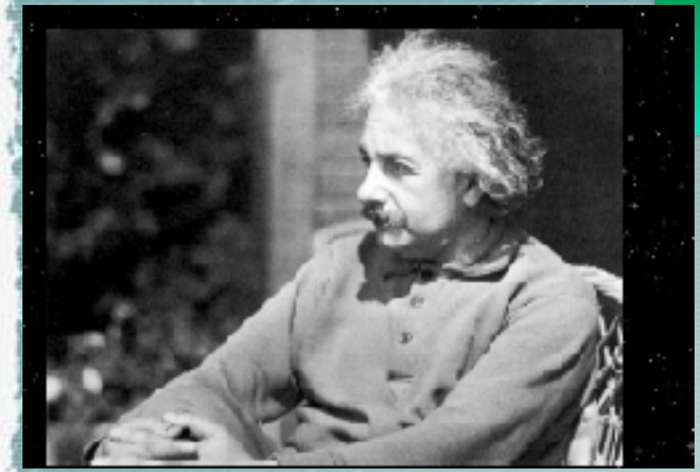
Electrons, photons, other particles and gravitational waves: a guided tour in Fundamental Physics

Luciano Maiani,
Universita' La Sapienza e INFN, Roma
Torino, 12 Aprile 2018

Summary

1. Photons and Electrons
2. Virtual Photons
3. Matter constituents and interactions as in 1932
4. Constituents and fundamental forces: circa 2016
5. Cosmos and Microcosmos
6. LHC and the Brout-Englert-Higgs boson
7. Gravitational Waves from Cosmos
8. Challenges (a personal list)
9. What's next?



1. Photons and Electrons

- ***1905: Einstein's famous three papers:***
  - Brownian motion
  - Special Relativity
  - Light is made of photons
- ***Photons***: light propagates in the form of quanta of energy that ***cannot be emitted or absorbed partially***. Starting from Plack's quantum of action, this work has opened the way to the formulation of a new mechanics, Quantum Mechanics, which describes atomic and subatomic phenomena.
- QM reconciles the dual ***particle-wave*** nature of light. This "reconciliation" still surprises us

Nobody understands quantum mechanics
Richard Feynman, 1965

20 years later...

- ..in 1924, the French physicist Luis de Broglie discovered that well known particles, like the electron, sometime behave like waves;
- wave-particle duality is a universal property of both matter and radiation!
- ***Electrons and Photons*** have been the first identified elementary constituents of matter and radiation;
- Elementary Particle Physics descends from these discoveries.

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

One century after Einstein's discovery, electrons and photons still described as elementary particles, but some suspect that they may not be so (preons? strings?)

nei versi scherzosi di Enrico Persico, da Torino agli amici romani, E. Fermi e collaboratori, circa 1930:

Credon poi, con fé profonda

Cui s'inchina la ragion

Che la luce è corpo e onda

Onda e corpo è l'elettron.

Realism and Reality...

- Quantum Mechanics: we can only predict the probability of the different outcomes of an experiment;
- QM describes what we find in the Laboratory with extraordinary accuracy;
- in our Universe: a photon from the Moon reflects on a desert lake: what happens to it? "where" does it go? are there parallel Universes ?
- Dirac: the probabilities the a photon is absorbed or reflected is *all we can reasonably ask about a photon*
- Einstein believed that QM is incomplete…

•Feynman says *it looks absurd but…this is the way it is*.

•John Bell proved certain inequalities that hold in the "local realism" of Einstein but are violated by QM;

•Alain Aspect, 1981-1982, proved that experiments support QM !!

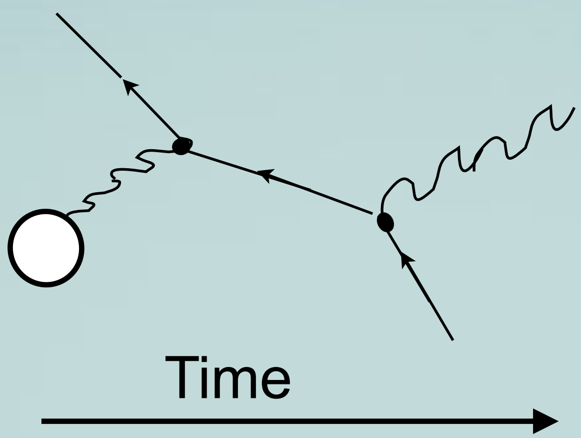
Speakables and Unspeakables in Quantum Mechanics

John S. Bell (Autore), G. Lorenzoni (a cura di)

Is the Moon there when nobody looks?
D. Mermin

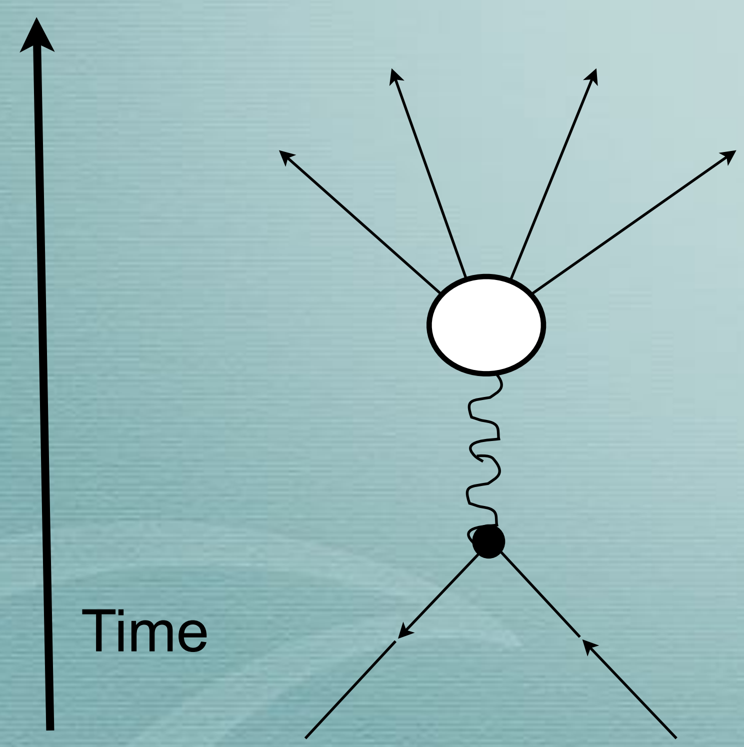
2. Virtual Photons

- Photon's propagation includes the effect of the electrostatic interaction;
- electron in a crystal:



- space momentum exchanged, **q**, is absorbed by the crystal
- the electron takes all the energy, $q_0=0$
- $q^2=q_0^2 - \mathbf{q}^2 <0$

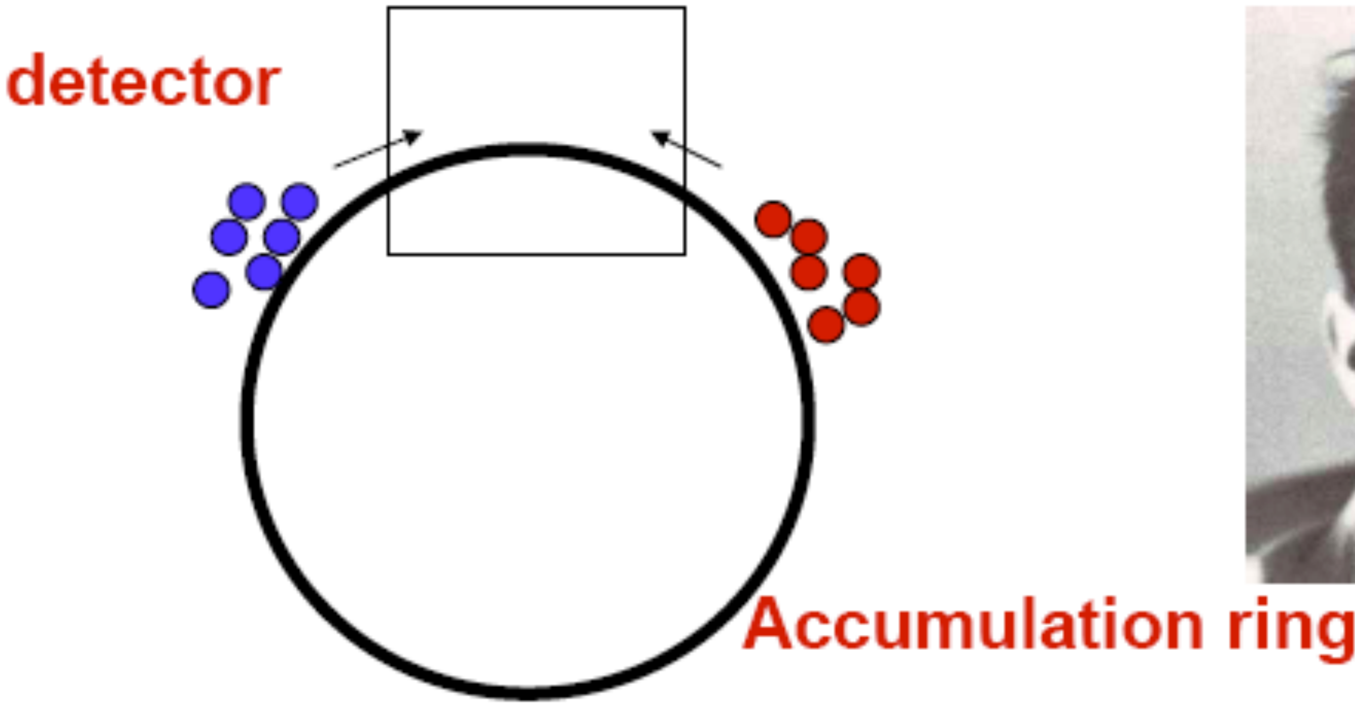
the Coulomb field : we speak of a "virtual photon with space-like momentum $q^2<0$.
But we can have situations where we have a "time-like" photon, with $q^2>0$

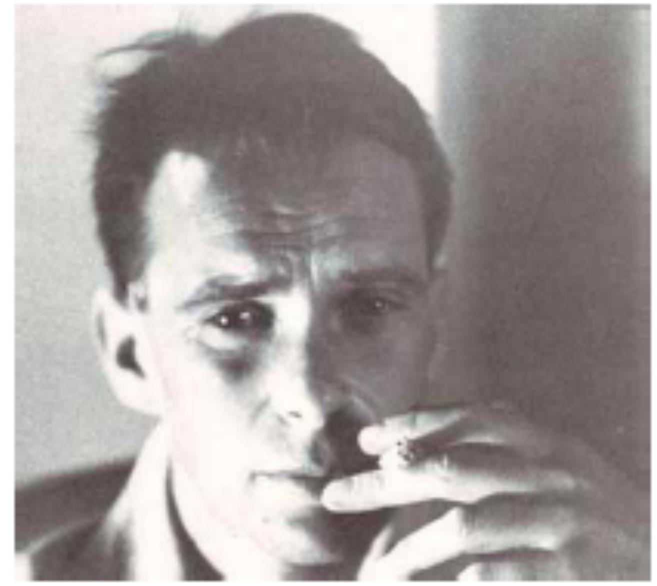


- The product of the electron-positron annihilation is "virtual time-like" photon, with $q^2>0$,
- this photon can transform into pairs of matter-antimatter particles
- if energy is enough, we can create in the laboratory ***every kind of matter existing in Nature*** and coupled to the photon
- electron-positron annihilation informs us "democratically"

da un Seminario di C. Guaraldo

Bruno Touscheck at Frascati:



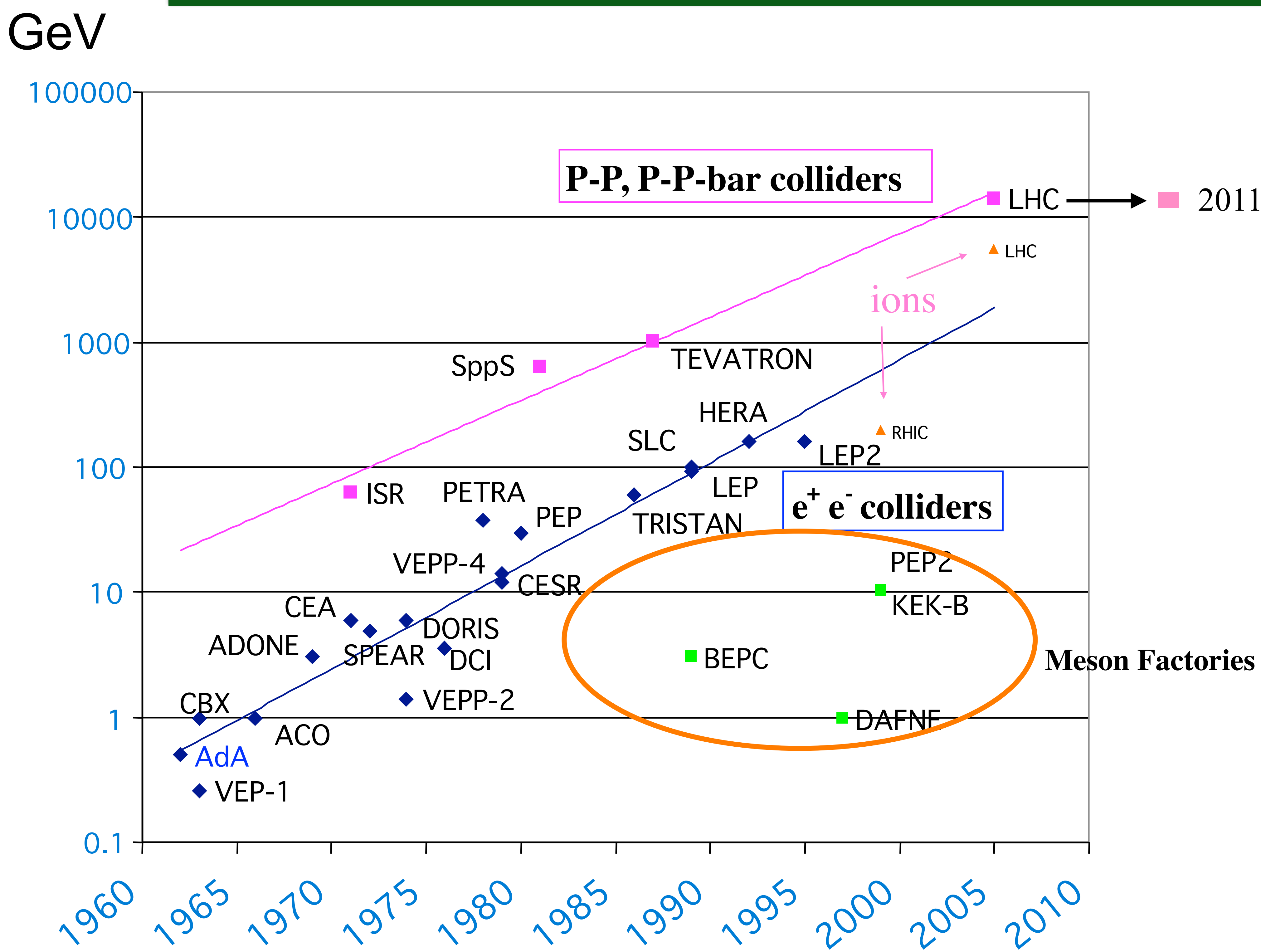


Bruno Touschek

After escaping from a concentration camp during the Second World War, the Austrian-born Touschek began work in Göttingen and Glasgow, and eventually reached Rome in 1952. On 7 March 1960 he gave a historic seminar at Frascati that would change the face of physics. Pointing out the importance of carrying out a systematic study of electron-positron collisions, he suggested that this could be achieved by constructing a single magnetic ring in which electrons and positrons circulate at the same energy but in opposite directions. Soon afterwards, the first electron-positron accumulation ring, AdA, was built under his leadership in Frascati.

