Particle Physics Perspectives From Experiment

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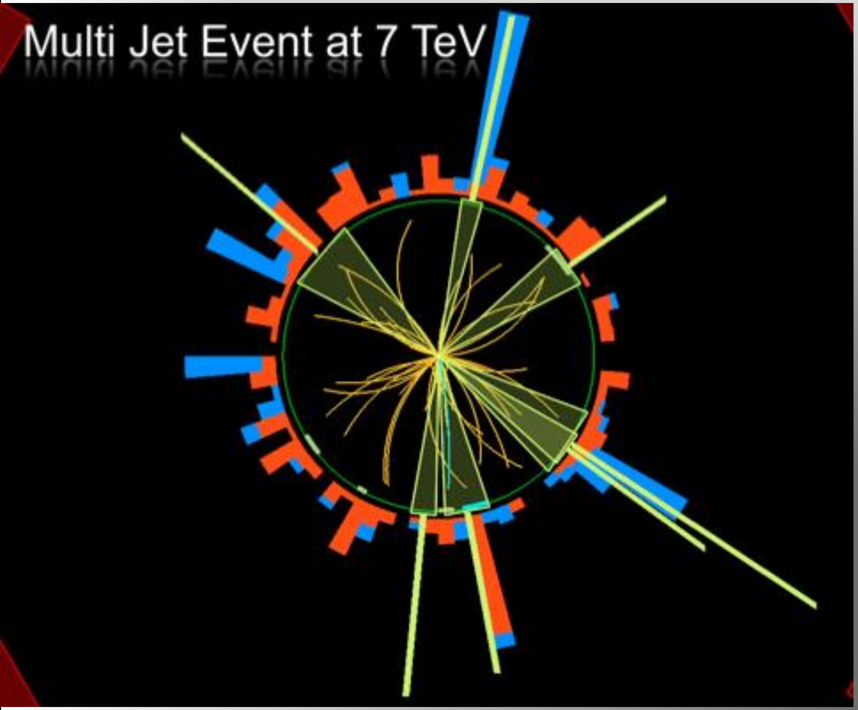
15 th August 2014 Dakar

THE THIRD BIENNIAL AFRICAN SCHOOL OF FUNDAMENTAL PHYSICS AND ITS APPLICATIONS

Cheikh Anta Diop University
Dakar, Senegal
August 3-23, 2014

CERN

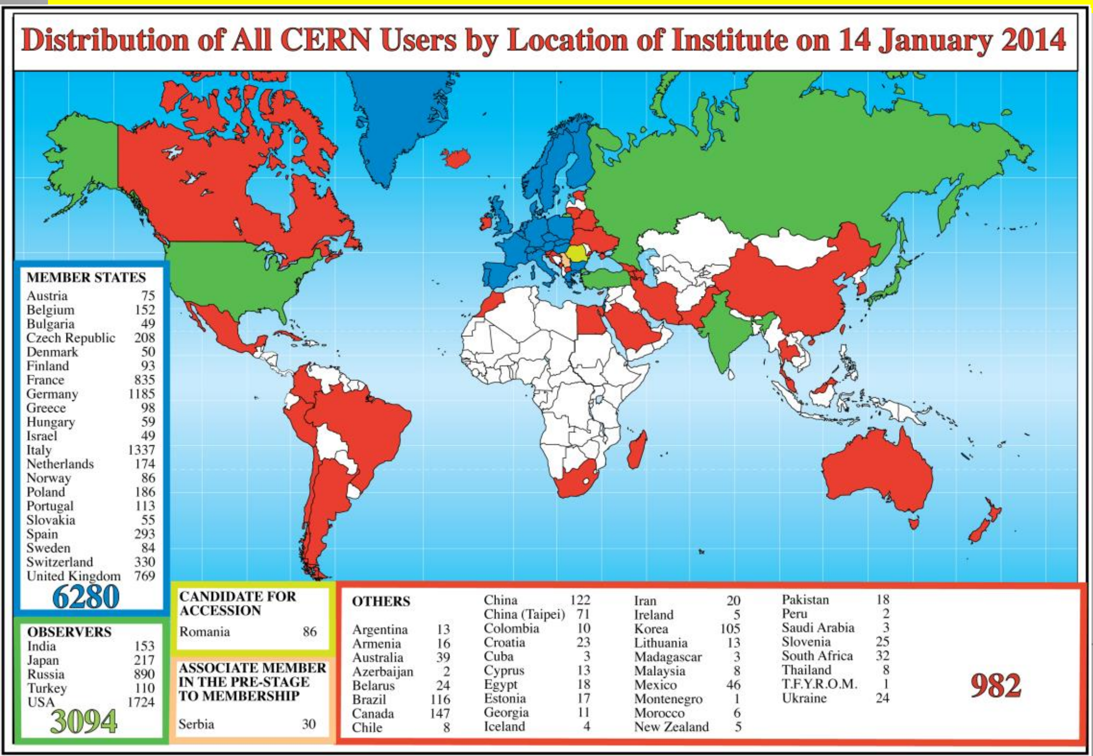


Outline

- Introduction: Particle Physics at the Colliders
- 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

CERN: The European Laboratory for Particle Physics

- CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
- It is now commonly referred to as European Laboratory for Particle Physics
- It was founded in 1954 and has 21 member states + several observer states.
- CERN employees ~4000 people + hosts ~11000 visitors from >500 universities.
- Annual budget ~ 1000 MCHF/year (2014)



Where the World Wide Web was born...


What is the world made of?
What holds the world together?
Where did we come from?

Accelerators are Powerful Microscopes

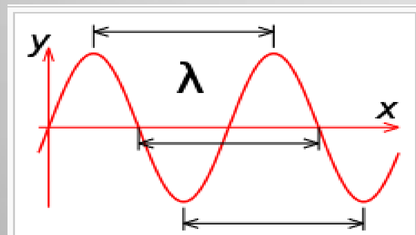
They make high energy particle beams that allow us to see small things.

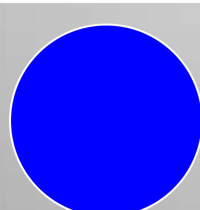
$$\lambda = \frac{h}{p}$$

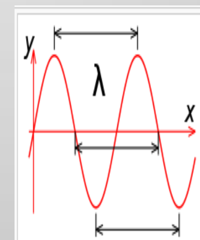
Planck constant

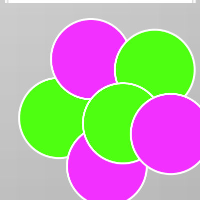
wavelength

momentum ~ energy





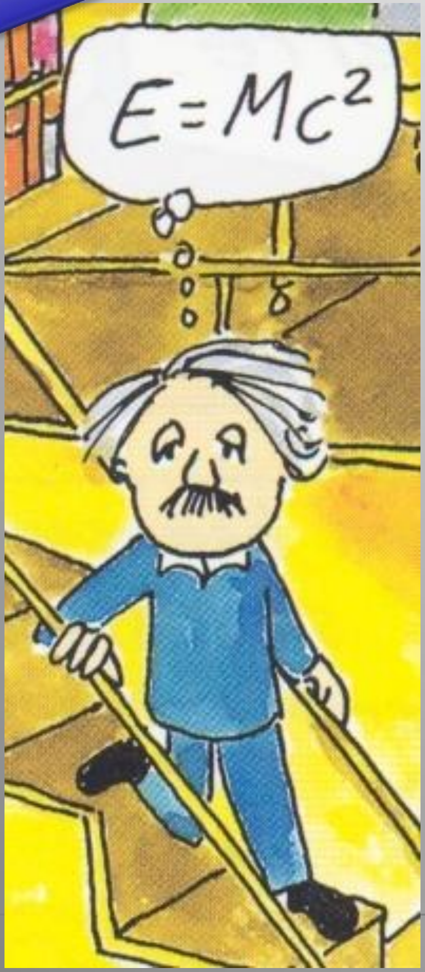


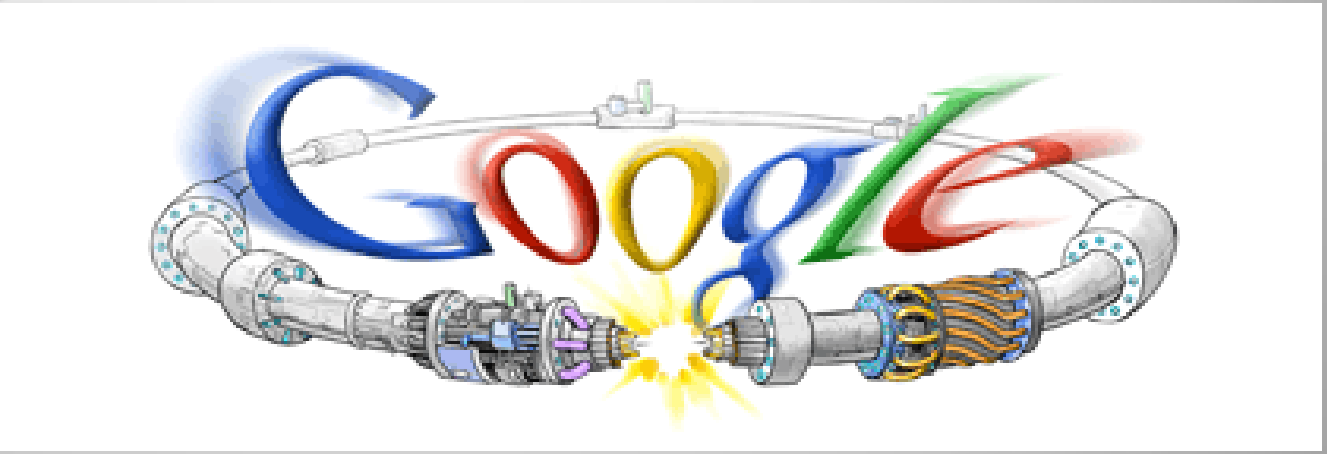


seen by low energy beam of particles (poorer resolution)

seen by high energy beam of particles (better resolution)

We can create particles from energy

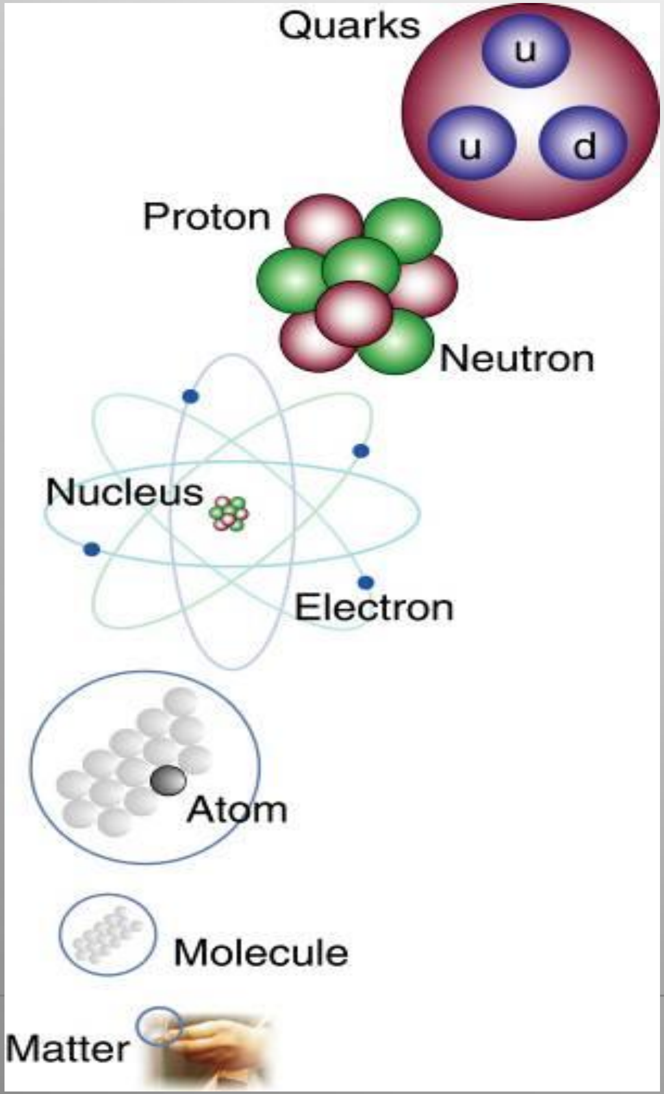




- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

The Structure of Matter

Matter



Quarks and electrons are the smallest building blocks of matter that we know of today.

Are there still smaller particles?

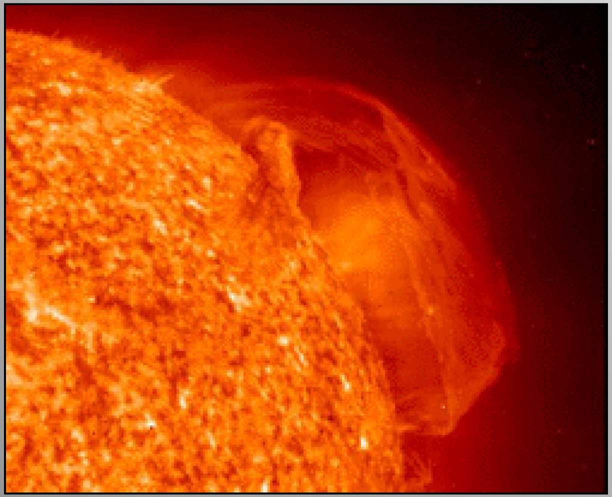
The Large Hadron Collider will address this question!

The Fundamental Forces of Nature

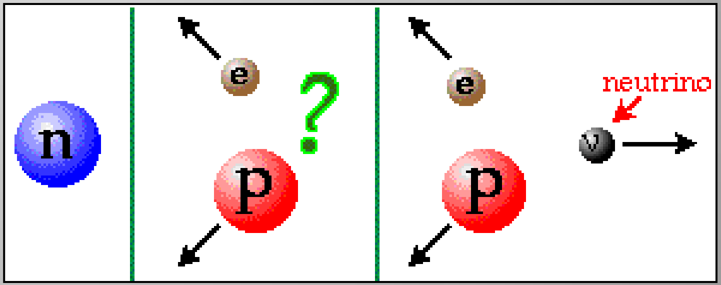
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together they make the Sun shine



Gravity: holds planets and stars together

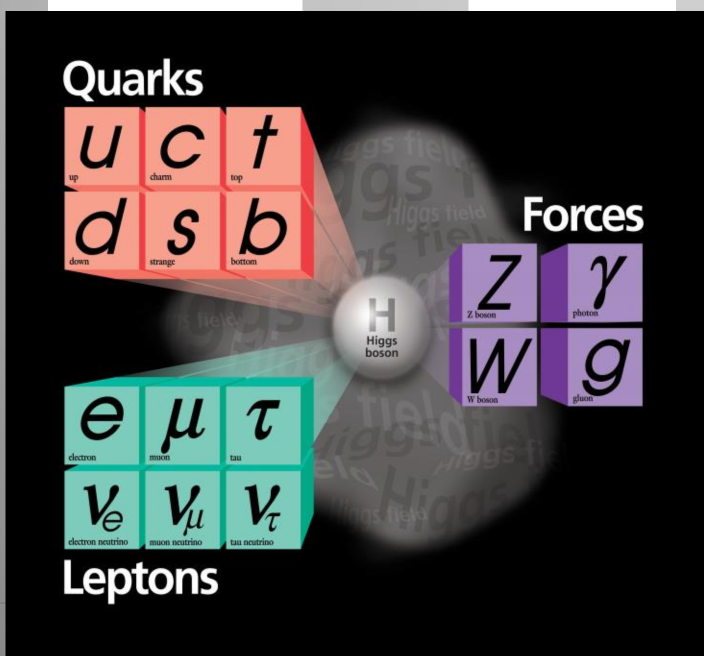
The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions

Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

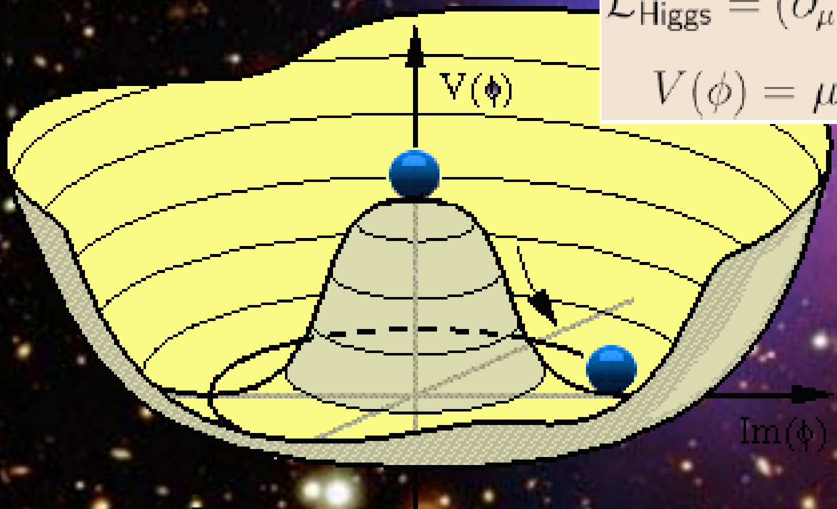
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV

The Higgs Field and the Cocktail Party

By David Miller

Imagine a cocktail party

This is the Higgs field

Enters a famous person…

He is slowed down on his way to the drinks!!

This Search Requires…….

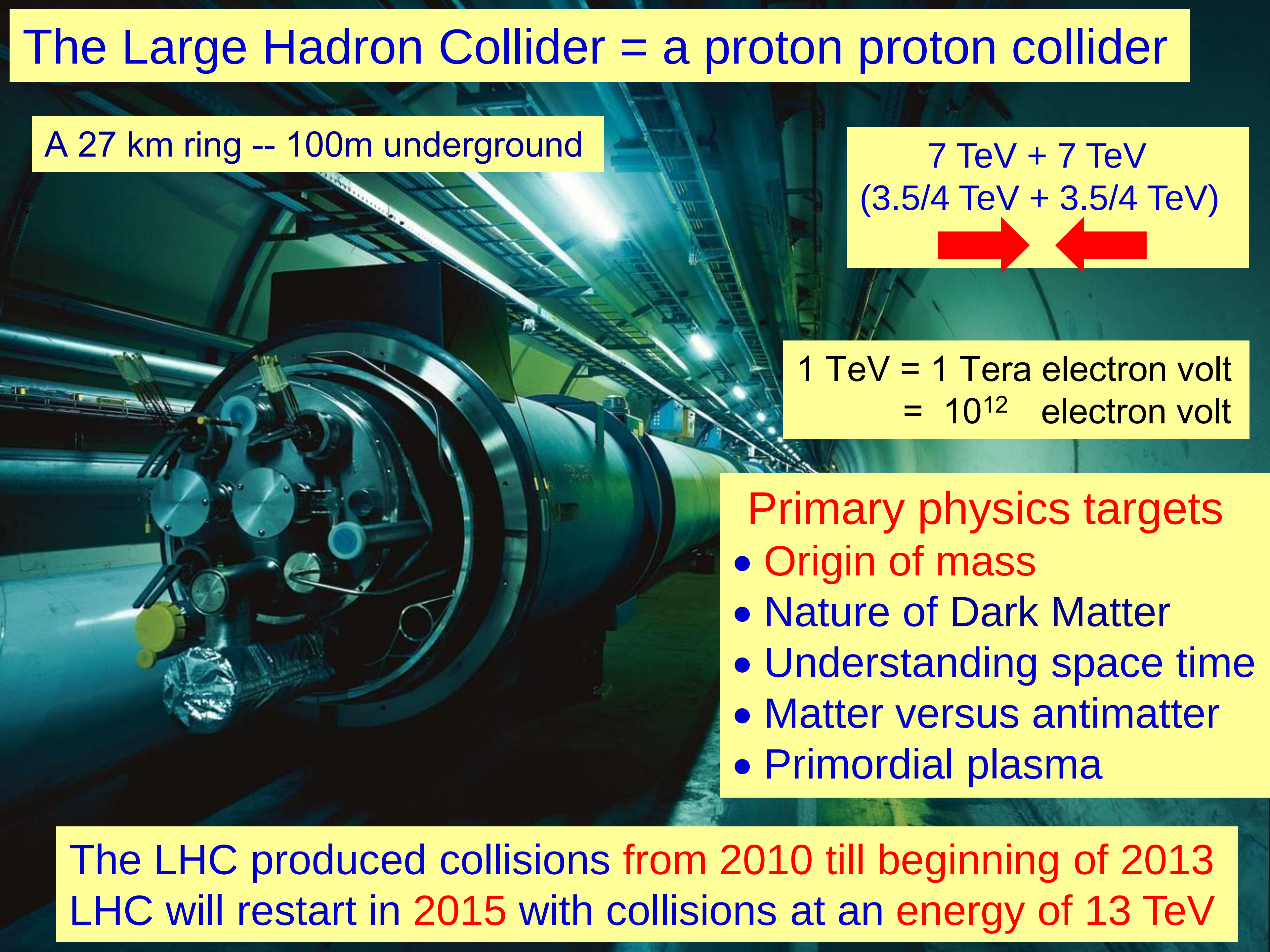
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

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

The LHC is an Extraordinary Machine

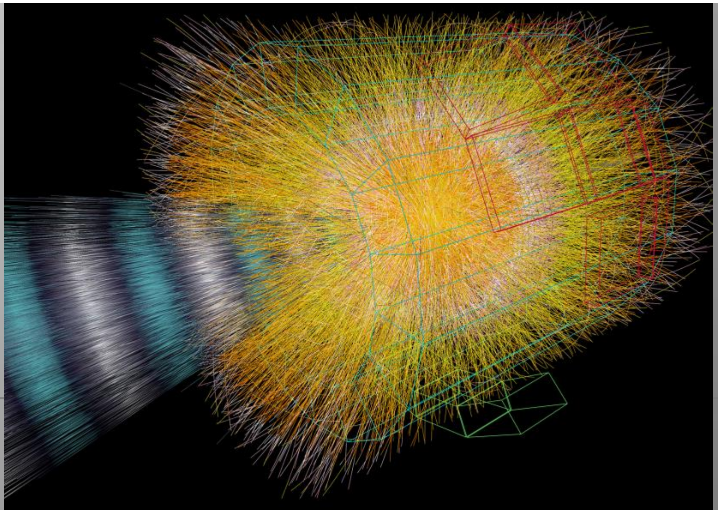
LHC facts

The LHC is …

Colder than the empty space in the Universe: 1.9K ie above absolute zero

The emptiest place in our solar system. The vacuum is better than on the moon

Hotter than in the sun: temperature in the collisions is a billion times the one in the centre of the sun



Experiments at the LHC

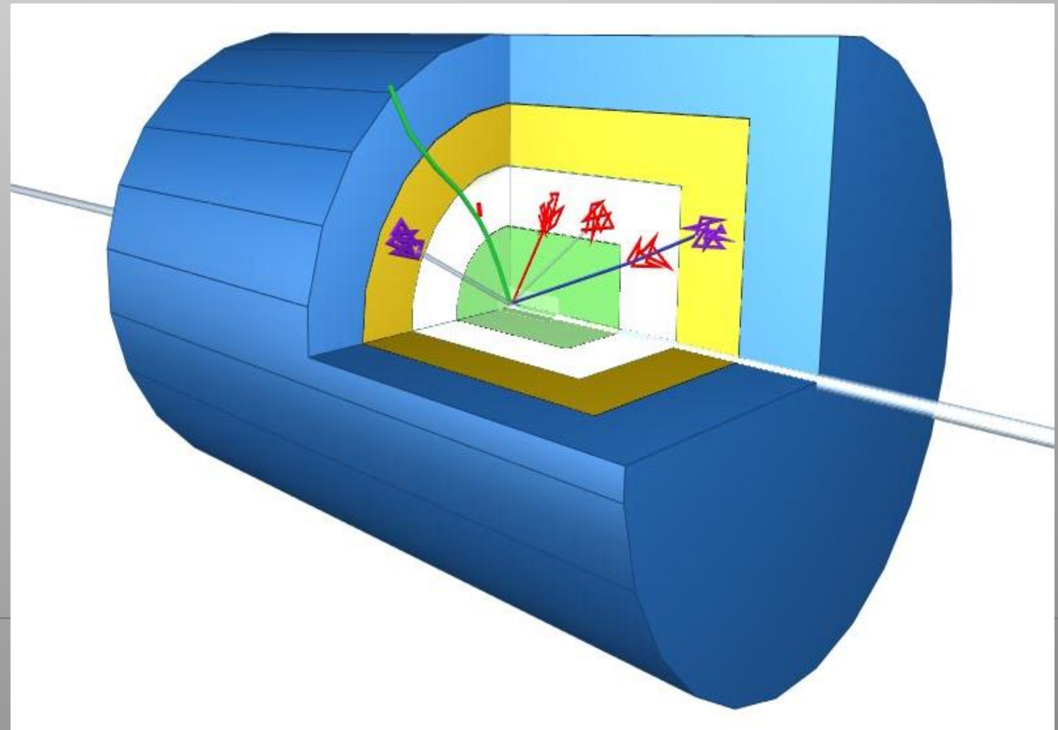
Schematic of a LHC Detector

Physics requirements drive the design!

