Theory perspective

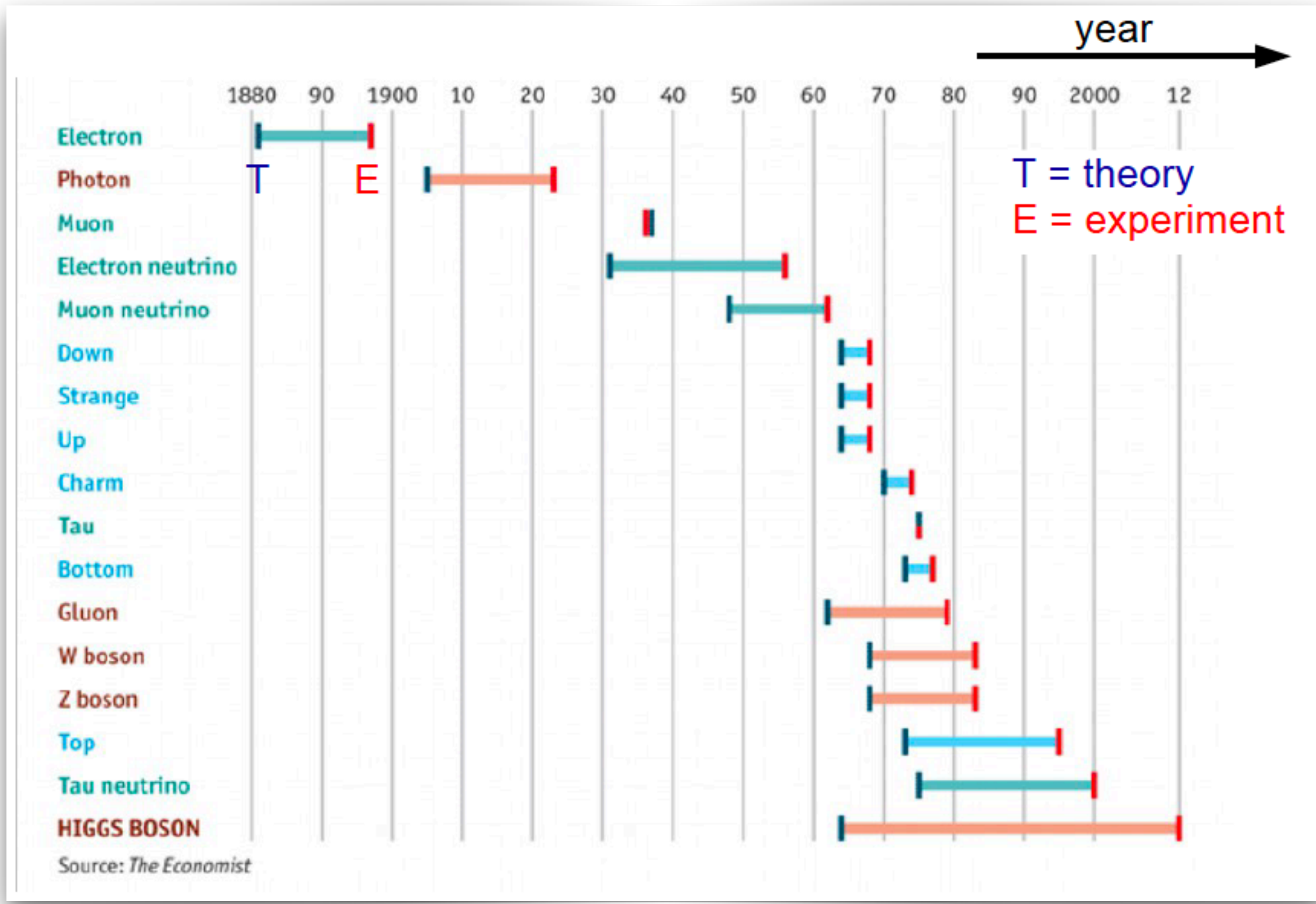
Disclaimer: my own theory perspective

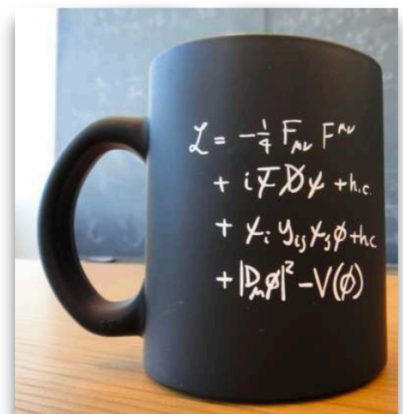
Stefania Gori
UC Santa Cruz

11th edition of the Large Hadron Collider Physics Conference (LHCp)
Belgrade,
May 26, 2023

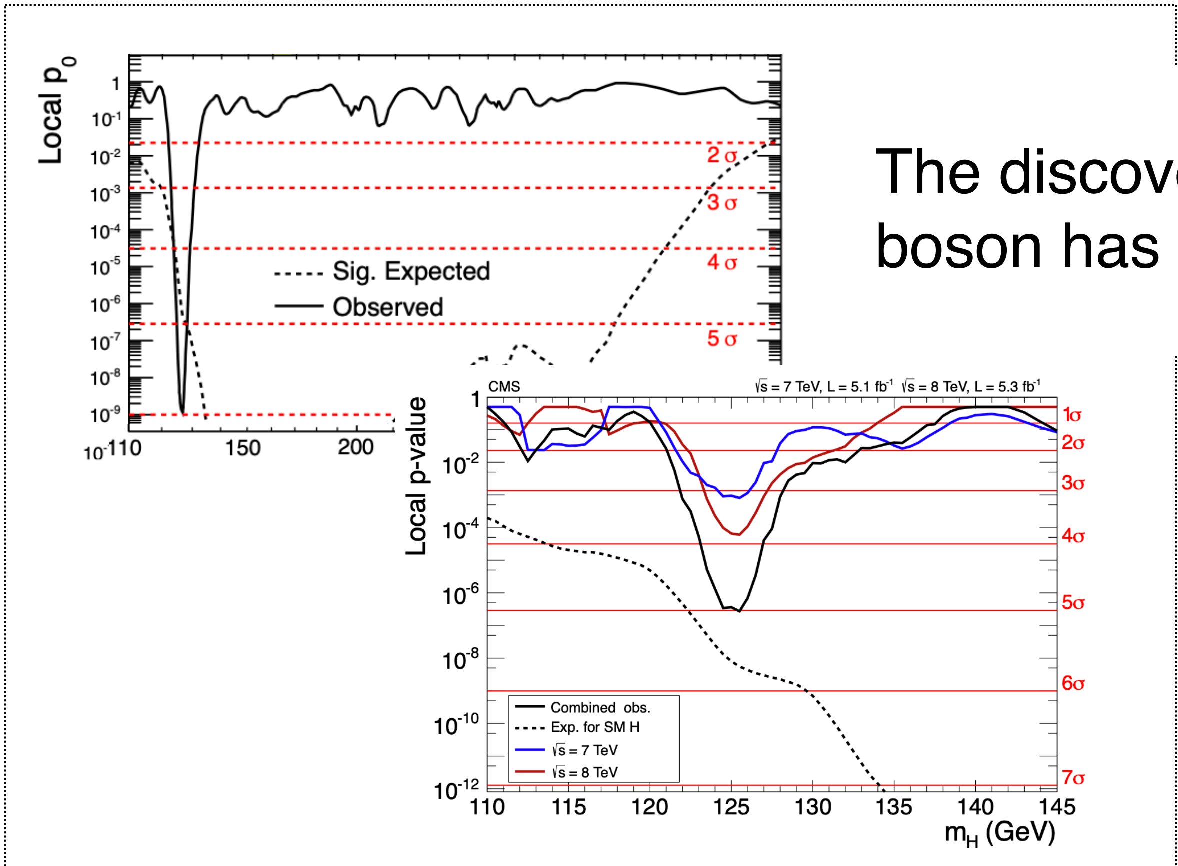
Particle physics: past, present & future

Big success of HEP in the past 50+ years. HEP has enjoyed the remarkable achievement of uninterrupted fundamental discoveries!