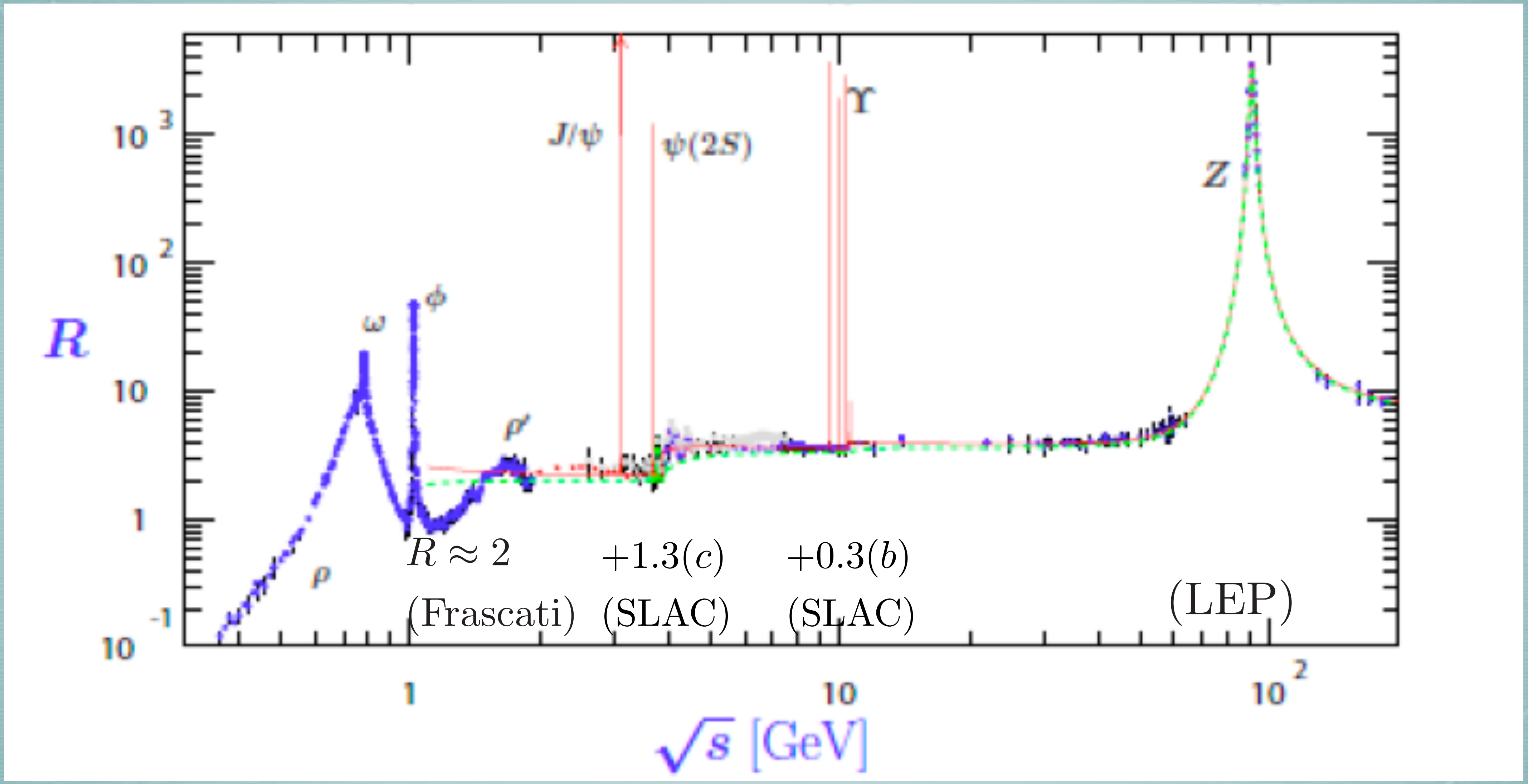
AdA at Frascati: history

Collider energy vs time



Electron-Positron annihilation

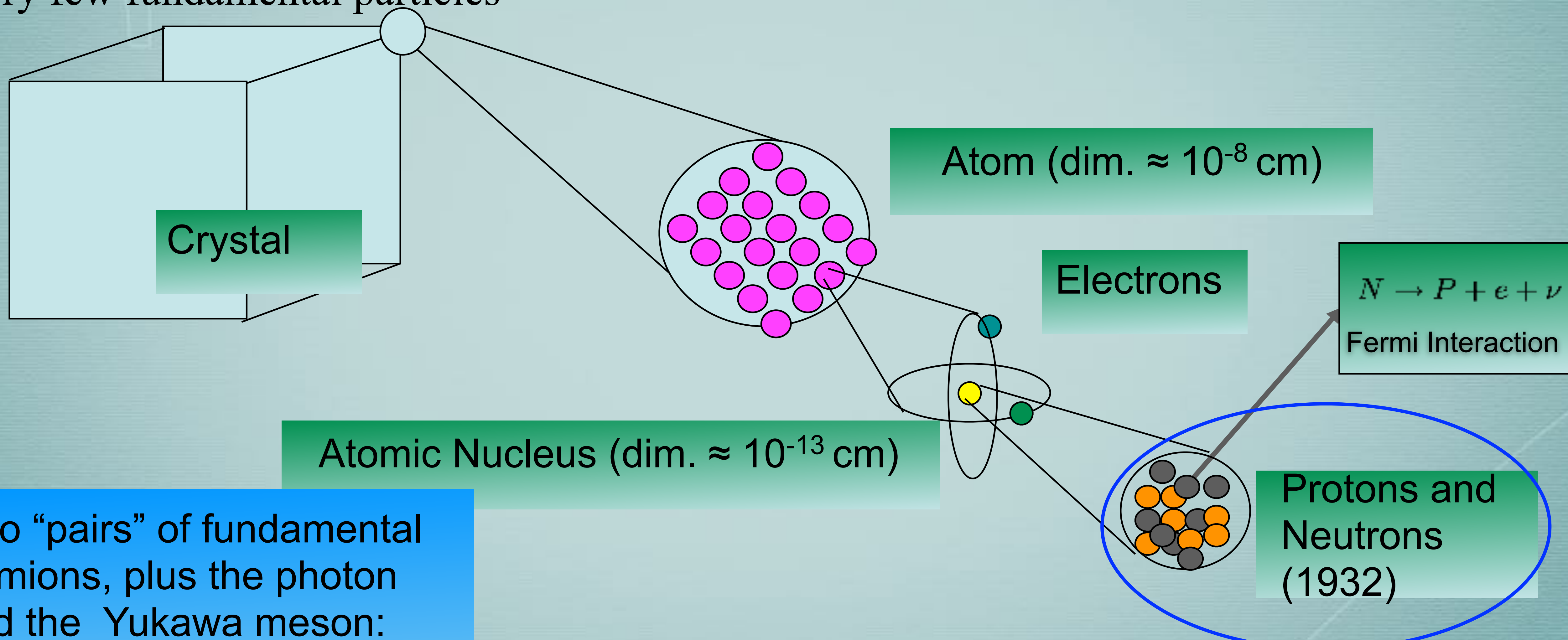
An universal probe for any form electrically charge matter



$$R = \frac{\text{Prob.}(e^+e^- \to \text{subnuclear particles})}{\text{Prob.}(e^+e^- \to \mu^+\mu^-)}$$

3. Matter constituents and interactions after neutron's discovery (1932)

- What we are told at school;
- quite adequate, even today, for a first orientation;
- three fundamental forces plus gravity: electromagnetic, strong (nuclear), weak (beta decay);
- very few fundamental particles

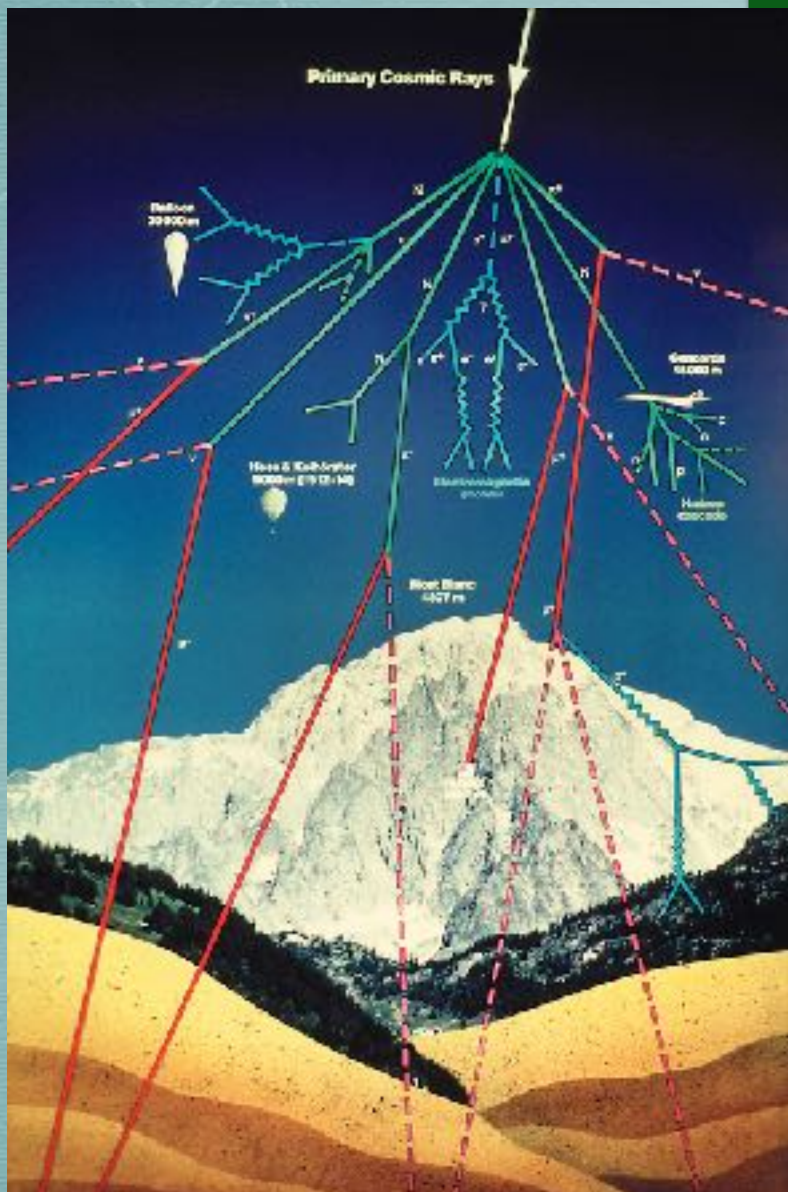


Two "pairs" of fundamental fermions, plus the photon and the Yukawa meson: can they "explain" all we see in the World?

$\begin{pmatrix} P \\ N \end{pmatrix}$ $\begin{pmatrix} \nu \\ e \end{pmatrix}$ γ π ?

H. Yukawa. Nuclear forces are transmitted by a particle with mass ≈ 200 times the electron's mass : the π meson

1937: Mesotron



•In 1937, C. Anderson and S. Neddermeyer discover a new particle in the debris of cosmic ray collisions with the atoms of the upper part of the atmosphere.
•The new particle has a mass intermediate between the electron and proton assess and is dubbed “mesotron”.
•Its mass is close to the mass predicted by Yukawa for the π meson, as to suggest that: “mesotron”= mesone π: the last missing boson!
• It looked so reasonable …

From Cosmic Rays to Particle Accelerators

• 1946 (Rome): M. Conversi, E. Pancini e O. Piccioni, prove that the mesotron (today "μ particle") ***is not*** the carrier of nuclear forces;

• The mesotron looks like a heavier copy of the electron, as suggested by B. Pontecorvo in 1947.

• I. Rabi comments: ***who ordered that*** ?????

• 1940-1950: a new particle zoo emerges from cosmic ray studies: the "strange" particles;

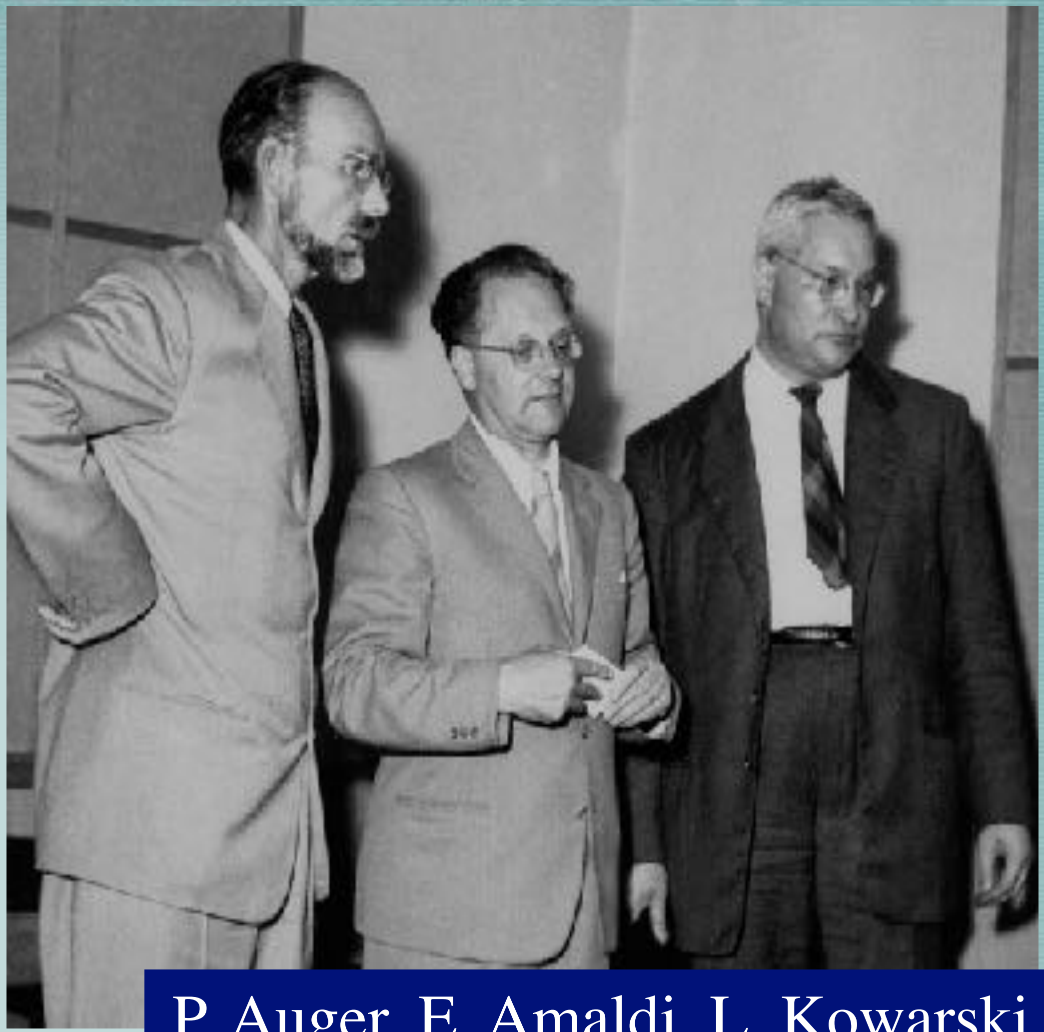
• the "new particles" are not present in the ladder of the constituent of matter: atom, nucleous, nucleons…

• but they must have a role in the architecture of fundamental forces

• …and can be studied in depth only in the high energy collisions which are abundantly produced with ***particle accelerators***.

Long term visions

L. De Broglie, 1949".. *a laboratory or institution where it would be possible to do scientific work, but somehow beyond the framework of the different participating states. Being the product of a collaboration between a large number of European countries, this body could be endowed with more resources than national laboratories and could, consequently, undertake tasks which, by virtue of their size and cost, were beyond their scope.*"

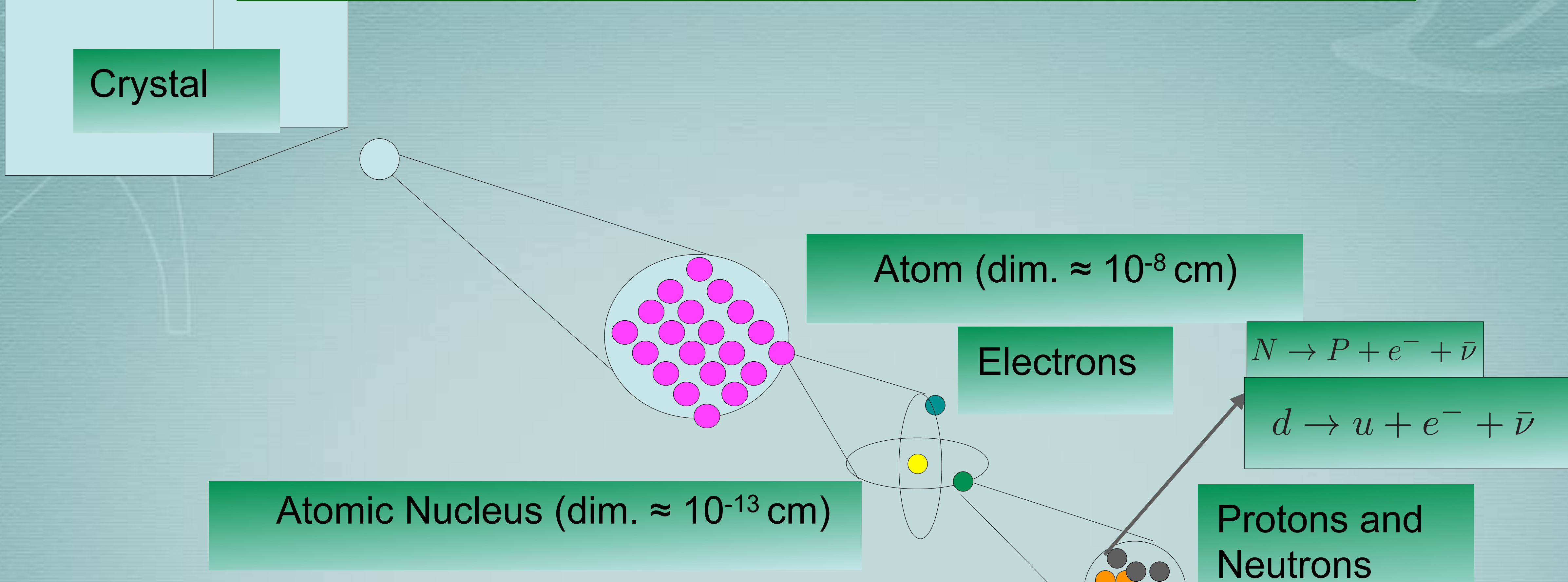


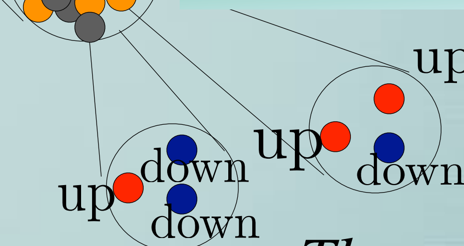
P. Auger, E. Amaldi, L. Kowarski

The History of CERN, Vol.1, p.130
"Their goal was not merely to construct a medium-sized accelerator, it was to awaken Europe and, through the construction of a giant accelerator, to make her understand the urgency and necessity of developing fundamental scientific research on a large scale as had happened in the US since the war".

Established in 1954, CERN is the European Laboratory for Elementary Particle physics.

4. Quarks, a new level of reality





Nuclear Forces are transmitted by the π meson and by several other types of mesons: K, ρ, ω, φ... up to exhaustion of latin and greek alphabets.

There are also new heavy particles called baryons: Λ, Σ…

The explosion of particle discoveries was so great, Fermi famously said, "If I could remember the names of all these particles, I'd be a botanist."

Baryons and Mesons are made by quarks: (qqq) and (q-anti q) respectively, including a third type of quark: the ***strange quark.***

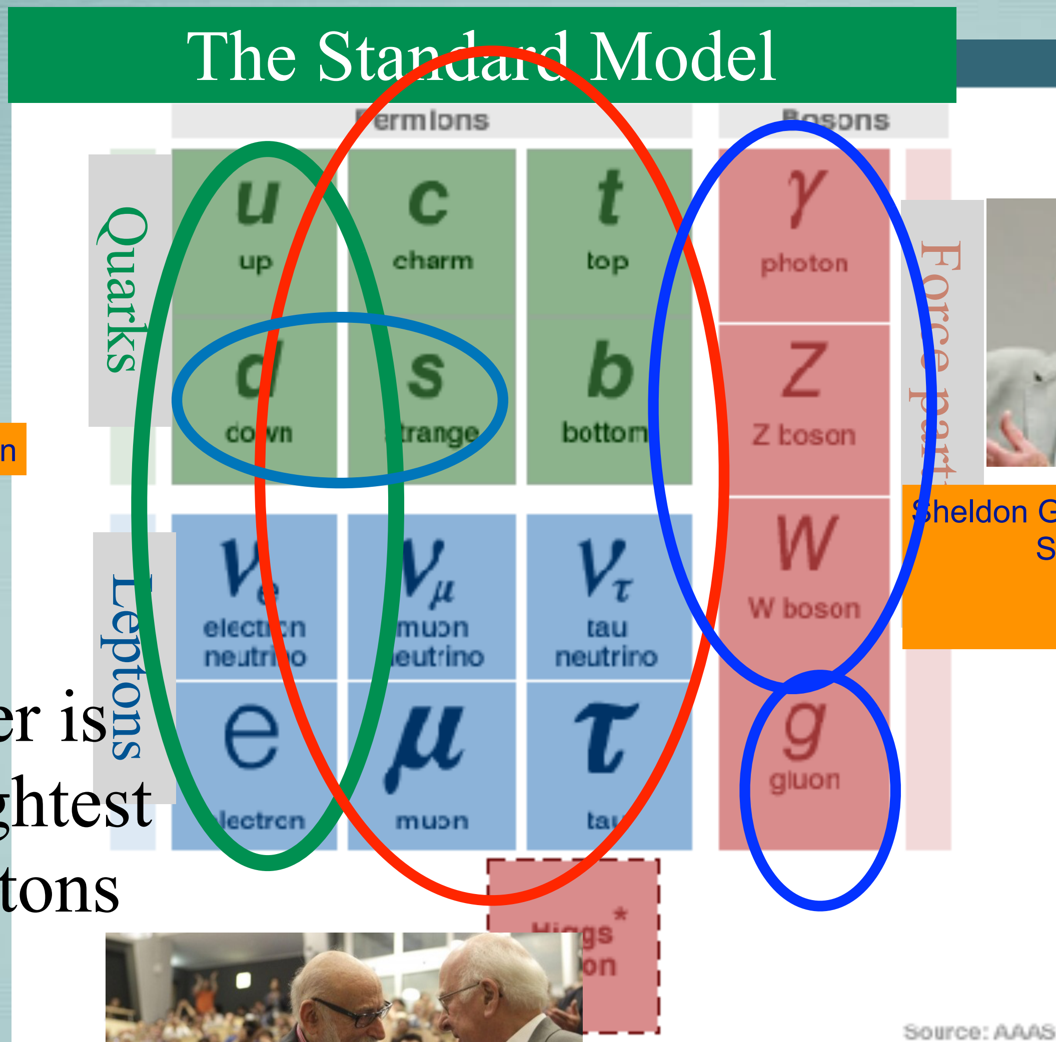
Three Quarks for Master Mark! Gell-Mann, 1963, from: *The Finnegan's Wake* of James Joyce

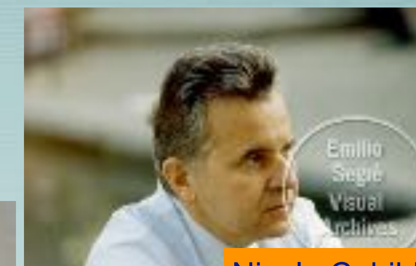
$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Baryons have only negative strangeness.

