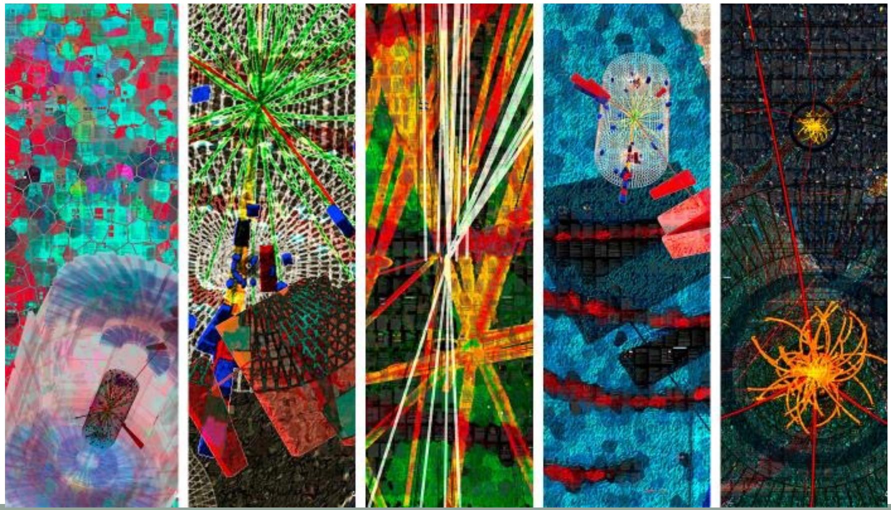
POSTCARDS FROM THE FUTURE: BIG QUESTIONS @ THE ENERGY FRONTIER

Meenakshi Narain
Brown University

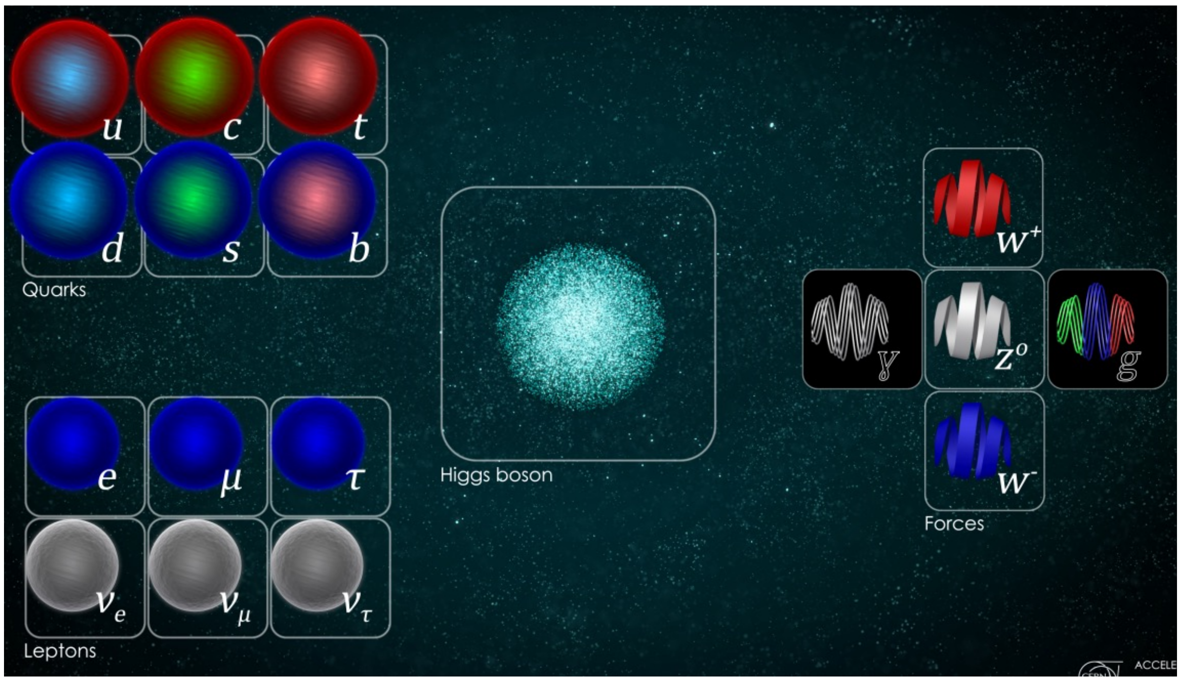


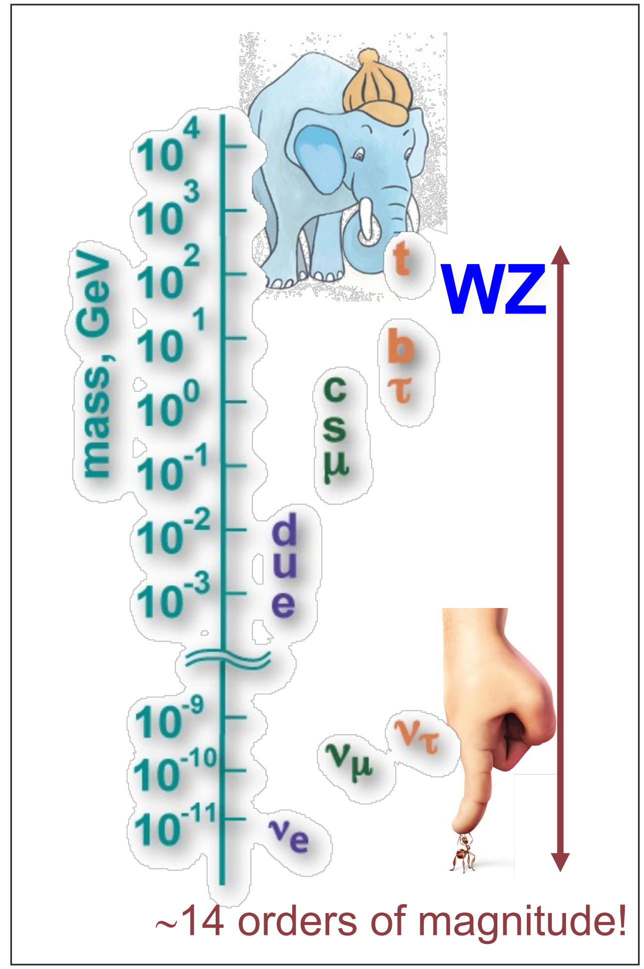
November 15, 2022

Outline

- The Energy Frontier
- The Current Landscape
- Proposed Future Colliders and the Physics Landscape
- Vision of the Energy Frontier

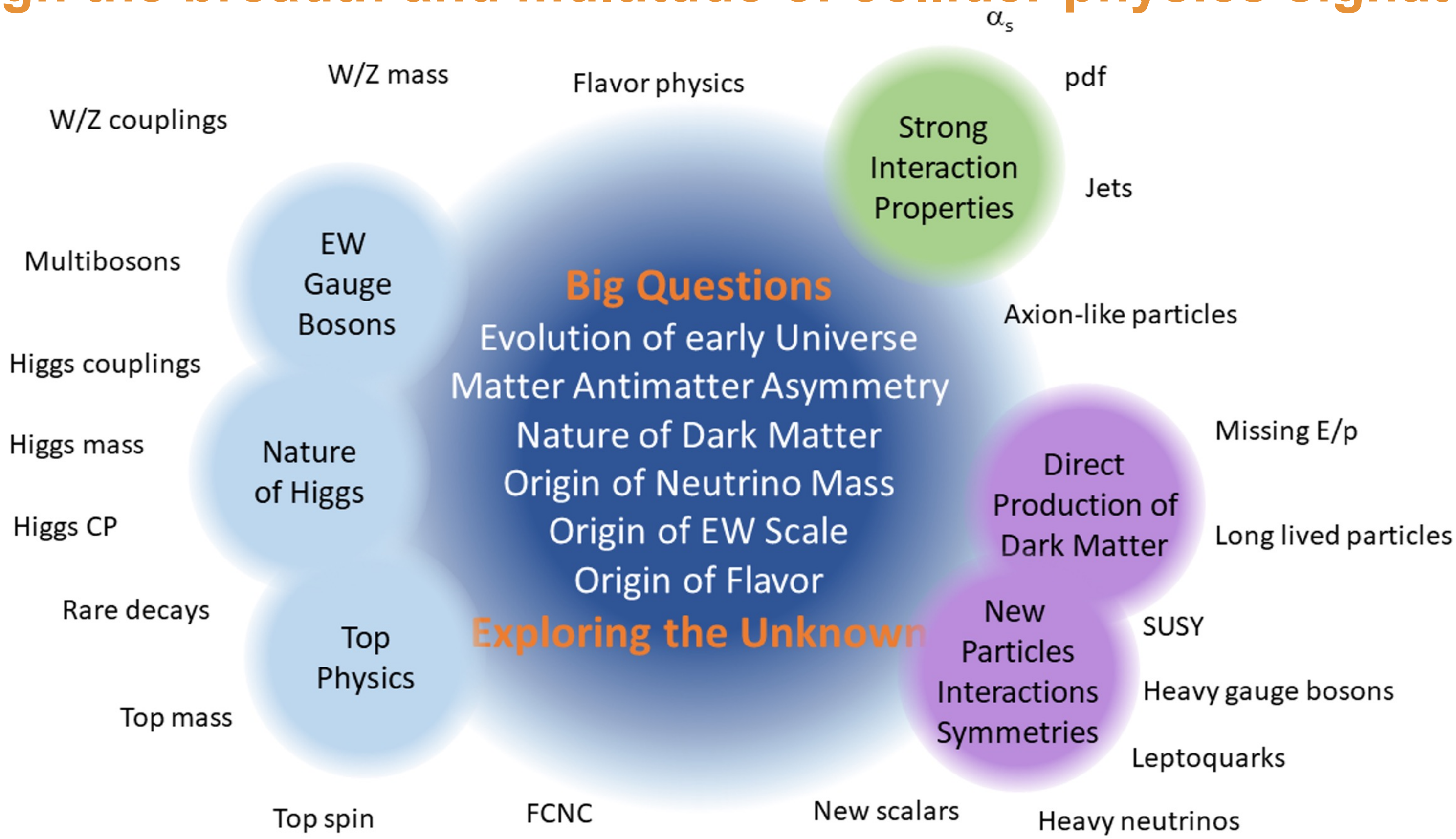
“Standard Model” of Particles and Forces





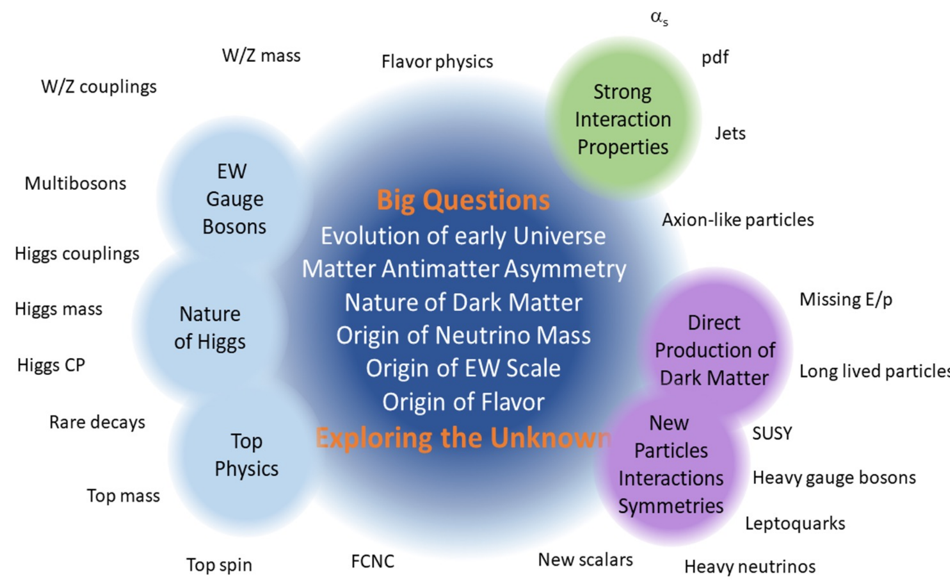
Energy Frontier: explore the TeV energy scale and beyond

Through the breadth and multitude of collider physics signatures



Addressing the **“Big Questions”** and “**Exploring the unknown**” are the main scientific goals of the EF

to be pursued following

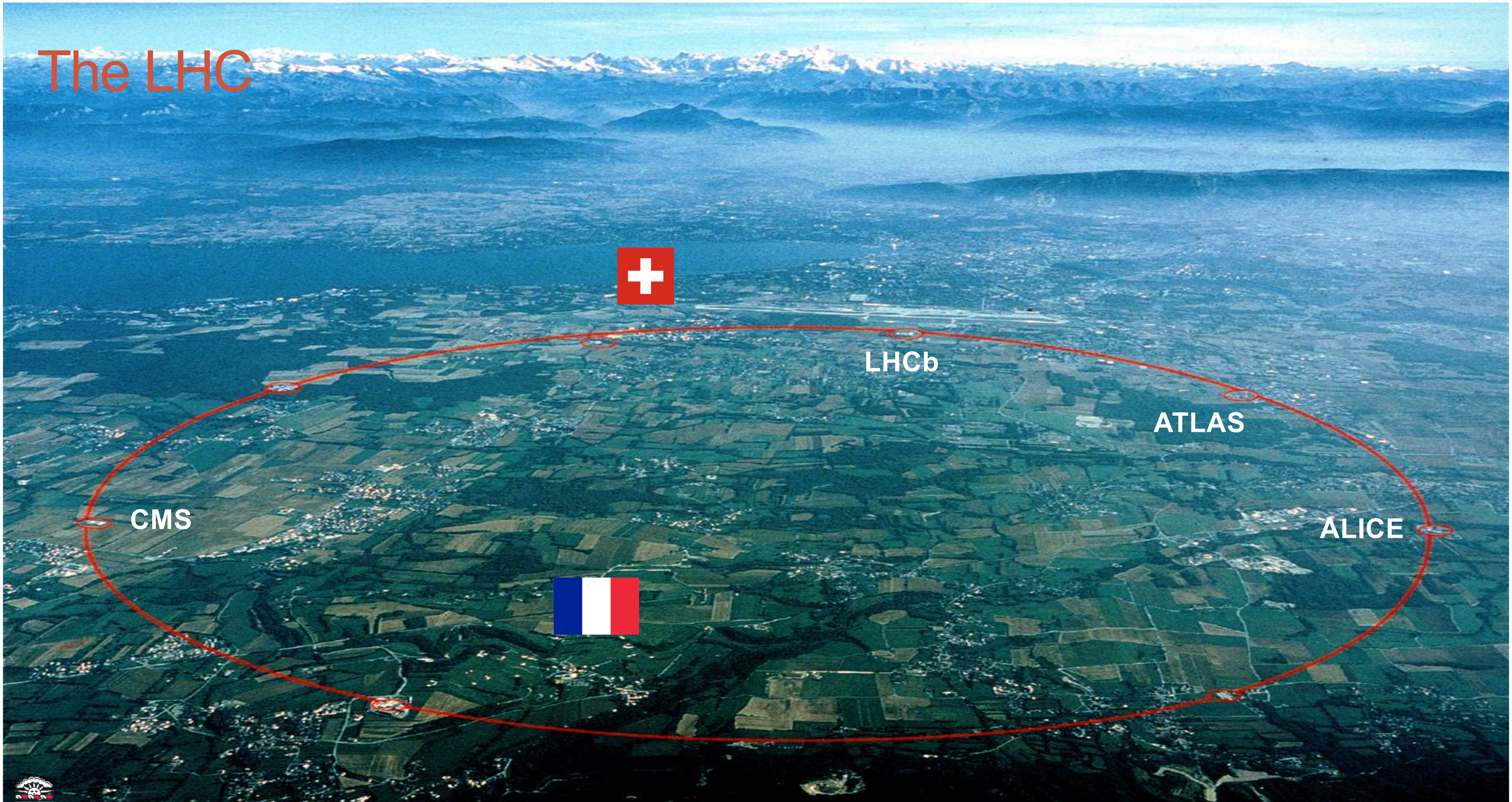


Two main avenues

- **Study known phenomena at high energies looking for indirect evidence of BSM physics**
  - Need **factories of Higgs bosons** (and other SM particles) to probe the TeV scale via precision measurements
- **Search for direct evidence of BSM physics at the energy frontier**
  - Need to directly reach the **multi-TeV scale**

