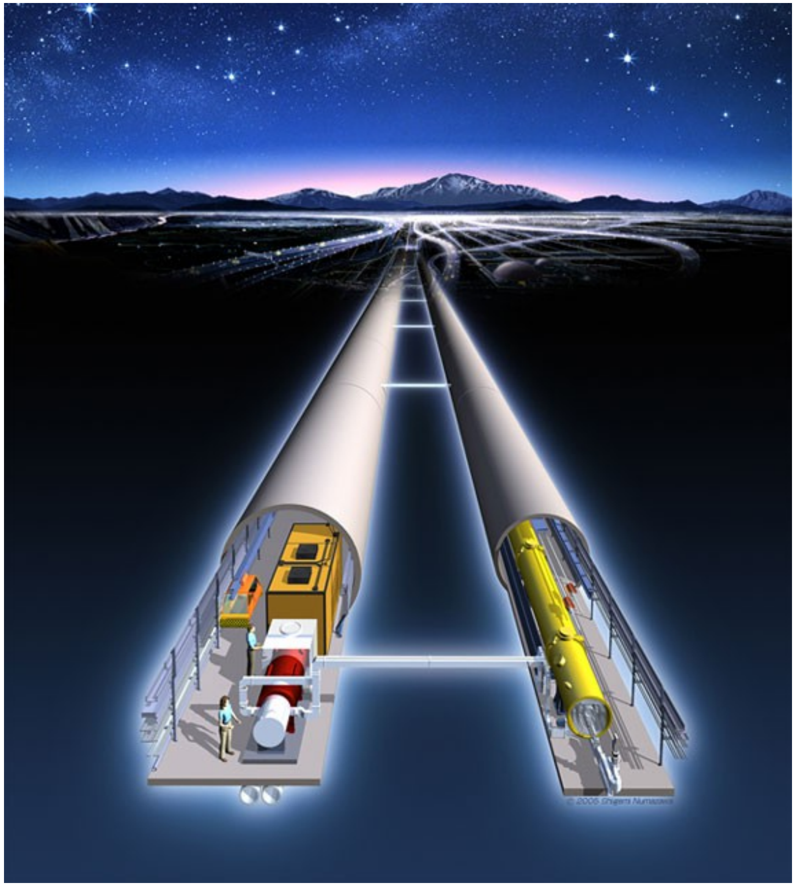
Towards the (I)LC
or
Why precision matters



Roman Pöschl
Directeur de la Recherche of CNRS

LC physics school – DESY/Hamburg October 2013

Let's start with the end

Standard Model

... but

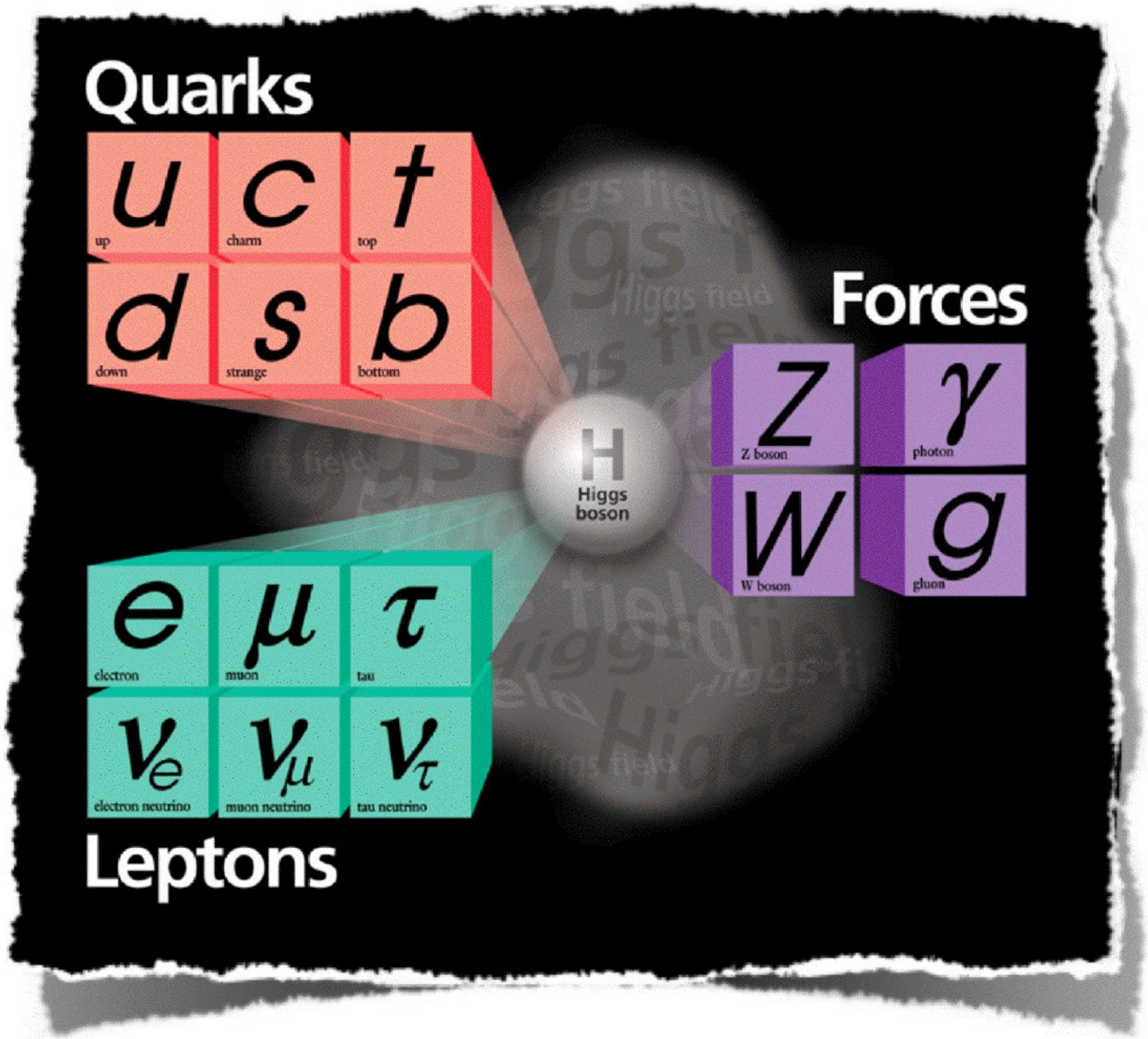
LC School DESY Oct. 2013

"Can you send a message saying –
'I'm leaving you, good-bye?"'

A brief hommage …

The Standard Model of Particle Physics

Fermions
Spin 1/2

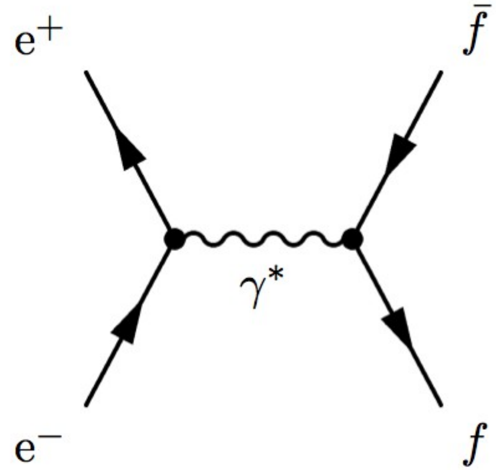


Bosons
Vector Bosons
Spin 1
Scalar Boson
Spin 0

... one of the greatest discoveries of the 20th century !

Standard Model is relativistic Quantum Field Theory

Conserved quantities <-> Gauge symmetries

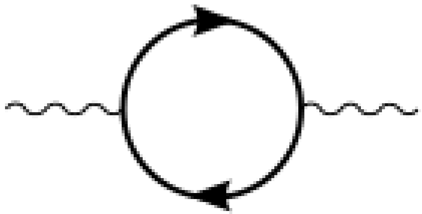


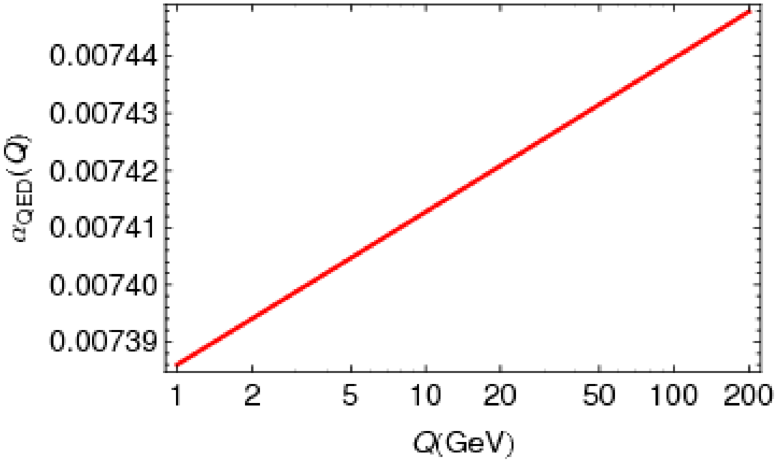
Introduction of gauge bosons
Photon, W, Z, Gluon
as carriers of interaction between fermions

Remark: Massive gauge bosons violate gauge symmetries

Renormalisability

No infinities -> Running charges, masses

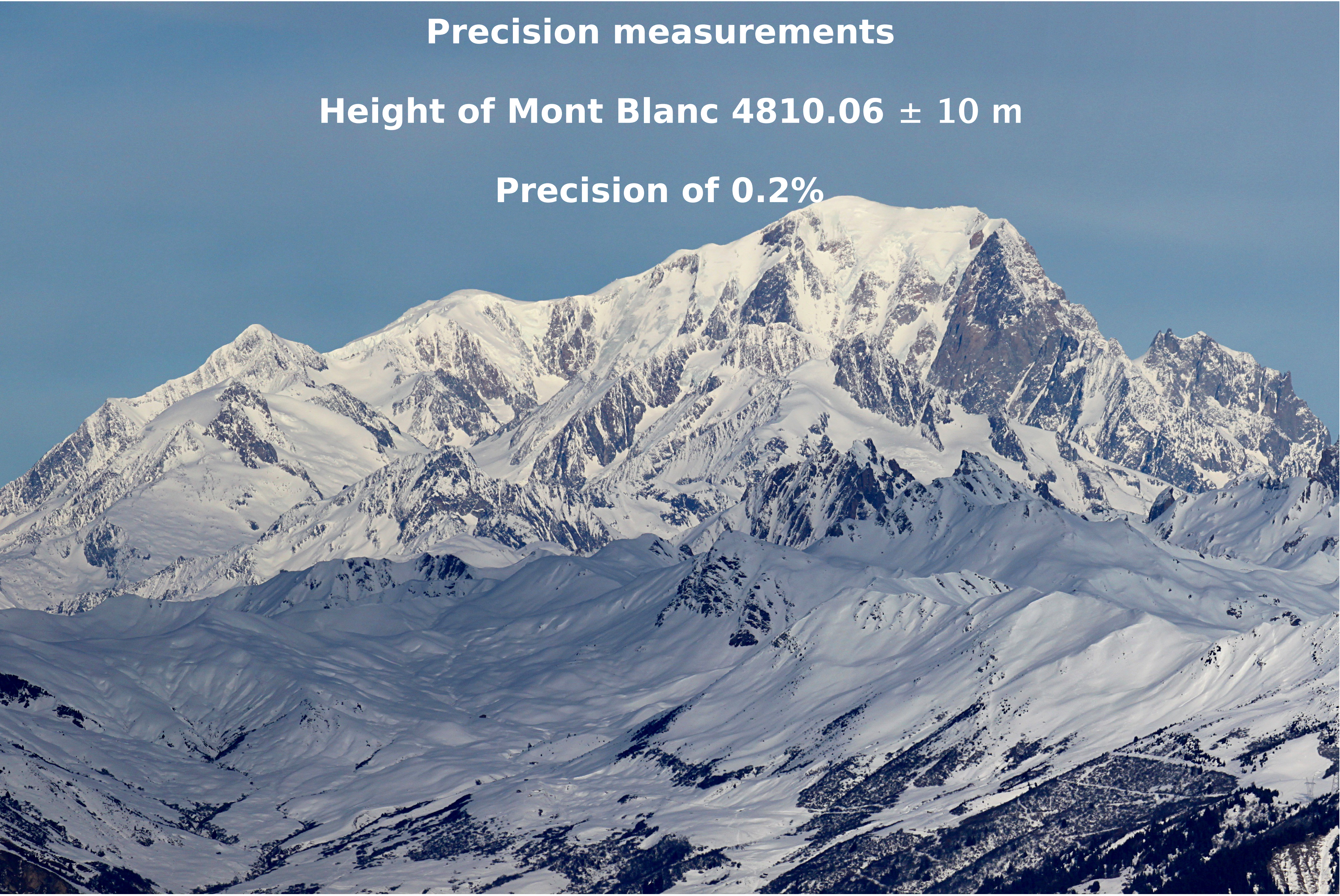




Precision measurements

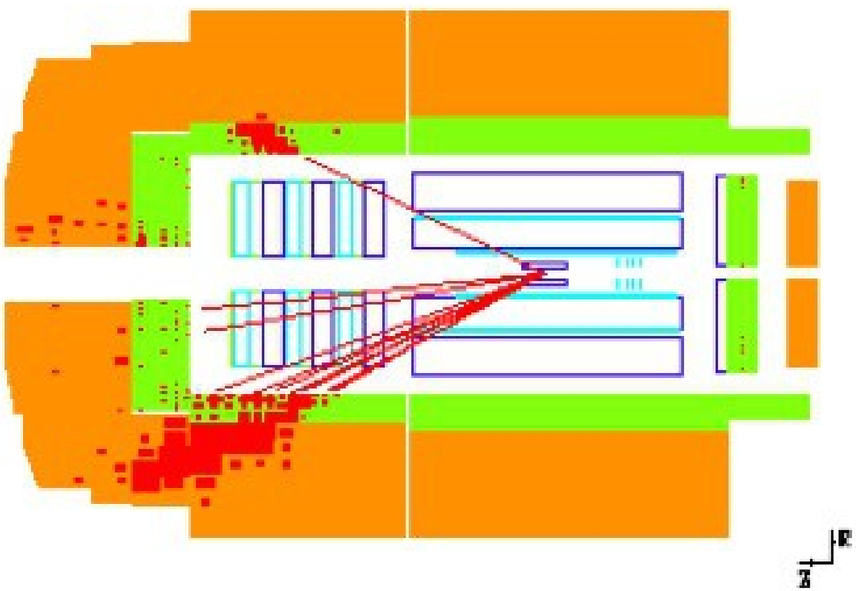
Height of Mont Blanc 4810.06 ± 10 m

Precision of 0.2%

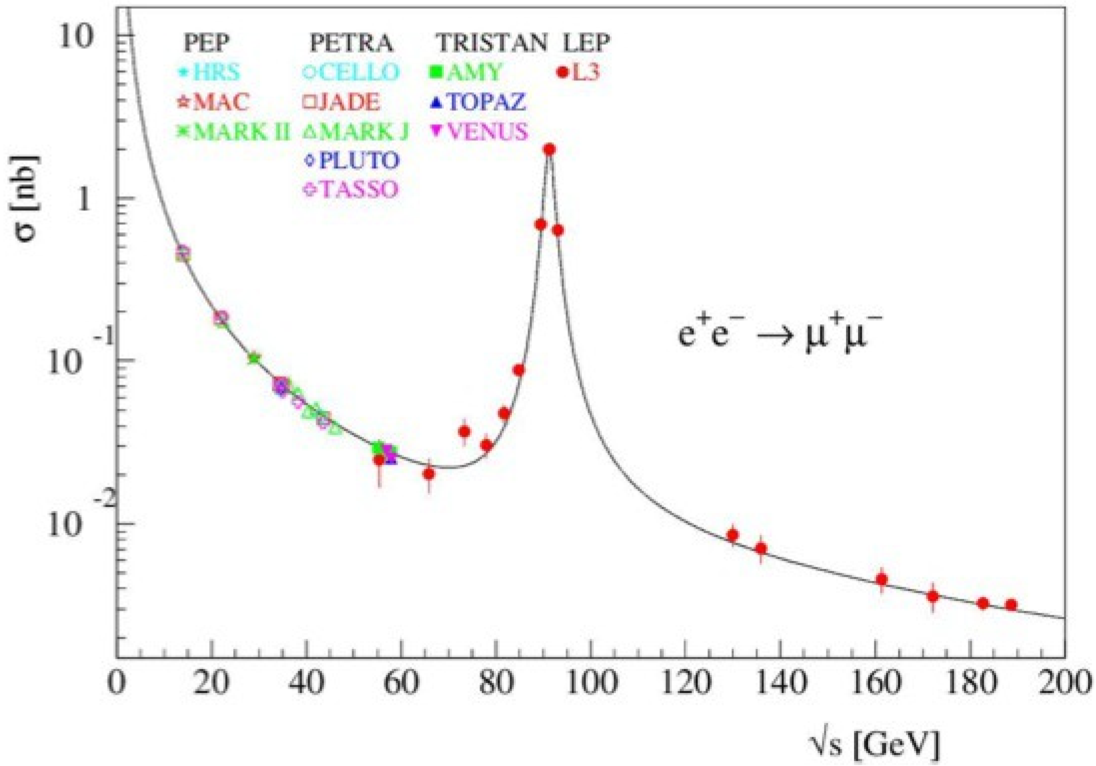


Some examples for validation of the Standard Model

e quark scattering at HERA



$e^+e^- \rightarrow \gamma/Z \rightarrow$ hadrons



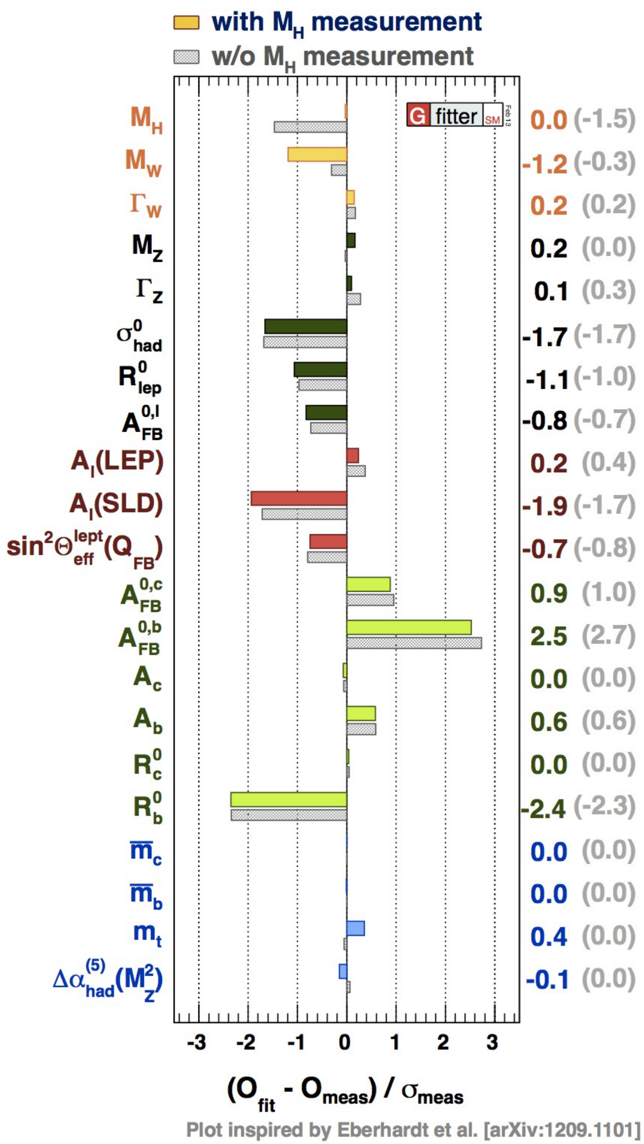
Particles manifest themselves as tracks in the detector

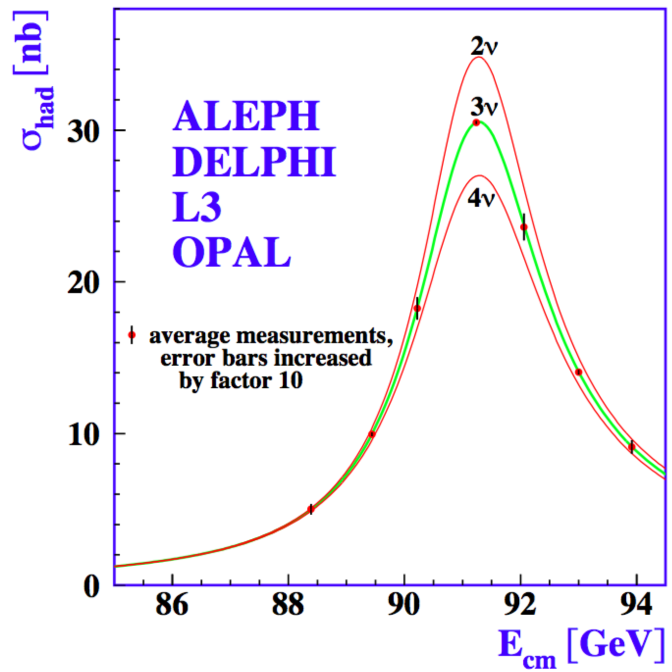
or by a large increase of the cross section - Resonance

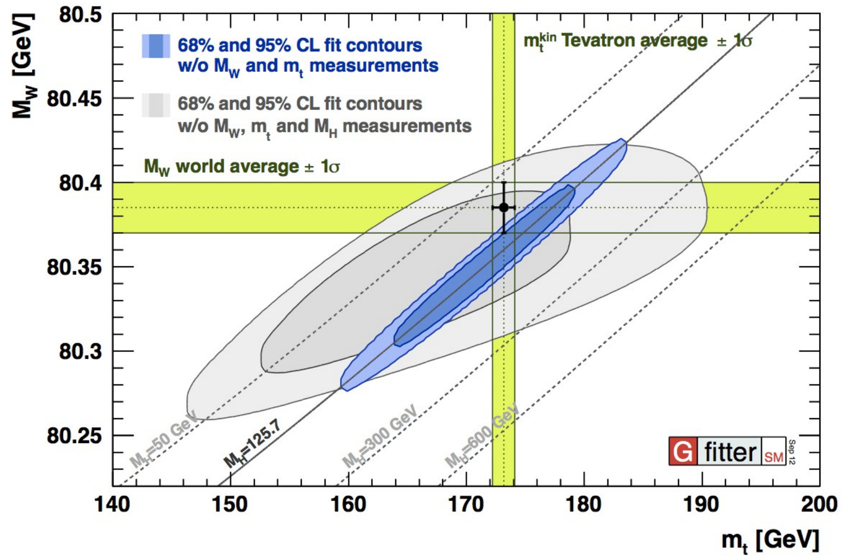
For example the resonance of the Z boson

Precision tests of the Standard Model

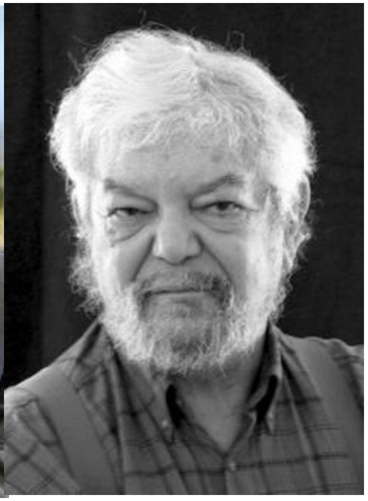
(LEP, TEVATRON, HERA, LHC)

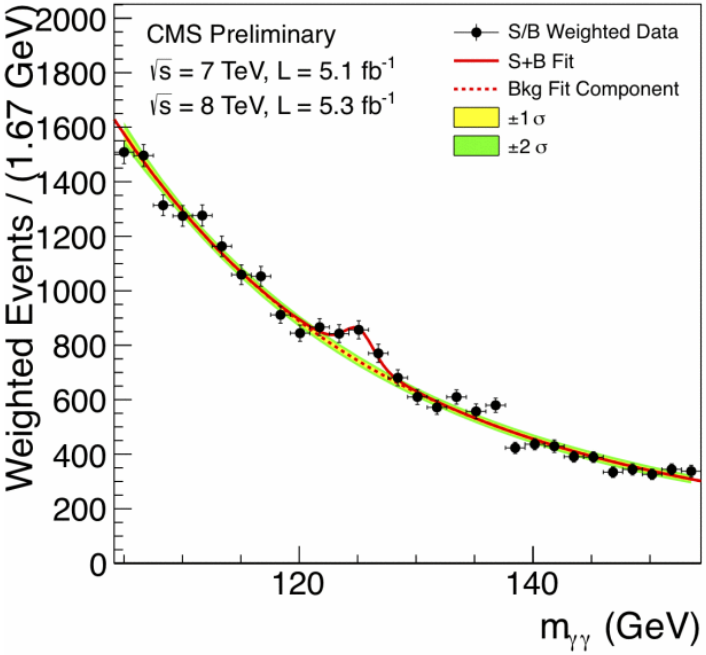


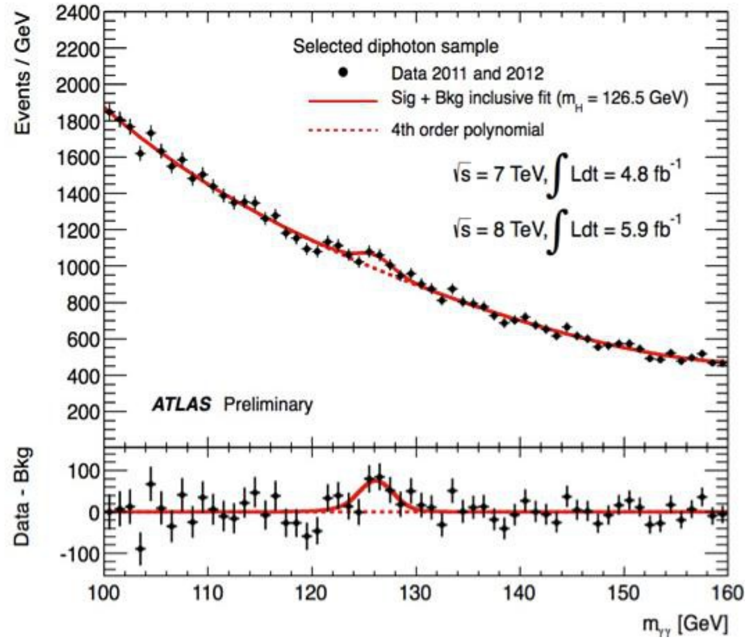




4th of July 2012







How do the Particles get their Masses?

