WHAT DID WE LEARN FROM THE LEP MACHINE?

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- ♠ THE STANDARD MODEL (SM) IN BRIEF
- **A CONCISE RECORD OF THE LEP PROGRAM**
- **◇ CHECKING IN DEPTH THE VALIDITY OF THE SM**
- **♦ INDIRECT SEARCHES: WHAT DID WE "FEEL"?**
- **DIRECT SEARCHES: WHAT DID WE "SEE"?**
- **A FIRST APPROXIMATION OF A Z FACTORY**

LEP : Large Electron Positron Collider at CERN (1989–2000)

 $SLC : SLAC Linear Collider (e^+-e^-)$ in Stanford, now stopped

TEVATRON: proton-antiproton collider in FERMILAB, in operation (2 TeV)

LHC : proton–proton collider at CERN (14 TeV), planned for 2007

WE WILL TALK ABOUT "ELEMENTARY" CONSTITUENTS, LEPTONS AND QUARKS.

HOWEVER THE PARTICLES WE DETECT ARE LEPTONS AND HADRONS.

HADRONS ARE "BAGS" CONTAINING CONFINED QUARKS AND GLUONS.

WHEN A QUARK OR A GLUON IS PRODUCED IN A REACTION, IT DOES NOT APPEAR AS SUCH, BUT MANIFESTS ITSELF AS A JET OF PARTICLES.



THE COLLIDERS LIKE LEP OR LHC ARE ACTUALLY "MICROSCOPES" WITH A RESOLUTION POWER OF 10^{-3} TO 10^{-4} OF A FERMI.

A FERMI IS 10^{-13} CM, ABOUT THE PROTON RADIUS.



LEP AND LHC PERFORM SOME ARCHEOLOGY OF THE UNIVERSE, RECREATING AT A MICROSCOPIC SCALE THE PHYSICS WHICH PREVAILED AT $\sim 10^{-11}$ SEC AFTER THE BIG BANG.

Creation of the Universe





Colour (for quarks)

THESE FERMIONS APPEAR AS POINTLIKE DOWN TO OUR ULTIMATE RESOLUTION POWER OF 10⁻⁴ FERMI LEPTONS ARE FREE, QUARKS ARE CONFINED INSIDE HADRONS

The Zoo of particles is complex, but the principle of their interactions is simple



"Carrier of Force"

- Photon electromagnetic interaction
- W,Z weak interaction
- **Gluon** strong interaction

The interactions are described by Gauge Theories

Building blocks are mysterious, but interactions are simple



AN IDEA TO KEEP

** BESIDES EXISTING IN SPACE-TIME, THESE CONSTITUENTS LIVE THEIR LIVES IN OTHER SPACES, CALLED "INTERNAL".

** THE QUARKS DO SO IN THE COLOUR SPACE.

** FERMIONS DO SO IN THE WEAK ISOSPIN SPACE, WHERE THEY LIVE IN COUPLES OR DOUBLETS (IF LEFT-HANDED), AS BACHELORS OR SINGLETS (IF RIGHT-HANDED).

$$\dots \left(\begin{array}{c} \nu_{\mu} \\ \mu \end{array}\right) \dots \left(\begin{array}{c} c \\ s \end{array}\right) \dots \dots$$

- ** IN THESE SPACES, ONE CAN PERFORM "ROTATIONS", FOR INSTANCE TRANSFORMING A MUON-NEUTRINO INTO A MUON (ROTATION IN WEAK ISOSPIN SPACE) OR A BLUE QUARK INTO A RED QUARK ("ROTATION" IN COLOUR SPACE).
- ** THESE "ROTATIONS" OR SUBSTITUTIONS LEAVE THE PHYSICS INVARIANT.
- ** THESE OPERATIONS ARE PERFORMED BY THE BOSONS, EMITTED OR ABSORBED.

