Beyond the Higgs Discovery

Research at the LHC & the future of Collider Physics

Christos Leonidopoulos

THE UNIVERSITY of EDINBURGH

Higgs Maxwell Particle Physics Workshop
Royal Society of Edinburgh – 26 February 2014

4 July 2012

8 October 2013

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Nobel Prizes and Laureates

Physics Prizes 2013

▼ About the Nobel Prize in Physics 2013
- Summary
- Prize Announcement
- Press Release
- Advanced Information
- Popular Information
- Greetings
- Award Ceremony Video
- Award Ceremony Speech

▶ François Englert
▶ Peter Higgs

All Nobel Prizes in Physics
All Nobel Prizes in 2013

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

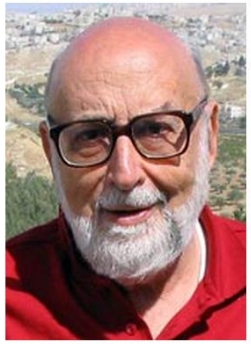


Photo: Pnicolet via Wikimedia Commons
François Englert

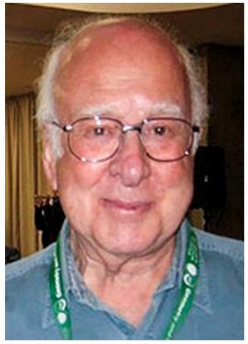


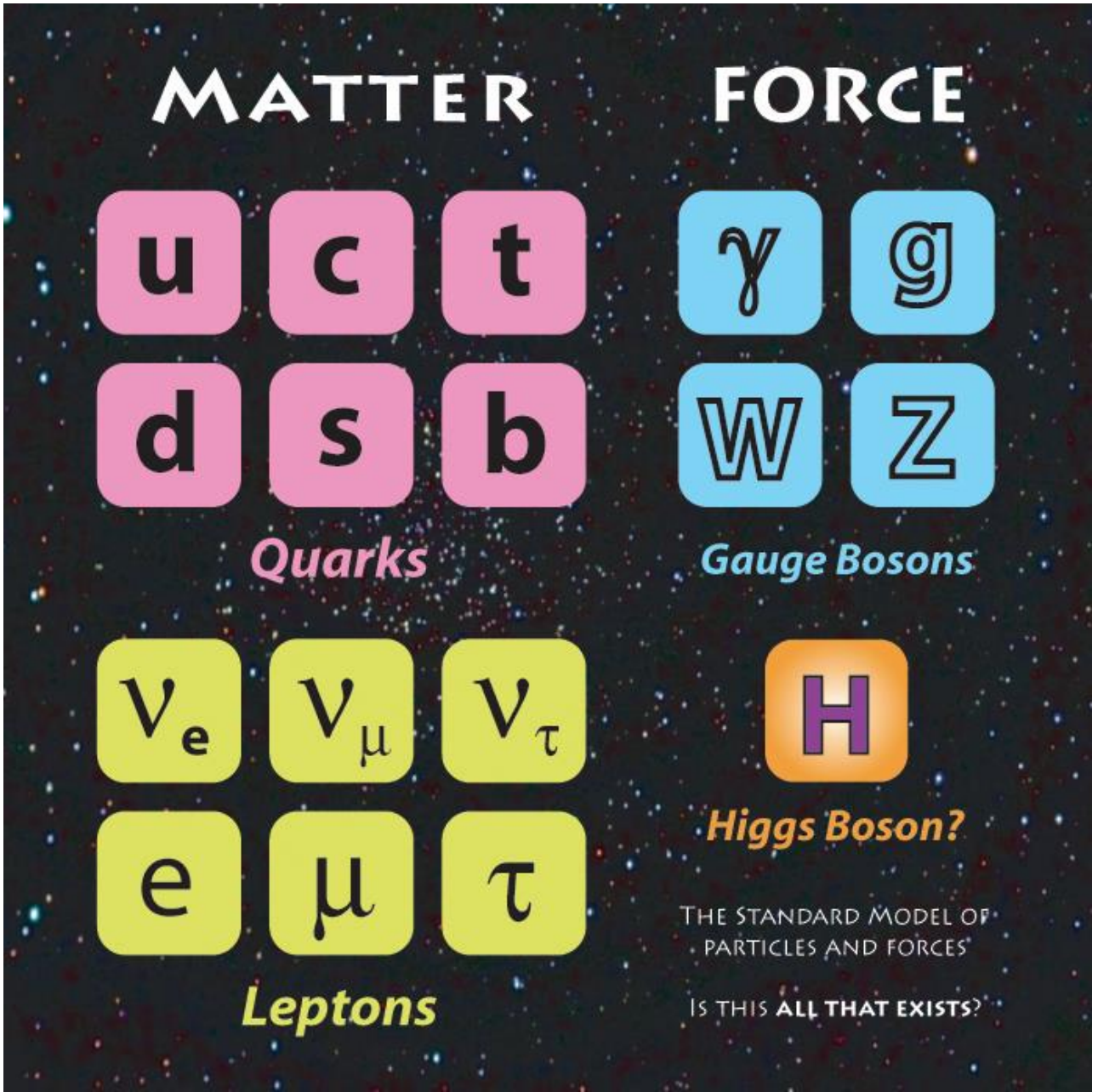
Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