Higgs Mechanism

Scalar field which doesn't vanish in the vacuum

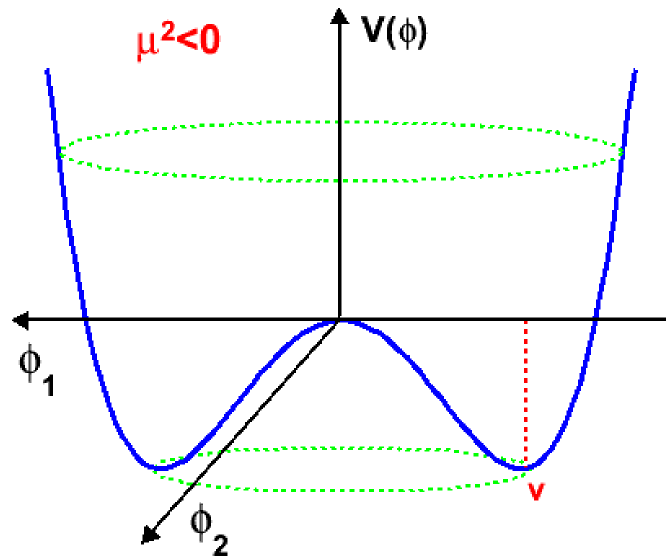
Choice in SM:
Doublet Field

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

4 degrees of freedom

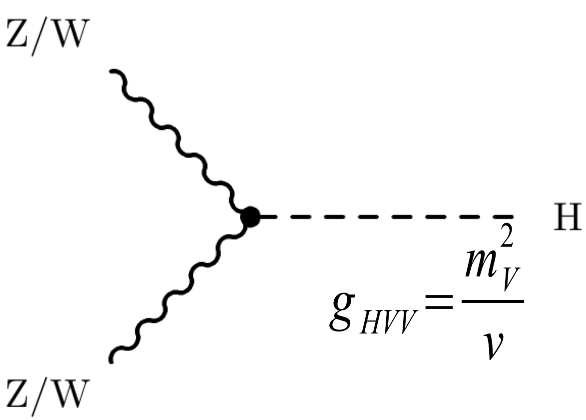
Higgs Boson

Longitudinally degrees of W,Z Bosons

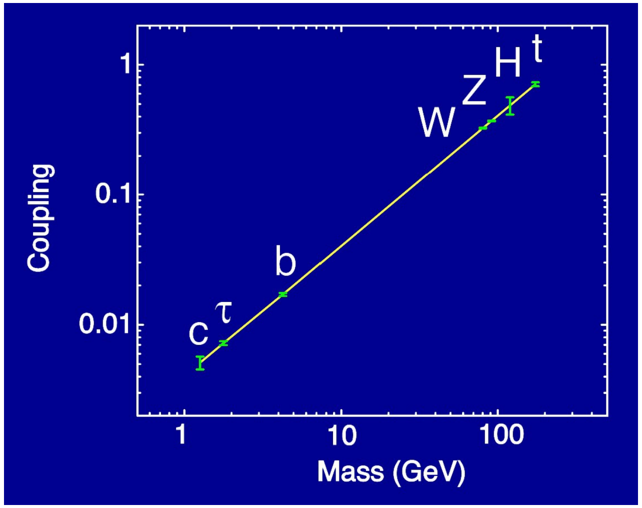


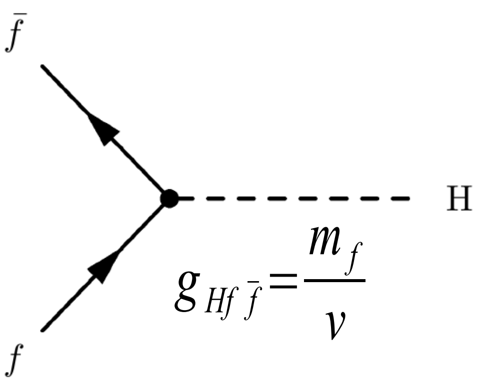
Couplings to Higgs Boson in Standard Model

Increase with particle mass



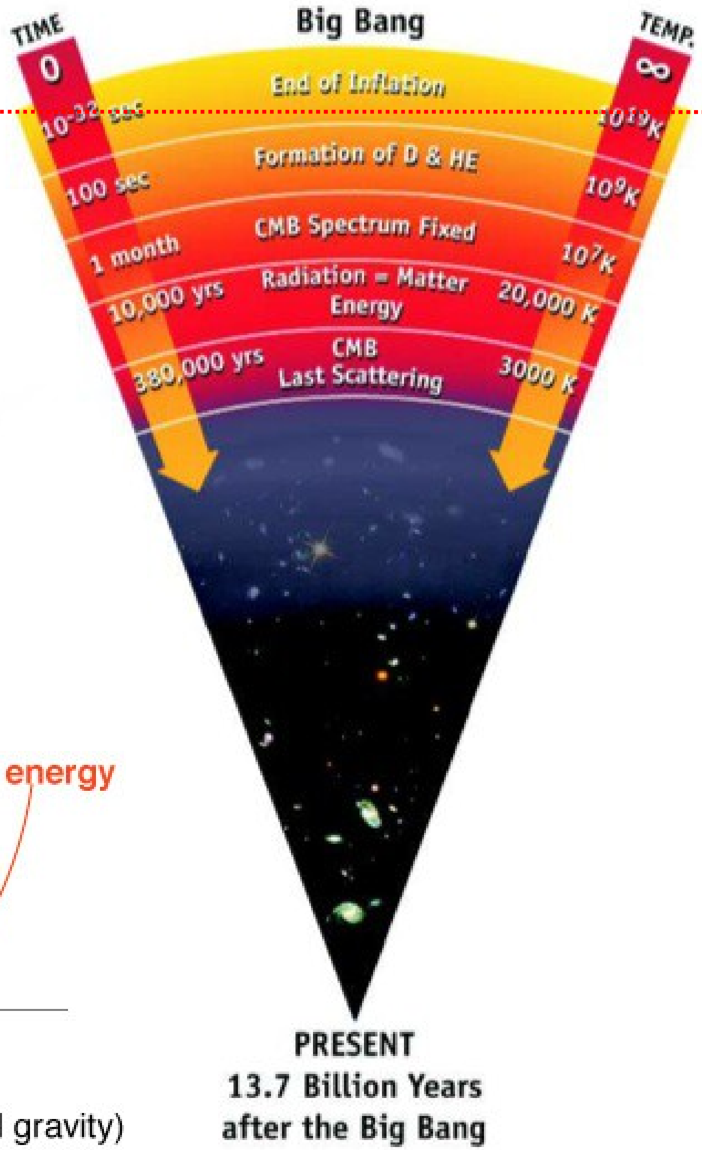
$$g_{HVV} = \frac{m_V^2}{v}$$





$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Two areas of the universe

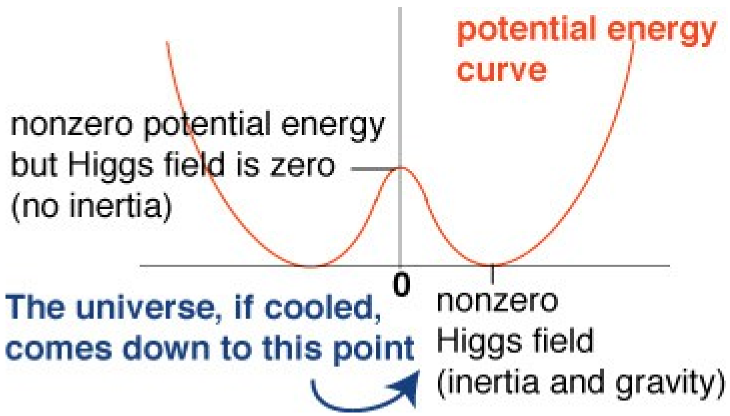


1 TeV

Massless particles

Massive particles

To learn more



11

We see particle physics through new glasses ...

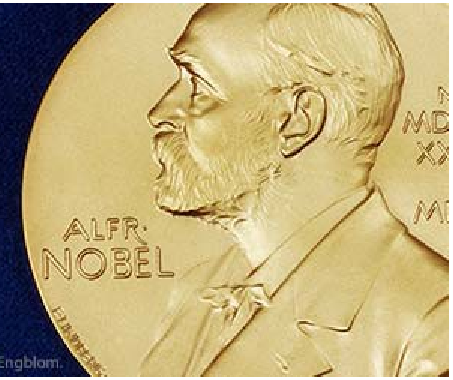
Coronation of the Standard Model
and
First step on a road yet largely unexplored

Slightly modified citation of Barbieri arXiv:1309.3447

Chip Brook, Snowmass Summary Talk

Where do we go from here?

Nobel Prices 2013 are going to be announced this week



Announcements of the 2013 Nobel Prizes

Physiology or Medicine:
Monday 7 October, 11:30 a.m. CET at the earliest

Physics:
Tuesday 8 October, 11:45 a.m. CET at the earliest

Chemistry:
Wednesday 9 October, 11:45 a.m. CET at the earliest

Peace:
Friday 11 October, 11:00 a.m. CET

Economic Sciences:
Monday 14 October, 1:00 p.m. CET at the earliest

Literature:
The date will be set later

▶ Full schedule

Physics tomorrow

Maybe striving for something like this …


Fine Flavours & Fragrances Ltd

Certification of Naturalness

Product Name: Vanilla flavour (Natural)
Product Code: FLV0004

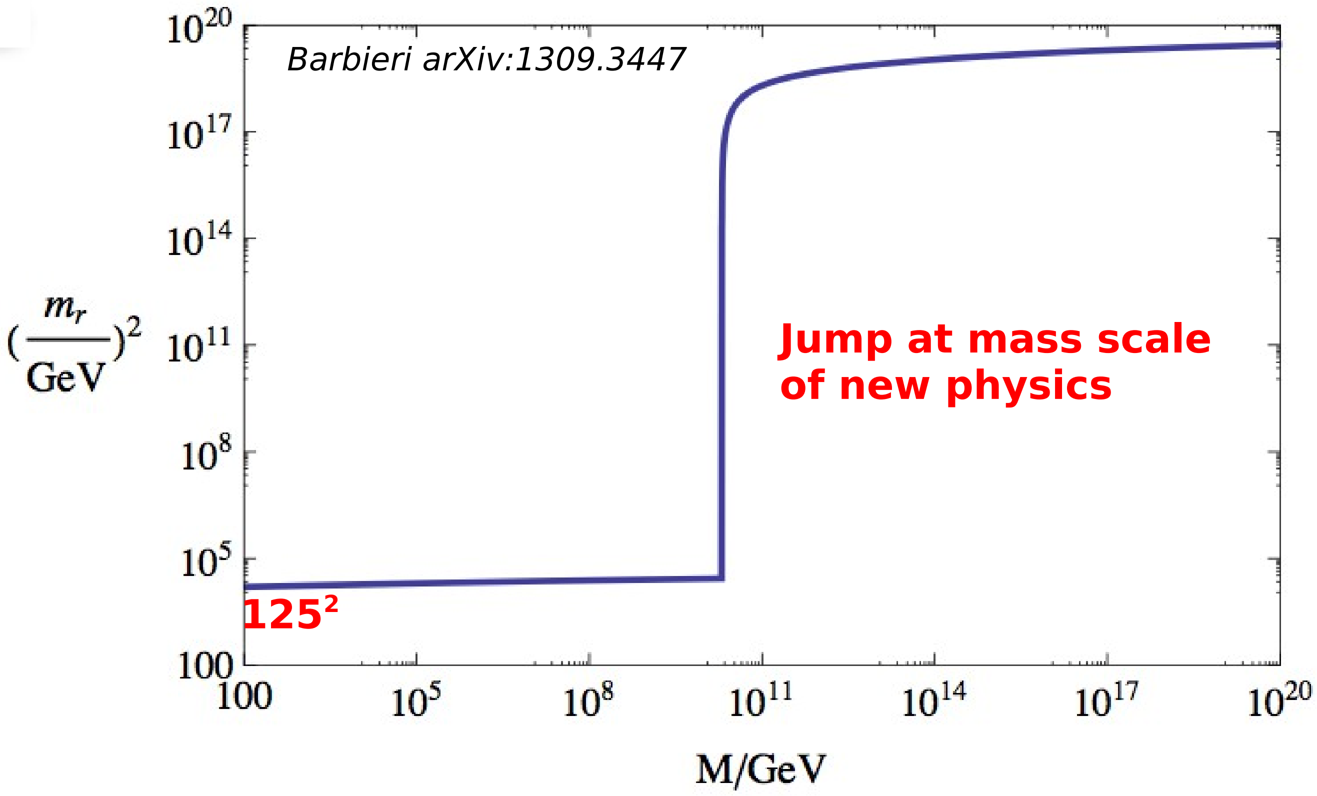
This is to certify that the above flavour supplied is Natural.

All the active ingredients in the flavour are certified as natural, and do not, to the best of our knowledge and belief, contain any artificial ingredient and we have added no artificial flavour to it.

All active ingredients of the flavour are FEMA approved.

More seriously ...

Renormalised running Higgs mass
(in dimensional regularisation)

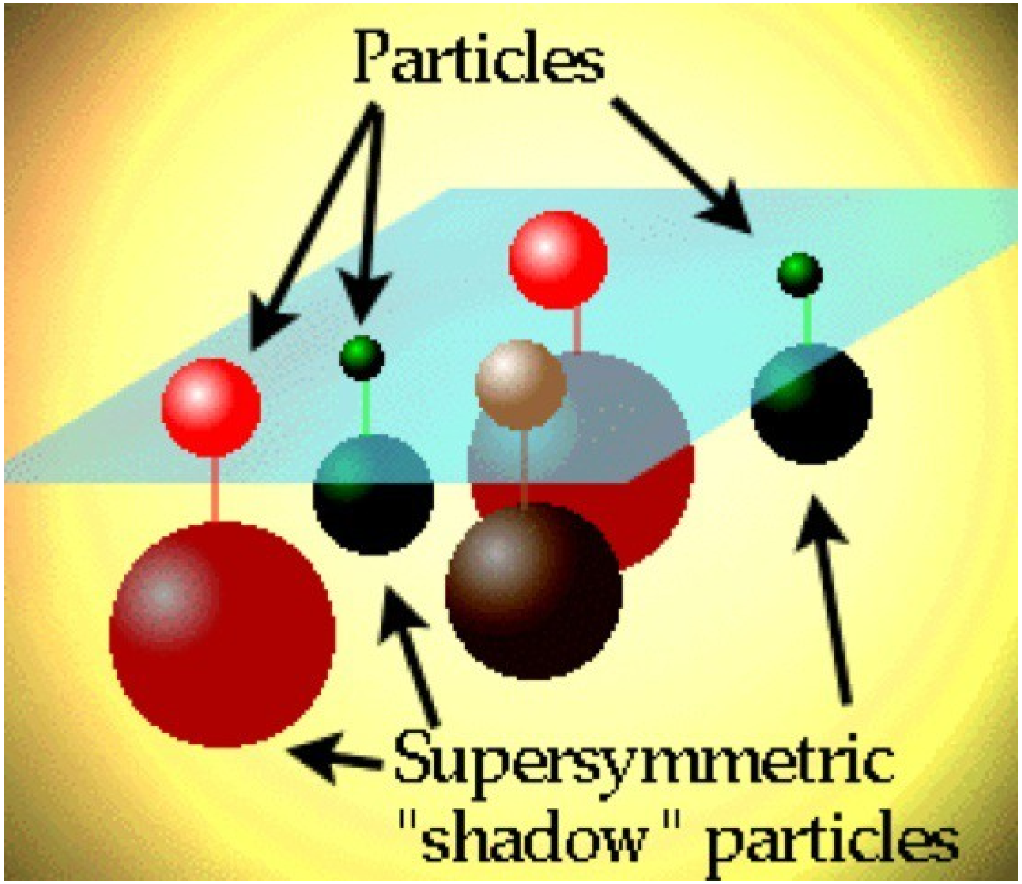


The higher the new physics is the more drastic is the Jump or the more carefully one has to tune the initial conditions at some high scale

Can one tame the jump?

Taming the jump I ...

Supersymmetry



Before LHC:

(Believe that)
Lightest supersymmetric
Particle has mass of O(1 TeV)

-> No jump anymore

Exclusions limits are pushed up
by LHC

However waiting/hoping for LHC14

Did/will/can LHC miss something?

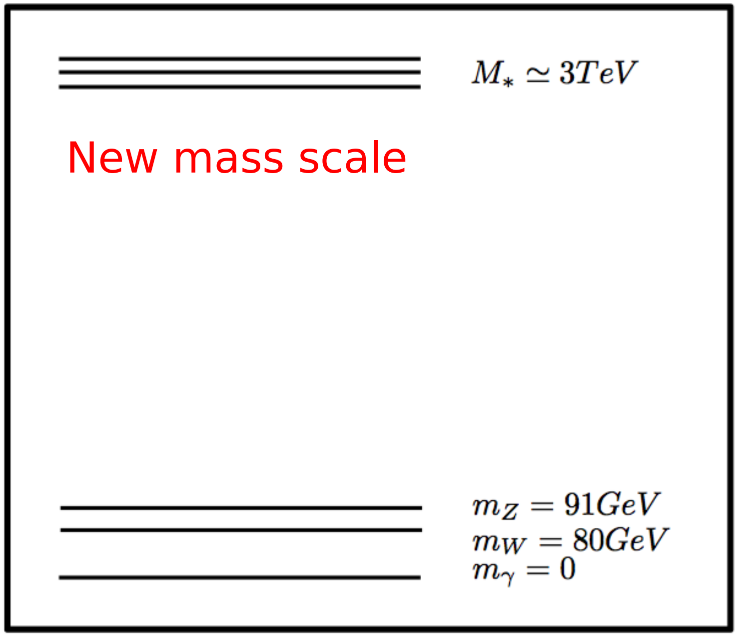
Taming the jump II ... - Compositeness

Compositeness:

à la G.M. Pruna, LC 13, Trento

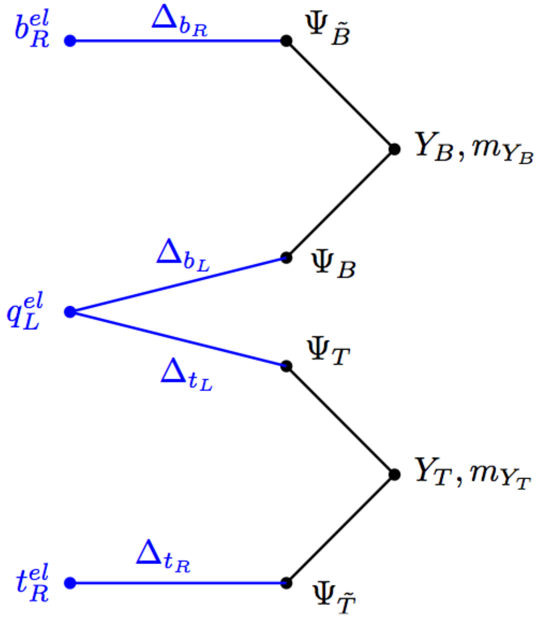
- ... provides elegant solution for naturalness
- ... few tensions with SM predictions
- ... composite Higgs hypothesis has only been marginally studied in comparison with other "fundamental" scenarios
- ... **all** scalar objects observed in nature turned out to be bound states of fermions

Bosonic sector mass spectrum



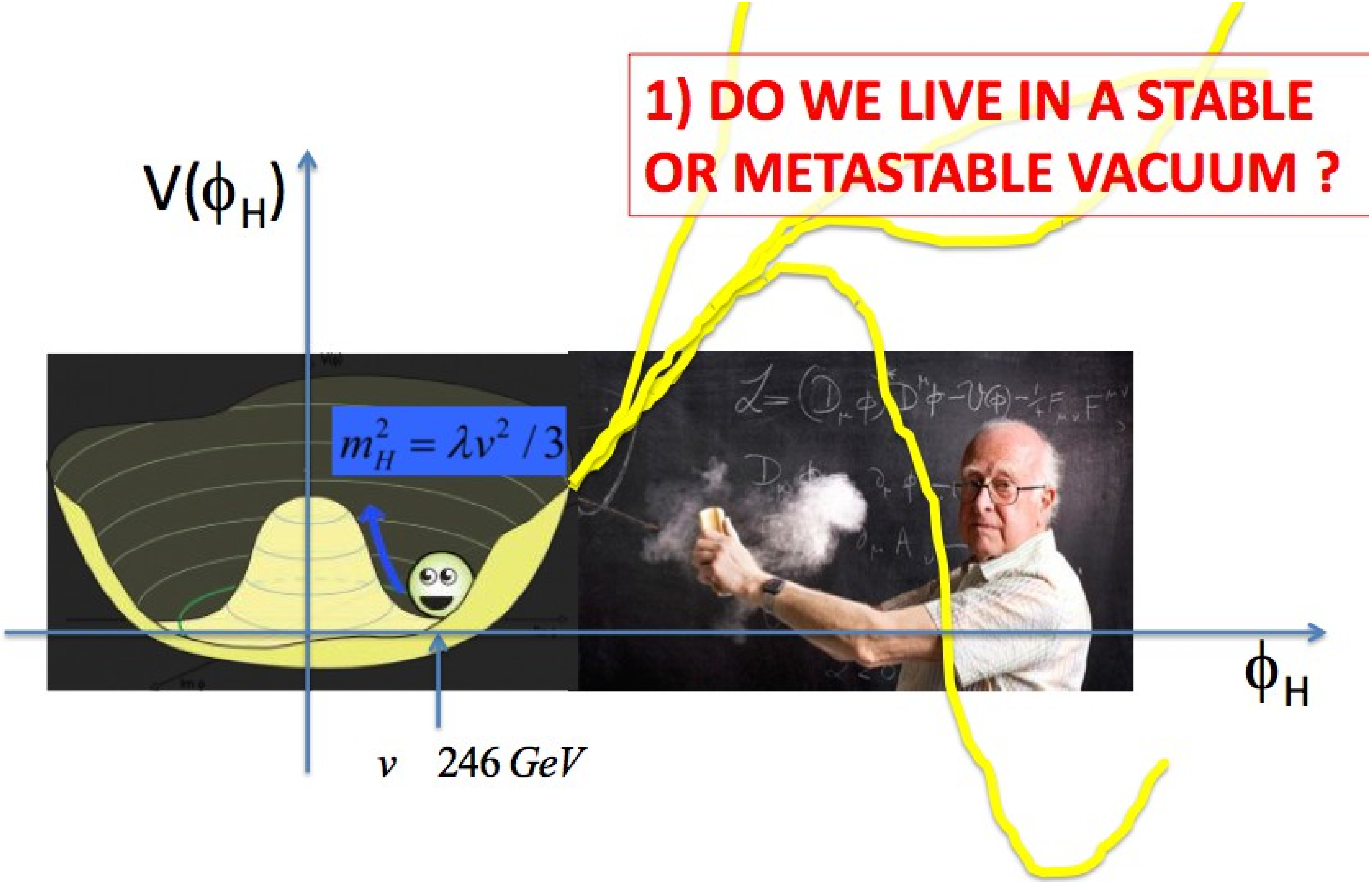
Fermionic resonances

From heavy left handed SM doublet
and heavy right handed SM singlet



Physics modify Yukawa couplings and Ztt, Zbb
Heavy fermion effect!