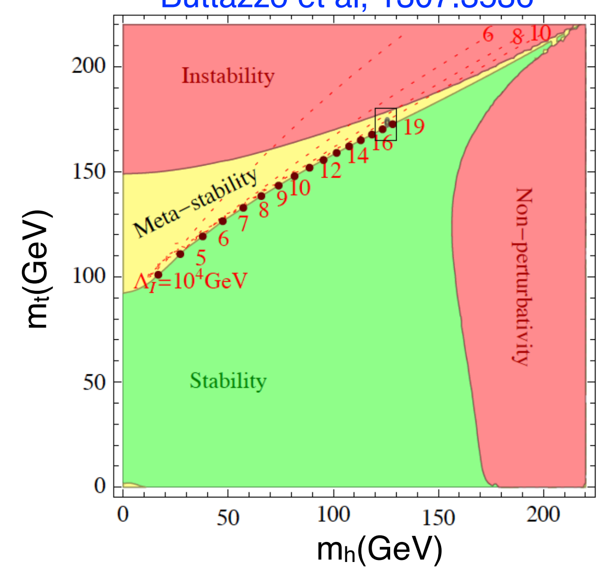


The LHC: a discovery machine



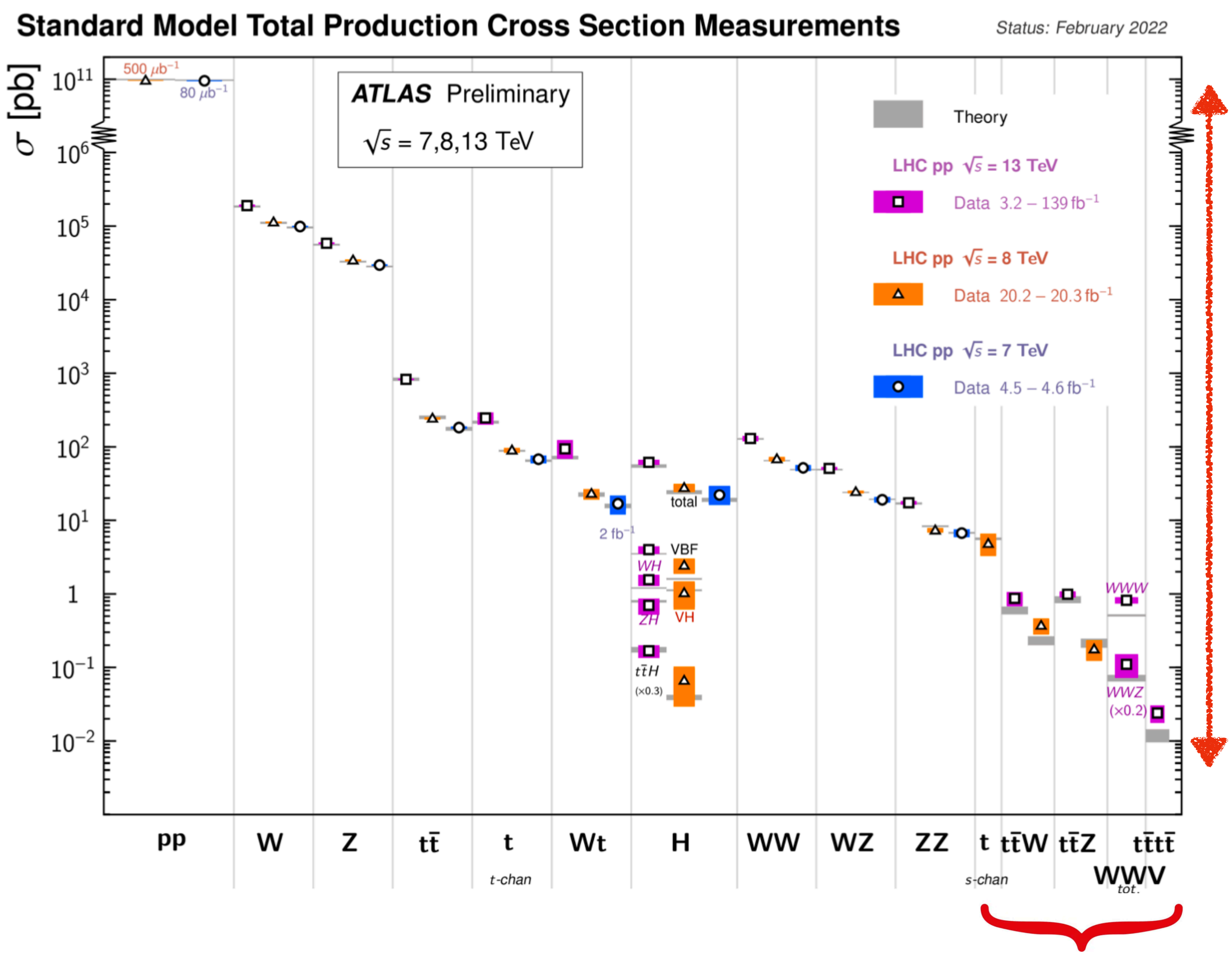
The discovery of the Higgs boson has been a turning point.

Buttazzo et al, 1307.3536



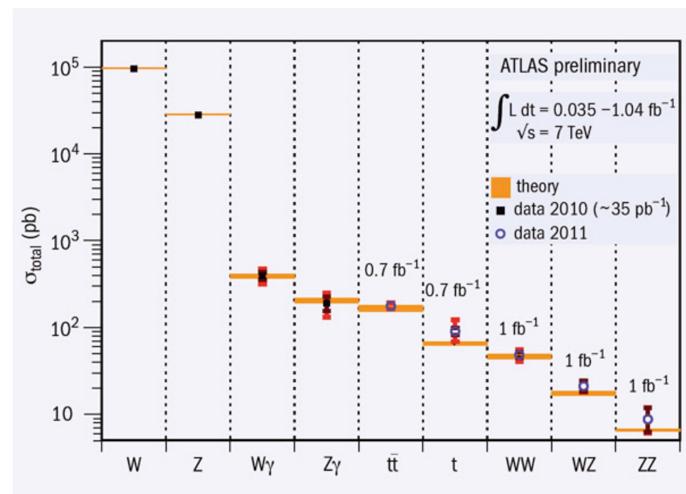
With the discovery of the Higgs at 125 GeV, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

The LHC: a precision machine



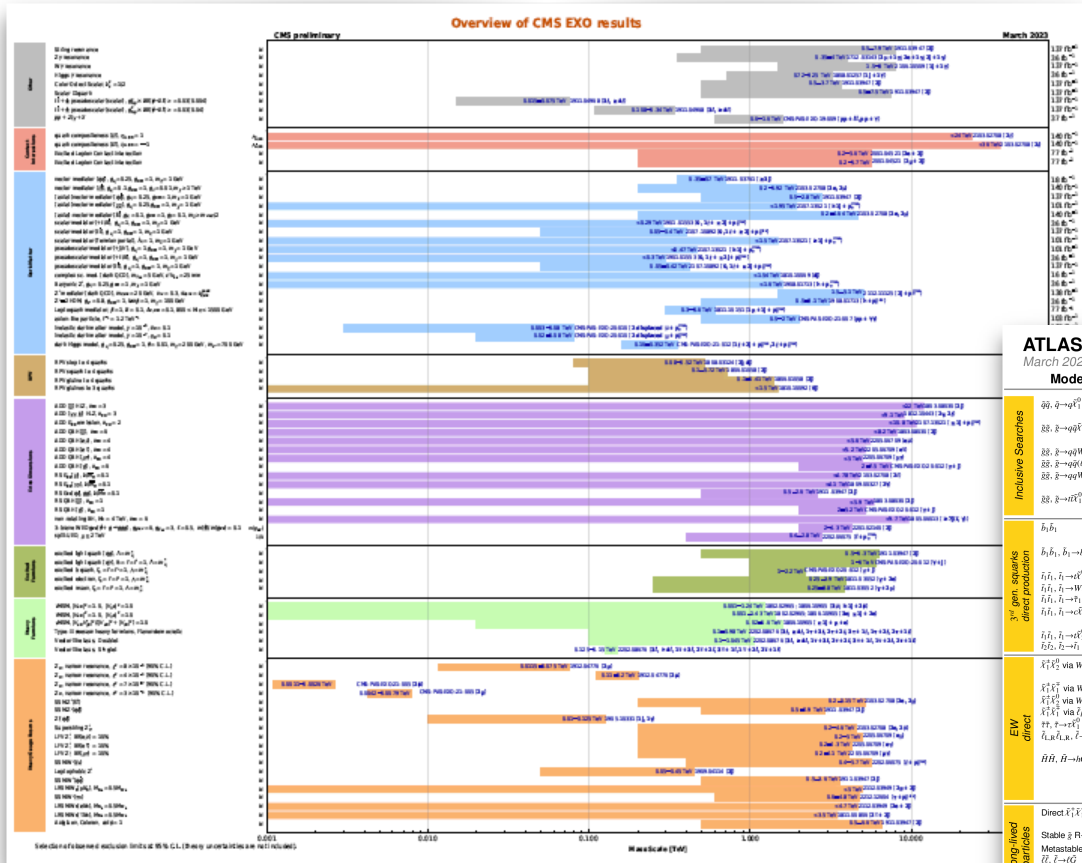
13 orders of magnitude

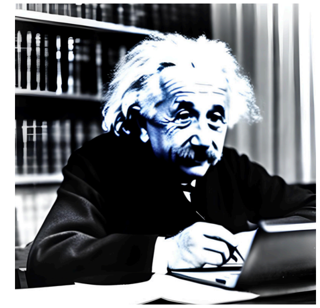
As at the end of 2011:



LHC Run 1 & 2: Experimental and theoretical triumph

The LHC: a machine that challenges us theorists!





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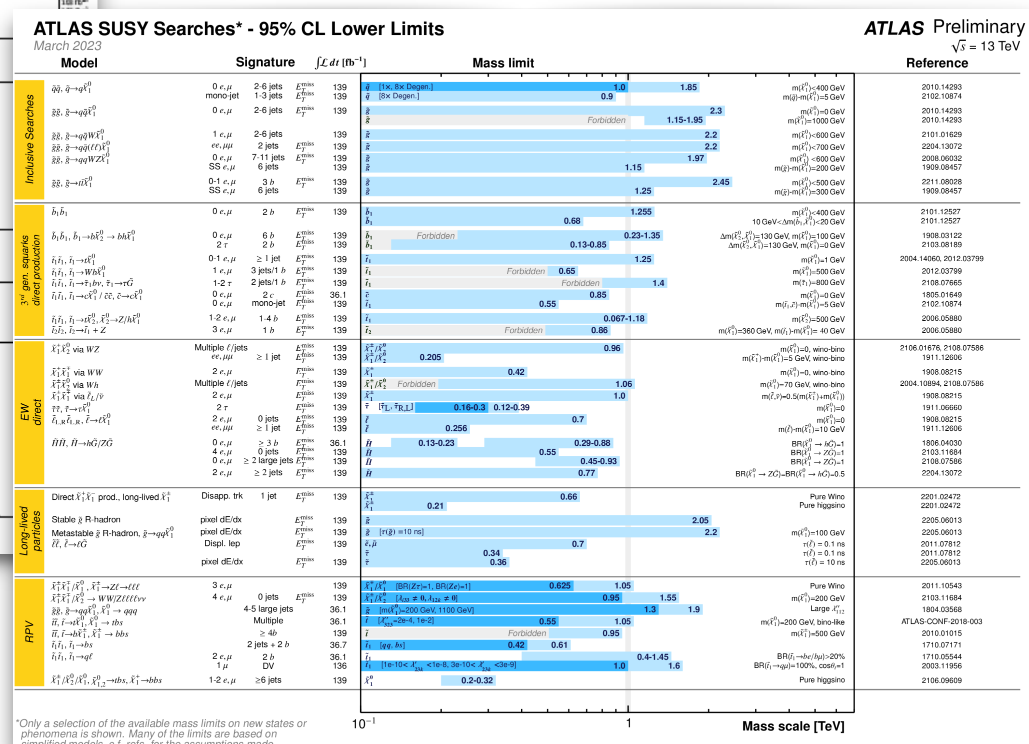

Where do we go from here?