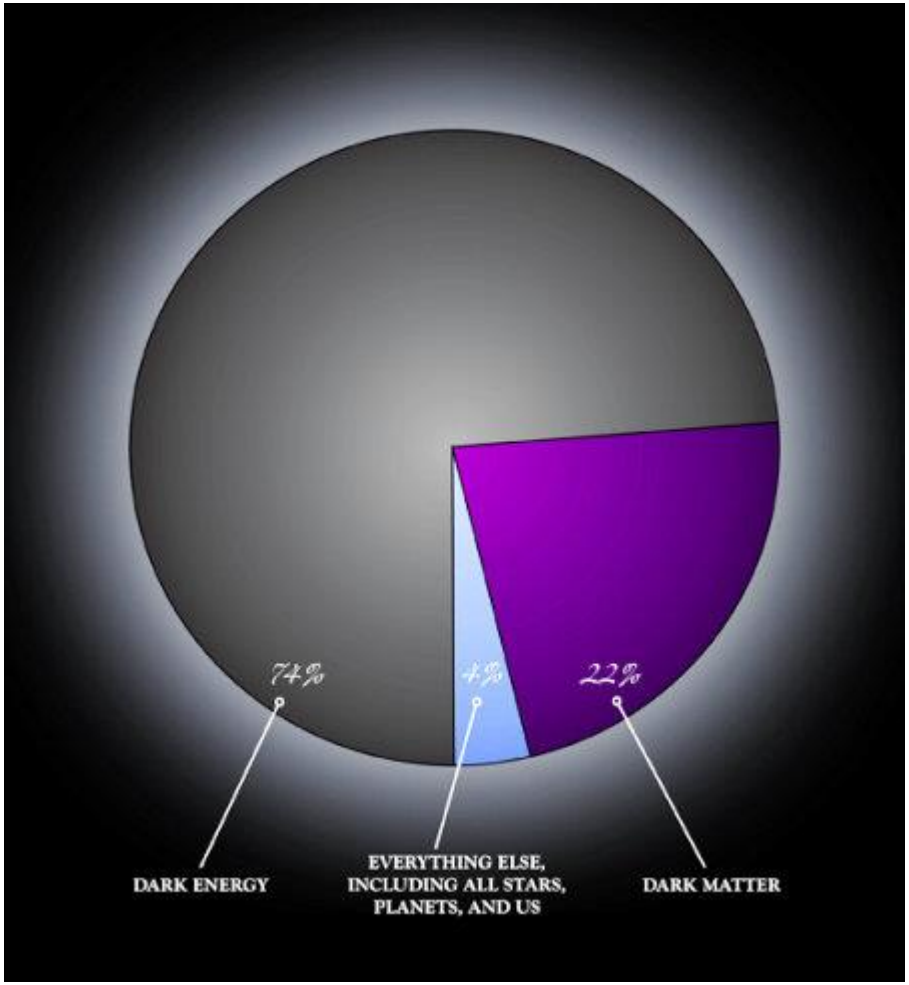
The Completion of the Standard Model

- We have managed to consolidate the SM
  - Detailed studies at the LHC ($\sqrt{s}$=7, 8 TeV)
- Complements & completes a decades-long programme of work
- It works beautifully!

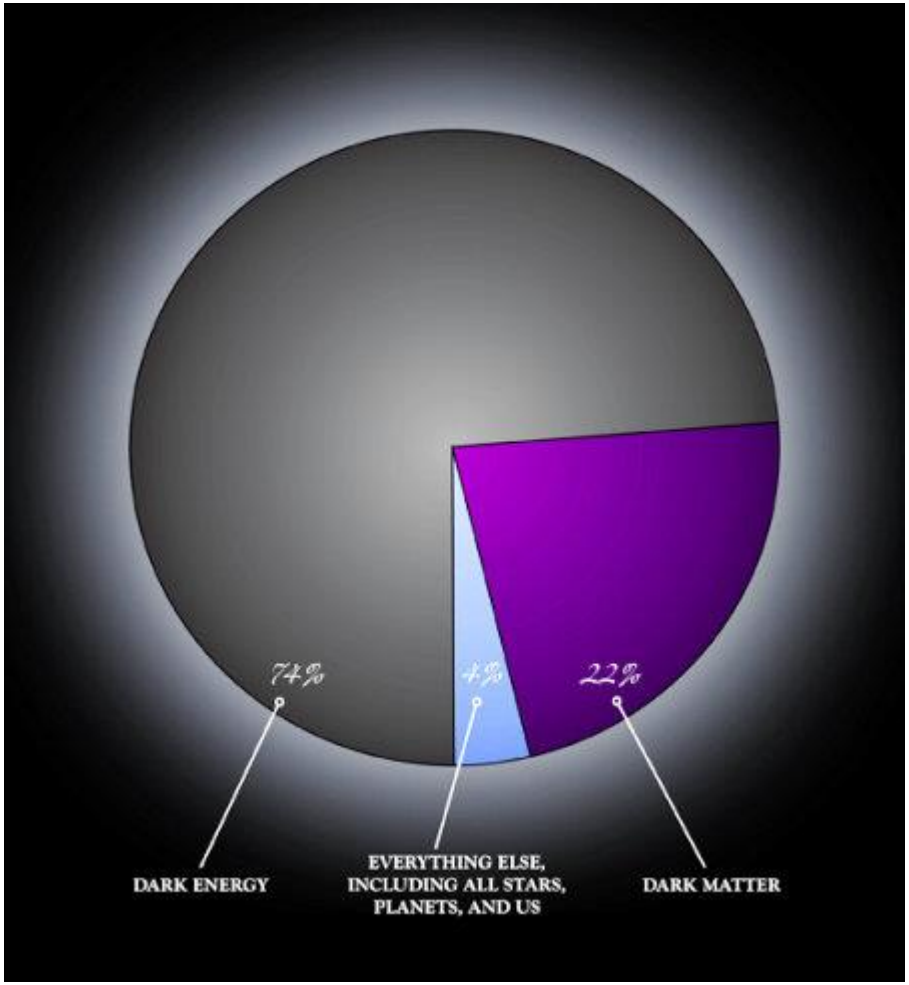
The Consolidation of the Standard Model

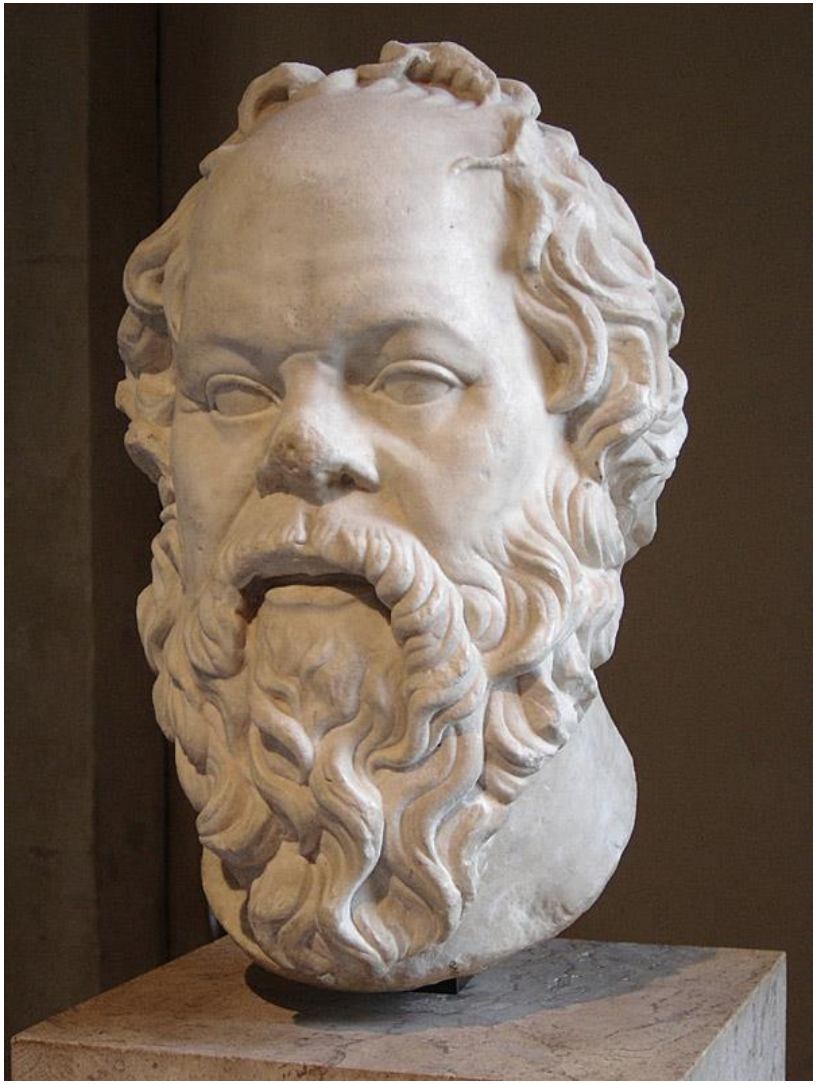


The Great Paradox



Is that all there is?

