Big Questions in Particle Physics

A Snowmass Colloquium Series by SEC-Inreach

Friday Nov 12th @ 12-1:30pm ET

Future Colliders

Featuring

Derun Li & Meenakshi Narain

Registration Required:

https://indico.fnal.gov/event/51595

50 years down the line, what questions might we hope to answer?
And what will it take to get there?
Each month, 2 new speakers share their thoughts, and ask for yours.

Image credit: FCCS

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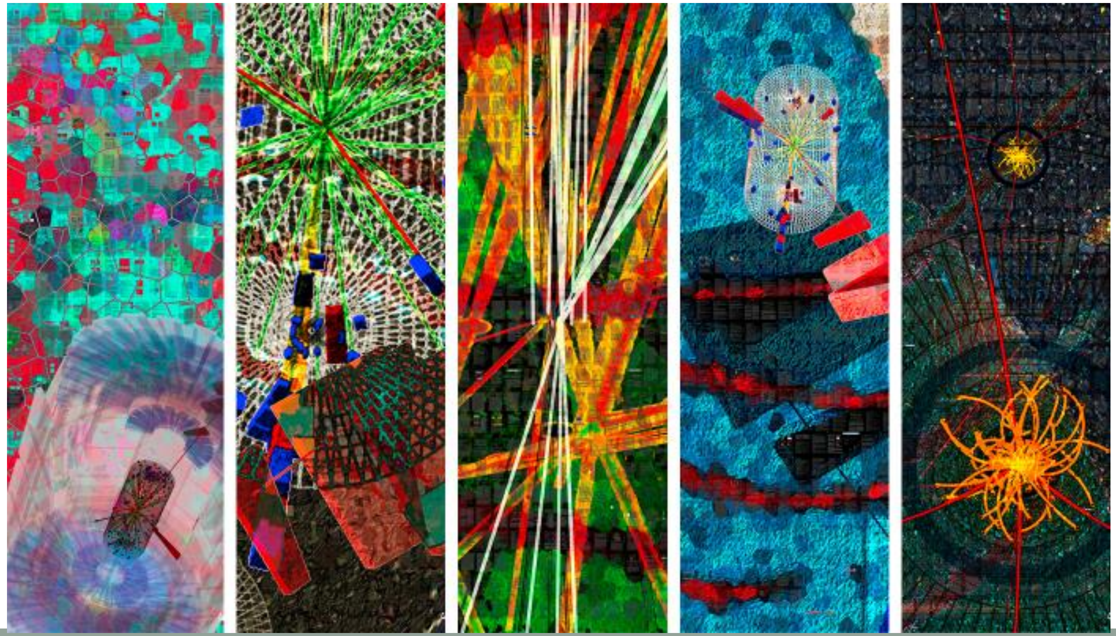
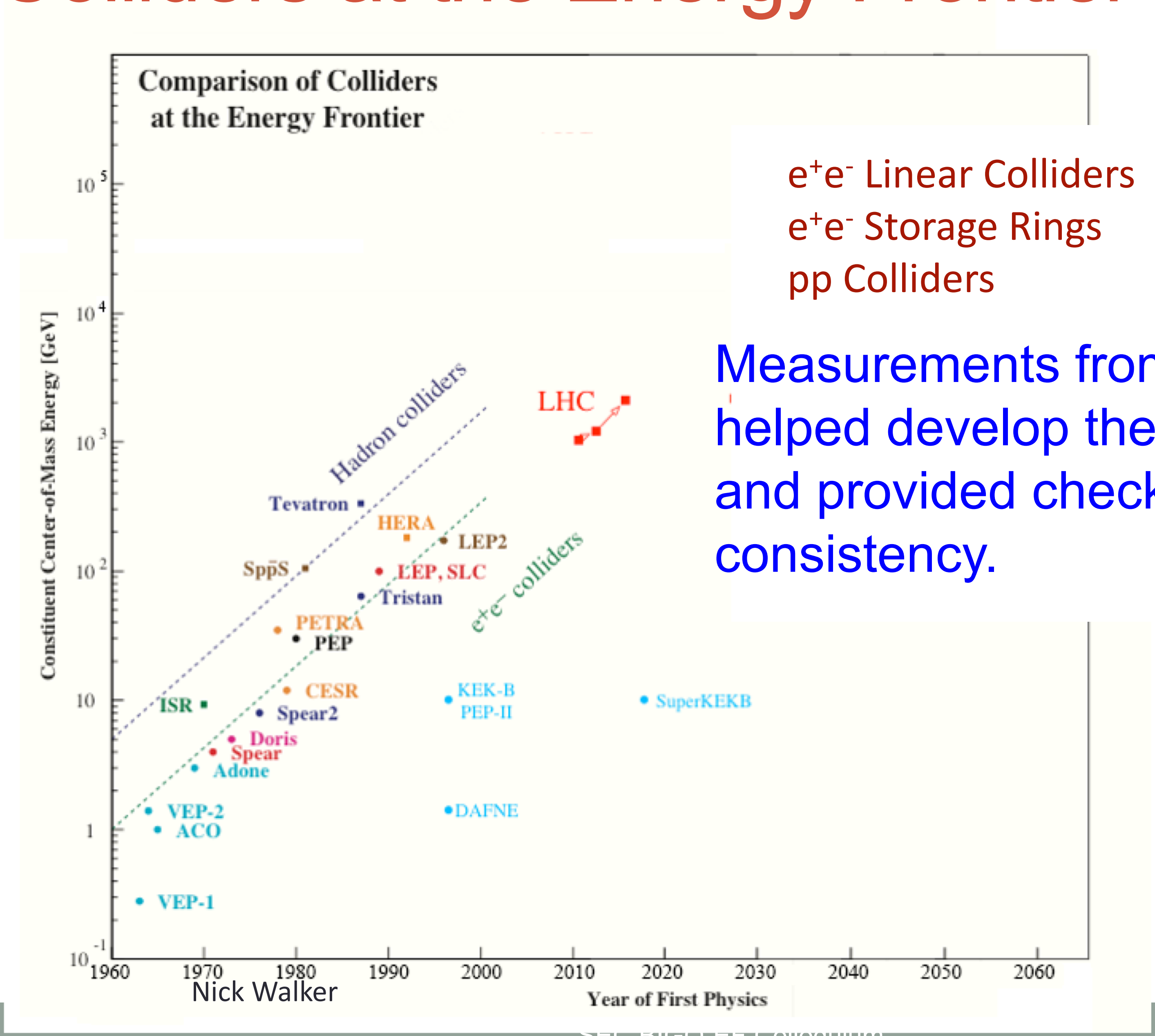
PHYSICS CASE FOR FUTURE COLLIDERS

Meenakshi Narain
Brown University

November 12, 2021



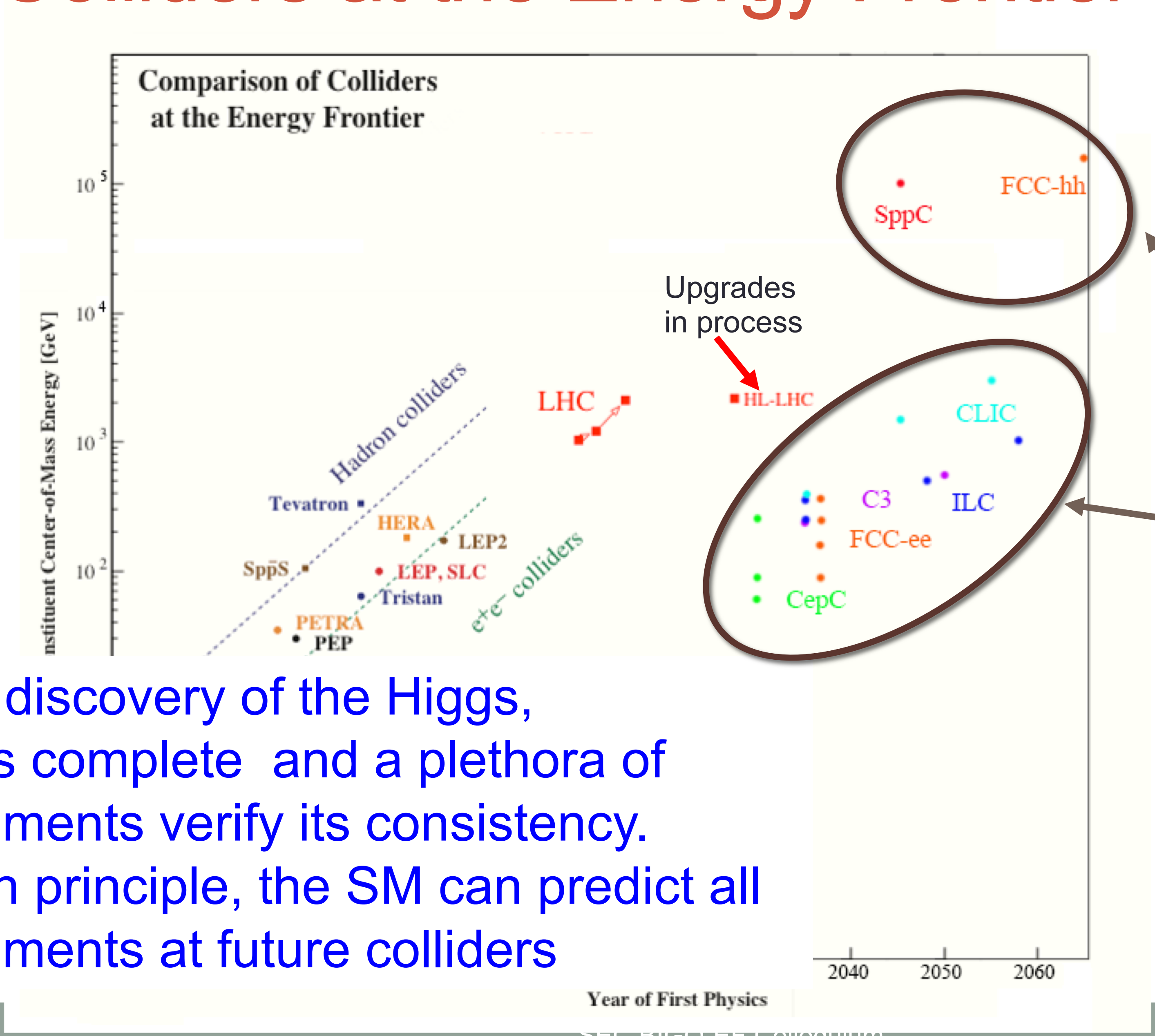
Colliders at the Energy Frontier



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

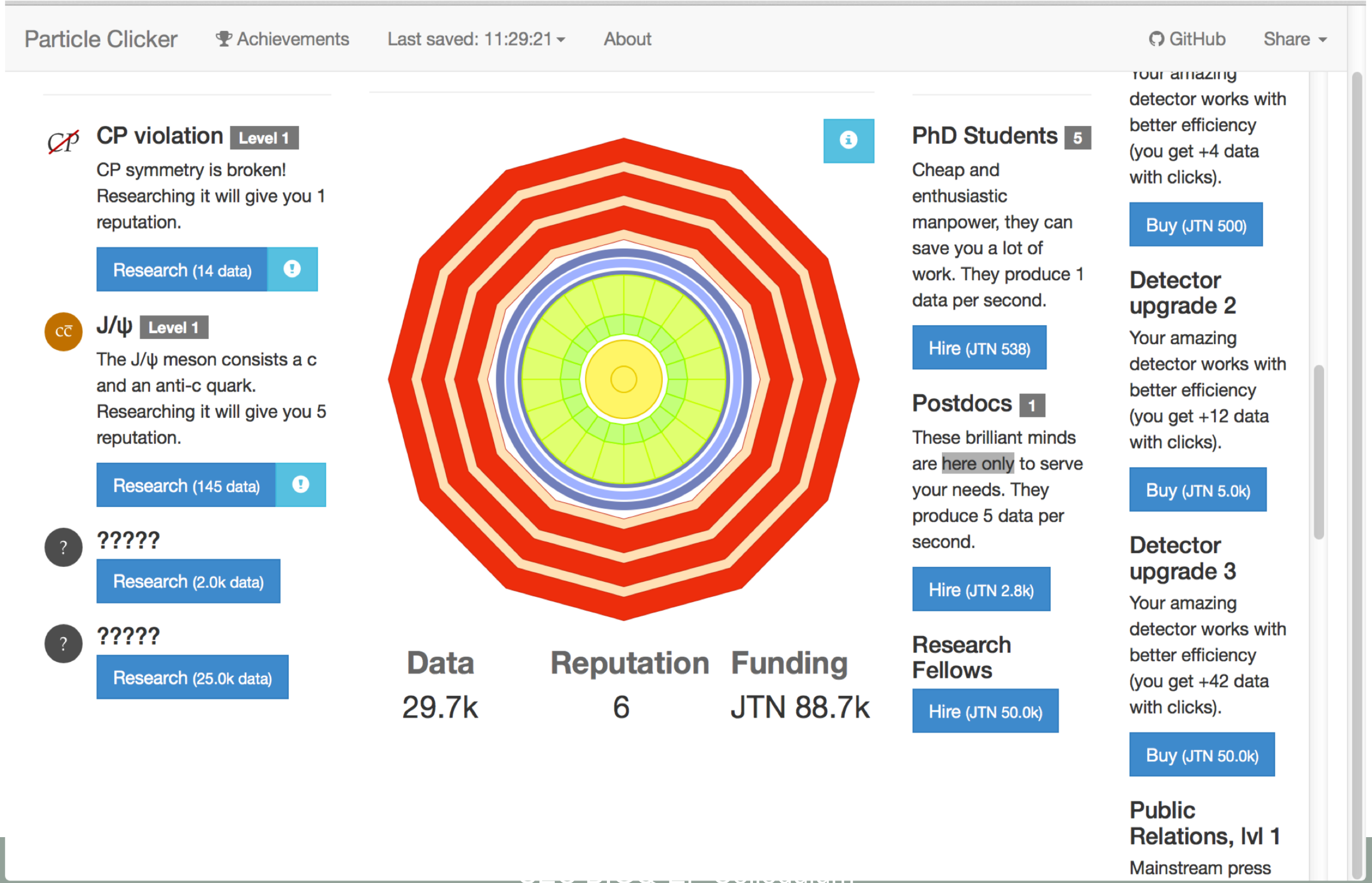


With the discovery of the Higgs, the SM is complete and a plethora of measurements verify its consistency. Hence, in principle, the SM can predict all measurements at future colliders

