Present and Future of Particle Physics: the Role of Europe in the Global Context

Varenna, July 11, 2015

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CERN

Where we stand

After LHC Run 1:

- We have consolidated the Standard Model
  (a wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)

- We have completed the Standard Model: discovery of the messenger of the BEH-field, the Higgs boson discovery

- We found interesting properties of the hot dense matter

- **We have NO evidence of New Physics**

Main outstanding questions in today's particle physics

Higgs boson and EWSB
- m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- elementary or composite Higgs ?
- is it alone or are there other Higgs bosons ?
- origin of couplings to fermions
- coupling to dark matter ?
- does it violate CP ?
- cosmological EW phase transition (is it responsible for baryogenesis ?)

Neutrinos:
- ν masses and and their origin
- what is the role of H(125) ?
- Majorana or Dirac ?
- CP violation
- additional species → sterile ν ?

Dark matter:
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- one type or more ?
- only gravitational or other interactions ?

The two epochs of Universe's accelerated expansion:
- primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is Λ so small?) or gravity modification ?

Quarks and leptons:
- why 3 families ?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
- baryon and charged lepton number violation

Physics at the highest E-scales:
- how is gravity connected with the other forces ?
- do forces unify at high energy ?

At what E scale(s) are the answers ?

Looking for "unknown unknowns"

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, short/long baseline, reactors, $0\nu\beta\beta$ decays),
- cosmic surveys (CMB, Supernovae, BAO, Dark E)
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- .....

Facts today

Particle Physics is the most global science community.

Examples:

- Experiments
- WLCG
- Communication
- Detector R&D
- Accelerator R&D
- Accelerator construction (or the path to global projects): HERA / LHC
- GDE/LCC

Facts today

Facilities for HEP (and other sciences) becoming larger and more expensive

- Funding is not increasing
- Fewer facilities are realisable
- Time scales are becoming longer
- Laboratories are changing missions
- Accelerator technologies slowly saturating.

Need

→more coordination/collaboration

→new disruptive technologies

→a consistent educational effort

Global vs Regional/National Facilities

Regional and National Infrastructures are key to

- Push the envelope of the current technologies
- Maintain and propagate the accelerator culture
- Connect across different fields
- Connect to societal challenges

From the Update of the European Strategy for Particle Physics

The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN.

Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.

The scale of the facilities required by particle physics is **resulting in the globalization of the field**. The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.

From the P5 report

Particle physics is global.

The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions **if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere**.

Strong foundations of international cooperation exist, with the Large Hadron Collider (LHC) at CERN serving as an example of a successful large international science project.

Reliable partnerships are essential for the success of international projects. Building further international cooperation is an important theme of this report, and this perspective is finding worldwide resonance in an intensely competitive field.

From Japan HEP Community

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, **Japan should take the leadership role in an early realization of an e+e- linear collider**. In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.

Should the neutrino mixing angle $\boldsymbol{\theta}_{13}$ be confirmed as large, **Japan should aim to realize a large-scale neutrino detector through international cooperation**, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.
This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

