The Deepest Symmetries of Nature

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Outline

- Symmetries in particle physics
- *CPT* invariance
- Symmetries of the Standard Model
- Supersymmetry
- Search for new particles: LEP and LHC

Symmetries

Deeper microstructure ⇒ greater role of symmetries

More basic role in particle physics than in chemistry or solid state physics (origin!)

Field theory: Noether's theorem

Global symmetry	⇒	conserving quantity
Spatial displacement	⇒	momentum
Time displacement	⇒	energy
Rotation	⇒	angular momentum
Mirror reflection	⇒	parity
Gauge invariance	⇒	charge (electric, color, fermion)

Popular journal of Fermilab and SLAC:
symmetry — dimensions of particle physics

Elementary particles

	fermion doublets ($S = 1/2$)	charge Q	isospin I
leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	0 -1	$+1/2$ $-1/2$
quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L \begin{pmatrix} c \\ s' \end{pmatrix}_L \begin{pmatrix} t \\ b' \end{pmatrix}_L$	$+2/3$ $-1/3$	$+1/2$ $-1/2$

colored quarks $\Rightarrow$ *colorless* **composite hadrons**

hadrons = mesons ($q\bar{q}$) + baryons (qqq)

Nucleons ($I = \frac{1}{2}$): p = (uud) n = (udd) $\bar{p} = (\bar{u}\bar{u}\bar{d})$

Pions ($I = 1$): $\pi^+ = (u\bar{d})$ $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ $\pi^- = (\bar{u}d)$

Interactions

Derived from local gauge invariance: no masses, divergence

Standard Model:

Free Dirac (point-like) fermion

+ local $U(1) \otimes SU(2)$ symmetry

$\Rightarrow$ electroweak interaction (γ, Z, $W^{\pm}$)

+ local $SU(3)$ symmetry

$\Rightarrow$ strong interaction (8 gluons)

+ Higgs field with spontaneous symmetry breaking

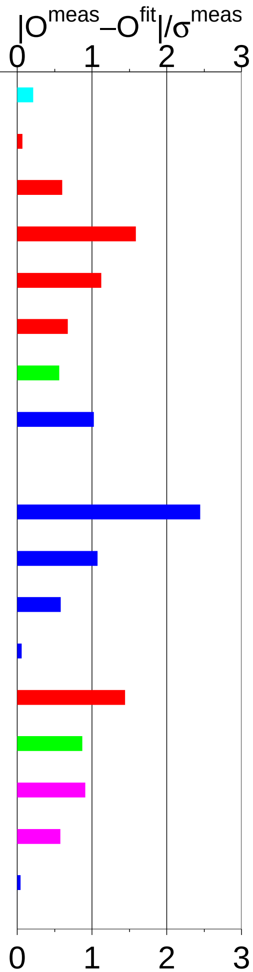
$\Rightarrow$ masses, convergence (+ Higgs boson)

Fundamental job of particle physics: study symmetries

Glory road of SM at LEP

Summer 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



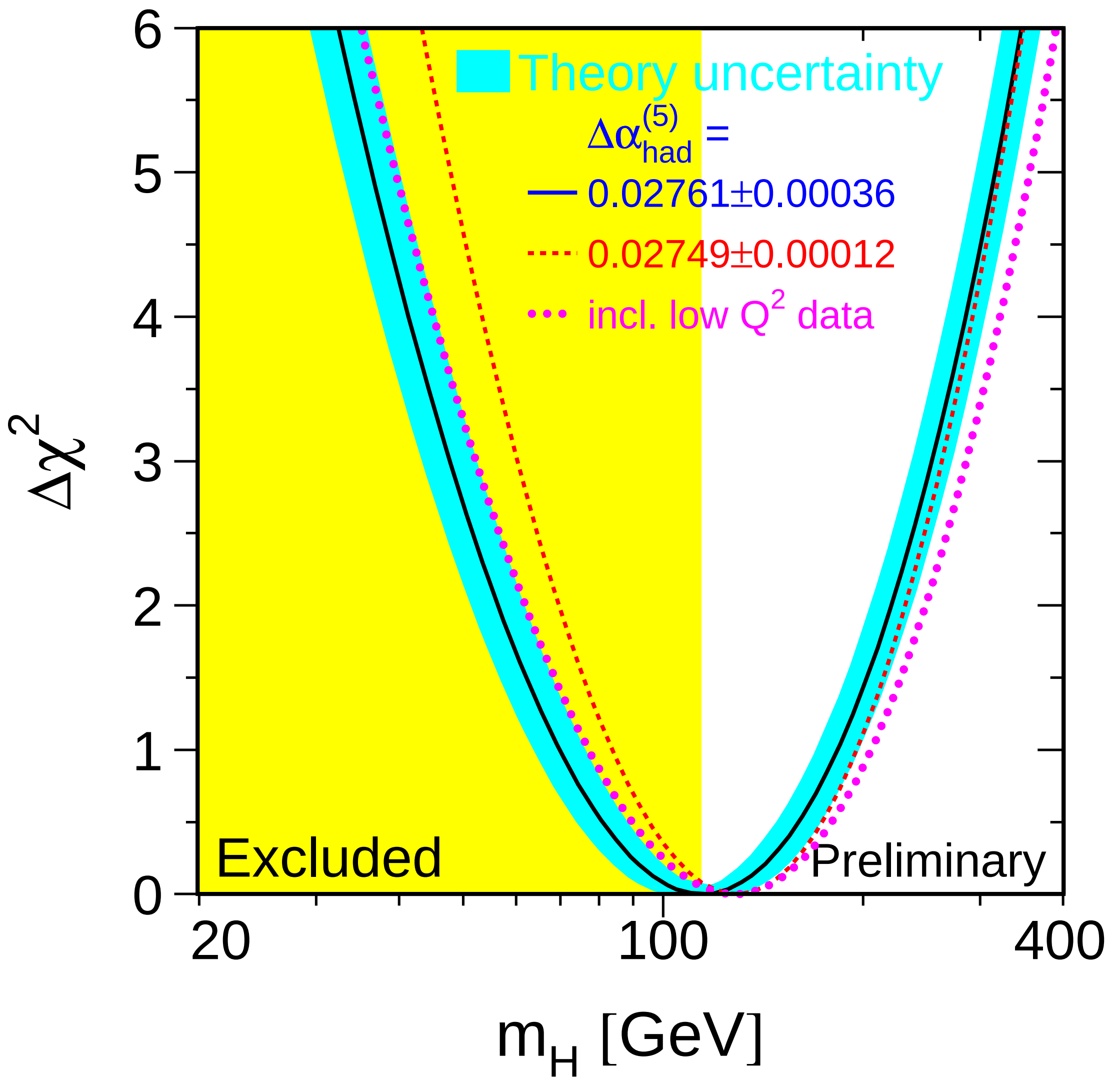
Includes hundreds of measurements of all experiments