Constituentsof matter and fundamental forces (circa 2016)

Murray Gell-Mann





Nicola Cabibbo

Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste

Carlo Rubbia

Sheldon Glashow, John Iliopoulos, Luciano Maiani

Makoto Kobayashi , Toshihide Maskawa

Ordinary matter is made of the lightest quarks and leptons

Robert Englert e Peter Higgs

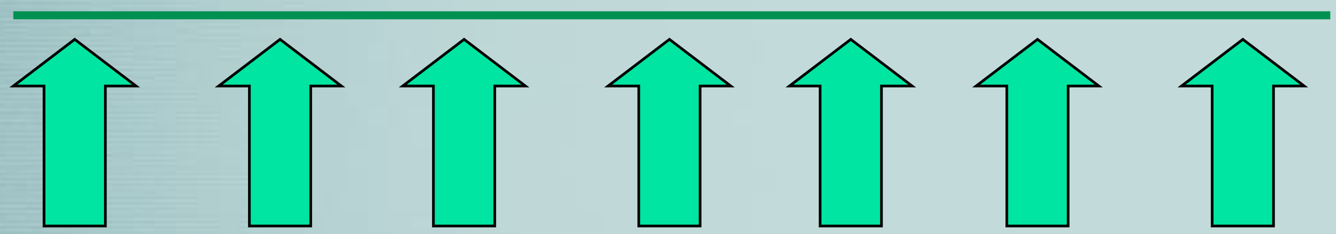
Heavier quarks are unstable: what is their role in the Universe?

Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free Gross&Wilczeck, Politzer (1973)

The Higgs Boson

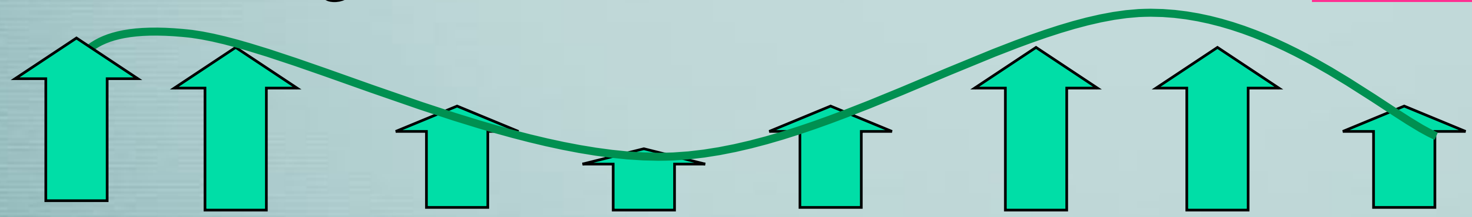
The origin of masses

• A field fills all space and it interacts with particles;
• The field is able to "distinguish" between particles, according to their symmetry properties…W, Z, quarks.. take a mass, photon stays at zero mass.



•VACUUM is like the surface of a perfectly calm lake.

• Collisions generate waves…



... which correspond to a new particle: the **HIGGS BOSON**

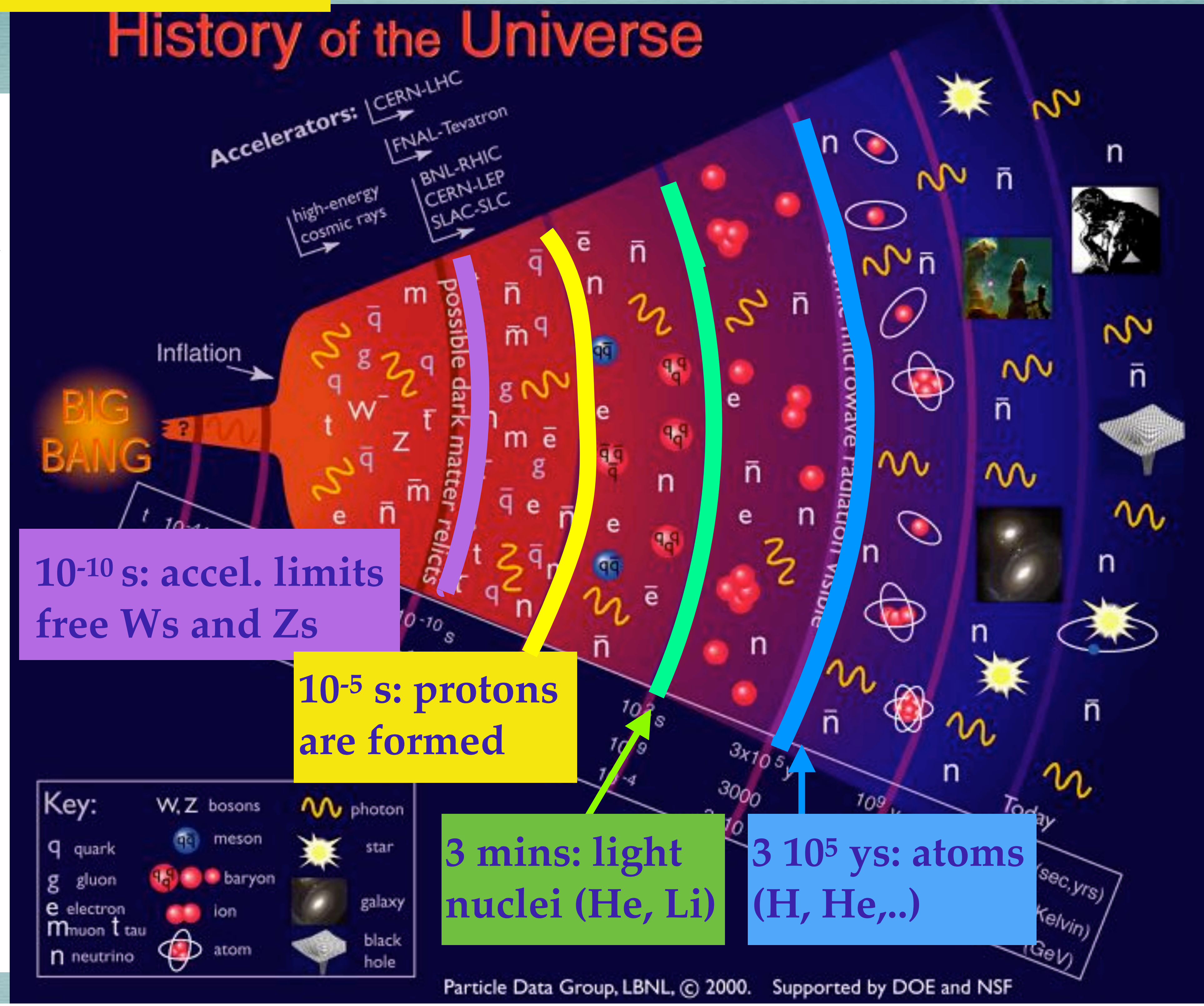
• The Higgs boson is needed for theory to agree with Nature... but the Higgs mechanism gives a vision of Vacuum which may explain new phenomena : (inflation, chaotic universe, …)

5. Cosmos and Microcosmos

Particle accelerators are « time machines » where we can reproduce the conditions of the primordial Universe

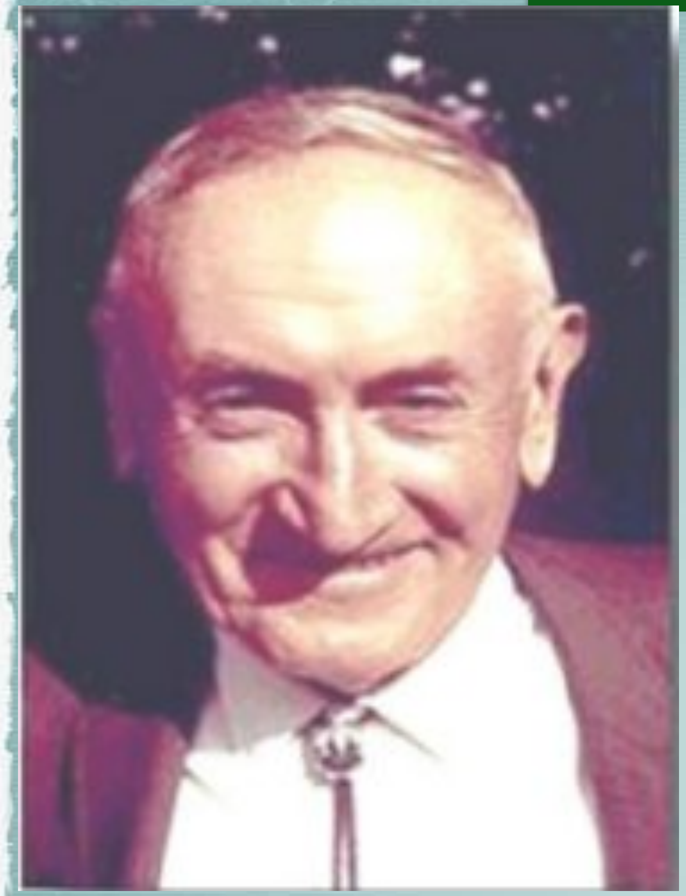
when it was populated by unstable particle of all generations

..and primordial fluctuations have generated the « seeds » of today cosmic structures: clusters of galaxies, galaxies, stars planets.



With the Standard Theory we describe the conditions of the Universe ***3 minutes*** after Big Bang (when light nuclei where produced) down to ***10^{-5} secs*** protons formed from the primordial soup of quarks and gluons) to ***10^{-10} secs*** (limit of present accelerators).

Fritz Zwicky discovers Dark Matter in Coma Cluster



Fritz Zwicky
1898 Varna, Bulgaria
1974 Pasadena, California, USA
Residence: USA
Citizenship: Svizzera

In the '30s, Zwicky observed an anomalous ratio mass/luminosity in the cluster of galaxies in Coma. Zwicky interpreted the anomaly as indicating the presence of non luminous "dark matter", in addition to the usual matter making stars and interstellar gases.

The image, from Spitzer Space Telescope and Sloan Digital Sky Survey, shows some of the thousands of galaxies of the Coma cluster © NASA, JPL-Caltech, SDSS.

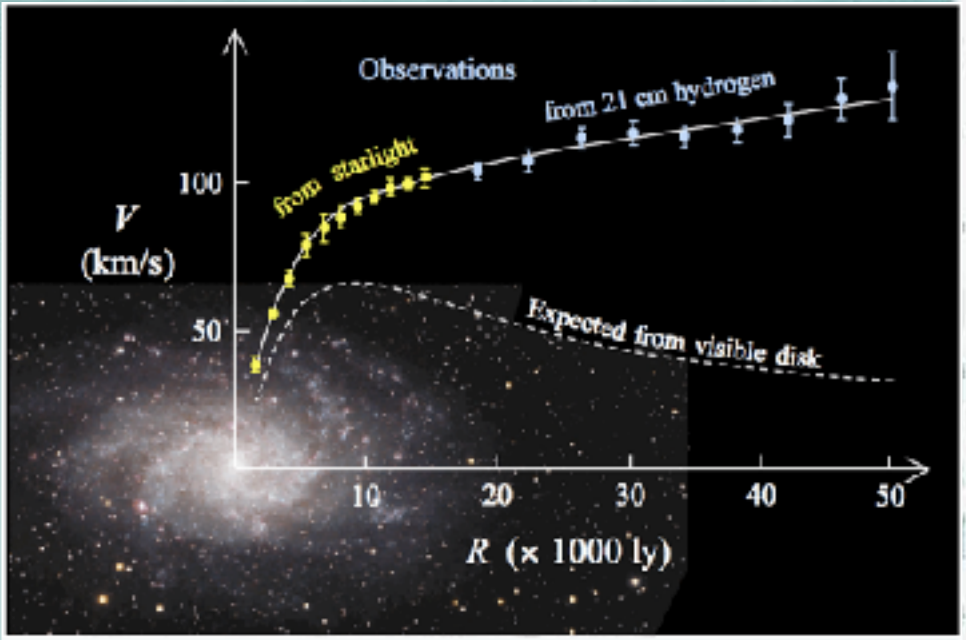
18

Dark Matter in Galaxies

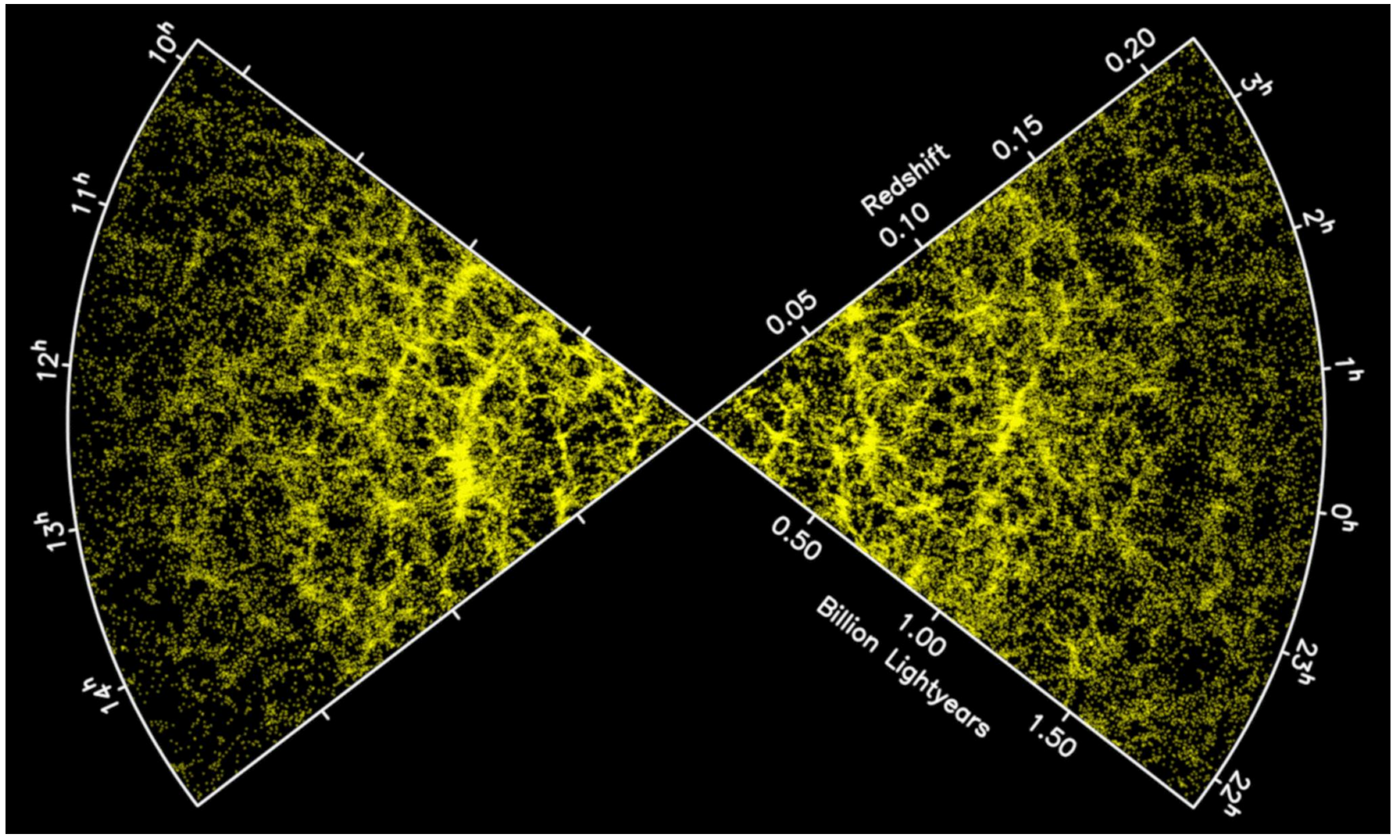
Vera Cooper Rubin

Vera Cooper Rubin at the Lowell Observatory. Kent Ford has his back to us. © Bob Rubin.

- The velocity of gas clouds orbiting in Galaxies does not fall down with the distance from the the luminous region, as required by Kepler's law, should matter be associated to stars or interstellar gases only



The Large Scale Distribution of Galaxies in the Universe



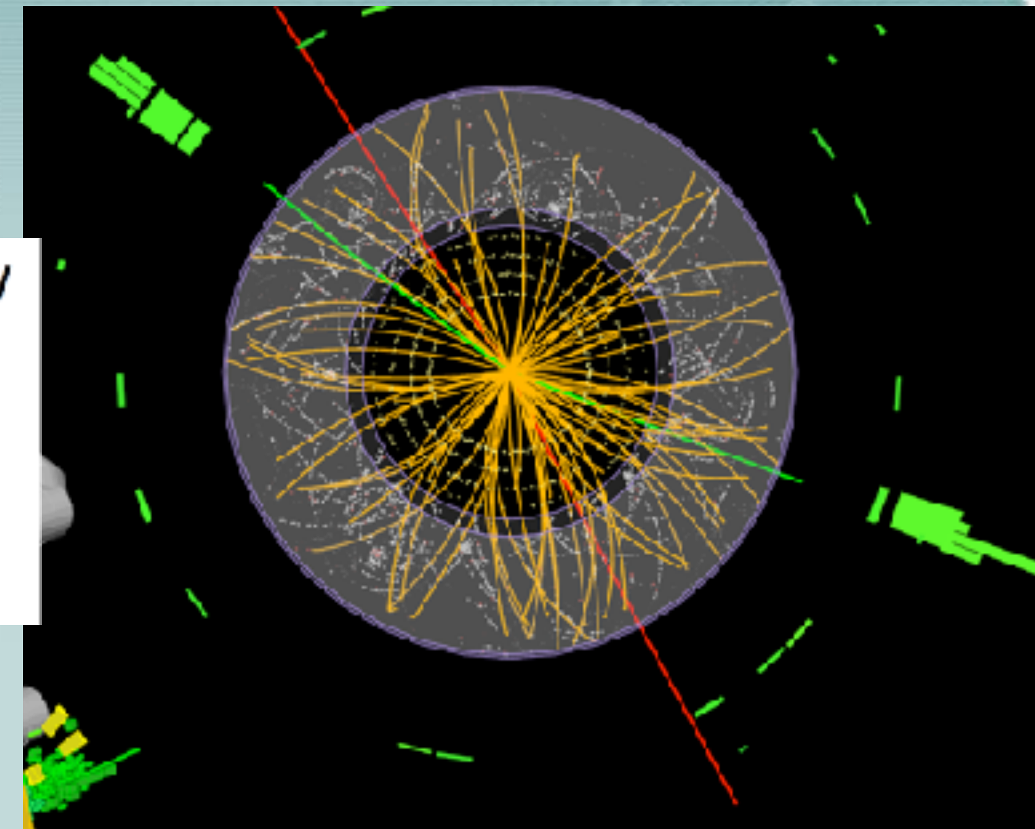
- Dark matter condenses due to the gravitational attraction
- ordinary matters "falls" into the gravitational wells
- to make the observed large scale structures: galaxy clusters and superclusters

6. LHC and the discovery of the Brout-Englert-Higgs boson

Superconducting Magnets in stock and installed in the LHC tunnel

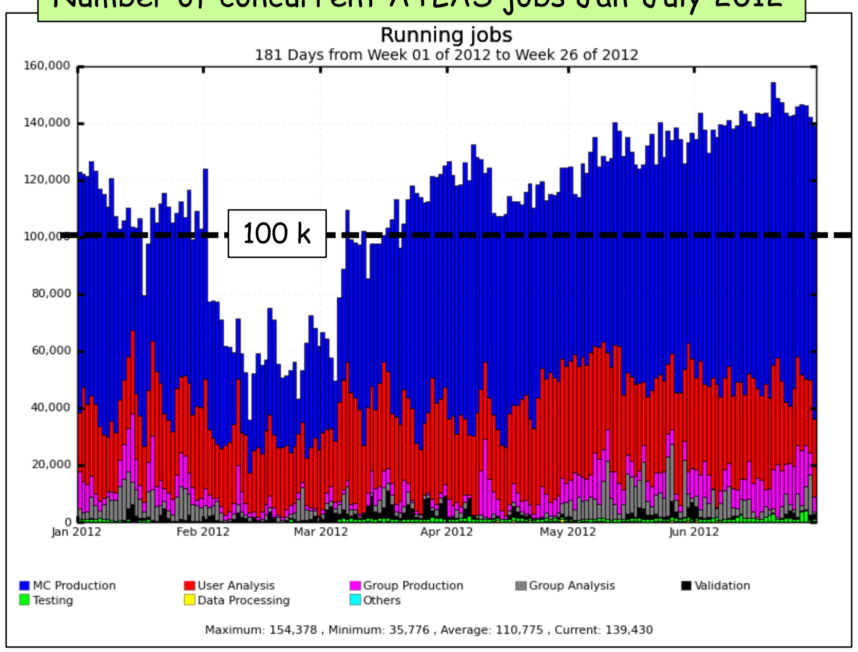
CMS and ATLAS

We have observed a new boson with a mass of
125.3 ± 0.6 GeV
at
4.9 σ significance !