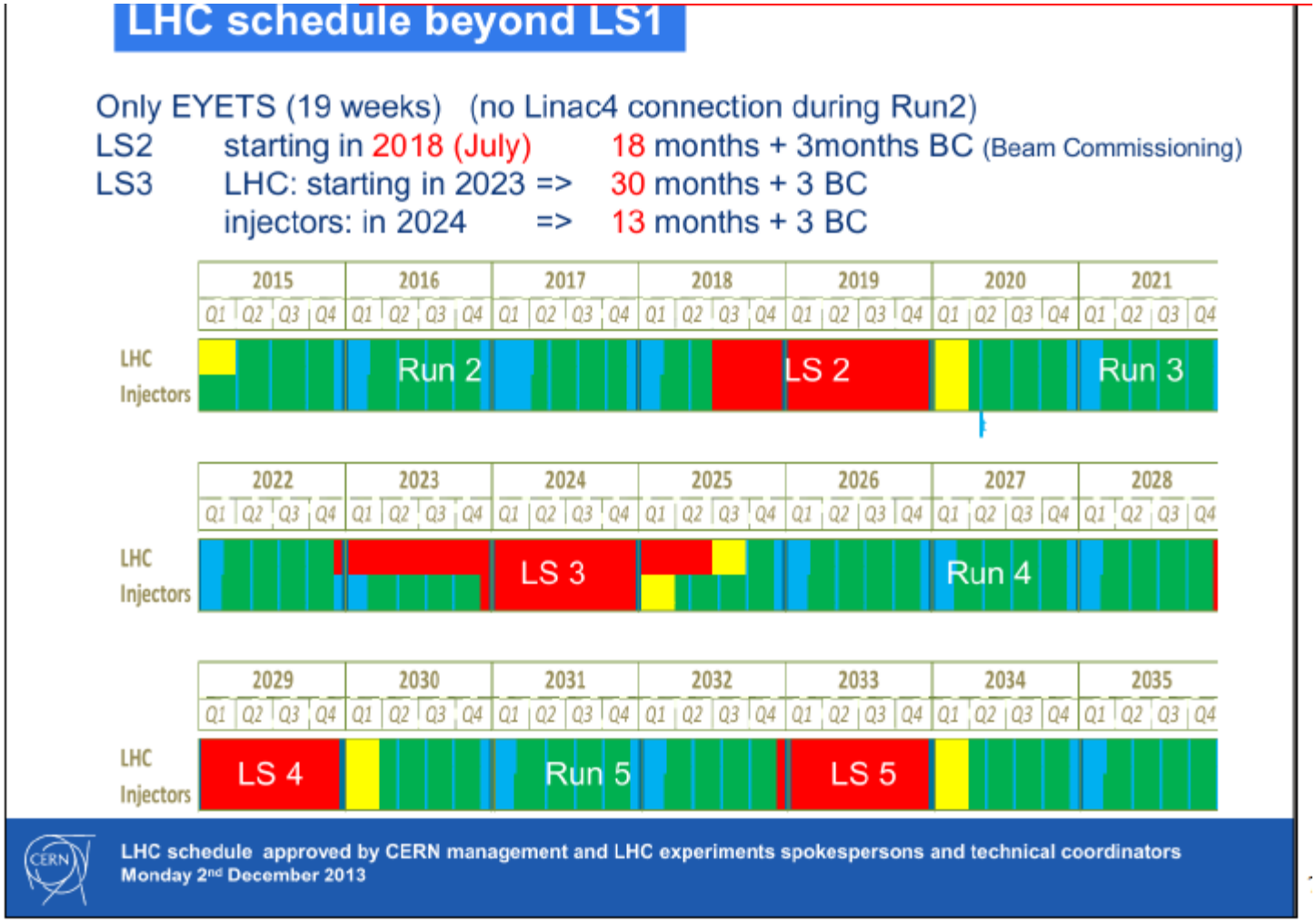




"I know nothing except the fact of my ignorance"

The LHC Programme

LHC: Run 2 and beyond



LHC: Run 2 at $\sqrt{s} = 13$ TeV

Two axes of work:

- Measurement of the Higgs properties (*)
  - (Precise determination of) Couplings
  - Spin/CP: CP-odd component? CP violation?
  - Width: window into invisible matter

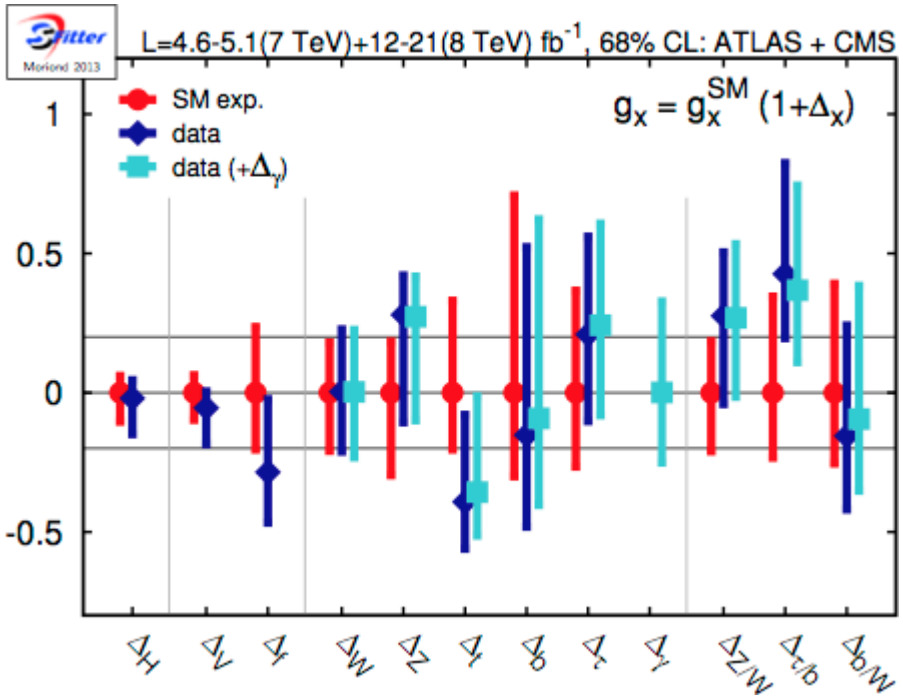
  - Huge momentum and detailed work plan

- Exotic (and SUSY) Searches
  - Exploit the increase in collision energy

(*) See talks by Klaus Moenig and Kathryn Grimm

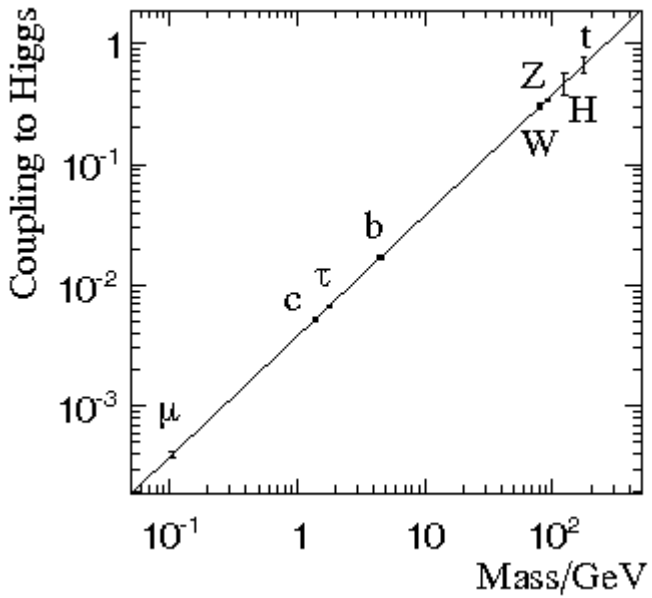
Why Higgs Physics?