Big unanswered questions

Origin of the electroweak scale

Nature of Dark Matter (DM)

Strong CP problem

Matter-antimatter asymmetry

Origin of neutrino masses

Flavor problem

the known unknown

Old questions but **remarkable progress** has been done in the past ~decade

Big unanswered questions

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<u>Overarching question:</u>
what is the unknown?

the unknown unknown

Old questions but **remarkable progress** has been done in the past ~decade

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

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

Axions &
Axion-like-particles

Extended Higgs sectors

Effective field theories

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?

Discoveries in particle physics

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

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

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In this sense, we had several "Higgs discoveries" after the 2012 discovery:

- Latest Higgs discovery:

Higgs interacting with **bottom quarks**
(August 2018, ATLAS: Phys. Lett. B 786 (2018) 59, CMS: PRL 121 (2018) 121801)

- Latest Higgs evidence for:

$H \to \mu\mu$ (July 2020, ATLAS: Phys. Lett. B 812 (2021) 135980, CMS: JHEP 01 (2021) 14)
$H \to ll\,\gamma\gamma$ (March 2021, ATLAS: 2103.10322)

Discoveries in particle physics

Part 2
of this talk

Particle physics is **not only about discovery new particles**.
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Part 1
of this talk

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Part 1
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Particle physics is about the laws of nature, which include the interactions and properties of the particles that we have already discovered.

The future Higgs discoveries

"The Higgs is SM-like" but…

We need to understand if the Higgs	Unanswered questions
* interacts with the 2nd generation	the flavor puzzle
* interacts with itself	the matter antimatter asymmetry, the origin of the electroweak scale
* is CP violating	the matter antimatter asymmetry
* interacts with DM/a dark sector	the origin of DM, the strong CP problem(?)
* interacts with new Higgs bosons	the origin of the electroweak scale

…

The future Higgs discoveries

Happy 10th Birthday Higgs

"The Higgs is SM-like" but…

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

Before the Higgs discover, 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! (the first coupling to 2^{nd} generations!)

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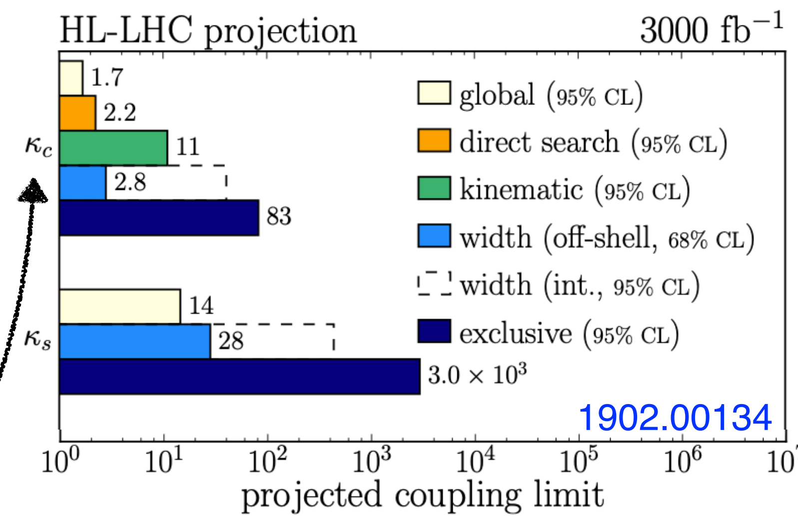
Muon: ~2-3σ evidence at Run II
Expected discovery at Run III.
~5% level measurement at the HL-LHC



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

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

Higgs

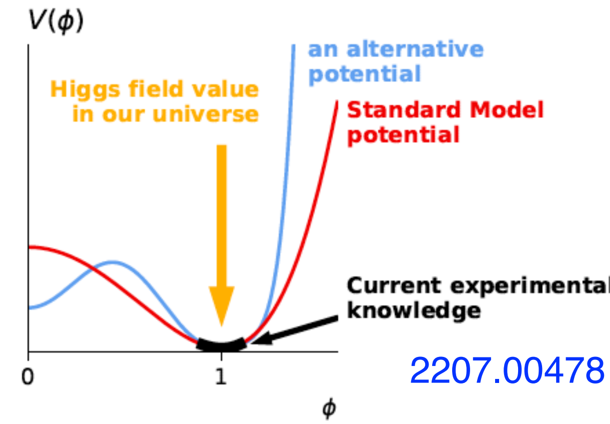
"The Higgs is SM-like" but…

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

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

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

First self-interacting fundamental particle ever seen in Nature?



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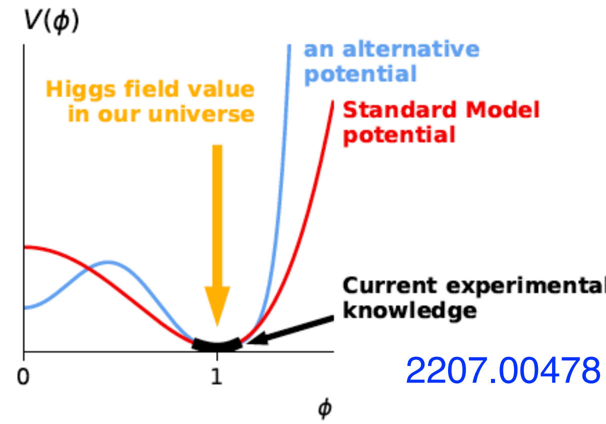

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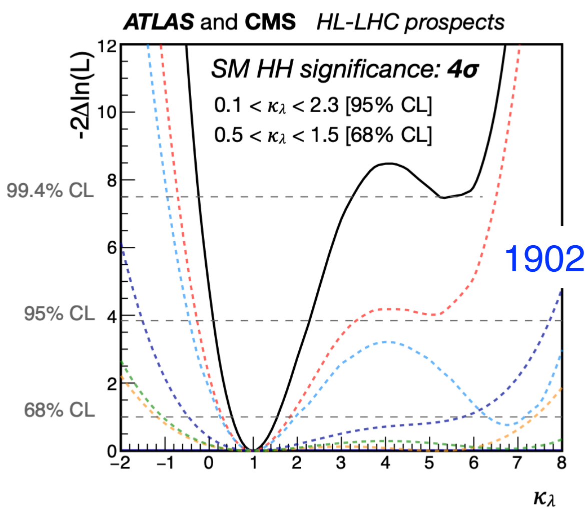

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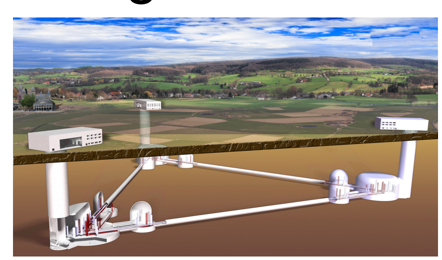
Hope for a discovery?

Deep implications on the fate of the universe

If the phase transition that led to electroweak symmetry breaking is different than in the SM, chances to have observation in gravitational wave detectors



The Higgs precision program (theory)

"The Higgs is SM-like" but…**Do we really know?**

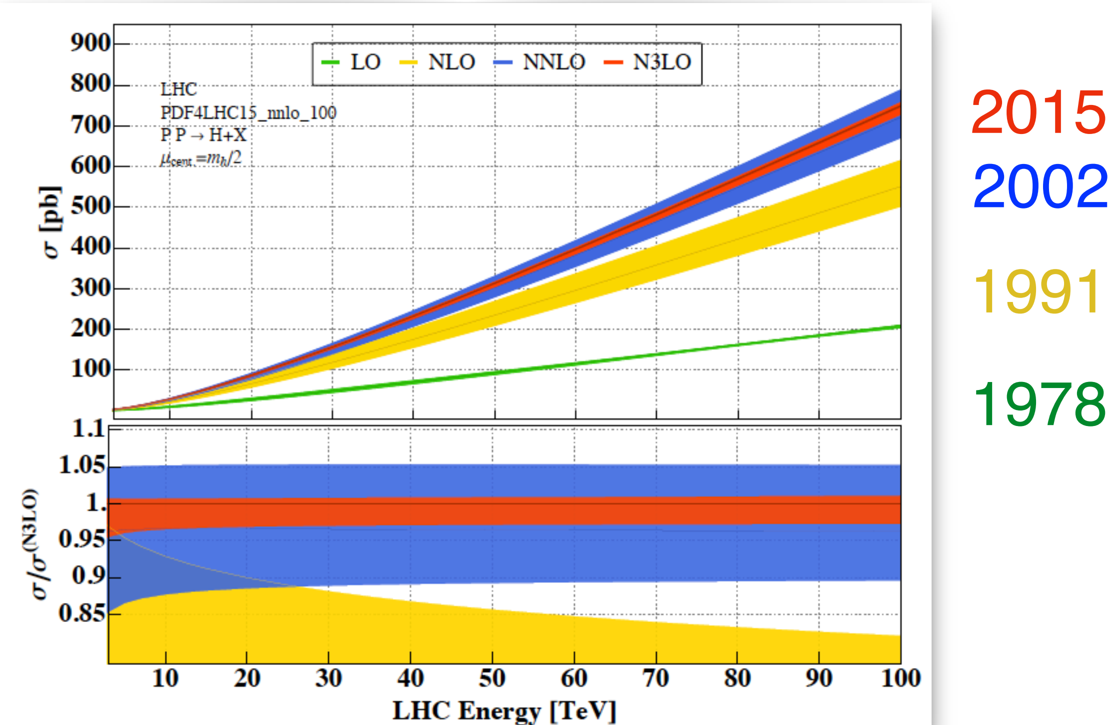
The measurement of the Higgs boson productions and decays represent a concrete deliverable for present and future collider projects.