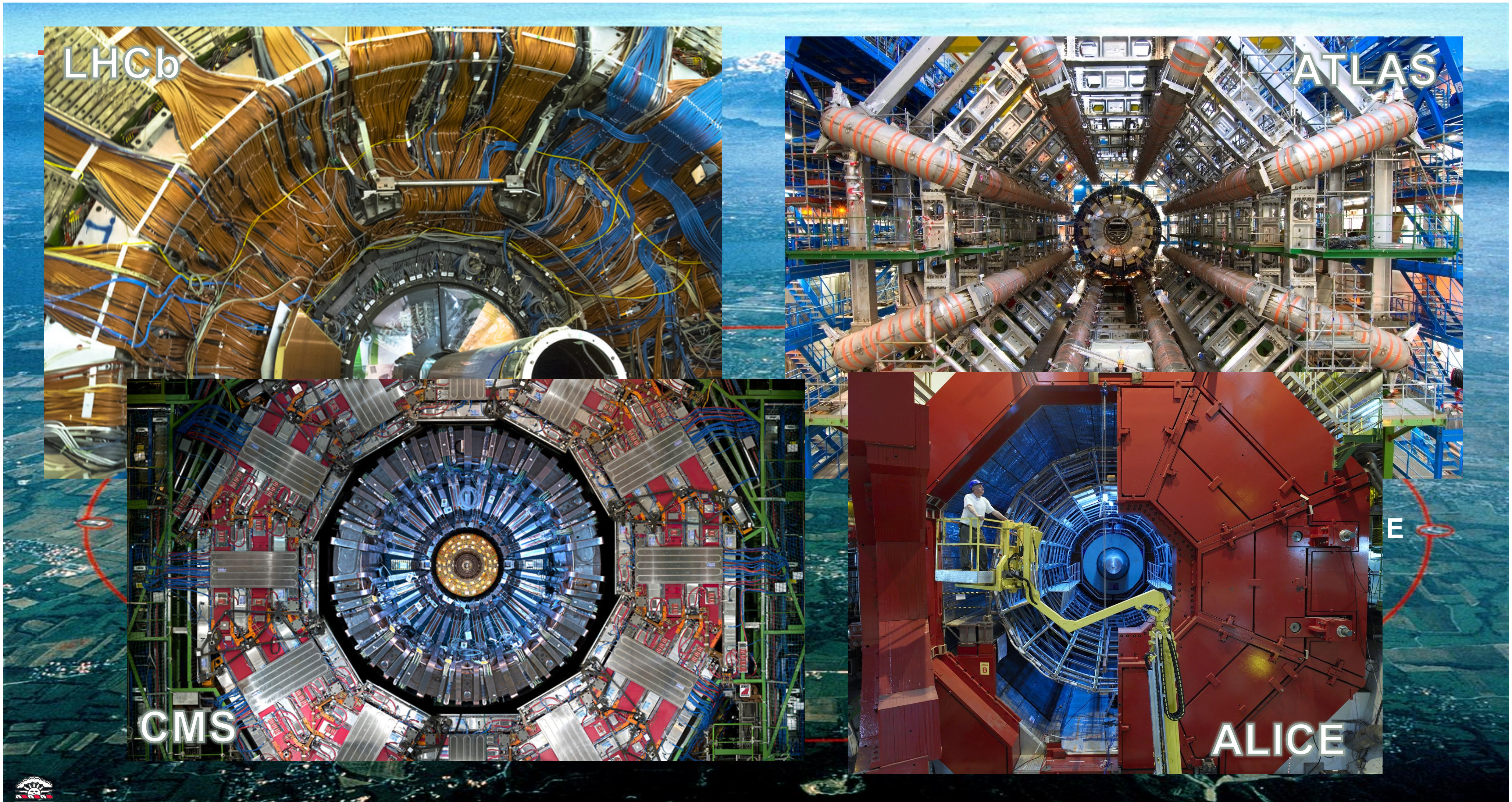
OUR MICROSCOPE: THE LHC @ CERN

The LHC



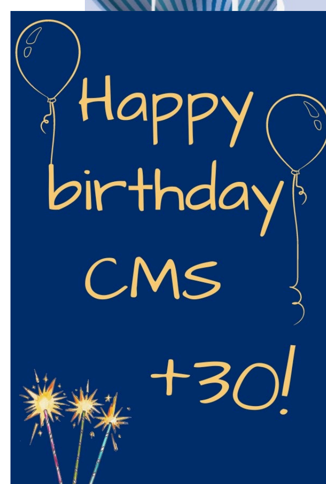
LHC Parameters

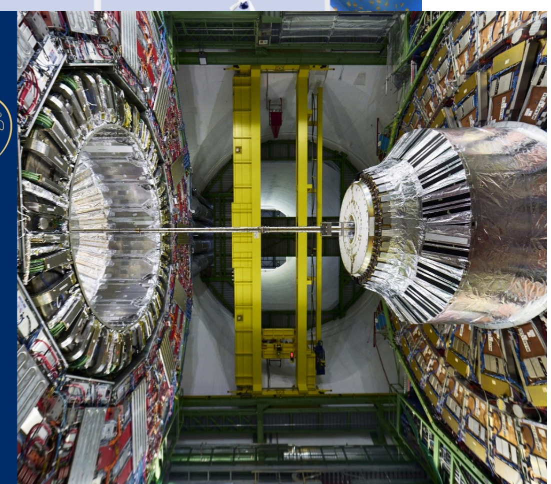
The proton beams are structured into 2808 bunches
Each bunch consists of about 10^{11} protons
circles it around the ring 11245 times per second
Collisions between bunches occur every 25 ns


LHCb
ATLAS
CMS
ALICE
E

Happy 30th Birthday ATLAS and CMS

- On 1 October 1992, the two collaborations each submitted a letter of intent (LOI) for the construction of a detector to be installed at the proposed LHC.
- These LOIs, each around one hundred pages long, are considered the birth certificates of the experiments.



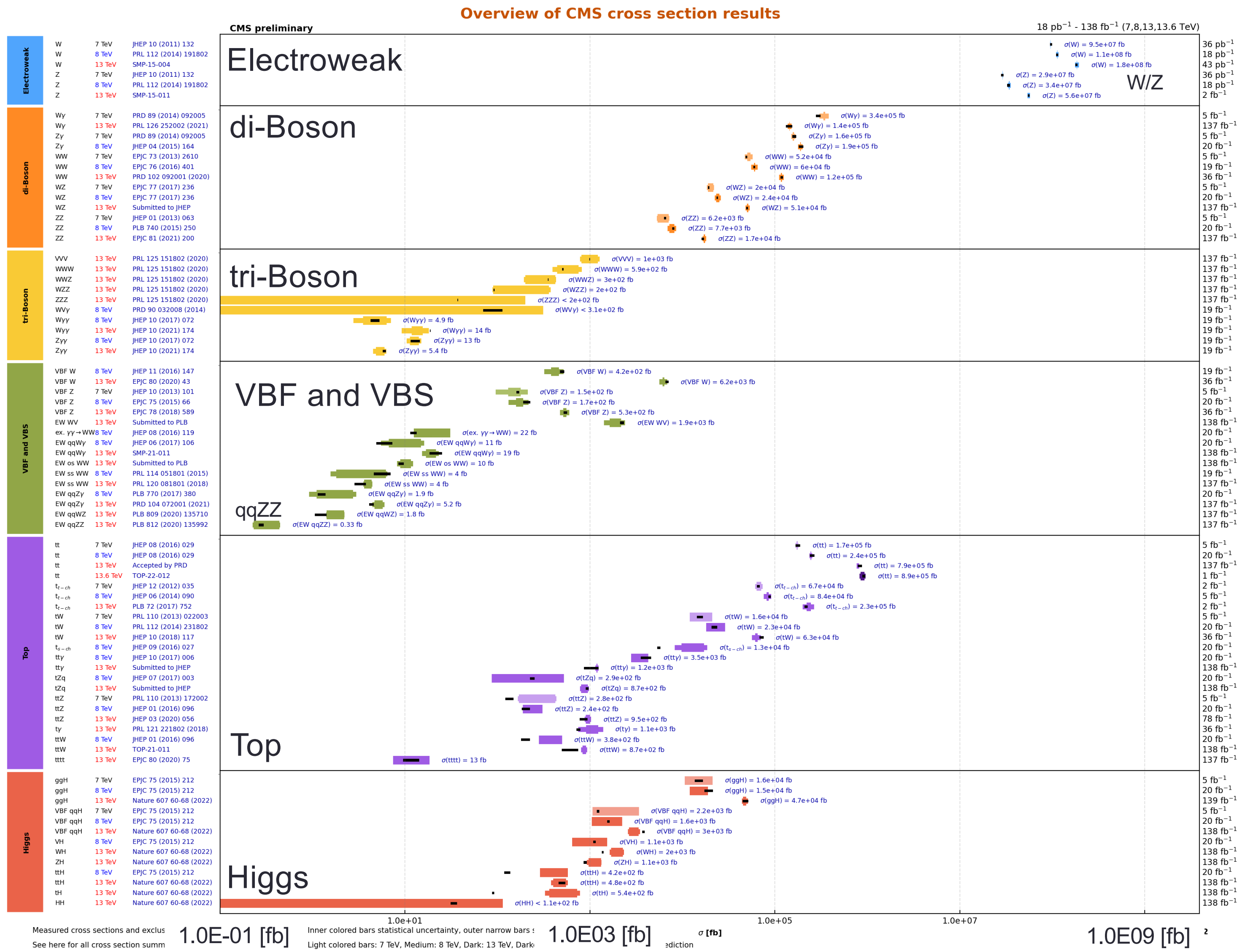


THE CURRENT ENERGY FRONTIER PHYSICS LANDSCAPE

SM Stairway…

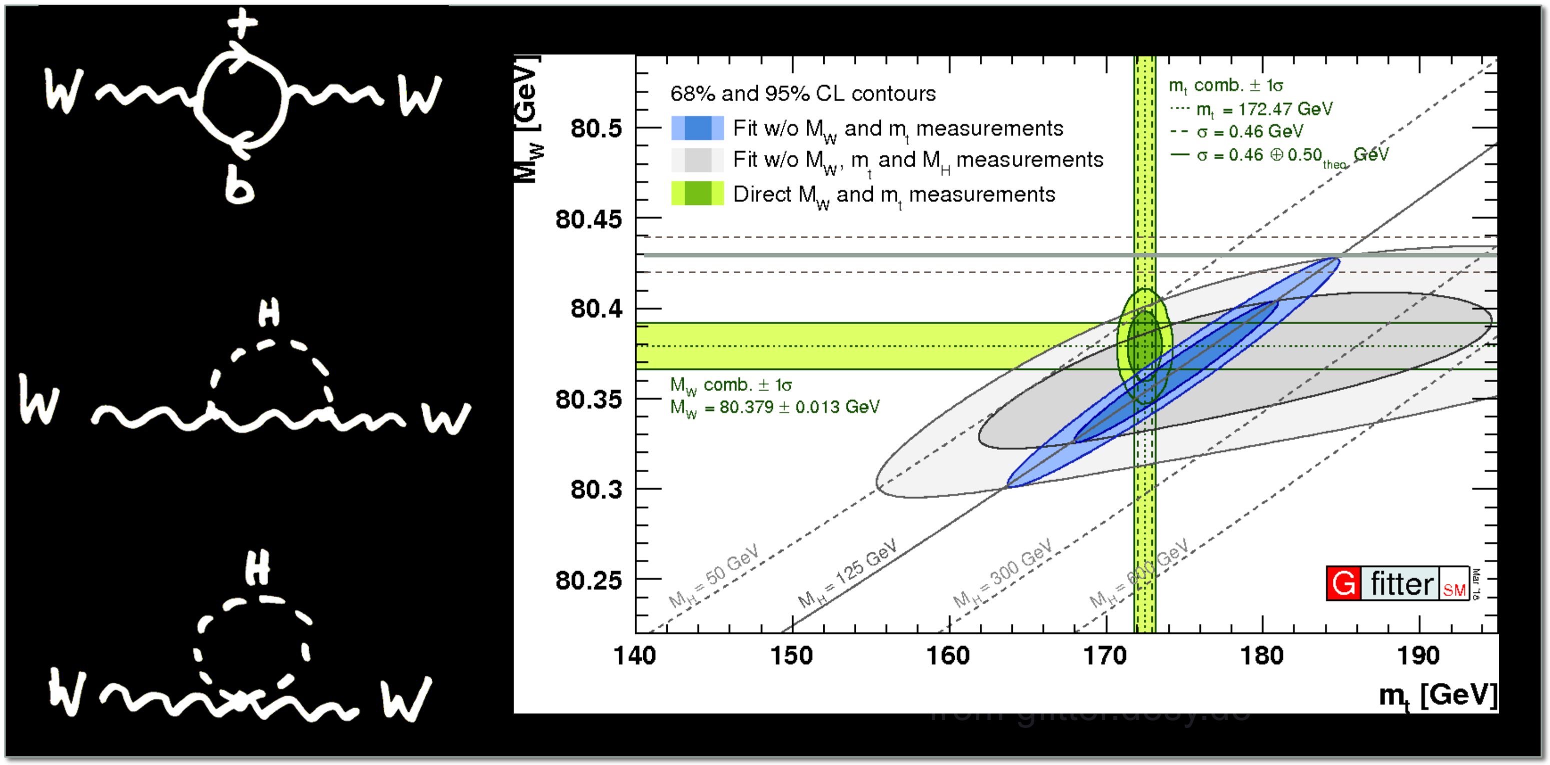
precision tests of the Standard Model

- Cross section measurements of W/Z bosons, di-/tri-bosons, VBF, VBS, top and Higgs production
- From 10^8 fb to 0.33 fb



Consistency of SM: a success story

- Higgs, W boson mass and top quark mass



Understanding the Higgs Boson

- Happy 10th Anniversary Higgs Boson!

