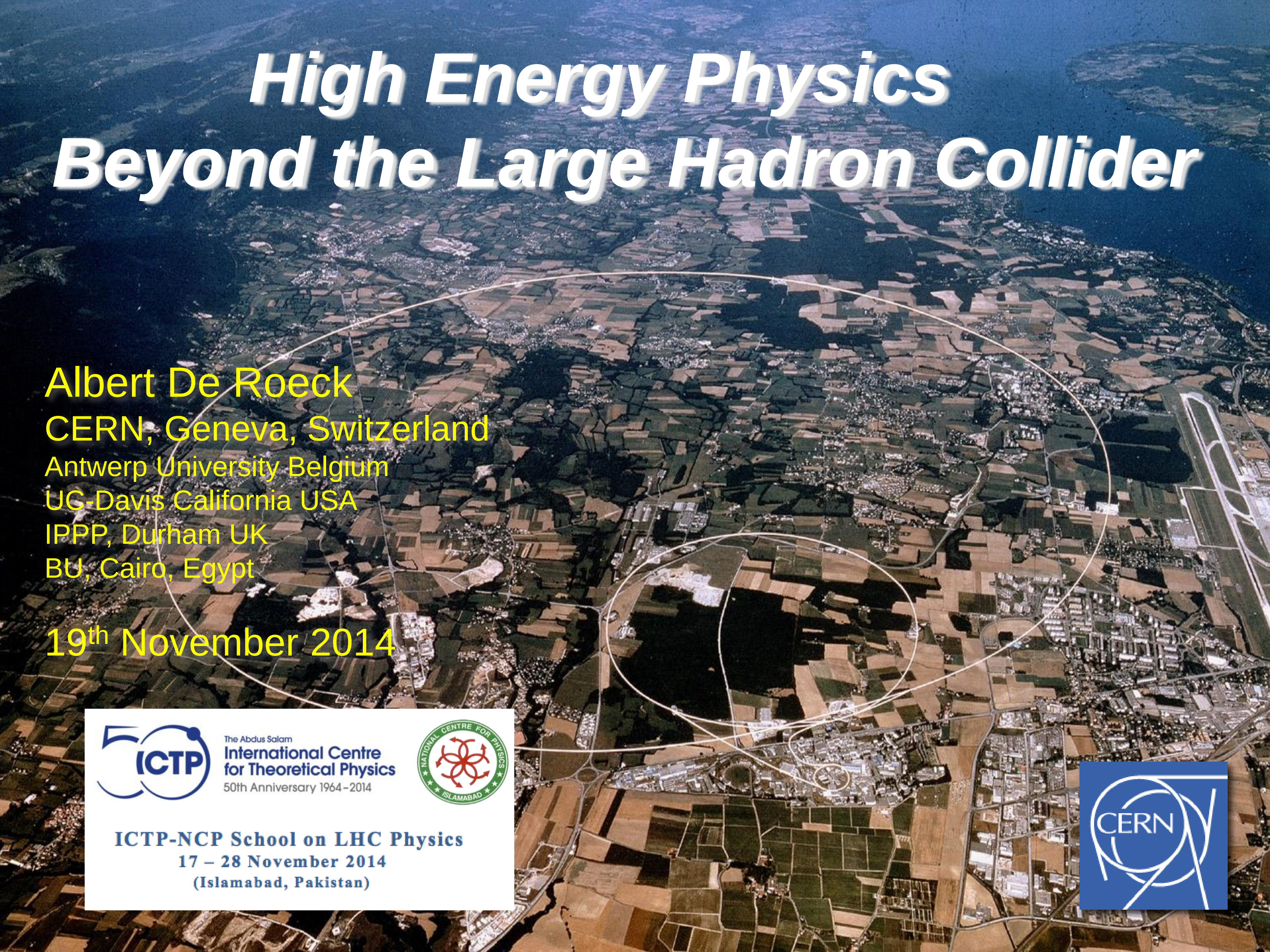
High Energy Physics Beyond the Large Hadron Collider



Albert De Roeck

CERN, Geneva, Switzerland

Antwerp University Belgium

UC-Davis California USA

IPPP, Durham UK

BU, Cairo, Egypt

19th November 2014

The Abdus Salam International Centre for Theoretical Physics

ICTP 50th Anniversary 1964–2014

NATIONAL CENTRE FOR PHYSICS ISLAMABAD

ICTP-NCP School on LHC Physics

17 – 28 November 2014

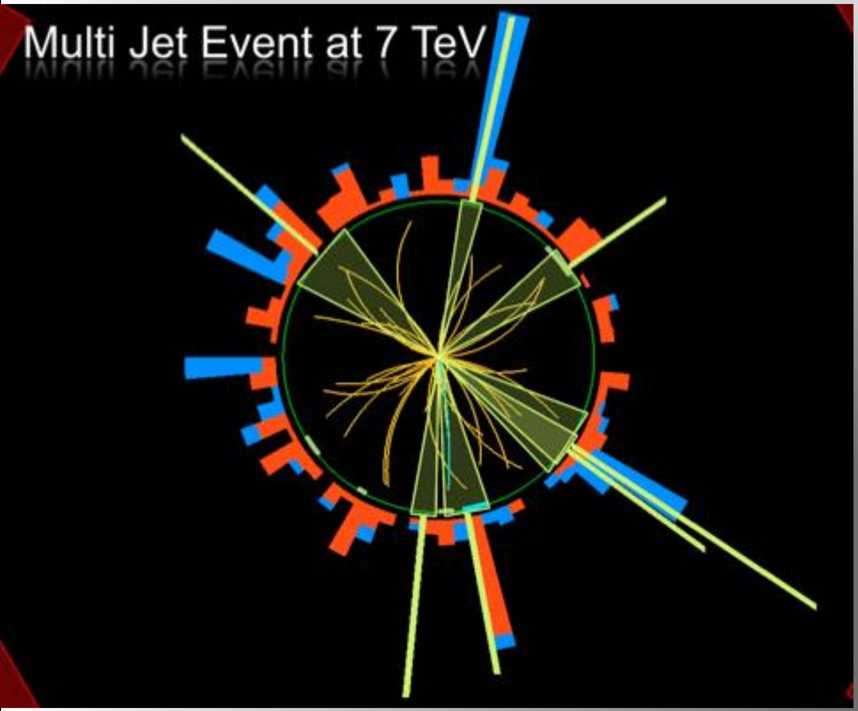
(Islamabad, Pakistan)

CERN

Lecture Plan

Overview of the 3 lectures in the next days

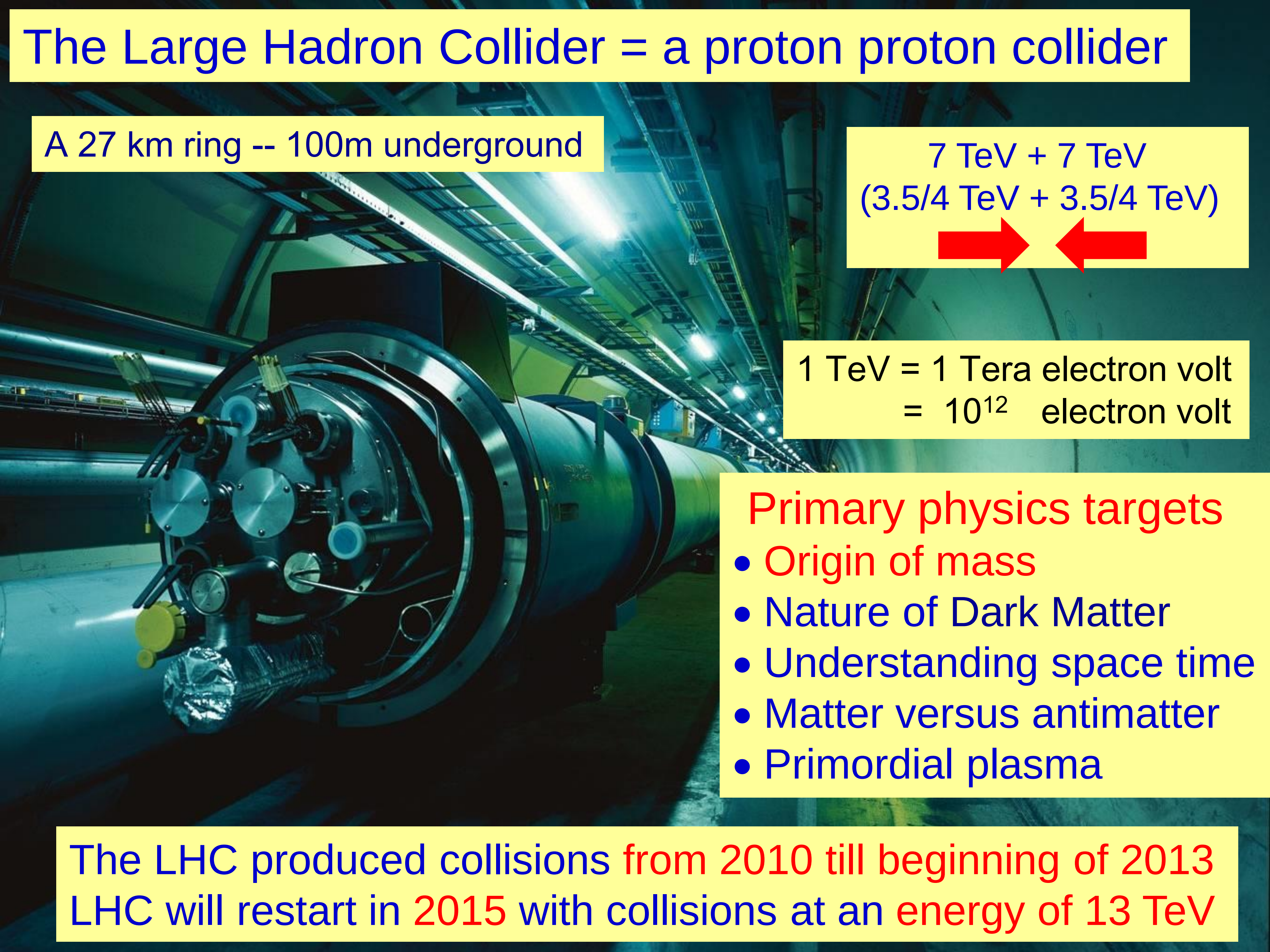
- Lecture 1: Searching for Physics Beyond the Standard Model: exotic signatures
- Lecture 2: The next ultimate challenge: identifying Dark Matter in the Universe, and its connection to Supersymmetry
- Lecture 3: The future program at the LHC and the studies/ideas for ‘beyond the LHC’



Outline

- Introduction: the world after the first run of the LHC
- LHC schedule for the next years of operation
- LHC upgrade plans/projects
- Beyond the LHC: where do we go from here?
- Conclusion

The Large Hadron Collider = a proton proton collider



A 27 km ring -- 100m underground

7 TeV + 7 TeV
(3.5/4 TeV + 3.5/4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

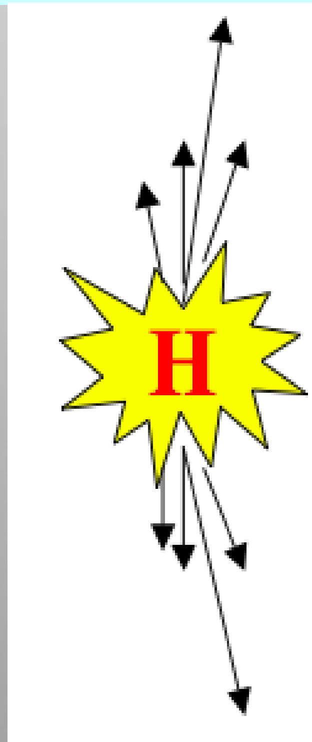
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC produced collisions from 2010 till beginning of 2013
LHC will restart in 2015 with collisions at an energy of 13 TeV

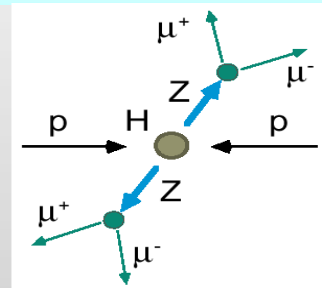
2012: A Milestone in Particle Physics

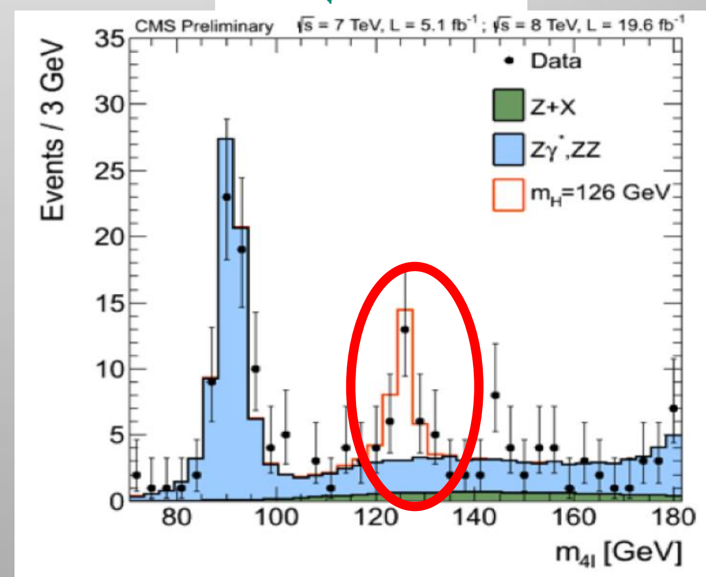
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it

proton



proton





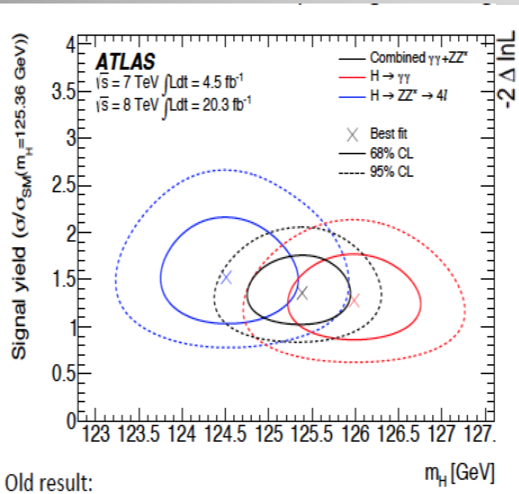
2013

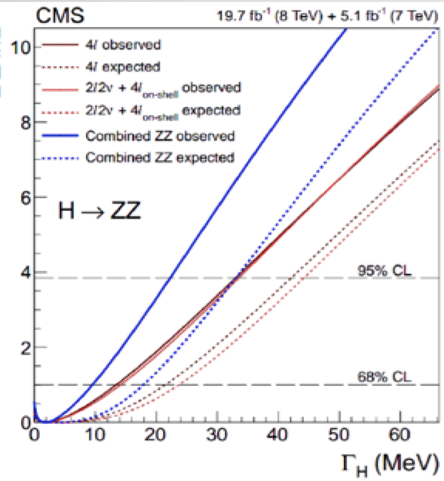
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

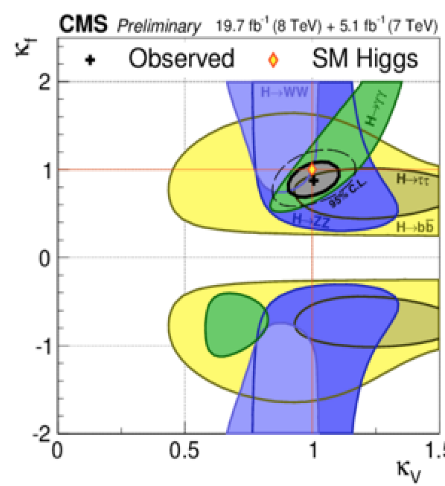
The Higgs… our New Tool!

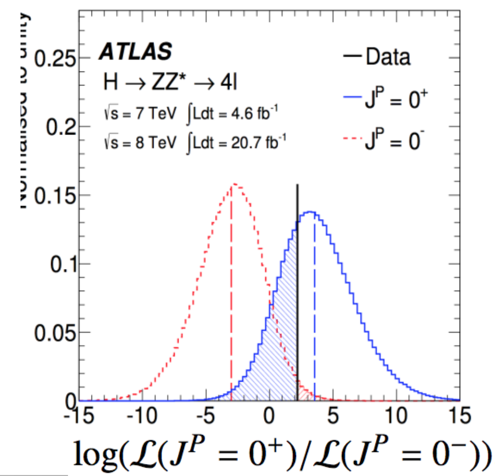
We know already a lot on this Brand New Higgs Particle!!