Slightly deviating quantity changes from year to year

Now it is forward-backward asymmetry of $e^+e^- \to Z \to b\bar{b}$

LEP Electroweak Working Group: http://lepewwg.web.cern.ch/LEPEWWG/

Fitting Higgs mass



Sensitivity of SM parameters to Higgs mass

$114 < M_H < 260$ GeV
(95 % confidence)

LEP Electroweak Working Group: http://lepewwg.web.cern.ch/LEPEWWG/

CPT Invariance

Charge conjugation: $C|\mathrm{p}(r,t)> = |\bar{\mathrm{p}}(r,t)>$

Space reflection: $P|\mathrm{p}(r,t)> = |\mathrm{p}(-r,t)>$

Time reversal: $T|\mathrm{p}(r,t)> = |\mathrm{p}(r,-t)>$

Basic assumption of field theory:

$$CPT|\mathrm{p}(r,t)> = |\bar{\mathrm{p}}(-r,-t)> = |\mathrm{p}(r,t)>$$

meaning antiparticle $\sim$ particle
going backwards in space and time.

Giving up CPT one has to give up:

- locality of interactions $\Rightarrow$ causality, or
- unitarity $\Rightarrow$ conservation of matter, information, ... or
- Lorentz invariance

CPT Invariance: violation?

Theoreticians in general: CPT is **NOT** violated

CPT-violating theories: Ralf Lehnert's talk!

- Standard Model valid up to Planck scale ($\sim 10^{19}$ GeV). Above Planck scale new physics $\Rightarrow$ Lorentz violation possible
- Quantum gravity: fluctuations $\Rightarrow$ Lorentz violation loss of information in black holes $\Rightarrow$ unitarity violation

Motivation for testing CPT at low energy

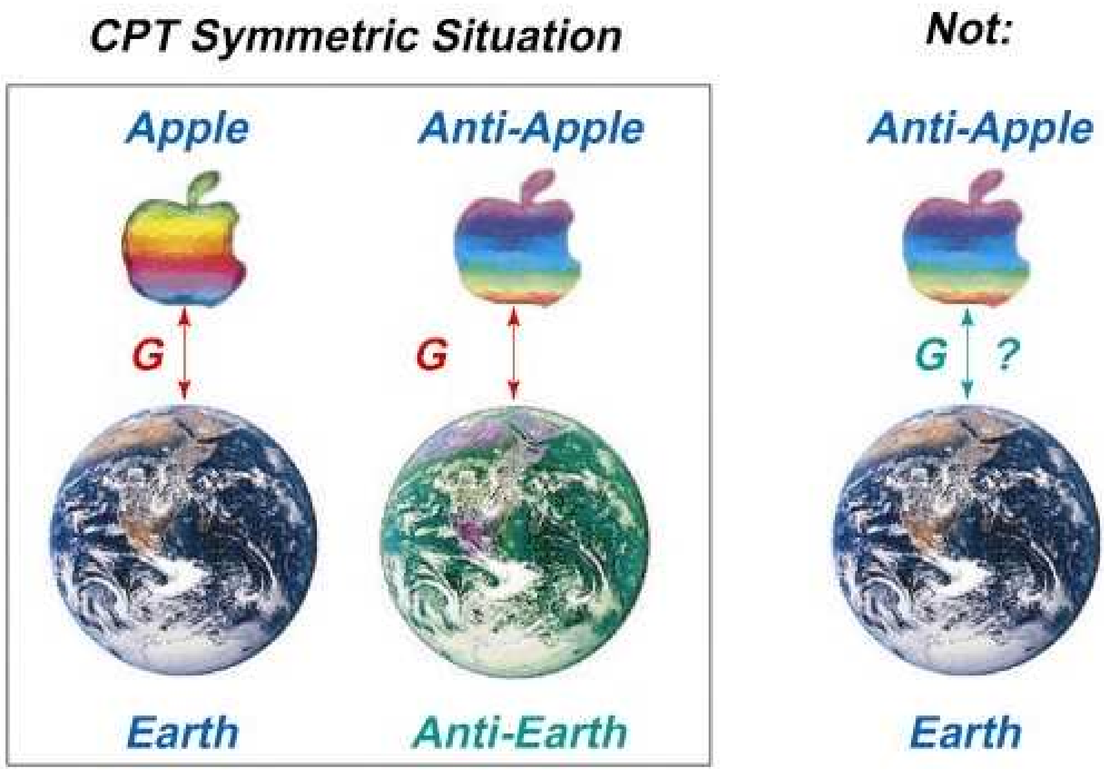
- Quantitative expression of Lorentz and CPT invariance needs violating theory
- low-energy tests can limit possible high energy violation

How to test CPT?

Particle = – antiparticle ?

- $m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)/m(\text{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen? ($2S - 1S$)
- $\nu \sim \bar{\nu}$ mass, mixing (LSND data?)

Exception: antigravity?