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.*

CERN

Table 1
Summary of Scenarios

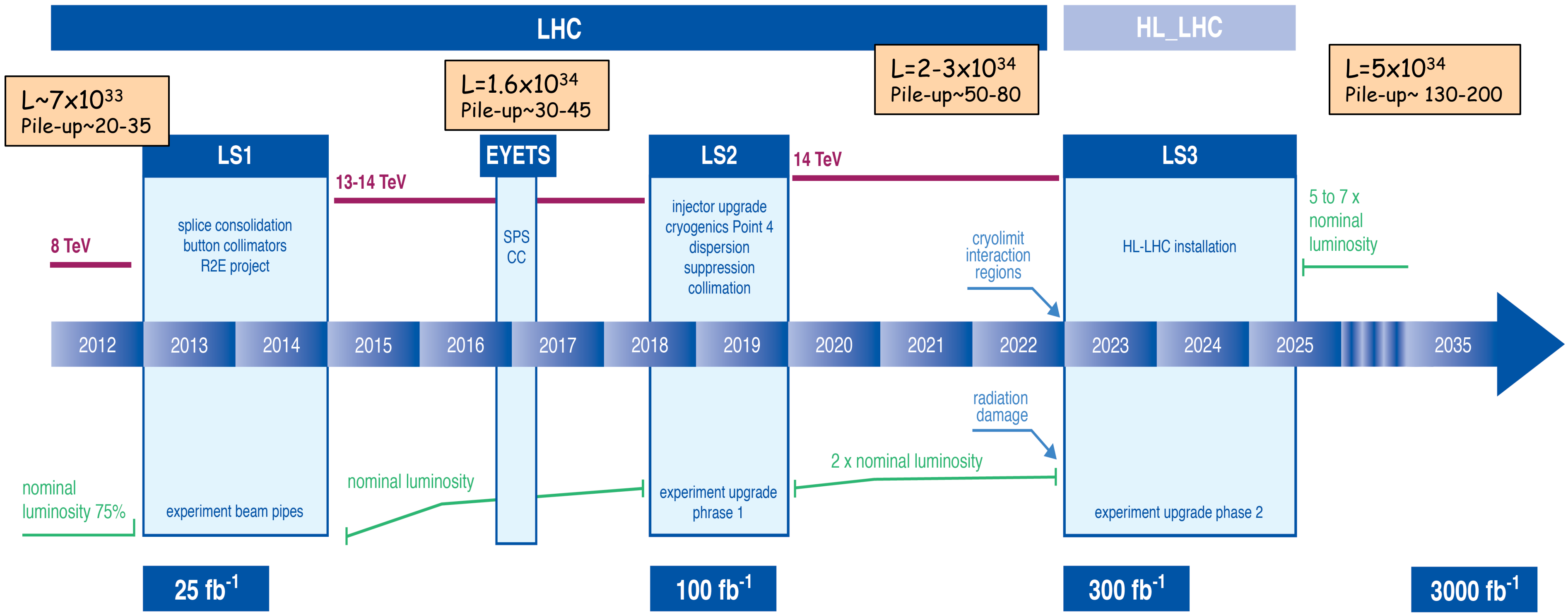
Project/Activity	Scenarios: Scenario A	Scenarios: Scenario B	Scenarios: Senario C	Science Drivers: Higgs	Science Drivers: Neutrinos	Science Drivers: Dark Matter	Science Drivers: Cosm. Accel.	Science Drivers: The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e 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 contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

