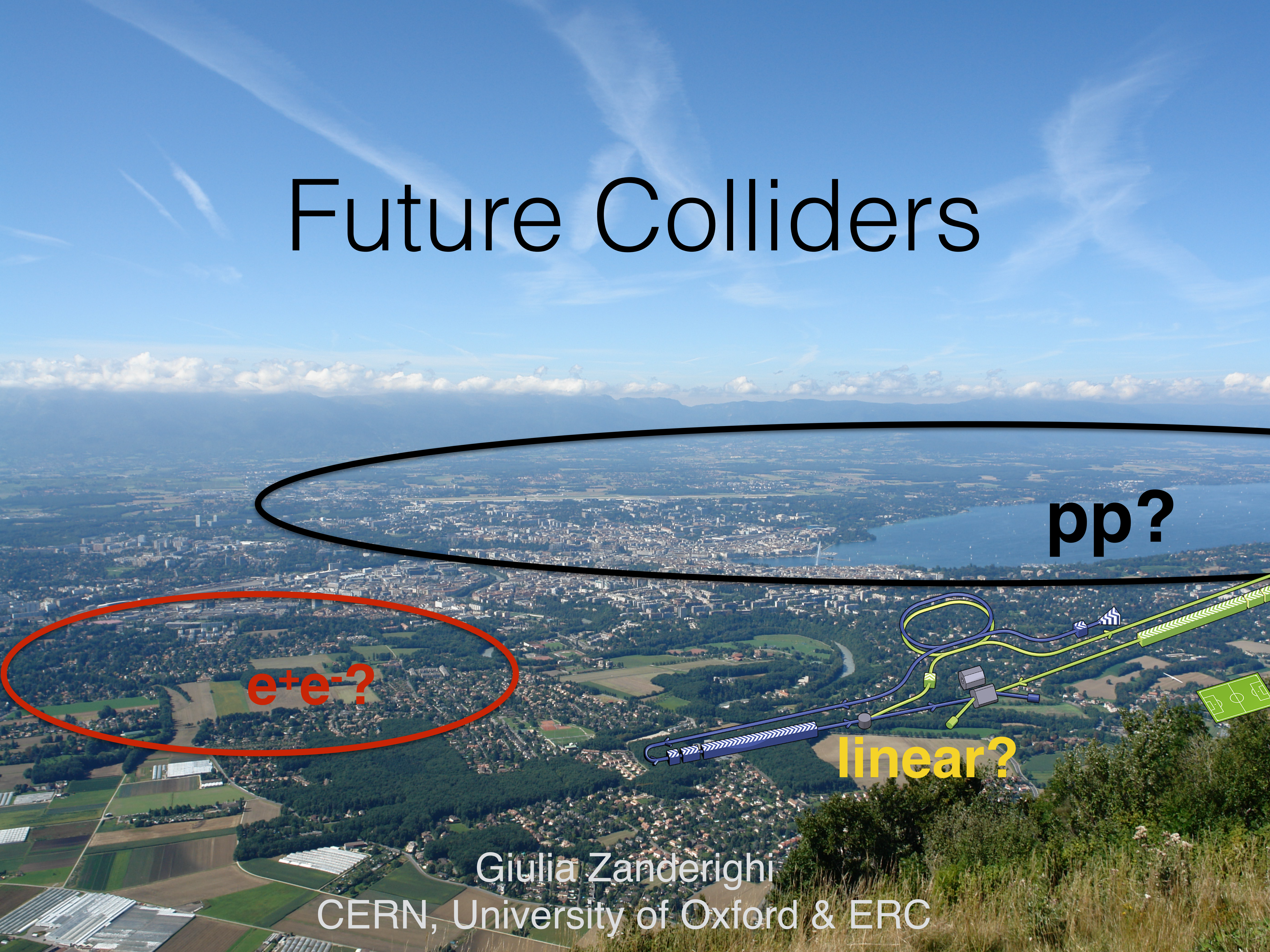
Future Colliders

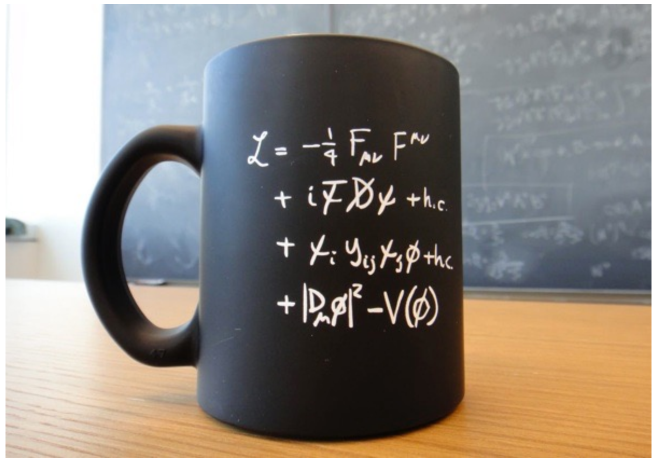


Giulia Zanderighi
CERN, University of Oxford & ERC

Outline

- The present questions in particle physics
- How can the LHC and future collider experiments address them

Where we are now



- With the discovery of the Higgs boson, Standard Model is complete

- SM has been tested with very high precision (wealth of different measurements):
  - ➡ it works beautifully
  - ➡ no significant deviation *at colliders*

- However we know that the SM is not a complete theory as many outstanding questions remain, both theoretical issues and questions raised by experimental observation

Open questions today

My top 10 questions:

- is the Higgs mass natural or fine-tuned? (If natural, what is the new physics/symmetry?)
- what is the nature of Dark Matter?
- why are fermion masses so different?
- what resolves the strong CP problem (CP=Charge Parity)?
- what is the origin of matter-antimatter asymmetry?
- what is the origin of neutrino masses?
- how is gravity connected to other forces?
- do forces unify at high energy?
- what is the physics associated to the vacuum energy?
- are these the good questions to ask …?

Some questions driven by experimental data (have an answer), most driven by theoretical curiosity and ambition (might have an answer)

Approaches to these questions

	High-Energy Colliders	High-precision experiments	Cosmic surveys	Dedicated experiments
Higgs, EWSB	X			
Dark Matter	X		X	X
New particles New forces	X	X		X
Neutrinos	X			X
Flavour CP violation	X	X		X
Dark energy			X	

Approaches to these questions

	High-Energy Colliders	High-precision experiments	Cosmic surveys	Dedicated experiments
Higgs, EWSB	X			
Dark energy			X	

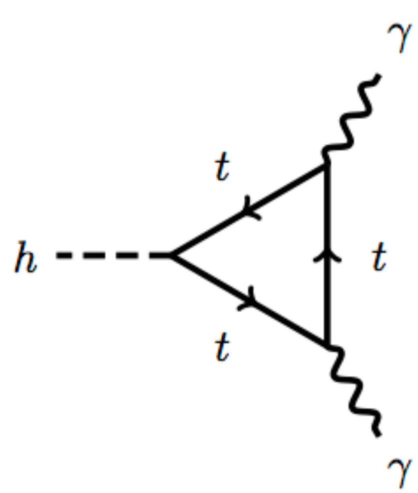
A combination of all approaches crucial to explore the large range of energy scales and phenomena, to interpret hints from experimental data and, ultimately, to build a coherent picture of the underlying theory