The Higgs precision program (theory)

"The Higgs is SM-like" but…**Do we really know?**

Theory uncertainties have decreased significantly over the years.

2209.06138



Unprecedented accuracy is needed to interpret future data.

The measurement of the Higgs boson productions and decays represent a concrete deliverable for present and future collider projects.

The Higgs precision program (theory+exp)

We need to go further! Both in measurements and in theory predictions

Kappa framework and differential distributions

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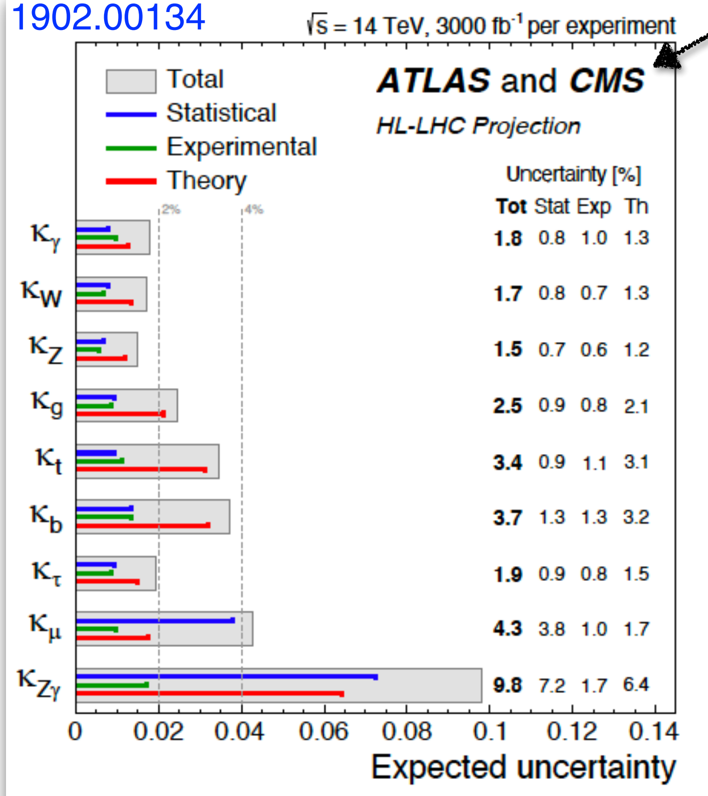
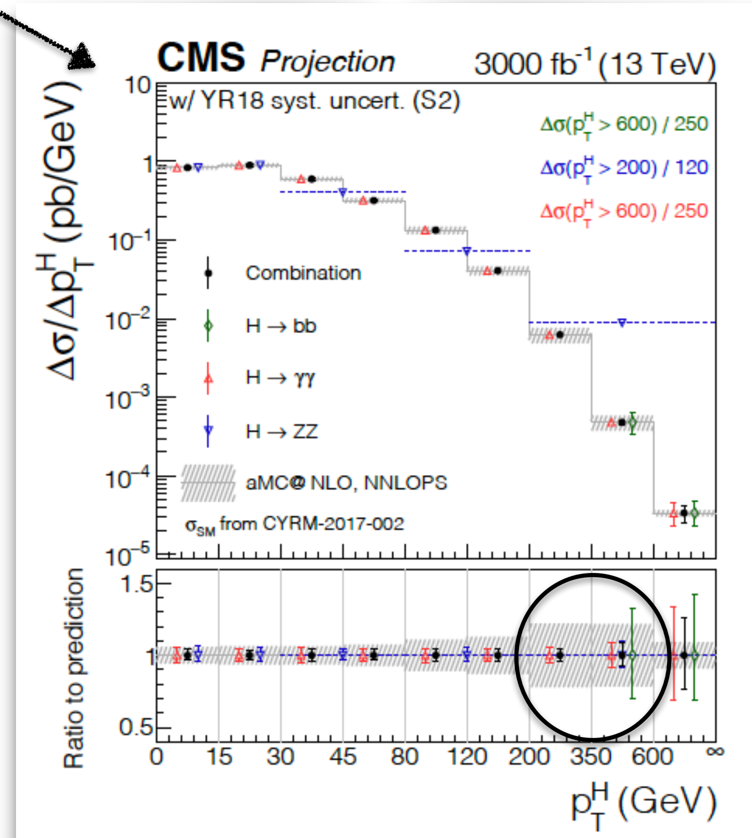


Projections assume theory uncertainties are halved!



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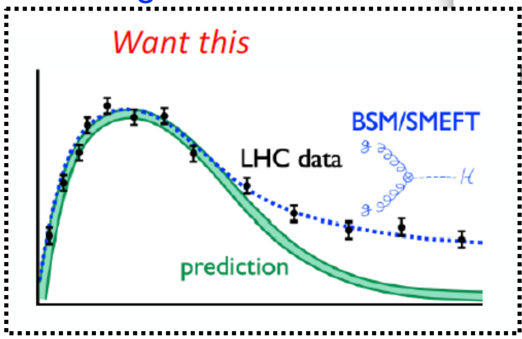
Learning about the Higgs at its best

Higgs precision measurements and EFTs

$$\text{Experiment} = \text{Theory}_{\text{SM}} + \sum_i \frac{C_i^6}{\Lambda^2} + \cdots$$

Zanderighi



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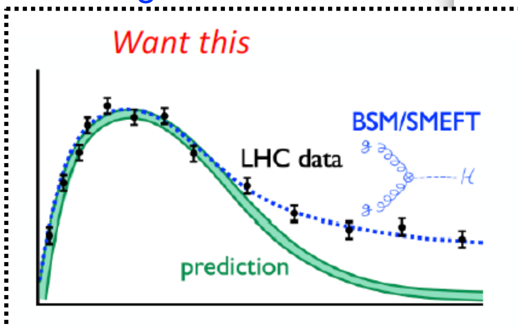
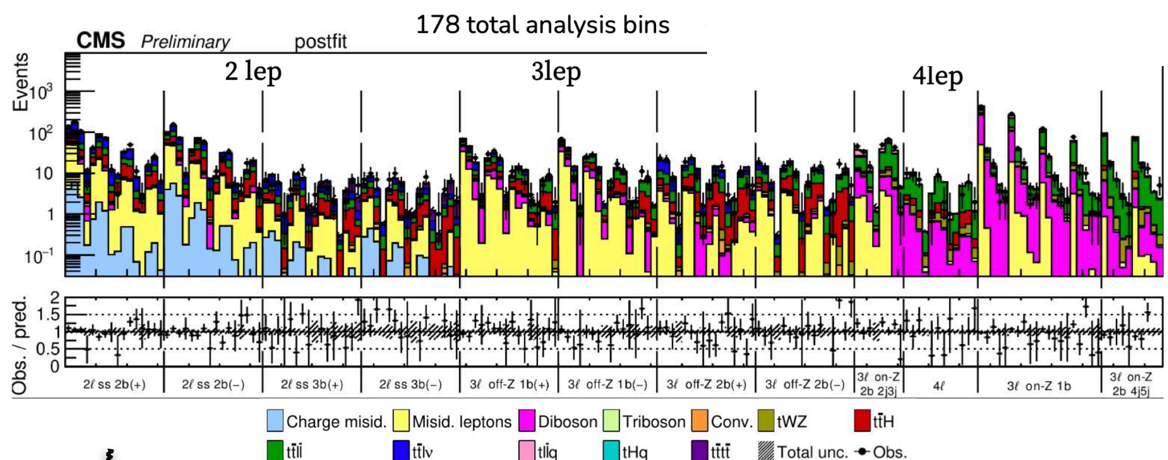


Theorists are at the forefront of SMEFT fits.

Lot of work still needed for better understanding uncertainties.

CMS PAS TOP-22-006



It's not just the Higgs anymore.

- Higgs data,
- top quark data,
- gauge boson pair production,
- EW precision observables

all contribute to SMEFT predictions.

Operator category	WCs
Two heavy quarks	$c_{t\varphi}, c^{-}_{\varphi Q}, c^{3}_{\varphi Q}, c_{\varphi t}, c_{\varphi tb}, c_{tW}, c_{tZ}, c_{bW}, c_{tG}$
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}, c^{-(\ell)}_{Q\ell}, c^{(\ell)}_{Qe}, c^{(\ell)}_{t\ell}, c^{(\ell)}_{te}, c^{S(\ell)}_{t}, c^{T(\ell)}_{t}$
Two light quarks two heavy quarks	$c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}$
Four heavy quarks	$c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}$

Future indirect discovery of a New Physics scale, Λ?

The flavor precision program

Incredible success of the LHC flavor physics program.

Many discoveries

For example:

discovery of the $B_s \to \mu\mu$ decay

first observation of CP violation in charged B meson and B_s meson decays,

first observation of CP violation in charm meson decays,

first observation of charm mixing at a single experiment,

discovery of many new hadrons

world's best measurement of CP asymmetries in both B_d mixing and B_s mixing

multifaceted determination of $b \to sll$ transitions

Theory enabling experiments and experiments enabling theory.

