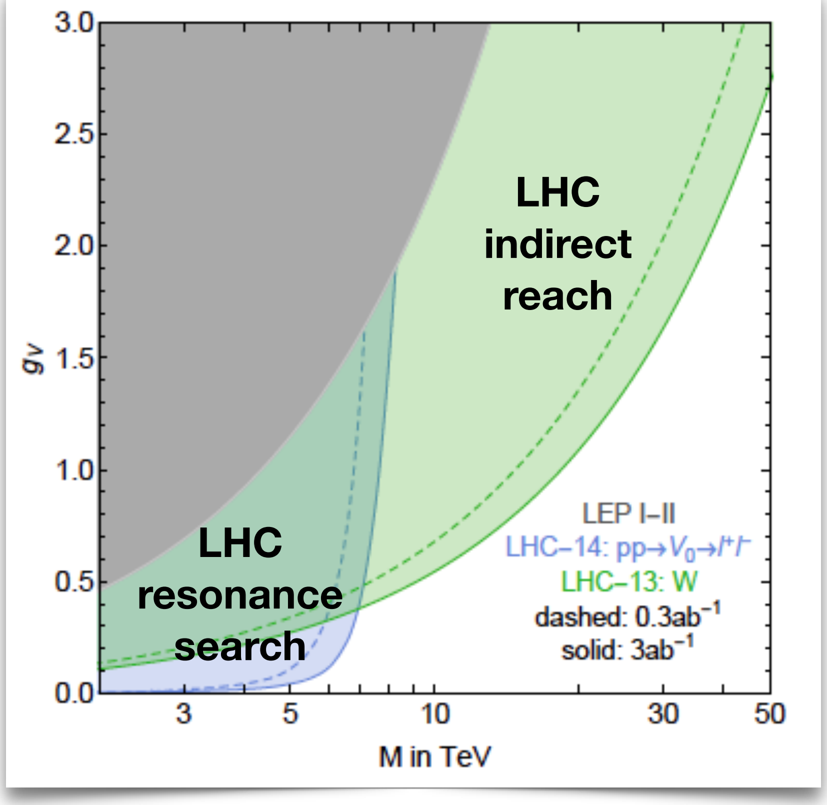
$$\Lambda_{max} \sim g\frac{\sqrt{s}}{\sqrt{\Delta\sigma/\sigma}}$$

← kinematic reach

← precision

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

$$pp \to Z' \to e^+e^-$$



Farina et al., 1609.08157

Flavor physics and precision

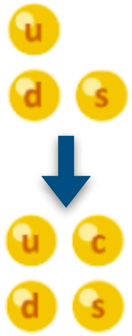
We do not know if the flavor symmetry of quarks and leptons ($(SU(3)^5)$) is only broken by the Standard Model Yukawa couplings.

→ New contributions to flavor transitions can occur.

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

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

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



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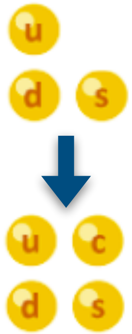

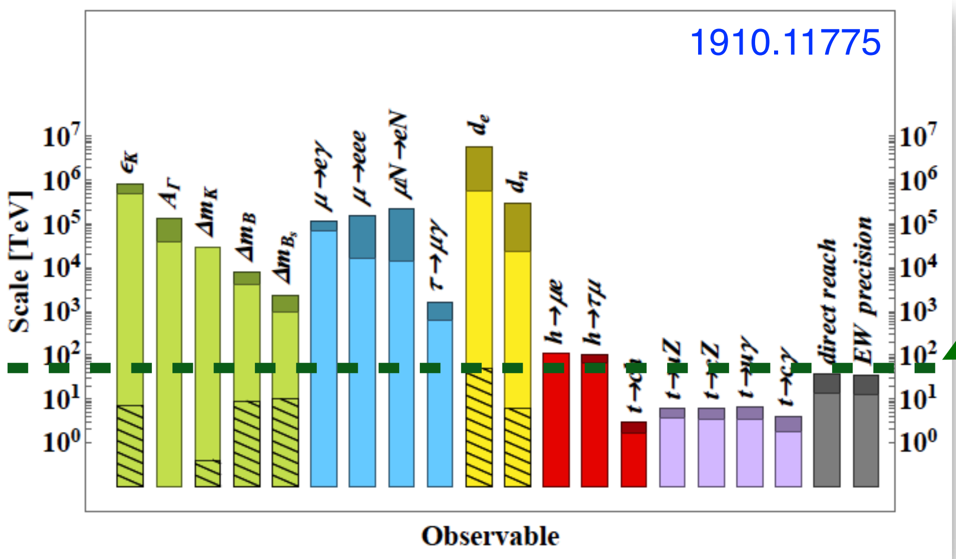

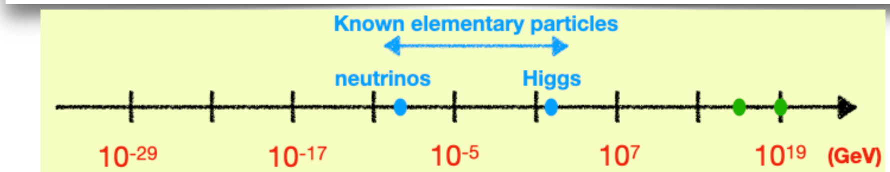

Flavor transitions: access to very high New physics scales, not directly accessible at collider experiments.

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]

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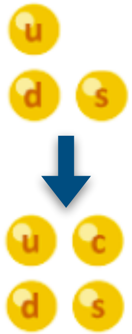

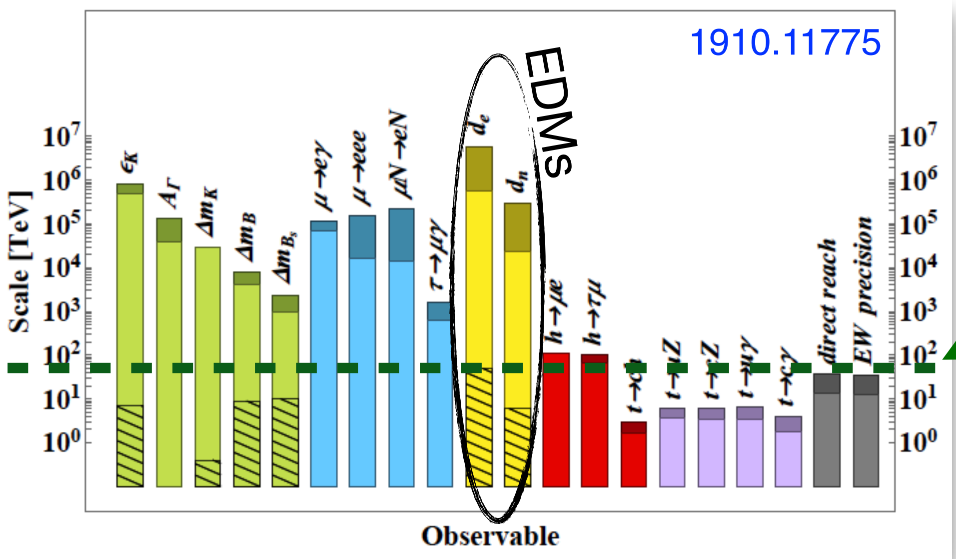

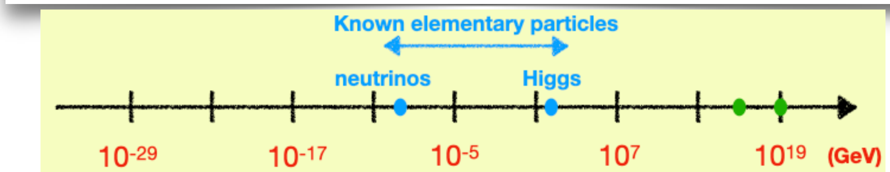

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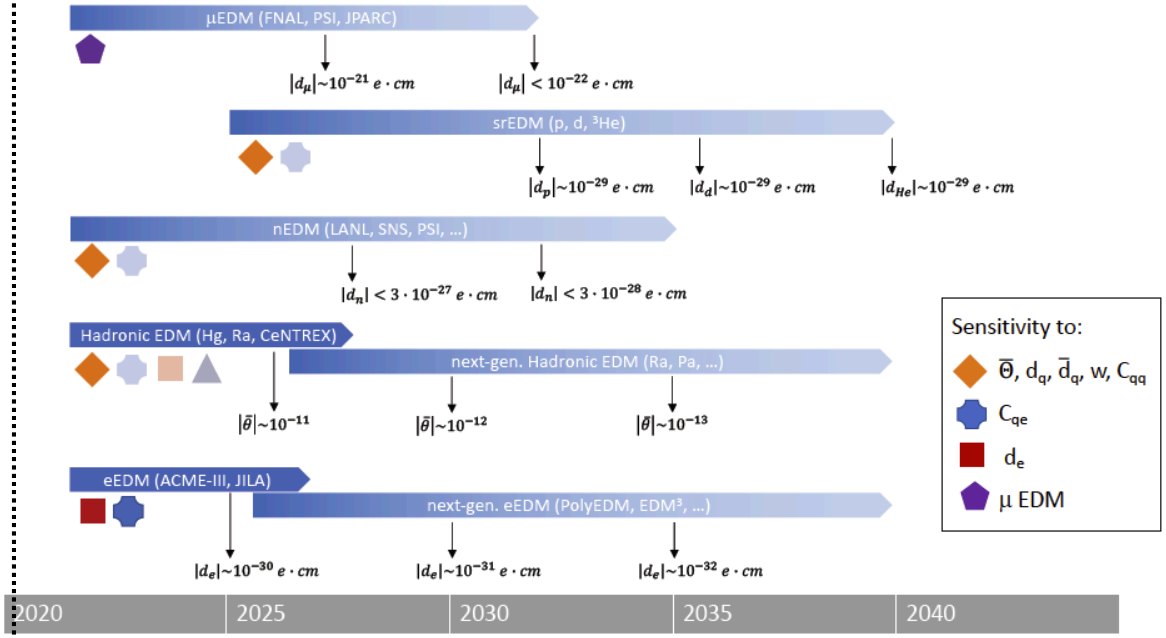
Electric dipole moments (EDMs)

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.