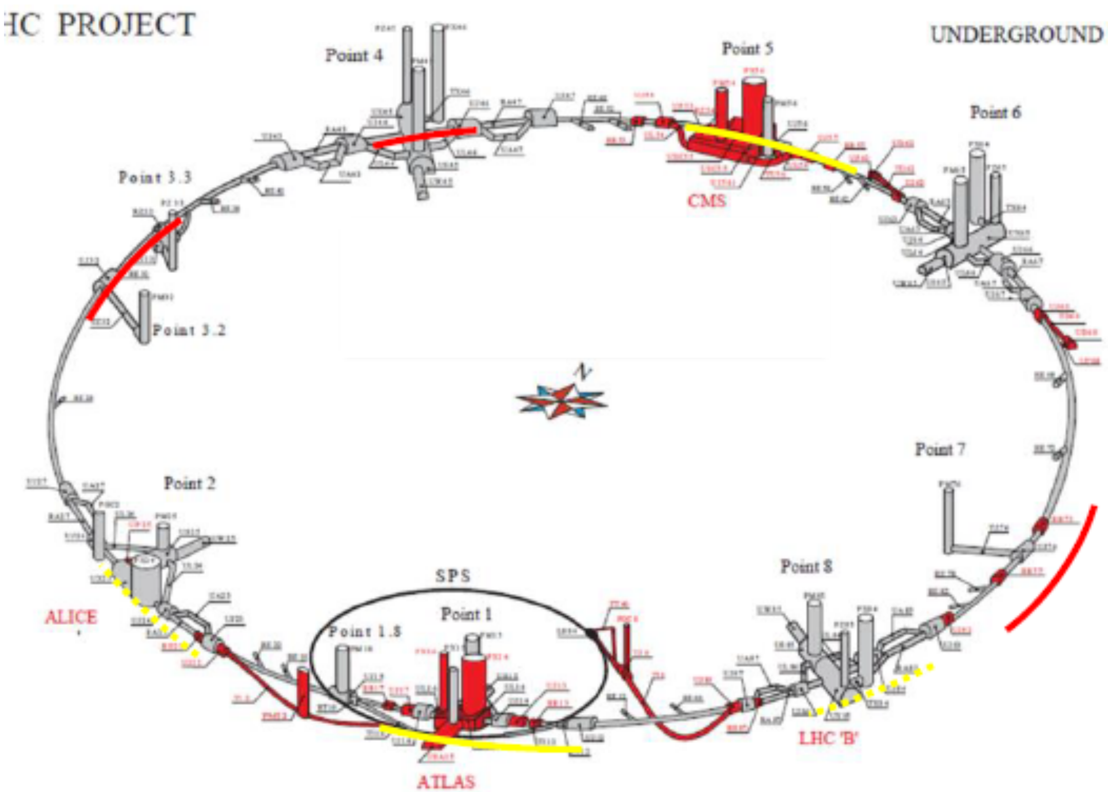
The LHC timeline

L.Rossi

New LHC / HL-LHC Plan



The HL-LHC Project



- 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

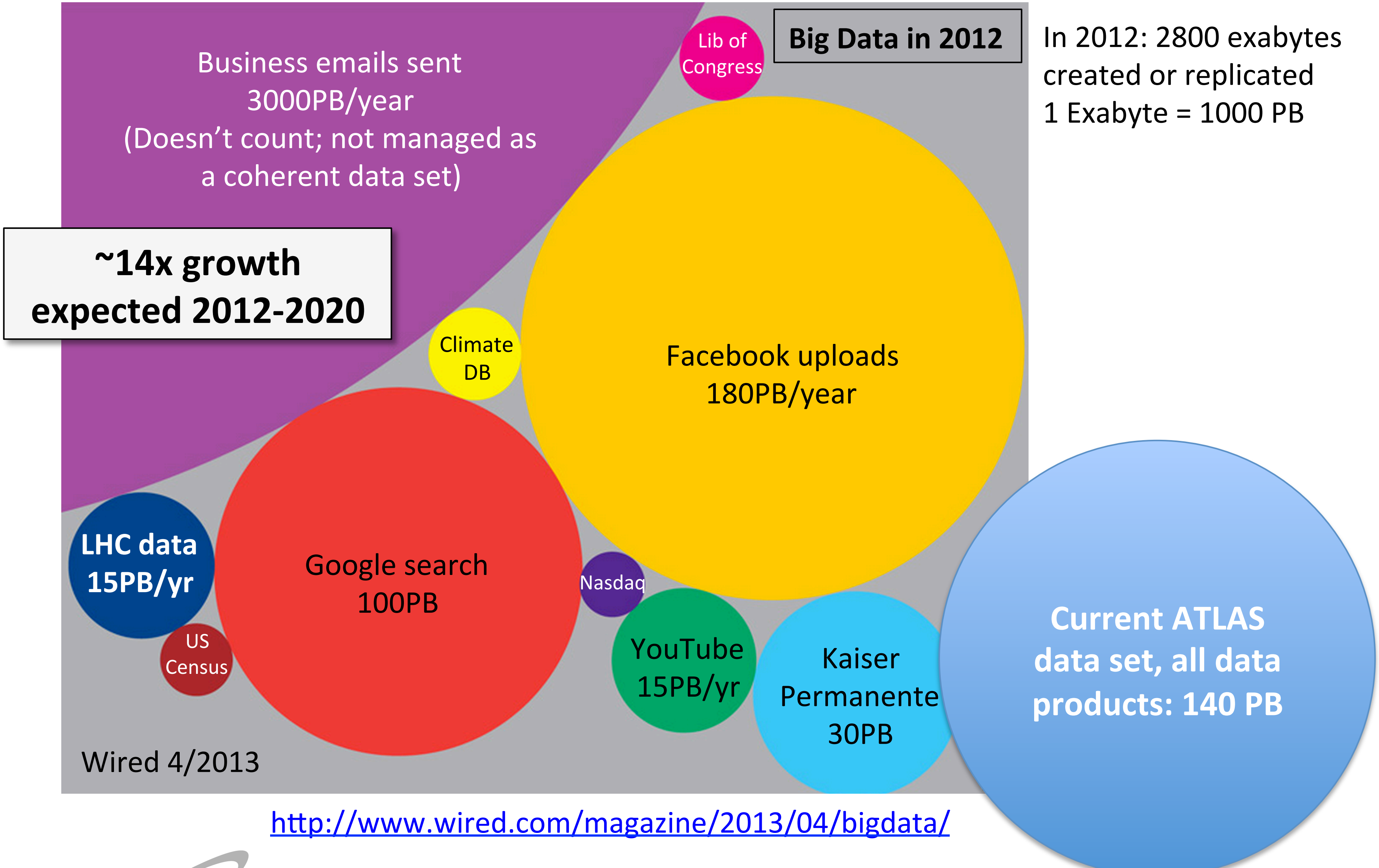
Project leadership: L. Rossi and O. Brüning

CERN

From: Torre Wenaus, CHEP 2013

Data Management

Where is LHC in Big Data Terms?



In 2012: 2800 exabytes created or replicated
1 Exabyte = 1000 PB

http://www.wired.com/magazine/2013/04/bigdata/

European Strategy for Particle Physics

High-priority large-scale scientific activities

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To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. ***CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.***