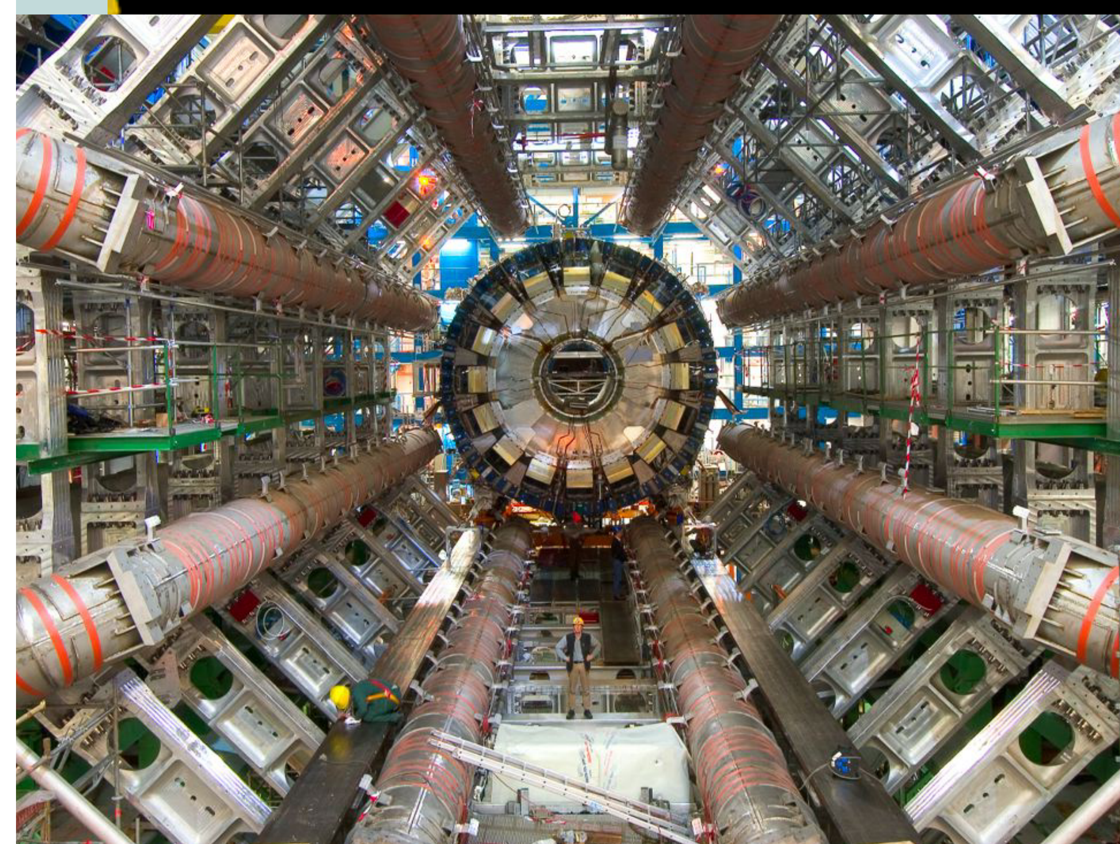
It would have been impossible to release physics results so quickly without the outstanding performance of the Grid (including the CERN Tier-0)

Number of concurrent ATLAS jobs Jan-July 2012



Includes MC production, user and group analysis at CERN, 10 Tier1-s, ~ 70 Tier-2 federations → > 80 sites

> 1500 distinct ATLAS users do analysis on the GRID



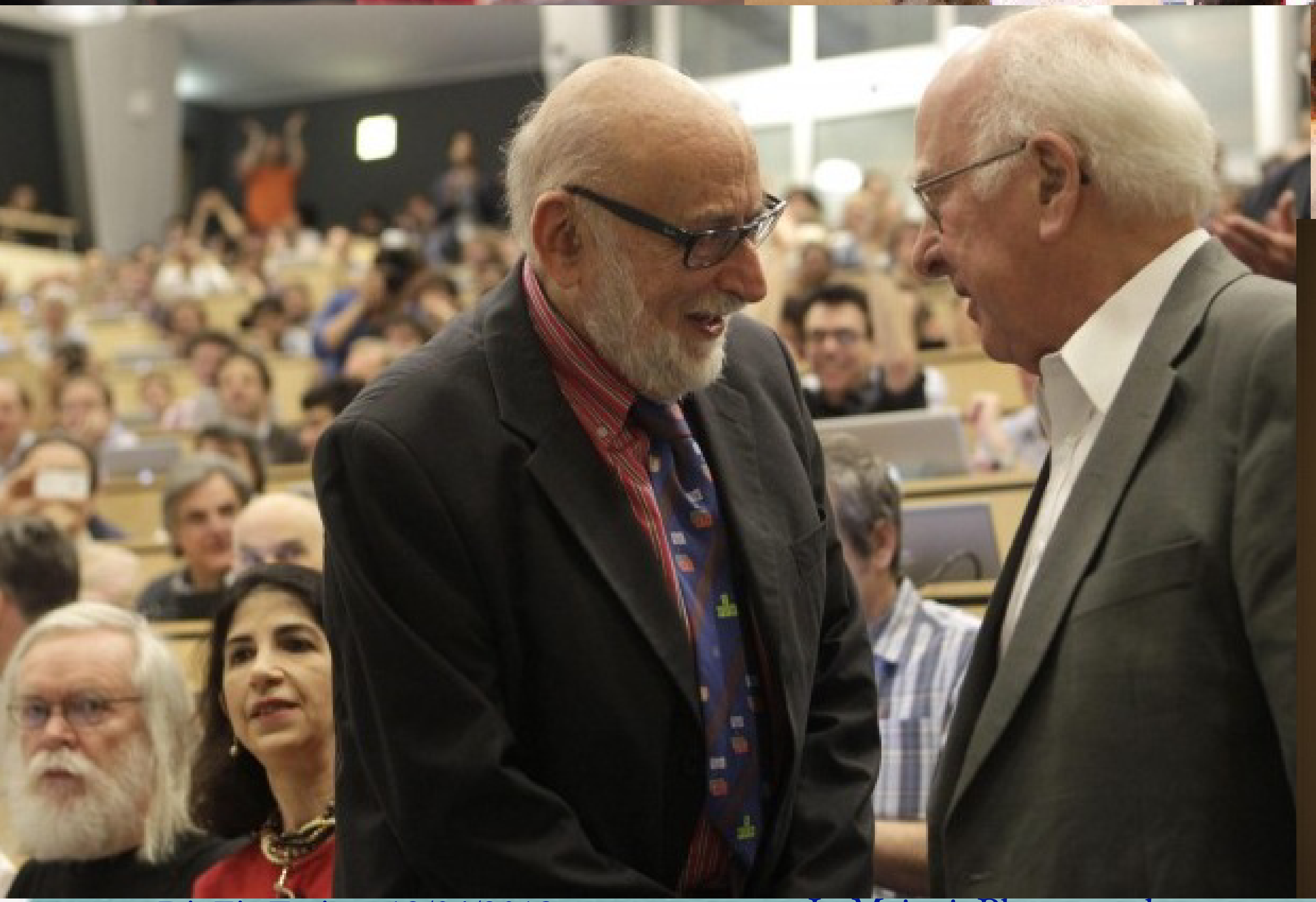
- ❑ Available resources fully used/stressed (beyond pledges in some cases)
- ❑ Massive production of 8 TeV Monte Carlo samples
- ❑ Very effective and flexible Computing Model and Operation team → accommodate high trigger rates and pile-up, intense MC simulation, analysis demands from worldwide users (through e.g. dynamic data placement)

12

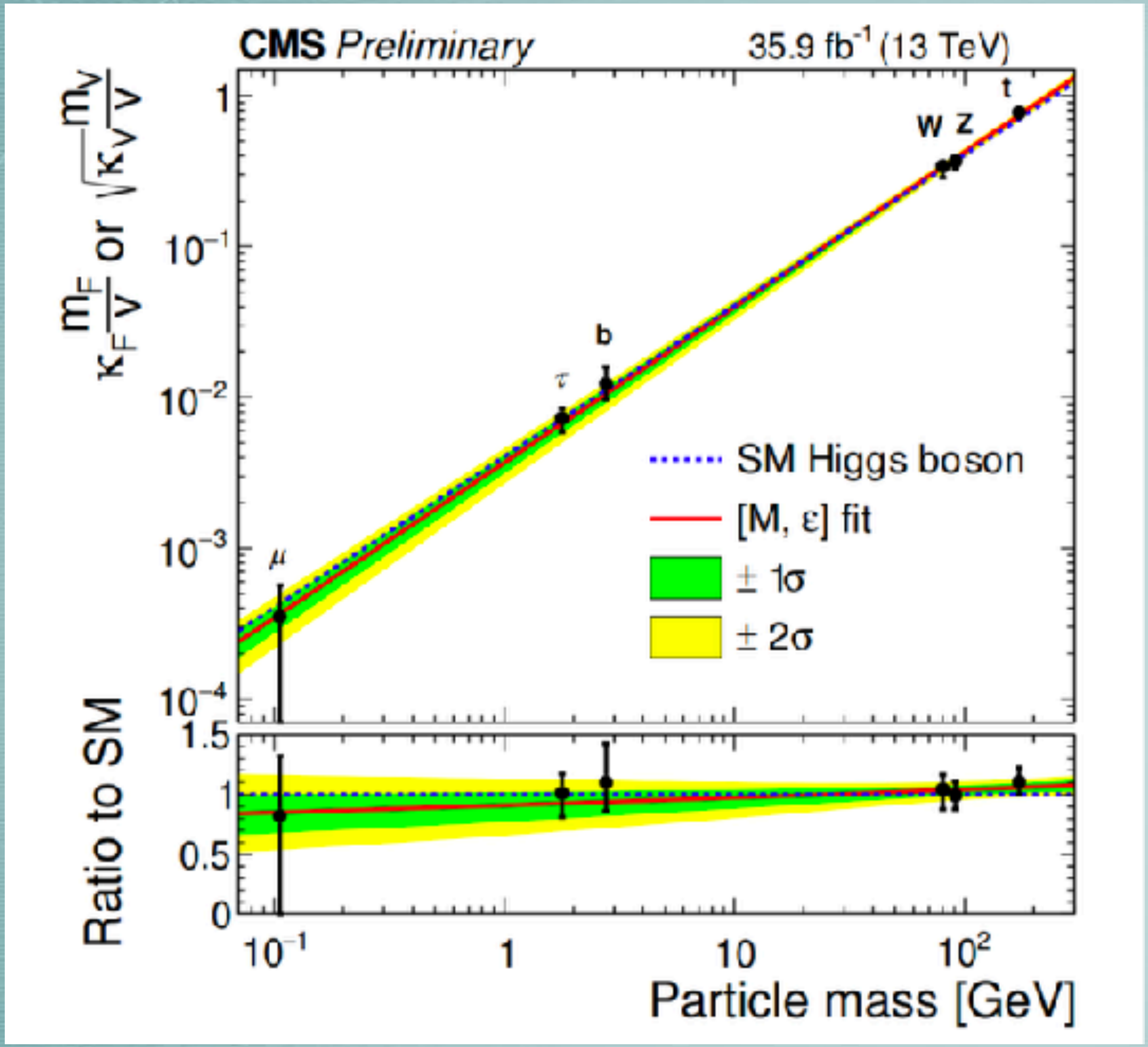
Italy enterprises in LHC

- 17% of LHC contracts for machine and experimental areas attributed to Italian companies, in open calls for for tender
- Italy's contribution to CERN's budget of ~12%;
- Fundamental role of Istituto Nazionale di Fisica Nucleare;
- A bright example of technology transfer between basic research and industry.

Discovery (2012)



Higgs boson branching ratios vs. particle masses



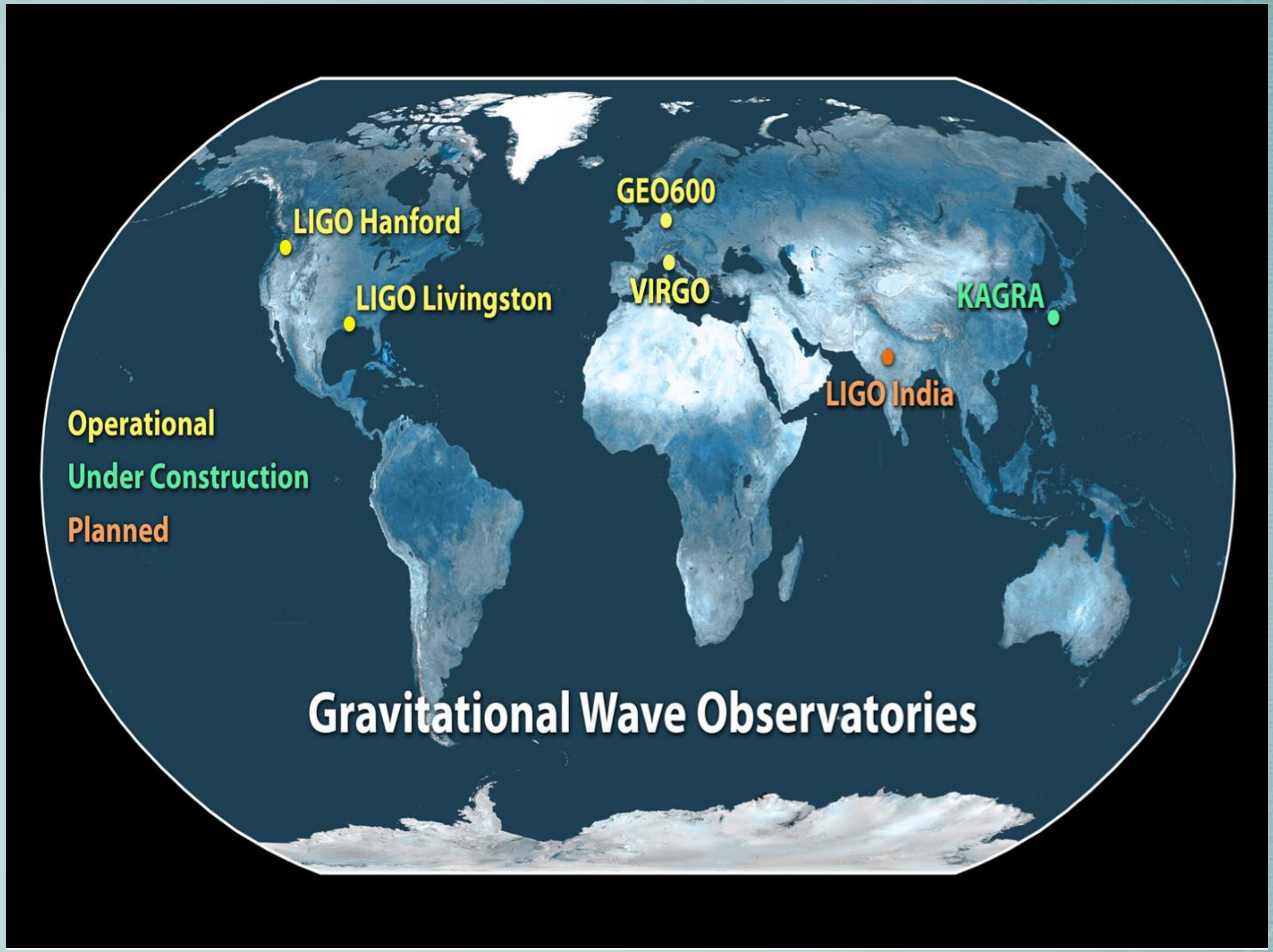
Moriond Electroweak 2018 David Sperka (Florida)

- The dashed line indicates the predicted dependence on the particle mass in the case of the SM Higgs boson. Red line: best fit

- As expected…but very unconventional
- the first ***scalar*** elementary particle
- coupled not to currents but to masses
- ***the true signature of the Higgs mechanism***

7. Frontiers: Gravitational Waves from catastrofic events in Cosmos

•Catastrophic collapses of stars produce bursts of ***Gravitational Waves***
•ripples in space and time that propagates with the velocity of light and can be seen by the deformation of massive objects caused by their passage



• In Italy: pioneered in by E. Amaldi and G.Pizzella (1970)
•continued by A. Giazotto, M. Cerdonio, G. V. Pallottino, F. Ricci and others with Criogenic Antennae and Laser Interferometers.

Signatures of the Virgo approval

La firma dell'accordo tra Luciano Maiani e Francois Kourlisky

Adalberto Giazotto (1940-2017)

Alain Brillet

ACCORD
concernant la Réalisation de
l'Antenne de Détection
des Ondes Gravitationnelles
VIRGO

Le Centre national de la Recherche scientifique, Etablissement Public à caractère Scientifique et Technologique - ci-après désigné par les initiales CNRS et dont le siège social est sis 3, rue Michel-Ange, F75794 Paris Cedex 16, représenté par son Directeur Général, M. François Kourilsky,

et

l'Istituto Nazionale di Fisica Nucleare, institut publique pour la recherche scientifique - ci-après désigné par les initiales INFN et dont le siège social est sis via Enrico Fermi 40, I 00044 Frascati, représenté par son Président, M. Luciano Maiani,

ci-après désignés les Parties ;

CONSIDÉRANT que la détection des ondes gravitationnelles offrira

dans le domaine de la physique fondamentale

- une preuve directe de l'existence des ondes gravitationnelles ;
- un mode d'investigation des caractéristiques tensorielles du champ gravitationnel ;

dans le domaine de l'astronomie et de l'astrophysique

- un nouveau moyen d'observation des objets lointains, en sus des ondes électromagnétiques et des neutrinos ; il s'agira d'un instrument unique pour la détection des phénomènes très énergétiques tels que l'effondrement des supernovae et des binaires serrées ;

CONSIDÉRANT qu'une collaboration dans ce domaine existe déjà depuis de nombreuses années entre scientifiques français et italiens ;

- 1 -

ARTICOL[...]