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

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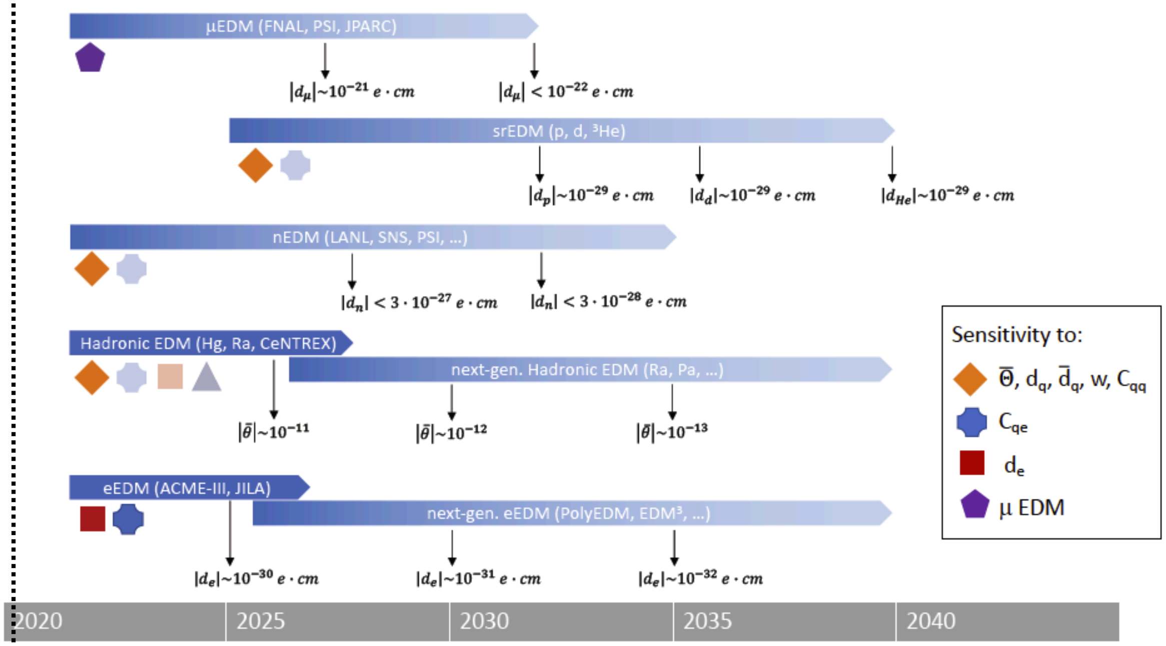

Blum, Winter, et al., Snowmass, 2209.08041

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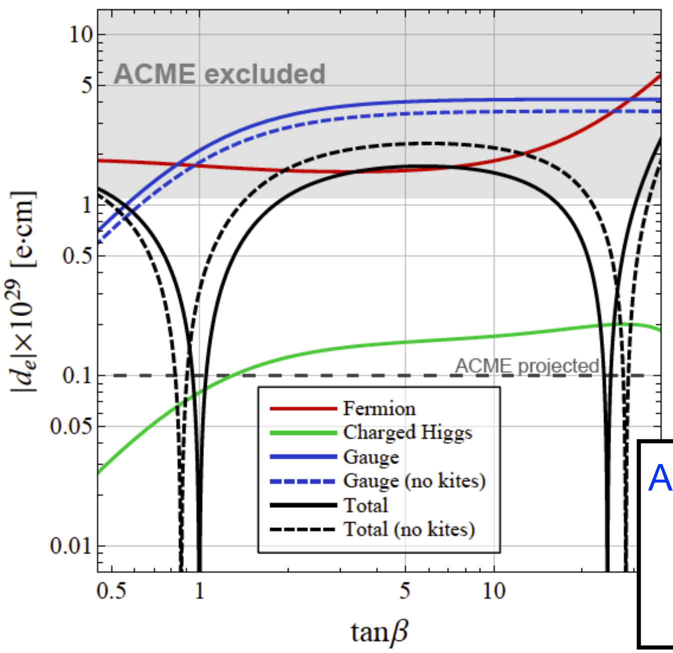
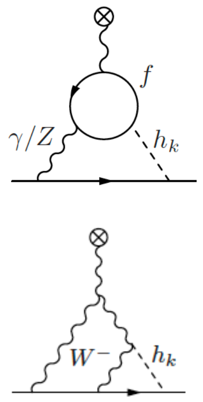
E.g., in a CPV Two-Higgs-Doublet-Model





Altmannshofer, SG, Hamer, Patel, 2009.01258

Complementarity with direct searches for CPV at the LHC

see also Alarcon et al., Snowmass, 2203.08103

3. Direct searches for new particles

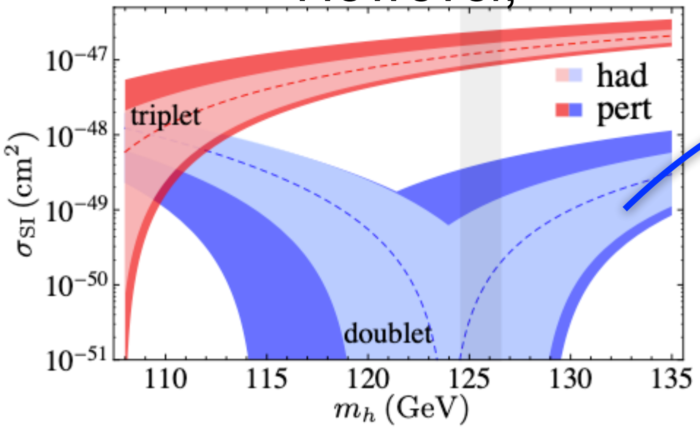
Direct searches for WIMPs

Thermal freeze-out DM at around the electroweak scale is a very predictive framework. This has motivated a large experimental endeavor.

Milestone:

vanilla WIMPs have been probed!

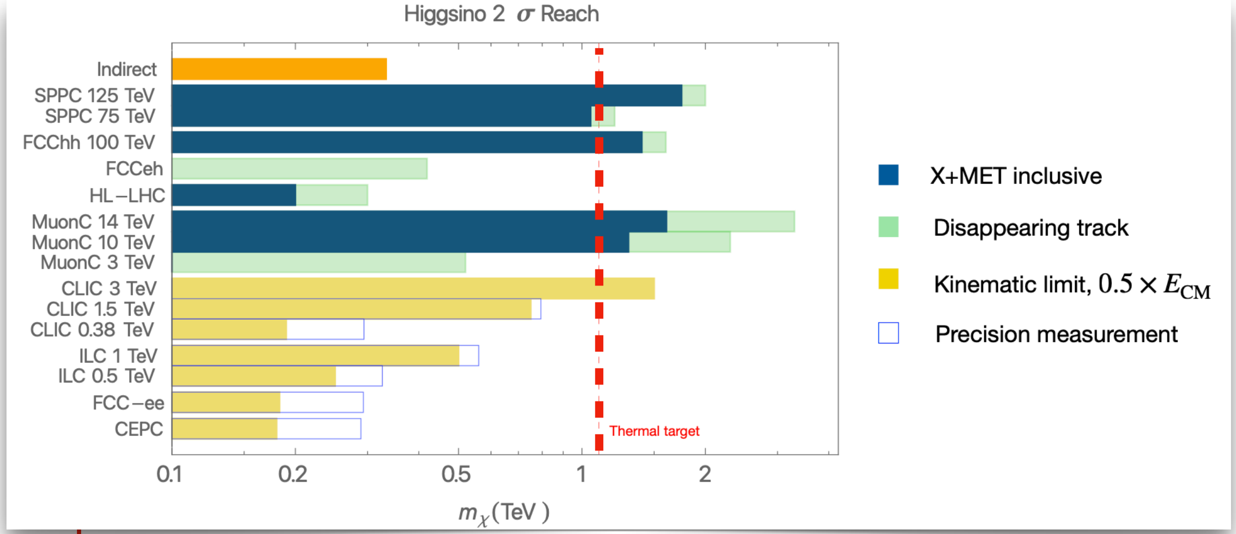
However,



Hill, Solon, 1309.4092

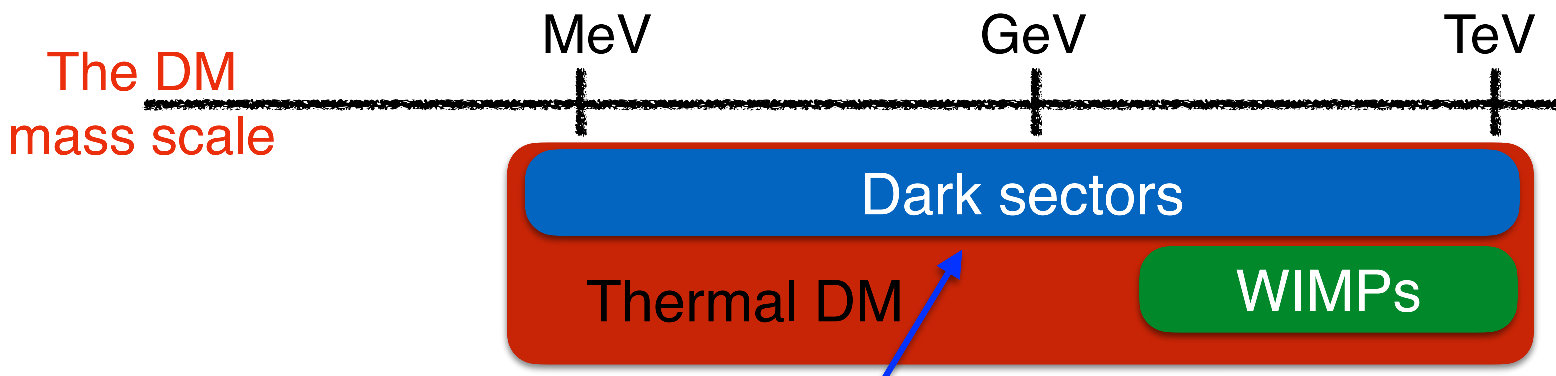
though "mostly" explored, solid motivation to complete WIMP program