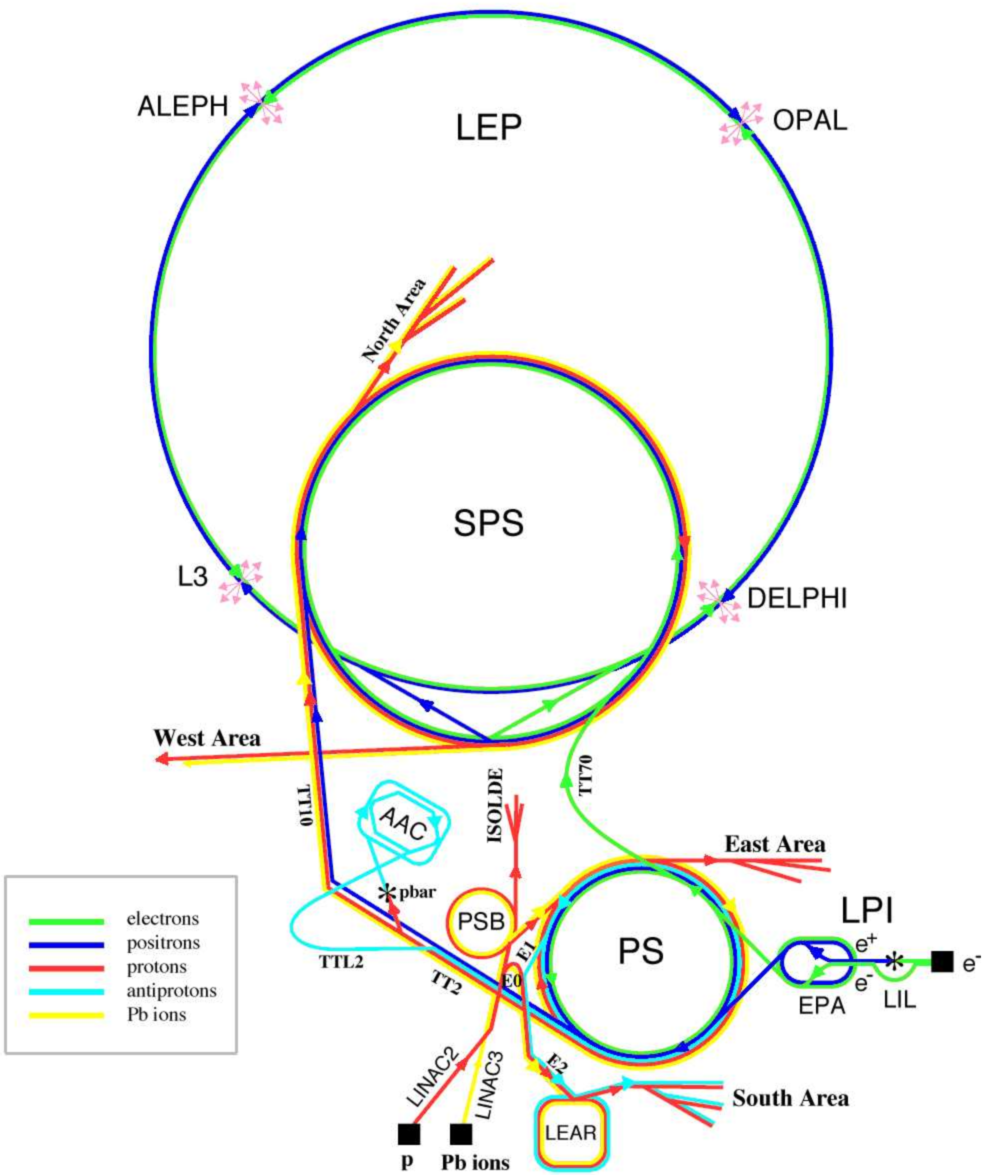
ATHENA home page

(http://cern.ch/athena/)

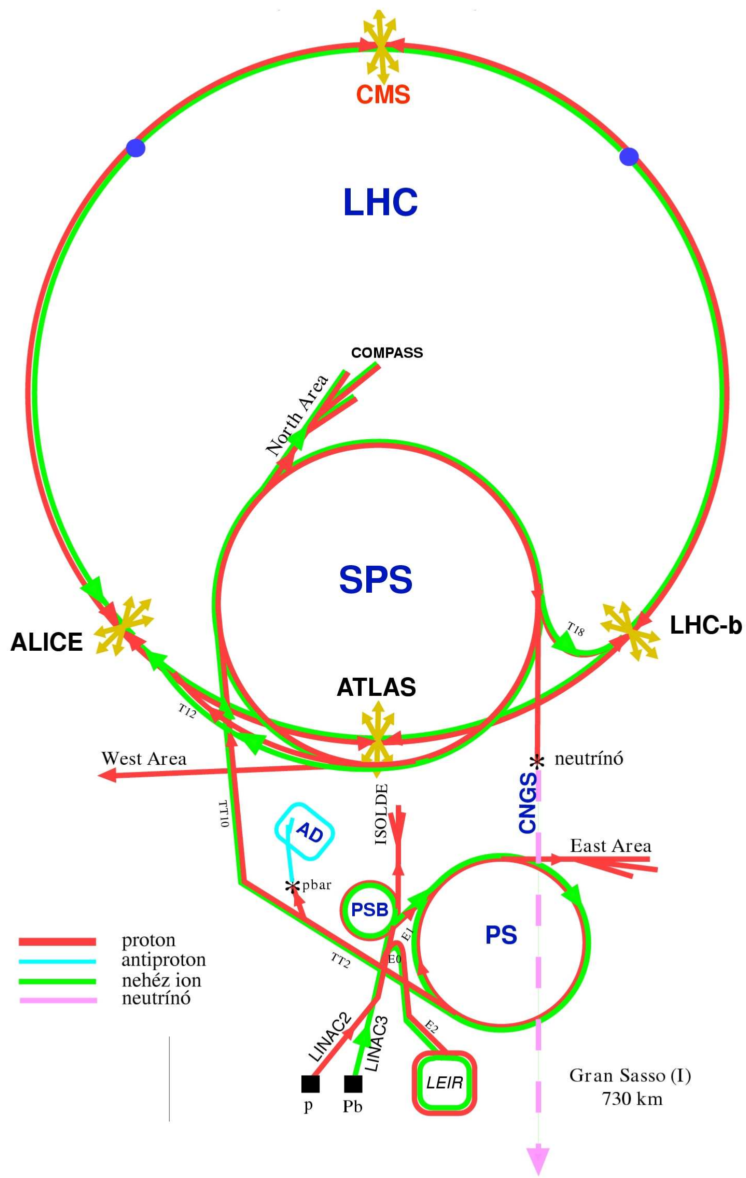
- *CPT*: particle – Earth $\sim$ antiparticle – antiEarth
- weak equivalence:
  particle – Earth $\sim$ antiparticle – Earth

Accelerators at CERN

Until 1996



From 2007?



The Antiproton Decelerator at CERN

is built to test *CPT* invariance

Three experiments test CPT:

ATRAP: $q(\bar{\mathrm{p}})/m(\bar{\mathrm{p}}) \leftrightarrow q(\mathrm{p})/m(\mathrm{p})$

$\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ATHENA: $\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ASACUSA: $q(\bar{\mathrm{p}})^2 m(\bar{\mathrm{p}}) \leftrightarrow q(\mathrm{p})^2 m(\mathrm{p})$

$\mu_\ell(\bar{\mathrm{p}}) \leftrightarrow \mu_\ell(\mathrm{p})$

$\overline{\mathrm{H}} \leftrightarrow \mathrm{H}$ HF structure

RED: done, GREEN: planned

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Lost symmetries?

„.. the fundamental equations of physics have more symmetry than the actual physical world does"

Frank Wilczek: *In search of symmetry lost,* Nature **433** (2005) 239

- CPT **invariance:** fundamental, absolute, no violation
- $SU(3)$ **gauge invariance**
  - conserves color charge
  - gives rise to strong interactions
  - no violation
- $U(1) \times SU(2)$ **gauge invariance**
  - spontaneously broken by Higgs field
  - gives rise to electroweak interaction
  - produces Higgs boson
- What else?

Supersymmetry (SUSY): motivation

Theoretical problems of Standard Model:

- Naturalness (hierarchy): Mass of Higgs boson quadratically diverges due to radiative corrections. Eliminated if fermions and bosons exist in pairs.
- Dark matter and energy is dominant mass of Universe. What is it that we observe its gravity only?
- Gravity: does not fit in system of gauge interactions (strong, electromagnetic, weak)
- Convergence of interactions: in SM the three gauge couplings converge at $\sim 10^{16}$ GeV but do not meet

All these would be solved by a universal fermion $\Leftrightarrow$ boson supersymmetry.

