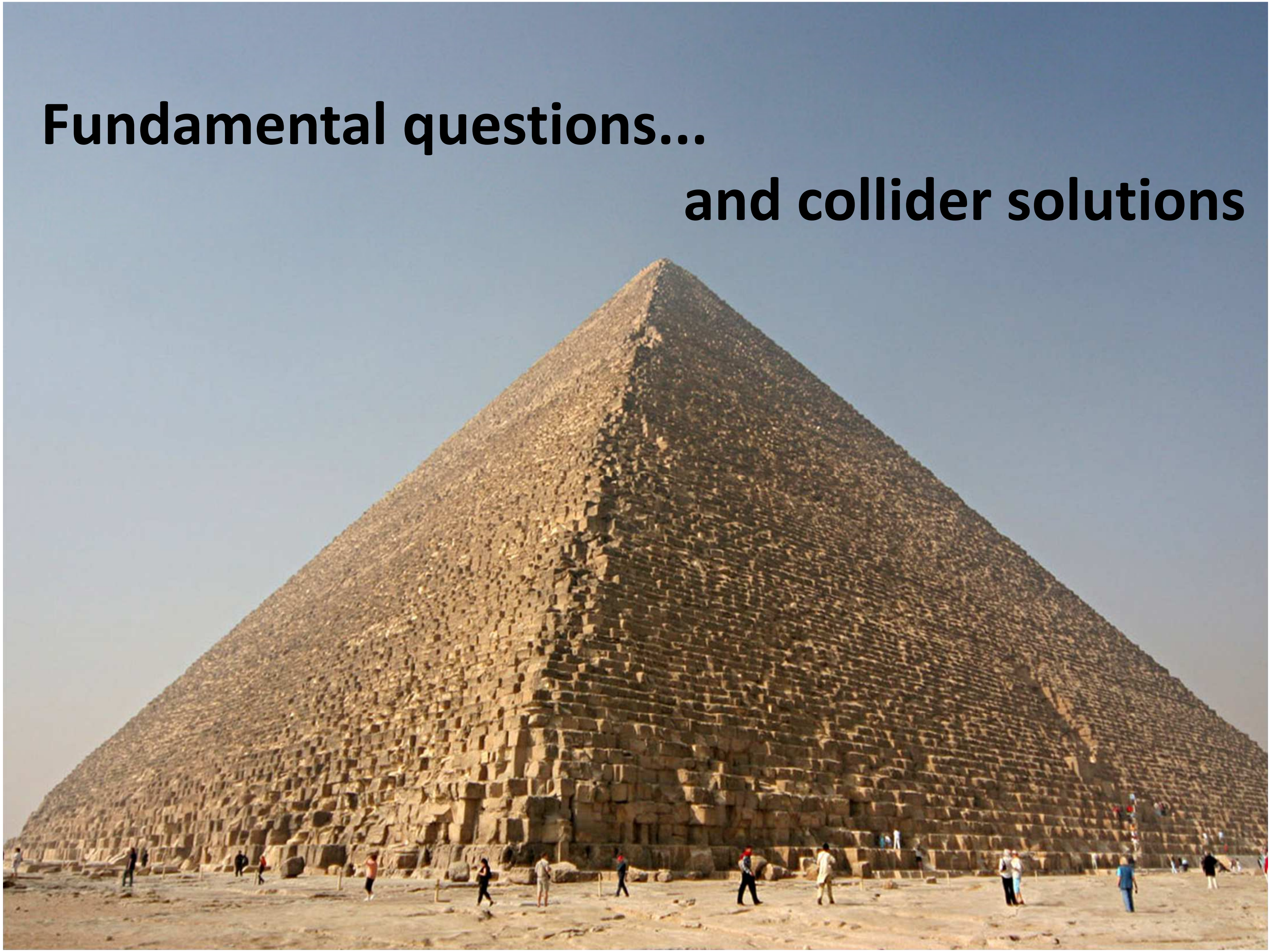
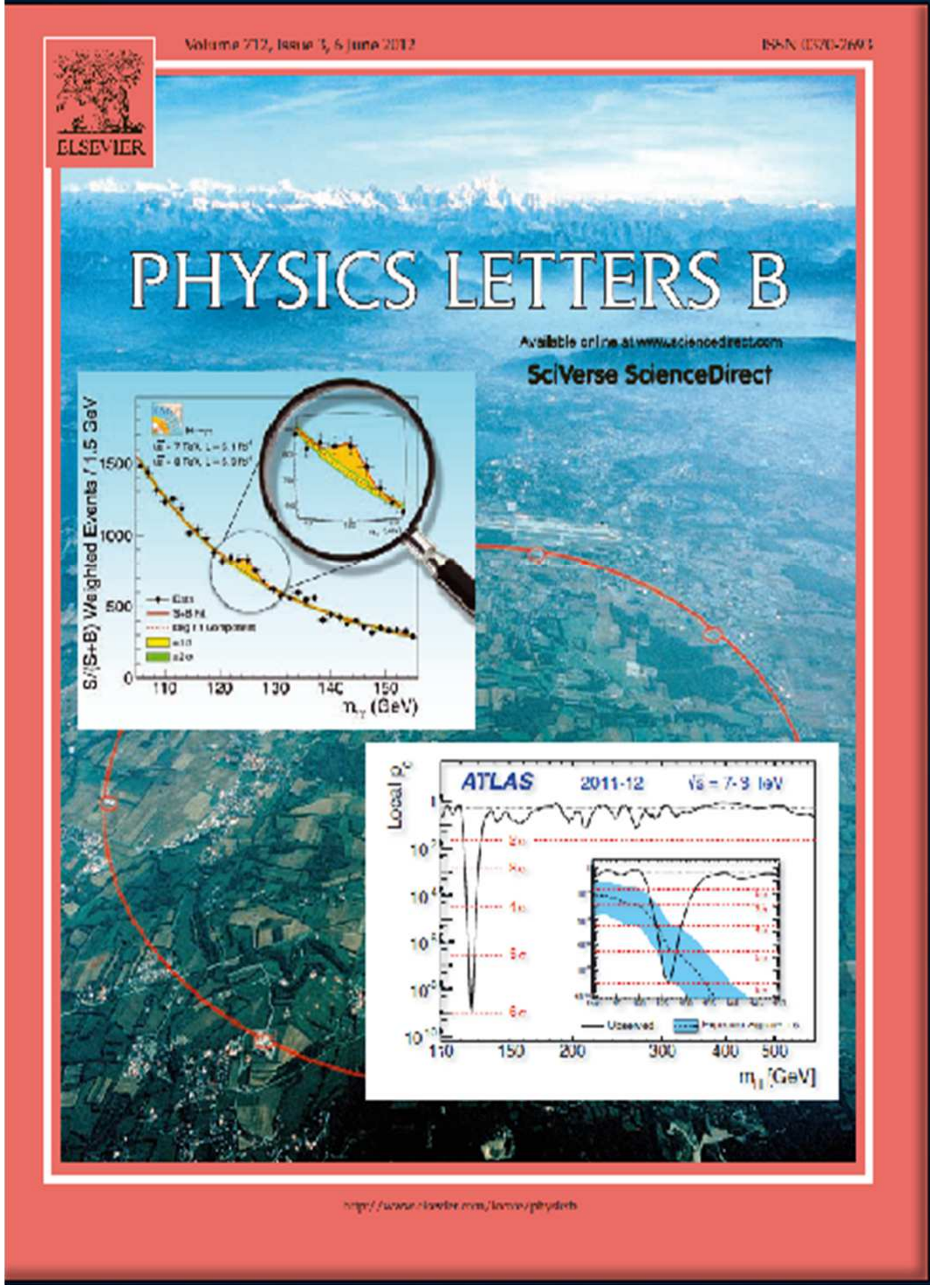
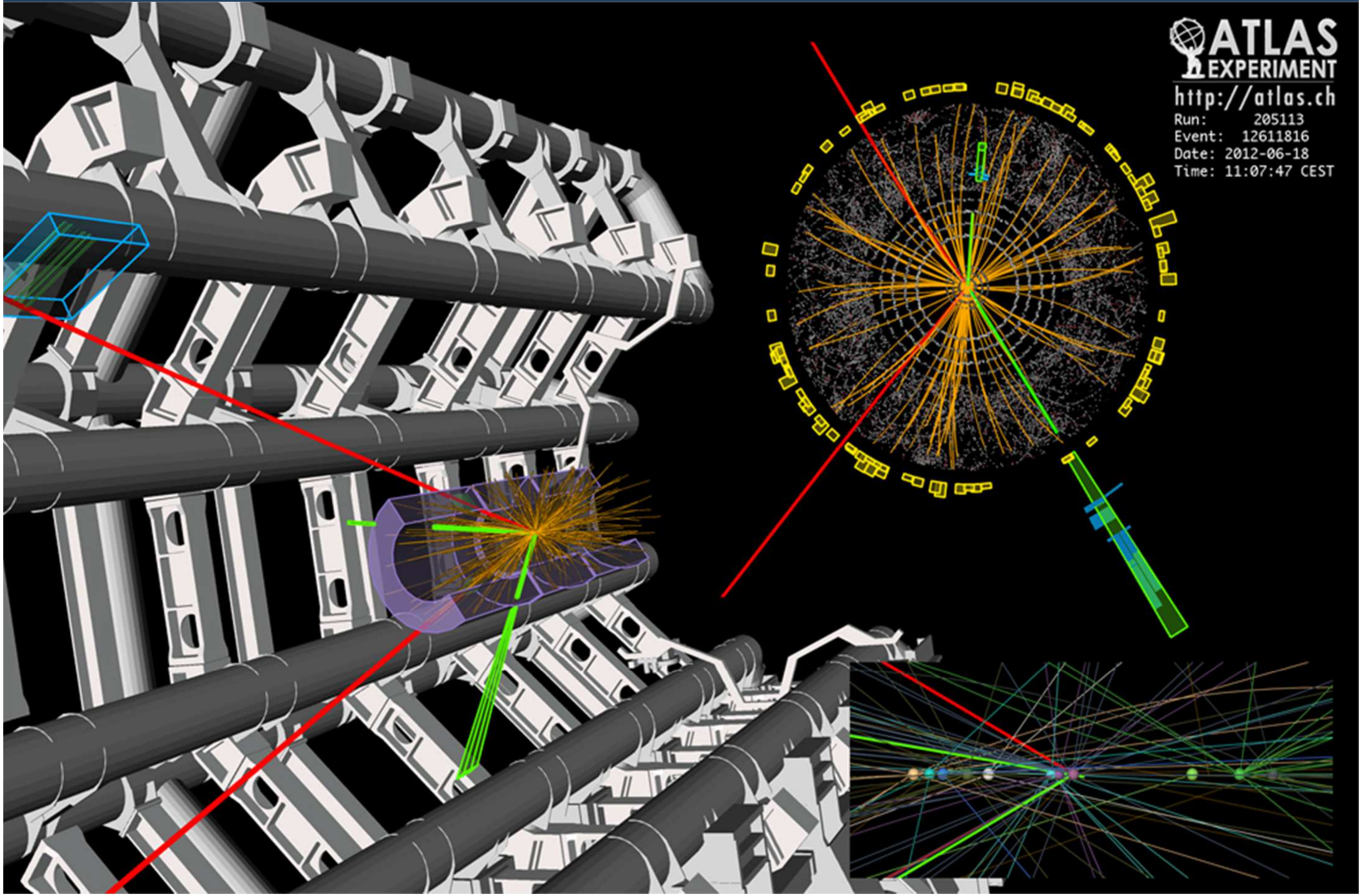

Fundamental questions...
and collider solutions

Seven years ago… Discovery of the Higgs boson



A collision of 4 +4 TeV protons (8 000 000 000 000 eV) in the ATLAS experiment at LHC produces a **Higgs boson** decaying into **e+, e-**, μ+, μ-



Discovering (or not) the Higgs boson was the main goal of the Large Hadron Collider colliding protons of 7 + 7 TeV.

The Large Hadron Collider (LHC) was a **~5’000’000’000 €** construction occupying CERN (2000+ employees) during 15 years.
LHC is in a 27km circular tunnel, built in 1983-89 (and imagined in 1976), for an electron positron collider which ran 1989-2000 for important measurements and a big discovery (that there are only 3 families of neutrinos).

A successful model!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

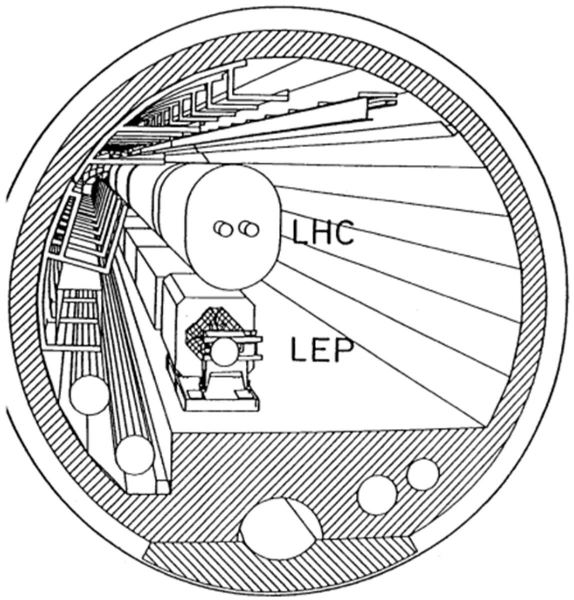
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



p p 2009-2037

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

Why was the discovery of the Higgs boson so important to particle physicists?

DISCOVERY: noun, *oxford dictionary*

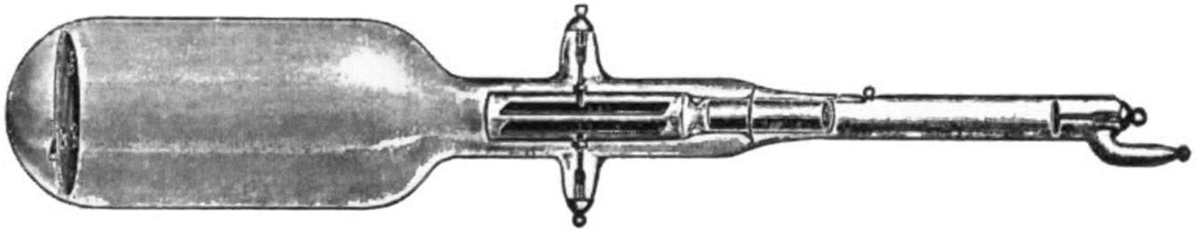
the fact of finding out something
that was not ***known*** *before*

we knew that something had to be there ....
But didn't know for sure that it would be a Higgs boson

The Higgs boson was the simplest answer to the question: why do Z and W particles have a mass, while the – similar-- photon has no mass?