Higgsinos at future colliders



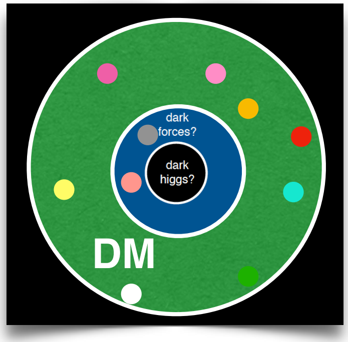
Snowmass, 2211.11084

Broadening the idea of thermal Dark Matter

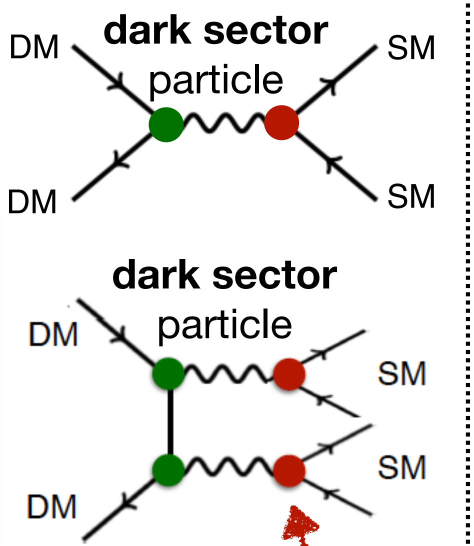


If thermal, Dark Matter **generically**
<u>needs</u> additional (dark) particles
to annihilate with.

Predictive framework ("thermal targets")



the "dark sector"



generically
small couplings
(need precision)

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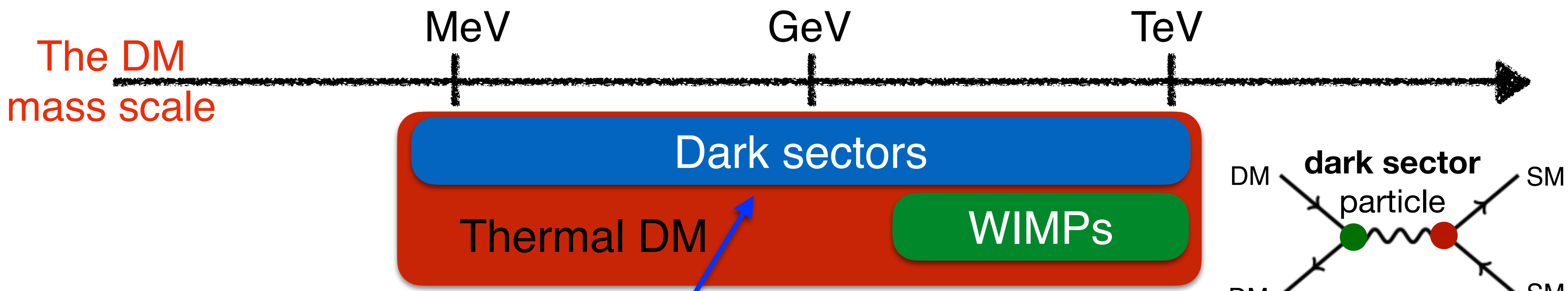

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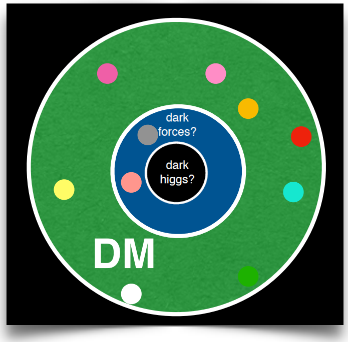

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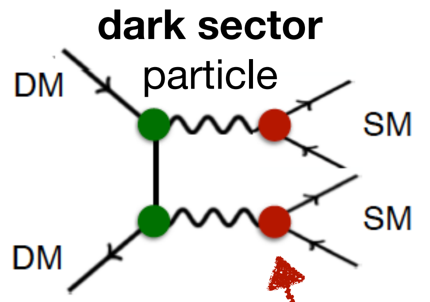

Predictive framework (“thermal targets”)

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; …

generically
small couplings
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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 **(P5: ASTAE experiments)**

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

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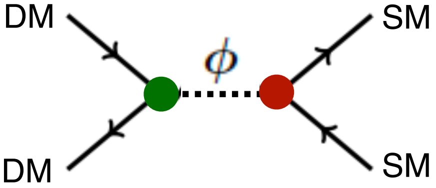
High and low energy colliders

Meson factories

Fixed target (beam dump) experiments
(P5: ASTAE experiments)

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

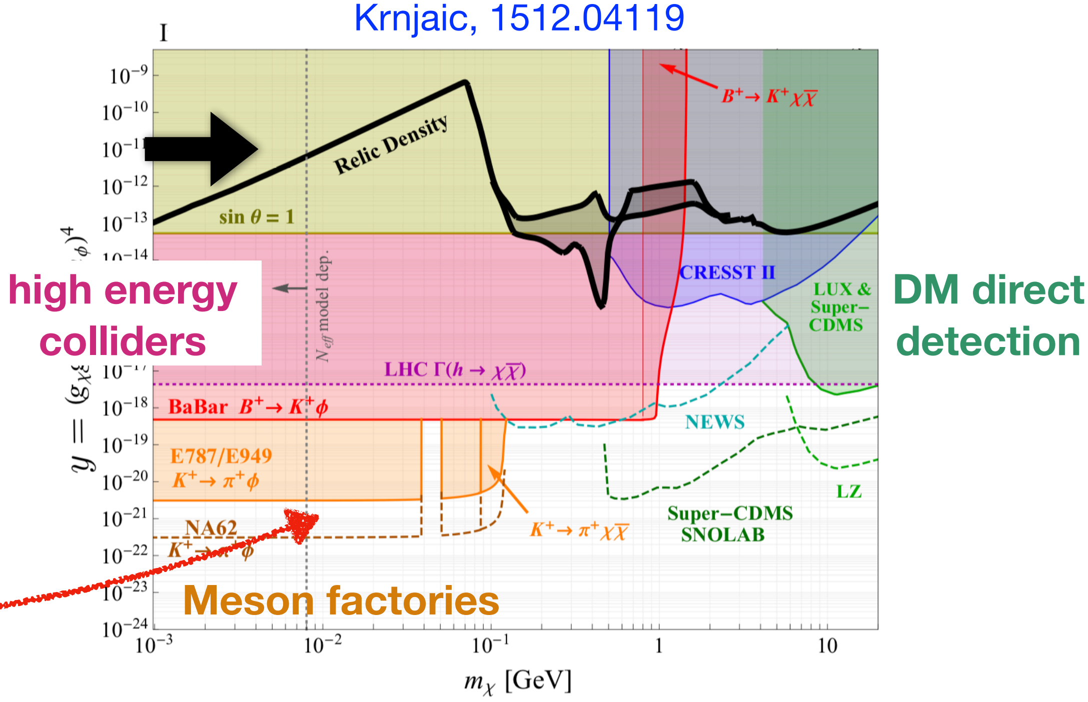
Minimal scalar-mediated thermal DM is fully probed.



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.

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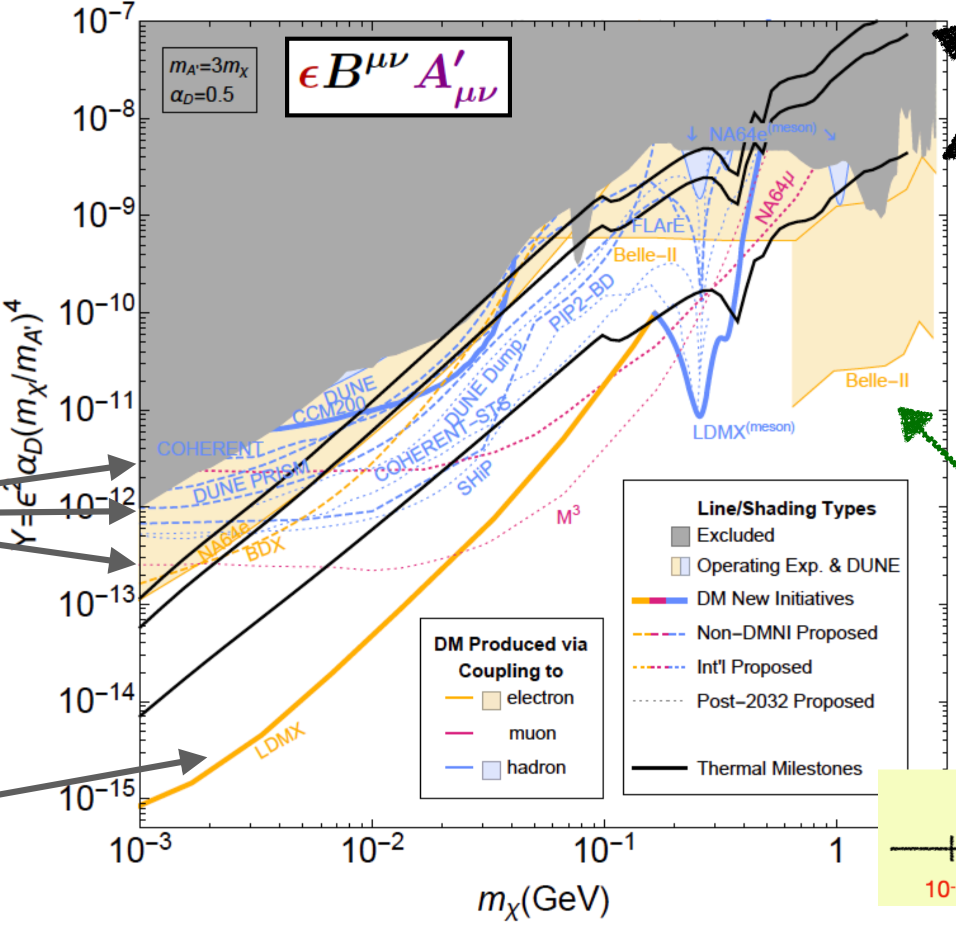
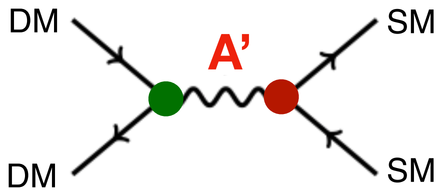
In the coming decade, we will have the opportunity to **broadly probe the thermal freeze-out framework**

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



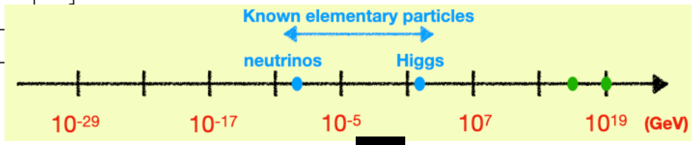
benchmarks for thermal DM



Meson factories (missing energy)

Beam dump (Re-scattering)

Fixed target (Missing momentum)



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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.