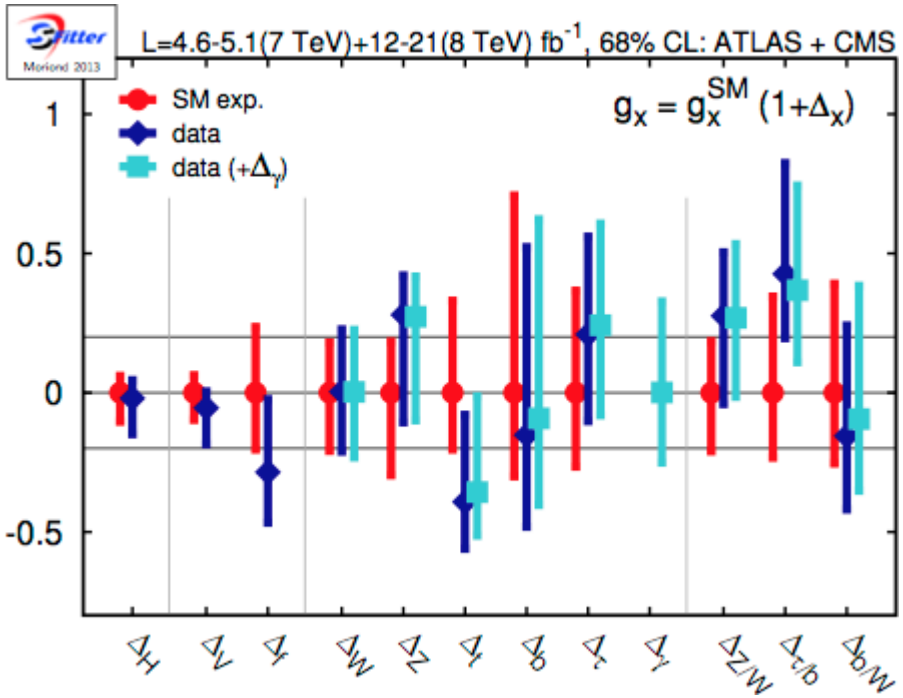
Measurement of Higgs properties



One way of looking for New Physics is via the measurement of Higgs couplings and their comparison to the SM predictions

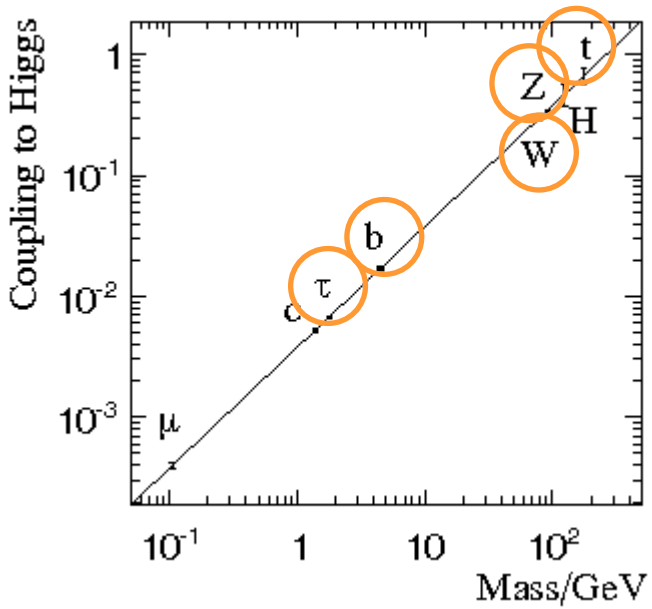
Measurement of Higgs properties

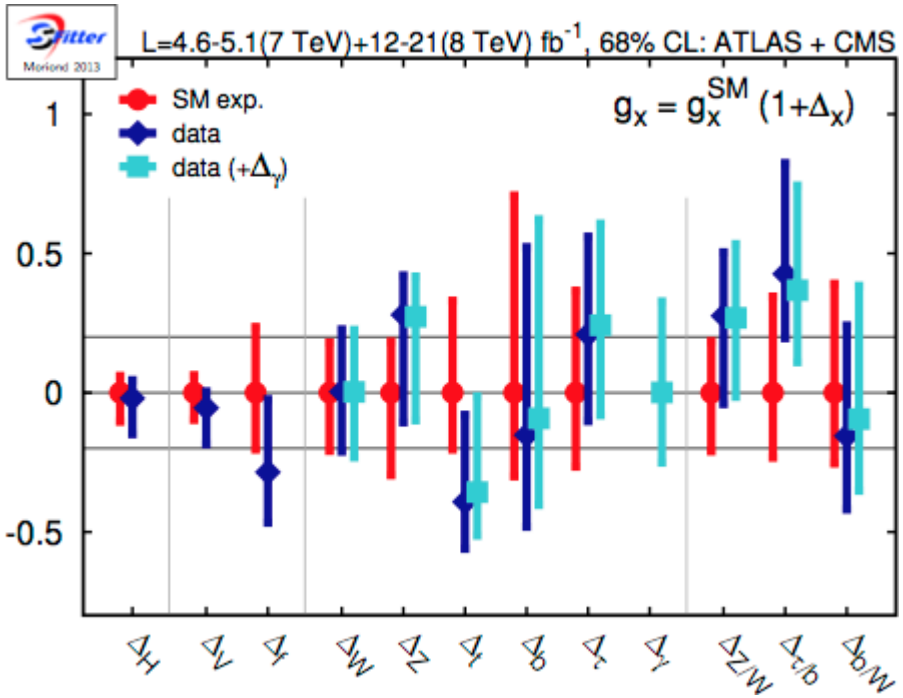




Measuring the Higgs decay rate to different final states is a stringent test of the EWK breaking mechanism & SM