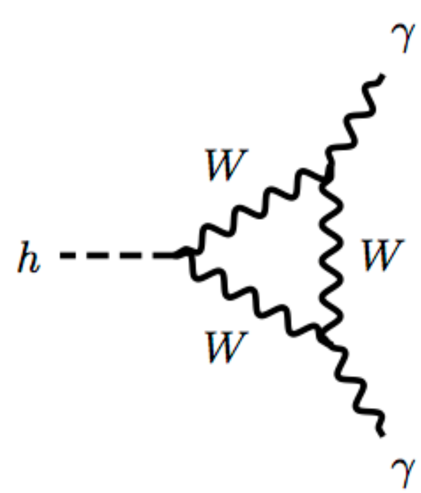
Searches

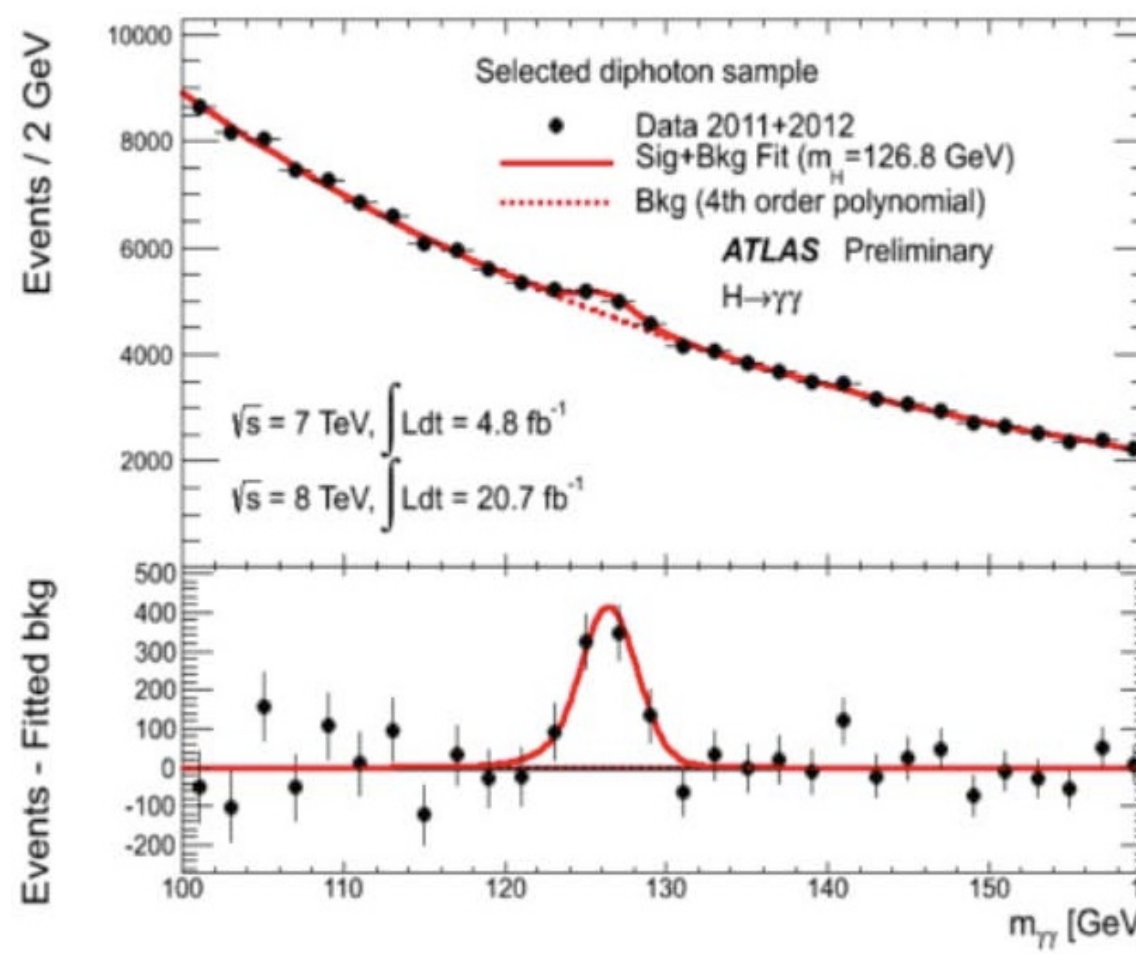
Three main complementary ways to look for New Physics

1. Direct production: production of (onshell) new particles. Typically seen through their decay products (peak in invariant mass distribution of decay products)

<u>Example: Higgs</u>





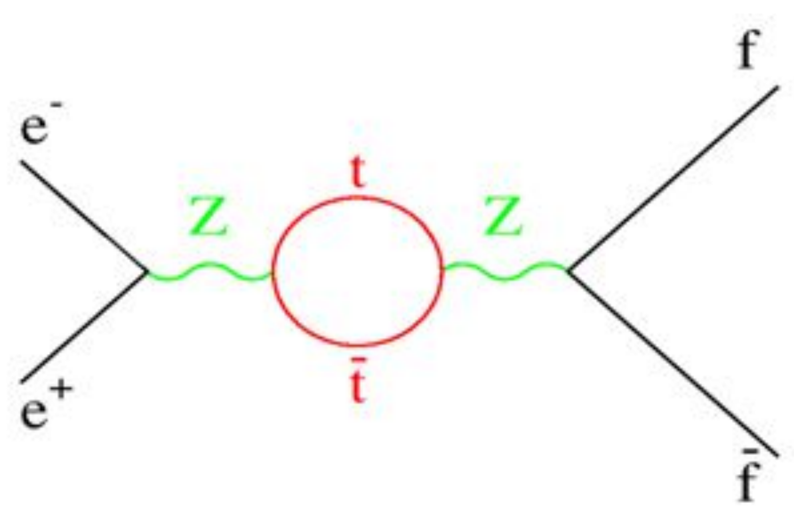


Searches

Three main complementary ways to look for New Physics

2. Indirect searches: look at deviations from SM predictions due to quantum loop effects of virtual new particles circulating in a loop.

Example: top



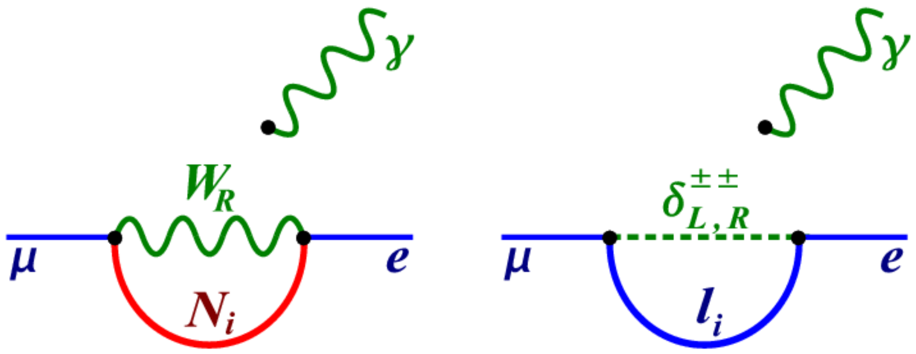
- Mass of the top quark from indirect determinations at Lep1 and SLC in 1993: m_{top} = 177 ± 10 GeV
- First direct production at the Tevatron in 1994: m_{top} = 174±16 GeV

Searches

Three main complementary ways to look for New Physics

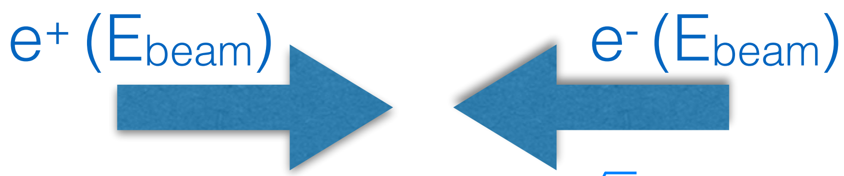
3. Rare processes: some decays are forbidden or extremely suppressed in the SM. New Physics can lift the suppression and give rise to branching ratios that are much larger than in the SM. Typically these searches involve high intensity beams and very sensitive detectors

Example: μ → e γ gamma conversion experiment

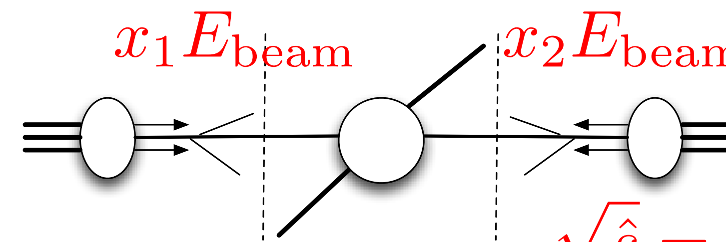


Vanishes in SM, could be allowed by new particles in the loop

e^+e^- collider versus pp collider



$\sqrt{s} = 2E_{\rm beam}$



$\sqrt{\hat{s}} = 2x_1 x_2 E_{\rm beam}$

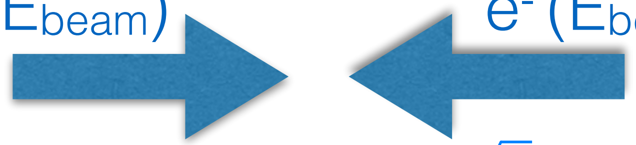
e^+e^- collider

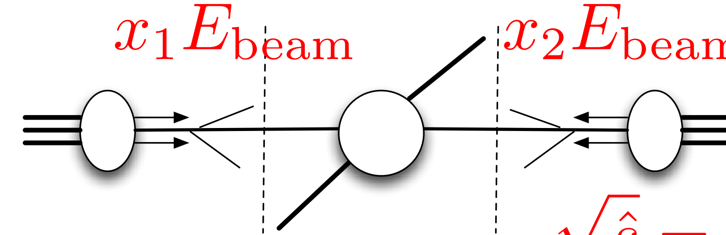
- energy of elementary collision known (equal twice energy of the electron)
- elementary collision, no quarks and gluons in the initial state clean environment
- since electrons do not interact via strong force, mainly production of W, Z, photons, Higgs….
- energy limited by synchrotron radiation $E_{\rm rad} \propto \frac{1}{R}\frac{E^4_{\rm beam}}{m^4_e}$