Supersymmetry (SUSY): partner particles

Property	particle	ordinary	SUSY
R parity		+1	-1
Spin	fermion	$S = \frac{1}{2}$	$S = 0$
	gauge boson	$S = 1$	$S = \frac{1}{2}$
	Higgs boson	$S = 0$	$S = \frac{1}{2}$
	graviton	$S = 2$	$S = \frac{3}{2}$
Chirality	fermion	$\mathrm{X}_L, \mathrm{X}_R$	$\tilde{\mathrm{X}}_1, \tilde{\mathrm{X}}_2$
Mass	fermion	$M(\mathrm{X}_L = \mathrm{X}_R)$	$M(\tilde{\mathrm{X}}_1) \neq M(\tilde{\mathrm{X}}_2)$

Charges (electric, color, fermion) identical

R parity: $R = (-1)^{2S+3B+L}$

S: spin, B: baryon number, L: lepton number

SUSY partners of fermions

Leptons $(S=\frac{1}{2})$	scalar leptons $(S=0)$
e, μ, τ	$\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$
ν_e, ν_μ, ν_τ	$\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$
Quarks $(S=\frac{1}{2})$	scalar quarks $(S=0)$
u, d, c, s, t, b	$\tilde{u}$, $\tilde{d}$, $\tilde{c}$, $\tilde{s}$, $\tilde{t}$, $\tilde{b}$

Antiparticle $\leftrightarrow$ antipartner

X_L, X_R $\leftrightarrow$ $\tilde{X}_1$, $\tilde{X}_2$

SUSY partners of bosons

Elementary boson	spin	SUSY partner	spin
photon: γ	1	photino: $\tilde{\gamma}$	$\frac{1}{2}$
weak bosons:	1	zino: $\tilde{Z}$	$\frac{1}{2}$
Z, W^+, W^-	1	wino: $\tilde{W}^+, \tilde{W}^-$	$\frac{1}{2}$
gluons: $g_1, \ldots g_8$	1	8 gluinos: $\tilde{g}_1, \ldots \tilde{g}_8$	$\frac{1}{2}$
Higgs fields	0	higgsinos	$\frac{1}{2}$
$H_1^0, H_2^0, H_1^+, H_2^-$		$\tilde{H}_1^0, \tilde{H}_2^0, \tilde{H}_1^+, \tilde{H}_2^-$	
graviton	2	gravitino	$\frac{3}{2}$

Two Higgs doublets $\Rightarrow$ 5 Higgs bosons: h, H, A, H^+, H^-

Supersymmetry?

Supersymmetry is obviously broken:
no such particles,
or maybe with much larger masses

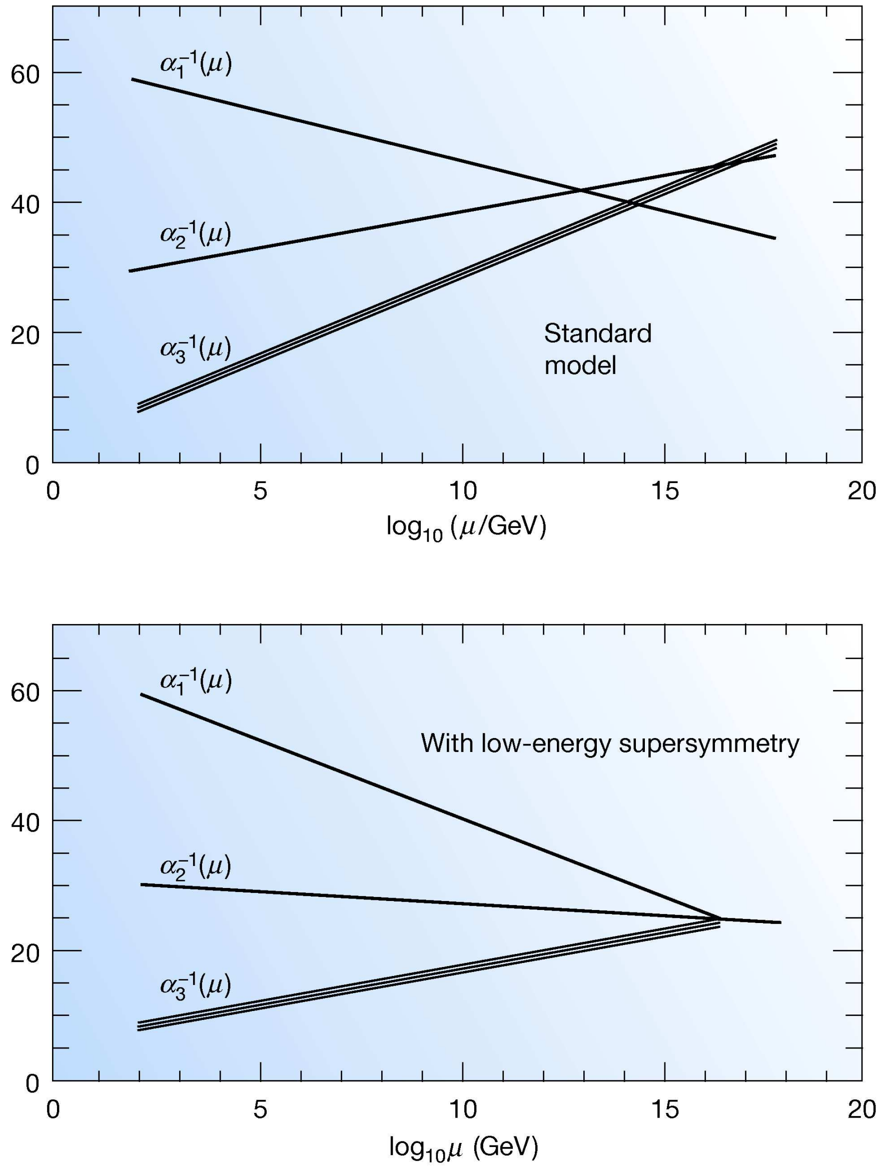
What is a broken symmetry good for?

