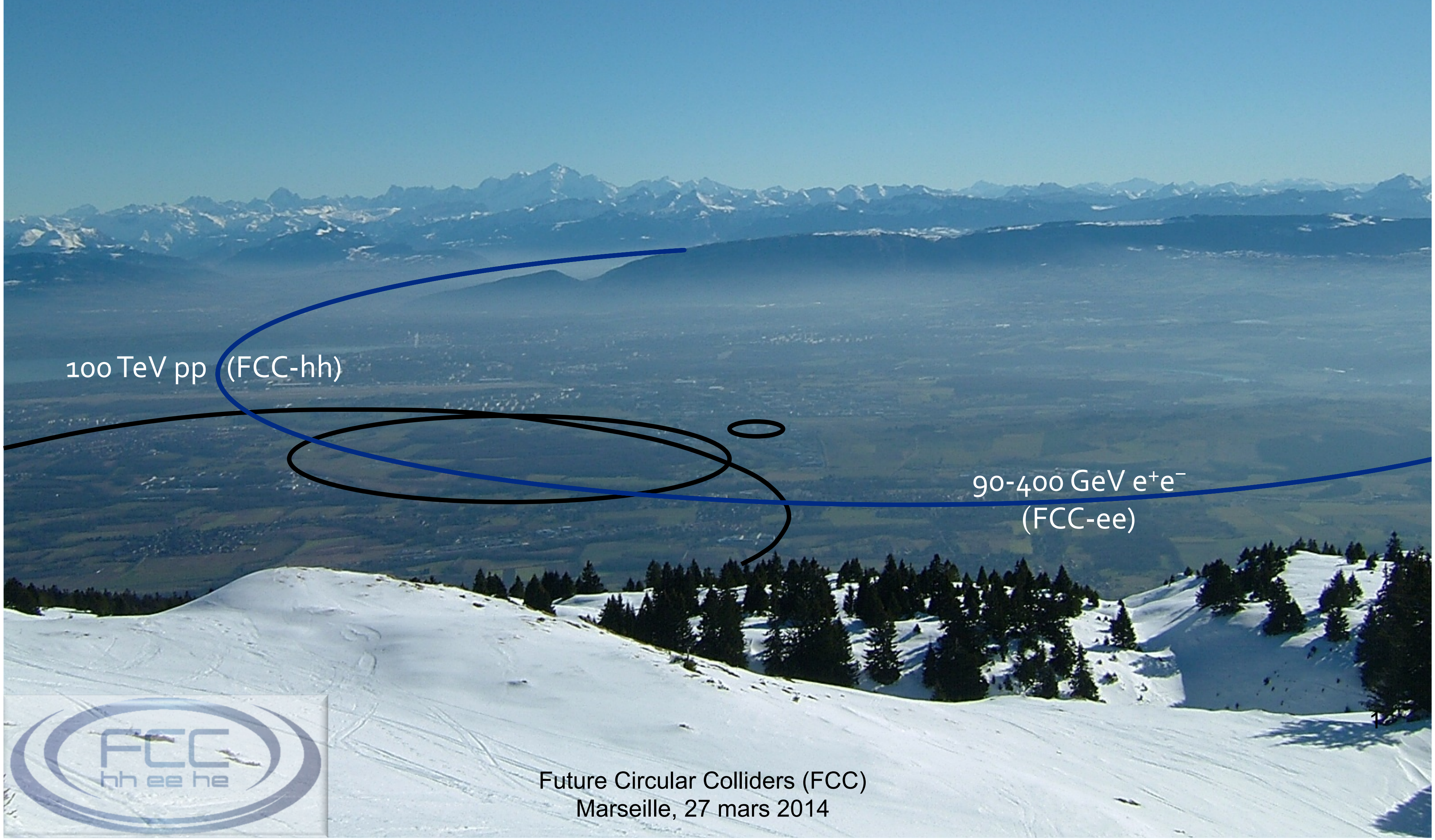
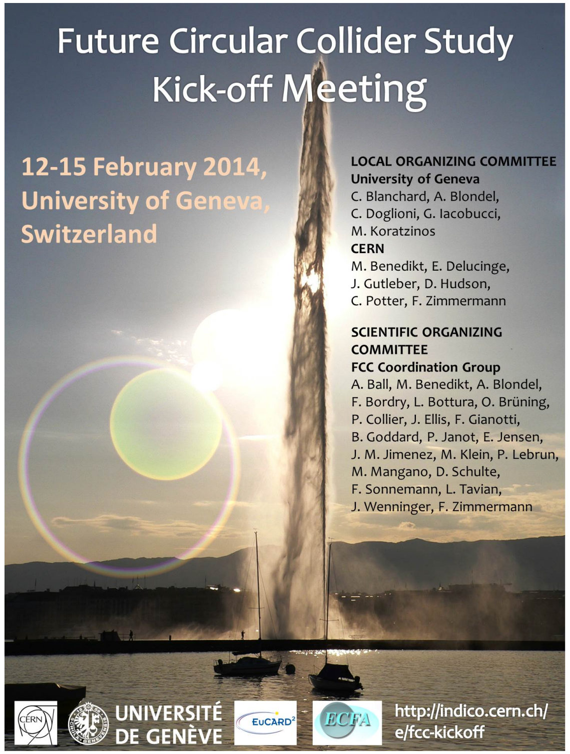
Future Circular Colliders @ CERN (FCC)

A global and long-term vision for High-Energy Physics



It's already happening !

- FCC studies launched last month in Geneva
  - ~330 registered participants from Europe, Americas and Asia



  - Discussion of all FCC aspects, towards establishing international collaboration
    - Scope, schedule, milestones, R&D, physics, experiments, accelerators, safety, …

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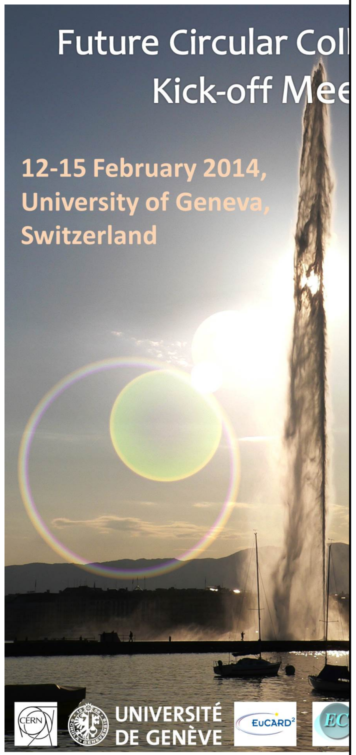


ASK NOT WHAT
BIG CIRCULAR COLLIDERS
CAN DO FOR YOU, ASK
WHAT YOU CAN DO FOR
BIG CIRCULAR COLLIDERS!

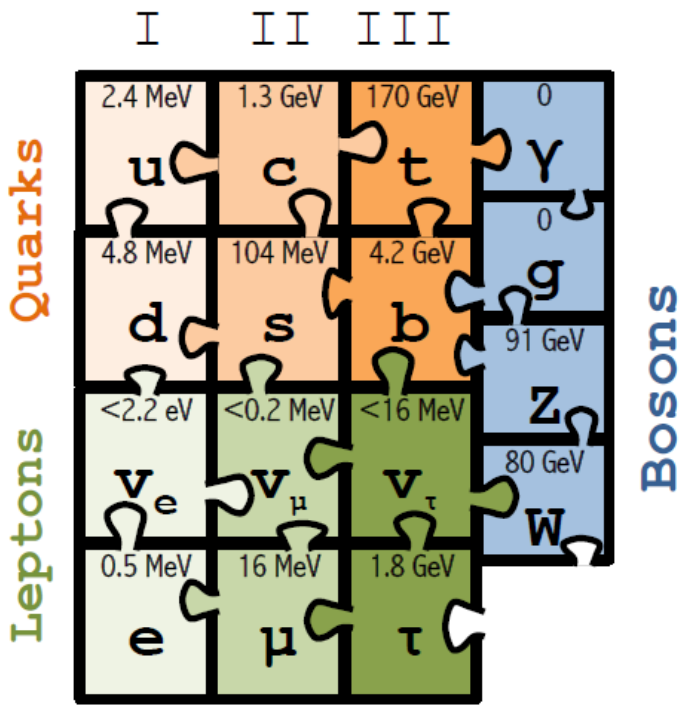
Nima ARKANI-HAMED

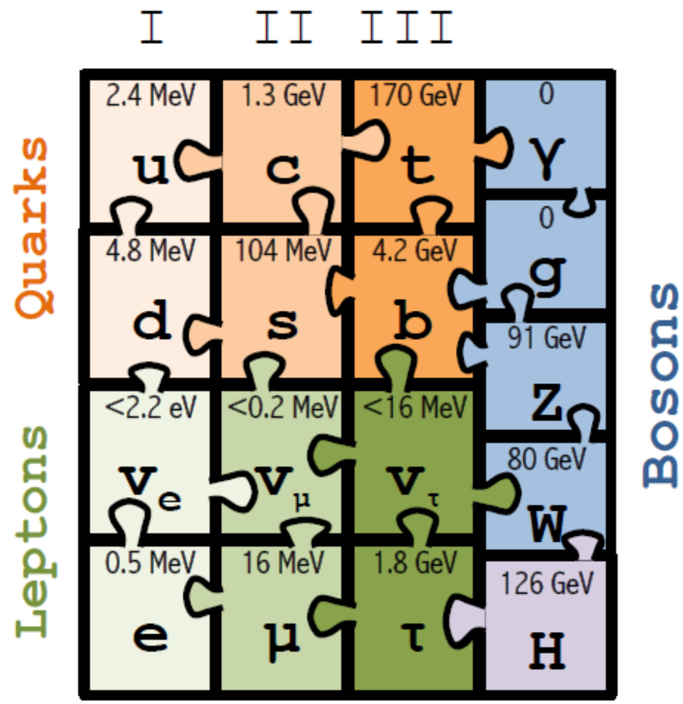
  - **Discussion of all FCC aspects, towards establishing international collaboration**
    - **Scope, schedule, milestones, R&D, physics, experiments, accelerators, safety, …**

A summary of why, when, who, how (much), and what, follows.

Why? The big picture today (1)

- **The standard model is complete and has become the Standard Theory**
  - 1993-1999
    - m_{top} predicted (LEP)
    - Top quark discovered (Tevatron)
    - t'Hooft and Veltman Nobel Prize
  - 1997-2013
    - m_H cornered (LEP, Tevatron)
    - Higgs boson discovered (LHC)
    - Englert and Higgs Nobel Prize





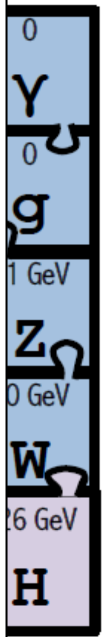
Why? The big picture today (1)

- **The standard model is complete and has become the Standard Theory**
  - 1993
    - ron)
    - LHC)
    - Prize

Quarks

Leptons

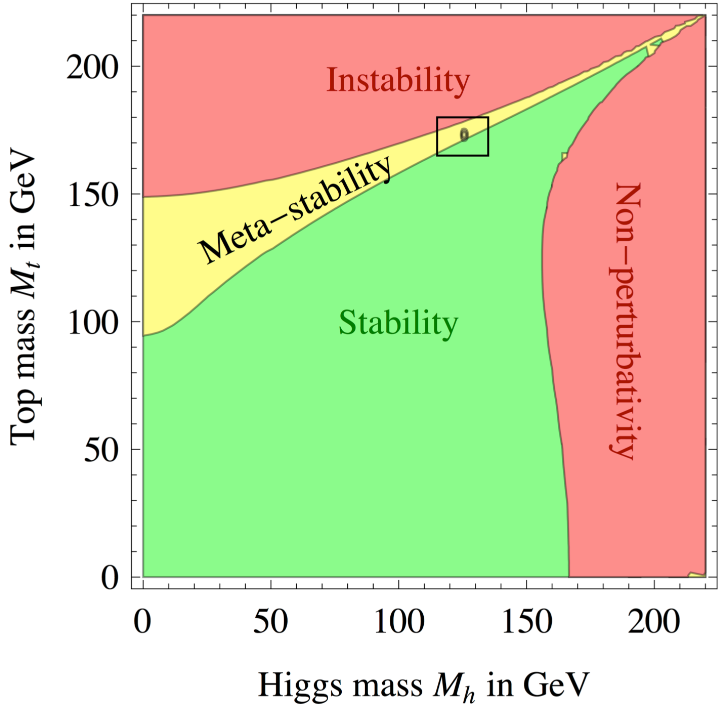
> With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.
>
> Nima ARKANI-HAMED



Bosons

Why? The big picture today (2)

- **Is is the end ?**



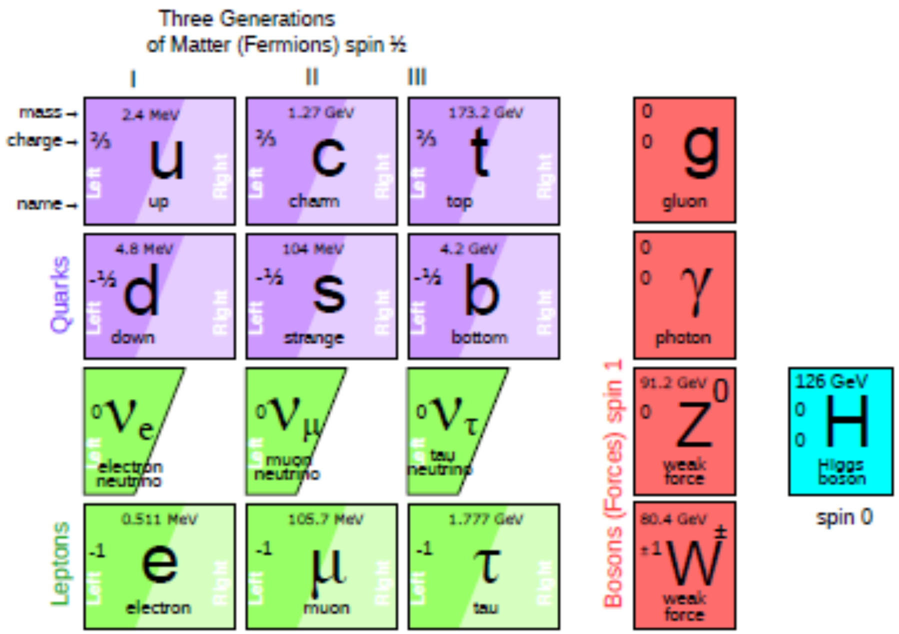
- **Certainly not !**
  - Cosmological dark matter (DM)
  - Baryon asymmetry of the Universe (BAU)
  - Non-zero, but small, neutrino masses
    - are experimental proofs that there is more to understand beyond the standard theory
      - ➡ We must continue our quest.

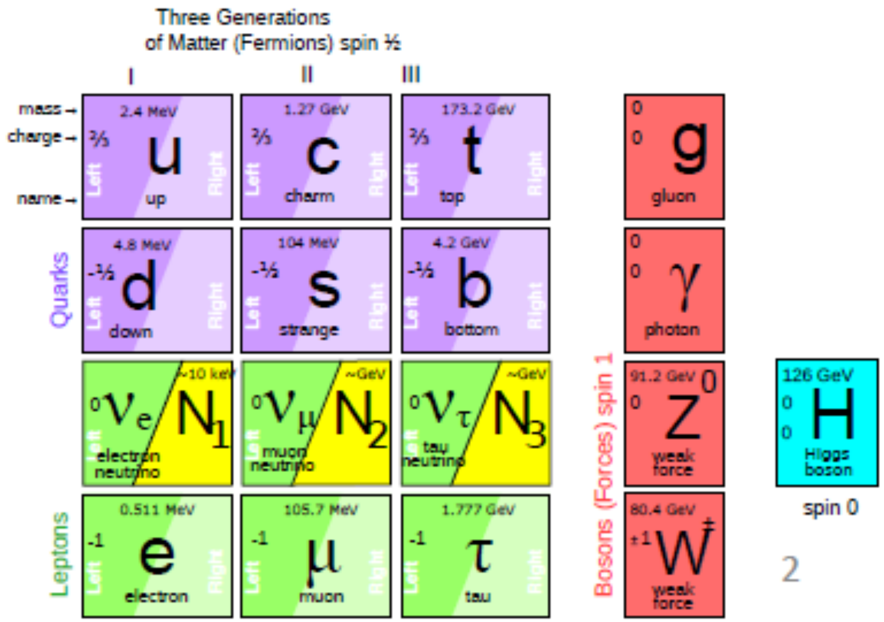
But Where Is Everybody?