THE STANDARD MODEL IN BRIEF

- **A** IT IS THE MATHEMATICAL DESCRIPTION OF WHAT HAS JUST BEEN SAID IN SENTENCES.
- ♡ THE TITLE IS MODEST, BUT IT IS A REMARKABLE CONSTRUCTION WHICH ALLOWS TO COMPUTE VERY PRECISELY A GREAT NUMBER OF QUANTITIES
- ♠ THE SM IS VERY SUCCESSFUL: UP TO NOW IT HAS WITHSTANDED ALL CONFRONTATIONS WITH THE EXPERIMENT TO A PER MIL OR BETTER.
- IT RESTS ON TWO BIG PRINCIPLES:
 - 1. ITS FORMULATION IS INVARIANT WHEN ONE INTERCHANGES PARTICLES WHICH ARE A PRIORI DIFFERENT.
 - 2. THIS CAN ONLY BE DONE IN A COHERENT WAY IF ONE INTRODUCES THE REQUIRED BOSONS, WHICH WILL OPERATE THE ROTATIONS MENTIONED.

THE STANDARD MODEL IN BRIEF (CONTINUE)

- ** THIS GIVES A LOCAL INVARIANCE, NAMELY THE FREEDOM TO PERFORM ARBITRARY "ROTATIONS" IN EACH POINT OF SPACE-TIME. IT IS THE LOCALITY OF THE INVARIANCE WHICH GIVES ALL ITS POWER TO THE THEORY.
- ** UP TO THIS STAGE, AND HISTORICALLY THIS WAS THE CASE FOR LONG, THE SM IS A BEAUTIFUL CONSTRUCTION, BUT WHICH APPLIES ONLY TO MASSLESS PARTICLES.
- ** THIS WORLD IS DEFINITELY NOT OURS.
- ****** FORTUNATELY THERE IS A HAPPY END TO THE STORY.
- ** PARADOXICALLY, WHAT WILL SAVE THE MODEL IS THAT THIS FREEDOM WE REQUIRED AND ACHIEVED IS ACTUALLY DENIED BY SOME EXTERNAL CIRCUMSTANCES.

THE HIGGS MECHANISM IN BRIEF

AS WE SAW, THE FREEDOM OF PERFORMING "ROTATIONS" IN INTERNAL SPACES INDEPENDENTLY AT ANY POINT OF SPACE-TIME IS GRANTED PROVIDED YOU "INVENT" THE RELEVANT BOSONS.

HOWEVER THERE MAY BE SOMETHING IN NATURE WHICH REFUSES THIS FREEDOM.

FOR INSTANCE IN ELECTROMAGNETISM:

INSIDE A SUPERCONDUCTOR, THERE EXISTS A FIELD, THE FIELD OF COOPER PAIRS, BOSONS ACTING COHERENTLY, WHICH LOCKS THE PHASE OVER MACROSCOPIC DISTANCES.

THE FREEDOM OF ROTATING THE PHASE OF THE WAVE FUNCTION OF AN ELECTRON ARBITRARILY IN EACH POINT OF SPACE-TIME IS THUS LOST.

THE PHOTON REACTS TO THAT SITUATION: BY INTERACTING WITH THE FIELD OF COOPER PAIRS, IT GETS A MASS m

$\mathbf{m} \sim \sqrt{\mathbf{DENSITY} \, \mathbf{OF} \, \mathbf{COOPER} \, \mathbf{PAIRS}}$

THIS IS THE MEISSNER EFFECT: A MAGNETIC FIELD CANNOT PENETRATE THE SUPERCONDUCTOR BY A DISTANCE LARGER THAN $\sim 1/m$

THE HIGGS MECHANISM MIMICS SUCH A SITUATION

THE ASSUMPTION IS THAT, IN THE SPACE OF WEAK ISOSPIN, A FIELD, THE HIGGS FIELD, GIVES AN ORIENTATION AND SUPPRESSES THE FREEDOM TO ROTATE ARBITRARILY.

THE WEAK BOSONS REACT BY GETTING A MASS:

$$m M_W = 1/2 \, \, g \, \, v$$

$$\mathrm{M_Z} = 1/2 \; \sqrt{\mathrm{g}^2 + \mathrm{g'}^2} \; v = \mathrm{M_W} \; / \; \mathrm{cos} heta_\mathrm{W}$$

WHERE v is the vacuum expectation value of the higgs field. WITH g and g', it is the third basic entry of the SM and is EQUAL TO 246 GEV.