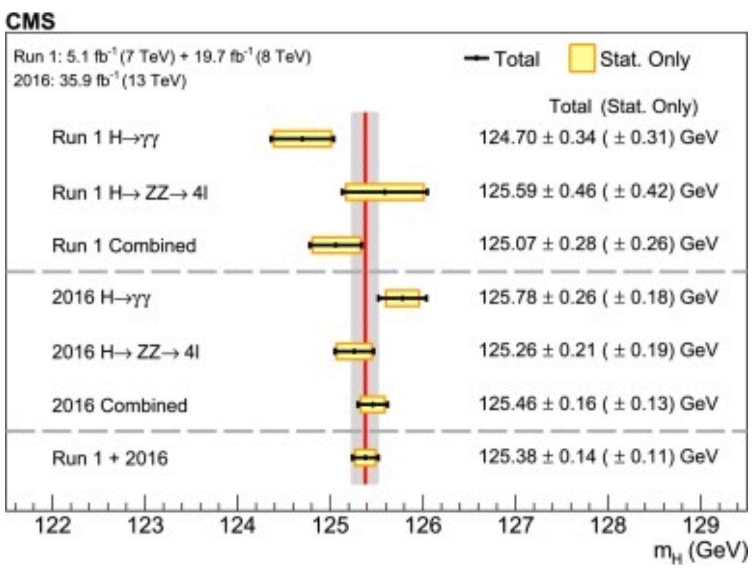
Credit: Abigail Malate for *Physics Today*

July 2012

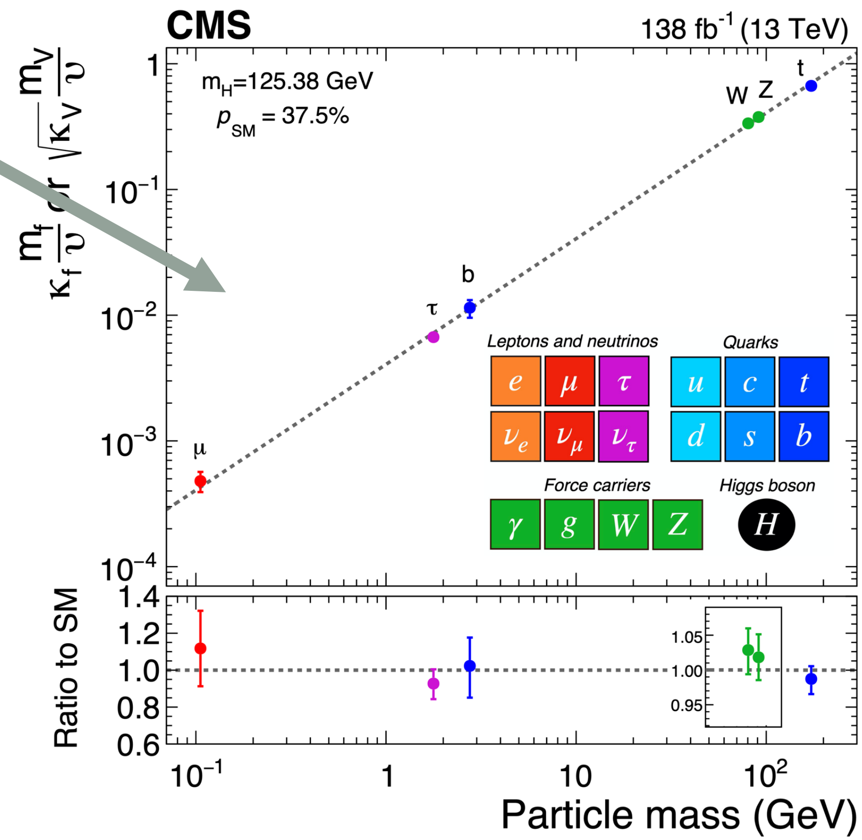
Understanding the Higgs boson

Very precise predictions in the SM

- Couplings to fermions proportional to mass
- Couplings to gauge bosons proportional to $(\text{mass})^2$
- Higgs self-couplings proportional to M_H^2



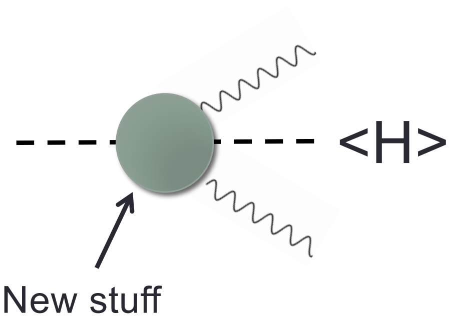
Higgs Boson Mass (GeV)



The LHC is a Higgs Factory: measurement of Higgs properties continue…

Higgs Couplings and New Physics

- New particles lead to deviations in Higgs couplings



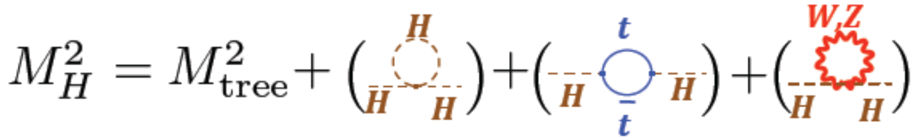
Generic effects scale with $1/m^2$ of new particles

Typically: Target precision for Higgs couplings < 5%

- As limits on new particles or energy scale of new physics increase, the target measurement precision decreases
- Progress requires 2-prong approach:
  - Search for new Higgs bosons and measure Higgs couplings

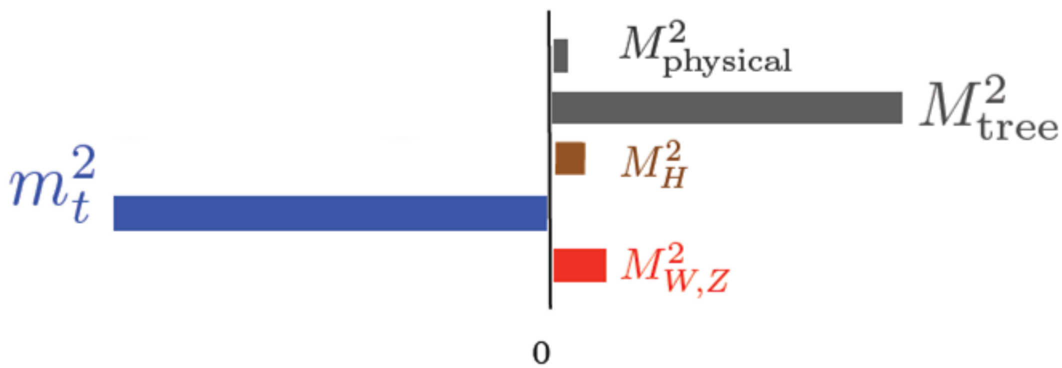
Is light Higgs a problem?

- compute the Higgs boson mass in the standard model



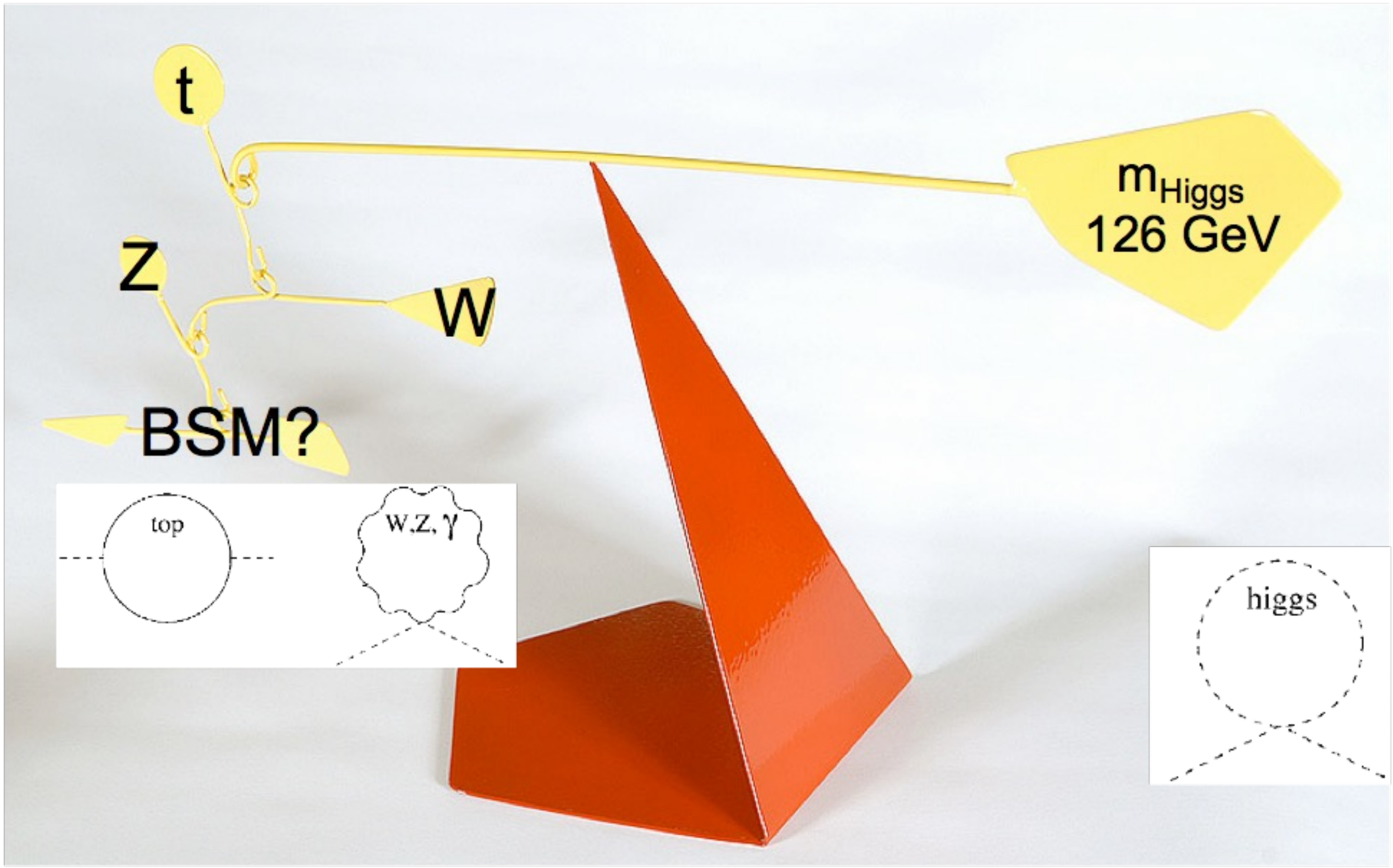
$$M_H^2 = \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n60,000}$$
$$- \text{nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, nnn, n44,375}$$

- or graphically



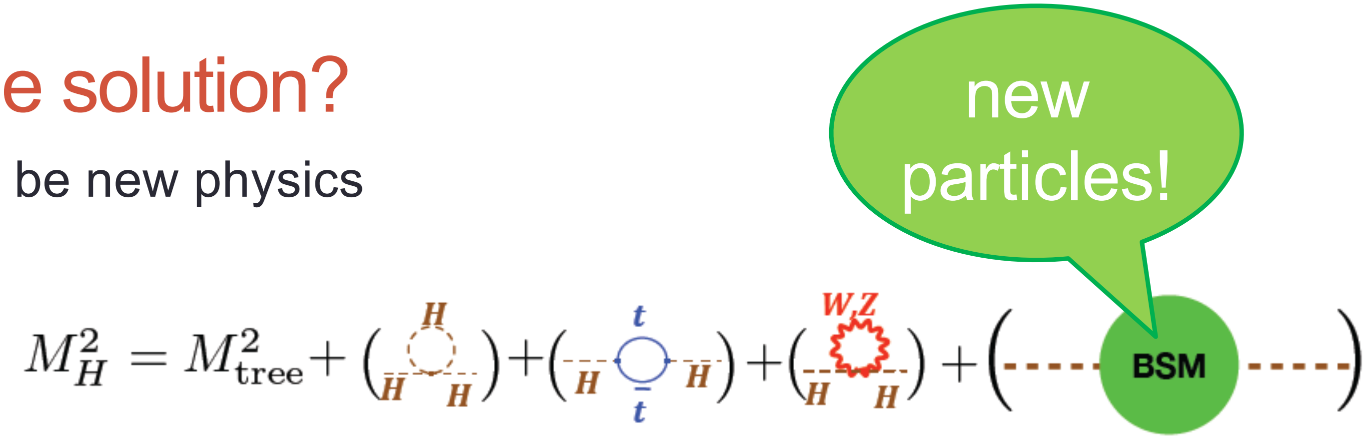
- could it really be that the two terms happen to cancel with this precision?

Naturalness

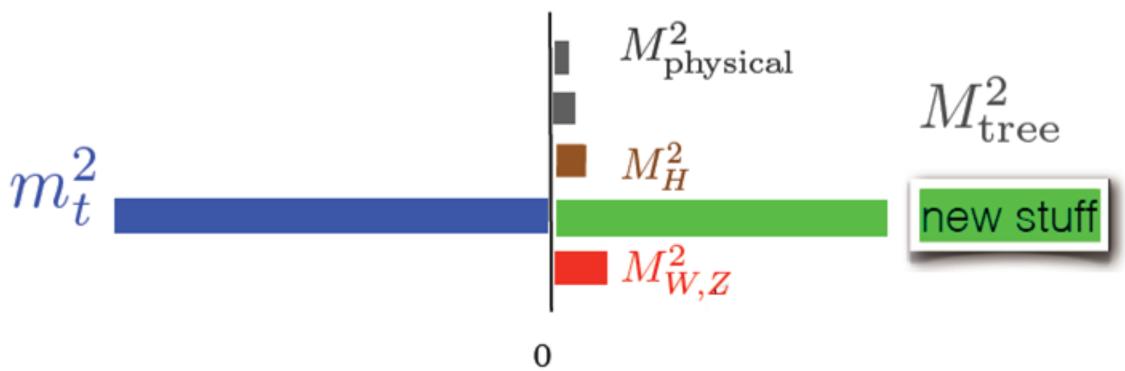


What is the solution?

- there has to be new physics



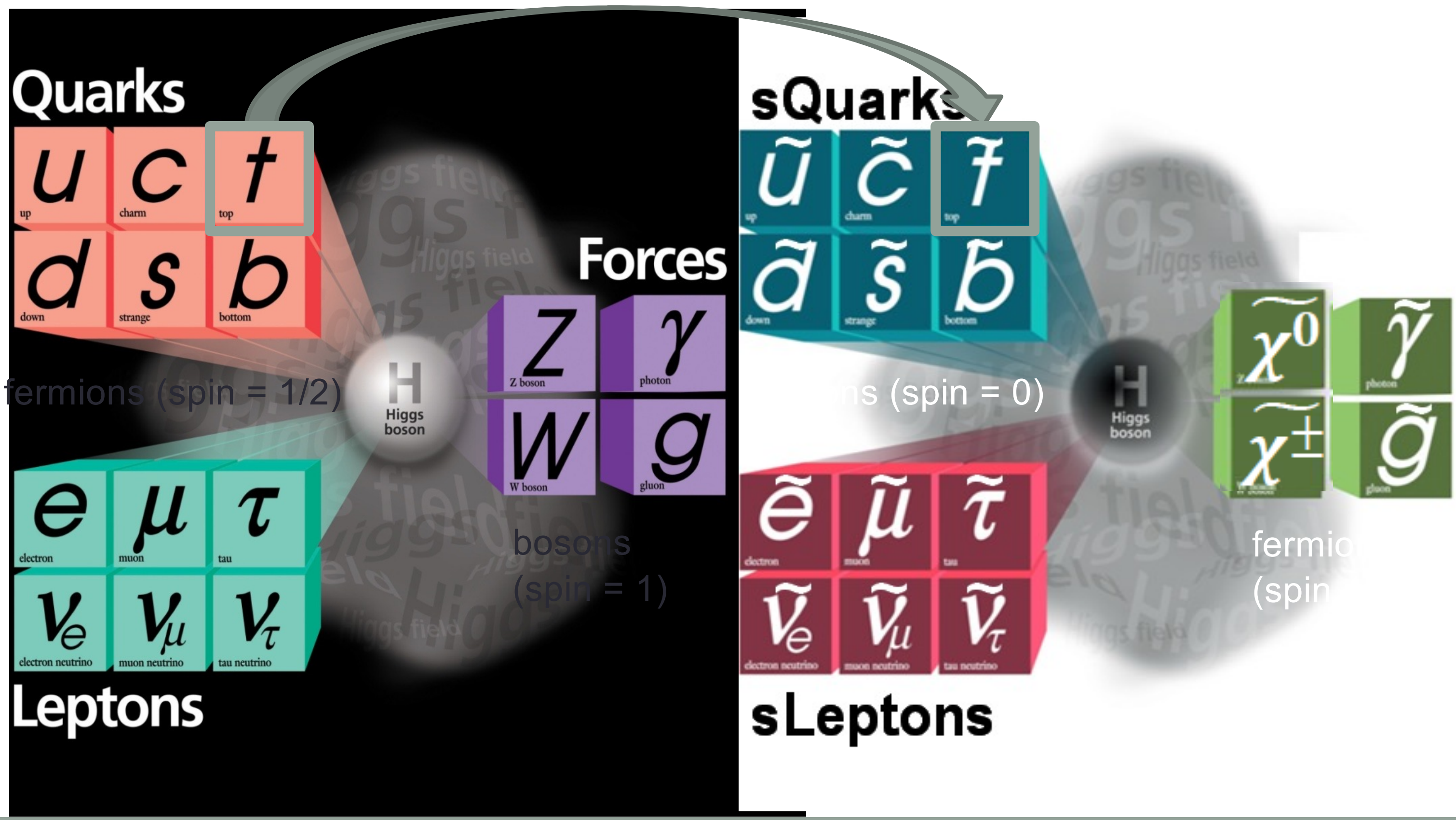
- or graphically



- the new particles must be related by some symmetry to the top quarks so that they cancel the top quark contribution