Il presente Accordo entrerà in vigore dopo essere stato approvato dalle Autorità competenti delle Parti.

ARTICOLO 17 - DURATA

A meno che decidano di comune accordo di mettere fine alla loro collaborazione, le Parti si impegnano a partarla avanti, oltre alla fase di costruzione, per una durata minima di gestione di cinque anni, conformemente a quanto previsto dall'articolo 1. del presente Accordo.

ARTICOLO 18 - DISPOSIZIONI FINALI

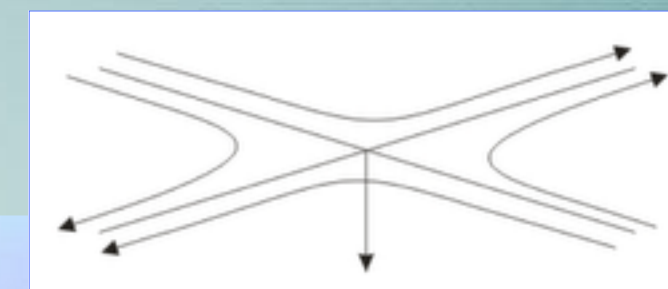
Il presente Accordo é redatto in quattro esemplari originali, due in versione francese e due in versione italiana, entrambe facenti ugualmente fede.

Pisa, li, 27 Juin 1994

Per il CNRS	Per l'INFN
François KOURILSKY Direttore Generale	Prof. Luciano MAIANI Presidente

La frontiera piu’ promettente

- •Interferometri laser su lunga distanza
- •misurano le fluttuazioni dello spazio-tempo dovute al passaggio di un’onda gravitazionale, ad es. dovuta alla coalescenza di due pulsar
- •Negli USA: LEGO observatory in due siti, Hanford e Livingstone
- •In Italia: Virgo-European Gravitational Observatory (Cascina, Pisa)

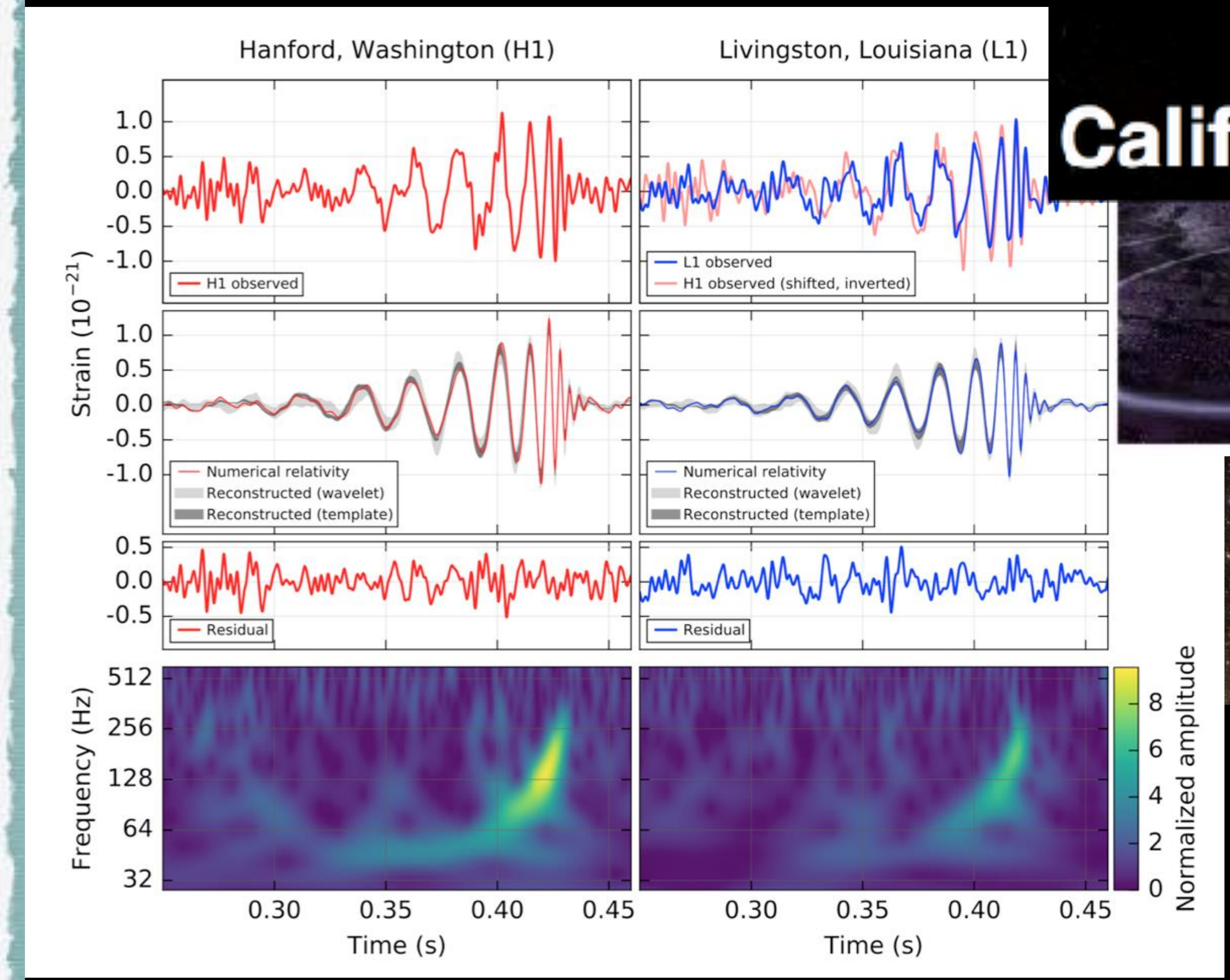


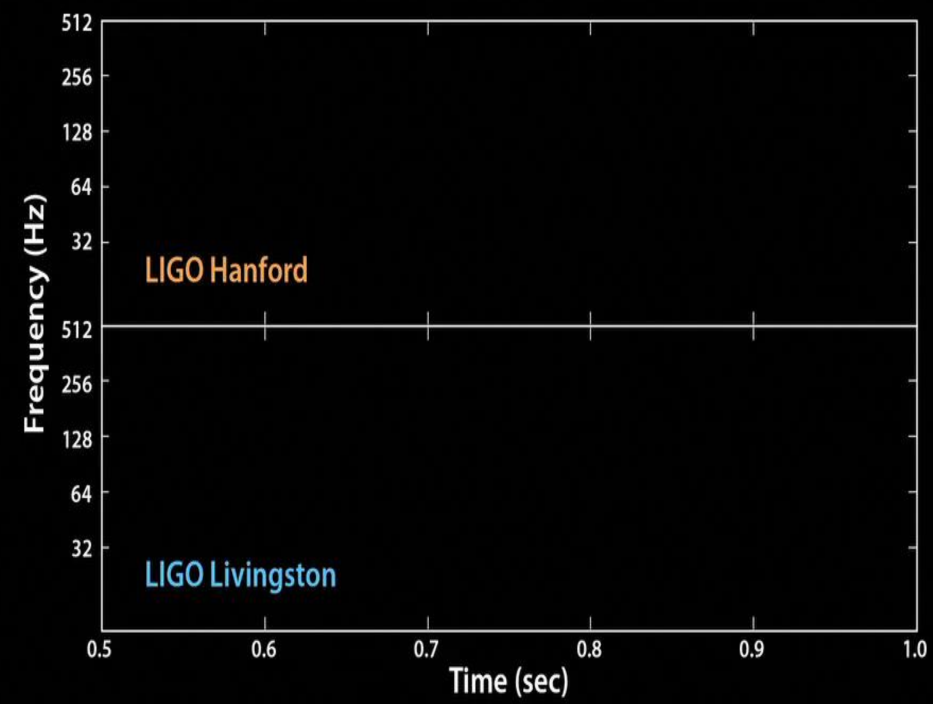
LIGO @ Hanford e Livingstone, USA

Osservatorio VIRGO @ Cascina, PISA

cnrs dépasser les frontières
EGO EUROPEAN GRAVITATIONAL OBSERVATORY
INFN

GW150914: The First Binary Black Hole





Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Observation of Gravitational Waves from a Binary Black Hole Merger” Phys. Rev. Lett. 116, 061102 (2016)

Coalescence of binary system of neutron stars

Loosing energy by emission of gravitational waves, stars become closer and closer until they fall into each other in a catastrophic clash

- Ligo-Virgo can identify the direction from where gravitational waves are coming
- optical-radio telescopes can be pointed in that direction to study the post-collapse supernova
- is this the way the heavy elements (gold..) are produced in the Universe ??

The birth of Gravitational Wave astronomy, complementing optic, radio and neutrinos into a Multi-Messenger astronomy!!!

8. Challenges

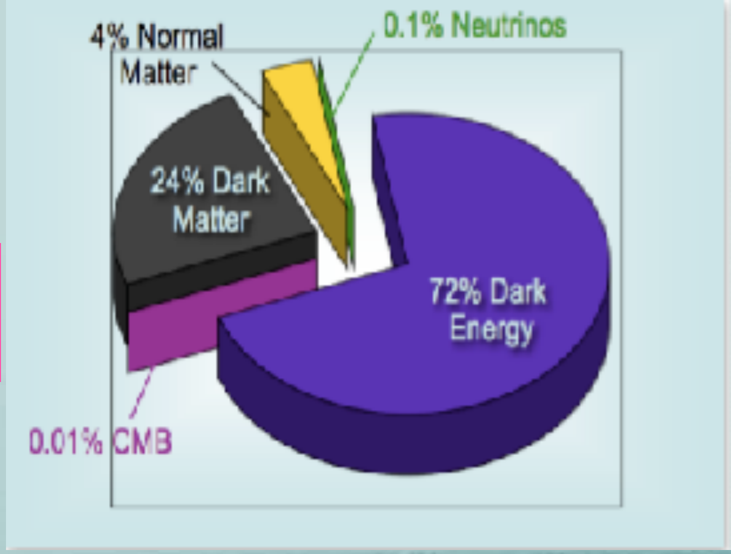
- Find the Higgs Boson **The Origin of mass**

- Find the Supersymmetric Particles **The Origin of Spin**

The Unification of Forces **requires** a Symmetry to relate different spins: this is the SUPERSYMMETRY discovered at CERN in the 70s by J. Wess and B. Zumino

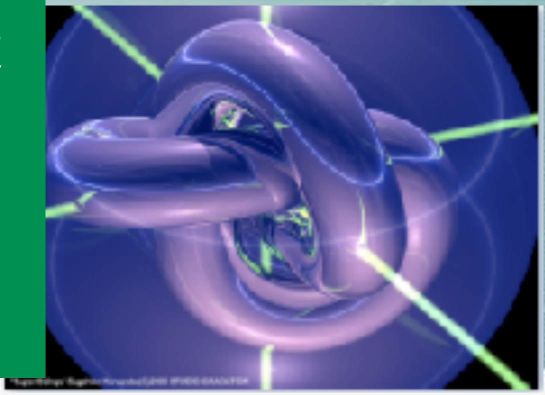
- Identify the nature of the Dark Matter

Cosmic Supersymmetry ?



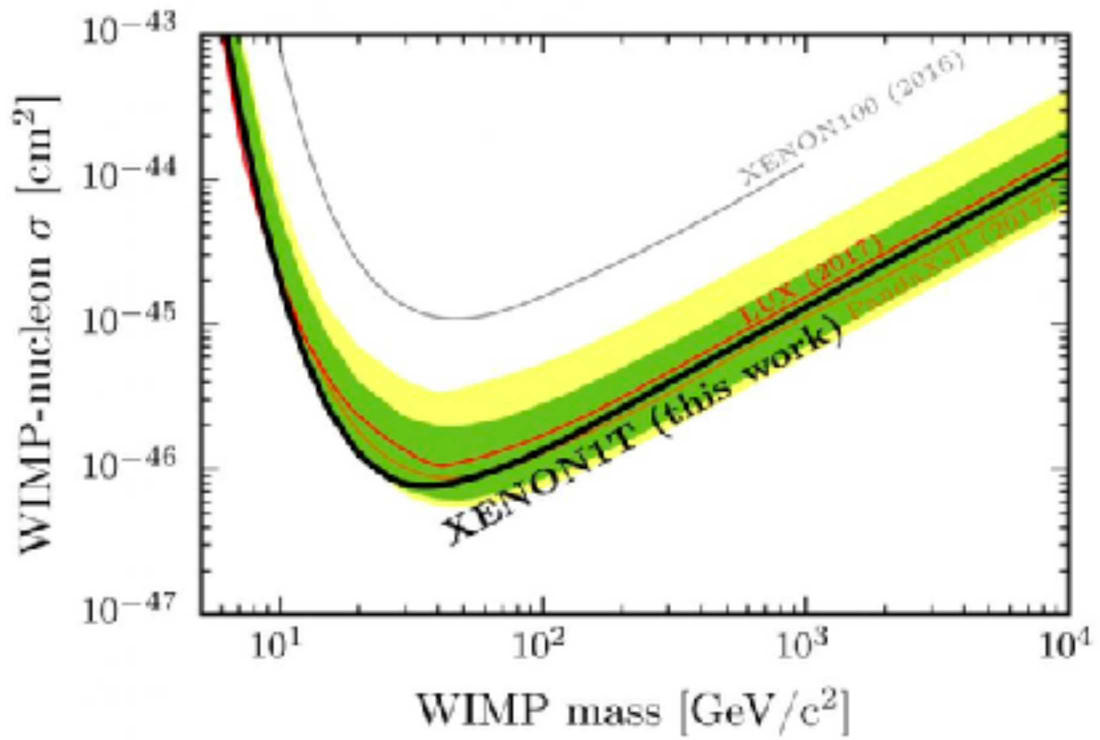
- Test for new space-dimensions

- The String formulation of Quantum Gravity is not consistent in 3+1 dimensions. Curved extra-dimensions are needed.
- How small is R ?



Dark Matter-WIMP-searches @LNGS: Xenon1T

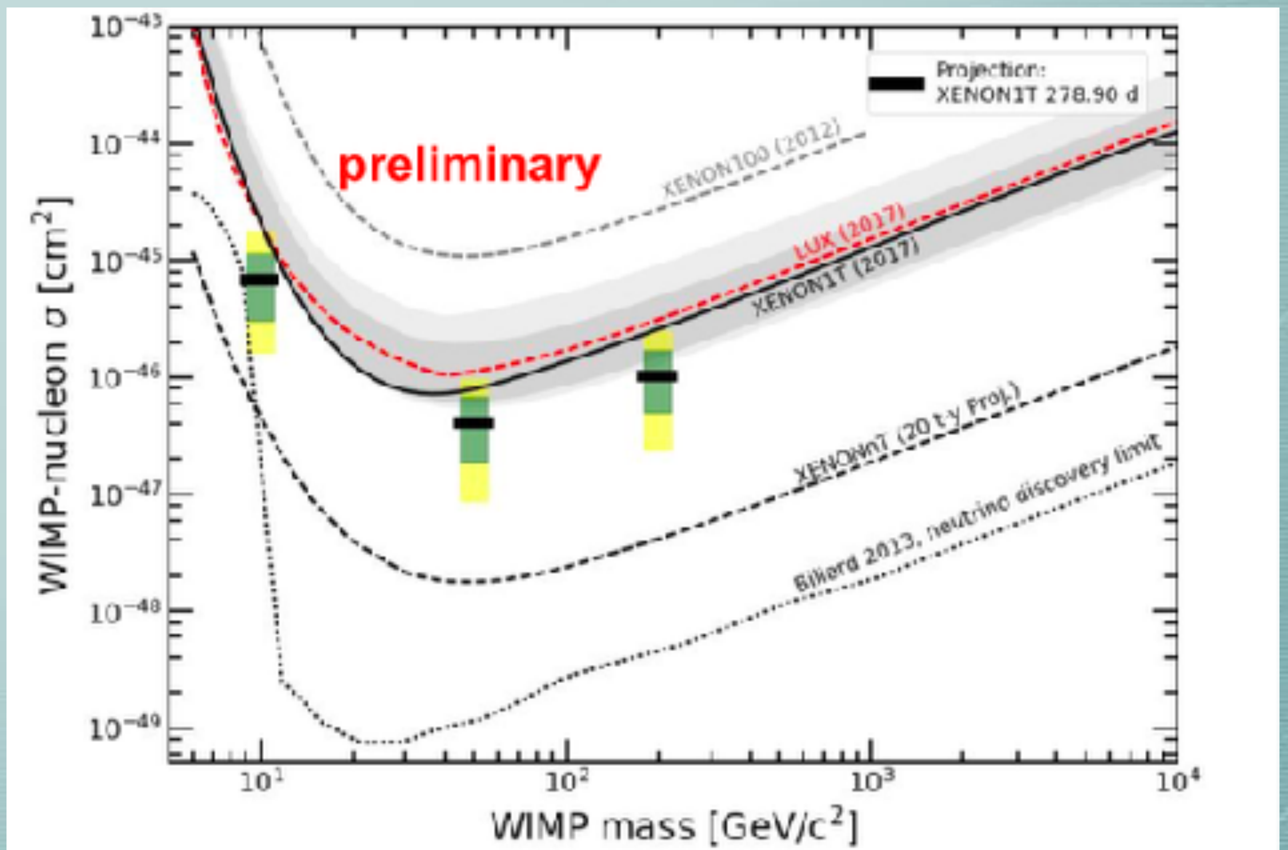
- 34 live days dark matter exposure Oct 2016-Jan2017
- No evidence of a signal → upper limit
- Additional 247 live days of data collected to date
  - the rest of this talk



Daniel Coderre
University of Freiburg
Moriond-EW 2018
La Thuile

XENON Dark Matter Project

For the XENON Collaboration



Is there life beyond the LHC ?
a) low energy riddles

•The muon g-2 $\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 288(63)(49) \times 10^{-11}$,

-a 3-4 σ discrepancy of experiment at BNL from Standard Theory prediction

recent review: A. Hoecker, W.J. Marciano, PdG 2013.