- **Higher masses ? Smaller couplings ? Both ?**
  - In absence of definite theoretical guidance, the answers to these questions
    - Need collisions with significantly larger energies – the larger the better
    - Require measurements with unprecedented precision

Why? The big picture today (3)

- **An attractive/minimal possibility with smaller couplings**
  - Three pieces are obviously missing in the standard theory

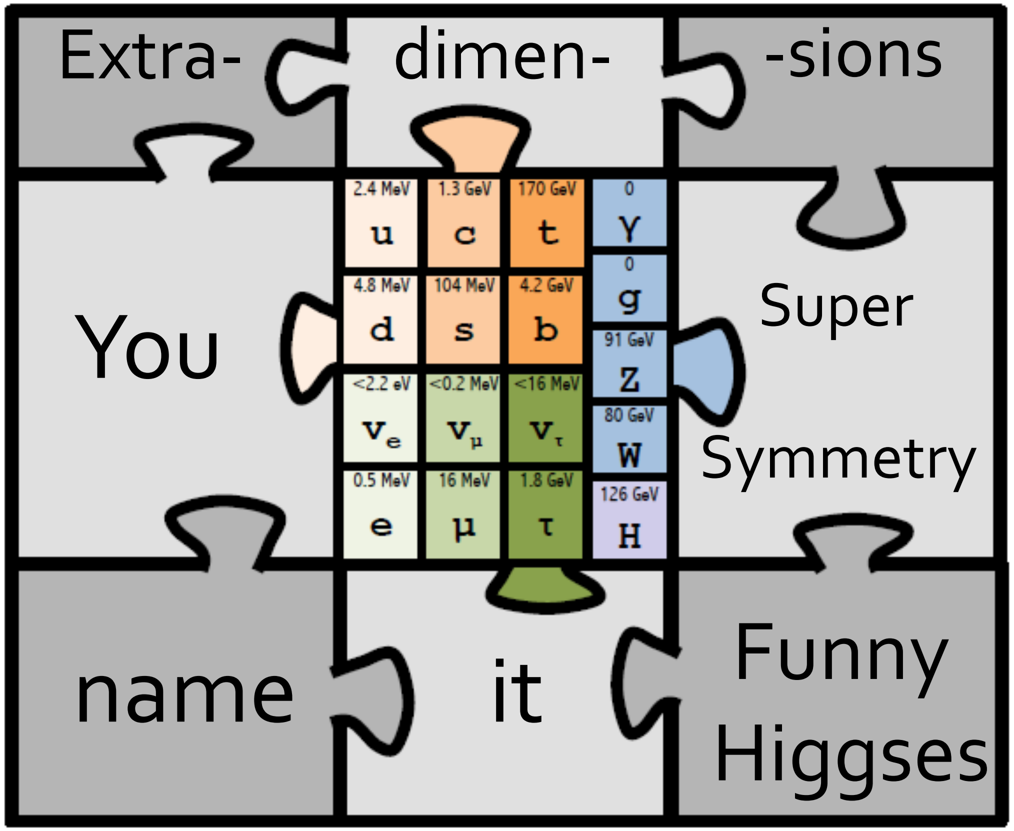




- **Three sterile right-handed neutrinos ?**
  - Nearly impossible to find, but could perhaps explain it all !
    - Very small couplings, small m_ν (see-saw), DM (light N_1), and B.A.U. (leptogenesis)
  - Need very-high-precision experiments: a possibility with the FCC ?

Why? The big picture today (4)

- **Others lean towards higher-energy SM replicas**



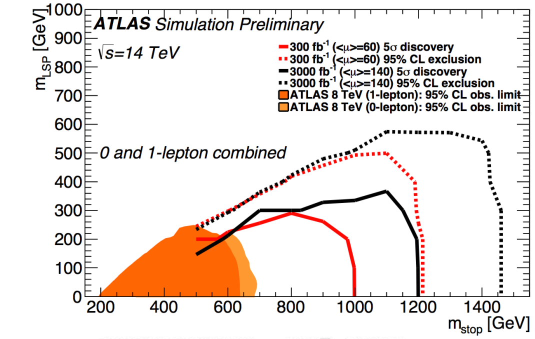
- **Direct searches at higher energies, rare decays, ultra-precise measurements, needed**
  - **Another possibility with the FCCs ?**

A first step with the LHC (1)

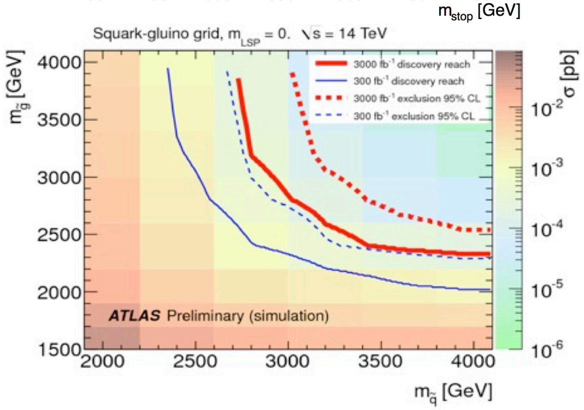
Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

30 fb^{-1} with LHC13 → 300 fb^{-1} with LHC14 → 3 ab^{-1} with HL-LHC (?)

- **Clearly, how to proceed exactly will depend on the first LHC13 results**
  - **But will they change the big picture in a significant way?**

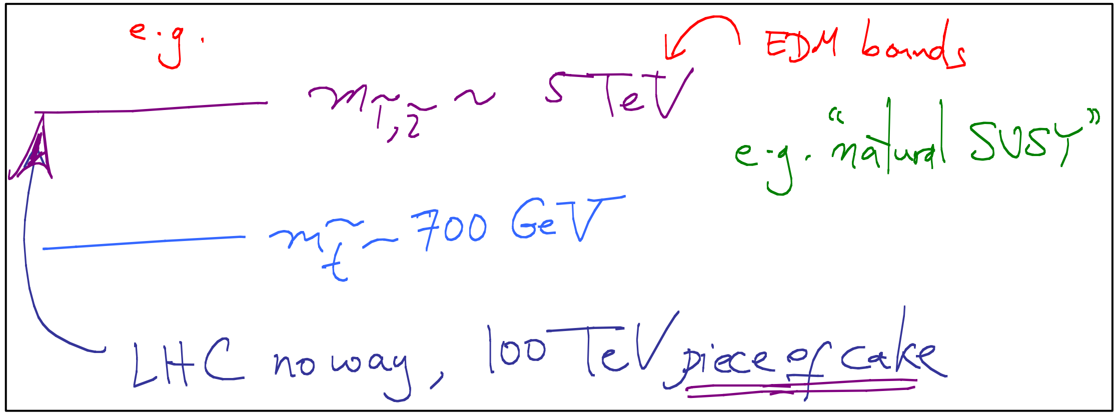


- **1st case: A light Higgs boson + nothing else in 2017**
  - **The previous slides statements are made stronger**
    - **Need collisions with significantly larger energies**
    - **Requires measurements with unprecedented precision**
  - **The case of the HL-LHC may have to be revisited**
    - **Discovery potential not compelling ?**
    - **Trilinear Higgs coupling measurement marginal ?**
    - **Higgs coupling measurements ok with ~0.5 to 1 ab^{-1} ?**



A first step with the LHC (2)

- **2nd case: The LHC discovers a "relatively" natural spectrum by 2017?**
  - **What we already know from LHC makes it implausible that we'll see the whole spectrum**



  - **It's not 1995: "Discover light SUSY at LHC, then precision study at 500 GeV ILC"**

- **So… in summary:**

But in every scenario I can imagine,
we will need the 100 TeV
pp machine

Next steps for High-Energy Physics (1)

- The European Strategy (CERN council – 05/13) does not say anything else

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy 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 should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

FCC-hh

CLIC

- Worldwide studies clearly outlined
  - Towards a project at CERN
- CLIC CDR has already been delivered
  - There is a plausible need to go beyond this energy frontier
    - ➨ Study of a circular high-energy pp collider (FCC-hh) required
    - ➨ Result of the studies requested by 2018 (next strategy update)

Choice to be made at that time

Next steps for High-Energy Physics (2)

Circular e^+e^- machine
Higgs Factory plays very important, complementary role

Tera-Z particularly exciting + powerful probe!

- **The European Strategy from the CERN council (05/13) concurs:**

  e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

  ILC
  FCC-ee

  - **ILC TDR has already been delivered, project to be hosted by Japan**
    - **There is a plausible need to go beyond this precision frontier**
      - **A circular high-luminosity e^+e^- collider (FCC-ee) is a tool of choice**
      - **Would use the same tunnel as FCC-hh, as a possible first step**

        Synergies with linear collider detectors should be considered
      - **Results of the studies requested by 2018 (next strategy update)**

        Choice to be made at that time

Next steps for High-Energy Physics (3)

- **Grand summary of the motivation for the FCC study**
  - The LHC physics case so far relied on a theoretically-guided no-lose theorem
    - Either find the standard-model Higgs boson ← So far, we are here
    - Or find new physics at the TeV scale — Not yet… LHC Run 2 ?
  - We have made use of the theorem: it is now gone.
    - On the theory side, we won't be again in such a favourable situation for a long time
      - ➨ Observations, however, tell us that new physics must be "around the corner"
  - But where is the corner ?
    - Only way to find: go look !
      - ➨ Need to explore all options towards highest energies and best accuracies

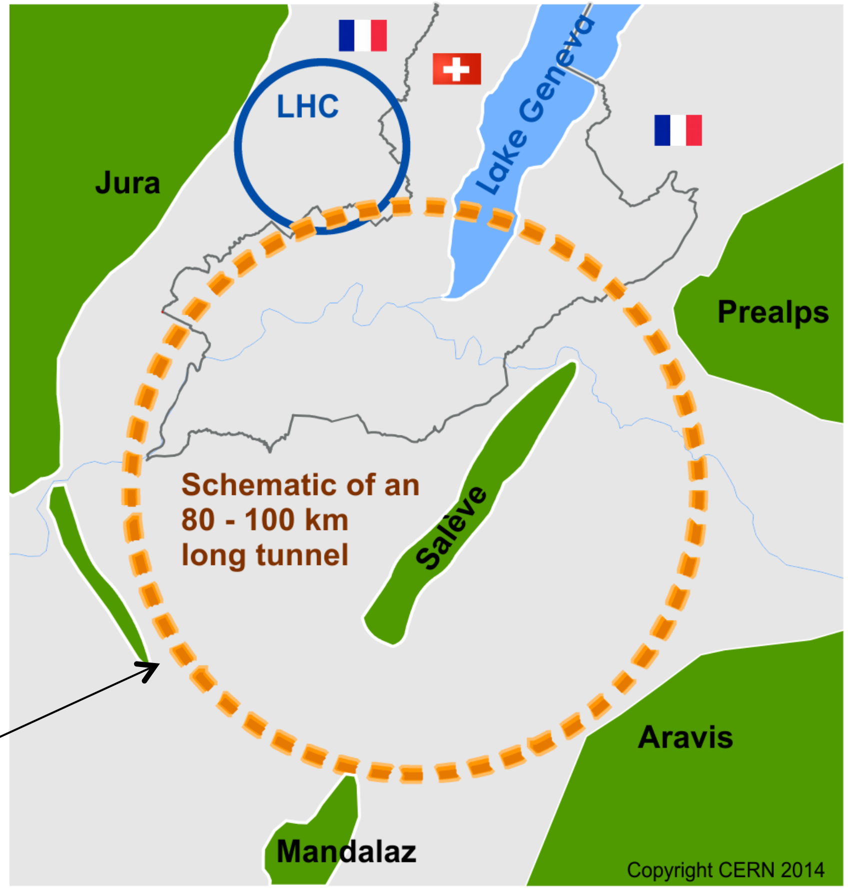
Beyond the LHC Run2, the combination of FCC-ee and FCC-hh offers, for a great cost/infrastructure effectiveness, the best precision and the best search reach of all options presently on the market.

"First look at the physics case of TLEP", arXiv:1308.6176

  - This statement must be confirmed (or not) by a dedicated global study

The FCC design study: Official scope

- **Form an international collaboration to study**
  - A 100 TeV pp collider (FCC-hh)
    - Defining infrastructure requirements
      - 16 T magnets require 100 km
      - 20 T magnets require 80 km
    - Long-term goal of the FCC
  - A high-luminosity e^+e^- collider (FCC-ee)
    - As a possible first step
    - c.m. energy from 90 to 400 GeV
  - An e-p option (FCC-he)
    - And also heavy ion collisions
  - A 80-100 km infrastructure
    - In the Geneva area

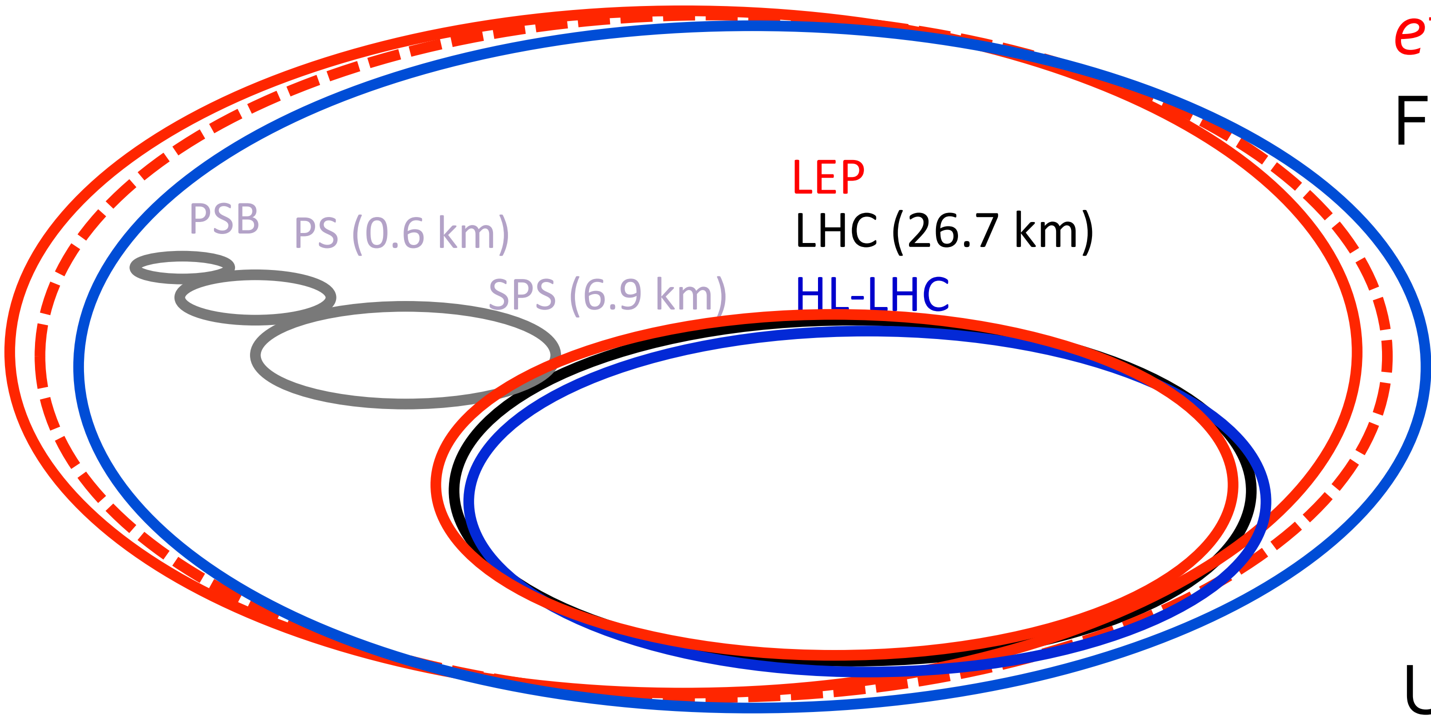


The FCC design study: a long-term vision

60 years ago, CERN was born…

FCC-ee (80-100 km, e^+e^-, 90-400 GeV

First step



FCC-hh (*pp*, up to 100 TeV c.m.)