Measurement of Higgs properties

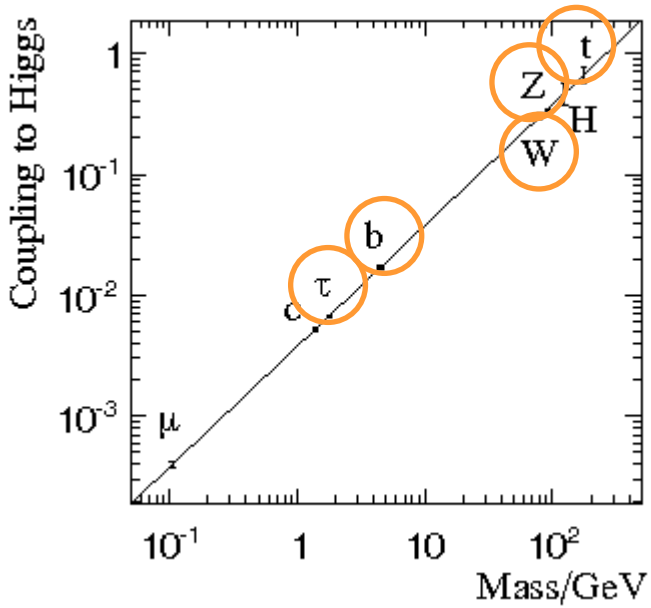


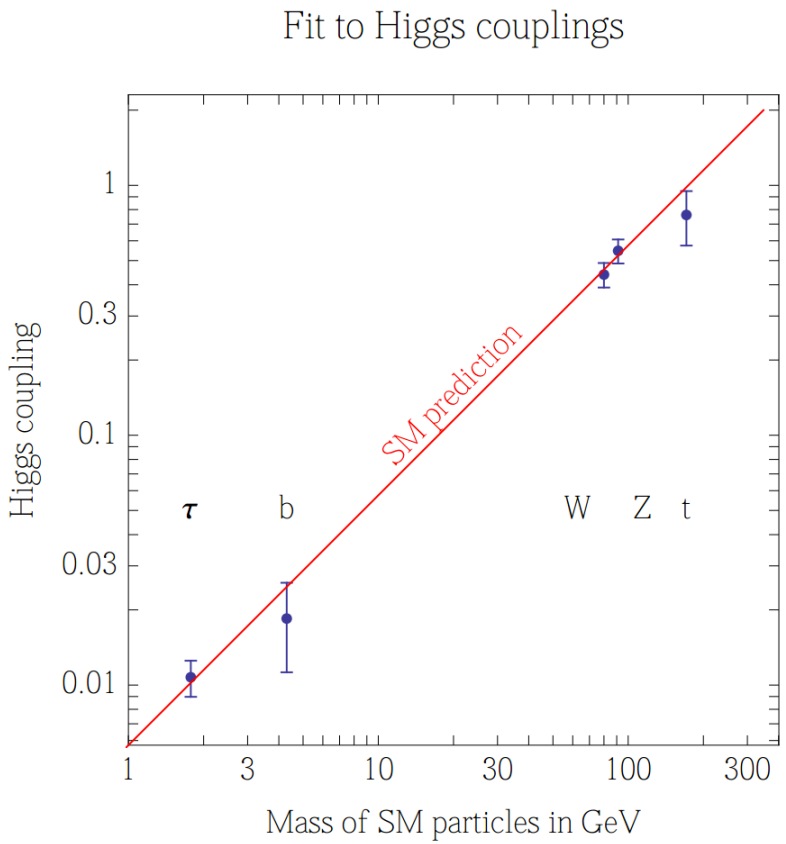


Measuring the Higgs decay rate to different final states is a stringent test of the EWK breaking mechanism & SM

Measurement of Higgs properties

P.P. Giardino et al: arXiv:1303.3570



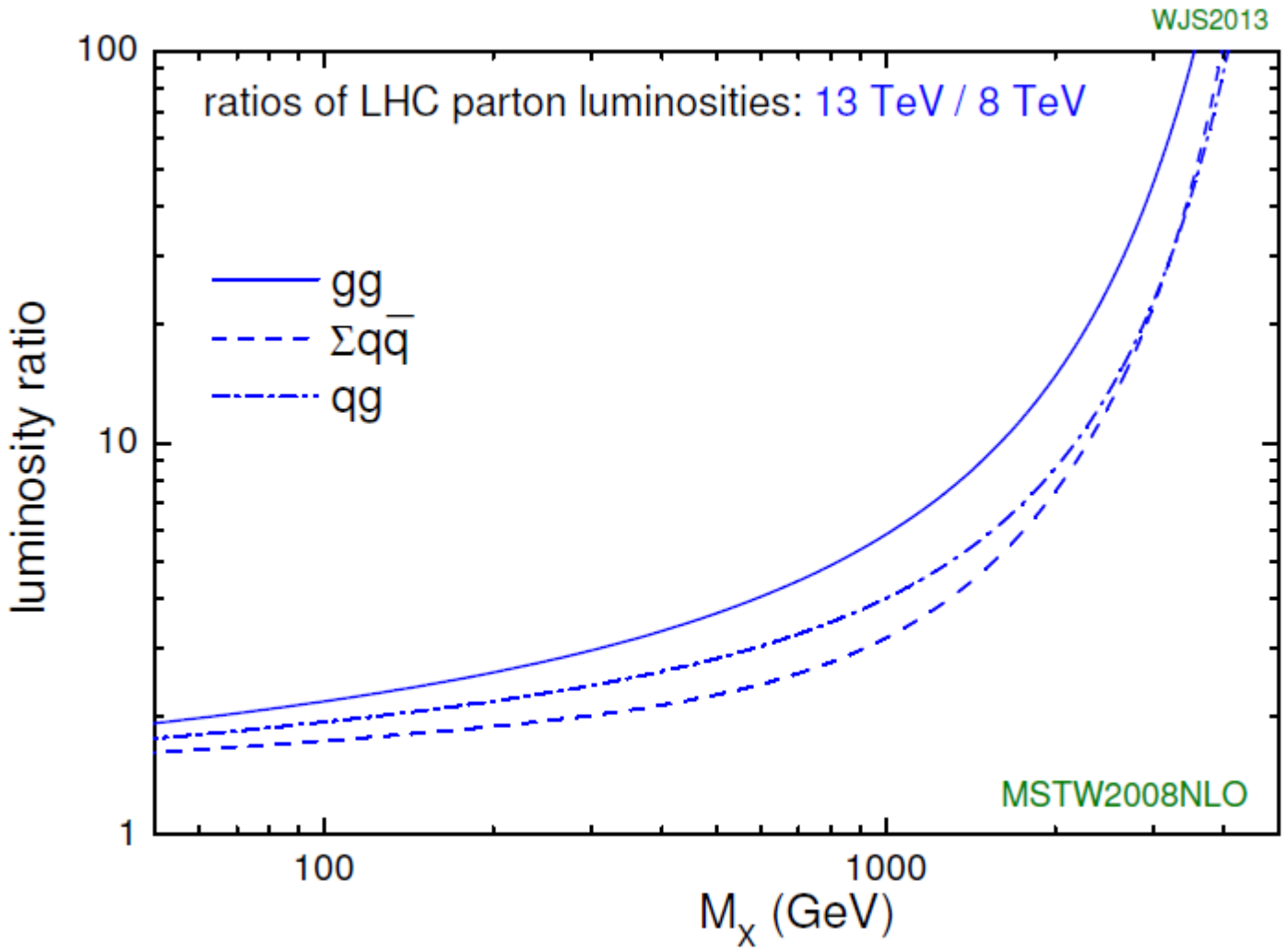


Measuring the Higgs decay rate to different final states is a stringent test of the EWK breaking mechanism & SM

"Nearly impossible to reproduce by accident" • Guido Altarelli

Why Searches?