For example:

* many new lattice calculations (B and D-meson form factors, quark masses, …)
  Continuous updates of the Flavor Lattice Average Group (FLAG) website,
  http://flag.unibe.ch
* development of very sophisticated EFT fits for $b \to sll$ transitions

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Many discoveries

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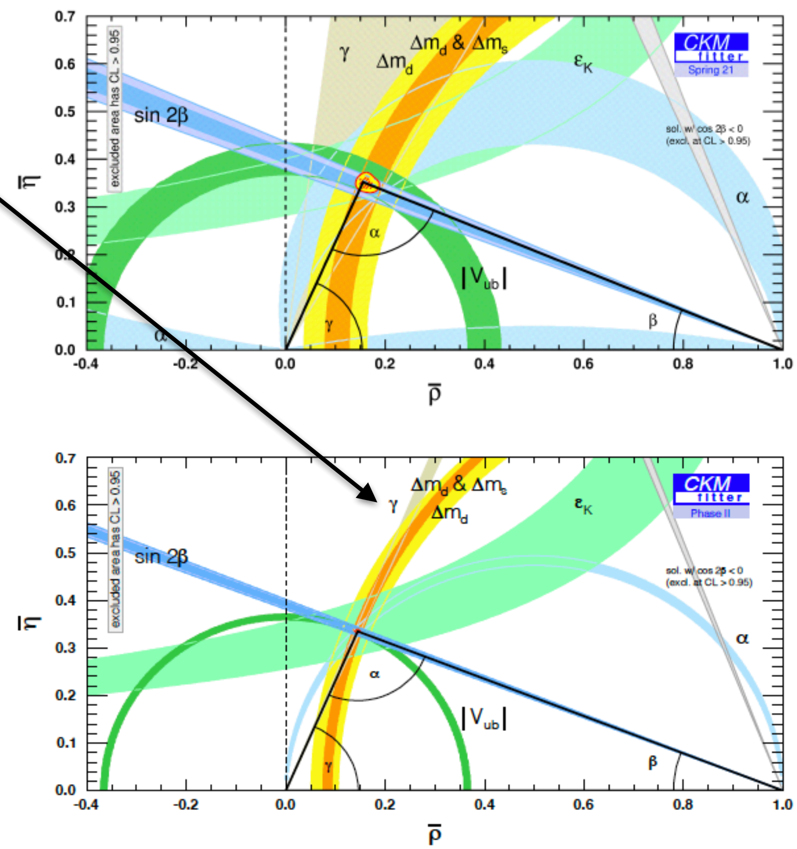
Observable	Current LHCb	Upgrade II
EW Penguins		
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.044 [6]	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.12 [19]	0.009
CKM tests		
γ	4° [5]	0.35°
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [20]	0.003
ϕ_s, with $B^0_s \to J/\psi\phi$	32 mrad [21]	4 mrad
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [23]	9 mrad
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	154 mrad [24]	11 mrad
$a^s_{\rm sl}$	33×10^{-4} [26]	3×10^{-4}
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [27]	1%
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$		
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [4,28]	11%
$\tau_{B^0_s \to \mu^+\mu^-}$	14% [4,28]	2%
$S_{\mu\mu}$	–	0.2
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**		
$R(D^*)$	0.026 [30,31]	0.002
$R(J/\psi)$	0.24 [32]	0.02
Charm		
$\Delta A_{CP}(KK - \pi\pi)$	29×10^{-5} [7]	3.3×10^{-5}
A_Γ $(\approx x \sin\phi)$	11×10^{-5} [33]	1.2×10^{-5}
Δx $(D^0 \to K^0_S \pi^+\pi^-)$	18×10^{-5} [34]	1.6×10^{-5}

1808.08865



Future insights on the flavor structure of Nature

Precision flavor physics and New Physics

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

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

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

- Observation of CP violation in kaon anti-kaon oscillations

  ➡ prediction of the 3rd generation quarks (Kobayashi, Maskawa, 1973)

50th Anniversary last February

https://www-conf.kek.jp/KM50/

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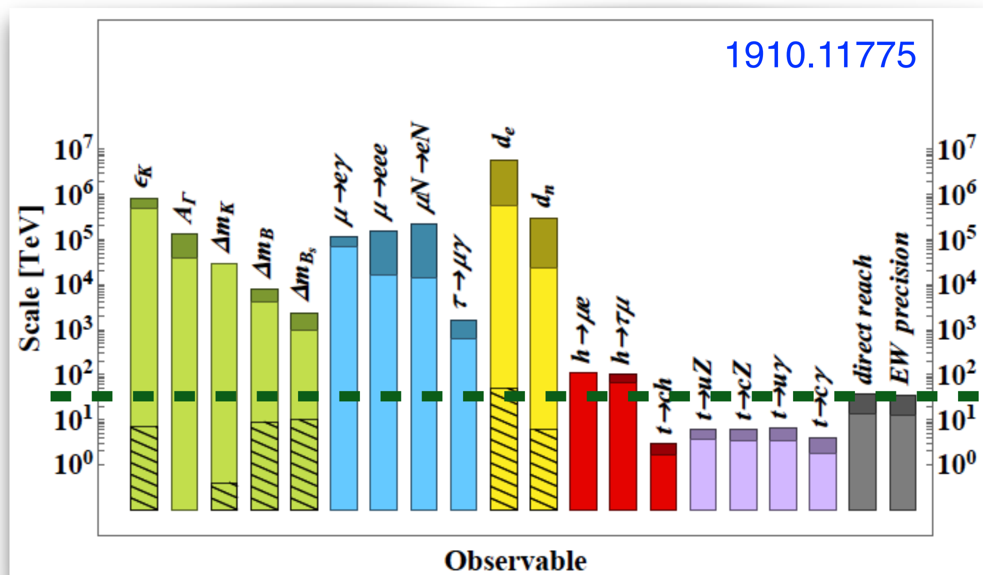
Flavor transitions: access to very high New physics scales, not directly accessible at collider experiments.

→ Future indirect discovery of a high new physics scale?



Discovery through precision measurements

We have discussed the importance of the Higgs and the flavor precision programs.

More in general,

"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

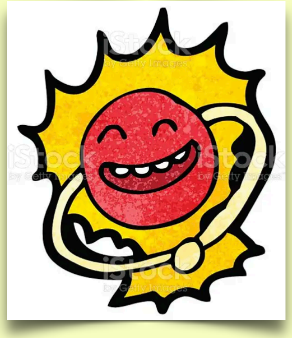
CERN Director-General Fabiola Gianotti and Gian Giudice, Head of CERN's Theory Department, comment on the scientific vision and priorities for the field laid out in the recently updated European Strategy for Particle Physics

2 OCTOBER, 2020

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

Part 2
of this talk

The direct quest for new particles



the known unknown

Probing broad ideas motivated by big open problems
(1. origin of EW scale, 2. Dark Matter,
3. strong CP problem)

theoretical prior

the unknown unknown

Searching for exotics.
Model independent searches.

no theoretical prior

1.

Probing broad ideas: the origin of the EW scale

Several classes of models have been proposed

Signals for the LHC:

* Solutions based on symmetries (SUSY, composite Higgs, neutral naturalness, …) → weak scale dynamics, new Higgs bosons
* Solutions based on symmetries + low cutoff (relaxion, 1504.07551) → Higgs portal, $\xi|H|^2|\phi|^2$ 1610.02025
* …

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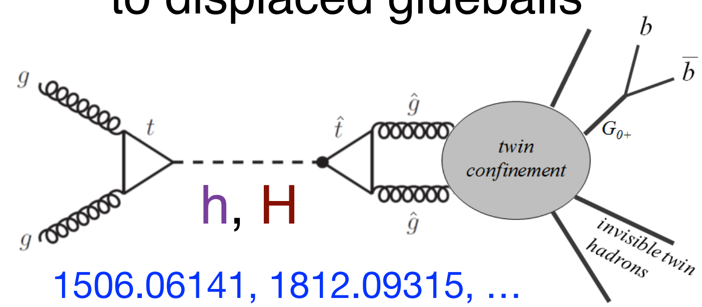
* …

Lots of info from future Higgs measurements.

Motivation for new searches for **additional Higgs bosons.**

Example:

Higgs exotic decays +
Heavy Higgs decays
to displaced glueballs



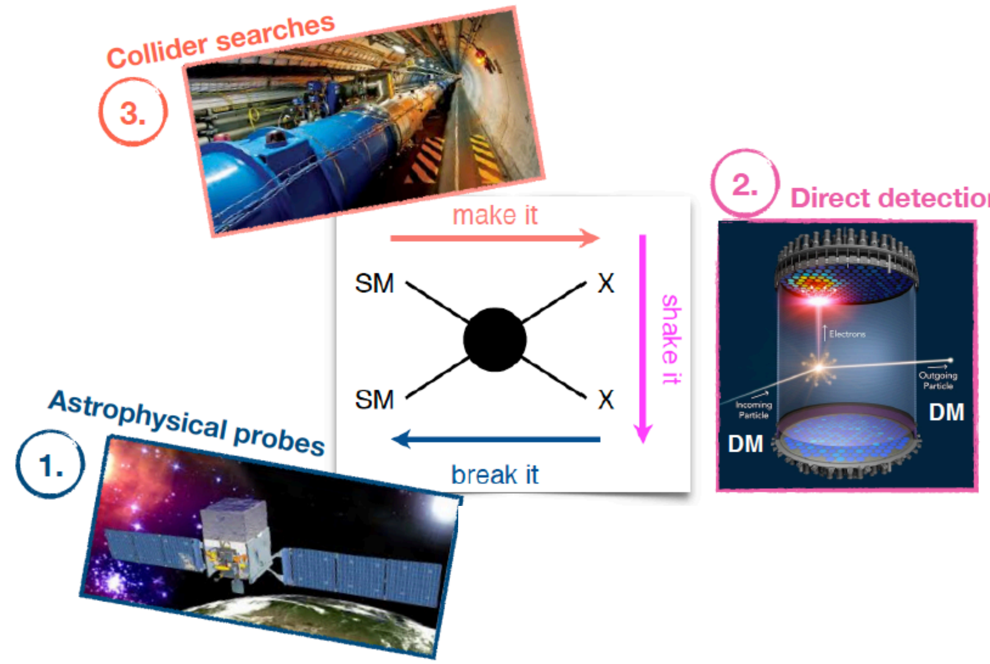
1506.06141, 1812.09315, …

2.

