Future Colliders for the Energy Frontier

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(Centro de Ciencias de Benasque Pedro Pascual)

OVERLOOK

- Particle accelerators immensely powerful tools for understanding the standard model and to search for new physics.
- Long history of colliding beam experiments with spectacular results
- Short report of our actual energy frontier (LHC), as input to to guide the future

  (many think already seen in Ignacio Redondo talk).
- Future possibilities are examined will examine.

- Sorry for any technical mistake (I am just a accelerator user).
- This is also a very personal view.

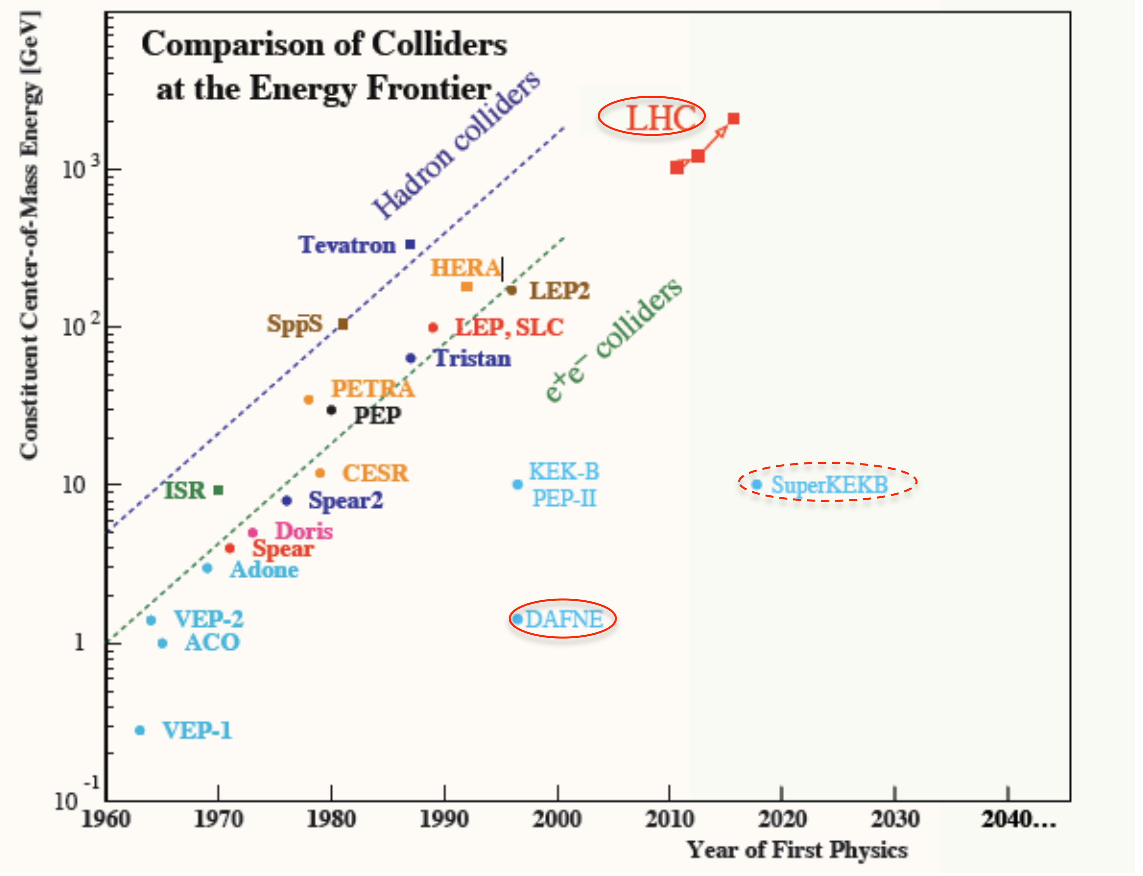
Evolution of Colliders - past and present

Long history of high energy acceleration

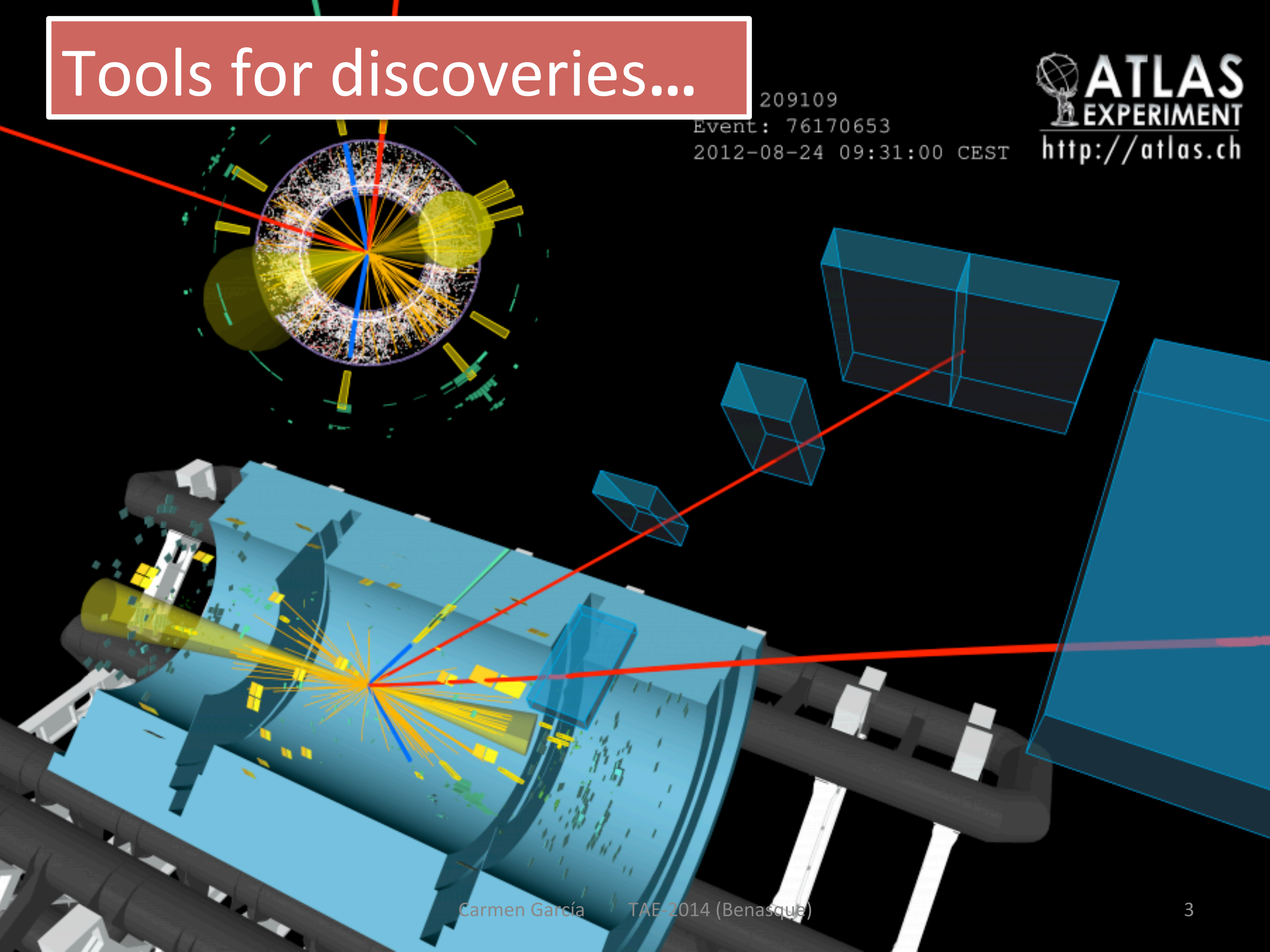
- Proton-(anti-)Proton
- Electron-Positron
- Electron-hadron

Exponential increase in beam energy

N. Walker



Tools for discoveries…

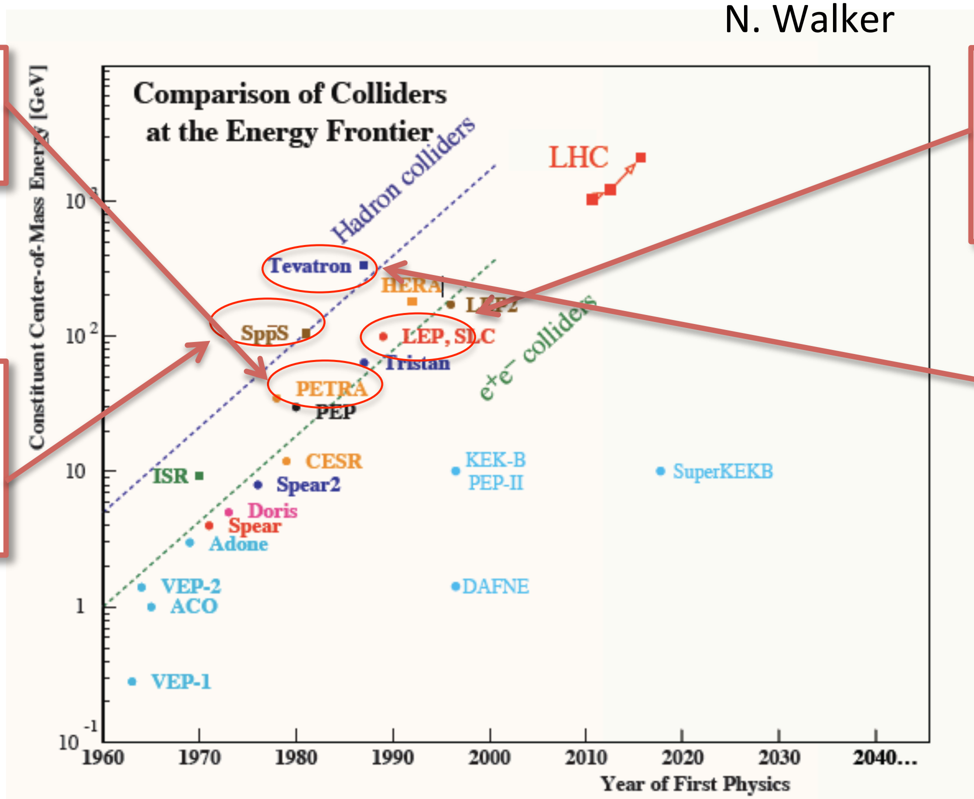


High energy acceleration has given some of the most powerful insights into constituents of matter and their interactions

N. Walker

Strong nuclear force: gluons discovery

Electroweak vector bosons: dicovery of (W,Z)

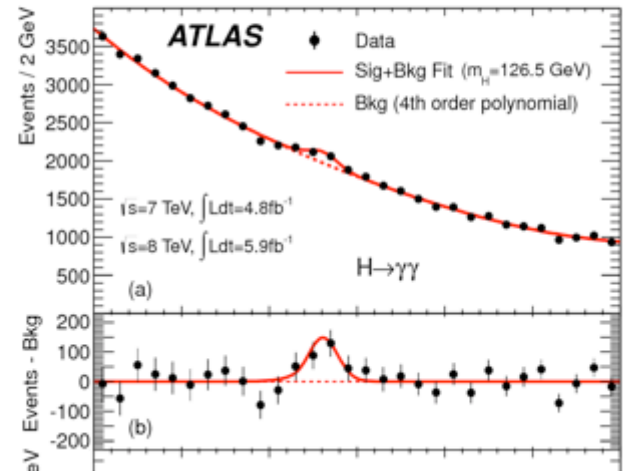


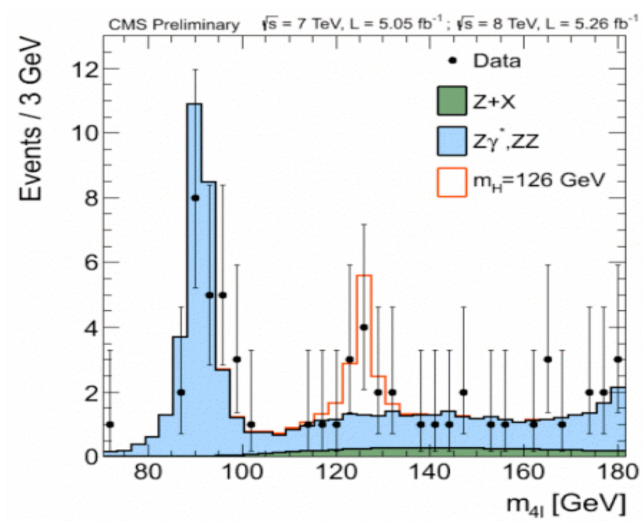
Electroweak vector bosons: precision measurements

Top discovery

The Current Energy Frontier: LHC

Higg Discovery





Priorities of collider physics after Higgs discovery

- **The recently discovered of a Higgs boson drives to a number of fundamental open points that are top priority for the physics programme for LHC and FUTURE COLLIDERS :**
  - Precision measurement of the **mass** and **natural width** determination.
  - Determination of the **quantum numbers** spin and parity, J^P, and CP violation.
  - Measurement of **couplings** to elementary fermions and bosons
  - Measurement of the **Higgs boson pair** production.
  - **Comparison** of these physics properties with those predicted by Standard Model.
  - **Search for possible partners** (neutral and/or charged) of this boson
  - Is this particle a **fundamental object, or it is composite**?.
- **However, the investigations of the electroweak symmetry breaking cannot be limited to the study of the Higgs sector only. Several points still to be addressed, among these:**
  - The dependence with energy of the **Vector Boson Scattering** cross section $d\sigma/dm_{VV}$ (WW, WZ and ZZ)
  - The hierarchy problem, motivated **new theories beyond SM**, such as Supersymmetry, Extra-Dimensions, Technicolor models. Searching for physics BSM include:
    - Direct search for new particle (SUSY partners , resonances, etc.).
    - Indirect effect: FCNC in top decays…

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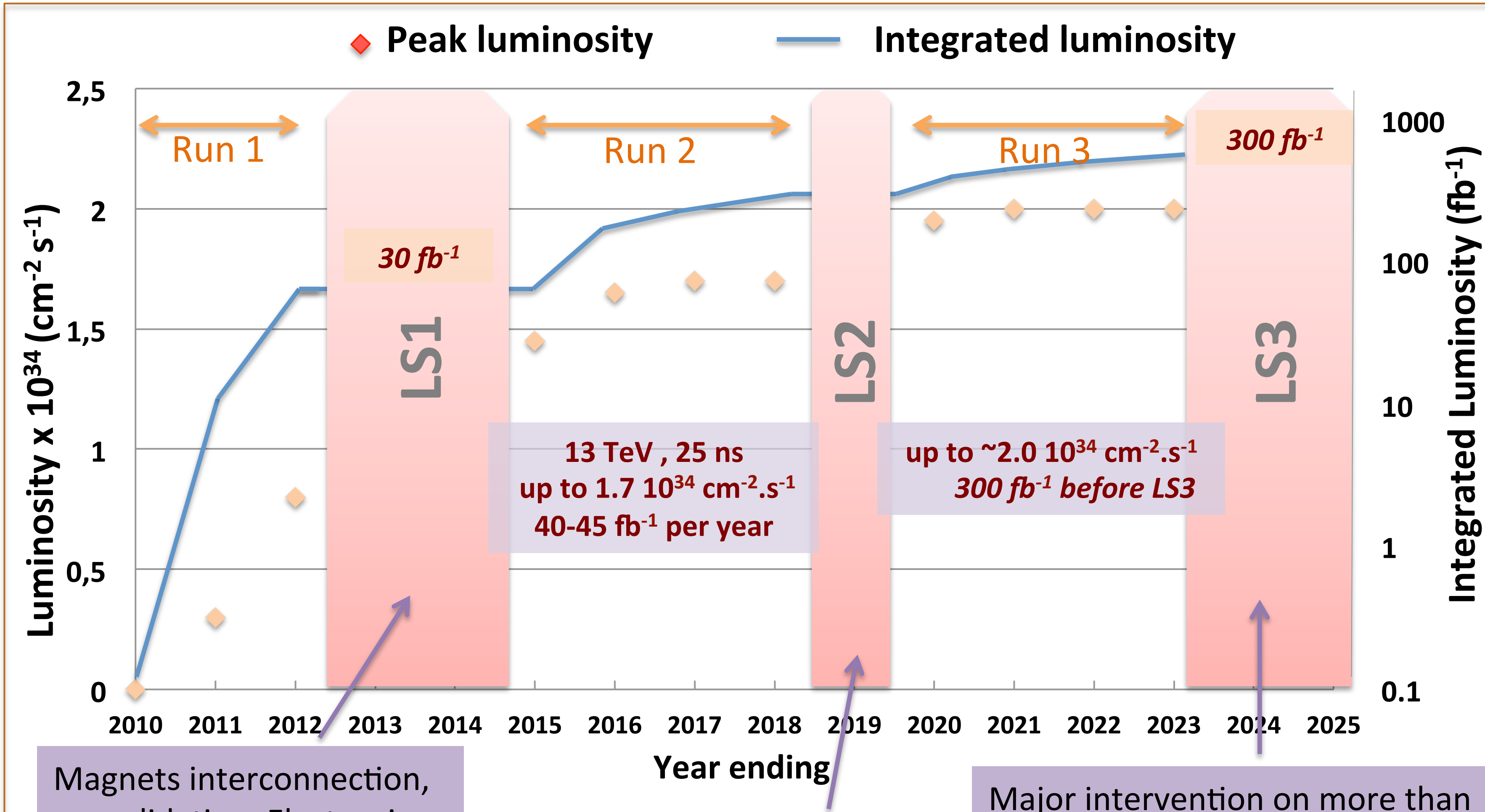
More data and/or Energy