pp collider

- energy of elementary collision unknown (parton distribution functions)
- complicated initial state: spectators, multiple interactions, pile-up …
- mainly production of quarks and gluons (QCD jets). Electroweak processes smaller cross section
- synchrotron radiation is $(m_{\rm proton}/m_{\rm electron})^4 \sim 10^{13}$ smaller

e+e- collider versus pp collider





Because of those differences folklore says:

e^+e^- colliders provide a clean environment that allows very precise measurements: **precision machines**

At pp collider higher energies (needed to produce new states) are achieved more easily: **discovery machines**

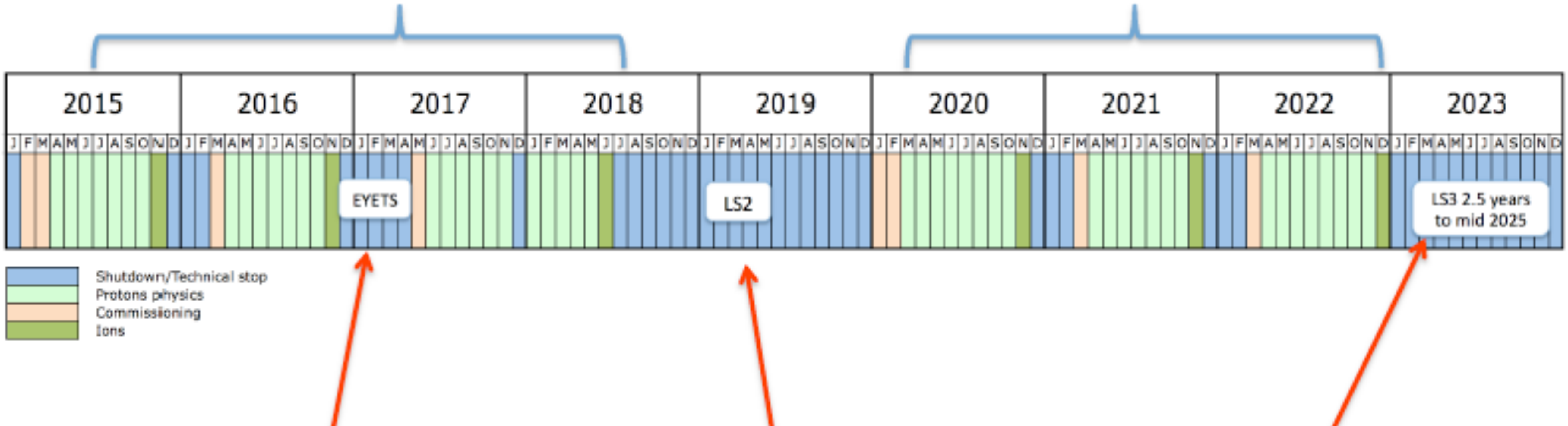
But this is to some extend an oversimplification.

Many high-precision measurements performed at the LHC today

Short and medium term future

Run 2: 13 to 14 TeV c.m. with peak luminosity of ~1.7×10^{34} cm^{-2} s^{-1}

Run 3: 14 TeV c.m. with peak luminosity of ~2×10^{34} cm^{-2} s^{-1}

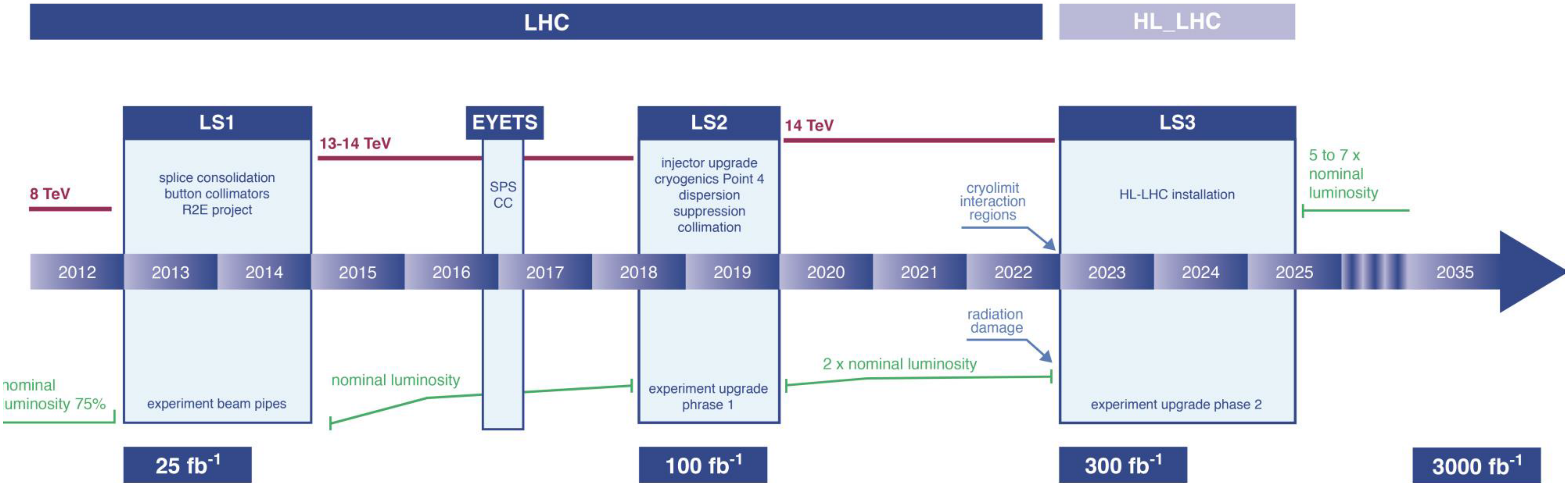


EYETS ~5 months
Extended year end technical stop (CMS)

LS2: 18 months
Connection of LINAC4
LHC Injectors Upgrade

LS3: 30 months
High Luminosity LHC

Short and medium term future



With High-Lumi phase of the LHC (HL-LHC)

- precision measurements of Higgs properties (in some cases to few percent)
- direct exploration of energy scales up to few TeV
- wealth of other precision measurements (better PDF determination, measurements of other SM parameters)

⇒ Legacy results from the LHC physics program

Long term future

Long terms future not decided yet. Most discussed possibilities include

- ILC (International Linear Collider)
- CERN CLIC (Compact Linear Collider)
- HE-LHC (high-energy upgrade using same LHC ring)
- Chinese CepC (e+e-) followed by SppC (pp) in same tunnel
- CERN FCC-e^+e^-, (FCC-ep,) or FCC-hh (Future Circular Collider)