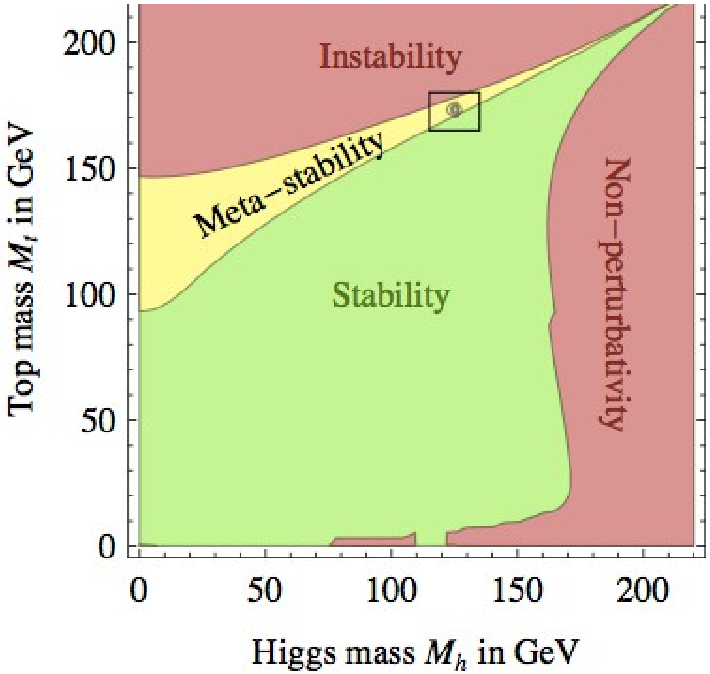
The fate of the universe

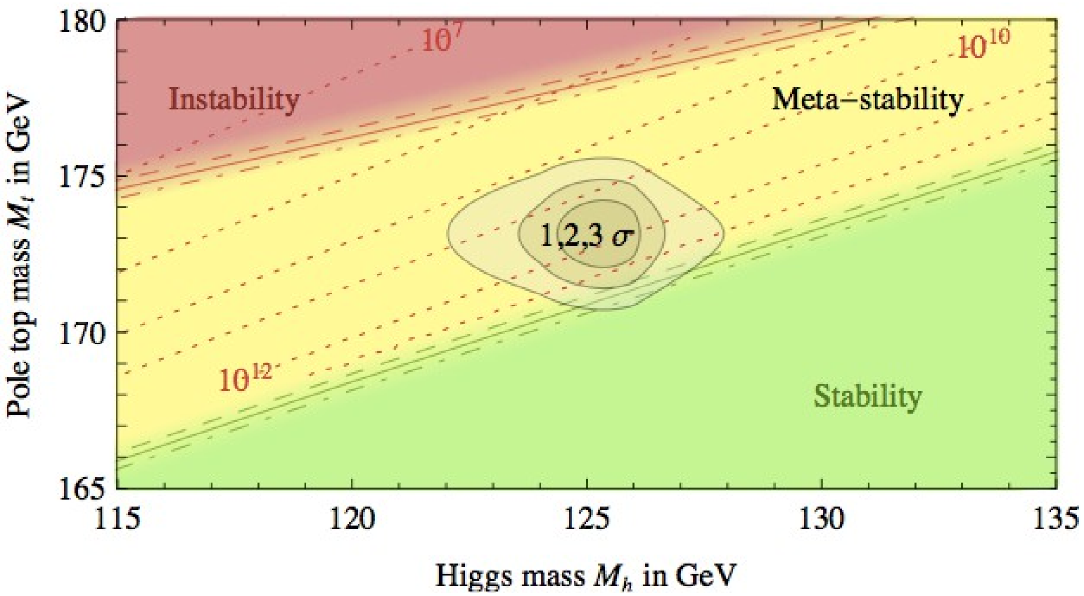


Vacuum stability and top quark mass

Degrassi et al.
arXiv:1205.6497

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$



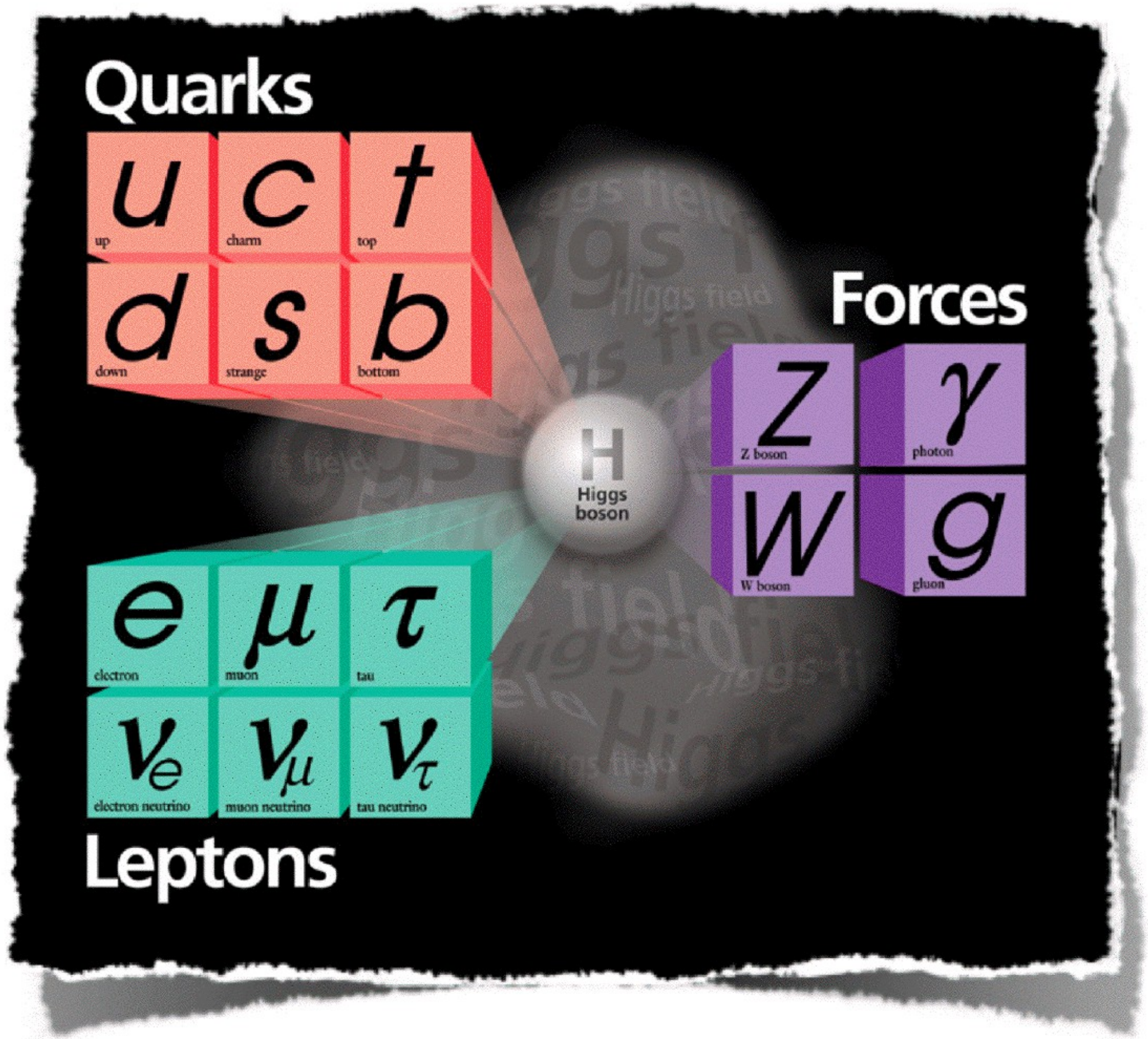


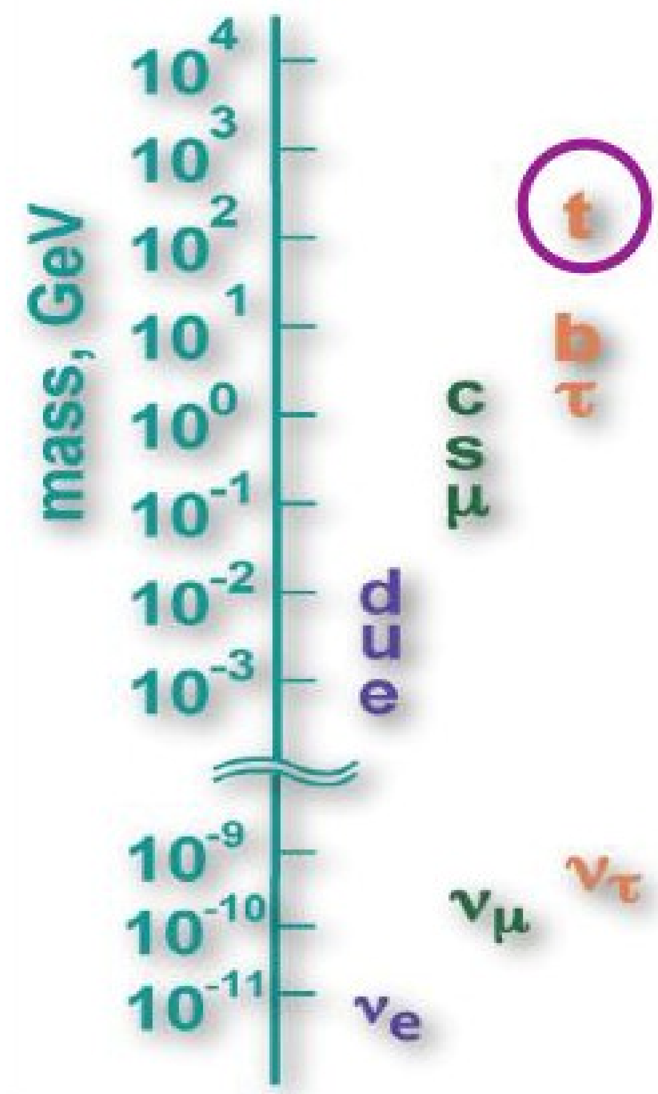
Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	**Total combined in quadrature**	**± 1.5 GeV**
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\mathrm{QCD}})$ correction to M_t	± 0.6 GeV
y_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	± 0.2 GeV
Theory	**Total combined in quadrature**	**± 1.0 GeV**

Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

(argument is repeated In literature!)

Striking hierarchy



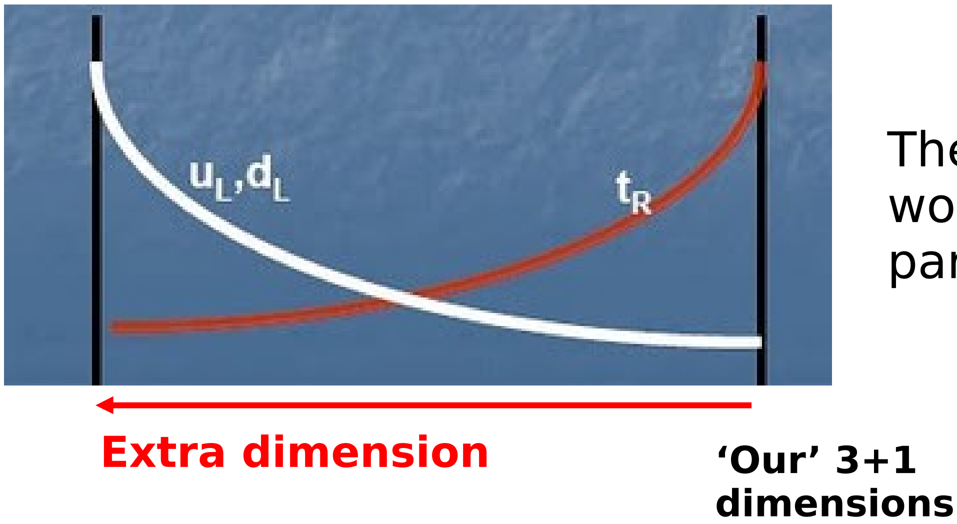


Heavier than a gold atom

Barbieri: "... there is no reason to be proud of the lij parameters
Jaegerlehner: "... issues like the unknown origin of the hierarchy of the Yukawa couplings"

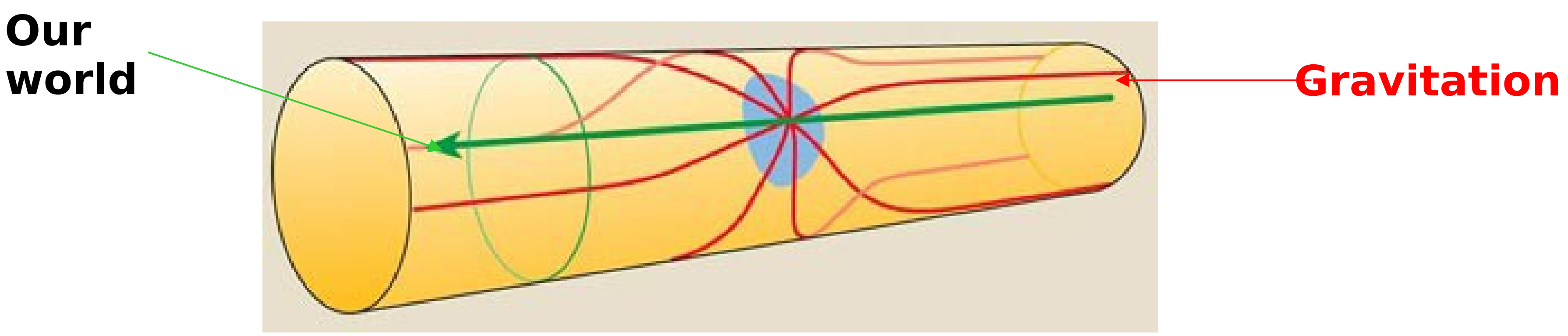
Mass hierarchy and extra dimensions

The introduction of one (or more) extra dimensions allow for arranging the wave functions along this new dimension



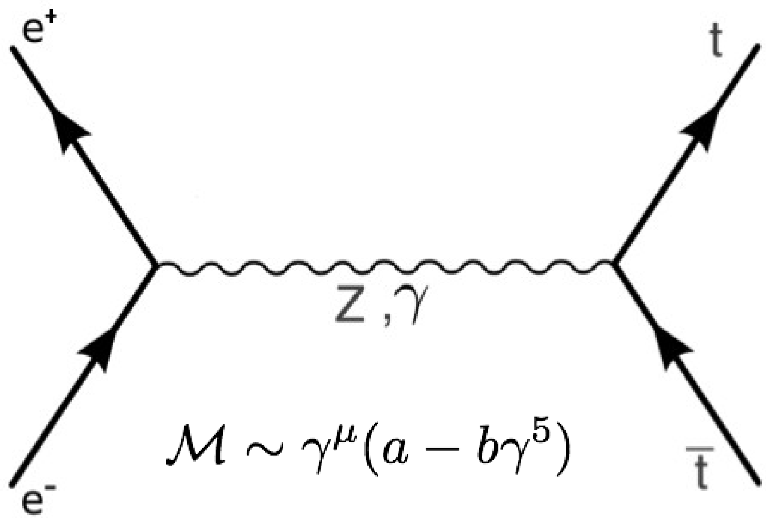
The particle mass oberved in 'our' world depends of the position of a particle in the extra dimension

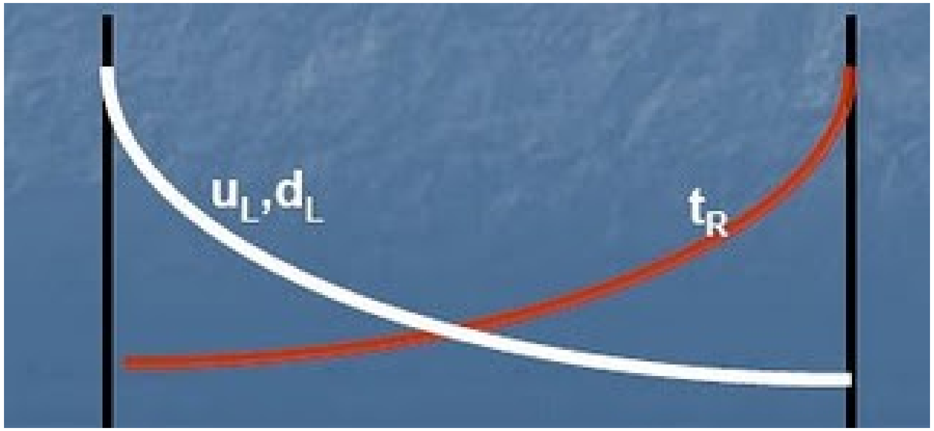
Most likely extra dimensions are curved



Remark: Extra dimension models are dual to compositeness models

Closer look to helicity states ...

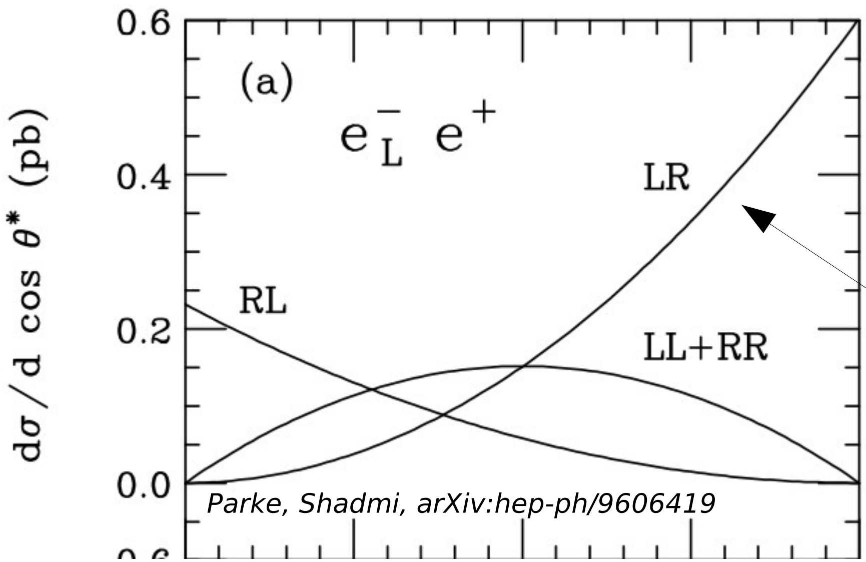




Standard model 'prefers' left handed particles

New physics may alter this 'preference'

Beam polarisation allows to study left and right handed particles seperately



cos θ*

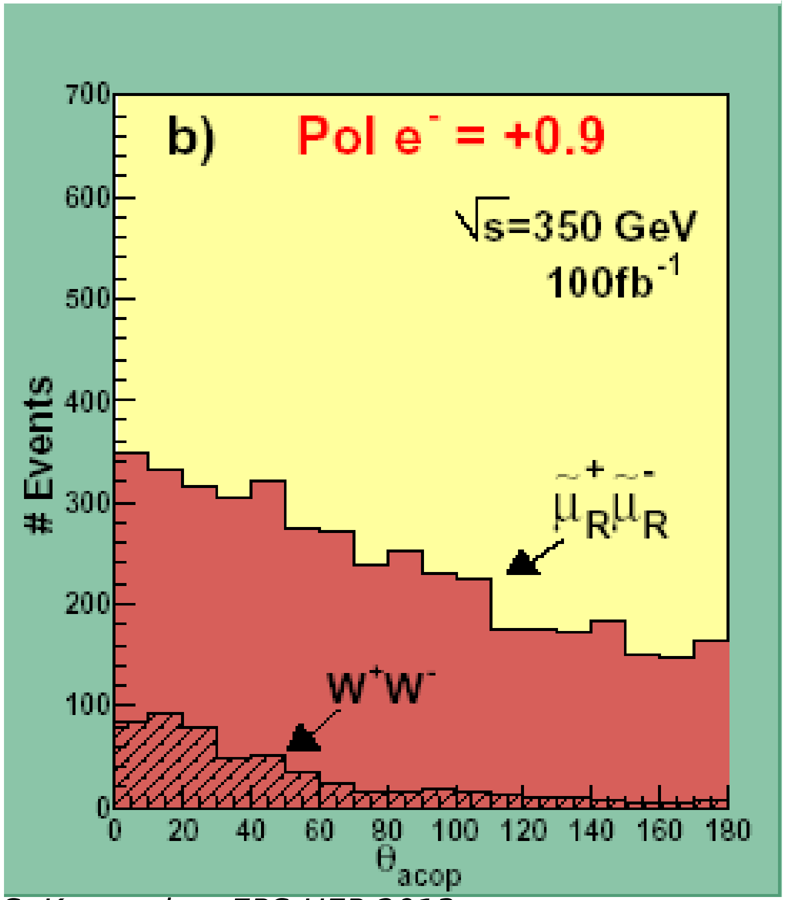
(Generic) example

Top quark production in e+e- at 400 GeV

Enrichment of let handed top quarks in forward region

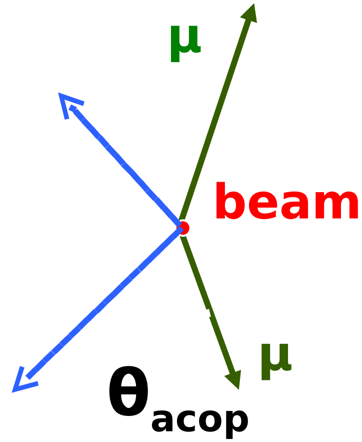
Power of (electron) polarisation

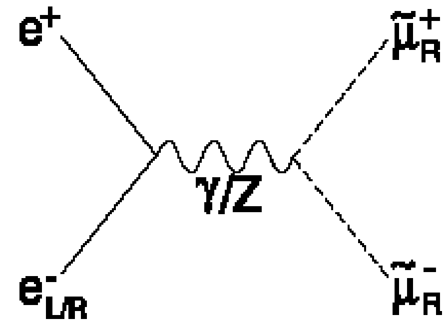
Scalar muon production

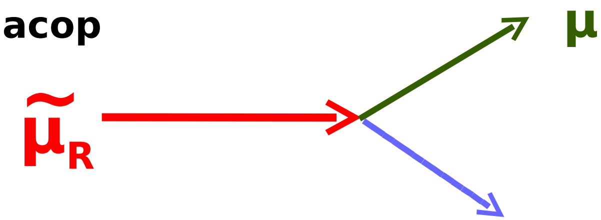


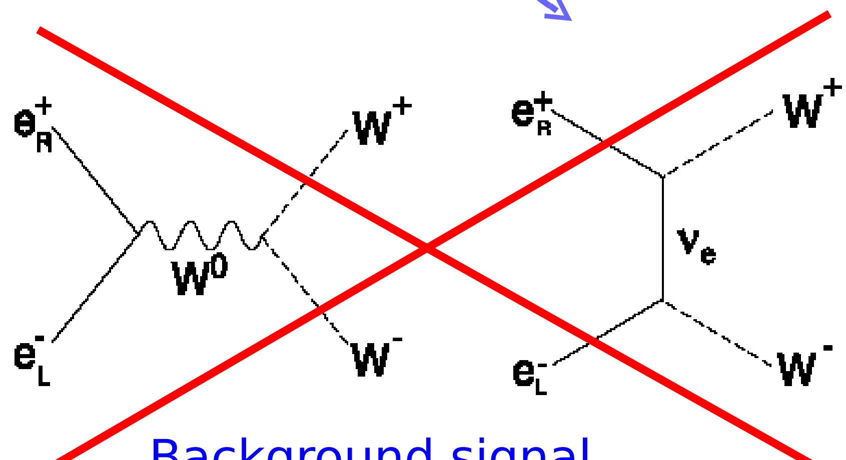
S. Komamiya, EPS-HEP 2013

Polarized (90% e^-_R)