Probing broad ideas: WIMP (present)

Idea of WIMP DM has motivated a large experimental endeavor

Thermal freeze-out DM at around the electroweak scale is a very predictive framework



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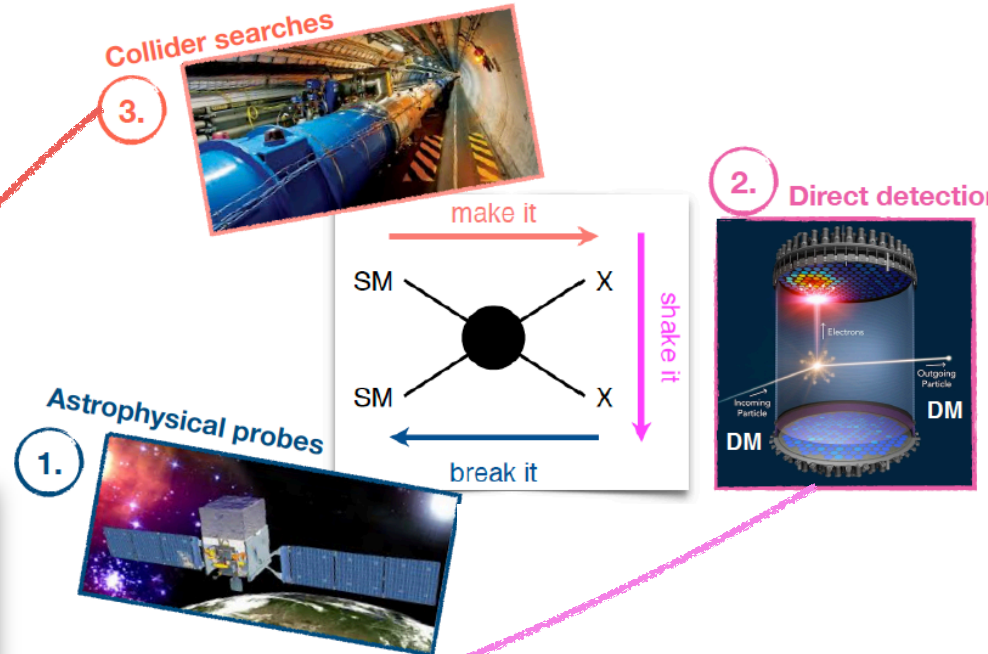
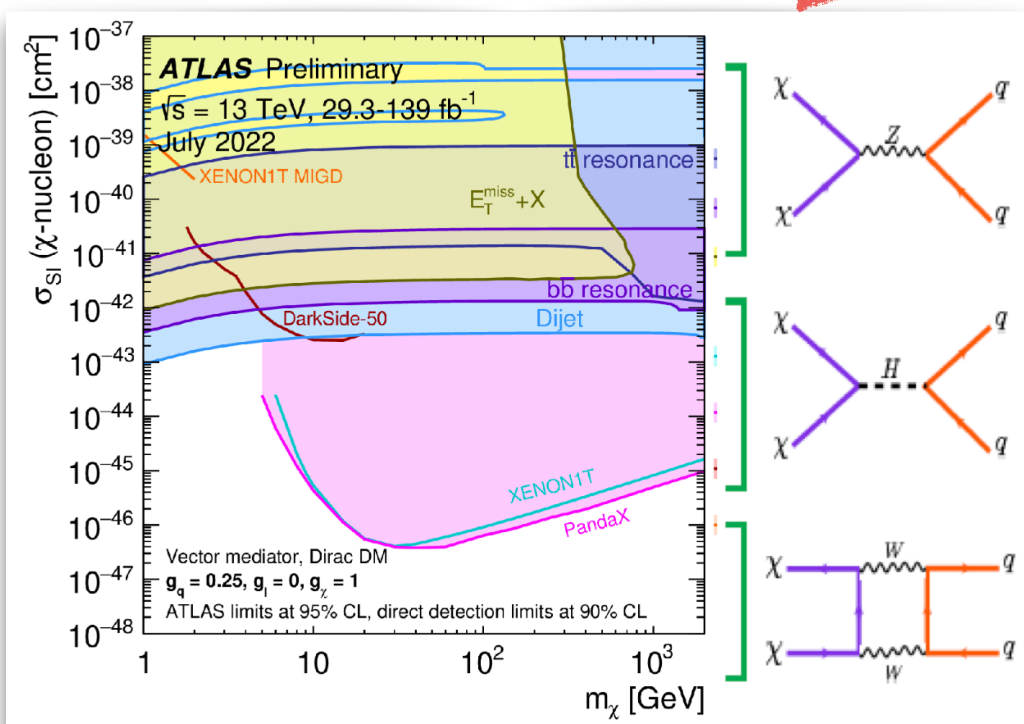




(interpretations on this plane are strongly model dependent)

Milestone:

vanilla WIMPs have been probed!

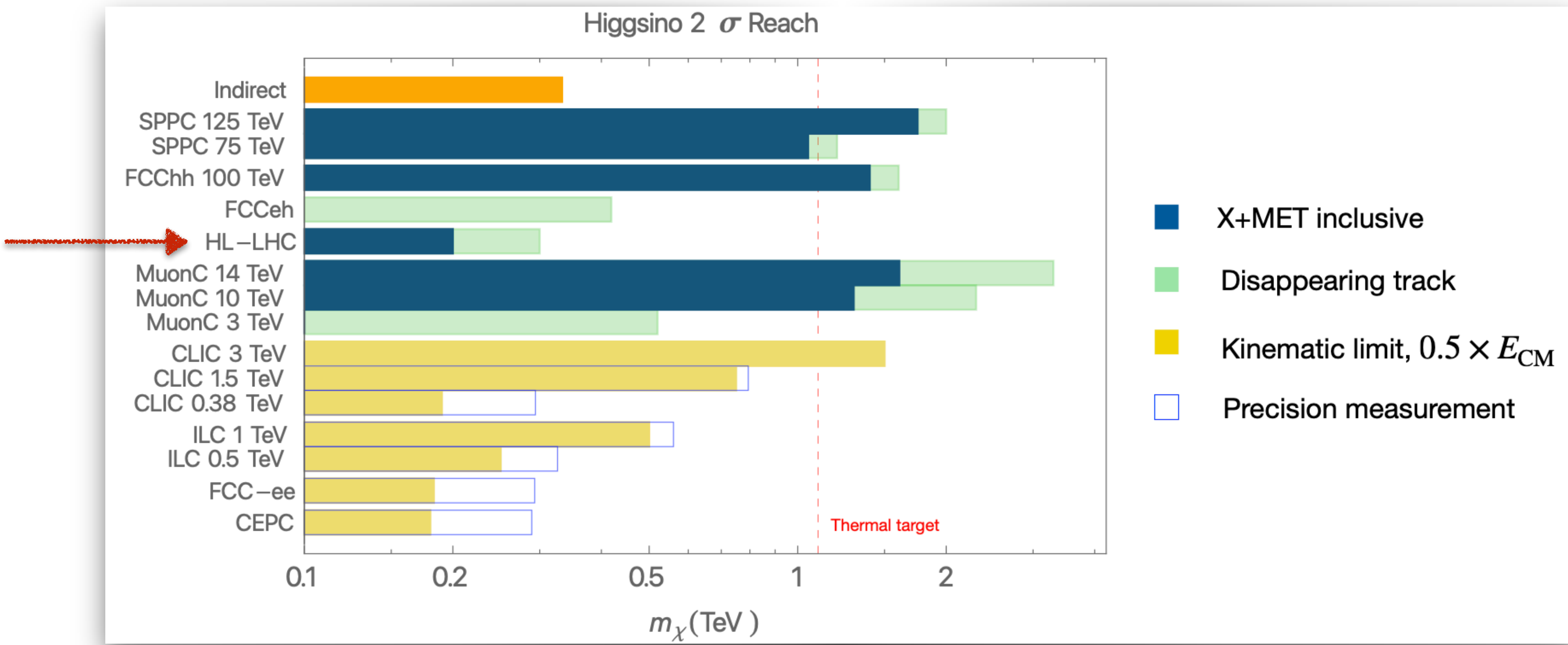
Some models are more challenging: Higgsino DM

2.

Probing broad ideas: WIMP (future)

Towards a more comprehensive coverage…

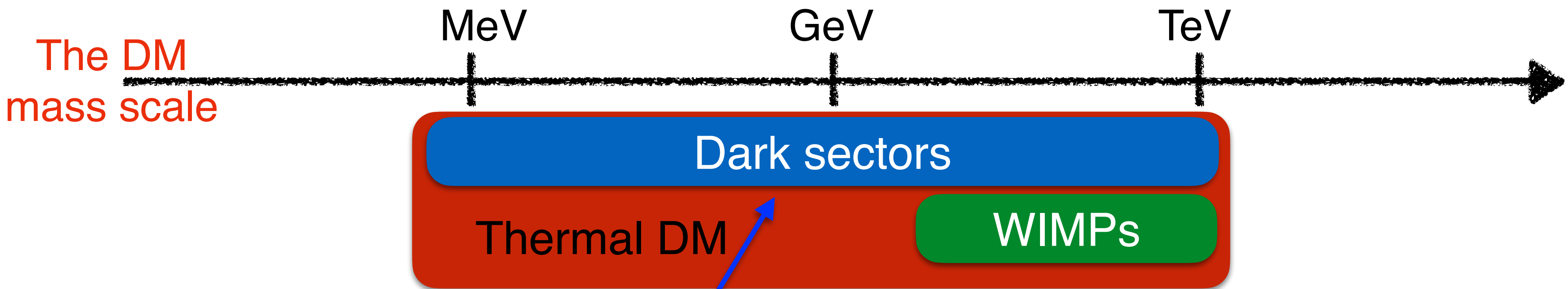
Higgsinos at future colliders



Snowmass, 2211.11084

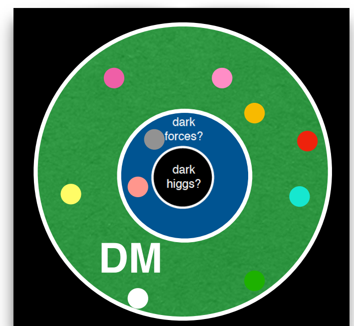
2.