-could be due to strong interactions in light-by-light scattering

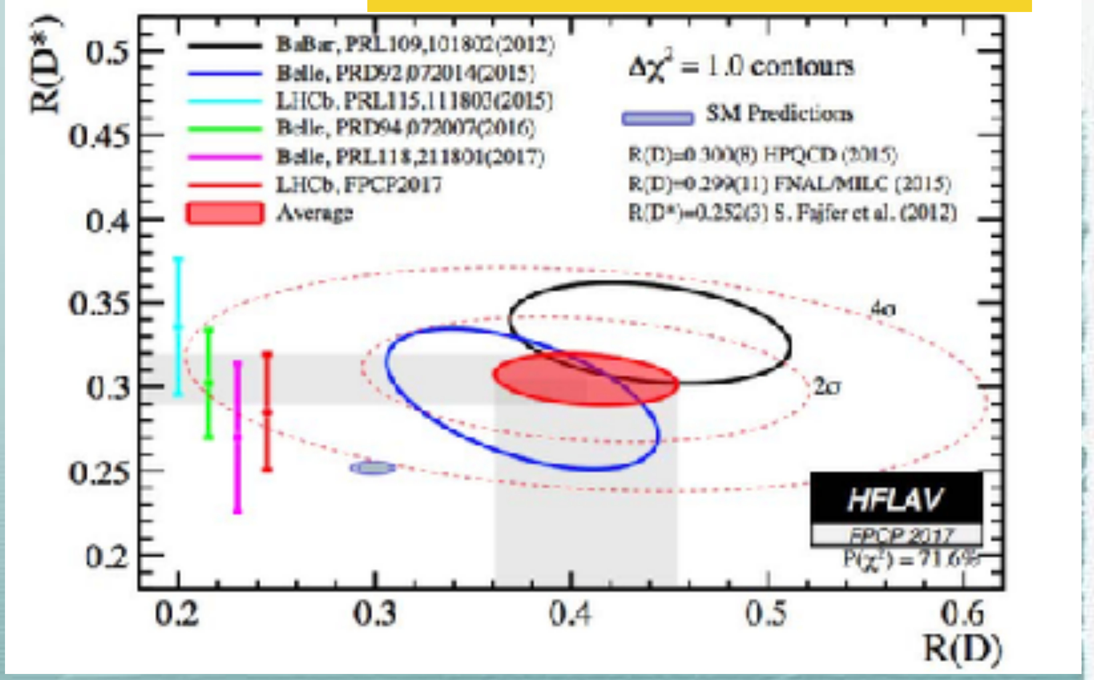
-new experiment at FermLab (E989) to reduce the experimental error, but improving on theoretical prediction very hard

-rather large (EW corrections are ~150 x 10^{-11}): if due to new particles, e.g a new vector boson, they should be around the corner

see: LHCb Workshop at CERN, 2016

- Anomalies in semileptonic B decays into D and D*
- there are also anomalies in Flavor Changing Neutral Current transitions: $b \to s\ \mu^+\ \mu^-$
- leptoquarks????

C. Langenbruch in Moriond 2018



are we demanding too much to our understanding of QCD corrections?

b) new hadrons ?

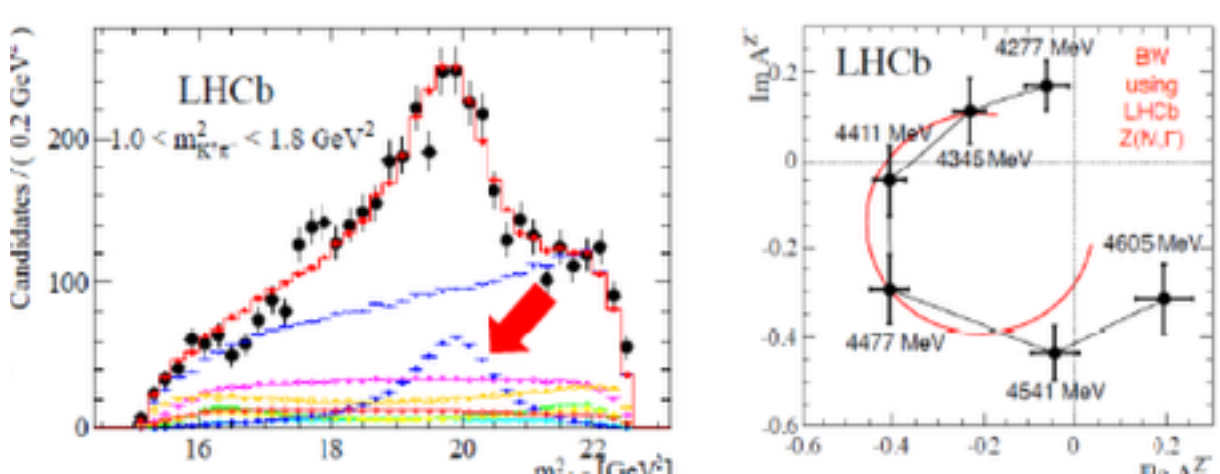
LHCB:

- confirms BELLE's observation of a bump

Can NOT be built from standard states:
D^*D_1= in S-Wave may have J=1 but has negative parity

- Argand Plot shows 90^0 phase: Z is a genuine resonance

[PRL 112 (2014) 222002]



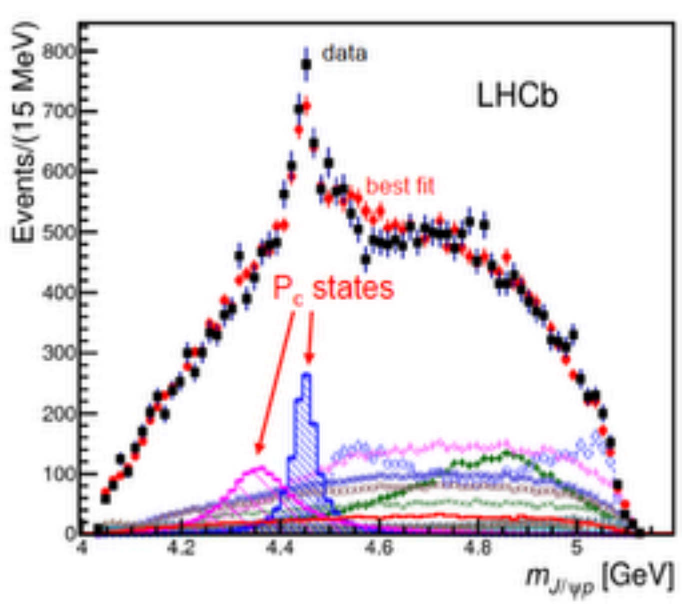
$J/\Psi p$ resonances consistent with pentaquark states

[PRL 115 (2015) 072001]

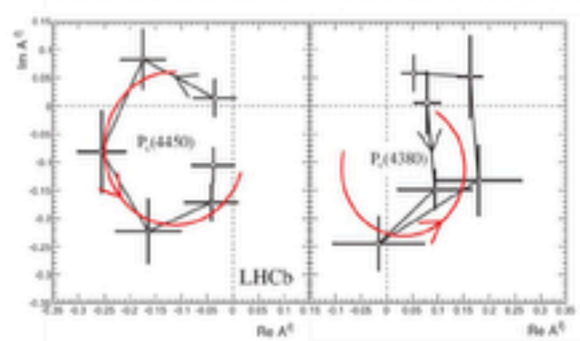
Need to add two states with content uudccbar.
Best fit has J=3/2 and 5/2 with opposite parities.

$P_c(4380)$:
$M = 4380 \pm 8 \pm 29$ MeV,
$\Gamma = 205 \pm 18 \pm 86$ MeV
$P_c(4450)$:
$M = 4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV

decay into p +J/Ψ
P(4380)=3/2$^-$,
P(4450)=5/2 $^+$



Clear resonant behaviour for narrow state.
Need more statistics to elucidate other state.



- Valence quark composition:

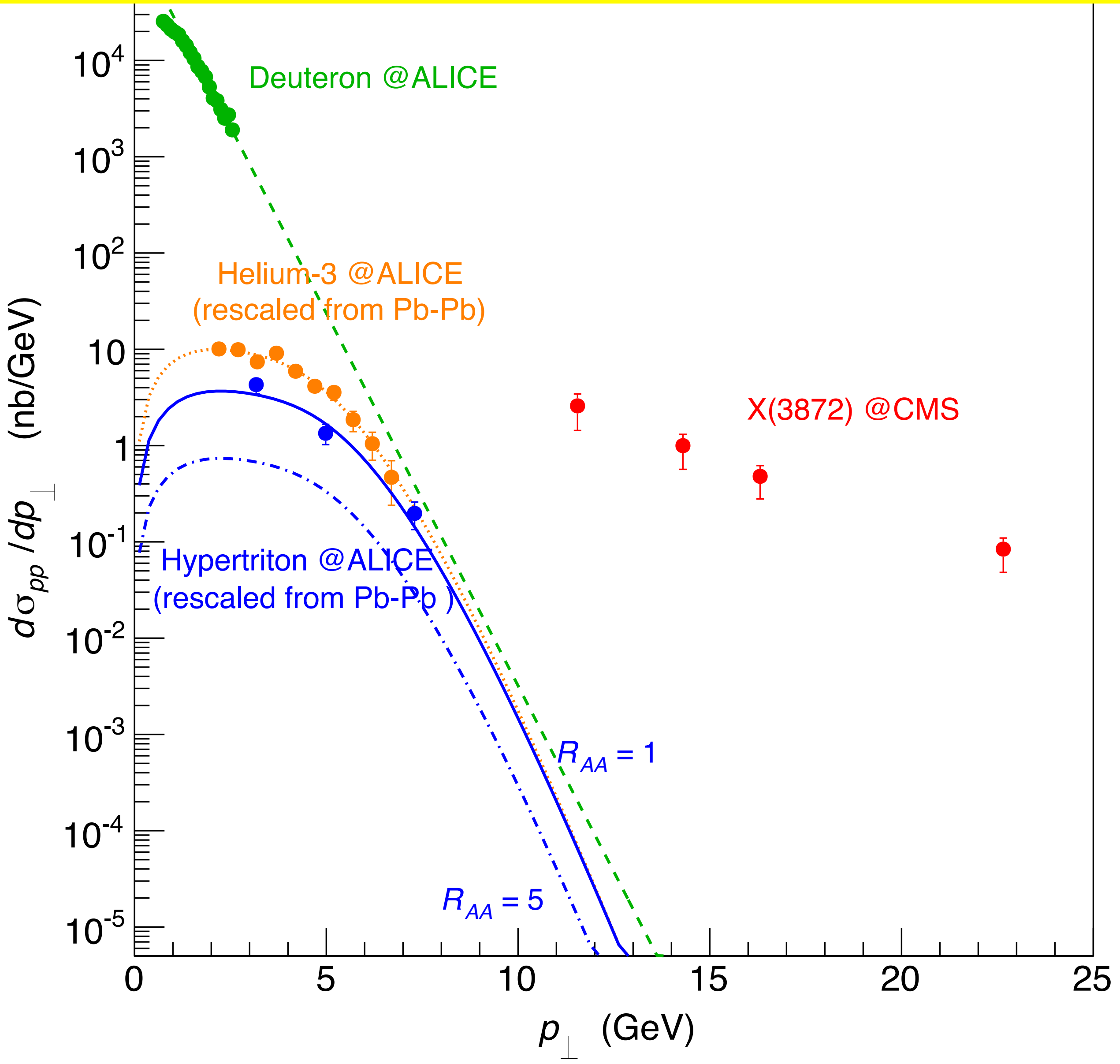
$$Z^+ : c\bar{c}u\bar{d}$$

$$\mathcal{P}^+ : c\bar{c}uud$$

- QCD can accomodate in two ways:
  - -hadron molecules (like nuclei)
  - - compact tetra/ penta quarks

Production of X(3872) versus light nuclei at ALICE (Pb-Pb) and CMS (p-p)

A. Esposito *et al.* Phys. Rev. D **92** (2015) 3, 034028



Rescaling ALICE Pb-Pb cross sections of light nuclei to p-p CMS cross section is done with blast-wave function (R_{AA} or R_{CP} =1)

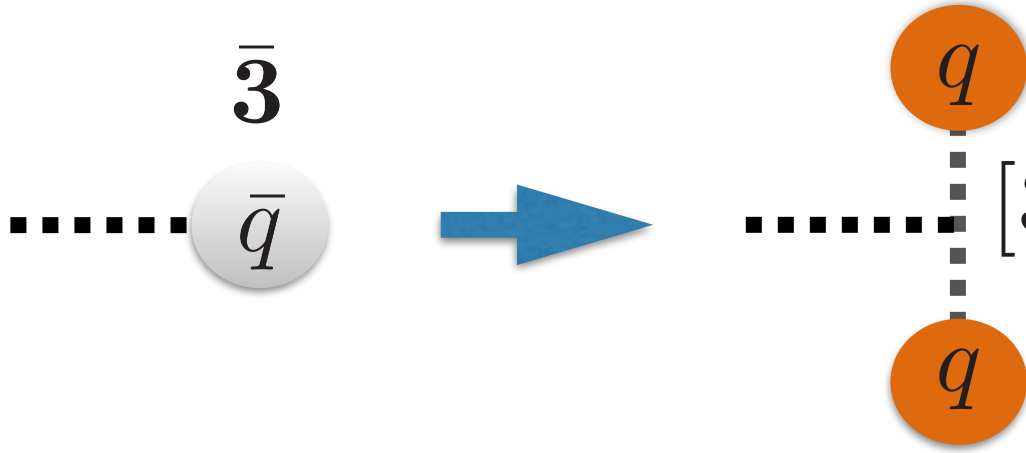
Collective effects in Pb-Pb (e.g.quark-gluon plasma) **enhance nuclear cross sections** and therefore **reduce the cross section rescaled to p-p**.

- There is a vast difference in probability for producing X(3872) or light nuclei, the true "hadronic molecules", at high p_{perp}
- high energy production of suspected exotic hadrons in p-p and Heavy Ion colliders is a very effective tool to discriminate different models
- a long list of suspects: f0(980), X(3872), Z(3900), Z(4020), Z(4430), X(4140)…

Can mixing with charmonium save the molecule?

Replacing: antiquark → diquark makes new objects

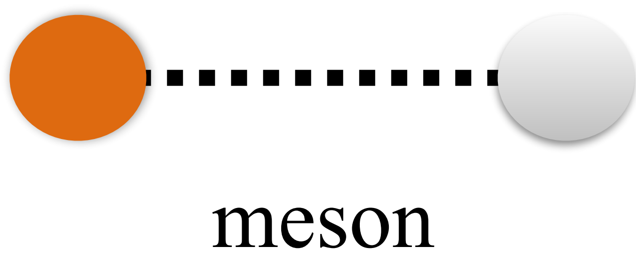
rule:

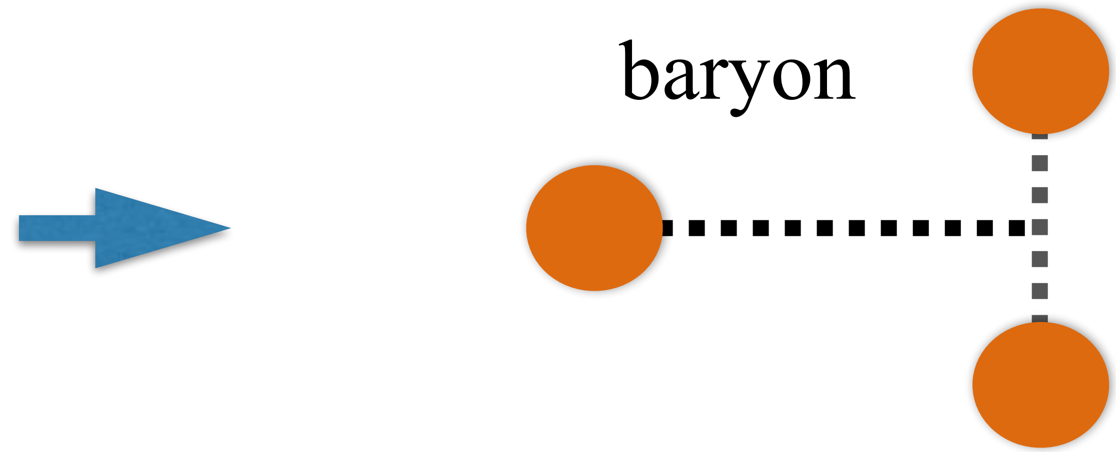


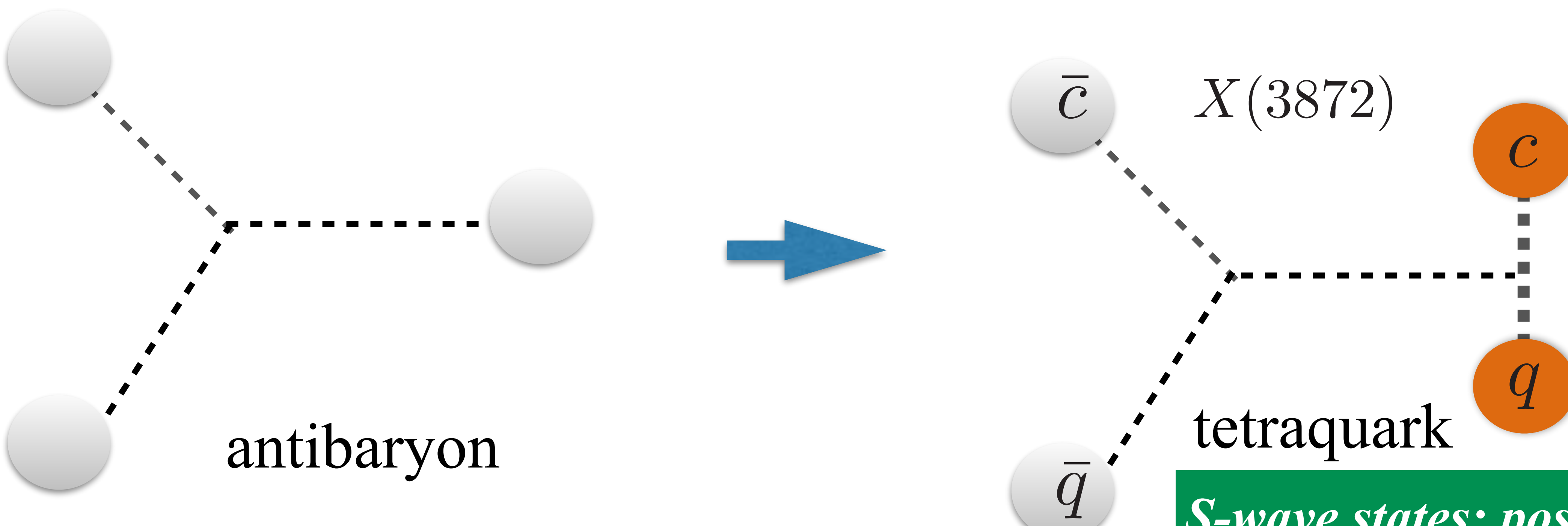
$[\mathbf{3} \times \mathbf{3}]_{Antisymm} = \bar{\mathbf{3}}$