Parton Luminosity Ratio: LHC13/LHC8



"You can run but you cannot hide"

The (Real) Future

Future Colliders

Why is the LHC not going to be the last collider

- Incentive for higher collision energies
- Incentive for high precision measurements

Future Colliders

Why is the LHC not going to be the last collider

UNIVERSITÉ DE GENÈVE

CERN

FCC hh ee he

Future Circular Collider Study Kickoff Meeting

12-15 February 2014
University of Geneva - UNI MAIL
Europe/Zurich timezone

Search

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Study Kickoff Meeting

- Overview
- FCC Information
- Organizing Committees
- Important dates
- Timetable
- Contribution List
- Registration
  - Registration Form
- Payment of fee
- Participant List
- Social events
- al information

This meeting is the starting point of a five-year international design study called "Future Circular Collider" (FCC) with emphasis on a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new 80-100 km tunnel as a long-term goal. The design study includes a 90-400 GeV lepton collider, seen as a potential intermediate step. It also examines a lepton-hadron collider option. The international kick-off meeting for the FCC design study will be held at the University of Geneva, Unimail site, on 12–15 February 2014. The scope of this meeting will be to discuss the main study topics and to prepare the groundwork for the establishment of international collaborations and future studies. The formal part of the meeting will start at noon on Wednesday 12 February and last until noon on Friday 14 February. It will be followed by break-out sessions on the various parts of the project on the Friday afternoon, with summary sessions until noon on Saturday 15 February.

Starts 12 Feb 2014 08:00
Ends 15 Feb 2014 14:00

University of Geneva - UNI MAIL
MR380

rn.ch/event/282344/

FCC kick-off meeting

Planning for 2035: Three hundred people discussing Future Circular Colliders

Is Higgs the answer?

(On the measurement of Higgs properties and couplings)
Important & nice to see progress, but “this question carries a similar potential for surprise as a football game between Brazil and Tonga”

http://resonaances.blogspot.jp/2012/10/higgs-new-deal.html

(Biased!) Quotes from FCC kick-off meeting

Why higher energies?

Nima Arkani-Hamed:
“It’s not 1995….
‘Discover SUSY at LHC, precision study @500 GeV with ILC’ ”

Why higher energies?

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“LHC is not going to be a gluino factory, no matter what”

Why higher energies?

Nima Arkani-Hamed:
"It's not 1995….
'Discover SUSY at LHC, precision study @500 GeV with ILC' "

"LHC is not going to be a gluino factory, no matter what"

"Dark Matter candidates: most theories place their mass at TeV, not couple-of-hundred GeV. LHC cannot be a DM factory"

Future Collider Projects

Any future collider project must satisfy certain criteria

- Physics case
- Project plan:
  - Technical feasibility
  - Financial cost
- Business plan: technology spinoffs, jobs
- Political support

Future Collider Options

- ILC (CLIC): Japan (*)
- FCC: Europe → the focus of the next few slides
- CEPC-SppC: China

(*) See talk by Brian Foster

Political Support

- Push the energy frontier beyond LHC
- High Priority item within the European Strategy for Particle Physics

Rolf Heuer, DG CERN, FCC kickoff meeting

➢ "High Priority": 2nd item on priority list for European Strategy for Particle Physics

➢ Second only to LHC running

Political Support

Scope

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 in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies.

The conceptual design study shall also include a lepton collider and its detectors, as a potential intermediate step towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered.

Options for e-p scenarios and their impact on the infrastructure shall be examined at conceptual level.

The study shall include cost and energy optimisation, industrialisation aspects and provide implementation scenarios, including schedule and cost profiles.