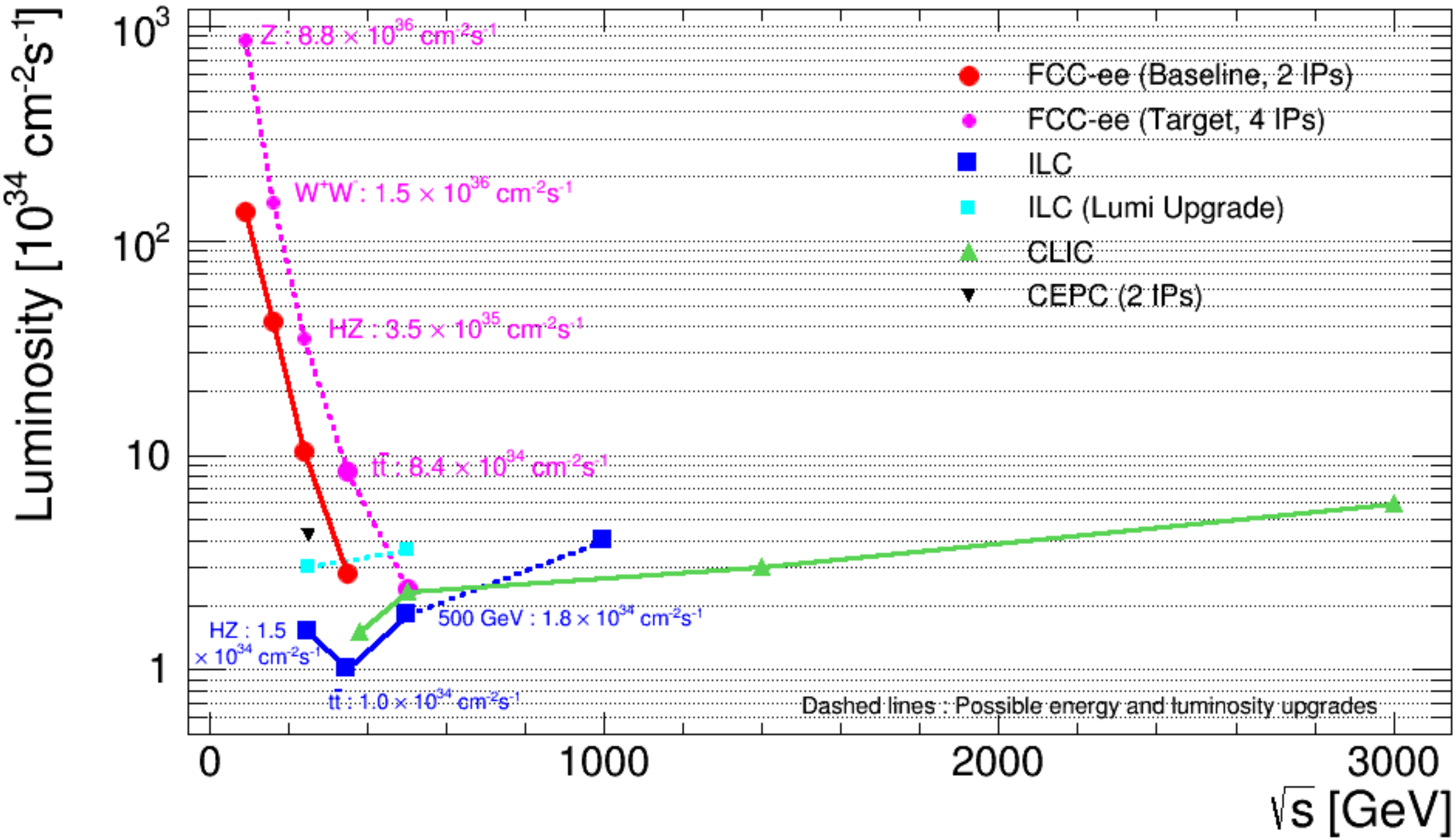
e^+e^- energy benchmarks

CM energy (GeV)	Physics motivation
91.2	Z-pole precision measurements
160.8	WW precision measurements
182.4	ZZ precision measurement
216	HZ threshold
350	Top-pair production threshold
500	ttH threshold, ZHH (self-coupling)
above 500	direct searches for New Physics

Possible e^+e^- colliders

	Circular Collider	Linear Collider
Energy reach	limited to < 500 GeV due to synchrotron radiation	feasible up to multi-TeV
Luminosity	large number of bunches (large beam, smaller energy spread, cleaner environment)	large lumi reached from squeezing beams, large bremsstrahlung
Lumi vs E	Increases at low E	Increases with high E (beam squeezed)
Interaction regions	several	1
Injection	continuos injection due to short lifetime	new injection at each cycle

Possible e^+e^- colliders



What is the International Linear Collider?

The International Linear Collider will give physicists a new cosmic doorway to explore energy regimes beyond the reach of today's accelerators. A proposed electron-positron collider, the ILC will complement the Large Hadron Collider, a proton-proton collider at the European Center for Nuclear Research (CERN) in Geneva, Switzerland, together unlocking some of the deepest mysteries in the universe. With LHC discoveries pointing the way, the ILC – a true precision machine – will provide the missing pieces of the puzzle.

Physicists ponder the physics of the proposed International Linear Collider – a next generation particle accelerator that will explore some of the most fundamental questions about the universe.
Image: Fermilab

Consisting of two linear accelerators that face each other, the ILC will hurl some 10 billion electrons and their anti-particles, positrons, toward each other at nearly the speed of light. Superconducting accelerator cavities operating at temperatures near absolute zero give the particles more and more energy until they smash in a blazing crossfire at the centre of the machine. Stretching approximately 31 kilometres in length, the beams collide 14,000 times every second at extremely high energies – 500 billion-electron-volts (GeV). Each spectacular collision creates an array of new particles that could answer some of the most fundamental questions of all time. The current baseline design allows for an upgrade to a 50-kilometres, 1 trillion-electron-volt (TeV) machine during the second stage of the project. There are also plans for a staged approach starting with a 250-GeV Higgs factory to study the properties of the particle discovered at the LHC in 2012 and then upgrading to 500 GeV.

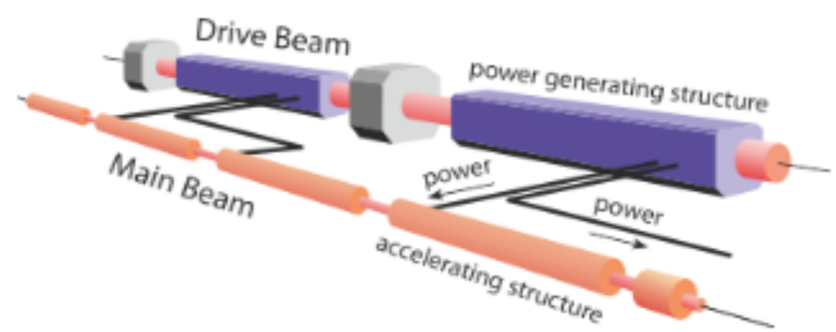
CLIC in a nutshell

CLIC – the Compact Linear Collider – is a study for a future accelerator that will reach unprecedented energies for electrons and their antimatter twins, positrons. When they come into contact in the collision they will annihilate each other, liberating all their energy for the production of new particles.

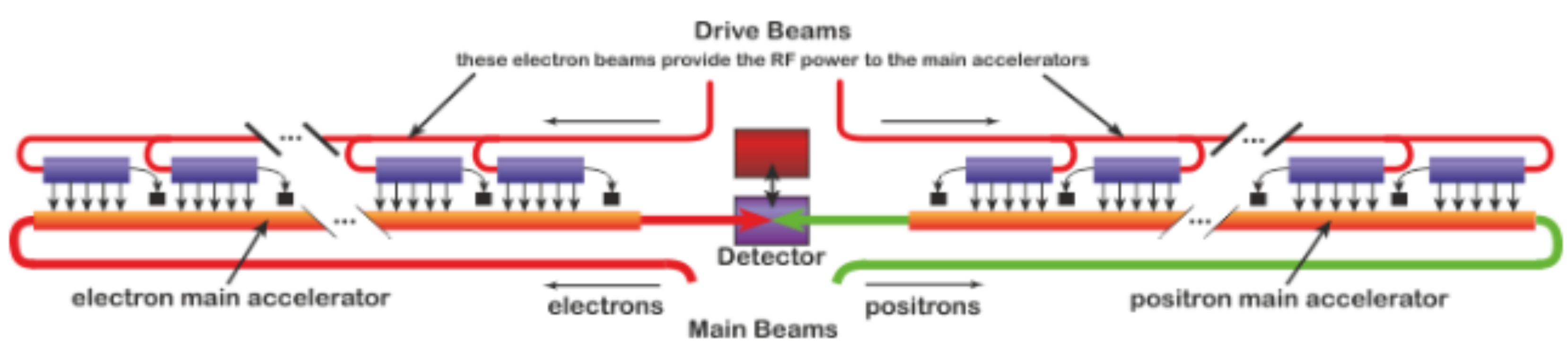
Electrons and positrons are fundamental particles, and their collisions can provide extremely detailed information about the laws of nature. So CLIC would offer significant fundamental physics insight beyond that available from the Large Hadron Collider (LHC) and a lower-energy linear electron/positron collider, as a result of its unique combination of experimental precision and high energy.