A= ATLAS C= CMS









Mass =
A: 125.4 ±0.4 GeV
C: 125.0 ±0.3 GeV

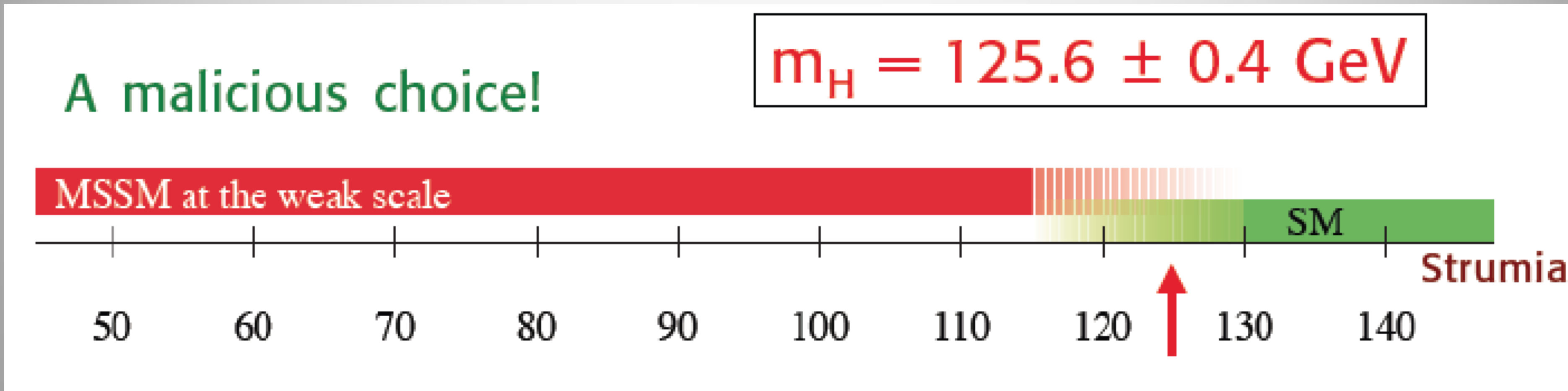
Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

Couplings are within 20% of the SM values

Spin =
0^+ preferred over 0^-,1,2

The Higgs is the new playground: Room for new experimental/theoretical ideas!!
We have already ~1 Million Higgses produced at the LHC (but use less than a %)

A Higgs…



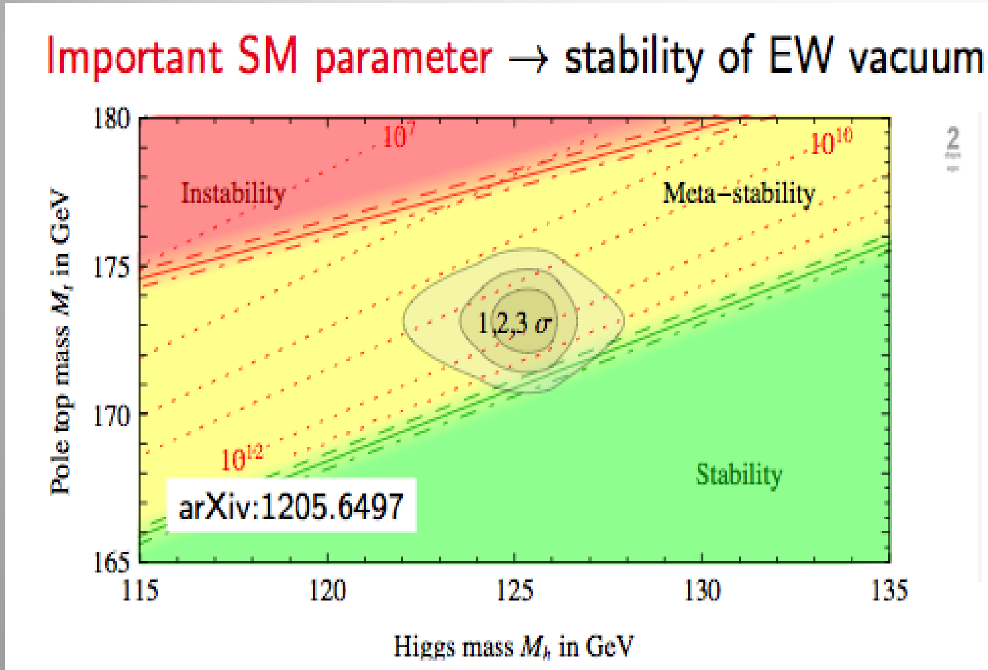
The Higgs:
so simple yet so unnatural

Guido Altarelli

Stockholm Nobel Symposium
May 2013

But there there still a lot of questions…

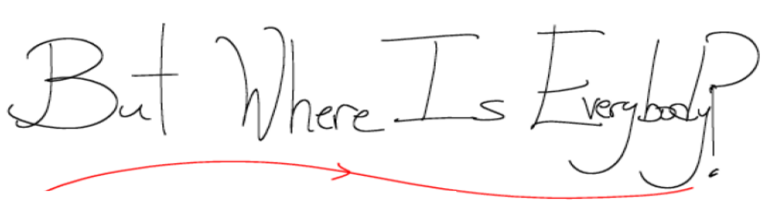
Consequences for our Universe?



Precise measurements of the top quark and first measurements of the Higgs mass:

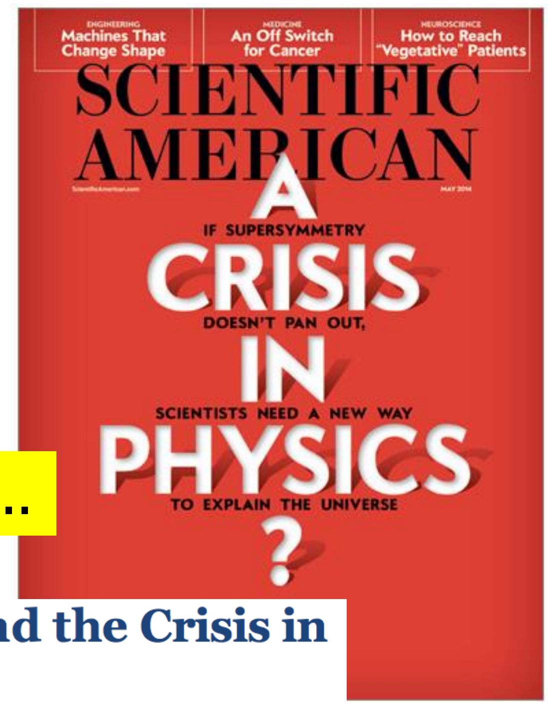
Our Universe meta-stable ? Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

New Physics inevitable?
But at which scale/energy?



N. Arkani-Hamed

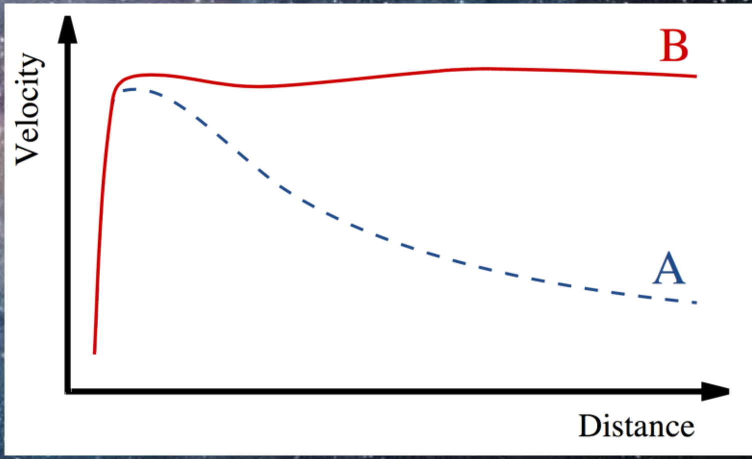
...The May Issue...



Supersymmetry and the Crisis in Physics

Dark Matter: The Next Challenge !?!

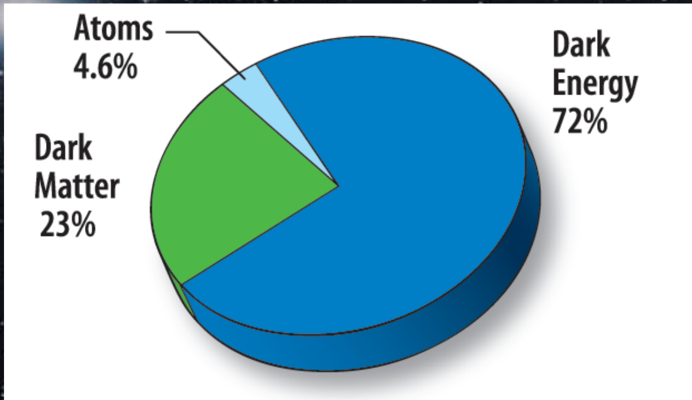
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

F. Zwicky 1898-1974

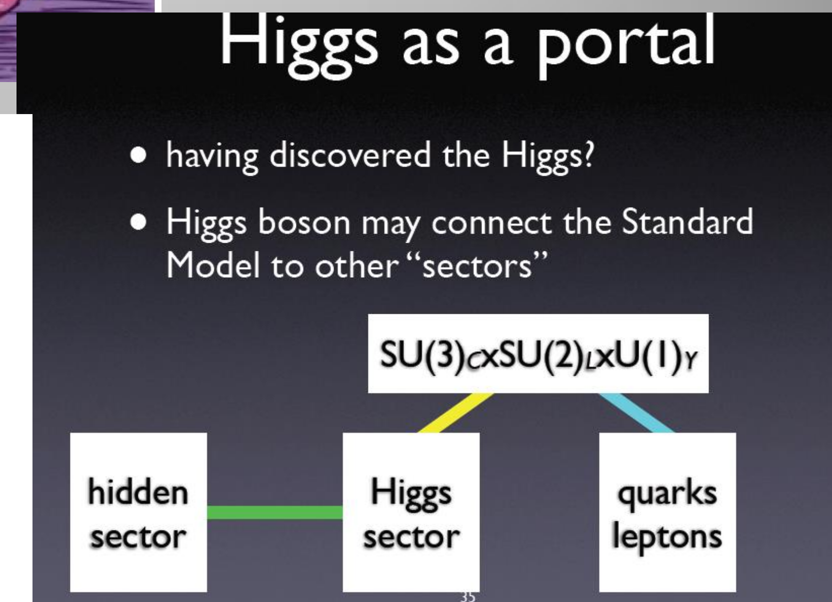
Vera Rubin ~ 1970



The Future: Studying the Higgs…

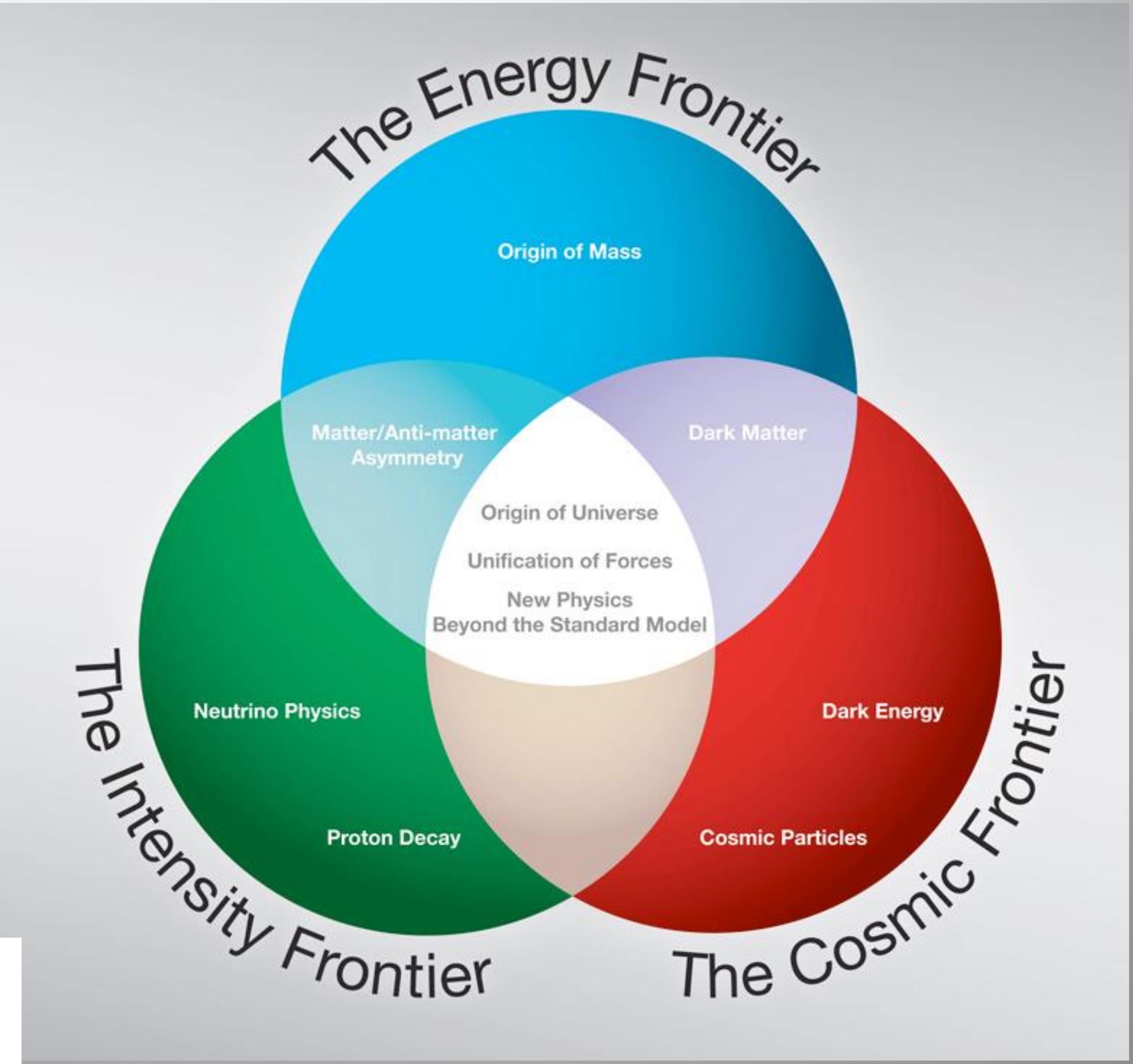
The Higgs is the new particle that may give us crucial insight into the new physics world
We will have to study it!!

Many questions are still unanswered:
- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Neutrino masses and properties?
- Where is the antimatter in the Universe?
- ⑤



The Future…

The Three Frontiers



Evaluated in all regions: Europe Asia, the Americas

2012-2014

- European strategy group
- Snowmass study and IP5
- Japan strategy group

Will concentrate here on the Energy Frontier

Projects Discussed in 2012/2013

pp colliders

	Years	E_{cm} TeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Int. Luminosity 300 fb^{-1}
Design LHC	2014-21	14	1-2	300
HL-LHC	2024-30	14	5	3000
HE-LHC	>2035	26-33*	2	100-300/y
V-LHC**	>2035	42-100		

e+e- colliders

	Years	E_{cm} GeV	Luminosity $10^{34}cm^{-2}s^{-1}$	Tunnel length km
ILC 250	<2030	250	0.75	
ILC 500		500	1.8	~30
ILC 1000		1000		~50
CLIC 500	>2030	500	2.3(1.3)	~13
CLIC 1400		1400(1500)	3.2(3.7)	~27
CLIC 3000		3000	5.9	~48
LEP3	>2024	240	1	LEP/LHC ring
TLEP	>2030	240	5	80 (ring)
TLEP		350	0.65	80 (ring)

+ proposals for photon colliders, muon collider,..

Which Future Collider to Build?