Rolf Heuer, DG CERN, FCC kickoff meeting

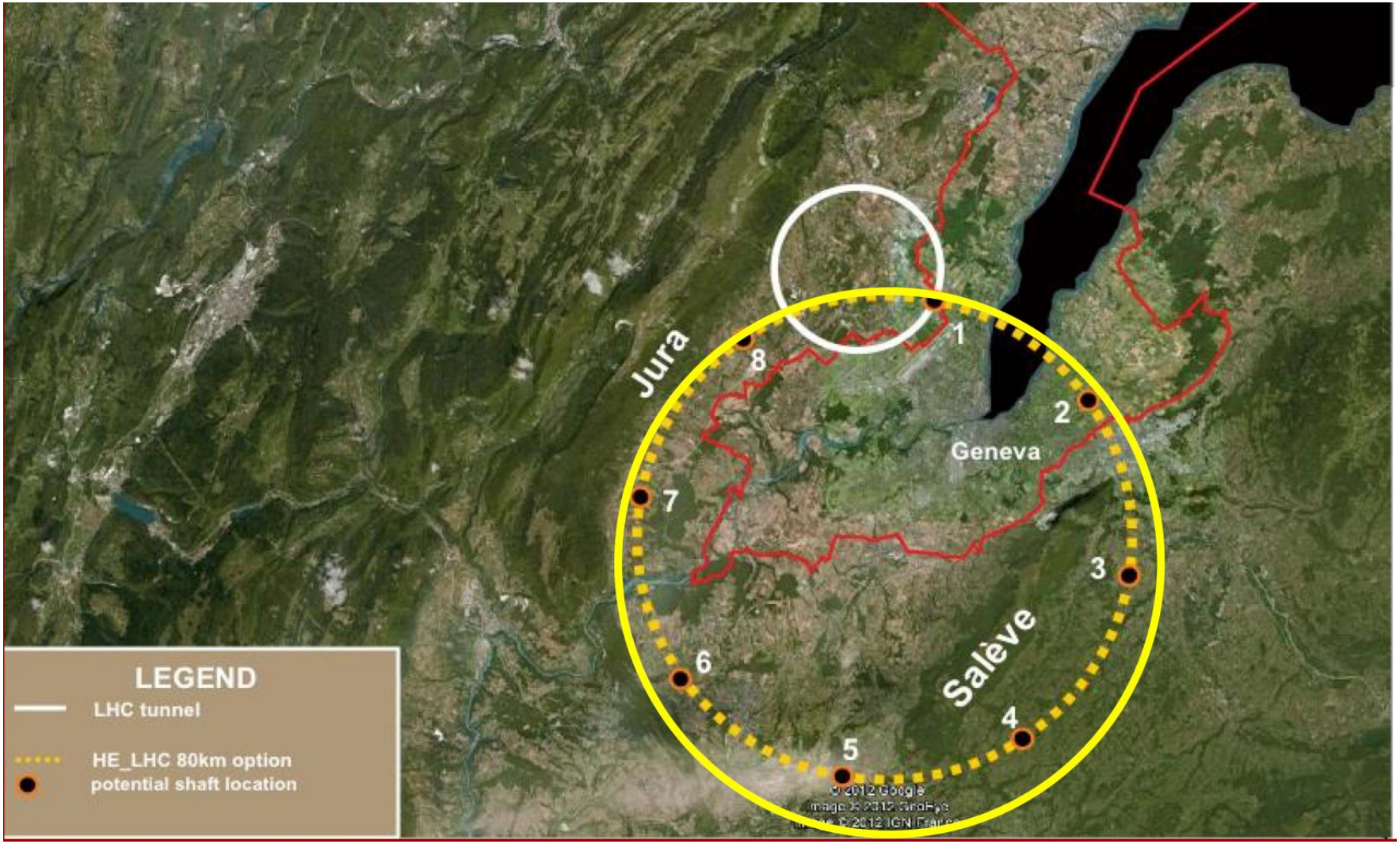
Political Support

Summary

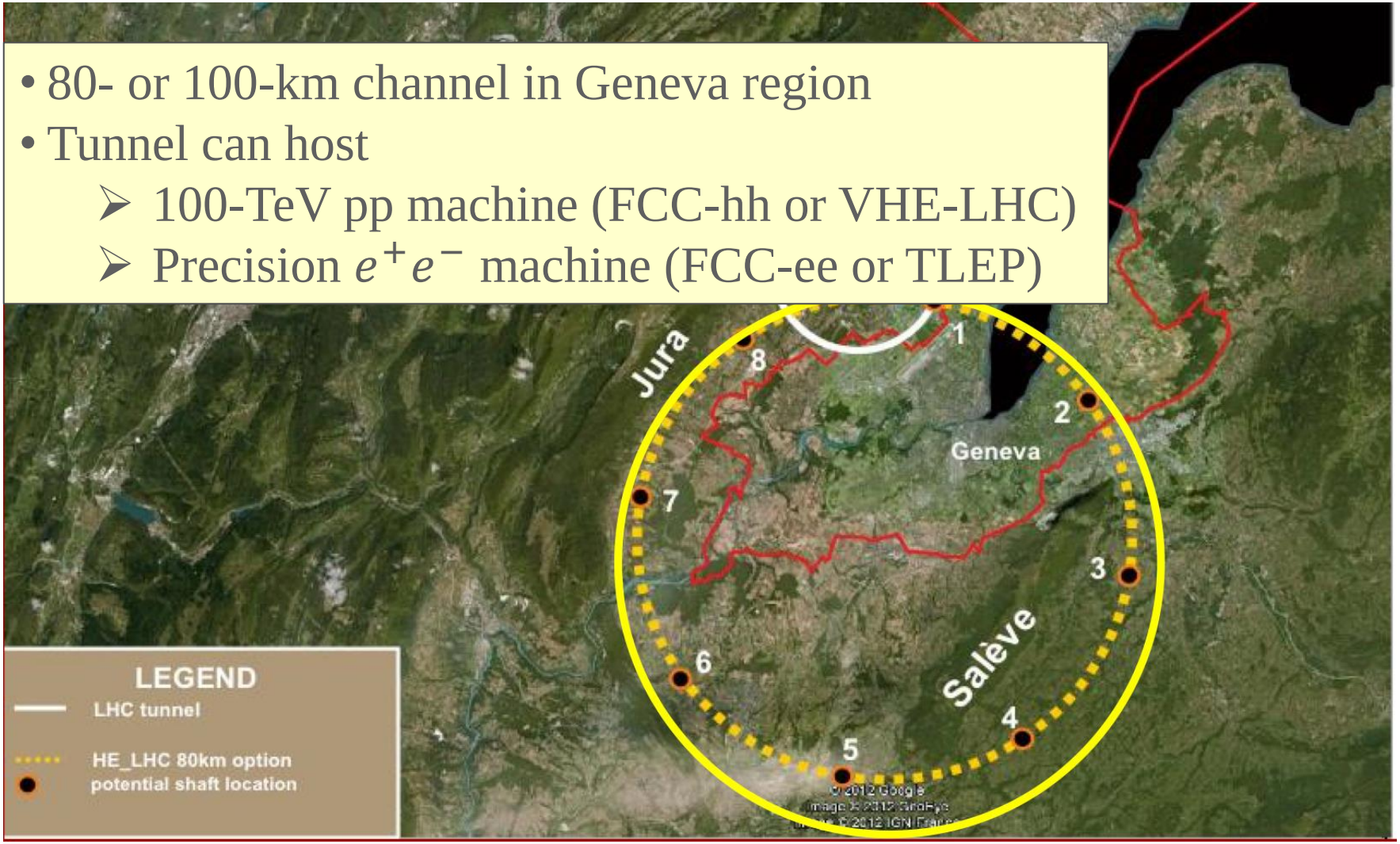
- In line with the **European Strategy**, CERN is launching a **5-year international design study** for Future Circular Colliders (FCC); unique road up to 100 TeV energy scale
- **Worldwide collaboration in all areas** - physics, experiments and accelerators – **is essential** to bring this study to fruition (and to arrive at a CDR by 2018)
- Need to present (additional) **benefits to society** from the very beginning of the study (examples: sc technologies)
- Need to have **excellent communication and outreach** accompanying the study
- Make **efficient use of existing efforts/investments** and interconnect with other projects/studies

Rolf Heuer, DG CERN, FCC kickoff meeting

Future Circular Colliders



Future Circular Colliders



TLEP: a Physics Study

JHEP

Published for SISSA by Springer

Received: *September 23, 2013*
Accepted: *December 25, 2013*
Published: *January 29, 2014*

First look at the physics case of TLEP

The TLEP Design Study Workin

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G.
C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. H
A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Go
L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Gl
C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G.
U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G.
M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,
F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d
G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C. I
F. Moortgat,[z] P. Musella,[z] J. A. Osborne,
A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà
J. Wenninger,[z] H. Woehri,[z] F. Zimmerma
P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E.
D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P
Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am]

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.

Keywords: e+-e- Experiments

ArXiv ePrint: 1308.6176

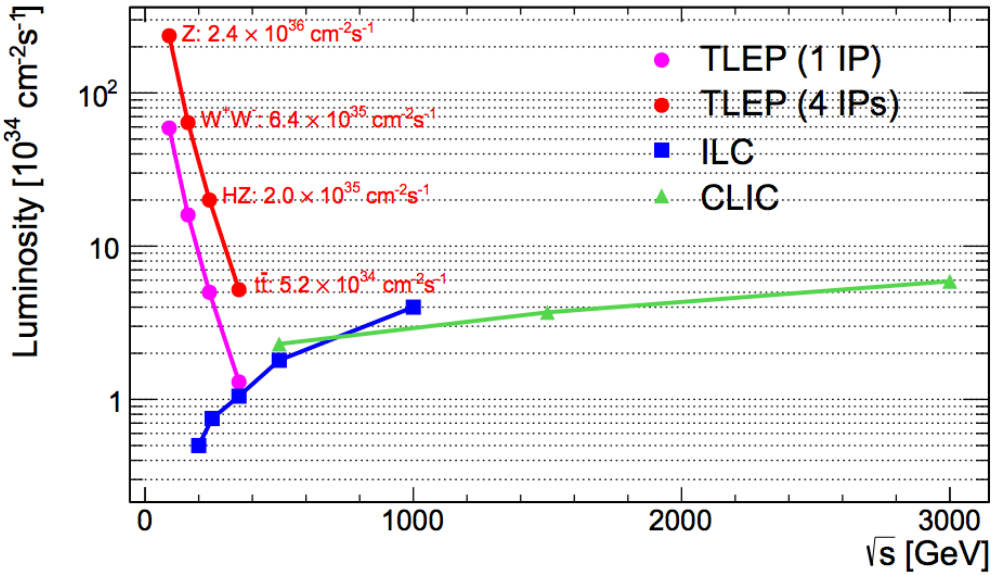
arXiv: 1308.6176

TLEP: a Physics Study

	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L (10^{34} cm^{-2}s^{-1})	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

Table 2: Indicative costs for the main cost drivers of the TLEP collider.