LHC: Scheduling and Baseline Luminosity

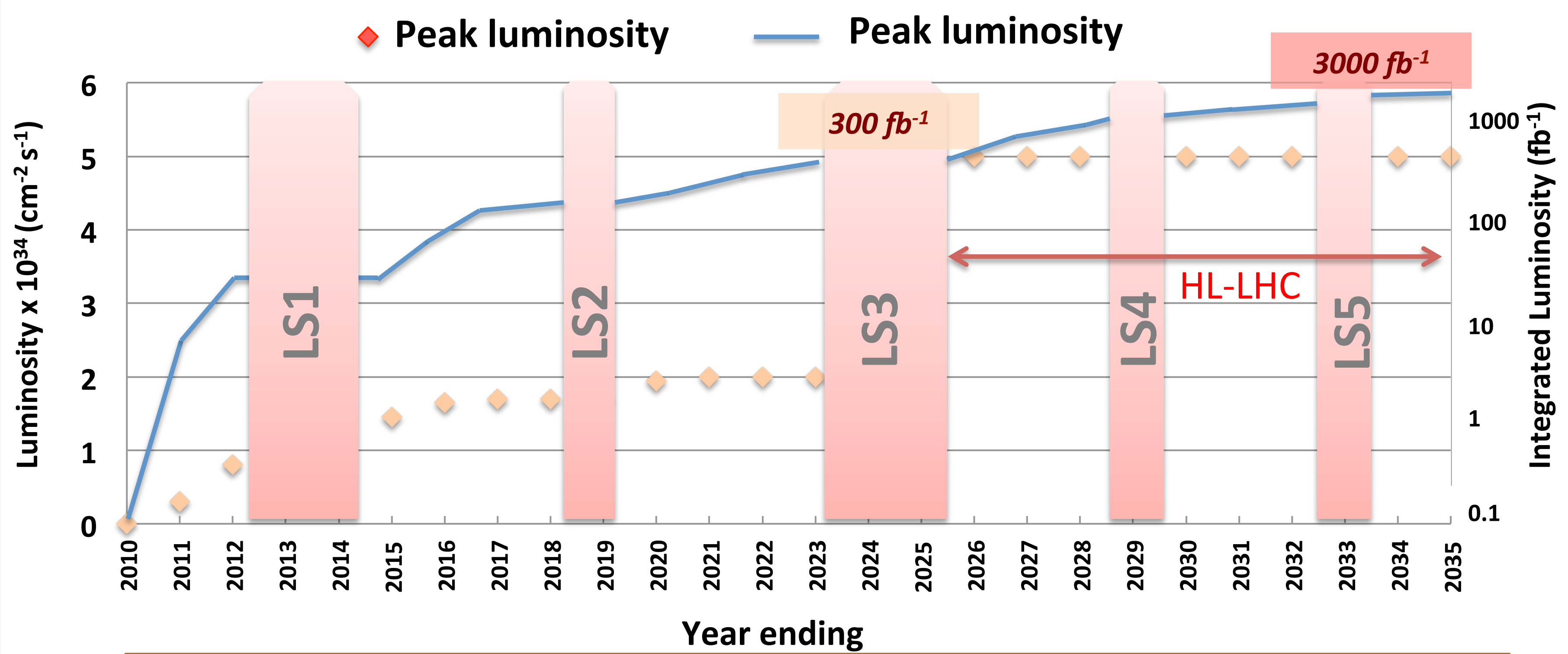


Magnets interconnection, consolidation, Electronics Radiation Mitigation Prj.

Injector upgrades (Linac4, PS Booster and SPS)

Major intervention on more than 1.2 km of the LHC (inner triplets, collimation, Cryogenic, Machine protection....) +Injector upgrades

The plan of HL-LHC (Baseline)



At 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035-2036, with LSs taken into account and 1 month for ion physics per year.

Update of the European Strategy for Particle Physics adopted 30 May 2013 in a special session of CERN Council at Brussels.

Statement c:

c) 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.*

Very Important step in the approval of the HL-LHC project, but it still needs formal approval.

The present CERN Mid Term Plan approved by CERN Council covers up to 2018 (LS2), but not beyond.

- Need to further elaborate physics capabilities.
- Need experiments and machine to demonstrate feasibility, and consolidate timeline and cost estimates.
- Convince funding agencies.

Strategic Plan for U.S. Particle Physics (P5)

HL-LHC is a Global effort

Table 1
Summary of Scenarios

	Scenarios			Science Drivers					
	Few money	A bit of money	A lot of money						
Project/Activity	Scenario A	Scenario B	Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

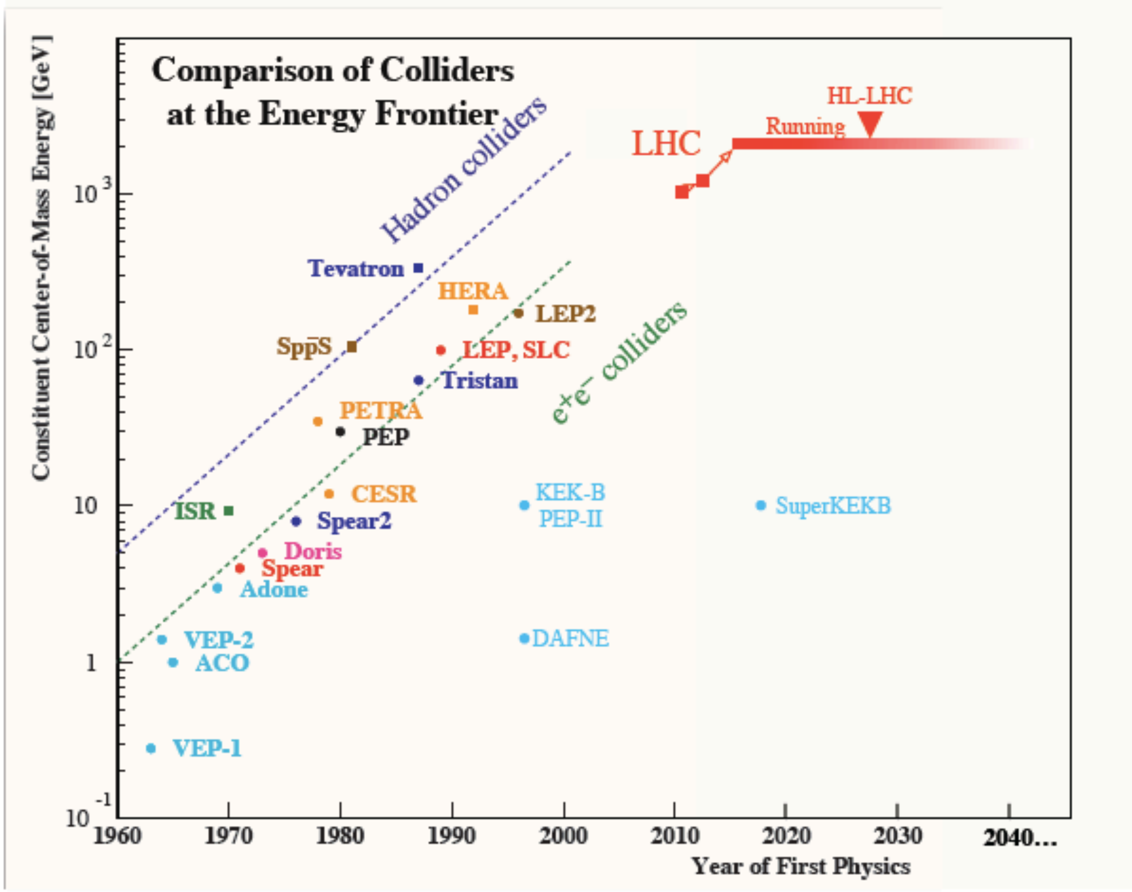
The road to define Physics Capabilities

MAIN MILESTONES

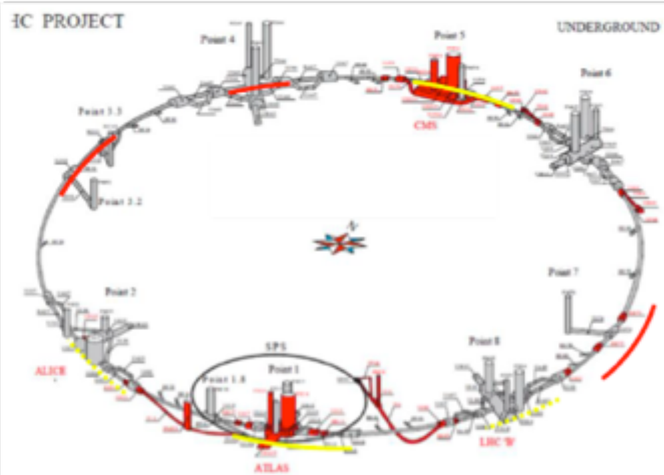
- Update of the **European Strategy** for Particle Physics (signed on 30th of May 2013)
- **Snowmass** (summer 2013)
- **ECFA HL-LHC** Upgrade workshop
  - The first large meeting of the community
  - The start of a series of regular workshops (next: October 2014)

Evolution of Colliders - the future

N. Walker



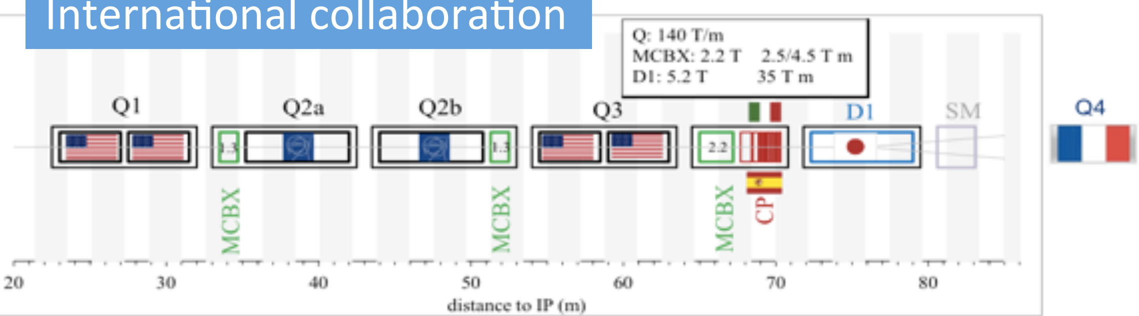
HL-LHC



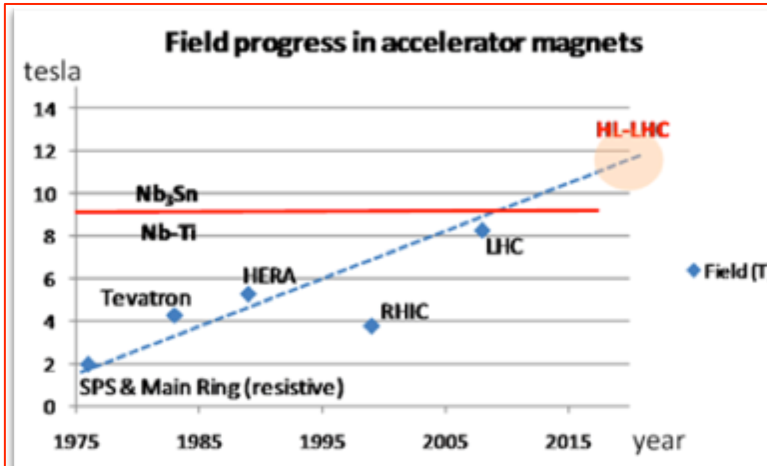
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