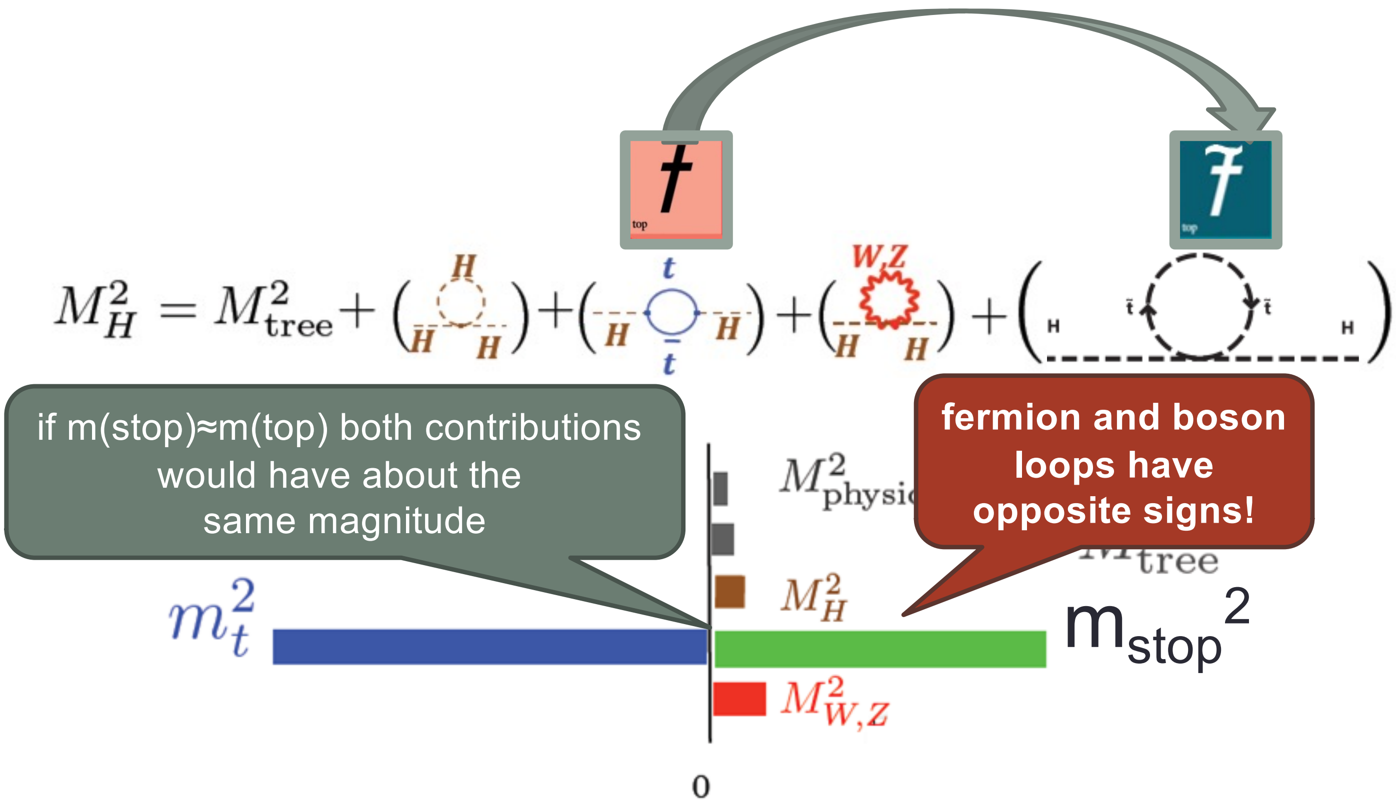
Supersymmetry

every known particle has a partner with the same properties but different spin by 1/2



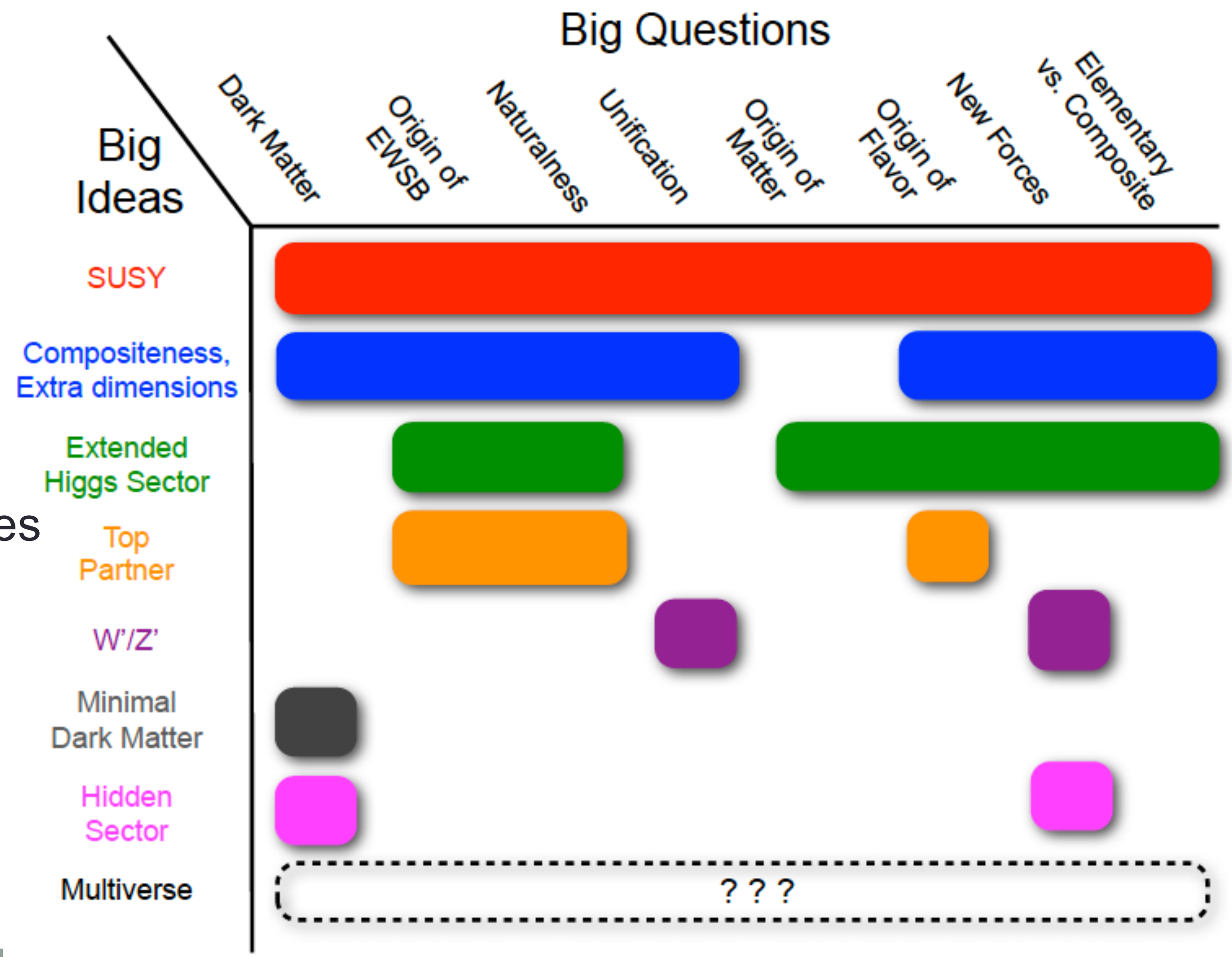
Solution: New Physics ? e.g. Supersymmetry

every known particle has a partner with the same properties but different spin by 1/2



BSM Physics

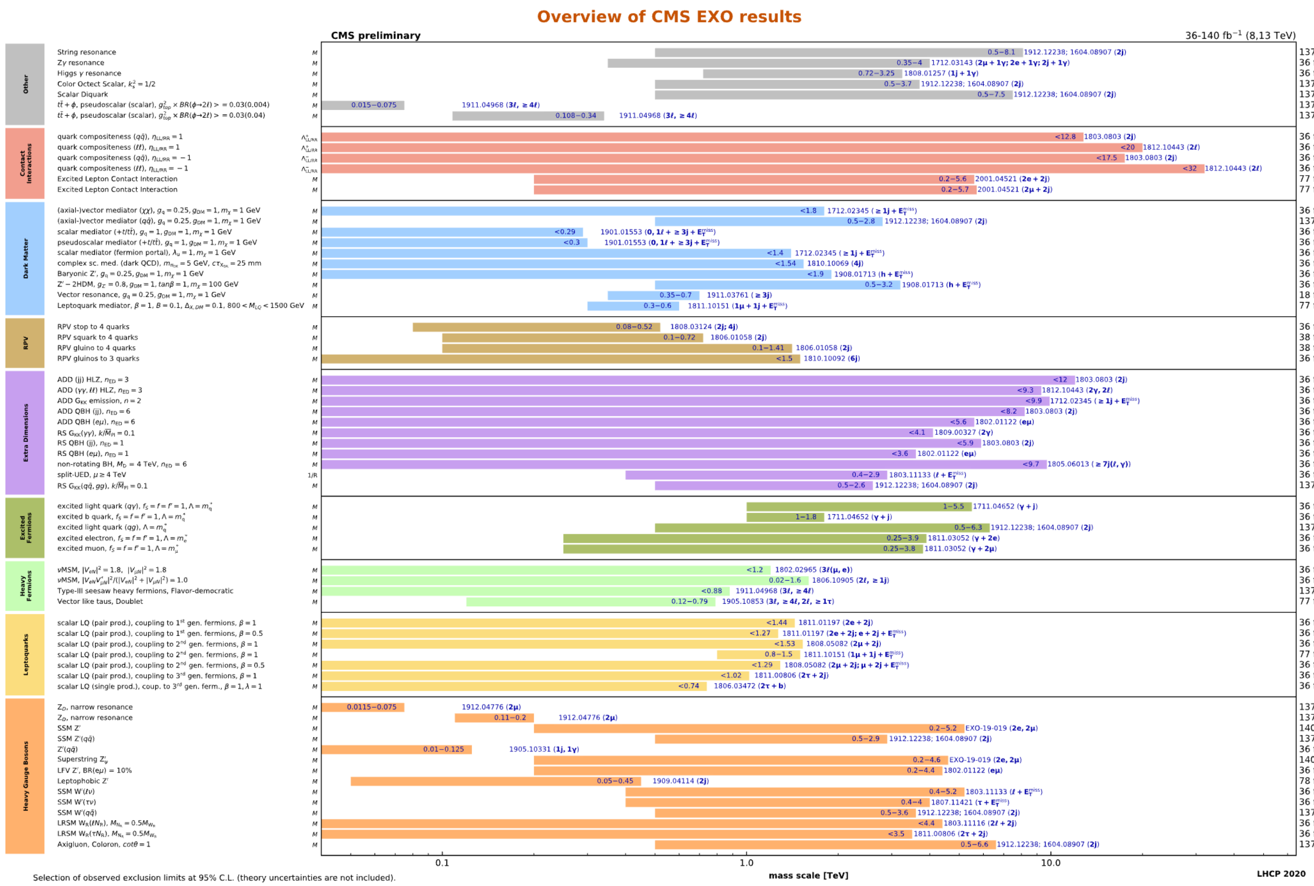
- Plethora of models
- Predict:
  - New heavy particles
    - Some with large lifetimes
  - New signatures



Warning: not a complete list

Current Status of BSM Searches:

- Probe new particles with mass ~ few TeV
- Leaving no stone unturned in the search.
- Going from traditional searches to exploiting new techniques.
- Is BSM hiding in difficult corners of the phase-space?



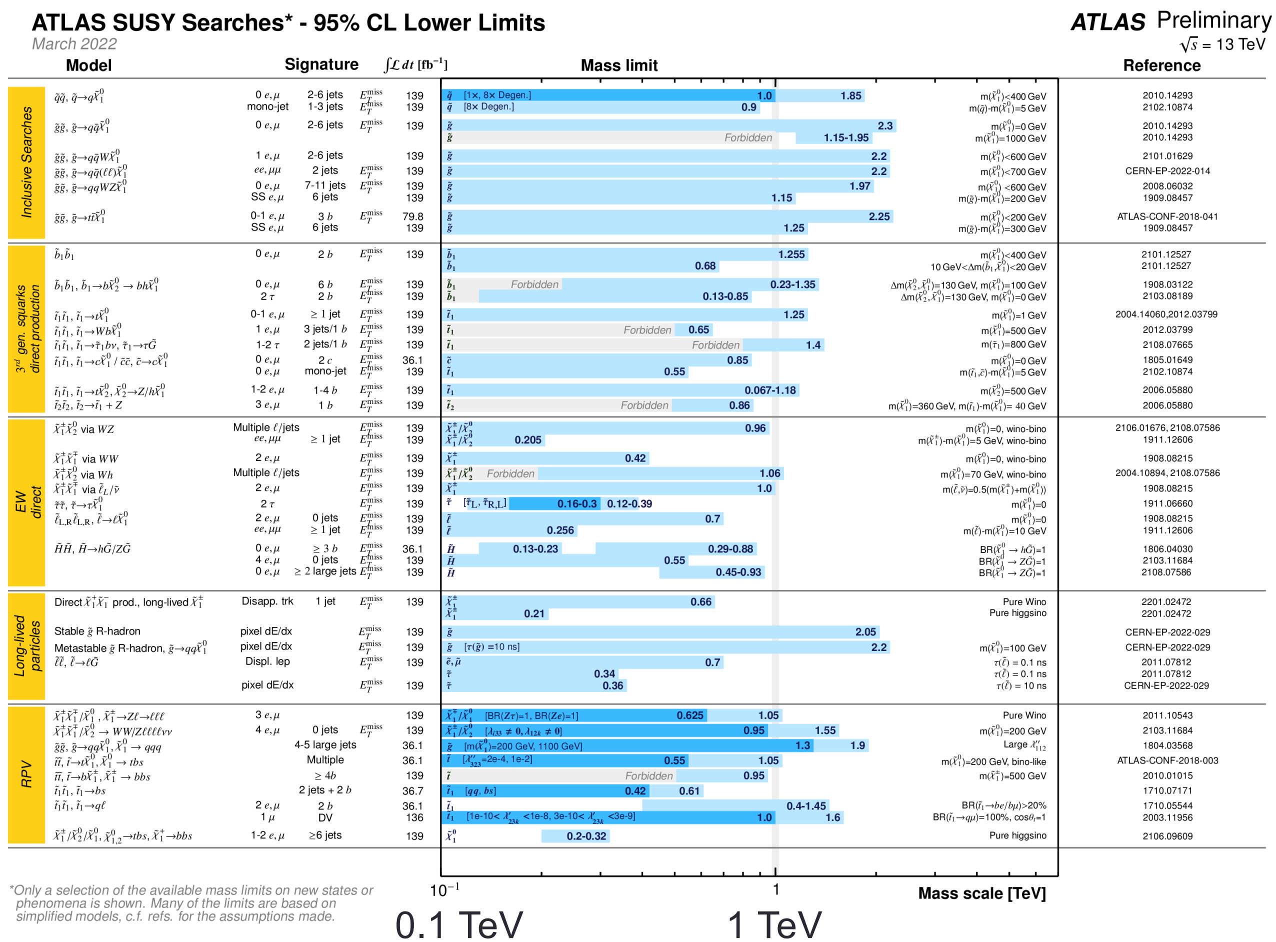
0.1 TeV 10 TeV

Warning: not a complete list

Current Status of BSM Searches (SUperSYmmetry):