Ultimate goal

& $e^\pm$ (120 GeV)–*p* (7, 16 & 50 TeV) collisions (FCC-eh)

≥60 years of e^+e^-, *pp*, *ep/A* physics at highest energies

The FCC design study: Preparation team

- **Study preparation team (since October 2013)**

Future Circular Colliders - Conceptual Design Study
Study coordination, **M. Benedikt, F. Zimmermann**

Hadron collider	Hadron injectors	e+ e- collider and injectors	Infrastructure, cost estimates	Technology	Physics/Exp'ts
D. Schulte	**B. Goddard**	**J. Wenninger**	**P. Lebrun**	High Field Magnets **L. Bottura**	Hadrons **A. Ball, F. Gianotti, M. Mangano**
				Supercon-ducting RF **E. Jensen**	e+ e- **A. Blondel, J. Ellis, P. Janot**
				Cryogenics **L. Tavian**	e- p **M. Klein**
				Specific Technologies **JM. Jimenez**	

e- p option
Integration aspects **O. Brüning**

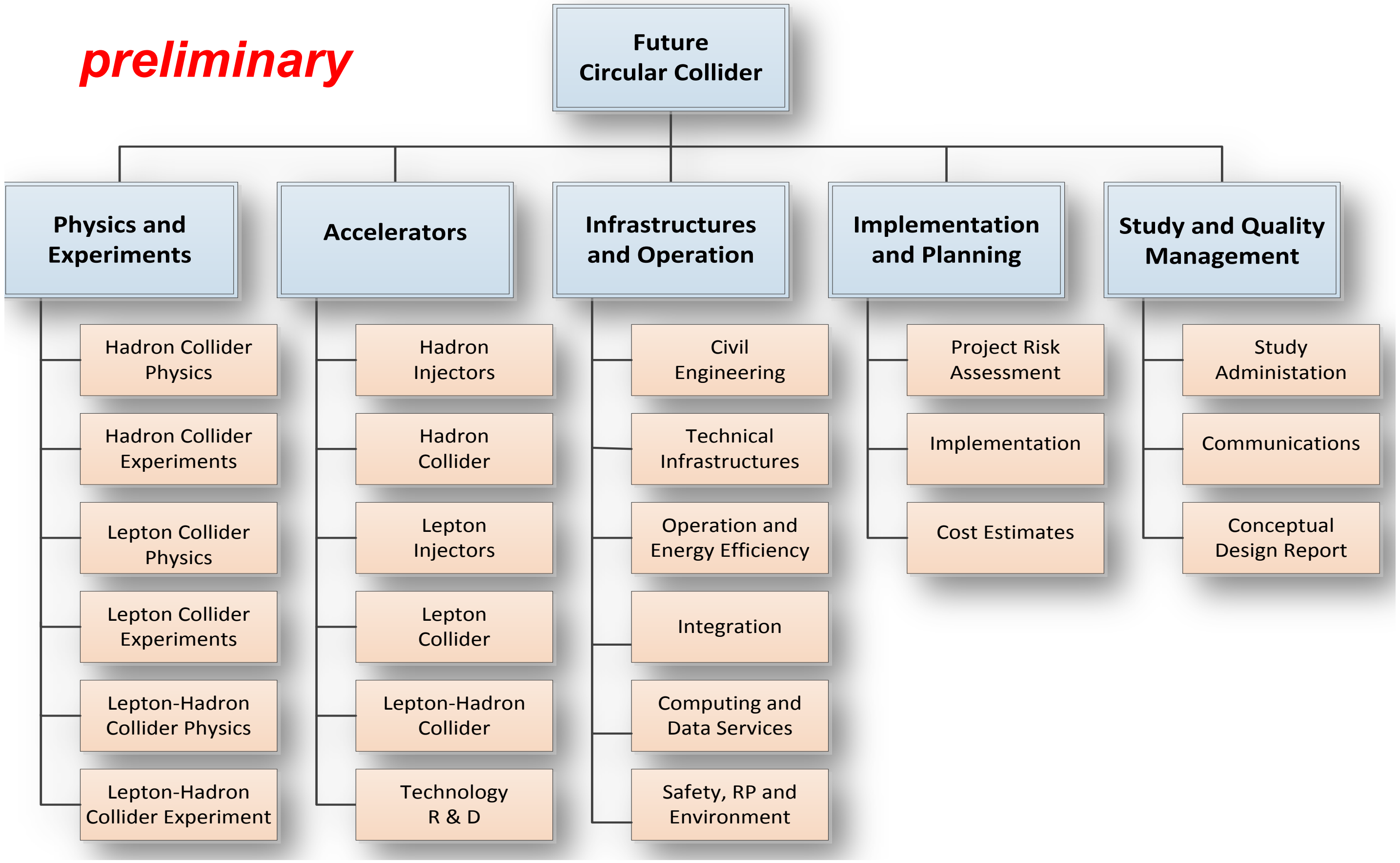
Operation aspects,
energy efficiency, safety, environment **P. Collier**

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann, J. Gutleber

- Aims at defining the work breakdown structure (see next slide)
  - And at gathering working unit (worldwide) coordinators to start the study

The FCC design study: WBS (top level)

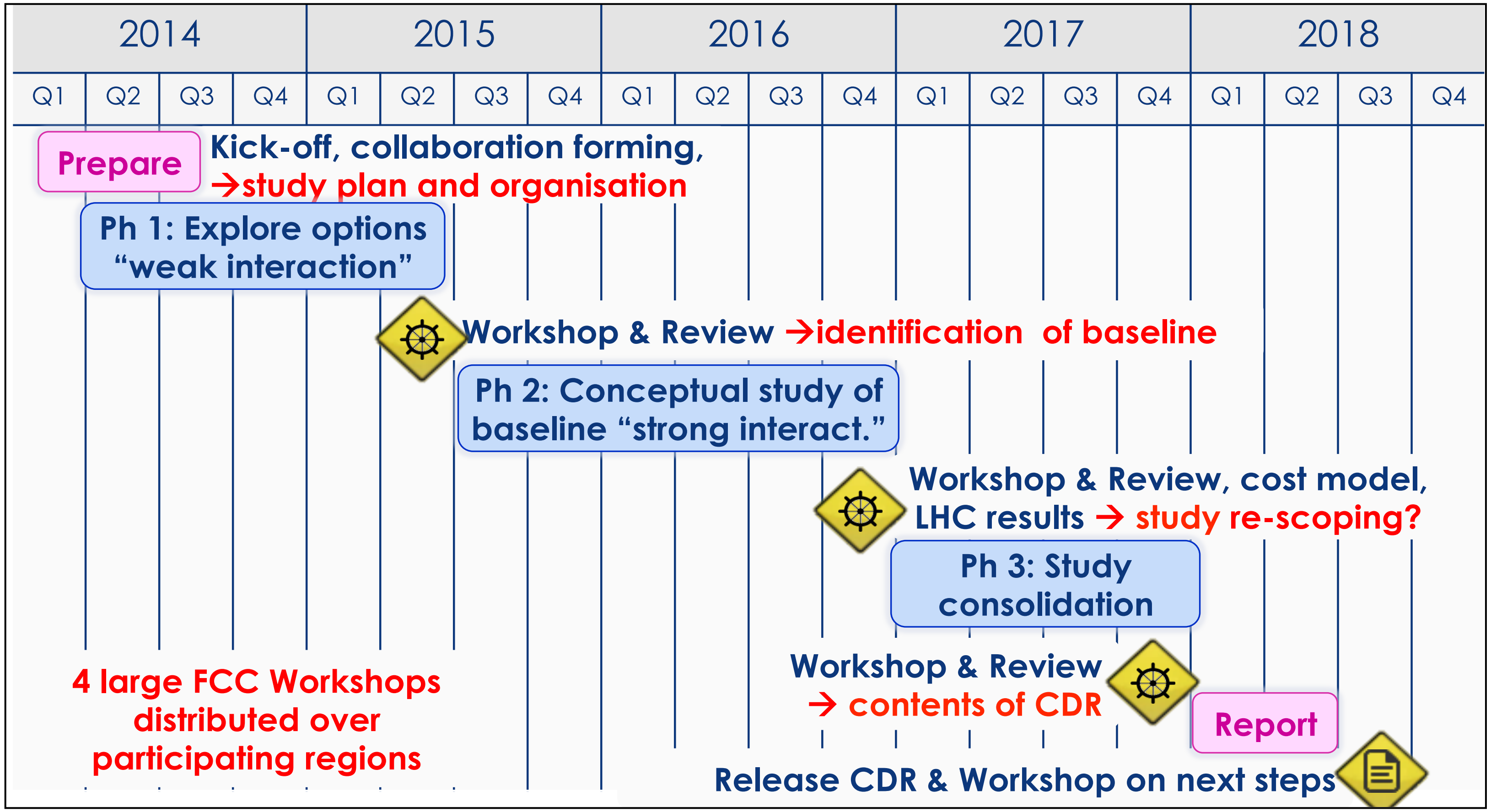
- Lots of boxes (and sub-boxes) towards systematic & global organization



- But this extraordinary project will need thinking out of the box(es)
  - To solve the many challenges ahead, by 2018.

The FCC design study: Timeline

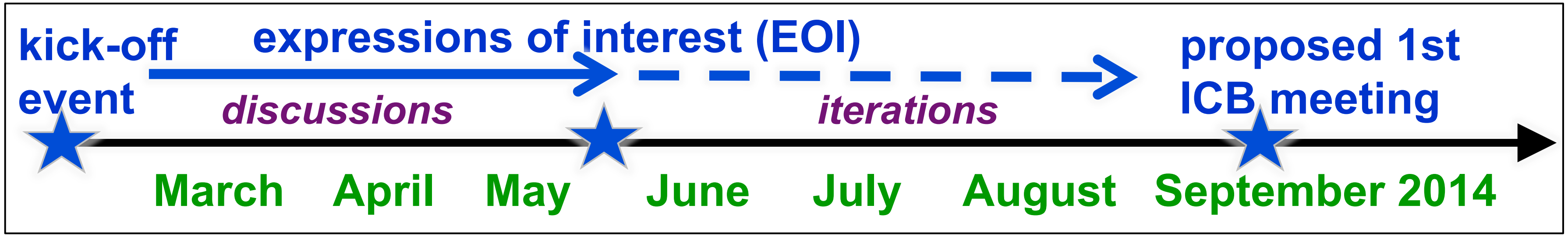
- Three main phases



- Large FCC workshops planned in Spring 2015, Autumn 2016 and Autumn 2017
  - Deliver the final conceptual design report (with cost review) in Summer 2018

The FCC design study: Process in 2014

- **Build the international collaboration after the kick-off meeting**
  - Call for comments/suggestions from international community
    - Discussion on study content, organization, and resources
  - Invite non-committing expression of interest from worldwide institutes
    - By end of May 2014
      - ➨ Process remains open: further joining possible
  - Prepare the formation of an international collaboration board
    - Proposed first meeting in September 2014
      - ➨ To start the actual FCC international study
  - The process is monitored and moderated by the preparation team
    - Until an international team is put in place to conduct the study



The FCC design study: Main areas of work

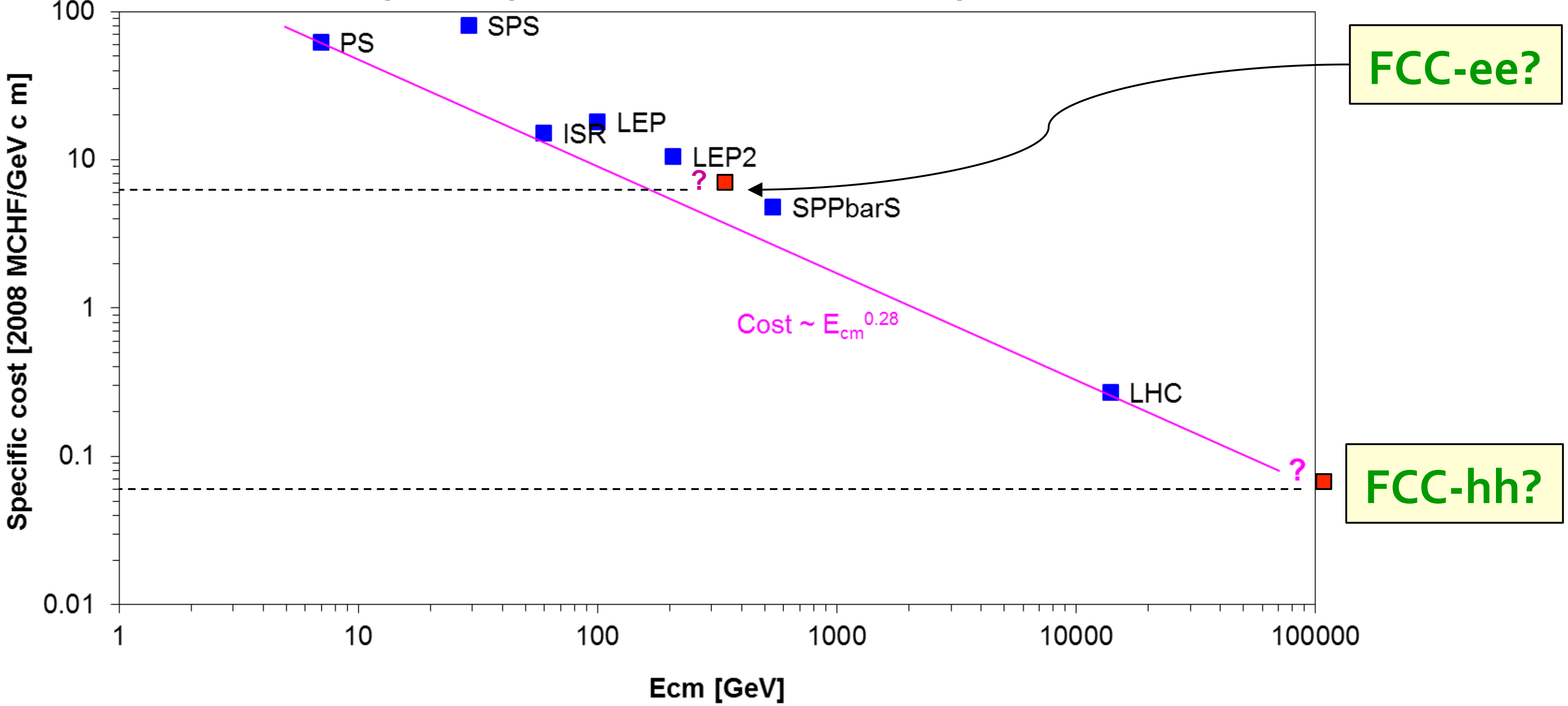
- **Integrates all aspects of machines, detectors, and physics**

Accelerators and infrastructure conceptual designs	Technologies R&D activities planning	Physics experiments detectors
Hadron collider conceptual design	High-field magnets	Hadron coll. physics experiments interface, integration
Lepton collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron and lepton injectors	Cryogenics	e^- - p physics, experiments, Interface, integration
Safety, operation, energy management environmental aspects	Specific technologies	
Infrastructure	Planning	