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

Colliders and Detectors for tomorrow

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



Colliders for tomorrow (ca. 2030 and beyond)

Snowmass 2021 Energy Frontier Collider Study Scenarios

Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
HL-LHC	pp	14 TeV		6
ILC	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
		1.5 TeV	$\pm80/0$	2.5
		3.0 TeV	$\pm80/0$	5
CEPC	ee	M_Z		16
		$2M_W$		2.6
		240 GeV		5.6
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		$2\ M_{top}$		1.5

Snowmass 2021 Energy Frontier Collider Study Scenarios

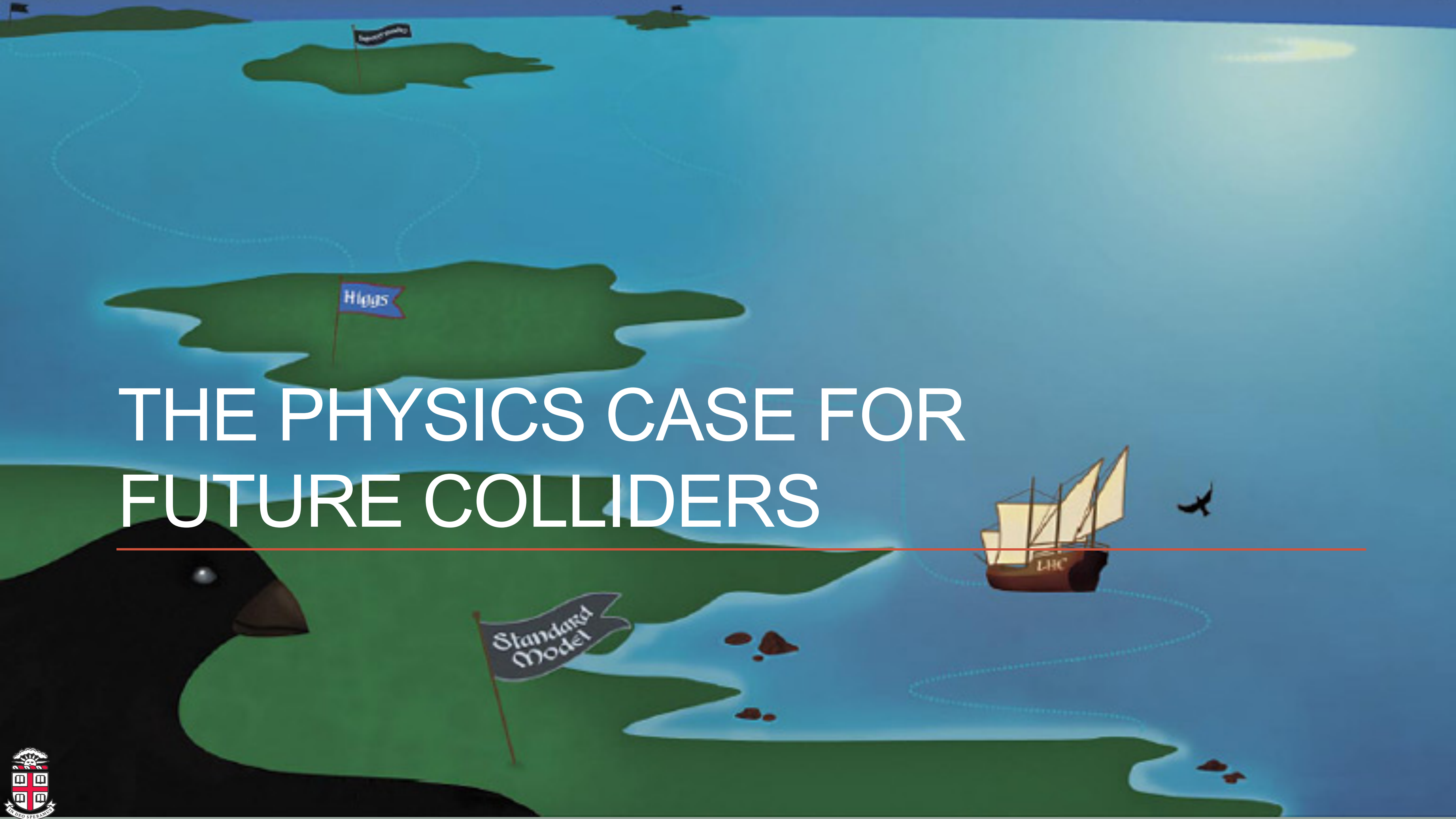
Collider	Type	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
FCC-hh	pp	100 TeV		30
LHeC	ep	1.3 TeV		1
FCC-eh	ep	3.5 TeV		2
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02
High energy muon-collider	$\mu\mu$	3 TeV		1
		10 TeV		10
		14 TeV		20
		30 TeV		90

Note for muon-collider: It is important to note that the plan is not to run subsequently at the various c.o.m etc. These are reference points to explore and assess the physics potential and technology. The luminosity can be varied to determine how best to exploit the physics potential.

Other options to explore:

- Muon collider at a very high energy (>30 TeV?) [Need to consolidate growing list of c.o.m. energies]
- FCC pp @200 TeV?
- Very high energy e+e- collider
- gamma-gamma collide
- Other emerging ideas:, e.g. γ-γ collider, and the C^3 e^+e^- collider [C^3=Cool Copper Collider]

THE PHYSICS CASE FOR FUTURE COLLIDERS

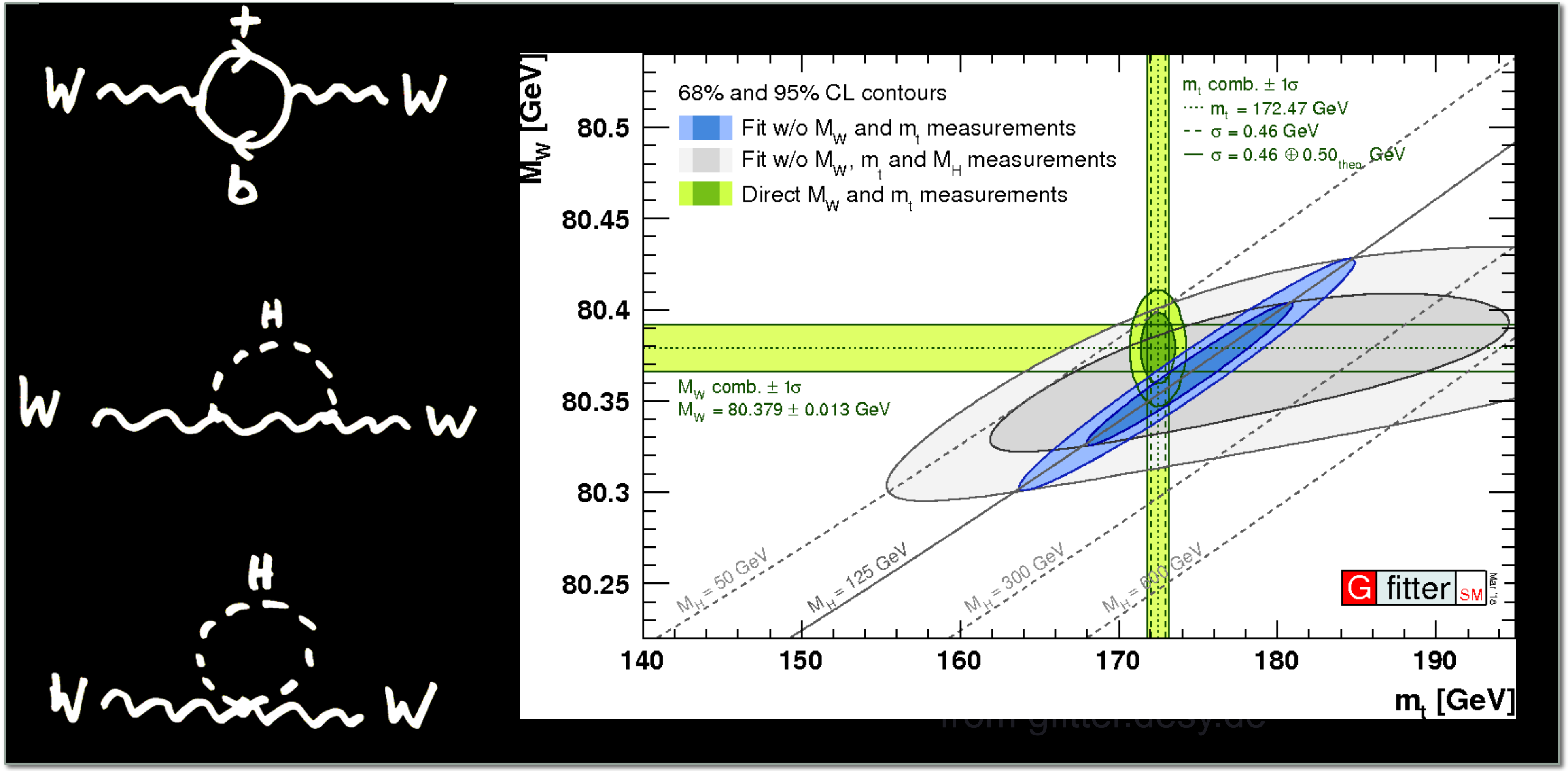


Energy Frontier: exploring the TeV scale

- Snowmass 2021: a very exciting time
  - LHC Run 2 is providing a wealth of new measurements.
  - Entering the era of precision Higgs physics.
  - The HL-LHC is a reality.
- Exciting results from other frontiers: rare processes, cosmology, …
  - Cracks in the SM paradigm
  - See anomalies in g-2, lepton flavor violation at LHCb, cosmological evidence for Dark Matter
- ...and we have no preferred way beyond the SM:
- ⇒ Great time to propose new ideas, new perspectives, new tools.

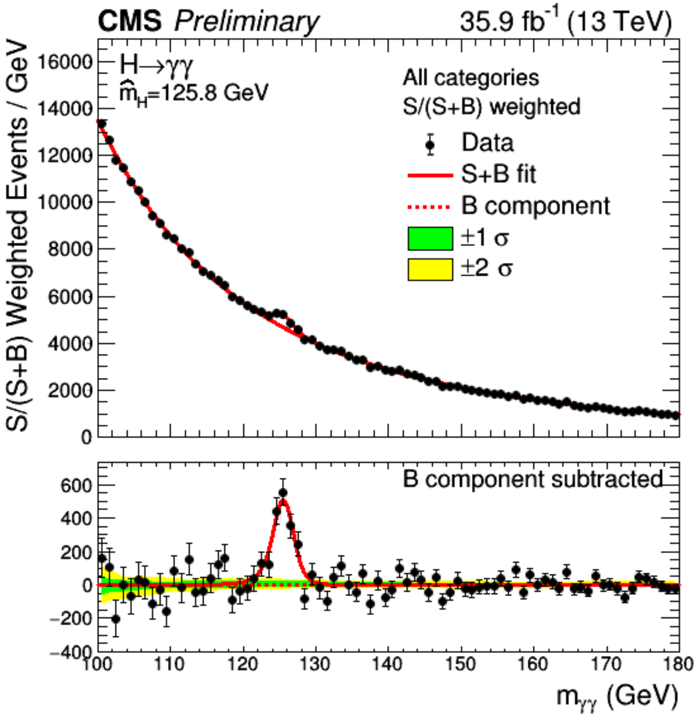
Consistency of SM: a success story

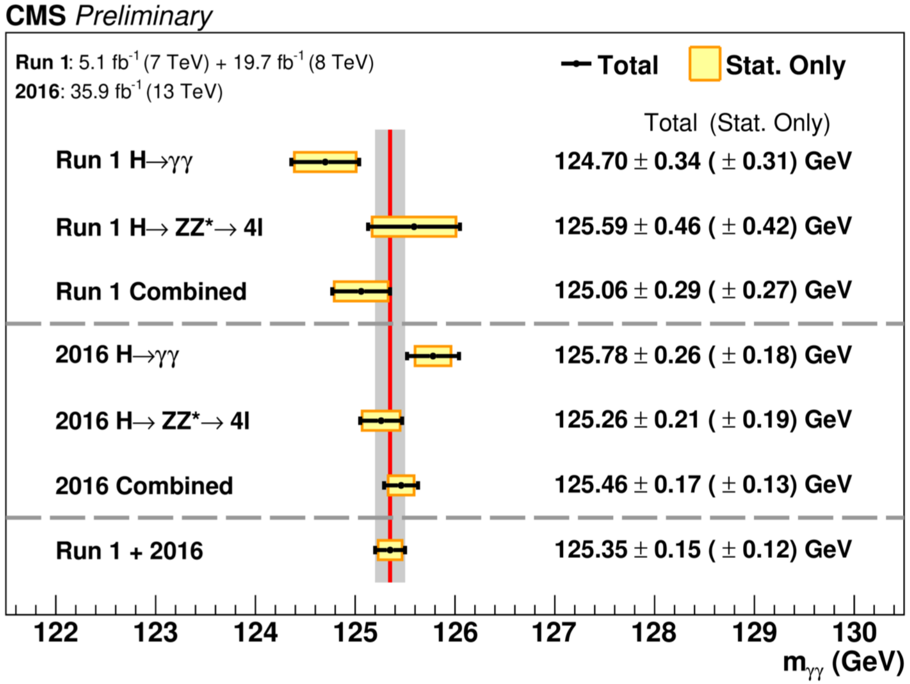
- Higgs, W boson mass and top quark mass