- Guidance from LHC
  - » Higgs at 125 GeV
  - » Possible New Physics discovery in Run II
- Guidance from Theory
  - » Stabilization of EW scale
  - » Unification of forces
  - » Explore possible symmetries in Nature
- Guidance from Cosmology
  - » Existence of Dark Matter
  - » Matter – antimatter asymmetry

J. Hewett Nov 2014

- 2 phases of discovery
  1) Discovery of a new particle
  2) Discovery of the theory behind the new particle

Both steps are necessary to understand Nature

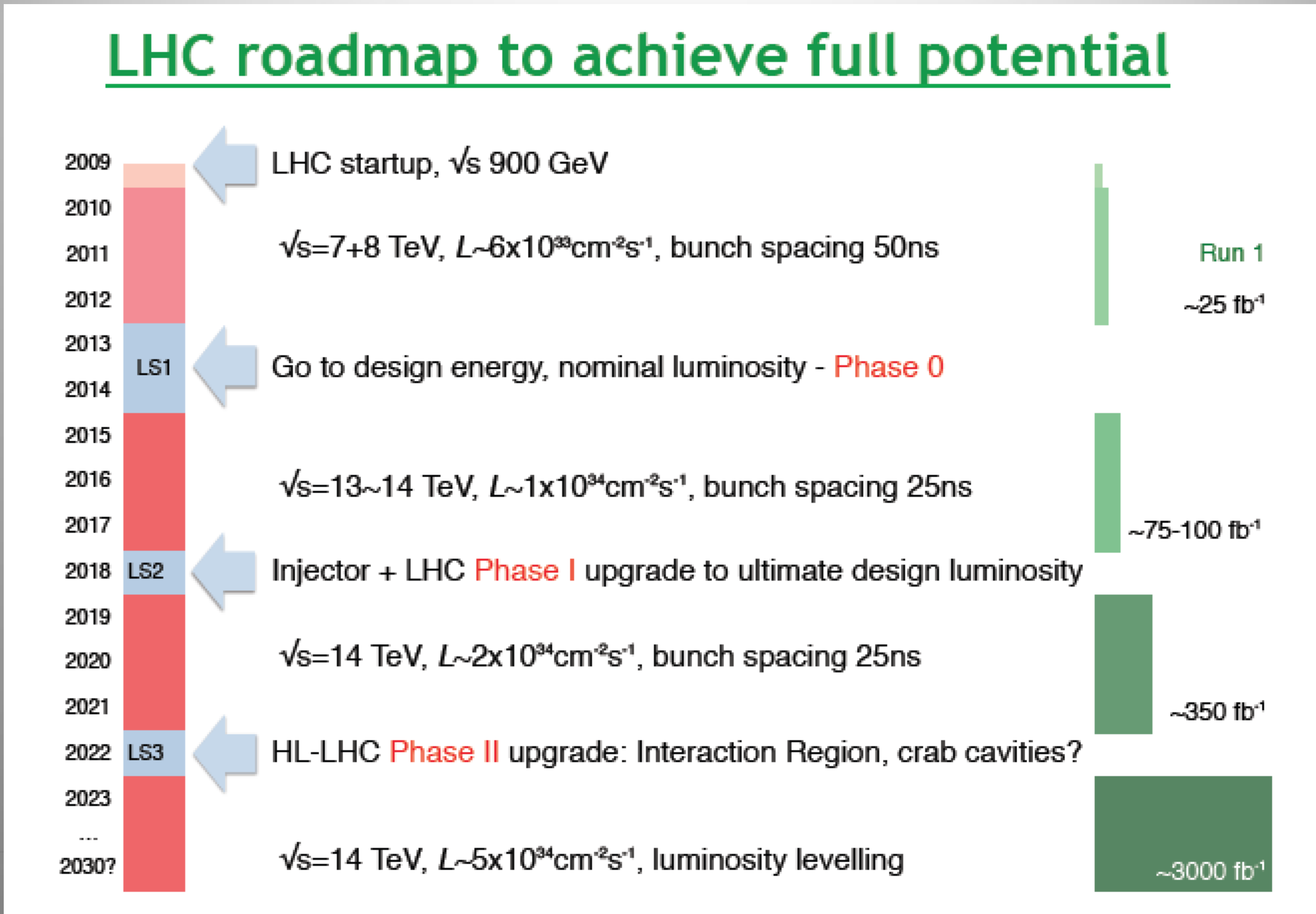
Europe Strategy Group

European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *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. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

European Strategy Update

The LHC Schedule



LHC 2015

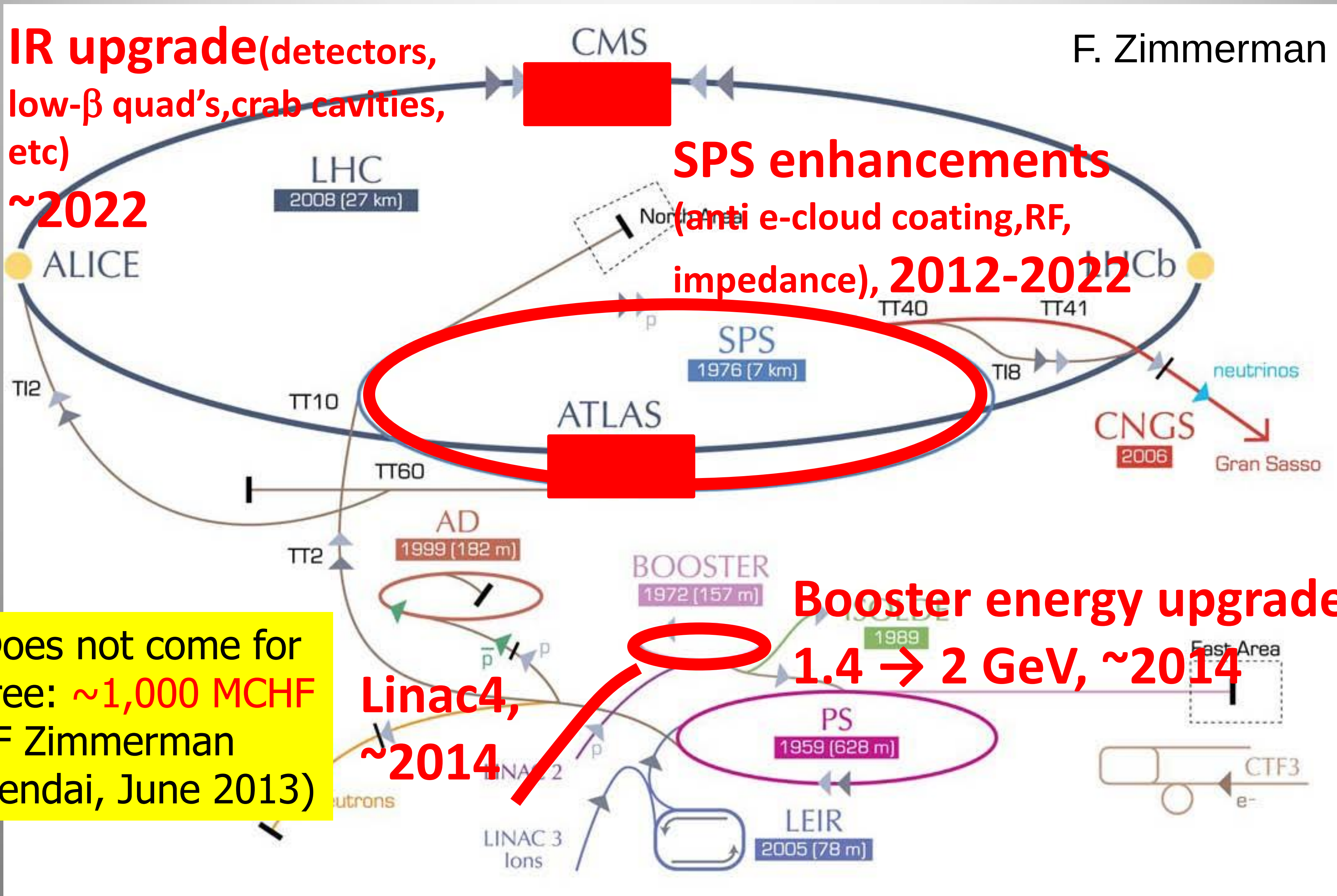
- Start with 50 ns – scrub – 25 ns operation
- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assuming same machine availability as 2012…

M. Lamont

	Nc	beta* [cm]	ppb	EmitN [um]	Lumi [cm-2s-1]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.6e33	21	**~1 fb^{-1}**	**27**
25 ns (1)	2496	80	1.1e11	2.5	7.4e33	75	**6.8 fb^{-1}**	**22**
25 ns (2)	2496	40	1.1e11	2.5	1.3e34	46	**9.2 fb^{-1}**	**39**

F. Zimmerman, 12/9/14

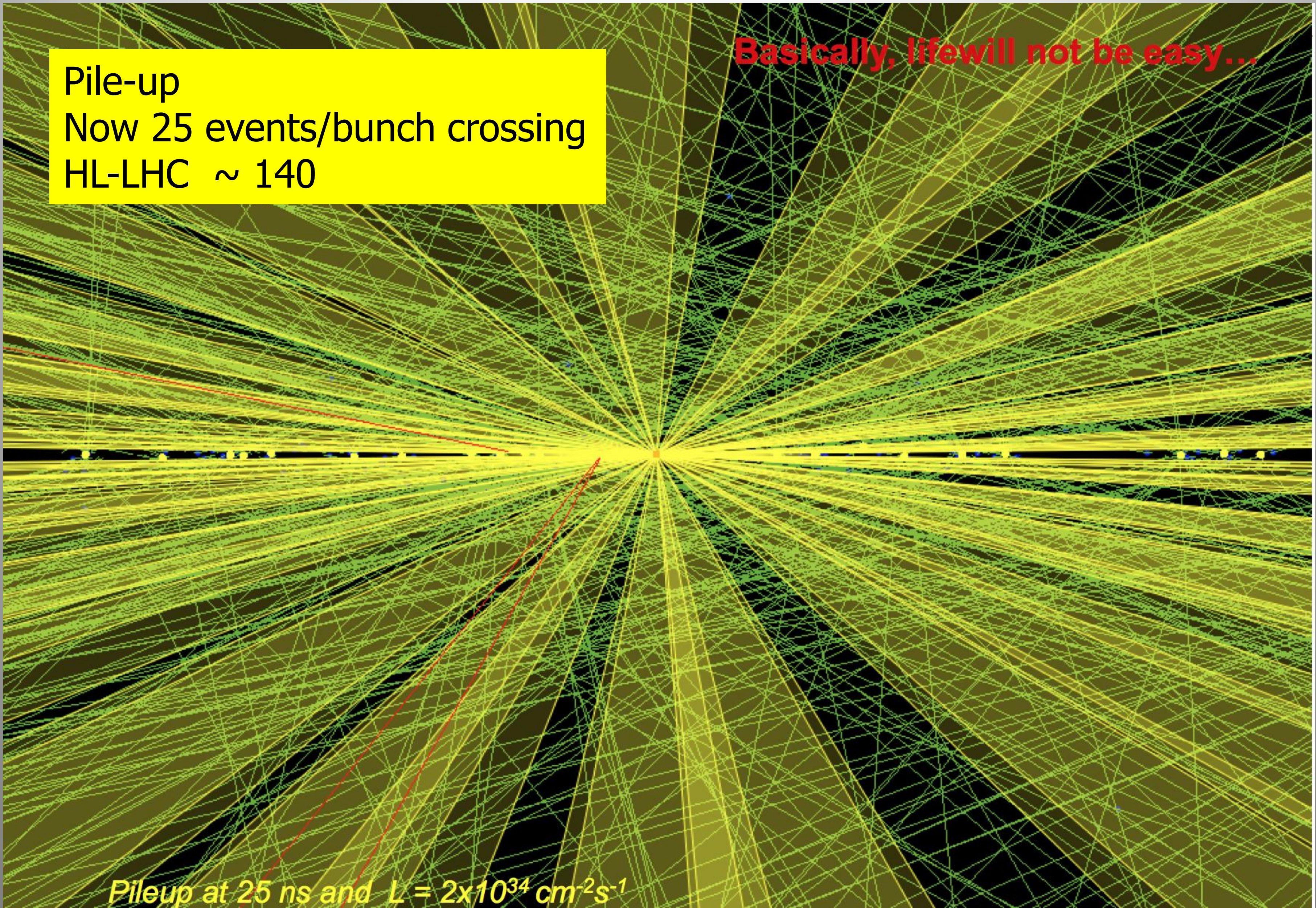
HL-LHC – LHC modifications



Does not come for free: ~1,000 MCHF (F Zimmerman Sendai, June 2013)

The Challenge for the Experiments

Pile-up
Now 25 events/bunch crossing
HL-LHC ~ 140



Beyond the LHC

- Proton-proton machines at higher energy…
- Electron-positron machines for high precision…
- Both? And allowing for electron-proton collisions..?

New projects will take 10-20 years before they turn into operation, hence need a vision & studies now!

From the European Strategy Group

….“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

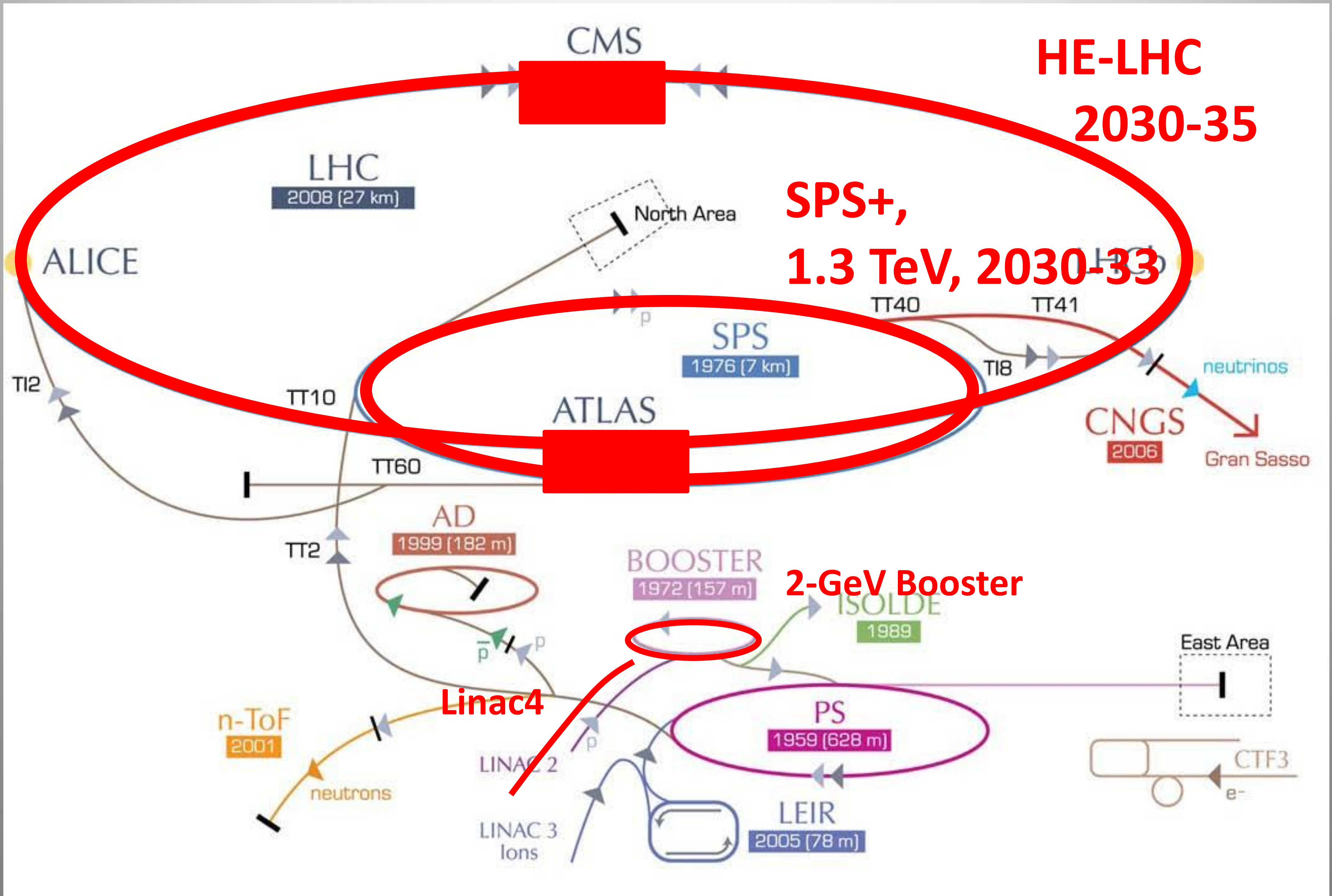
d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *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.***

- http://cds.cern.ch/record/1567258/files/esc-e-106.pdf

Similar recommendation from the Snowmass studies in the US

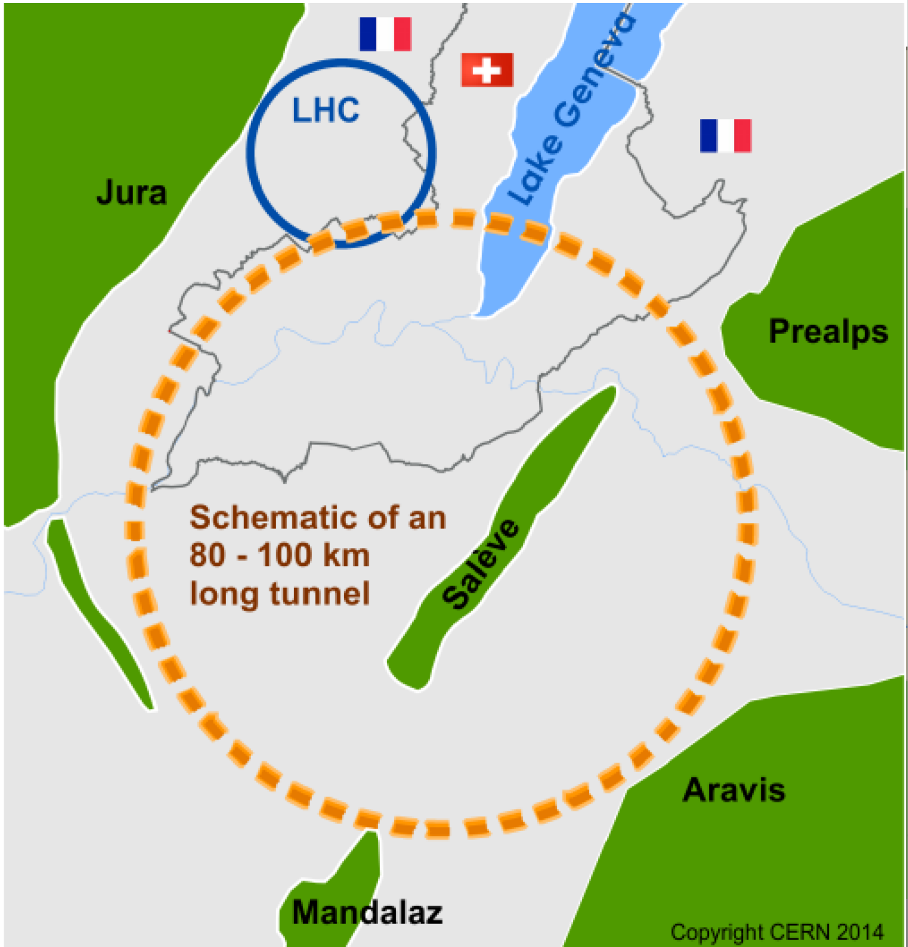
High Energy LHC (HE-LHC)