At these high energies, electrons and positrons would lose a huge fraction of their energy circulating in a ring collider like the LHC. So the particles have to be accelerated in two linear accelerators facing each other, such that the beams collide in the central physics detector. This implies that the particles have to gain their energy in a single passage through the accelerating cavities.

CLIC is designed to be built in stages of increasing collision energy: starting from 360 GeV, around 1.4 TeV, and up to a final energy of 3 TeV. In order to reach this energy in a realistic and cost efficient scenario, the accelerating gradient has to be very high - CLIC aims at an acceleration of 100 MV/m, 20 times higher than the LHC.



This drive beam is decelerated in special Power Extraction and Transfer Structures (PETS), and the generated RF power is transferred to the main beam. This leads to a very simple tunnel layout without any active RF components (i.e. klystrons).



The feasibility of CLIC has been demonstrated and documented for the accelerator and the detector in the CLIC Conceptional Design Report. The design is currently being further optimized and adapted after the discovery of the Higgs boson at the LHC. CLIC is one of the options for a future accelerator built at CERN, which will be decided depending on future LHC physics results.

FCC-ee

The FCC-ee in a few words

The FCC-ee, formerly known as TLEP, is a high-luminosity, high-precision e^+e^- circular collider envisioned in a new 80-100 km tunnel in the Geneva area. With a centre-of-mass energy from 90 to 400 GeV, the physics program could pave the way towards the discovery of physics beyond the Standard Model, casting light on unanswered questions, such as dark matter, the baryon asymmetry of the Universe, the hierarchy problem, the stability of the Universe or the nonzero neutrino masses.

The FCC-ee project is part and parcel of the Future Circular Collider design study (FCC) at CERN, and would be the first step towards the long-term goal of a 100 TeV proton-proton collider. It is expected to deliver its conclusion in 2018, just prior the next update of the European Strategy. There are many challenges facing the study, starting with a realistic design that allows these promises to be fulfilled, so feel free to join the design study group if you wish to collaborate with us!

The CEPC Project

The Circular Electron Positron Collider (CEPC) is a long-term collider project, which will be divided into two phases. The first phase will construct a circular electron-positron collider in a tunnel with a circumference of 50 – 70 km, and detectors installed at two interaction points. The machine is expected to collide electron and positron beams at the center-of-mass energy of 240 – 250 GeV, with an instantaneous luminosity of 2×1034 cm^{-2} s^{-1}. The baseline design considers a single ring in a 50/70 km tunnel and electron/positron beams following a pretzelled orbit in the ring. CEPC will serve as a Higgs Factory where precise measurement of Higgs properties will be its top priority. In addition, CEPC will allow stringent tests of the Standard Model (SM) with precision measurements at the Z pole and WW thresholds. The second phase of the project will upgrade the machine to a proton-proton collider with an unprecedented center-of-mass energy of 50 – 70 TeV. The machine will offer a unique opportunity for direct searches for New Physics in the high-energy range far beyond LHC reach. Find out more in Prof. Yifang Wang's talk.

Possible Timeline

Pre-studies and preparation work are being carried out and will last till 2015. The pre Conceptual Design Report (CDR), as the first milestone of the CEPC project, will be released by the end of 2014. Intensive R&D efforts will be launched between 2016 and 2020, with the Technical Design Report (TDR) to be accomplished by 2020. The electron positron collider will start construction in 2021 and complete in 2027. The machine is expected to start data taking in 2028 and will run effectively till 2035.

The R&D efforts on the proton-proton collider will be pursued between 2020 and 2030, followed by the engineering design to be finished by 2035. From 2035 to 2042, the machine will be constructed in the same tunnel as the electron-positron collider. The machine will start to take data as early as 2042.

Where to Build the Machine?

Qinghuada(秦皇岛), with great geological conditions and strong support from the local municipal government, could be the potential site.

The FCC-hh

A 100 TeV proton-proton collider

The study of the FCC-hh implements the following statement of the European Strategy document approved by the CERN Council in May 2013:

"To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitions post-LHC accelerator project at CERN by the time of the next Stratefy update, when physics results from the LHC running at 14 TeV will be available. CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies shoud be coupled to a vigourous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and university worldwide."

Preliminary parameters for FCC-hh are listed in this document, and summarized in the table below.

Version 1.0 (2014-02-11)	**LHC**	**HL-LHC**	**FHC-hh**
C.M. Energy [TeV]	14		100
Circumference *C* [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Injection energy [TeV]	0.45		3.3
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)

A possible implementation of the 80 km tunnel (dashed) that would host FCC-ee and FCC-hh. 100 km version under study

33 TeV vs 100 TeV

- Another option is NOT to build a new tunnel but go for the LE-LHC (High Energy LHC) option, i.e. upgrade the energy from 14 TeV to 33 TeV (100 not feasible in the LHC tunnel).
- There is no question that 100 TeV is better than 33 TeV
- But is it worth waiting decades to build this machine?
- Would a 33 TeV option (which can use the same LHC tunnel) be instead a good plan B?

No clear answer yet to the questions above

Slide from G. Landberg, KITP 2016

Plan A and Plan B!

Consider two scenarios:

- **LHC Run 2 and HL-LHC do not find new physics**
  - The measurement of the Higgs boson couplings becomes the raison d'être for the HL-LHC
  - After ~1/ab (~2030) still have fairly good detectors, but are facing diminishing return
  - If the high-field magnet technology is ready, stop the HL-LHC and upgrade to run at 33 TeV in ~2035 (less than 20 years from now!)
  - Get ~3/ab @ 25ns with the HL-LHC pileup and ATLAS+CMS Phase II detectors, with the focus on the Higgs boson self-coupling measurement
- **Possibly the only machine we could afford in this scenario**
  - If HE-LHC finds new physics (or CEPC points to a concrete energy scale), go for ~100 TeV machine and reuse the HE-LHC magnets (1/3 of the full number needed for the FCC)

- **LHC Run 2 finds new physics (e.g., X(750))**
  - The scope of the program shifts toward study of its properties
  - Almost all the models predict other partners, which may very well be reachable at 33 TeV
  - Do not want to wait 35 years for the new machine - want to build it as soon as possible
- **Possibly revolutionize the field and break the spell of a flat funding**
  - Consider a 33 TeV machine to be a 30% demonstrator of the FCC at a ~10% cost
  - N.B. cost(33) ~ (cost(100) - CHF 10B)/3 ~ 5B [10B = tunnel + 2 detectors]

Slide from G. Landberg, KITP 2016

Building a Physics Case

- **Taking a 33 TeV machine as a necessary step toward an "ultimate" pp machine is a good argument to bring up**
  - People and funding agencies like "demonstrators" and proof of feasibility
  - It also helps "safety" arguments [prove that a 100 TeV machine won't destroy the world - barely did this for the LHC!]
  - No serious studies have been done since the Higgs boson discovery, and the time is ripe to make this happen
- **Many of the FCC physics studies made available in the last year can be directly propagated to the 33 TeV machine**
  - Clearly the reach is not going to be as impressive, but there is good physics to be done, particularly if one takes into account funds saved by cutting the HL-LHC program short
  - In fact, this will be a HL-HE-LHC, combining the best of both options

Physics at 100 TeV pp collider

1. **Physics at a 100 TeV pp collider: Standard Model processes**
   M.L. Mangano (CERN) *et al.*. Jul 6, 2016. 257 pp.
   CERN-TH-2016-112, FERMILAB-FN-1021-T
   e-Print: **arXiv:1607.01831 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server; ADS Abstract Service
   Detailed record - Cited by 11 records