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

Explaining the mass of the Higgs Boson

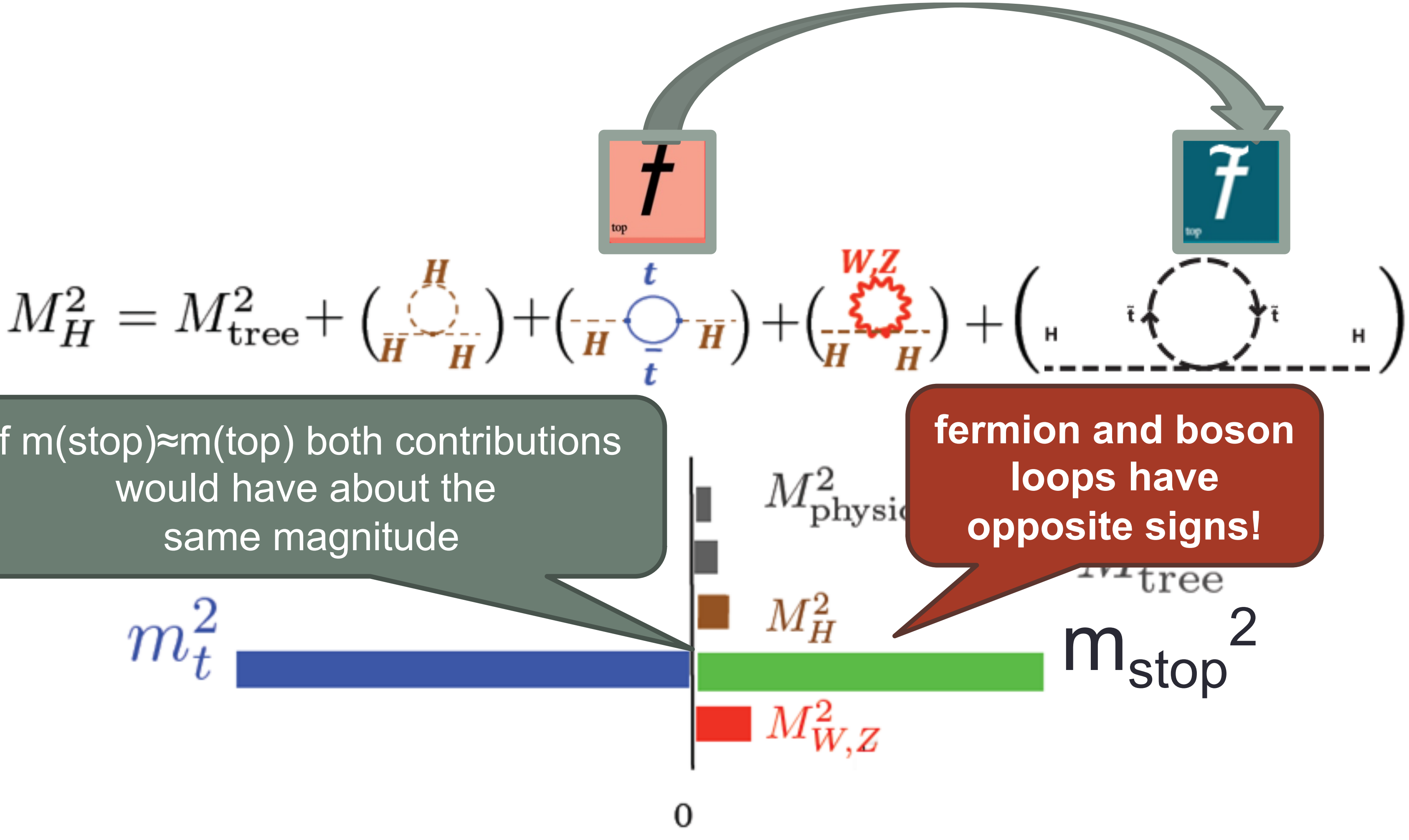




- We do **not** have an explanation for the Higgs mass itself in the standard model! One has to **rely on BSM** to explain the Higgs mass.
- Explaining the Higgs mass (aka the naturalness/fine-tuning puzzle) has been a major drive for BSM physics for the past 40 years.
- No matter what one's tolerance level of fine-tuning is, **we need an explanation for the Higgs mass**!
- The emergence of some "**folk-lore" knowledge**: new physics at O(10 - 100) TeV in a broad range of BSM models aiming at explaining the Higgs mass.

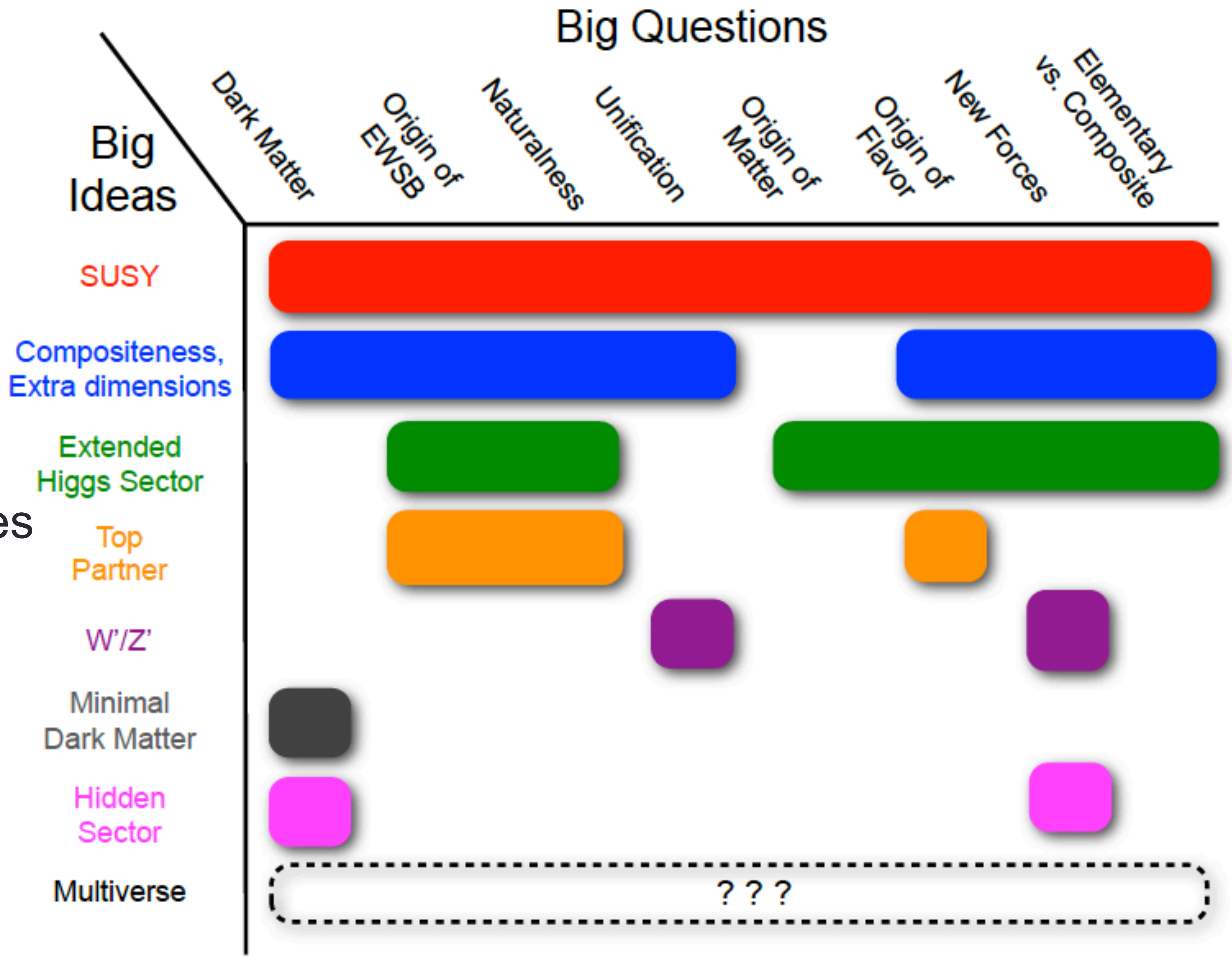
Solution: New Physics ? e.g. Supersymmetry

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



BSM Physics

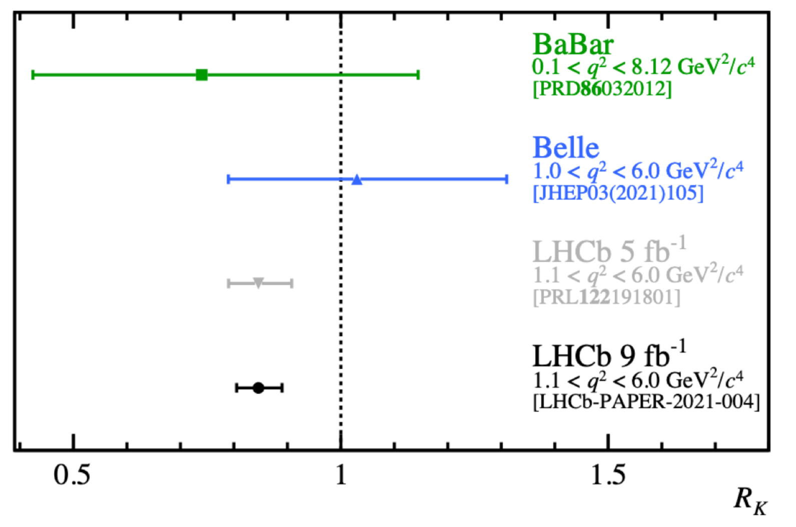
- Plethora of models
- Predict:
  - New heavy particles
    - Some with large lifetimes
  - New signatures

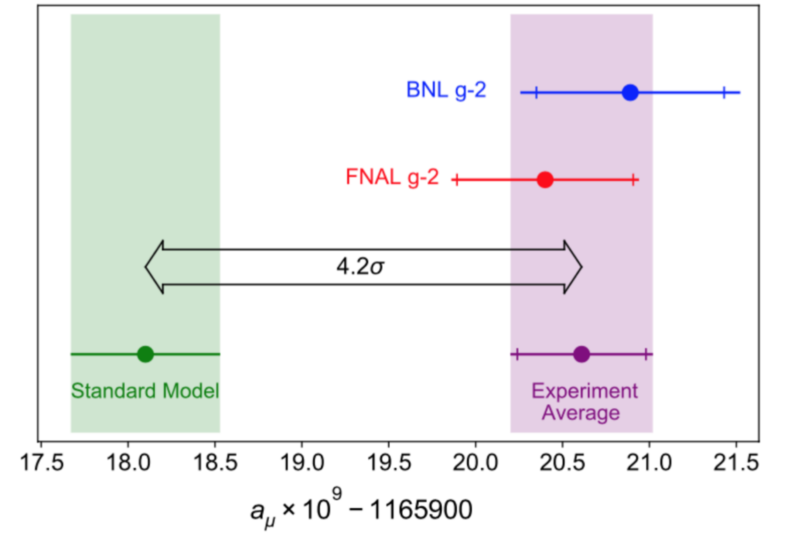


The search for a new paradigm beyond the SM

- 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?

Evidence of Lepton Flavor Universality violation at 3.1σ at LHCb



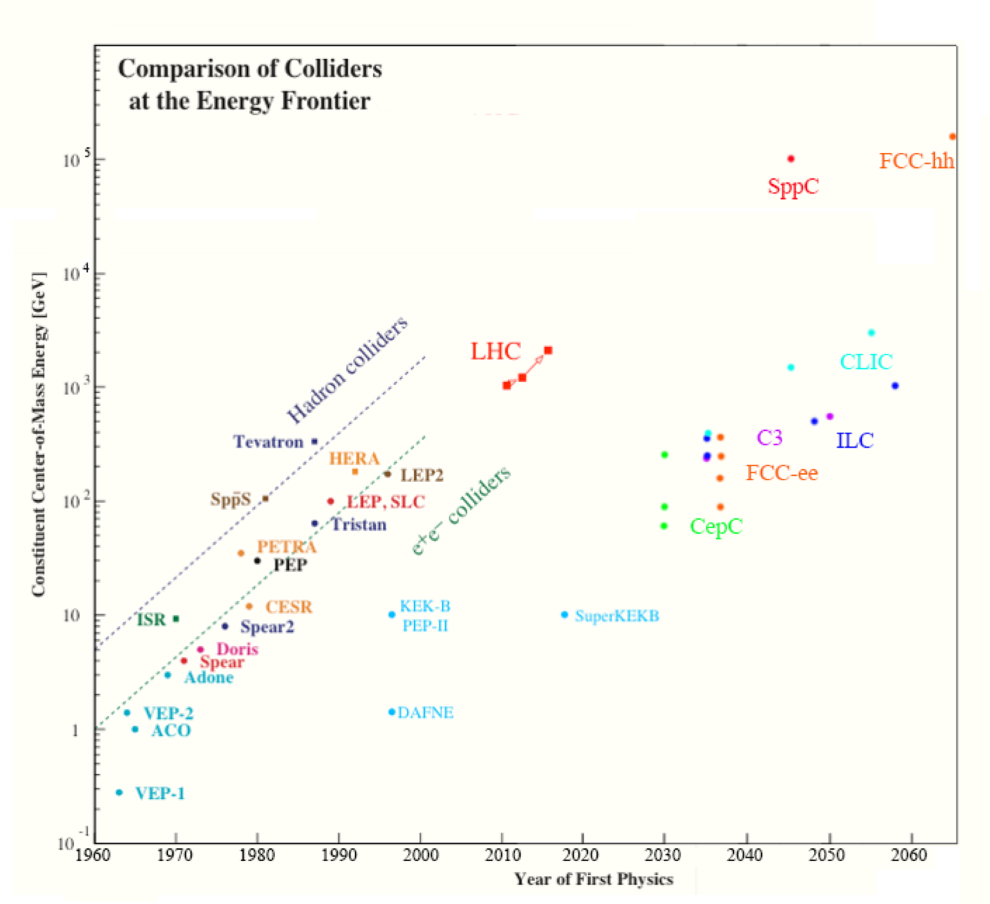


Data-theory discrepancy on g-2 at 4.2σ

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."

FUTURE STRATEGY

Snowmass 2021

European Strategy for Particle Physics

Towards the future…

- Since Snowmass 2013
  - P5 report: science drivers
    - Use the Higgs boson as a new tool for discovery
    - pursue the physics associated with neutrino mass
    - Identify the new physics of dark matter
    - Understand cosmic acceleration: dark energy and inflation
    - Explore the unknown: new particles, interactions, and physical principles
  - Pursue the most important opportunities.
  - Pursue a program to address the five science Drivers

- Next Steps to build a vision for 2025+
  - European strategy report July 2020
  - This activity: US community study Snowmass 2021
- Solution/Proposal - an ambitious post-HL-LHC project

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...

- These questions were discussed in the Panel: **"The importance of the Energy Frontier in the US HEP future planning"** at the "Energy Frontier Workshop - Open Questions and New Ideas", July 20-22, 2020
  - By Jorgen D'Hondt, Nima Arkani-Hamed, Sarah Eno, Vladimir Shiltsev, Xinchou Lou, Young-Kee Kim
  - See Zoom recording of Panel Discussion

https://www.symmetrymagazine.org/article/november-2012/a-bouquet-of-options-Higgs-factory-ideas-bloom

WHICH COLLIDERS?