Recent CERN Initiative: FCC

Future Circular Colliders:

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)



FCC-hh: a Proton-Proton Collider

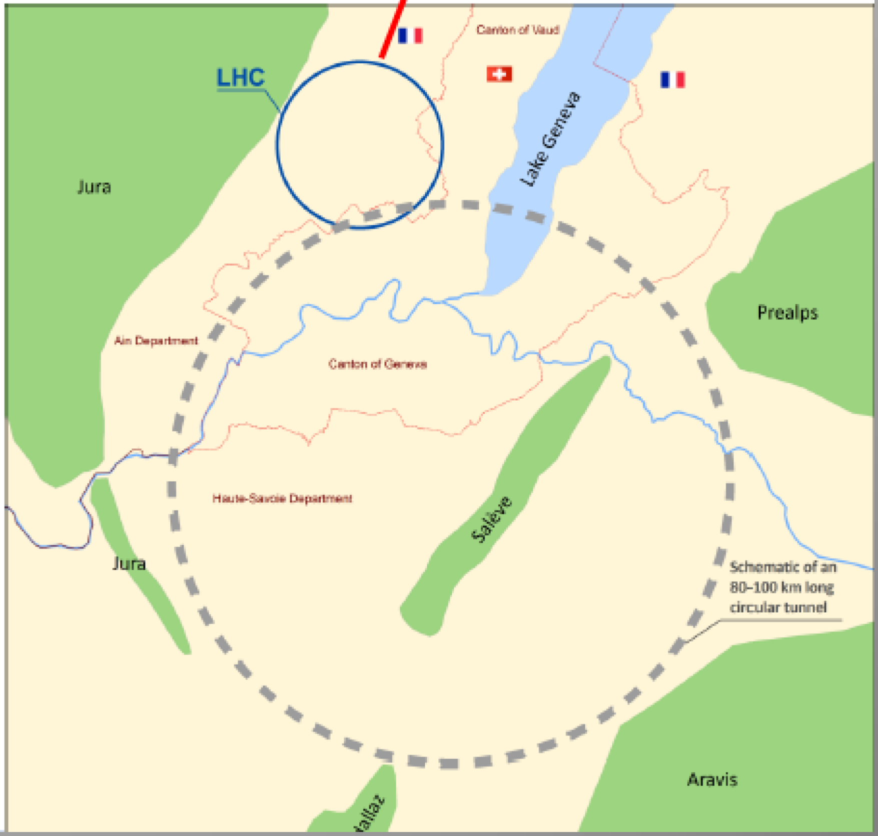
"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

First studies on a new 80 km tunnel in the Geneva area

- **42 TeV with 8.3 T using present LHC dipoles**
- **80 TeV with 16 T based on Nb_3Sn dipoles**
- **100 TeV with 20 T based on HTS dipoles**

Magnet R&D ongoing…



FCC-ee: the Electron-Positron Option

- In July 2011 a proposal was made to (re)install a 120 GeV / beam e^+e^- collider in the LEP-LHC tunnel – named LEP3. Work on LEP3 started in a series of workshops.
- The 80 km TLEP machine appeared in 2012 in parallel with the feasibility study for a 80 km ring for a future hadron collider around CERN. TLEP and LEP3 were presented in September 2012 at the European Strategy meeting in Krakow.
- In October 2013 TLEP was integrated into the FCC study and is now known as FCC-ee.

Circular e+e- collider with √s energy in the range of 90-350 GeV

Can serve 4 experiments simultaneously!

Challenging but no showstoppers!! (2 rings)
Energy loss/turn ~ 11 GeV

√s (GeV)	<L >(ab-1/year)*	Rate (Hz) ee—>hadrons	Years	Statistics
90	5.6	$2\ 10^4$	1	$2\ 10^{11}$ Z decays
160	1.6	25	1-2	$2\ 10^7$ W pairs
240	0.5	3	5	$5\ 10^5$ HZ events
350	0.13	1	5	$2\ 10^5$ ttbar

* each interaction point

Tera-Z, Oku-W, Mega-H, Mega-top

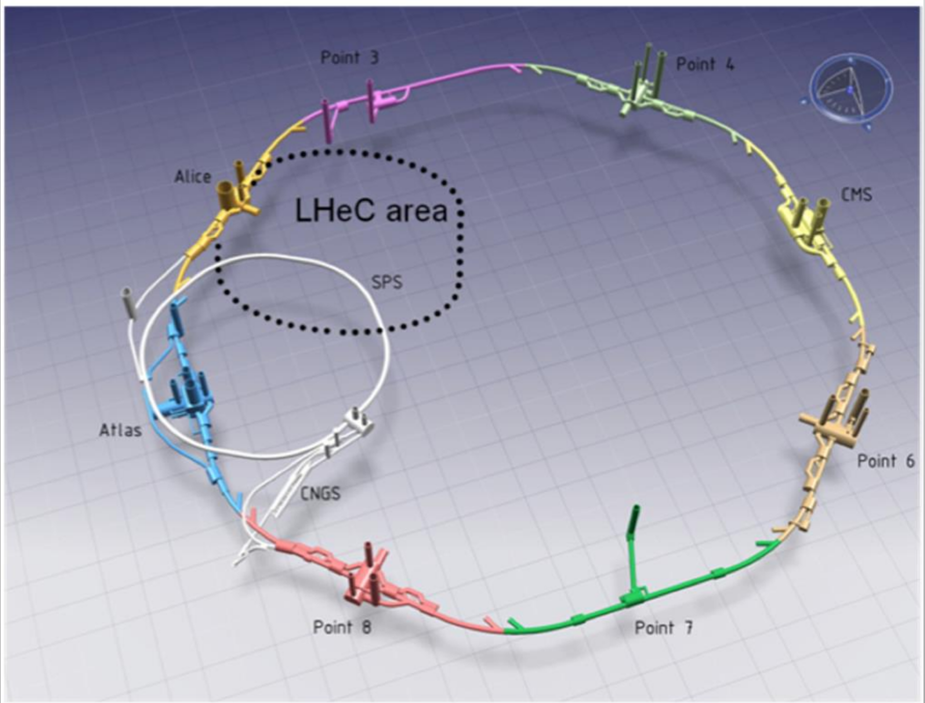
The Physics Case includes

- Precise measurement (0.1% to 1%) of the Higgs Couplings
- Improve precision (statistics x 10^5) on the measurements of the Z parameters [M_Z, Γ_Z , R_ℓ, R_b, R_c, Asymmetries & weak mixing angle]. Z rare decays.
- Scan W threshold (aiming at 0.5 MeV precision). W rear decays
- Scan ttbar threshold (aiming at 10 MeV)

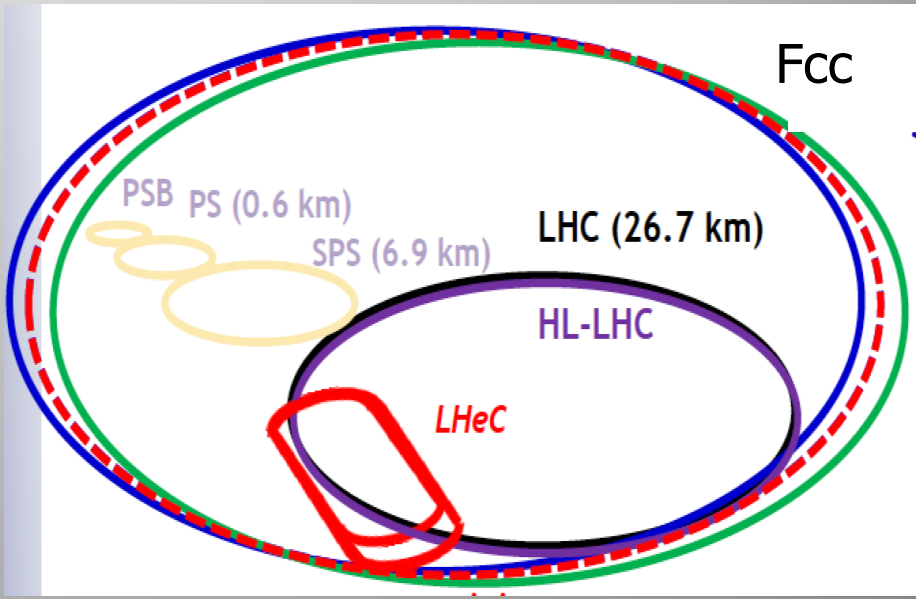
FCC-he: the Electron-Proton Option

- Future possible hadron and lepton colliders will be excellent QCD explorers
- High luminosity (10^{34}-10^{35}) and/or energy lepton-hadron colliders
  ->Dedicated facilitie studies include the LHeC (Europe) and EIC (US) projects and now FCC-he

ep: 60 GeV x 7 TeV

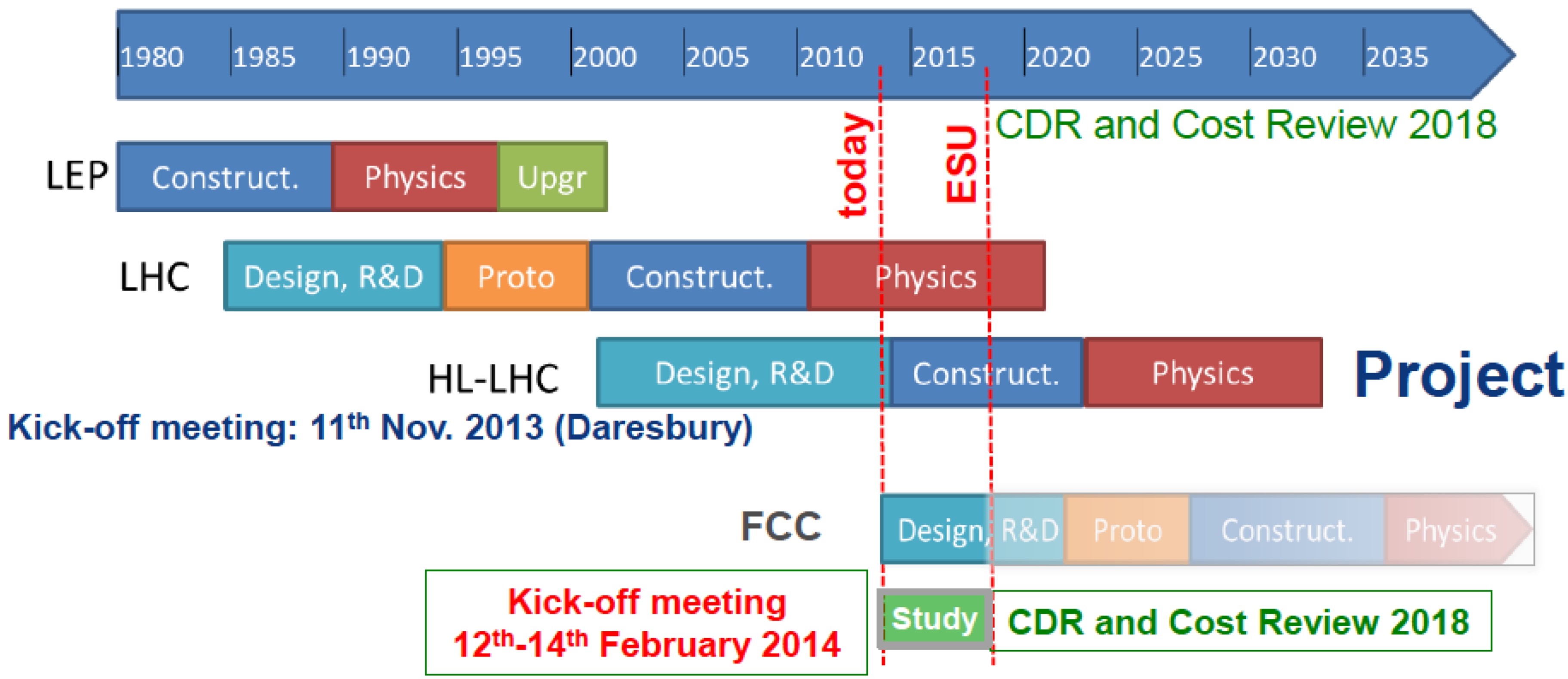


ep: 60-175 GeV x 50 TeV



Use FCC-ee ring or
Energy Recovery Linac

FCC Schedule: First Step



Study reports requested for the next strategy meeting in 2018

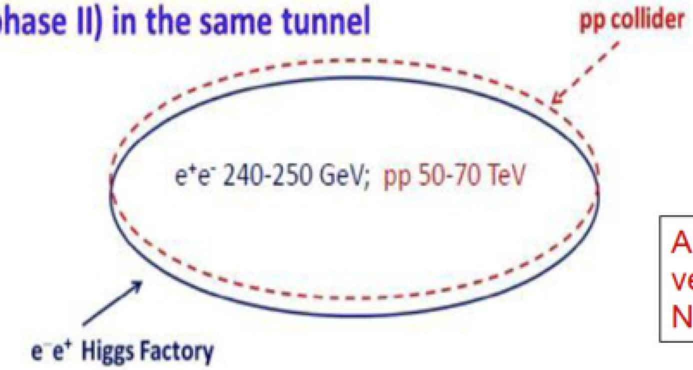
In Particular in China…

China expressed has interest in the construction of a new large accelerator, first as an e+e- Higgs factory and then as a high energy pp machine.

Aim: design completed in 2020

Contribute to the world effort

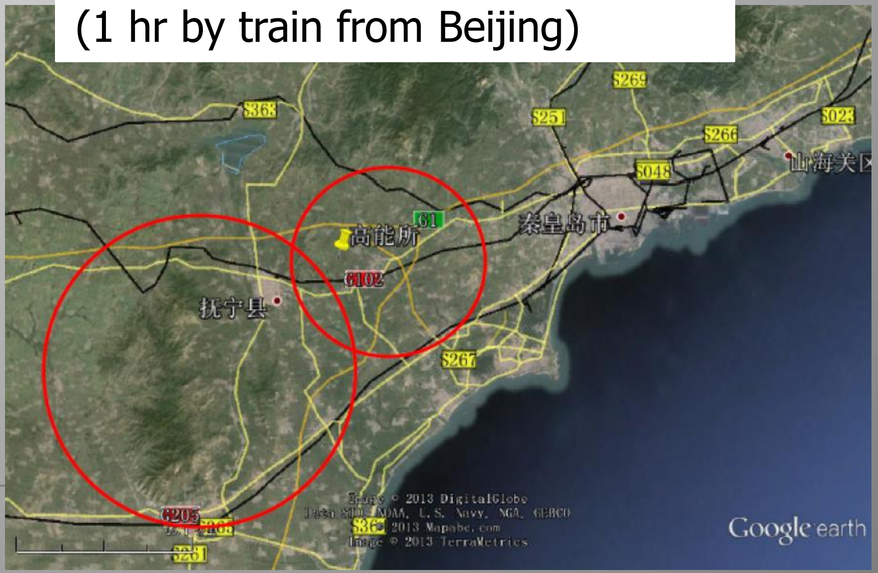
- Circular Higgs factory (phase I) + super pp collider (phase II) in the same tunnel



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

"Center for Future High Energy Physics (CFHEP)"

Possible site: Qinhuangdao
(1 hr by train from Beijing)



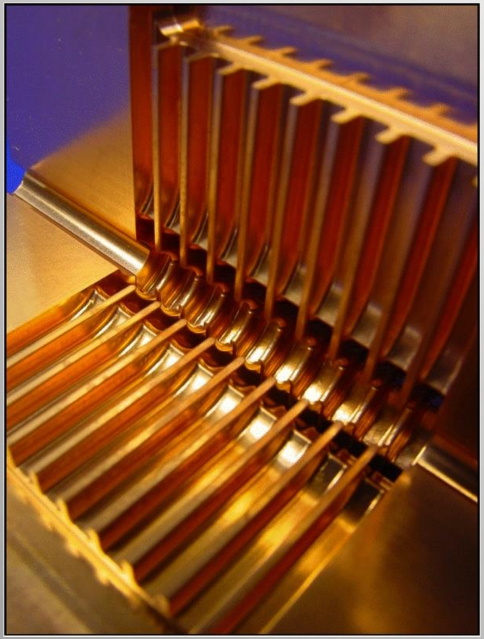
Linear e+e- Colliders

Electron-positron machines for high precision and possibly high energy (few TeV) …
Avoid Synchrotron radiation from a circular machine

Studies and R&D work on linear colliders started in the '90's and they have achieved a very high level of maturity now…