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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.

Minimal **&** **Non-minimal models**

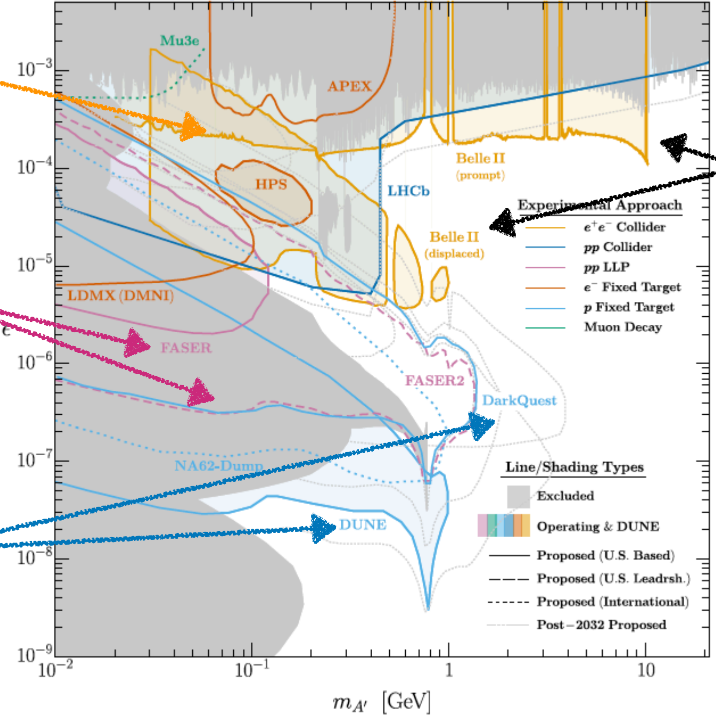
Dark photon, A’ → SM SM

Dark photon-mediated SIMP

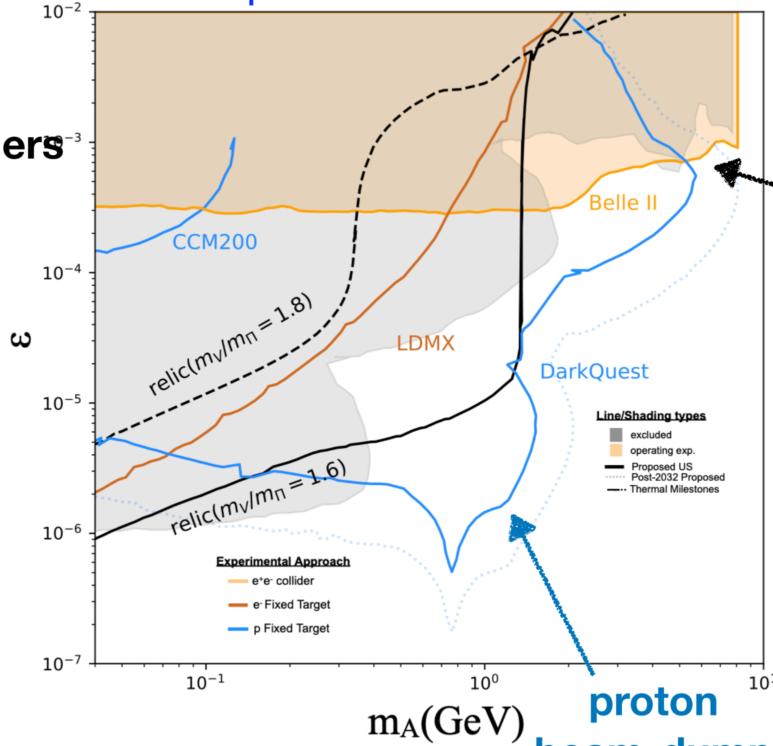
electron fixed target

LHC auxiliary detectors

proton beam-dump



Colliders

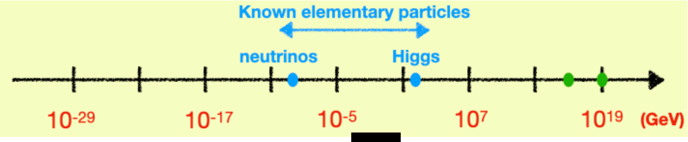


Colliders

proton beam-dump

Snowmass report,
Batell et al., 2207.06905

Snowmass report,
Harris et al., 2207.08990



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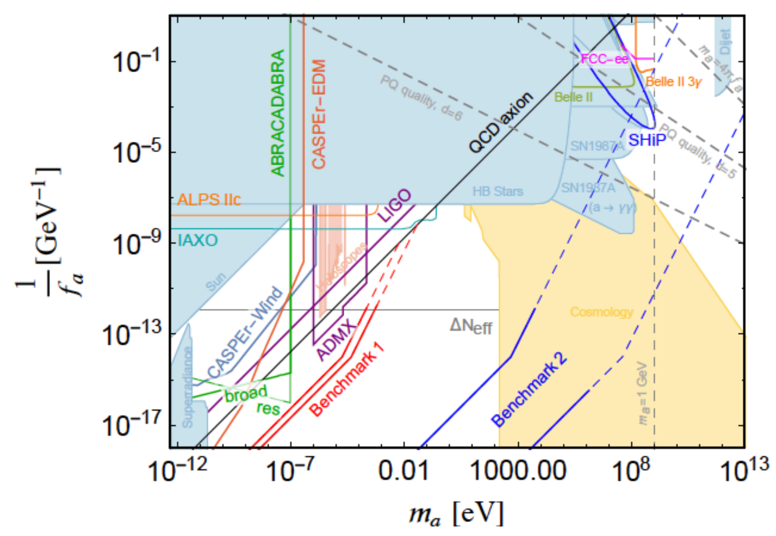
Axions and axion-like-particles (ALPs)

Axions have been one of the leading candidates for physics beyond the SM. They can address the strong CP problem and the DM puzzle simultaneously.
New physics scale: sub-eV

More and more studies of generic axion-like-particles (ALPs) that can address the strong CP problem. Extended QCD models with ALPs at around the keV scale and beyond

Easier to address the <u>axion quality problem</u> with heavier axions and lower f_a.

Agrawal, Howe, 1710.04213



Lot of freedom in the (m_a-f_a) plane

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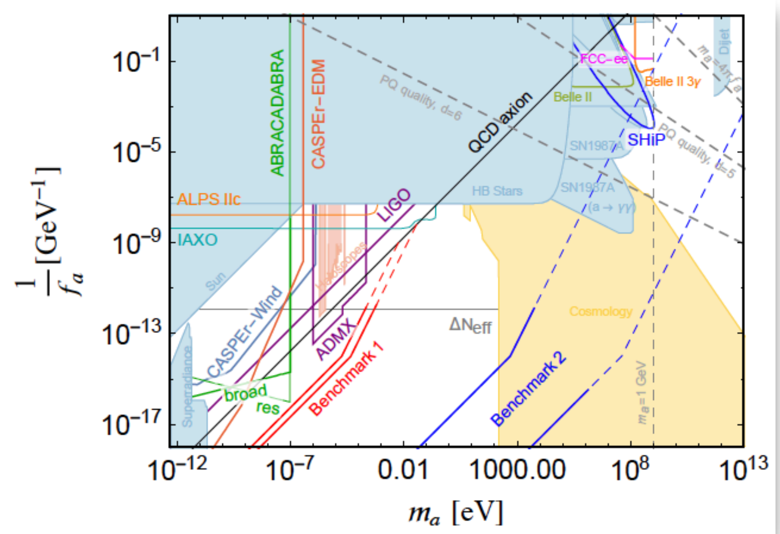

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At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

$$\boxed{g_i \propto \frac{1}{f_a}}$$

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu} + i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

ALP new signals at flavor experiments

Several of the ALP production modes and decays have not been searched for yet.

➡ Potential for many new signatures.