Accelerators and Instrumentation for the Energy Frontier

- EF science goals currently envision two types of future colliders
  - **Higgs** (and other known elementary particles) **factory**
  - **Energy frontier machine**

- Discoveries at the Energy Frontier are intricately linked to the progress in accelerators and instrumentation
- Evaluate *trade-offs and narrow the range of collider options* to explore

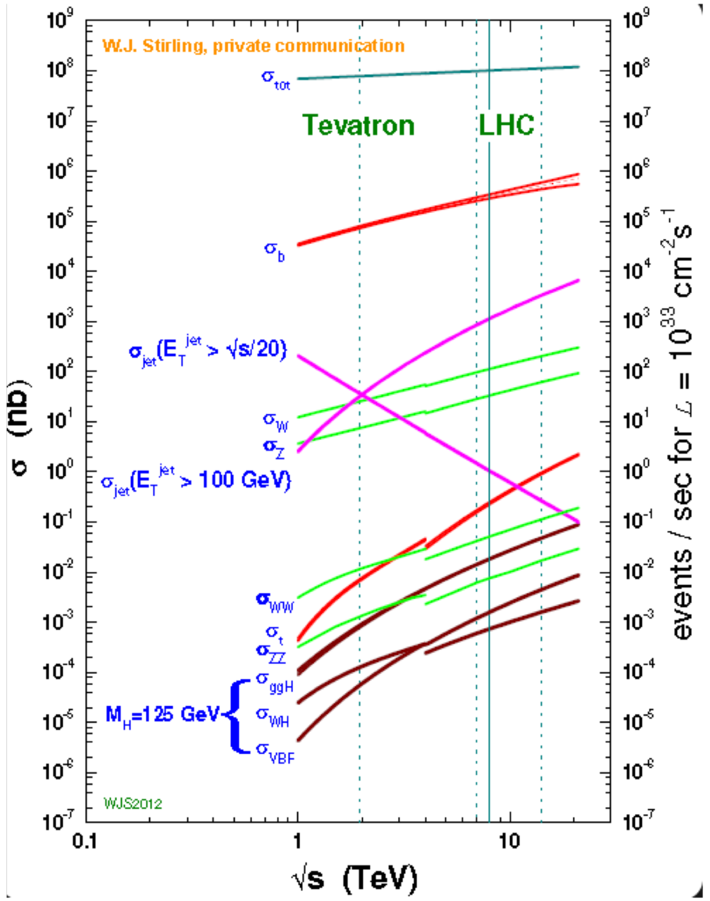
- For physics studies, and to make a physics case, *machine parameters*, and estimates of *luminosity* and *backgrounds* are needed for the proposed options
- In addition to "readiness" other major features for classifications considered are:
  - for accelerator builders: *performance* (luminosity reach), *cost* and *power efficiency* (total power);
  - and for particle physicists – *physics reach* (energy) and *detectors* (backgrounds)

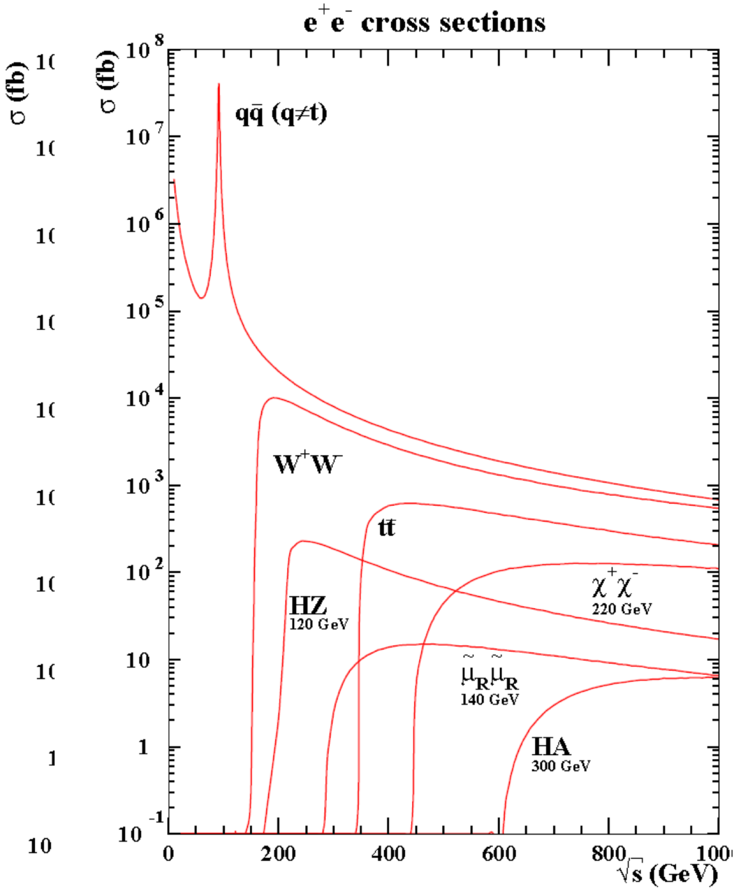
Two possibilities: hadron and lepton colliders

pp → H W/Z is 10⁻⁹ of pp → bb

e+e− → HZ is 1% of e+e− → qq

cross sections

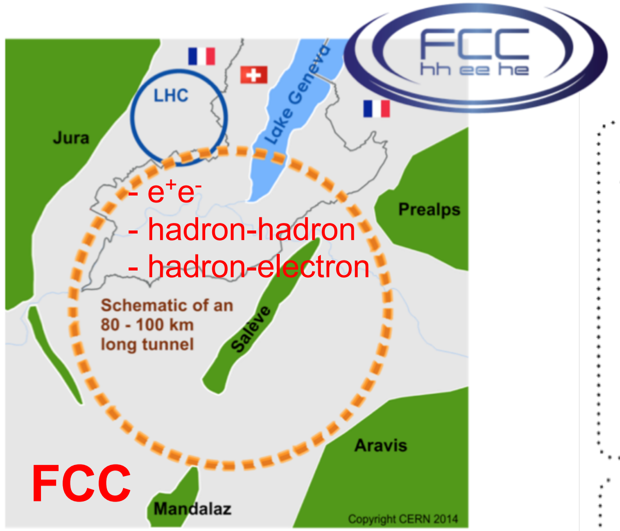




Backgrounds for hadron production are huge. Multi-level triggers must be used and calibrated.

Interesting processes are a large fraction of the total rate. Cross sections can be calculated to O(0.1%) accuracy..

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

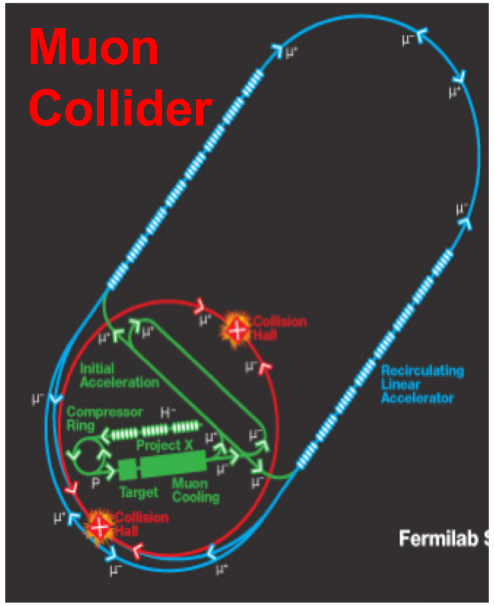
- higher luminosity
- several interaction points
- precise E-beam measurement (O(0.1MeV) via resonant depolarization)
- $\sqrt{s}$ limited by synchroton radiation

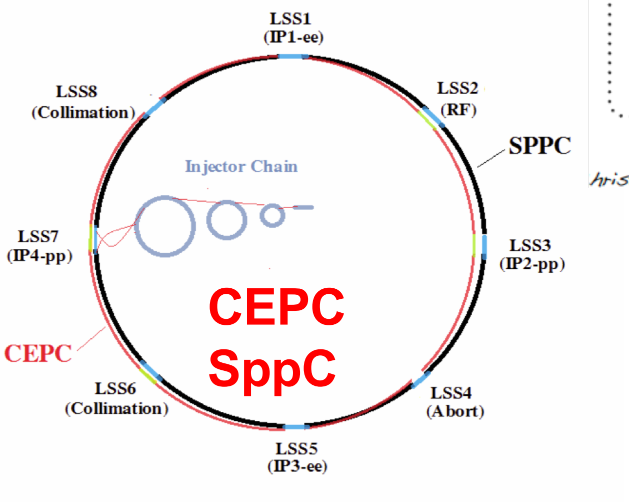
Linear

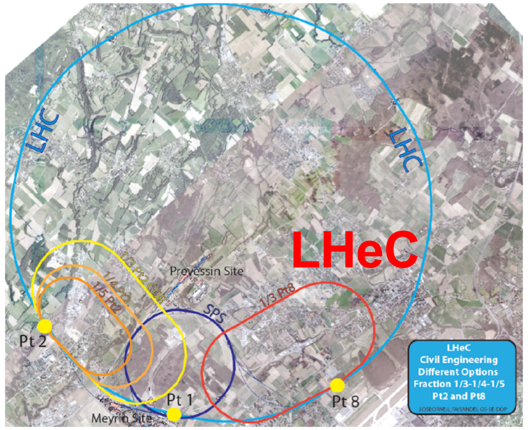
- easier to upgrade in energy
- easier to polarize beams
- "greener": less power consumption*
- large beamsthralung
- one IP only

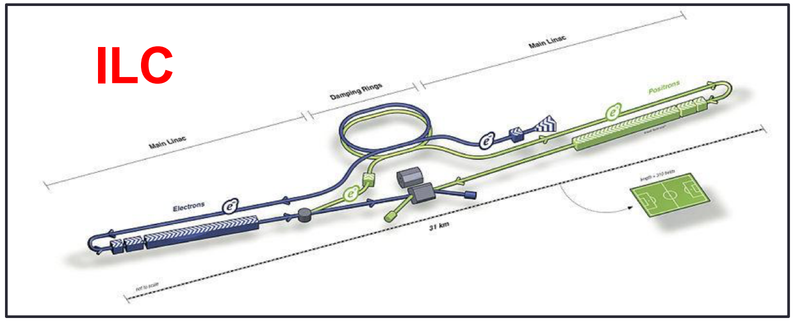
*energy consumption per integrated luminosity is lower at circular colliders but the energy consumption per GeV is lower at linear colliders

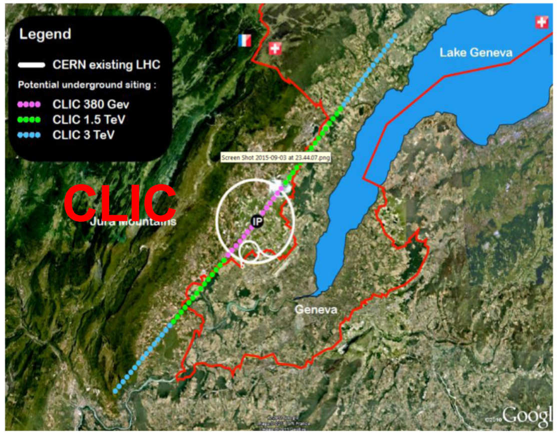
hristophe Grojean — Future Measurements — 9 — Inst. Pascal, Dec. 4, 2019











gamma-gamma colliders?

HL-LHC – projected to start operation 2026+

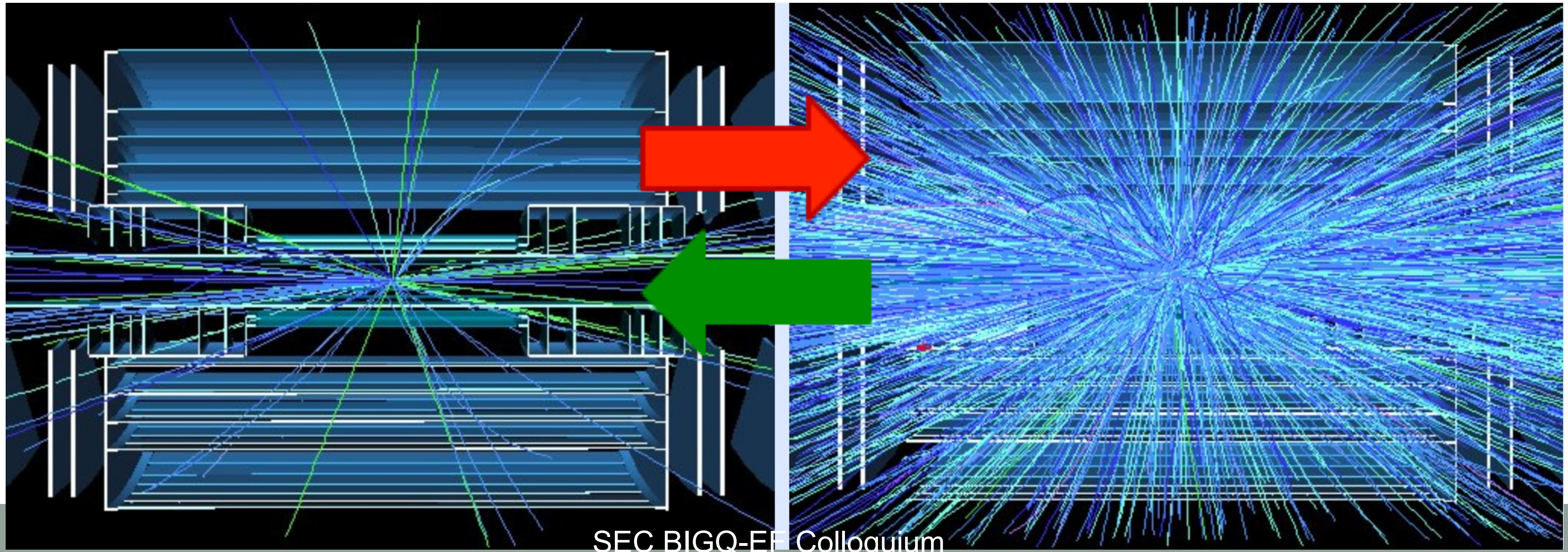
- A major upgrade to the LHC complex to increase its luminosity by a factor of 10 beyond its design value.
- A peak luminosity of **5×10^{34} $cm^{-2}s^{-1}$ with levelling,** allowing:
  - An integrated luminosity of **250 fb^{-1} per year**, enabling **3000 fb^{-1}** twelve years after the upgrade
- As a highly complex and optimized machine, such an upgrade requires about 10 years to develop and implement.