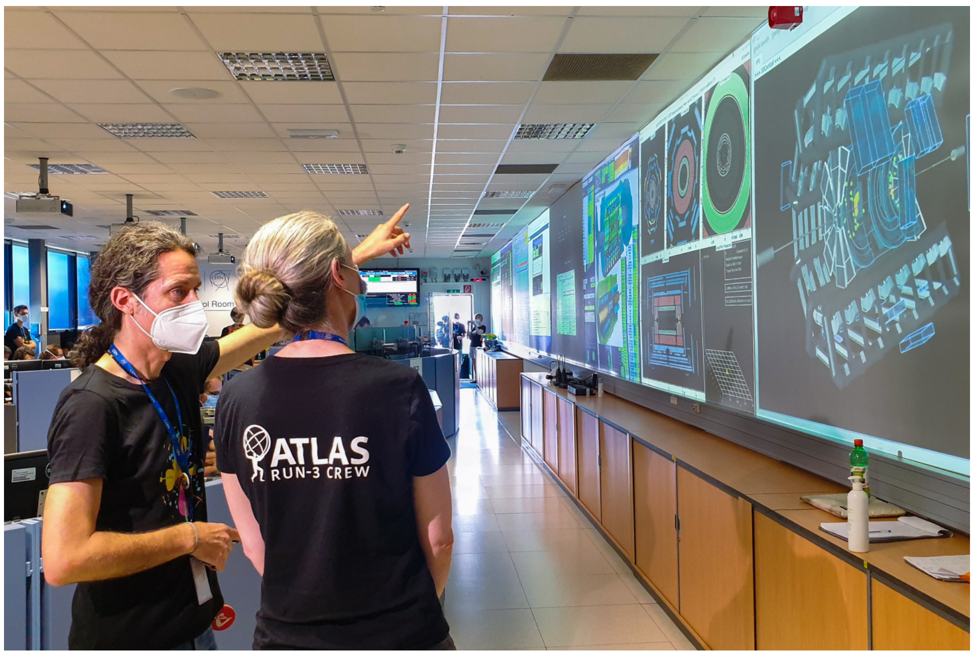
- SUperSYmmetry

- Leaving no stone unturned in the search.
- Going from traditional searches to exploiting new techniques.
- Is BSM hiding in difficult corners of the phase-space?

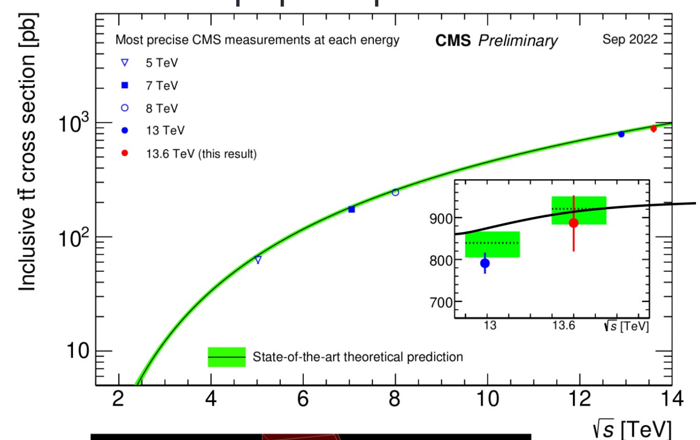


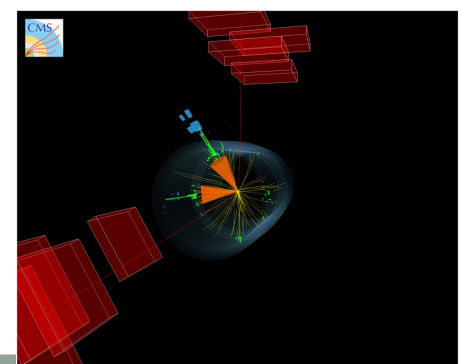
Continuing with Run 3 of LHC

- The Run 3 data taking phase started in July 2022.
  - the LHC surpassed the previous energy limits of experimental particle physics, breaking its own record by achieving stable proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 13.6 TeV
- An opportunity to expand the physics program.



top quark production





What has the LHC taught us?

- **Higgs mechanism** ✓
- **Supersymmetry** ✗
- **Vector-lik** ✗
- **imensions** ✗
- **Dark matter** ✗

no new physics at the TeV scale ?!

What has the LHC taught us?

Higgs mechanism

Supersymmetry

Vecto

sions

Dark matter

In particle physics, failure isn't necessarily a bad thing.
In fact, it can generate as much excitement
and curiosity as success.*

*: Science Friday, 2016, pri.org

FUTURE STRATEGY

DPF Community Planning Exercise - aka Snowmass

- The charge of the Snowmass Process:
  "define the most important questions in the field of particle physics and identify promising opportunities to address them."
- Timescale:
  Planning for 2025-2035 with a view toward 2050
- Sponsored by Division of Particles and Fields of the APS
- Discussions and studies started in 2020
- ⇒ Great time to propose new ideas, new perspectives, new tools.
- The future of the Energy Frontier in the U.S and internationally is up to us!
- Sharp physics questions brought focus to issues pertaining to EF future directions
- Snowmass provides a platform to think BIG, innovate and set new directions without barriers and constraints set by our collaborations.

The Snowmass Frontiers

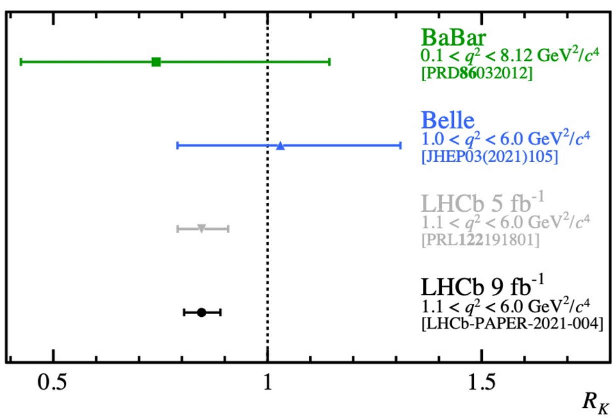
Energy Frontier Co-convenors: Meenakshi Narain (Brown), *Laura Reina (FSU)*, *Alessandro Tricoli (BNL)*
Ten Topical Group (TGs) Conveners.

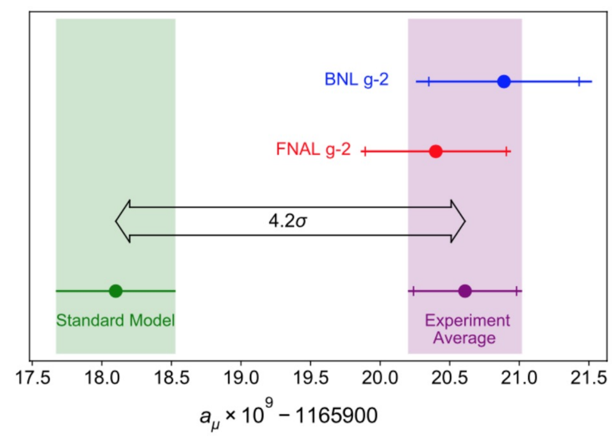
The search for a new paradigm beyond the SM

- How can we address the puzzles of Nature to an extent that either *new physics* will appear or a new paradigm of thinking about the *naturalness problem* can emerge?
- What is the additional source of CP violation needed to explain the *matter-antimatter asymmetry* in our universe? How can we address its origin *via future colliders*?
- Can the underlying explanation of the *flavor structure of the SM* be probed with existing or future machines?
- Best techniques to search for *lepton universality violation*? What do we learn from high energy searches?
- What is the *fundamental composition of Dark Matter*, what are the best ways to probe the composition of DM and whether it interacts weakly?

Cracks in the SM paradigm:

Evidence of Lepton Flavor Universality violation at 3.1σ at LHCb





Data-theory discrepancy on g-2 at 4.2σ

How to get the experimental answers?

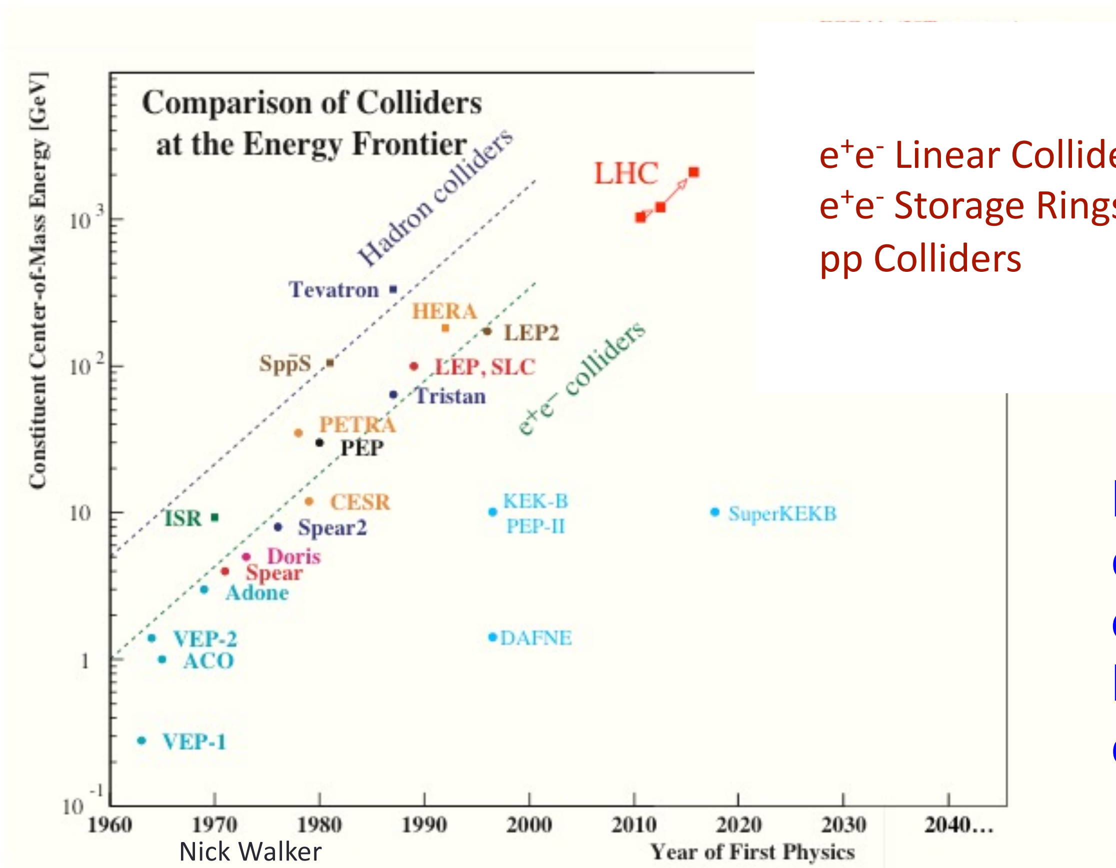
- There are two distinct and complementary strategies for gaining new understanding of matter, space and time at future particle accelerators

- HIGH ENERGY
  - direct discovery of new phenomena i.e. accelerators operating at the energy scale of the new particle
- HIGH PRECISION
  - Access to new physics at high energies through the precision measurement of phenomena at lower scales
- Lepton and hadron colliders at high energy provide powerful and complementary tools to explore TeV-scale physics

"If you mix both types of collider together, you'll bake yourself the potential to reveal particles and processes never before seen."

https://www.symmetrymagazine.org/article/may-2013/cherries-in-the-bean-cake?language=es https://physicstoday.scitation.org/doi/10.1063/1.1349610

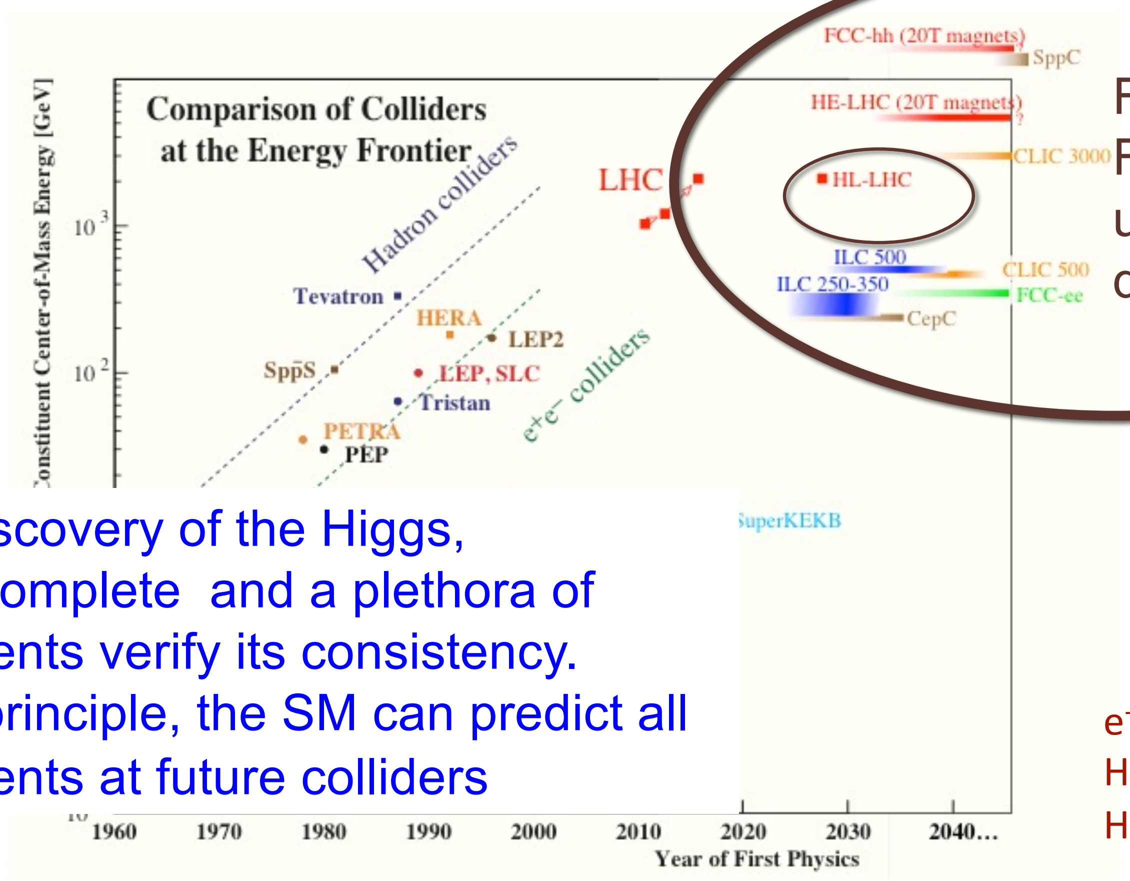
Colliders at the Energy Frontier



e^+e^- Linear Colliders
e^+e^- Storage Rings
pp Colliders

Measurements from colliders have helped develop the Standard Model and provided checks of its consistency.