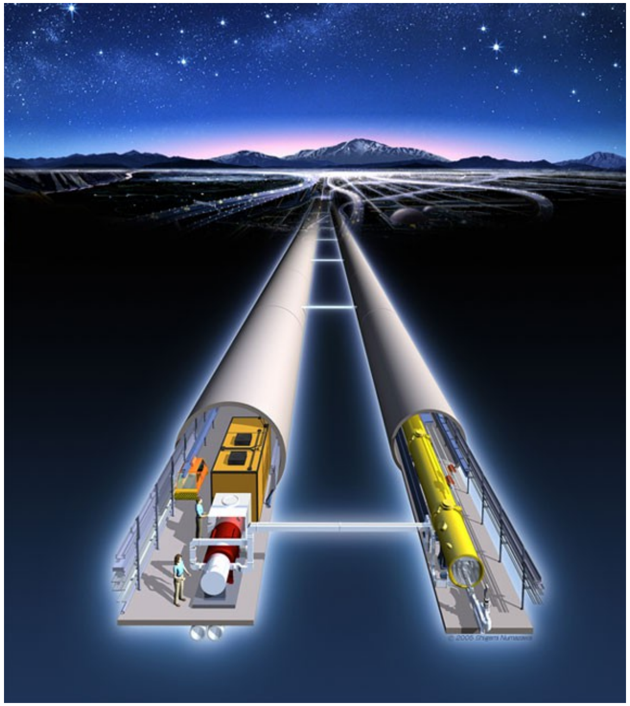
Background signal

Beam polarisation is efficient tool to suppress (Standard Model) background

'Tools' to understand nature

The Aristoteles way

Telescopes et instruments for astrophysics make observations

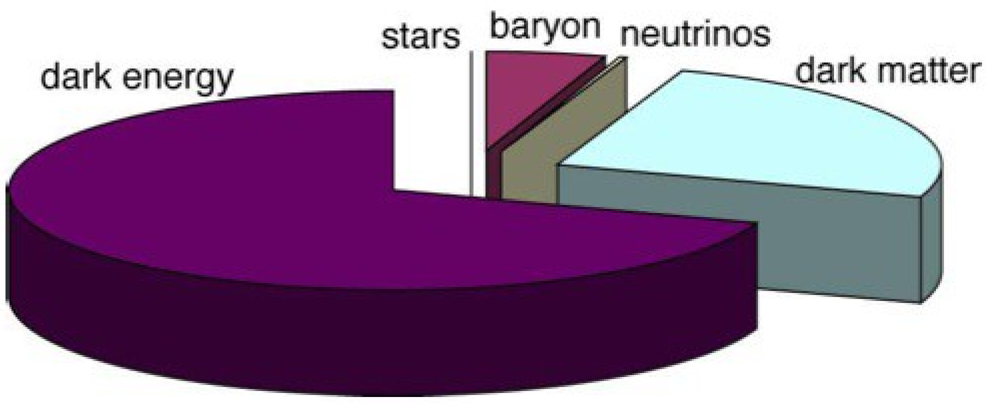


The Galilleian way

Accelerateurs permit to arrange

Well controlled conditions

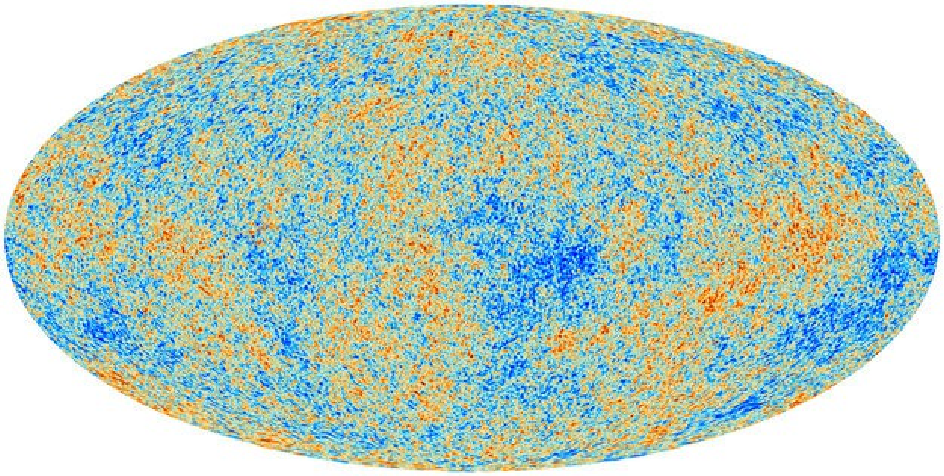
The camembert of the universe – Energy distribution



- 5% of matter known from SM

- 25% Dark matter

- 70% Dark energy



Planck:

Precision measurements of fluctuations in the “Cosmic Microwave Background”

The Standard Model cannot explain Dark Matter
(neither dark energy)

Impact of Precision Measurement

A. Wagner

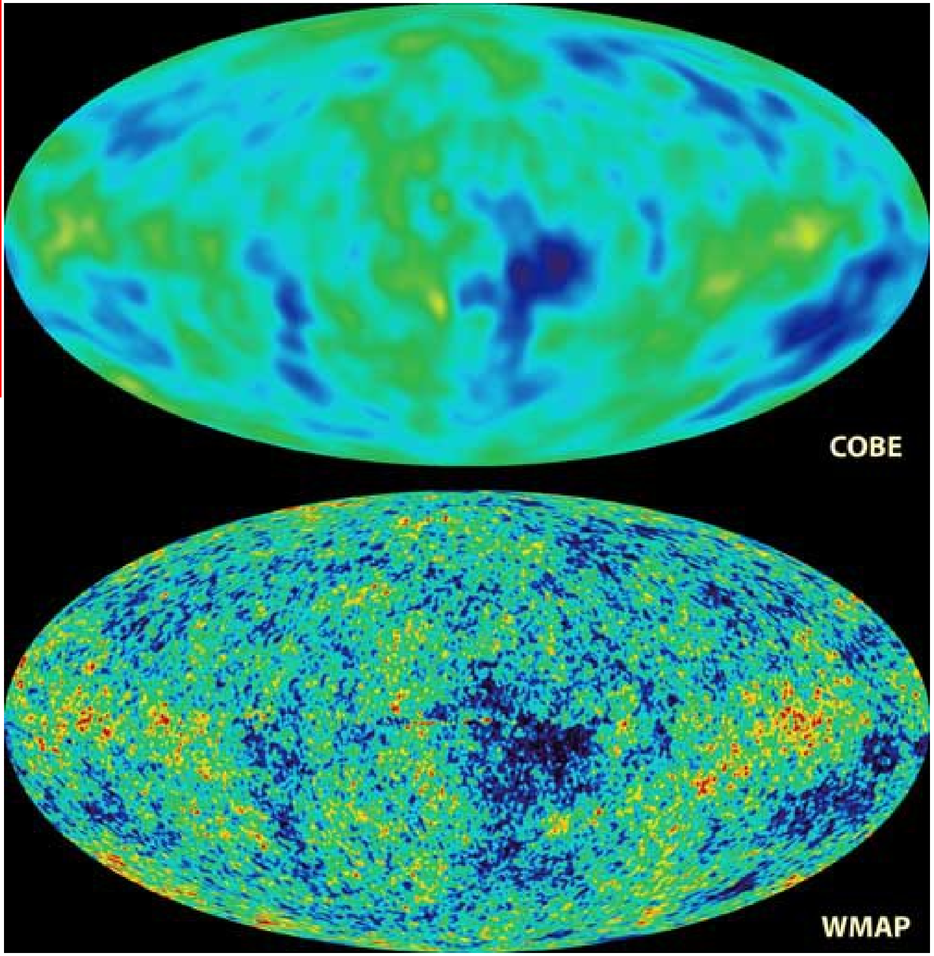
COBE 1990
Angular resolution = 10°
Temperature fluctuation 10^{-5}K

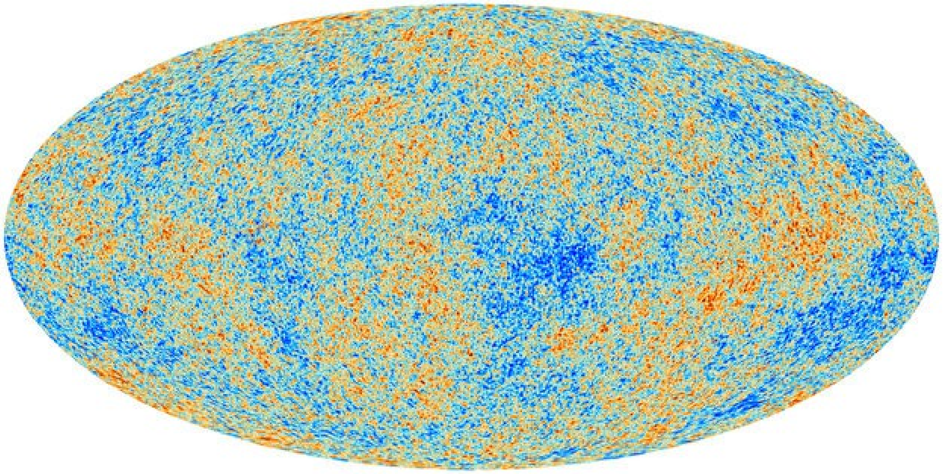
WMAP 2003
Angular resolution = 10’

τ(the Universe) =13.69±0.13 Gyr

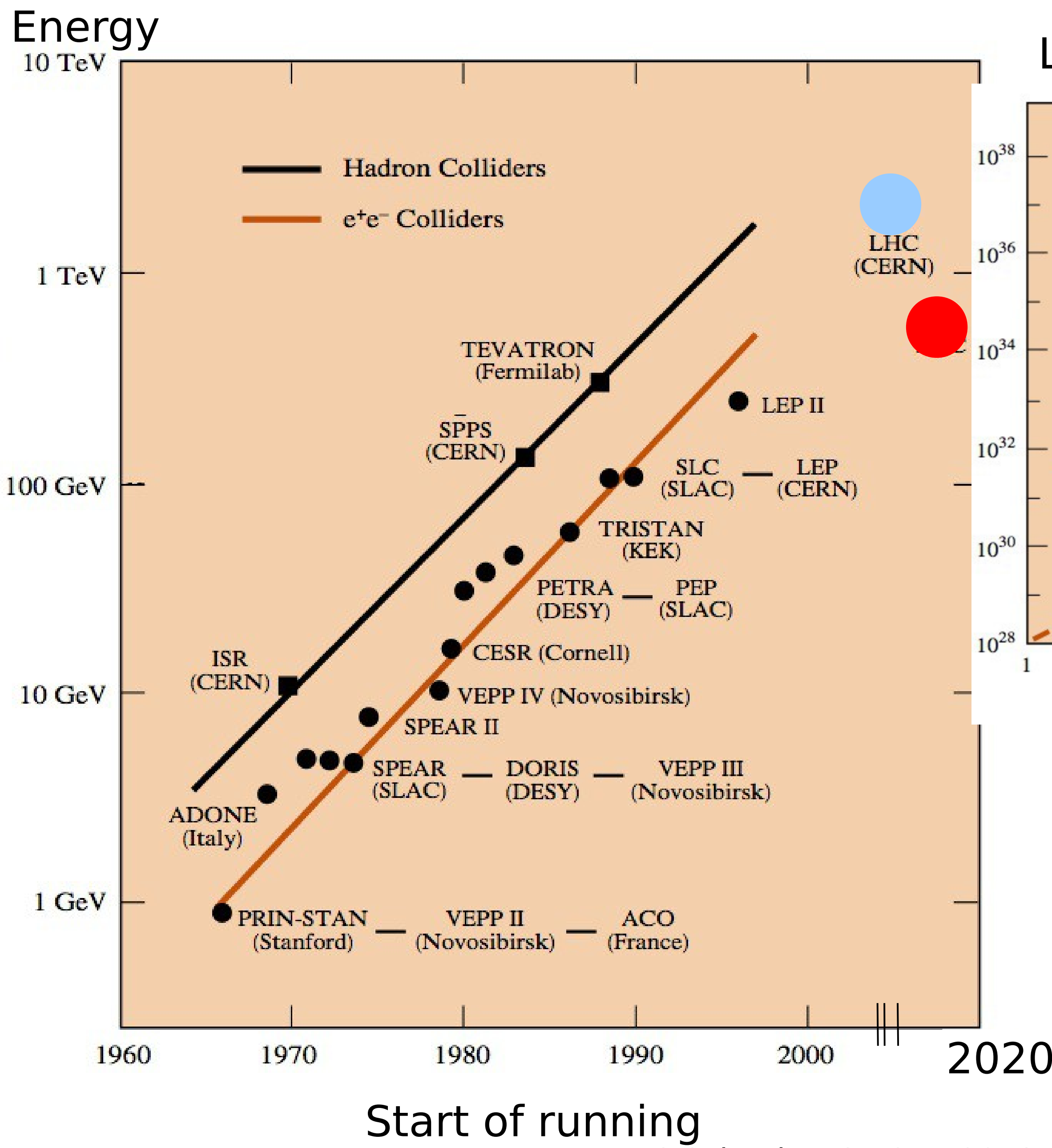
Polarization measurement

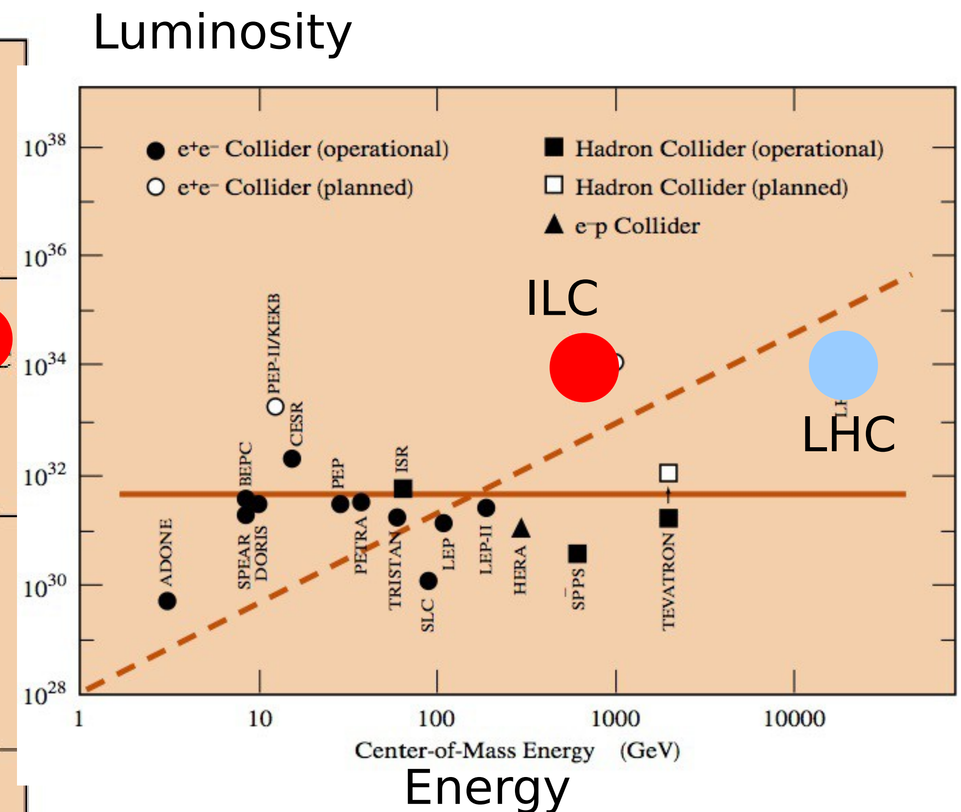
Planck 2013
τ(the Universe) =13.796±0.058 Gyr





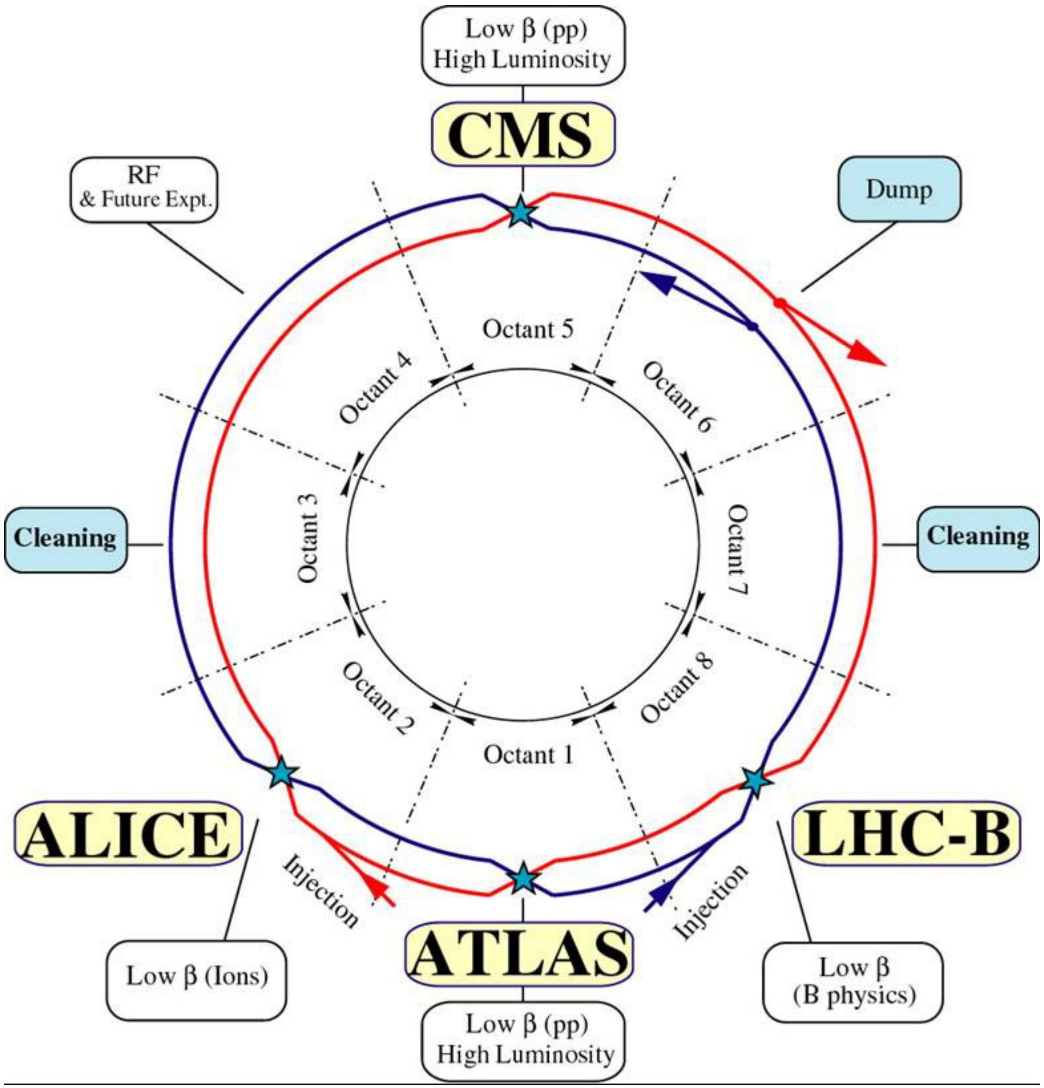
Brief history of particle accelerators





Parallel operation of Hadron and lepton machines

The LHC



Collisions entre proton-protons at √s = 14 TeV (>2015)
√s = 7/8 TeV (2008-2012)

Higgs discovery

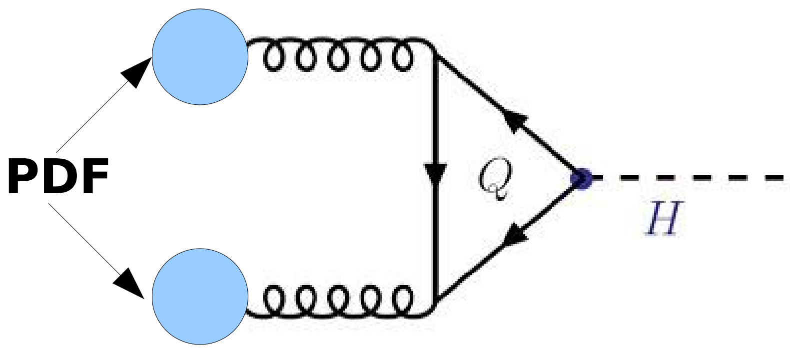
New physics (???) at a scale of 1-10 TeV

Full energy > 2015

Opens the window and settles the scene for precision measurements

LHC – A closer look

QCD dominates reactions of composed objects

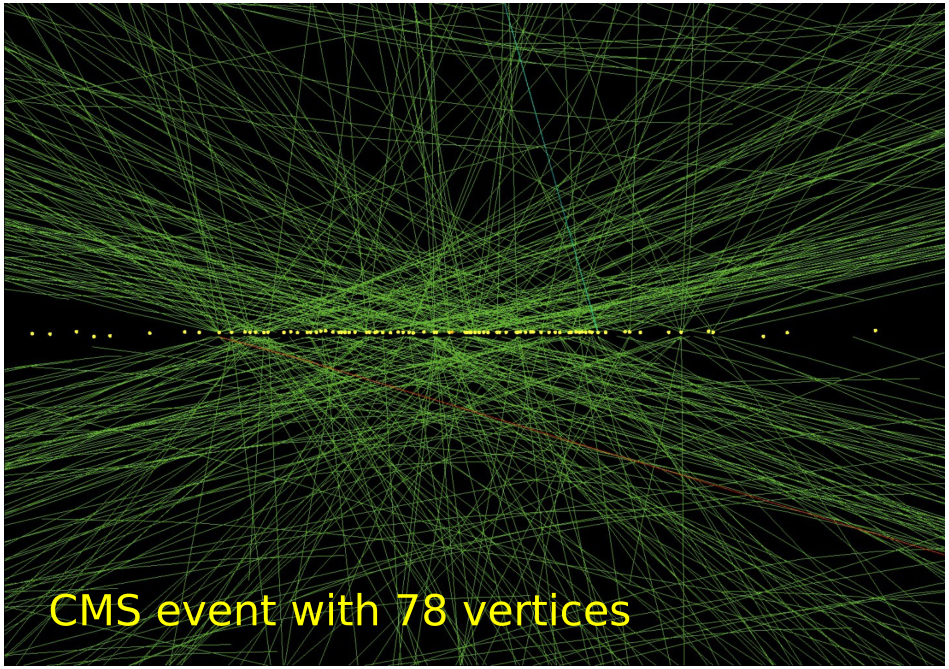


- huge QCD background
- Scale uncertainties
  in soft and hard part of scattering

“QCD-wall” renders it difficult to precisions well below 10%

Difficult event reconstruction

Achievements are most impressive though!!!



Up to 200 vertices after LHC lumi upgrade
Underlying events scatter ~TeV into detectors

(Only) Remedy to these fundamental issues are excellently working detectors and “army” of brilliant scientists

Why electron positron collisions ?

Proton:

Composited particel (hadron)
Unknown energy of collision partners
Parasitic reactions
Strong interaction
=> Considerable physics background

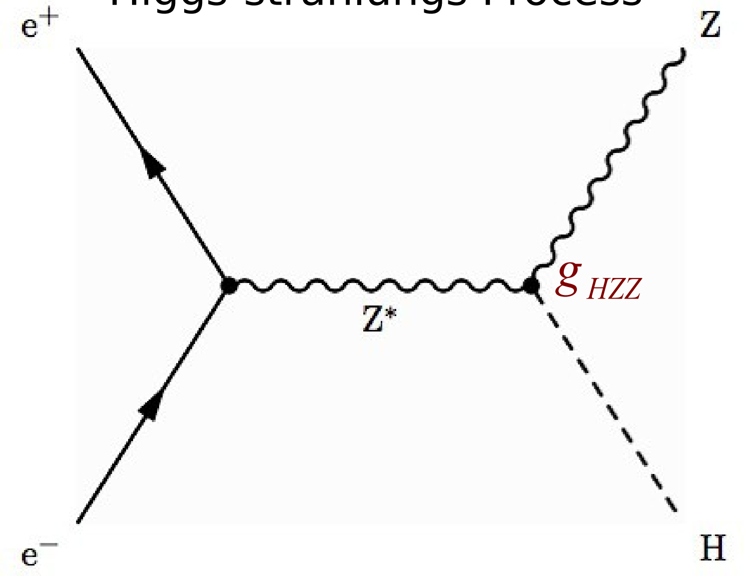
Electron:

Elementary particle
Well known and adjustable energy of collision partners

High precision measurements

Example Higgs-strahlung

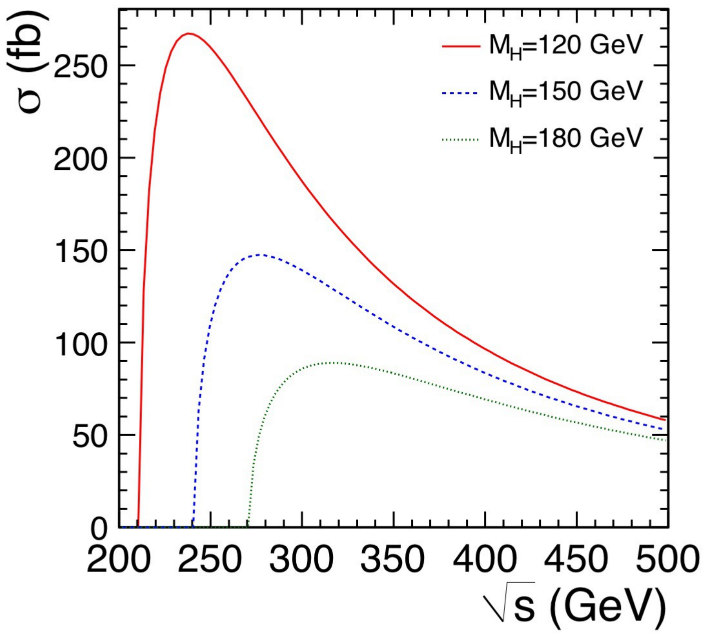
Higgs-strahlungs Process



Golden Plated Channel at e^+e^- Colliders

Sensitive to coupling at HZZ Vertex

Model independent due to clean Reconstruction of Z boson



Production Cross Section of SM Higgs Boson

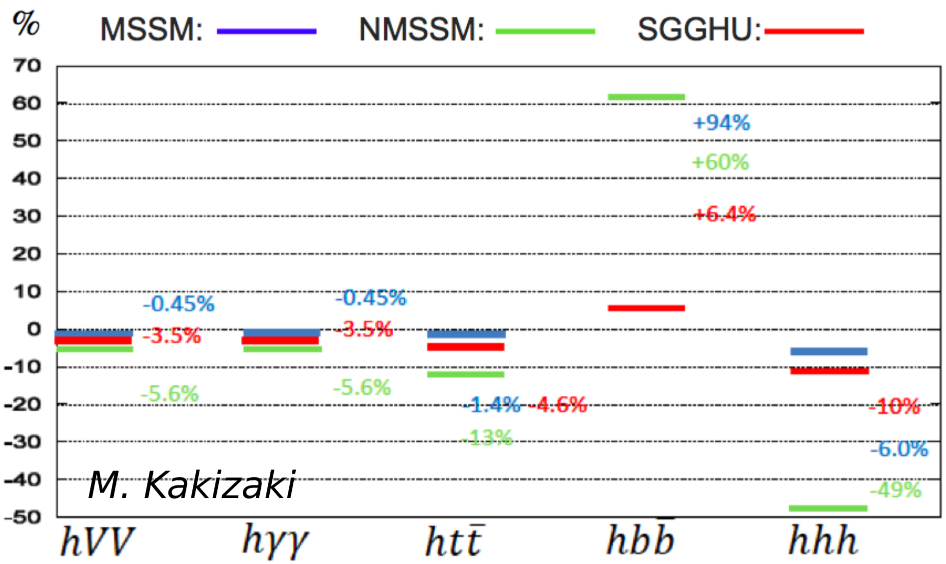
Maximal at HZ production threshold

Higgs Strahlung at $\sqrt{s}$ = 250 GeV for m_H = 120 GeV

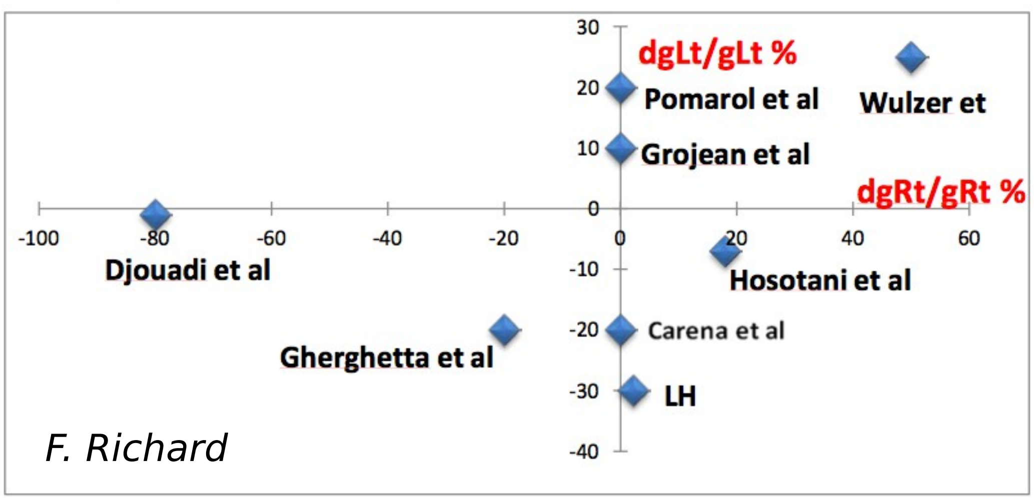
New Physics through precision measurements