Higgs mechanism:
symmetry violating field $\Rightarrow$ masses, renormalisation

Higgs field violates an existing symmetry
$\Updownarrow$
SUSY introduces a non-existing one

All this for a rational, cosistent theory

Unification of gauge interactions



Standard Model:

Gauge couplings get close but do not converge at high energies

SUSY:

Perfect convergence at $\sim 10^{16}$ GeV

Difference:
extra particles $\Rightarrow$ more corrections

Frank Wilczek: Nature **433** (2005) 239

Supersymmetry: $+$ és $-$

$+$

- naturalness of theory
- cold dark matter of the Universe (23 %) = LSP
- unification of interactions
- including gravitation

BUT:

$-$

- Mechanism of SUSY breaking ??
- Many different models
- Many new parameters
- Not seen below $\tilde{m} \sim 100$ GeV

MSSM

Minimal Supersymmetric Standard Model

Many simplifying constraints (boundary conditions), $> 100 \Rightarrow$ 5 or 6 parameters, e.g.:

- $m_{1/2}$: fermion masses at Grand Unifi cation energy (GUE $\sim 10^{14} - 10^{16}$ GeV)
- m_0: boson masses at GUE
- A_0: SUSY breaking (X–Y–Higgs) coupling constants at GUE
- $\tan\beta = v_1/v_2$: vacuum expectation values of upper and lower Higgs fi elds
- m_A: mass of a Higgs boson
- μ: mixing parameter of higgsinos

How to detect SUSY particles?

If particle states can mix, they will

Experiment looks for mass eigenstates

Charginos: $\{\tilde{W}^+, \tilde{W}^-, \tilde{H}_1^+, \tilde{H}_2^-\} \Rightarrow \{\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm\}$

Neutralinos: $\{\tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0\} \Rightarrow \{\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\}$

Let us search for SUSY partners!

Properties depend on models and parameters

Search for SUSY particles

Assume R-parity conserved

$\Downarrow$

Creation in pairs, decay to ordinary and SUSY particles

Lightest SUSY particle (LSP) unobservable

$\Rightarrow$ missing energy observed

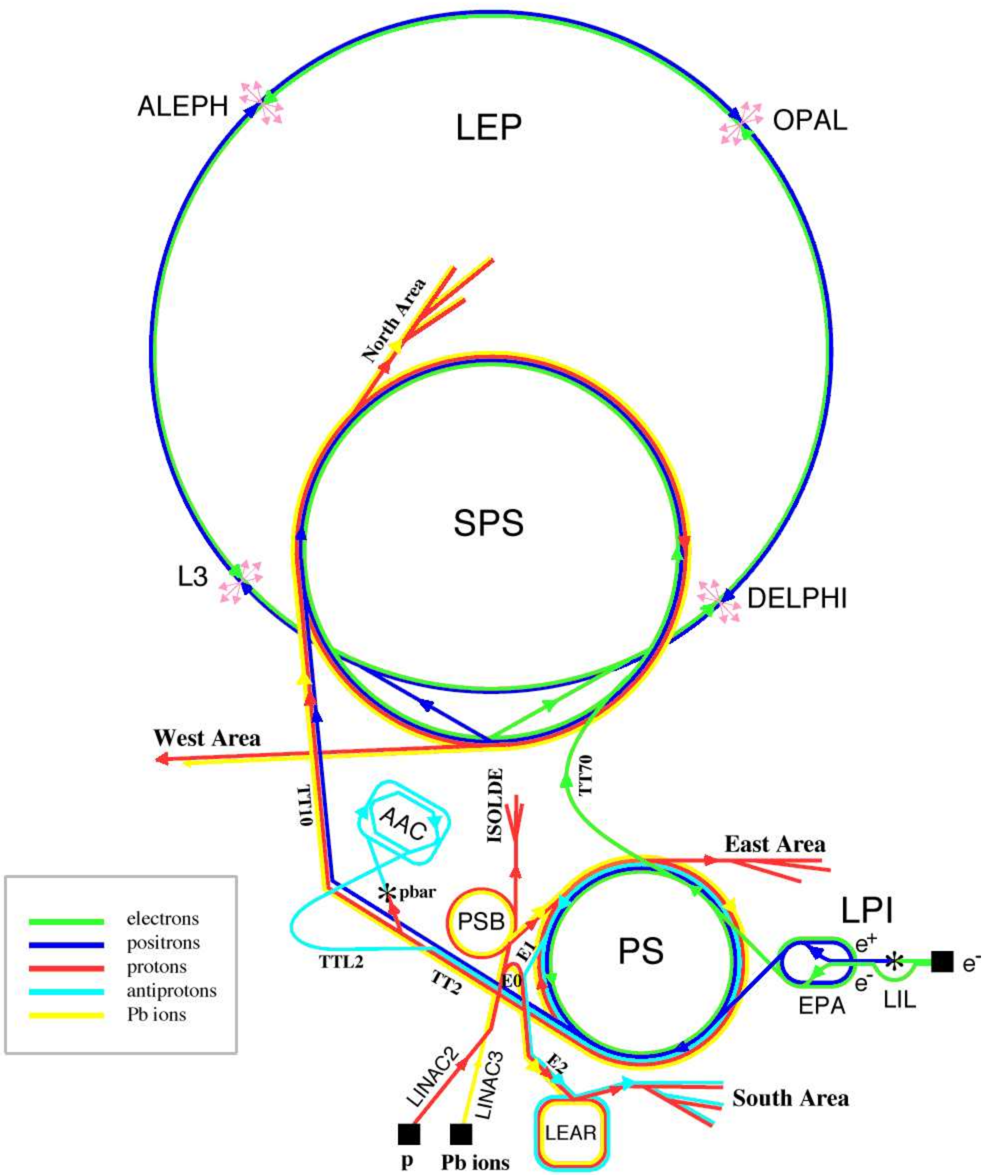
Which one is LSP?