Colliders at the Energy Frontier



Future Collider Facilities under discussion

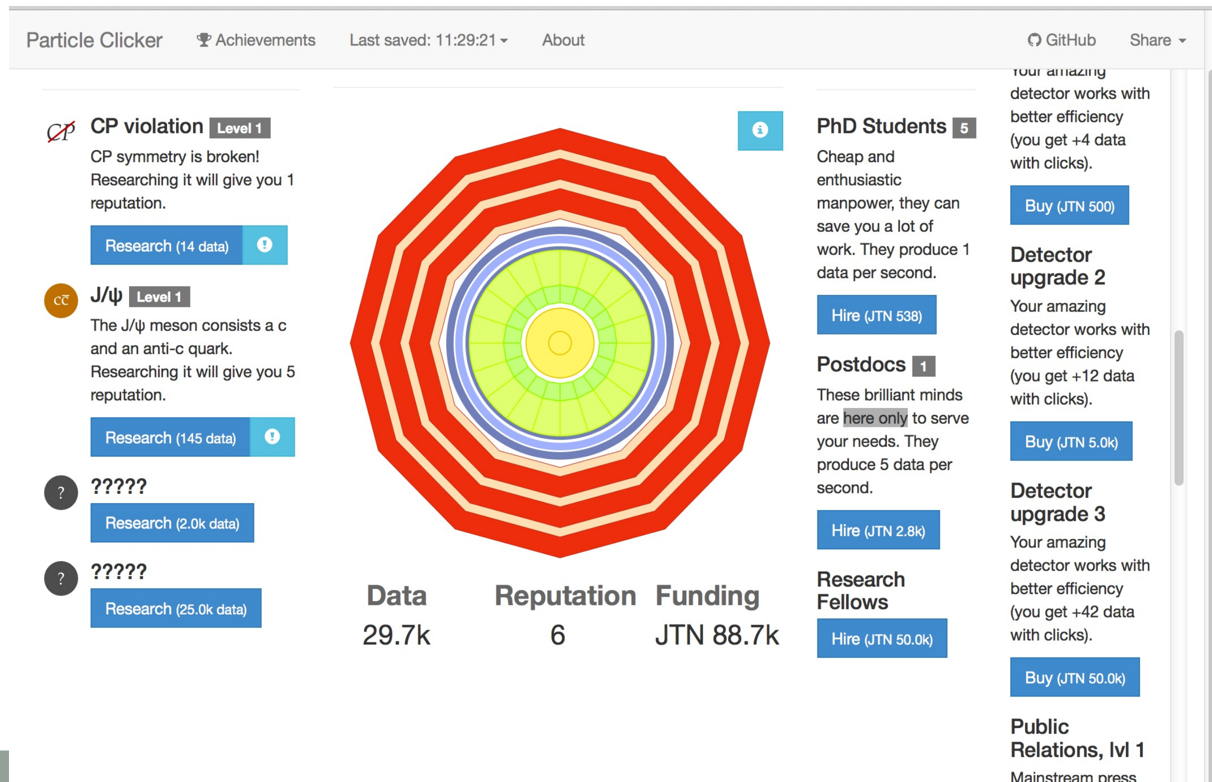
With the discovery of the Higgs, the SM is complete and a plethora of measurements verify its consistency. Hence, in principle, the SM can predict all measurements at future colliders

e^+e^- Linear Colliders
HE e^+e^- Storage Rings
HE pp Colliders

WHICH COLLIDERS?

Colliders and Detectors for tomorrow

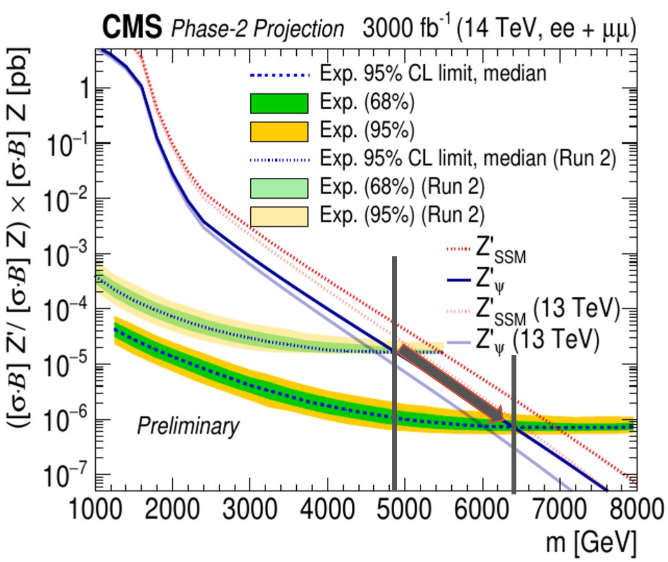
http://particle-clicker.web.cern.ch/particle-clicker/

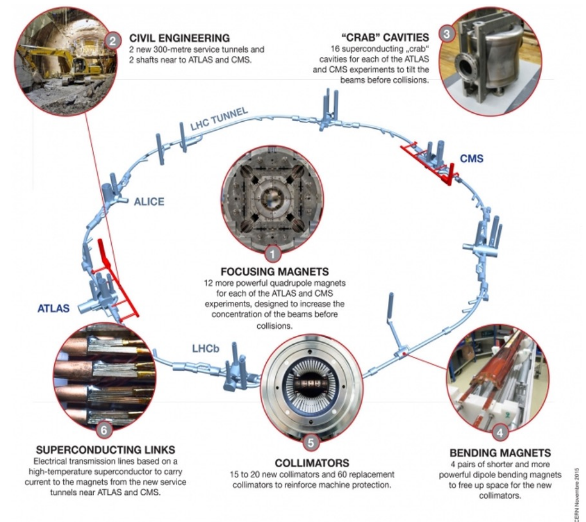


The HL-LHC: exploring the TeV scale

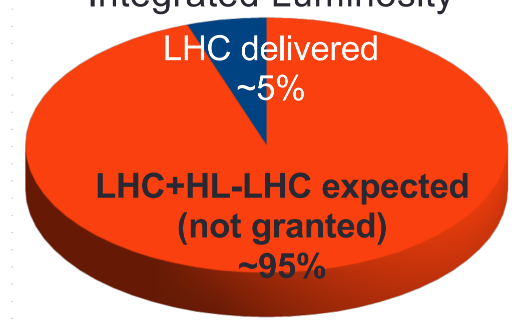
HL-LHC
@CERN

- LHC is providing a wealth of new measurements. Entering the era of precision Higgs physics.
- The High Luminosity upgrade of the LHC is a reality
  - **Ongoing construction**
  - **Operation: 2029 to ~2040**
- Large integrated luminosity allows access to higher energy scales

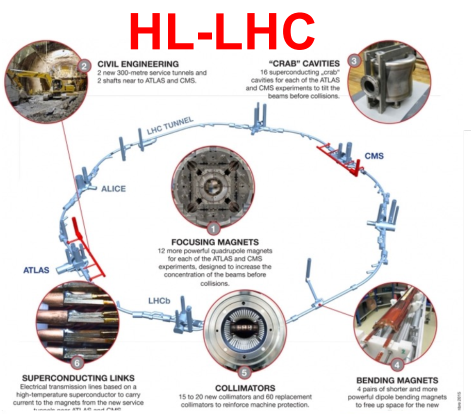


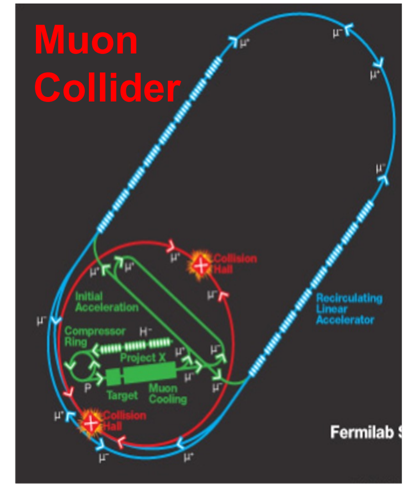


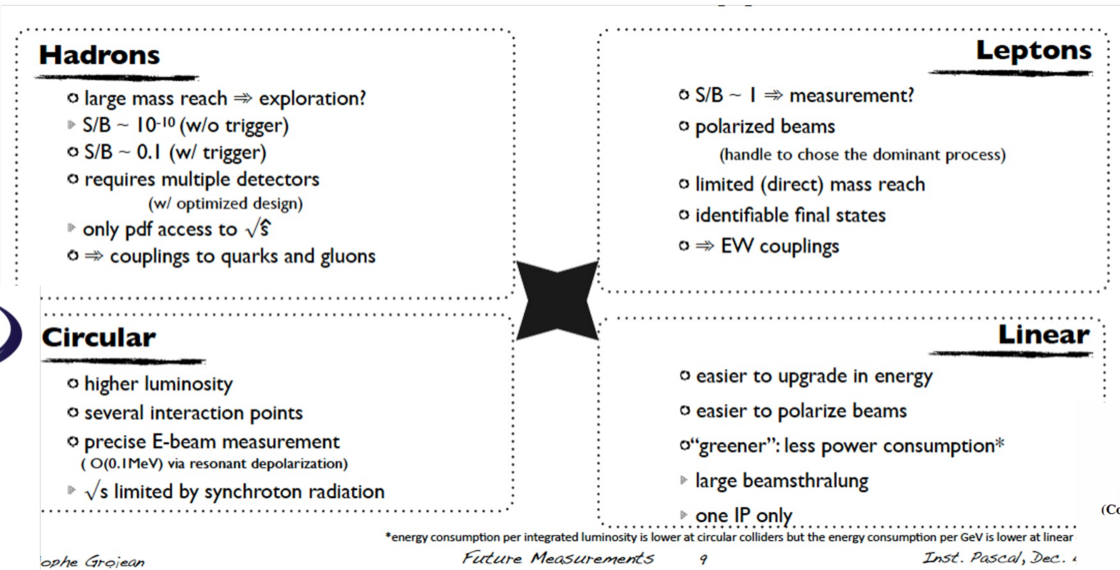
Integrated Luminosity



Which machines?







Hadrons

- large mass reach ⇒ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇒ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇒ measurement?
- polarized beams (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇒ EW couplings

Circular

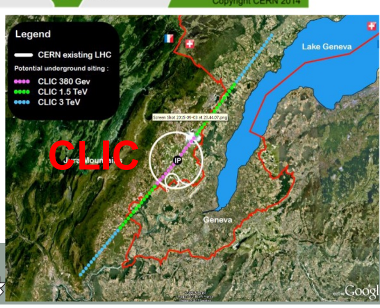
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchrotron radiation

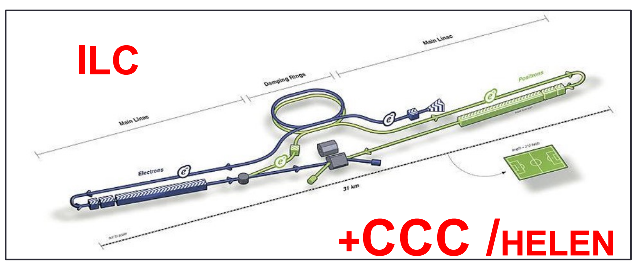
Linear

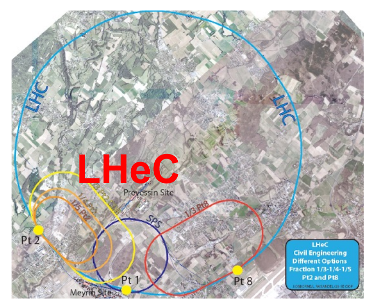
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

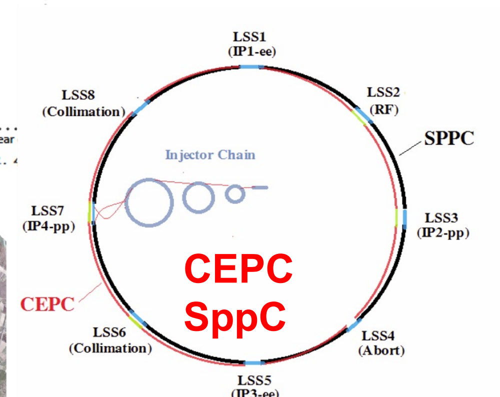
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear

ophe Grojean   Future Measurements   9   Inst. Pascal, Dec.









Colliders for tomorrow (ca 2030 and beyond)

Higgs Factory proposals

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

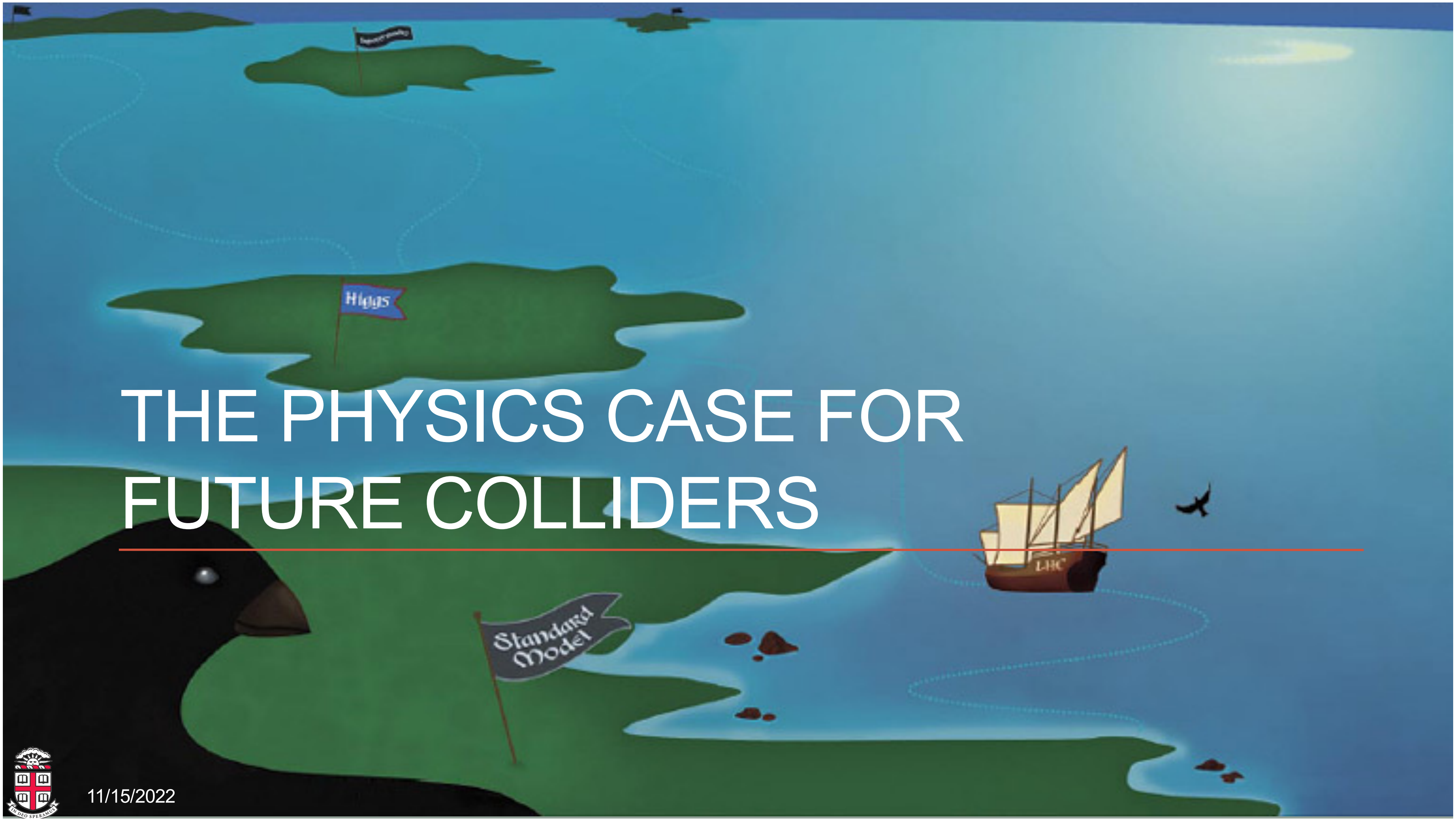
Multi-TeV Colliders

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Big Picture Questions

- Why is physics at the energy frontier important?
- *How should the US be involved in near future and far future energy-frontier machines after HL-LHC?*
- What could be the energy-frontier machines that follow the HL-LHC?
- *How can the US continue to play a leadership role in energy-frontier experiments?*
- *How can the Snowmass process help develop a plan* for the energy-frontier research and convince the community about our priorities?
- *Should we start entertaining the idea of a future collider in the US again?* If so, what are our goals, the benefits for the US and the international community, and how can we get there?
- etc...