Deviation from SM couplings = Discovery of new physics

Higgs sector



Top sector



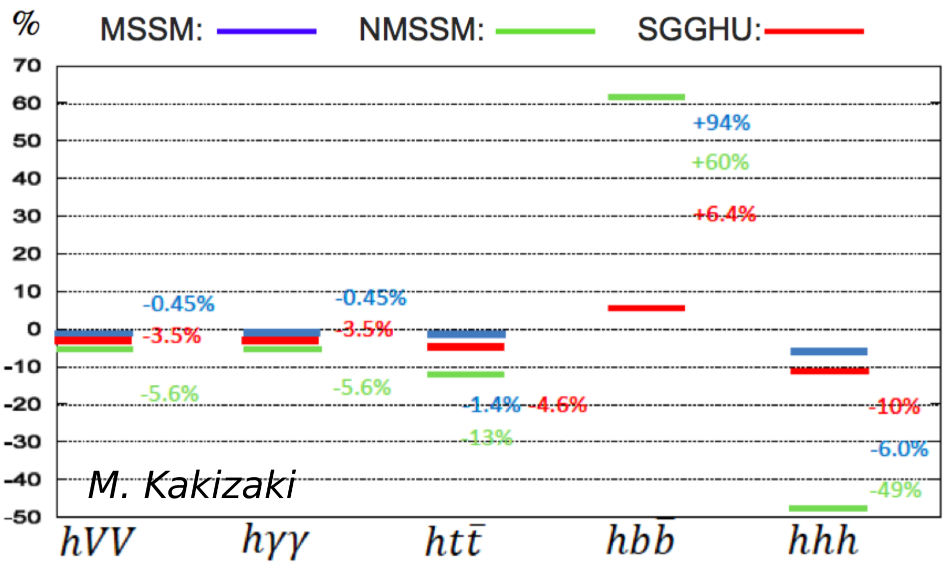
Precision measurements should be able to pin down nature of New Physics and – in absence of new particles – set the scale of New Physics

Exploration of Higgs and top (+W) sector
=> Compelling arguments for lepton machine with centre of mass energy m_Z - ~1-2 TeV

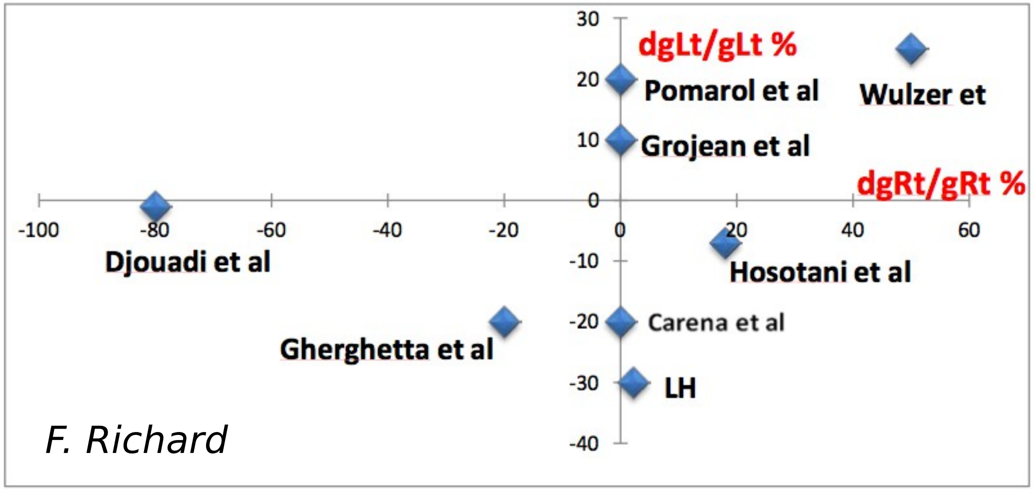
New Physics through precision measurements

Deviation from SM couplings = Discovery of new physics

Higgs sector



Top sector

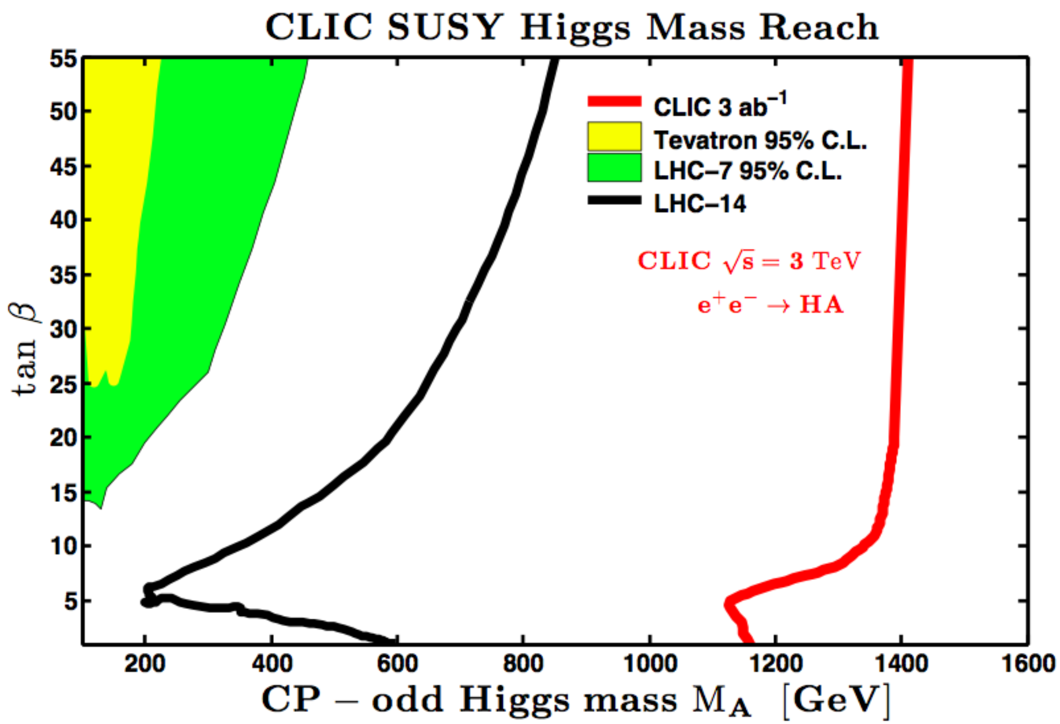


Precision measurements should be able to pin down nature of New Physics and – in absence of new particles – set the scale of New Physics

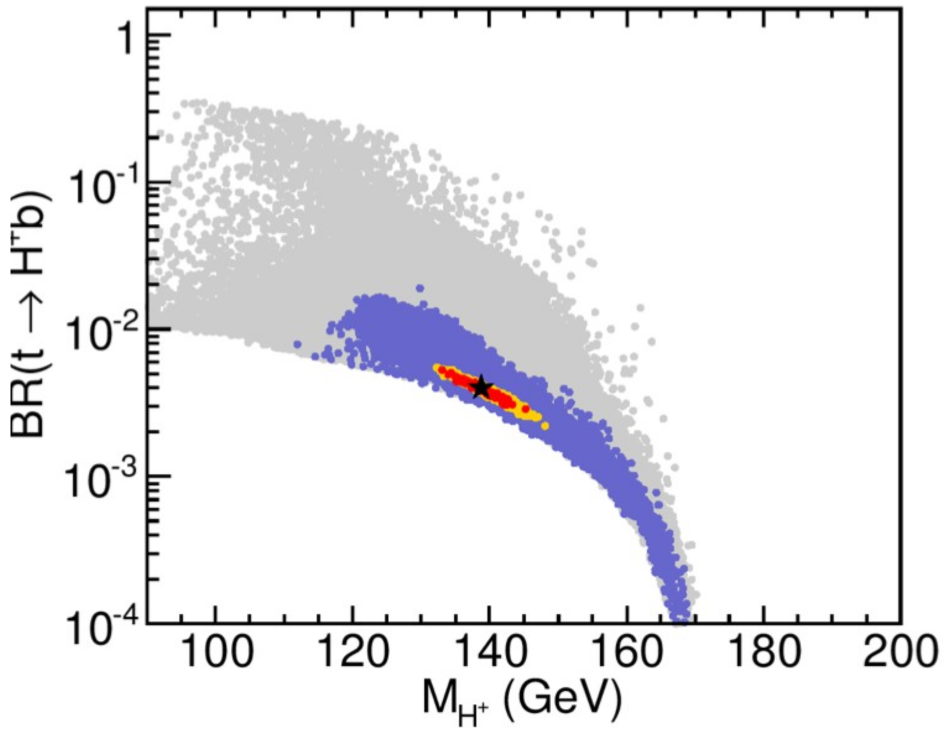
New physics through direct observation

Discovered state is ....

... light Higgs



... heavy Higgs



Multi-TeV e+e- collider extends mass reach and discovers further Higgs particles

Sub-TeV e+e- collider discovers new particles

N.B.: LHC may miss light color neutral SUSY particles

Key message so far

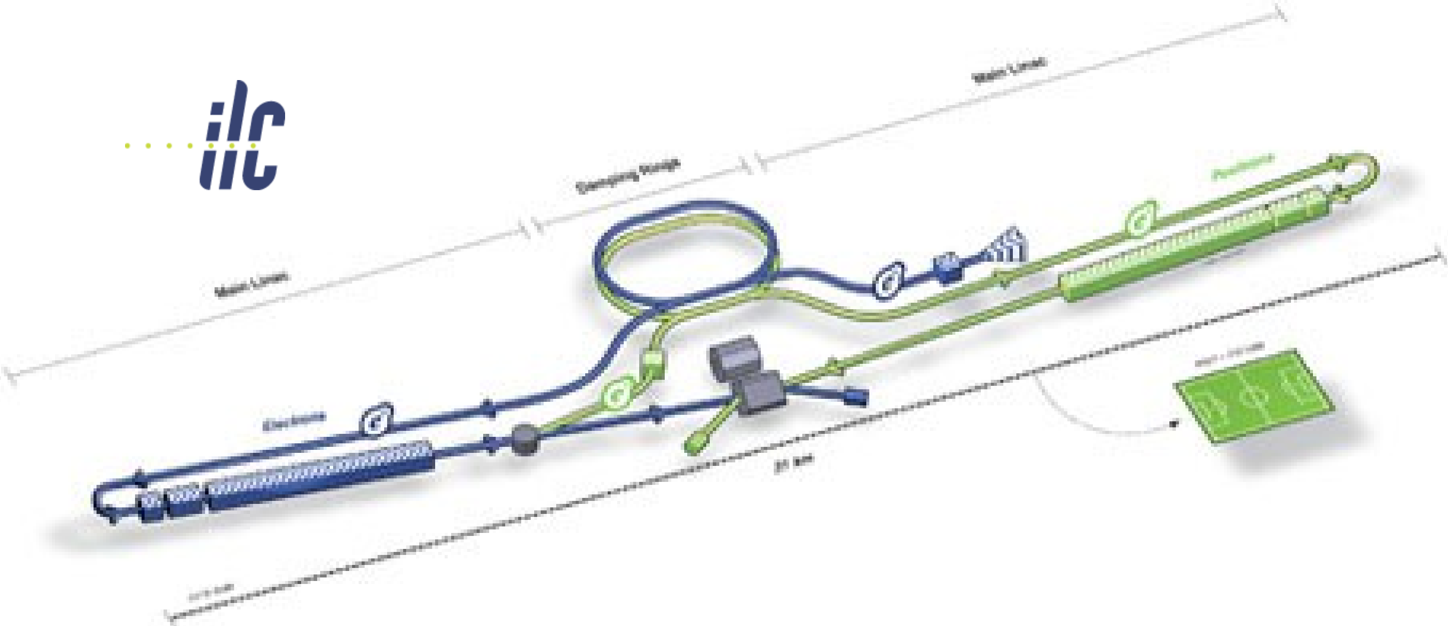
Exploration of Higgs and top (+W) sector

=> Compelling arguments for lepton machine with centre of mass energy m_z - ~1-2 TeV

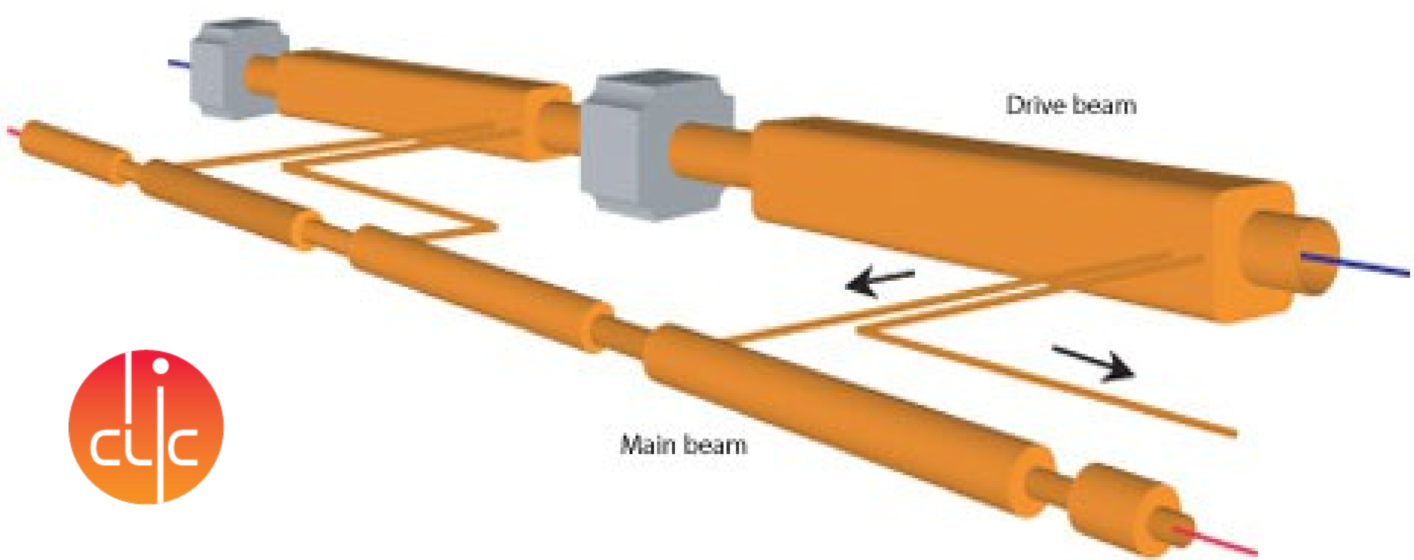
25 year – long effort towards a very high performance e+ / e- collider

Year	1987	1992	1998	2004	2006	2012
Phase	**SLC @ SLAC**		LC Design	Global Design Effort - ILC		
500 GeV Linear Collider R & D	**8 schemes**		**4**		**2** →	
Comparative Reviews		Technology Review 1995	Technology Review 2002	International Technology Review Panel 2004		'General issues' ILC/CLIC
Beam Test Facilities - Linac (cost-driver)	**(SLAC)**	**NLCTA, TTF / FLASH**				**NML, STF, CTF**
Beam Test Facilities - Emittance		**FFTB**	**ATF**		**CesrTA**	**ATF2**

(Future) Linear electron-positron colliders



Energy: 0.1 - 1 TeV
lectron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Possible timeline for project see later

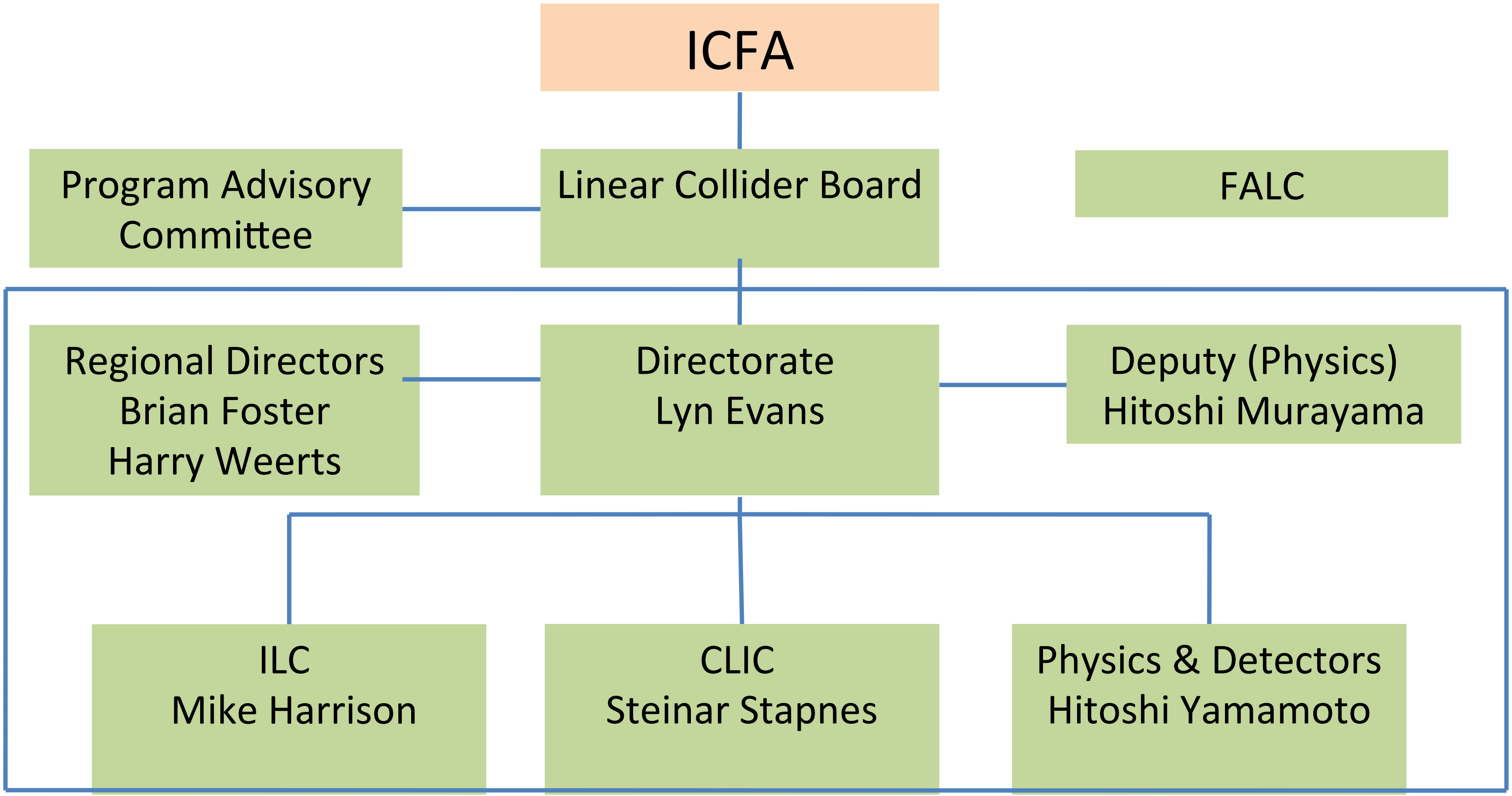


Energy: 0.5 - 3 TeV

CDR in 2012

Linear Collider Collaboration

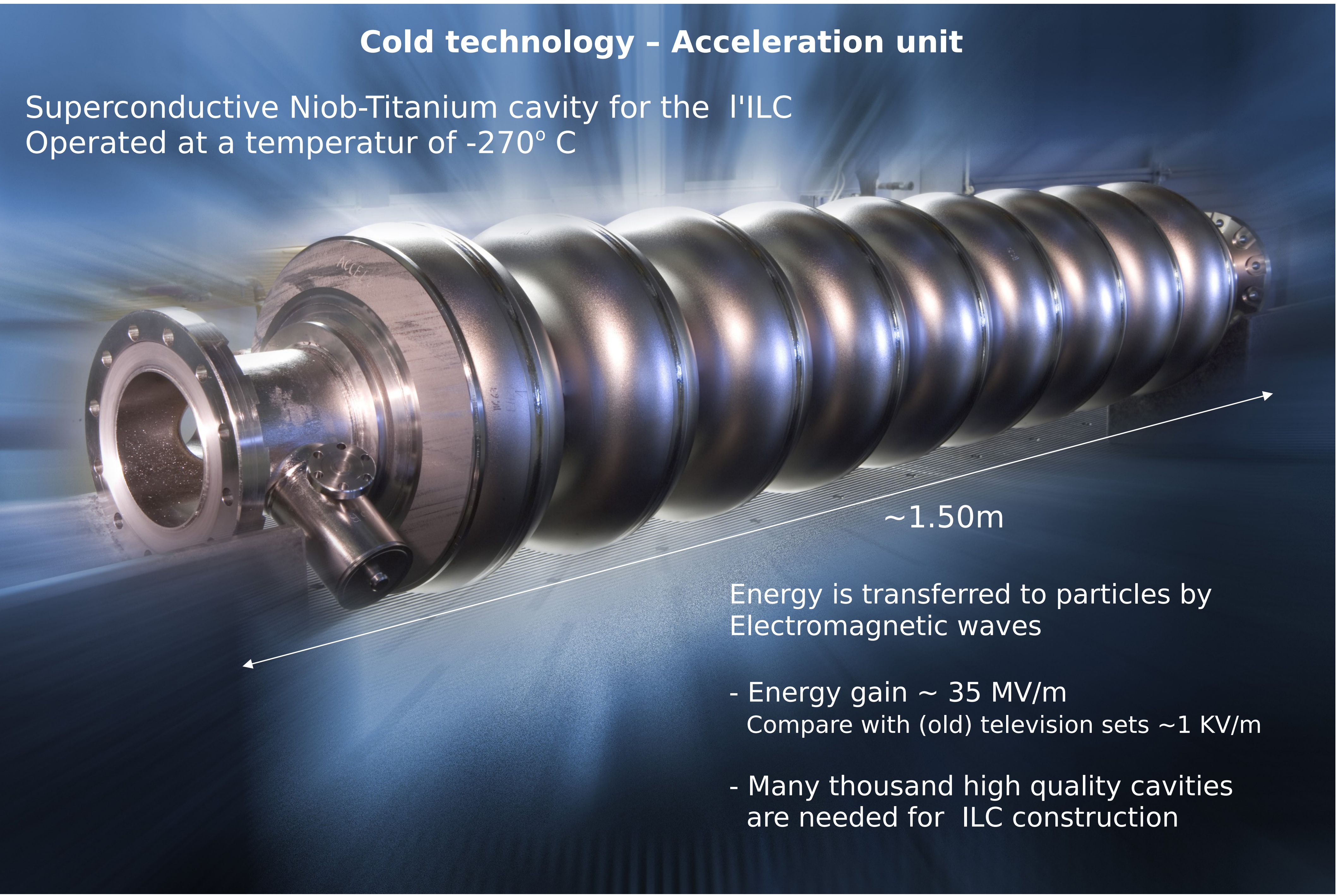
Organization



Worldwide project
Regional balance

Cold technology – Acceleration unit

Superconductive Niob-Titanium cavity for the l'ILC
Operated at a temperatur of -270° C