- **Most aspects of collider/detector designs and R&D are not site specific (global study)**
    - **Tunnel and site study in Geneva area, as European Strategy requested.**

The cost optimization challenge

- It would be purely speculative to give any estimate of the FCC cost now
  - It will have to be reviewed, understood, optimized, in the course of the 5-year study
    - Can learn from past experience: cost/GeV steadily decreases



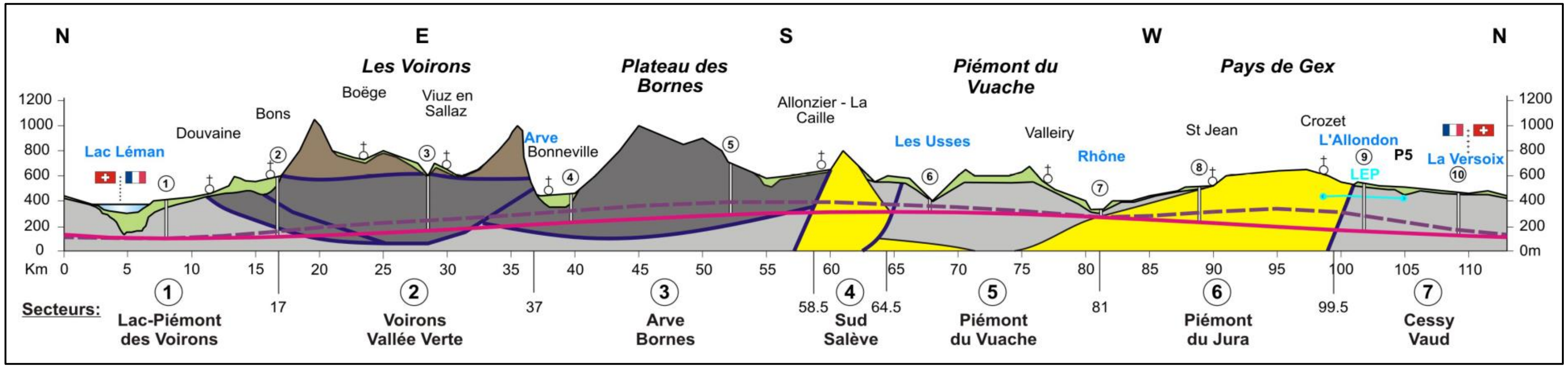
- To be affordable/competitive, the cost will probably need to be reduced to
  - Less than 100 kCHF / GeV for the FCC-hh
  - Less than 5 MCHF / GeV for the FCC-ee

} Inventive solutions are required

The tunnel / infrastructure challenge (1)

- **Getting closer to the Alps …**
  - Deep vertical shafts ?
  - Inclined accesses ?
  - A second campus ?
  - Etc.

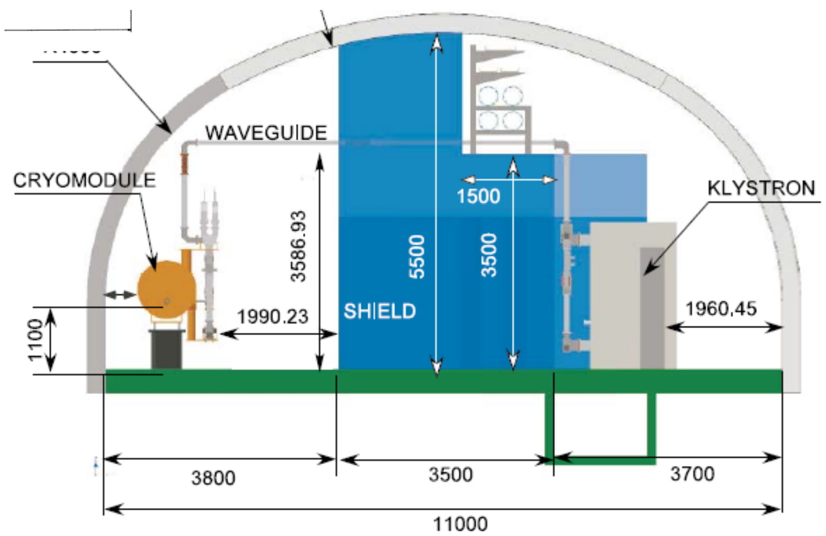
- **Lots of studies needed**
  - In a short time (Phase 1)
  - Profile for a 113 km tunnel: (2001 study)



The tunnel / infrastructure challenge (2)

- **One or several tunnels ?**
  - Equipment (electronics) needs to be radio-protected
    - FCC-hh “clean” in the arcs, but not in the experimental straight sections
    - FCC-ee relatively clean in the straight sections, but not in the arcs
      - ➨ Might need a service tunnel (or a large split tunnel) for the equipment
  - Yet another tunnel ?
    - Safety (personnel evacuation)
    - Transport (infrastructure installation)
    - Access over 100 km (quick intervention)
      - ➨ Reliability is the key here
  - Consensus that one tunnel is not enough

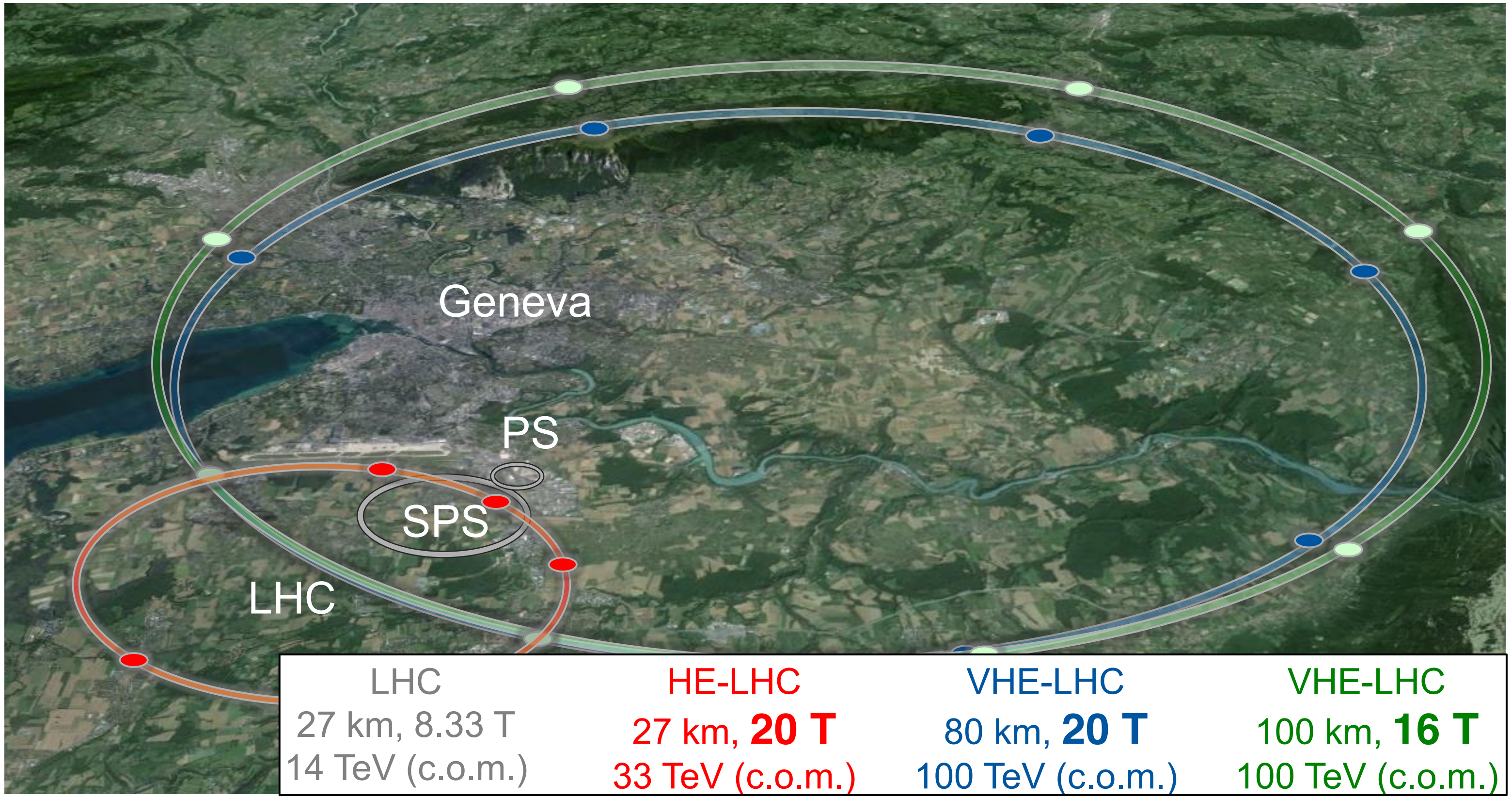
e.g., the ILC tunnel



- **Again, lots to do in a short time**
  - To reduce the number of possible options and start optimization
    - Other labs with related experience are welcome (and keen) to contribute

Superconducting magnet R&D targets (1)

- **Dipole magnets dictate hadron collider cost**



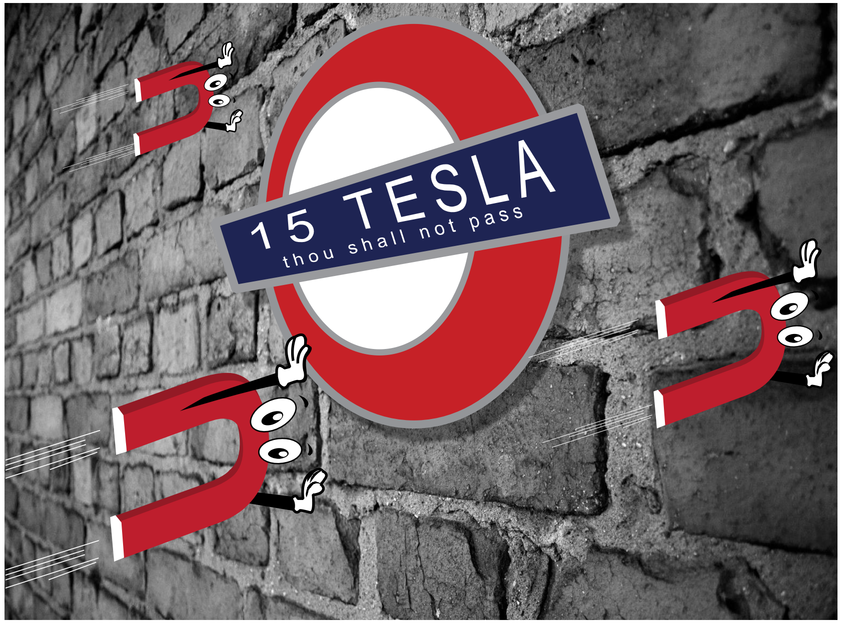
LHC	HE-LHC	VHE-LHC	VHE-LHC
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

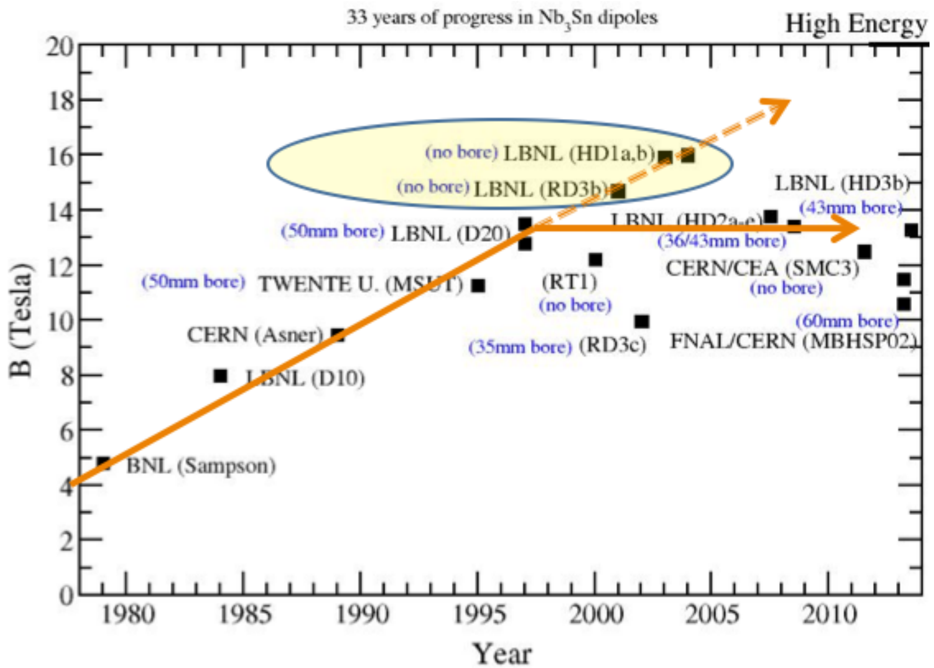
8T: 60% of the cost; 16T: 70% of the cost; 20T: 80% of the cost

- **Must increase magnet field while reducing magnet cost**
  - **Innovative solutions, if not breakthroughs, are needed**

Superconducting magnet R&D targets (2)

- **Increasing magnet field is not easy**
  - Fields above 16T have been reached at LBNL in three configurations with Nb_3Sn
  - But a wall at 14T is hit with realistic bores are incorporated – no progress in 20 years
    - Probably mechanical limitations: New paradigm needed





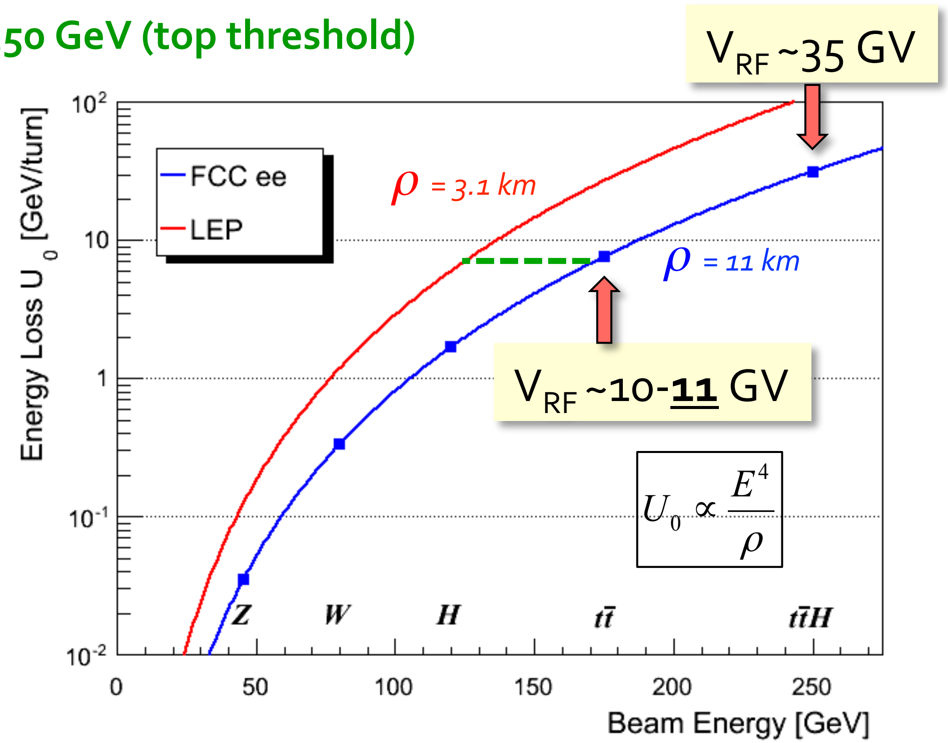
  - Going to 20T requires High Temperature Superconducting magnets
- **Lots of R&D ahead, with America, Asia, Europe**

Superconducting RF R&D targets (1)

- **SC-RF dictates lepton collider cost**
  - Must compensate for the energy lost at each turn by synchrotron radiation
    - About 7.5 GeV lost / turn at √s = 350 GeV (top threshold)
    - < 40 MeV/turn at √s = 90 GeV
  - For a given SR power (50 MW/beam) Two very different regimes
    - High gradients for tt
      - Up to 11 GV

        Was 3.6 GV at LEP2
    - High beam loading at the Z pole
      - Up to 1.5 A beam current

        Was 4 mA at LEP1



  - SC-RF cavities able to function in both regimes do not exist
    - New developments and ideas needed

  - High gradient regime, 20 MV/m: Total RF length = 902 m (cf. LEP2: 812 m)

Superconducting RF R&D targets (2)

- **Main R&D areas**

SC cavity R&D

- **Large Q_0 at high gradient and acceptable cryogenic power**
  - Recent results at 4 K with Nb_3Sn coating on Nb at Cornell
  - $800\ ℃ \div 1400\ ℃$ heat treatment at JLAB
  - Beneficial effect of impurities observed at FNAL
- **Relevant for many other accelerator applications**

High efficiency RF power generation from grid to beam

- Power converter technology
- Klystron efficiencies beyond 65%, alternative RF sources as Solid State Power Amplifier or multi-beam IOT (inductive output tube), etc.
- **Relevant for all high power accelerators, intensity frontier (drivers):**
  J-PARC, SNS, νstorm, LBNE, XFEL, μcoll, ESS, MYRRHA, …

Overall RF system reliability → relevant for *FCC-hh* and *FCC-ee*

R&D Goal is optimization of overall efficiency, reliability and cost!