Model dependent. MSSM: $\tilde{\chi}_1^0$; GMSB: $\tilde{G}$

Susy search at CERN: LEP, 1989 – 2000; LHC, 2007 –

Accelerators at CERN

Until 1996



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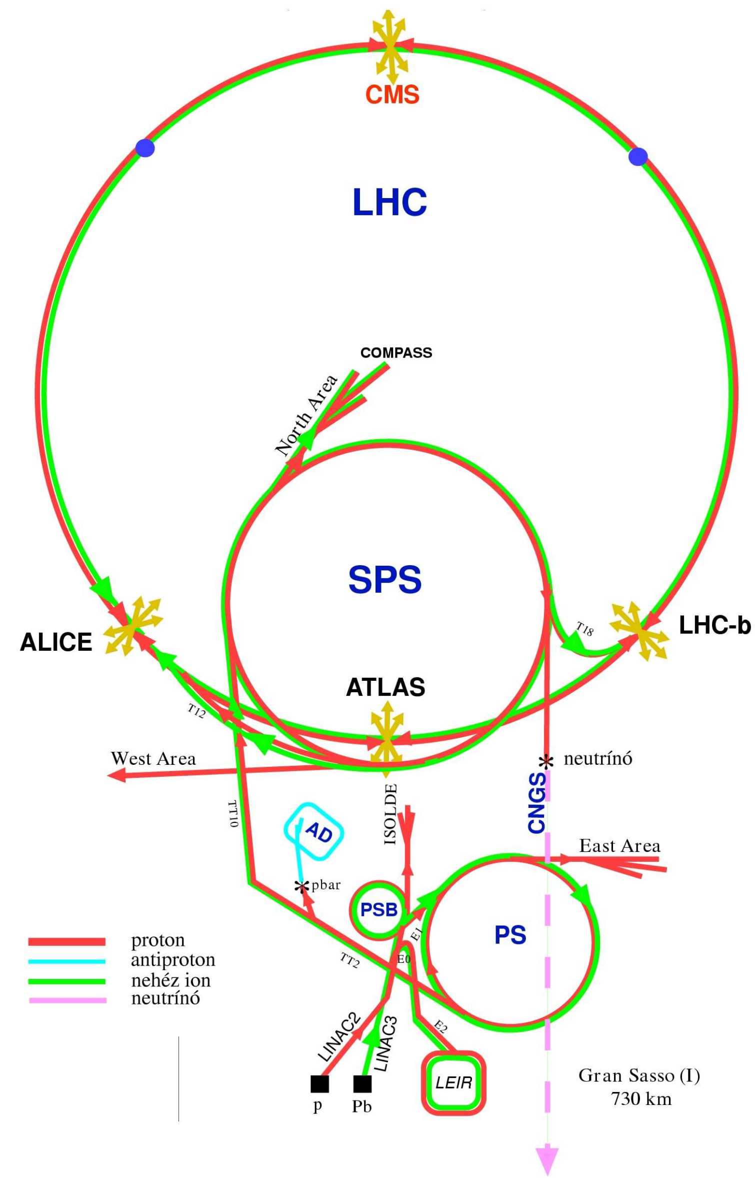


Tipical
OPAL event

$e^+e^- \rightarrow W^+W^-$

$\Downarrow$

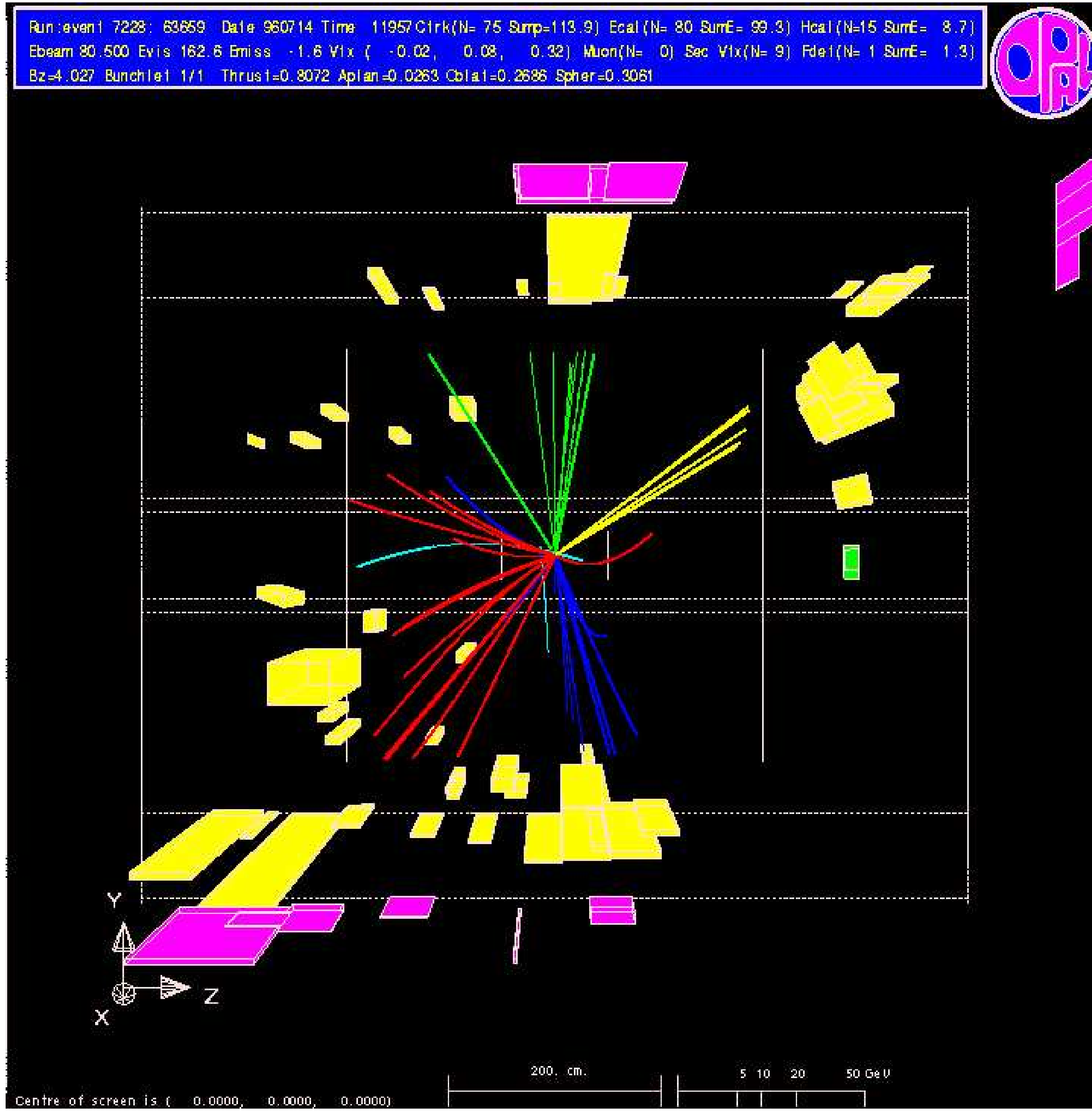
4 quarks

$\Downarrow$

4 hadron jets

$\Downarrow$

75 charged particles



Search for SUSY particles at LEP

Difficult: hard to distinguish from SM reactions.