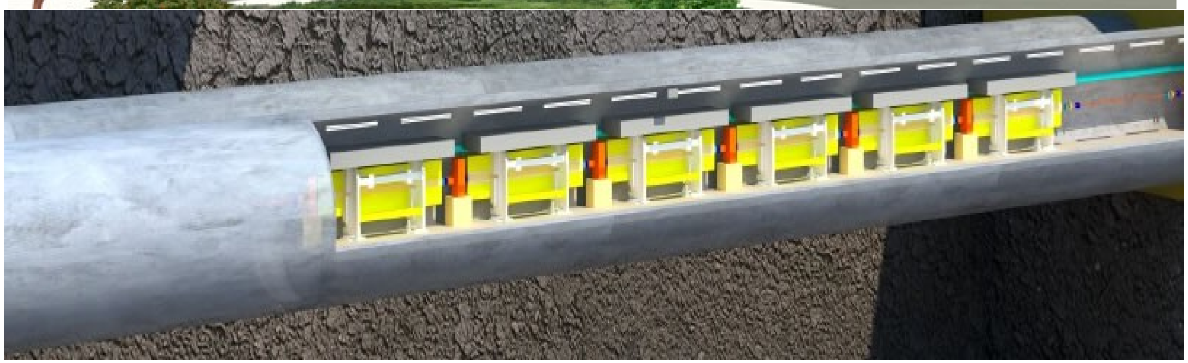
Energy is transferred to particles by Electromagnetic waves

- Energy gain ~ 35 MV/m
  Compare with (old) television sets ~1 KV/m

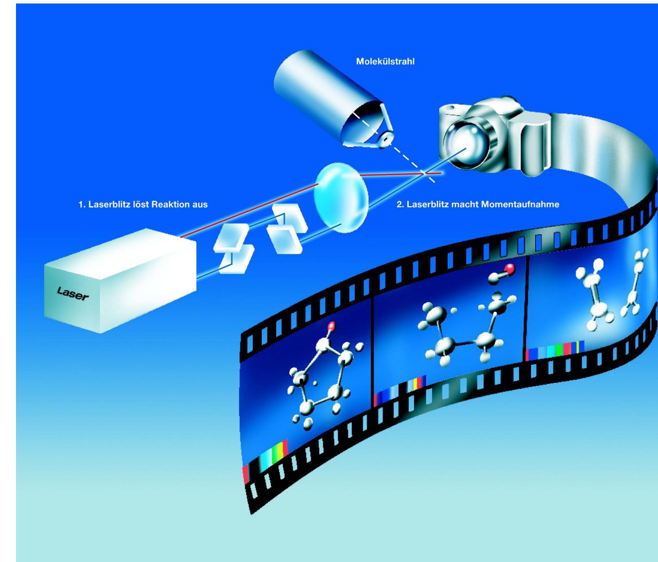
- Many thousand high quality cavities are needed for ILC construction

'Intermediate step' – European XFEL – DESY Germany

X rays with high brilliance



Large variety of applications



Example: Film of a chemical reaction

3.4km long accelerator based on ILC technology

Big scientific project by itself but also a large scale test for ILC

Validation of technology

Industrialisation of accelerator elements

Detector requirements

Track momentum: $\sigma_{1/p}$ < 5 x 10^{-5}/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < 5 \oplus 10/(p[GeV]\sin^{3/2}\theta)$ (1/3 x SLD)

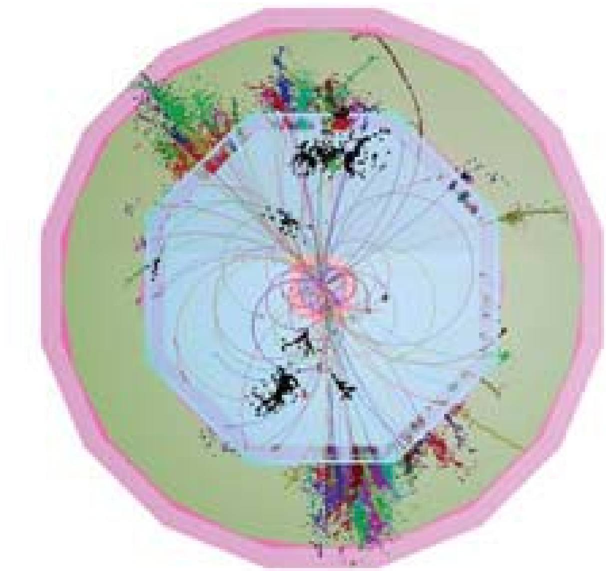
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(GeV))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g. SUSY)



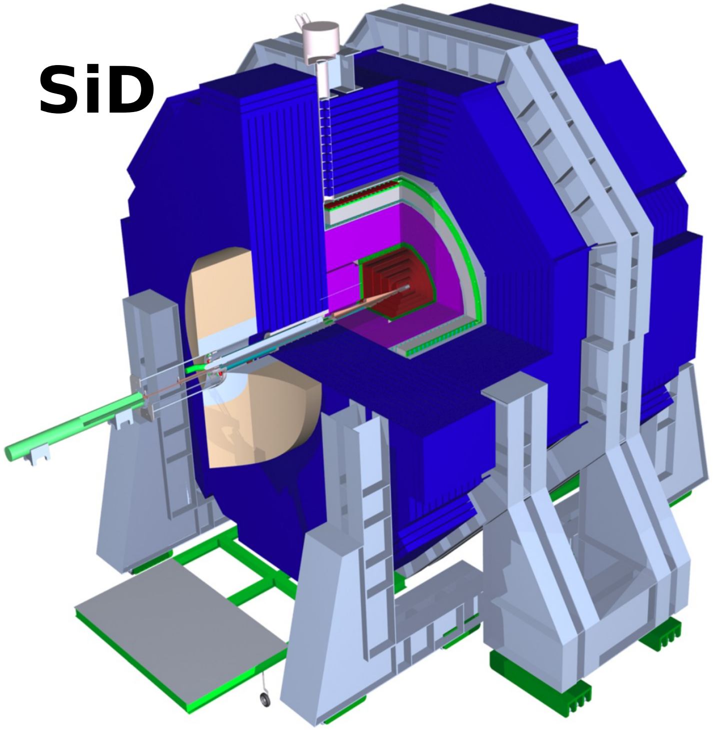
Final state will comprise events with a large number of charged tracks and jets(6+).

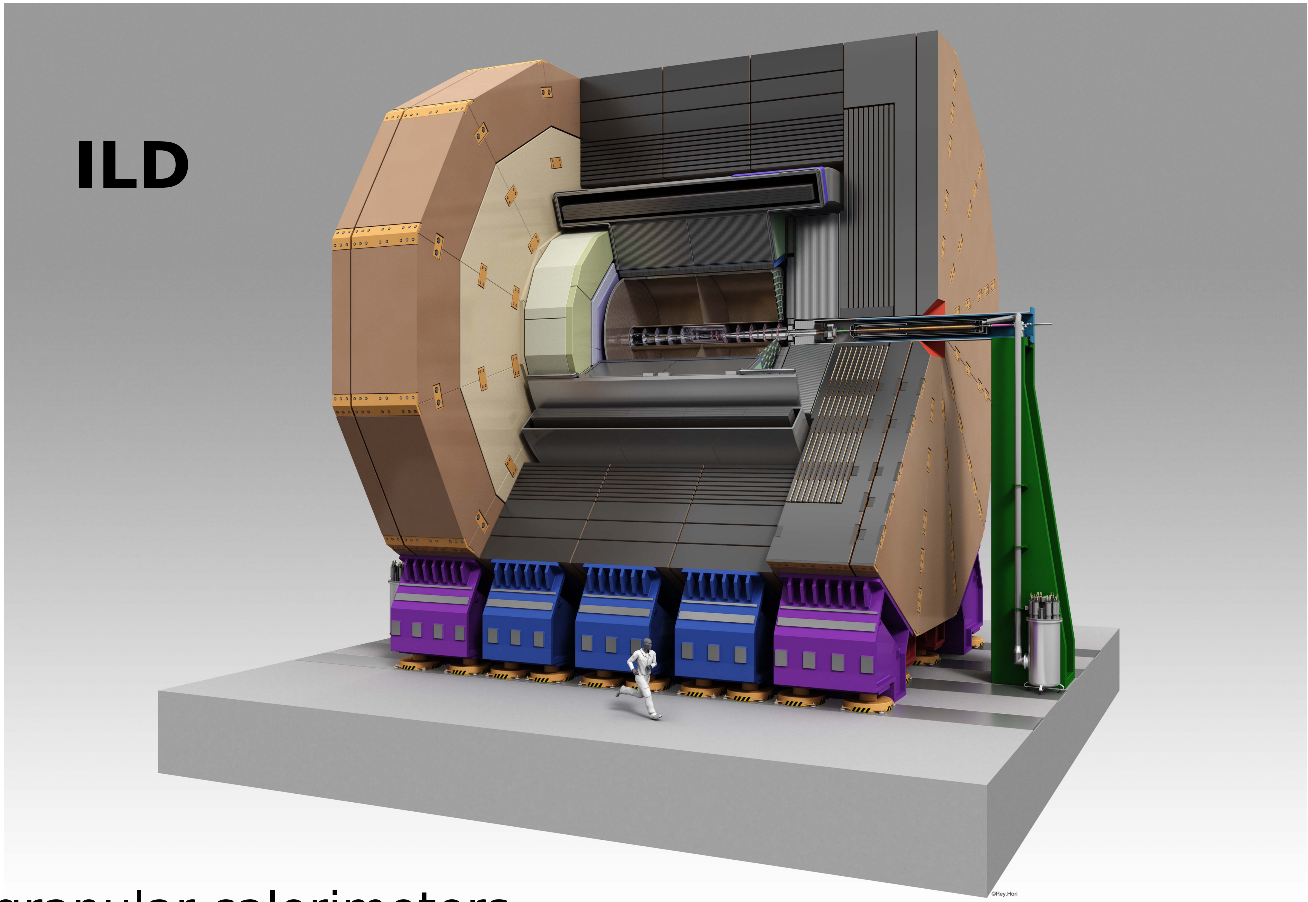
- **High granularity**
- **Excellent momentum measurement**
- **High separation power for particles**

-> 2 approches différentes

Detector concepts SiD et ILD

Detector concepts





Highly granular calorimeters

Central tracking with silicon

Central tracking with TPC

Inner tracking with silicon

- LOI's Validated by IDAG in 2009
- Publication of **D**etector **B**aseline **D**esign in 2013, together with TDR
- Concepts based on input from physics studies and detector R&D organised in R&D collaborations

Examples for detector R&D collaborations

Time Projection Chamber
for Linear Collider

Highly granular calorimeters
for Linear Collider

Forward calorimeters
for Linear Collider

Silicon tracking for the
International
Linear
Collider

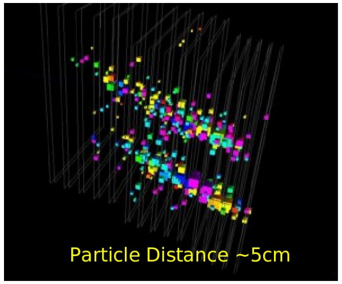
PLUME

- Oriented towards LC but very generic R&D

R&D RPCs, Micromegas, SiPMs, ultrathin vertex layers, diamond sensors
Large scale integration of electroncis, small power consumption

Detector R&D

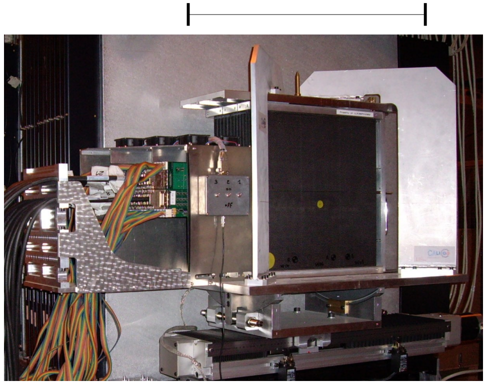
Precision physics at LC require highly granular calorimeters



Physics Prototypes

Proof of principle

2003 - 2011

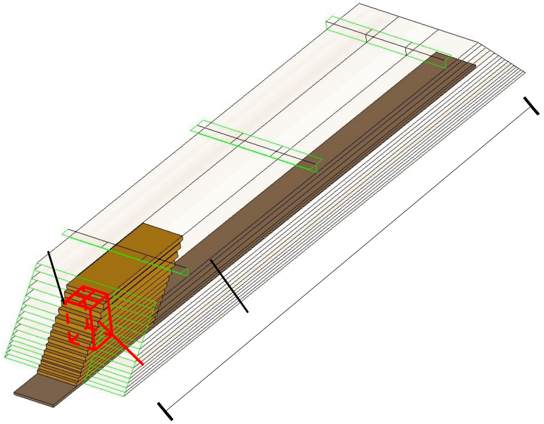


- **Number of channels : 9720**
- **Weight : ~ 200 Kg**

Technological Prototypes

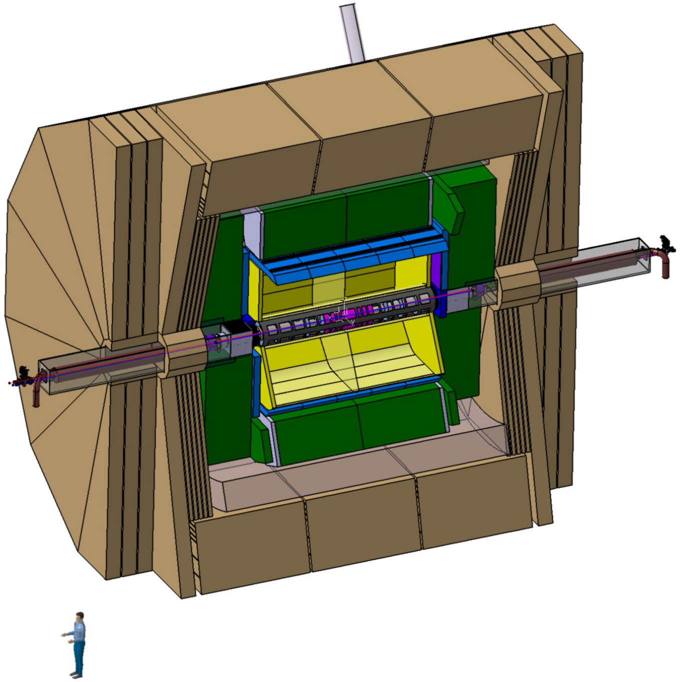
Engineering challenges

2009 - ...



- **Number of channels : 45360**
- **Weight : ~ 700 Kg**

LC Detector

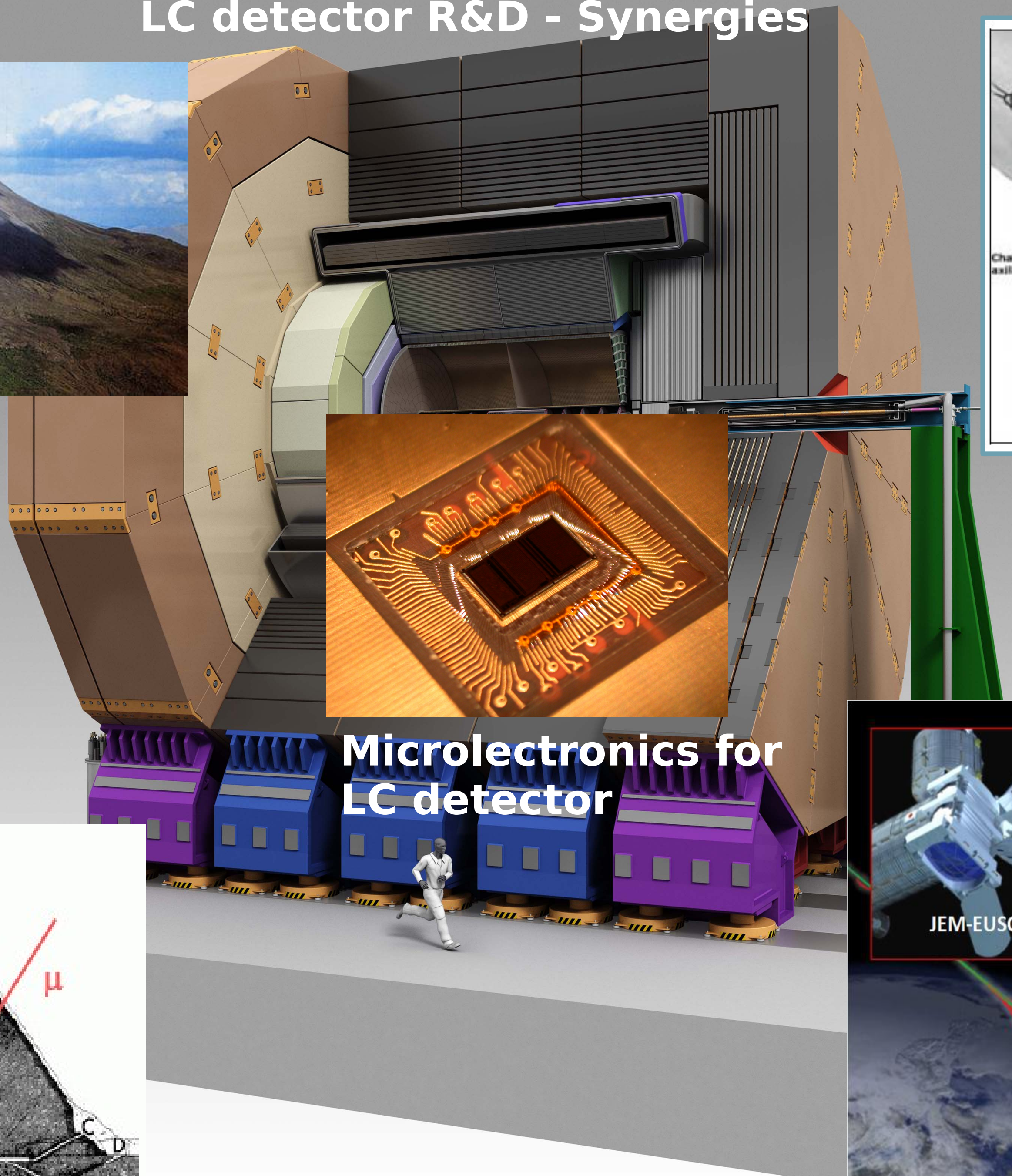


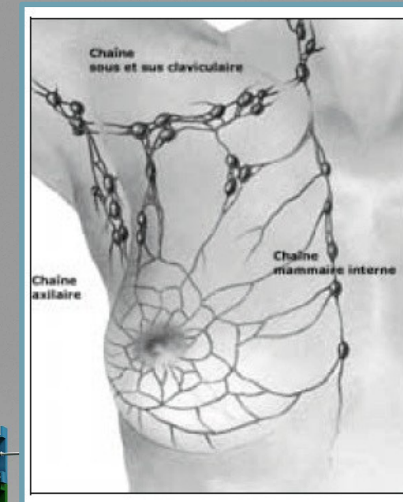
Electromagnetic Calorimeter :

- **Channels : 110 10^6**
- **Total Weight : ~130 t**

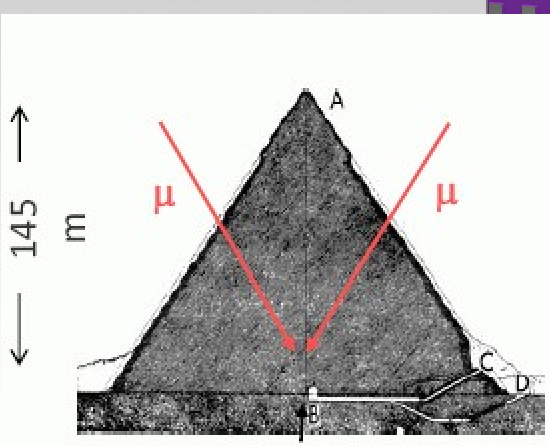
Detector prototypes essectial input to DBD

LC detector R&D - Synergies

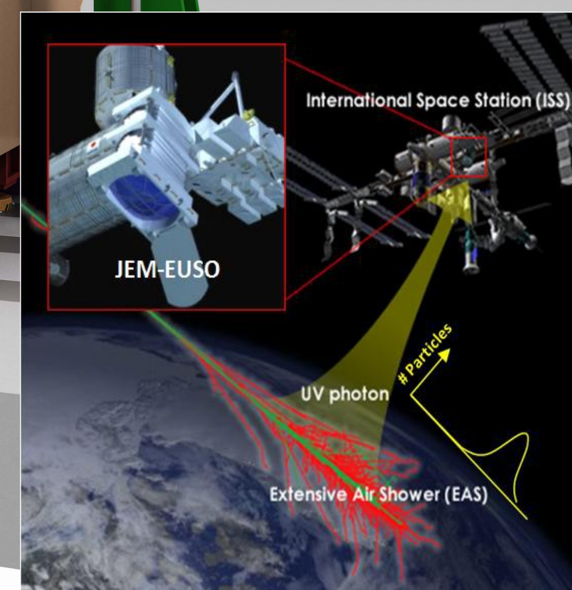




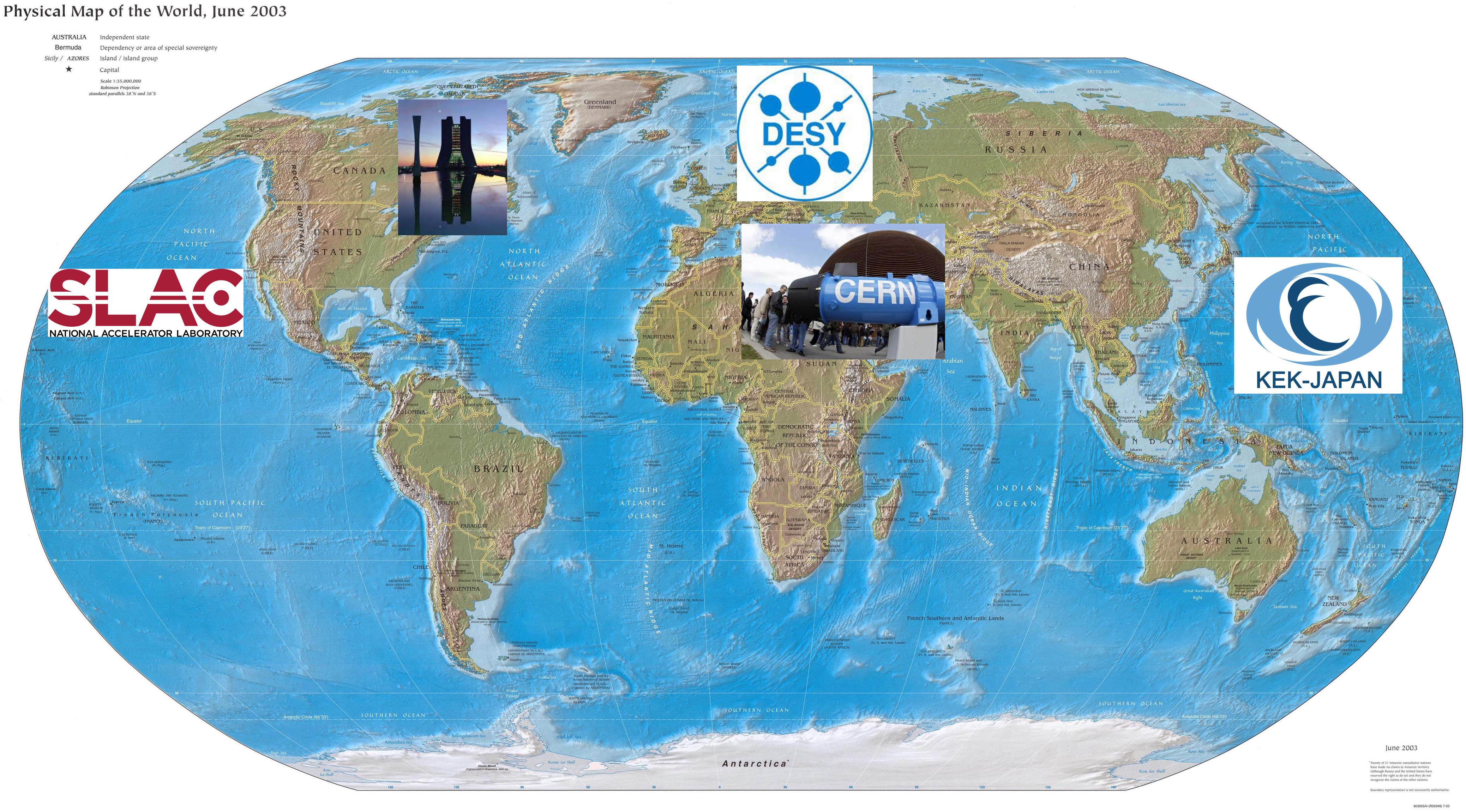
Microlectronics for LC detector



Telescope in Belzoni chamber



Worldwide network for LC



- Network of big research centers and strong national institutes
- (Maybe) the first real worldwide project