TO PERFORM ITS JOB THE HIGGS FIELD HAS TO BE A COMPLEX DOUBLET OF WEAK ISOSPIN. OF THE FOUR REAL COMPONENTS, THREE ARE "EATEN" BY THE W AND Z. THE SINGLE REMAINING ONE IS THE

HIGGS BOSON,

A LORENTZ SCALAR.

THE "HOW" OF THE HIGGS MECHANISM IN THE STANDARD MODEL: ONE CHOOSES (ARBITRARILY) A "MEXICAN HAT" POTENTIAL.

 μ^2 positive

 μ^2 negative

ENERGY ADDED BY THE HIGGS FIELD

 $\mathbf{E} = \mu^2 \ \Phi^2 + \lambda \ \Phi^4$ with λ positive.

WHAT LEP DID

LEP1: FROM 1989 TO 1995

THE MASS PRODUCTION OF THE Z^0 BOSON.

17 MILLIONS OF Z⁰ HAVE BEEN REGISTERED. THIS ALLOWED TO PERFORM WITH AN UNPRECEDENTED ACCURACY TESTS OF THE SM PREDICTIONS CONCERNING Z⁰ PROPERTIES AND DECAY MODES.

LEP200: FROM 1995 TO 2000

BY A GRADUAL INCREASE OF THE ENERGY, THE PRODUCTION AND STUDY OF W^+W^- PAIRS AND THE SEARCH FOR HIGGS BOSONS AND SUPERSYMMETRIC PARTNERS AT MASSES AS HIGH AS POSSIBLE, REACHING GENERALLY ~ 100 GEV.

LEP IS ALSO:

** THE WEB

- ** AN ULTRA–VACUUM OVER 27 KM : 10⁻¹¹ TORR, BY USING GETTER PUMPING
- ** SUPRACONDUCTIVITY ON A LARGE SCALE: RF CAVITIES, QUADRUPOLES, SOLENOIDS
- ** THE FIRST SYSTEMATIC EXPLOITATION OF MICROSTRIPS AND MICROPIXELS (~ 10 MICRON RESOLUTION) AT A COLLIDER
- ** THE MASSIVE USE OF SCINTILLATING CRYSTALS (BGO), PAVING THE WAY TO THEIR APPLICATION IN MEDECINE, ...
- ** A WORLDWIDE COLLABORATION OF \sim 1500 PHYSICISTS, FROM THE FOUR EXPERIMENTS COMBINING THEIR RESULTS, AND OF MANY THEORISTS

** ETC

. SPACE FOR ALL ELECTROWEAK ACCURATE MEASUREMENTS, THE ACHIEVEMENTS WERE BETTER, OFTEN MUCH BETTER, THAN FORESEEN. THIS IS DUE TO :

** THE OUTSTANDING PERFORMANCES OF THE MACHINE ** THE RELATIVE EASINESS OF LEP PHYSICS ** THE REDUNDANCY OF ALL EXPERIMENTAL PROCEDURES

** THE DEVELOPMENT OF NEW TECHNIQUES (SMALL ANGLE LUMINOMETERS, MICROVERTICES,...)

**** THE EXISTENCE OF FOUR DETECTORS**

**** THE HIGH QUALITY OF THEORETICAL ESTIMATES**

♠ ♠ FULL SECTORS OF PHYSICS, LIKE TAU PHYSICS AND B PHYSICS, WERE ABUNDANTLY COVERED : LEP WAS A FIRST APPROXIMATION OF A Z FACTORY, HENCE OF A TAU AND B FACTORY

THE SUPRACONDUCTIVITY

RF voltage (design and actual):

Beam energy follows available RF voltage...

Microvertex detectors at LEP (silicon strip)

BEAUTY DECAYING DIRECTLY TO STRANGENESS WITHOUT GOING THROUGH CHARM

A VERY EARLY AND CLEAR ANSWER FROM LEP:

THERE EXIST THREE FAMILIES OF FERMIONS AND ONLY THREE, AT LEAST WITH A VERY LIGHT NEUTRINO.