For example:
$$\begin{aligned} \pi^+ &\to a\ell^+\nu \\ K^+ &\to a\ell^+\nu \\ W^+ &\to a\ell^+\nu \end{aligned} \qquad \text{with} \quad a \to \ell^+\ell^-$$

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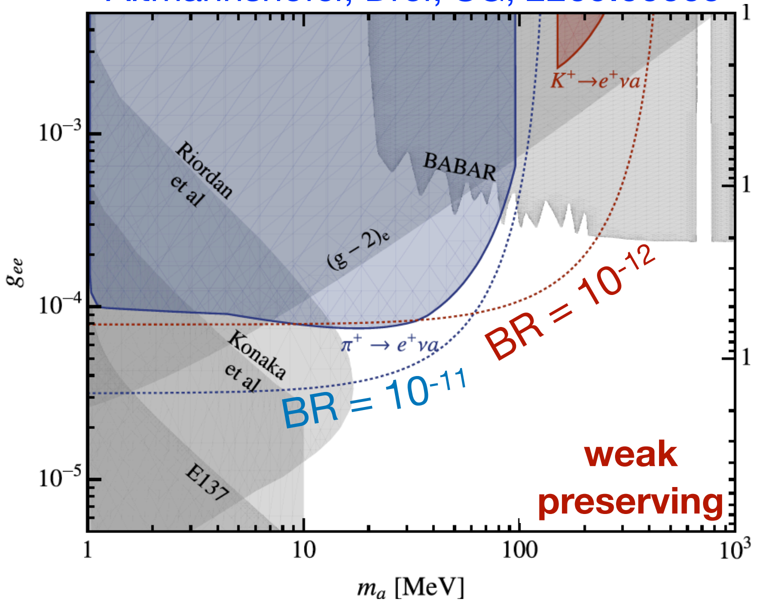
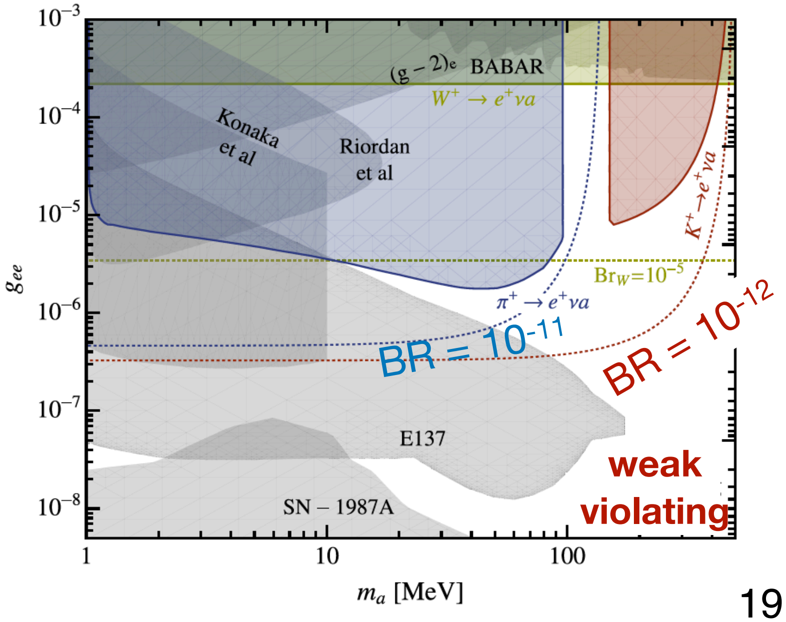
$$\mathcal{L} = \frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu(\bar{g}_{ee} + g_{ee}\gamma_5)e + g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

$$\mathrm{BR}(\pi^+ \to e^+ a\nu) = \frac{1}{384\pi^2}\frac{m_\pi^4}{m_e^2 m_\mu^2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2}\left[\overbrace{(g_{ee} - \bar{g}_{ee} + g_\nu)}^{\neq 0 \text{ only if weak SU(2) violation}}{}^2 f_0\left(\frac{m_a^2}{m_\pi^2}\right) + \frac{4m_e^2}{m_\pi^2}\left(3(g_{ee})^2 f_3\left(\frac{m_a^2}{m_\pi^2}\right) + 3(\bar{g}_{ee} - g_\nu)^2 f_4\left(\frac{m_a^2}{m_\pi^2}\right) + 2g_{ee}(\bar{g}_{ee} - g_\nu) f_5\left(\frac{m_a^2}{m_\pi^2}\right)\right) + \mathcal{O}\left(\frac{m_e^3}{m_\pi^3}\right)\right]$$

Altmannshofer, Dror, SG, 2209.00665



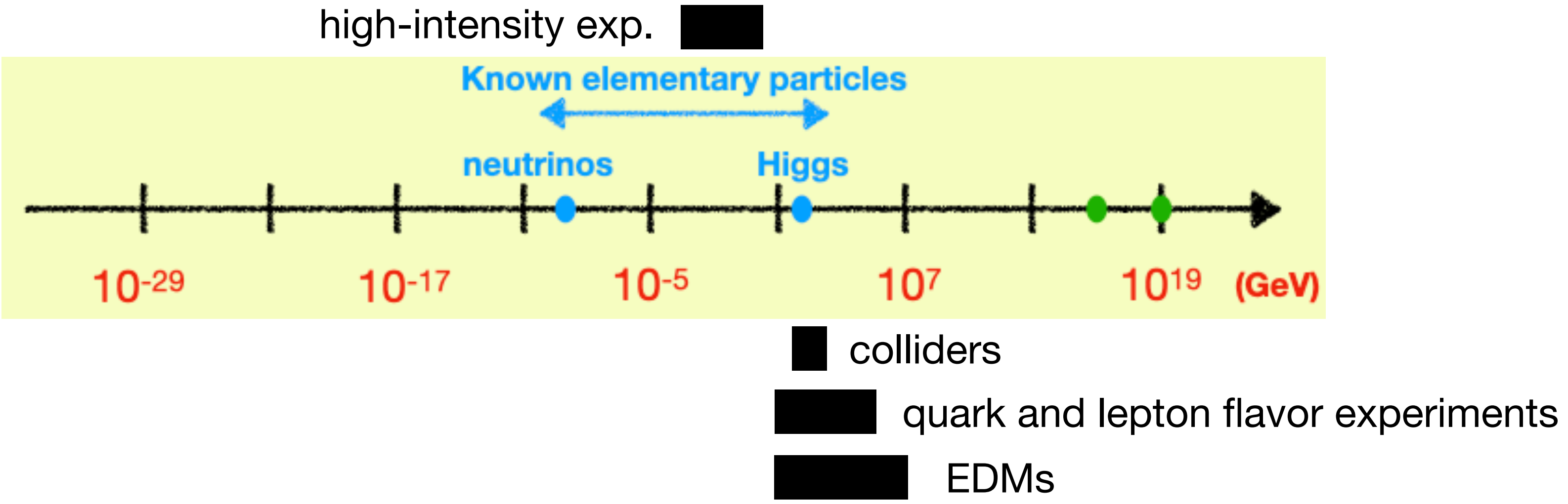


Outlook & take home messages

What's a discovery in particle physics

- Detecting for the first time a new fundamental process
- Discovering new particles (indirectly or directly)

We do not know what the next New Physics scale will be.



Open problems in particle physics and cosmology (both observational and theoretical) should be seen as good guiding principles.

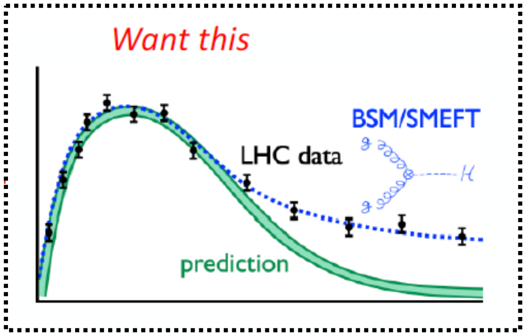
New exciting measurements and searches coming up in the next few years.

Higgs distributions & SMEFT

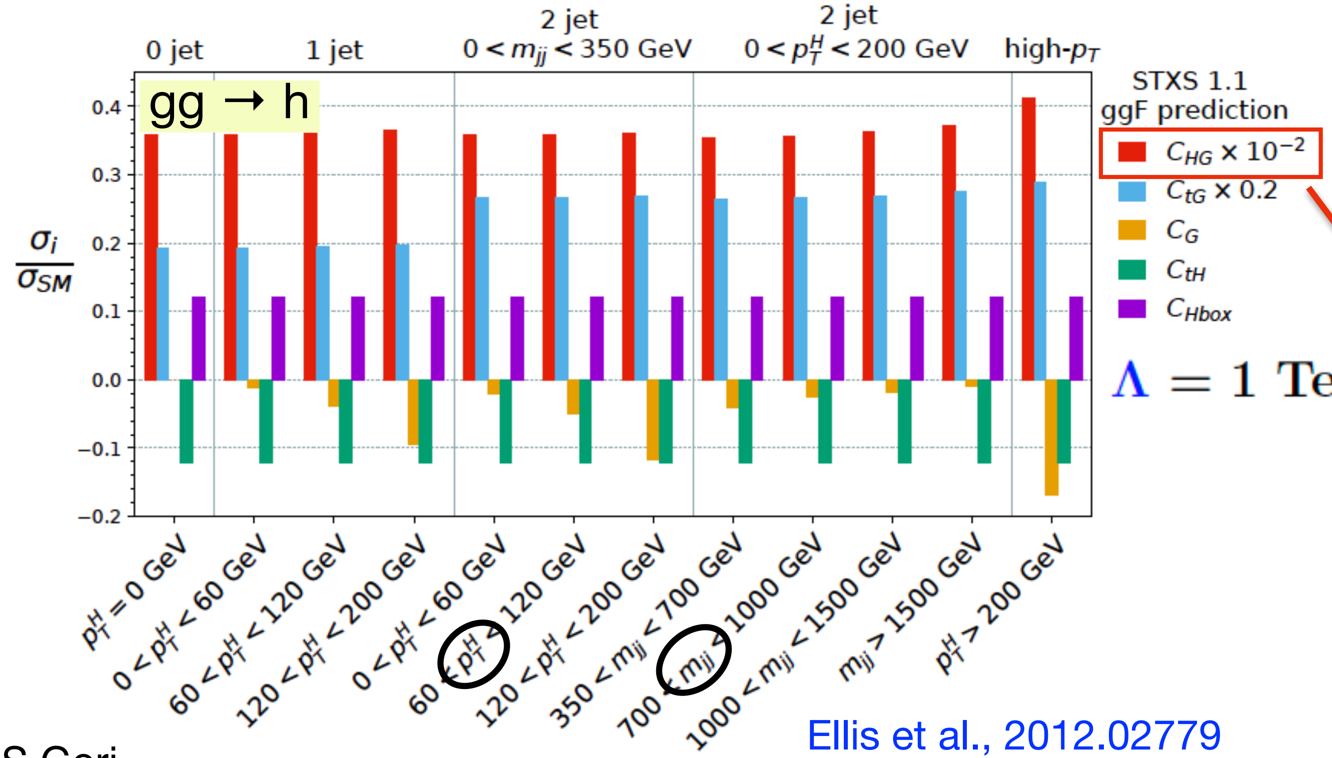
The LHC not only measures Higgs rates but also Higgs event distributions.