Political and scientific actors

General public

Sociological, cultural and economical added value

Gouvernements
Political decisions

FALC — Funding Agencies for Large Collaborations

ICFA — International Committee for Future Accelerators

LINEAR COLLIDER COLLABORATION

Internal organisation and communication with external authorities/committees

General status of LC project

No serious scientist doubts utmost relevance of LC project

Linear collider collaboration established

ILC:

- TDR and DBD prove mature technology
- Serious interest of Japan to host the machine (-> see next slides)
- Positive reactions from other regions
  - -> European strategy published in spring 2013
  - -> American strategy in making
    - ILC played great role in “Snowmass” process

(Personal view) Hour of politics did come

CLIC:

- Not yet ready for a proposal
- R&D will continue to assure readiness for e.g. Next European Strategy

Very Recent Activities

2013 May ECFA LC (DESY, Hamburg)

2013 June ILC Event TDR Review is completed

(Tokyo ⇒Geneva ⇒Chicago)

2013 June-August In Science Council of Japan

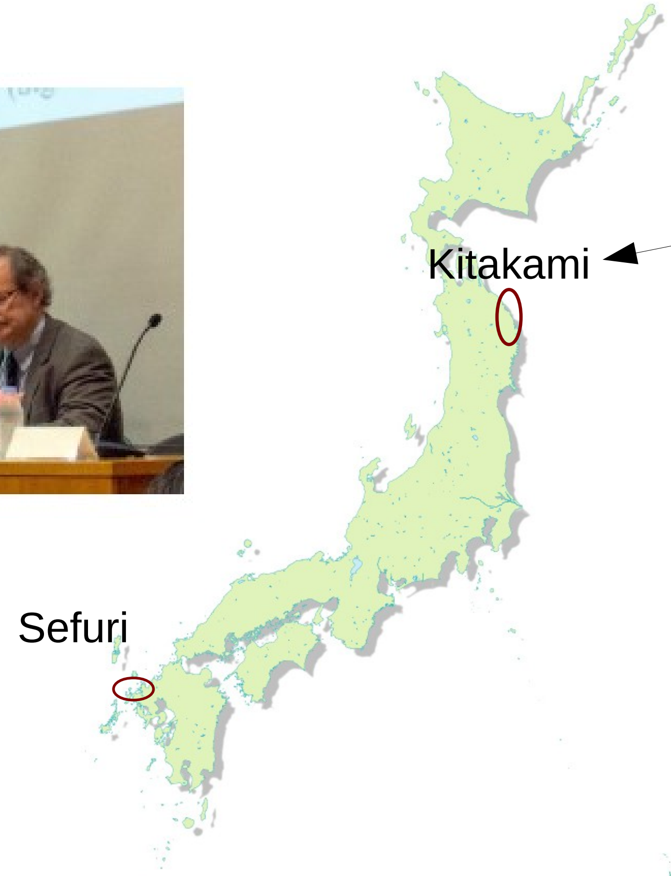
ILC Review Committee was formed

2013 April ILC Taskforce started in MEXT Japan

2013 August A site in Japan has been chosen by scientists (MEXT, Politicians all agree to the process)

2013 Nov. 11-15 LCWS2013 The University of Tokyo

23 August 2013 – Selection of Japanese Site for ILC



Prefectures
Iwate and Miyage

Japan strives for truly international project
Concrete site allows to tailor accelerator and detector design

Summary

- Together with the LHC a LC will lead the research landscape and the philosophy of the 21st century and maybe beyond

  Higgs and top quark are physics guaranteed
  (My conviction) both are messengers to New Physics

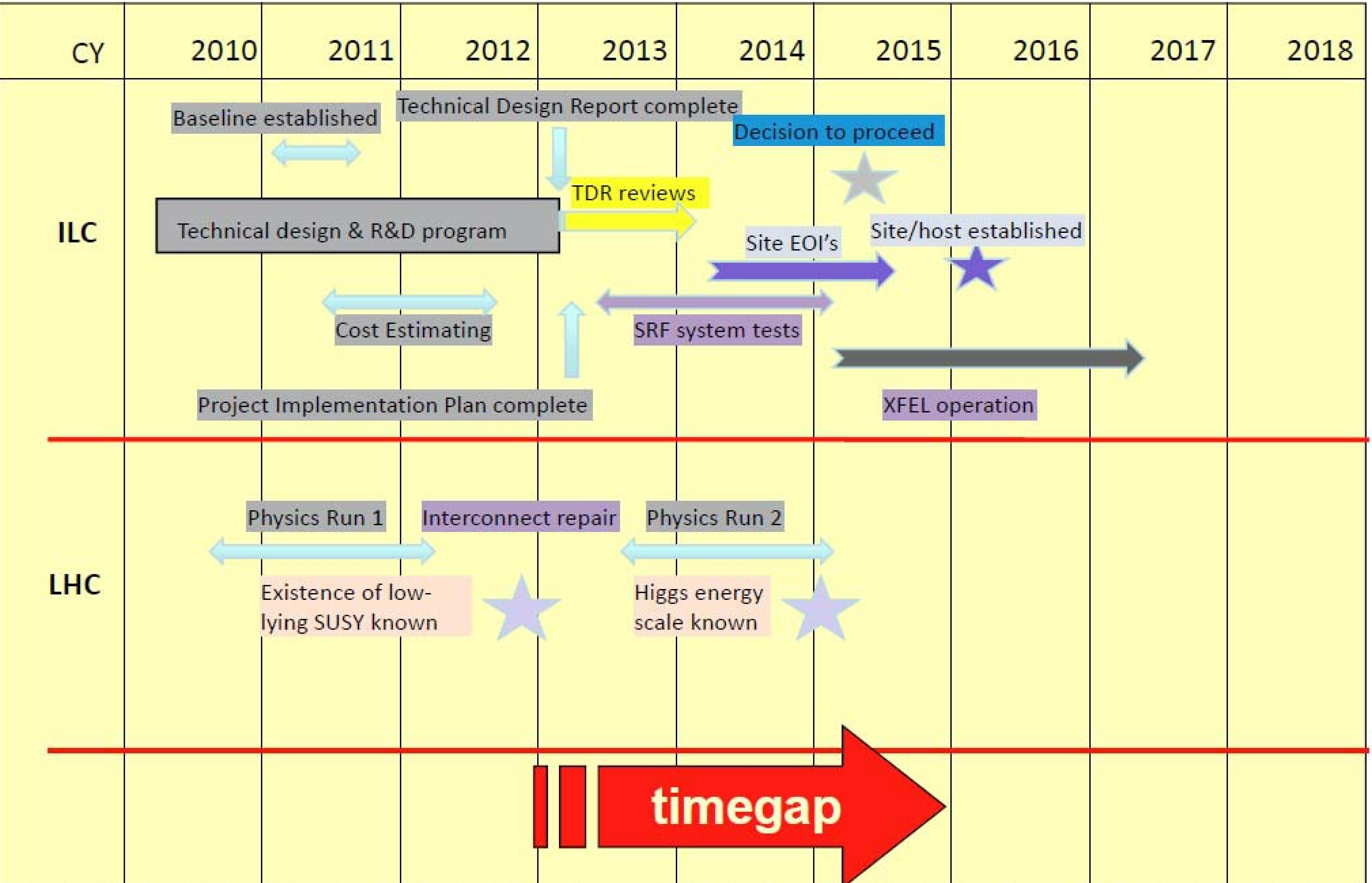
- A intellectual, sociological and technological adventure

- Technologies are getting mature
  - ILC is ready to be constructed
  - CLIC made remarkable progress
  - Sharing well advanced detector technologies

- Requires a world wide organisation

For learning more: www.linearcollider.org
or even better
pay great attention to the lectures at this school !

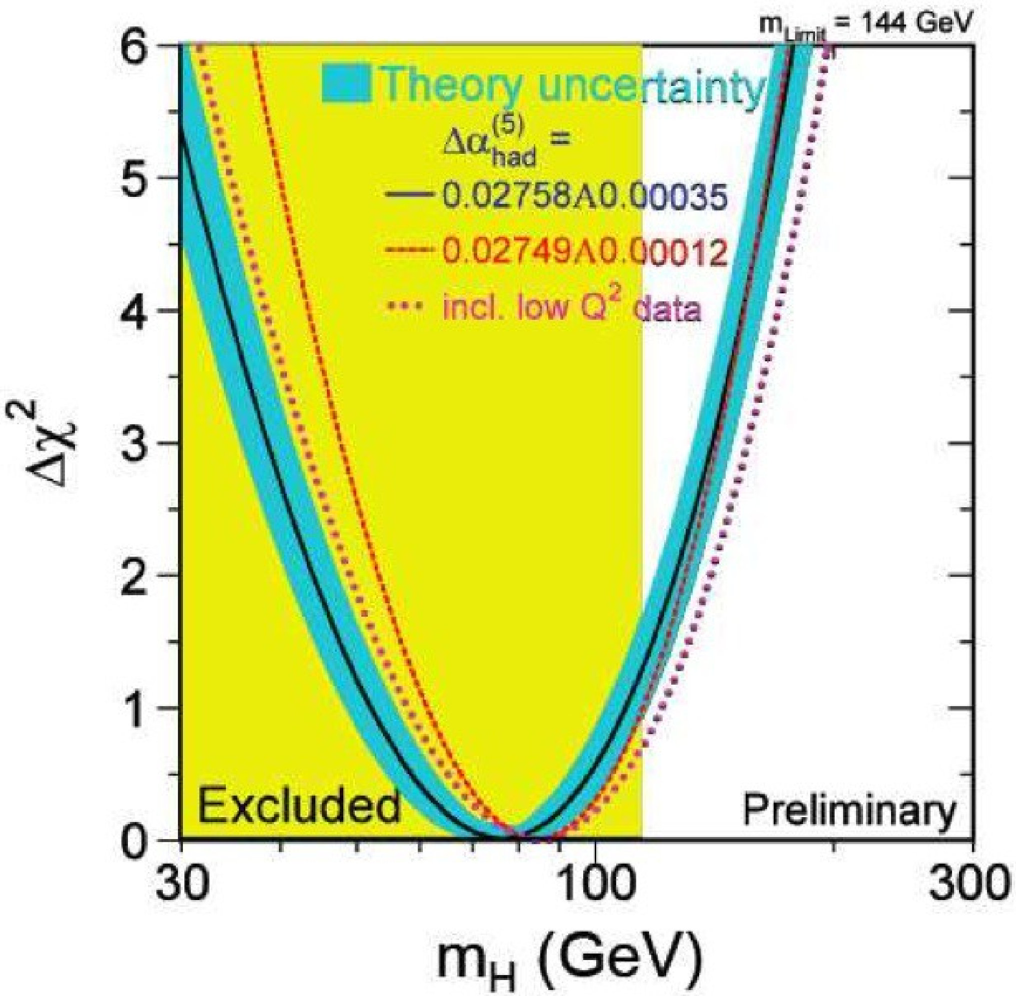
ILC possible timeline



Mais ... D'où vient la masse des particules (et la nôtre) ?

Le Modèle Standard postule l'existence d'une autre particule

Le Boson de Higgs

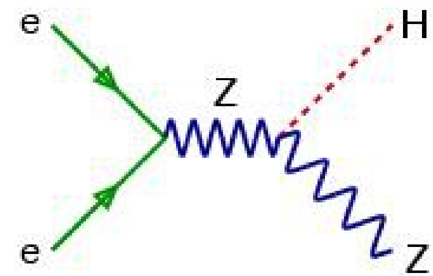


Synthèse des toutes expériences

- Nécessaire afin que les particules obtiennent leurs masse
- Jamais observée dans une expérience

Mais tiens, la particule doit avoir une masse d'environ 100 GeV = 0.1 TeV

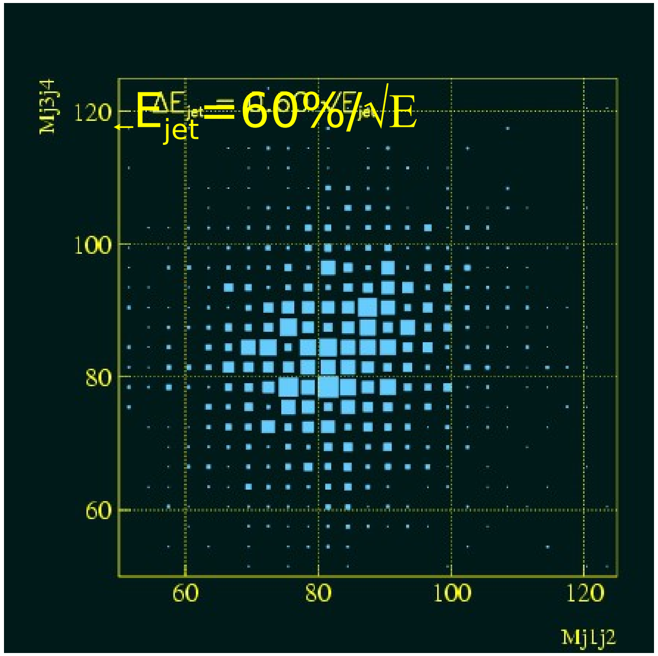
Bien accessible à l'ILC



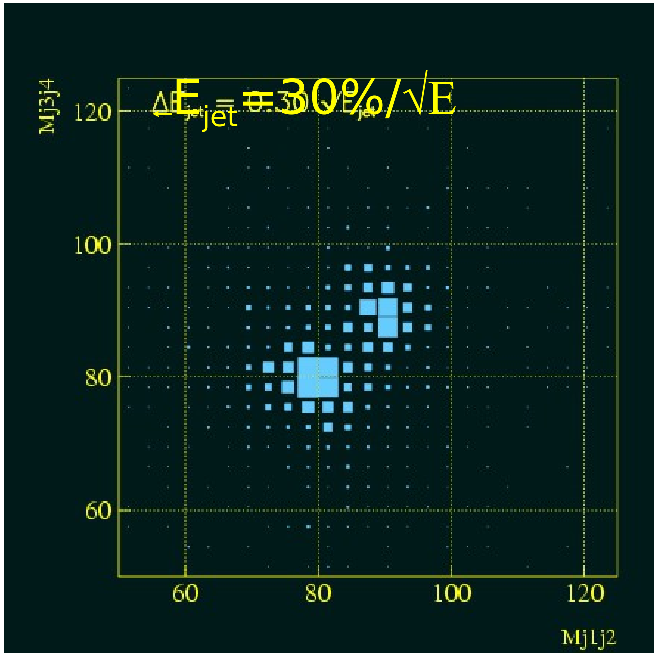
Mettons des lunettes ....

Reconstruction des jets en e^+e^- ‖WW��, ZZ��

Séparation des WW et ZZ: 4 Jets + énergie manquante



Détecteur à LEP



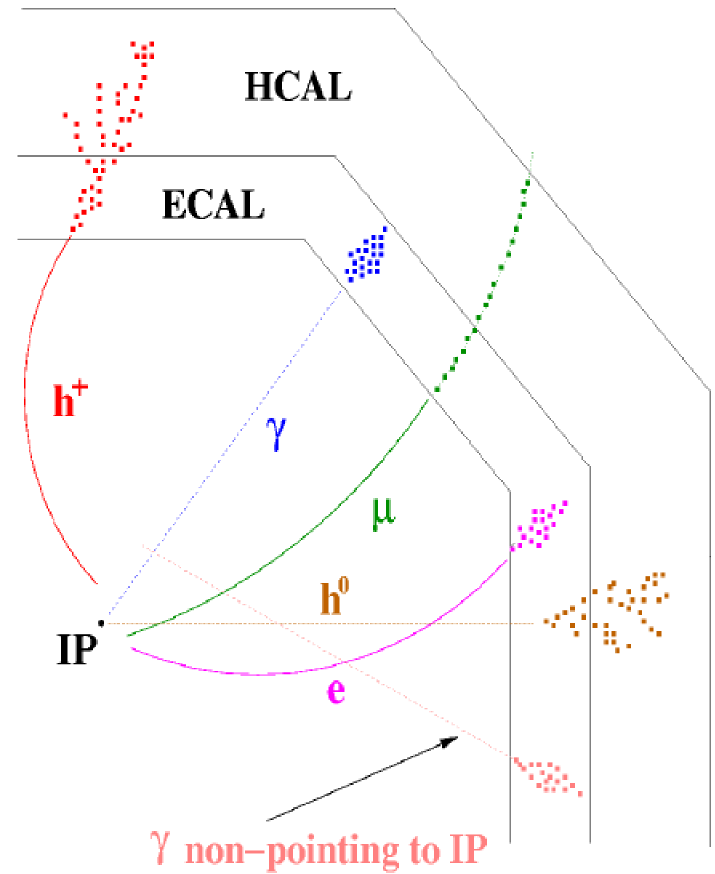
Détecteur à l'ILC

30%/√E Jet de résolution de l'énergie nécessaire @ ILC

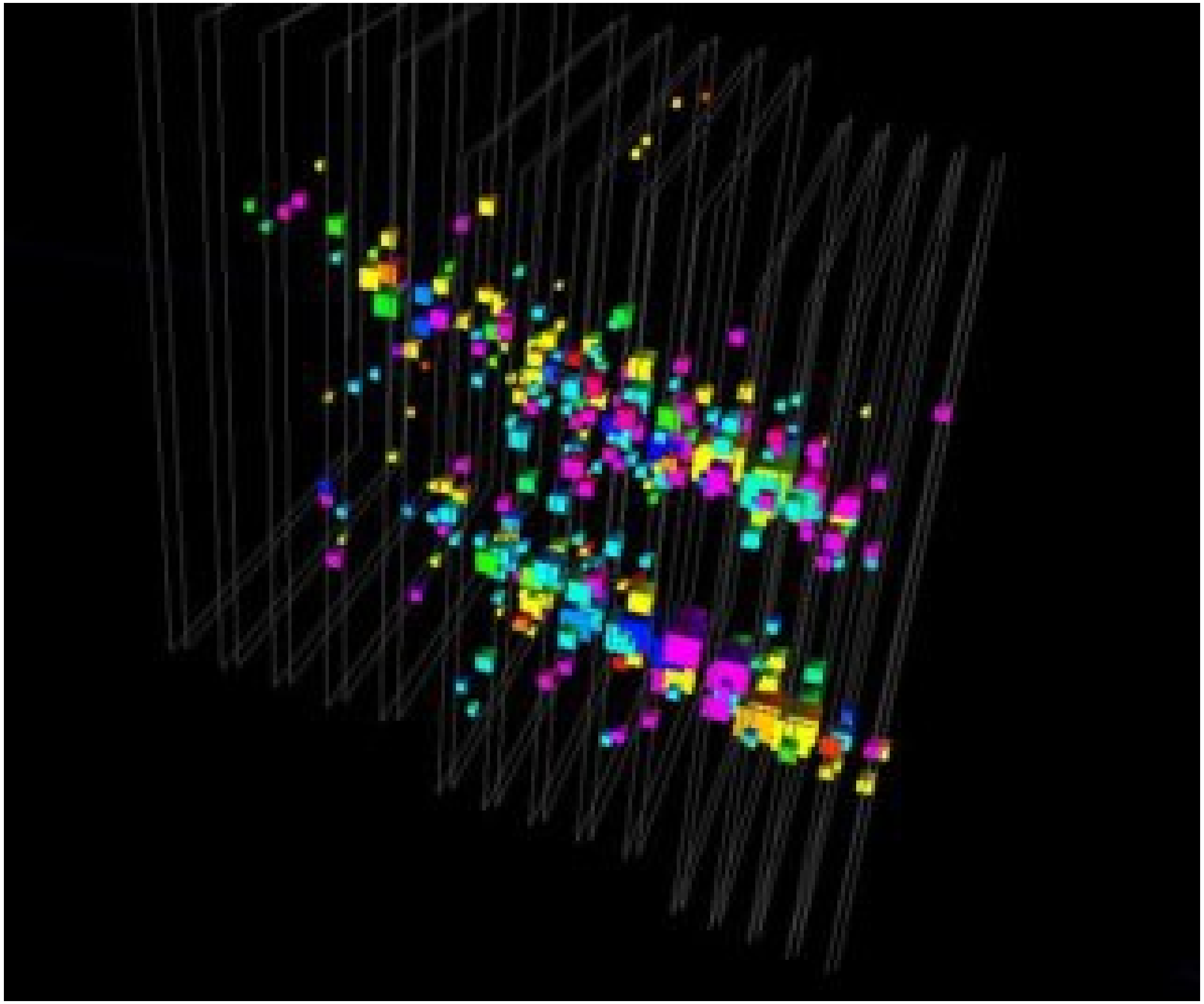
Conception du Détecteur et 'Particle Flow'

Résolution optimale d'énergie:
Detéction de chaque particule
dans un événement ‖ “Particle Flow”

- Particule chargée avec chambre à traces
  et leurs signaux associés dans le calorimètre
  (Shower Track Matching)
  Remplacement de l'énergie calorimétrique par
  l'énergie des traces
- Photons en ECAL
- Hadrons neutres en HCAL



Ecal en test en faisceau @ CERN



... et voilà une bonne séparation des particules !!!

Distance entre particule ~5cm – Pas de confusion !!!!

Unités et échelles

1 eV = Énergie acquise par une particule chargée après le passage d'une différence de tension électrique de un Volt

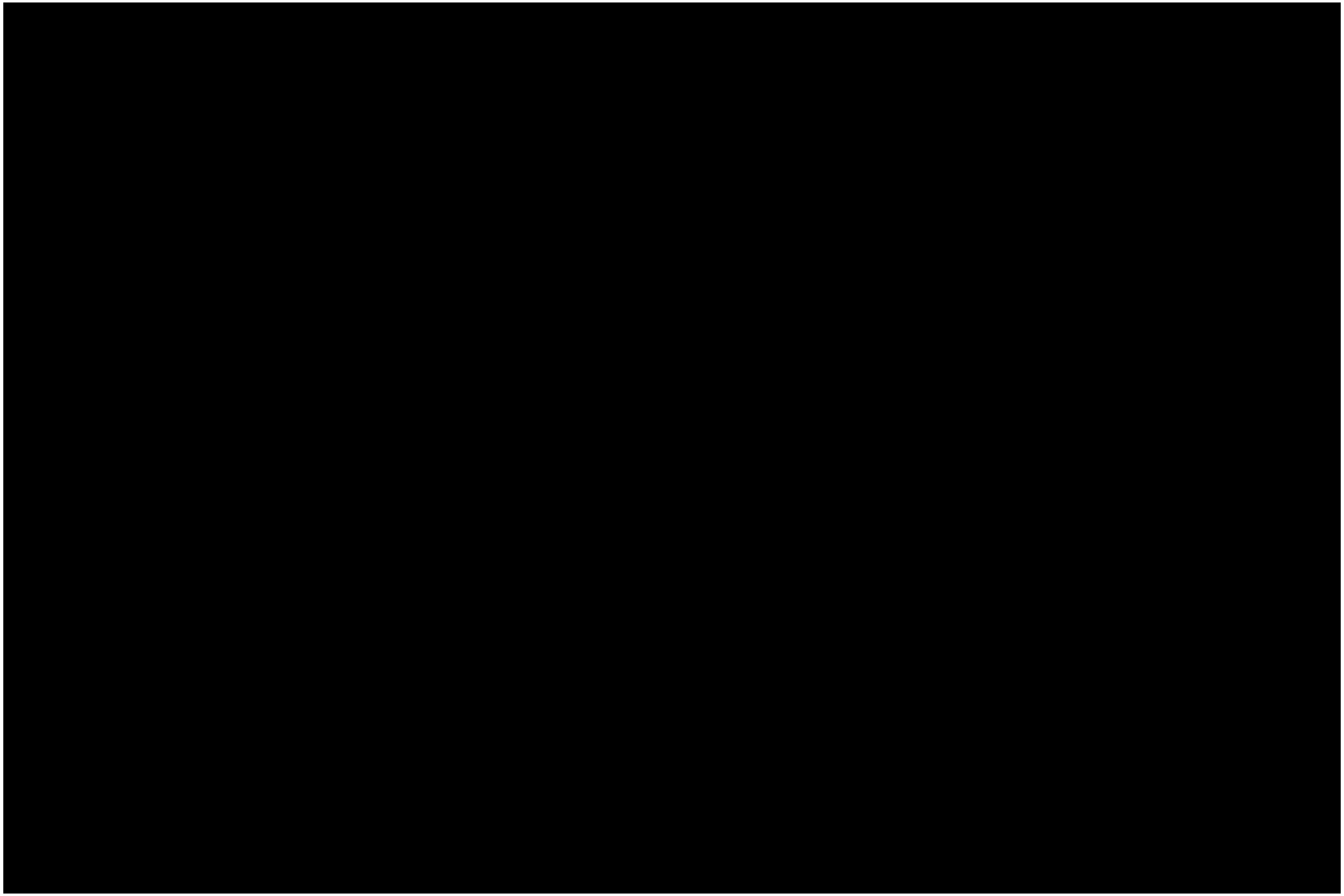
1 eV correspond à une température de ~ 10000 K (= 9727 ºC)