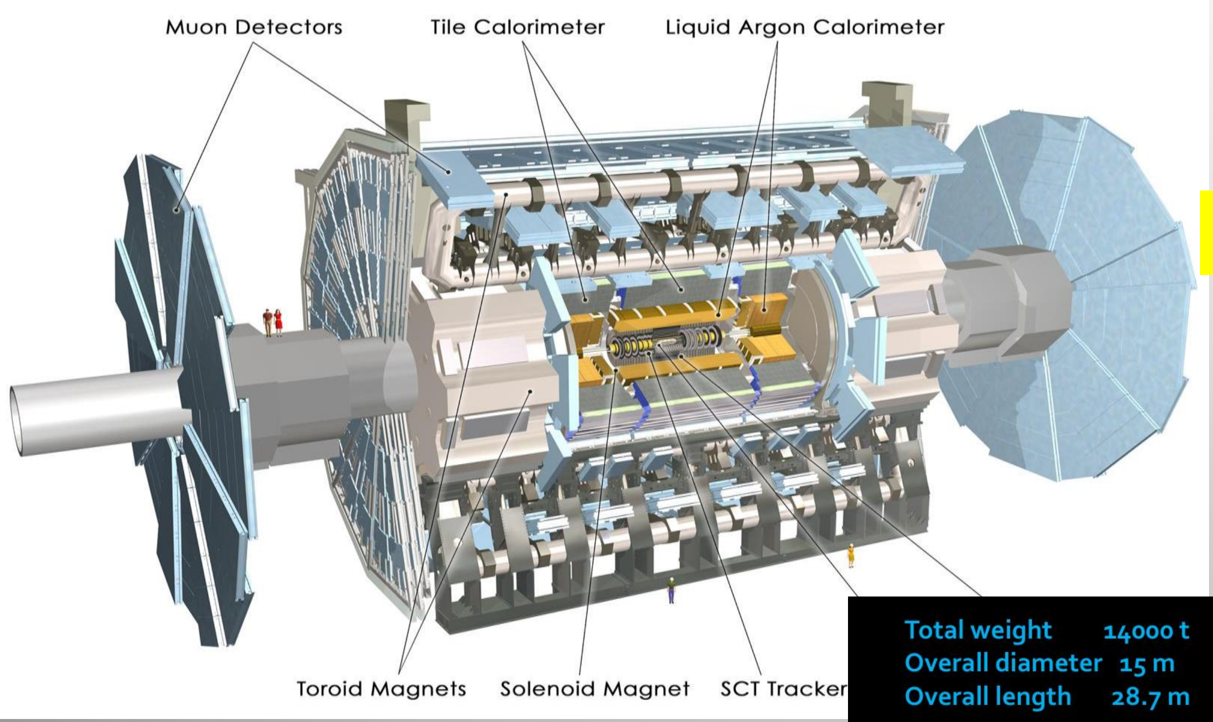
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

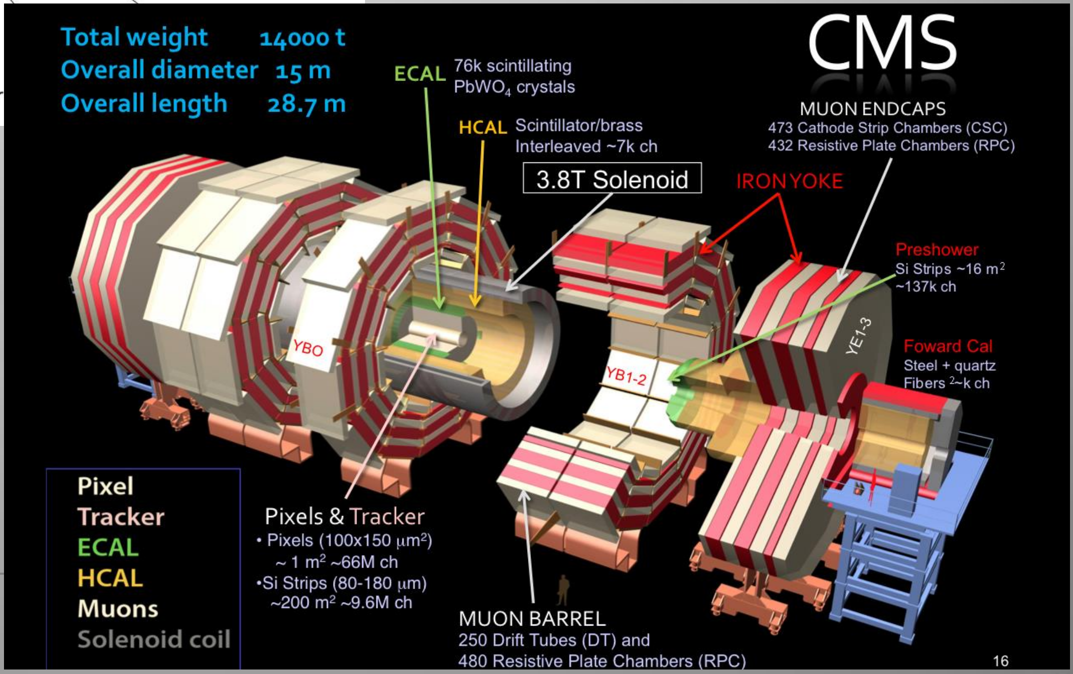
Such an experiment has ~ 100 Million read-out channels!!



The Higgs Hunters @ the LHC

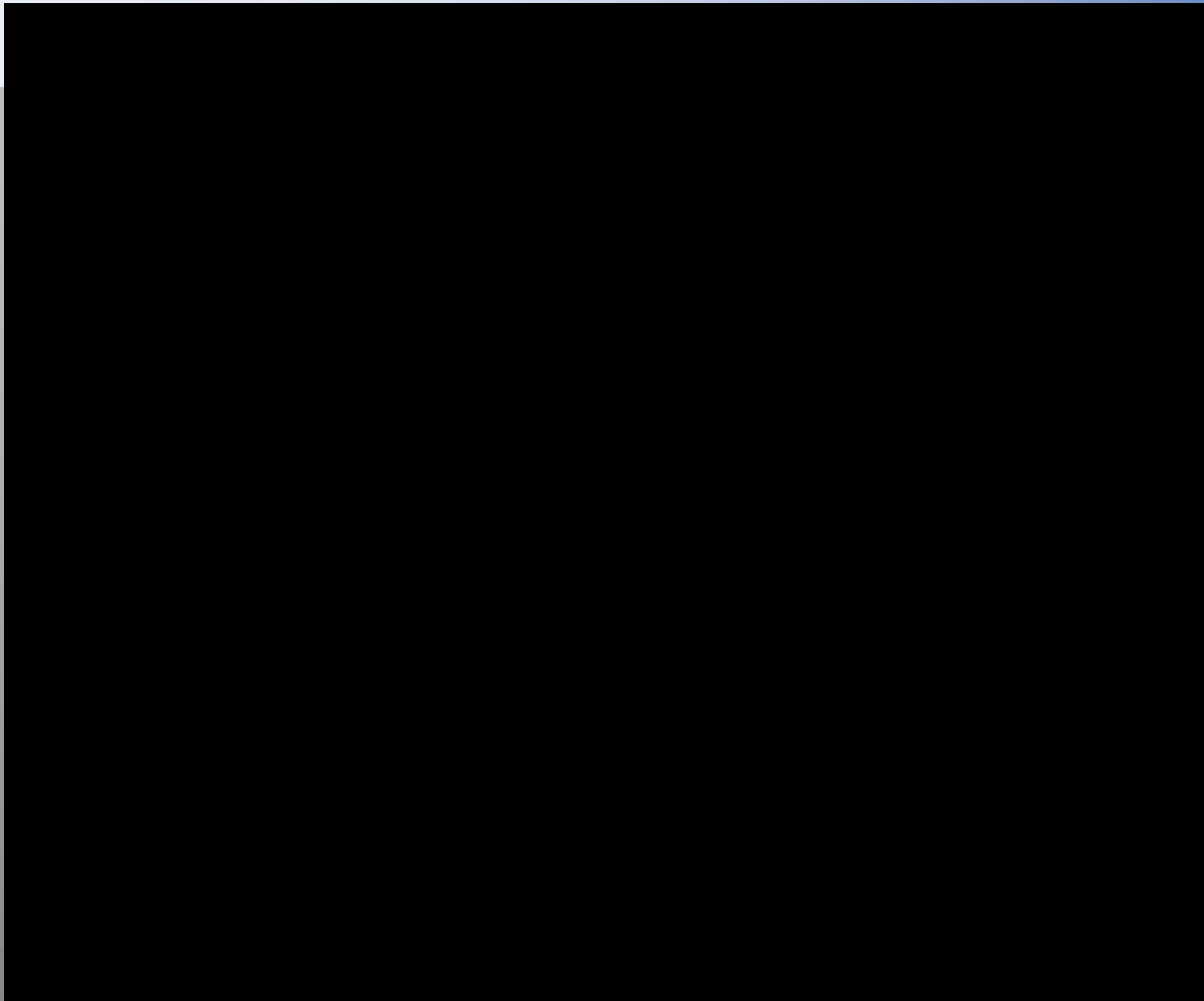


The ATLAS experiment



The CMS experiment

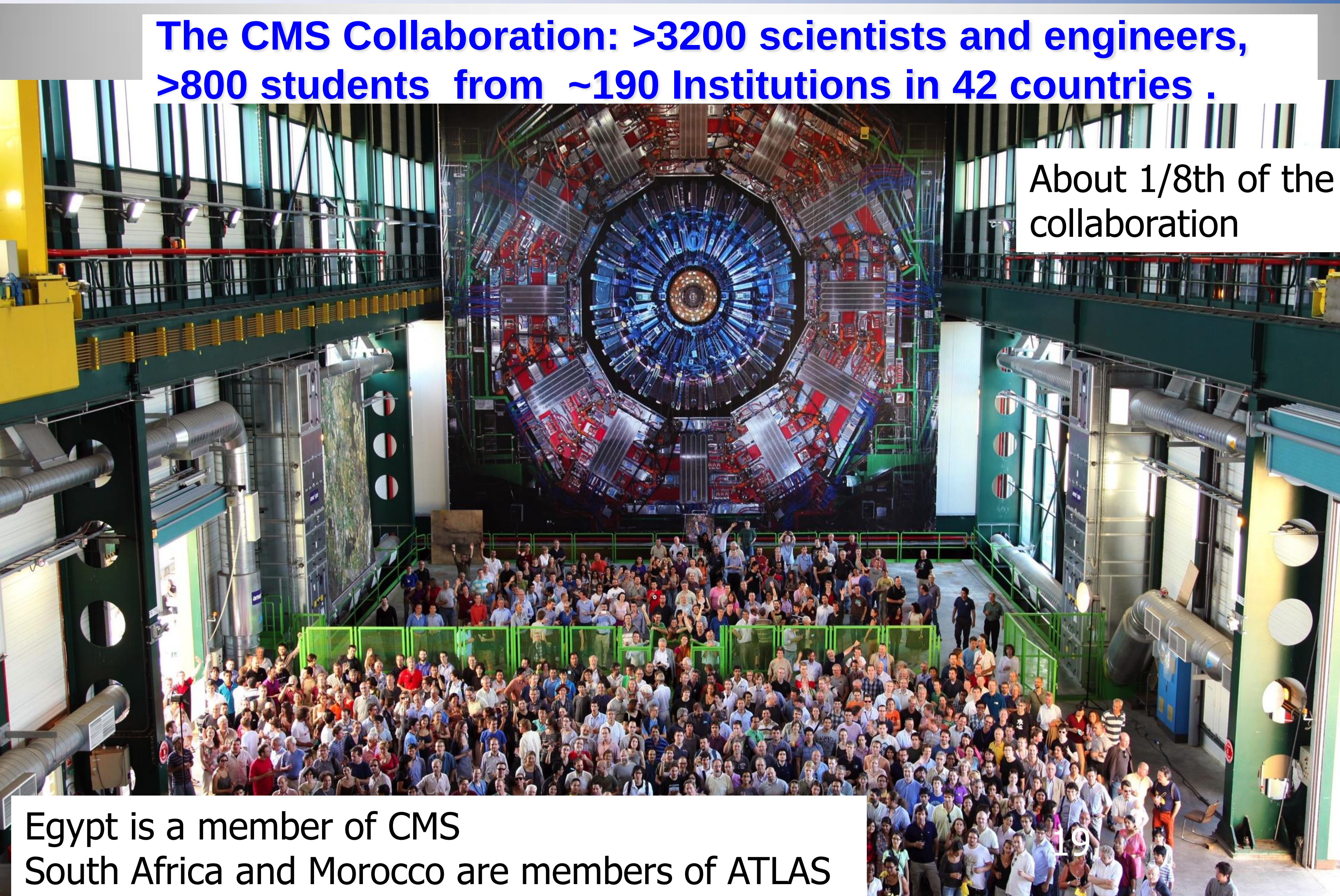
These experiments use different technologies for their detector components



CMS before closure

CMS Collaboration June 27, 2012

The CMS Collaboration: >3200 scientists and engineers, >800 students from ~190 Institutions in 42 countries .



About 1/8th of the collaboration

Egypt is a member of CMS
South Africa and Morocco are members of ATLAS

The LHC Data Challenges

Experiments were anticipated to produce about **15 Million Gigabytes** of data each year (~20 million CDs!)

The total volume in eg ATLAS is 5 billion detector events and several billion Monte Carlo events amounting to 100 Million Gigabytes of data in 3 years

LHC data analysis requires a computing power equivalent to **~100,000 of today's fastest PC processors**

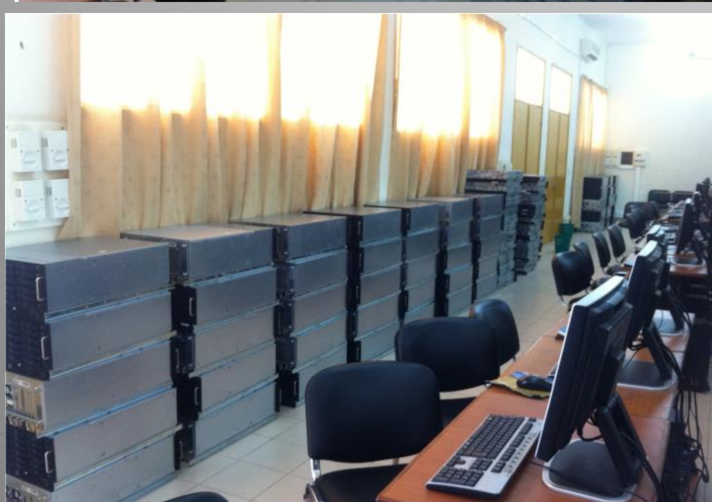
=> Requires many cooperating computer centres, as CERN can only provide ~20% of the capacity

GRID Computing

Tier-Centers Building up in Africa

"Decomissioned" CERN processors

Senegal

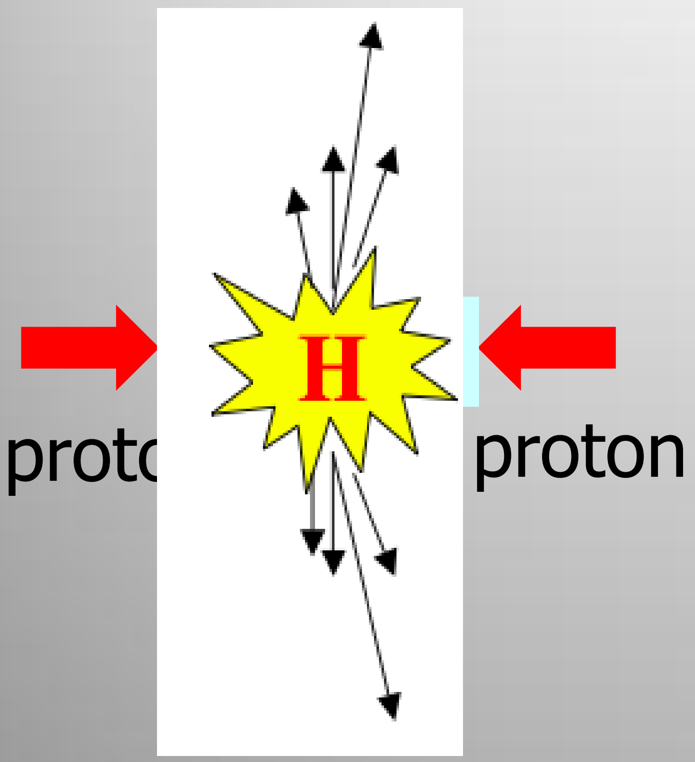


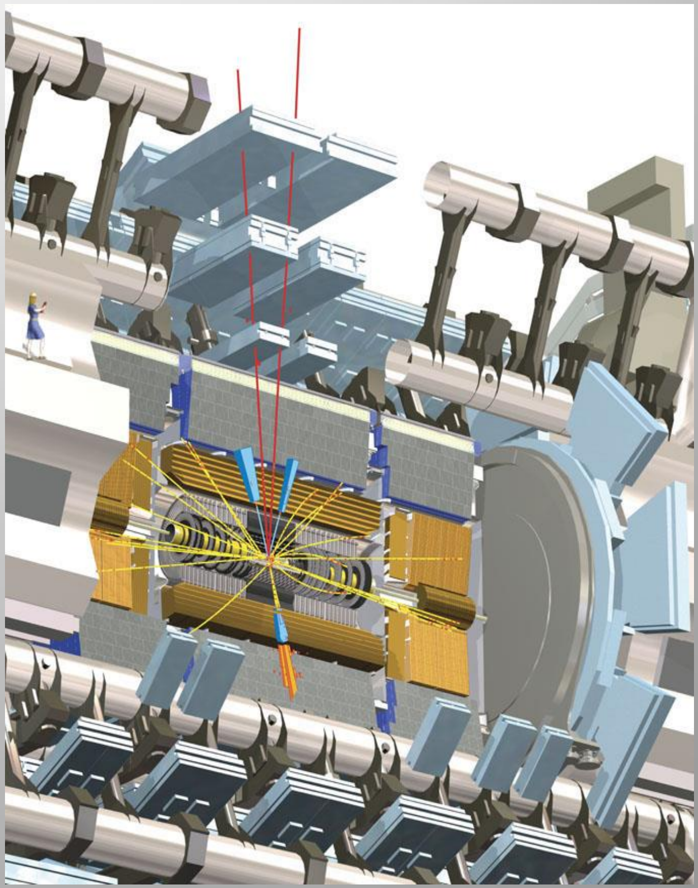
Egypt: about 400 processors,
1PB storage server and switches.

+ Ghana, Morocco…

The Higgs Particle

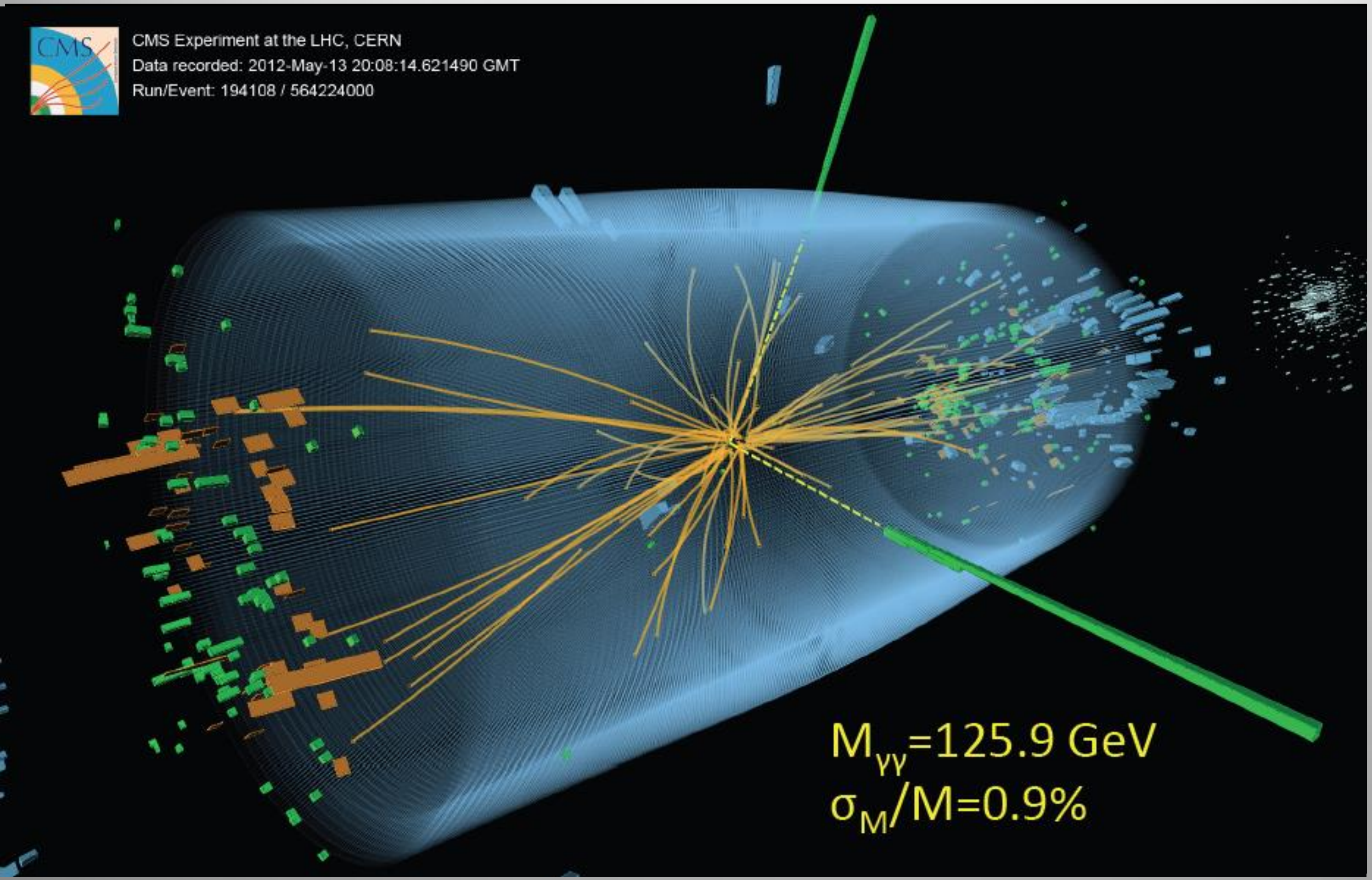
Technique: Produce and detect Higgs Particles at Particle Colliders

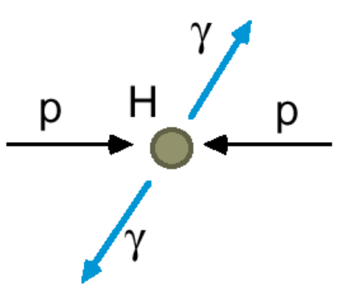




The Higgs particle is the last missing particle in the Standard Model

A Collision with two Photons

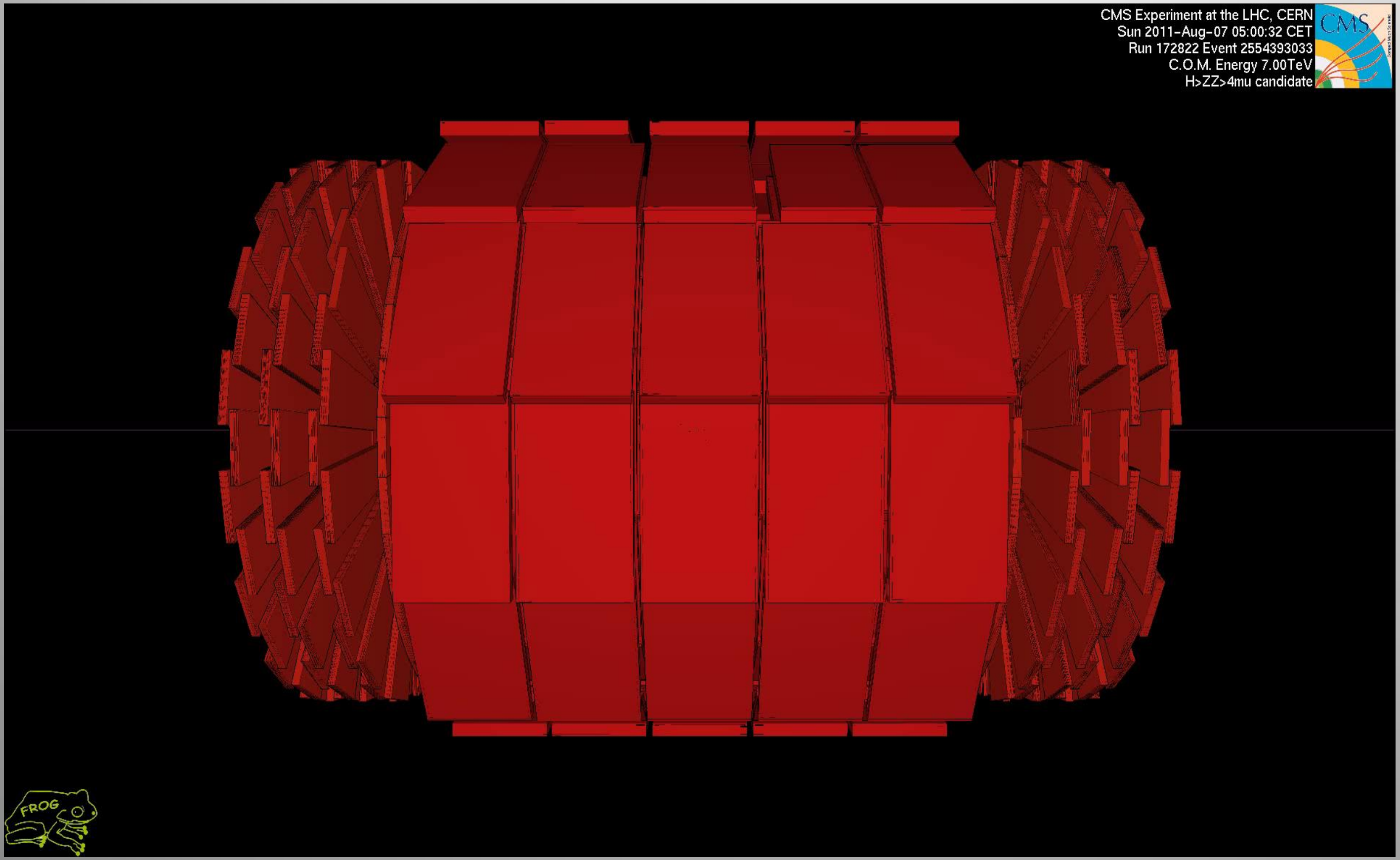


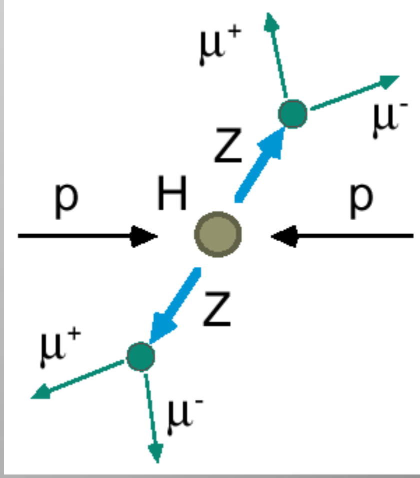


A Higgs or a 'background' process without a Higgs?