INTRODUCED IN THE BIG BANG MODEL THIS RESULT LEADS TO PREDICT 24 PERCENT OF PRIMORDIAL HELIUM IN THE UNIVERSE, WHICH IS THE OBSERVED VALUE.

A MODERN EPIC: THE MEASUREMENT OF THE Z^0 MASS AT LEP WITH AN ACCURACY OF 20 PPM.

ONE HAD TO TAKE INTO ACCOUNT THE TIDAL FORCE FROM THE MOON, THE LEVEL OF WATER IN THE LAKE AND THE TIMETABLE OF THE TGV!

 $\sin^2 \theta_W$

THE VARIOUS DETERMINATIONS OF THE W MASS:

THE DIRECT MEASUREMENT AT LEP HAS REACHED AN ACCURACY OF HALF A PER MIL.

HOWEVER THE INDIRECT ONE, THROUGH THE ACCURATE MEASUREMENT OF Z^0 OBSERVABLES AND M_{top} IS STILL MORE PRECISE, AND IN REASONABLE BUT NOT PERFECT AGREEMENT.

Summer 2002

	Measurement	Pull	(O ^{meas} –O ^{fit})/σ ^{meas}
			-3-2-10123
$\Delta \alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-0.24	•
m _z [GeV]	91.1875 ± 0.0021	0.00	
Γ _z [GeV]	2.4952 ± 0.0023	-0.41	-
$\sigma_{\sf had}^0$ [nb]	41.540 ± 0.037	1.63	
R _I	20.767 ± 0.025	1.04	
A ^{0,I} _{fb}	0.01714 ± 0.00095	0.68	-
Α _I (Ρ _τ)	0.1465 ± 0.0032	-0.55	-
R _b	0.21644 ± 0.00065	1.01	
R _c	0.1718 ± 0.0031	-0.15	•
A ^{0,b}	0.0995 ± 0.0017	-2.62	
A ^{0,c} _{fb}	0.0713 ± 0.0036	-0.84	-
A _b	0.922 ± 0.020	-0.64	-
A _c	0.670 ± 0.026	0.06	
A _l (SLD)	0.1513 ± 0.0021	1.46	
$sin^2 \theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.87	
m _w [GeV]	80.449 ± 0.034	1.62	
Γ _w [GeV]	2.136 ± 0.069	0.62	-
m _t [GeV]	174.3 ± 5.1	0.00	
sin ² θ _w (νN)	0.2277 ± 0.0016	3.00	
Q _W (Cs)	-72.18 ± 0.46	1.52	

-3 -2 -1 0 1 2 3

THE LEP IMPACT: IN THE PLANE OF TWO MUCH SIGNIFICANT ELECTROWEAK VARIABLES, ONE WENT FROM THE BIG ELLIPSE TO THE TINY ONE DURING THE LEP ERA.

THE LEP IMPACT: ZOOMING ON THE SMALL ELLIPSE, ONE SEES THAT THE INFORMATION COMES MOSTLY FROM THE Z⁰ LINESHAPE, THE WEAK MIXING ANGLE AND THE W MASS.

THE INFLUENCE OF M_{top} AND OF THE HIGGS MASS ON THE PREDICTION OF THE SM ARE INDICATED.

THE WW CROSS-SECTION

SHOULD ONE NEGLECT THE "SELF-INTERACTION" OF W BOSONS, ONE WOULD MISS THE OBSERVED CROSS-SECTION OF W PAIRS BY A HUGE AMOUNT.

THE ELECTROWEAK THEORY IS INDEED A NON-ABELIAN GAUGE THEORY.

THE QUANTUM WORLD IS HOWEVER MORE COMPLICATED AND MORE INTERESTING.

ALL EXISTING PARTICLES CAN PLAY A ROLE AS VIRTUAL STATES, EVEN IF, BY LACK OF AVAILABLE ENERGY, THEY ARE NOT PRODUCED IN THE FINAL STATE AS REAL ONES.

"LOOP" PROCESSES, LIKE THE ONE OF THE FIGURE, SLIGHTLY MODIFY THE MEASURED VALUES OF THE OBSERVABLES.