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



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

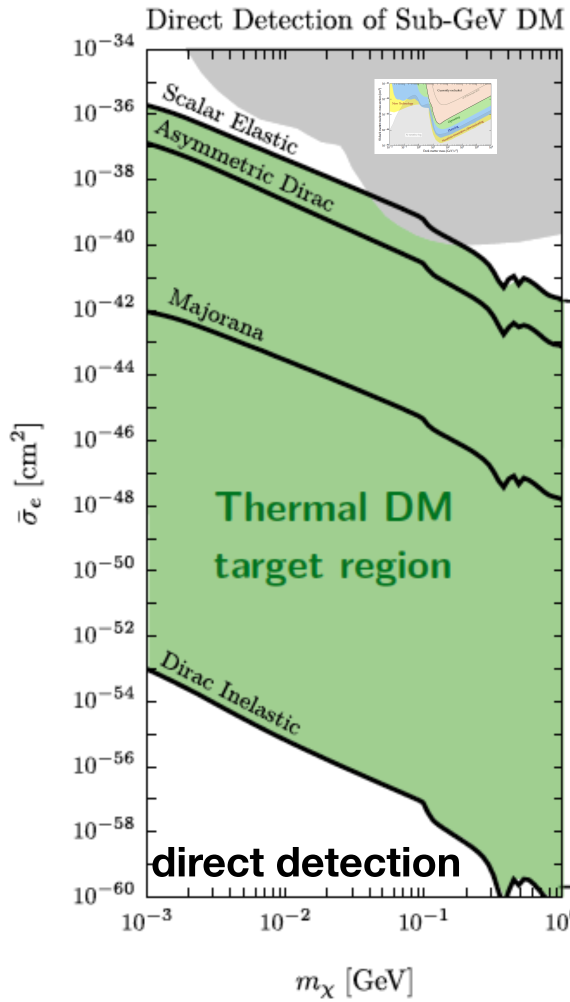
Example:

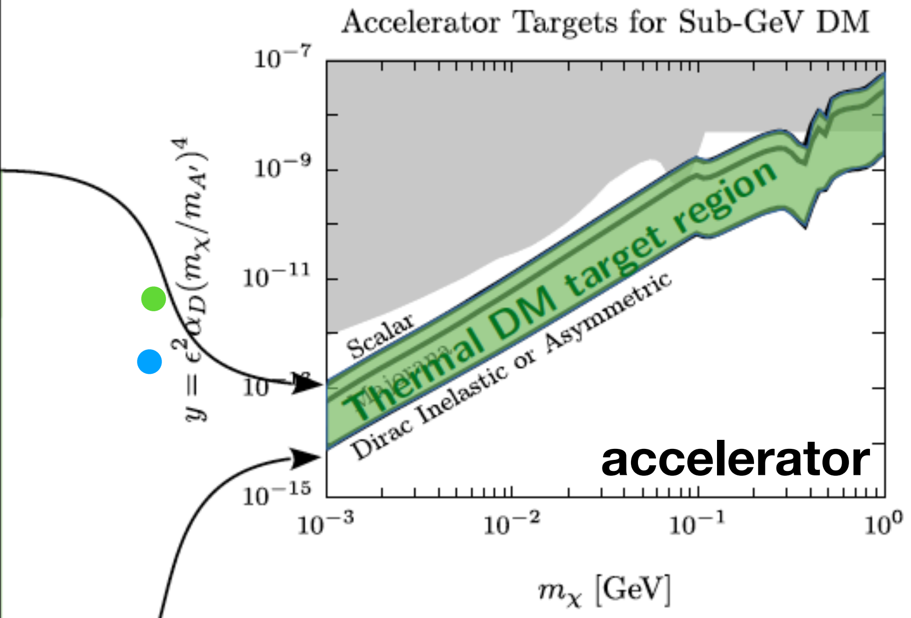
$$\boxed{\mathcal{O}_{HG}} = H^\dagger H G^A_{\mu\nu} G^{\mu\nu A}$$

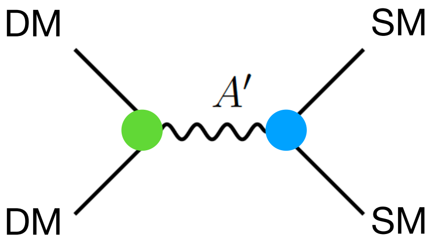
Ellis et al., 2012.02779

Complementarity with DM direct detection

To connect these two probes,
one need to make
model assumptions







if $m_{A'} > 2m_{DM}$

$$\sigma \propto \frac{y}{m_{\rm DM}^2},$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_{\rm DM}}{m_{A'}}\right)^4$$

● ●

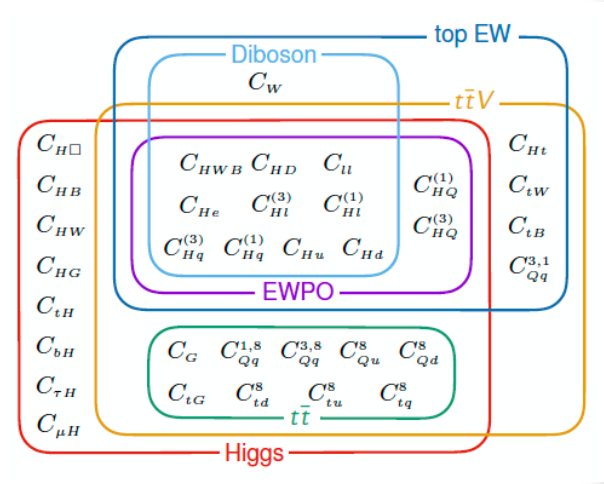
Accelerator production recreates the kinematic conditions of the early universe.

It is ~ unaffected by the nature of DM

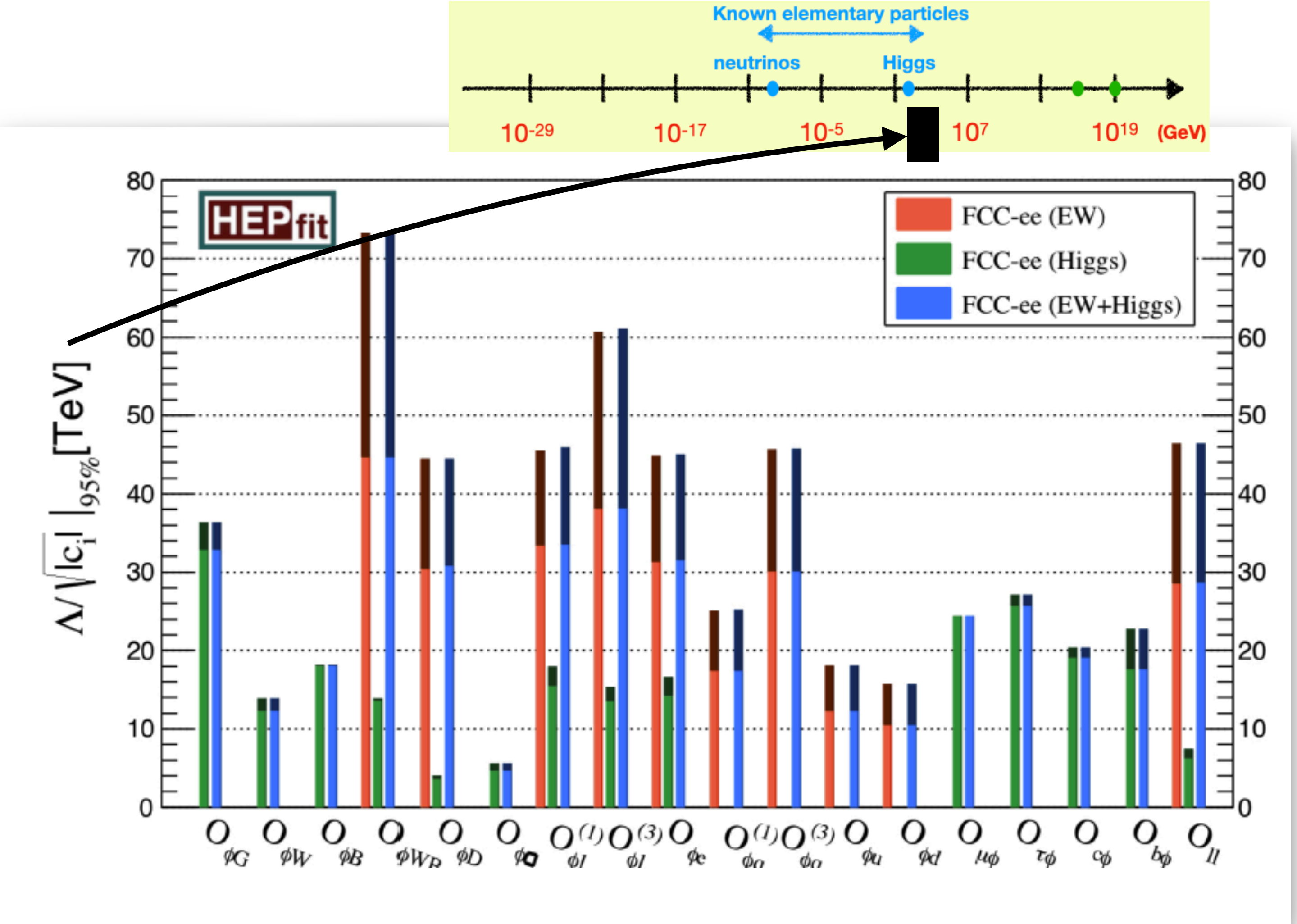
A broad experimental program encompassing both accelerator and direct detection searches is necessary