- Power source efficiency, low-loss high-gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.

The power consumption challenge

- **The FCC will be greedy: innovative solutions needed.**
  - FCC-hh power consumption (LHC×4)
    - Dominated by cryogenics (SR)

System	LHC	FCC-hh
Power Converters	20	80
Machine Cryogenics	35	140
Cooling	20	80
Ventilation	14	56
RF	18	72
Other Machine	2.5	10
Experiments	22	30?
Total / MW	131.5	468

FCC-ee power consumption

Dominated by RF (55% efficiency)

TLEP (175)	MW
RF System	218
Cryogenics	24
Cooling & Ventilation	60
Magnet Systems	6
General Services	15
Experiments	25
Total	353

Reduction/Minimization of the total power required

- Power efficiency in equipment design
- High Efficiency RF power sources (FCC-ee)
- Cryogenic system design and cold mass optimization (FCC-hh)

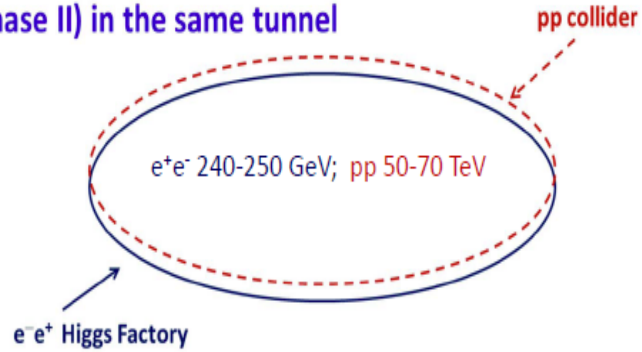
Total (annual) Energy Consumption

- ~~Run less?! (not exactly an option)~~
- Waste heat recovery
- Power reduction during idle periods when beam not available

A global effort (1)

- **Chinese activities for circular colliders**
  - CEPC + SppC

- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



  - Aggressive timeline: 2028 – 2035 for CEPC running, 2042 – 20xx for SppC running
    - Pre-CDR at the end of 2014 !

- We hope to closely collaborate with FCC@CERN

- **It is difficult**
- **But it is very exciting**
- **Even if it is not in China, it is still very beneficial to our field and to the Chinese HEP & Science community**
- **We fully support a global effort**

- **Let's us work for our dream**

A global effort (2)

- **US activities for circular colliders**
  - **Lot of experience due to past and present hadron collider activities**
    - **Tevatron (2 TeV), SSC (40 TeV), V-LHC (200 TeV)**
    - **Major participation to LHC accelerator and experiments (+upgrades)**
  - **Snowmass 2013**

    > The Snowmass study identified, in particular, the promise of a 100 TeV-class hadron collider (VLHC), which would provide a large step in energy with great potential for new insights into electroweak symmetry breaking and dark matter. The feasibility of such a machine should be clarified through renewed accelerator R&D and physics studies over the next decade.

  - **Unique technological expertise**
    - **High field magnet for HL-LHC, SC-RF developments for lepton colliders**
  - **Summary**
    - There is broad acknowledgement that any future collider will need to be a global enterprise, requiring resources (financial, human) from across the globe
    - The U.S. community wants to play a role in any future collider
    - A collaborative focus on magnet and SCRF technologies, and the beam dynamics aspects of large hadron and lepton colliders aligns well with US expertise at the national labs and universities

A global effort (3)

- **ECFA and ICFA are now (back) in the game**
  - **Statement from Rolf Heuer (CERN DG) about ECFA, during the FCC kick-off meeting**

    The design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.

  - **From the minutes of the last ICFA meeting in DESY (21-Feb-2014)**
    - ***"ICFA supports studies of energy frontier circular colliders and encourages global coordination."***
      - ➨ **ICFA also approved the 55th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders**

        This series of meetings had been discontinued in 2012 (!)

        The Workshop will take place on 8-11 Oct. 2014 in Beijing (IHEP)

        The focus will be on Higgs factory

A first step: FCC-ee (TLEP)

The conceptual design study shall also include a lepton collider and its detectors (currently referred to as TLEP), as a potential intermediate step towards realization of the hadron facility. The design of the lepton collider complex shall be based on the hadron collider infrastructure and any substantial incompatibilities with respect to the hadron collider infrastructure requirements shall be analysed and quantified. Potential synergies with linear collider detector designs should be considered.

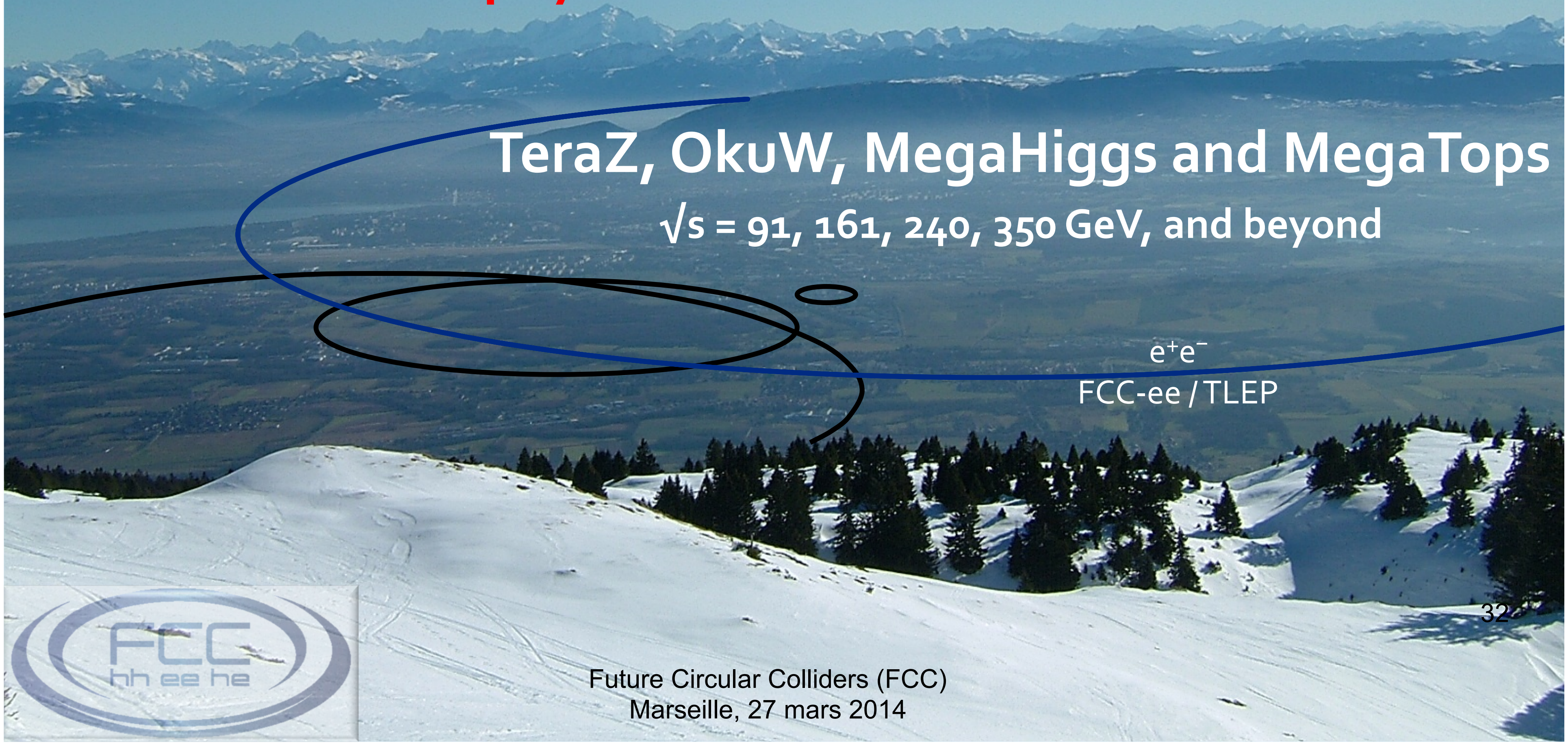
Rolf Heuer

Director General
CERN

Precision physics at the electroweak scale

TeraZ, OkuW, MegaHiggs and MegaTops

$\sqrt{s}$ = 91, 161, 240, 350 GeV, and beyond



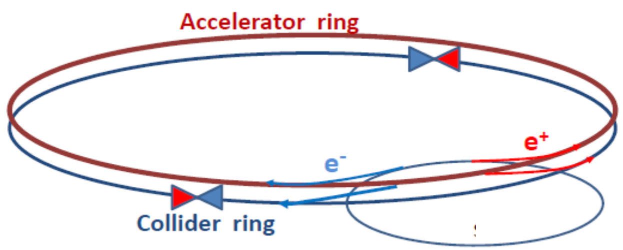
An unprecedented precision (1)

- **Key parameters to achieve high luminosity with TLEP**
  - **Inspired from the progress made from LEP to B Factories**

- Many bunches
- Small vertical β^*
- Flat beams
- Several IPs

Parameter	Z	W	H	tt	LEP2
E_{beam} (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	**16'700**	**4'490**	**1'330**	**98**	**4**
β^*_y (mm)	1	1	1	1	50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (nm)	0.06	0.007	0.002	0.002	0.25
Lifetime (min)	213	52	21	15	300
L (10^{34} cm^{-2}s^{-1})	28	12	**5.9**	1.8	0.012

- **Compensate small lifetime (Bhabha x-section) with continuous top-up injection**



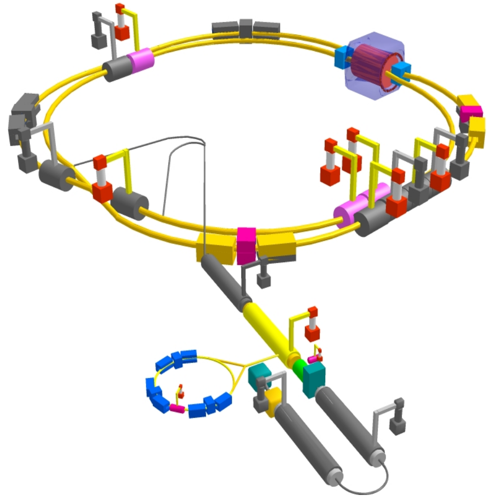
At the Z, 20 ns (or smaller) bunch spacing
Requires 2 separate vacuum chambers for e^+ and e^-, in addition to the booster !

An unprecedented precision (1)

- **Key parameters to achieve high luminosity with TLEP**
  - **Inspired from the progress made from LEP to B Factories**

Parameter	Z	W	H	tt	LEP2
E_{beam} (GeV)	45	80	120	175	104
					4
					4
					50
					30-50
					0.25
					300
					0.012

SuperKEKB will be a TLEP demonstrator



To be commissioned in 2015

Some SuperKEKB parameters :

Beam Lifetime : 5 minutes
TLEP : 15 minutes

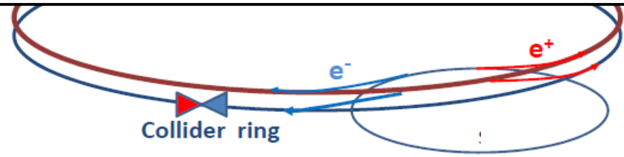
β^*_y : 300 μm
TLEP : 1 mm

σ_y : 50 nm
TLEP : 100 nm

$\varepsilon_y/\varepsilon_x$: 0.25%
TLEP : 0.2% to 0.1%

e^+ production rate : 2.5×10^{12} / s
TLEP : < 1×10^{11} / s

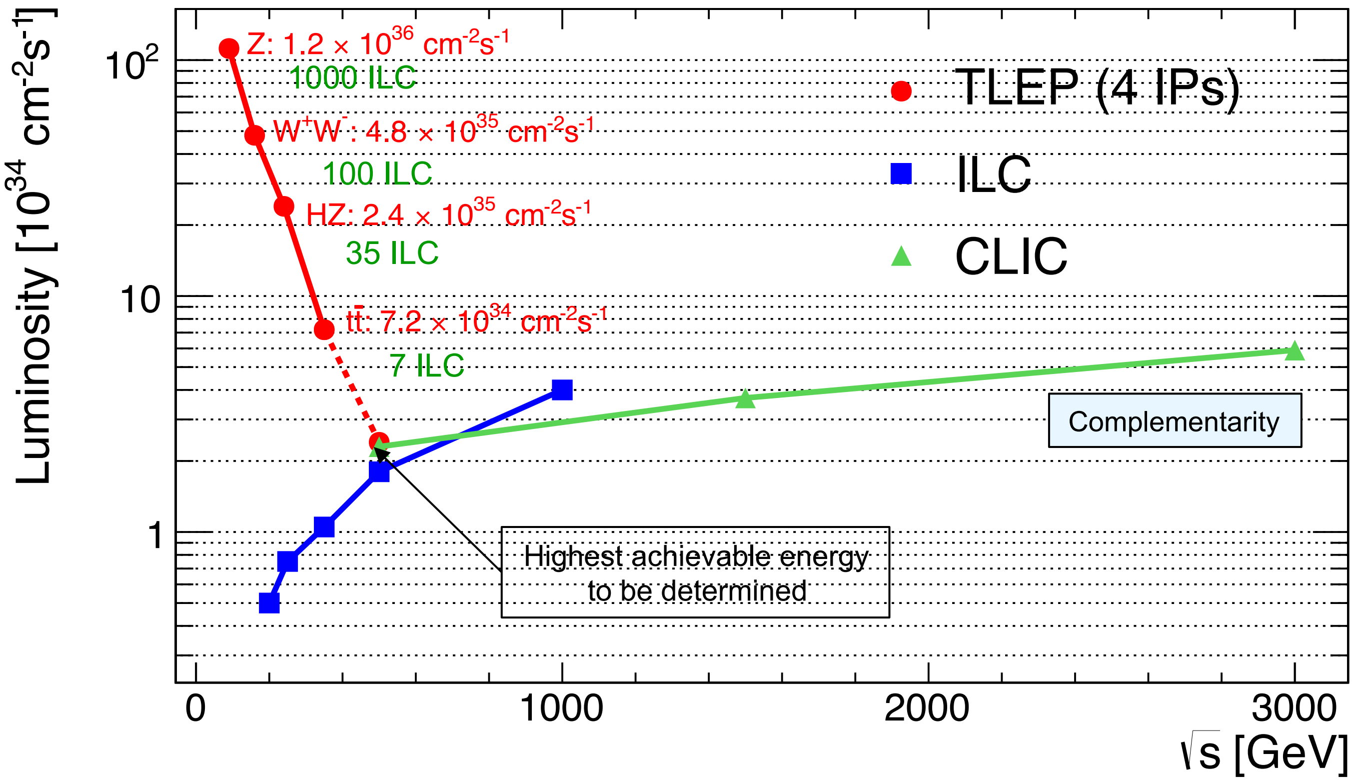
Off-momentum acceptance at IP : ±1.5%
TLEP : ±2.0% to ±2.5%



At the Z, 20 ns (or smaller) bunch spacing Requires 2 separate vacuum chambers for e^+ and e^-, in addition to the booster !