THIS HAS TWO CONSEQUENCES:

** ONE CAN GET INFORMATION ON PARTICLES TOO HEAVY TO BE "REALLY" PRODUCED, LIKE THE TOP AT LEP, AND THE HIGGS BOSON.

** CONSTANTS, LIKE COUPLINGS AND MASSES, ARE NOT CONSTANT, BUT DEPEND ON THE RESOLUTION POWER OF THE MEASUREMENT, HENCE FROM THE ENERGY SCALE.

THE MOST REMARKABLE AGREEMENT OF THE DIRECT (TEVATRON) AND INDIRECT (LEP AND OTHER ACCURATE MEASUREMENTS) DETERMINATIONS OF THE TOP MASS.

Top-Quark Mass [GeV]

EVOLUTION OF THE TOP MASS ALONG THE YEARS.

OPEN POINTS ARE LEP INDIRECT MEASUREMENTS, FULL ONES ARE TEVATRON DIRECT ONES.

Concept of Precision Measurements

Through accurate measurements get information about particles, even if they are too heavy to be produced in the final state Examples: top mass, Higgs mass ?

THE CHI2 DISTRIBUTION OF THE HIGGS MASS DEDUCED FROM INDIRECT MEASUREMENTS, IN THE FRAME OF THE SM.

UNFORTUNATELY THE INFORMATION IS ONLY LOGARITHMIC.

Summer 2002

COUPLING "CONSTANTS" ARE NOT CONSTANT!

MEASURED VERY ACCURATELY AT LEP SCALE, AND EXTRAPOLATED WITHIN A GIVEN THEORY, THEY CONVERGE: BUT THEY DO NOT MEET IN THE SM (BY 8 STANDARD DEVIATION), WHILE THEY DO MEET QUITE ACCURATELY IN AN EXTENSION OF THE SM CALLED SUPERSYMMETRY.

THIS IS A HINT OF A "GRAND UNIFICATION" AT $E = 10^{16}$ GEV, AND THAT SUPERSYMMETRY COULD BE A RELEVANT

Unification of the Coupling Constants in the SM and the minimal MSSM

0.1

2000 0.4 0.3 $\alpha_{s}(\mu)$ 0.2 R_{e*e}-0.1 e+e-jets

2

5

10

0.0└─ 1

History

0 10 100 Q(GeV) $\alpha_{\rm s}(M_{\rm Z}) = 0.11 \pm 0.01$

 $\alpha_{\rm s}(M_{\rm Z}) = 0.118 \pm 0.002$

μ (GeV)

20

50

100

200

Physics at LEPI (after Altarelli)

Particle Data Group 2000

SUPERSYMMETRY

♠ SUSY RESTORES THE SYMMETRY BETWEEN FERMIONS AND BOSONS, BY ASSOCIATING TO EACH KNOWN FERMION A BOSON AND VICE−VERSA.

♠ IT IS A BROKEN SYMMETRY.

♦ HOWEVER THE PARTNERS CANNOT BE TOO HEAVY (\leq 1 TEV).

♠ IN THE HIGGS SECTOR OF THE MINIMAL THEORY THERE IS A SHARP PREDICTION OF A LIGHT NEUTRAL BOSON OF MASS ≤ 130 GEV

♠ LEP HAS PERFORMED THE SEARCH OF ALL SUSY PARTNERS AND GAVE MASS LIMITS, USUALLY CLOSE TO 100 GEV.

♠ SUSY, IN ITS SIMPLEST VERSION, PREDICTS THE EXISTENCE OF A STABLE NEUTRAL LIGHTEST SUPERSYMMETRIC PARTICLE (LSP) WHICH IS A GOOD CANDIDATE FOR THE COLD DARK MATTER OF THE UNIVERSE. LEP HAS HOWEVER EXCLUDED THE EXISTENCE OF SUCH AN OBJECT UP TO A MASS OF 45 to 50 GEV.

THE "WHY" OF THE HIGGS MECHANISM IN THE SUPERSYMMETRIC SM: A SIMPLIFIED EXPLANATION

ONE CHOOSES A NORMAL POTENTIAL AT VERY HIGH ENERGY.