Scalar lepton formation $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$

Decay e.g. $\tilde{\ell}^\pm \to \tilde{\chi}^0_1 \ell^\pm$, model-dependent cross sections

Look for $e^+e^- \to \ell^+\ell^-$ + missing energy

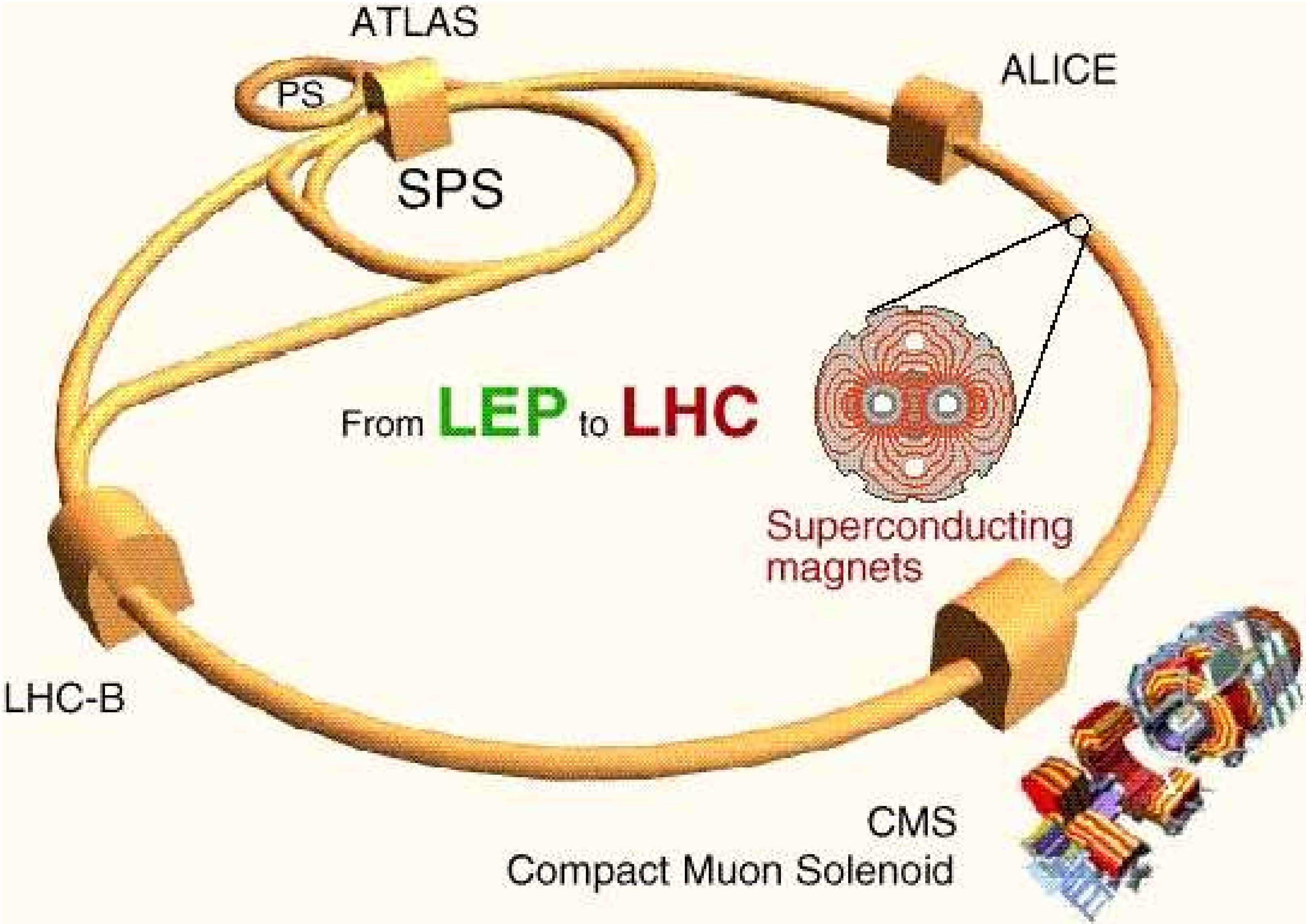
Main background: $e^+e^- \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$

LEP result (ALEPH + DELPHI + L3 + OPAL):

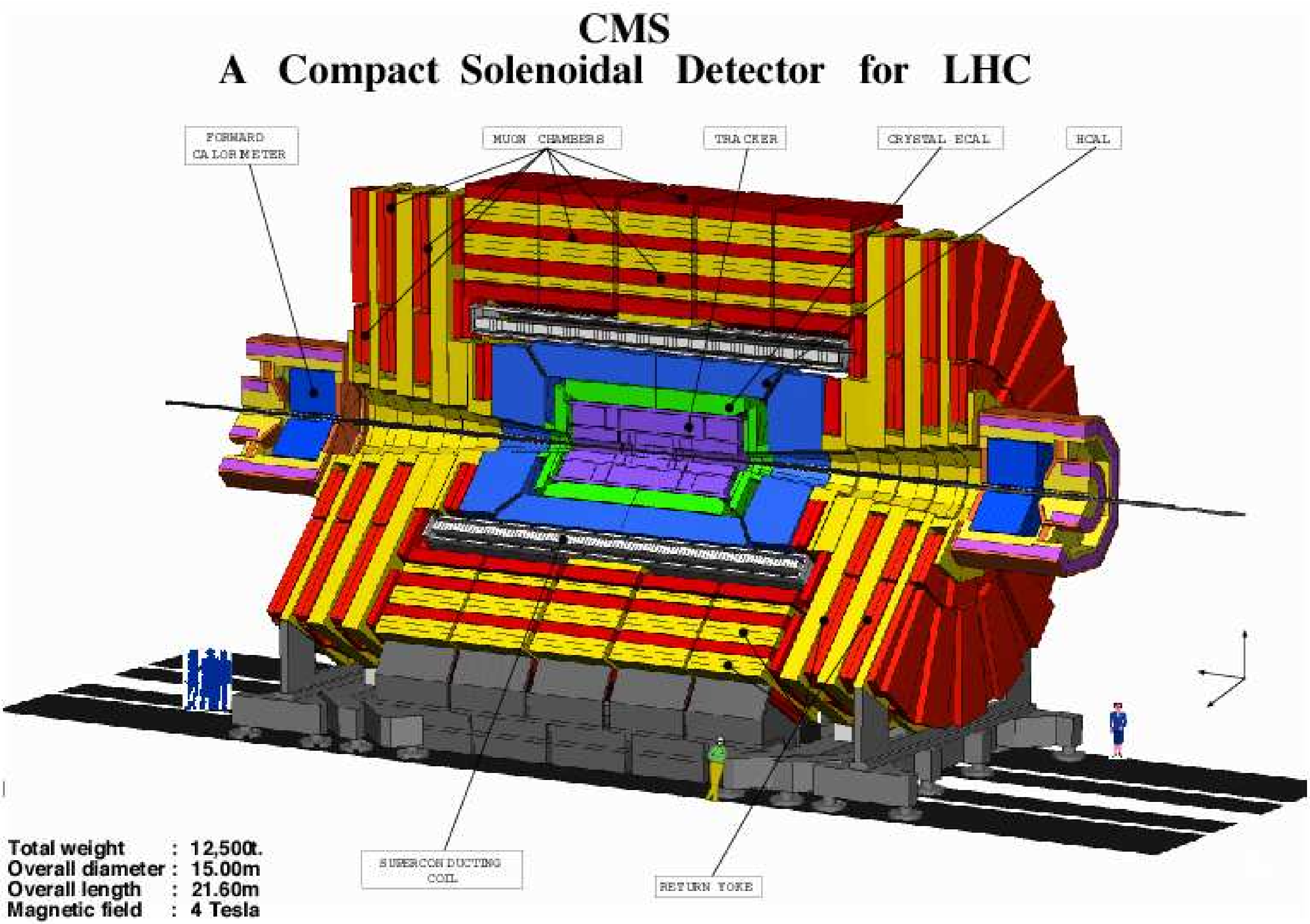
No supersymmetric particle below $\tilde{m} \sim 90-100$ GeV (kinematical limit)