Item	Cost (Million CHF)
RF system	900
Cryogenics system	200
Vacuum system	500
Magnets systems for the two rings	800
Pre-injector complex	500
Total	**2,900**



arXiv: 1308.6176

(More on the) Physics Case

- LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV

→ strong case for a 100 TeV pp collider: complete the spectrum and measure it in some detail

- LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Λ Compositeness)

→ strong case for a 100 TeV pp collider: directly probe the scale of new physics

LHC and HL-LHC find NO new physics nor indications of the next E scale:

- several Higgs-related questions (naturalness, HH production, $V_L V_L$ scattering) may require high-E machines (higher than a 1 TeV ILC)
- a significant step in energy, made possible by strong technology progress (from which society also benefits), is the only way to look directly for the scale of new physics

Although there is no theoretical/experimental preference today for new physics in the 10-50 TeV region, the outstanding questions are major and crucial, and we must address them. This requires concerted efforts of all possible approaches: intensity-frontier precision experiments, astroparticle experiments, dedicated searches, neutrino physics, high-E colliders, …

Fabiola Gianotti, FCC kickoff meeting

(More on the) Physics Case

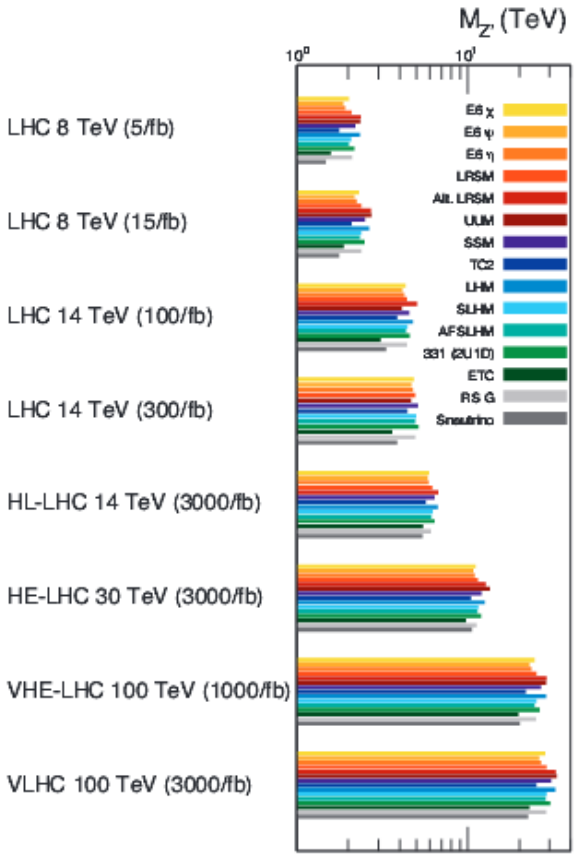


FIG. 1: Z' discovery reach at high energy hadron colliders.

Experimental discovery reach for Z'

- ~2 TeV ($\sqrt{s}$=8 TeV)
- ~5 TeV ($\sqrt{s}$=14 TeV)
- >30 TeV ($\sqrt{s}$=100 TeV)

arXiv: 1309.1688

Technical Feasibility

Machine parameters: $\sqrt{s}$ vs ring size and magnets

Facility	Ring (km)	Magnets (T)	$\sqrt{s}$ (TeV)
(SSC)	87	6.6	40
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
FHC	80 80 100	8.3 20 16	42 100 100

Fabiola Gianotti

Note:
- ❑ big jump in technology from 15-16T magnets (Nb_3Sn) to 20T magnets (HTS)
- → the latter may require many more years of R&D than the former
- → optimum balance between tunnel size (cost ?) and magnet technology (time and cost ?)
- ❑ for a cost-affordable and technically-viable (big) machine need "routine" industrial production of magnets …

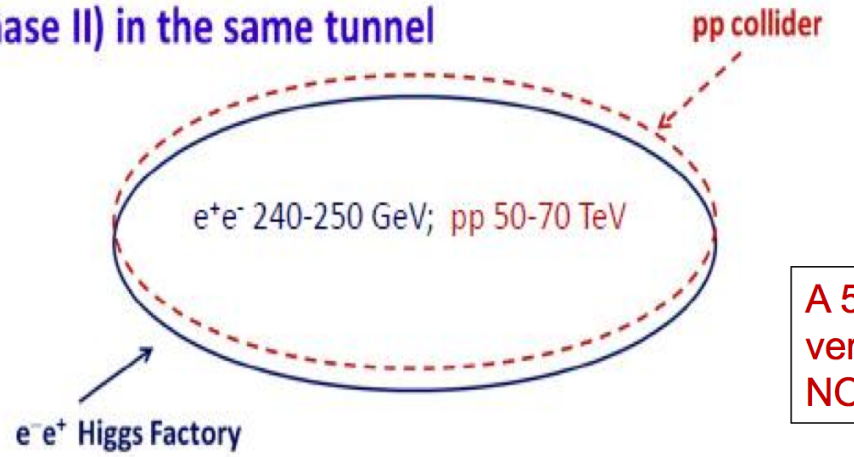
"Obviously, how to proceed will depend on LHC results at 13 TeV"
Nima Arkani-Hamed

A few words on China

CEPC+SppC

- For about 8 years, we have been talking about “What can be done after BEPCII in China”
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012

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



A 50-70 km tunnel is very affordable in China NOW

Yifang Wang, FCC kickoff meeting

A few words on China

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR by the end of 2014 for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

Yifang Wang, FCC kickoff meeting

A few words on China

Major advantages

- Low cost
- Technological feasibility
- Ambition

My personal opinion

- If Europe (&US) does not step up, have no doubts that China will get there

Outlook

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- …But the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Michelangelo Mangano

Summary

- The Higgs boson has been discovered!
  Mission accomplished!

Summary

- The Higgs boson has been discovered!
- Concrete Plans for Run 2 at LHC
- Collider Physics community is exploring its options for future colliders
- Longer term: The Future is uncertain

"Making predictions is very difficult, especially about the future"

Epilogue

"Ask not what big circular colliders can do for you.
Ask what you can do for big circular colliders"

Nima Arkani-Hamed