C'est, environ, la température de la surface du soleil

ourd'hui nous parlerons d'une (autre) machine qui va créer des particules jusq

1 000 000 000 000 eV = 10^{12} eV = 1000 GeV = 1 TeV

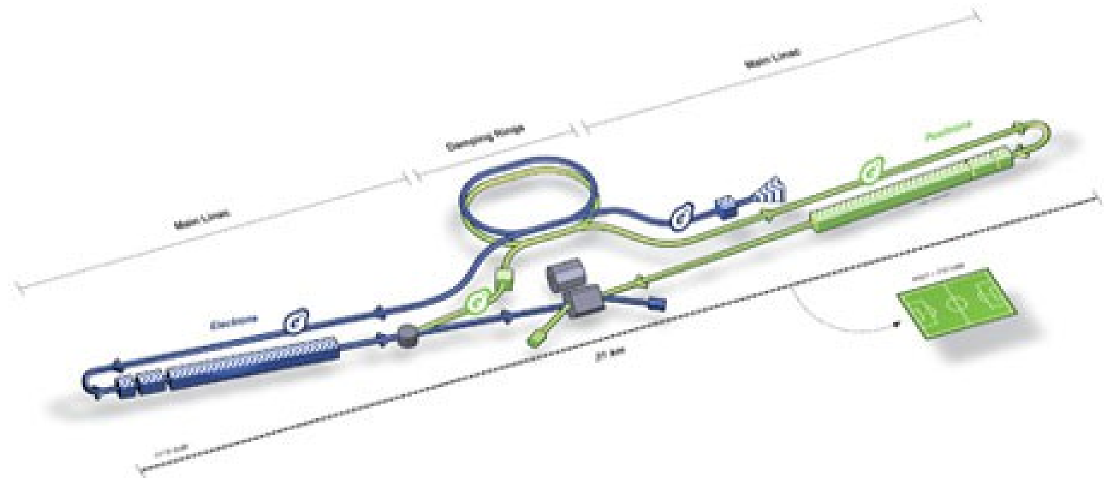
L’ILC en animation



Source: http:www.linearcollider.org

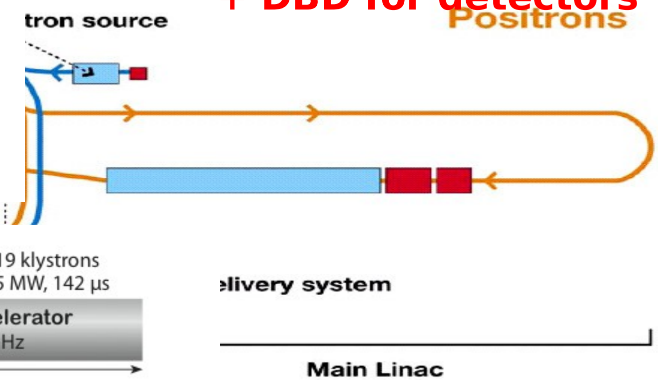
Longueur d’empreint 31 km
Energie disponible pour les collisions 0.2 GeV – 1 TeV
Taille de faisceau au point de collision ~10 nm (10^{-9}m)

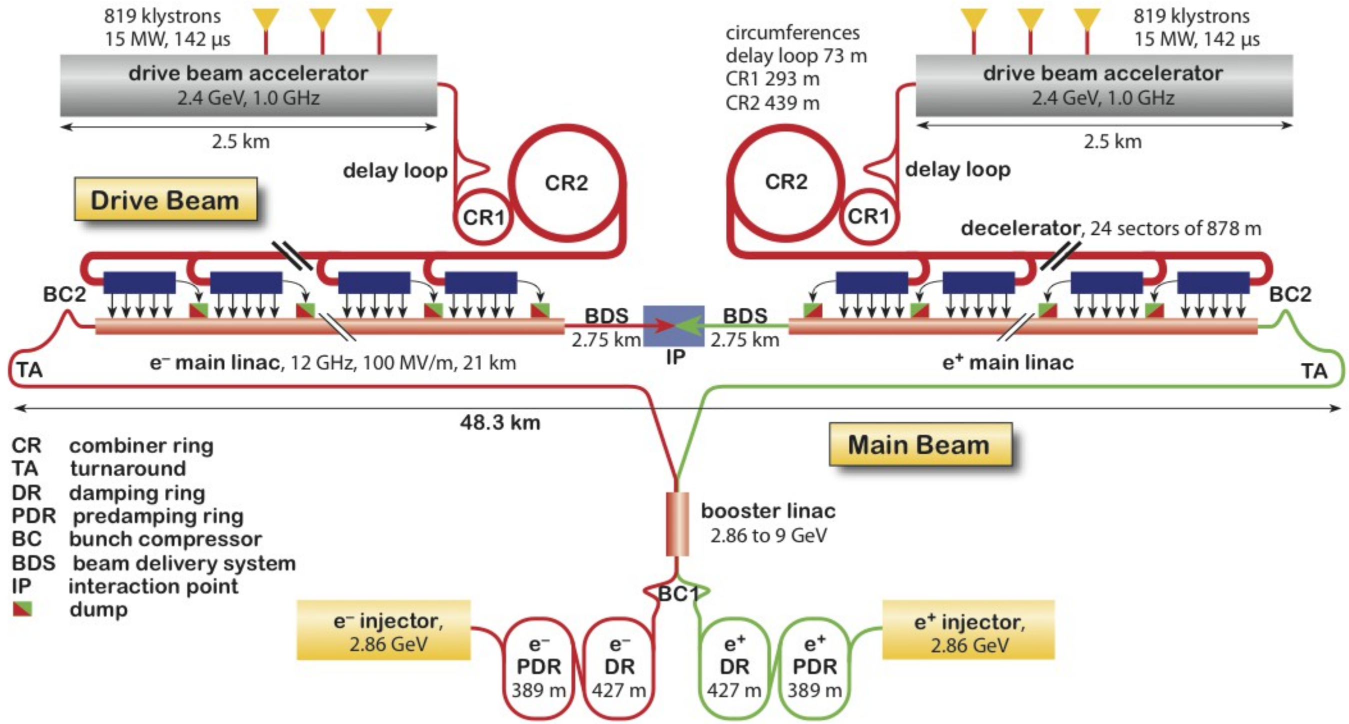
(Future) Linear electron-positron colliders



Energy: 0.1 - 1 TeV

TDR in 2012
+ DBD for detectors





Energy: 0.5 - 3 TeV

CDR in 2012

Etapes R&D – Développement et tests des prototypes

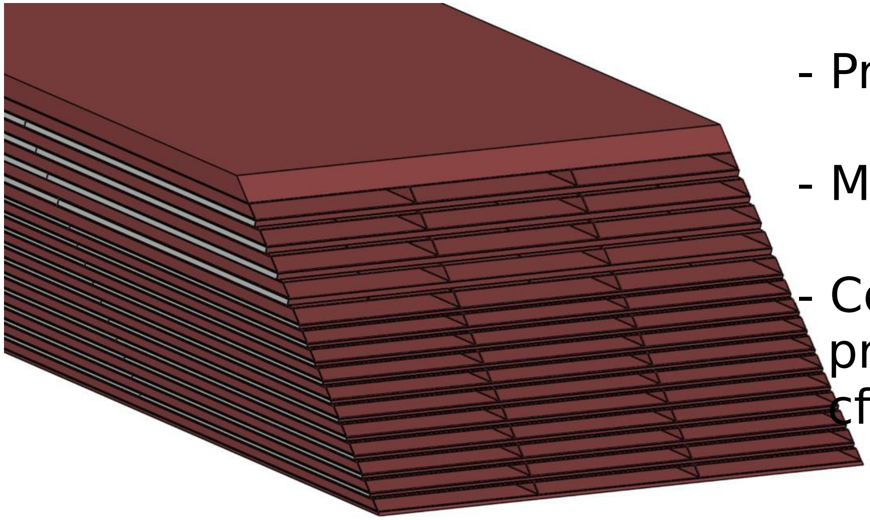
Phase 1 (2003-2011): Demonstration du principe

Prototypes des calorimètres en test sous faisceau

- Test des concepts dans des conditions (quasi) réelles

- Contraints relaxés aux composants

Phase 2 (2006-...): Prototypes technologiques



- Prototypes très proches des modules finaux

- Maitrise des enjeux technologiques

- Contact avec l'industrie pour preparer la production de masse des composants d'un détecteur cf. 3000 m² de silicium

Brève histoire de l'univers

10^{-20}sec
après
le Big Bang

1 TeV = 10^{16} K

Physique du XXème siècle

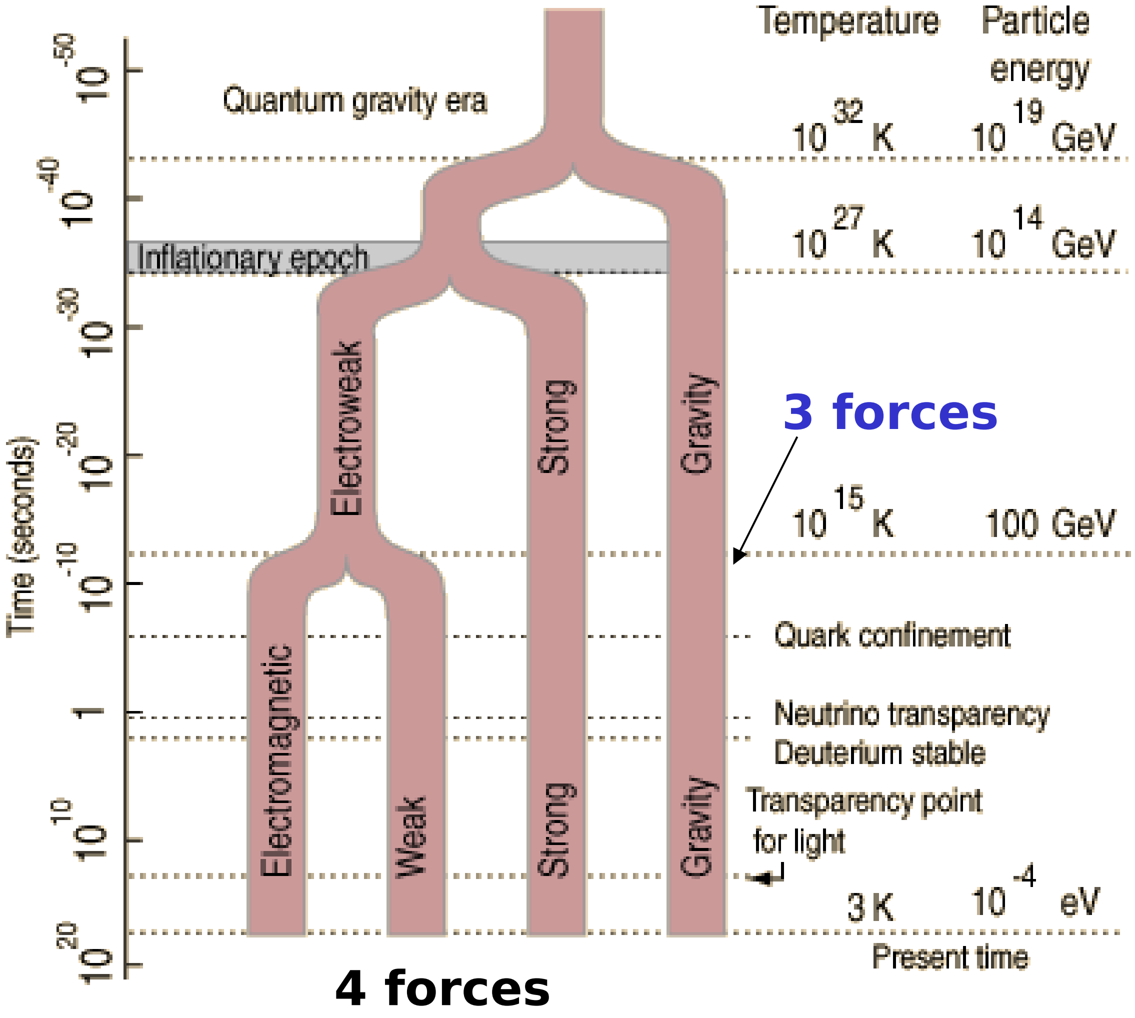
300000 années
après
le Big Bang

A 3000 K la lumière
pouvait pénétrer
l'univers

Refroidissement de l'univers

Aujourd'hui
13.7 Milliards d'années
après le Big Bang
Température 3 K = -270 °C

Histoire de l'univers – Les forces



Fin de l'inflation
Meilleure compréhension par le Higgs

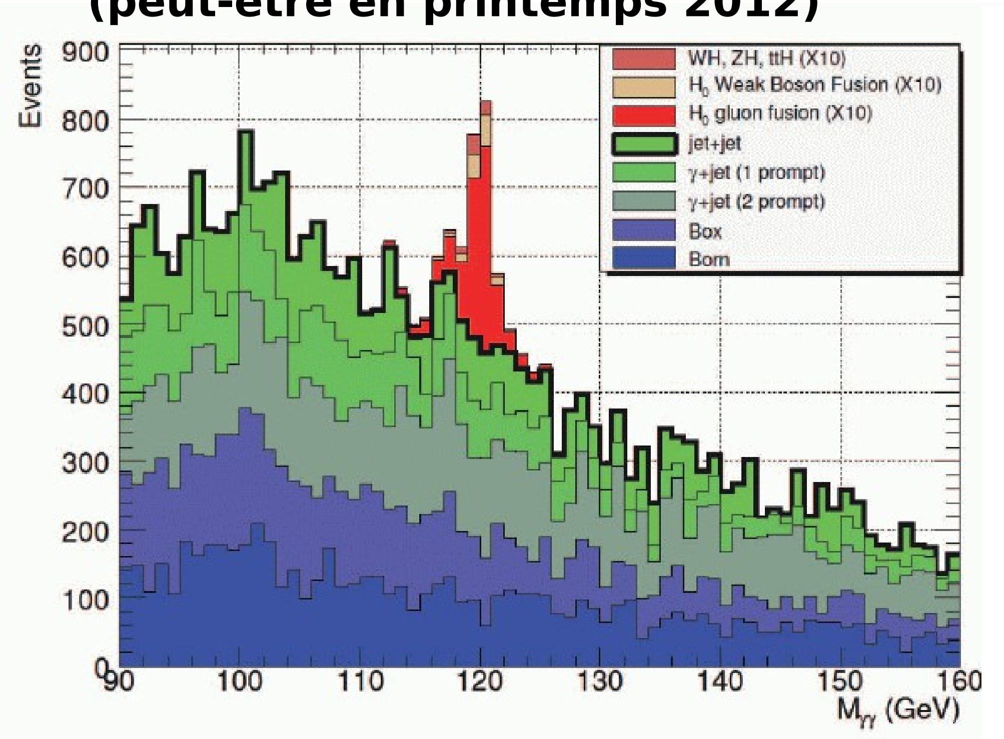
Unification of forces electromagnétic and weak Evidence through discovery of Z boson

Bref histoire du Z:
- **Postulated ~1970 (Glashow, Salam, Weinberg)**
- **Observé 1983 (SPS au CERN)**
- **Deep understanding by LEP au CERN (1989 – 2000)**

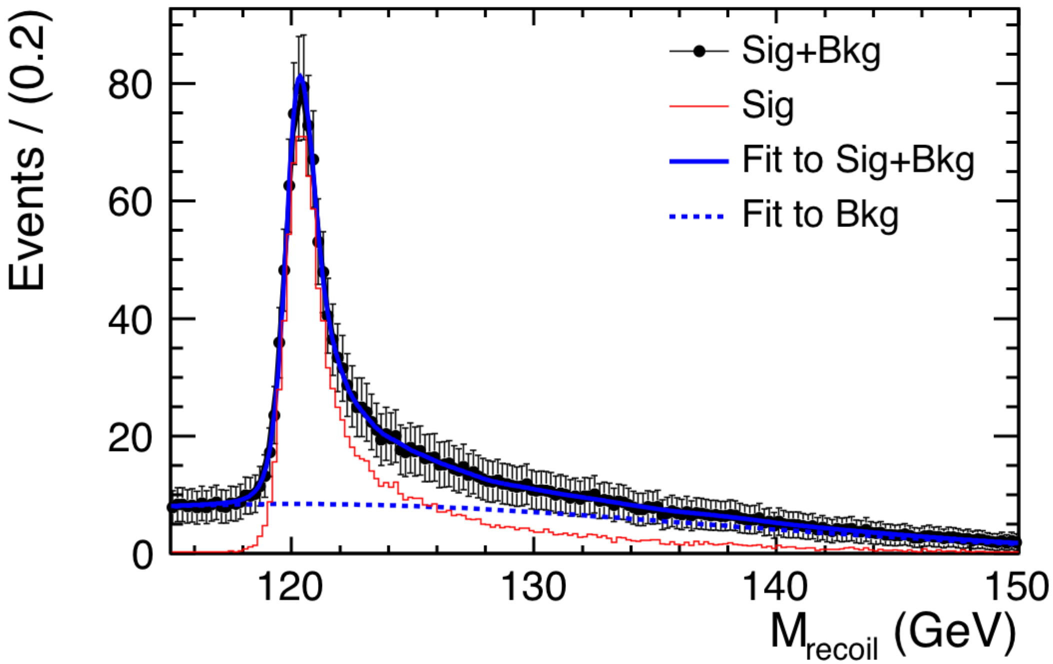
Remarque: LEP a été proposé avant l'observation du Z

Précision

Simulation du signal de Higgs attendu au LHC (peut-être en printemps 2012)



Simulation du signal de Higgs attendu au ILC 'beaucoup plus propre'



Si le Higgs existe ….

l'ILC est la machine idéale pour effectuer une tomographie complète du boson de Higgs

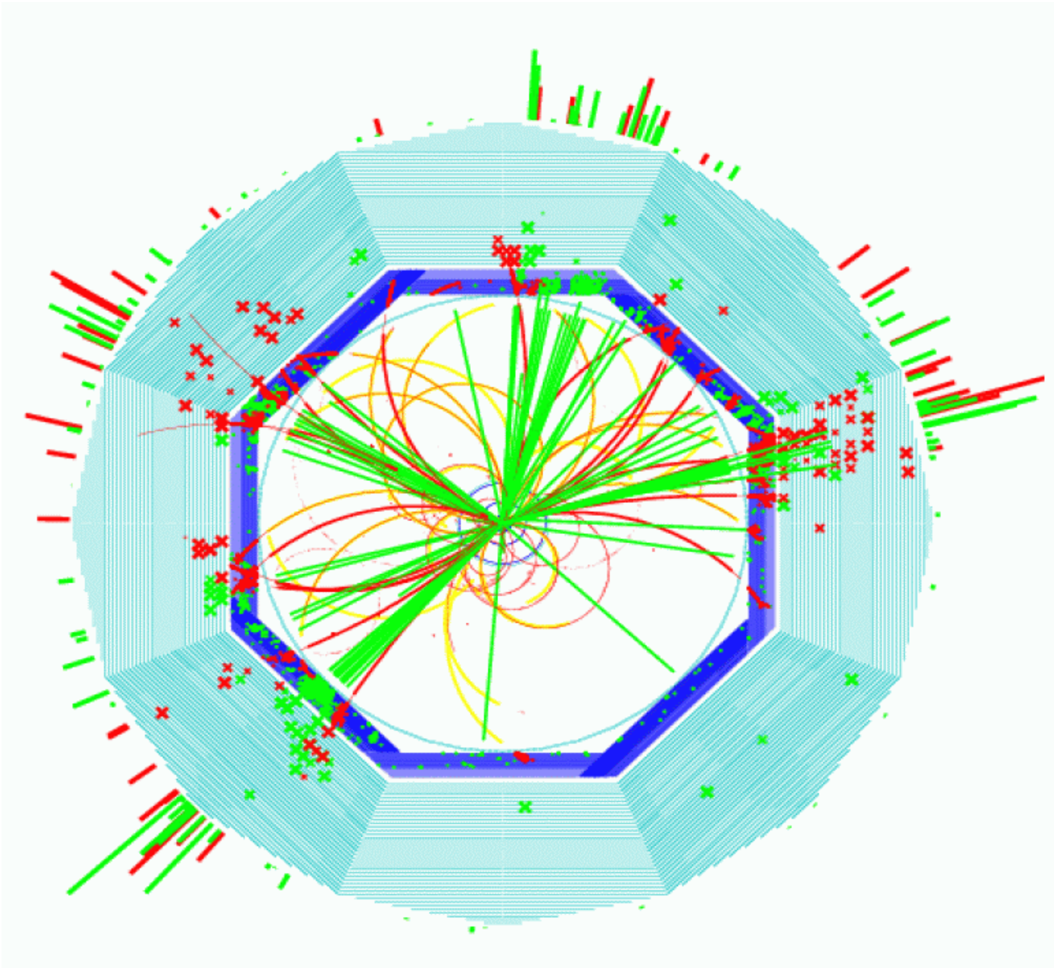
- A vérifier: Masse Higgs

Interactions du Higgs avec des autres particules

ICFA Séminaire 2011: "Once discovered one has to measure the Higgs to death"

Measurement steps

An LC Event



Vertex detectors
Interaction point and decay
Vertices of secondaries

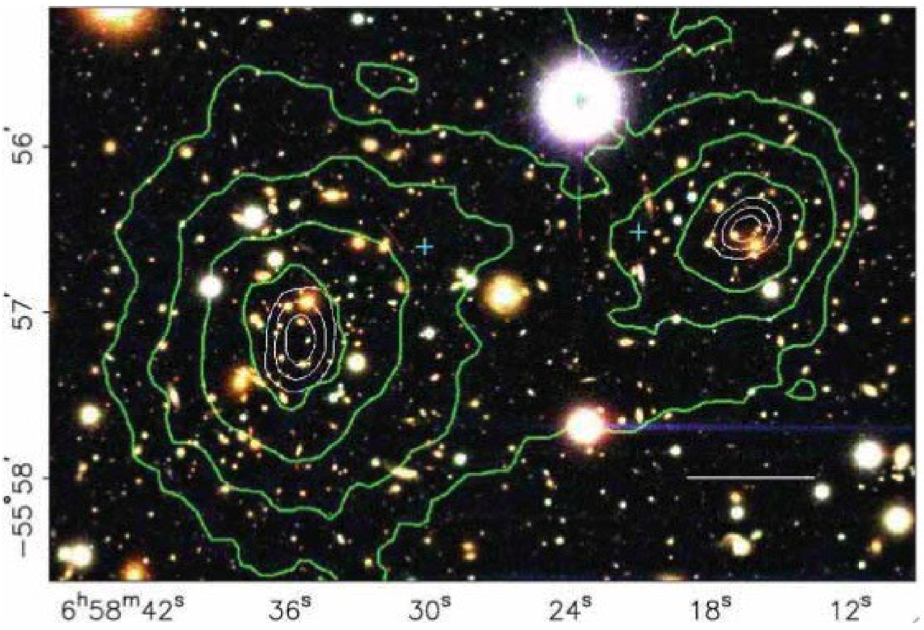
Tracking system
Central part
Trajectories of charged particles

Calorimeters
Outer part
Measurement of energy of charged and neutral particles

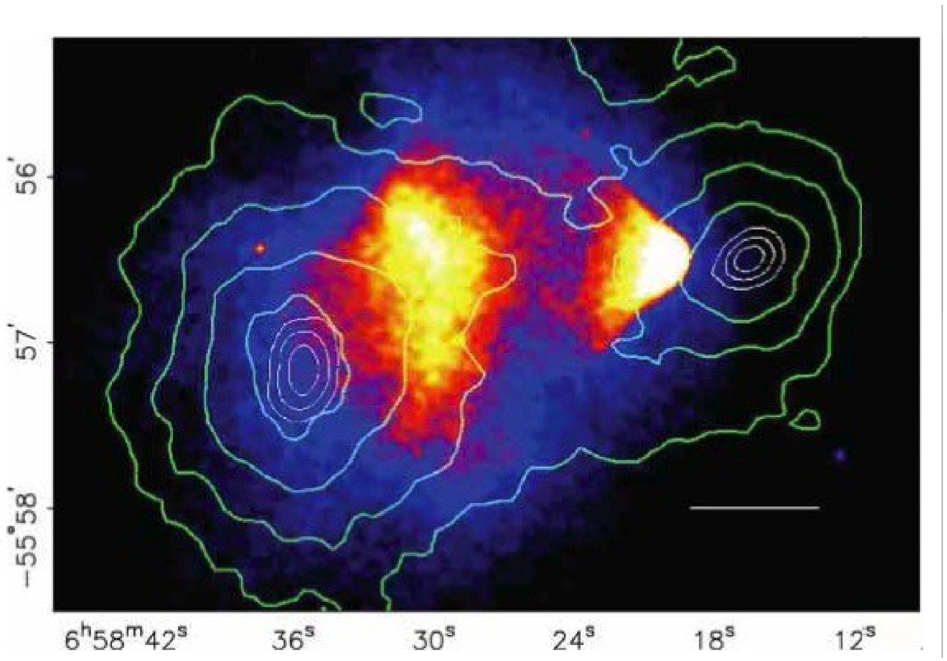
Cosmological questions

Galaxy cluster 1E0657 - 558

Seen by Hubble
Visible light



Seen by Chandrasekhar
X-Rays



Real centres of gravity displaced from observed centres of gravity

There must be dark matter in the universe