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements

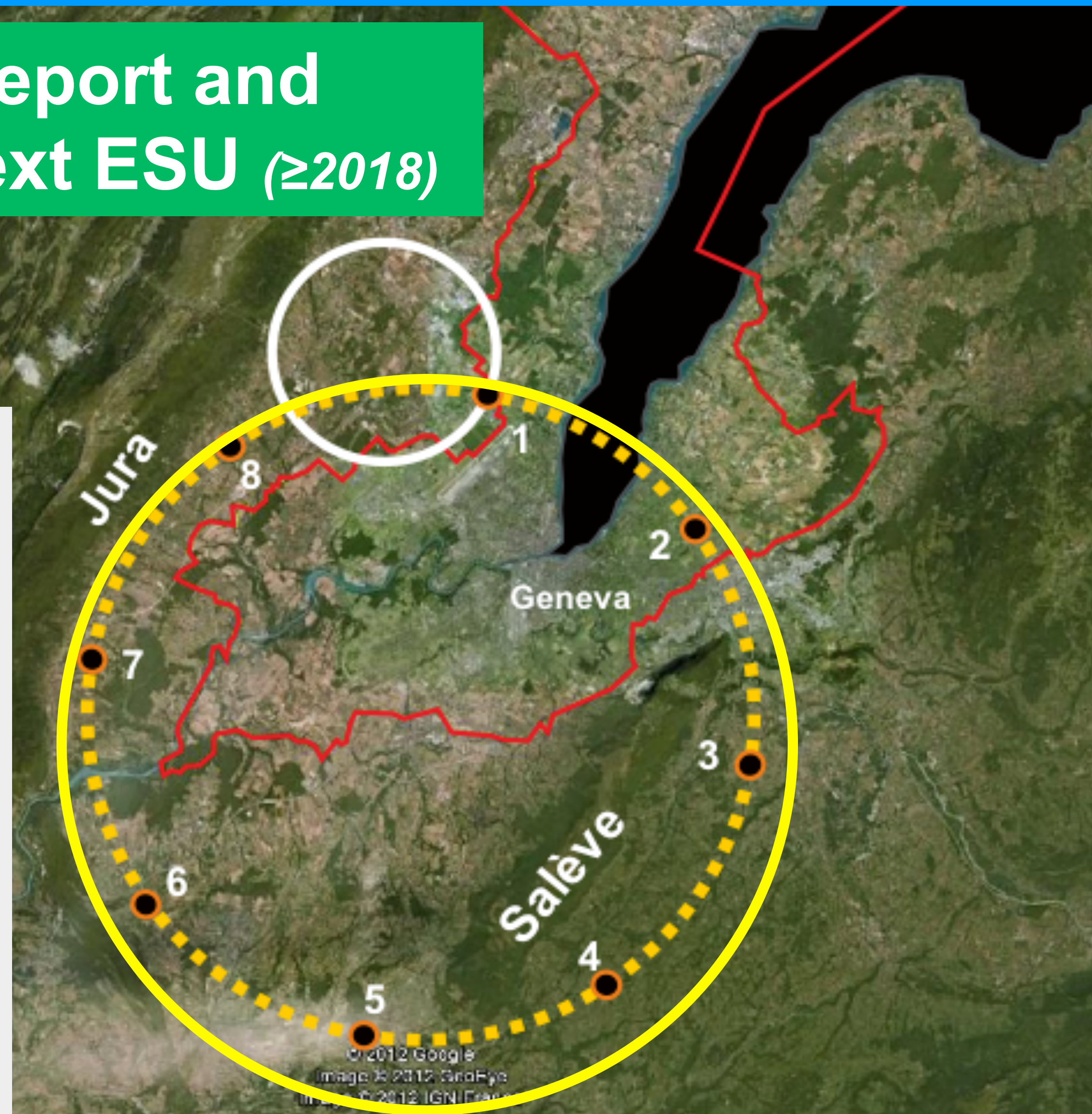
with possibility of e+-e- (TLEP) and p-e (VLHeC)