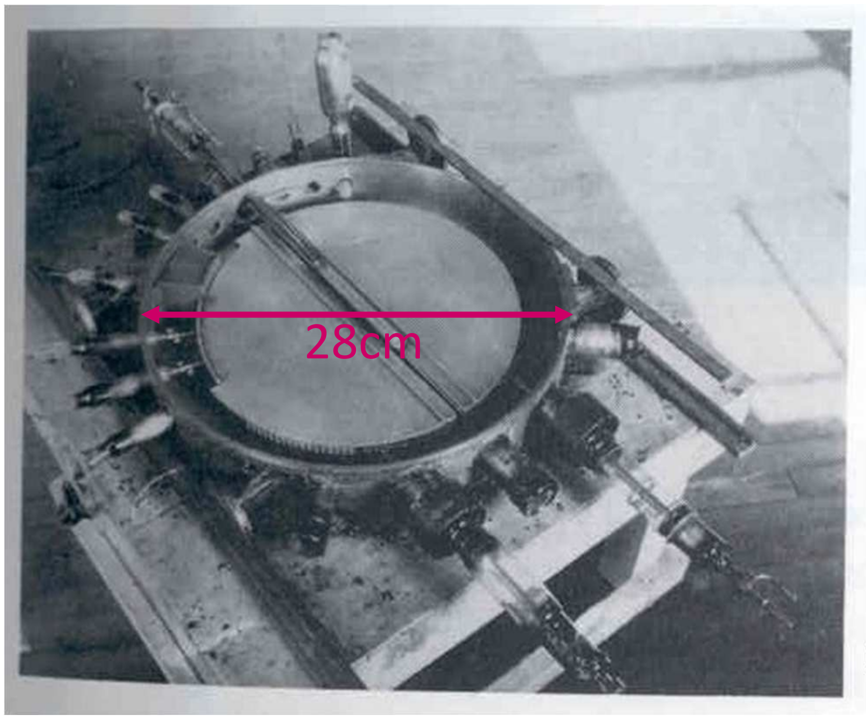
Particle Accelerators

The most basic accelerator is an old TV tube. Electrons are accelerated in an electric field a 25‘000 Volts and acquire an energy of 25 kilo electron-volts or 25 keV



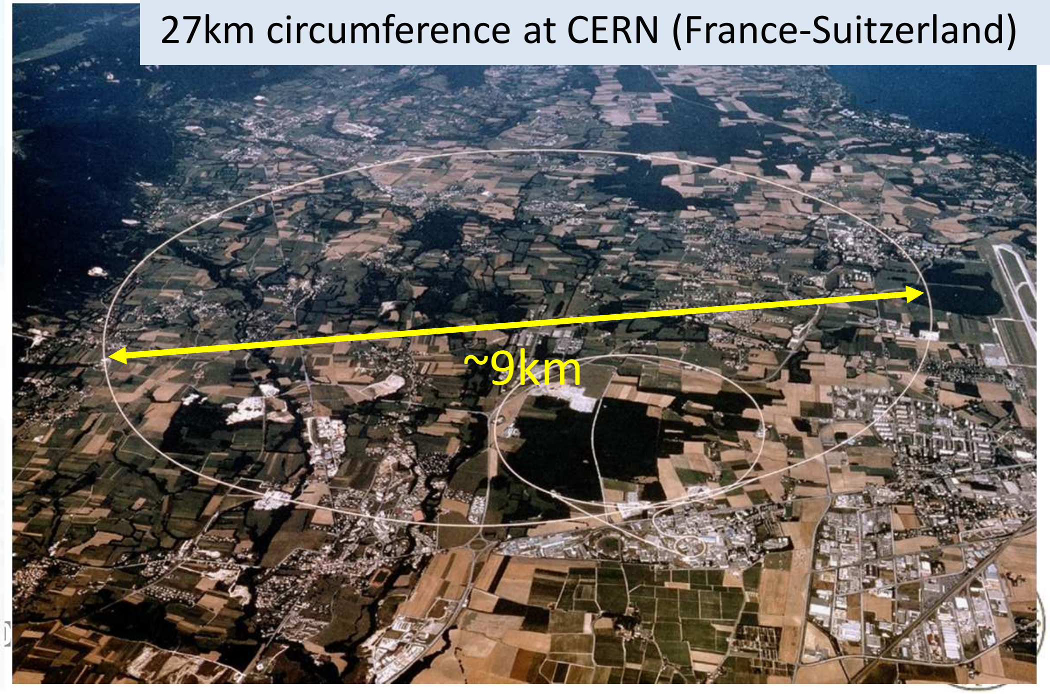
1897 Braun tube

94 cm Cyclotron at Lawrence Berkeley Lab in 1937



Large Electron Positron Collider (LEP) 100+100 GeV
27

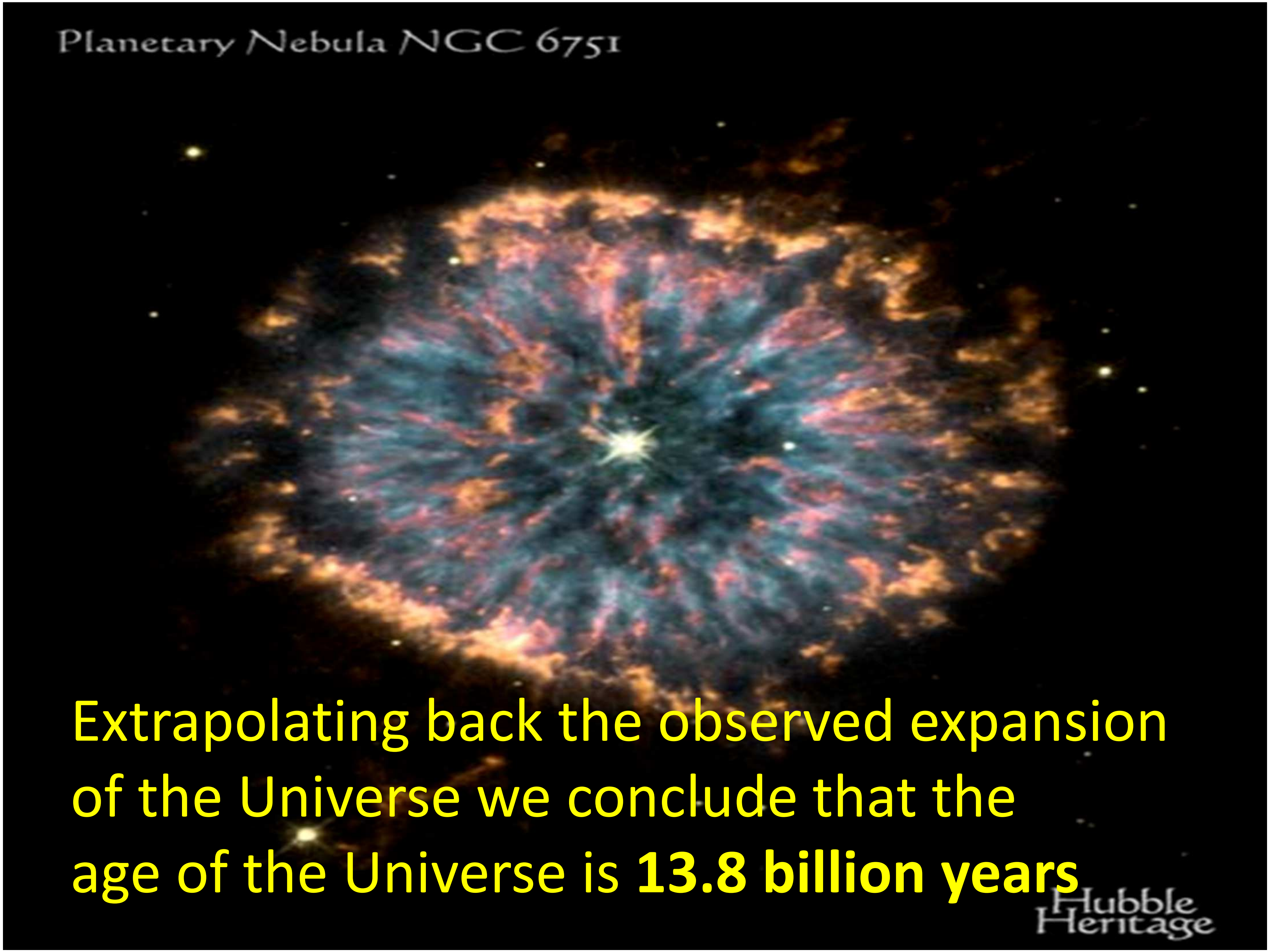
Large Hadron pp Collider (LHC) 7000+7000 GeV
27km circumference at CERN (France-Suitzerland)



Until the middle of the XVIIIth century it was commonly assumed that the world had been created as it is, 4004 years BC.

When dinosaur bones were discovered (ca 1800) people started to realize that the world *changes*. Not only the living world changes (*evolution of species* Lamarck, Darwin ~1850) **but the whole universe changes** – it was discovered that it expands by Hubble 1929

This discovery answered many questions, in particular why the sky is dark at night.



Extrapolating back the observed expansion of the Universe we conclude that the age of the Universe is **13.8 billion years**

Since the discovery of quantum mechanics we know that space and velocity are related by the ‘uncertainty’* principle

$$\Delta x \, \Delta p \geq \hbar/2$$

energy and time are also related

$$\Delta E \, \Delta t \geq \hbar/2$$

in the limit of t=0, E is infinite, velocity also and size is zero. ➔ **BIG BANG**

*’size’ principle would be more accurate

SCALES

Smaller and smaller:

man	1.8 metres	
usual mesure (vernier)	0.1 mm = 1/10 000 m	10^{-4} m
microscope	1 micron = 1/1 000 000 m	10^{-6} m
electronic microscope	1 atome = 1/10 000 000 000 m	10^{-10} m
nuclear physics	1 nucleus = 1/1 000 000 000 000 000	10^{-15} m
particle physics	...	$<10^{-19}$ m

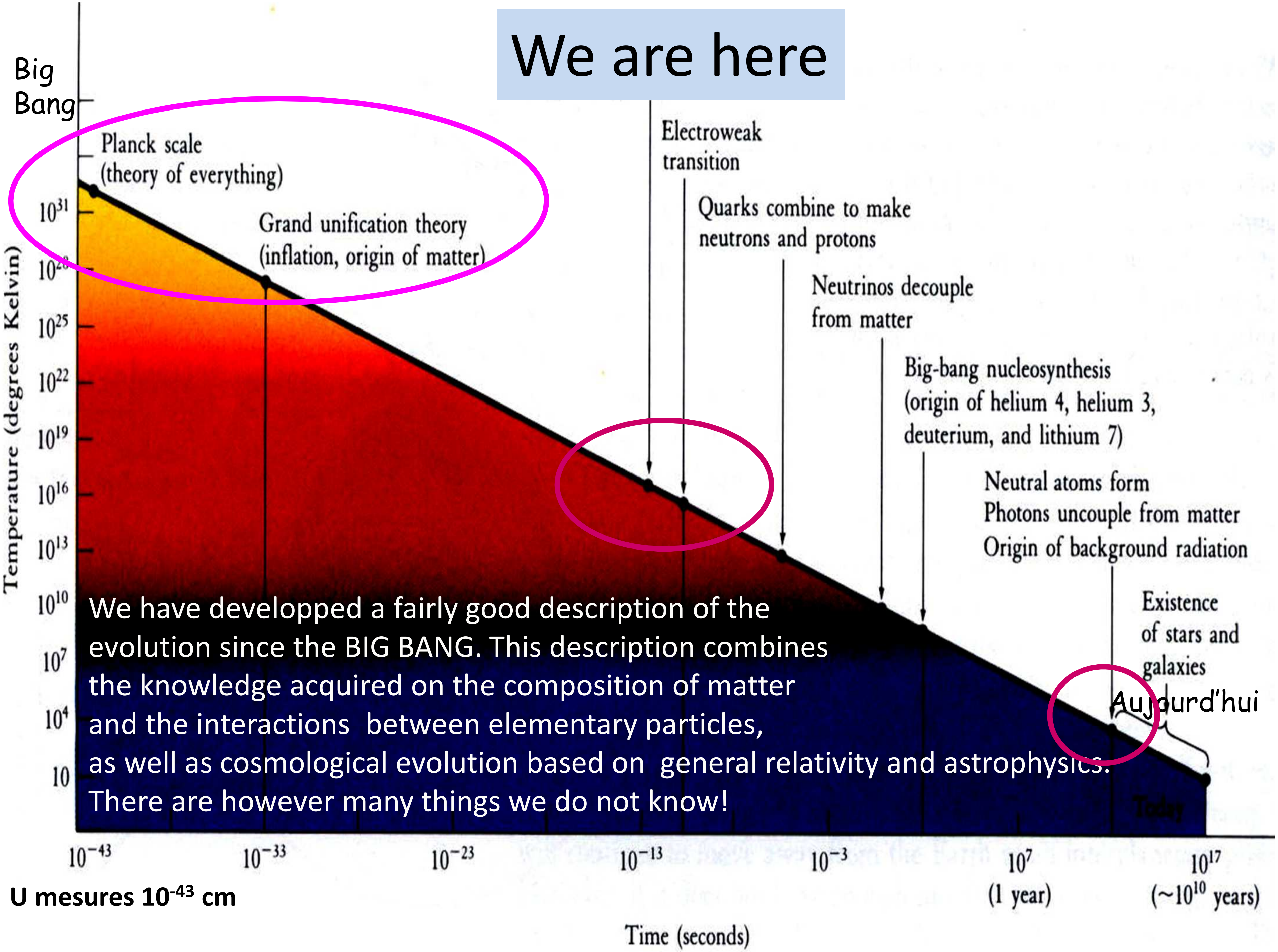
More and more energetic

Visible light (0.6 microns):	2.5	electrons-volts
electrons in a TV tube	25000	electrons-volts
electrons in LEP at CERN (2000)	100 000 000 000 = 100 GIGA eV (GeV)	électron-volts
protons in LHC at CERN (2016)	7 000 000 000 000 = 7 TERA eV (TeV)	électron-volts

Closer and closer to the origin of the UNIVERSE

10^{-19} m = 1 TeV = energy per particle = 10^{-11} seconds after the BIG BANG

1 calorie = 2.6 10^{19} eV



U mesures 10^{-43} cm

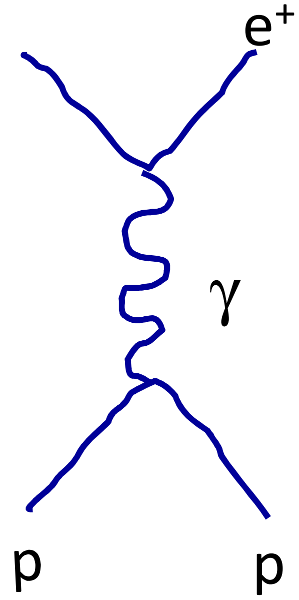
When I started physics 45 (1973) years ago the main **question** was: to understand what matter was made and how it worked.

all these particles are spin ½ particles

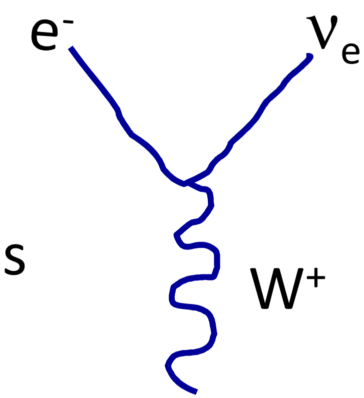
We knew matter was made of
atoms (electrons and nuclei)
nuclei (protons and neutrons)
and there were also strange particles,
muons (who ordered this?)
the two neutrinos, electron ν_e and muon ν_μ
There were 'guesses' as to how this works
some of them sound pretty funny today
(«bootstrap», and the «Tao of Physics»)

It was known that there were four forces

Gravitation
Electromagnetic interaction
mediated by **photons γ of spin 1**



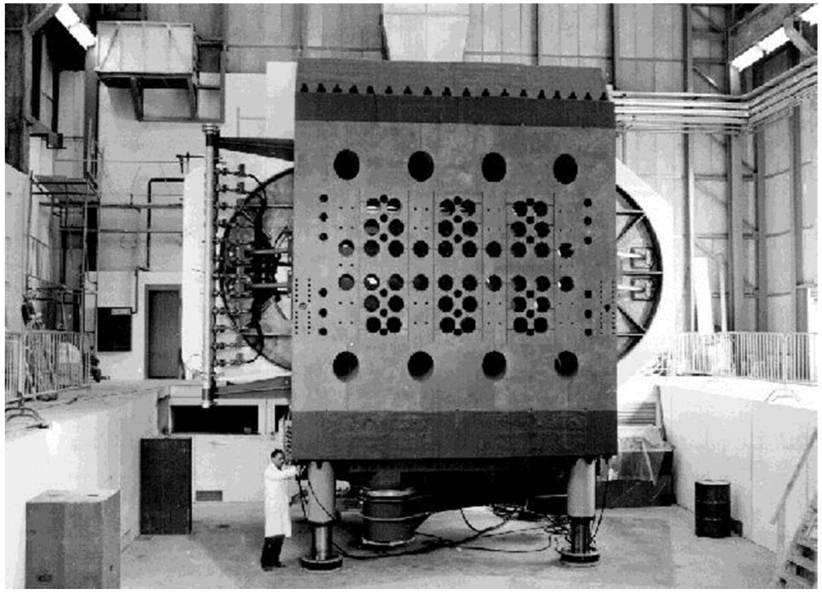
Weak interaction mediated (maybe)
by a **heavy charged photon (W?) of spin 1**
and producing neutrinos



Strong interaction which was
poorly understood but tied protons and neutrons
together in the nucleus

Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN

Discovery of **weak neutral current**

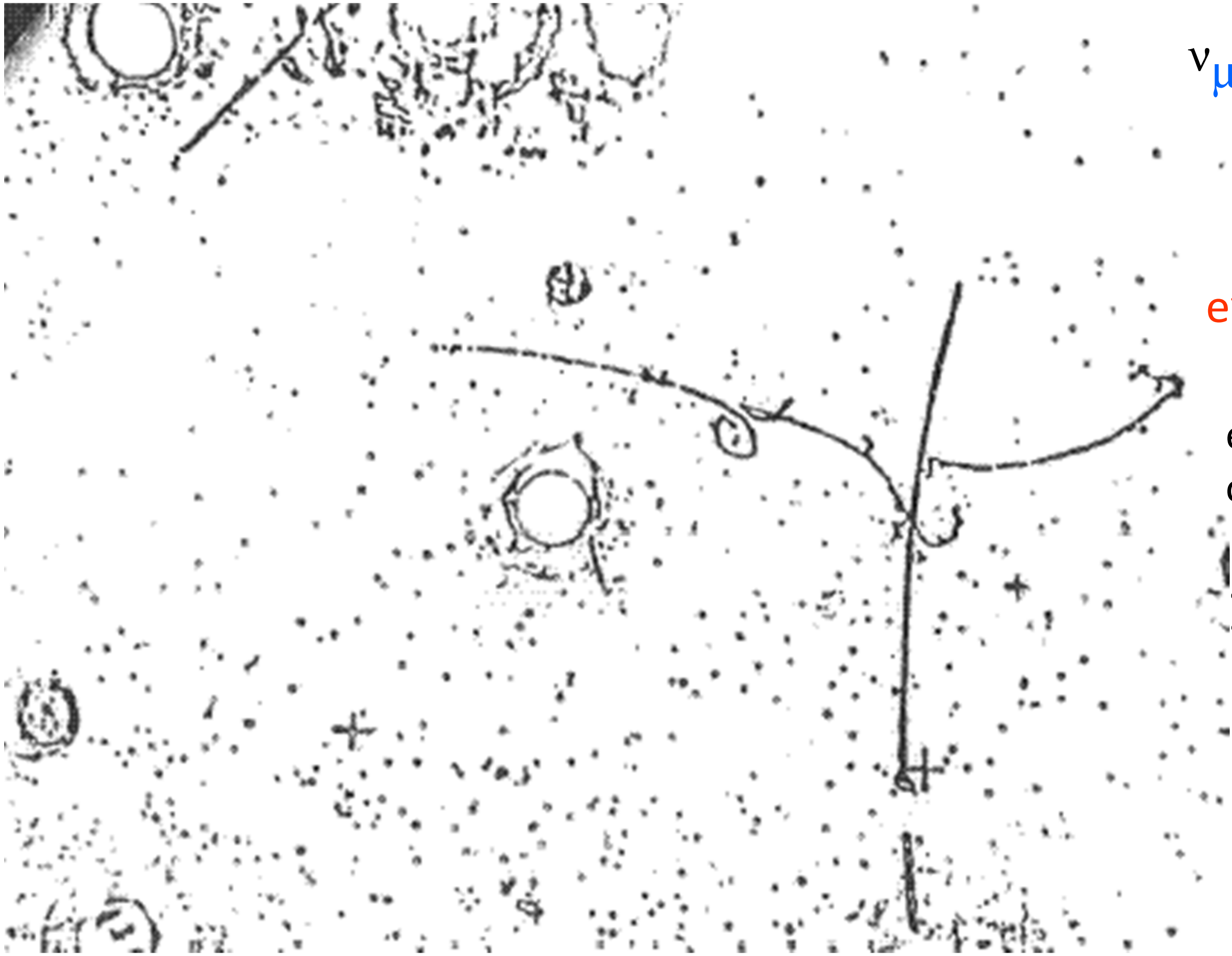
$\nu_\mu + e \rightarrow \nu_\mu + e$

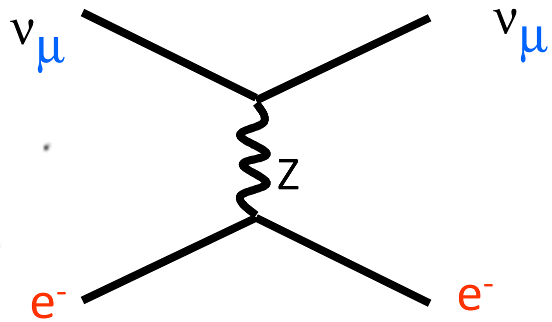
$\nu_\mu + N \rightarrow \nu_\mu + X$ (no muon)

1973

previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \to \mu\mu$) leading to extremely stringent limits (10^{-7} or so)

early neutrino experiments had set their trigger on final state (charged) lepton!





elastic scattering of neutrino off electron in the liquid

1973 Gargamelle

experimental birth of the Standard model

The Standard Model: 3 families of spin 1/2 quark and leptons interacting with spin 1 vector bosons (γ, W&Z, gluons)

charged leptons	e	μ	τ
	mc^2=0.0005 GeV	0.106 GeV	1,77 GeV
neutral leptons = neutrinos	ν_e	ν_μ	ν_τ
	mc^2 ?=? <1 eV	<1 eV	<1 eV
quarks	d	strange	beauty
	mc^2=0.005 GeV	0.200 GeV	5 GeV
	u	charm	top
	mc^2=0.003 GeV	1.5 GeV	mc^2=175 GeV
	First family	Seconde family	Third family

elementary particles

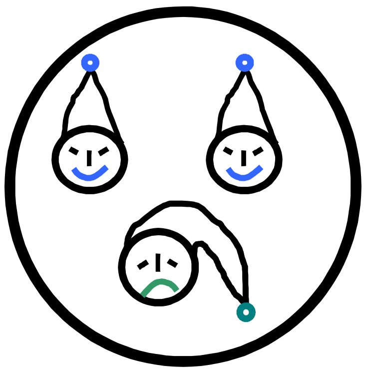
10^{-10} m   Atom = nucleus + electrons

10^{-15} m   Nucleus = protons+neutrons

$<10^{-18}$ m   protons & neutrons = 3 quarks

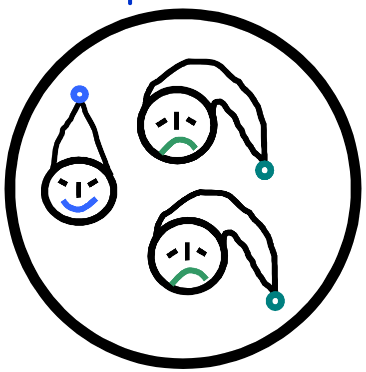
Quarks are never alone and form 'mènage à trois' or couple with an antiquark.

Proton=
2 up + 1 down

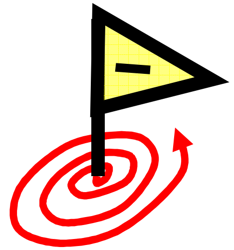


Charge=

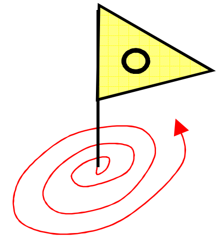
Neutron=
1 up + 2 down



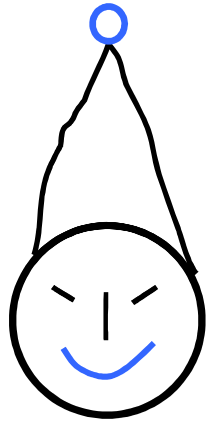
Charge=



Electron
charge -1



Neutrino
charge 0



Quark up
charge 2/3

Quark down
charge -1/3

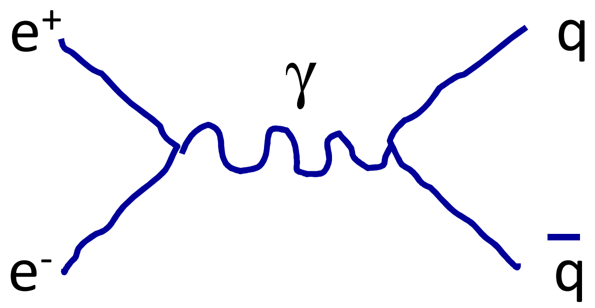
Any resemblance with real particles is pure coincidence

Interaction vectors

électromagnetic (neutral)

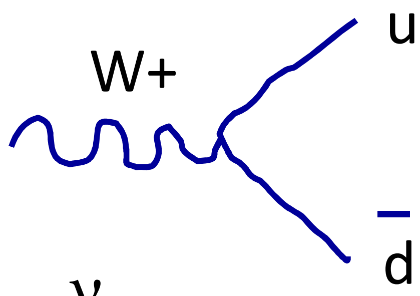
$e^+ + e^- \rightarrow \gamma \rightarrow q + \bar{q}$

(photon 'virtuel')



weak and charged

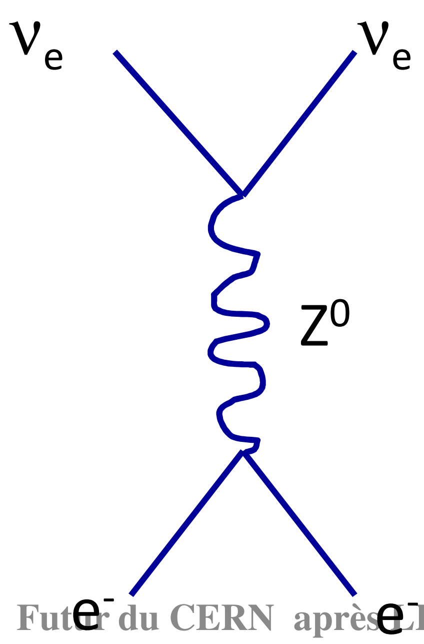
$W^- \rightarrow u + \bar{d}$

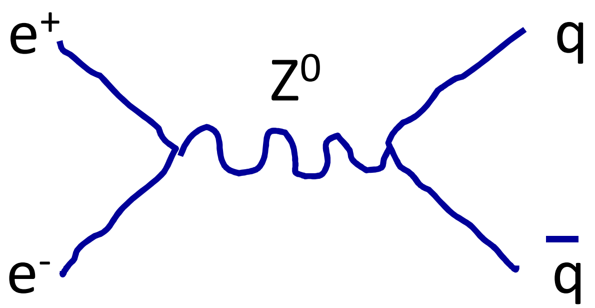


weak and neutral

$\nu_e\, e^- \rightarrow \nu_e\, e^-$

$e^+ + e^- \rightarrow Z \rightarrow q + \bar{q}$





all BOSONS, spin 1

Since then we have understood that all works with a Standard Model of 3 famillies of quarks and leptons of spin ½, interacting via bosons of spin 1 (g, W&Z, gluons)

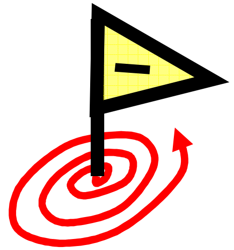
charged leptons	e	μ	τ
	mc^2=0.0005 GeV	0.106 GeV	1,77 GeV
neutral leptons = neutrinos	ν_e	ν_μ	ν_τ
	mc^2 ?=? <3 eV	<3 eV	<3 eV
quarks	d	strange	bottom
	mc^2=0.005 GeV	0.200 GeV	5 GeV
	u	charm	top
	mc^2=0.003 GeV	1.5 GeV	mc^2=172 GeV
	Family 1	Family 2	Family 3

Remarkable symmetry

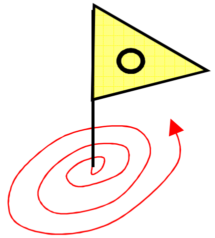
Each quark appears with 3 colors in such a way that the
-- the charge of the proton and the charge of the electron are opposite
and the charge of each family sums up to zero.

$$-1 + 0 + 3 \text{ x } (2/3 \; - 1/3) = 0$$

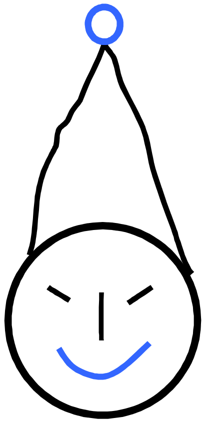
this is a necessary condition for the stability of the Universe.