- This upgrade relies on a number of key innovative technologies, representing exceptional technological challenges:
  - cutting-edge 13 Tesla superconducting magnets,
  - very compact and ultra-precise superconducting cavities for beam rotation,
  - and 300-metre-long high-power superconducting links with zero energy dissipation

Environment at a hadron collider: e.g. HL-LHC

- Collisions of composite particles, strong interaction
  - interacting partons are distributed in momentum within the beam particles,
- Background events due to strong interactions are large:
- Signal to background for interesting events is small.
- Require sophisticated trigger to select interesting events.
- 100's of particles produced: event reconstruction is a challenge.
- Large event rate leads to event pileup
- Large radiation dose.

25 pileup



200 pileup

Environment at a linear collider: e.g. ILC

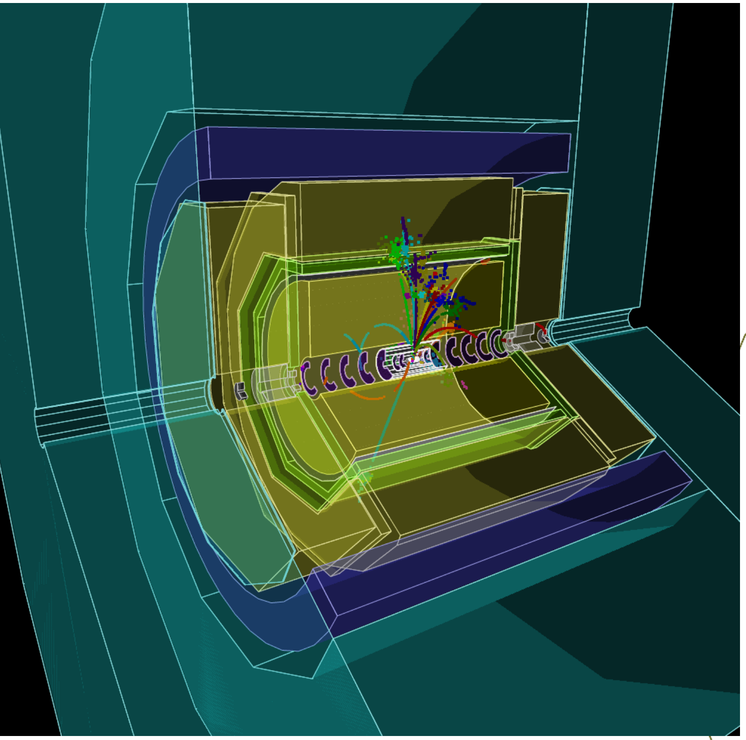
- Collisions of point-like particles, electroweak interaction
  - The partonic collision energy in e+e− is thus nearly a δ-function at $2E_{beam}$
  - polarization of e+ and e- possible .

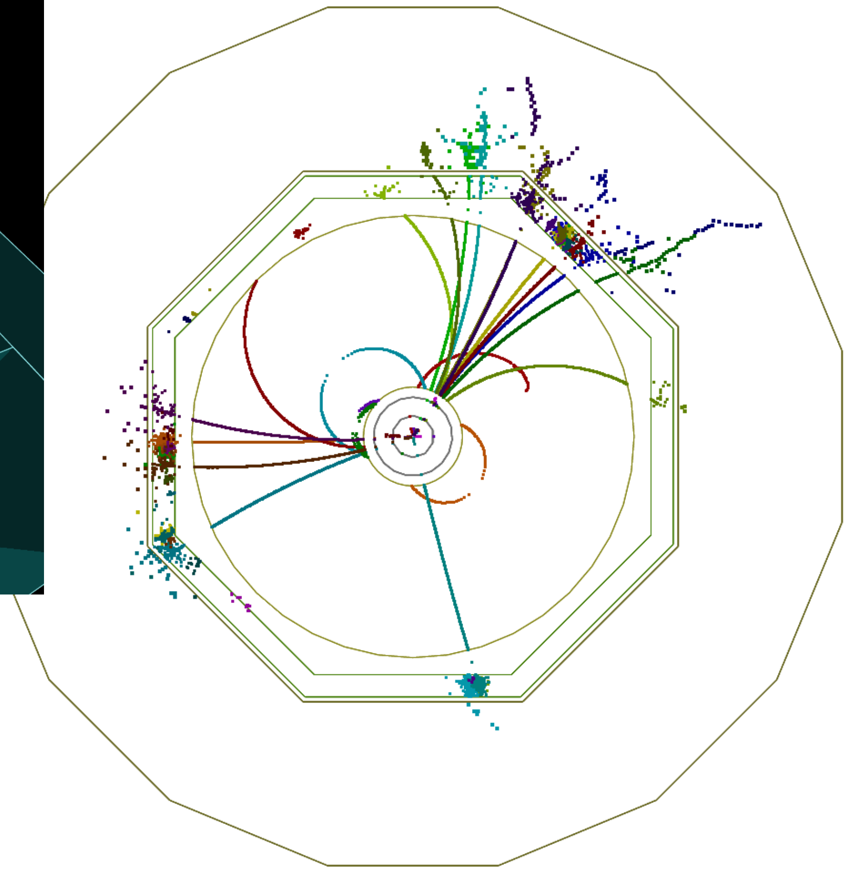
- Compared to hadron colliders, the events are "clean"
  - one observes just the hard process, without extra particles produced in the primary collision, and without pileup from additional collisions during the bunch crossing
- Rate of collisions is rather low (good for backgrounds, bad for high statistics studies), and number of produced particles is typically small.
  - Total e+e- annihilation XS (500 GeV) = 5 pb
  - e+e- → ZZ cross section = 1 pb
  - e+e- → ZH cross section = 0.05 pb
- Signal to background for interesting events is large.
  - at high energies, right- and left-handed fermions are distinct particles, one can enhance signal processes or suppress backgrounds by appropriate choices of beam polarization.

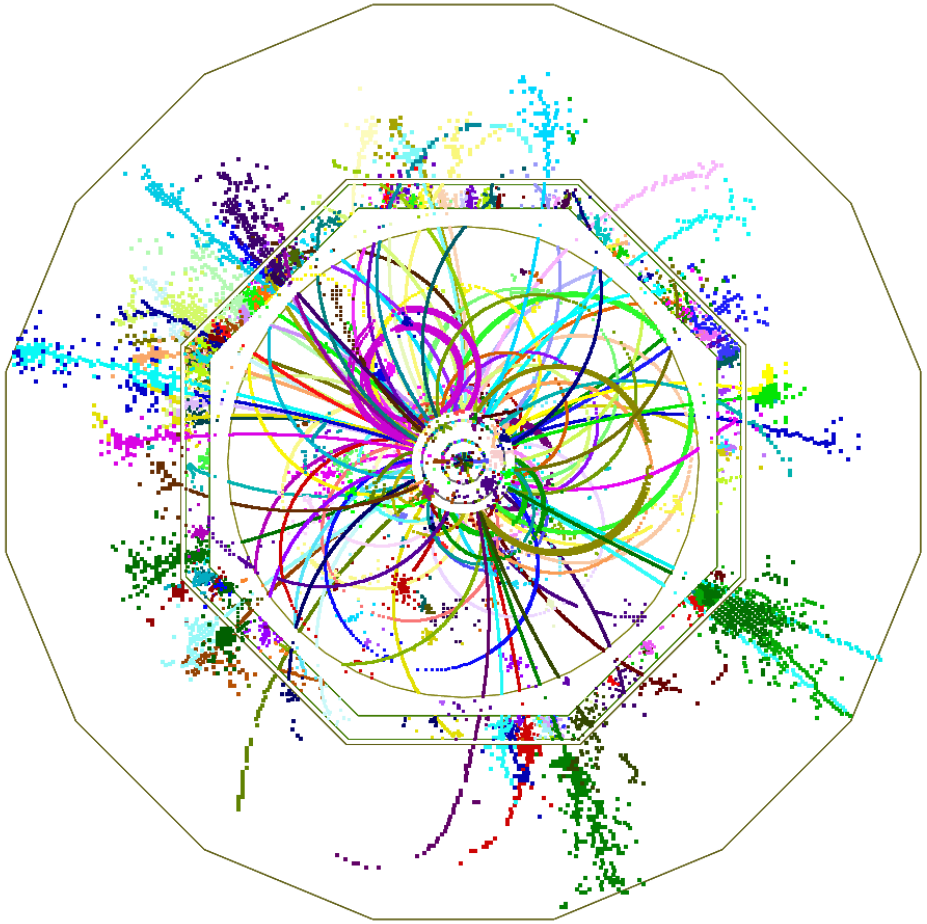
ILD simulation

$\sqrt{s} = 250$ GeV: $e^+e^- \rightarrow$. $Zh \rightarrow e^+e^- h$

$\sqrt{s} = 1$ TeV: $e^+e^- \rightarrow tth$, $tt \rightarrow 6q$, $h \rightarrow bb$







Instrumentation

- Understand the impact of detector designs on physics
  - Conversely study the improvement of physics sensitivity as function of a detector parameters
  - The detectors must maintain excellent precision and efficiency for all basic signatures
  - This performance has to be maintain over an immense range of momentum and angle because the detectors must excel at measuring both the relatively low energy decay products of the Higgs boson and the highest energy particles ever produced at an accelerator
  - For example: the 100 TeV pp collider will produce particles with momenta between a few GeV and 20 TeV over $0<|\eta|<6$.
    - **These momentum and angular ranges are ten times and twice those achieved at the LHC!**

- The proposed collision energies and data rates of the next generation of EF colliders impose unprecedented requirements on detector technology.
- A few examples motivated by Higgs physics at future colliders, which were considered for the DOE Basic Research Needs (BRN) exercise for future instrumentation
  - Low-mass, high-granularity, radiation-hard, tracking detectors with picosecond timing
  - High-granularity, radiation hard, imaging calorimeters with picosecond timing
  - Integrated high-bandwidth, low-latency, ML-ready trigger and readout

Example: Requirements for detectors from Higgs Physics

- Technical requirements mostly from existing detector proposals.
- Technical requirements drive technology development
- We should develop further the technical requirements from Physics assessments
  - Is the physics sensitivity limited by a given detector parameter?
  - Work with Instrumentation Frontier to understand the constraints and future technology directions which may improve on the detector performance parameters.

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	**18**, **19**, **20**, **23**
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e^- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	**16**, **17**, **18**, **19**, **20**, **23**, **26**
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of 0.5×0.5 cm^2, hadronic cells of 1×1 cm^2 TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	**1**, **3**, **7**, **10**, **11**, **23**
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e^- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\text{n}_{\text{eq}}/\text{cm}^2$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	**1**, **2**, **3**, **7**, **9**, **10**, **11**, **16**, **17**, **23**, **26**
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	**16**, **17**, **21**, **26**

from DOE Instrumentation BRN

BIG QUESTIONS FROM THE ENERGY FRONTIER

Snowmass 2021

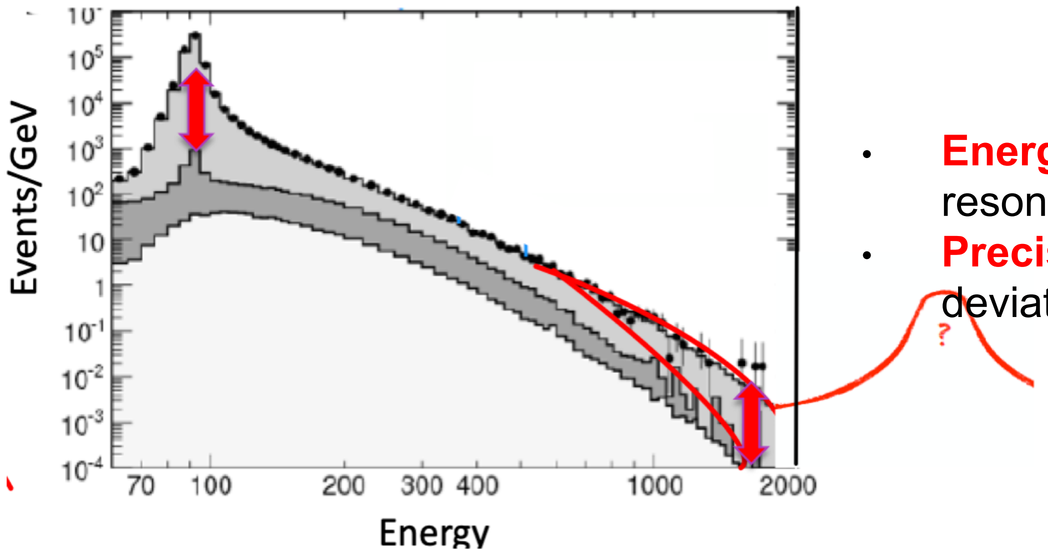
European Strategy for Particle Physics

Ongoing Physics Studies

- Strong physics case for each of the future colliders is needed, including pros and cons for each of them.
  - also to convince the funding agencies
  - however, keep in mind that directions may change as discoveries are made along the way
- HL-LHC studies documented in TDRs, lots of R&D, will start pre-/production soon.
- Studies for linear colliders documented in TDRs since ~ 15 or 20 years, regularly updated. Recently detector designs being updated, workshop on potential experiment was held.
- FCC-ee, CepC studies are in a mature state.
- FCC-hh, SppC, and FCC-he studies started also about ~10 years ago .
- Muon collider studies have made considerable progress in the last year.