An unprecedented precision (2)

- **Targeted performance of e^+e^- colliders**



TLEP Statistics
10^{12} Z decays (Tera Z)
2×10^8 WW pairs (Oku W)
2×10^6 HZ events (Mega Higgs)
10^6 top pairs (Mega Top)

- **TLEP is a Z, W, Higgs and top factory**
  - **10 to 1000 times the ILC targeted statistics at the same energies**
    - ➨ **Potential statistical accuracies are mind-boggling !**

Caution: Unprecedented challenges

Conclusion (1)

- FCC-ee is designed to be a Z, W, H and t factory.
- This machine has many challenges:
  - *high power and high gradient RF system,*
  - *loads of synchrotron radiation,*
  - *a double ring and a booster (plus an injector chain),*
  - *optics with very low β^*, large acceptance, possibly with crab-waist,*
  - *low lifetime and beamstrahlung,*
  - *polarization,*
  - *4 experiments to serve… and much more.*
- We have to build on the experience from past colliders, and soon from SuperKEKB.

Best of FCC-ee / TLEP measurements

- **Published !**

First look at the physics case of TLEP

The TLEP Design Study Working Group

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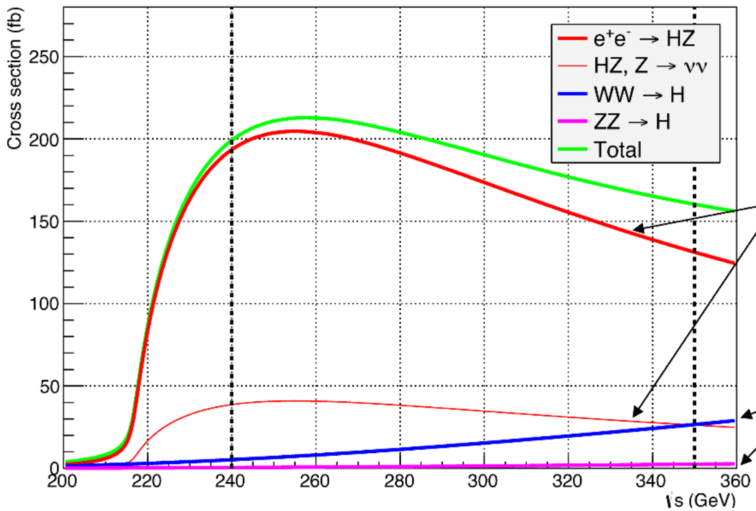
JHEP01(2014)164

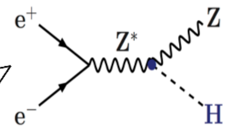
Abstract: The discovery by the ATLAS and CMS experiments of a new boson with mass around 125 GeV and with measured properties compatible with those of a Standard-Model Higgs boson, coupled with the absence of discoveries of phenomena beyond the Standard Model at the TeV scale, has triggered interest in ideas for future Higgs factories. A new circular e^+e^- collider hosted in a 80 to 100 km tunnel, TLEP, is among the most attractive solutions proposed so far. It has a clean experimental environment, produces high luminosity for top-quark, Higgs boson, W and Z studies, accommodates multiple detectors, and can reach energies up to the $t\bar{t}$ threshold and beyond. It will enable measurements of the Higgs boson properties and of Electroweak Symmetry-Breaking (EWSB) parameters with unequalled precision, offering exploration of physics beyond the Standard Model in the multi-TeV range. Moreover, being the natural precursor of the VHE-LHC, a 100 TeV hadron machine in the same tunnel, it builds up a long-term vision for particle physics. Altogether, the combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market. This paper presents a first appraisal of the salient features of the TLEP physics potential, to serve as a baseline for a more extensive design study.

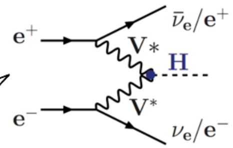
Best of FCC-ee / TLEP: Higgs Factory (1)

- **About 2.5×10^6 tagged Higgs after 4 years at 240 and 350 GeV**

	TLEP 240	TLEP 350
Total Integrated Luminosity (ab^{-1})	**10**	**2.6**
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	**340,000**
Number of Higgs bosons from boson fusion	**50,000**	**70,000**







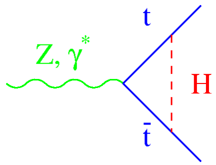
Meas't	Precision
g_{HZZ}	0.05%
g_{HWW}	0.09%
g_{Hbb}	0.23%
g_{Hcc}	0.68%
$g_{H\tau\tau}$	0.49%
$g_{H\mu\mu}$	6.2%
$g_{H\gamma\gamma}$	1.4%
g_{Hgg}	0.79%
Γ_{inv}	0.16%
Γ_{tot}	0.9%
g_{Htt}	13%
g_{HHH}	28%

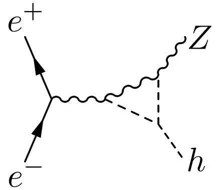
Sensitive to new physics at tree level ~ 5% / Λ^2_{NP}

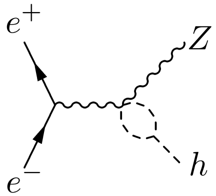
Sensitive to new physics in loops

Sensitive to dark matter (χ, sterile ν, …)

Better done at hadron colliders (HL-LHC, FCC-hh)







Best of FCC-ee / TLEP: Higgs Factory (2)

- **From Snowmass '13**
  - **Model-independent fit of the couplings**

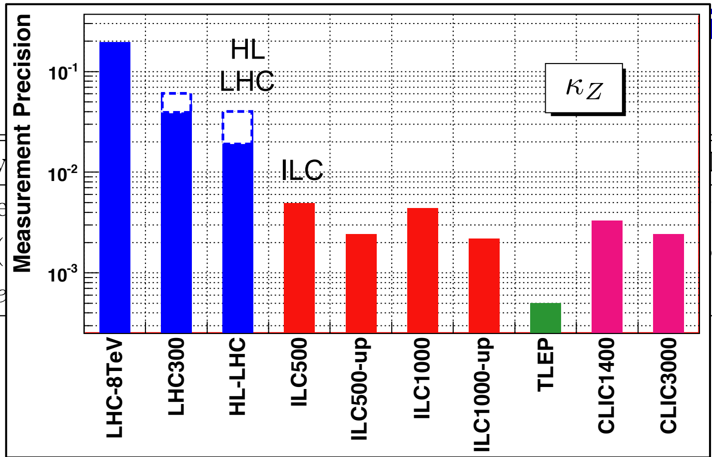
Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

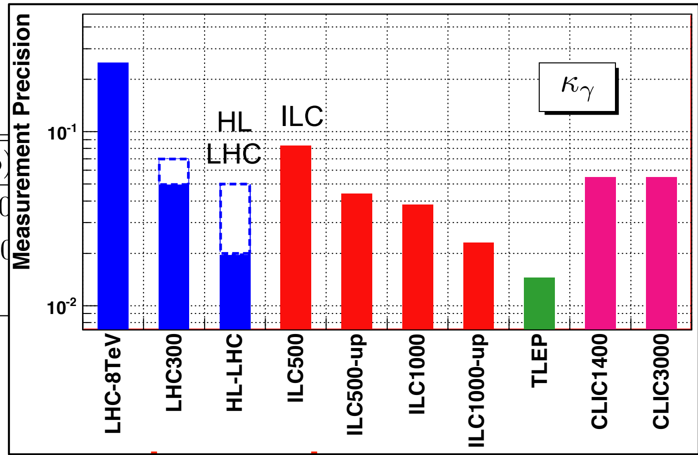
The 10B$ ILC, 10 years
1-10% precision

TLEP, 10 years
0.1-1% precision

Best of FCC-ee / TLEP: Higgs Factory (2)

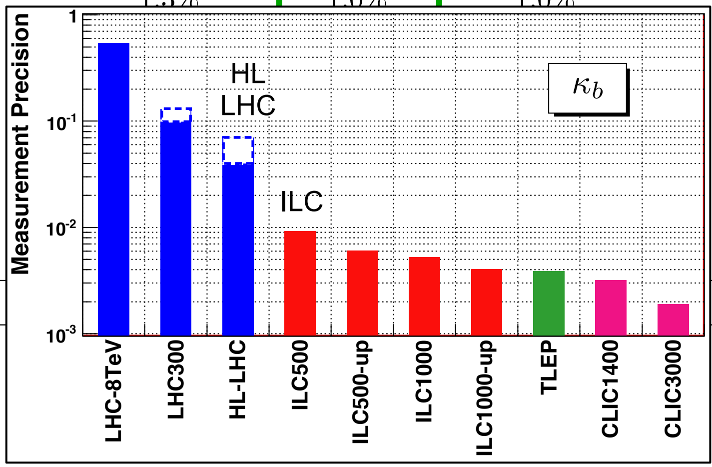
- **From Snowmass '13**

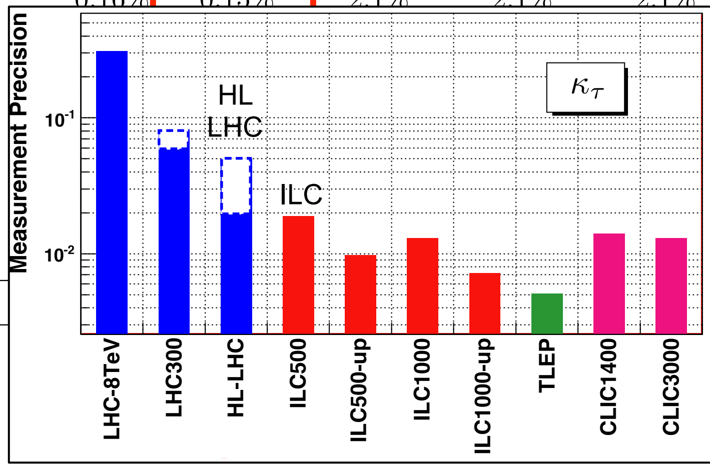




...ings

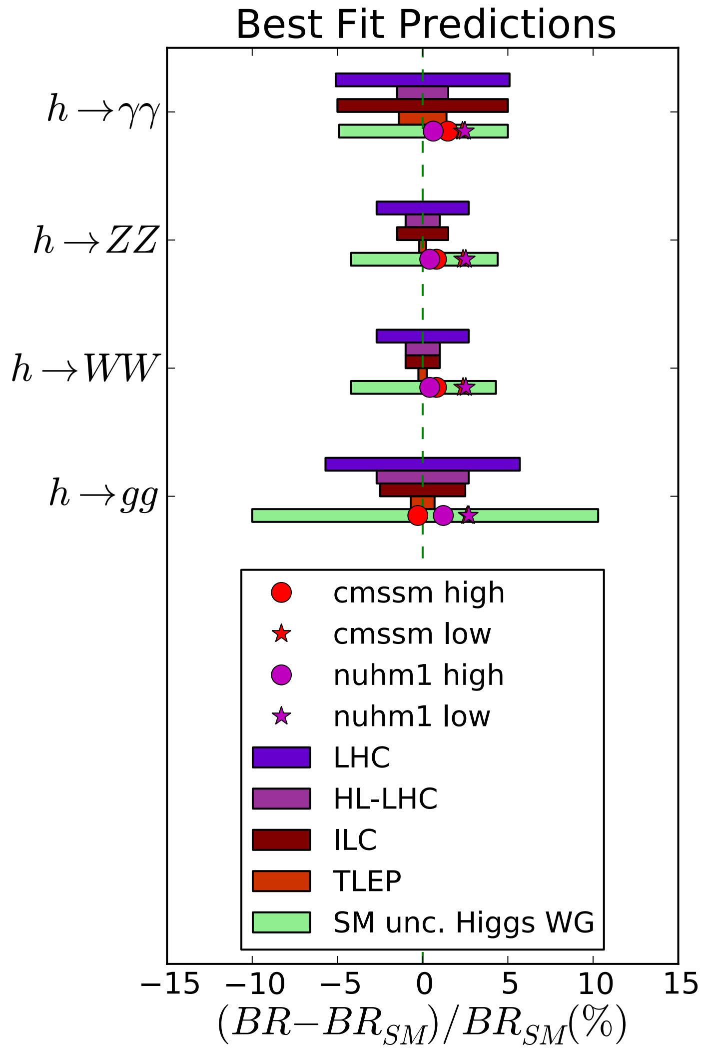
Facility				LC(LumiUp)					
$\sqrt{s}$ (Ge				50/500/1000					
$\int \mathcal{L}dt$ (				0+1600+250					
$P(e^-, e$				(same)					0)
Γ_H				2.5%					
κ_γ				2.4%					
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ				10%					
κ_τ				1.0%					
κ_c				1.1%					
κ_b				0.8%					
κ_t				2.0%					
BR_{inv}				0.4%					





Best of FCC-ee / TLEP: Higgs Factory (3)

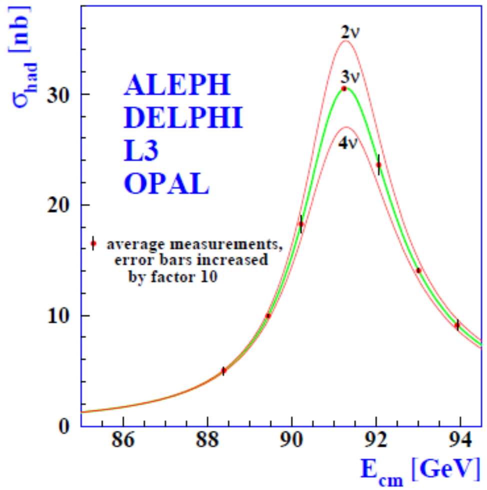
- **Impact of Higgs measurements**
  - Compare the predictions of the current best fits in simple SUSY models
    - With SM predictions and current uncertainties in SM calculations (LHC Higgs Working Group)
  - And with LHC, HL-LHC, ILC, TLEP
- **TLEP is able to distinguish from SM**
- **Need to reduce theoretical uncertainties to match experimental potential**
  - Essential for new physics interpretation
    - Feasible at the timescale of TLEP
      - Can already do much better than current LHCWG estimates (Kuhn)



Best of TLEP: Precision EW measurements (1)

- **TeraZ – Z resonance scan at $\sqrt{s}$ ~ 91 GeV : 1-2 years**
  - Get 10^{12} Z decays at 15 kHz/IP. Repeat LEP1 physics programme every 15 minutes

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics



- Predicting accuracies with 250 times smaller statistical precision than at LEP is difficult
  - Used LEP experience for systematics. Will be revisited – this is just the start.

- **Longitudinally polarized beams at $\sqrt{s} = m_Z$ with reduced lumi : 1 year**
  - Get ~10^{11} Z decays, and measure A_{LR}, A_{FB}^{pol}, etc.

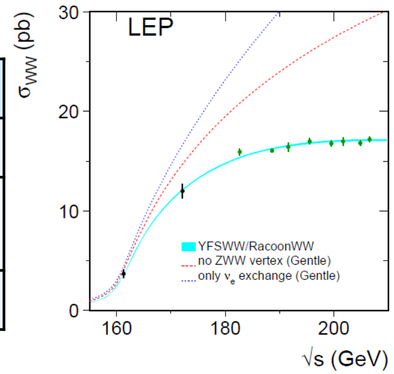
Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
A_{LR}	Z peak, polarized	0.1514 ± 0.0022	0.000015	< 0.000015	Design Expt

Polarization wigglers, Spin rotators, etc.