Linear e+e- Colliders: ILC and CLIC

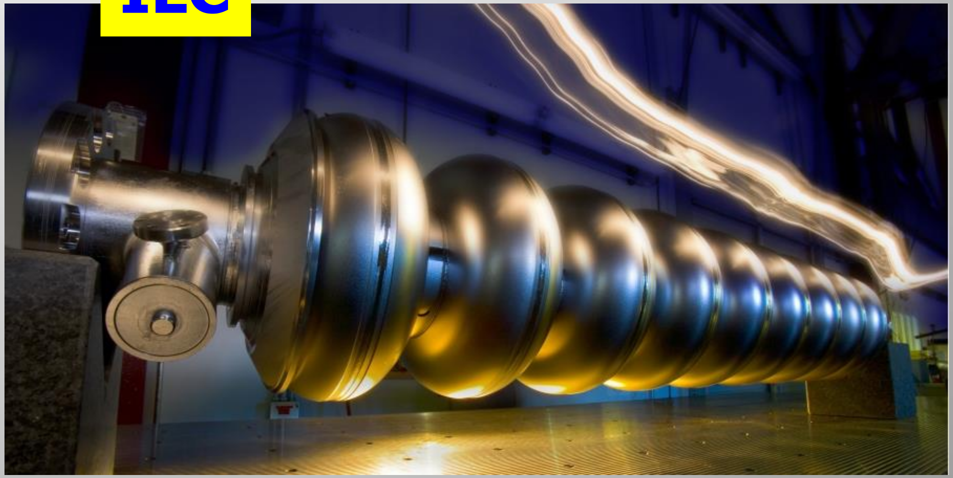
CLIC



- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- $\sqrt{s}$ up to 3 TeV
- Physics + Detector studies for 350 GeV - 3 TeV

Linear e^+e^- colliders
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

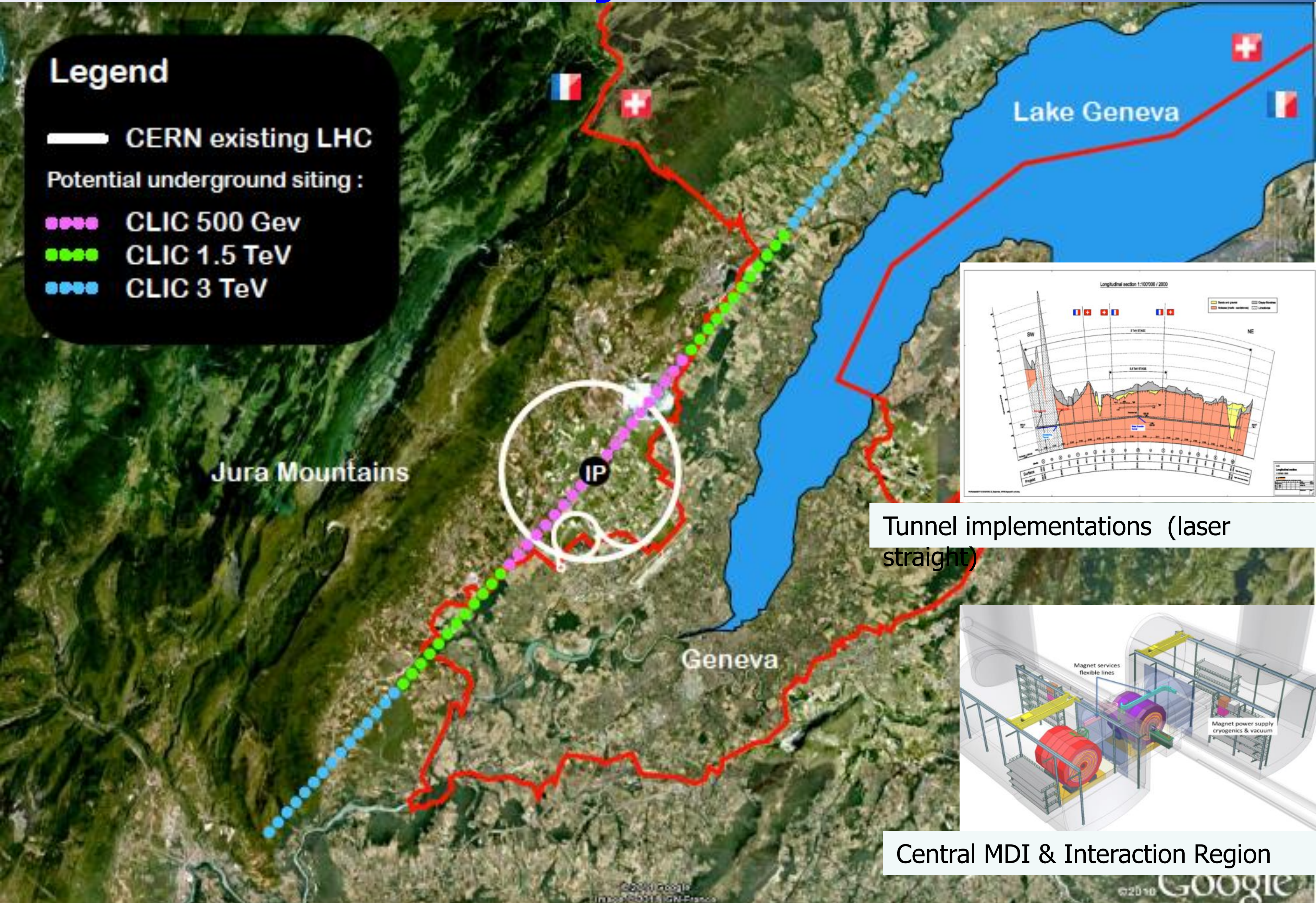
ILC



- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- $\sqrt{s} \leq 500$ GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

The ILC is basically ready to be build now!

CLIC Layout @ CERN

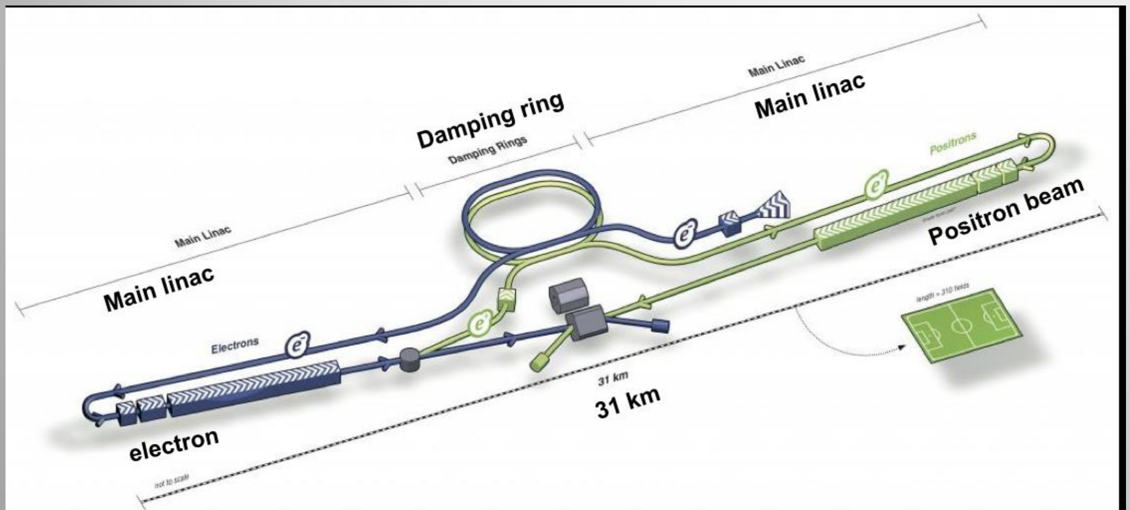


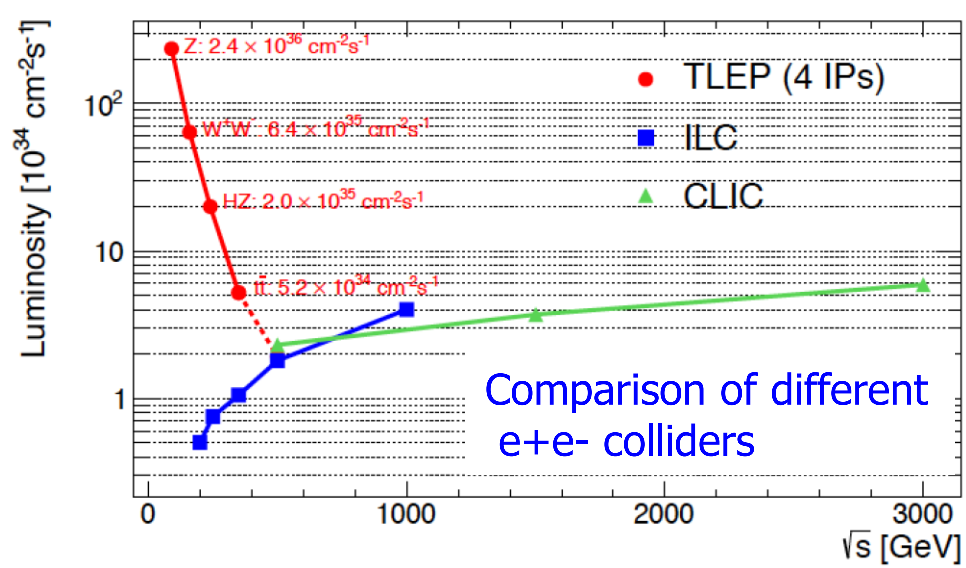
Tunnel implementations (laser straight)

Central MDI & Interaction Region

ILC Layout

Japan has expressed a strong interest to host this collider! Under discussion…





Comparison of different e+e- colliders

Note: in 2013 ILC produced a plan to double the luminosity (not included in the figure)

The Physics at the Future Colliders

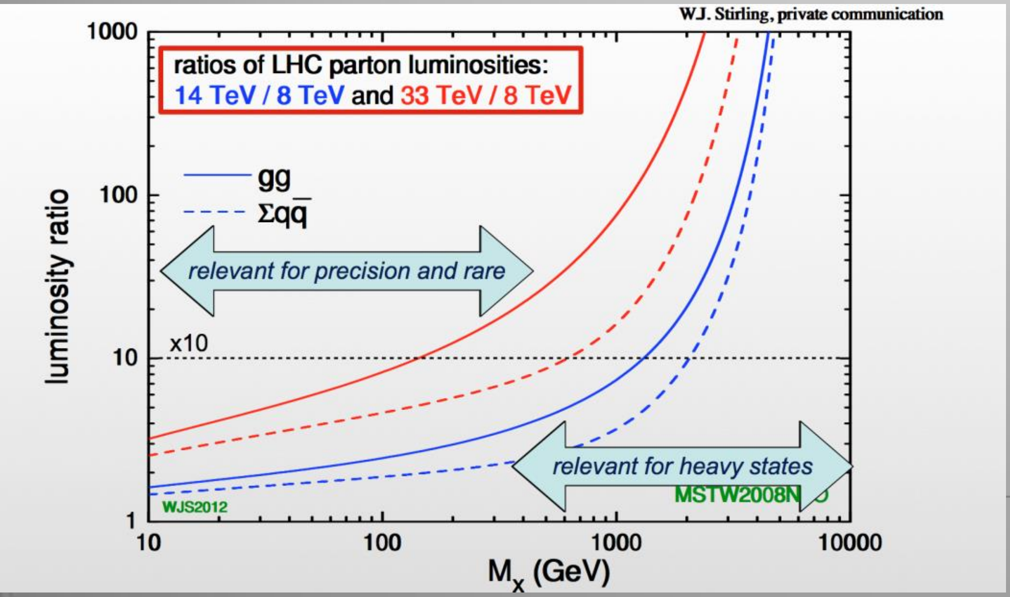
- Studies for linear colliders documented in TDRs since ~ 15 years, regularly updated
- HL-LHC studies started in 2012, ongoing
- FCC-ee studies started in 2012, ongoing
- FCC-hh and FCC-he studies started end of last year

Apart from LC studies, most of the future collider studies are just at the beginning. (-> volunteers welcome!!)

Physics Program: Key Topics

- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare process

-> However, no "no-loose theorem" know, as yet.

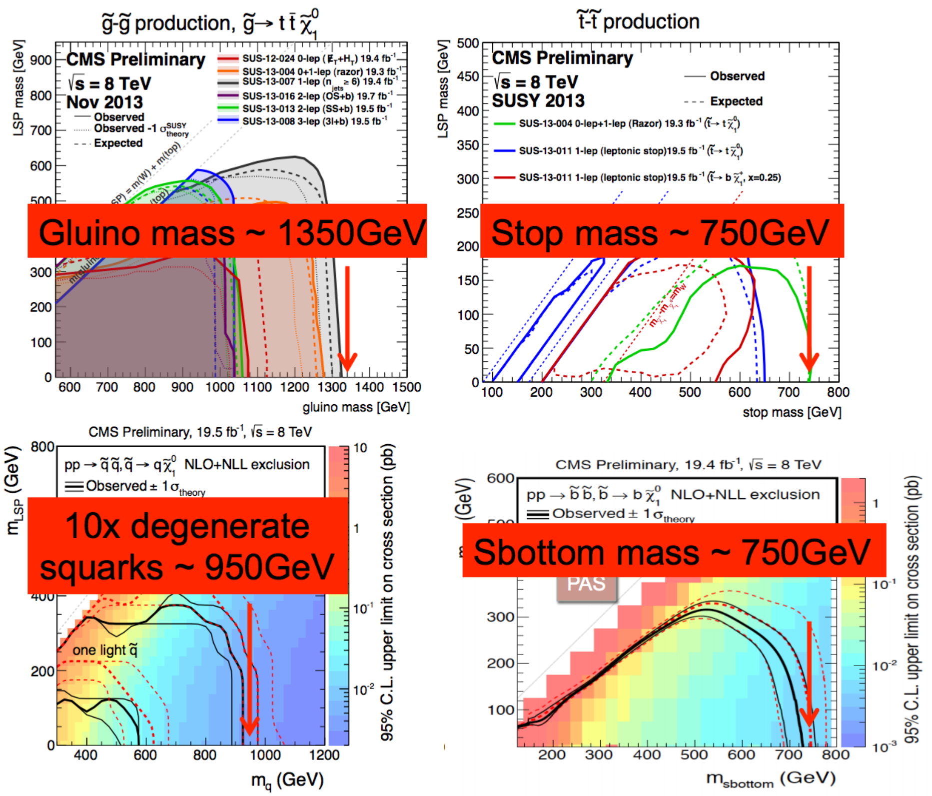


- Higgs mass precisions ~ 100-200 MeV enough?
- Higgs self-coupling precision Better than 20% needed?
- Higgs couplings? Few %? Better? (J. Wells et al., arXiv:1305.6397)

SUSY Prospects @ 2015/2016

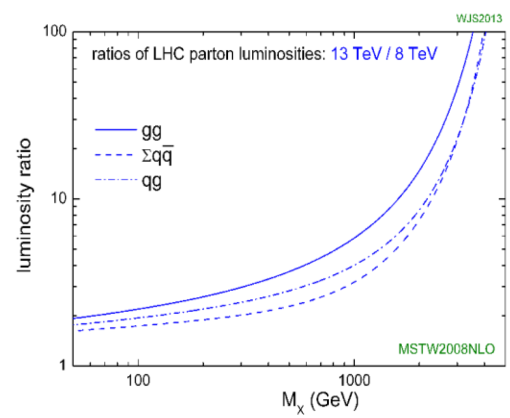
Expect ~ 10-20 fb^{-1} in 2015 & 40 fb^{-1} in 2016 (present guestimates)

Now 2014



2015-2016

Cross Section Scaling 8 -> 13 TeV



Xsection Ratios 13/8 TeV

1350GeV gluino: x30
950GeV squark: x20
750GeV squark: x9
350GeV $X^{+-}X^0$: x3
top pairs: x4

~1/fb of 13TeV data surpasses our best gluino limits.
~3/fb of 13TeV data surpasses our sbottom and stop limits.
There will be no relevant SM measurements at 13TeV by the time we have already stepped well into new territory!!!

0.5-1 fb^{-1} would be enough for first analyses entering new territory
We expect that have such a sample by Summer 2015!!

Use the Higgs as a tool for Discoveries

- Higgs offers unique portal for discovery
- Key properties we need to understand
  - Total width
  - Couplings to SM particles
  - Shape of Higgs potential: self-interactions
  - Is there a CP-odd component?
  - Do Higgs couplings violate flavor?
  - How does Higgs interact with neutrinos?
  - Does the Higgs generate mass for Dark Matter?
  - How many Higgs Bosons are there?
  - Is Higgs elementary or composite?
  - Is the universe in a false vacuum?