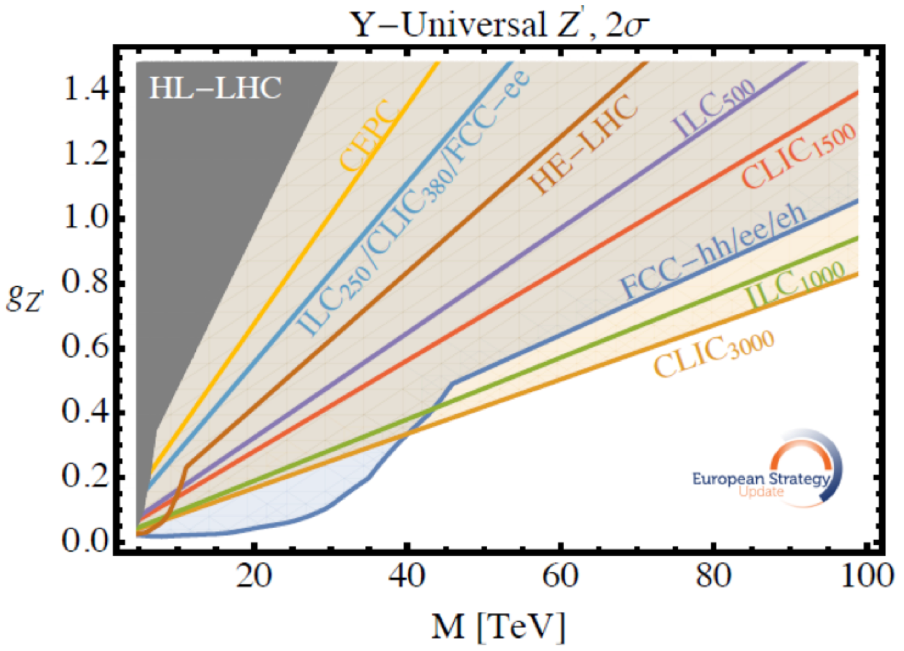
Higgs, Electroweak, Top and QCD sectors

- The scale of New Physics can be probed with direct searches and precision measurements
  - *Precision needed in SM Higgs measurements* to probe BSM physics scenarios?
  - *What theory calculations are needed* to enable the theory precision to match the projected experimental precision of future measurements?



- **Energy:** direct access to new resonances
- **Precision:** indirect evidence of deviations at low and high energy.

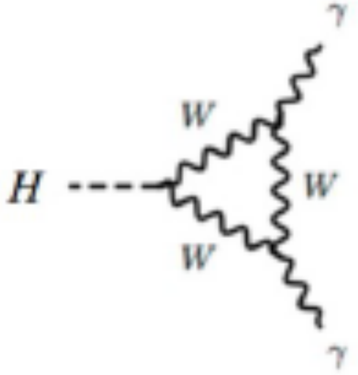
Benchmark: simple sequential Z' mode



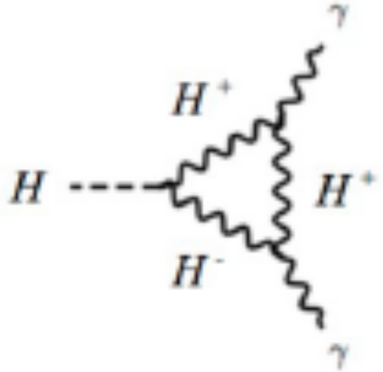
low energy: Higgs couplings, Z-pole, ... better studied
high-energy: EFT effects (enhanced), new resonances, ...less studied
High and low energy are complementary, and
they both need theoretical accuracy at the percent level or less.

Effects of New Physics in Higgs Couplings

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:



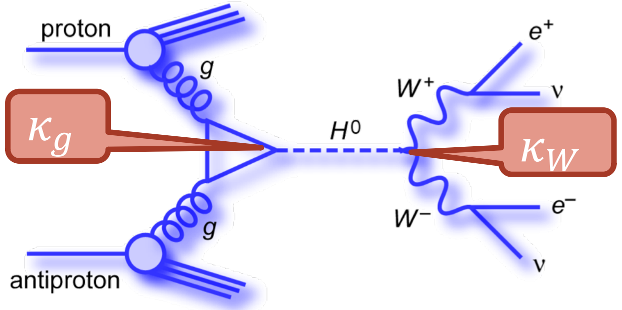
H^+, H^- : hypothetical particles (part of extended Higgs sector)

- 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

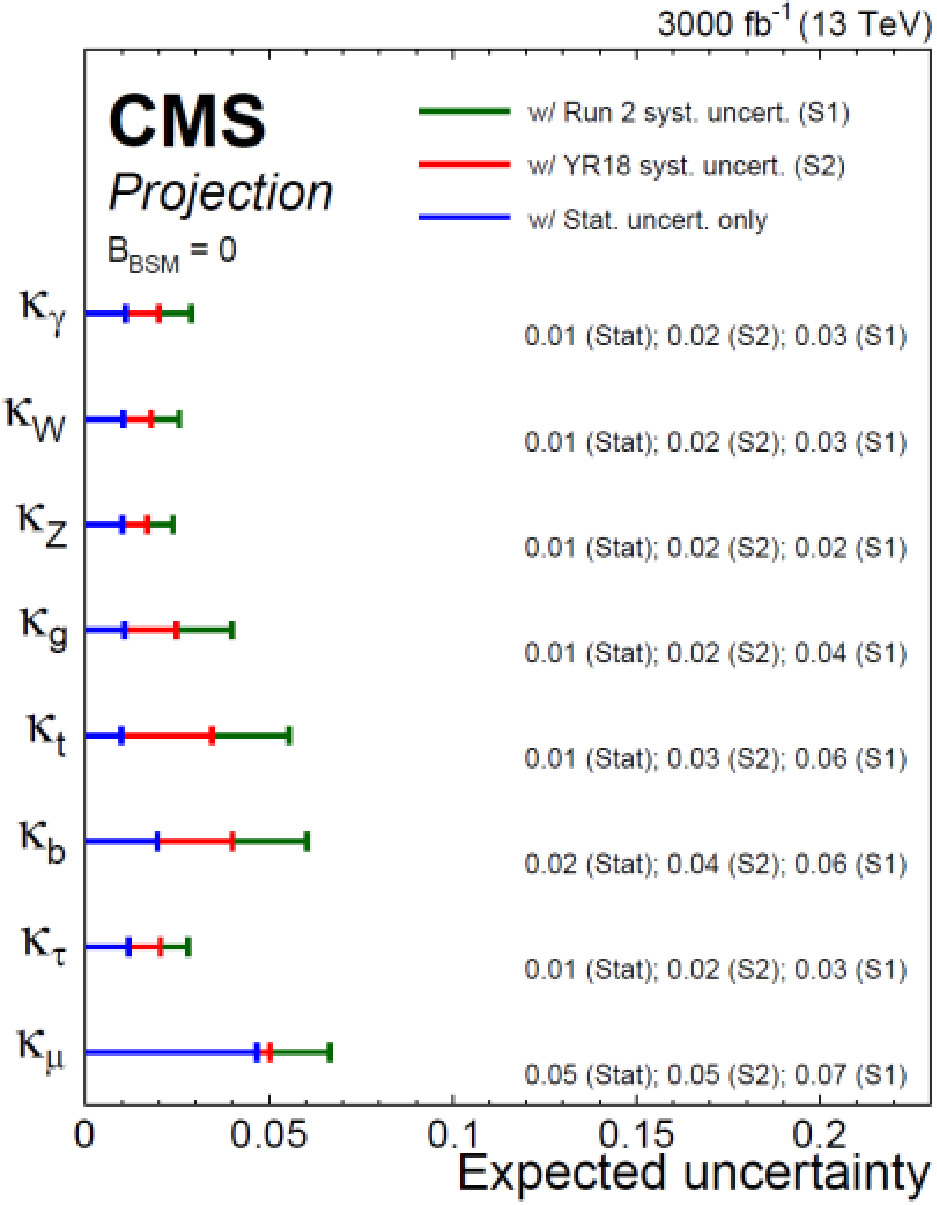
gg→h→WW: $\sigma B \propto \frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$



- 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

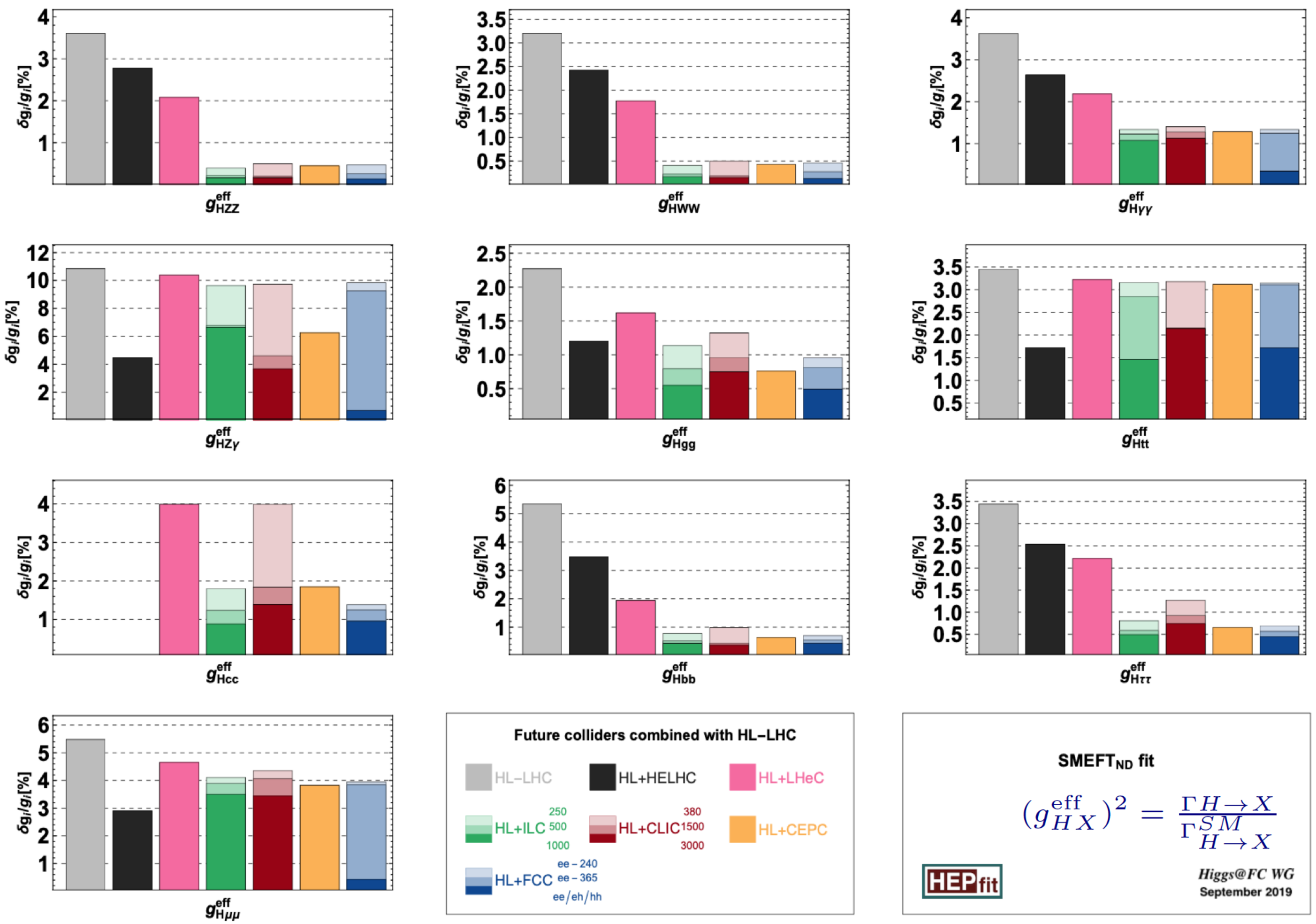
- Currently κ's are typically measured to ≈20%.
- Expected deviations from SM predictions by various models predicted to be between 1-10%.

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



Higgs, Top, EW

Coupling interpretations of precision Higgs measurements



$$(g^{\rm eff}_{HX})^2 = \frac{\Gamma_{H\to X}}{\Gamma^{SM}_{H\to X}}$$

- Stress-testing the Higgs sector
- **Sensitivity to new physics: higher precision probes higher scales**

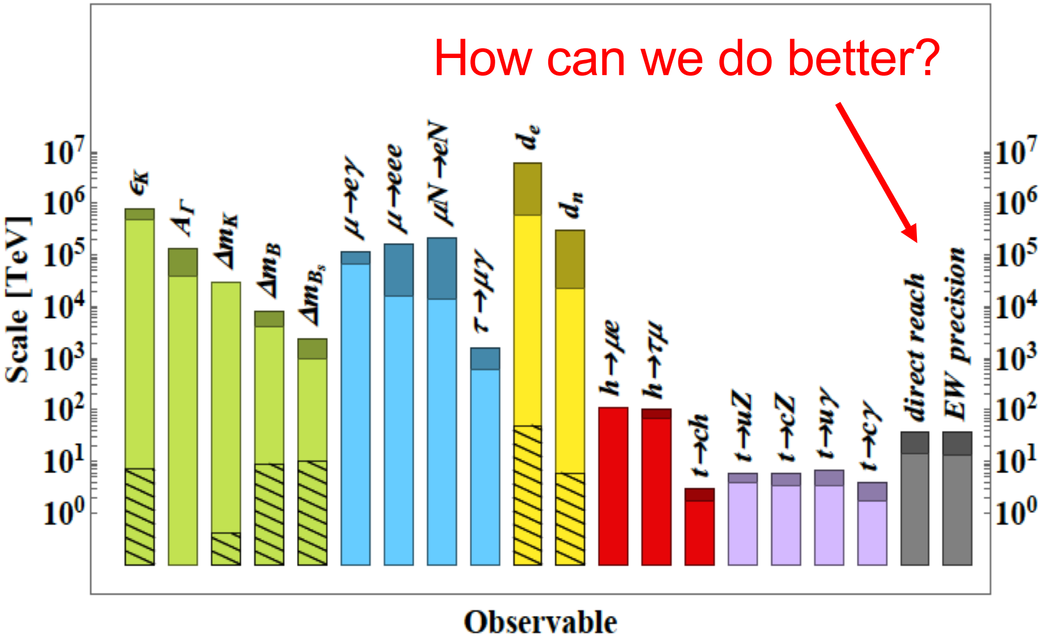
- Future colliders under consideration will improve the understanding of the Higgs boson couplings wrt HL-LHC - 0.5 - few%
  - At low energy top-Higgs coupling is not accessible at future colliders
  - HL-LHC does not yet probe Higgs-charm
  - Couplings to μ , $Z\gamma$ benefit the most from the large dataset available at HL-LHC and not really improved at future colliders

probing EWSB → Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings

Probing the energy scale for new physics

Reach in new physics scale from generic dim-6 operators

Probing the energy scale for new physics



Complementarity with other Frontiers

While slow at the start, the energy frontier is ultimately needed to "win the race"

Patrick Meade

Nevertheless if we get indirect hints from existing

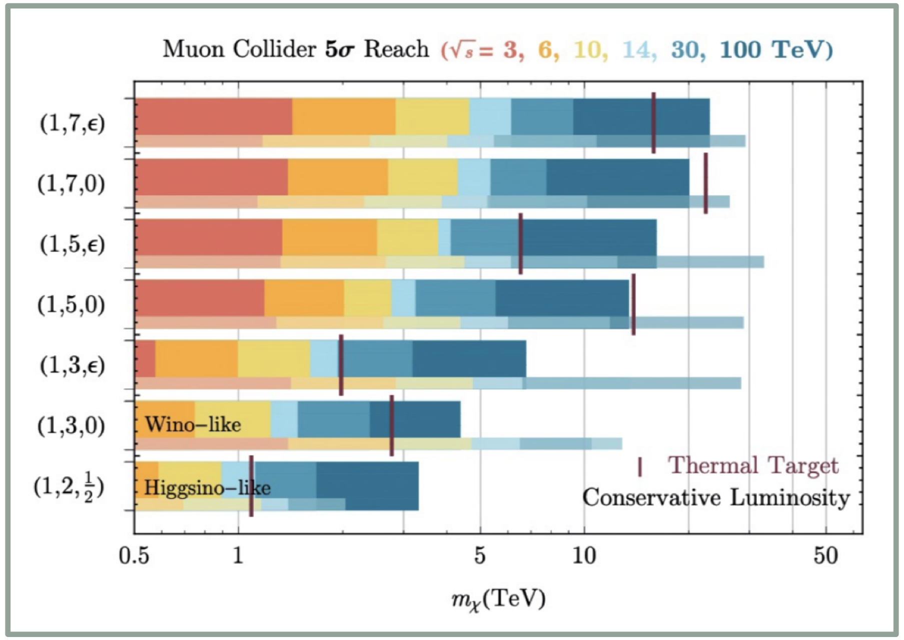
or planned experiments its important to know how to test them!