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present luminosity

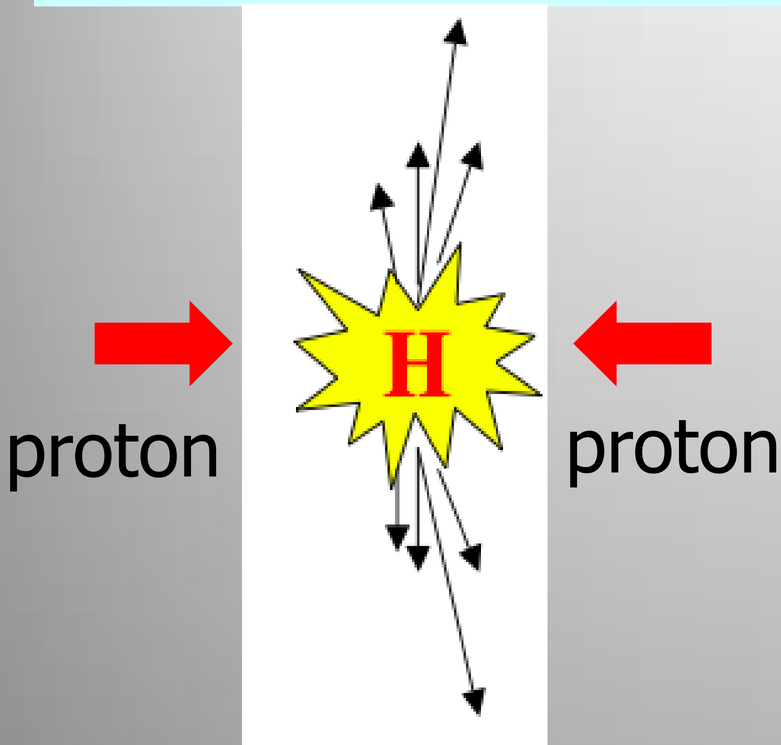
A real collisions: ZZ-> 4 muons

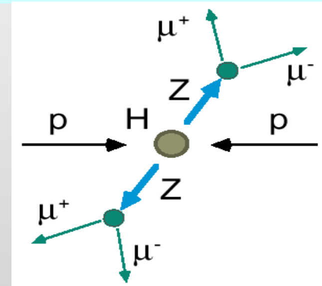


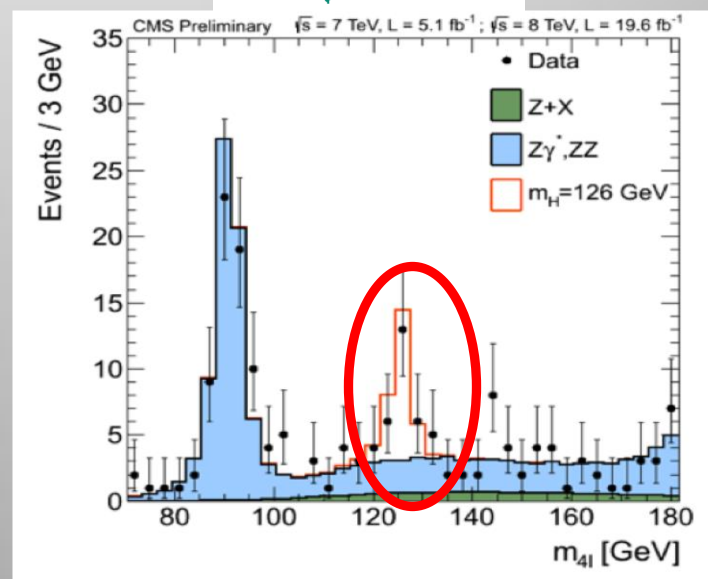


2012: A Milestone in Particle Physics

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





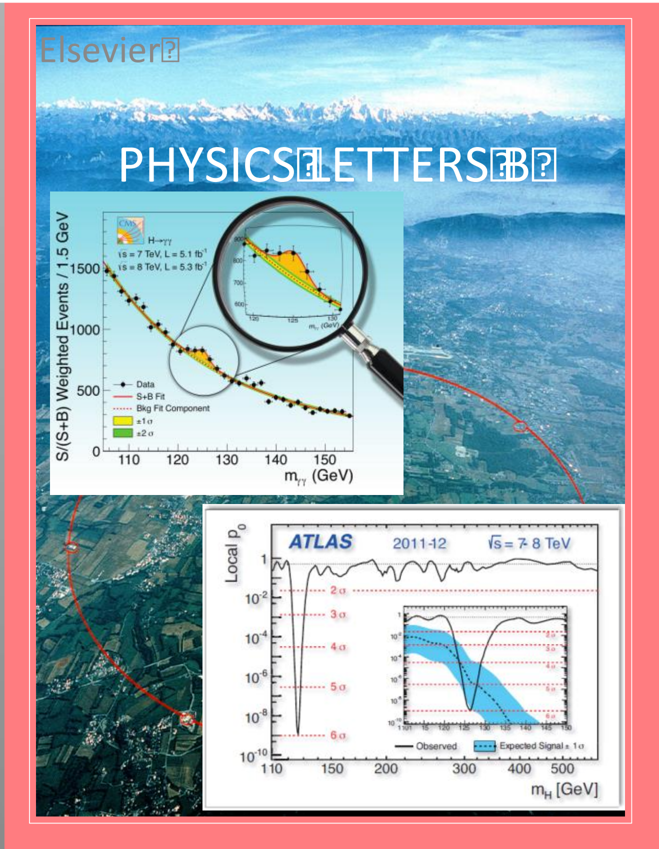


2013

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

Higgs Publications...

Special Physics Letters B edition with the ATLAS and CMS papers

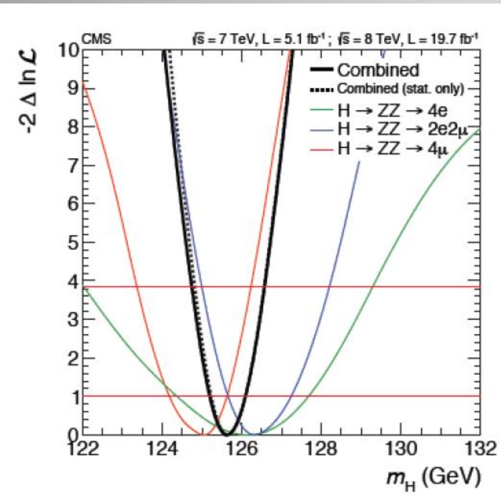


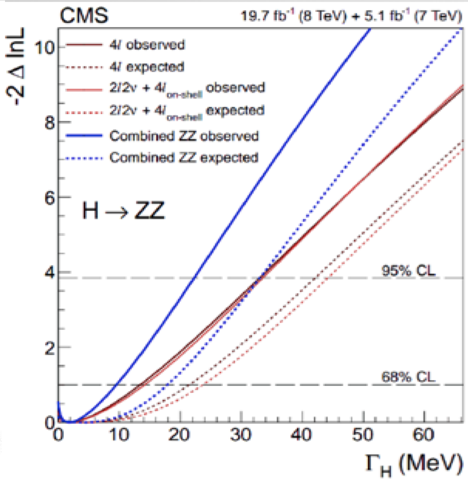
Also…

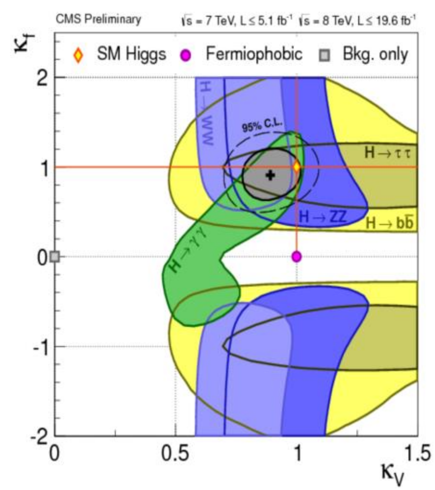
We called the new particle a “higgs-like” particle

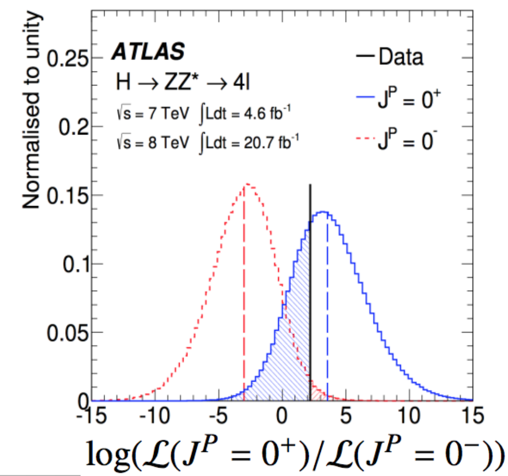
A Higgs…

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









Mass =
125.5 ±0.5 GeV

Width =
< 22 MeV
(95%CL)

Couplings are
within 20% of
the SM values

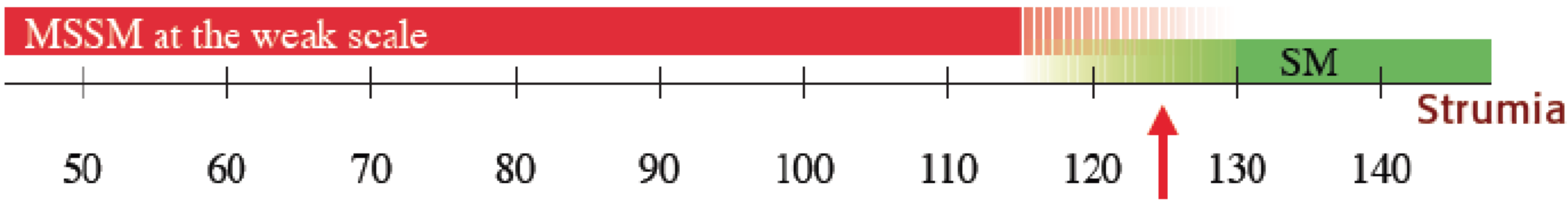
Spin =
0^+ preferred
over 0^-,1,2

The Higgs is the new playground: Room for new experimental/theoretical ideas!!
Remember: we have already ~1 Million Higgses produced at the LHC

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



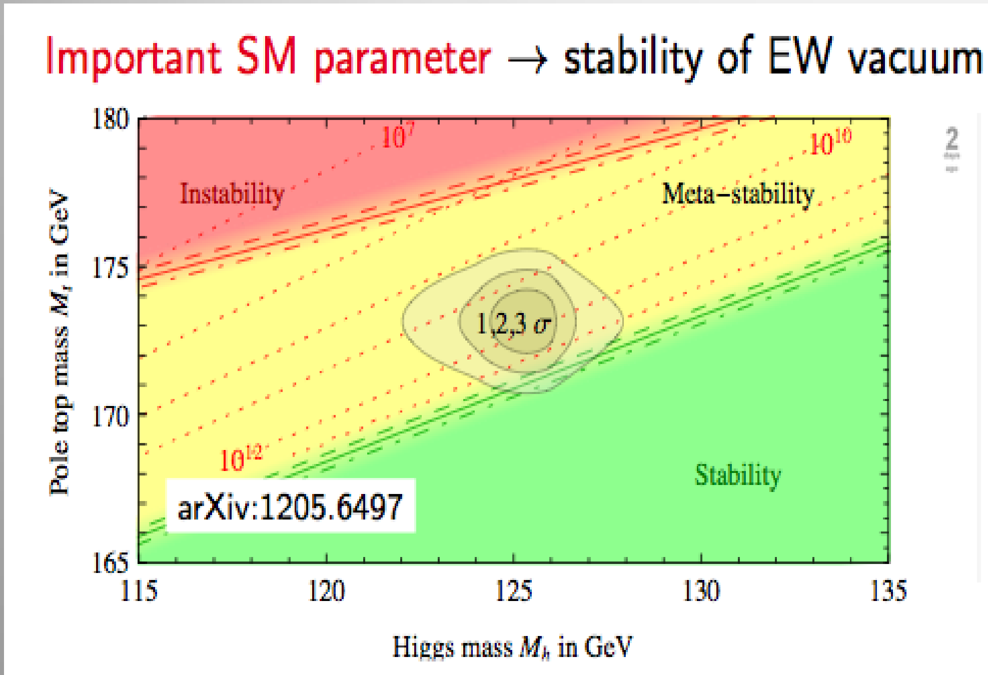
The Higgs:
so simple yet so unnatural

Guido Altarelli

Stockholm Nobel Symposium
May 2013

But there there still a lot of questions…

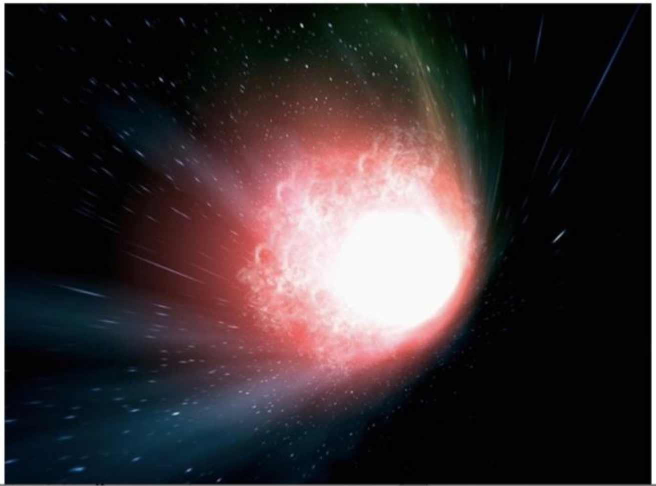
Consequences for our Universe?



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)

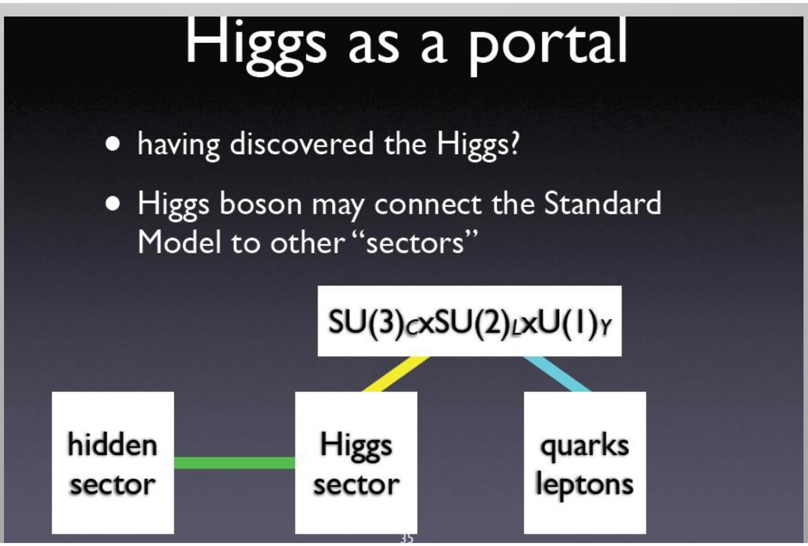
Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



New Physics inevitable?
But at which scale/energy?

Many questions still Unanswered

- Is it THE Standard Model Higgs or a messenger of New Physics ?
- How can we explain a Higgs mass ~ 126 GeV? What stabelizes its mass? New Physics e.g. Supersymmetry?
- What explains the mass pattern of the particles we observe?
- What is Dark Matter and Dark energy?
- Neutrino masses and properties?
- Where is the antimatter in the Universe? How did it disappear??

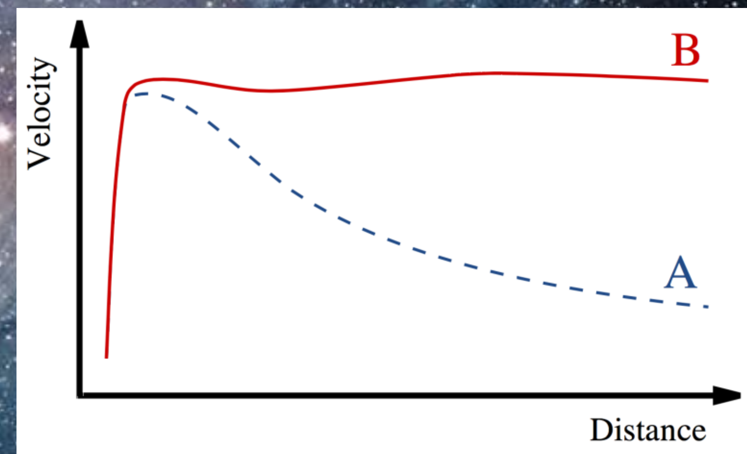


Need for precision measurements with ~100x the present statistics

LHC upgrade ! Experiment upgrades!! New machines!?!

Dark Matter: The Next Challenge !?!

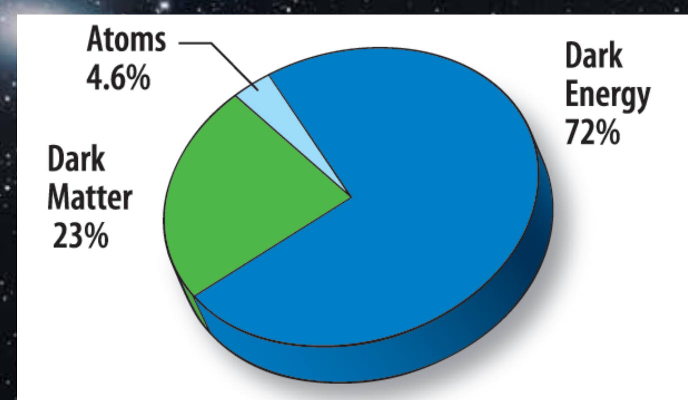
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970



Supersymmetry? New Physics?

But Where Is Everybody?

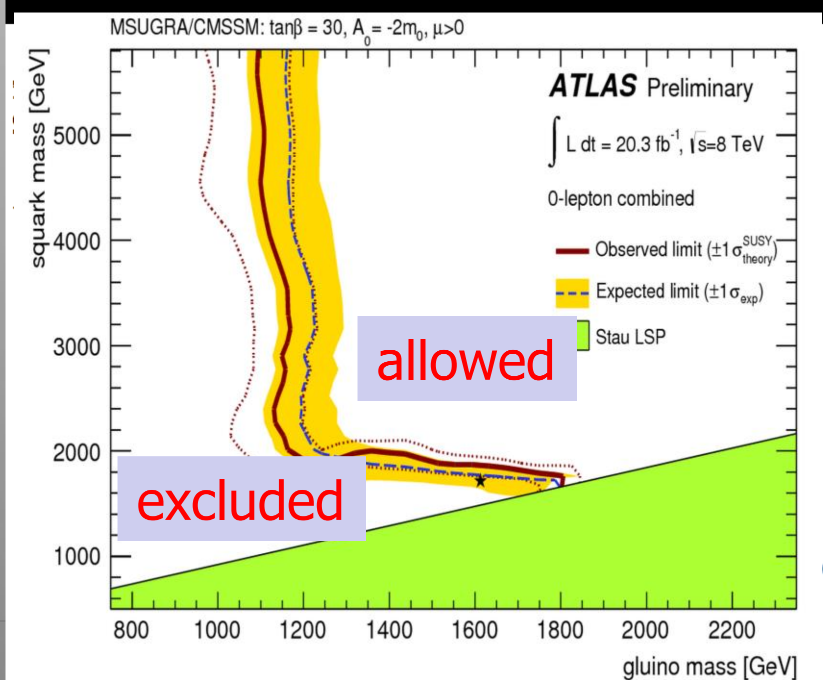
N. Arkani-Hamed

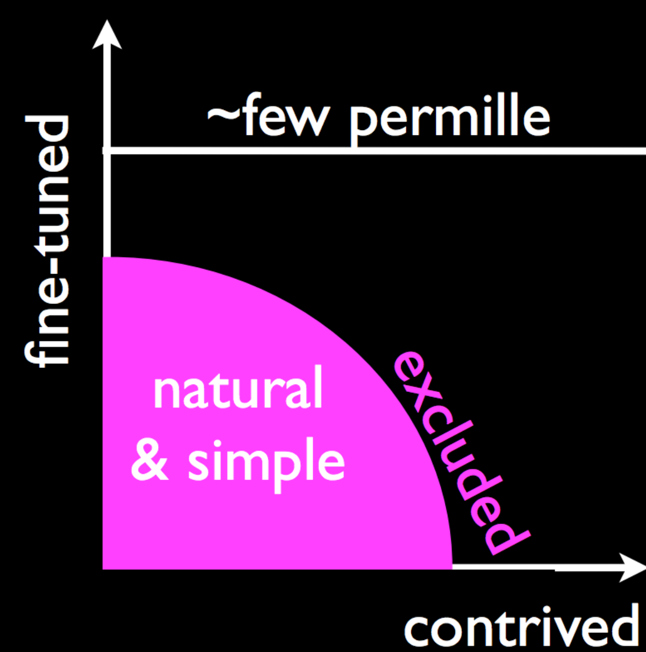
...The May Issue...