Statistical analysis $\Rightarrow$ excluded parameter regions

No SUSY at LEP, let’s build LHC



Compact Muon Solenoid (CMS)



The CMS detector of LHC

(Compact Muon Solenoid)

Weight: 12500 tons, more iron, than in Eiffel tower

>2000 participants

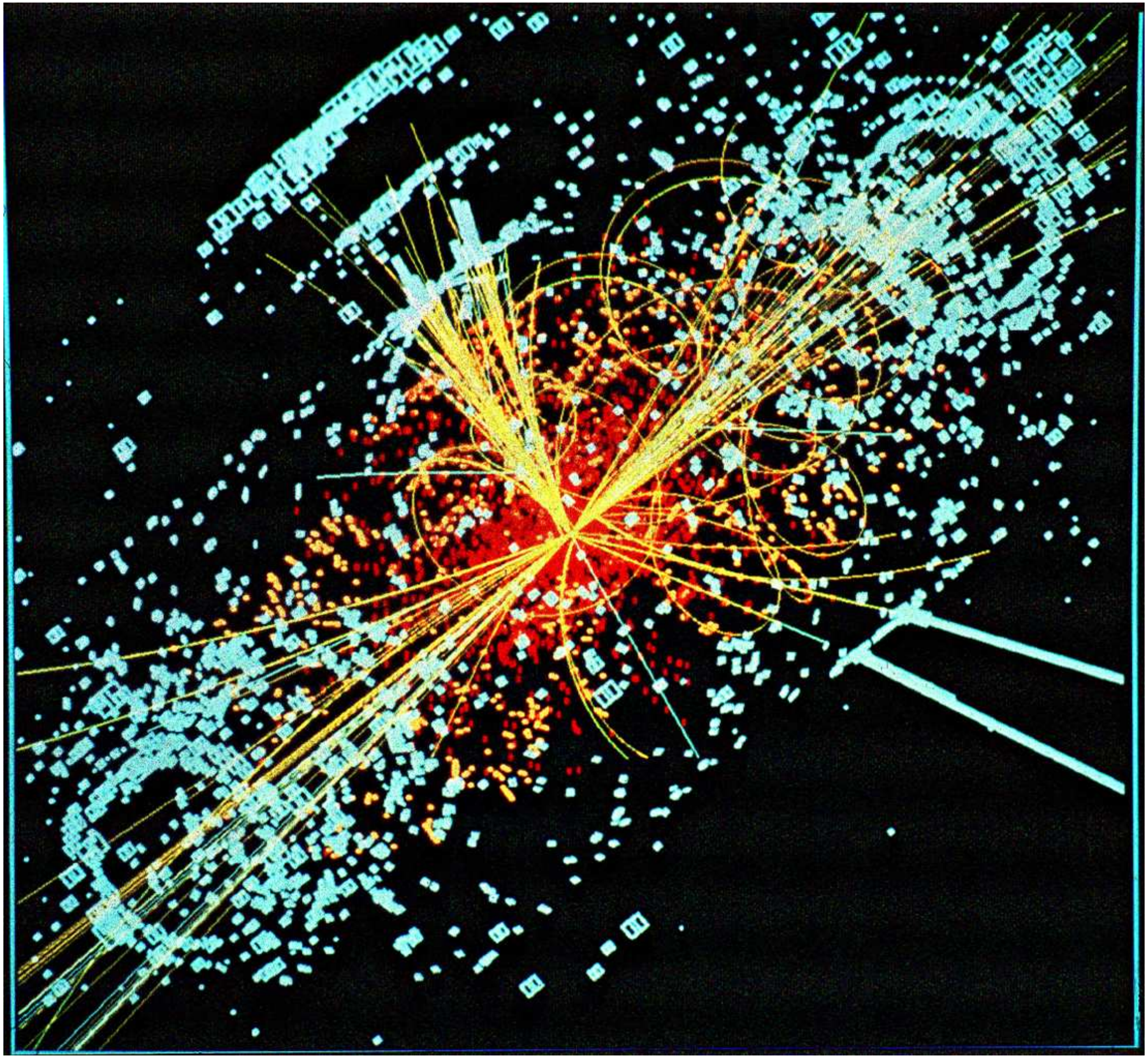
Largest (superconducting) solenoid:
diameter ~ 8 m, $B = 4$ Tesla

Proton bunches collide at 40 MHz (25 ns!)
(uud + uud) $\Rightarrow$ many hadrons
Each event contains 10-15 p-p interactions

Event filter: ≈ 4000 PC, 500 GBit/sec
Event storage: ≈ 10 PB data, 10 PB MC per year
Data handling: LHC Computing Grid

Signal: lepton or jet orthogonal to beam,
Larger mass easier to identify

Simulated H → ZZ → eeqq at CMS



SUSY search with CMS

Signal: Particles of SUSY pair $\longrightarrow$ fermion + lighter SUSY $\longrightarrow$ ... $\longrightarrow$ fermions + LSP

Fermion cascade with missing transverse momentum

$$\tilde{g} \longrightarrow \tilde{b}\,\bar{b} \longrightarrow \tilde{\chi}_2^0\,\bar{b}\,b \longrightarrow \tilde{\ell}^+\,\ell^-\,\bar{b}\,b \longrightarrow \tilde{\chi}_1^0\,\ell^+\,\ell^-\,\bar{b}\,b$$

Mass measurement: maximum of

$$M_{\mathrm{inv}}(\ell^+\,\ell^-) \Rightarrow M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$$

Measurements for all parameter values of all models??

Collaboration with theorists:
check benchmark points in parameter space

Given model and parameters $\Rightarrow$
quantitative prediction of SUSY properties
and reaction probabilities $\Rightarrow$
can be tested experimentally

SUMMARY

"There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

"There is another theory which states that this has already happened."

Douglas Adams: *The Restaurant at the End of the Universe*

SUMMARY

LHC starts in 2007 with low luminosity
We hope for discoveries from 2008
14 TeV collision energy is enough for everything:
Higgs boson(s), SUSY particles

For precise studies one needs e^+e^- collider:
International Linear Collider (ILC)

LHC design started before LEP construction
ILC plans are developing

ITER example is bad,
we must have a really International LC

SUSY models

A SUSY-sértés eredete ismeretlen:
– különböző modellek
– sok paraméter