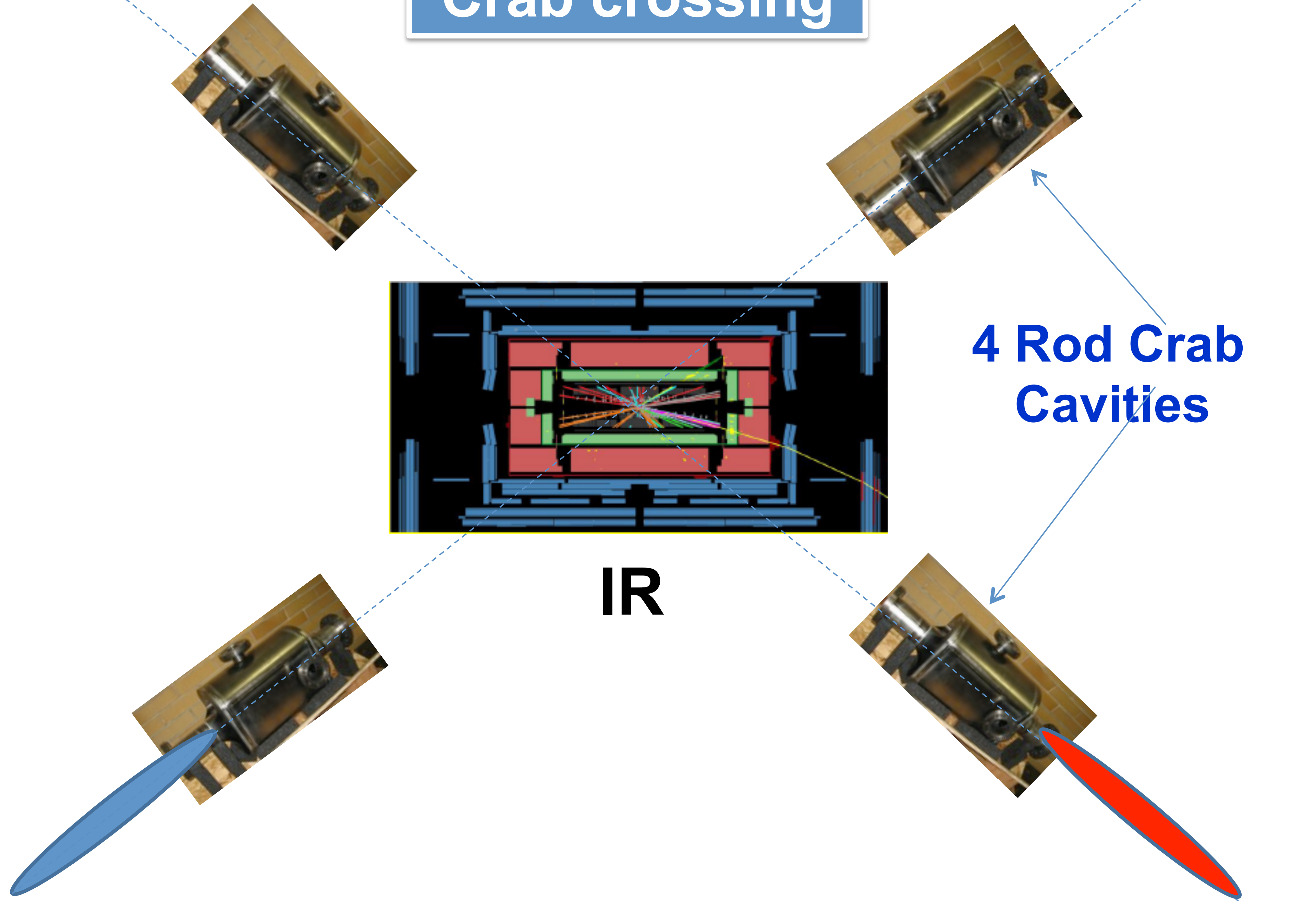
International collaboration



Baseline layout of HL-LHC IR region

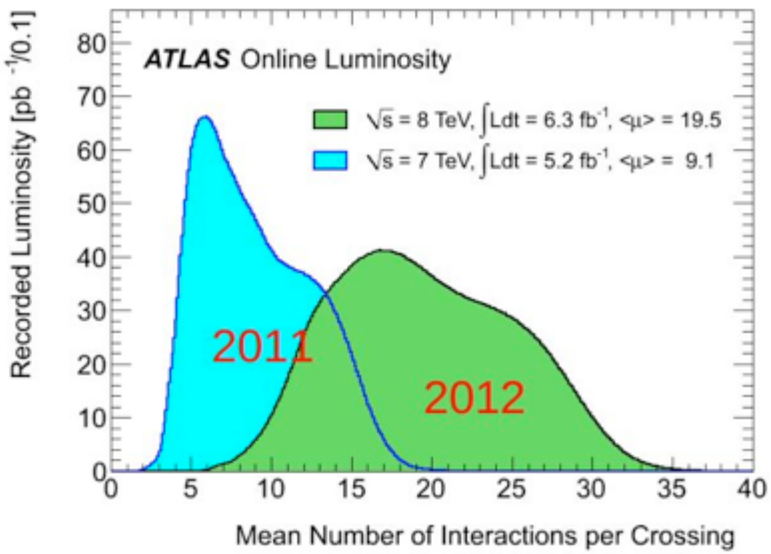


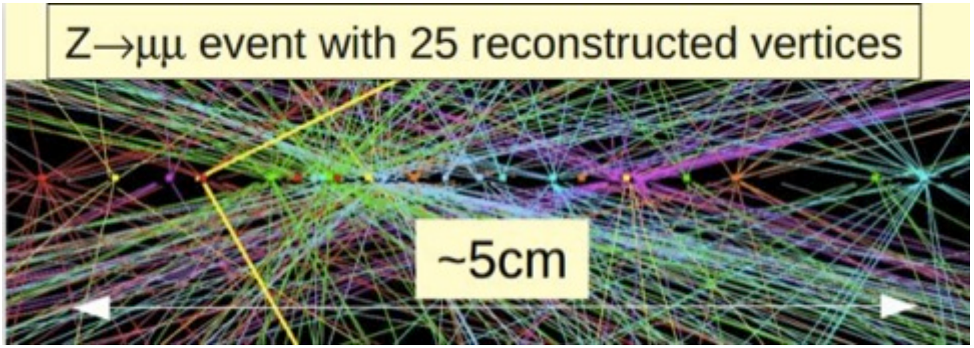
Crab crossing

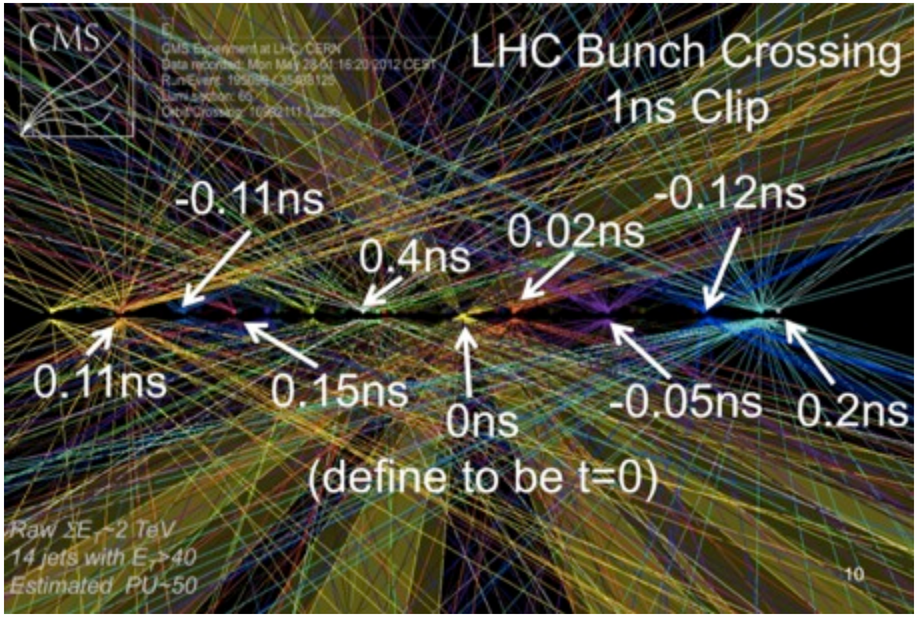


Pile-up @ Run-1

Challenge for detectors and data analysis

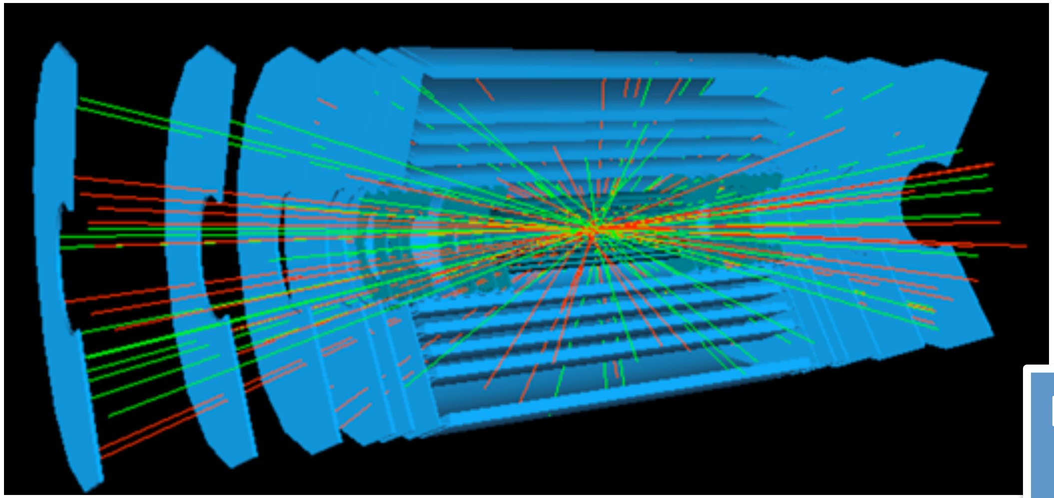






Pile-up @ HL-LHC

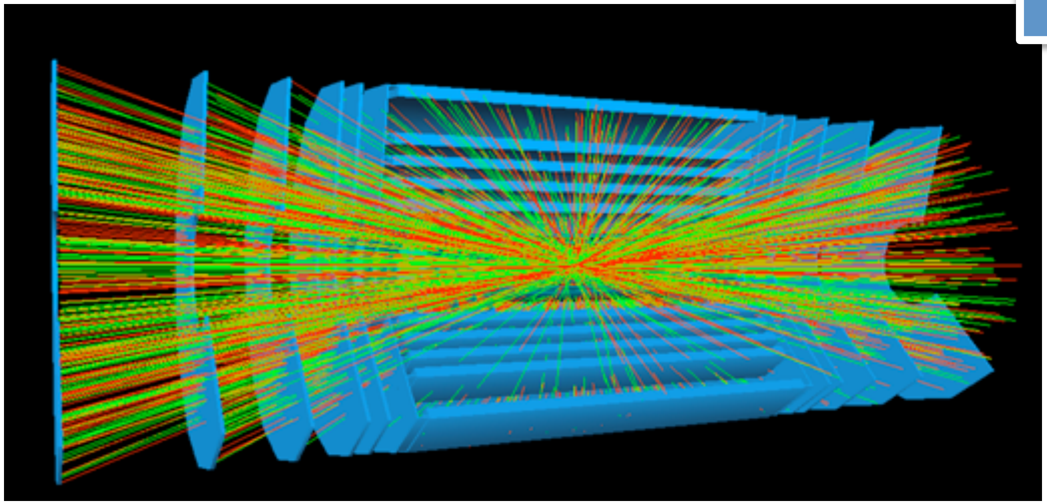
Run-1



23 pile-up event

Even more challenge for detectors and data analysis

HL-LHC



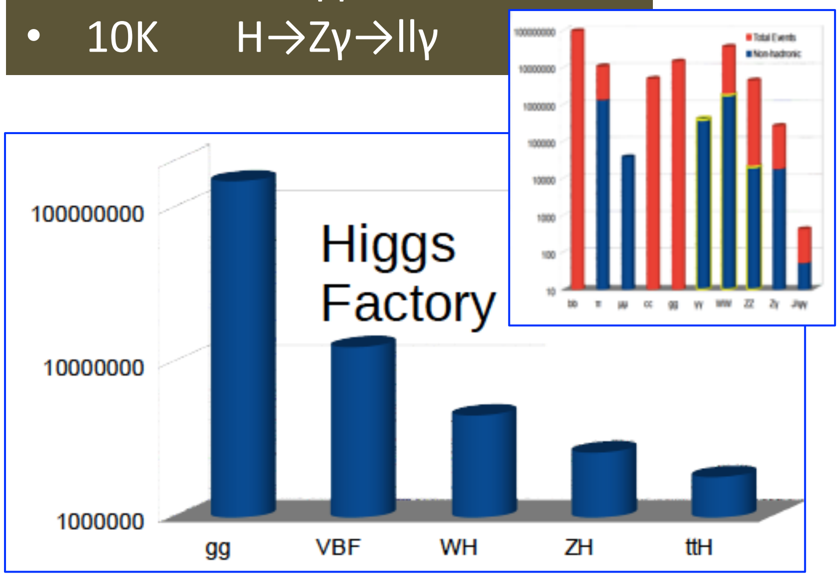
230 pile-up event

HIGGS AT HL-LHC

Precision measurements of the Higgs sector are priority in future programme of particle physics.

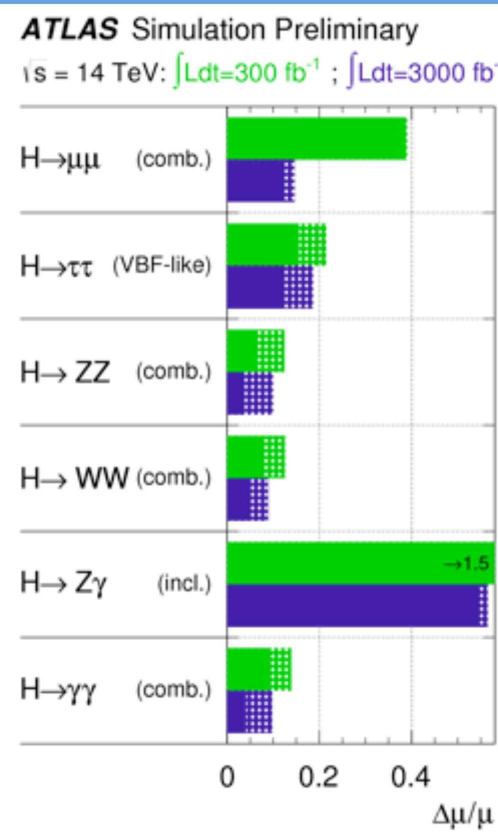
<u>Higgs production at HL-LHC</u>

- Over 100M Higgs bosons
- 20K H→ZZ→llll
- 400K H→γγ
- 10K H→Zγ→llγ



B . Murray. ECFA HL-LHC. 2013

(Δμ/μ) with μ=(σxBR)/(σxBR)$_{SM}$

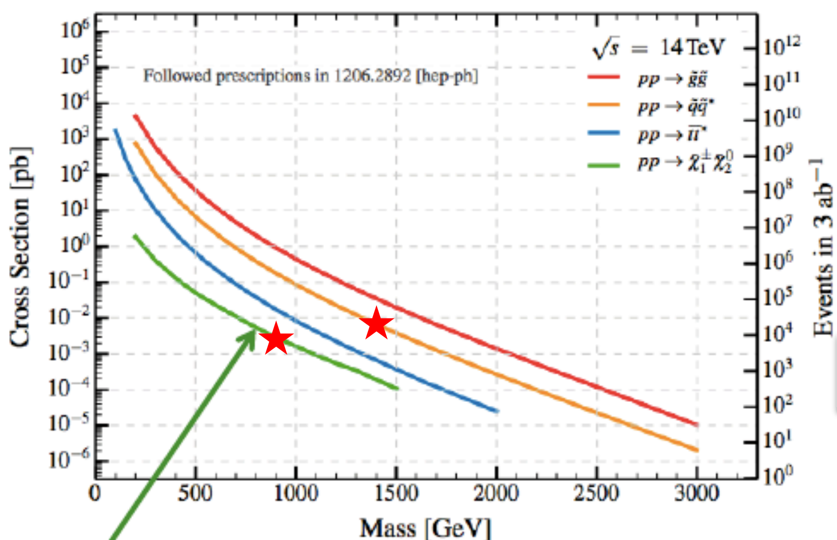


- Some channels are limited by systematic uncertainties
- Even at HL-LHC there are channels which are still highly statistic limited.

ATL-PHYS-PUB-2013-014

HL-LHC: Not the end of the Higg story

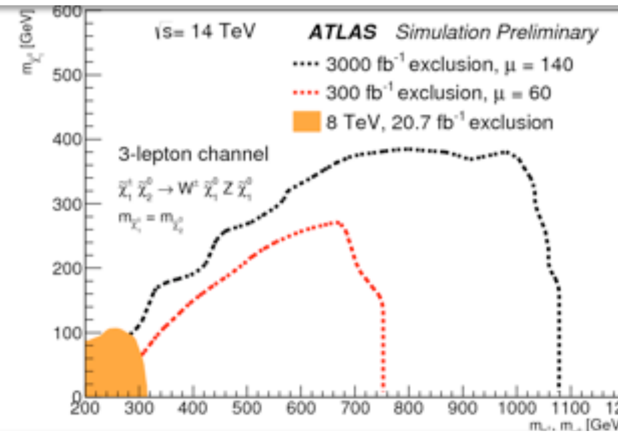
SUSY AT HL-LHC



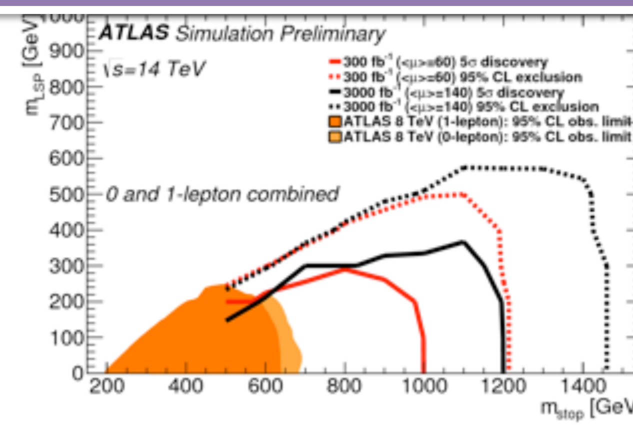
Neutralino/chargino cross sections (here assuming Wino states) are very small
→ need high luminosity!!!

ATL-PHYS-PUB-2013-011

Search for direct production of charginos



Search for direct production of top squarks

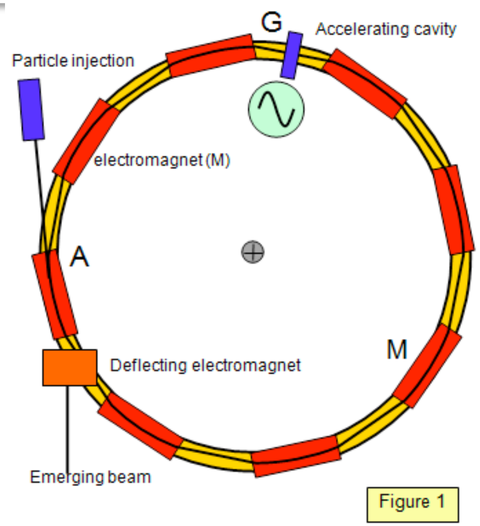


HL-LHC: Not the end of the SUSY story

What is next?

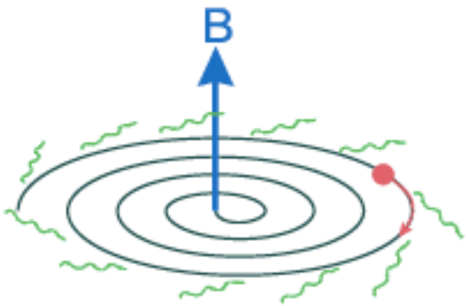

Linear
Circular
$$ Linear
$$$$$$ Circular
Hmmm, which one should we get?

Synchrotrons



IN FAVOR

- Efficient, many interaction with the same beam
- Multiple interaction points
- Accelerating systems used of each revolution of the accelerator
- Requires magnetic bending (a fact)



Loss of energy per orbit:

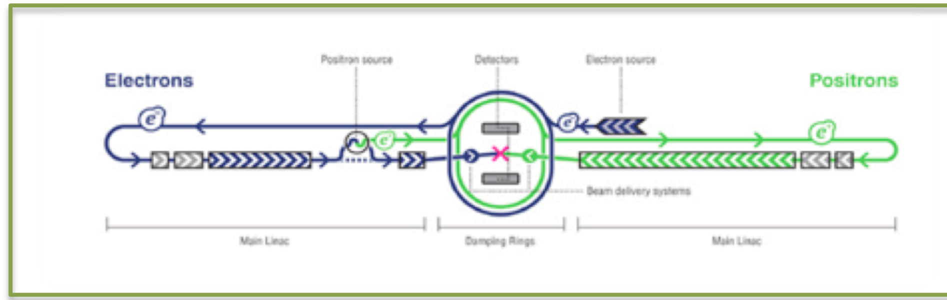
$$\Delta E = P\left(\frac{2\pi r}{v}\right) = \frac{4\pi K e^2 \gamma^4 \beta^3}{3r}$$

LIMITATIONS

- Power loss due to synchrotron radiation
- Energy must be replaced by accelerator
- Higher energies also require higher luminosities

The loss rate for the electron over 10^{13} times the loss for a proton of the same energy in the same synchrotron

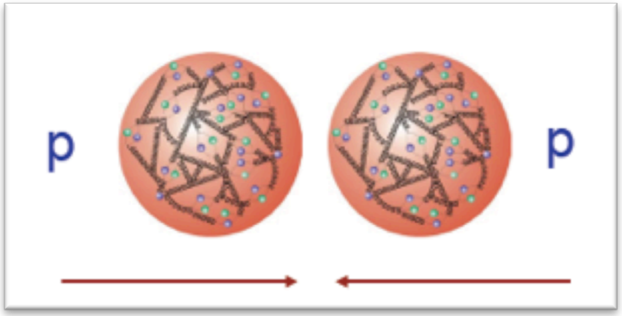
Linear vs Circular

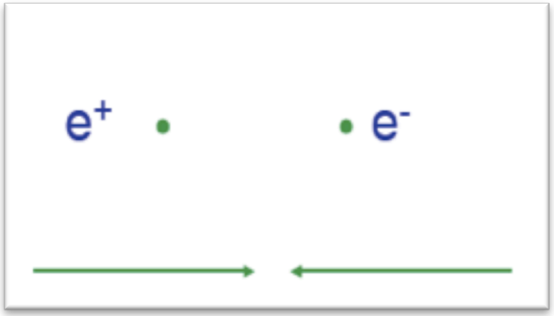


- The particles in a circular accelerator (synchrotron) go around many times, getting **multiple kicks of energy each time around**
- Synchrotrons can provide **very high-energy** particles without having to be of tremendous length.
- The particles go around many times means that there are **many chances for collisions** at those places where particle beams are made to cross.

- Much **easier to build** than circular accelerators because they don't need the large magnets.
- **Circular accelerators** also need an enormous radii in order to get particles to high enough energies, so they **are expensive to build**.
- **Less radiation loss**.
- The radiation loss is much worse for accelerating light electrons than for heavier protons. **Electrons and positrons can be brought to high energies only in linear accelerators or in circular ones with large radii**.