Supersymmetry and the Crisis in Physics

H. Murayama

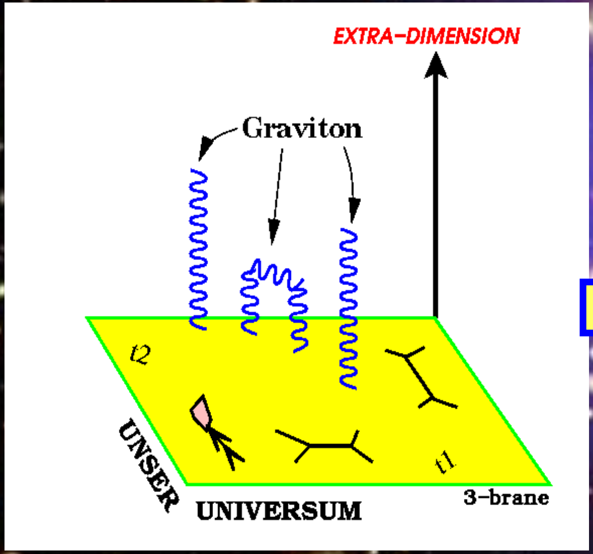
no sign of new physics

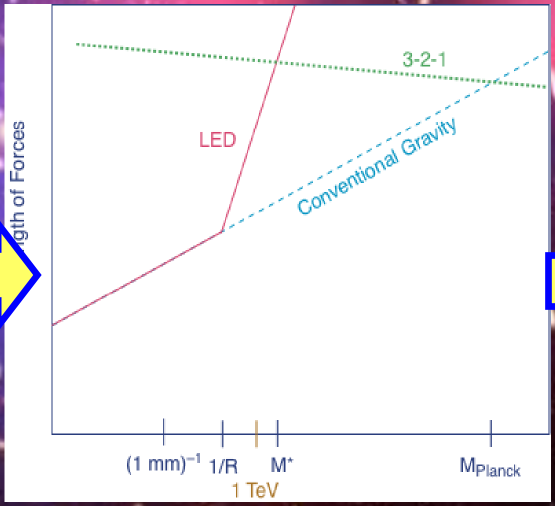


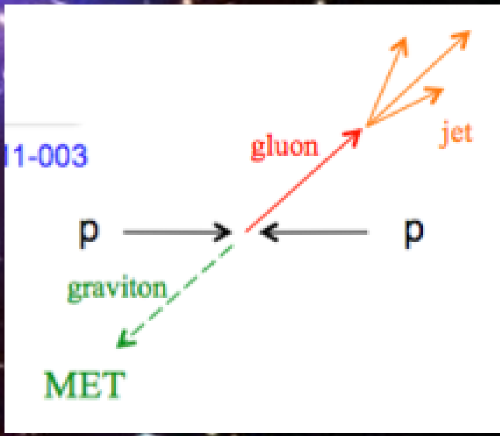


Extra Space Dimensions

Problem: $$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV} \quad \Longleftrightarrow \quad M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \text{GeV}$$







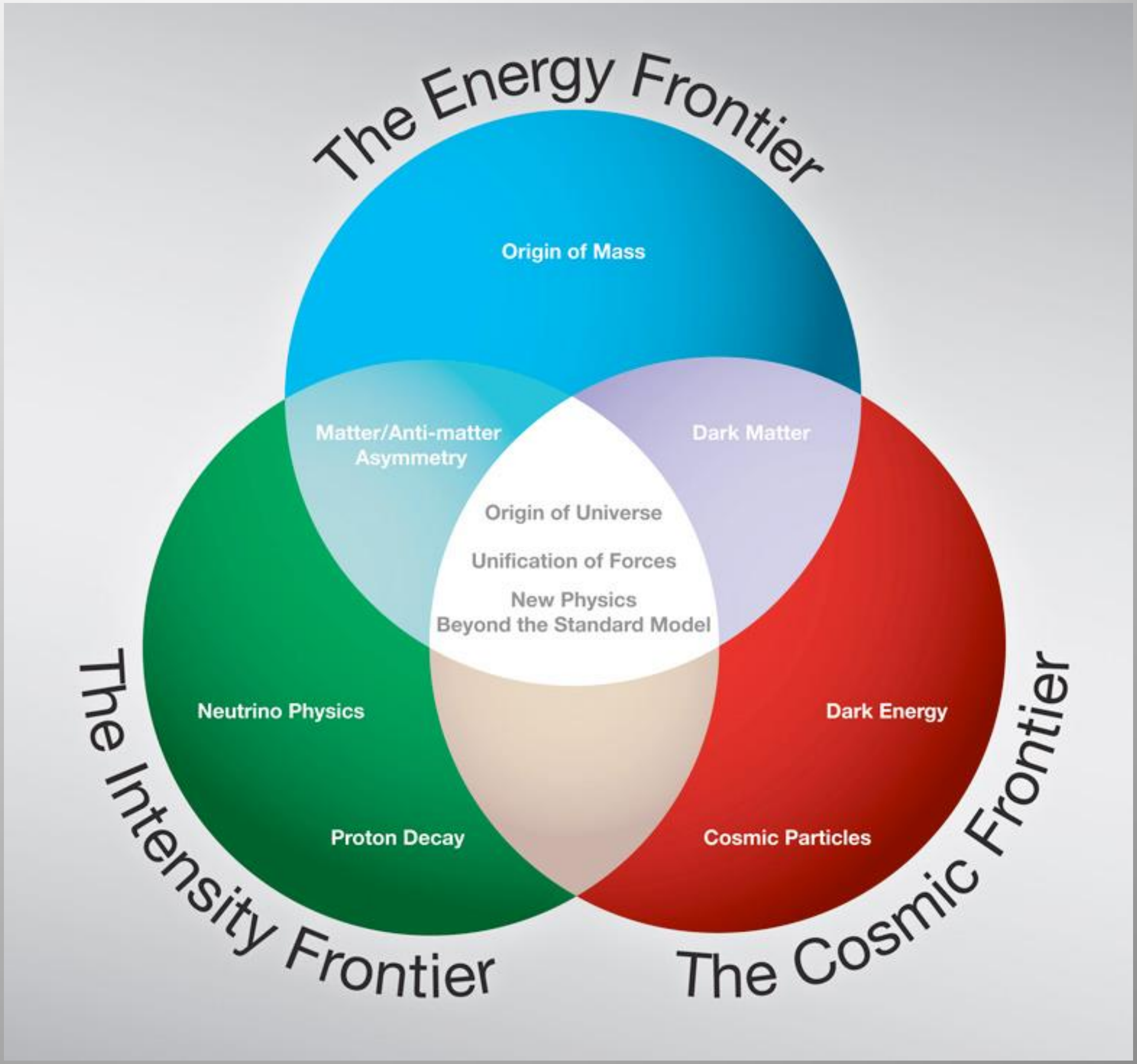
The Gravitational force becomes strong!

No signal found yet
New Planck scale is larger than 3 TeV

The Future…

The Three Frontiers

Evaluated in all regions: Europe Asia, the Americas



2012-2014

- European strategy group
- Snowmass study and P5
- Japan strategy group

Recent released P5 report much in accord with Europe

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,..

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

P5 Strategy Group

Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.

First recommendation on the list naming a project

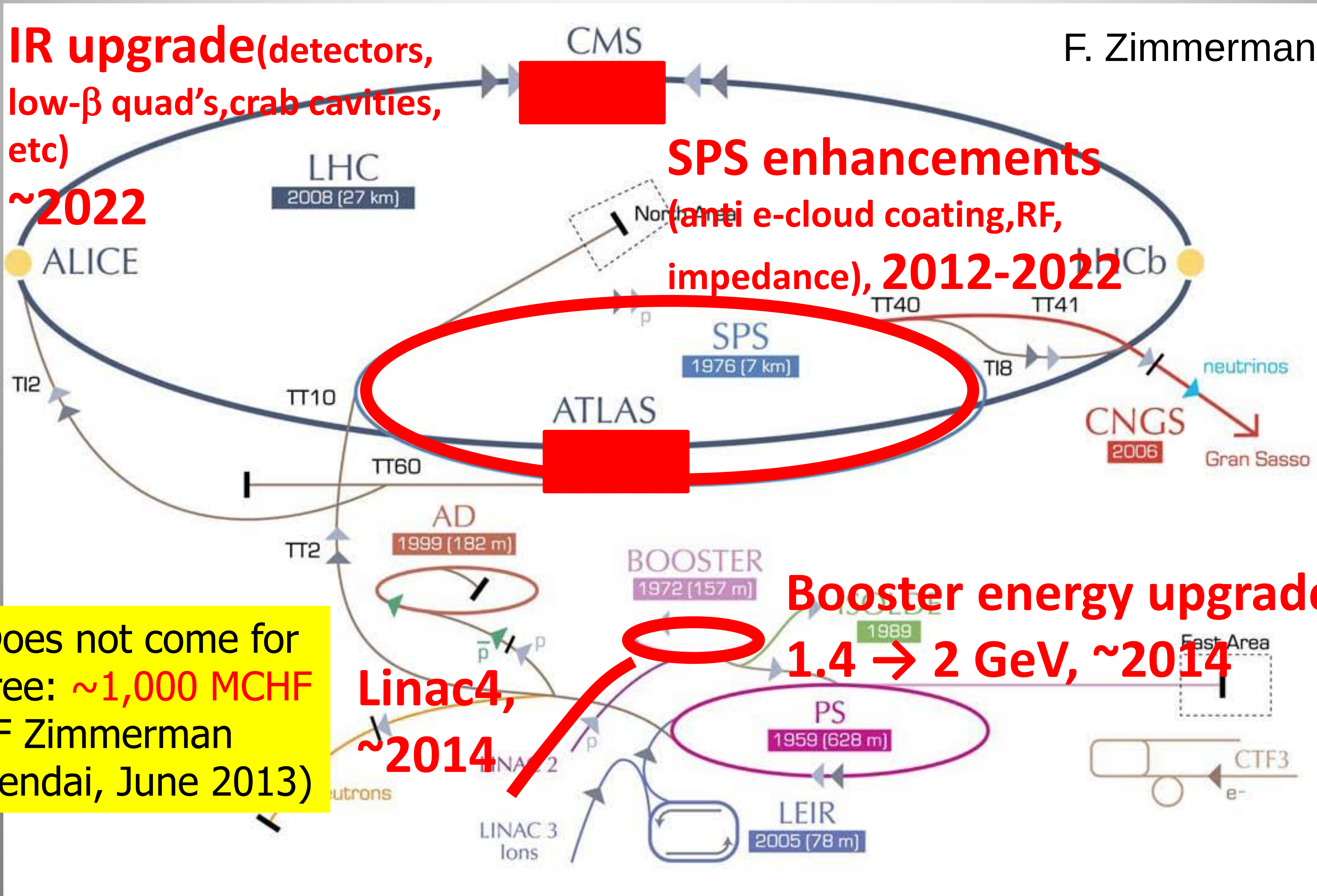
The LHC schedule

Last update - December 2013

Year	Period	Description	Run	Integrated luminosity
2009		LHC startup, $\sqrt{s}$ 900 GeV		
2010–2012		$\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns	Run 1	~25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity - Phase 0		
2015–2018		$\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 2	~75-100 fb^{-1}
2018–2019	LS2	Injector + LHC Phase I upgrade to ultimate design luminosity		
2020–2022		$\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns	Run 3	~350 fb^{-1}
2023–2025	LS3	HL-LHC Phase II upgrade: Interaction Region, crab cavities?		
2025 … 2035?		$\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling		~3000 fb^{-1}

HL-LHC – LHC modifications

F. Zimmerman



IR upgrade(detectors, low-β quad's,crab cavities, etc)
~2022

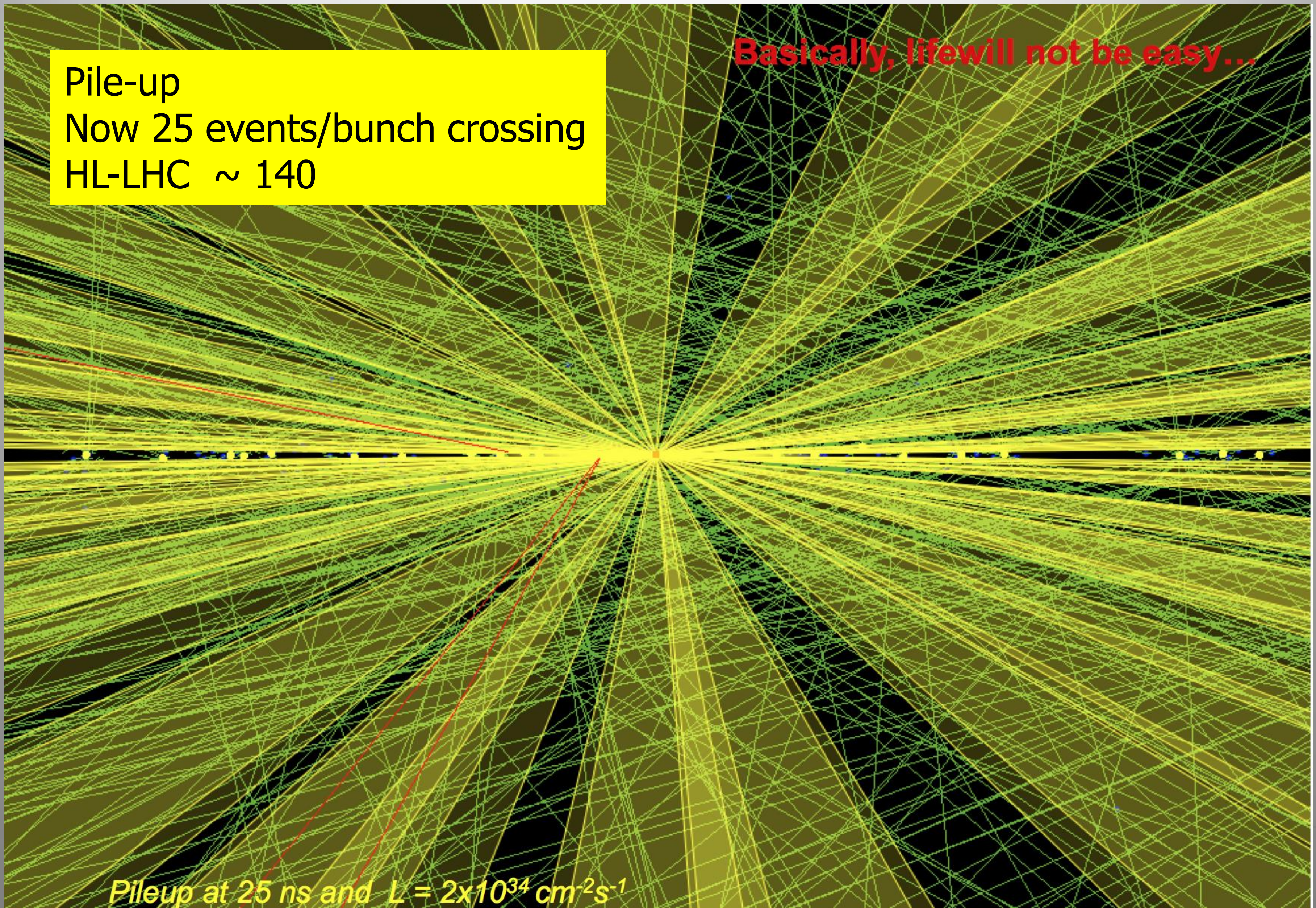
SPS enhancements
(anti e-cloud coating,RF, impedance), **2012-2022**

Booster energy upgrade
1.4 → 2 GeV, ~2014

Linac4, ~2014

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

The Challenge for the Experiments



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”:

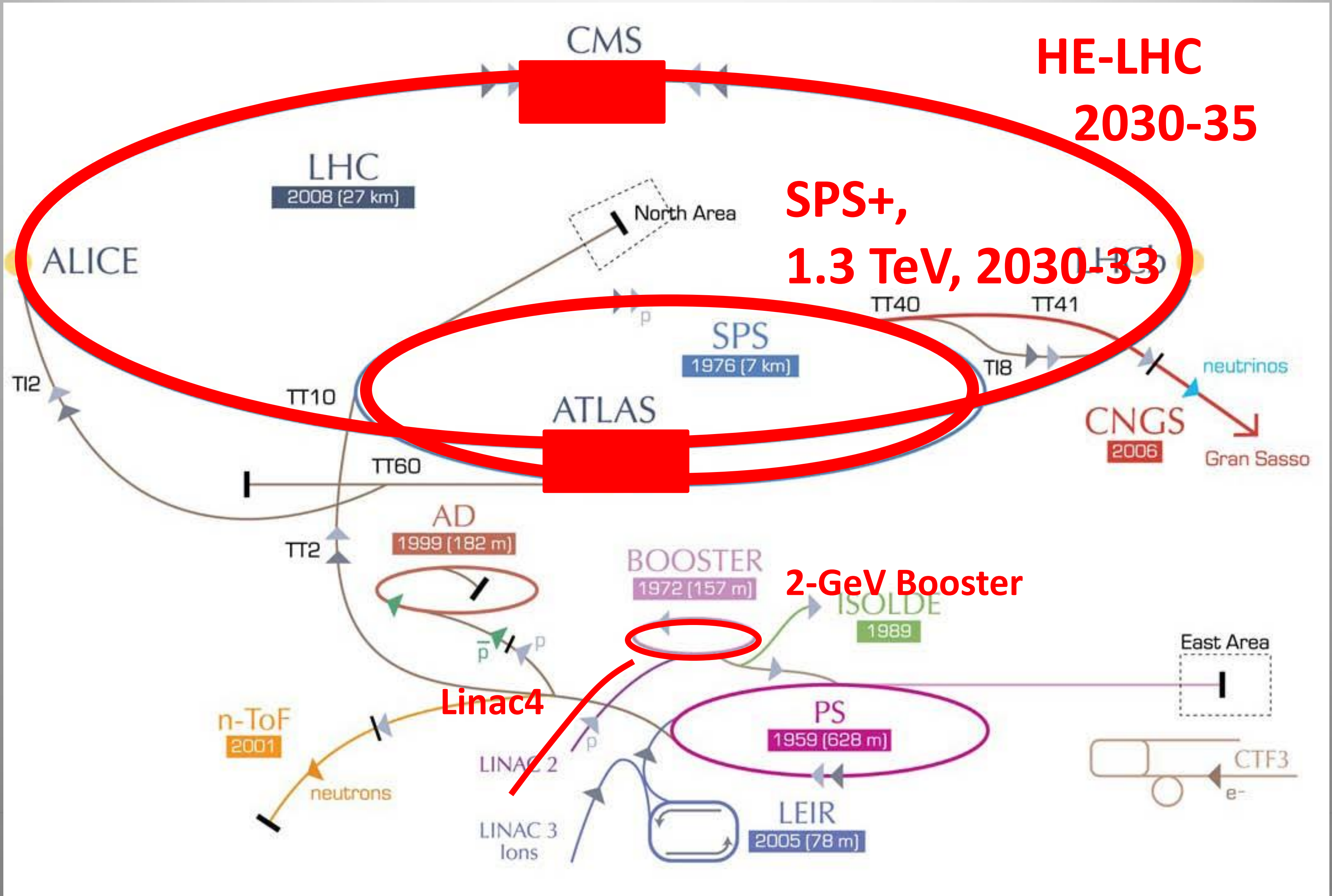
d) ***CERN should undertake design studies for accelerator projects in a global context,***

- *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

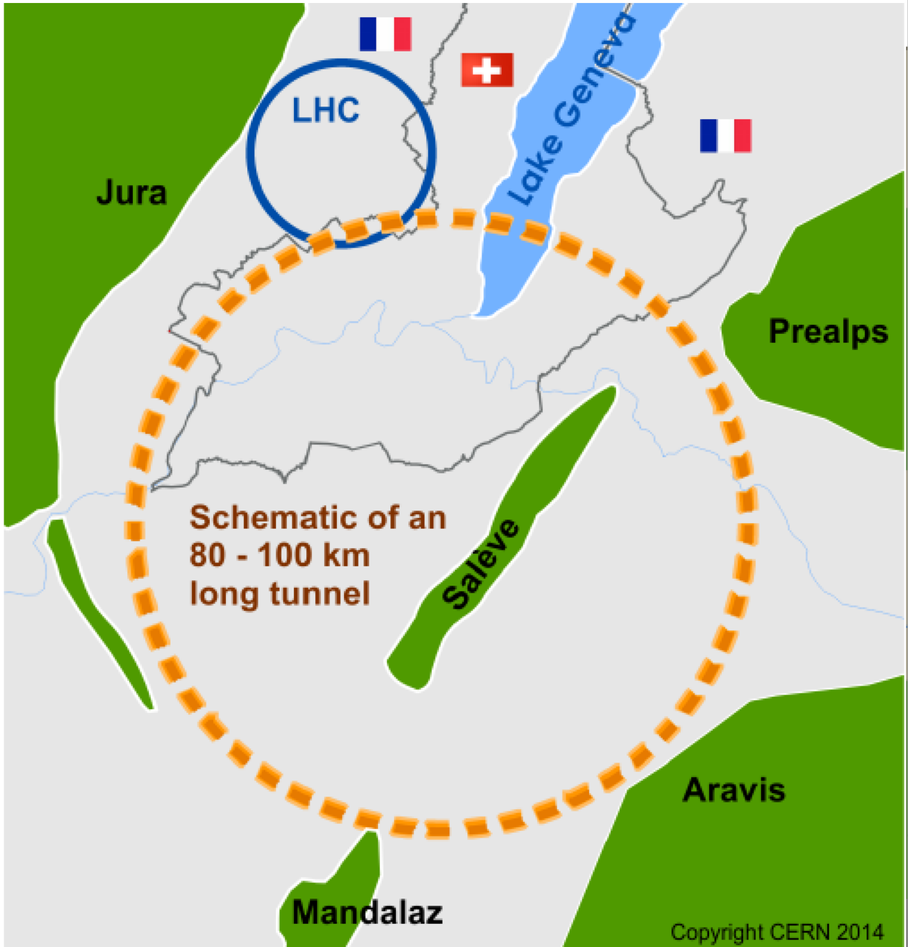
High Energy LHC (HE-LHC)



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)



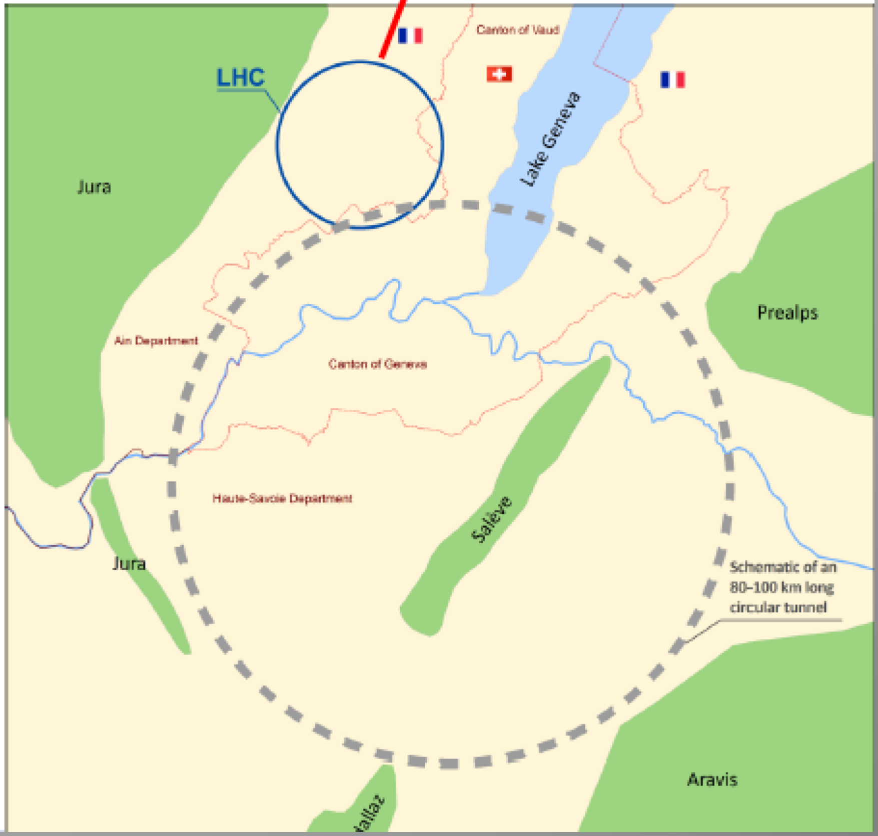
FCC-hh: a Proton-Proton Collider

"High Energy LHC"

HE-LHC :33 TeV with 20T magnets

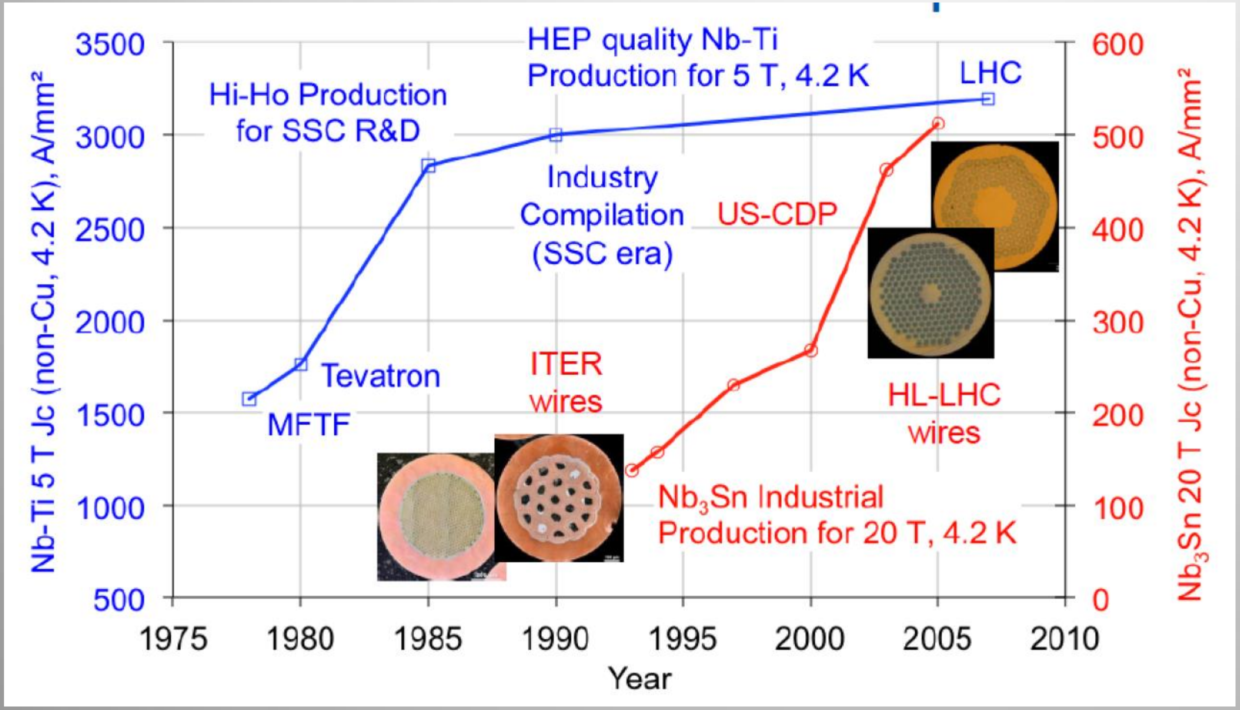
First studies on a new 80 km tunnel in the Geneva area

- 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

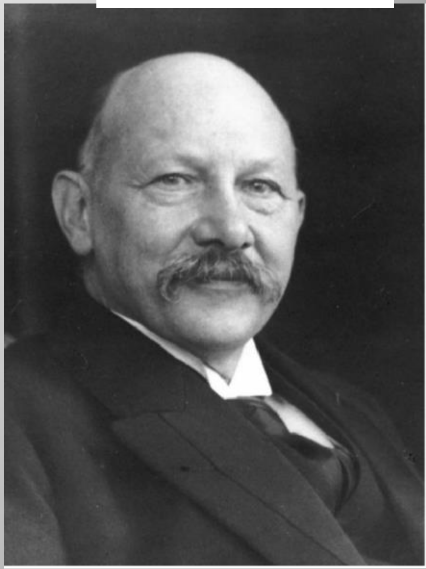


Magnet Developments

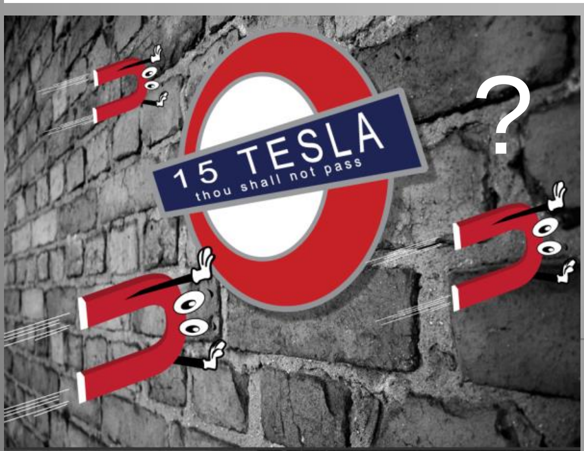
Key Components: The superconducting magnets



A propos…



Tribute to
Kammerlingh Onnes
Groningen, (Leiden,
Delft) !!!