Conceptual Design Report and cost review for the next ESU *(≥2018)*

FCC Design Study Kick-off Meeting: 12-14. February 2014 in Geneva

Establishing international collaborations

- ***Set-up study groups and committees***



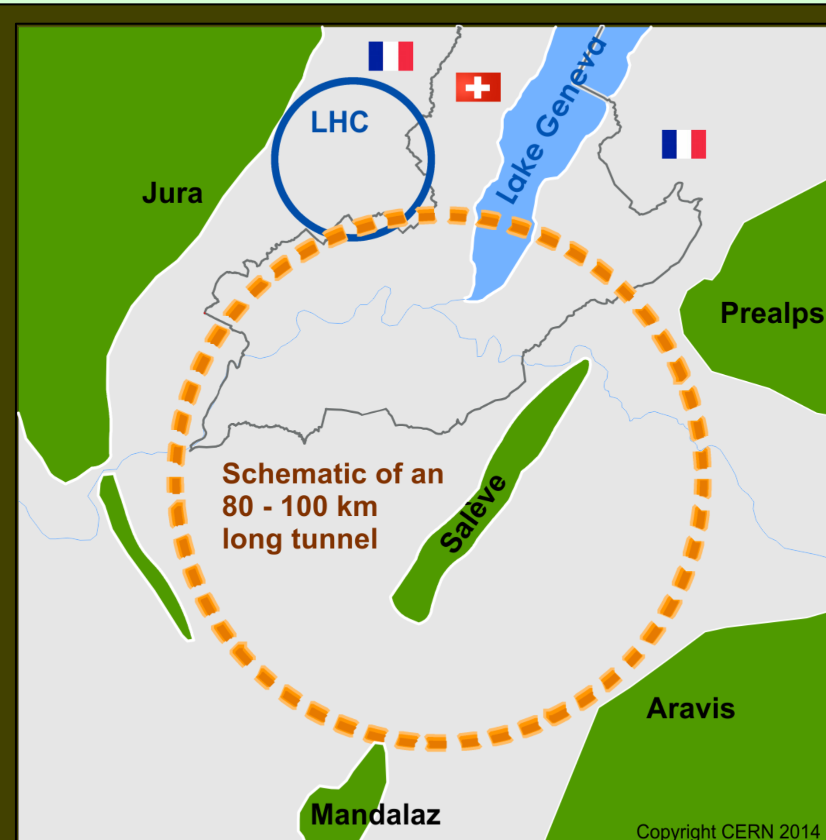
Future high-energy circular colliders

Parameters are indicative and fast evolving, as no CDR yet

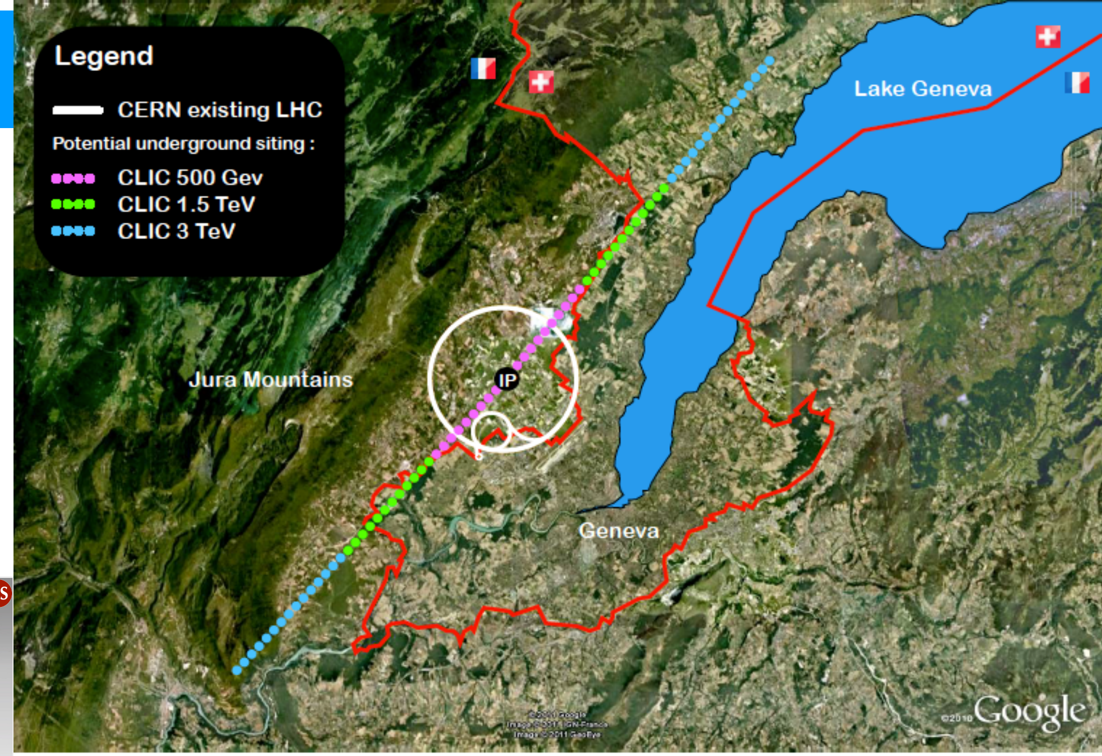
China: 50-70 km e^+e^- $\sqrt{s}$=240 GeV (CepC) followed by 50-90 TeV pp collider (SppC) in same tunnel
50 km e^+e^- machine + 2 experiments:
- ❑ pre-CDR: end 2014
- ❑ construction: 2021-2027
- ❑ data-taking: 2028-2035
- ❑ cost (material): ~3 B$