Electron
charge -1



Neutrino
charge 0



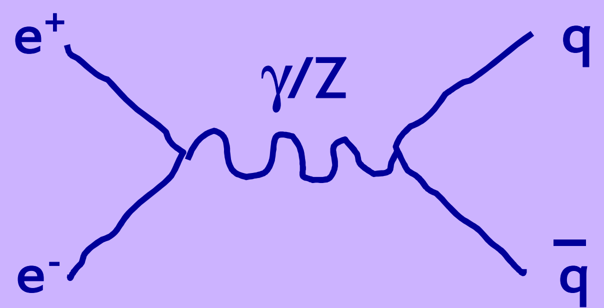
3 Quarks up
charge 2/3

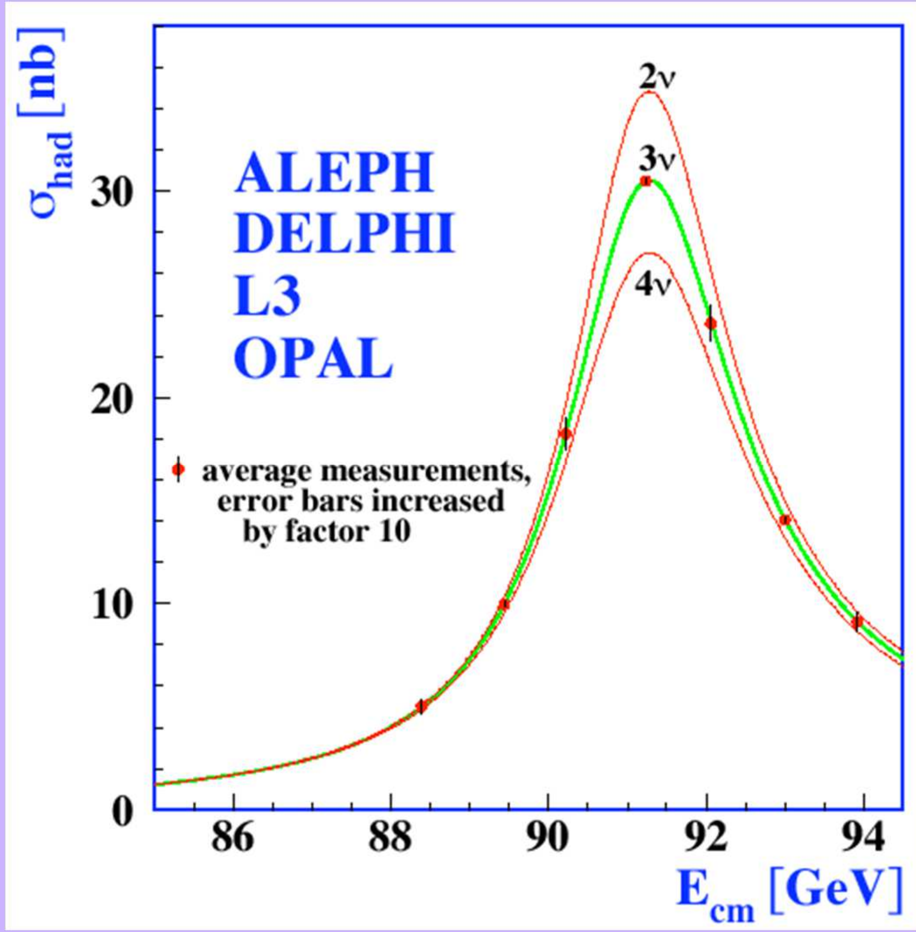
3 Quarks down
charge -1/3

We know from LEP that there are only three families of neutrinos

$N_\nu = 2.9841 \pm .0083$

$e^+ e^- \rightarrow \gamma/Z \rightarrow q\,\bar{q}$

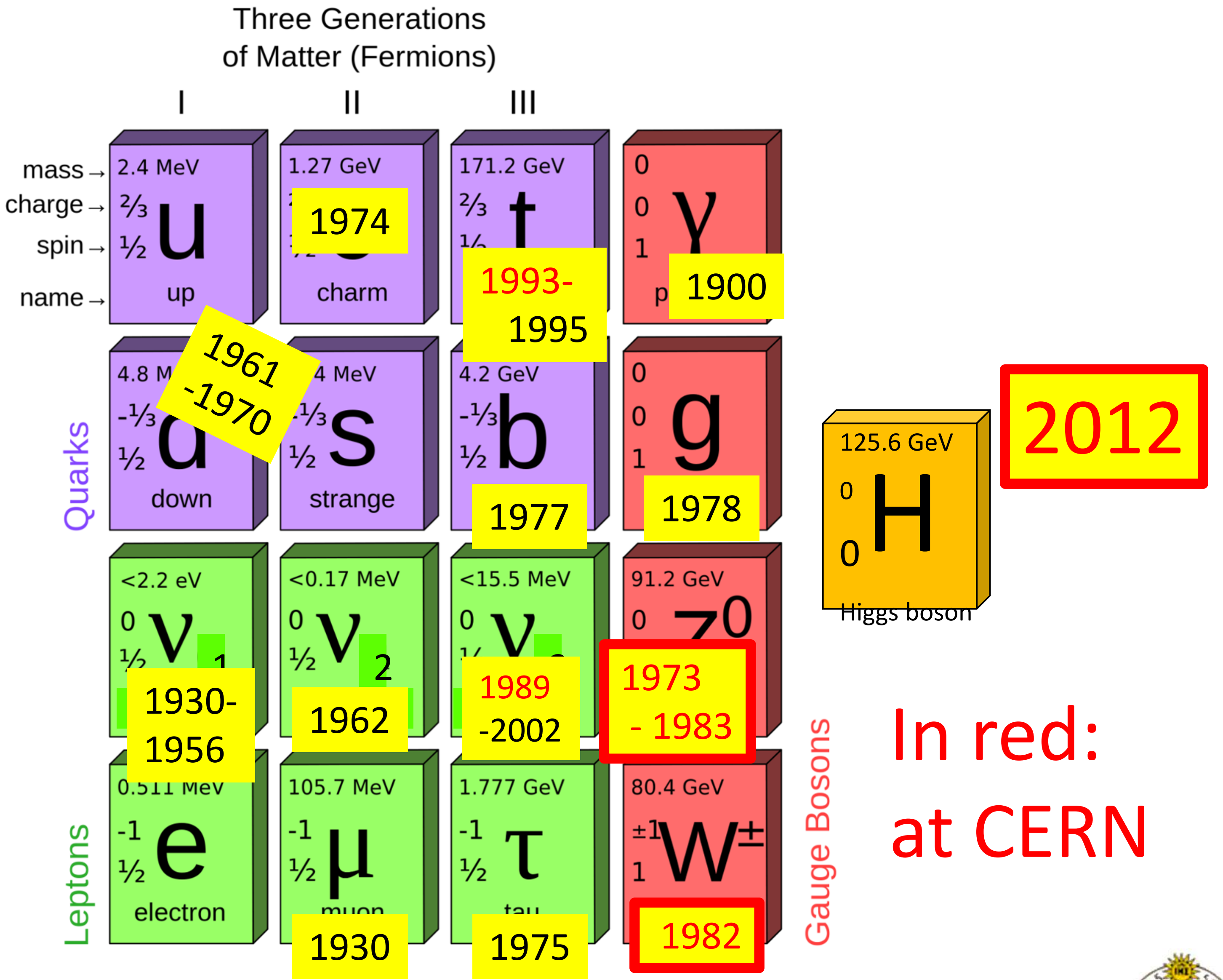




Nombre of Z produced in e^+e^- collisions
as function of energy with the prediction for 2, 3 or 4 families.

And we know from the Higgs production at the LHC there there are no more families of charged quarks and leptons!

CONSTRUCTION of the Standard Model



1897

The detailed theory is based on symmetries

One of the mysteries had been
why do Z and W particles have a mass,
while the – similar-- photon has no mass?

The solution was proposed in 1964
(Englert, Higgs) → Higgs boson
The masses of the W and Z were predicted
in 1974 after the discovery of neutral currents
and the W and Z were discovered in 1982/3.

Why was the discovery of the Higgs boson so important to particle physicists?

➔ because it represents the «completion» of the Standard Model.

Is it the end?

A more mundane formulation:

Is there a future for CERN after the LHC and the discovery of the Higgs boson?

With the Higgs Boson, the Standard Model is a

complete coherent and predictive
theory of particles and their interactions

Are we done?

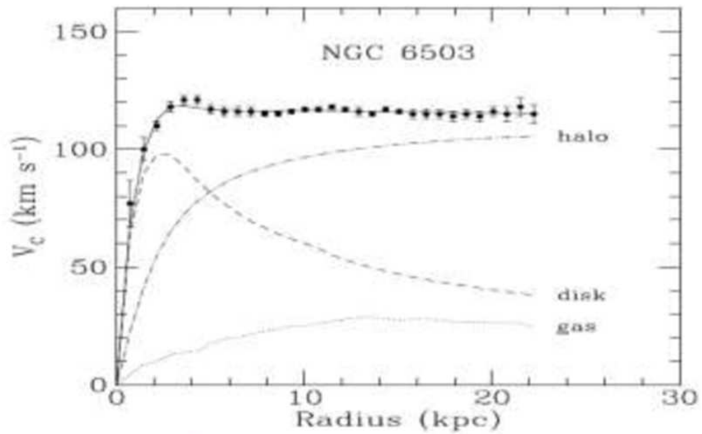
NO!

We are *certain* that exist other particles and/or phenomena!

We cannot explain:

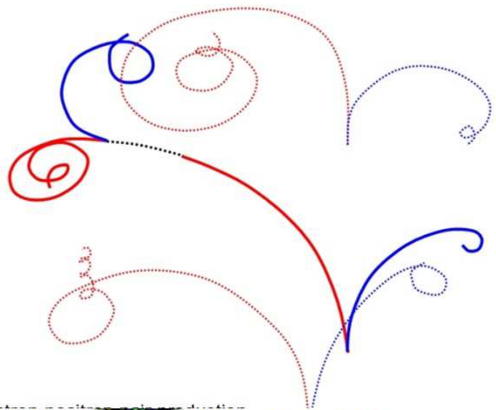
Dark matter

Standard Model particles constitute only 5% of the energy in the Universe



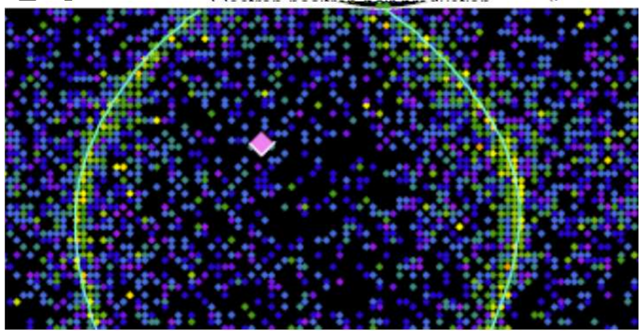
Rotation curve for Galaxy

Were is antimatter gone?



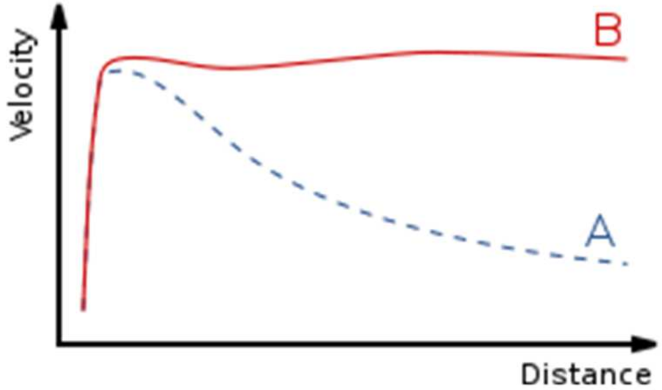
What makes neutrino masses?

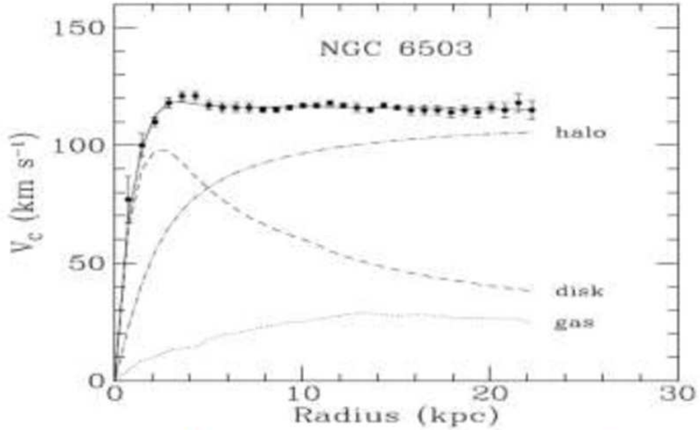
Not a unique solution in the SM --
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw...)
➔ heavy right handed neutrinos?



Dark Matter

Andromeda Galaxy





Rotation curve for Galaxy

$$v \propto \sqrt{\frac{G.M}{d}}$$

M= mass contained inside the orbit

We observe B $\Rightarrow$ mass increases linearly with distance, while it looks as is there is much more mass in the center!

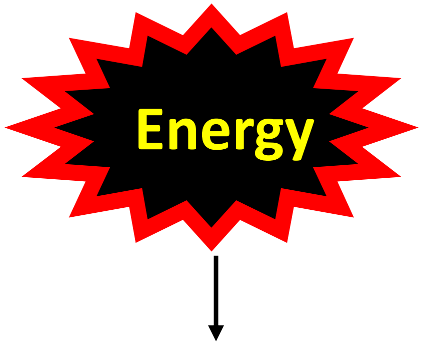
The Universe contains a continuum of dark matter!

Dark matter hypotheses

-- balck holes ?	not enough
-- big planets 'Jupiters' and dead stars	not enough
-- new supersymmetric particles with weak interaction? (WIMP)	not seen yet
-- the neutrinos we know?	too light!
-- sterile neutrinos ?	maybe!
-- very light spin 0 particle (axion)	maybe!

A Mystery

Big Bang



Particule + anti-particule

there should be as much matter as antimatter in the UNIVERSE!

Where is Antimatter ?

This is an obvious problem of astrophysics and cosmology.
we need (Sakharov)

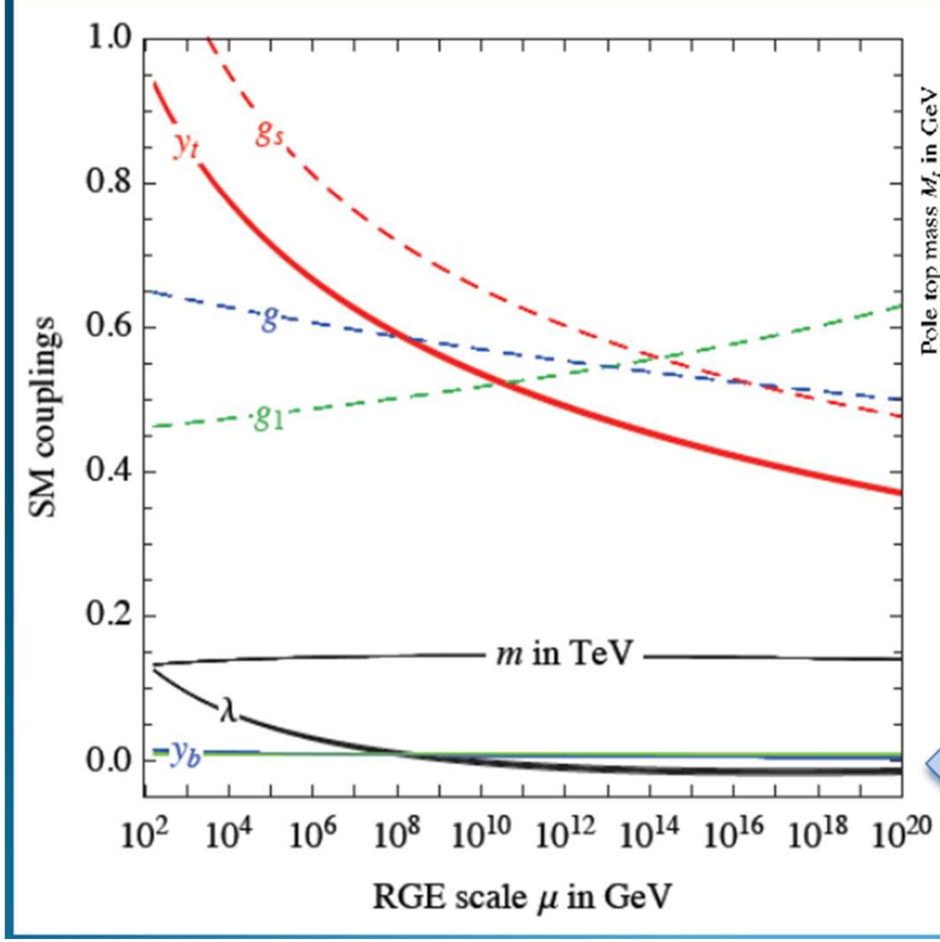
1. **Non equilibrium condition** — **Big Bang OK**
2. **A matter antimatter transition**
3. **Violation of the symmetry between matter and antimatter**

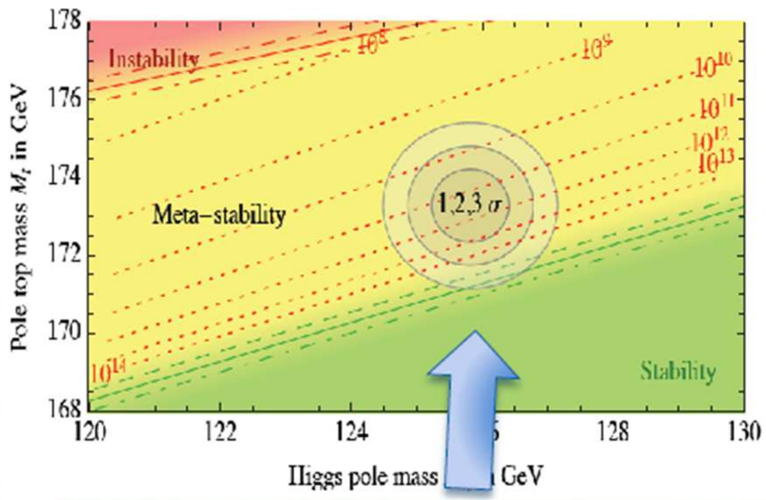
Big Bang gives (1)
Neutrinos may provide (2) AND (3)

SOME SAY WE CAN EXTRAPOLATE ***directly*** TO PLANCK SCALE...

What is m≈125.8 GeV telling us?

Strumia
Elias-Miro





We are safe!

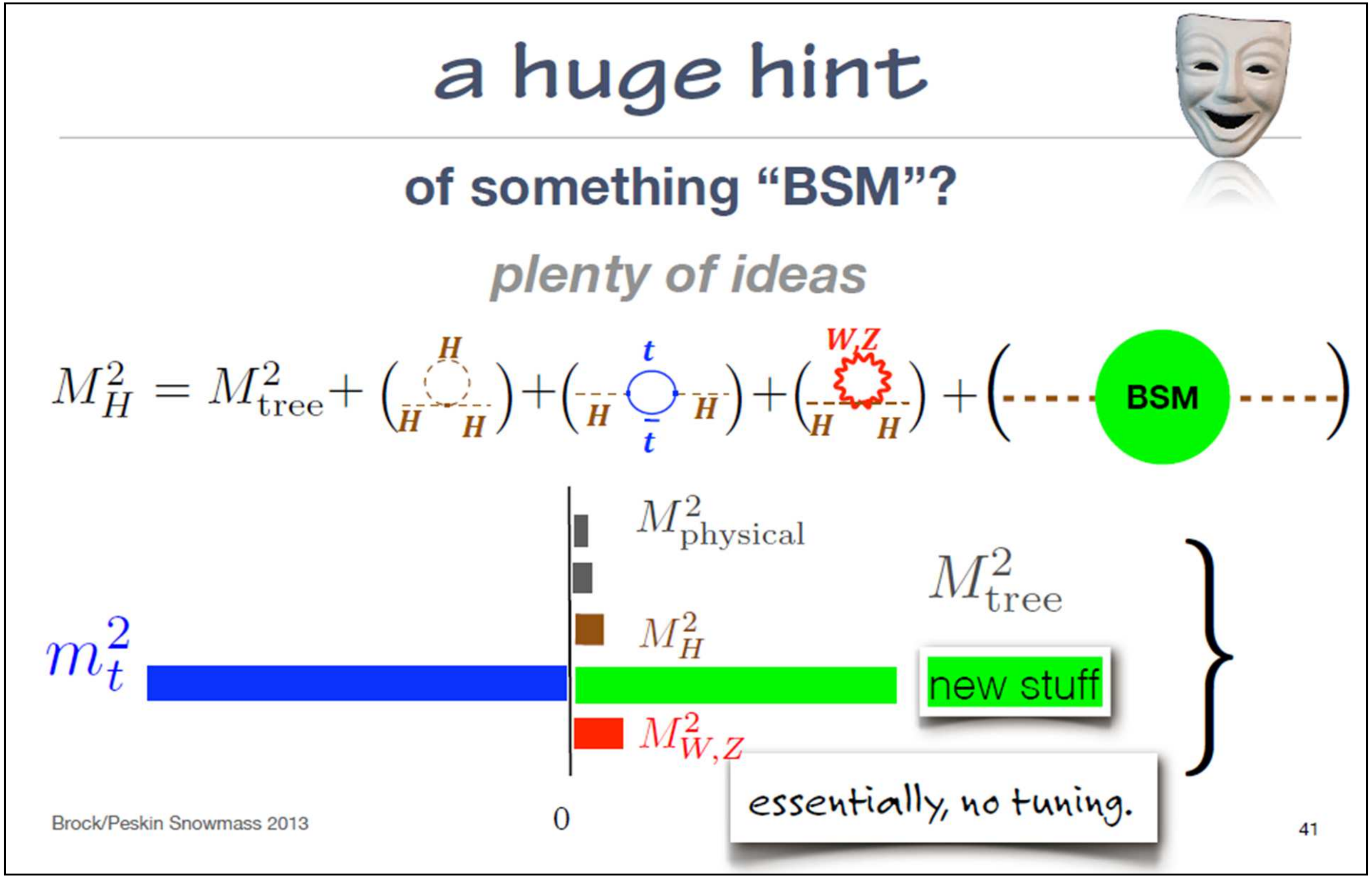
λ & β_λ nearly 0 for $\mu > 10^8$ GeV

F. Zwirner, Moriond 2013 Summary

AB: too good to be true... I will believe it when I see it!