Best of TLEP: Precision EW measurements (2)

- **OkuW – WW threshold scan at √s ~ 161 GeV: 1-2 years**
  - **Get ~10^8 W decays; Measure the W mass and Γ_Z^{inv}; Precise W studies.**

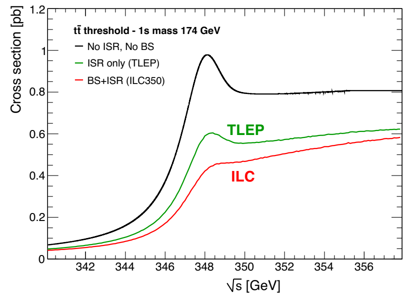
Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix



- **Caution: 2000 times smaller statistical precision than at LEP at WW threshold**

- **MegaTops – top threshold scan at √s ~ 350 GeV: 5 years**
  - **Get ~10^6 top pairs; Measure top mass, width and Yukawa coupling**

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$



- **Watch out the moon: up to 1.5 GeV excursions of the c.m. energy!**

Best of TLEP: Precision EW measurements (3)

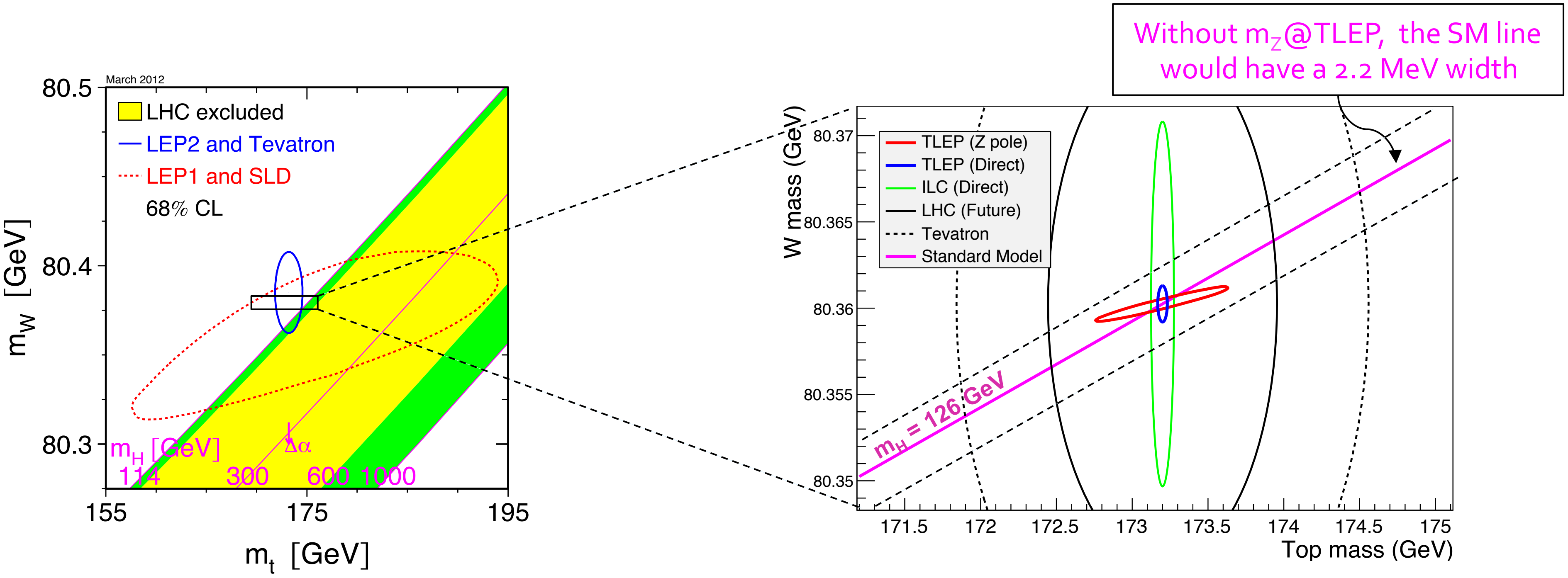
- **Important assets unique to circular e^+e^- machines**
  - Large luminosity
    - Statistics is the key for precision
      - ➨ In many cases, will also allows systematic uncertainties to be reduced
  - Beam energy calibration with resonant depolarization of "single" bunches
    - Use "single" bunches while running: no interpolation errors due to tides, etc.
      - ➨ Beam energy can be measured continuously to better than 100 keV

        Essential for the measurement of Γ_Z, m_Z and m_W
  - Centre-of-mass energy definition
    - Negligible beamstrahlung – luminosity spectrum known from first principles
      - ➨ Negligible related systematic uncertainties

        Important for the measurement of m_{top}
  - Small IP backgrounds and pile-up
    - Negligible beamstrahlung (photons, e^+e^- pairs, …) ; no bunch train
      - ➨ Places reasonable requests on detectors

Best of TLEP: Precision EW measurements (4)

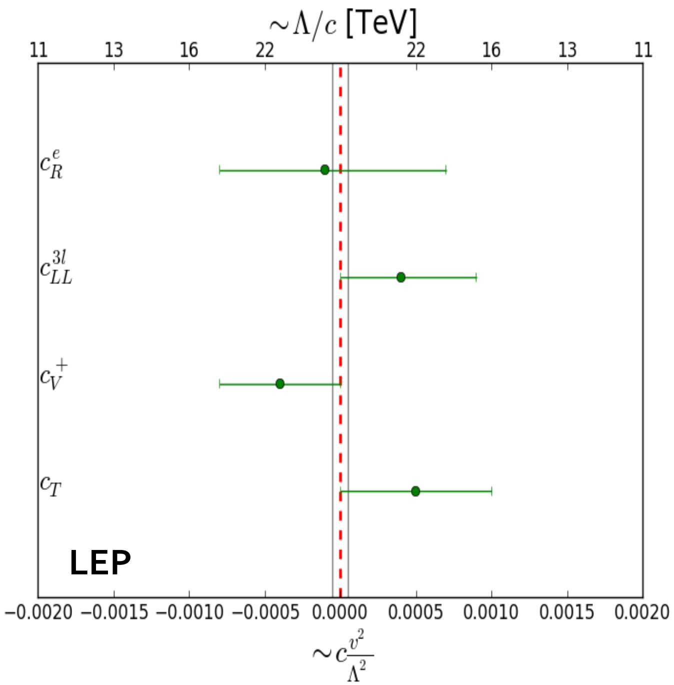
- When m_W, m_{top} and m_H are known with precision …
  - The standard model has nowhere to go !

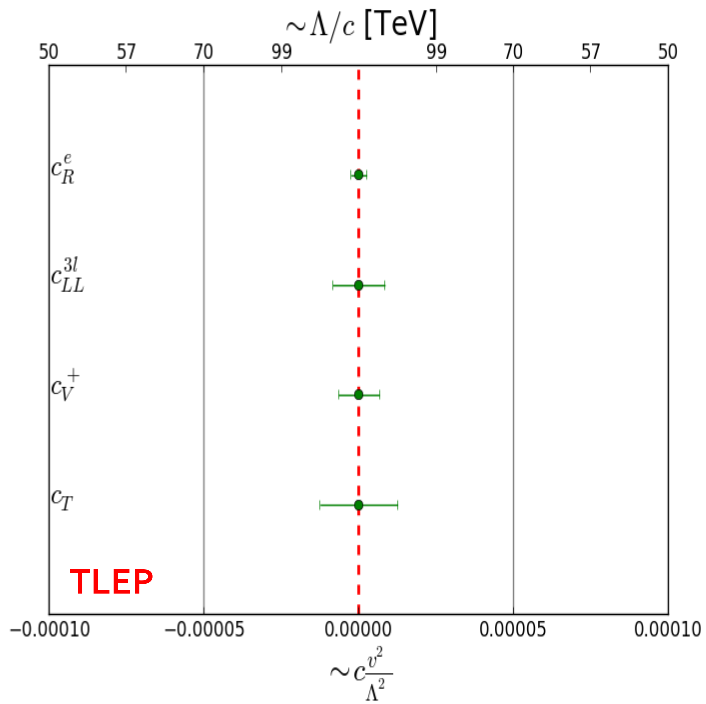


Best of TLEP: Precision EW measurements (4)

- When m_W, m_{top} and m_H are known with precision …
  - The standard model has nowhere to go !
    - Sensitivity to higher-dimension operators $\Delta\mathcal{L}_{\rm input} = \frac{c_T}{v^2}\mathcal{O}_T + \frac{c_V^+}{m_W^2}(\mathcal{O}_W + \mathcal{O}_B) + \frac{c_{LL}^{(3)\,l}}{v^2}\mathcal{O}_{LL}^{(3)\,l}$

m_W [GeV]





Today: Λ_{NP}> 10 TeV

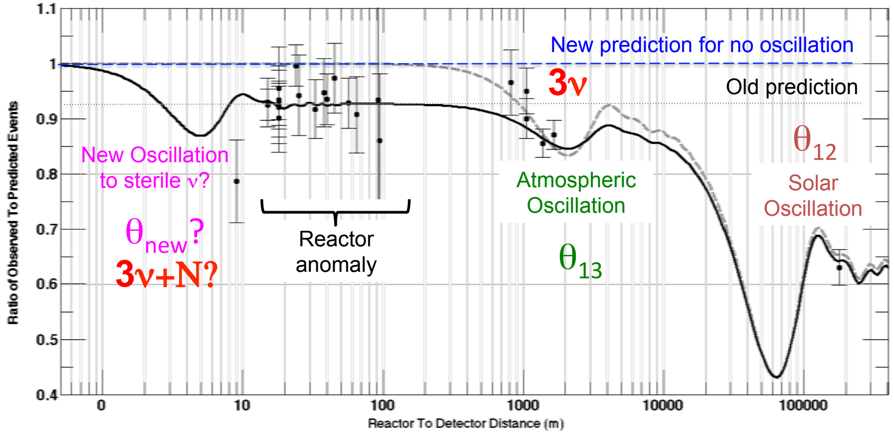
Sensitivity to Weakly-coupled NP

After TLEP: 100 TeV ?

Best of TLEP: Rare decays and new physics

- **Rare decays: the twin frontier of TLEP beyond precision measurements**
  - How far can we go with 10^{12} Z (hence 10^{11} b, c, τ), $>10^8$ W, $>10^6$ Higgs, $>10^6$ top quarks ?
    - FCNC, LFV, Invisible/exotic Higgs decays (e.g., $H \to \nu N$, $\chi\chi$), heavy neutrinos, ...
    - Dark matter search through $e^+e^- \to \chi\chi + \gamma$ from ISR, down to minute couplings
- **Example : neutrino counting and measurement of Γ_Z^{inv}**
  - Makes the connection with the neutrino / dark-matter sector
    - Two hints of sterile neutrinos N_i, mixing with active neutrinos ν_i
      - ➨ Reactor anomaly : deficit at short distance

$>3\sigma$ effect



- ➨ Z invisible width deficit at LEP (PMNS matrix unitarity violation?)

$N_\nu = 2.984 \pm 0.008$, ~2σ effect. Would become 16σ @ TLEP

TLEP/FCC-ee Design Study: Physics WBS (1)

- **Experimental Physics (coordinators A. Blondel, P. Janot)**
  - **Study the properties of the Higgs and other particles with unprecedented precision**

Electroweak Physics at the Z pole **R. Tenchini**	Di-boson Physics m_W measurement **R. Tenchini**	H(126) Properties **TBA**	Top Quark Physics **P. Azzi**

QCD and $\gamma\gamma$ Physics (Joint exp/th) **D. d'Enterria**	Flavour Physics (Joint exp/th) **S. Monteil**	Exp'tal signatures of New Physics **M. Pierini**

  - **Develop the necessary tools** — **Understand the experimental conditions**

Offline Software and Computing **TBA**	Online Software and Computing **C. Leonidopoulos**	Exp'tal Environment **N. Bacchetta**
Synergy with FCC-hh		Synergy with FCC-hh

  - **Set constraints on the possible detector designs to match statistical precision**

Detector Designs
G. Rolandi

Synergy with linear collider detectors

TLEP/FCC-ee Design Study: Physics WBS (2)

- **Phenomenology/Theory (coordinators J. Ellis, C. Grojean)**
  - **Set up a long-term programme to match theory predictions to experimental precisions**

QCD and $\gamma\gamma$ Physics (Joint exp/th) **P. Skands**	Precision EW calculations **S. Heinemeyer**	Flavour Physics (Joint exp/th) **TBA**

  - **Understand how new physics would show up in precision measurements, and in searches for rare decays (Z, W, t, H, b, c, τ, …) and rare processes**

Model Building and New Physics
TBA

Synergy with
FCC-hh physics
Linear collider physics,
LEP physics

  - **Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)**

Global Analysis, Combination, Complementarity
TBA

TLEP/FCC-ee Design Study: Physics WBS (3)

- The job of the conveners include
  - Define work areas
  - Assemble collaborators
  - Find co-conveners
    - In a global way

- If you are interested in contributing
  - Contact the relevant coordinators and conveners
    - And subscribe at http://cern.ch/fcc-ee
      - Already ~400 people joined the project – you won't be alone

- The work is starting now, for a duration of five years
  - Unique opportunity to contribute from the beginning to a major project
    - With significant synergies with other projects (ILC, CLIC, FCC-hh, SuperKEKB, …)
      - Physics (phenomenology and analysis)
      - Software
      - Detector designs

The ultimate goal: FCC-hh (VHE-LHC)

The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV (currently referred to as VHE-LHC) in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies. The hadron collider and its detectors shall determine the basic requirements for the tunnel, surface and technical infrastructures. The corresponding hadron injector chain shall be included in the study, taking into account the existing CERN accelerator infrastructure and long-term accelerator operation plans. The performance and cost of the hadron collider shall be compared to a high-energy LHC based on the same high-field magnet technology and housed in the LHC tunnel.

Rolf Heuer
Director General
CERN

Explore, Search, Measure

Physics at the highest energies

FCC-hh physics case

- **According to Chris Quigg and Michelangelo Mangano**

It is premature to develop the scientific case for the "100-TeV" collider,

but the right time to explore possibilities.