S-wave states: positive parity
L=1 states: negative parity

S-wave states: negative parity
L=1 states: positive parity







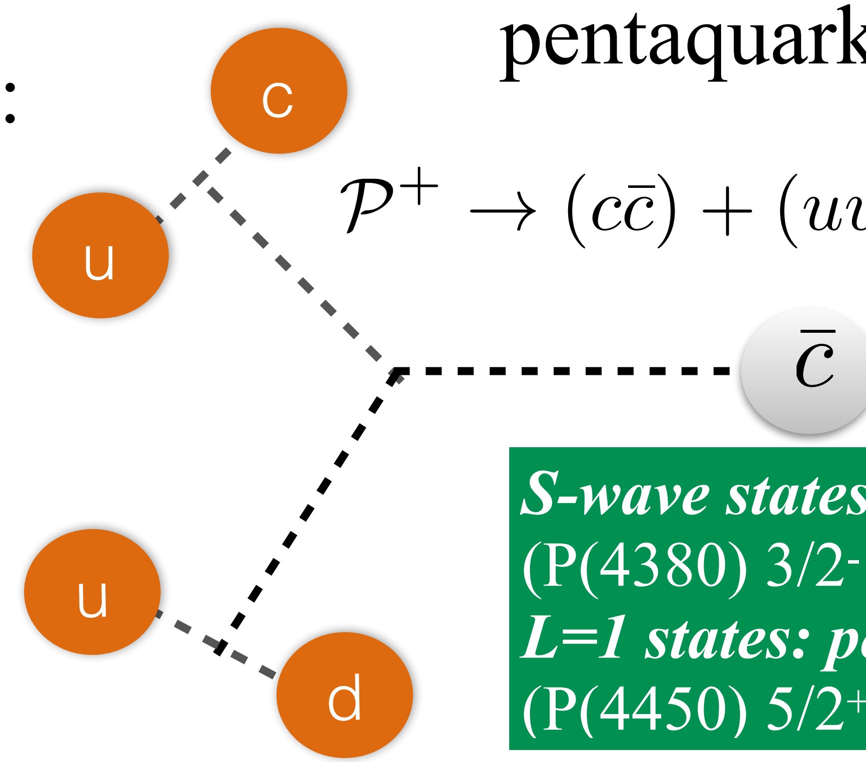
X, Y, Z mesons

S-wave states: positive parity, X,Z
L=1 states: negative parity, Y

L. Maiani, A. D. Polosa and V. Riquer, PLB **749** (2015) 289

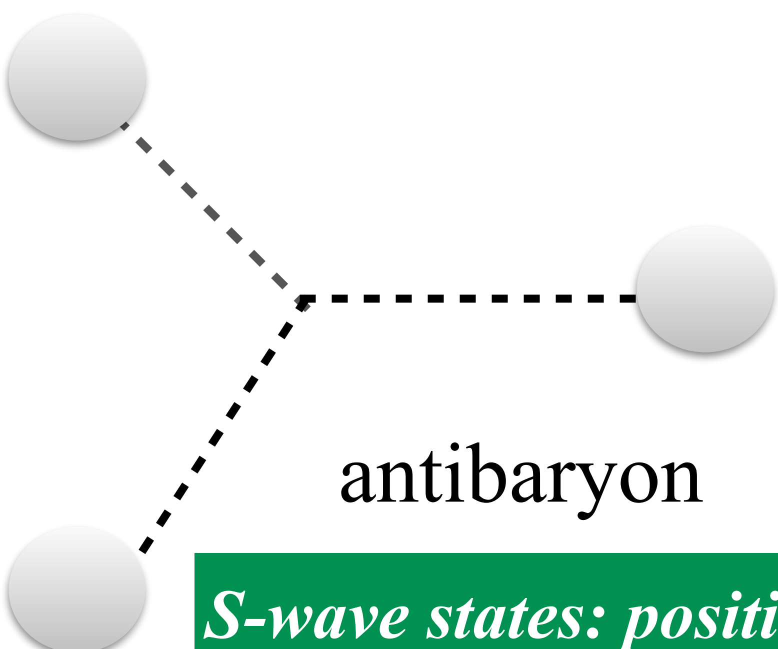
in baryon:

pentaquark



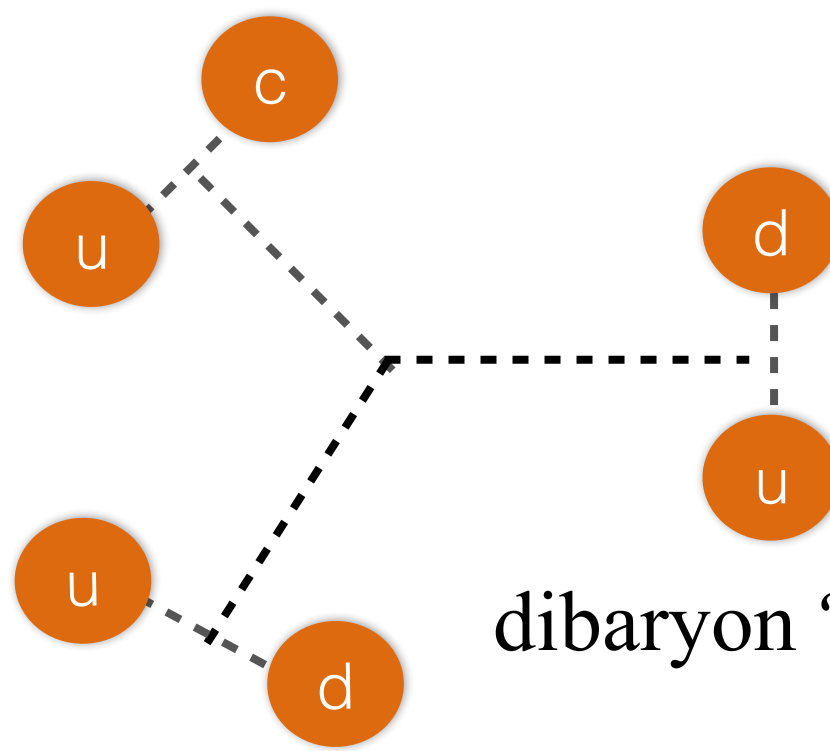
$$\mathcal{P}^{+} \to (c\bar{c}) + (uud) = J/\Psi + p$$

S-wave states: negative parity
(P(4380) $3/2^{-}$?)
L=1 states: positive parity
(P(4450) $5/2^{+}$?)



antibaryon

S-wave states: positive parity
L=1 states: negative parity

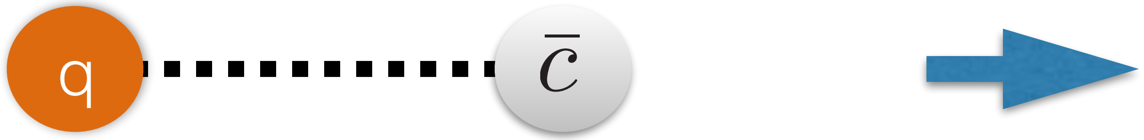


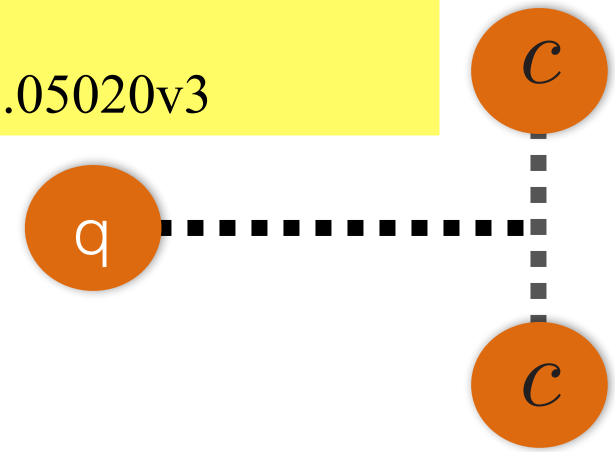
dibaryon ???

Substitution with diquark (antidiquark) reproduces qualitatively ***all we have seen in Exotic Hadrons until now***… and more

A new sensation: doubly heavy baryons

M. Savage, M. B. Wise, PLB **248**,1990;
N. Brambilla, A. Vairo and T. Rosch, PRD **72,** 2005; T. Mehen, arXiv:1708.05020v3

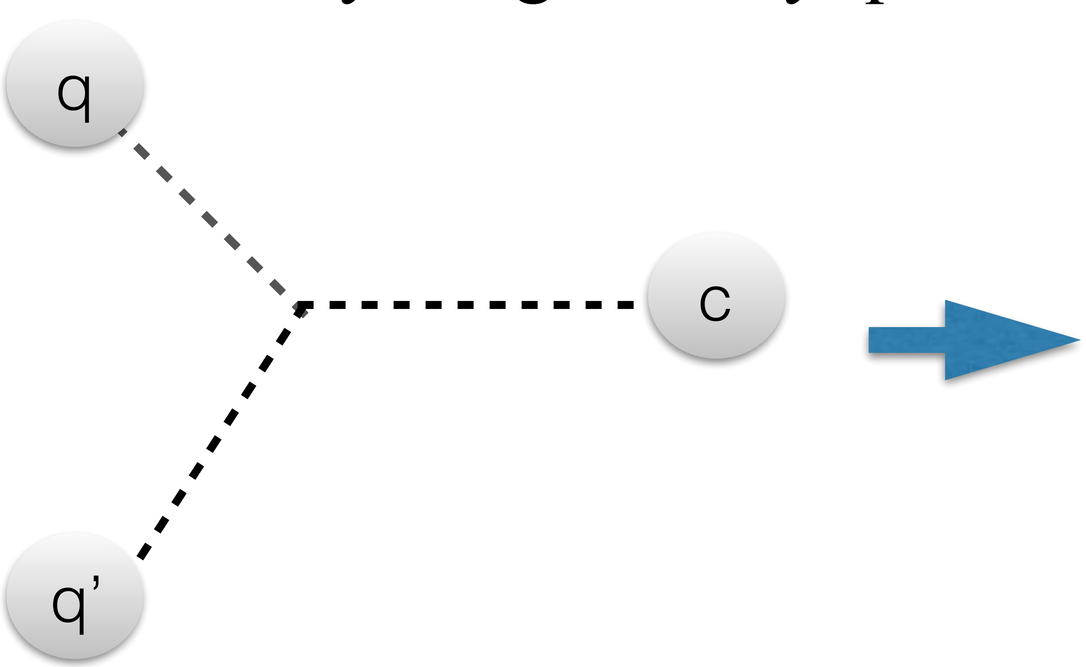




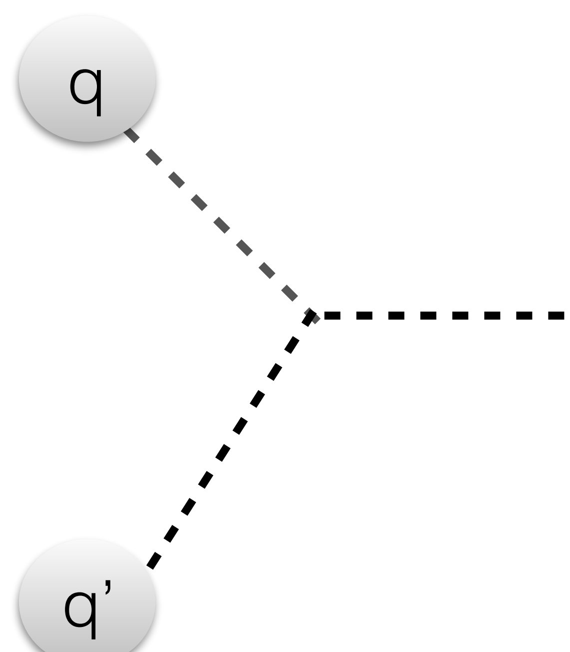
- Doubly heavy baryons are related to single quark heavy mesons
- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g.

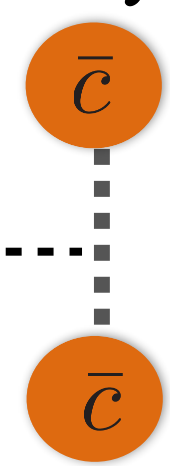
$$M(\Xi_{cc}^*) - M(\Xi_{cc}) = \frac{3}{4}[M(D^*) - M(D)]$$

similarly: single heavy quark baryons….



…. are related to doubly heavy tetraquark

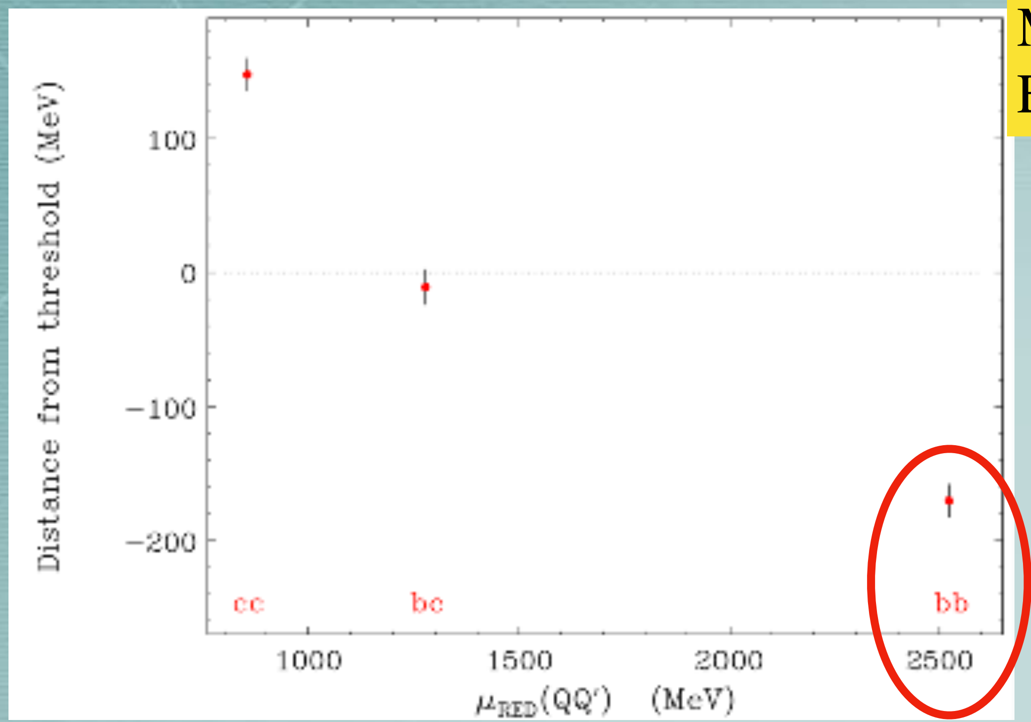




Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)
M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].

Double Beauty tetraquarks may be stable for the strong interactions !!

M. Karliner and J. L. Rosner, arXiv:1707.07666 [hep-ph].
E. J. Eichten and C. Quigg, arXiv:1707.09575 [hep-ph].



- binding energy with respect to BB threshold (constituent quark model) is negative beyond doubt
- only allowed: weak decays of constituent quarks

- cross sections may not be forbidding
  - -doubly charmed baryons observed at LHC
  - - bb pairs observed at LEP

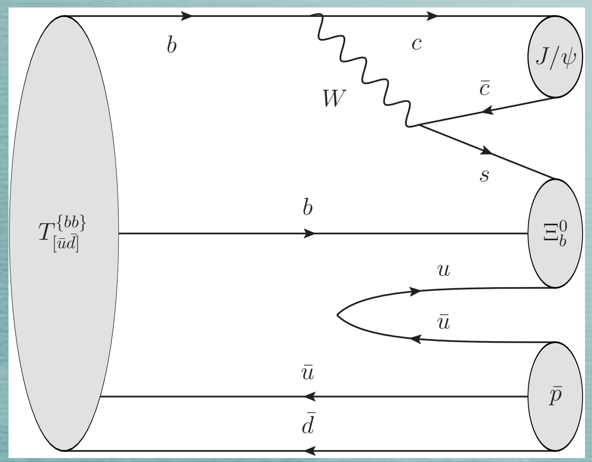
$$\mathcal{B}(Z^0 \to b\bar{b}b\bar{b}) = (3.6 \pm 1.3) \times 10^{-4} \text{ (LEP)}$$
$$\mathcal{B}(Z^0 \to T^{\{bb\}}_{[\bar{u}d]} + X) = 10^{-6} - 10^{-5}$$

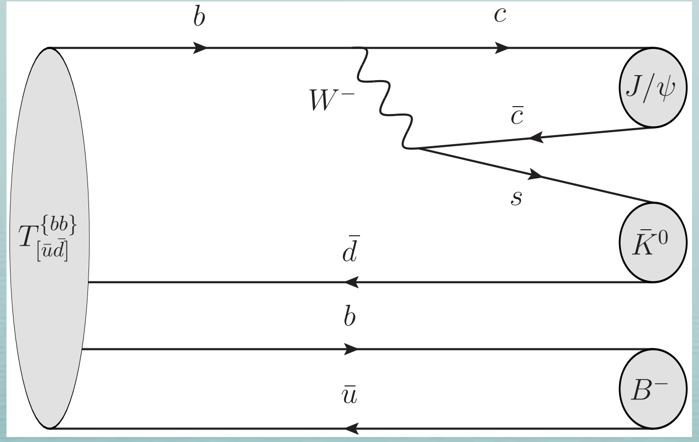
A. Ali and coll.

- spectacular weak decays

$T^{(bb)}_{[\bar{u}d]} \to J/\Psi\ K^0\ B^-$

$T^{(bb)}_{[\bar{u}d]} \to J/\Psi\ \Xi^0_b\ p$



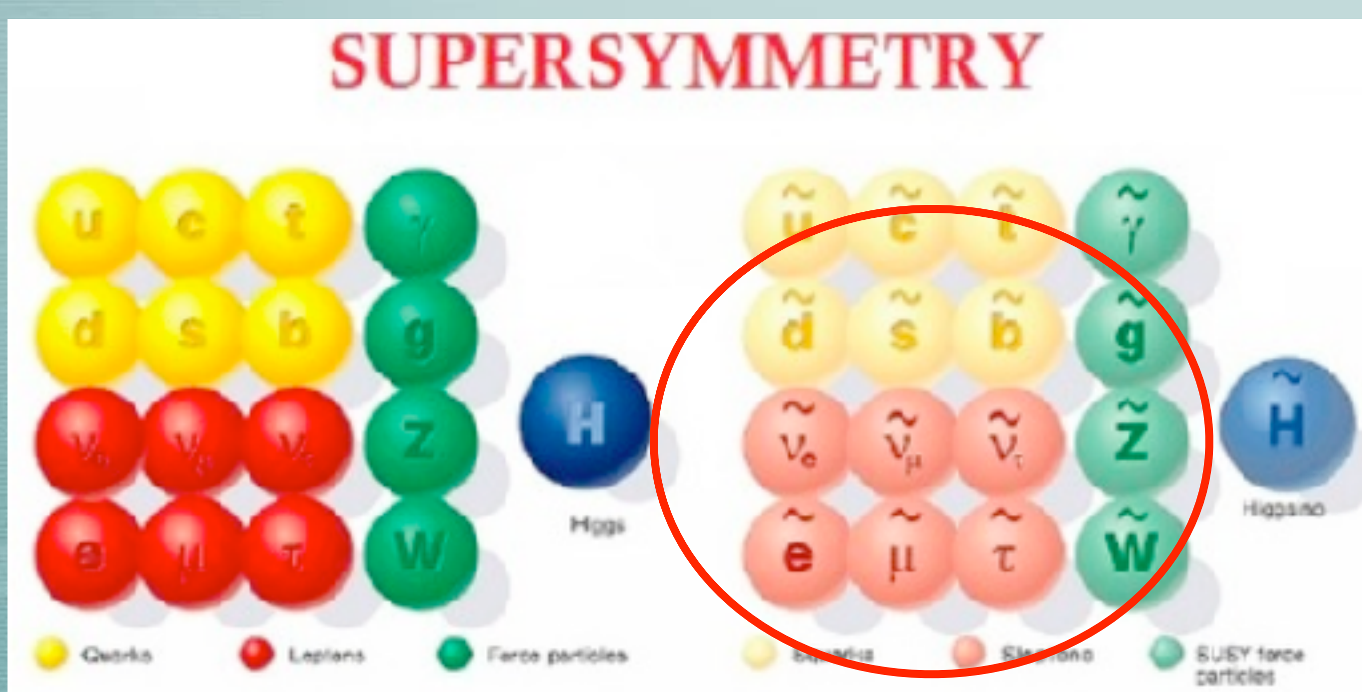


- LHC-HE
- Tera Z factory (FCC-ee, CepC) ?

A new territory for non perturbative methods in QCD

c) Supersymmetry @ the LHC ?

- The Higgs particle seen at CERN is relatively light, 125 GeV
- good news for Supersymmetry which predicts a mass < 135 GeV
- SUSY predicts two doublets of “Higgs bosons, for a total 5 scalar particles: h(125), H, A, $H^{\pm}$, the heavier bosons have undetermined masses: $m_H \sim m_{H\pm} \sim m_A$;
- the couplings of h are equal to the ST couplings only in the limit $m_A \to \infty$;
- and a duplication of the other particles of the ST, with a change of 1/2 unit of spin.