Break the wall with
High Temperature Superconductors!!

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 $\boxed{\text{LEP3}}$. Work on LEP3 started in a series of workshops.
- The 80 km $\boxed{\text{TLEP}}$ 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 $\boxed{\text{FCC-ee.}}$

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

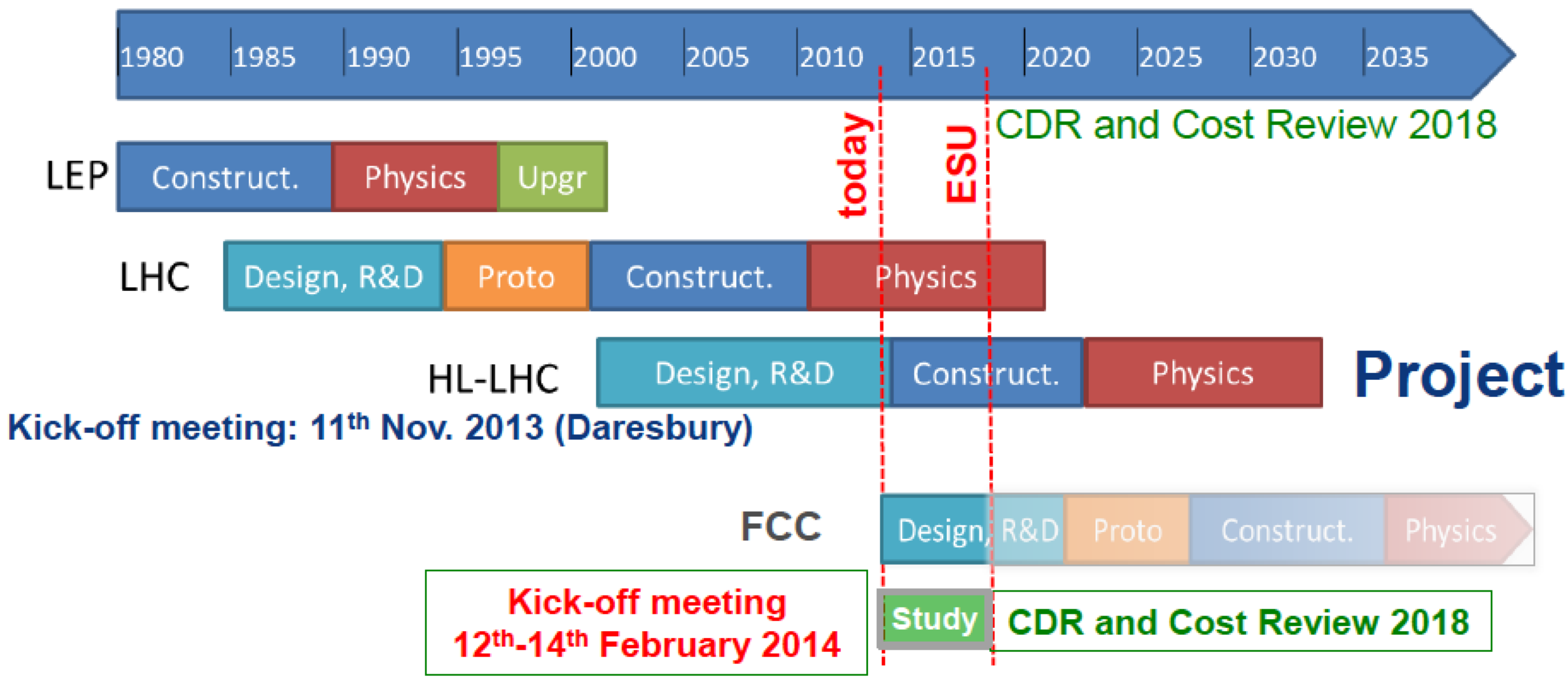
* each interaction point

Tera-Z, Giga-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 Schedule: First Step



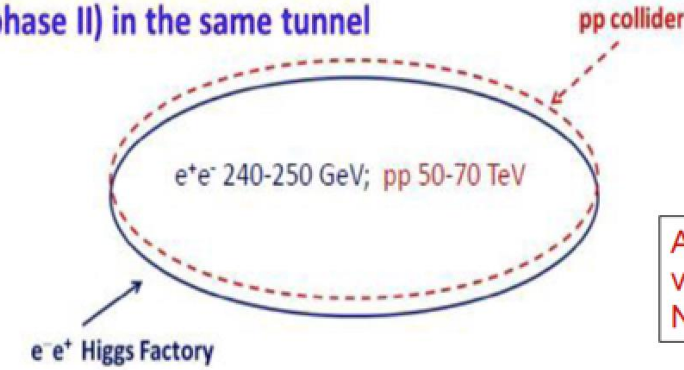
Study reports requested for the next strategy meeting in 2018

Interest 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)

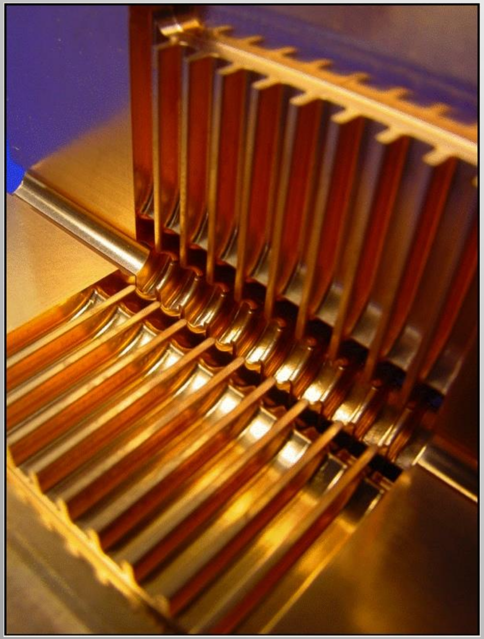
Linear e+e- Colliders

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

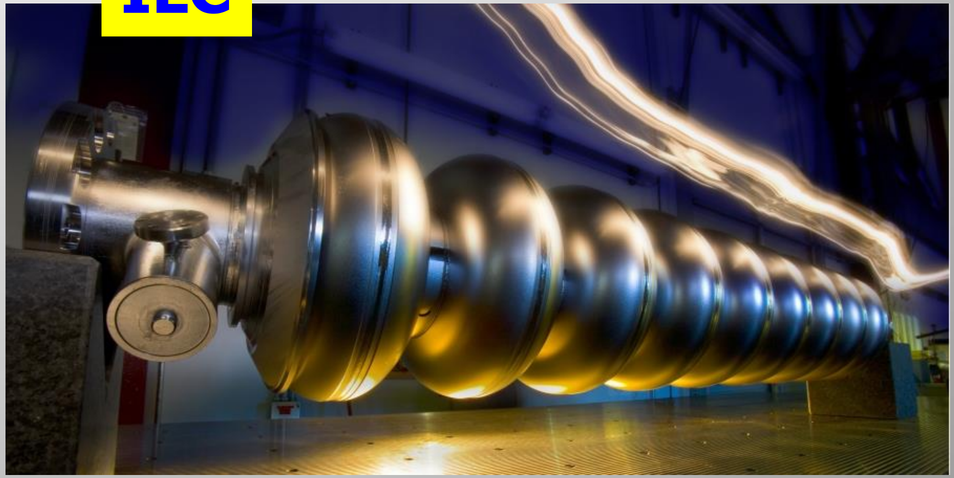
CLIC



- 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} $cm^{-2}s^{-1}$

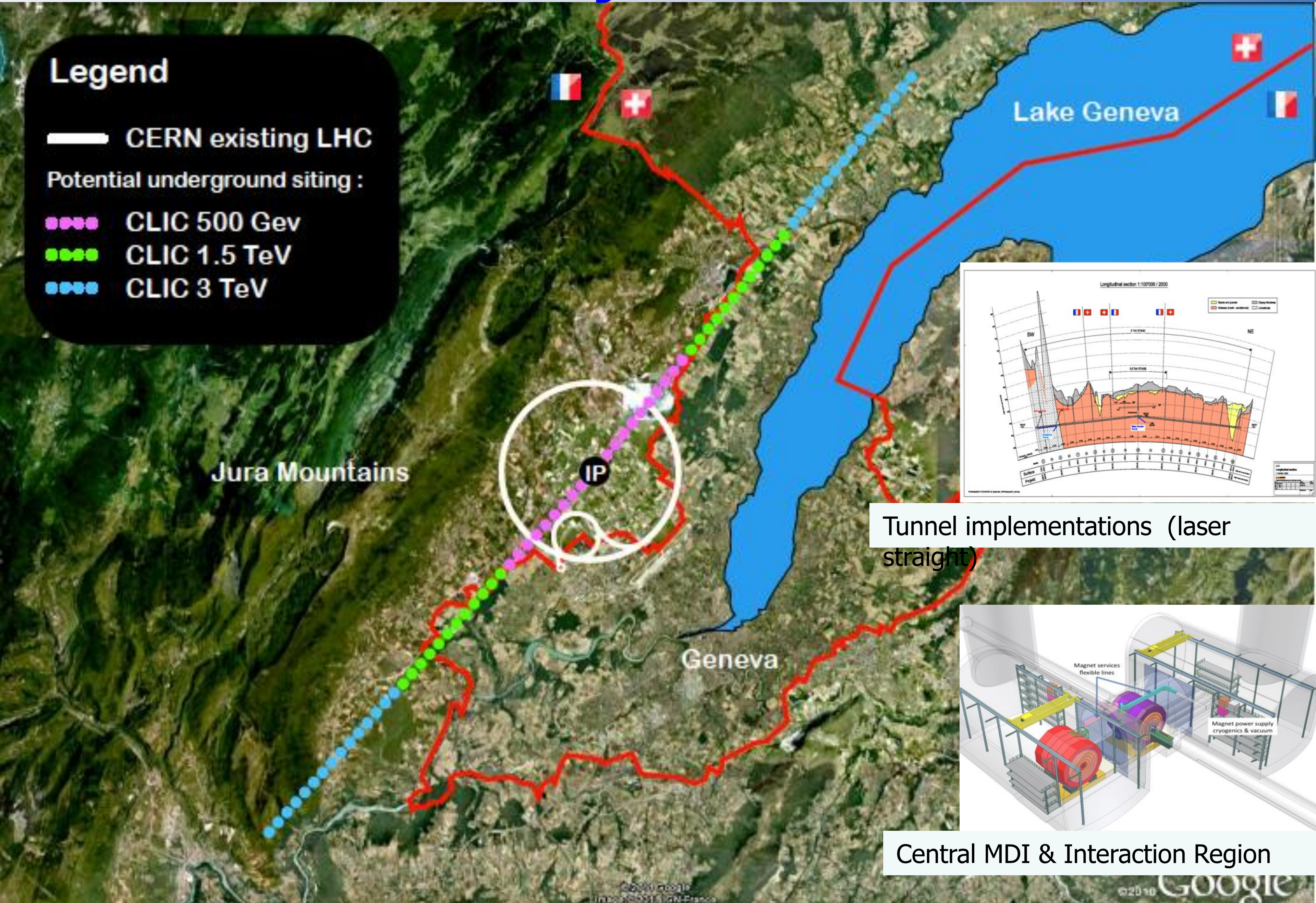
ILC



- 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

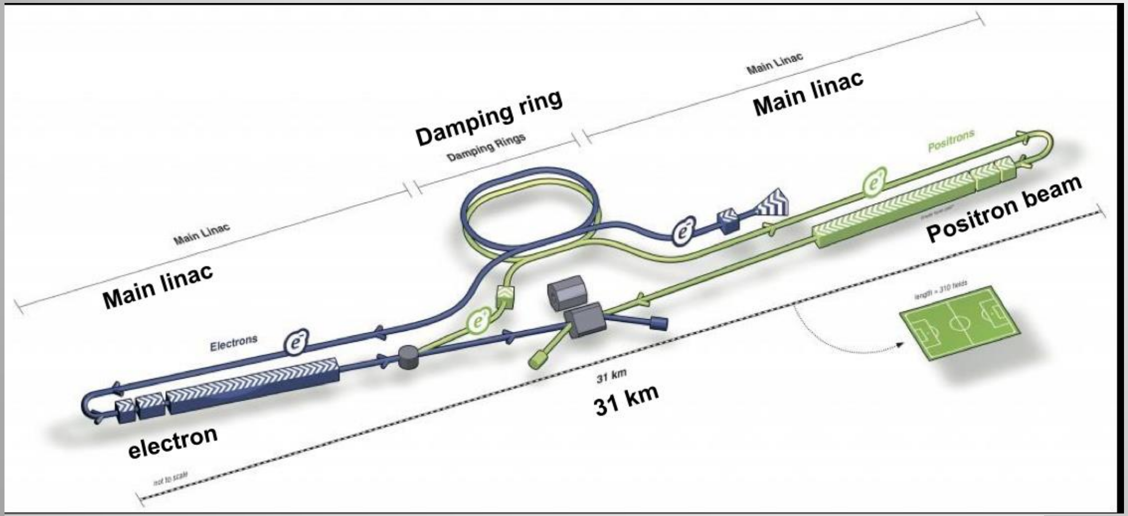


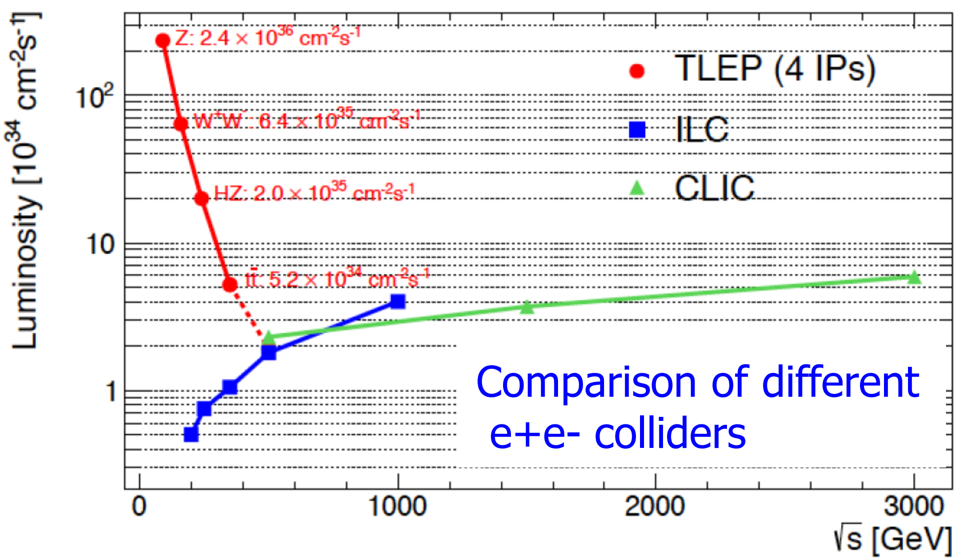
Tunnel implementations (laser straight)

Central MDI & Interaction Region

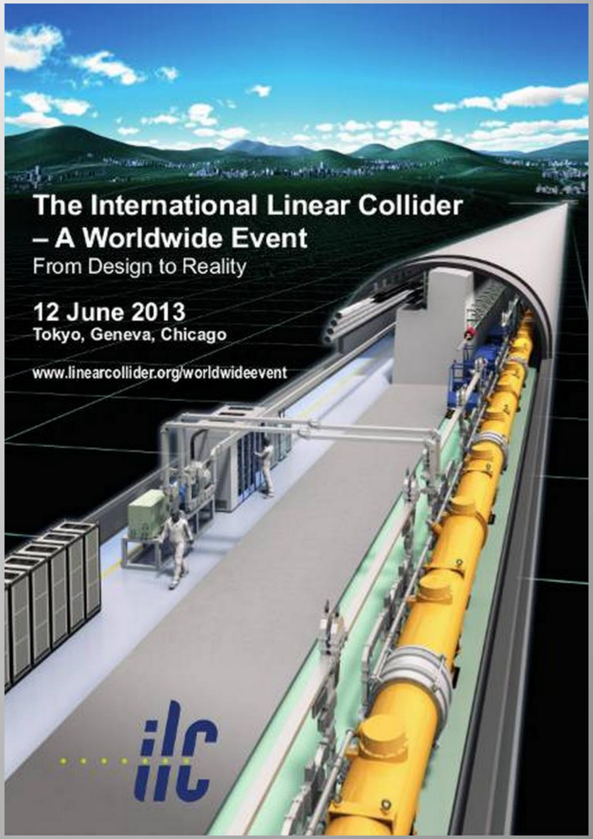
ILC Layout

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)

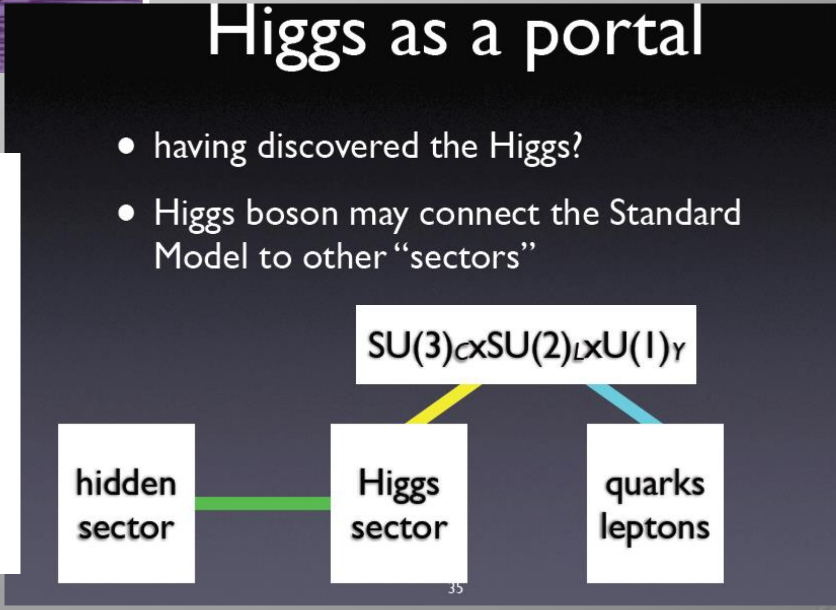
The Physics at the Future Colliders

- 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!!)

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!!



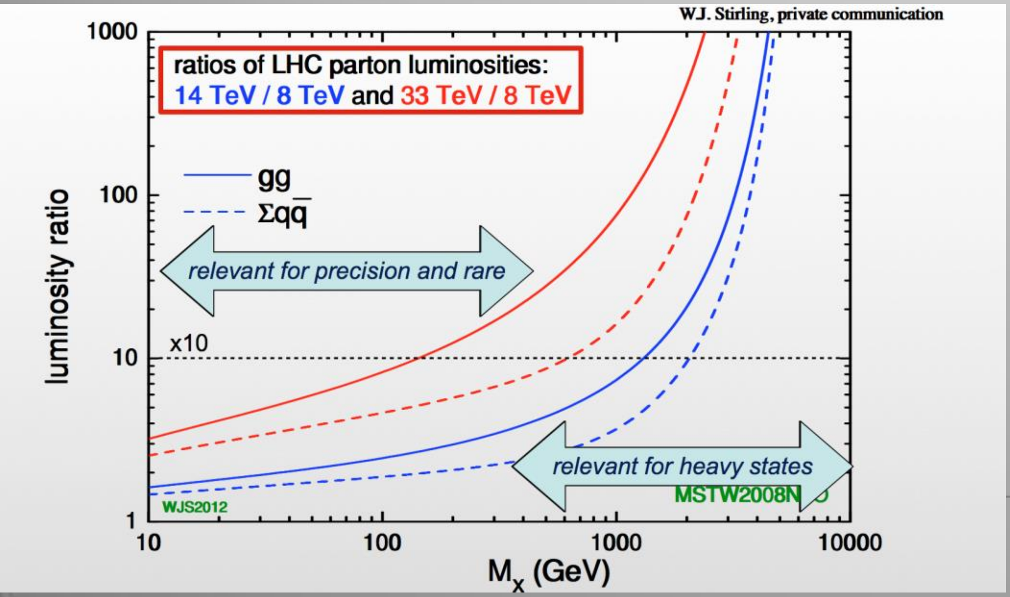
Many questions are still unanswered:

- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

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.

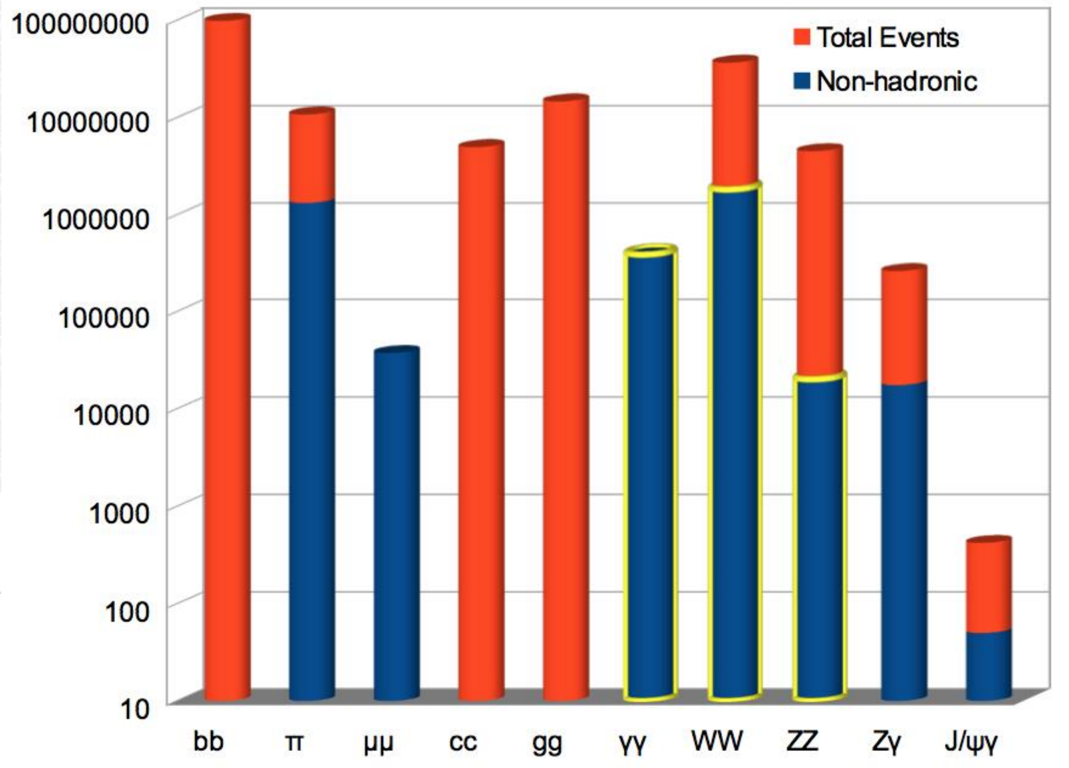


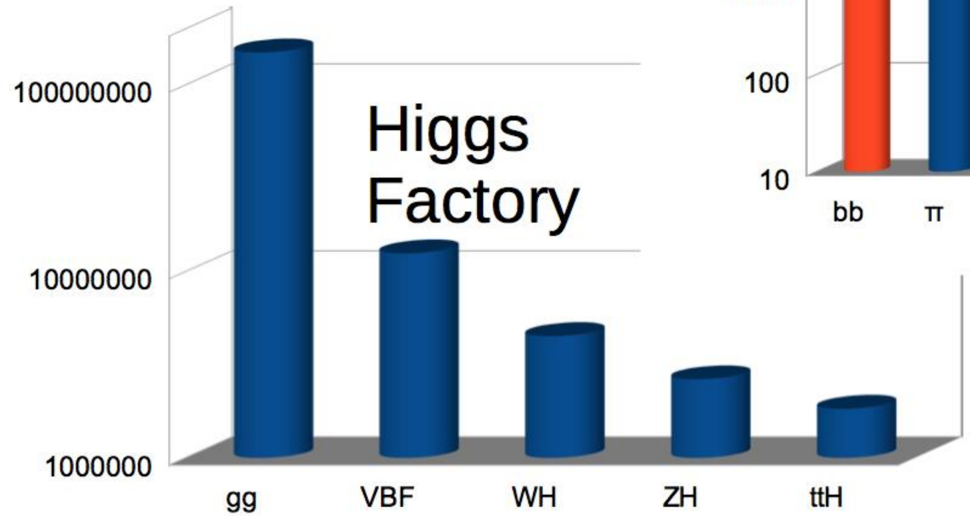
- Higgs mass precisions ~ 100-200 MeV enough?
- Higgs self-coupling precision Better than 20% needed?
- Higgs couplings? Few %? Better? (J. Wells et al., arXiv:1305.6397)