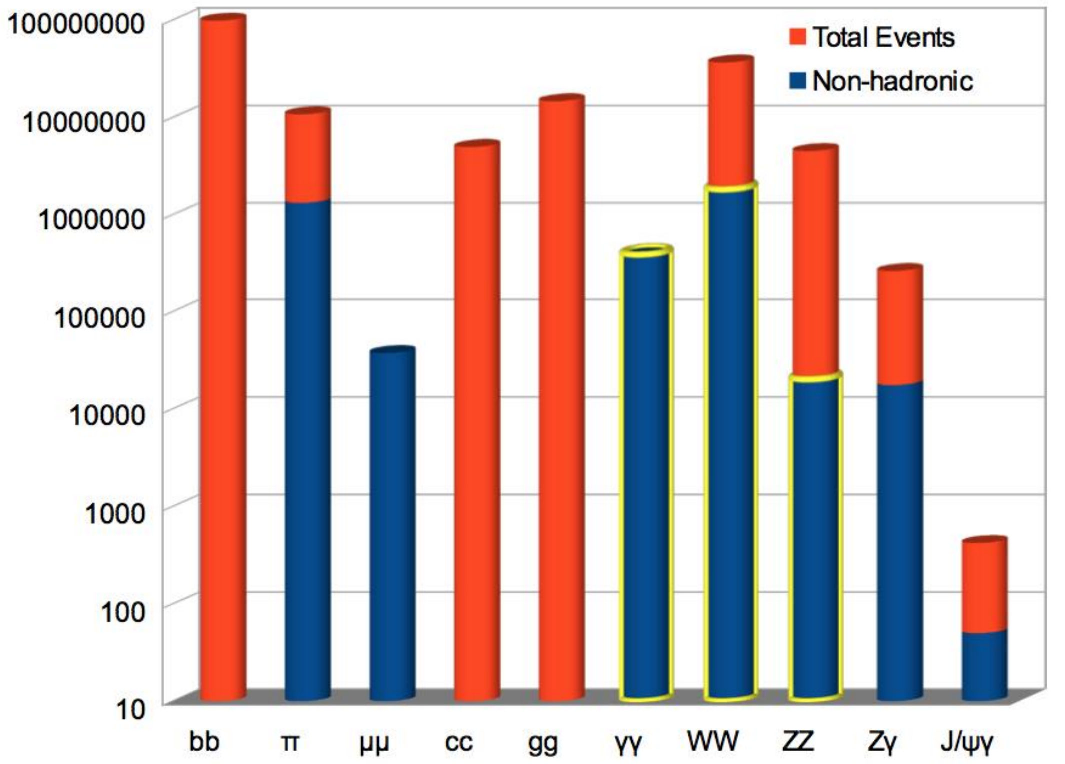
G. Weiglein Nov ‘14

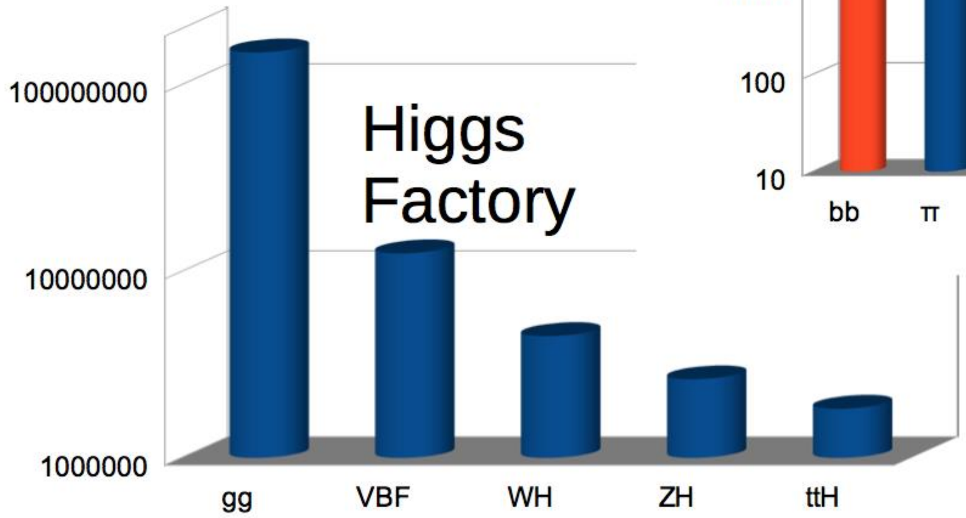
Study the Higgs in as much detail as possible!

High Luminosity LHC

Number of Higgs Bosons produced with 3000 fb^{-1}

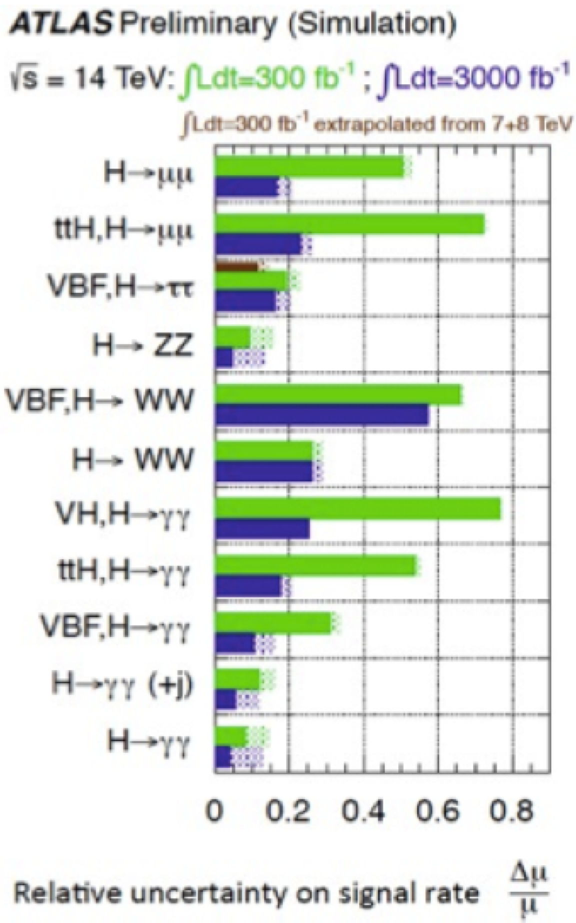
- Over 100M Higgs bosons
- 20K $H \rightarrow ZZ \rightarrow llll$
- 400K γγ
- 50 $H \rightarrow J/\psi\gamma$

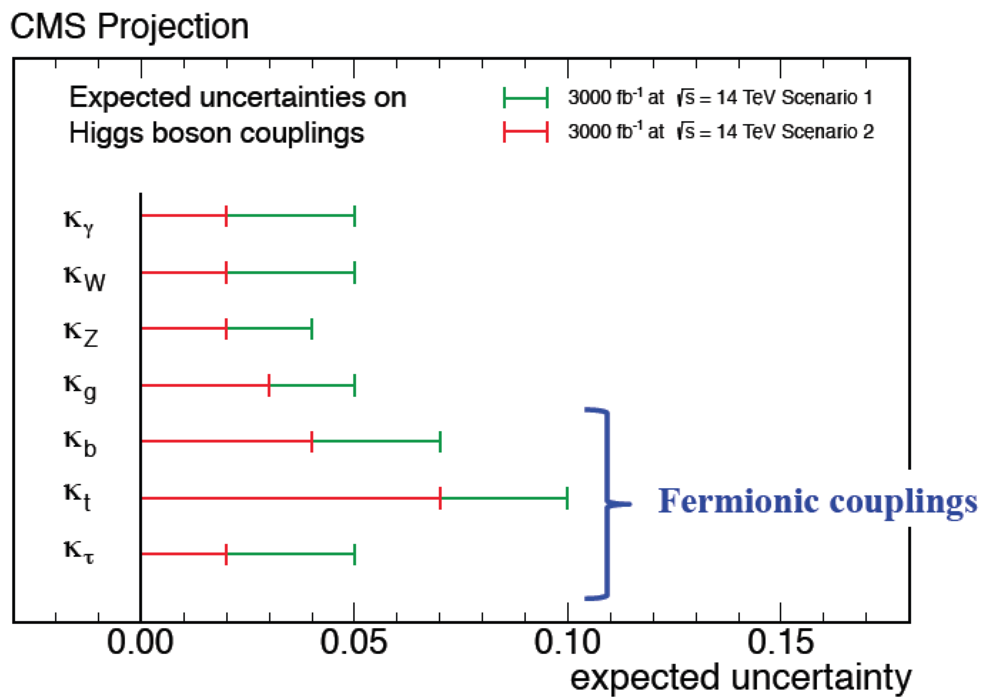




- Over 1M in all major production modes

High Luminosity LHC Precision





Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest $\propto 1/\sqrt{L}$

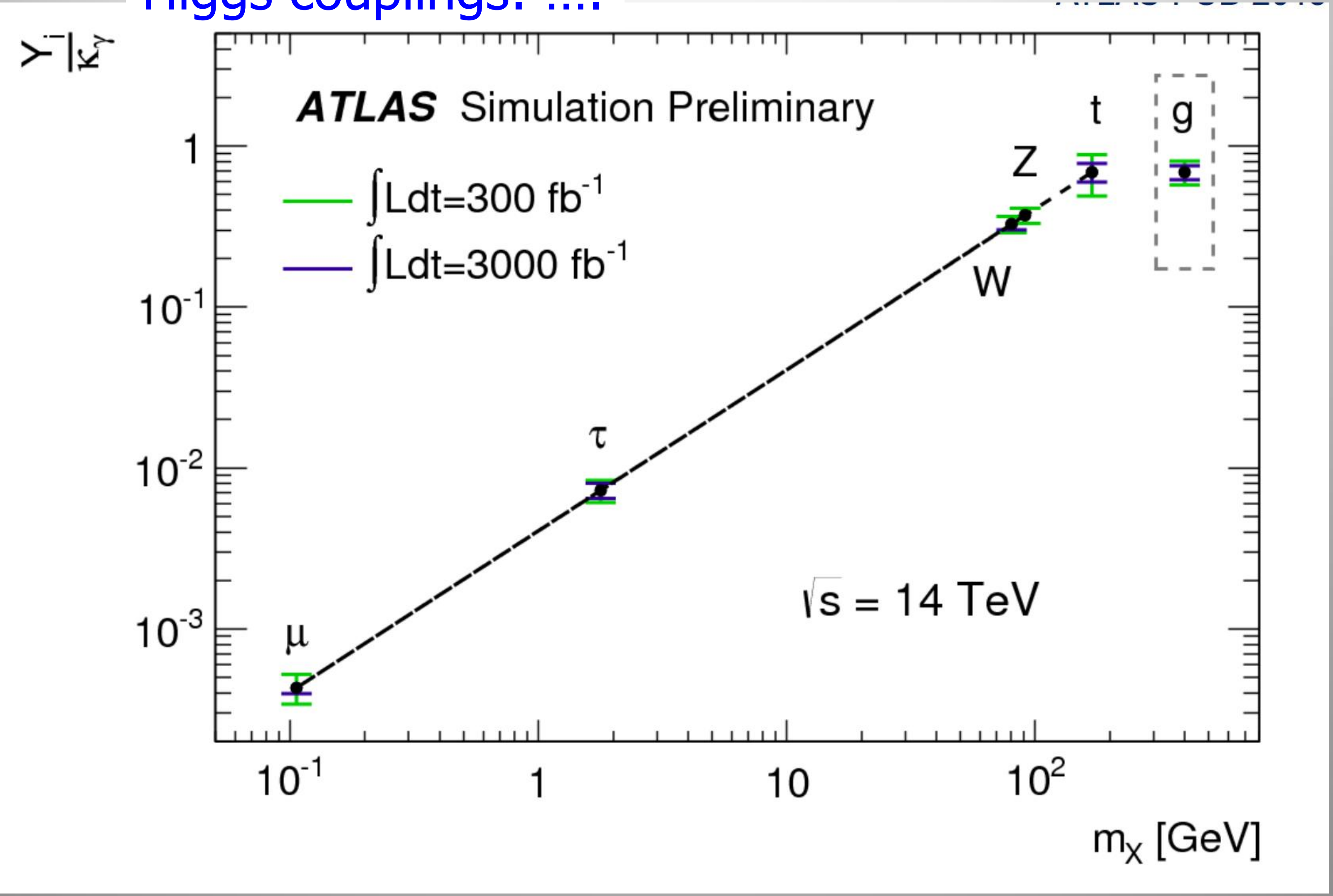
Based on parametric simulation

Extrapolated from 2011/12 results

Determine the Higgs couplings to a few % precision…

High Luminosity LHC Precision

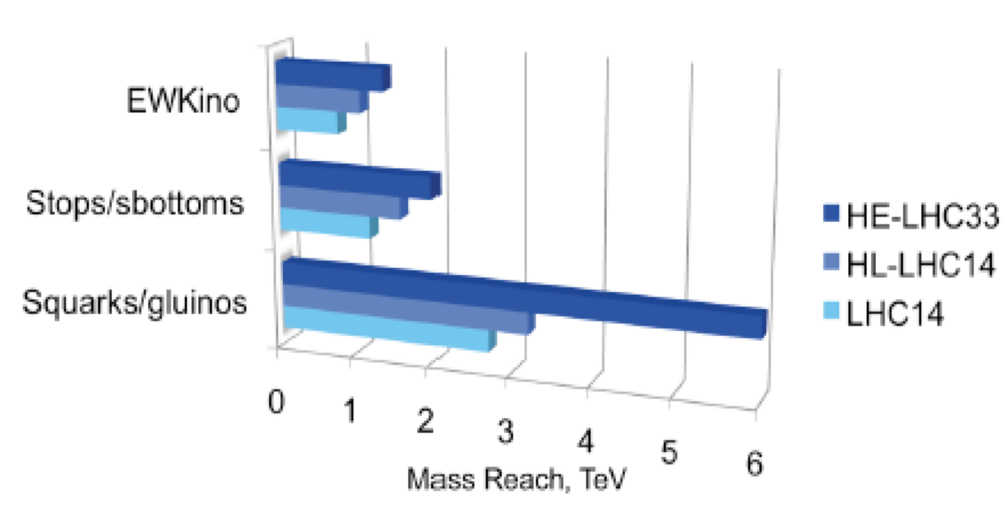
Higgs couplings: ….



Determine the Higgs couplings to a few % precision…

Searches for New Particles in pp

Searches for pair produced SUSY particles



FCC-hh

- Reach sparticle masses search up to about 20 TeV for squarks of light quarks and 6 TeV for stops
- Excited quarks probe the structure of quarks down to 4×10^{-21} m
- Discovery of resonances up to masses of 40 TeV

E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$ $\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1\ \mathrm{TeV}$

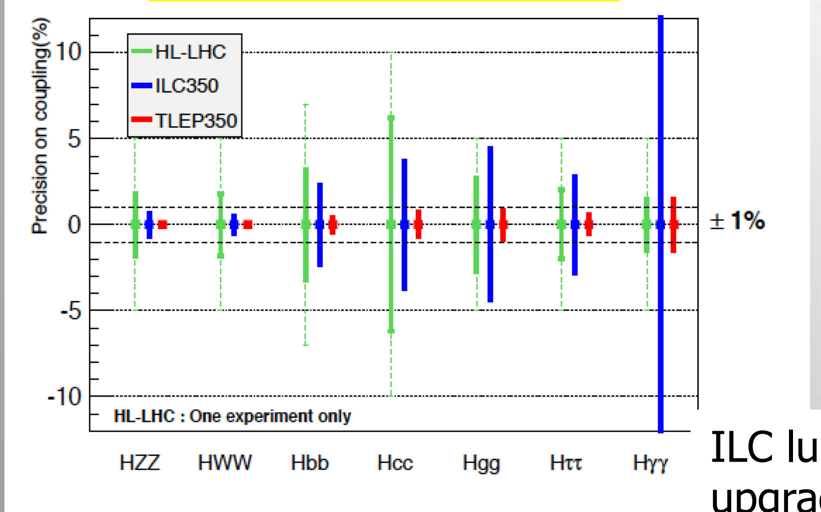
Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Upper limit for higher Higgs mass in 2HDM models?

- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB

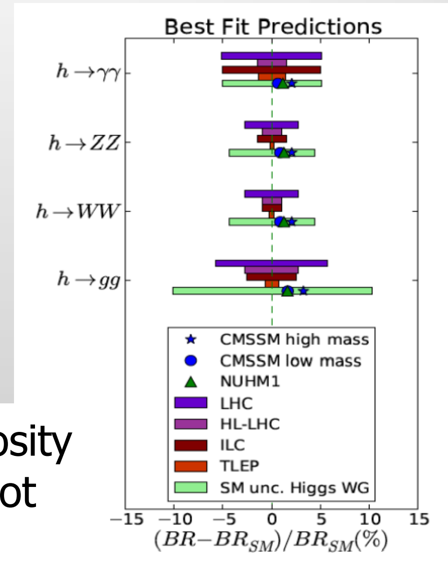
Physics at e+e- Colliders

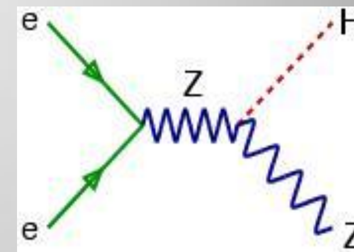
Higgs Boson Couplings



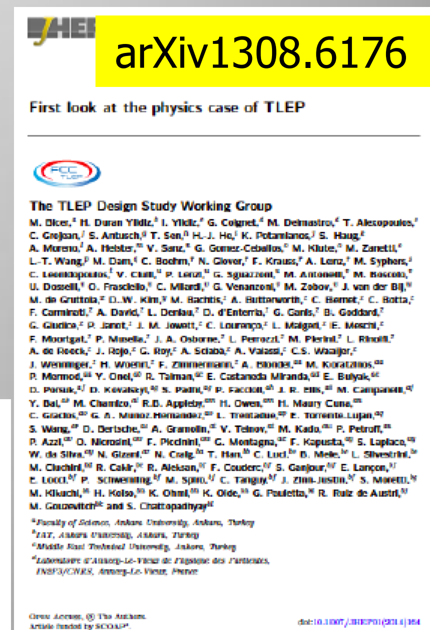
ILC luminosity upgrade not included

Higgs Boson decays



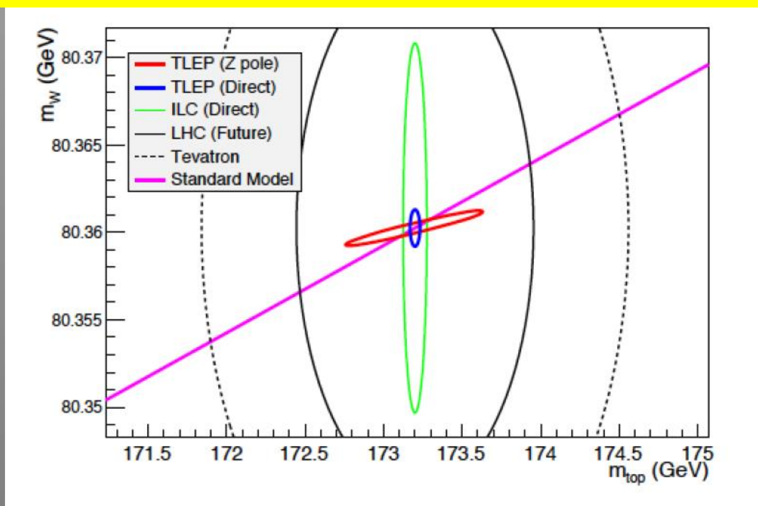


arXiv1308.6176

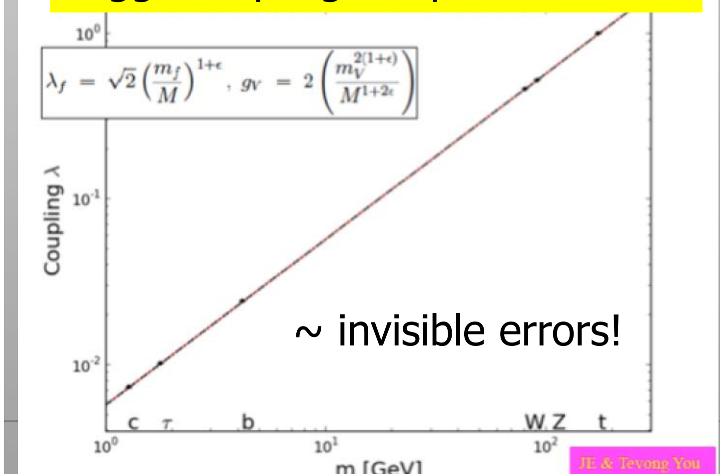

First look at the physics case of TLEP

The TLEP Design Study Working Group

Fit to all EWK precision measurements



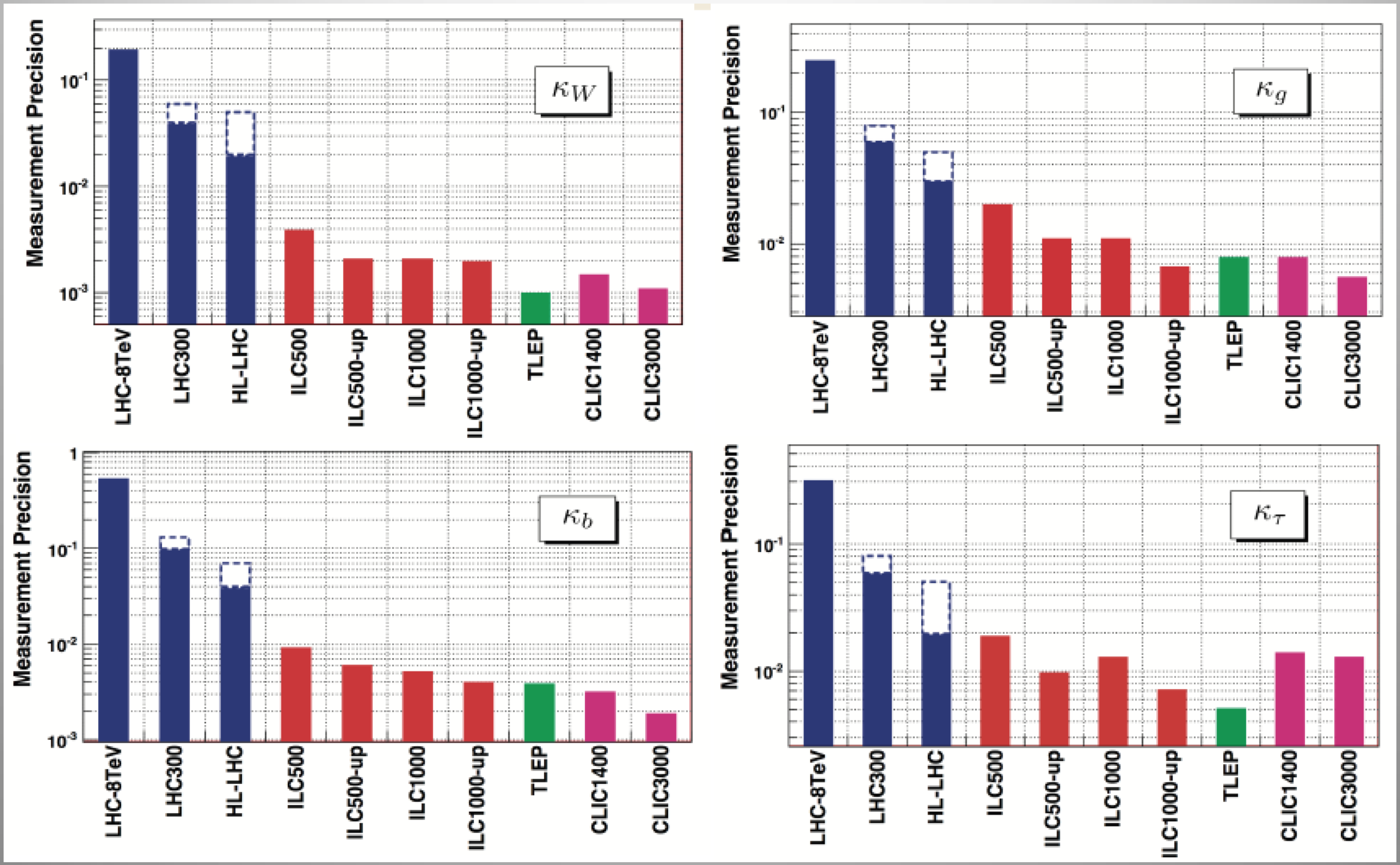
Higgs couplings vs particle mass



~ invisible errors!

FCC-ee delivers very precise measurements

Coupling Precision: Global Fits



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Target Precision for Higgs Couplings

- Generic size of coupling modifications for new particles with M=1 TeV

1310.8361

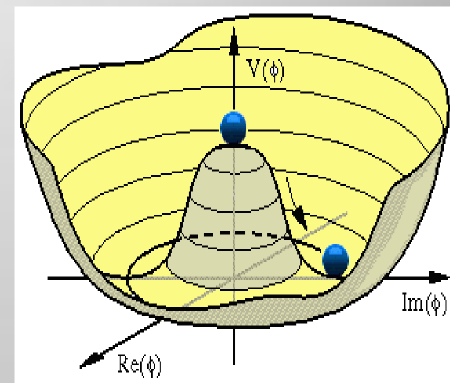
	$\delta\kappa_V$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet	~6%	~6%	~6%
2HDM	~1%	~10%	~1%
MSSM	~.001%	~1.6%	~-.4%
Composite	~-3%	~-(3-9)%	~-9%
Top Partner	~-2%	~-2%	~1%

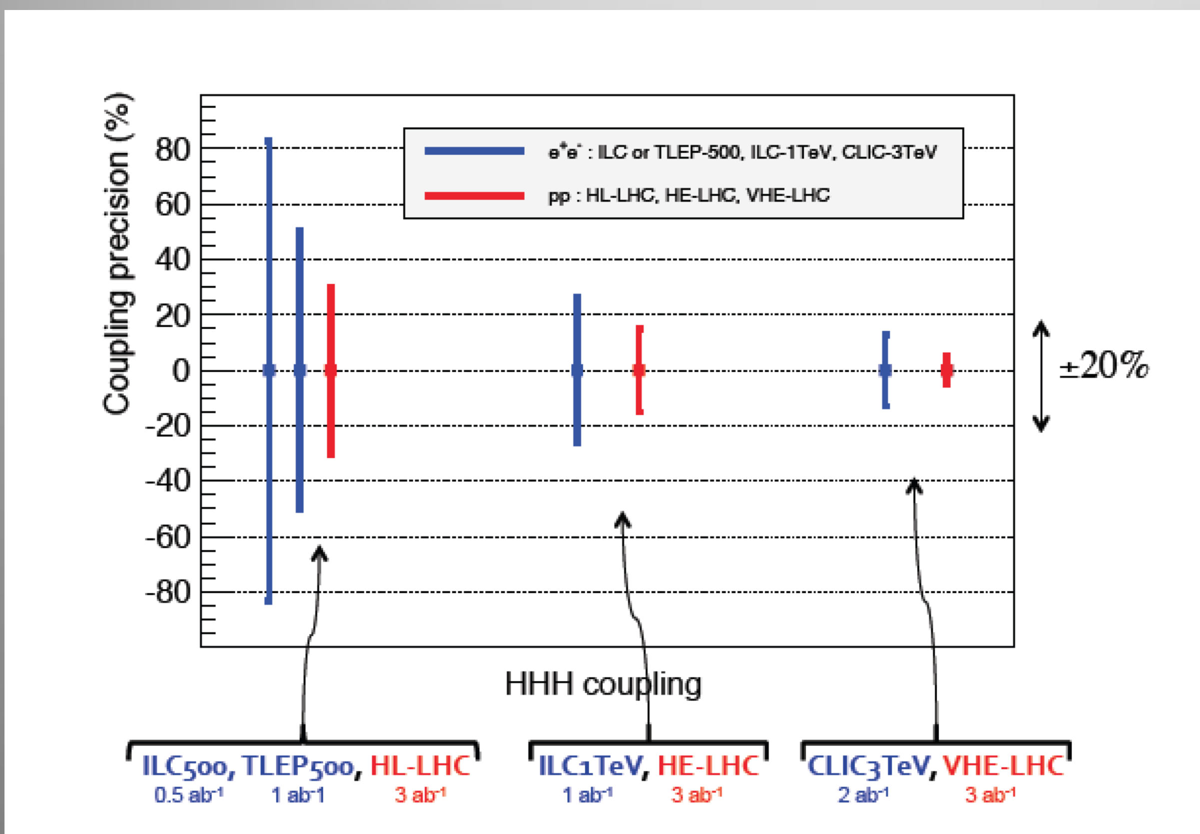
- Interplay between direct searches and indirect effects of new physics

The Higgs Self Coupling!

A key measurement for our understanding of the Higgs field potential!

in pp





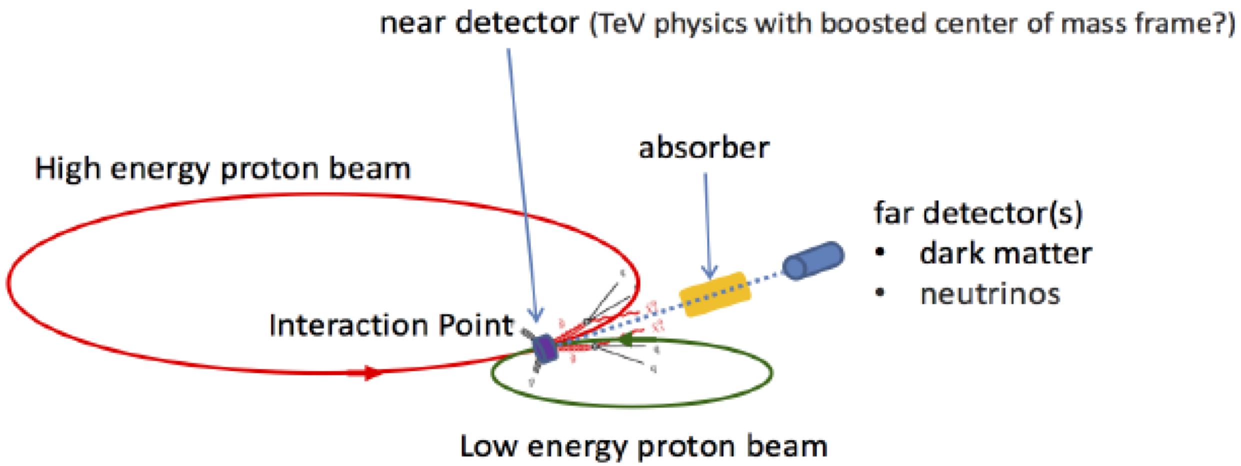
Difficult measurements!!:
Evaluation till ongoing for HL-LHC sensitivity

e+e- machines with sufficient energy and FCC-hh can measure this process

Room for Blue Sky Thinking!

Example: If we produce Dark Matter particles candidates, can we be sure it is really DM? Check the interaction with matter in a detector!!

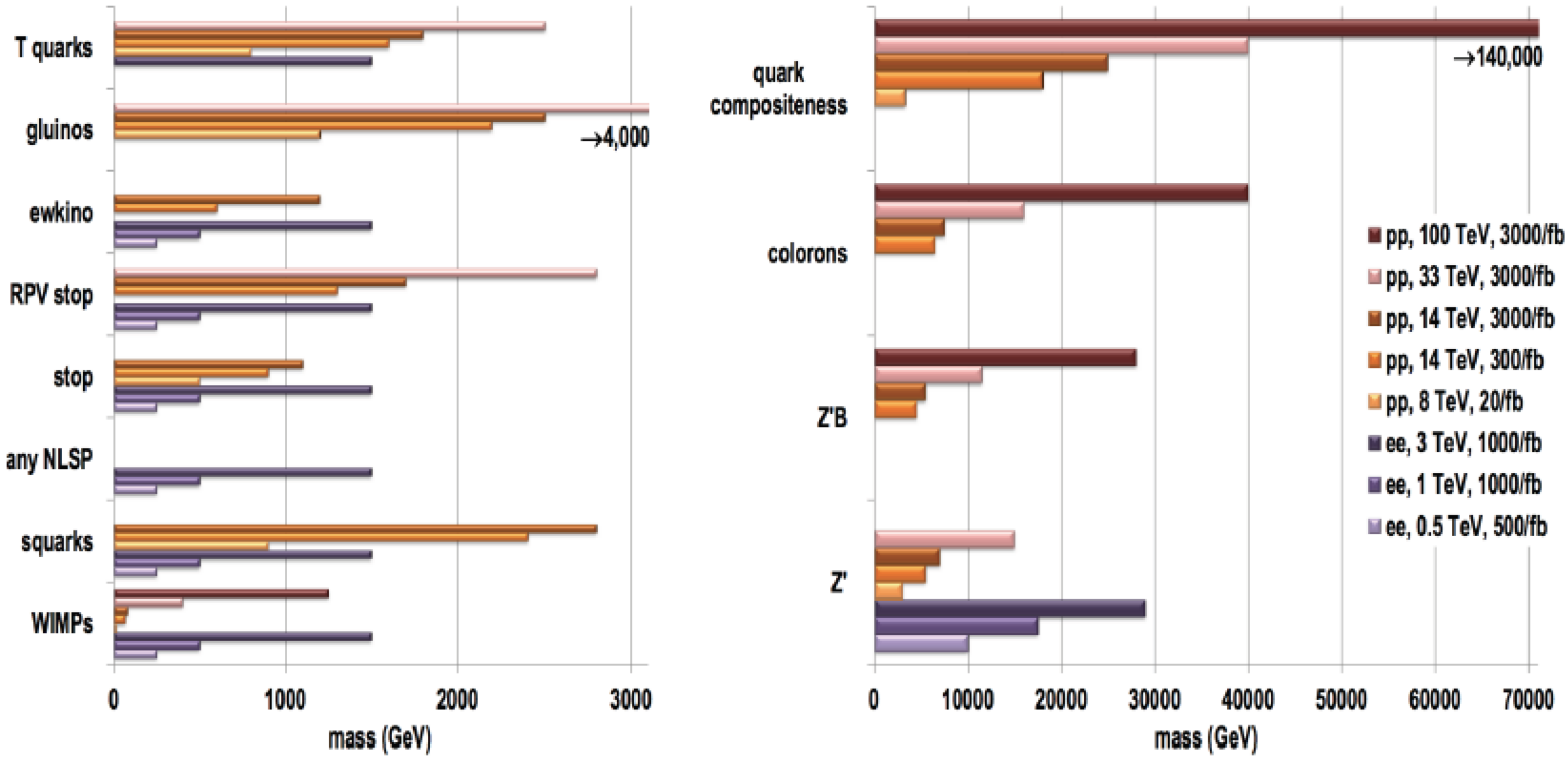
DM Beam from Asymmetric Collider



	E_{high} [TeV]	E_{low} [TeV]	E_{cm} [TeV]	
FHC→Fixed Target	50	0.001	0.3	← insufficient E_{cm}
FHC↔LHC	50	7.000	37.4	promising!
FHC↔Super-SPS	50	3.000	24.5	promising!