Hadron vs Lepton Colliders



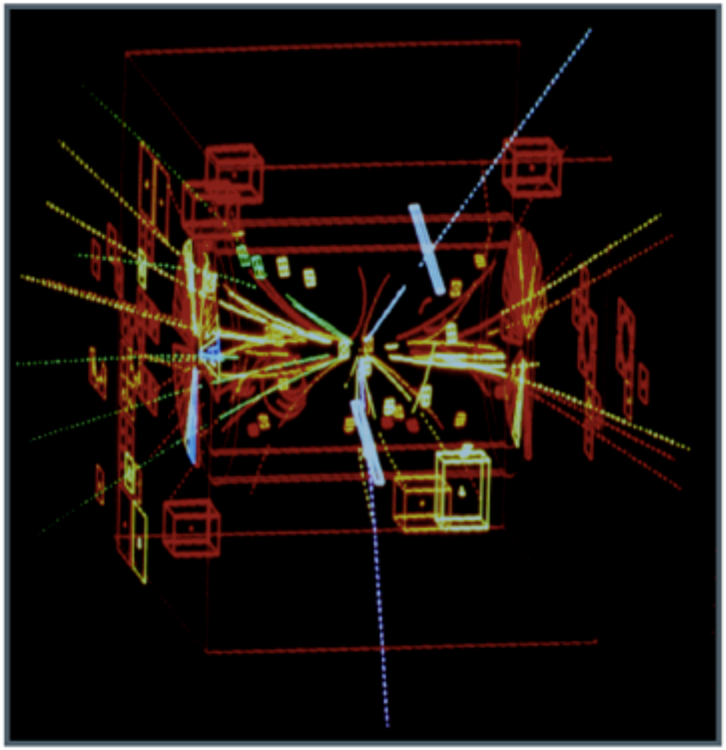


- **Proton (anti-) proton colliders:**
  - Energy range high (limited by bending magnets power)
  - Composite particles, different initial state constituents and energies in each collision
  - Difficult hadronic final states
- **Discovery machines**
- Precision measurement potential

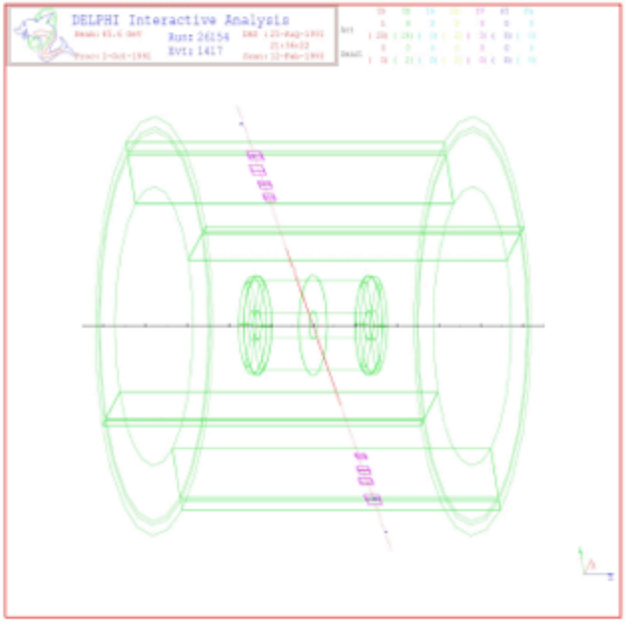
- **Electron positron colliders:**
  - Energy range limited (by RF power)
  - Pointlike particles, well defined initial state quantum numbers and energies
  - Easier final states
- **Precision machines**
- Discovery potential

Discovery and Precise Measurement

$p\bar{p} \rightarrow Z^0 + X$

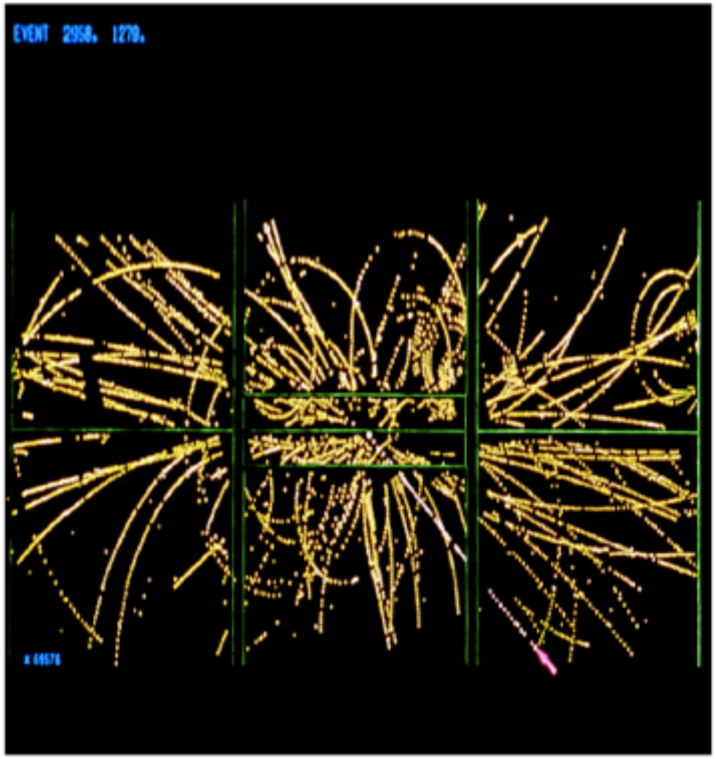


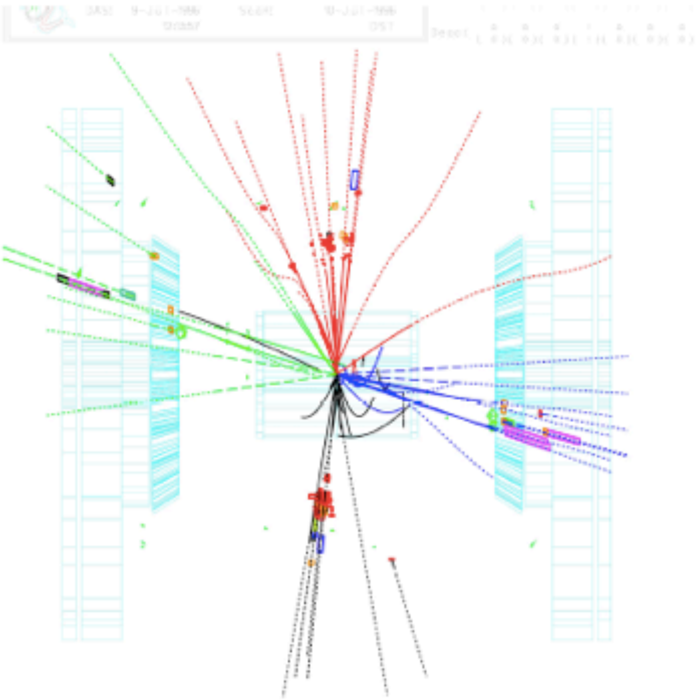
$e^+e^- \rightarrow Z^*/\gamma \rightarrow \mu^+\mu^-$



Discovery and Precise Measurement

$$p\bar{p} \rightarrow W^{\pm} + X \qquad e^+e^- \rightarrow W^+W^- \rightarrow q_1q_2 + q_3q_4$$



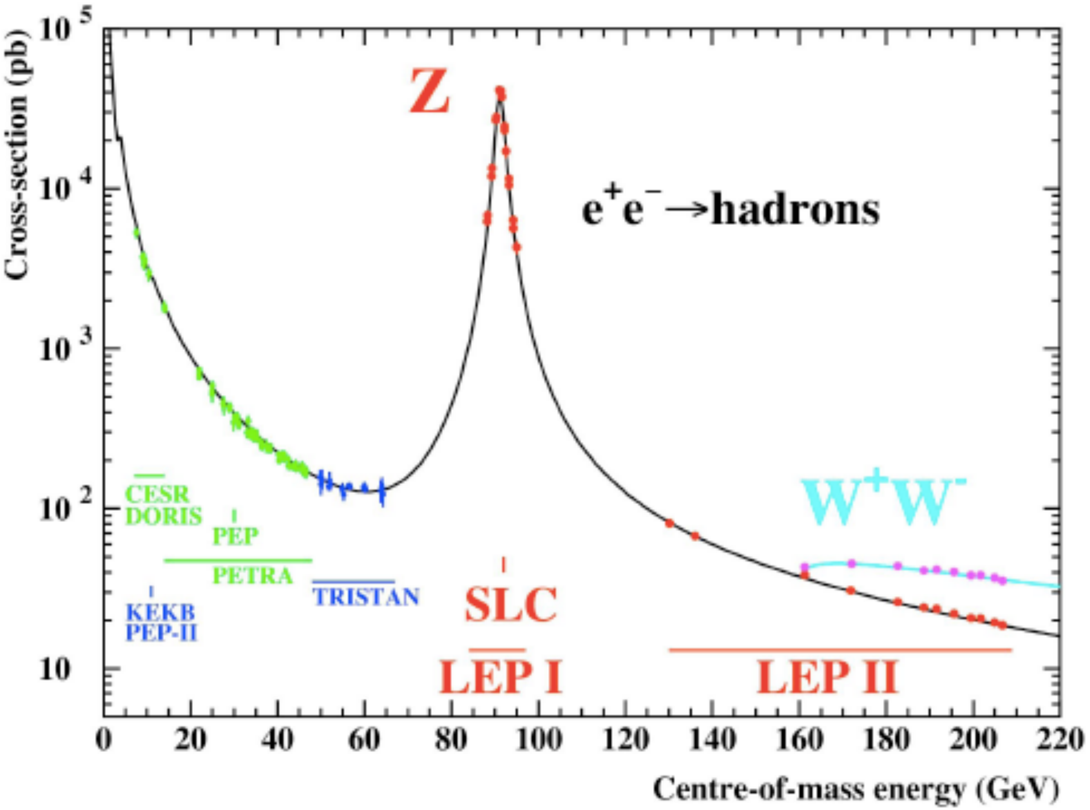


Precision Measurements

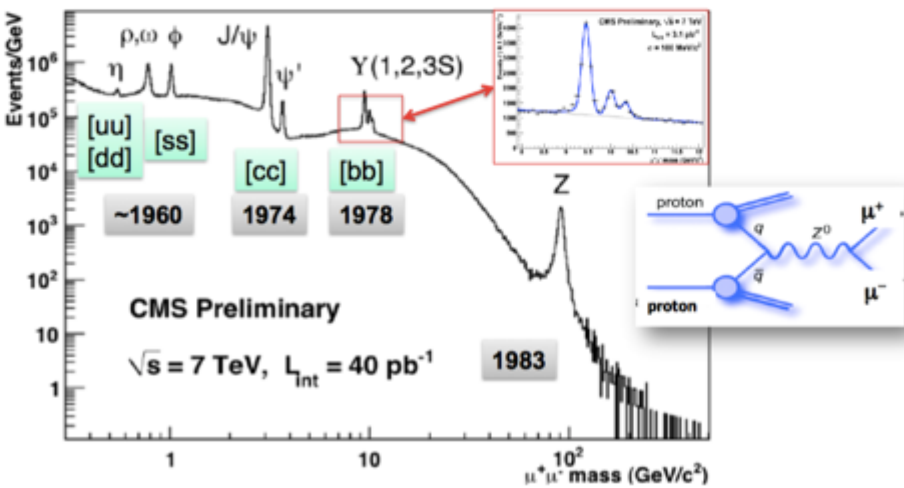
Pre-LEP
- Hardronic R-ratio
- Gluonic jets

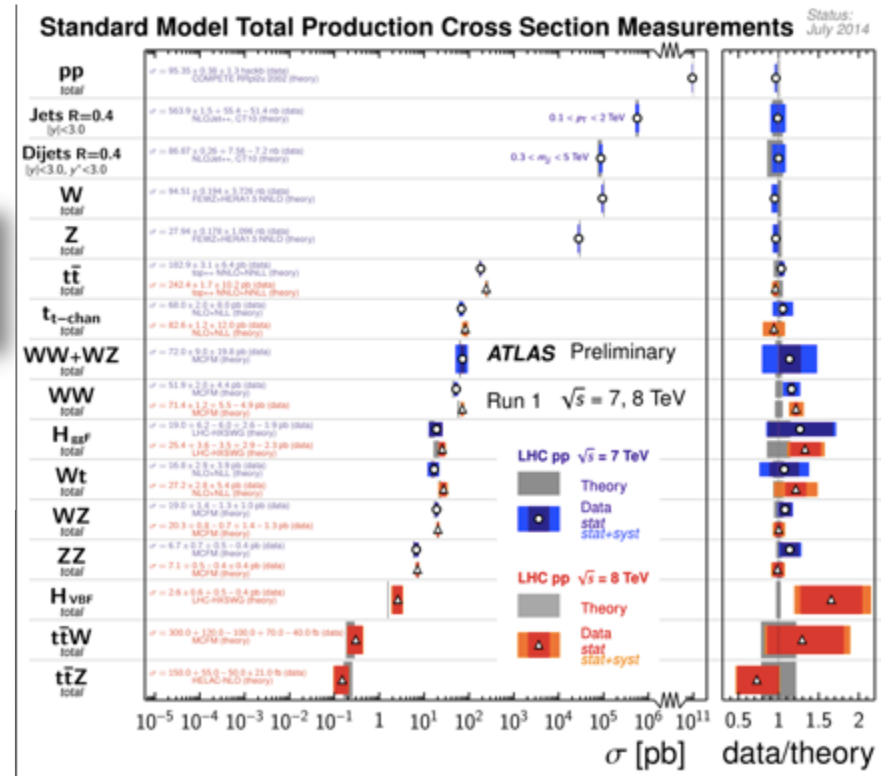
LEP I
- Z-line shape

LEP II
- W threshold



Precision Measurements @ HLHC





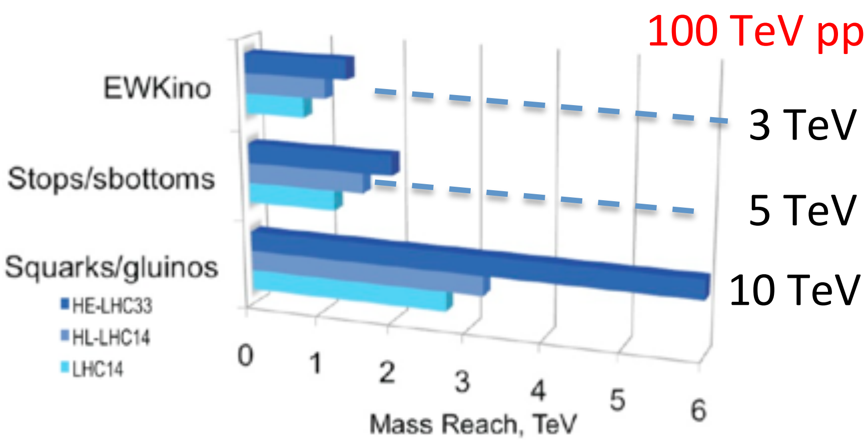
Precision is also determined by:

- High statistic
- More precise detectors
- Better analysis techniques
- More precise theoretical calculations
- ….

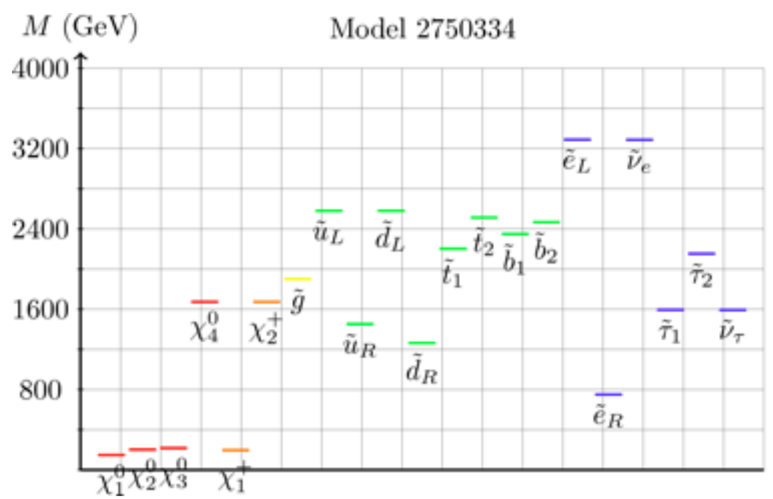
What is next?

- LHC results vital to guide the way at the energy frontier.
- None of the future projects on the market has as strong a physics case as LHC had. Because we do not know the scale of new physics.
- The LHC Run-2 will give answer in 2018 up to the TeV scale

New Physics: eg. Supersymmetry



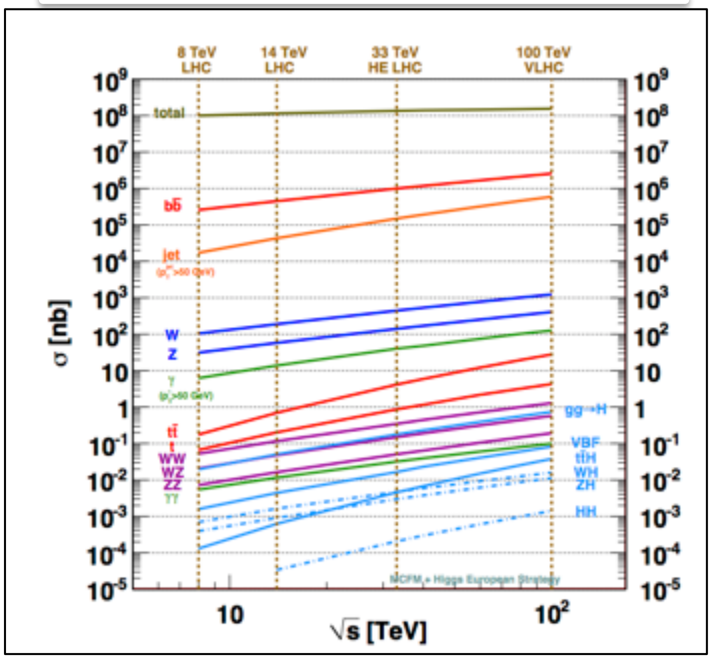
We do not see SUSY



We see SUSY: gluino, light neutralinos and charginos, some squarks, but not the rest.