High Luminosity LHC

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

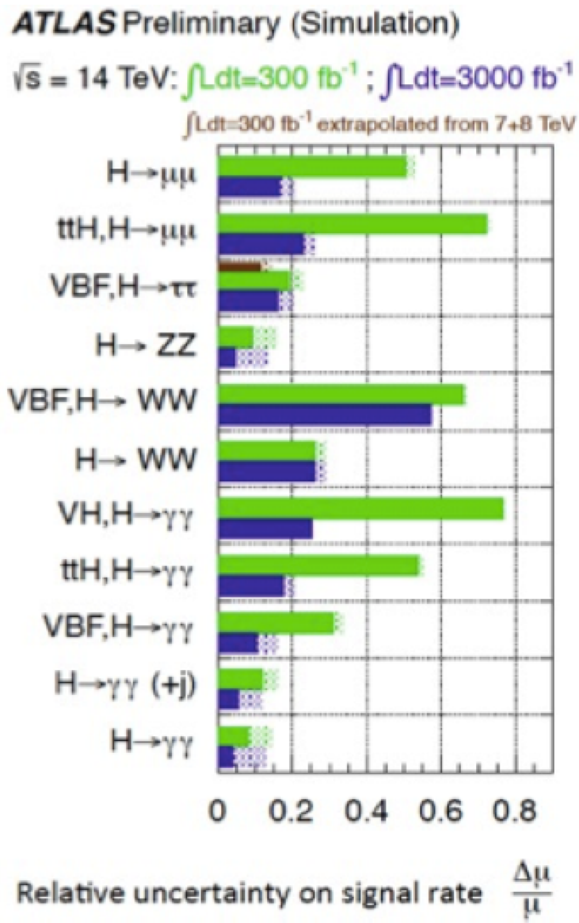
- Over 100M Higgs bosons
- 20K $H \rightarrow ZZ \rightarrow llll$
- 400K γγ
- 50 $H \rightarrow J/\psi\gamma$

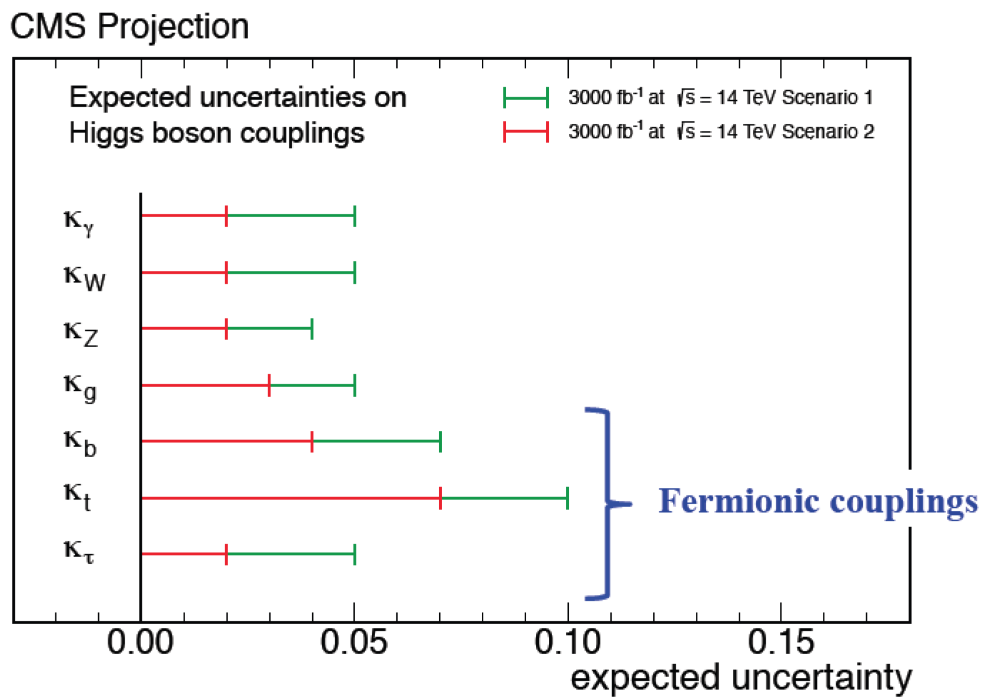




- Over 1M in all major production modes

High Luminosity LHC Precision





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

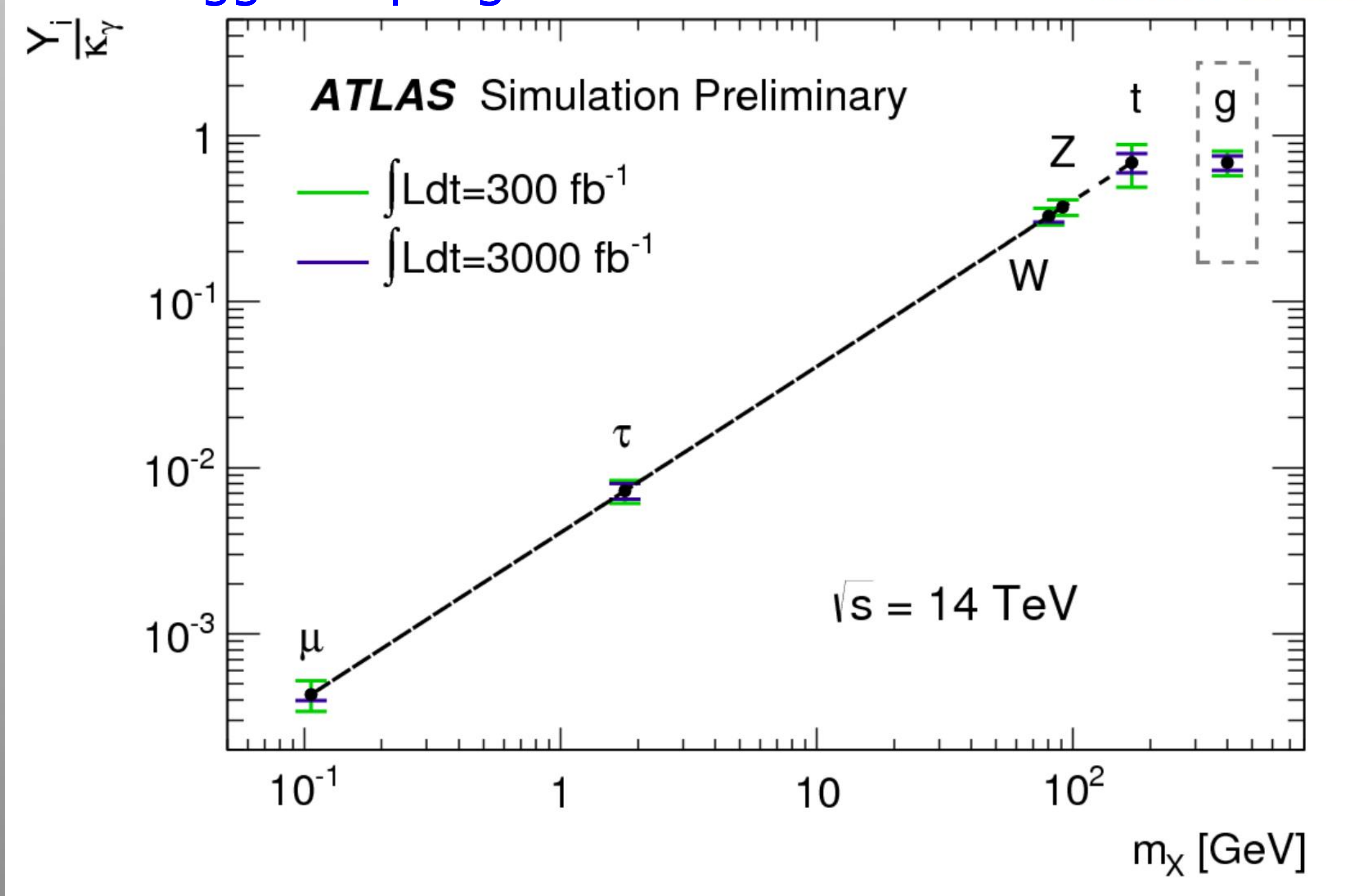
Based on parametric simulation

Extrapolated from 2011/12 results

Determine the Higgs couplings to a few % precision…

High Luminosity LHC Precision

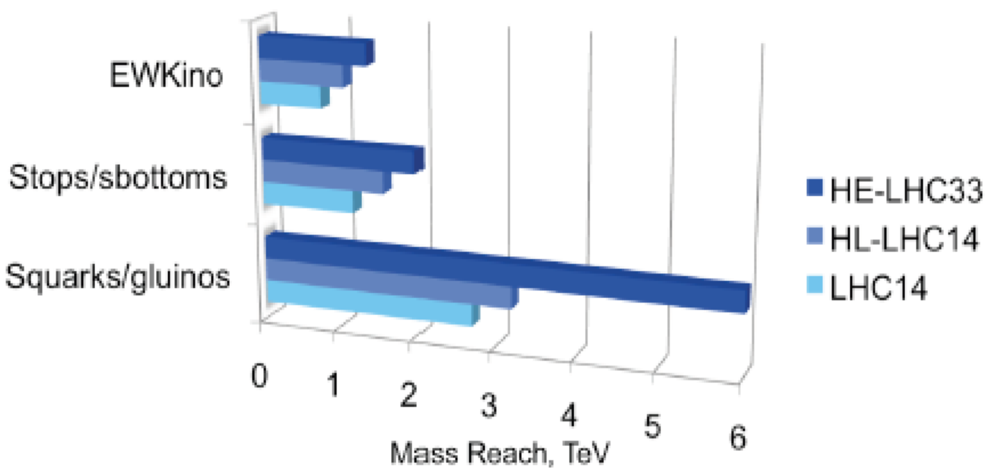
Higgs couplings: ....



Determine the Higgs couplings to a few % precision…

Searches for New Particles in pp

Searches for pair produced SUSY particles



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)

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

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

FCC-hh

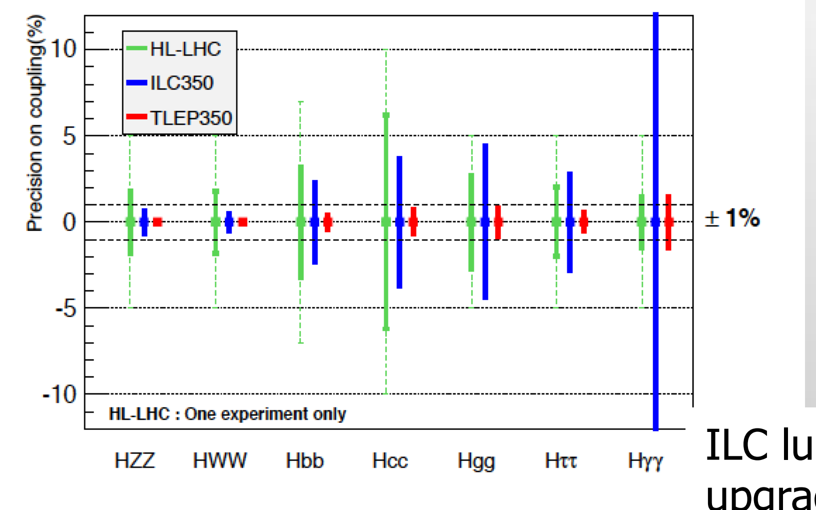
- -Reach sparticle masses search up to about 20 TeV for squarks of light quarks and 6 TeV for stops
- -Excited quarks searches probe the structure of quarks down to 4×10^{-21} m
- -Discovery of resonances up to masses of 40 TeV

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

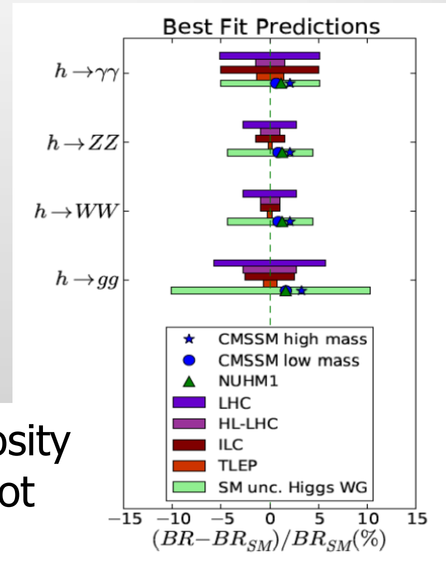
Physics at e+e- Colliders

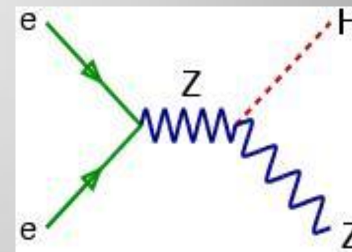
Higgs Boson Couplings



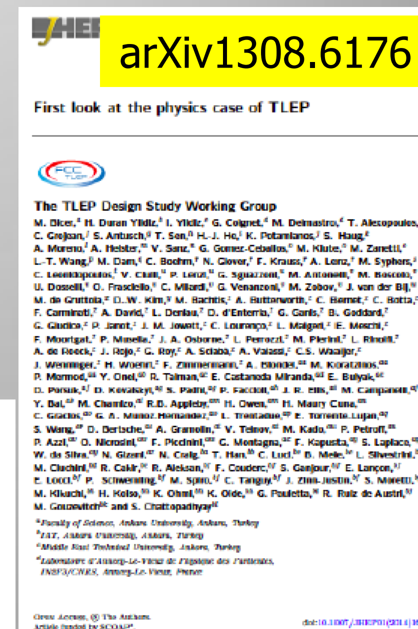
ILC luminosity upgrade not included

Higgs Boson decays

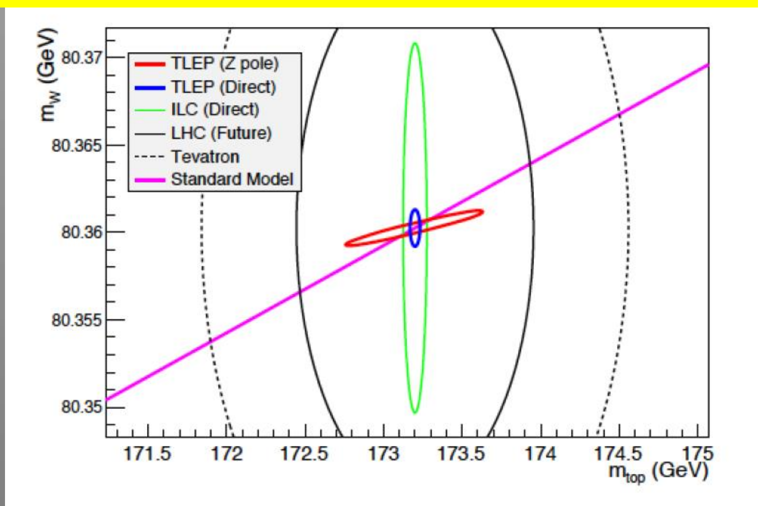




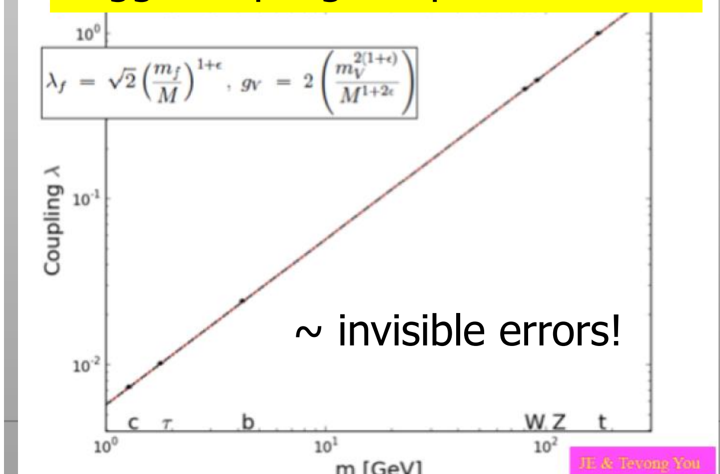
arXiv1308.6176



Fit to all EWK precision measurements



Higgs couplings vs particle mass



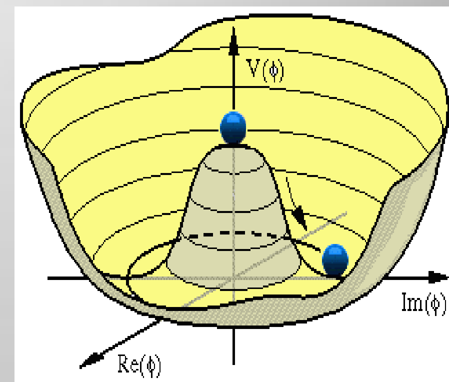
~ invisible errors!

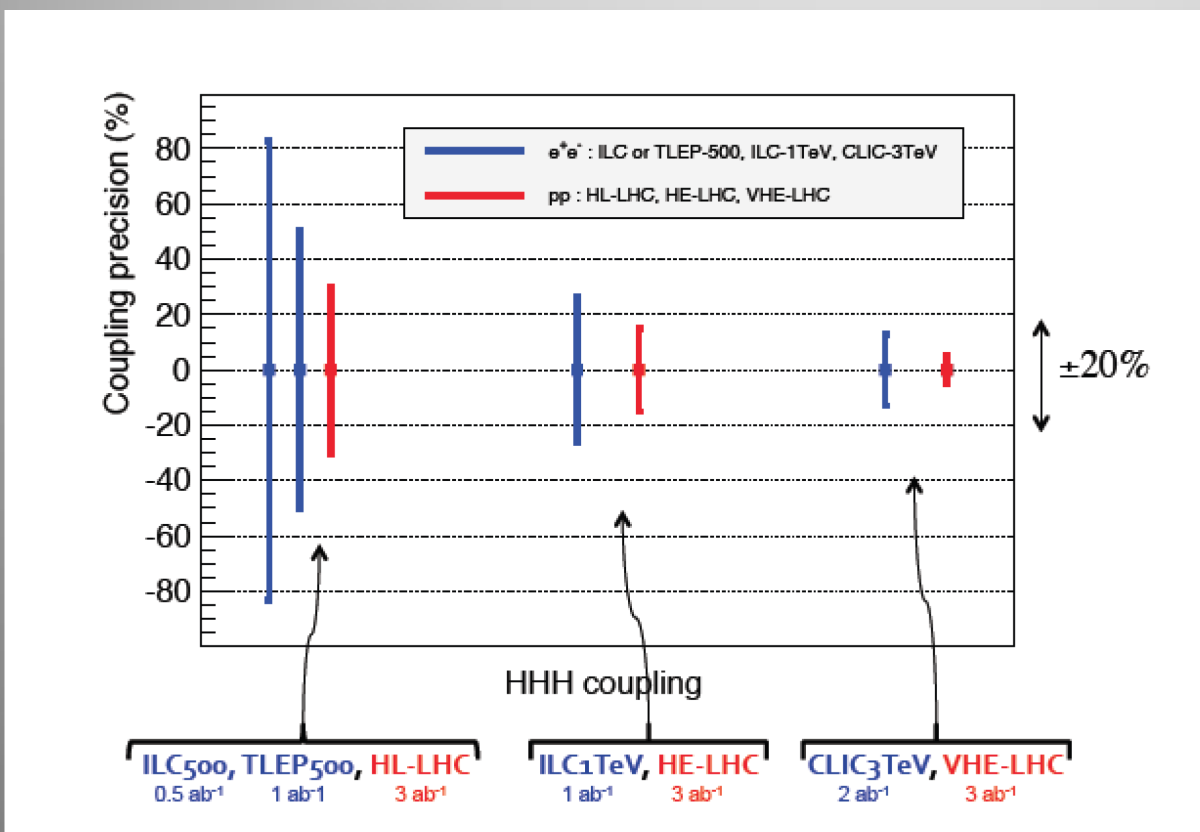
FCC-ee delivers very precise measurements

The Higgs Self Coupling!

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

in pp





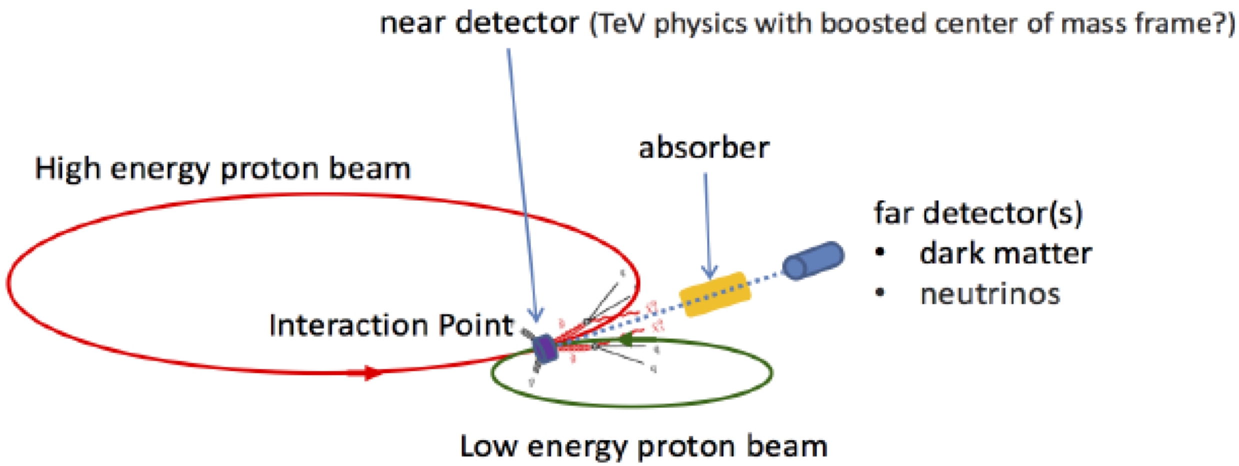
Difficult measurements!!: Evaluation till ongoing for HL-LHC sensitivity

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

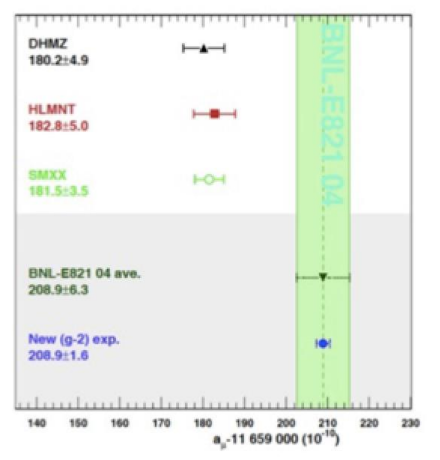


	E_{high} [TeV]	E_{low} [TeV]	E_{cm} [TeV]	
FHC→Fixed Target	50	0.001	0.3	← insufficient E_{cm}
FHC↔LHC	50	7.000	37.4	promising!
FHC↔Super-SPS	50	3.000	24.5	

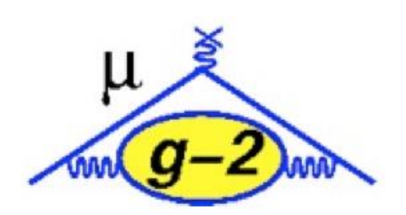
Long timescales: Time to explore new ideas!!

Other experiments: Examples

- A new g-2 measurement experiment at FNAL
- Solve the 3σ discrepancy seen by the BNL exp.
- Start taking data in 2017; in progress

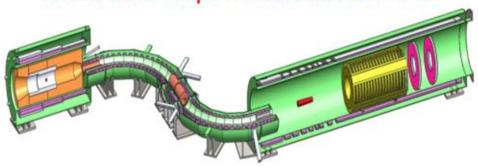


Intensity frontier!



- An improved μ-> e measurement experiment at FNAL
  - Discover μ to e conversion or set limit
    - Rμe < 6 × 10^{-17} @ 90% CL.
    - 10,000 × better than previous best limit.
    - Mass scales to O(10,000 TeV) are within reach.

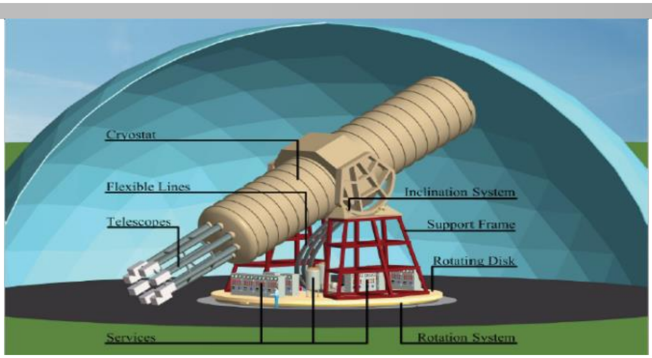
The Mu2e Experiment at Fermilab



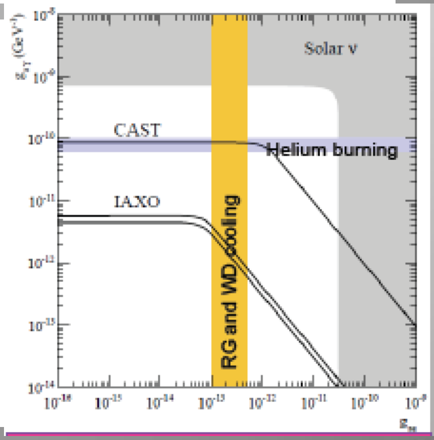
- begin construction in 2015? Start taking data in 2019, first results in 2020

- Solar axion searches: IAXO

At the stage of a proposal



Axion-Telescope

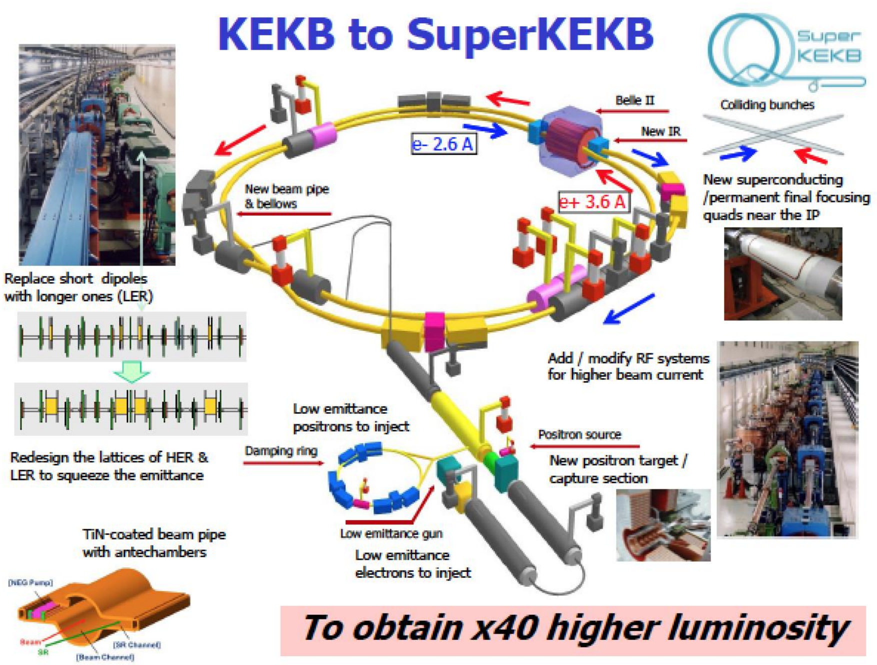


- Start taking data 6 years after approval/construction start

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. (HE-)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.
- Opportunities for young people from all over the world!!!