THE EVOLUTION WHEN THE ENERGY DECREASES IS SUCH THAT IT NATURALLY BECOMES MEXICAN HAT LIKE AT THE EW SCALE

THE CONDITION IS THAT THE TOP QUARK, DOMINATING THE FEATURE OF THIS EVOLUTION, IS HEAVY ENOUGH

ACTUALLY THE HIGGS SECTOR IS MORE COMPLICATED (TWO DOUBLETS, FIVE BOSONS) WITH HOWEVER AN INCONTOURNABLE PREDICTION IN THE MINIMAL MODEL:

ONE NEUTRAL BOSON AT LEAST IS LIGHTER THAN ~130 GeV.

PORTRAIT–ROBOT OF THE HIGGS BOSON

• IN THE STANDARD MODEL: FROM THE WAY IT WAS INVENTED, ONE KNOWS EVERYTHING ON THE HIGGS BOSON, EXCEPT ITS MASS.

♠ IT COUPLES PREFERENTIALLY TO THE HEAVIEST ACCESSIBLE PARTICLES AND THIS FACT DICTATES ITS PRODUCTION AND DECAY MODES.

THEORETICAL CONSIDERATIONS LEAD TO THE MASS RANGE $\sim 130~GEV~TO \sim 1~TeV.$

• IN MINIMAL SUPERSYMMETRY, A STRIKING PREDICTION IS THAT THE LIGHTEST NEUTRAL HIGGS BOSON IS LIGHTER THAN ~130 GEV . IT IS THUS A FALSIFIABLE THEORY.

AS AN EXAMPLE, A SM OR SM-LIKE BOSON OF 115 GEV IS PRODUCED AT LEP IN ASSOCIATION WITH A Z⁰ AND DECAYS TO BEAUTY-ANTIBEAUTY.

SHOULD WE EXPLORE OTHER POSSIBILITIES? YES, SURE. AND WE DO SO.

♠ THE HIGGS BOSON COULD BE "SPECIAL", FOR INSTANCE DECAYING INVISIBLY. THIS PARTICULAR CASE IS NOT A PROBLEM AT LEP....

THE HIGGS MECHANISM COULD LEAD TO SOMETHING ELSE THAN AN ELEMENTARY BOSON:

THE HIGGS BOSON COULD BE A COMPOSITE OBJECT THERE COULD BE NO HIGGS BOSON, BUT A CONTINUUM OF STATES INSTEAD!

♦ IN ANY CASE SOMETHING HAS TO BREAK THE ELECTROWEAK SYMMETRY!

FOR INSTANCE, NEW FERMIONS LINKED BY A NEW FORCE, COPIED, UP TO A CERTAIN EXTENT, ON THE COLOR FORCE: THIS IS CALLED TECHNICOLOR

THIS SCENARIO IS NOT PRESENTLY FAVOURED BY ACCURATE ELECTROWEAK MEASUREMENTS. HOWEVER WE HAVE LOOKED FOR IT. IN PRACTICE IT IS RATHER SIMILAR TO THE HIGGS SEARCH.

SM Mass plots medium S/B

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WHERE DO WE STAND?

♣ COMBINING THE DATA FROM THE FOUR LEP EXPERIMENTS, A LOWER BOUND IS SET ON THE HIGGS BOSON MASS, $M_{\rm H} \ge 114.4~GEV~AT~THE~95~\%$ CONFIDENCE LEVEL.

 ♡ A SLIGHT EXCESS IS OBSERVED, CONCENTRATED MAINLY IN THE DATA SETS WITH CM ENERGIES HIGHER THAN 206
 GEV: THE LIKELIHOOD TEST DESIGNATES THE RANGE FROM 115 TO 118 GEV
 FOR THE DEFERDED MASS, WHERE THE CONFIDENCE LEVEL

FOR THE PREFERRED MASS, WHERE THE CONFIDENCE LEVEL FOR THE SIGNAL PLUS BACKGROUND HYPOTHESIS IS 37 % WHILE THAT FOR THE BACKGROUND HYPOTHESIS IS 8 %.

♠ THIS DEVIATION FROM THE SM BACKGROUND IS MAINLY DRIVEN BY THE ALEPH DATA AND IS CONCENTRATED IN THE FOUR−JET FINAL STATE.