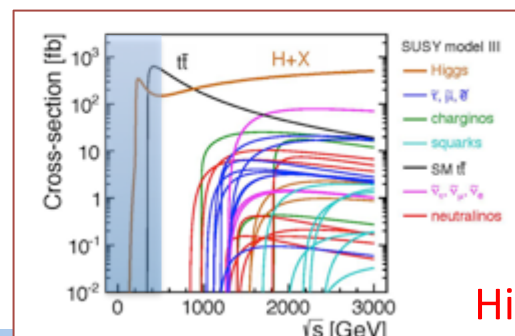
Higher energies open new oportunities both pp and e+e-

pp



Cross-sections close to mass reach:
σ (q*) ~ 10^{-2} fb M ~ 50 TeV
σ (Z' → ee) ~ 4×10^{-3} fb M ~ 30 TeV

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

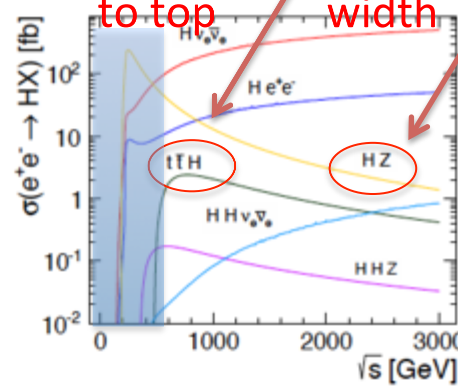


Higg and top factories

e+e-

Couplig to top

Invisible width

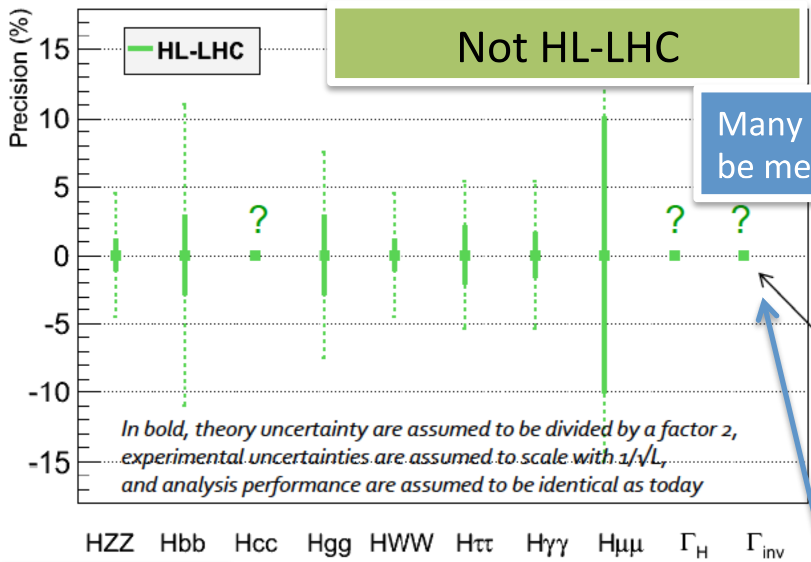


e+e- colliders have unique advantages over a hadron machine: able to measure absolute branching fractions and couplings to more states

Each supporter uses its best argument in pro of its favourite facility

Not HL-LHC

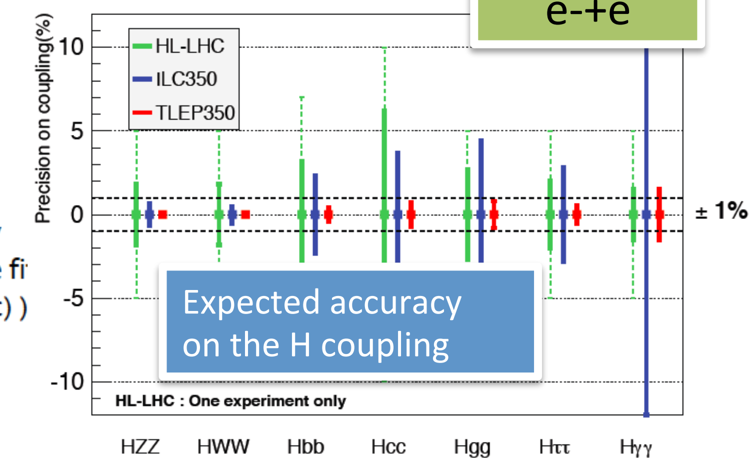
Many thinks can not be measured



1. No new decay
2. Γ_H fixed in the fi
(or fixed BR(cc))

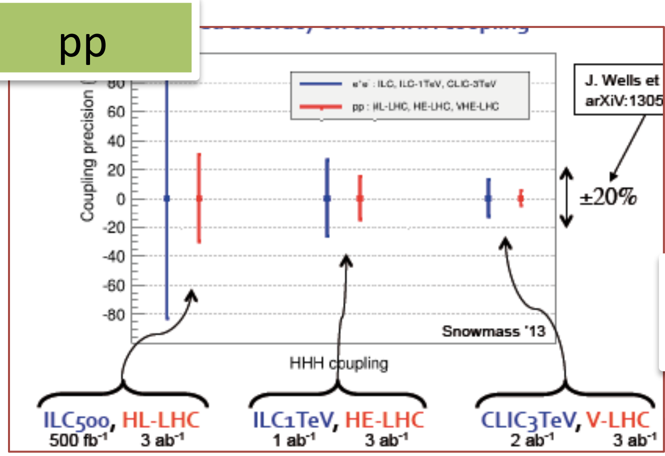
ATLAS upper limit at 65% (Moriond EW 2013)

e-+e



Expected accuracy on the H coupling

pp



HL-LHC: (16-8%)
- ZH → l^+l^- + invisible
- From couplings

Expected accuracy on the HHH coupling

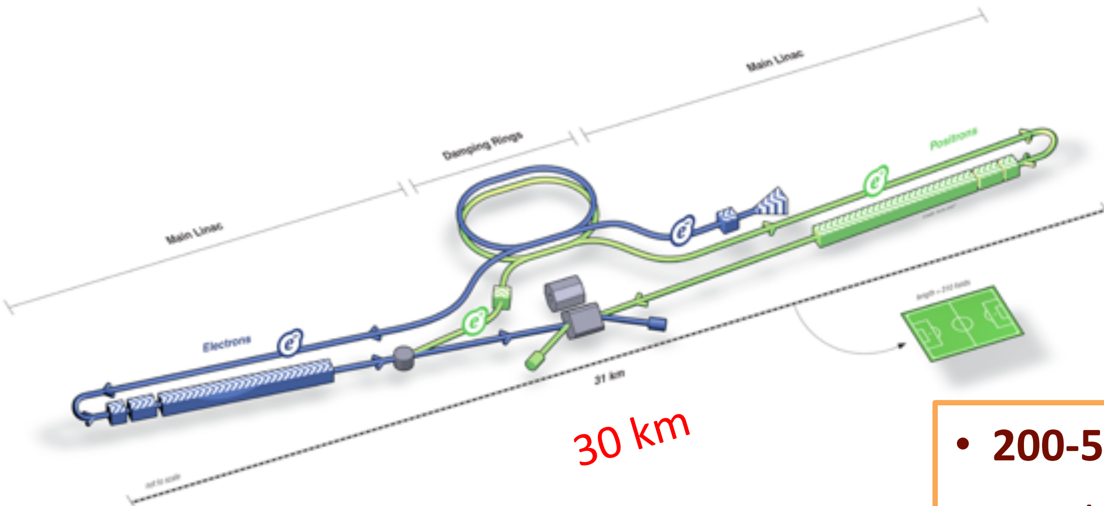
We have to elaborate the physics case for each facility

The facilities could be complementary

Planed facilities

- **Japon**
  - International Linear Collider (ILC)
- **China**
  - Circular Electron Positron Collider (CEPC)
  - Super p p Collider (SppS)
- **CERN Projects**
  - CLIC
  - HE-LHC
  - FCC-pp (FCC-ee, FCC-pe)
- **US**
  - Muon collider (not cover in this talk)

International Linear Collider (ILC)



Niobium cavities

- **200-500 GeV cm (extendable to 1 TeV)**
  - L ~ 1.8×10^{34} $cm^{-2}s^{-1}$ (@ 500GeV)
- **SCRF Technology**
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs

International Linear Collider (ILC)

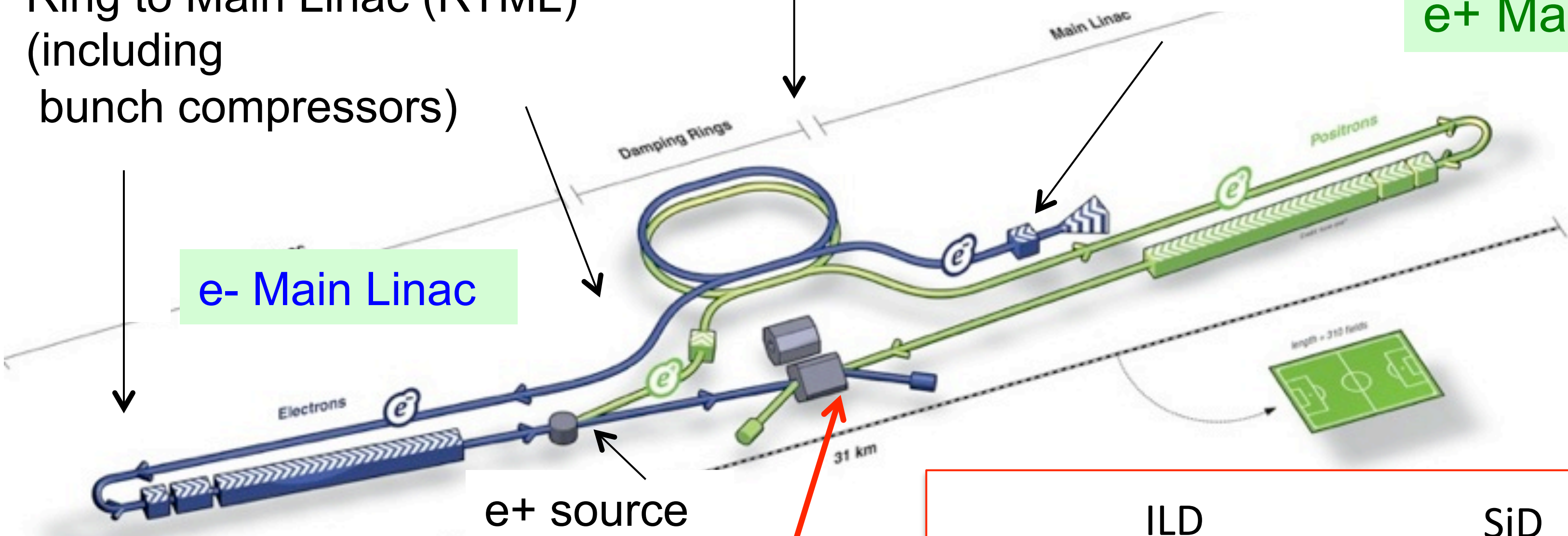
Damping Rings

Polarised electron source

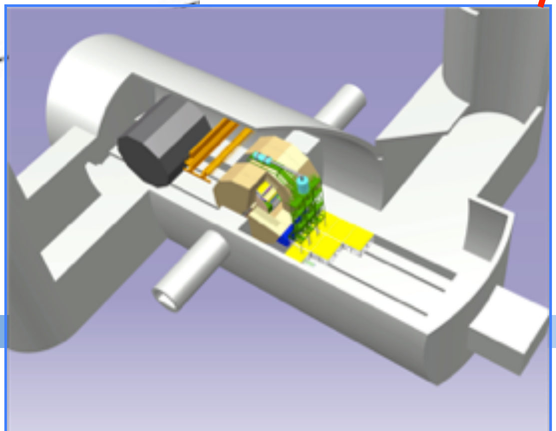
Ring to Main Linac (RTML) (including bunch compressors)

e+ Main Linac

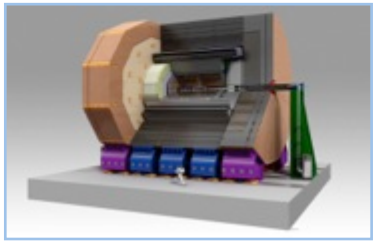
e- Main Linac



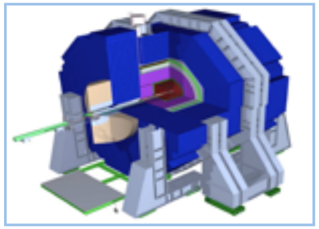
e+ source



ILD



SiD

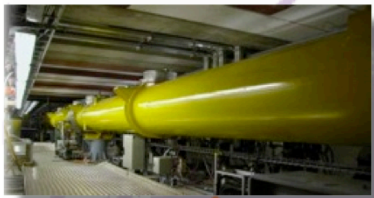


Detector push-pull

ILC is a Global Project

Developed as a truly global collaboration with ~130 institutes and **>20 years R&D worldwide**

TTF/FLASH (DESY) ~1 GeV
ILC-like beam ILC RF unit



STF (KEK) operation/construction
ILC-like Cryomodule test: S1-Gloabal
SRF beam acceleration : QB, STF2

CesrTA (Cornell)
electron cloud
low emittance

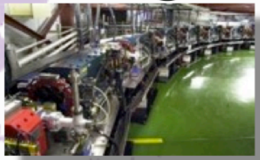
DESY

INFN Frascati

KEK, Japan

FNAL

Cornell



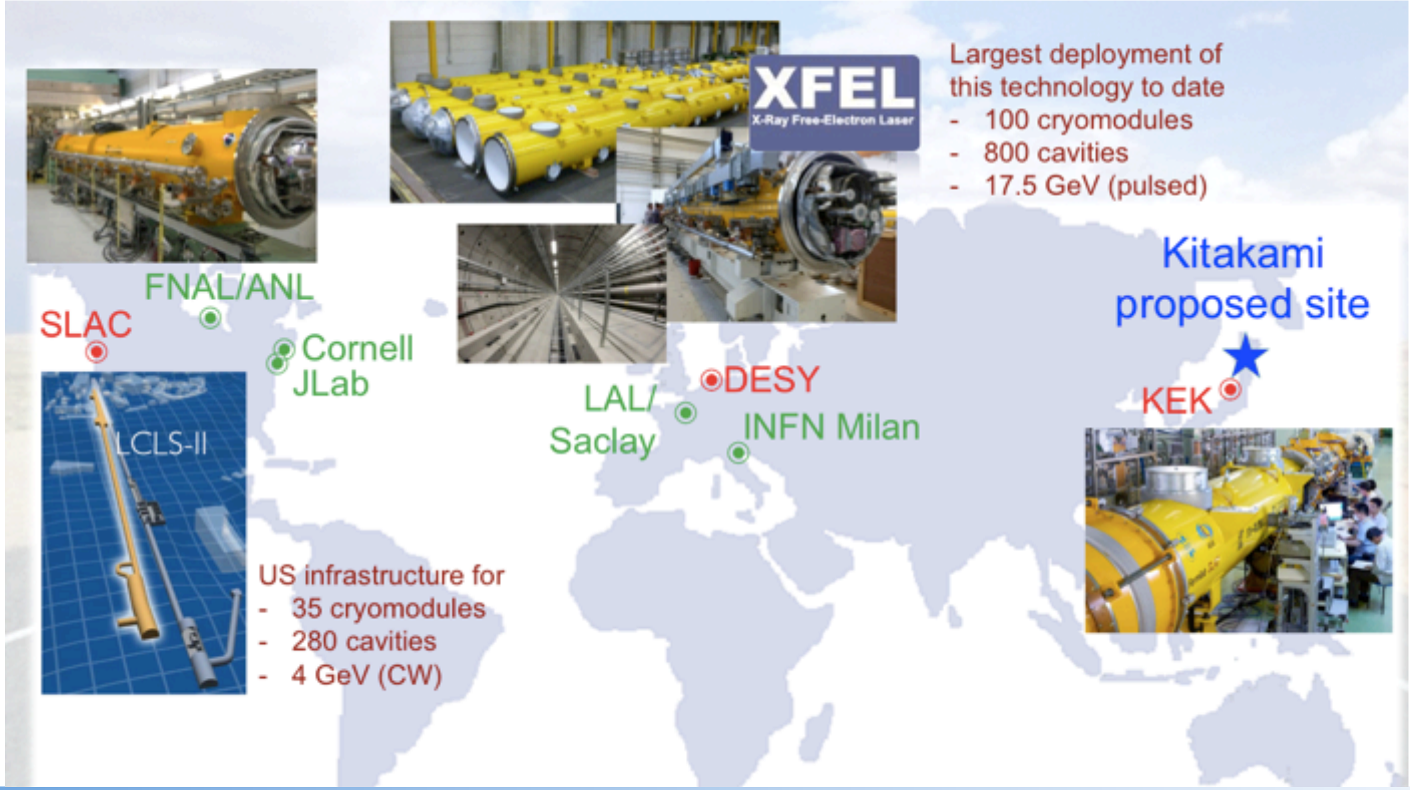
DAΦNE (INFN Frascati)
kicker development
electron cloud

ATF & ATF2 (KEK)
ultra-low emittance
Final Focus optics, nano-beam
KEKB electron-cloud

NML/ASTA facility
ILC RF unit test
Full-CM Test,
SRF beam acceleration, soon

ILC is a Global Project

US and EU (industrial) production and test capacity.
Perfectly placed for start of ILC construction endof this decade.