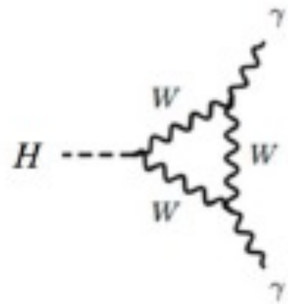
THE PHYSICS CASE FOR FUTURE COLLIDERS



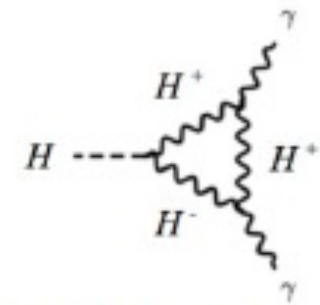
THE HIGGS, ELECTROWEAK, TOP AND QCD SECTORS

Higgs Coupling and modifiers

Example $H \rightarrow \gamma\gamma$:
In the SM, this process is described by diagram like this one:



In extensions of the SM, this process could also proceed via this other diagram:



H^+, H^- : hypothetical particles (part of extended Higgs sector)

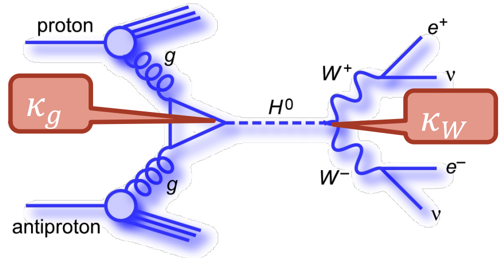
- Expected deviations from SM predictions by various models predicted to be between 1-10%.
  - Singlet mixing, 2HDM, Decoupling MSSM, Composite, Top Partner..)
- 5% precision on couplings: sensitive to BSM scales O(1 TeV).

  (sub-)1% precision → O(10 TeV)

Higgs Coupling and modifiers

- Rate of a given process depends on several couplings
- Example

gg→h→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$

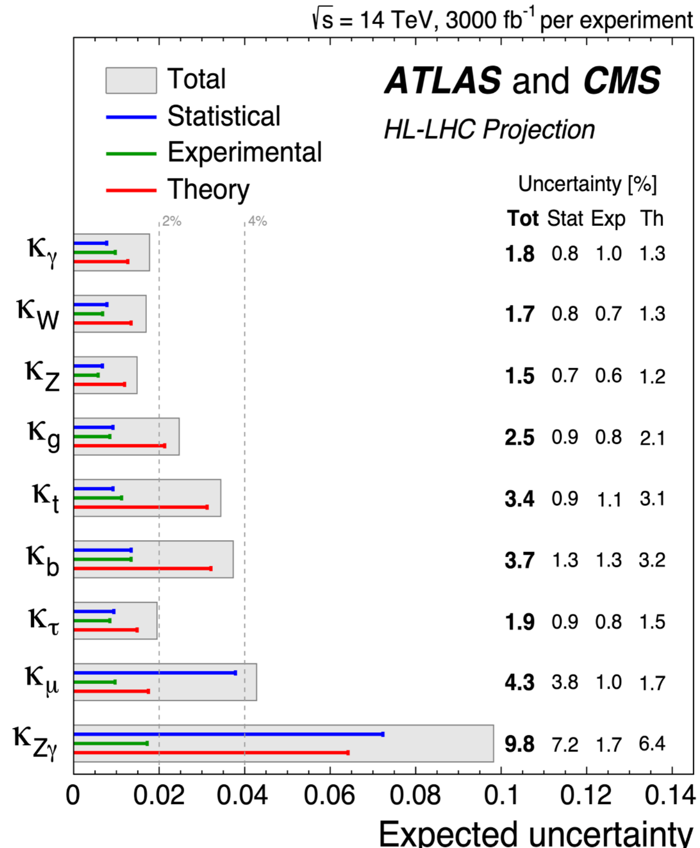


  - The κ's multiply the SM couplings. κ_g is a function of κ_t and κ_b.
  - κ_H multiplies the Higgs width and depends on all couplings

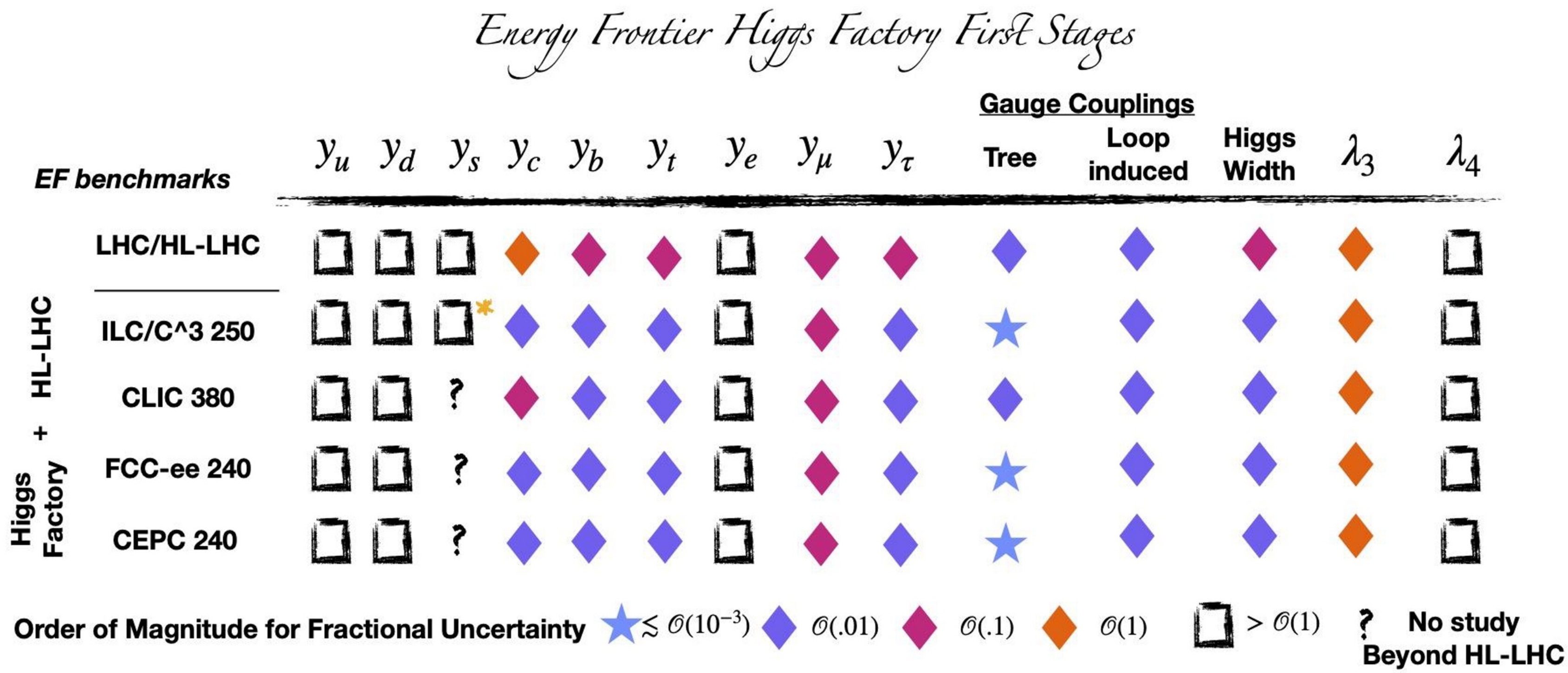
- Currently κ's are typically measured to ≈20%.
- Expected deviations from SM predictions by various models predicted to be between 1-10%.

- Projections with 3000 fb^{-1}: 2-5% (except for $Z\gamma$)
- HL-LHC will improve measurement precision by a factor 2-3!

Sensitivity to BSM physics in measurement of Higgs couplings

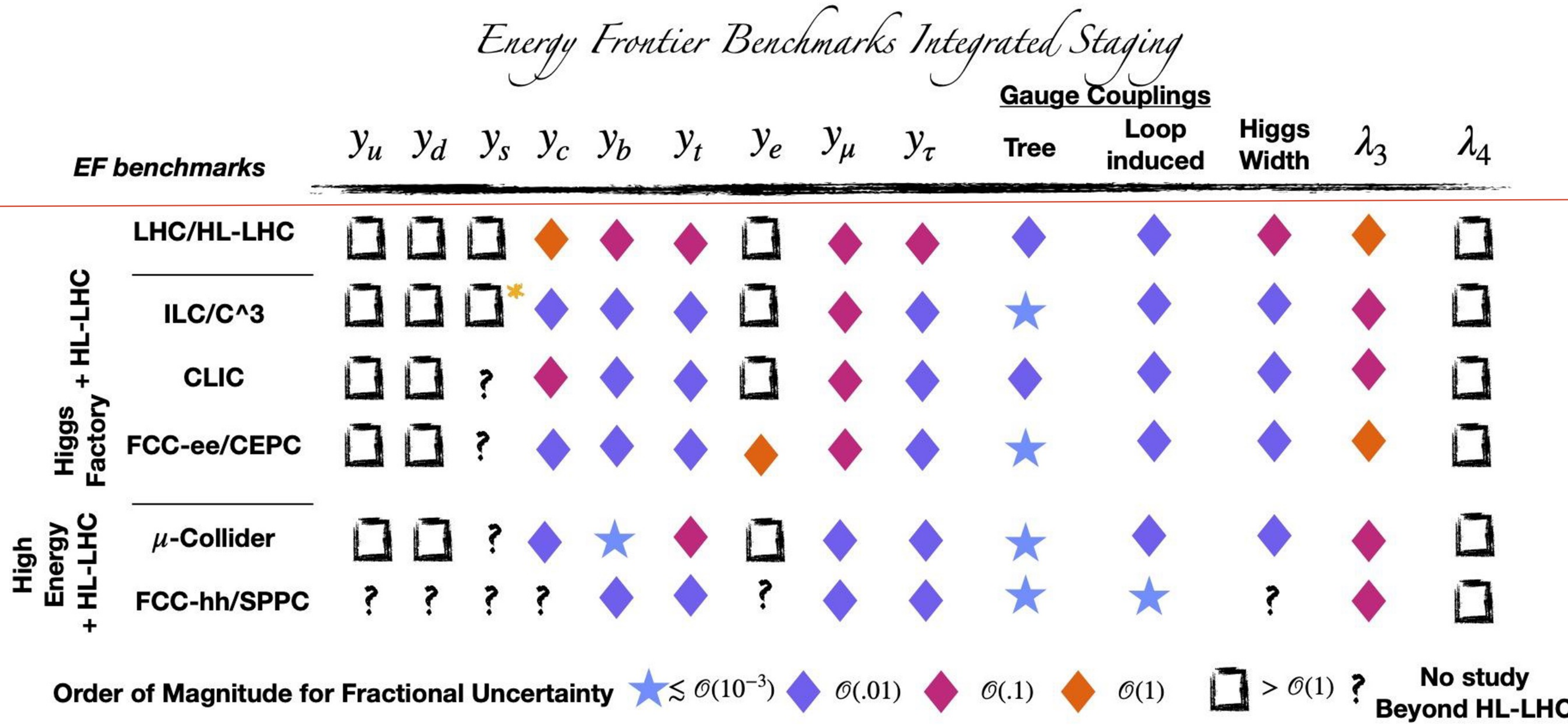


Stress Testing the Higgs Sector



Sensitivity to new physics: higher precision probes higher scales
All first stage Higgs factories are very similar.

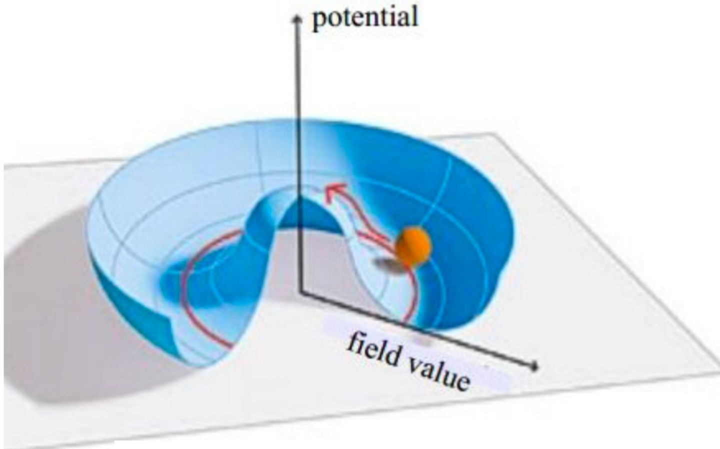
Stress Testing the Higgs Sector

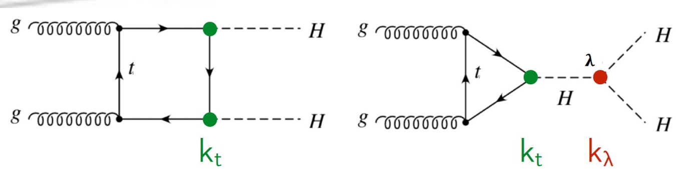


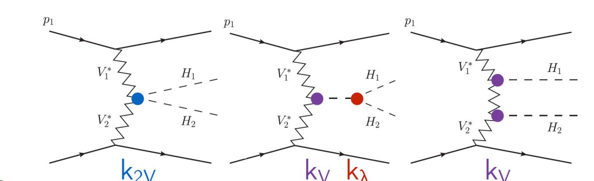
Linear colliders beginning to demonstrate advantages especially in the Higgs self coupling compared to circular e+e− colliders, whereas the circular colliders can potentially measure the electron Yukawa.

Higgs Pair Production and Self Coupling

- A measurement of the Higgs self-coupling is the only way to experimentally reconstruct the Higgs potential (reconstruct its shape close to the minimum).