Super KEKB



High Luminosity B-factory!

Building on the success of the SLAC and KEK B-factories

- First part of machine commissioning early 2015 (without final quads)
- Summer 2015: roll in of the detector, add final quads
- First collisions with final quads and detector in (but w/othe vertex part) by end of 2015 / early 2016
- Summer 2016 add vertex detector
- End of 2016 first physics run.

Complementary to LHCb

Observable	Expected th. accuracy	Expected exp. uncertainty	Facility
CKM matrix			
$\|V_{us}\|$ $[K \to \pi \ell \nu]$	**	0.1%	K-factory
$\|V_{cb}\|$ $[B \to X_c \ell \nu]$	**	1%	Belle II
$\|V_{ub}\|$ $[B_d \to \pi \ell \nu]$	*	4%	Belle II
$\sin(2\phi_1)$ $[c\bar{c}K_S^0]$	***	$8 \cdot 10^{-3}$	Belle II/LHCb
ϕ_2		1.5°	Belle II
ϕ_3	***	3°	LHCb
CPV			
$S(B_s \to \psi\phi)$	**	0.01	LHCb
$S(B_s \to \phi\phi)$	**	0.05	LHCb
$S(B_d \to \phi K)$	***	0.05	Belle II/LHCb
$S(B_d \to \eta' K)$	***	0.02	Belle II
$S(B_d \to K^*(\to K_S^0\pi^0)\gamma))$	***	0.03	Belle II
$S(B_s \to \phi\gamma))$	***	0.05	LHCb
$S(B_d \to \rho\gamma))$		0.15	Belle II
A_{SL}^d	***	0.001	LHCb
A_{SL}^s	***	0.001	LHCb
$A_{CP}(B_d \to s\gamma)$	*	0.005	Belle II
rare decays			
$\mathcal{B}(B \to \tau\nu)$	**	3%	Belle II
$\mathcal{B}(B \to D\tau\nu)$		3%	Belle II
$\mathcal{B}(B_d \to \mu\nu)$	**	6%	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb
zero of $A_{FB}(B \to K^*\mu\mu)$	**	0.05	LHCb
$\mathcal{B}(B \to K^{(*)}\nu\nu)$	***	30%	Belle II
$\mathcal{B}(B \to s\gamma)$		4%	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$		$0.25 \cdot 10^{-6}$	Belle II (with 5 ab^{-1})
$\mathcal{B}(K \to \pi\nu\nu)$	**	10%	K-factory
$\mathcal{B}(K \to e\pi\nu)/\mathcal{B}(K \to \mu\pi\nu)$	***	0.1%	K-factory
charm and τ			
$\mathcal{B}(\tau \to \mu\gamma)$	***	$3 \cdot 10^{-9}$	Belle II
$\|q/p\|_D$	***	0.03	Belle II
$arg(q/p)_D$	***	1.5°	Belle II

→Need both LHCb and super B factories to cover all aspects of precision flavour physics

- B. Golob, KEK FF Workshop, Feb. 2012

Intensity Frontier

- If the LHC searches for new physics in Run 2 will come empty-handed, there is little that could point to the next relevant energy scale
- Typically, flavor physics is sensitive to very high scales, way beyond the LHC reach
- The “small” experiments searching for $\mu \to e$ conversion or measuring g-2 of the muon to a new level of precision may lead to establishing the relevant energy scale
- If, one the other hand, LHC finds new physics, these experiments could help to elucidate its true nature

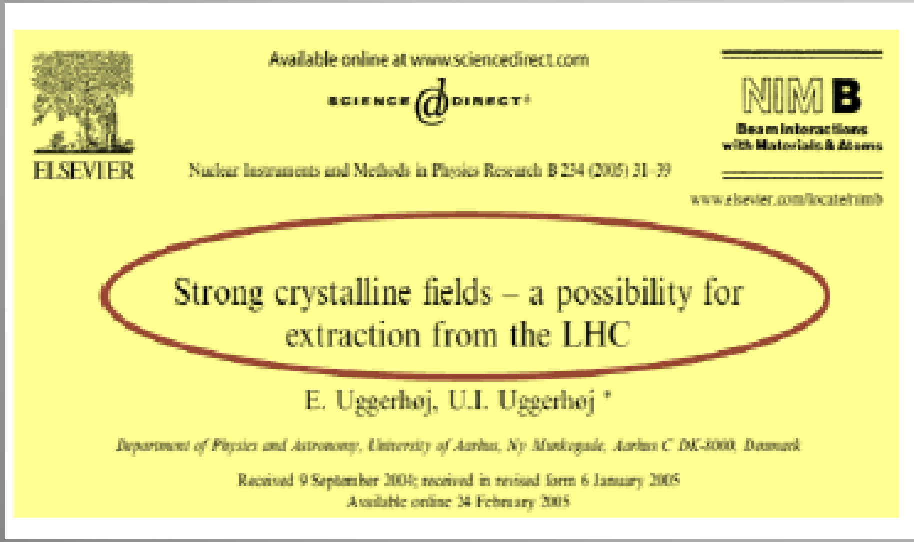
A Fixed Target ExpeRiment (AFTER)?

JP Lansberg et al.

Use crystals, brought to 7σ of the beam, to extract protons or ions for a fixed target experiment. Runs parasitically on the collider

- Extracting a few per cent of the beam → 5×10^8 protons per sec
- This allows for high luminosity *pp*, *pA* and *PbA* collisions at

$$\sqrt{s} = 115 \text{ GeV and } \sqrt{s_{NN}} = 72 \text{ GeV}$$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Nuclear Instruments and Methods in Physics Research B 234 (2005) 31–39

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Strong crystalline fields – a possibility for extraction from the LHC

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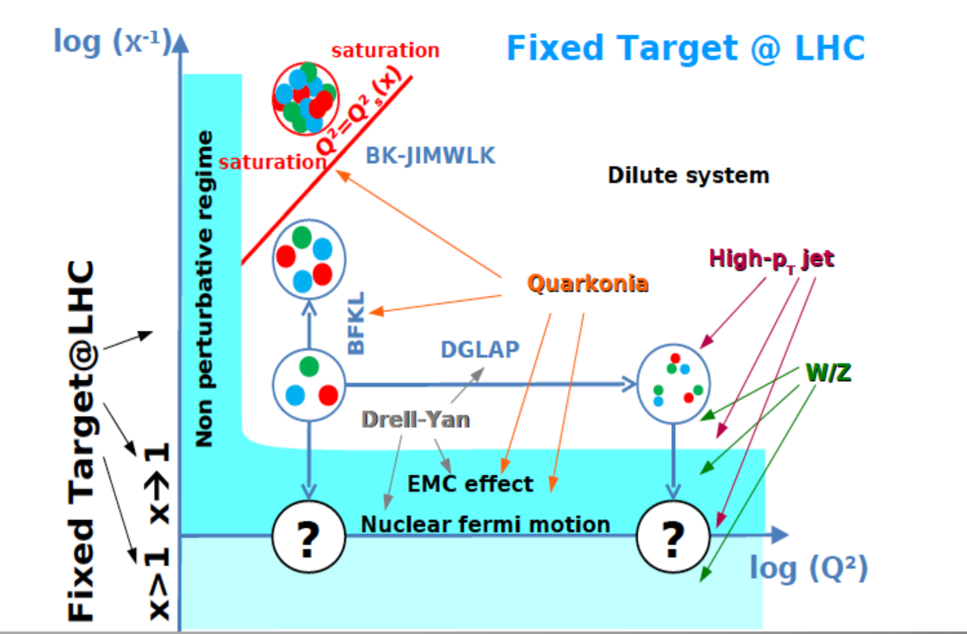
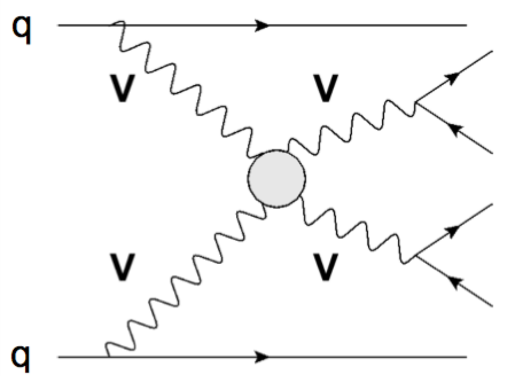
Available online 24 February 2005



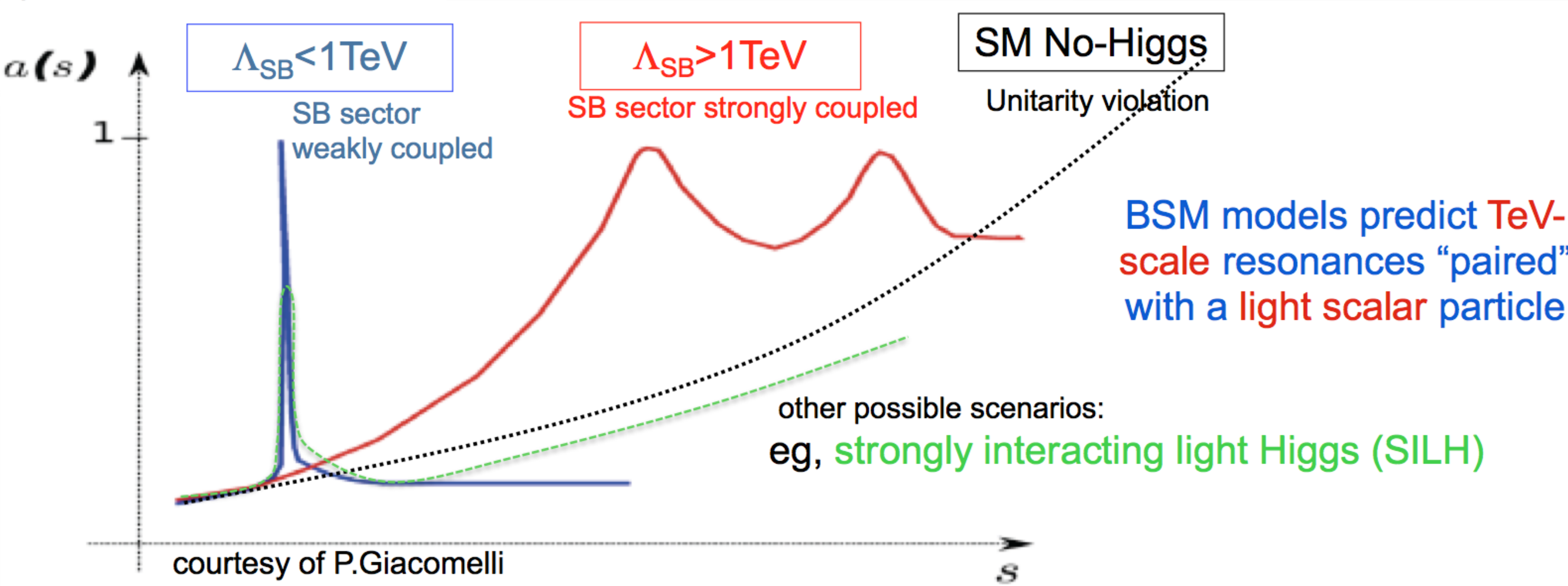
A QCD experiment for 2020+ ?

Conclusion

- The new 126 GeV Higgs boson so far sets the scene for the future facilities. How precise do we need to determine its properties??
- The nominal energy LHC (13-14 TeV) will start in 2015. HL-LHC should give 3000 fb^{-1} by ~2030-35, after a machine and detector upgrade.
- A High Energy LHC could be next. Needs a new machine in the present LHC tunnel for 28-33 TeV.
- pp at 100 TeV? Interest from CERN and China
- Future e+e- colliders. ILC, CLIC or TLEP? ILC could be build now. Japan expressed interest.
- Several other high intensity experiments planned.



- 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 ?)



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

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

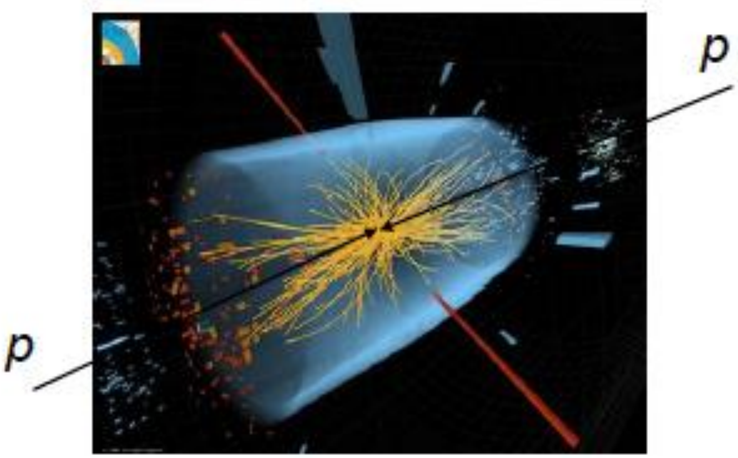
– need high energy:

$$E = mc^2$$

– need lots of data

non-deterministic and very rare

order 1 in 10^{10}



* for us finding the Higgs it was 48 years = 1,513,728,000 sec

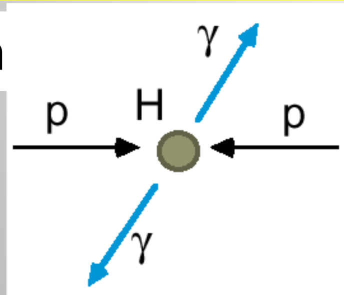
Higgs Boson Searches (simulation)

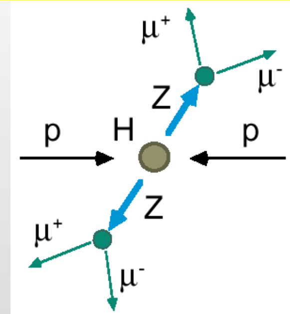
Low M_H < 140 GeV/c²

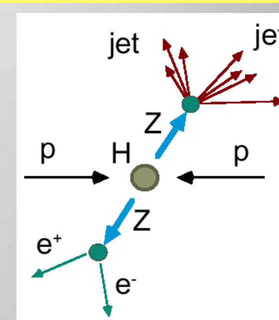
Medium 130<M_H<500 GeV/c²

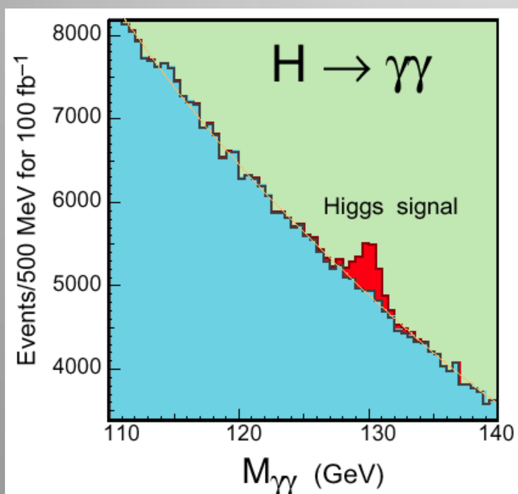
High M_H > 500 GeV/c²

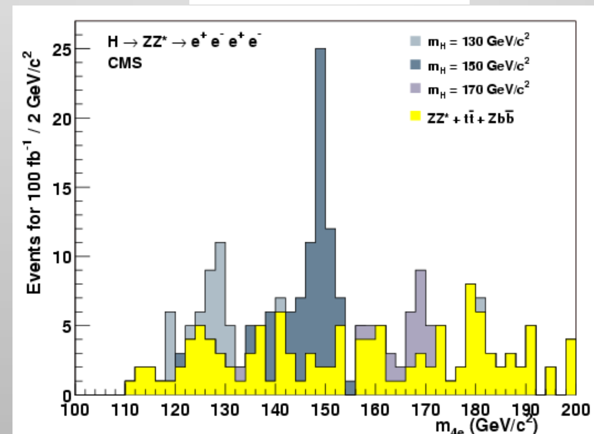
simulation

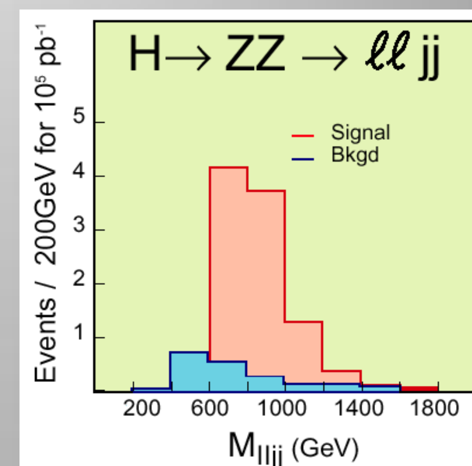


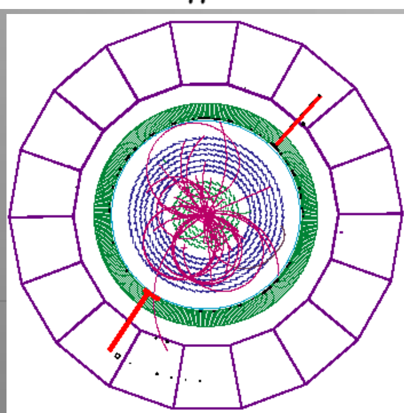


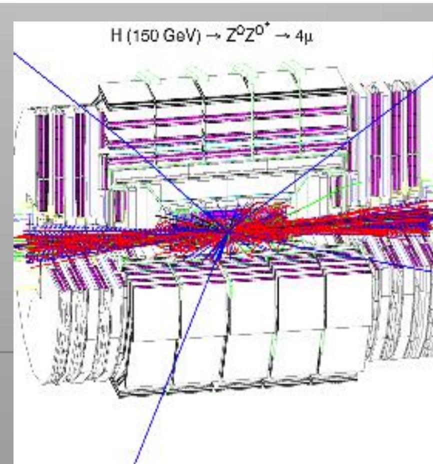


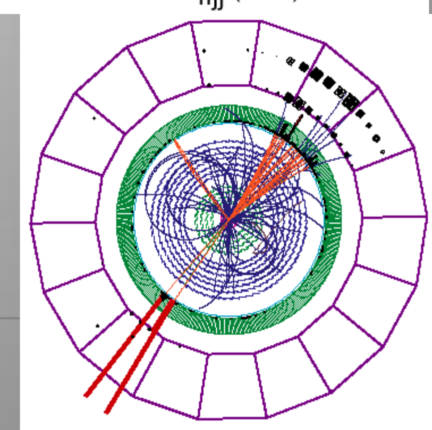












The Hunt for the Higgs

Where do the masses of elementary particles come from?

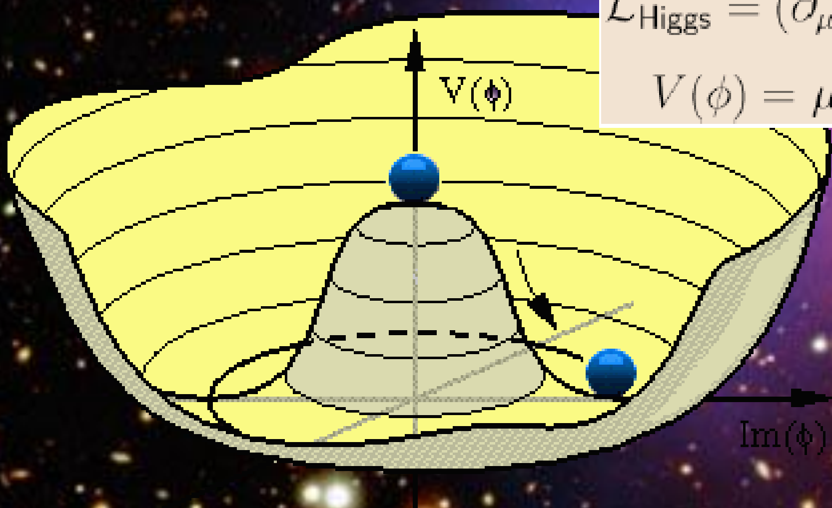
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV

July 4th 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Melbourne

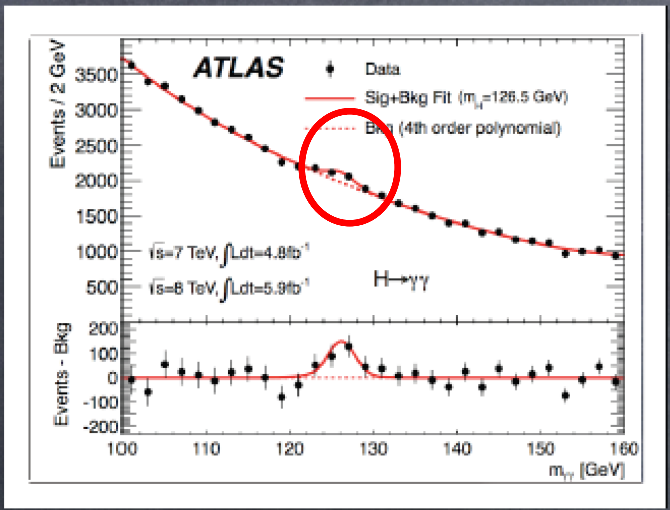
Followed live around the world…

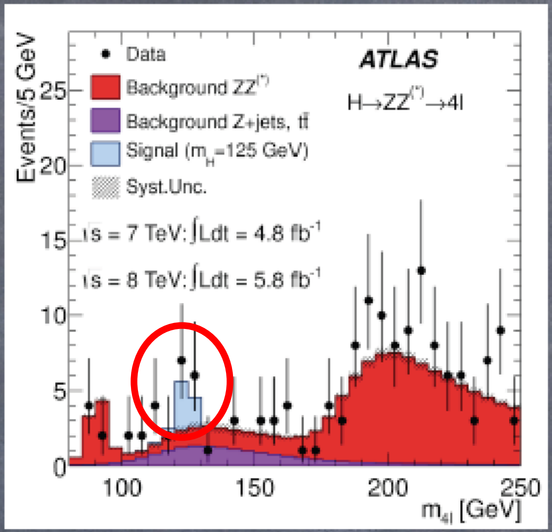
July 2012: Results

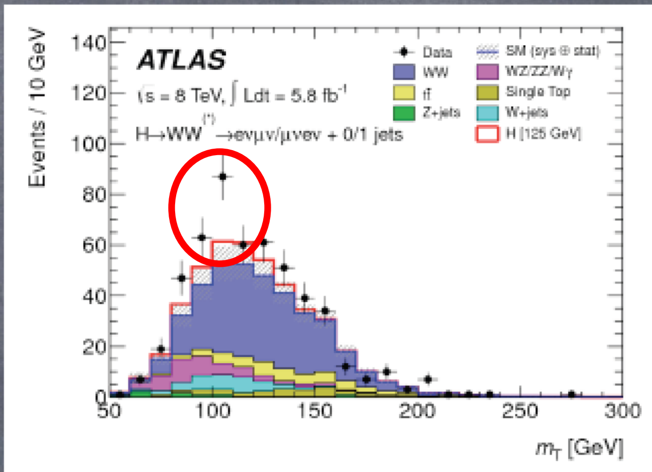
Higgs → 2 photons!!

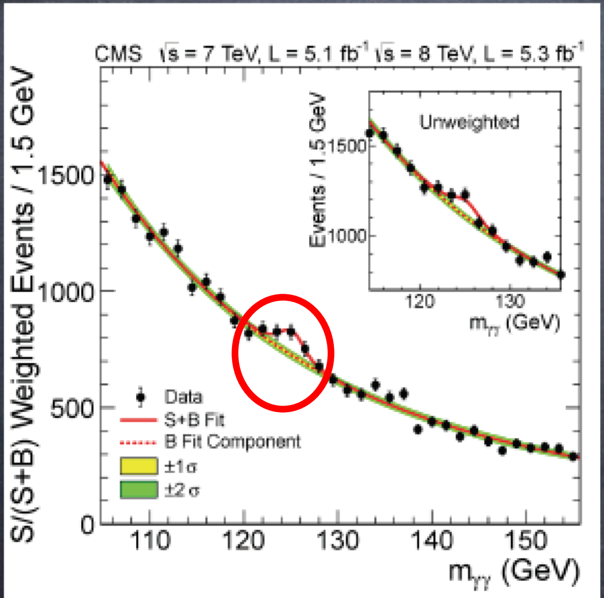
Higgs → 2Z →4 leptons!!