Towards global fits of SMEFT coefficients

Ellis et al., 2012.02779



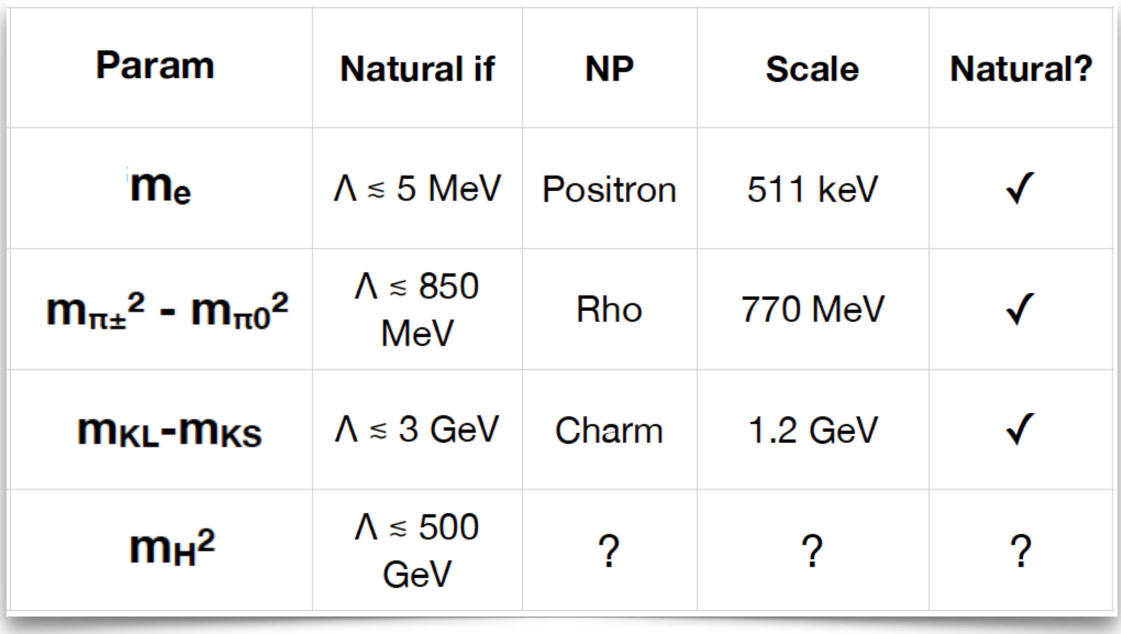
Theorists are at the forefront of SMEFT fits. Lot of work still needed for better understanding uncertainties.



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

Naturalness?

Adapted from N. Craig, Snowmass CSS



Param	Natural if	NP	Scale	Natural?
m_e	$\Lambda \lesssim 5$ MeV	Positron	511 keV	✓
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\Lambda \lesssim 850$ MeV	Rho	770 MeV	✓
$m_{K_L} - m_{K_S}$	$\Lambda \lesssim 3$ GeV	Charm	1.2 GeV	✓
m_H^2	$\Lambda \lesssim 500$ GeV	?	?	?

testability ↑

SUSY
Composite Higgs
Extra dimensions
Neutral naturalness
Relaxion models
Clockwork
NNaturalness
UV/IR mixing
…

There is not anymore a no-loose theorem that connects naturalness to discoveries at colliders

Is Naturalness still a good guiding principle/strategy?

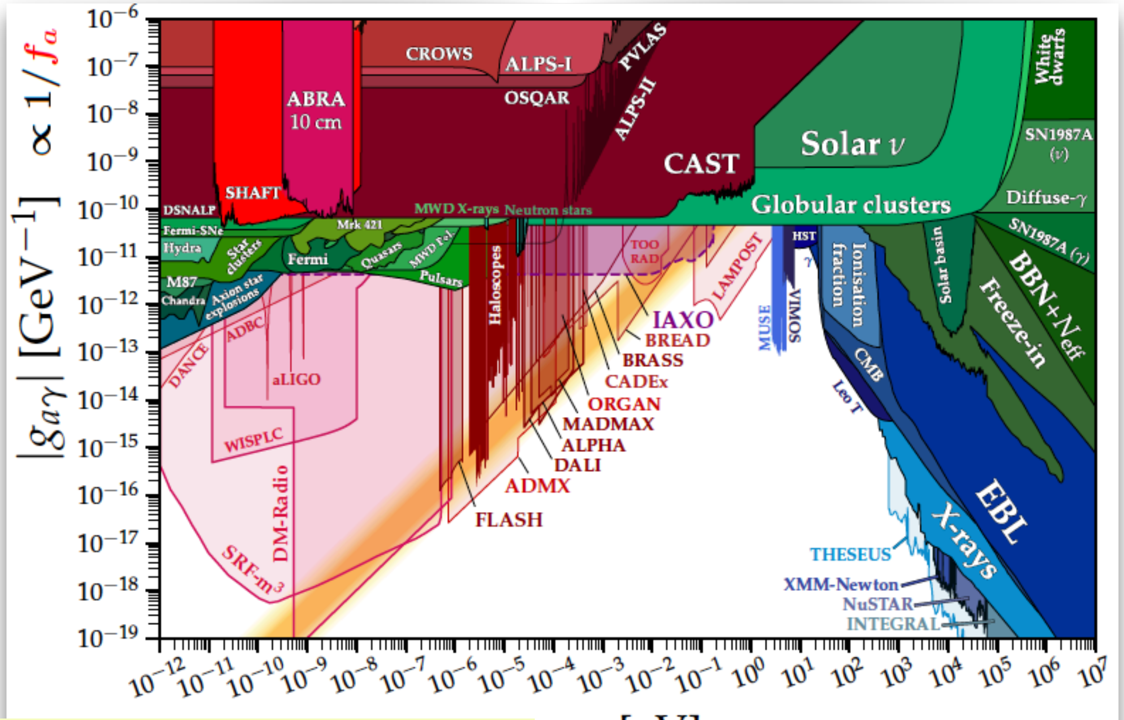
Present and future QCD axion detection prospects

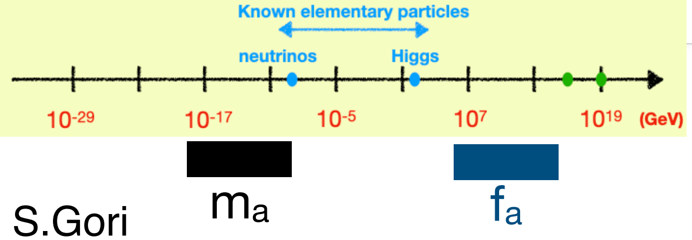
- Haloscopes: axions being the dark matter (ADMX, HAYSTACK, CAPP, MADMAX, DMRadio, ...);
- Helioscopes: axions produced inside the Sun (IAXO, ...);
- Experiments that produce and detect axions in the laboratory. No astrophysical or cosmological assumption (ALPS-II, ...)

future experiments

see talk by Lindner at this meeting

Adams at al., Snowmass white paper, 2203.14923





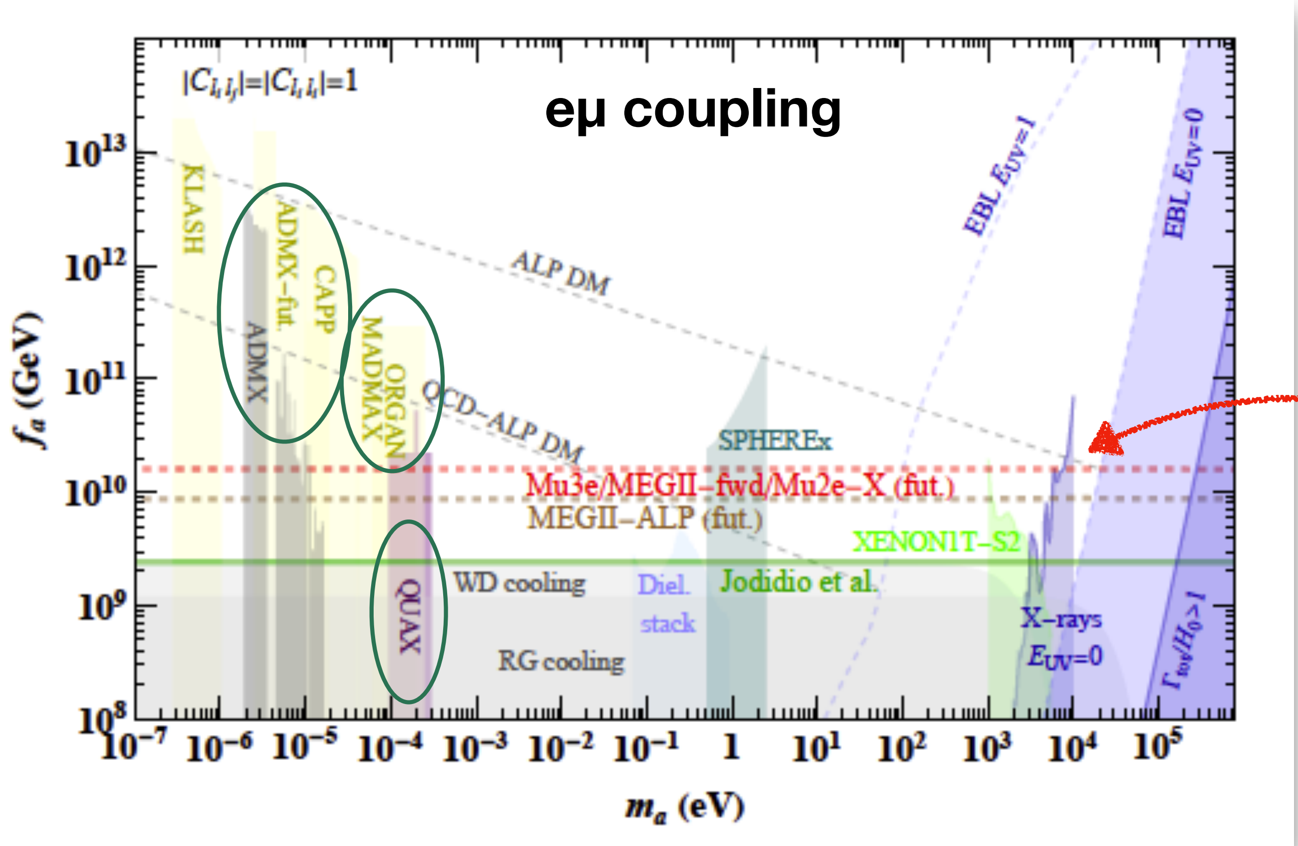
If we discover the axion in a cavity experiment, we have an automatic precision measurement of its mass

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

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

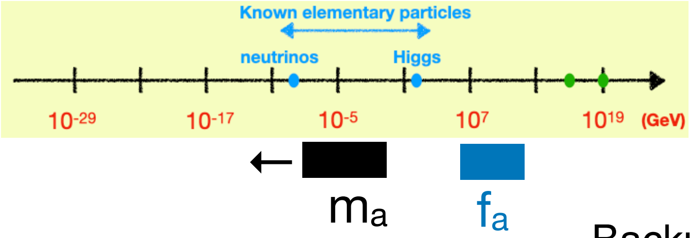
see also Calibbi et al., 2006.04795

High-intensity precision experiments discussed in chapter 2!