ILC is a Global Project

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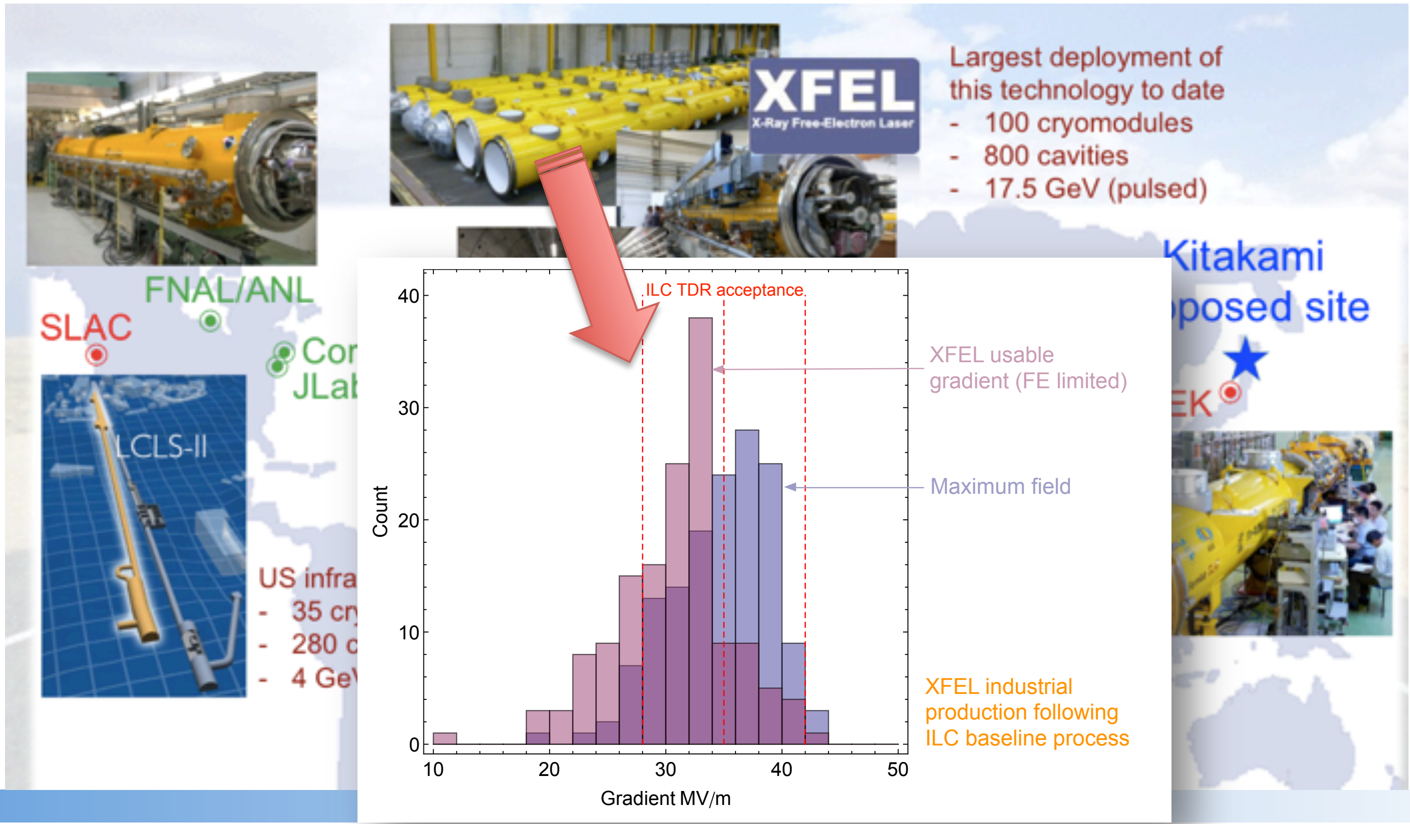
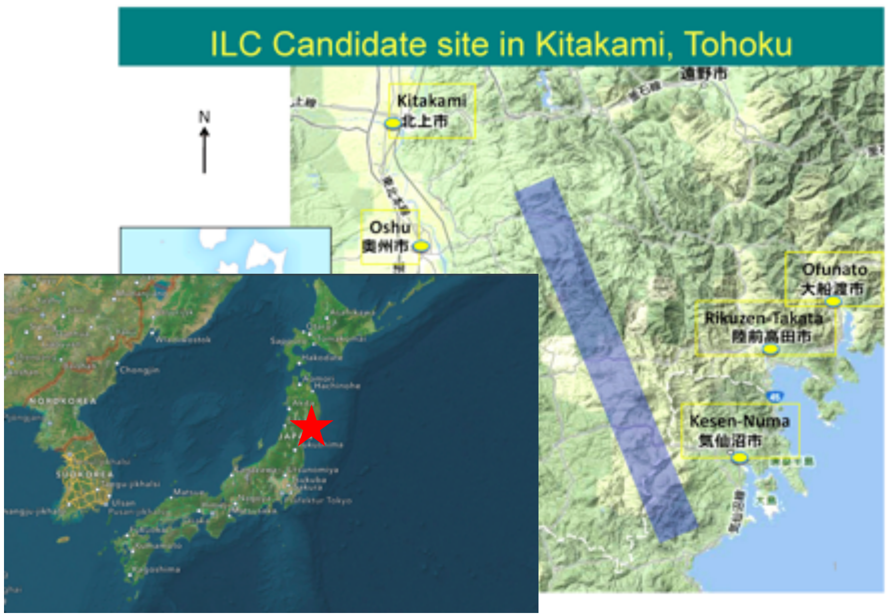
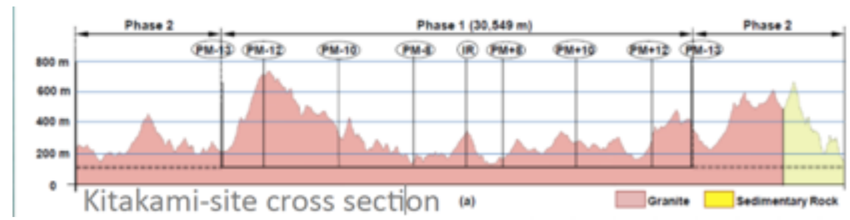


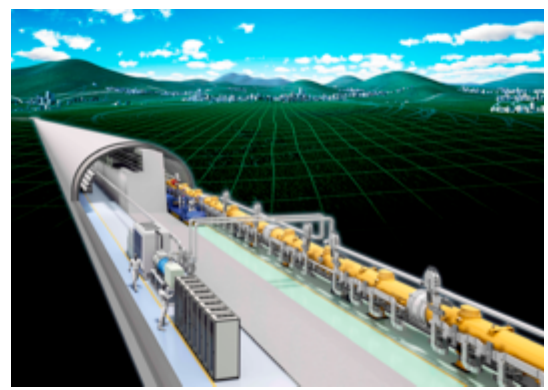
ILC in JAPAN

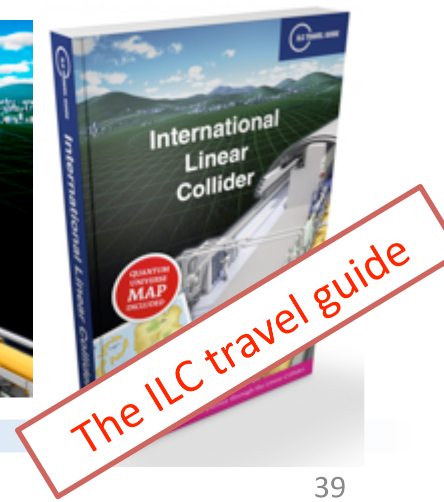
- Japanese government express interest to host ILC s an **international project**
- Initiative is welcomed in the HEP strategies of the US and Europe
- Japan has selected a potential site for the ILC in **Kitakami**

Safe from earthquake









ILC in JAPAN

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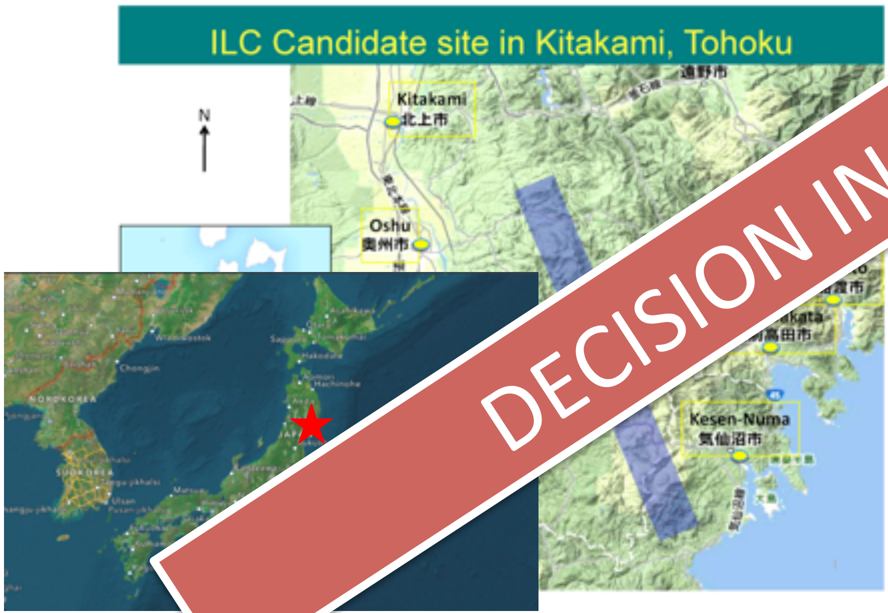
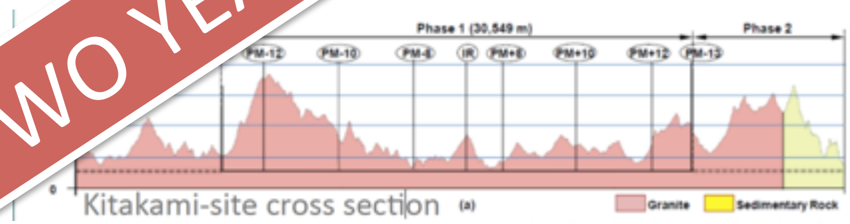
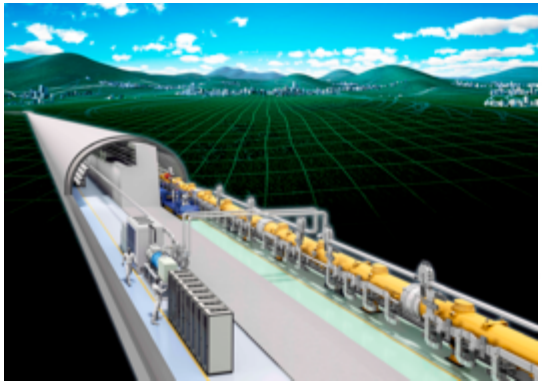
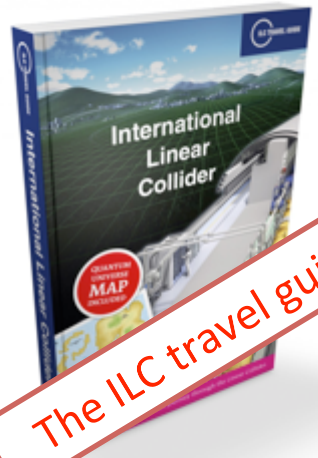
…om earthquake









DECISION IN TWO YEARS

The ILC travel guide

ILC is just a Budget question

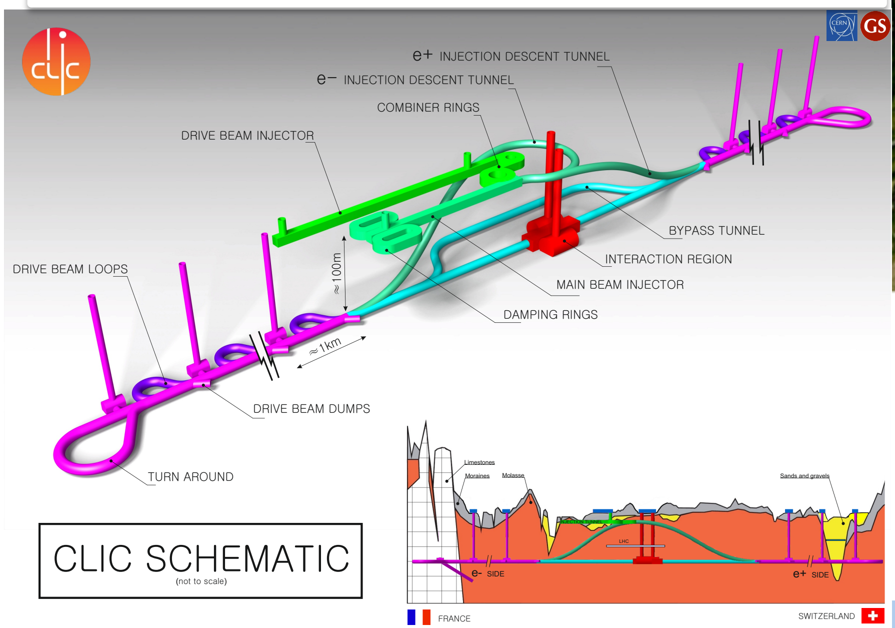
Table 1
Summary of Scenarios

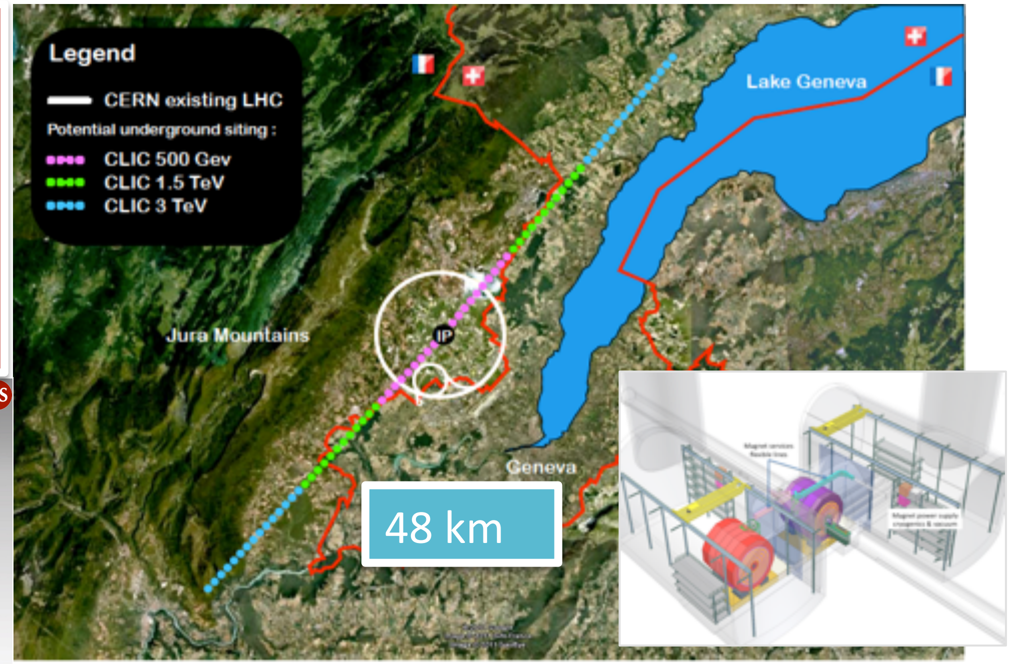
Project/Activity	Scenarios: Few money Scenario A	Scenarios: A bit of money Scenario B	Scenarios: A lot of money Senario C	Science Drivers: Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I

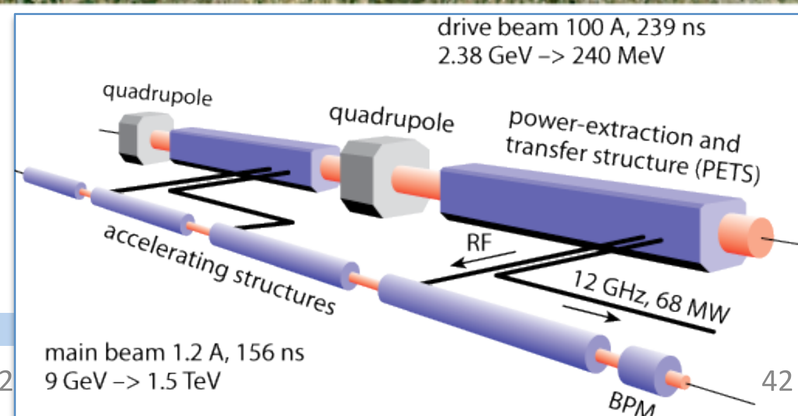
The CLIC project

- Double beam acceleration, up to ~3 TeV, ~$10^{34} cm^{-2} s^{-1}$
- With diferente phases.
- Very large gradientes :