A broader framework for thermal DM

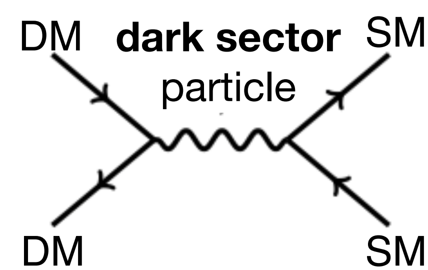


If thermal, Dark Matter **generically** **<u>needs</u> additional (dark) particles** to annihilate with.

Predictive framework (“thermal targets”).



the “dark sector”



2.

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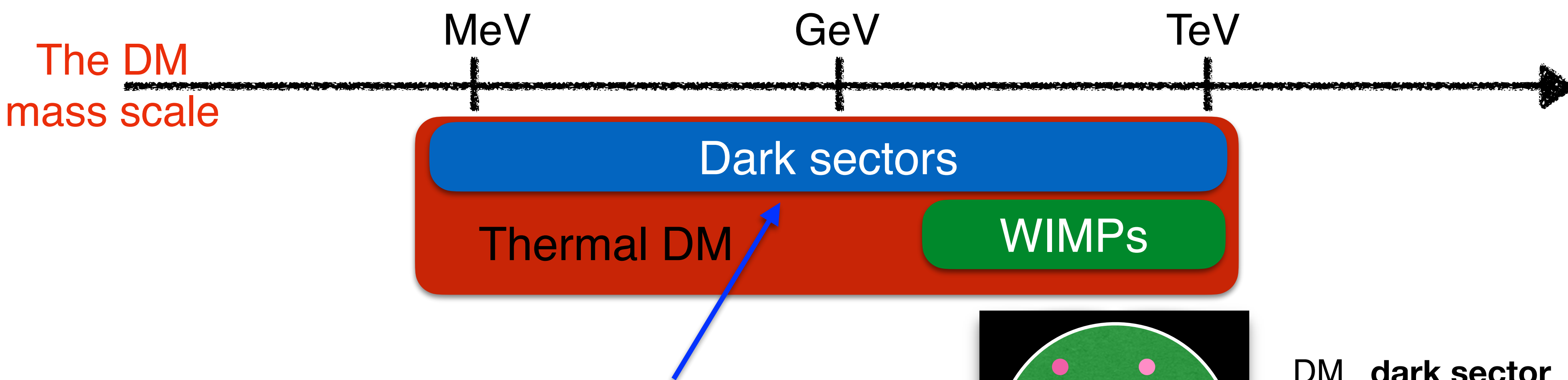

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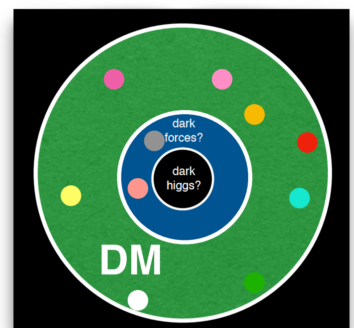

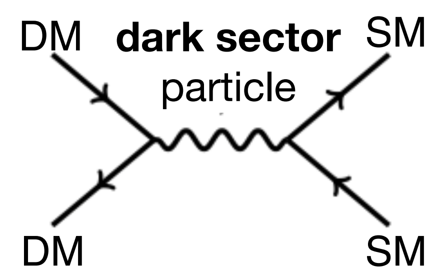

Predictive framework (“thermal targets”).

the “dark sector”

Several LHC search strategies to have access to the dark sector:

- Higgs exotic decays
- Long lived particles
- Low mass resonances
- …

\+ **New search strategies for DM direct detection experiments.** Collaboration with condensed matter physicists.

2.

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.

THE MILLIQAN EXPERIMENT, MoEDAL MAPP, SHiP Search for Hidden Particles, FASER, CODEX-b, MATHUSLA, FACET, SND@ LHC, ANUBIS, FPF Forward Physics Facility, SHADOWS

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.

Physics beyond colliders initiative (https://pbc.web.cern.ch) & Feebly Interacting Particles Physics Centre.

Complementarity with international efforts
(B-factories in Japan, neutrino experiments & fixed target experiments in the US, …)

2.

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In the coming decade, we will have the opportunity to broadly probe the thermal freeze-out framework
(similarly to what we have done in the past decade with WIMPs)

3.

Probing broad ideas: axions and axion-like-particles

Strong CP problem:
why is the QCD θ parameter so small? $\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$

QCD axion: elegant way to address this problem.
Dynamical solution to achieve: $\bar{\theta} \lesssim 10^{-10}$
in agreement with EDM constraints

Axions are a popular solution, but not much for the LHC to say.

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Non minimal models with heavier axion-like-particles (ALPs) have been proposed to address the strong CP problem. (e.g., 1710.04213; 2208.10504; …)
The ALP EFT at dim-5:

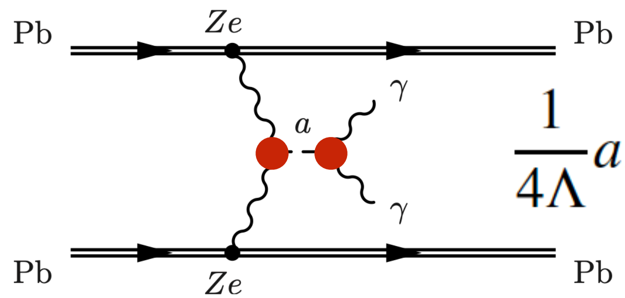
$$\mathcal{L} \supset -\frac{g_{ag}}{4}\,a\,G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\,a\,W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\,a\,B_{\mu\nu}\tilde{B}^{\mu\nu} + ig_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

→ Plenty of new opportunities for the LHC

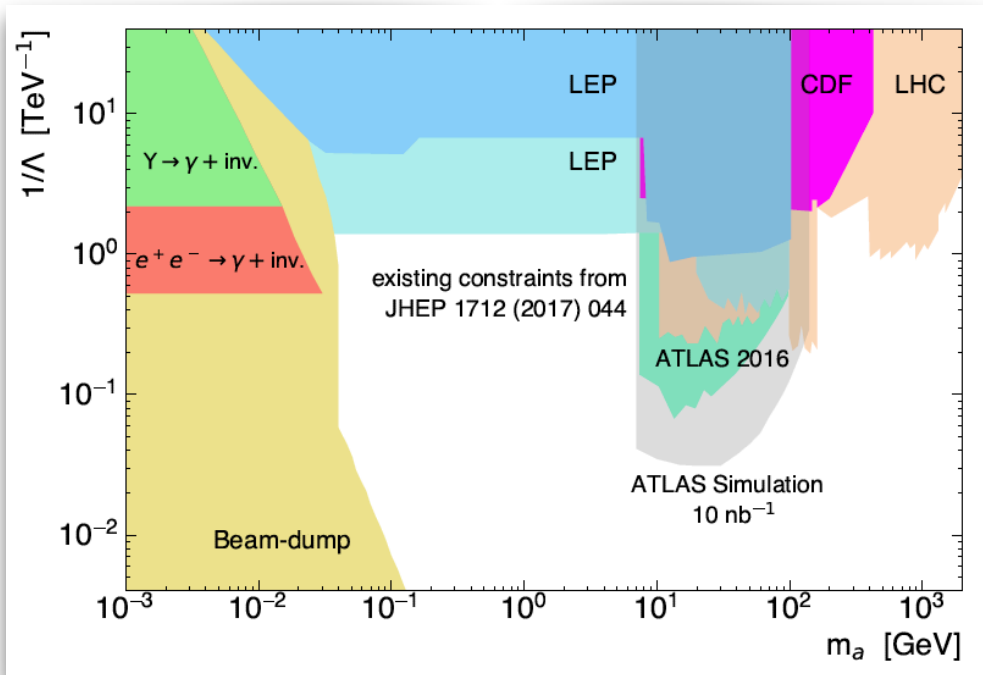
3.