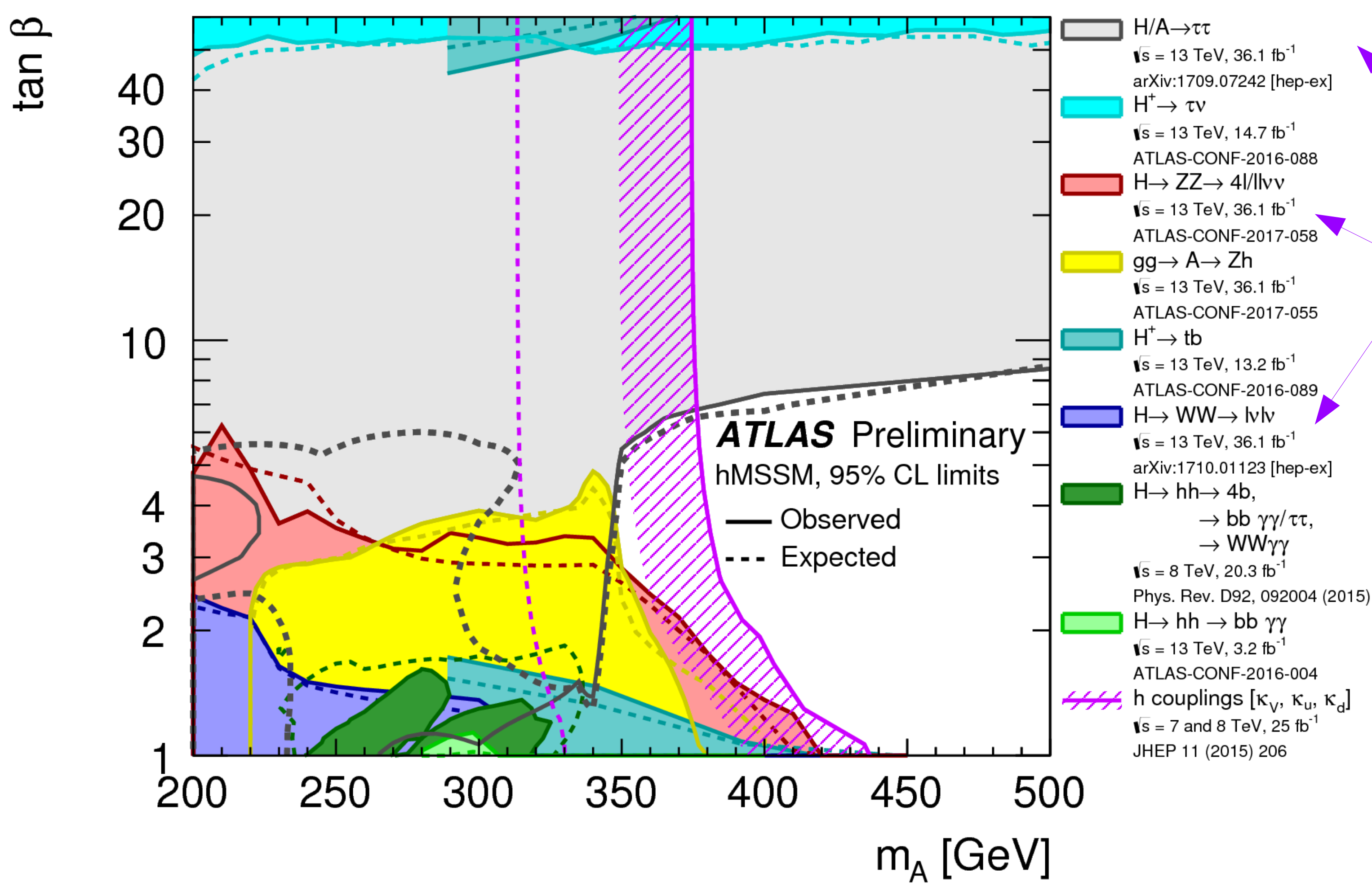
An entire world of new particles to discover!!

MSSM: Heavy Higgs

Comparing limits (e.g. in the hMSSM)

hMSSM: simplified version of MSSM, some radiative corrections are neglected, the dominant ones (from loops involving top quarks and stop quarks) are constrained using m_h.

At tree level, the properties of the Higgs sector of the MSSM depend on only two non-SM parameters; can be chosen to be m_A and $\tan\beta$.



shown in this talk

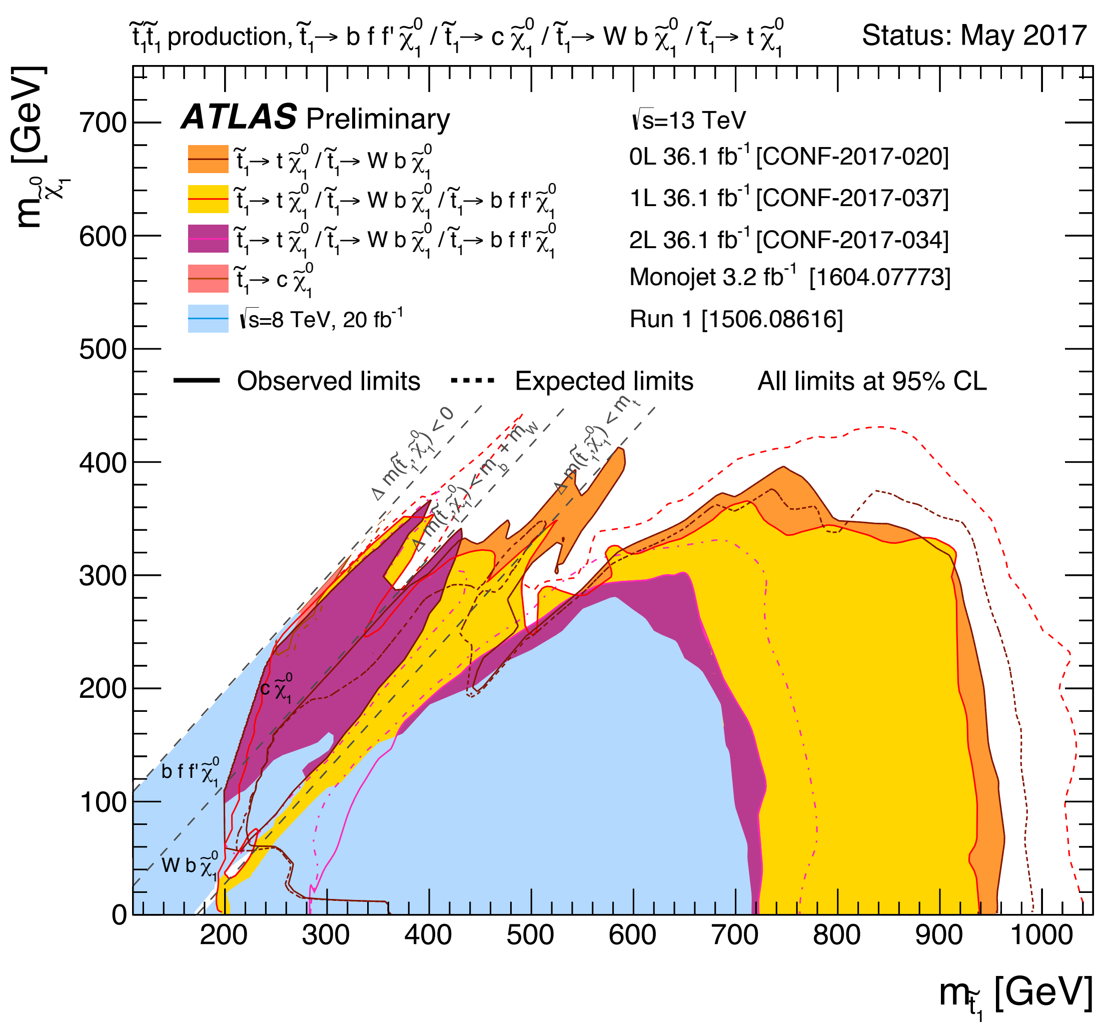
preliminary version of result shown in this talk

TH Analysis: A. Djouadi *et al.* (Orsay-Roma coll.) *The post-Higgs MSSM scenario: Habemus MSSM?* Eur. Phys. J., C73:2650, 2013.

Recent limits on Superparticles: scalar top (2017)

Conclusion

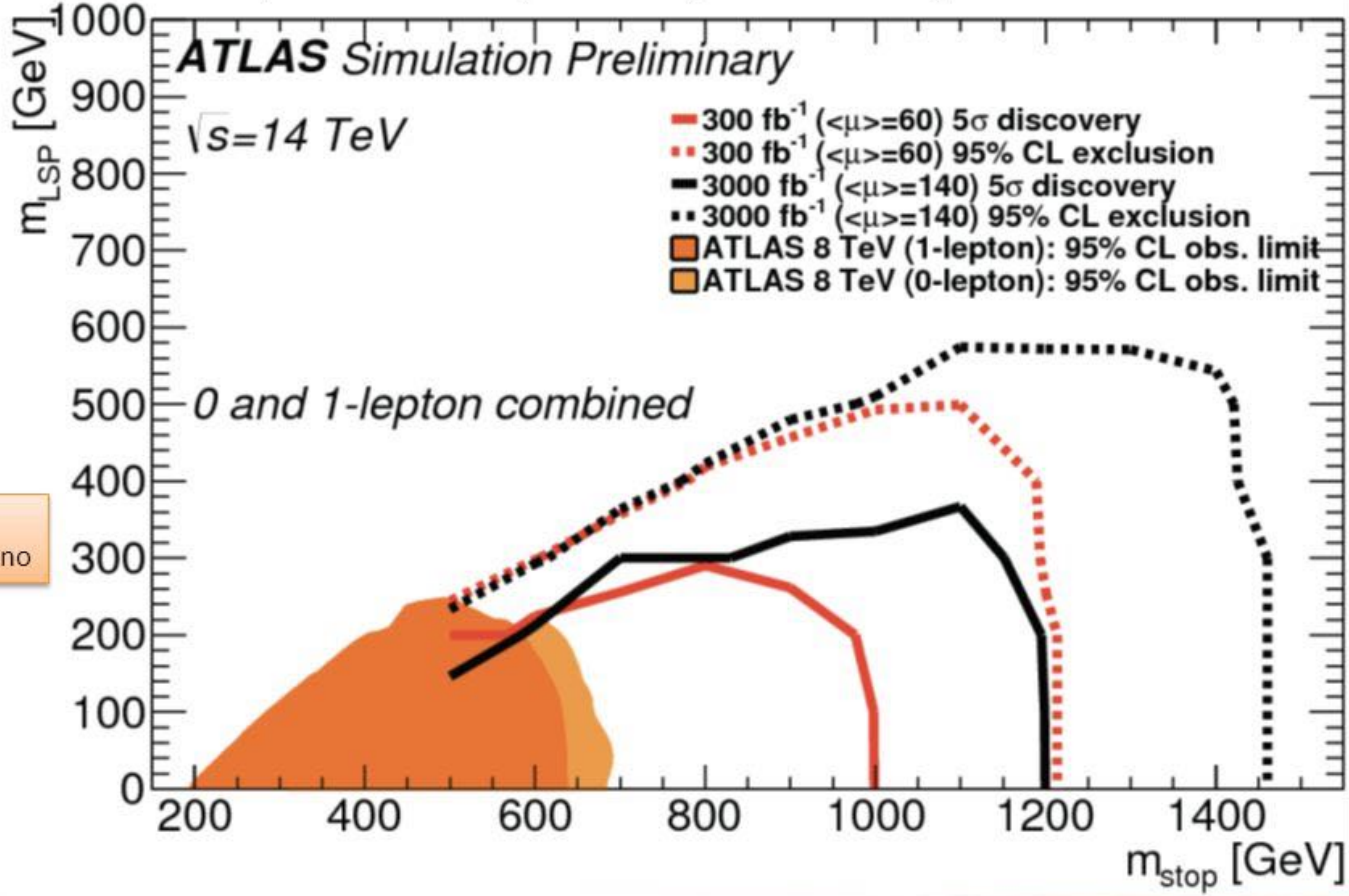
- Many new results from ATLAS for 3rd generation squark searches are presented based on full 2015+2016 data (36 fb^{-1}).



- No significant excesses this time around…
- Stringent constraints obtained on various pMSSM and simplified models.

Stay tuned!

HiLumi: more precision… and also new heavier particles (if they exists…)



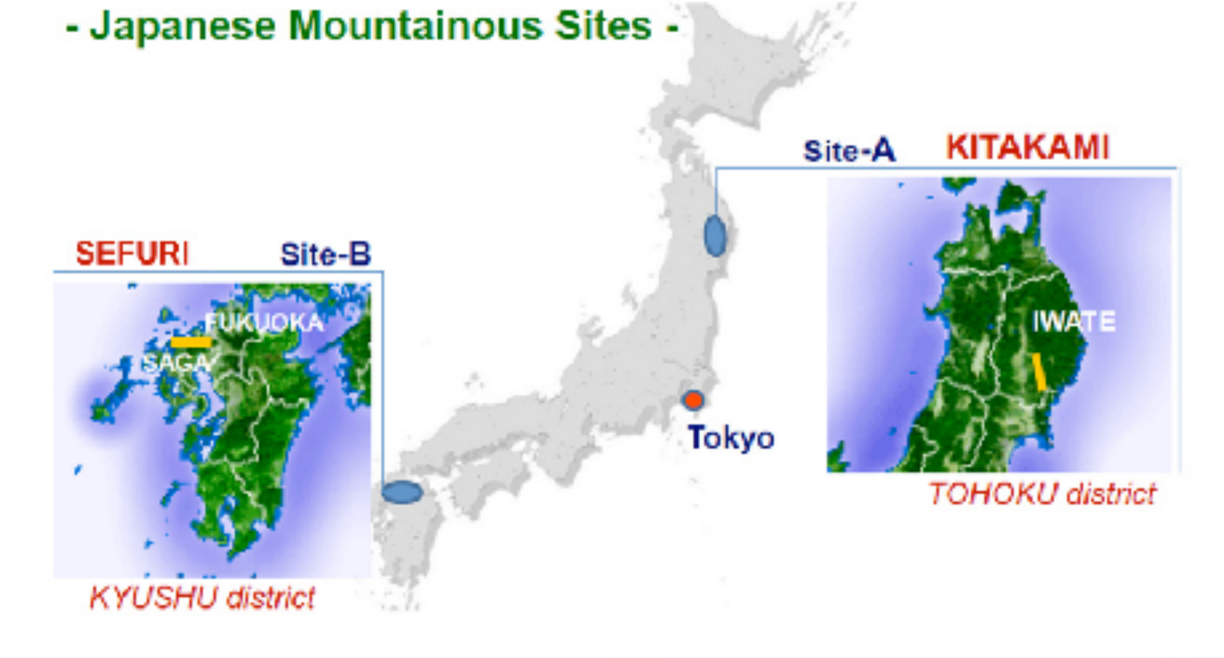
Courtesy
M. Mangano

9. What's next?

An electron-positron step

An $e^+ e^-$ Higgs boson factory, could aim at high precision to probe Higgs physics at high energies

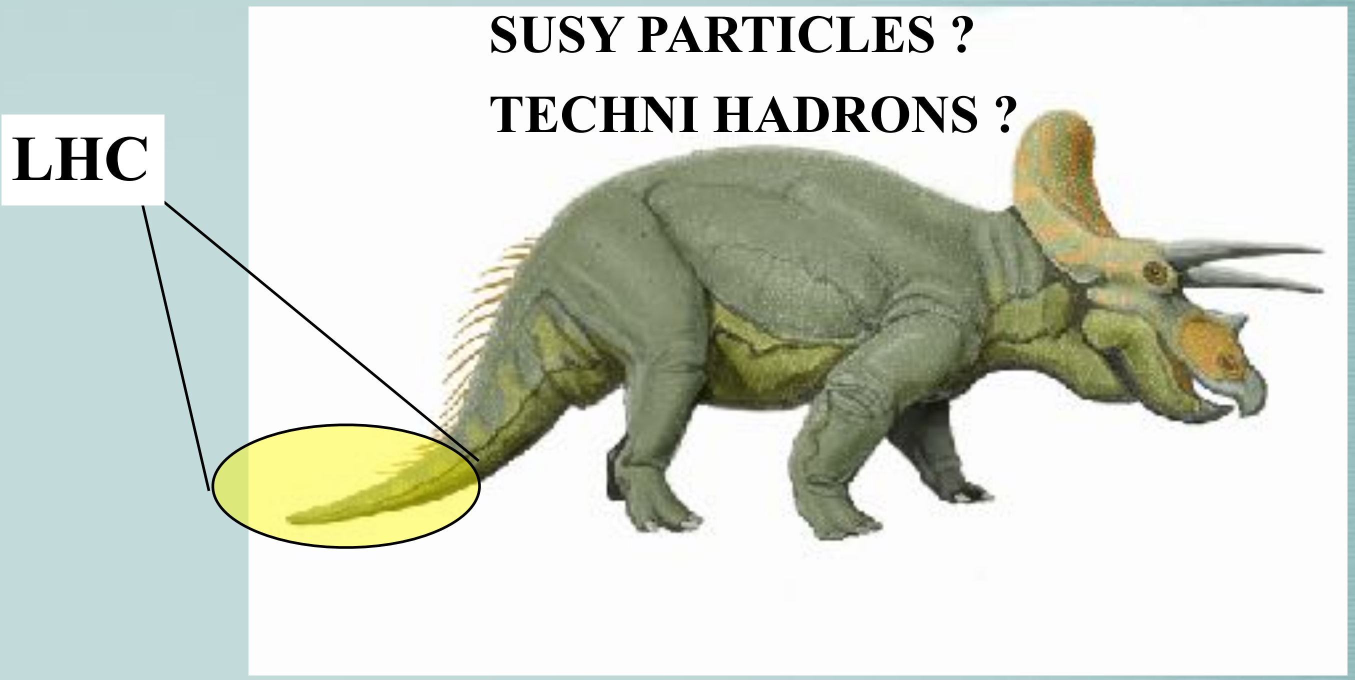
- International Linear Collider, e^+e^- @ 0.5 TeV:
  - site approved in Japan: (Kitakami)
  - a reserve site (Sefuri)



- Alternatively, ***repeat the LEP-LHC strategy***
- go for a circular e^+e^- @ 250-300 GeV in a large tunnel (Higgs factory)
- 70-100 km to make radiation losses acceptable,
- tunnel may host later a p-p collider @ 80-100 TeV, to explore the region left by LHC, 3 to 10 TeV
- projects are being made at CERN, (FCC-ee), and in China at IHEP (CEPC)

- With the LHC tunnel limitation, it is not likely that we can see all particles implied by SUSY or by Technicolor and find out which is the next step BEYOND the STANDARD THEORY

- but we may be able to see the tail of the dinosaur….
- or find other hints from other sources



- In the 80s it was thought that identification of unnaturalness could give the key to a complete theory of what is Beyond the Standard Theory
- we may have guessed some real point…. compositeness, supersymmetry …but there are so many things we do not fully understand (which SUSY, dark matter, hierarchy, strong interactions) that the physics we will find there will be, most likely, ***entirely new, strange and unexpected***.
- Only direct inspection will tell.

Dreams about the future??

- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted in the last 100 years

1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europe
2030's: Regional Laboratorie in Europe, America, Asia … will unite in a Global Accelerator Network - The World ??