E-LHC

And some say there MUST be new physics at TeV scale



AB: or is it just that the SM scalar self energy can't make sense perturbatively?

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

Share this: 951

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

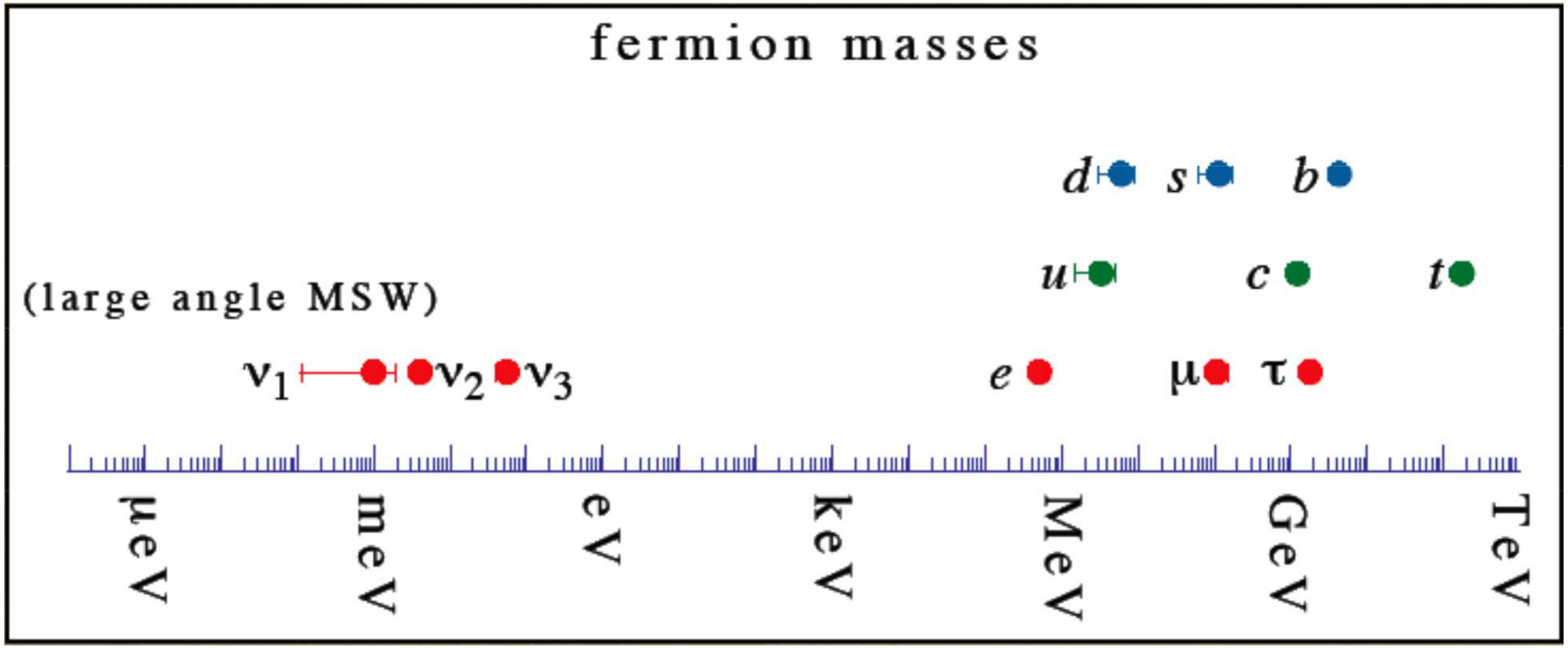
Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Q | Terms

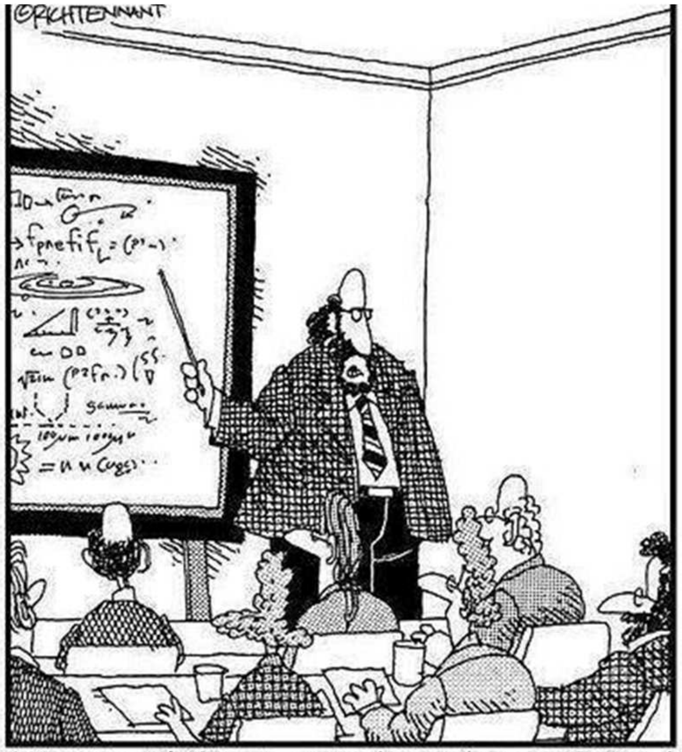


$10^{12\text{-}14}$

AB: is'nt THIS a hierarchy problem?

Electroweak eigenstates

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R \quad (\mu)_R \quad (\tau)_R$	Q= -1
	$(\nu_e)_R \quad (\nu_\mu)_R \quad (\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	



“Along with ‘Antimatter,’ and ‘Dark Matter,’ we’ve recently discovered the existence of ‘Doesn’t Matter,’ which appears to have no effect on the universe whatsoever.”

Right handed neutrinos
are singlets
no weak interaction
no EM interaction
no strong interaction

can’t produce them
can’t detect them
-- so why bother? –

Also called ‘sterile’

From neutrino oscillation experiments
we know that neutrinos have mass, but there
is no unique way to do this in the Standard Model

Because the neutrinos have no charge
it is possible that there is an interaction
that changes a neutrino into an anti-neutrino

in our jargon this is called ‘Majorana mass term’

If this is the case the sterile neutrinos
-- are not exactly sterile
-- much heavier than the normal ones
-- possible dark matter candidate and
-- good to explain the absence of antimatter

Is it the end?

Certainly not!

-- Dark matter

-- Baryon Asymmetry in Universe

-- Neutrino masses

are experimental proofs that there is more to understand.

We must continue our quest

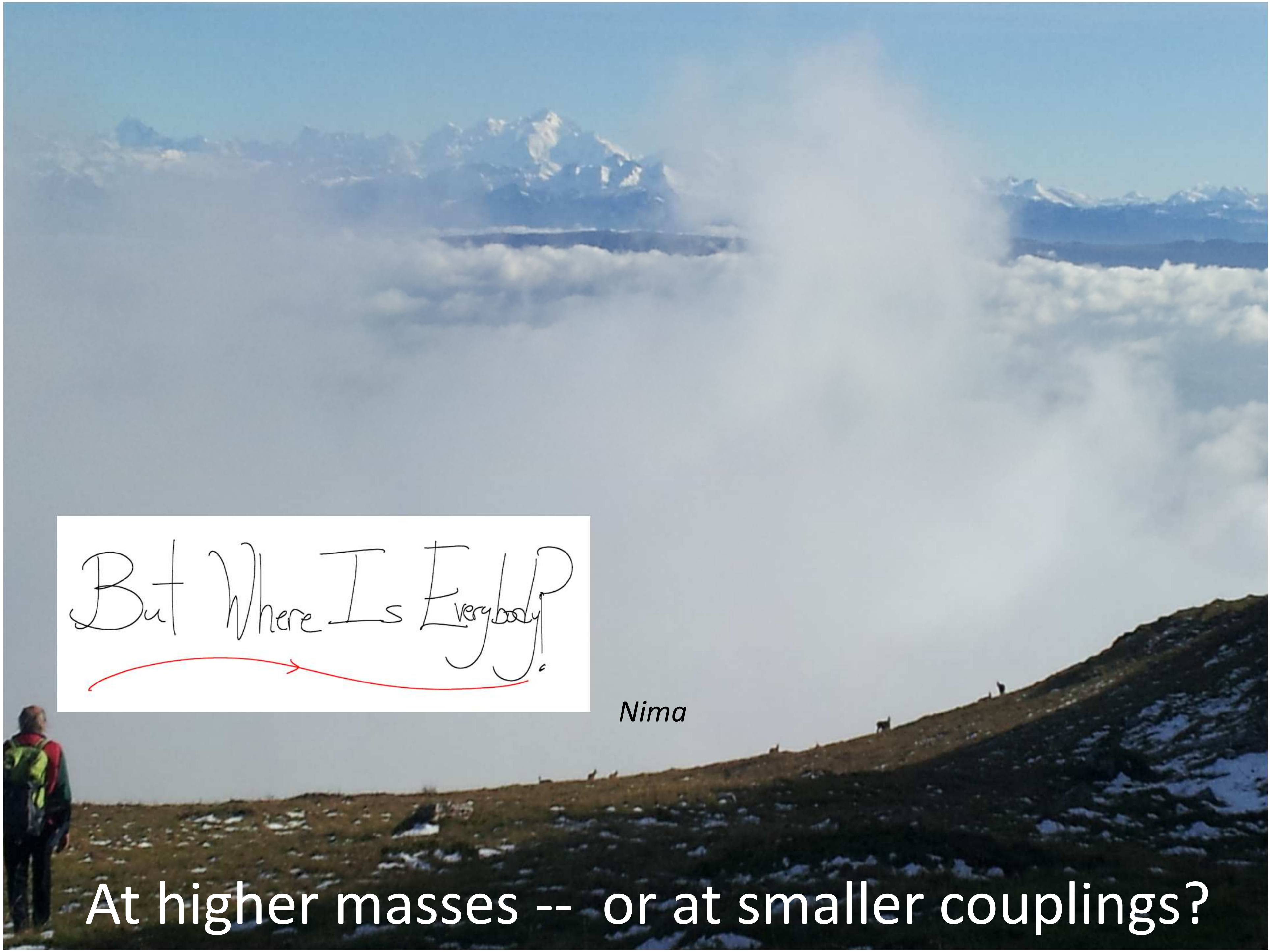
HOW?

Direct observation of new particles (but not only!)

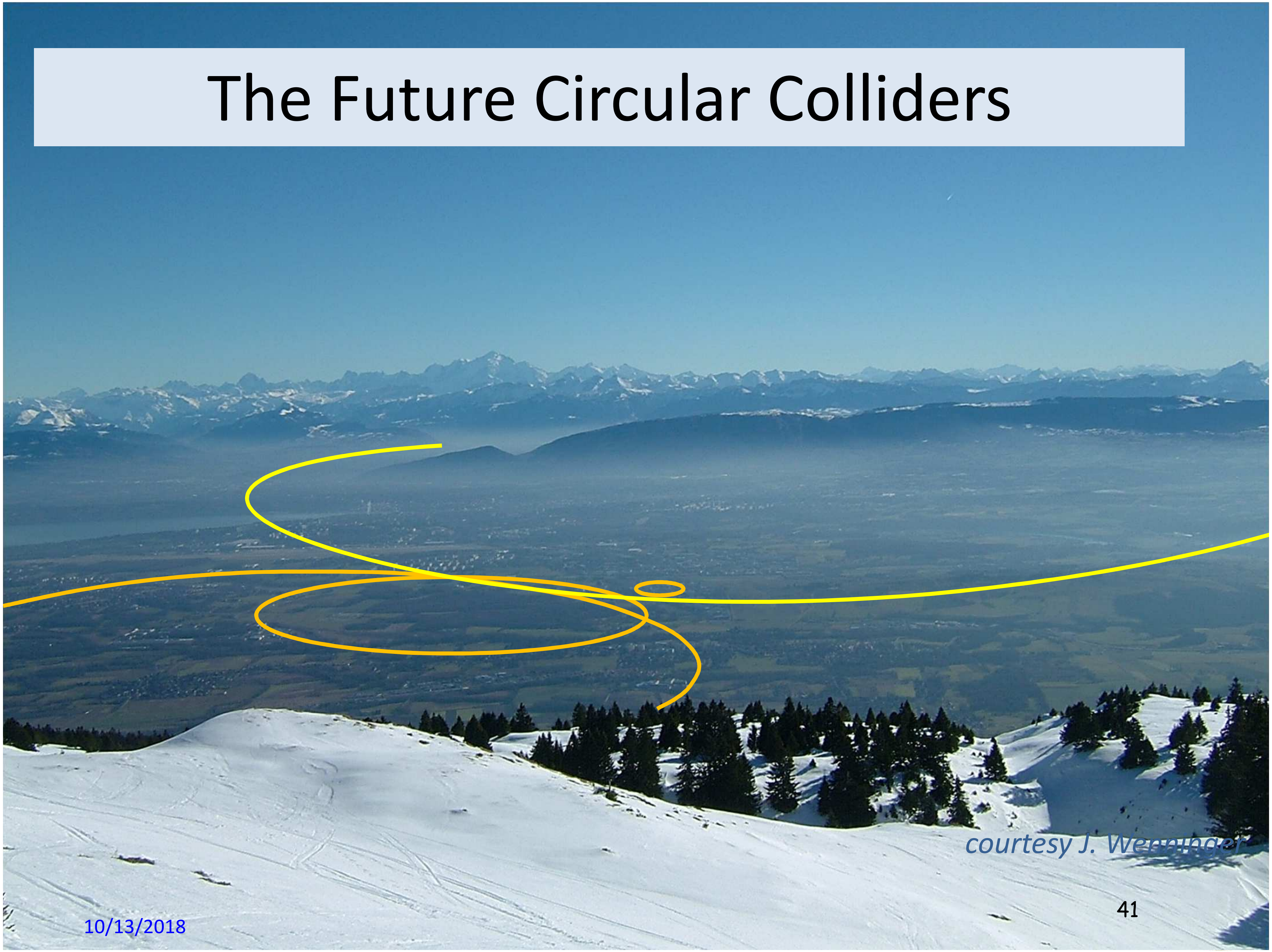
New phenomena (Neutral currents, CP violation, neutrino oscillations…)

Deviations from precise predictions

(ref. Uranus to Neptune, top and Higgs preds from LEP/SLC/Tevatron/B factories, g-2, etc…)


But Where Is Everybody?
Nima
At higher masses -- or at smaller couplings?