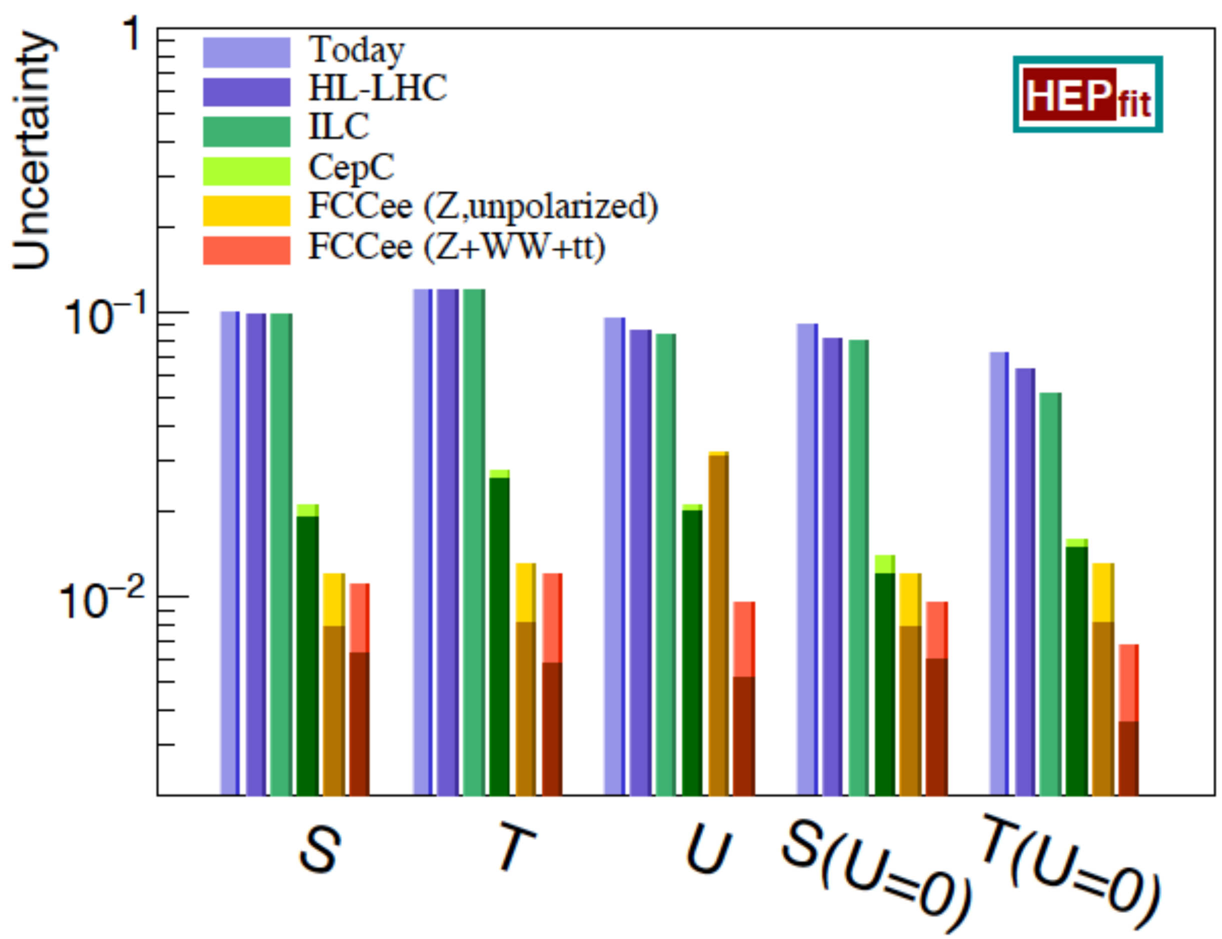
2. **Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies**
   R. Contino (CERN & LPHE, Lausanne) *et al.*. Jun 30, 2016. 187 pp.
   CERN-TH-2016-113
   e-Print: **arXiv:1606.09408 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server; ADS Abstract Service
   Detailed record - Cited by 8 records

3. **Physics at a 100 TeV pp collider: beyond the Standard Model phenomena**
   T. Golling (U. Geneva (main)) *et al.*. Jun 2, 2016. 197 pp.
   CERN-TH-2016-111, FERMILAB-PUB-16-296-T
   e-Print: **arXiv:1606.00947 [hep-ph] | PDF**
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server; ADS Abstract Service; Fermilab Library Server (fulltext available); Link to Fulltext
   Detailed record - Cited by 14 records

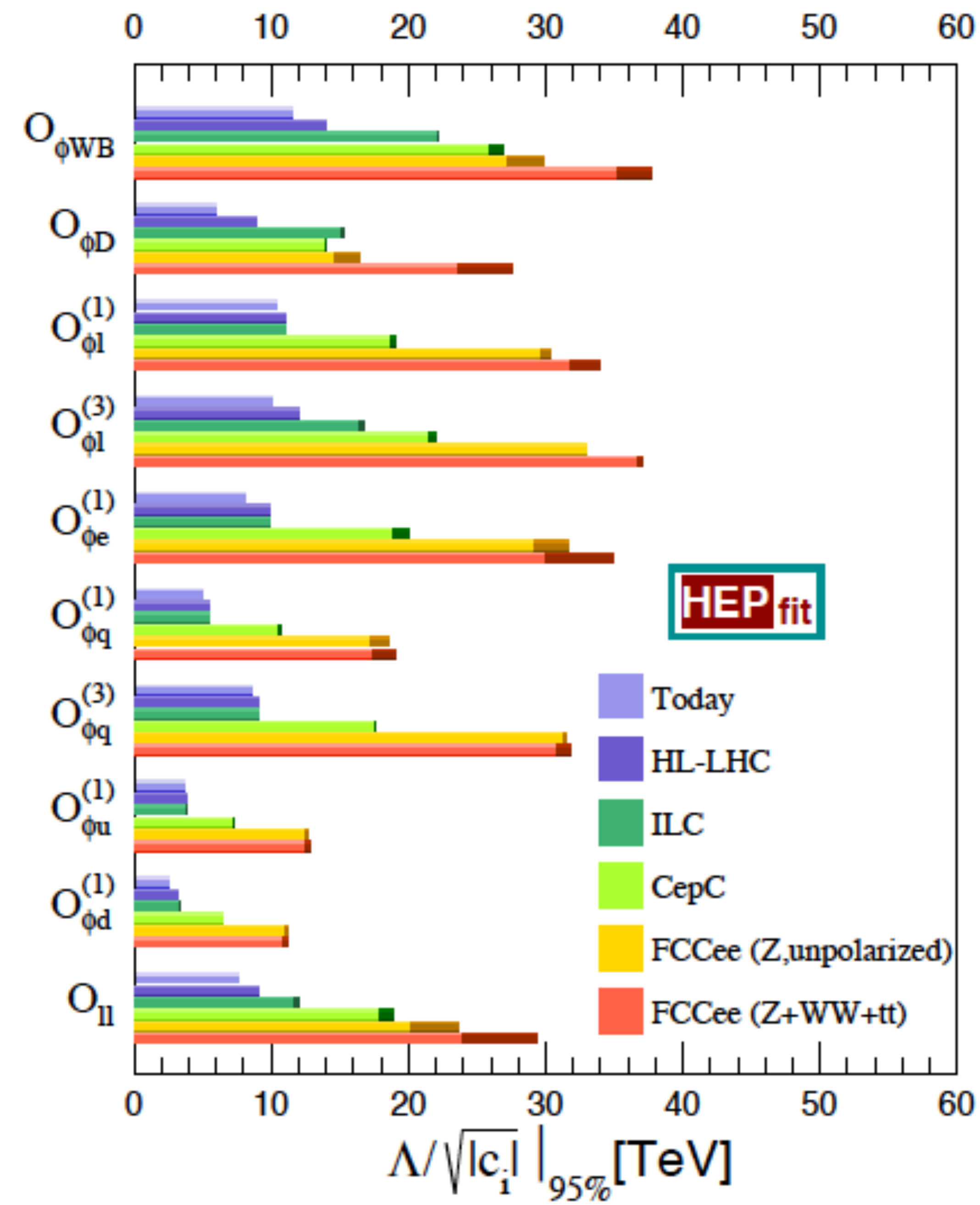
First systematic studies of physics at 100 TeV machine. Important to understand requirements on detectors