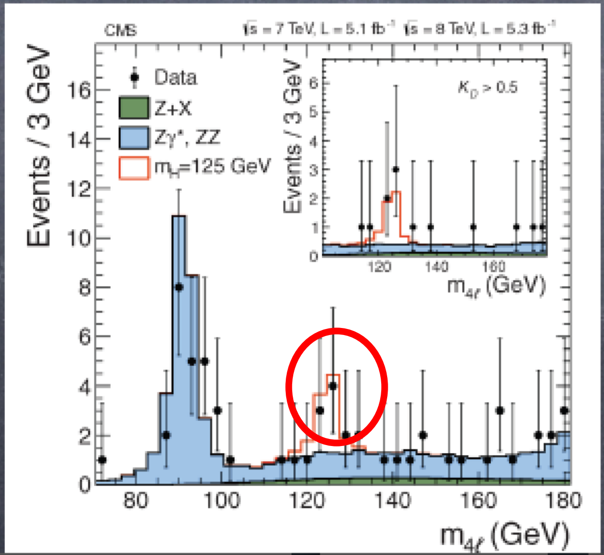
Higgs → 2W →2l2ν!!

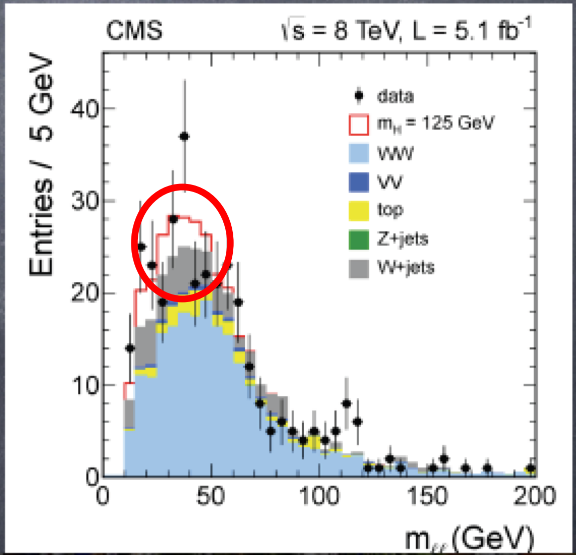












July 4th 2012
The discovery of a new particle

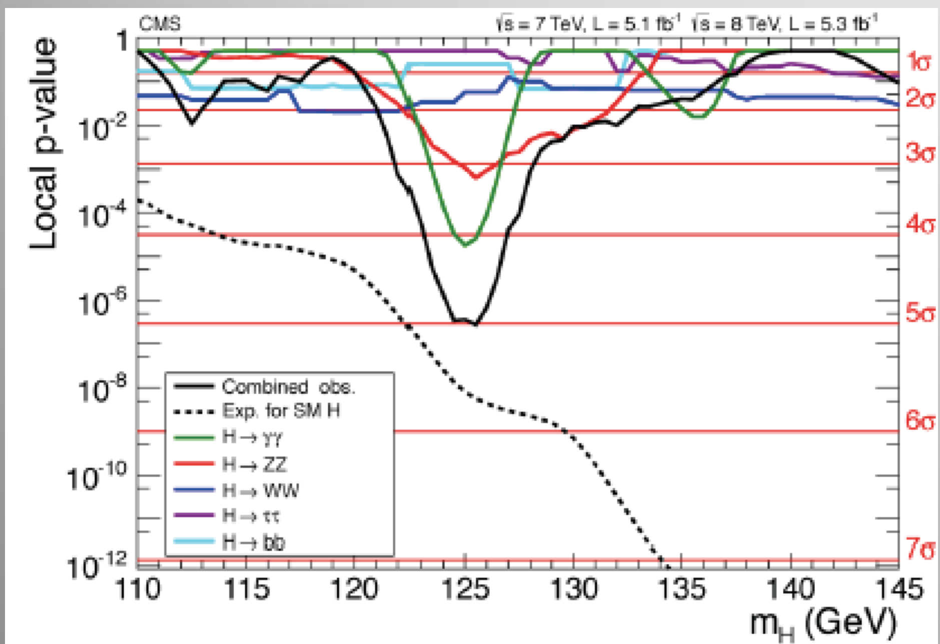
July 2012: Results

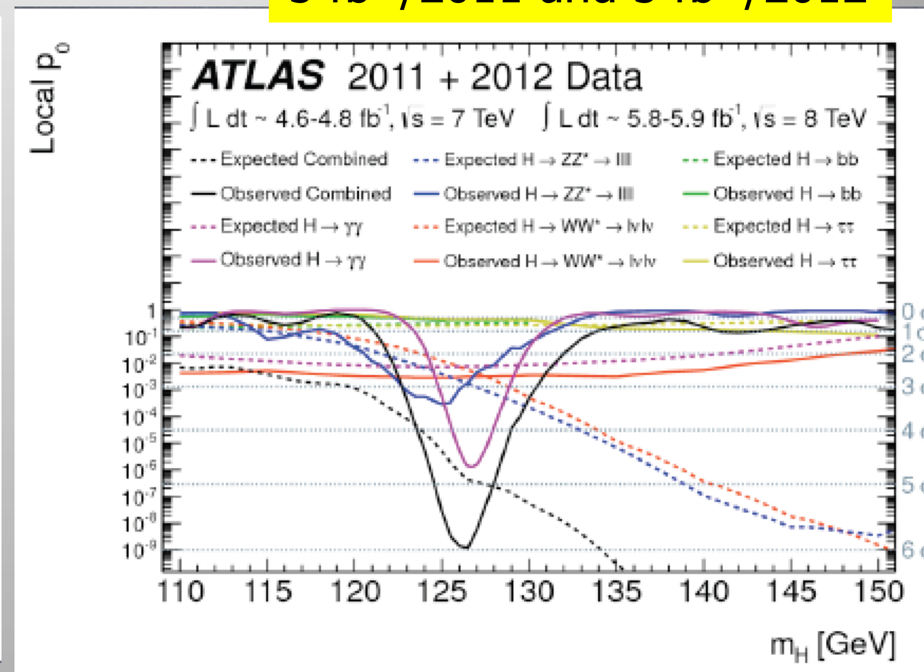
Both experiments see an excess ~125 GeV in the γγ, ZZ and WW channel

→Final result by adding up al the channels

Shown is the compatibility with a 'background only hypothesis"

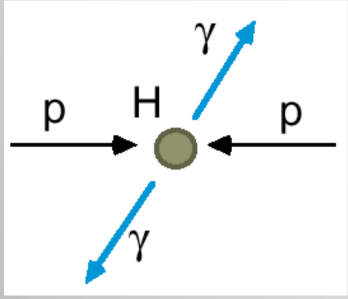
5 fb^{-1}/2011 and 5 fb^{-1}/2012



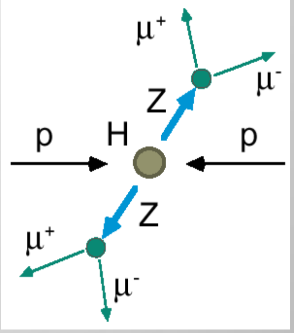


CMS and ATLAS observe a new boson with a significance of about 5 sigma (1 chance in 3 million to be wrong!!!)

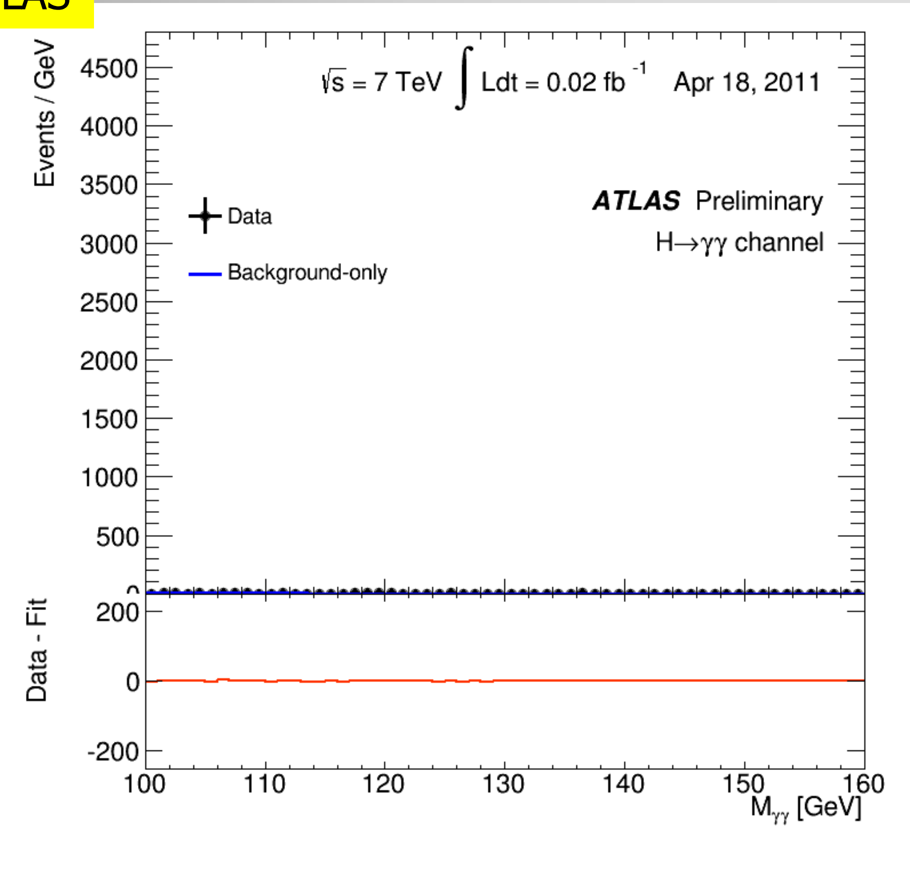
The Birth of a Particle



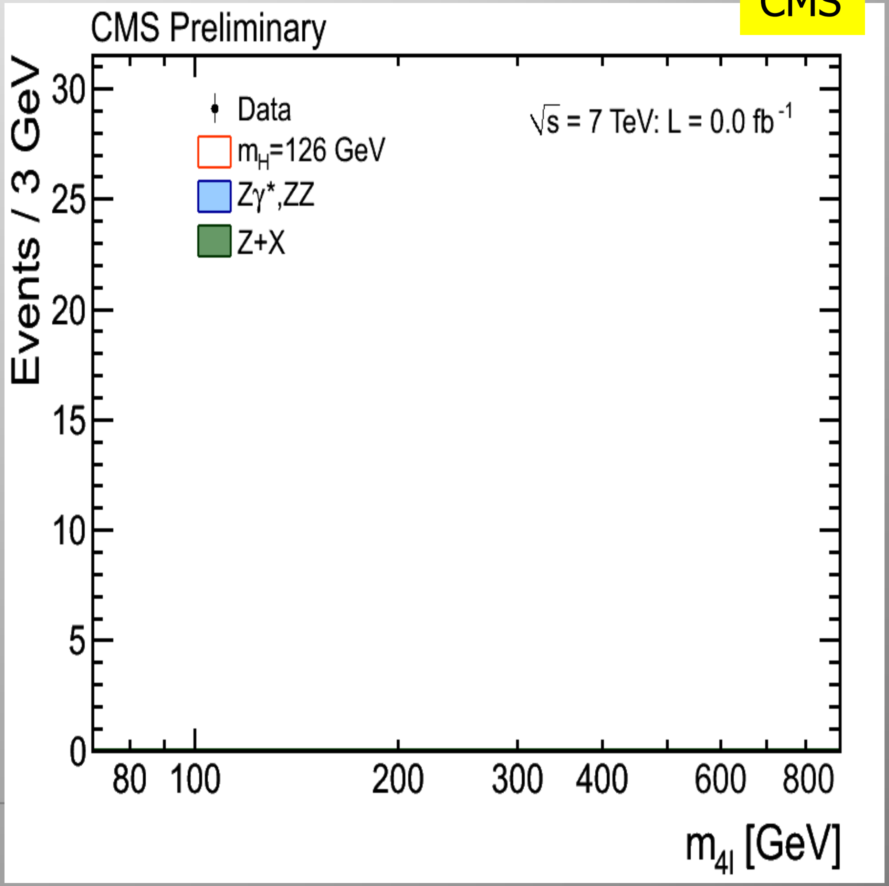
"History" of the data accumulation during the last two years



ATLAS



CMS

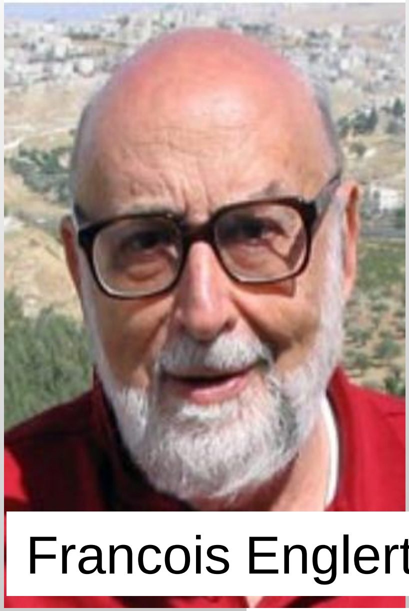


The News Since July 2012

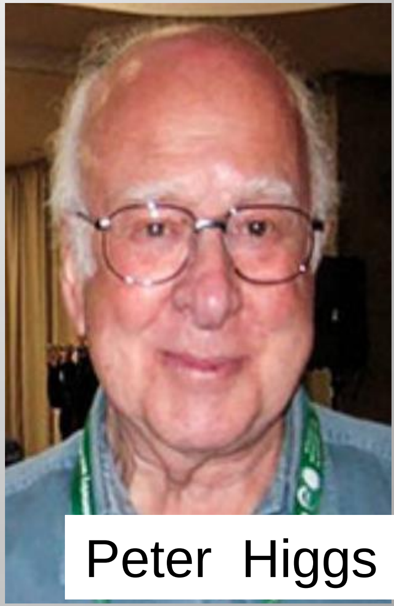
- The discovery of the new particle has been confirmed with more added collisions in 2012.
- Signals in the fermion-channels start building up
- We tested the spin: it is compatible with a 0^+ state and not with a 0^- or spin 2 states
- The mass is measured better with time, now in the range125-126 GeV. A naïve average gives 125.6 GeV
- The couplings to Bosons and Fermions are consistent with the SM predictions (but these are not very precise yet; Surprises possible…)

March 2013: We call it now “a Higgs particle”

Tuesday 8 October 2013



Francois Englert



Peter Higgs

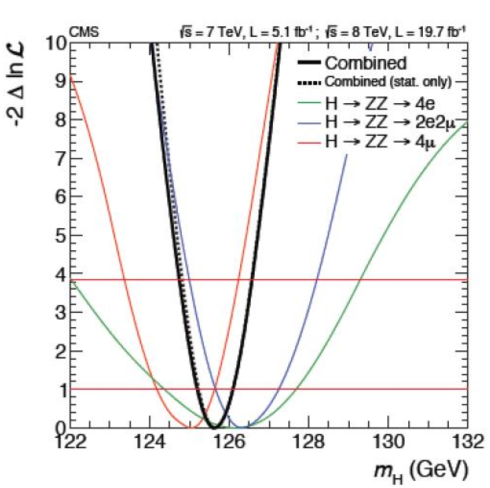
Congratulations!!!!

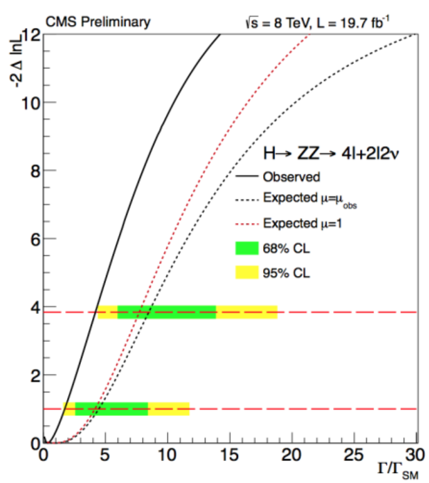
...and December 2013

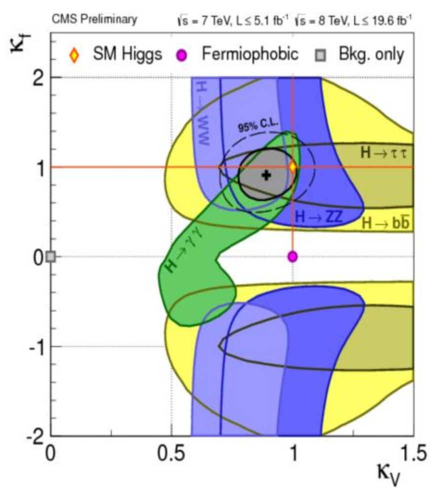
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental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

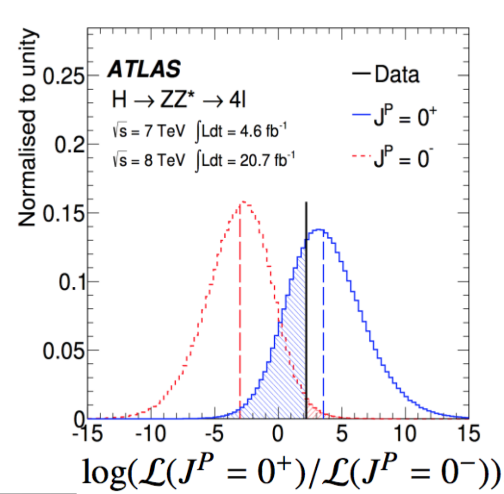
A Higgs…

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









Mass =
125.5 ±0.5 GeV

Width =
< 22 MeV
(95%CL)

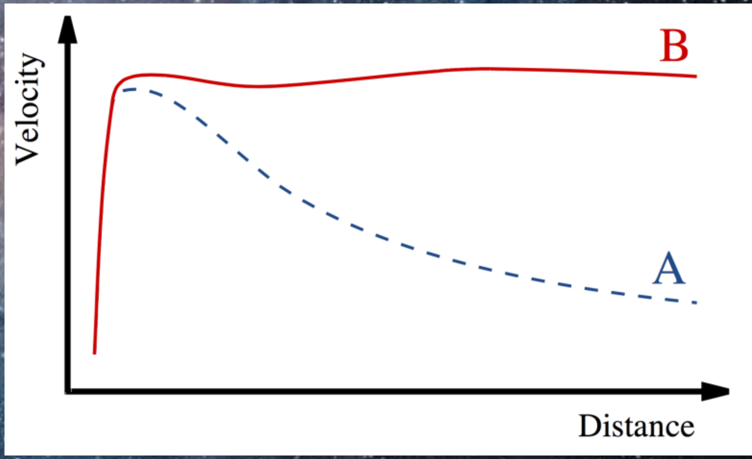
Couplings are
within 20% of
the SM values

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

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/minute with present lumi.

Dark Matter in the Universe

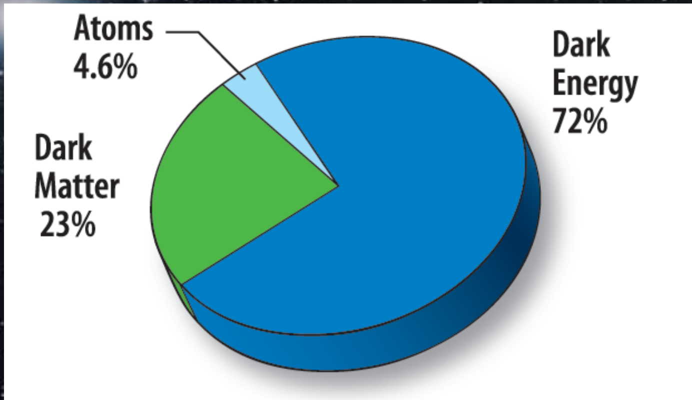
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?


F. Zwicky 1898-1974


Vera Rubin ~ 1970



Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar boson, postulated in 1964.

March 2013: The full statistics of 2011+2012 (about a factor 3 more data) confirms the existence of the new particle.

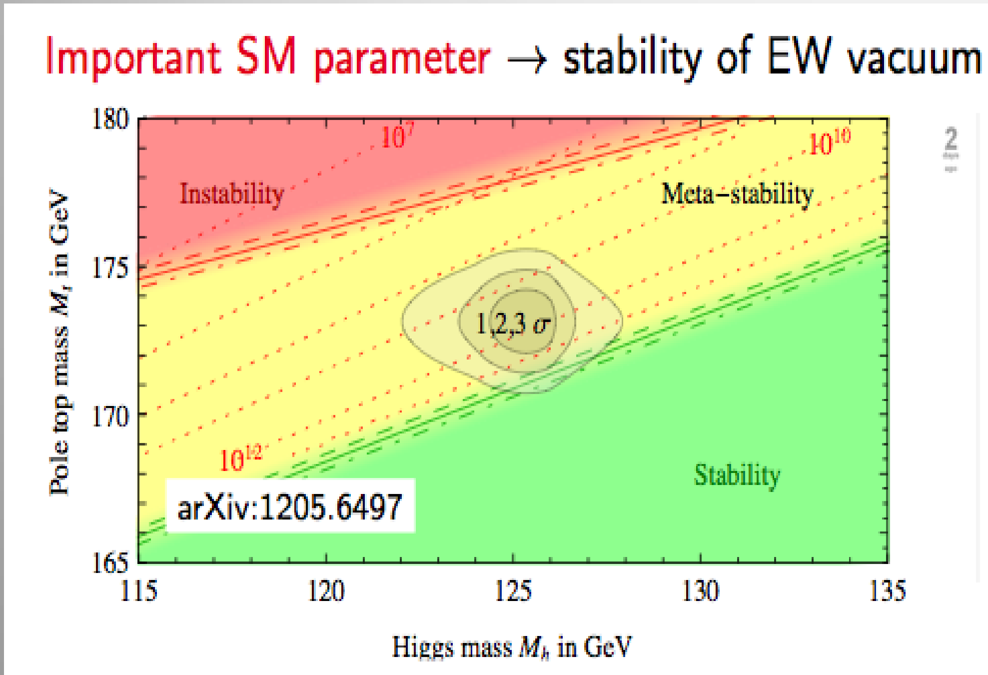
The spin and couplings to W and Z bosons are consistent with the expectation for a Higgs boson. Hence we call it now "a Higgs particle". This is a brand new fundamental particle, as we never seen before.

This Higgs boson is 'very light' which suggest new physics Beyond the Standard Model will be needed. Supersymmetry? Extra Dimensions? Other? The next years @ the LHC will tell…

We are on the verge of a revolution in our understanding of the Universe and our place within it. Turkish students and scientist have the opportunity to participate in this science adventure (ENHEP)

This is only the beginning!!!

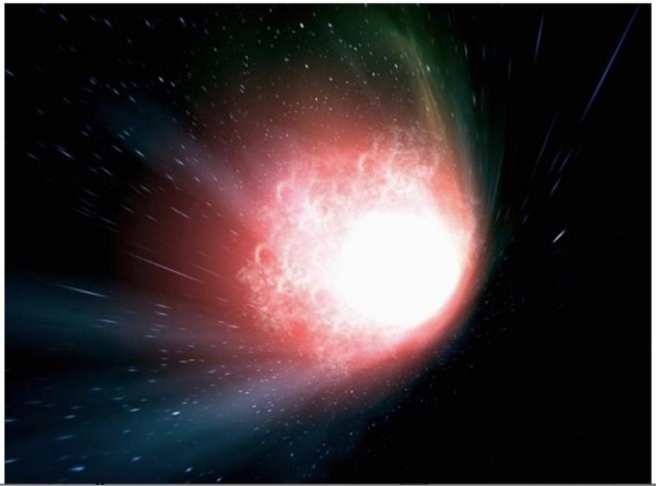
Consequences for our Universe?



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)

Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



New Physics inevitable?
But at which scale/energy?

Idea Proposed to the US P5 Panel

Could the tunnels we drilled for a collider in Texas house a Higgs factory? And add a bigger ring to it? 300 TeV collider???

Idea proposed to the US P5 Panel

Table 3. Main parameters of hadron colliders of 100 and 270 km circumference.

	Higgs factory	hadron collider			
Circumference	100	100	270		km
Collision energy	0.24	100	100	300	TeV
Dipole field	0.046	15	4.5	14.5	Tesla
Luminosity/I.P.	5	5	5	10	10^{34} $cm^{-2}s^{-1}$
β*	50x0.1	110	50	100, 10	cm
Total synch. power	100	4.2	1.0	34	MW
Critical energy	430	4.0	1.0	28	keV
Synch power/meter/bore	580	26	2	80	W/m
Emittance damping time		1	19	.66	Hr
Luminosity lifetime	0.3	18	20	3.7	hr
Energy loss/turn	2100	4.3	1.3	114	MeV
RF accel. voltage:	6000	100	50	250	MV
Acceleration time	.01		.42	.25	H
Bunch spacing	250	50	25	25	ns
Beam-beam tune shift	0.09	.01	.01	.01	
# IPs	4	2+2	2+2	2+2	
# particles per beam	4.1	100	220	86	10^{13}
Injection energy	0.12	>3	15	50	TeV
Superconducting temp.	1.8 K in SRF	4.5	8	4.5	K

Follow-up: 8 October 2013