Interplay between heavy ion physics and axion physics

Axion production in ultra-peripheral collisions of heavy ions



$$\frac{1}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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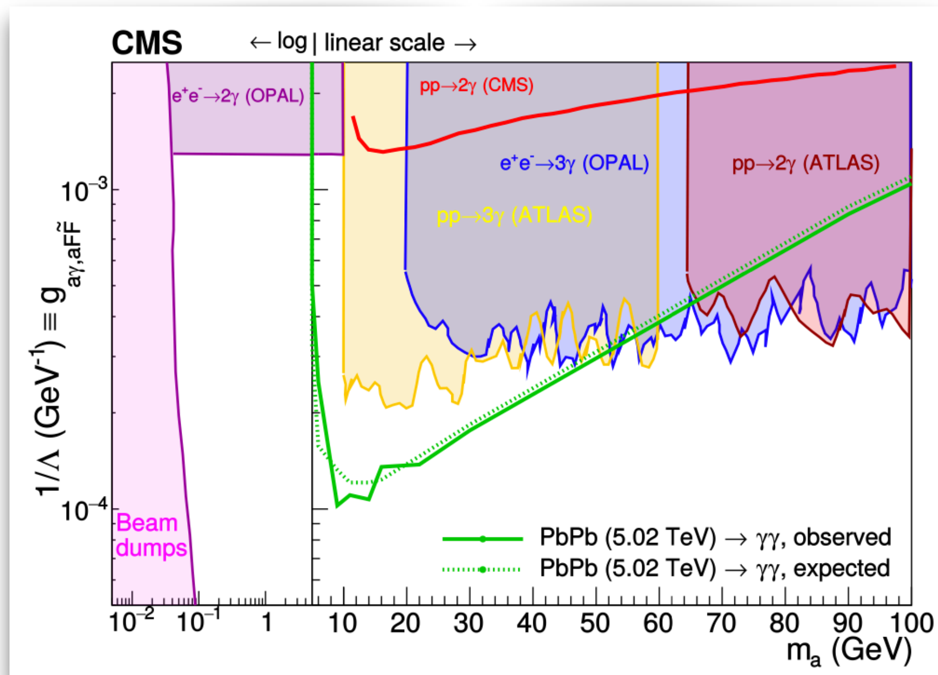

Theory paper: 1607.06083

1810.04602

Long-lived particles

Long-lived-particles generically arise in NP models.

NP particles can have a width that is suppressed by
- small mass splitting
- multi-body final states
- symmetry
- high NP scale

Examples

Models to explain the origin of the EW scale

SUSY: pure wino states

$$\delta m_\chi = M_{\chi^\pm} - M_{\chi^0} \simeq 166\text{MeV}$$

$$\tau_{\chi^\pm}^{-1} \propto \frac{G_F^2}{\pi} f_\pi^2\, \delta m_\chi^3 \sim \frac{1}{6\ \text{cm}}$$

Twin Higgs: glueballs

Models to explain the origin of neutrino masses

Sterile neutrinos

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Appreciable gaps

* Singly produced LLPs
* Low-mass (< 20 GeV)
* LLP from Higgs decays
* High multiplicities
* displaced taus
* small displacements
* …

Examples

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A flourishing effort in unconventional/exotic signals

the unknown unknown

We should leave no stone unturned
We do not know what is the ultimate theory of Nature

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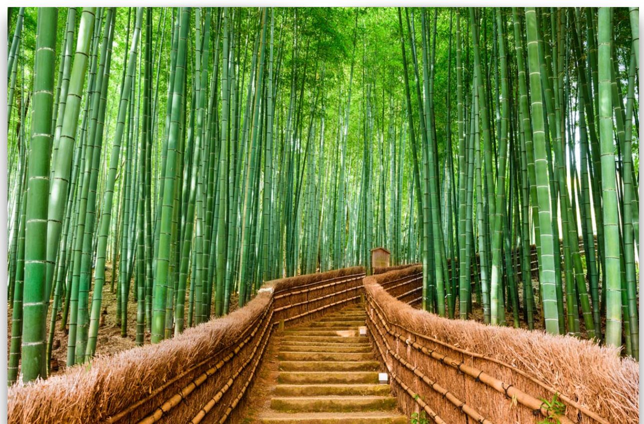
the unknown unknown

Just in the past year…

Periodic resonances
2305.10894

Forward proton scattering in association with light-by-light scattering mediated by an axion-like particle
2304.10953



Heavy long-lived multi-charged particles producing anomalously high ionization
2303.13613

Long-lived particles using trackless and out-of-time jet information
2212.06695

Fractionally charged particles with energy loss in the tracking detector
CMS PAS EXO-19-006

Creativity is important!

the unknown unknown

Let the data teach us

No clear evidence of New Physics from direct searches

⇒ Fully model independent searches are more and more motivated

Looking at Nature with no theoretical prior.

the unknown unknown

Let the data teach us

No clear evidence of New Physics from direct searches

→ Fully model independent searches are more and more motivated

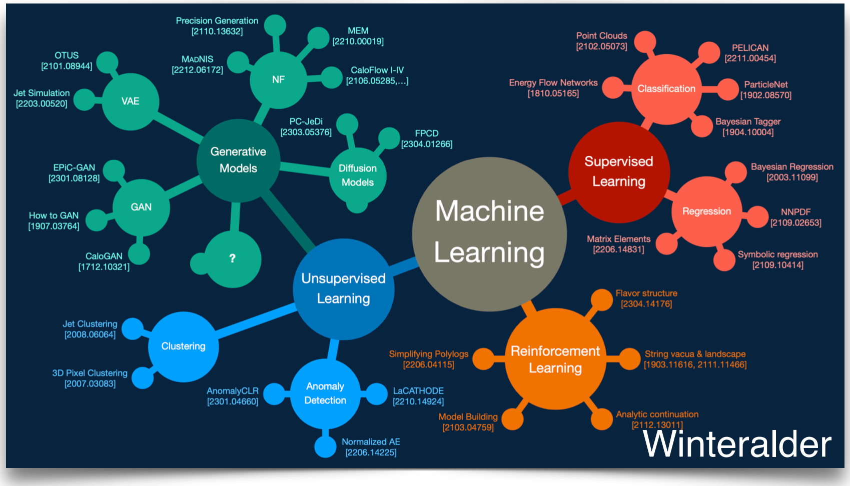
Looking at Nature with no theoretical prior.

1. Generic searches:
Phase-space not tailored to a specific model.
Comparison with Standard Model predictions.

2. Data itself can teach us!
Deep learning revolution since a few years

Machine learning (ML) for HEP

e.g. unsupervised learning for anomaly detection



the unknown unknown

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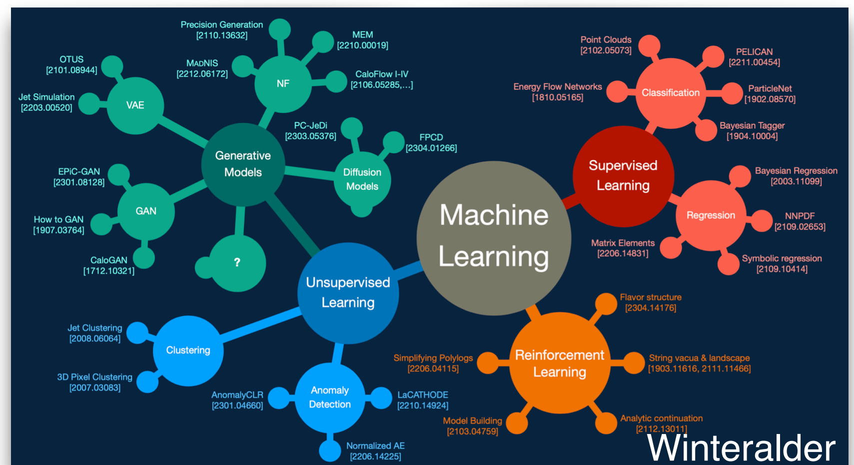
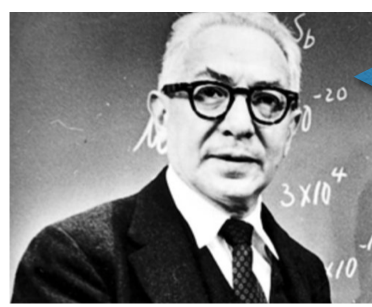


We should be ready for the (theoretically) unexpected



μ: who ordered that?

Exploring the unknown unknown

"Humanity's thirst for knowledge, curiosity and spirit of exploration have always been the engines that drive particle physics. Unsurprisingly, the more we dive into uncharted territory the more difficult it becomes to predict what future experimental endeavours could find. This is the very essence of research: if we knew for certain what future experiments will discover, we would not need to build them."

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)

Outlook & take home messages

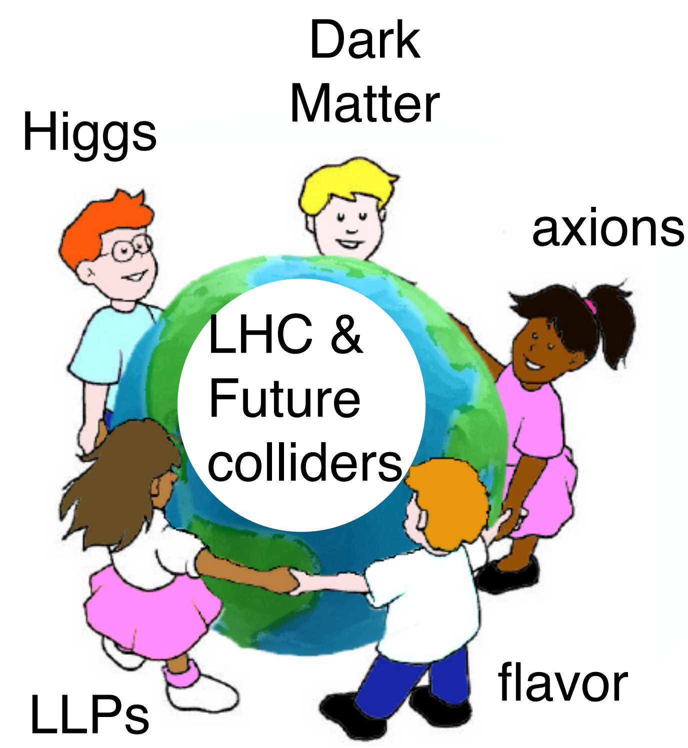
Particle physics is **not only about discovery new particles**.
It's about the laws of nature, which include the interactions and properties of the particles that we have already discovered.

The breadth of HEP is getting larger and larger.

Learning about Nature at the most fundamental level is a global effort.

The LHC and future colliders will play an essential role in this endeavor.

Looking forward to the future of HEP!



Interplay with other fields: gravitational waves, condensed matter, ML, …

the known unknown → the known known ← the unknown unknown