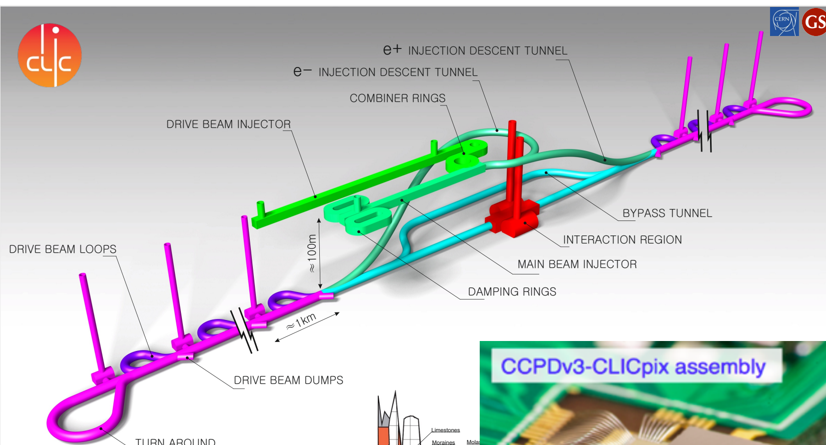
CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:
- ❑ 100 TeV pp: ultimate goal (FCC-hh)
- ❑ 90-350 GeV e^+e^-: possible intermediate step (FCC-ee)
- ❑ $\sqrt{s}$= 3.5-6 TeV ep: option (FCC-eh)

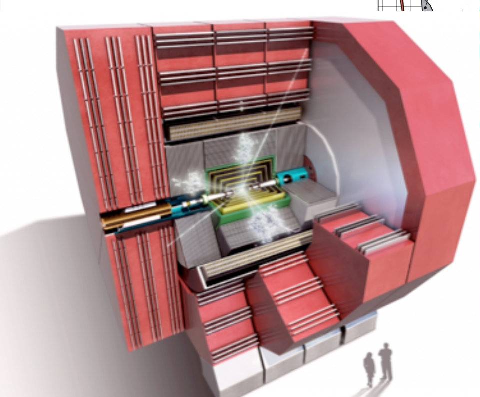
Goal of the study: CDR in ~2018.



The CLIC project



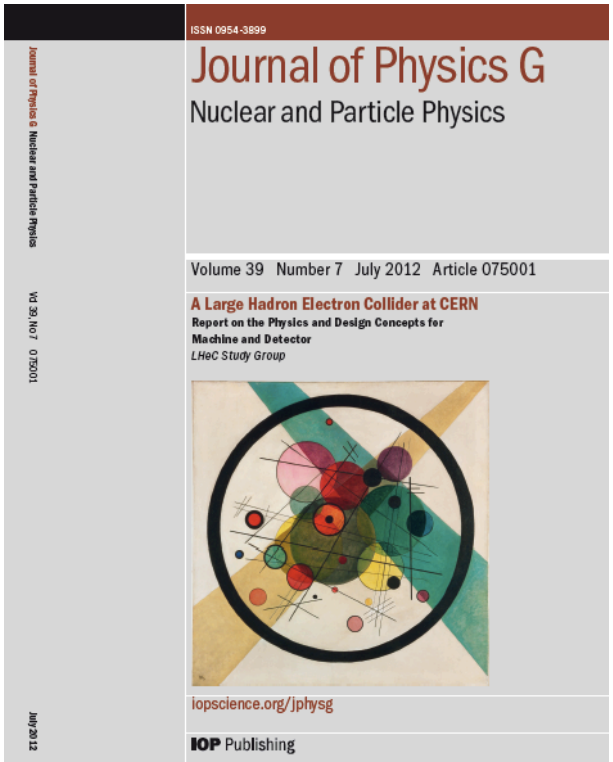


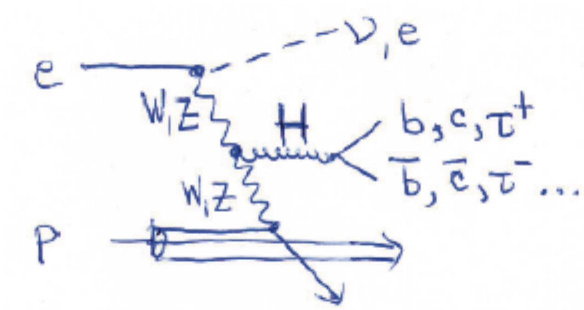


CALICE tungsten-DHCAL

Complete module, PETs (above), Acc. Structure (right)