Events / 3 GeV/c² Events / 3 GeV/c² 12 $\sqrt{s} = 200-210 \text{ GeV}$ $\sqrt{s} = 200-210 \text{ GeV}$ 7 10 6 + LEP medium + LEP tight 5 8 background background hZ Signal hZ Signal 4 6 (m_h=115 GeV) (m_h=115 GeV) 3 >109 GeV >109 GeV all 4 cnd= 34 5 cnd= 18 4 2 bgd= 35.69 3.93 bgd= 13.97 1.21 sgl= 5.3 3.88 sgl= 2.9 2.21 2 1 0 0 120 20 40 80 100 60 0 20 **40** 80 100 60 120 Reconstructed Mass m [GeV/c²] **Reconstructed Mass m** [GeV/c²]

IN ORDER OF INCREASING SEVERITY OF CUTS

HOW TO GO BEYOND THE SM?

EXTRA DIMENSIONS

One scenario: SM particles confined to a 4-dimensional "wall" Only gravitons can propagate in the n extra dimensions of volume V^n . M_D is the Planck mass in 4+n dimensions. $M_{Pl}^2 \sim V^n M_D^{n+2}$

"DIRECT" DETECTION: REAL GRAVITON EMISSION

"INDIRECT" DETECTION: VIRTUAL GRAVITON EXCHANGE

Typically, M_D larger than ~ 1 TeV.

TOWARDS A GRAND UNIFICATION

THE USUAL WAY, IN SUPERSYMMETRY.

POSSIBILITY WITH LARGE EXTRA DIMENSIONS.

THE TAU IS "NORMAL", A MERE RECURRENCE OF ELECTRON AND MUON.

ITS MEASURED LIFETIME AND LEPTONIC BRANCHING RATIO AGREE WELL WITH WHAT THE SM PREDICTS, GIVEN ITS MASS.

MACHINES FROM THREE CONTINENTS WERE NEEDED TO GET THIS RESULT, WITH A HUGE IMPACT FROM LEP.

LEPTONIC RATIO (CORNELL, LEP)

MASS (FROM BEIJING)

LIFETIME (MOSTLY FROM LEP)

BEAUTY PHYSICS AT LEP1

THE Z⁰ WAS A WONDERFUL SOURCE OF BEAUTY-ANTIBEAUTY STATES (22 PERCENT OF THE TOTAL). THESE WERE GIVING TWO BACK-TO-BACK JETS, WITH A STRONG LORENTZ BOOST TO THE BEAUTY PARTICLE IN THE JET. ALL VARIETIES OB B PARTICLES WERE PRODUCED.

THE PROGRESS IN B PHYSICS WAS OUTSTANDING: EVIDENCE FOR NEW STATES, LIFETIMES MEASUREMENTS, STUDY OF BEAUTY-ANTIBEAUTY OSCILLATION, STUDY OF QUARK MIXING, ETC....

THE LIFETIMES OF INDIVIDUAL SPECIES HAVE BEEN ACCURATELY MEASURED: THEY AGREE FAIRLY, BUT NOT COMPLETELY, WITH THE HEAVY QUARK EFFECTIVE THEORY.

CONCLUSIONS

LEP HAS BROUGHT THE QUANTITATIVE TESTS OF THE STANDARD MODEL TO A HIGH LEVEL OF ACCURACY: NO DEVIATION IS OBSERVED WITHIN THAT ACCURACY.

IN SPITE OF QUITE RELEVANT LIMITS ON THE HIGGS MASS, THE BREAKING OF THE ELECTROWEAK SYMMETRY KEEPS ITS MYSTERY.

SUPERSYMMETRY, ALTHOUGH IT IS STILL AN HYPOTHESIS, COULD BE THE RIGHT IDEA.

THE TEVATRON, TO A LIMITED EXTENT, AND, AFTER 2007, THE LHC WILL BRING THE NEXT ANSWERS. LHC SHOULD TELL WHAT BREAKS THE ELECTROWEAK SYMMETRY AND WHETHER SUPERSYMMETRY IS A REALITY. LHC EXPERIMENTS ARE BUILT IN SUCH A WAY THAT THEY SHOULD NOT MISS SURPRISES.