Long timescales: Time to explore new ideas!!

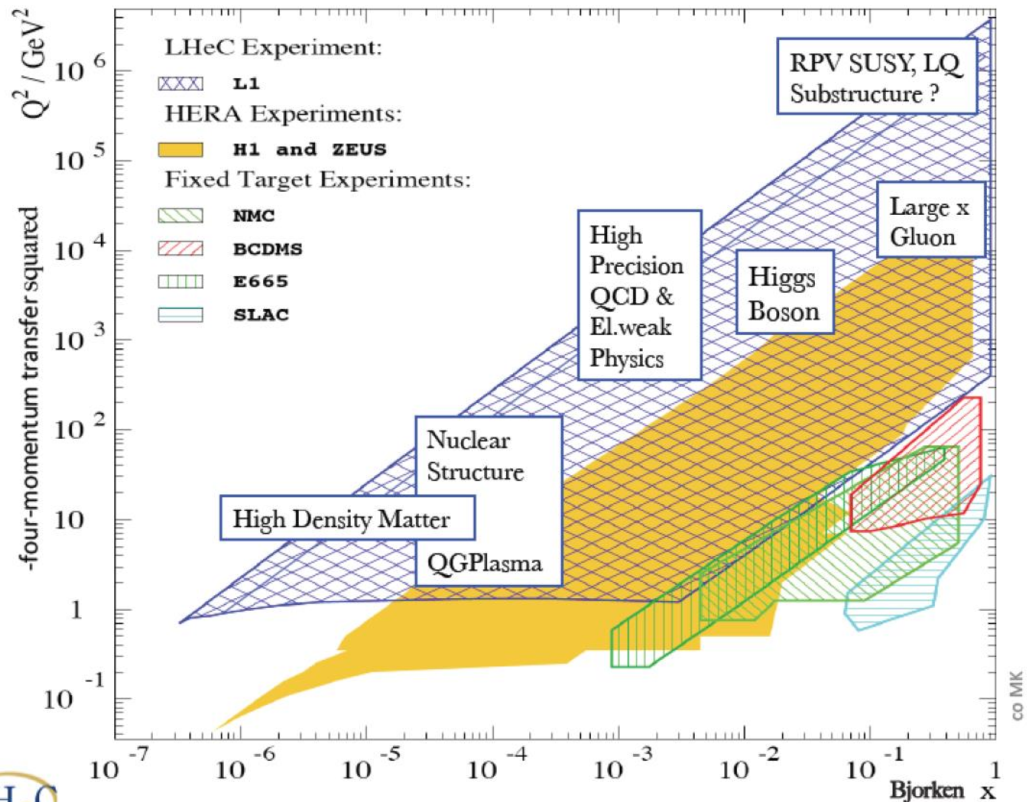
New Physics Reach Overview



1311.0299

Electron-Proton Collider

Always a useful complement to a hadron collider
eg via measurement parton distribution functions



Breaking of Factorisation

Free Quarks

Unconfined Color

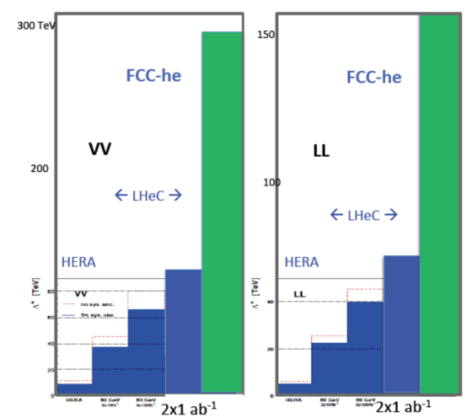
New kind of coloured matter

Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

Reach for CI (eeqq) at FCC-he



- Very preliminary scaling from LHeC
- Reach about O(100) TeV, expected to be competitive with FHC

- Access to specific Higgs couplings
- Reach for new physics eg Leptoquarks, CIs…

Conclusion

- In 2012 we found a Higgs Boson at the LHC. Next LHC run @ 14 TeV will hopefully reveal even more.
- The Higgs has started a new paradigm: Study the Higgs in detail. (HL-)LHC will be able to do a lot but very likely not everything.
- e+e- Higgs factories are being discussed & studied
- High energy pp colliders, eg at 100 TeV, will extend the reach for new particles and interactions
- A large international effort is coming together on the study for the high energy frontier, FCCs and LCs
- The path for new machines is long, and benefits for society (technology) will play an important role.

Conclusion

Discoveries await!

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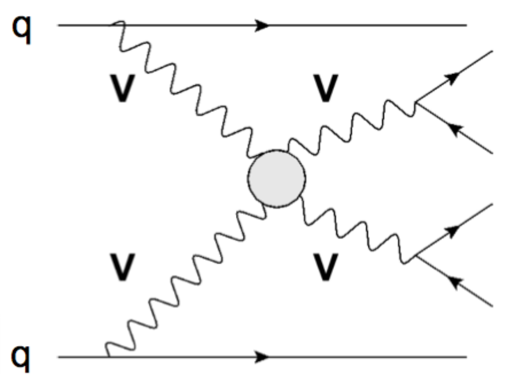
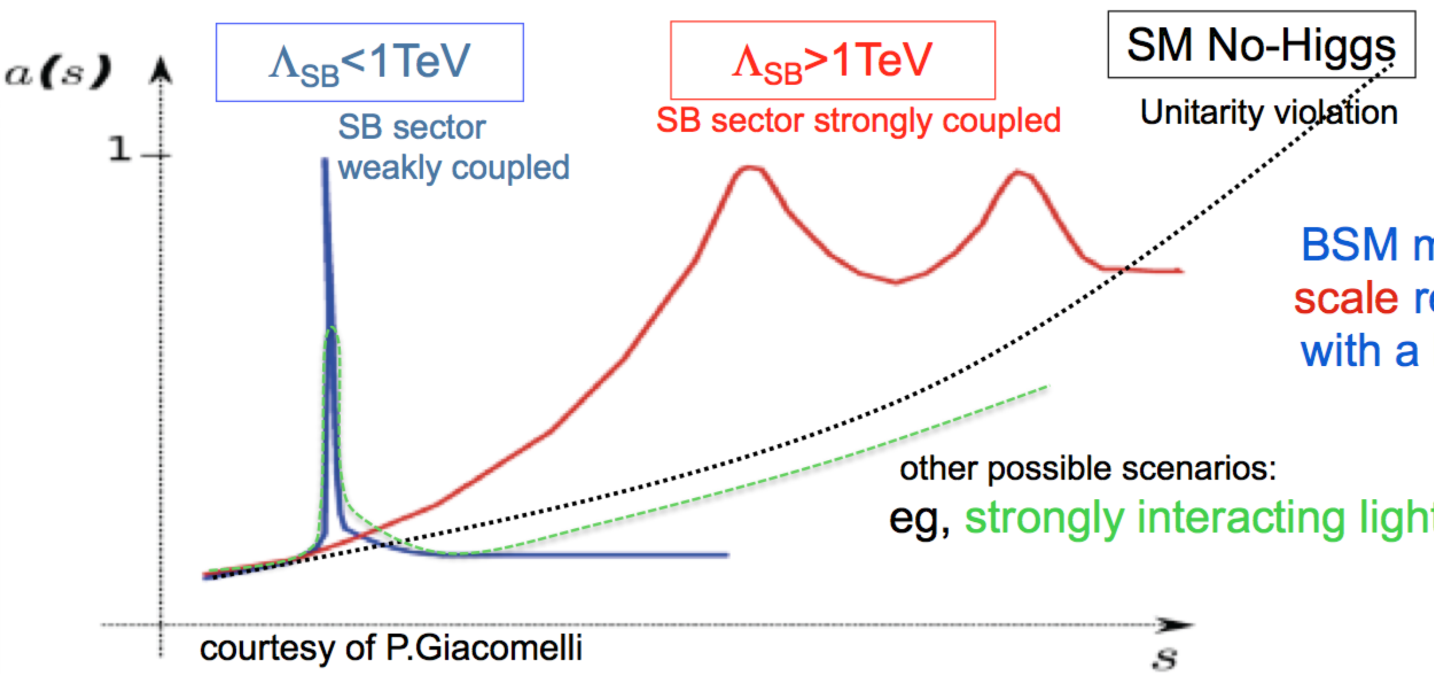


-unitarity restoration in VBS amplitudes strictly linked to EWSB mechanism.

-a SM Higgs does the job exhaustively.

-a non-SM Higgs needs further mechanism (heavy VV resonances ?)



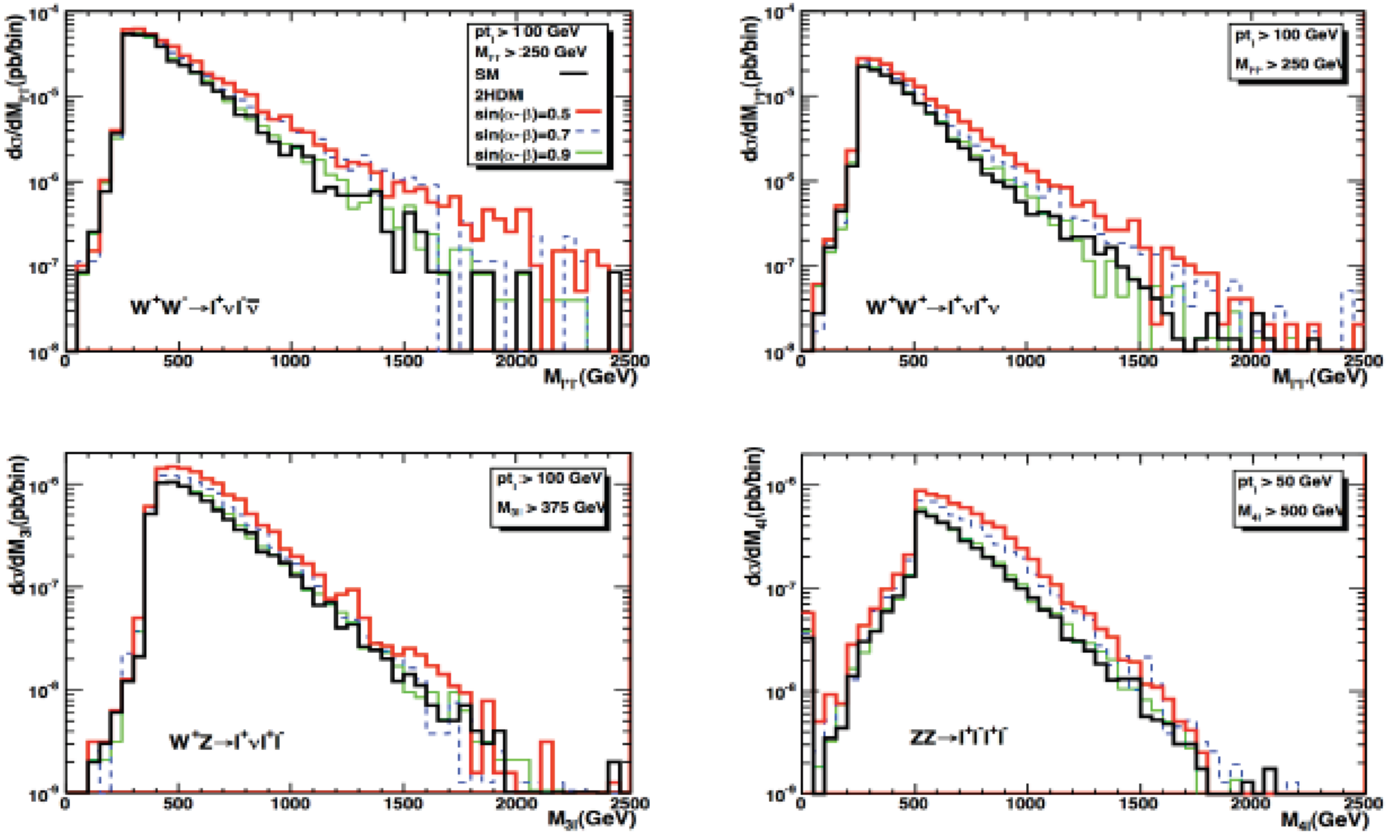
BSM models predict TeV-scale resonances “paired” with a light scalar particle

Challenging ! both for TH (interferences with qq→6f amplitudes) and EXP.s (small yields, wide y coverage, many channels) !!!

Vector Boson Scattering

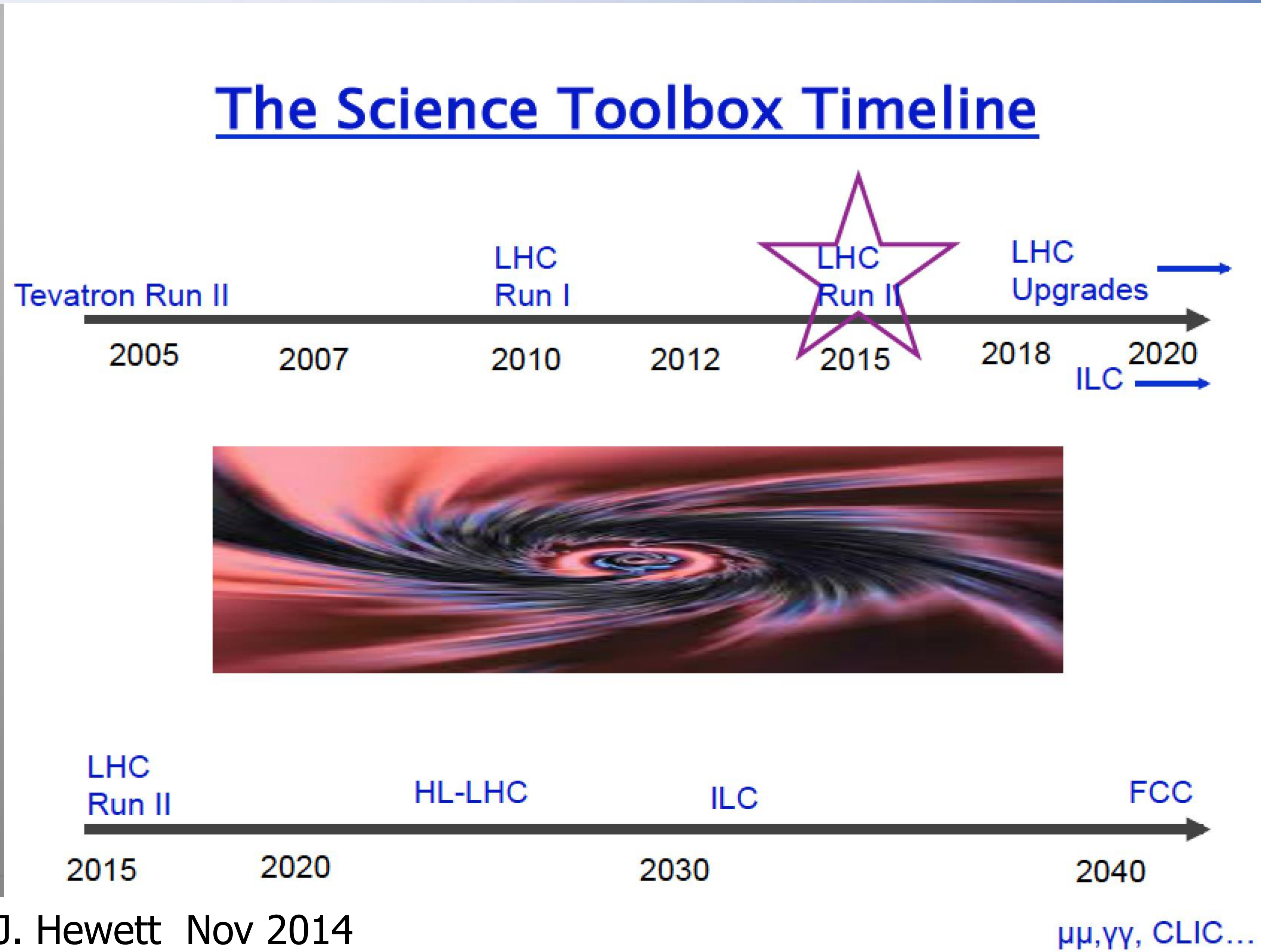
- Important for HL-LHC program!!
- Invariant mass distributions in Two-Higgs-Doublet-Model

Chang, Cheung, Luy, Yuan, 1303.6335



This is an area that needs more study!

The Past and the Future



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