The Future Circular Colliders



courtesy J. Wenninger

The Future Circular Colliders
CDR and cost review to appear Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** **~16 T magnets**
  ***100 TeV pp*-collider (*FCC-hh*)**

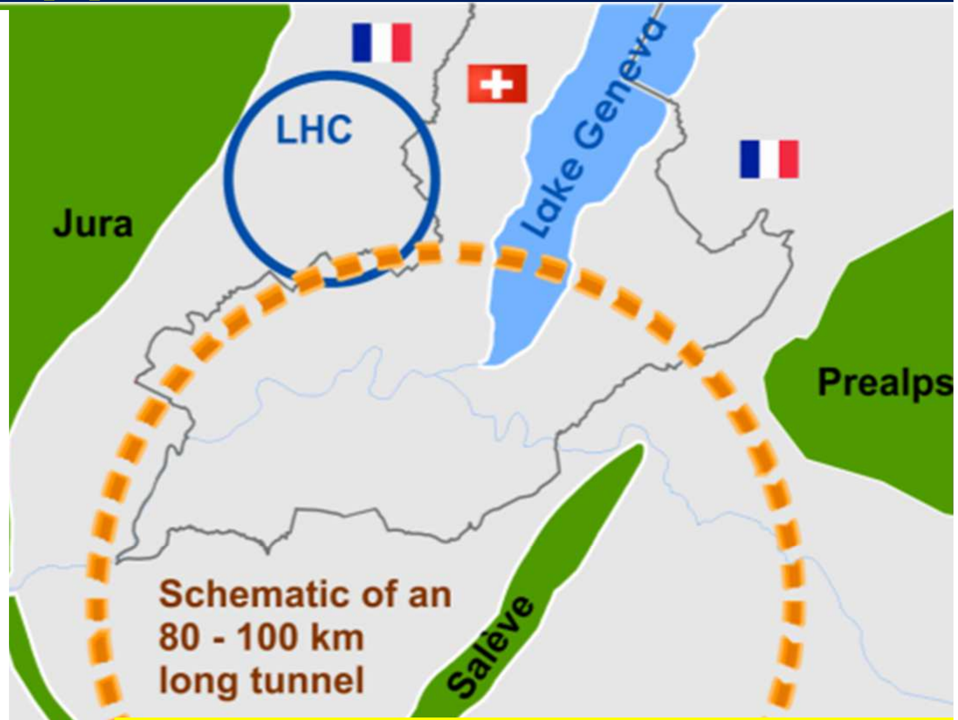
→ defining infrastructure requirements

Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC* 16T ⇒ 28 TeV**
  in LEP/LHC tunnel

Possible addition:

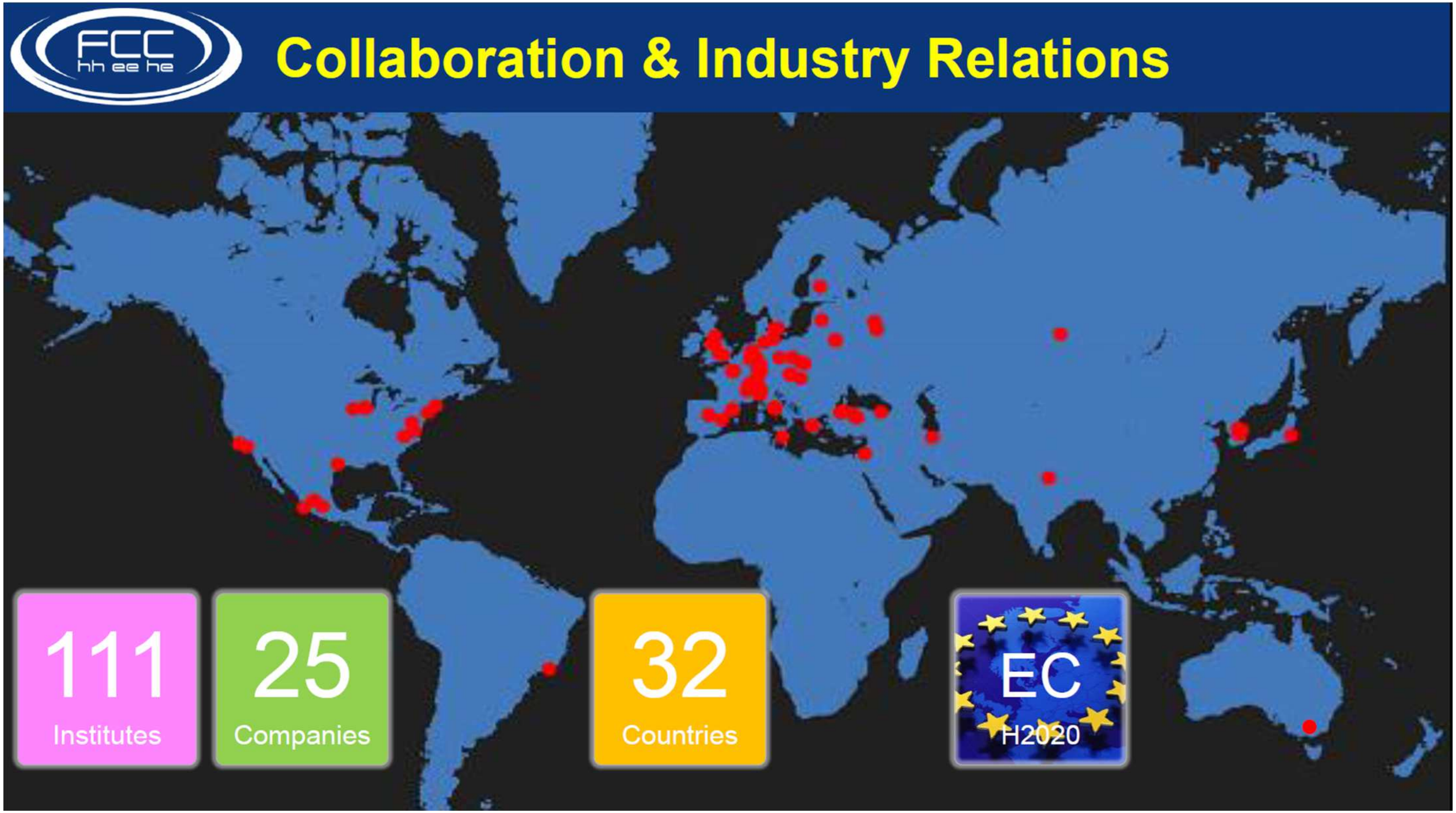
- ***p-e* (*FCC-he*) option**



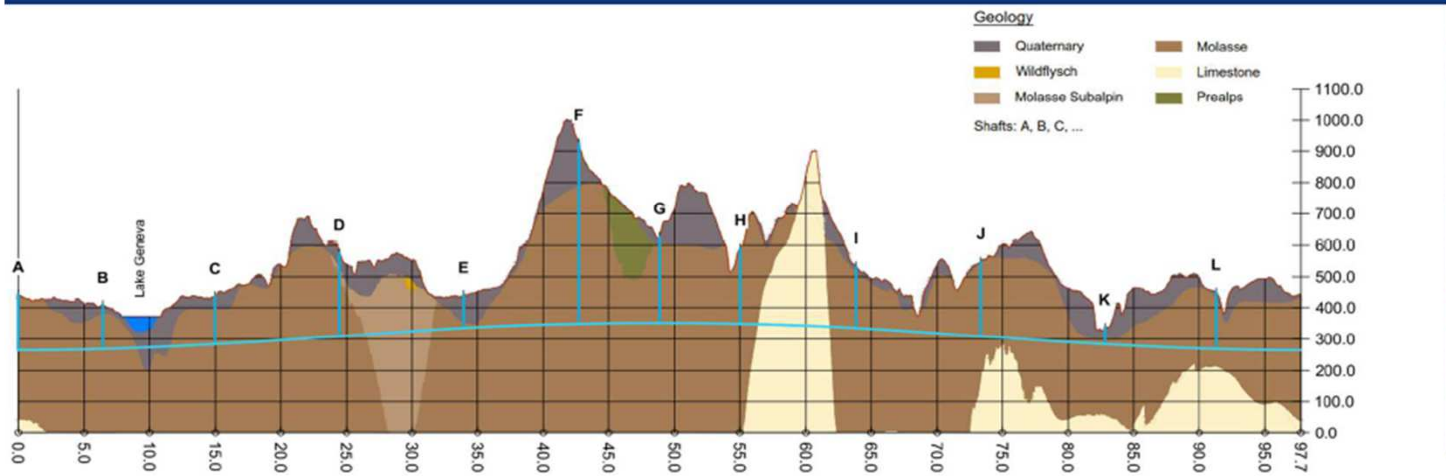
From what we know today :
the way by FCC-ee is probably the fastest and cheapest way to 100 TeV.
That combination also produces the most physics. It is the assumption in the following.

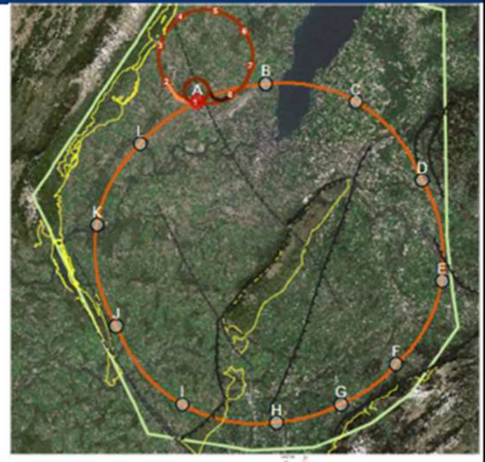
also a good start for μC!

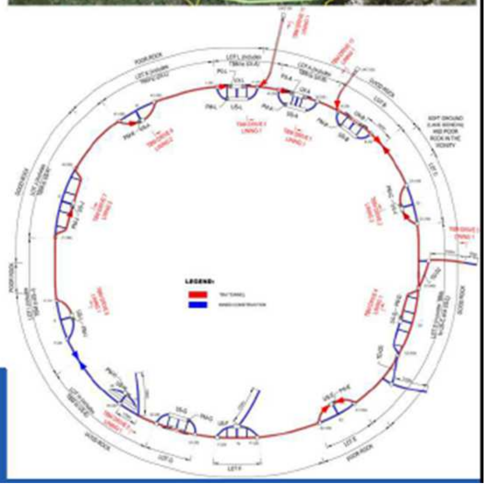
From European Strategy in 2013: "ambitious post-LHC accelerator project"
Study kicked-off in Geneva Feb 2014


Collaboration & Industry Relations
FCC
hh ee he
111
Institutes
25
Companies
32
Countries
EC
H2020

FCC implementation - footprint baseline







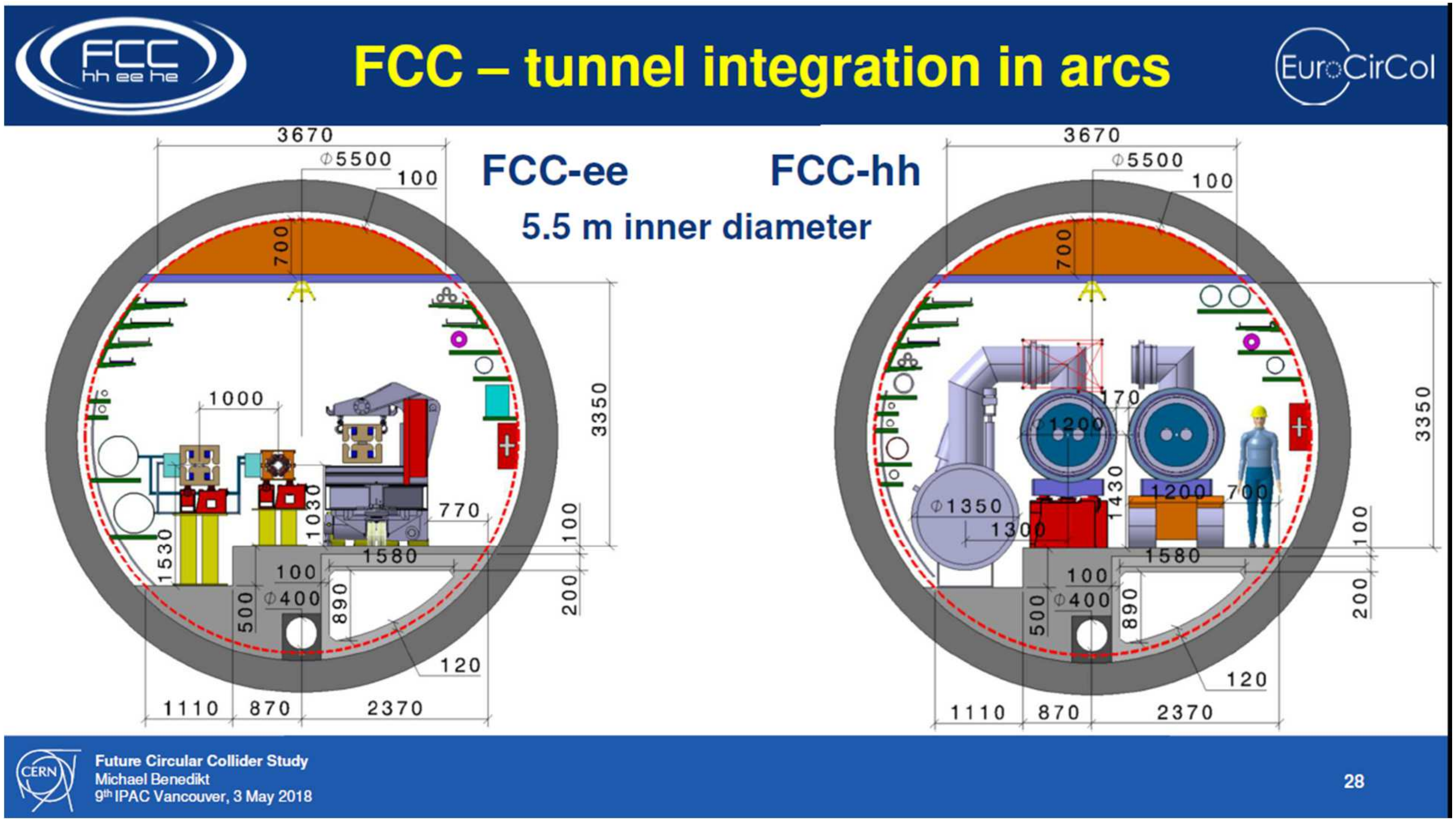
Present baseline position was established considering:

- lowest risk for construction
- fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

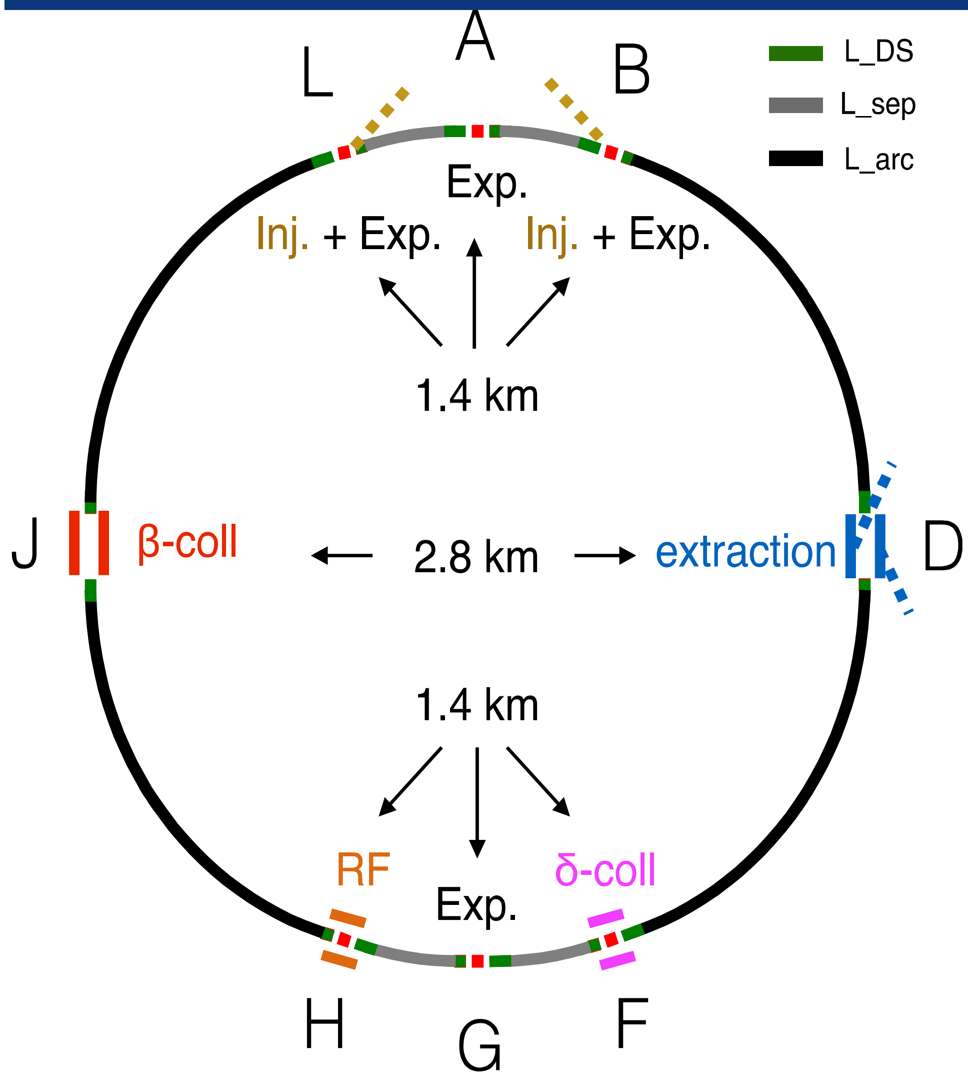
next step: review of surface site locations and machine layout