Physics at future colliders

S,T,U = 0 in the SM. Sensitive probes of BSM

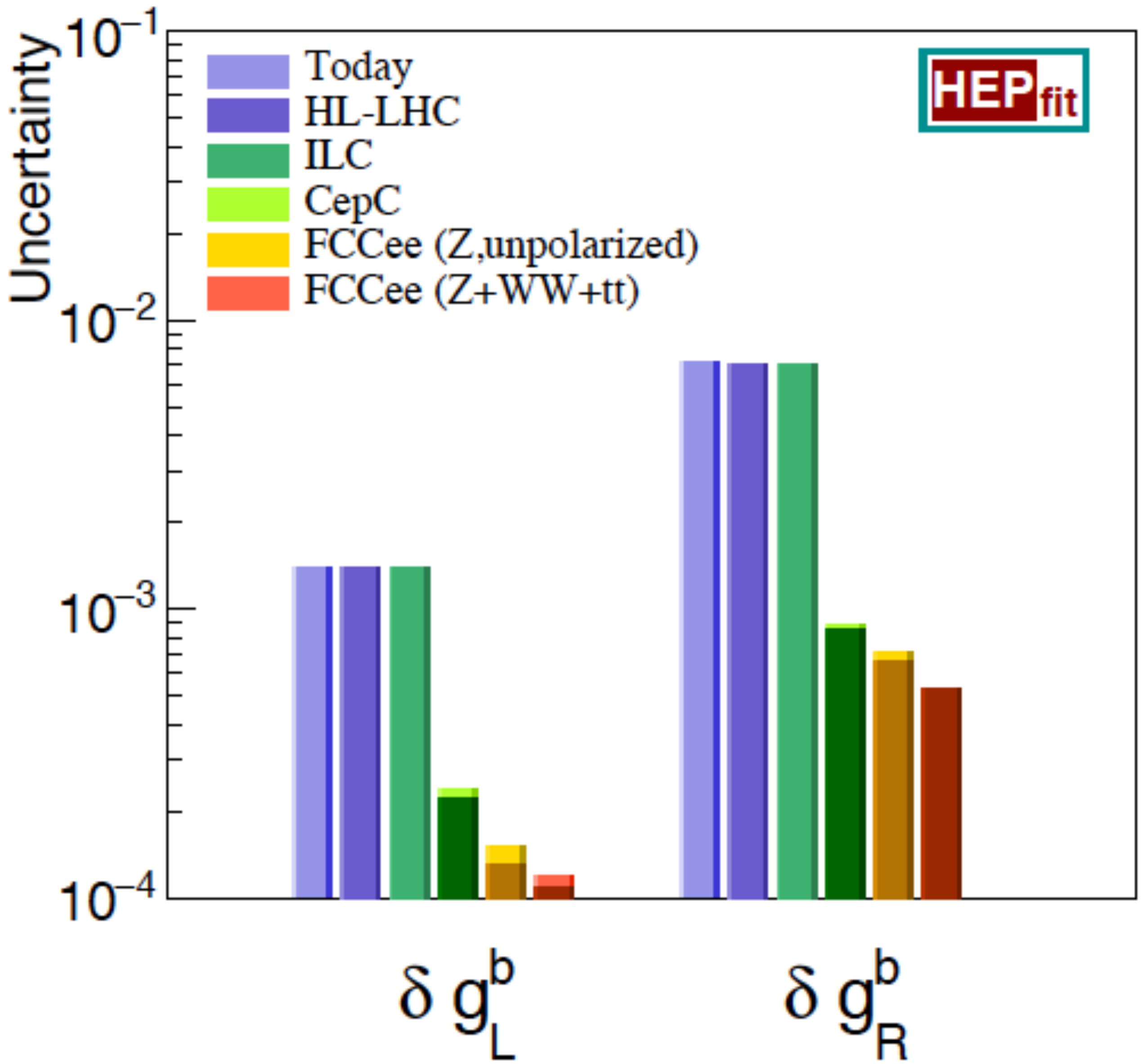


Energy scales explored by different colliders

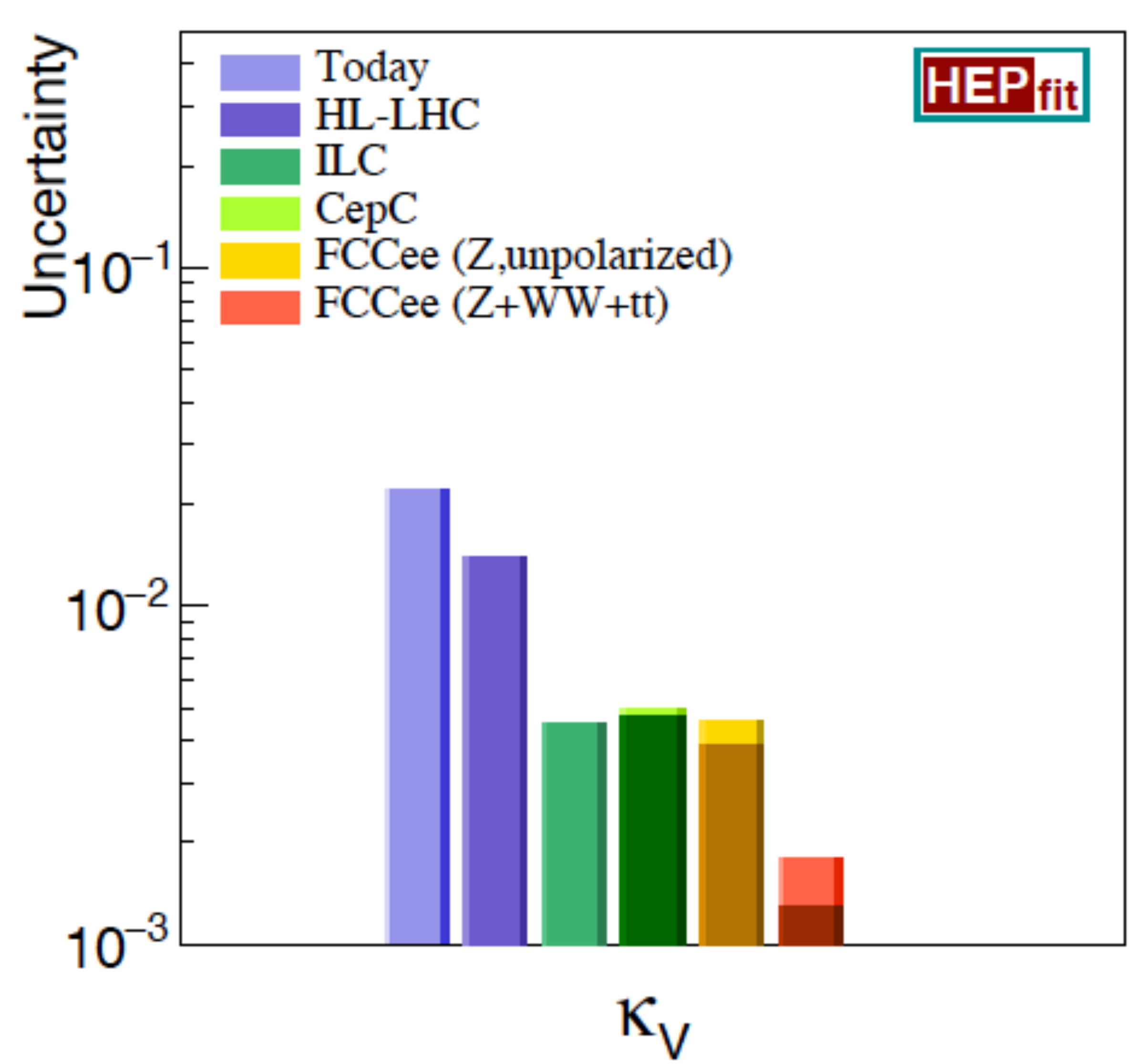


Physics at future colliders

Estimated accuracy in left/right couplings

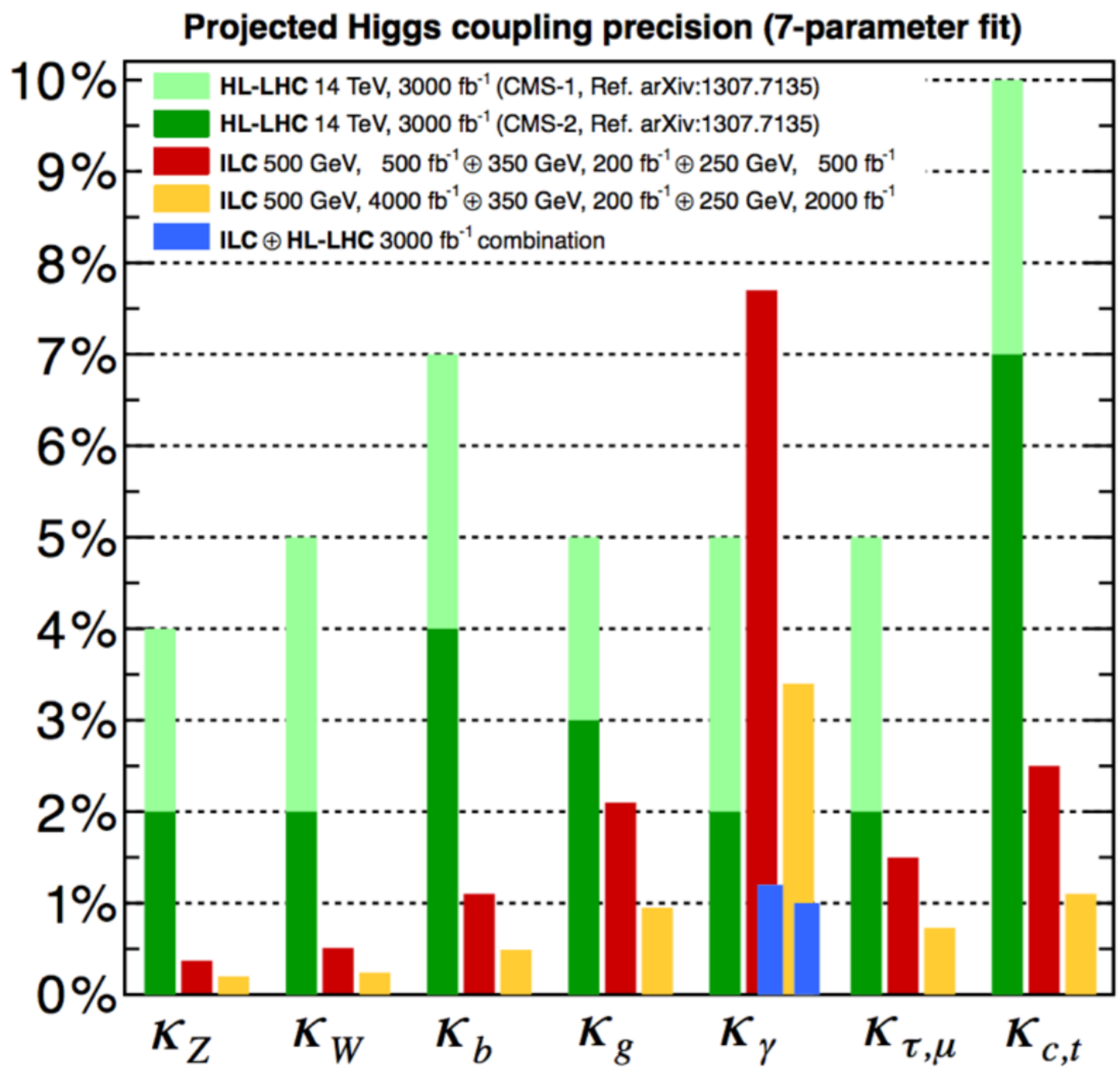


Estimated accuracy in coupling of vector bosons to the Higgs



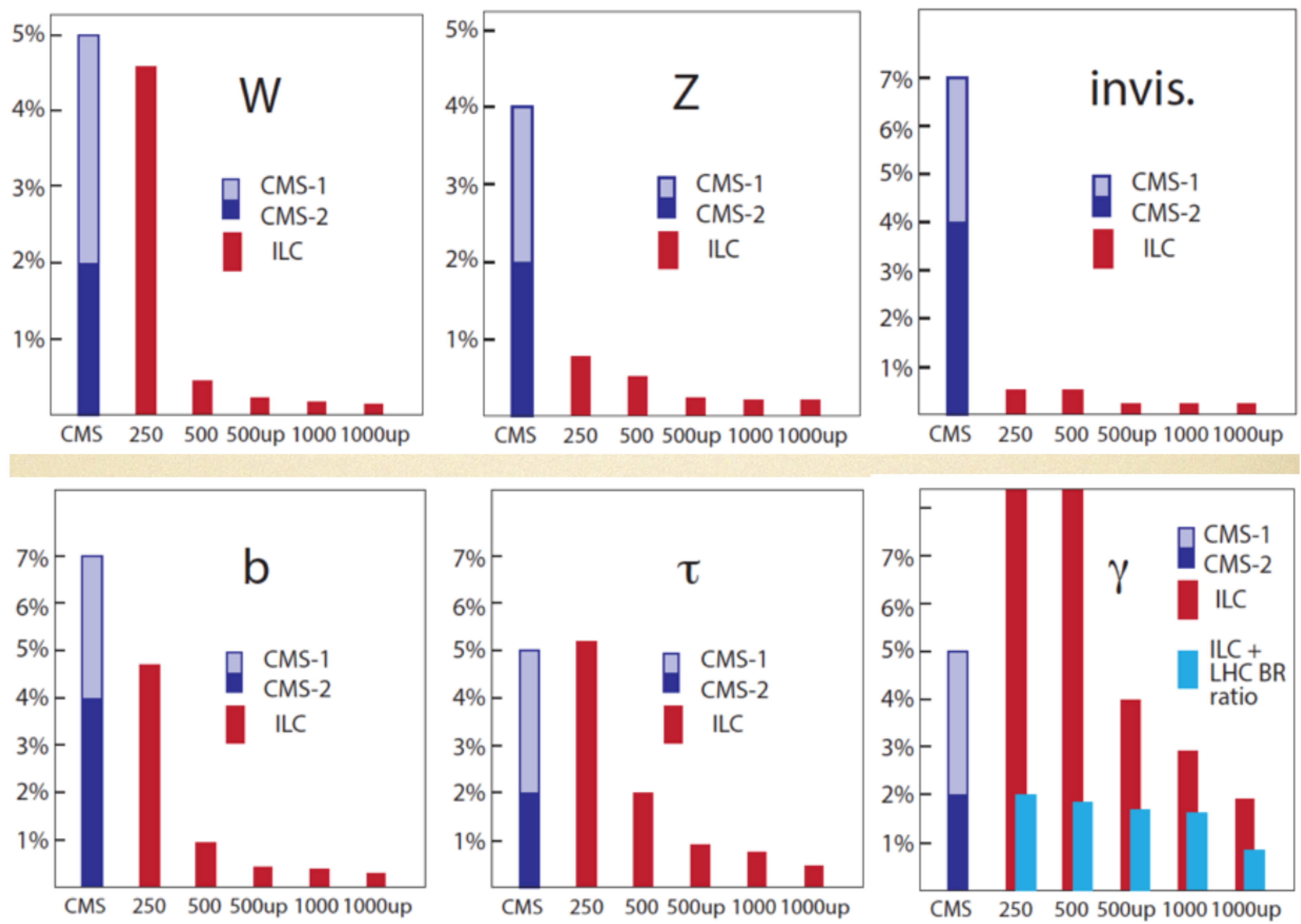
Physics at future colliders

Estimated accuracy in measurement of Higgs couplings to other SM particles



Physics at future colliders

Estimated accuracy in measurement of Higgs couplings to other SM particles



Conclusion

- The LHC owes its success to the long-term vision of the high-energy particle physics community in the 70s and 80s
- The discovery of the Higgs at the LHC marks a milestone in particle physics, but also leaves us with many open questions
- There is no doubt that a new accelerator machine will be required to explore those questions and extend our knowledge of fundamental particle physics
- There is no consensus yet on which type of machine/which energy. Exploit complementarity and synergy of different machines
- A variety of options are currently being explores
  - e^+e^- colliders: precision EW measurements, including Higgs and implications for BSM and naturalness
  - proton-proton colliders: direct probe if heavy new states, but also tool for studying deep issues (EW symmetry breaking, EW dark matter)

Conclusion

- Regardless of details, even in the absence of an indication of what is the right energy scale to explore the path to the followed it very clear
  - ➡ highest precision measurement ⇒ indirect probes of very high energy scales up to 100 TeV
  - ➡ highest energy possible ⇒ explore new energy frontier
- These projects are extremely challenging, both financially and technically
- The task of HEP is also to develop new technology to make our wishes affordable
- Leaps in technology will drive the future progress of the field
  (dipoles with fields of several tens of Tesla, the large-scale high-gradient cavities, validation of the CLIC with intensities of interest for particle physics, ability to store and collide high-energy muon beams, plasma-driven accelerators) acceleration concept, ability to store and collide high-energy muon beams, plasma-driven accelerators