  80 MV/m - 100MV/m
- With an affordable cost !!!

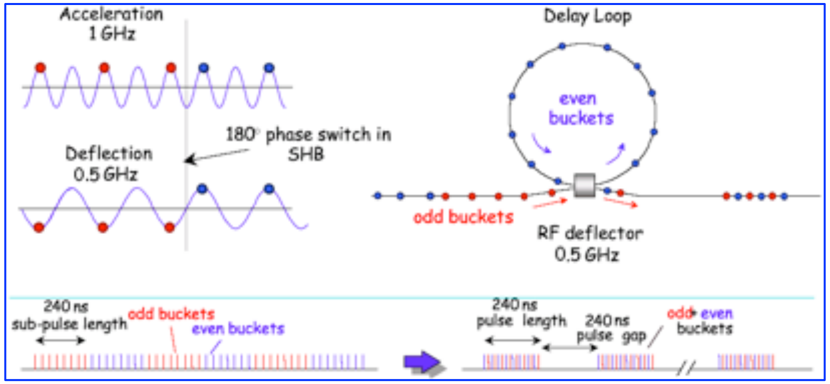


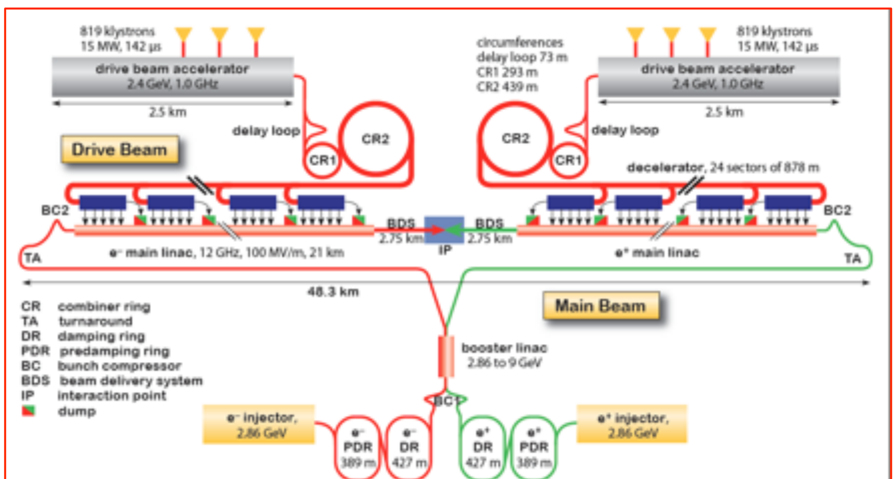




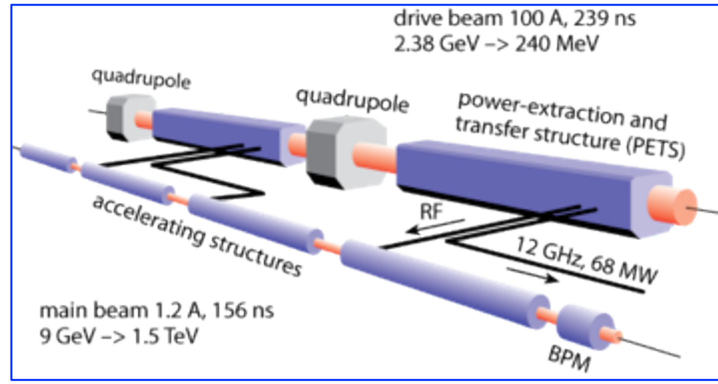
The CLIC project

CLIC frequency multiplication mechanism

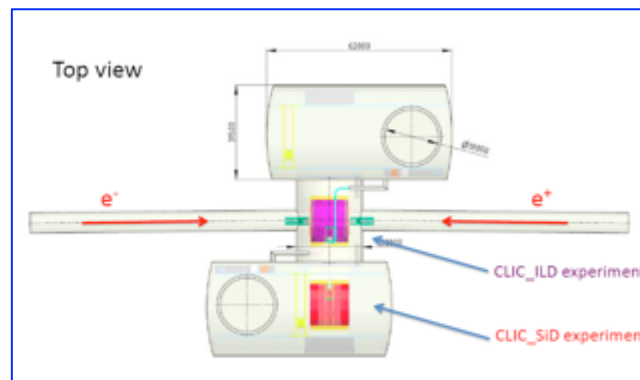




Power Extraction and Transfer Structures



CLICC detectors, push-pull system



Still many R&D required to be ready for construction

2013-18 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase

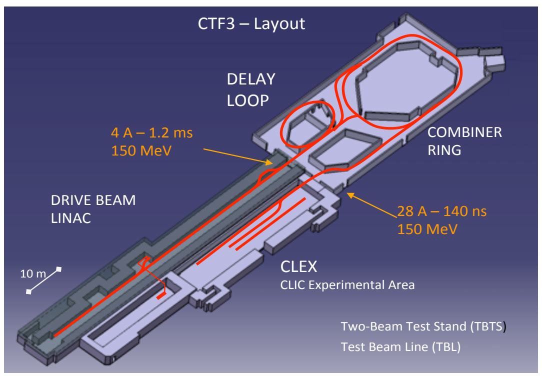
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

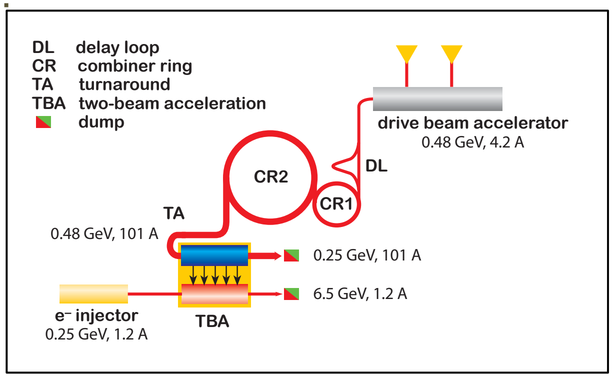
Prepare detailed Technical Proposals for the detector-systems.

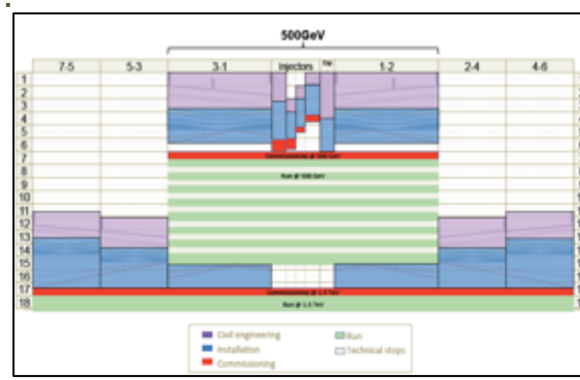
Construction Phase

Stage 1 construction of CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2018-19 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

2024-25 Construction Start

Ready for full construction and main tunnel excavation.

Commissioning

Becoming ready for data-taking as the LHC programme reaches completion.

CLIC Collaboration

29 Countries – over 70 Institutes

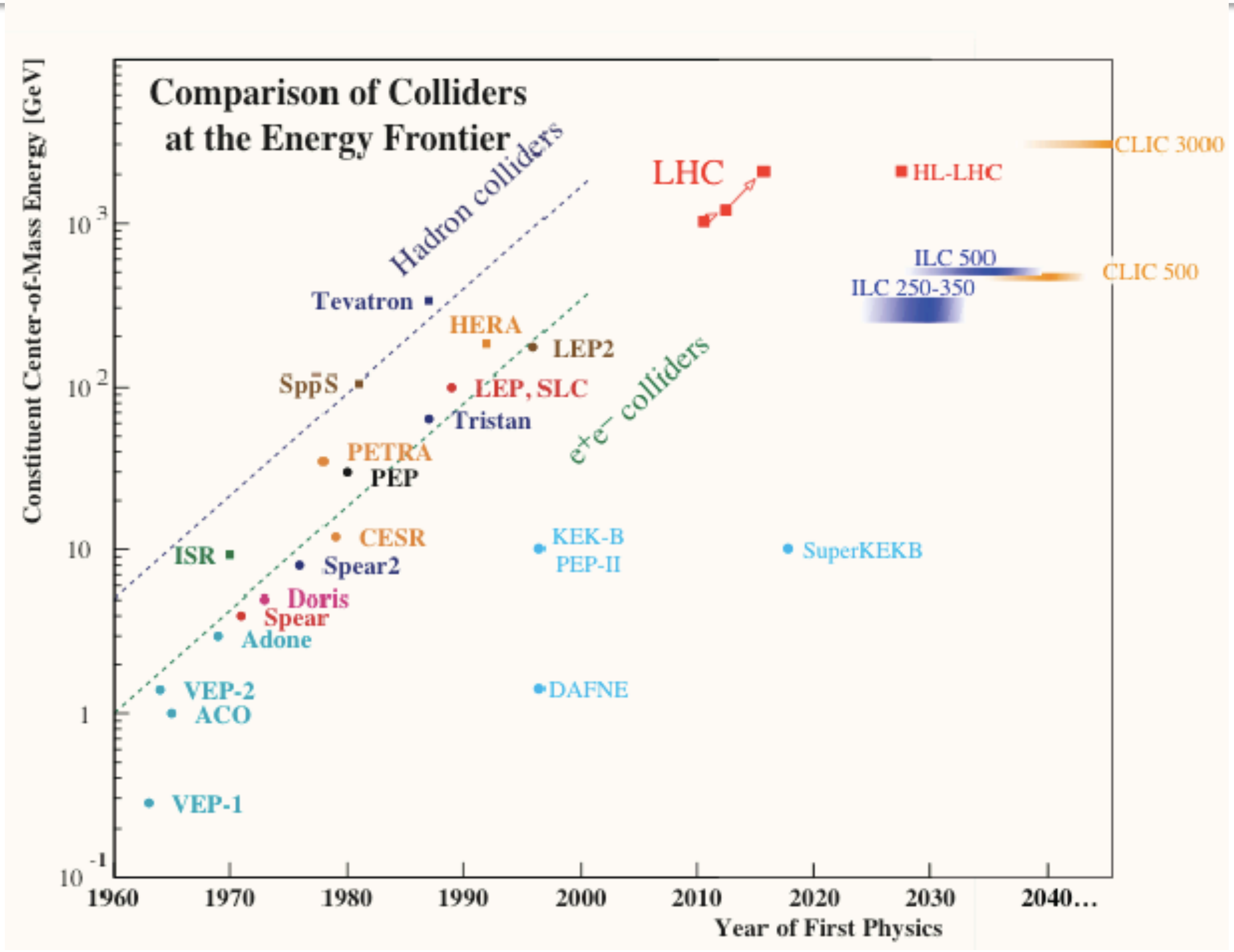
Accelerator collaboration

Detector collaboration

Accelerator + Detector collaboration

Detector collaboration operative with 23 institutes

Evolution of Colliders - the future?



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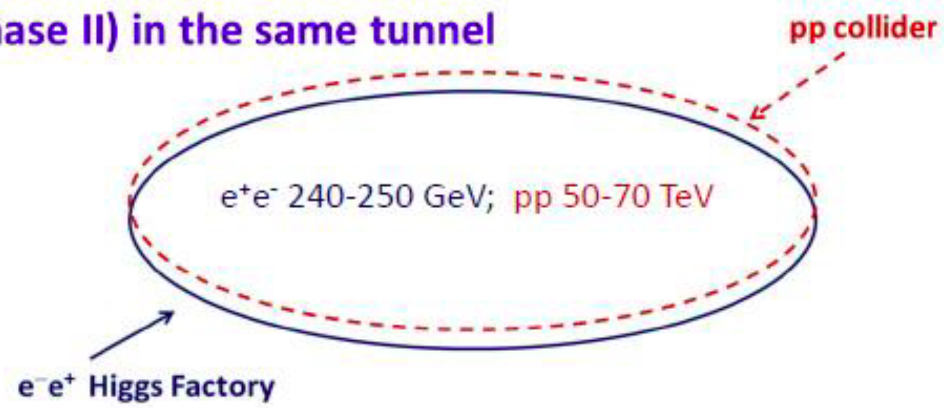
What's happening in China ?

- Starting in the last 2 years but things are happening fast since then
- Established "**Center for Future High Energy Physics**" (CFHEP)

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



Under consideration now:
- Circular Electron Positron Collider (CEPC).
- Super Proton Proton Collider (SPPC)

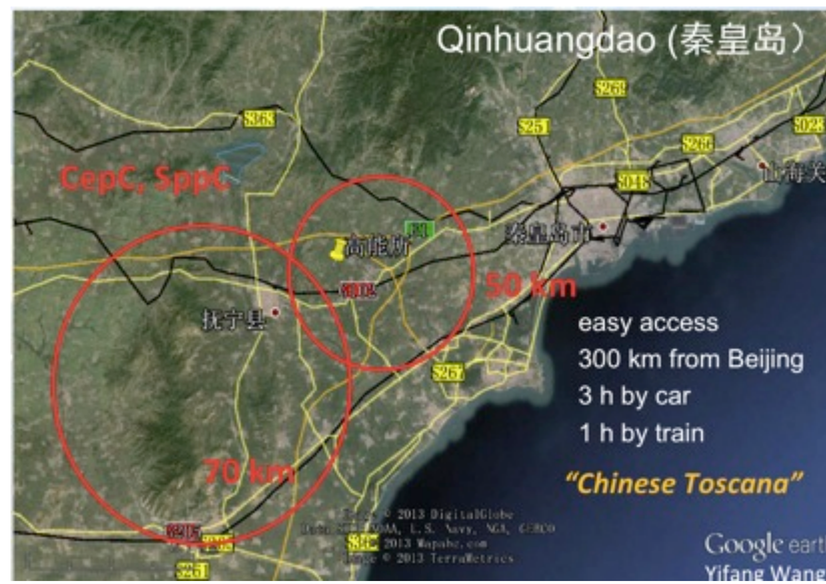
CpeC and SppC road map

CpeC

- Pre-study, R&D and preparation work
  - Pre-study: 2013-15
  - R&D and funding request 2014
  - R&D: 2016-2020
- Engineering Design: 2015-2020
- Construction: 2021-2027
- Data taking: 2028-2035 ← HL-LHC

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 -



Recent CERN Initiative: FCC

Study effort initiated by CERN, based on 80-100 km tunnel, with a primary goal for 100 TeV pp collider (FCC-hh). The tunnel could accommodate 350 GeV e+e- (FCC-ee), and ep colliders (FCC-ep).

intermediate step

Studies of viability for the next European Strategy in 2018

FCC-hh: a proton-proton Collider

FCC-hh

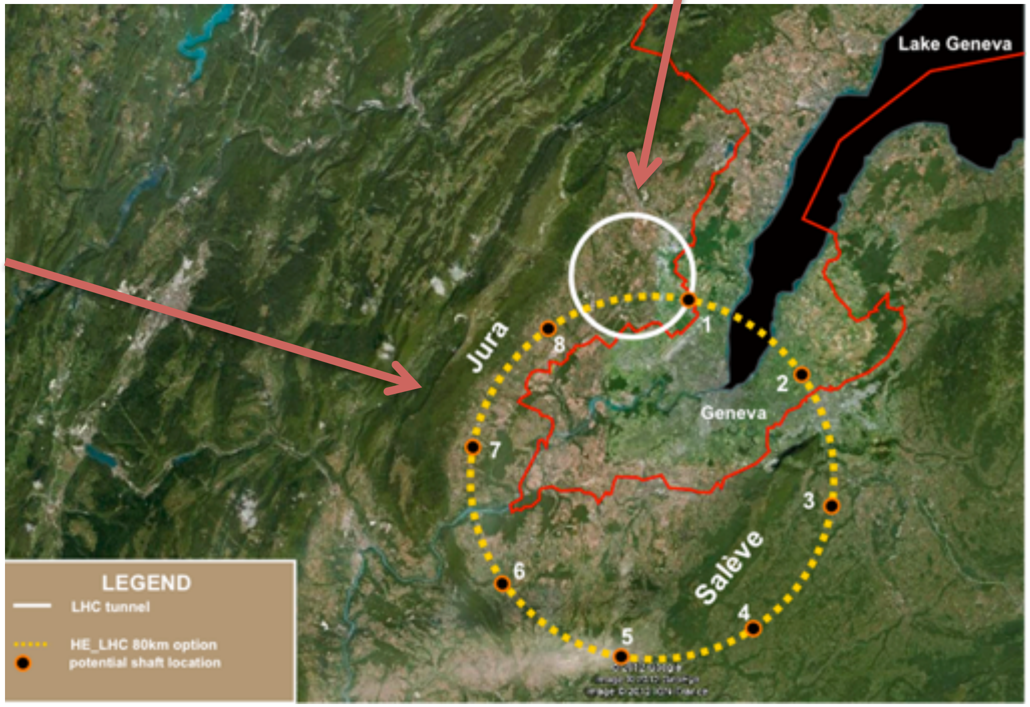
In a 80 km tunnel

- **42 TeV** with 8.3T LHC magnets
- **80 TeV** with 16T Nb_3Sn magnets
- **100 TeV** with 20T HTS magnets

In a 100 km tunnel

- **100 TeV** with 16T Nb_3Sn magnets

HE-LHC: 33TeV with 20T magnets



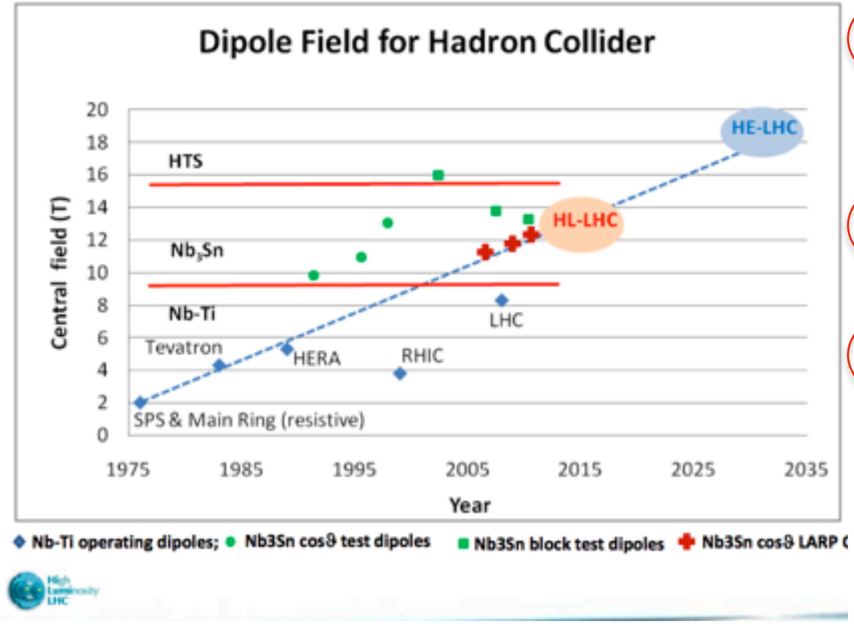
Programme of the design study

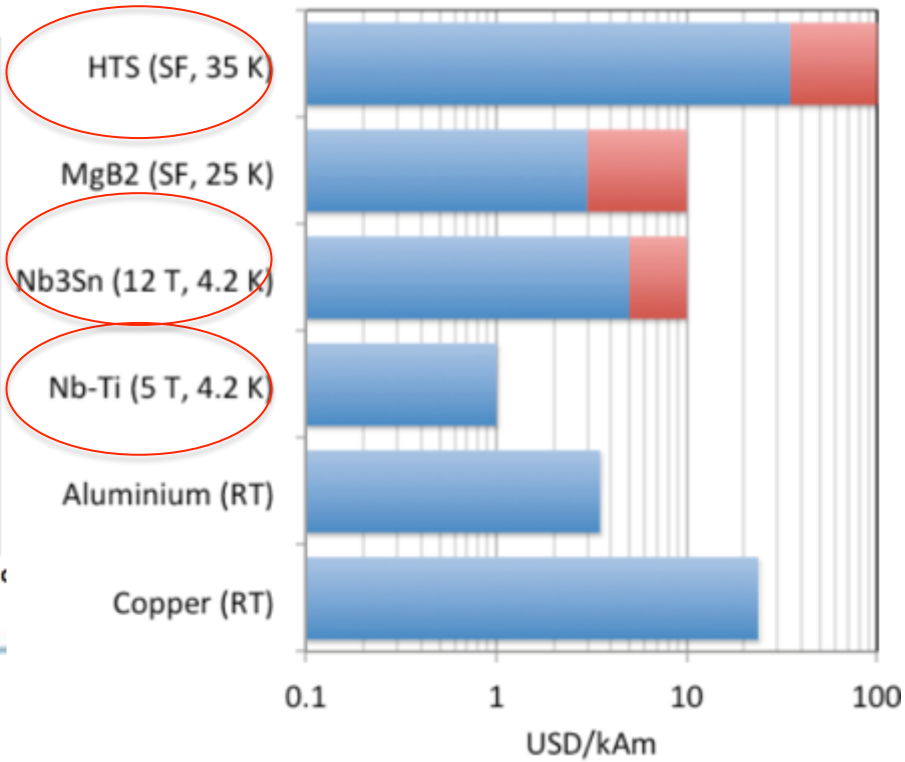
- Demonstrate 16T performance
- Develop 20T concepts

The Magnet Challenge

Is it really possibile to go so high?