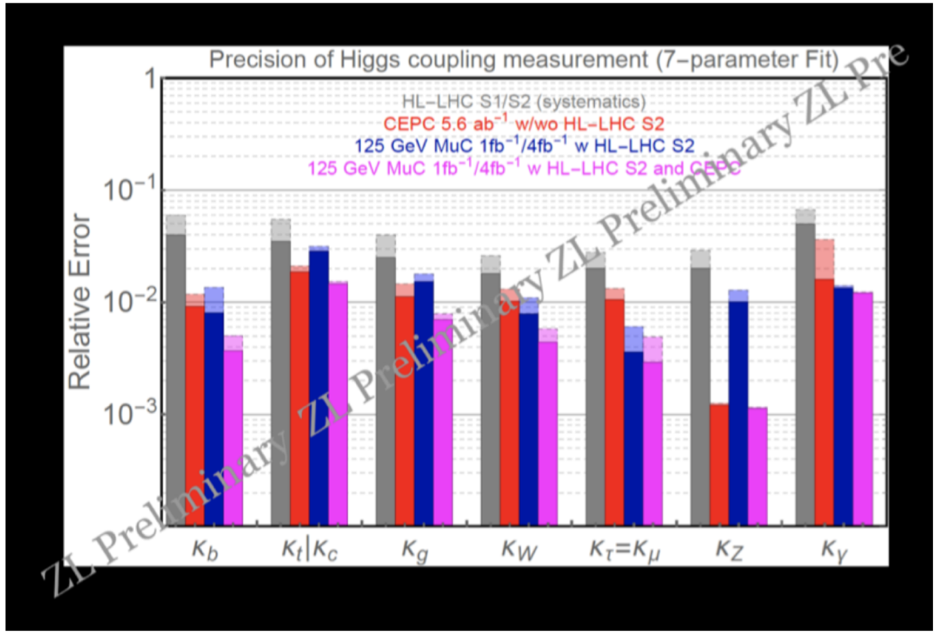
Gravitational Waves, Astrophysics, Dark Matter, Rare Processes

- **Collider reach much broader**: needed to test models across the spectrum of all collider observables
- **Unique complementarity** between elecrroweak precision fits and flavor observables.

Muon Collider: Physics Highlights

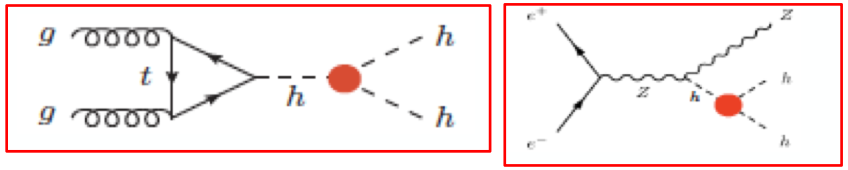
- High energy muon collider (6-10 TeV and above) has an incredible physics reach:
  - Precision Standard Model studies (including detailed exploration of the Higgs boson)
  - Access to trilinear and quartic (at higher energies) Higgs couplings
  - Searches for BSM with sensitivity way beyond what is achievable at the LHC and rivaling FCC-hh
    - Does 125 GeV Higgs Factory make sense as a staging option?
      - Improved luminosity projections with new technology advancements translates into better physics
      - Small footprint and modest cost (tbd), physics while the multi-TeV ring is being built, reuse the injection complex



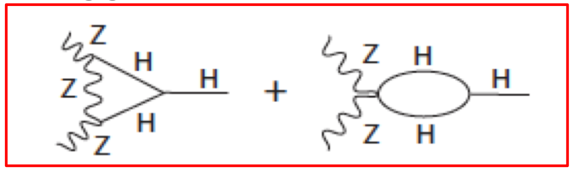


The ultimate goal: measuring the Higgs potential

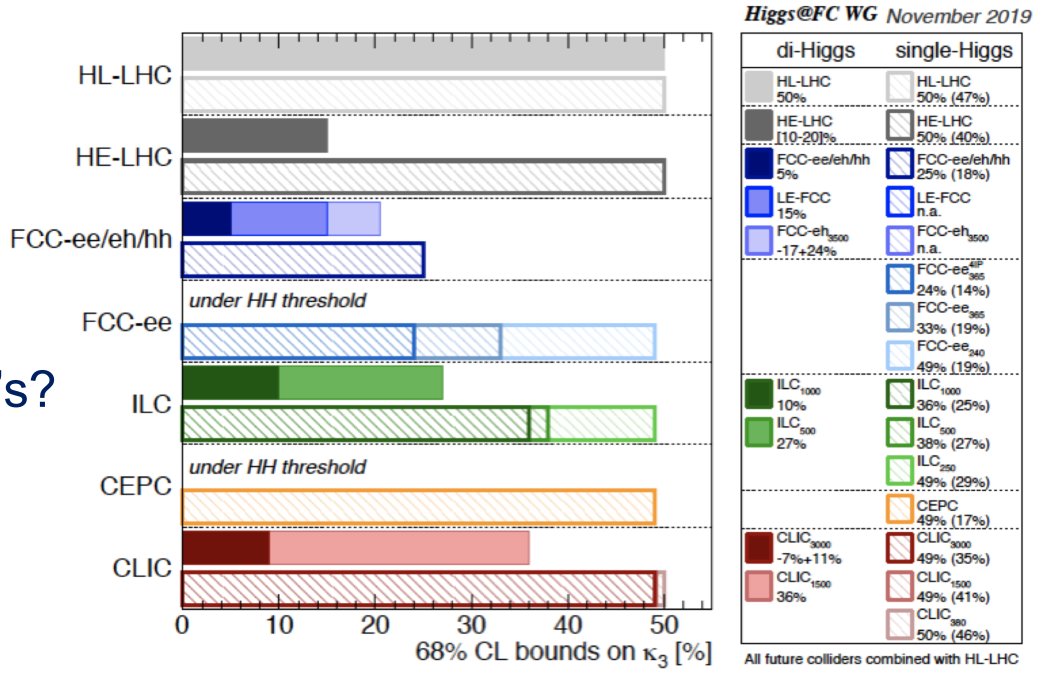
Double Higgs production



Single Higgs extraction via loop corrections



- Does the Higgs boson result from the *SM scalar potential*?
- How to improve *double Higgs and single Higgs* production measurements to better probe the potential?
- Future colliders will improve the understanding of Higgs couplings wrt HL-LHC (0.5 - few%) and λ_3 to the 5-10%
- What experiments allow greatest precision on λ_3, λ_4 Yukawa's?



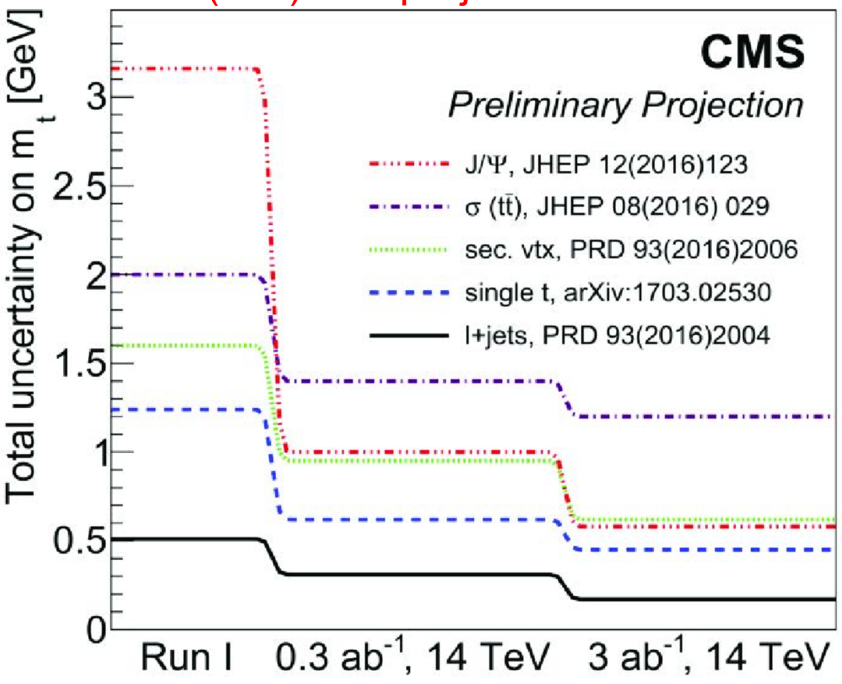
Precision Needed in Higgs Self-Coupling *ArXiv:1910.00012*

100%: sensitivity to models with largest new physics effects (few hundred GeV masses)
50%: establish that $\lambda_3 \neq 0$ at 95%CL *(expected HL-LHC reach)*
25-50%: sensitivity to mixing of Higgs boson with a heavy (1 TeV) scalar
1-10%: sensitivity to loop diagrams effects (e.g. light stop) and quantum corrections to Higgs potential

Top sector

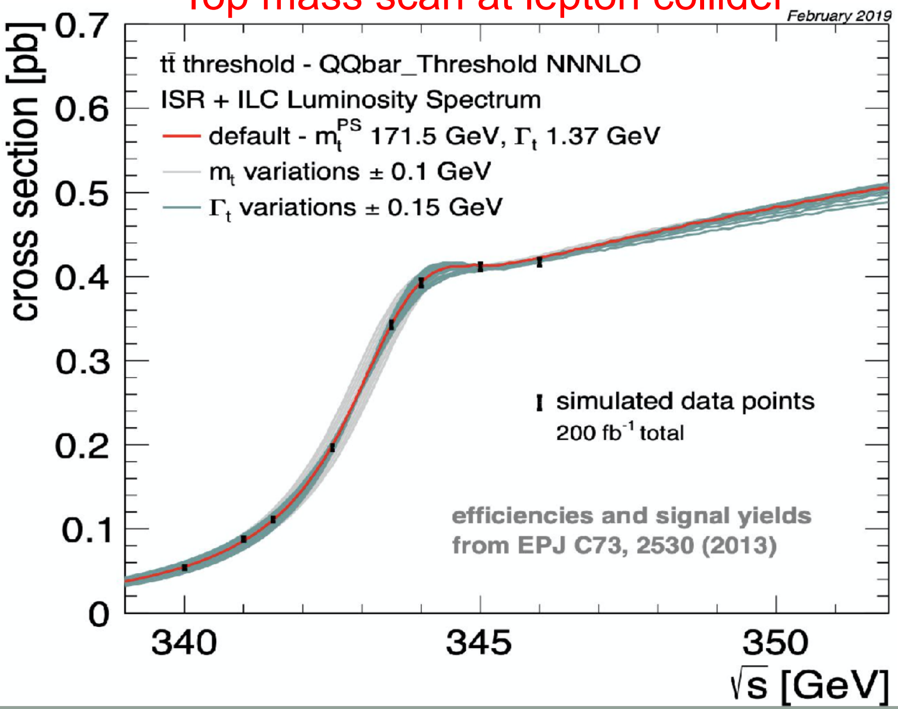
- How can the *top quark* help elucidate the *Higgs sector* and inform about possible BSM physics?
  - What is achievable/required precision for top-quark properties: m_{top} and *couplings*, *spin correlations*, *asymmetries*, *polarization* in new kinematic regimes
  - How much does it improve the reach of a *global EW precision fit*

(HL-)LHC projections



precision of ~200 MeV

Top mass scan at lepton collider

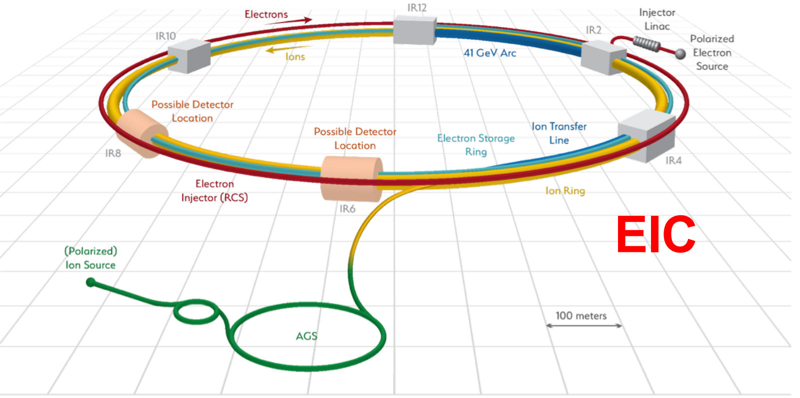


precision of ~50 MeV

QCD and Strong Interactions

- Precision QCD, Forward Physics and interplay with EW physics
  - What is the ultimate precision for α_s and how do we achieve it?
  - What theoretical developments are needed to support precision measurements of Higgs and top quark production and properties (including EW corrections, non-perturbative effects)?
  - *Prospects of running forward detectors* at the HL-LHC and at future hadron colliders? What will be their *sensitivity to anomalous couplings between photon, W, Z bosons, top quarks*.