Complementarity with QCD axion experiments.

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

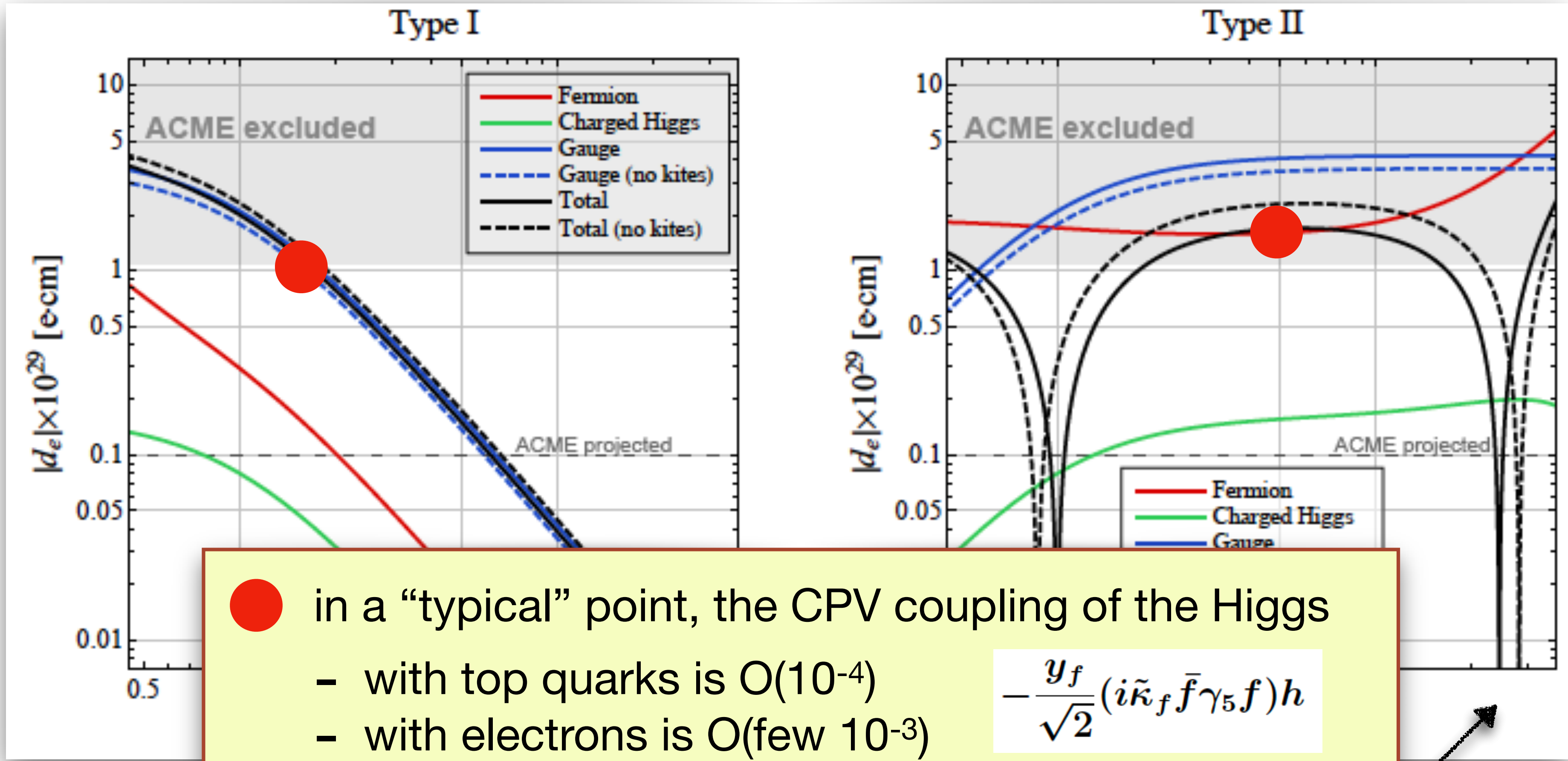
$$\mathrm{BR} \propto \left(\frac{m_\mu}{f_a}\right)^2$$



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(few 10^{-3})

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

Cancellations

In the decoupling limit:

$$\text{Type I:}\quad d_e = -1.06\times 10^{-27}\,e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2\text{Im}(\lambda_5)\quad\cos^2\beta\left[1+0.07\ln\left(\frac{M}{1\,\text{TeV}}\right)\right],$$

$$\text{Type II:}\quad d_e = \quad 0.47\times 10^{-27}\,e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2\text{Im}(\lambda_5)\left\{\sin^2\beta\left[1+0.16\ln\left(\frac{M}{1\,\text{TeV}}\right)\right]-1.26\cos^2\beta\right\}$$

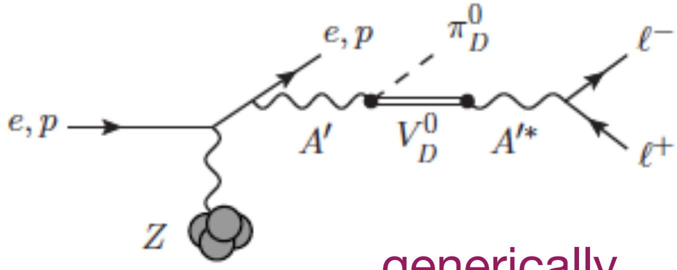
DM in a strongly interacting dark sector

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

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

The additional dark states will lead to a richer phenomenology

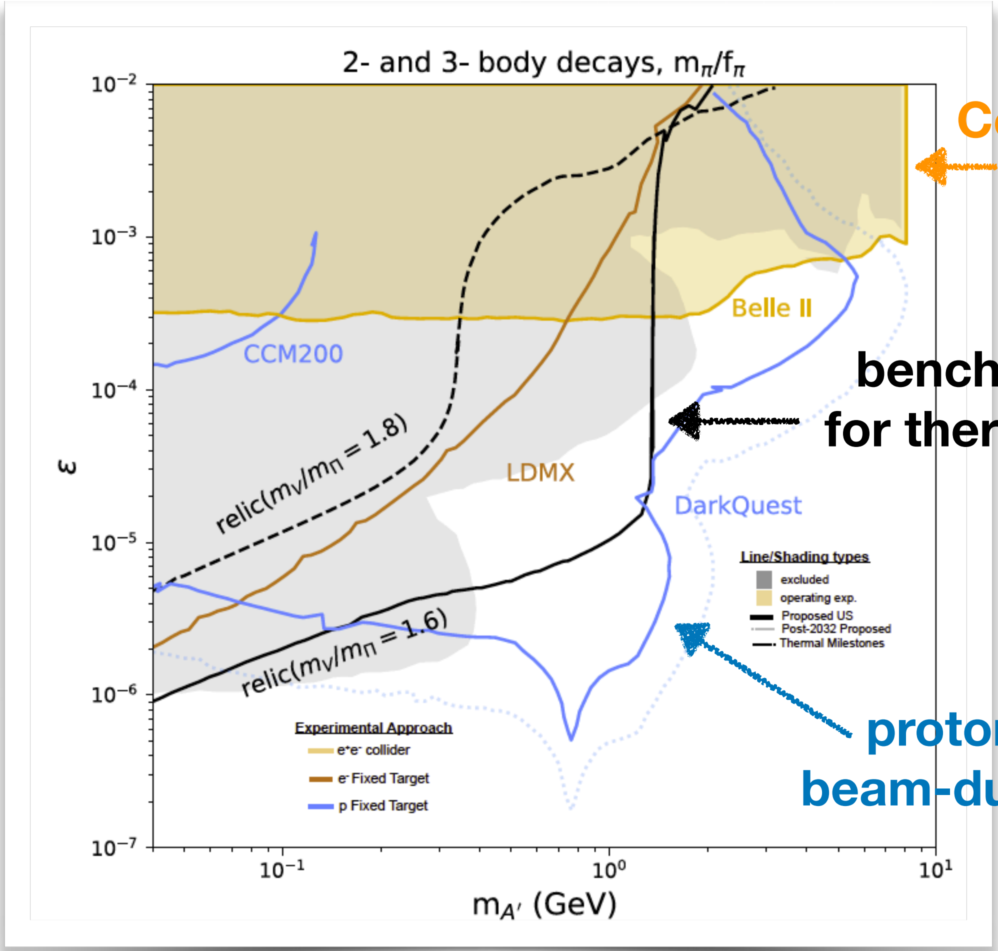
For example:



generically long-lived

$A' \to V_D \pi_D$ ← DM state

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



Colliders

benchmarks for thermal DM

proton beam-dump