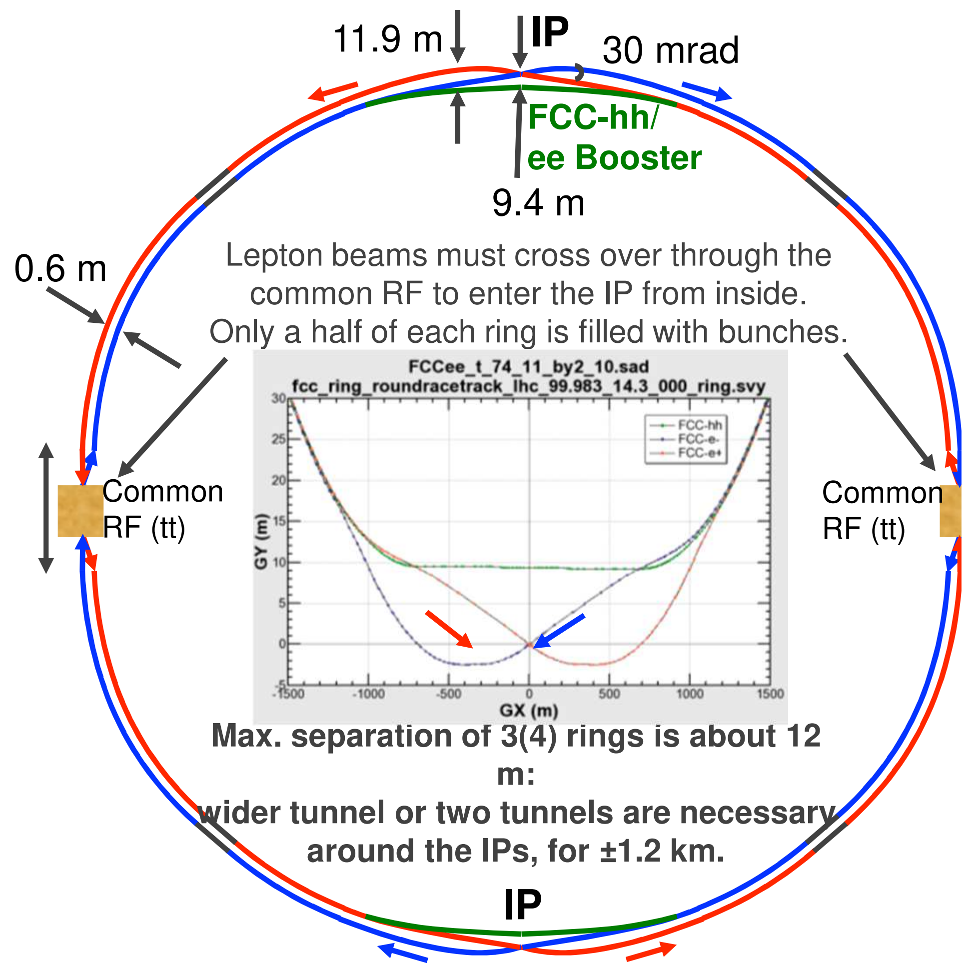
Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

Sharing the same tunnel


FCC hh ee he
FCC – tunnel integration in arcs
EuroCirCol
FCC-ee
FCC-hh
5.5 m inner diameter
3670
Φ5500
100
700
3350
1000
1530
1030
770
1580
100
Φ400
500
890
200
120
1110
870
2370
170
Φ1200
1430
1200
700
Φ1350
1300
Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018
28

common layouts for hh & ee





FCC-ee 1, FCC-ee 2,

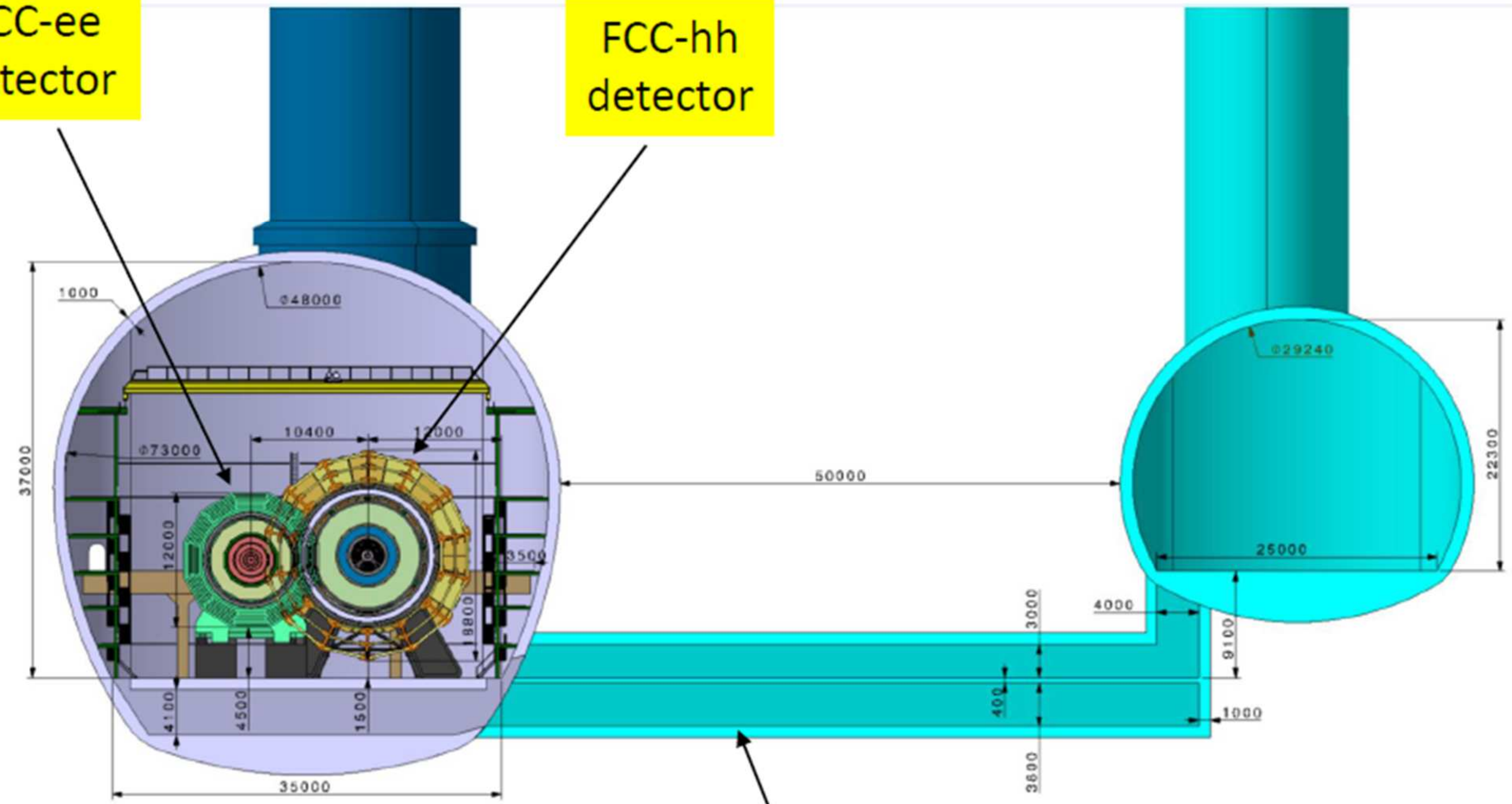
FCC-ee booster (FCC-hh footprint)

Asymmetric IR for ee, limits SR to expt.

2 main IPs in A, G for both machines

The same caverns

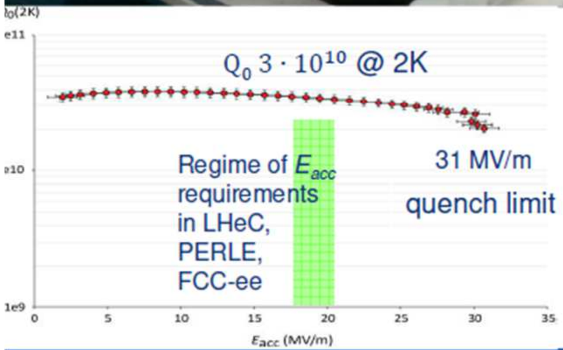
Distance between detector cavern and service cavern 50 m.



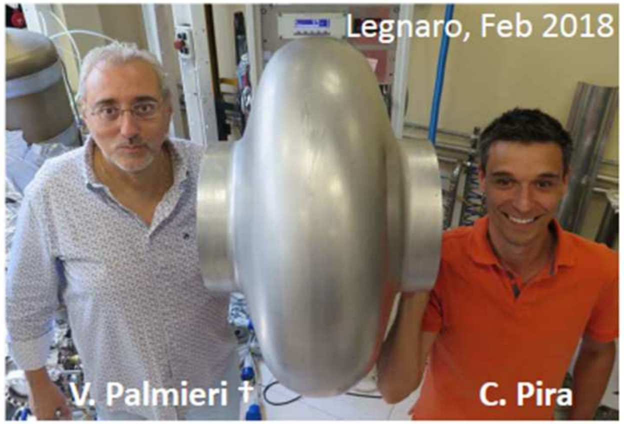
Preliminary design of access and cable path

SRF cavity development program (examples)

5-cell 800 MHz cavity, JLAB prototype for both FCC-ee (t-tbar) & FCC-eh ERL (PERLE)



Seamless 400 MHz single-cell cavity formed by spinning at INFN-LNL



Tooling fabricated and successfully tested with an Aluminium cavity.

† We're saddened about the sudden death of Vincenzo Palmieri few weeks ago.

CERN half-cells formed using Electro-Hydro-Forming (EHF) at Bmax.

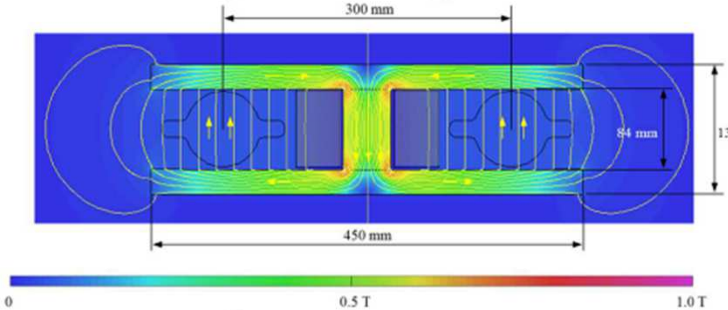
High strain rate technology using shockwaves in water from HV discharge. EHF investigated for half-cells and seamless Nb and Cu cavities.

Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

10

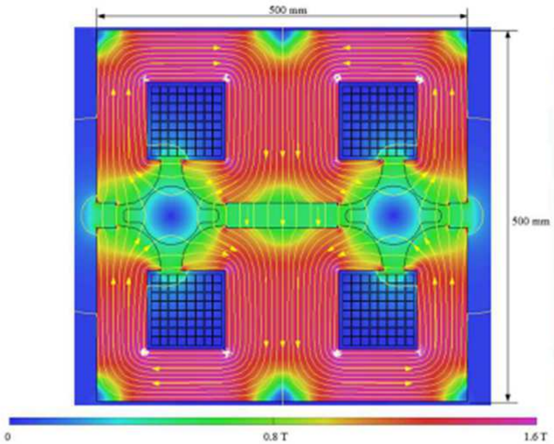
Low-power low-cost design for FCC-ee magnets

Twin-dipole design with 2× power saving
16 MW (at 175 GeV), with Al busbars

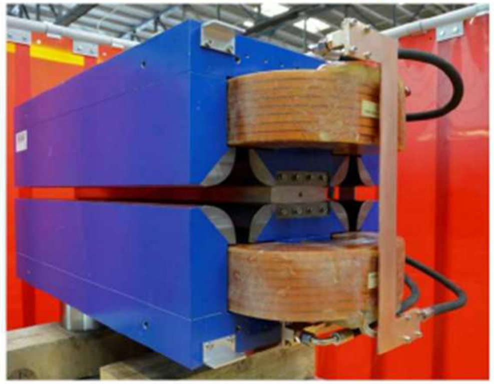


first 1 m prototype

twin F/D quad design with 2× power saving
25 MW (at 175 GeV), with Cu conductor



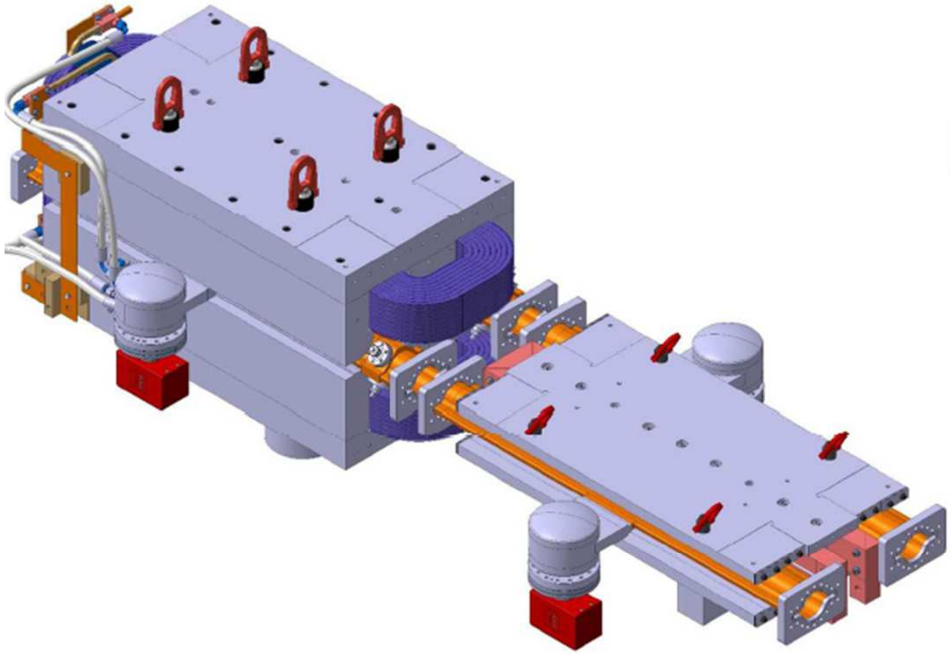
first 1 m prototype



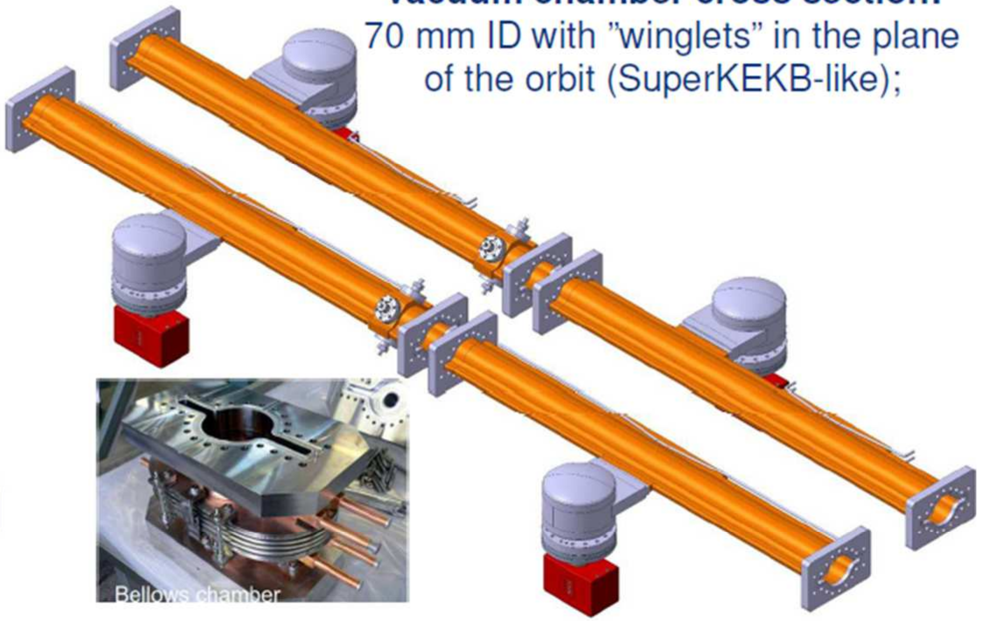
Future Circular Collider Study
Michael Benedikt
9th IPAC Vancouver, 3 May 2018