R&D needed to bring the cost down





FCC-ee: the Electron-Positron Option

- 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

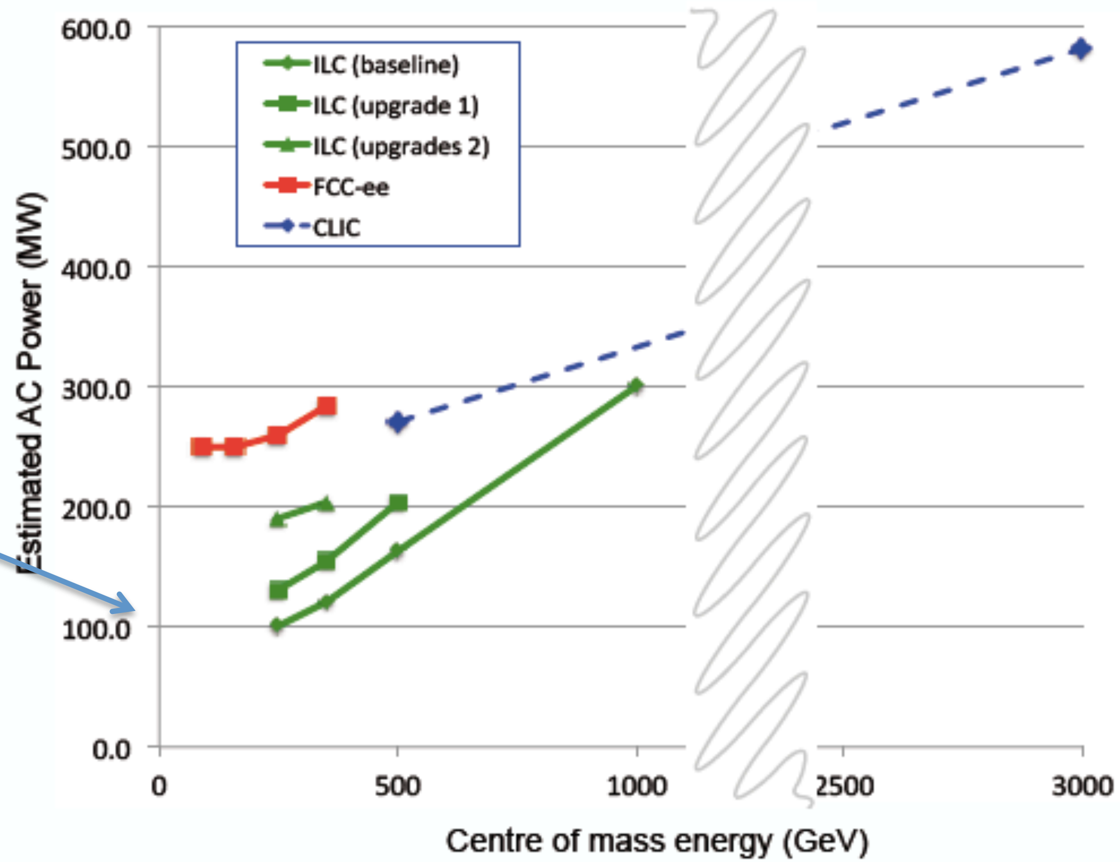
The idea has been around for a long time

- 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.

The Power Challenge

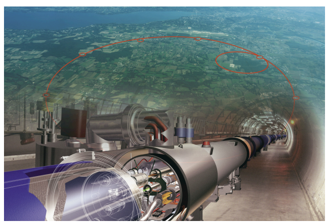
For lepton machines:
high luminosity means
high power consumption

- for comparison LHC machine <100 MW
- high power means high running costs...



What is next at CERN ?

- Studies for next ES (2018)
- LHC results to point the way
- Global context

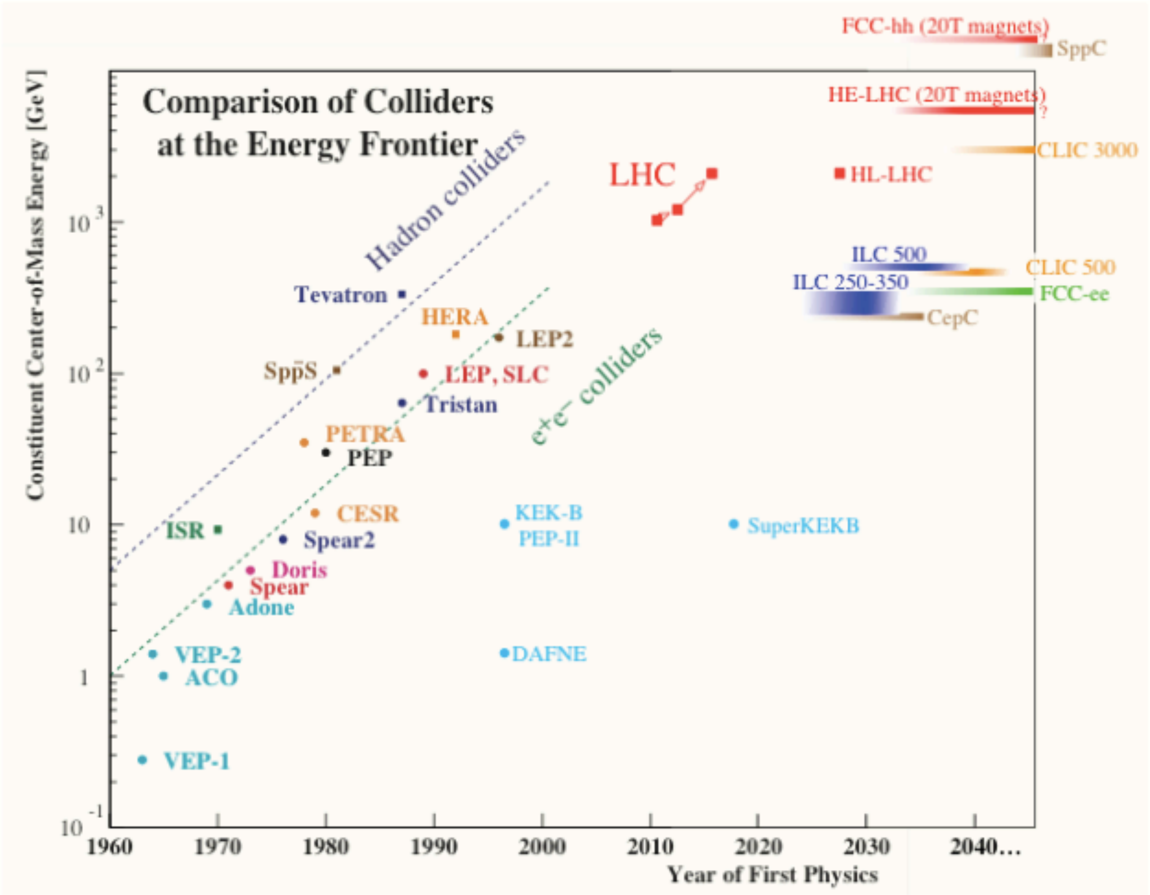


2035+ ?

Beyond LHC

- HE-LHC
  - pp 33 TeV CM
  - 20 T dipoles (HTS tech.)
  - $\mathscr{L}\sim 2\times10^{34}$
- CLIC
  - e+e- 500 - 3000 GeV
  - x-band accelerator technology
  - 2-beam acceleration
  - $\mathscr{L}\sim$ 2-6$\times10^{34}$
- FCC
  - FCC-hh
    - pp 80-100 km circumference
    - 100 TeV
    - 16 T dipoles (Nb_3Sn) — 20 T HTS
    - $\mathscr{L}\sim 5\times10^{34}$
  - (FCC-ee)
  - (FCC-he)

Evolution of Colliders - the future?



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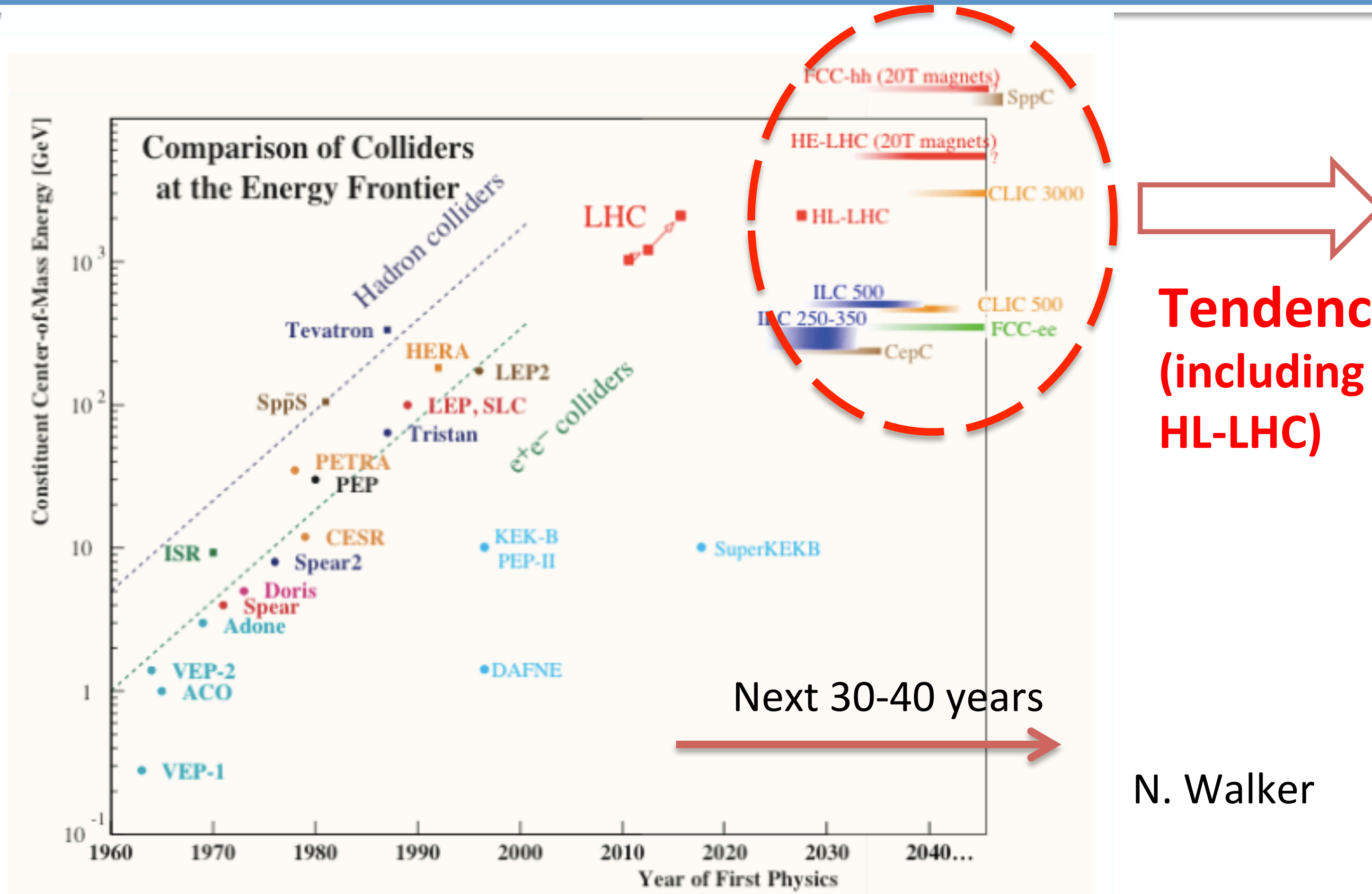
Evolution of Colliders - the future?



Tendency (including HL-LHC)

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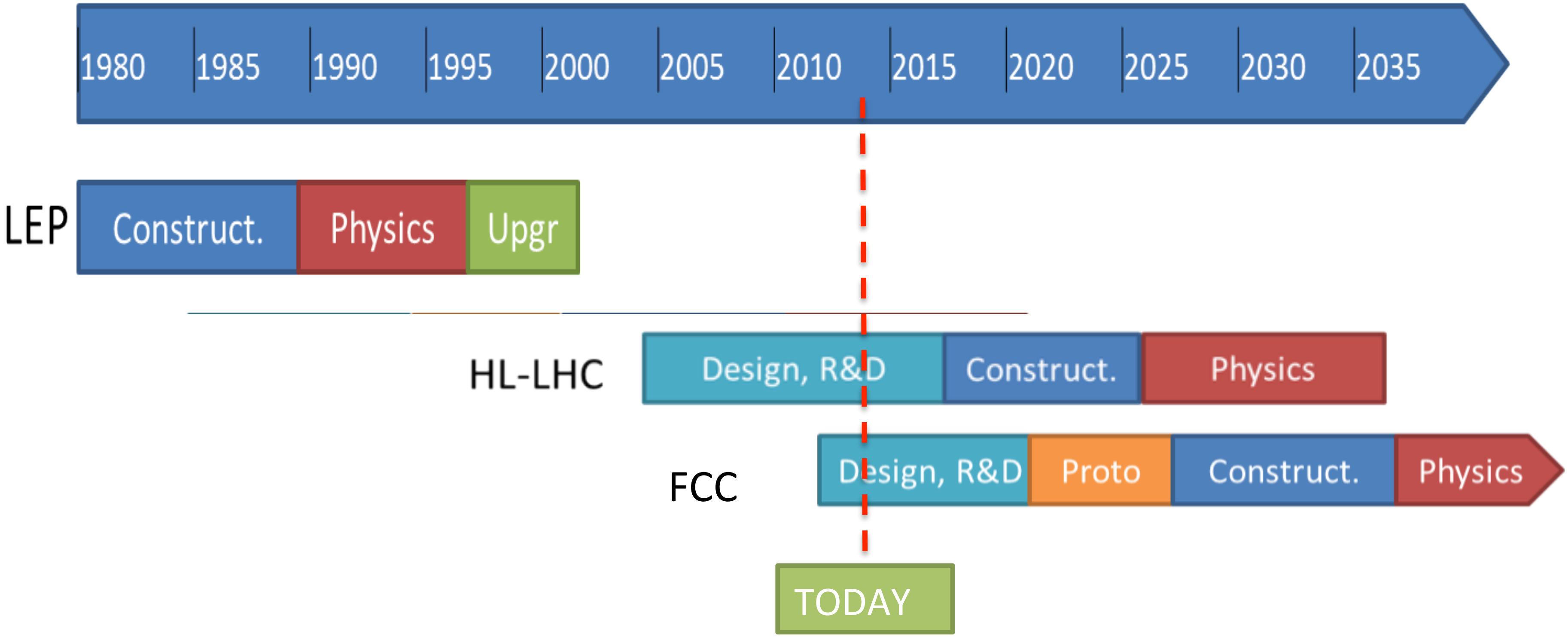
If somebody ask I could give my bet on the time scale

From R&D to physics



Conclusions

- The discovery of a Higgs boson brought new light on the next large Machines (HL-LHC, ILC) .
- HL-LHC will be un impressive Higgs (top) factory, with great potential for discovery.
- Electron-positron collider would complement the LHC results with precision measurements
  - Linear colliders are the most advanced path into ~200-500 GeV scale
  - Very large storage rings are attractive up to ~350 GeV: CepC, FCC-ee
  - Technologically possible
- Future very large hadron colliders for ~100 TeV energies under discussion
  - SppC, FCC-pp
  - no strong physics case yet
  - intensive R&D on superconductive magnets needed
- **The coming run at 13 TeV may discover something new, then we will have to re-asses the situation by then.**


CERN next exits
GET IN LANE
China next right
HE-LHC
construction
2028+??
physics 2038+??
FCC-pp
(FCC-ee)
construction 2028+??
physics 2038+??
CLIC
construction 2028+??
physics 2038+??
SppS
construction 2028+??
physics 2038+??
Muon Collider
construction 2030+?
physics 2040+?
LHC
for the next 20 years
ILC in Japan
construction 2018?
physics 2028?
CepC in China
construction 2018?
physics 2028?
VERY INTERESTING
ROAD AHEAD

N. Walker