What we do for "100-TeV" can enhance what we achieve with LHC

LHC might point to an energy landmark

Explore

Search

Measure

This process is starting now, a lot of work is required, and it premature to draw conclusions now

- **Join the study: subscribe to fcc-experiments-hadron@cern.ch**

FCC-hh physics studies (1)

- ## Working Group #1: Measure

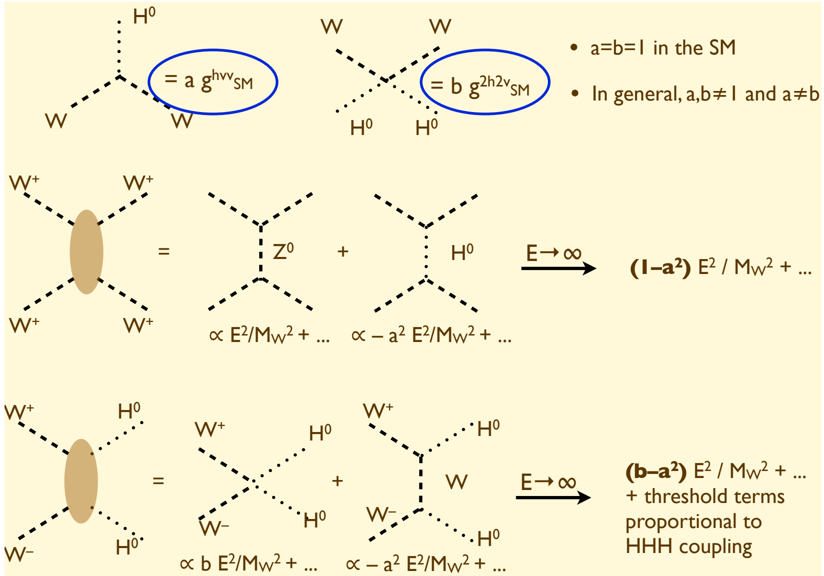
FHC.1.1 Exploration of EW Symmetry Breaking (EWSB)

FHC.1.1.1 High-mass WW scattering, high mass HH production

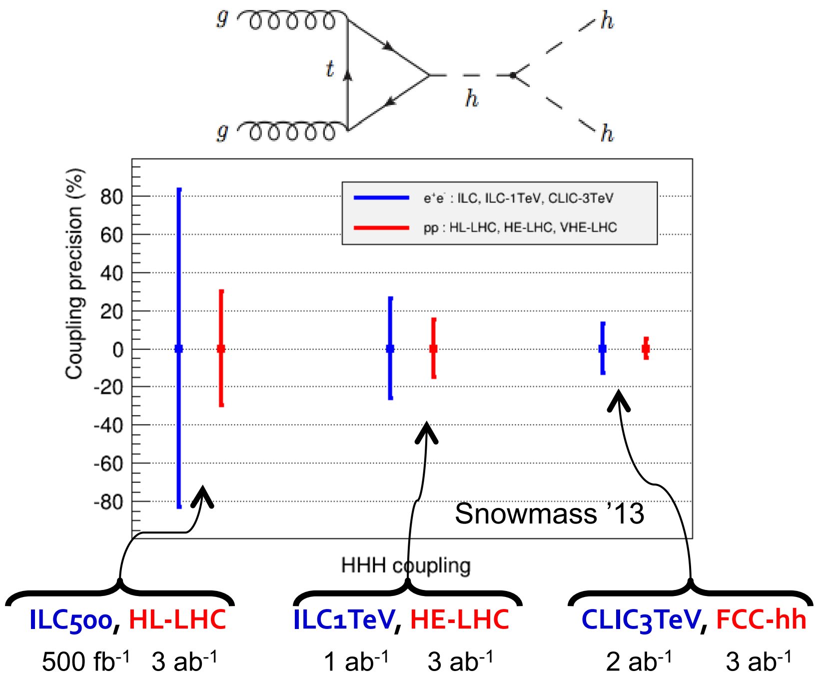
FHC.1.1.2 Rare Higgs production/decays and precision studies of Higgs properties

FHC.1.1.3 Additional BSM Higgs bosons: discovery reach and precision physics programme

FHC.1.1.4 New handles on the study of non-SM EWSB dynamics (e.g. dynamical EWSB and composite H, etc)



Precision on a and b with FCC-hh expected to be of the order of 1% **(vs 30% @ CLIC and 50% @ LHC-14)**



FCC-hh physics studies (2)

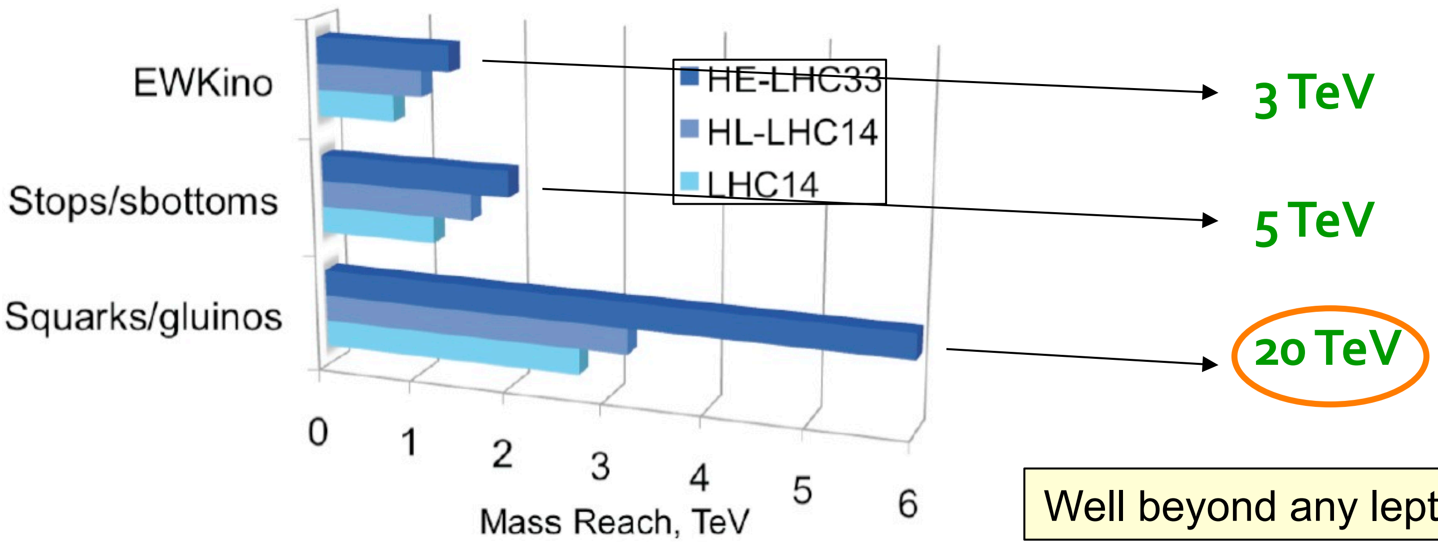
❑ Working Group #2: Search

FHC.1.2 Exploration of BSM phenomena

FHC.1.2.1 discovery reach for various scenarios (SUSY, new gauge interactions, new quark and leptons, compositeness, etc.)

FHC.1.2.2 Theoretical implications of discovery/non-discovery of various BSM scenarios,

- FHC.1.2.2.1 what remains of Supersymmetry if nothing is seen at the scales accessible at 100 TeV?
- FHC.1.2.2.2 which new opportunities open up at 100 TeV for the detection and study of dark matter?
- FHC.1.2.2.3 which new BSM frameworks, which are totally outside of the HL-LHC reach, become accessible/worth-discussing at 100 TeV ?



Sets the scale for possible reach

Well beyond any lepton collider reach

FCC-hh physics studies (3)

- **Working group #3: Explore**

FHC.1.3 Continued exploration of SM particles
FHC.1.3.1 Physics of the top quark (rare decays, FCNC, anomalous couplings, ...)
FHC.1.3.2 Physics of the bottom quark (rare decays, CPV, ...)
FHC.1.3.2 Physics of the tau lepton (e.g. tau -> 3 mu, tau -> mu gamma and other LFV decays)
FHC.1.3.2 W/Z physics
FHC.1.3.3 QCD dynamics

10 ab^{-1} at 100 TeV imply: 10^{12} top quarks => 5 10^4 x today

=> 10^{12} W bosons from top decays
=> 10^{12} b hadrons from top decays (particle/antiparticle tagged)
=> 10^{11} t $\rightarrow$ W $\rightarrow$ taus
=> few x10^{11} t $\rightarrow$ W $\rightarrow$ charm hadrons

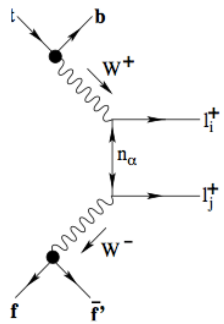
o BSM decays -- Are there interesting channels to consider?

-- Example

BNL-HET-06/9
OITS-784

Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]



FCC-hh experiments studies (1)

- **Three working groups**

2.2	**Hadron collider experiments**
2.2.1	**Detector performance**
2.2.1.1	Rapidity coverage for tracking, leptons, jets
2.2.1.2	Forward tracking and b-tag vs pile-up density
2.2.1.3	Electromagnetic calorimeter: dynamic range, forward granularity
2.2.1.4	Forward jet tagging
2.2.1.5	Muon resolution in the O(10 TeV) region
2.2.1.6	Optimisation of the bunch spacing (trigger and readout vs pile-up)
2.2.2	**Technical systems**
2.2.2.1	Technologies that require R&D
2.2.2.2	Detector technologies
2.2.2.3	Radiation effects
2.2.2.4	Shielding
2.2.2.5	ECAL
2.2.2.6	HCAL
2.2.2.7	Magnet system
2.2.2.8	Muon detection
2.2.2.9	Inner detector
2.2.2.10	Tracking
2.2.2.11	Trigger system
2.2.2.12	Data acquisition, detector controls and detector safety
2.2.3	**Detector machine Interface**
2.2.3.1	L*, TAS, TAN locations and specifications
2.2.3.2	Bunch structure, luminous region and crossing angle
2.2.3.3	Beam pipe and vacuum design
2.2.3.4	Fluencies, shielding, dose rates, activation, and radiological dose minimization
2.2.3.5	Physics and detector protection instrumentation in the long straight section

Performance requirements and experimental challenges

Detectors layout, R&D and technologies
→ synergies with FCC-ee, ILC and CLIC being established

Detector-machine interface issues

FCC-hh experiments studies (2)

- **Detectors will be a formidable challenge**
  - 171 in-time pile-up events with 25 ns bunch spacing, bunch length 5 cm
    - High-granularity calorimetry, tracking and vertexing required
  - Reduced to 35 in-time pile-up events with 5 ns bunch spacing
    - Ultra fast detectors required (out-of time pile-up)

  - Large longitudinal event boost
    - Enhanced coverage at large rapidity required (with tracking and calorimetry)
  - Zs, Ws, Higgses, tops, will also be boosted
    - Again, high-granularity detectors needed

  - Very energetic charged particles
    - Precise momentum measurement up to 10 TeV require large coil and tracker
  - Very energetic jets
    - Energy containment require thicker calorimeter

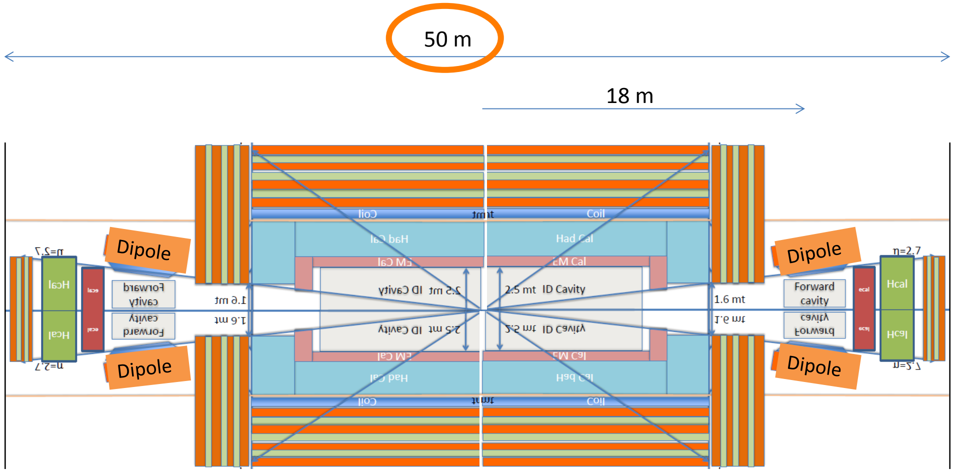
  - Construction and transport of large detector elements
    - Worlwide modular construction might not be possible. On-site construction ?

FCC-hh experiments studies (2)

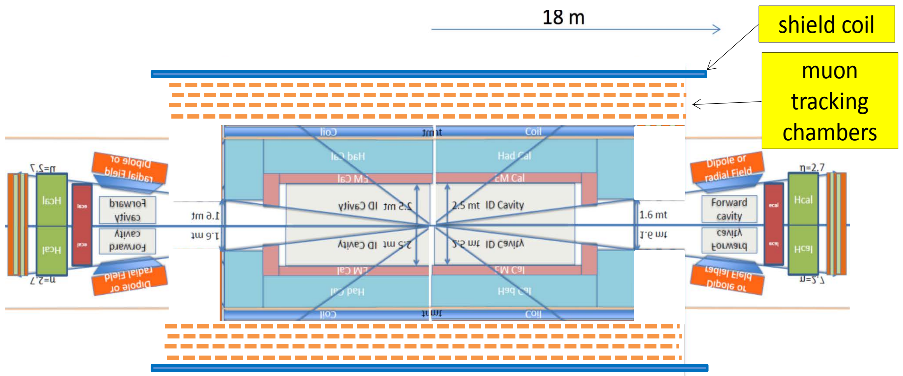
- Dete … e ch
  - 17 … 25 ns
    … ry, tr
  - R … ents
    … d (ou
  - La
    … e rap
  - Z … be boosted
    … tectors ne
    … ent up … er
    … icker
    … detec
    … n migh … n ?

FCC-hh experiments studies (3)

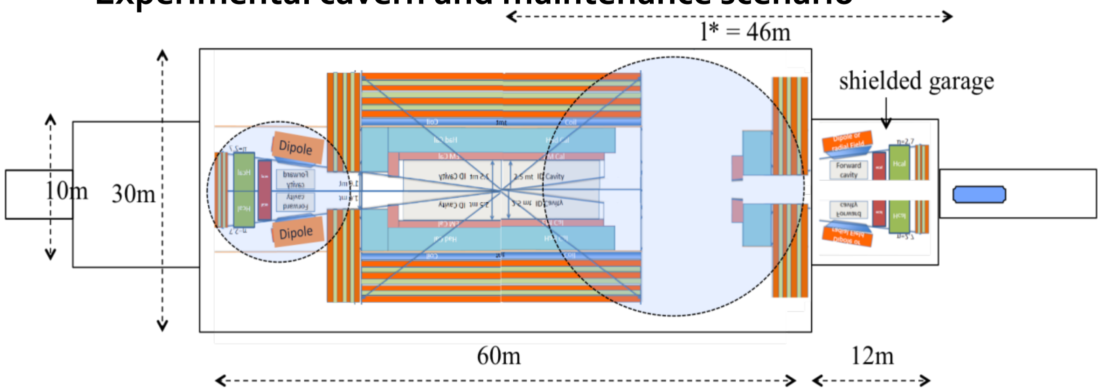
- **Bigger, thicker, faster, clever …**
  - **Example : long solenoid (6T) + dipoles (2T) + return yoke (a la CMS)**



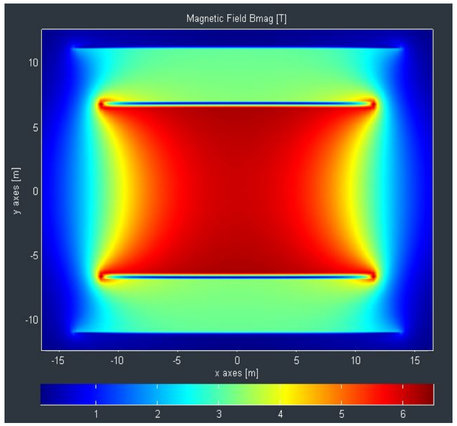
+ shield coil (3T) to avoid 120 kt yoke !



Experimental cavern and maintenance scenario



Some debate on how fields add up…



Conclusions

- The results of the LHC Run1/2 will be a precious input to the strategy
  - The next machine must bring order(s) of magnitude improvement wrt LHC
    - Both in precision measurements and in discovery potential
- The FCC opens a unique road towards the 100 TeV energy scale
  - "The combination of TLEP and the VHE-LHC offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market"

    "First look at the physics case of TLEP", arXiv:1308.6176
- The many challenges in front us will require worldwide collaboration
  - Using all expertise available in all areas
    - physics, experiments, machines and infractures
- The global design study for future circular colliders has begun at CERN
  - Funding agencies and institutes worldwide will shortly be / are being contacted
    - Mandate is to deliver a full design study for e^+e^- and pp, with extended cost reviews
      - ➨ by the next European Strategy (2019?)
  - It may be the birth of another 50 grand years of high-energy physics !

Conclusions