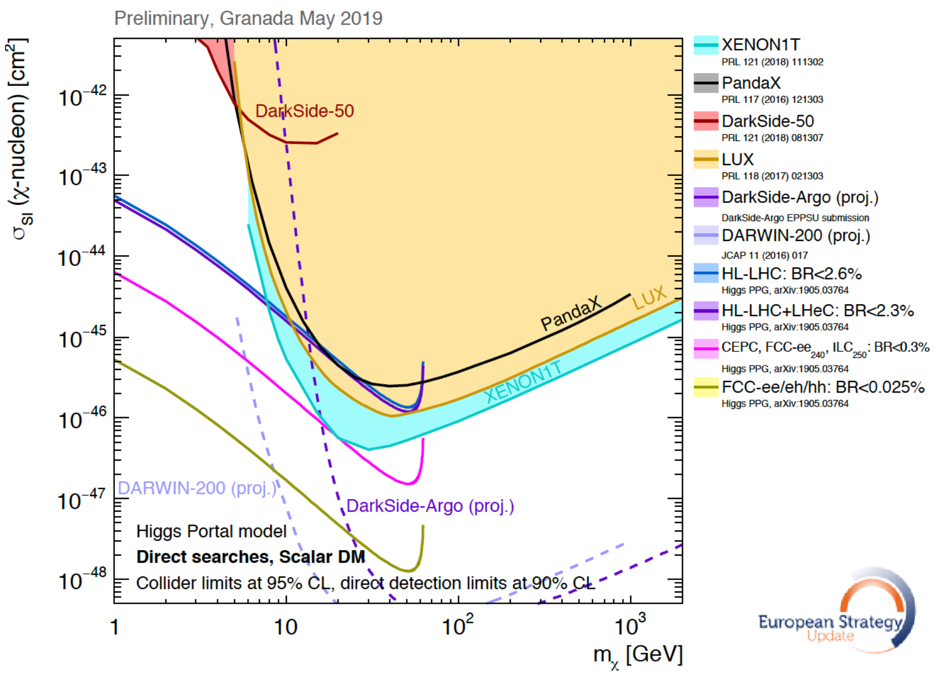
- Hadronic structure and Heavy Ions
  - Synergies between EIC, proton PDF fits, and LHC pheno
  - How do *excited hadronic states* with heavy quarks form and decay?
  - What are the *BSM connections for hadron spectroscopy and heavy Ions* at future facilities? connection to *new physics search at forward region and the studies of cosmic rays?*
  - What can we learn from *the jet and jet substructure* measurements about the nature of the *quark-gluon plasma*?

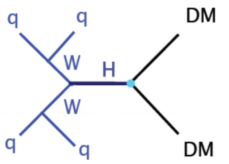


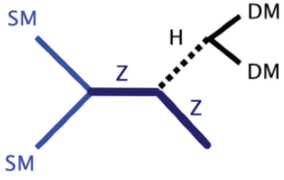
WIMPs and lighter DM at future colliders

- Work in collaboration within EF and Cross Frontier with Cosmic Frontier
- Complementarity within WIMP frameworks

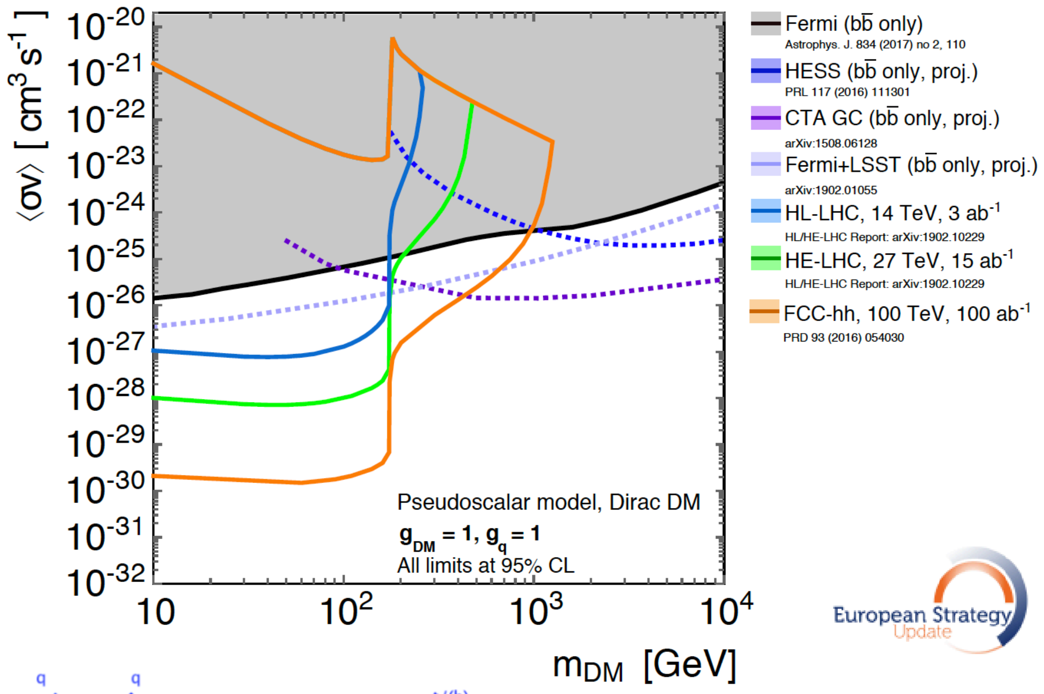
Invisible Higgs @ colliders and direct detection

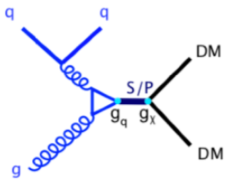


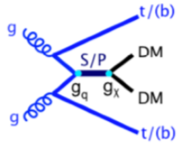




Scalar mediators and indirect detection

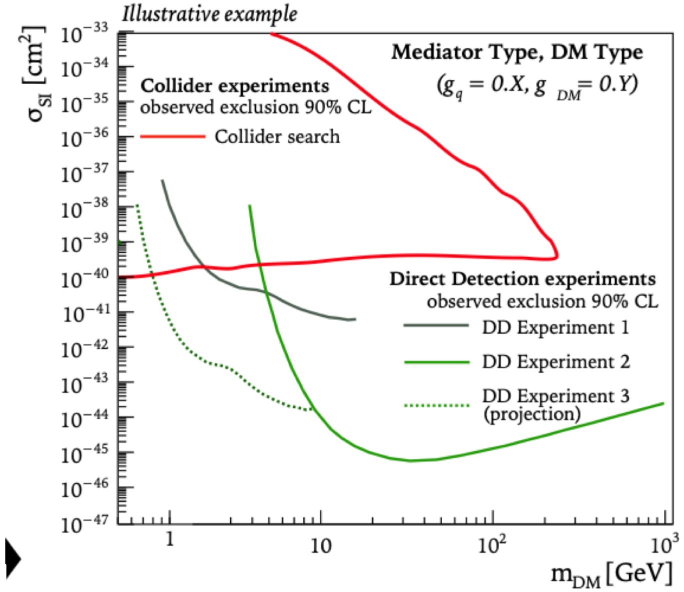


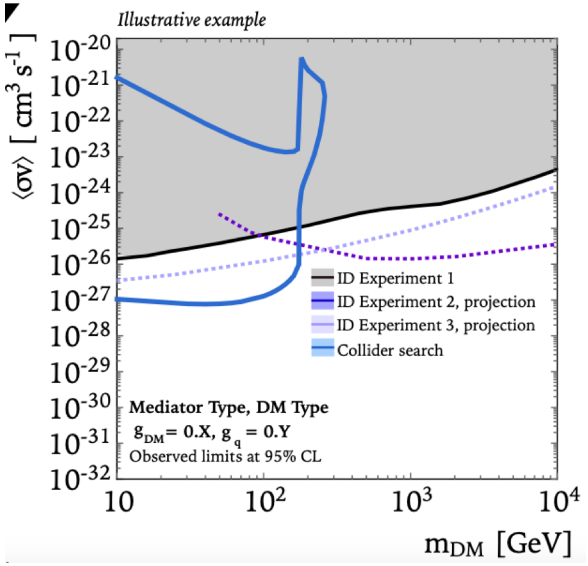




WIMPs and lighter DM at future colliders

- Work done within EF10 towards whitepaper was written up in Boyu Gao's thesis (Undergraduate @ OSU → Graduate school @ Duke):
  - Link to thesis: https://kb.osu.edu/handle/1811/92563
- Recruiting new members (with the help of SEC Matt LeBlanc and Grace Cummings) to compile list of DM @ collider curves for summary plots and update European Strategy ones if needed:



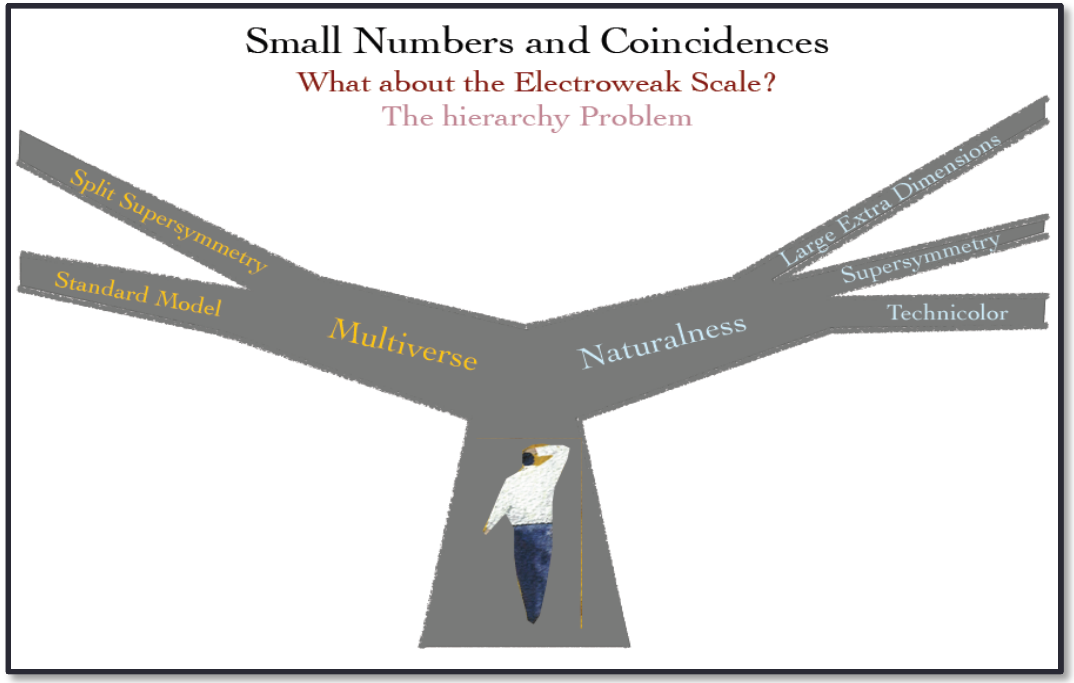


- Work also will include the planned DMWG whitepaper (and discussion with other Frontiers) on lowering the couplings for the simplified models used by the LHC

Tension w/ Naturalness?

What IF after all of these very high energy colliders we observe:

- Only Higgs and nothing else at ~O(1 TeV) → 1% fine-tuning
- Only Higgs and nothing else at ~O(10 TeV) → 10^{-4} fine-tuning



Savas Dimopoulus, CFHEP, 1st workshop

OUR DREAM….

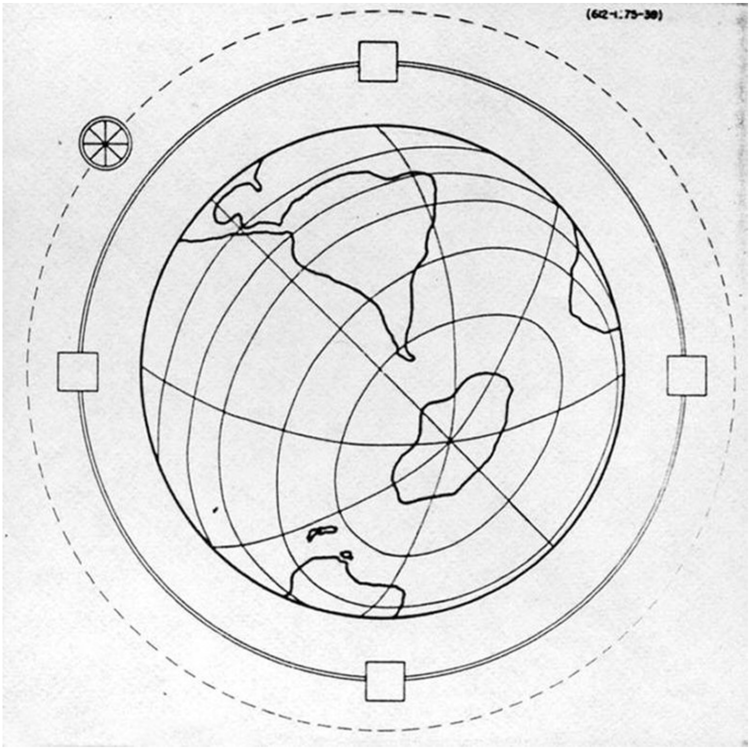
Snowmass 2021

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

Snowmass is our time to think BIG, innovate and set new directions without barriers and constraints set by our collaborations.

The Globatron
Energy: 5000 TeV collider
Cost: 170B USD(1954)
To be built by 1994



As we continue to "Dream"..

- The future of the Energy Frontier in the U.S and internationally is up to us!
- A large international effort to advance an energy frontier machine:
  - We definitely need **a Higgs Factory** as the next step after HL-LHC
    - A few options: ILC, CLIC, FCC-ee, CepC, & C^3…
  - We should continue to develop ideas and plans for R&D for a **"High Energy Discovery Machine"** after the Higgs Factory
    - A few options: FCC-hh @ 100 TeV, SppC @100 TeV, Muon Collider @?? TeV
- 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 EF conveners: Laura Reina and Alessandro Tricoli
- to all the EF topical group conveners and liasions

- 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.linearcollider.org/
- CLIC: https://home.cern/science/accelerators/compact-linear-collider
- CepC, SppC: http://cfhep.ihep.ac.cn/
- FCC: https://fcc.web.cern.ch/Pages/default.aspx
- C^3: https://arxiv.org/pdf/2110.15800.pdf