11

FCC-ee arc vacuum prototyping & integration



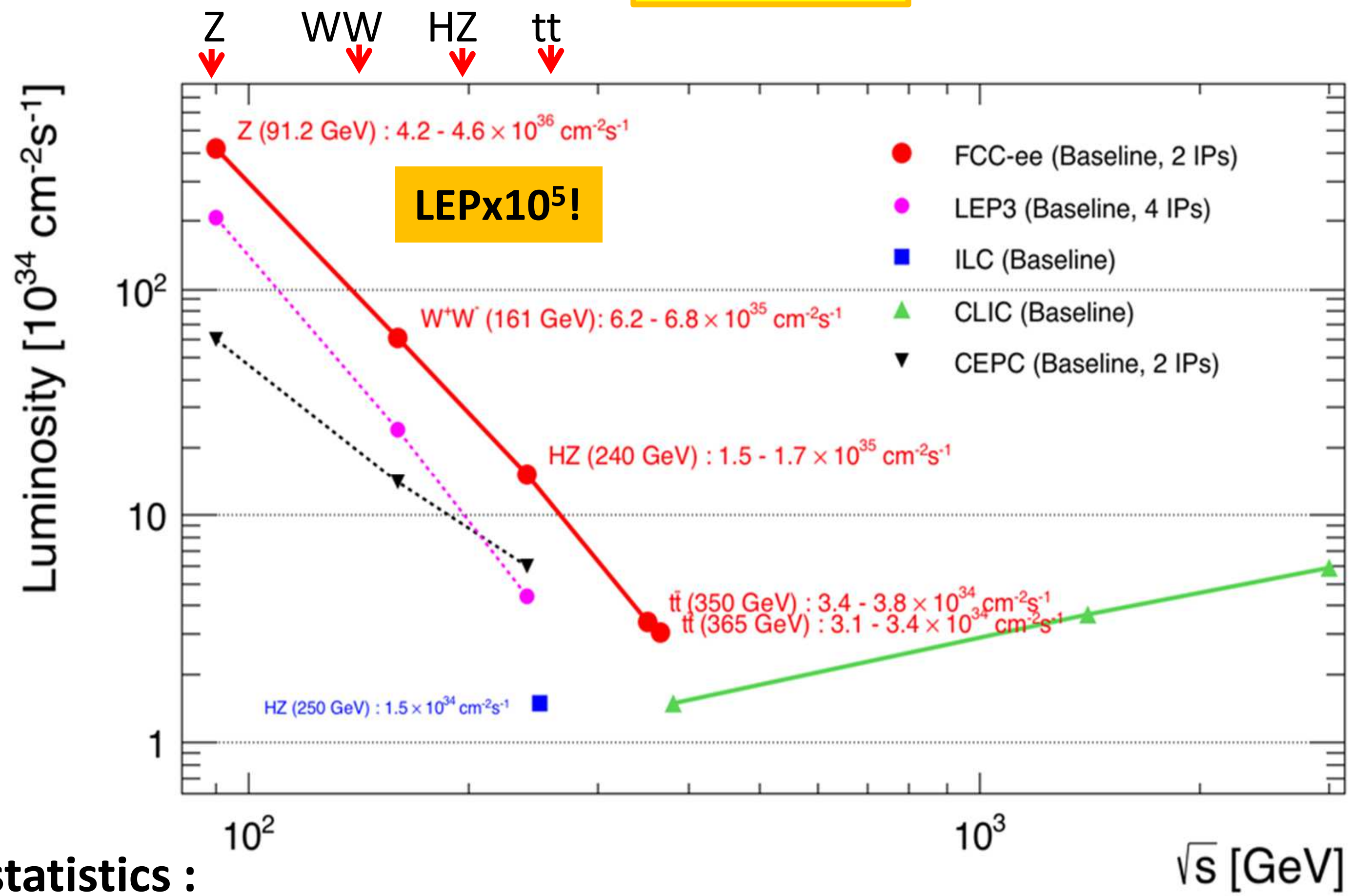
Vacuum chamber cross section:
70 mm ID with "winglets" in the plane of the orbit (SuperKEKB-like);



- The chambers feature **lumped SR absorbers with NEG-pumps** placed next to them.
- **Construction of chamber prototypes in coming months and integration with twin magnets**

Alain Blondel TH FCC

FCC-ee



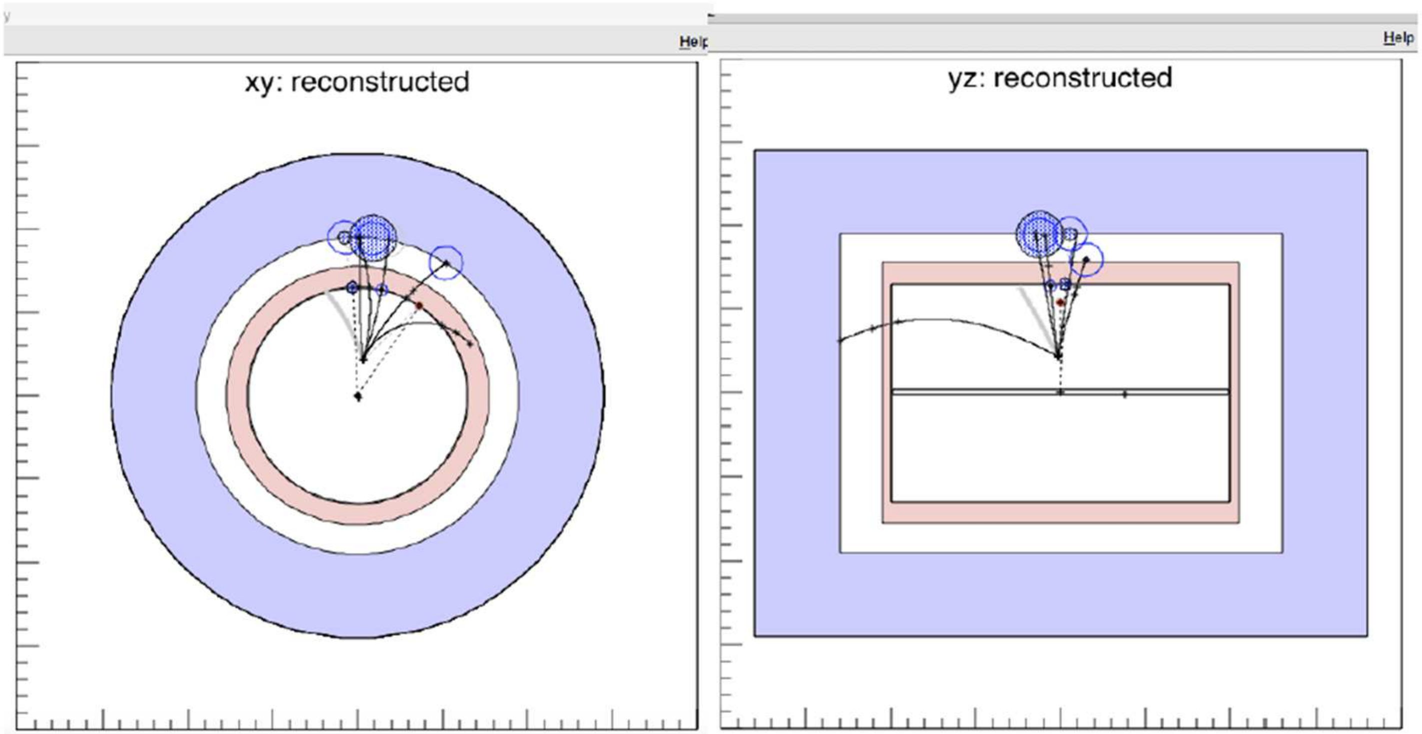
Event statistics :

E_{CM} **errors:**

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	1 MeV
$t\bar{t}$ threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

Great energy range for the heavy particles of the Standard Model.

Simulation of heavy neutrino decay in a FCC-ee detector



can be seen down to 10^{-12} SM coupling

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
m_{Z}, m_W, m_{top}, $\sin^2\theta_w^{eff}$, R_b, $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC ($Z \to \mu\tau$, $e\tau$) in $5\ 10^{12}$ Z decays and τ BR in $2\ 10^{11}$ $Z \to \tau\tau$
+ flavour physics (10^{12} bb events) ($B \to s\tau\tau$ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD ($H \to gg$) etc….

NB Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164

FCC-hh discovery potential
Highlights

FCC-hh is a HUGE discovery machine (if nature …), but not only.

FCC-hh physics is dominated by three features:

-- Highest center of mass energy –> a big step in high mass reach!

ex: strongly coupled new particle up to >30 TeV

Excited quarks, Z', W', up to ~tens of TeV

Give the final word on natural Supersymmetry, extra Higgs etc.. reach up to 5-20 TeV

Sensitivity to high energy phenomena in e.g. WW scattering

-- HUGE production rates for single and multiple production of SM bosons (H,W,Z) and quarks

-- Higgs precision tests using ratios to e.g. $\gamma\gamma/\mu\mu/\tau\tau$/ZZ, ttH/ttZ @<% level

-- Precise determination of triple Higgs coupling (~3% level) and quartic Higgs coupling

-- detection of rare decays H→ Vγ (V= ρ,φ,J/ψ,Υ,Z…)

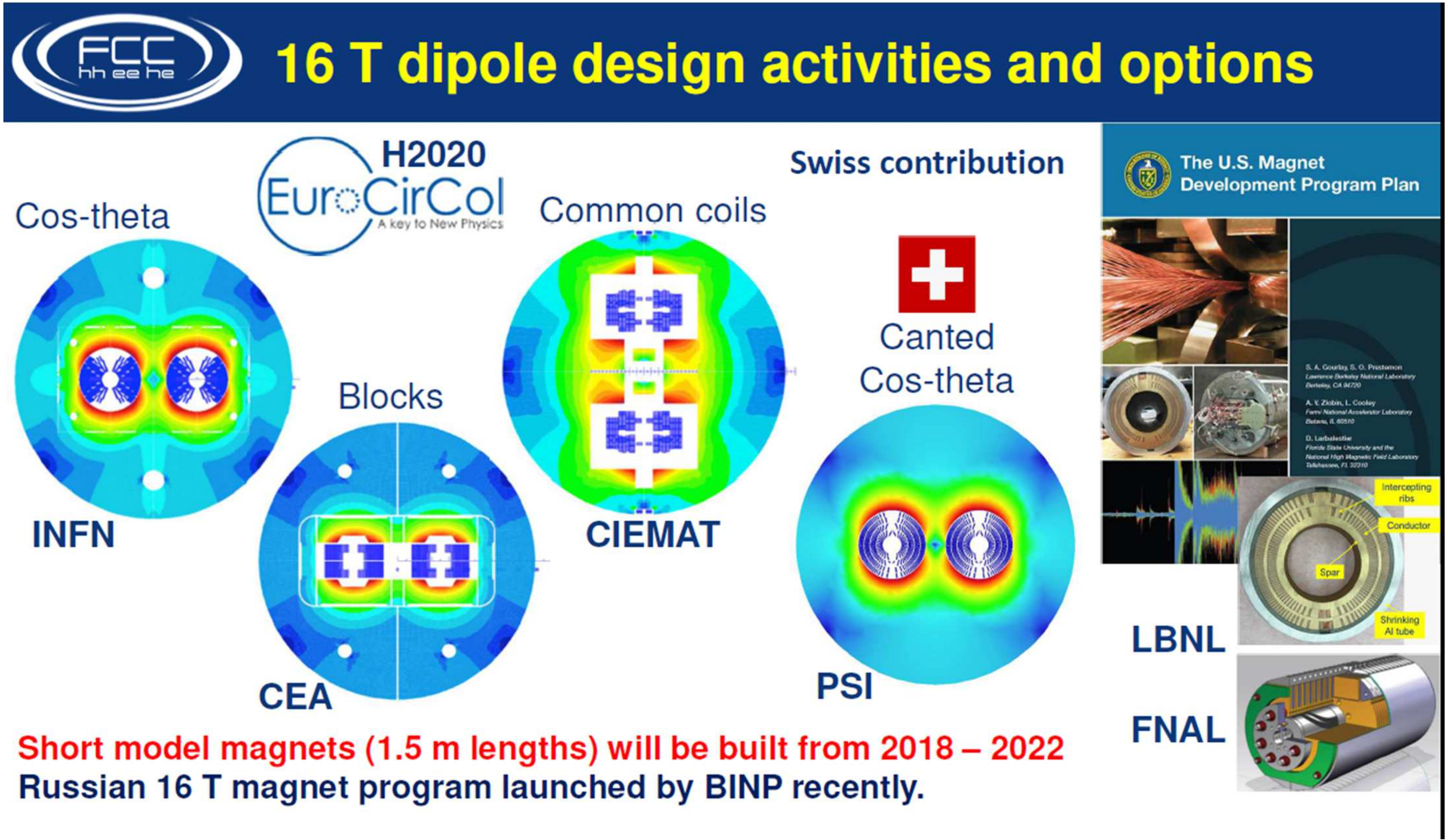
-- search for invisibles (DM searches, RH neutrinos in W decays)

-- renewed interest for long lived (very weakly coupled) particles.

-- rich top and HF physics program

-- Cleaner signals for high Pt physics

-- allows clean signals for channels presently difficult at LHC (e.g. H→ bb)


FCC hh ee he
16 T dipole design activities and options
H2020
EuroCirCol
A key to New Physics
Cos-theta
INFN
Blocks
CEA
Common coils
CIEMAT
Swiss contribution
Canted
Cos-theta
PSI
The U.S. Magnet
Development Program Plan
Intercepting ribs
Conductor
Spar
Shrinking Al tube
LBNL
FNAL
Short model magnets (1.5 m lengths) will be built from 2018 – 2022
Russian 16 T magnet program launched by BINP recently.

CONCLUSIONS

-- The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology. **The CDR is on its way**

-- Both FCC-ee and FCC-hh have outstanding physics cases

-- each in their own right

-- the sequential implementation of FCC-ee, FCC-hh, FCC-eh maximises the physics reach

-- Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities.

FCC (ee) could start seamlessly at the end of HL-LHC (~2038)
A powerful program of development for 16+ T magnets will be required to reach 100 TeV

A successful model!

PHYSICS WITH VERY HIGH ENERGY
e^+e^- COLLIDING BEAMS

CERN 76-18
8 November 1976

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field,
H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann,
K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter,
C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

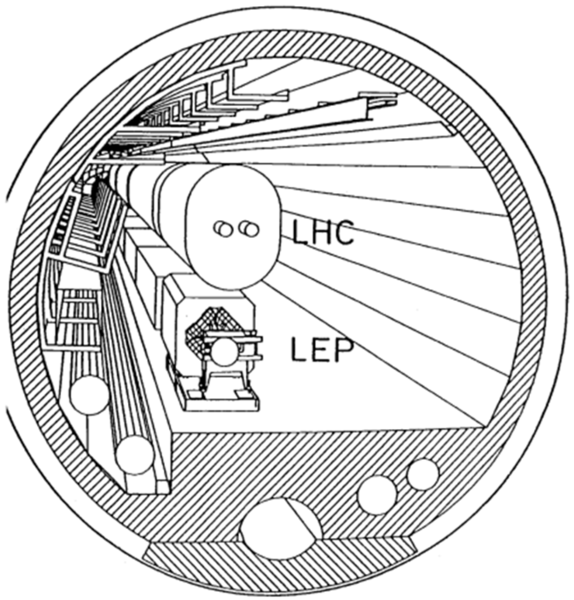
ABSTRACT

This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

Did these people know that we would be running HL-LHC in that tunnel >**60 years later?**

ECFA 84/85
CERN 84-10
5 September 1984

e+e- 1989-2000



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

p p 2009-2039

Let's not be SHY!