LHeC, not only PDFs





Continuing activity on
Physics
Detector
ERL

Goal: L~10^{34} $cm^{-2}s^{-1}$

European Strategy for Particle Physics

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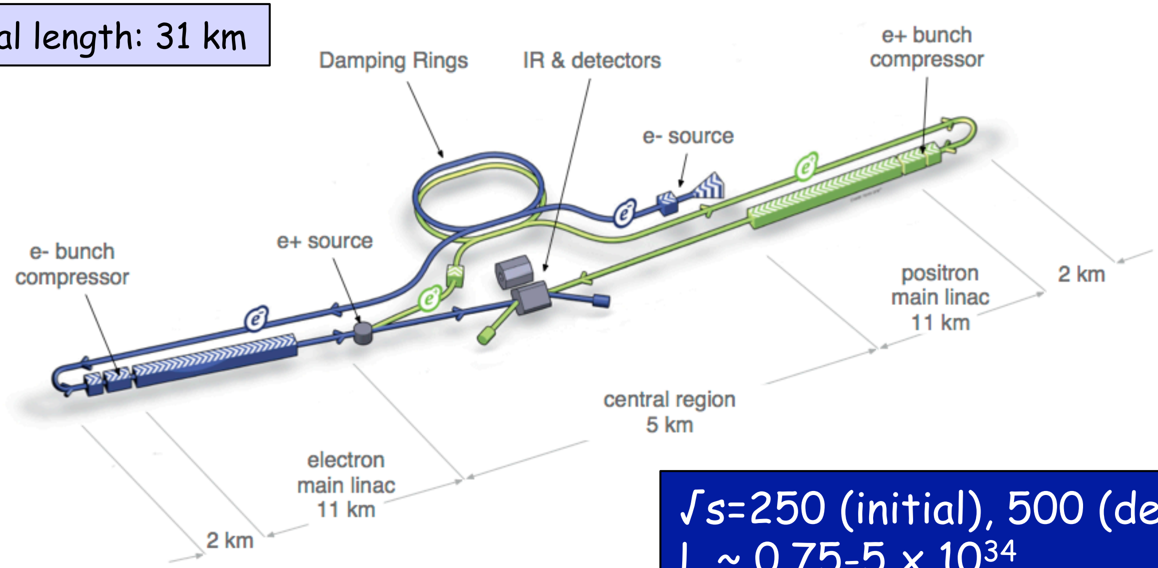
There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. ***Europe looks forward to a proposal from Japan to discuss a possible participation***

International Linear Collider (ILC)

Technical Design Report released in June 2013

Total length: 31 km



√s=250 (initial), 500 (design), 1000 (upgrade) GeV
L ~ 0.75-5 x 10^{34}
(running at √s=90, 160, 350 GeV also envisaged)

Main challenges:

- ❑ ~ 15000 SCRF cavities (1700 cryomodules), 31.5 MV/m gradient
- ❑ 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- ❑ Positron source; suppression of electron-cloud in positron damping ring
- ❑ Final focus: squeeze and collide nm-size beams

❑ Japan interested to host → decision ~2018 based also on ongoing international discussions
Mature technology: 20 years of R&D experience worldwide
(e.g. European xFEL at DESY is 5% of ILC, gradient 24 MV/m, some cavities achieved 29.6 MV/m)
→ Construction could technically start ~2019, duration ~10 years → physics could start ~2030

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.
CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

From the P5 Report

Recommendation 12 : In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt*MW*yr by the 2035 timeframe**, the far detector situated **underground** with cavern space for expansion **to at least 40 kt LAr fiducial** volume, and **1.2 MW beam power upgradable to multi megawatt** power. The experiment should have the demonstrated capability to search for **supernova (SN) bursts** and for **proton decay**, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

Japan Roadmap

Association of Japanese High Energy Physicists (community organisation) regards that ILC and Hyper-K are the two priority projects in Japan.

- Hyper-K, through international cooperation
- ILC: hosting ILC as a global project

DUNE (Deep Underground Neutrino Exp)

A merger of all previous efforts and any other interested parties to build, operate, exploit

- a (staged) 40 Kt LAr detector, at the SURF site, 1300 Km from FNAL
- An high granularity/high precision near detector

exposed to a **1.2 MW**, tunable ν beam produced by the PIP-II upgrade at FNAL **by 2024**, evolving to a power of **2.3 MW by ~ 2030.**

A 25+ years Physics Program

On the beam:

- Perform a comprehensive investigation of neutrino oscillations to:
  - test CP violation in the lepton sector
  - determine the ordering of the neutrino masses
  - test the three-neutrino paradigm
- Perform a broad set of neutrino scattering measurements with the near detector

Exploit the large, high-resolution, underground far detector for non-accelerator physics topics:

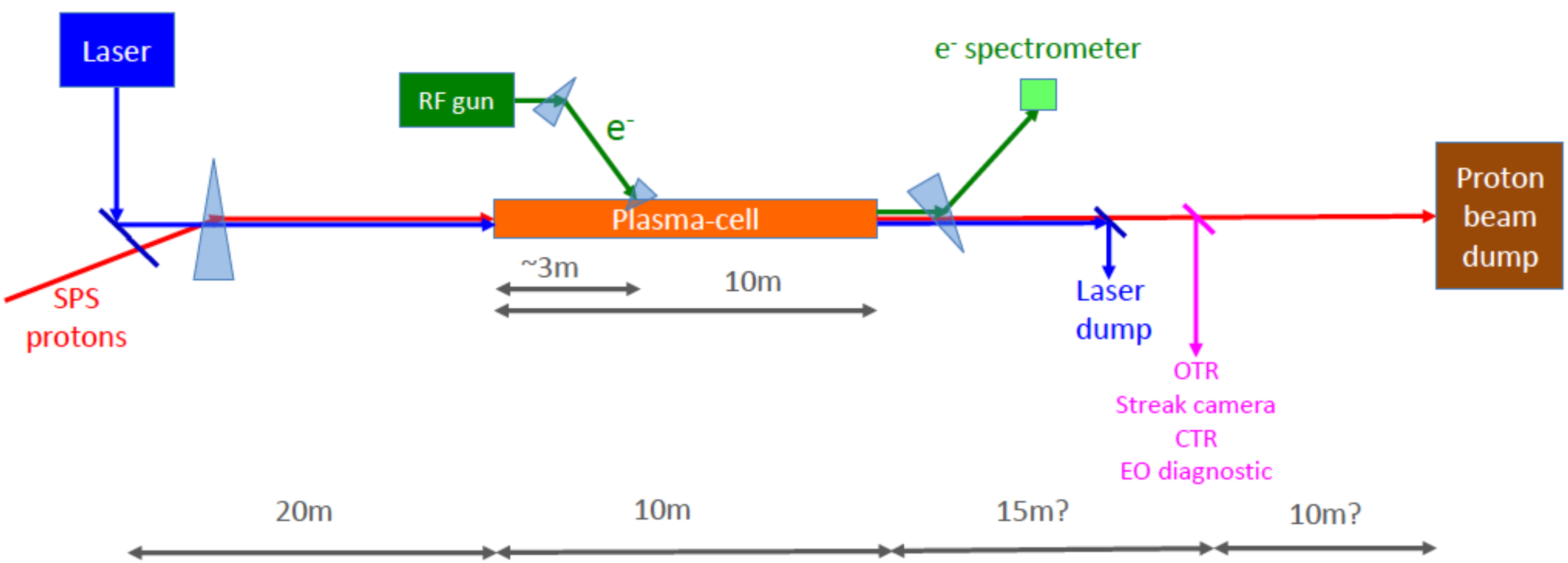
- atmospheric neutrino measurements
- searches for nucleon decay
- measurement of astrophysical neutrinos (especially those from a core-collapse supernova).

CERN ν Platform Initial Mandate (Coord. M.Nessi)

- Assist the various groups in their R&D phase (detectors and components) in the short and medium term and give coherence to a fragmented European Neutrino Community
- Provide to the ν community a test beam infrastructure (charged particles)
- Bring R&D at the level of technology demonstrators in view of major technical decisions
- Continue R&D on ν beam, as a possible base for further collaborations
- Support the short baseline activities (infrastructure & detectors)
- Support the long baseline activities (infrastructure & detectors)

Disruptive Technologies: Wakefield Acceleration

Experimental Layout



In summary

An exciting period in front of us:

- We have finished the inventory of the “known unknown”…
- …but we have a vast space to explore, and tools to do it exhaustively.
- We have a solid physics program for the next 15 – 20 years
- In this time period we have to prepare for the next steps, setting directions, technologies and political frames.

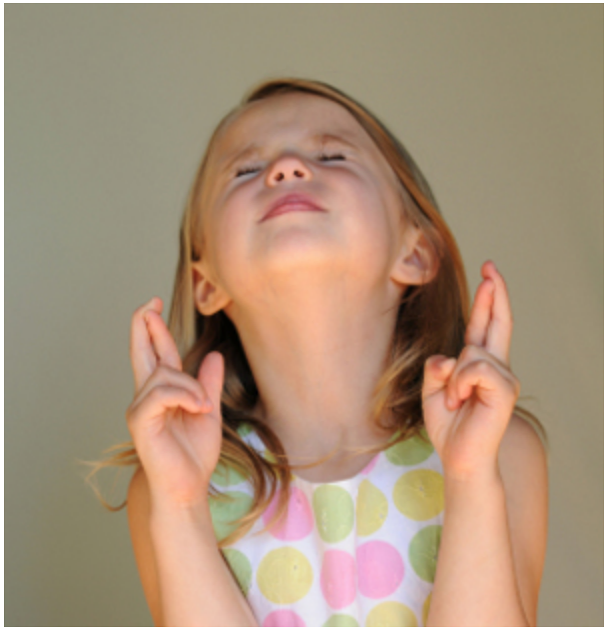
In summary

Experimental results will be dictating the agenda of the field.

We will need:

- Flexibility
- Preparedness
- Visionary global policies

- ...and a bit of luck!



Thank you!