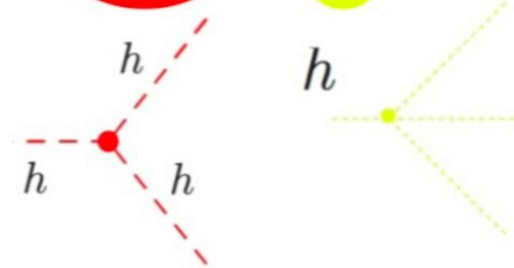


Higgs potential in the standard model:

$$V(\Phi) = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2$$

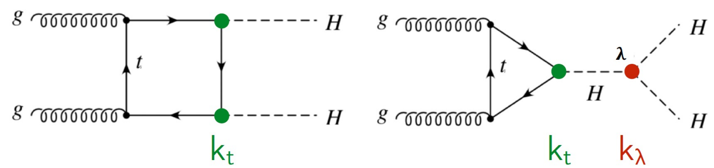
expansion around the minimum

$$\frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4$$



Reach for Higgs-self coupling

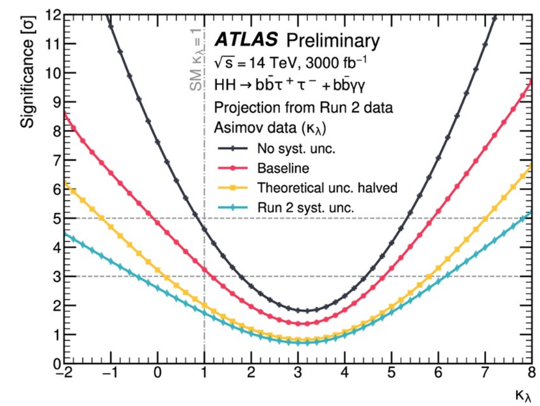
- HH production allows direct probing of the Higgs boson self-interaction thus probing the shape of Higgs potential

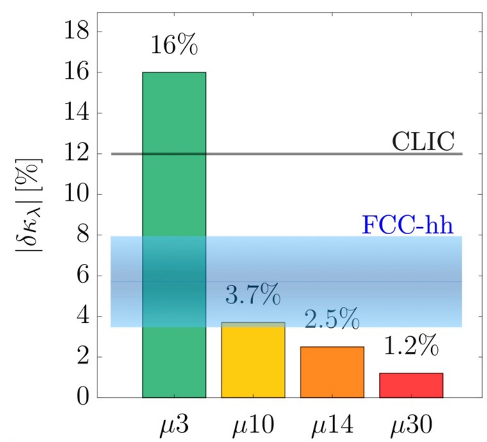


- **HL-LHC: Possible observation of HH production!**

collider	Indirect-h_{SM}	$h_{SM}h_{SM}$	combined
HL-LHC [24]	100-200%	50%	50%
ILC_{250}/C^3-250 [14, 17]	49%	–	49%
ILC_{500}/C^3-550 [14, 17]	38%	20%	20%
ILC_{100}/C^3-1000 [14, 17]	36%	10%	10%
$CLIC_{380}$ [19]	50%	–	50%
$CLIC_{1500}$ [19]	49%	36%	29%
$CLIC_{3000}$ [19]	49%	9%	9%
FCC-ee [20]	33%	–	33%
FCC-ee (4 IPs) [20]	24%	–	24%
FCC-hh [25]	-	3.4-7.8%	3.4-7.8%
μ(3 TeV) [23]	-	15-30%	15-30%
μ(10 TeV) [23]	-	4%	4%

HL-LHC: First bounds on Higgs self-coupling





- FCC-hh updated arXiv:2004.03505
- Muon Collider reach: arXiv:2203.07256

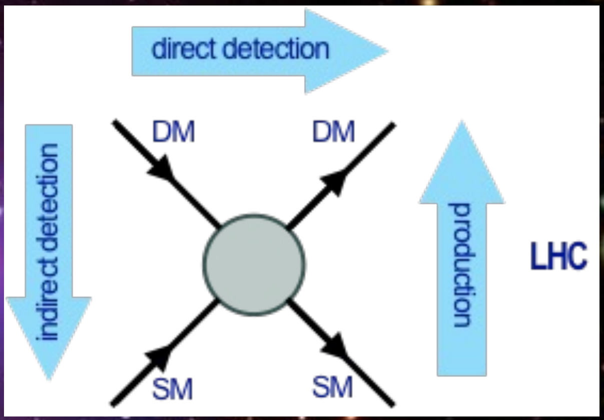
EXPLORING THE BSM SECTOR

Competitive and complementary Searches for Dark Matter

- Non-baryonic matter, no EM interactions observed (dark), ~84% of matter
- Evolution of dark matter density regulated by production/annihilation processes

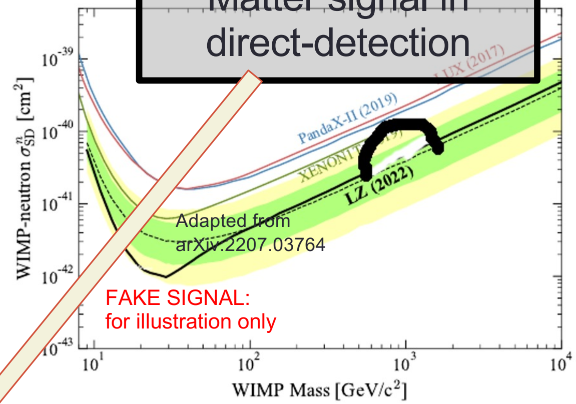
- Aim to create Dark Matter in laboratory and study its properties in detail
  - very complementary to direct searches in the cosmic frontier!
  - WIMP, Mediator searches, Beyond-WIMP

- In a minimal weakly-interactive model, DM is part of a EWK multiplet
  - Fixing its structure allows to compute rates
  - Comparing with observed density can derive a target DM particle mass

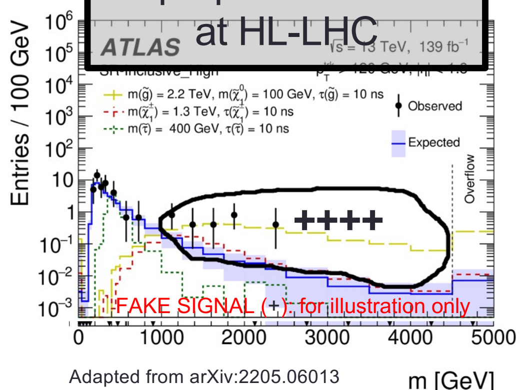


A discovery scenario

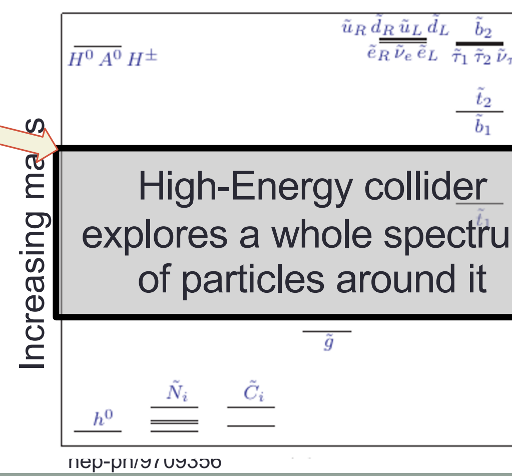
Discovery of a Dark Matter signal in direct-detection



Its properties studied at HL-LHC

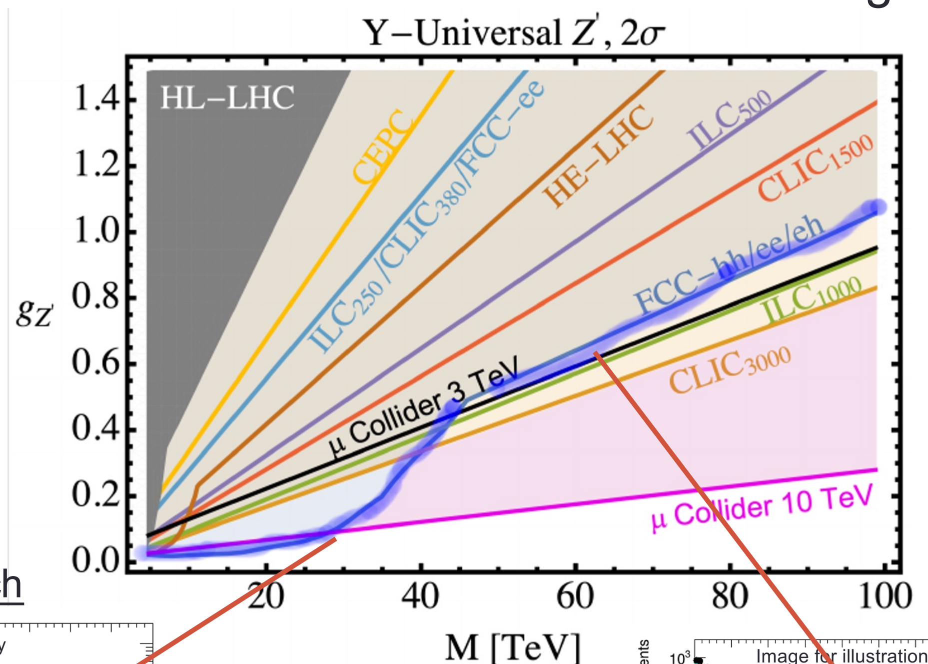


High-Energy collider explores a whole spectrum of particles around it

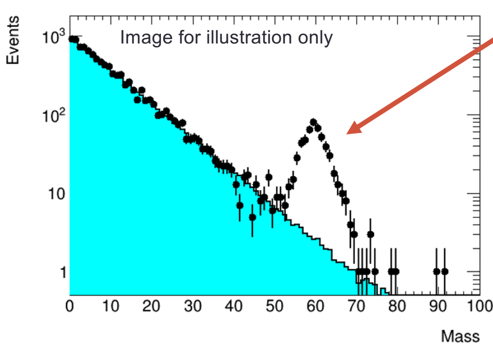


Exploring the unknown: new forces

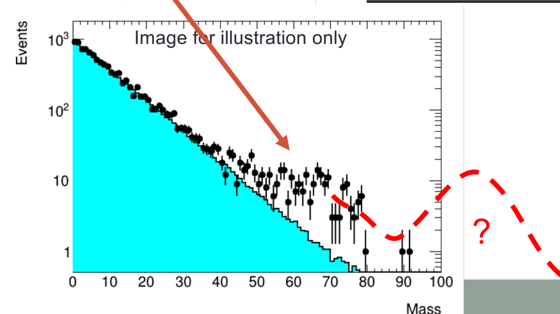
Probe mediator of new forces to the tens of TeV range!



Direct reach



Indirect reach



VISION OF THE ENERGY FRONTIER

The immediate future is the HL-LHC

- During the next decade it is essential to complete the **highest priority recommendation of the last P5** and to fully realize the scientific potential of the **HL-LHC collecting at least 3 ab^{-1} of data**.
- **Continued strong US participation is critical** to the success of the HL-LHC physics program, in particular for the Phase-2 detector upgrades, the HL-LHC data taking operations and physics analyses based on HL-LHC data sets, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades
- **For the next decade and beyond**
  - **2025-2030**: Prioritize HL-LHC physics program, including auxiliary experiments
  - **2030-2035**: Continue strong support for HL-LHC physics program
  - **After 2035**: Support continuing the HL-LHC physics program to the conclusion of archival measurements

The intermediate future is an e^+e^- Higgs factory

The intermediate future is an e^+e^- Higgs factory, either based on a linear (ILC, C^3, CLIC) or circular collider (FCC-ee, CepC).

- **The various proposed facilities have a strong core of common physics goals**: it is important to **realize at least one somewhere in the world.**
- **A fast start towards construction is important**. There is **strong US support** for initiatives that could be realized on a time scale relevant for early career physicists.
- **For the next decade and beyond**
  - **2025-2030**: Establish a targeted e^+e^- Higgs Factory detector R&D for US participation in a global collider
  - **2030-2035**: Support and advance construction of an e^+e^- Higgs Factory
  - **After 2035**: Begin and support the physics program of an e^+e^- Higgs Factory

The long-term future is a multi-TeV collider

- A 10-TeV **muon collider** (MuC) and 100-TeV **proton-proton collider** (FCC-hh, SppC) directly probe the order 10 TeV energy scale with different strengths that are unparalleled in terms of mass reach, precision, and sensitivity.

- The main limitation is technology readiness. **A vigorous R&D program** into accelerator and detector technologies **will be crucial.**

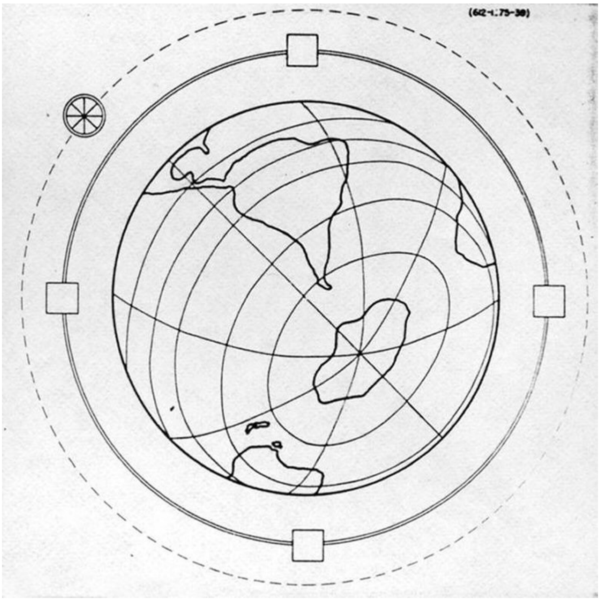
- **For the next decade and beyond**
  - **2025-2030**:
    - Develop an initial design for a first stage TeV-scale Muon Collider in the US (pre-CDR)
    - Support critical detector R&D towards EF multi-TeV colliders

  - **2030-2035**: Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider

  - **After 2035**:
    - Demonstrate readiness to construct a first-stage TeV-scale Muon Collider
    - Ramp up funding support for detector R&D for EF multi-TeV colliders

Our Dream: "The Ultimate Accelerator"

- In a 1954 speech to the APS Enrico Fermi fancifully envisioned a particle accelerator that encircled the globe.
- This would be the ultimate theoretical outcome, of the quest for the ever-more powerful accelerators needed to discover new laws of physics.
  - **How much energy you can put into a particle per meter corresponds directly to how big the machine is**



The Globatron
Energy: 5000 TeV
or $\sqrt{s}$=3 TeV collider
Cost: 170B USD(1954)

As we continue to "Dream"..

- A large international effort to advance an energy frontier machine:
  - We definitely need **a Higgs Factory** as the next step after HL-LHC
  - We should continue to develop ideas and plans for R&D for a **"High Energy Discovery Machine"** after the Higgs Factory
- The path to a new machine is long, and benefits for society (technology) will play an important role.
- It will be challenging – but the LHC also looked close-to-impossible in the '80s!

- ***Let's use our creativity to develop the technologies needed to make future projects financially affordable and technically achievable***
- ***Let's keep our passion for science***
- ***Let's follow our dreams!***

thank you to The Energy Frontier Group

- **My EF Co-convenors**: *Laura Reina (FSU), Alessandro Tricoli (BNL)*
- **Ten Topical Group (TGs) Conveners.**

Topical Group	Co-Conveners
EF01: EW Physics: Higgs Boson properties and couplings	**Sally Dawson (BNL), Caterina Vernieri (SLAC)**
EF02: EW Physics: Higgs Boson as a portal to new physics	**Patrick Meade (Stony Brook), Isobel Ojalvo (Princeton)**
EF03: EW Physics: Heavy flavor and top quark physics	**Reinhard Schwienhorst (MSU), Doreen Wackeroth (Buffalo)**
EF04: EW Physics: EW Precision Physics and constraining new physics	**Alberto Belloni (Maryland), Ayres Freitas (Pittsburgh), Junping Tian (Tokyo)**
EF05: QCD and strong interactions: Precision QCD	**Michael Begel (BNL), Stefan Hoeche (FNAL), Michael Schmitt (Northwestern)**
EF06: QCD and strong interactions: Hadronic structure and forward QCD	**Huey-Wen Lin (MSU), Pavel Nadolsky (SMU), Christophe Royon (Kansas)**
EF07: QCD and strong interactions: Heavy Ions	**Yen-Jie Lee (MIT), Swagato Mukherjee (BNL)**
EF08: BSM: Model specific explorations	**Jim Hirschauer (FNAL), Elliot Lipeles (UPenn), Nausheen Shah (Wayne State)**
EF09: BSM: More general explorations	**Tulika Bose (U Wisconsin), Zhen Liu (Maryland), Simone Pagan-Griso (LBL)**
EF10: BSM: Dark Matter at colliders	**Caterina Doglioni (Lund), LianTao Wang (Chicago)**

- **Liaison to other Frontiers included Dmitri Denisov (Accelerator Frontier).**
- **Monte Carlo Task Force and Production Team**: coordinated by **John Stupak** (U. Oklahoma)

thank you

- to all from whom I have shamelessly borrowed…

- interesting websites
- LHC: http://home.web.cern.ch/topics/large-hadron-collider
- HL-LHC: http://hilumilhc.web.cern.ch/HiLumiLHC/index.html
- CMS: http://cms.web.cern.ch/
- ATLAS: http://atlas.ch/
- Linear Collider: https://www.linearcollide
- CepC, SppC: http://cfhep.ihep.ac.cn/
- FCC: https://espace2013.cern.ch/fcc/F t.aspx